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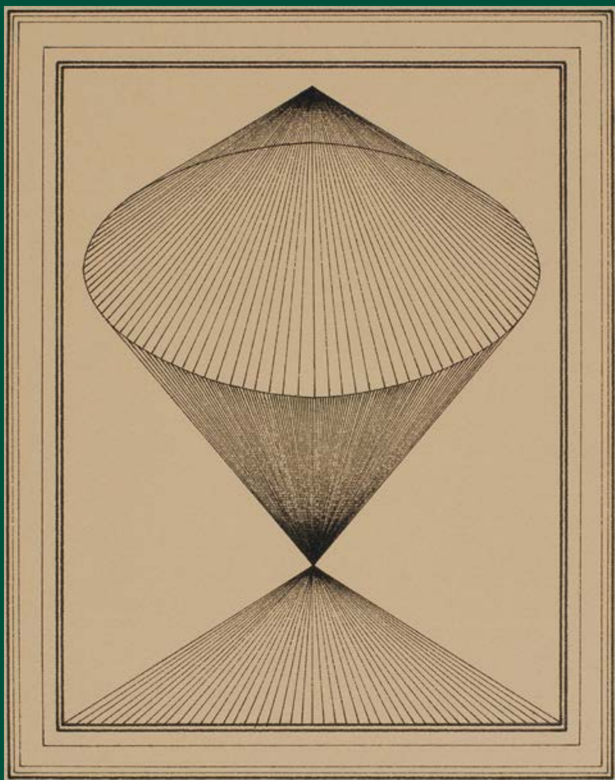
Colloquia

60 Years of Subnuclear Physics in Bologna



A cura di Luisa Cifarelli

Bononia University Press

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Accademia delle Scienze dell'Istituto di Bologna

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60 Years of Subnuclear Physics in Bologna

In Honour of Antonino Zichichi on the Occasion of his 90th Anniversary

Luisa Cifarelli Editor

Bononia University Press

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Premessa

Le storie generali di Bologna, anche le più recenti, hanno dedicato un modesto rilievo all'Università con il risultato di mettere in secondo piano uno degli elementi che le hanno conferito una dimensione e una fama internazionali. Gli studi dedicati in particolare al nostro ateneo hanno posto in evidenza la sua vita istituzionale, l'ingente presenza e la provenienza degli studenti da altre città e da altri paesi e l'eccellenza dei suoi maestri. Solo alcune indagini hanno sottolineato l'intensa attività scientifica che si è svolta per secoli nei suoi laboratori e nelle sue biblioteche. Per chi intende raccontare la vera storia della nostra università è decisivo intrattenersi a lungo e dettagliatamente su questo argomento. I pochi studi che vi si sono dedicati sono legati soprattutto alle numerose pubblicazioni che hanno accompagnato le celebrazioni del IX Centenario dell'Alma Mater, ma anch'esse si sono spinte raramente oltre la prima metà del ventesimo secolo. L'Accademia delle Scienze dell'Istituto non ha ritenuto di poter supplire a questa reticenza, o meglio, a questo timore della contemporaneità, ma non si è sottratta al compito di spronare i suoi dotti soci a riflettere su questo argomento e a promuovere piccoli colloqui dedicati esclusivamente alla ricostruzione dell'attività scientifica e alle sue connessioni con il contesto nazionale e internazionale senza per ciò trascurare i rapporti con le realtà istituzionali del territorio e le esigenze della vita quotidiana della nostra comunità.

Sono nati da questa esigenza e da questa disponibilità una serie di colloquia disciplinari che hanno ricapitolato esperienze, scuole e preziosi insegnamenti di maestri restituendo così l'ampia rete di connessioni e di relazioni che si sono sviluppate nel secondo dopoguerra e che hanno collocato l'ateneo bolognese tra i protagonisti della ricerca internazionale rendendo i suoi ricercatori portatori, non sempre consapevoli, di innovazioni delle quali oggi cogliamo ancora l'originalità e la fecondità.

I risultati di questi colloqui che hanno interessato la fisica, l'astronomia, la medicina, la biologia, la chimica, la geologia, l'economia e la statistica, l'ampia area delle discipline umanistiche e che proseguiranno con l'ingegneria, il diritto e le scienze politiche e sociali, saranno proposti al pubblico dei lettori in agili volumi che non intendono fornire una storia completa dello sviluppo della ricerca scientifica a Bologna quanto piuttosto mettere a disposizione materiali preziosi, vicende di maestri e dispie-garsi di scuole, memorie di imprese e di innovazioni sottratte all'oblio, indispensabili per chi vorrà cimentarsi nell'impresa più ampia di ricostruire la lunga sequenza di ricerche che ha dato una rilevanza planetaria all'Alma Mater Studiorum e della quale si avverte la mancanza.

Walter Tega
Presidente dell'Accademia delle Scienze dell'Istituto di Bologna

Foreword

The general histories of Bologna, even the most recent ones, have given limited emphasis to the University, thus overshadowing one of the cornerstones that have earned Bologna an international reputation. The studies dedicated in particular to our University have highlighted its institutional life, the huge number and heterogeneous origin of its students, coming from other Italian towns and other Countries and the excellence of its Teachers. Only few of these studies have underlined the intensive scientific work that has been taking place for centuries in its Laboratories and its Libraries. While if one wants to tell the real history of our University, it is highly important to dwell at length and in detail on this topic. The few existing texts on this subject are specially linked to the numerous publications that accompanied the celebrations of the IX Centenary of the "Alma Mater", but even these rarely went beyond the first half of the 20th century. The Academy of Sciences of the Institute of Bologna did not consider itself to be able to make up for this lack or better for this fear of contemporaneity, but could not avoid encouraging its erudite members to think about this topic, and to promote small colloquia exclusively dedicated to the reconstruction of the scientific activities and the resulting connections with the national and international contexts, without neglecting the relationships with the institutional organizations of the territory and the needs of the daily life of our community.

From the willingness to fulfil this demand a number of disciplinary colloquia have been organized to recall experiences, school methods and valuable lessons from Masters, making known the wide network of connections and relationships that have been established in the second post-war period and have contributed to position the University of Bologna among the main players of international research, and to make its scholars become the carriers, at times even unaware, of innovations of which today we still grasp the originality and fertility.

The results of these colloquia, concerning Physics, Astronomy, Medicine, Biology, Chemistry, Geology, Economy and Statistics, the wide area of the Humanities, followed by Engineering, Law, Political and Social Sciences, will be published for the interested readers as agile volumes that are not meant to provide a complete history of the scientific research development in Bologna, but rather a collection of valuable materials, stories of scholars and of the unfolding of schools of thought, memories of undertakings and innovations, subtracted from falling into oblivion, which are essential for all those who would like to take on the greater challenge to reconstruct the long sequence of research works which have given the Alma Mater Studiorum such a global relevance, and whose lack is deeply felt.

Walter Tega
President of the Academy of Sciences of the Institute of Bologna

Preface

This volume contains the proceedings of the International Symposium "60 Years of Subnuclear Physics in Bologna", which took place at the *Accademia delle Scienze dell'Istituto*, on November 7th, 2018.

The Symposium was organised by the Academy in collaboration with the Italian Physical Society (SIF), the "Enrico Fermi" Historical Museum of Physics and Study and Research Centre (Centro Fermi), the Italian National Institute of Nuclear Physics (INFN) and the University of Bologna.

It was meant to illustrate the achievements of the Physics Department of the University of Bologna and of the Bologna Unit of the INFN throughout the years in the major Italian and international laboratories with and without accelerators, and in space. It was focused on the scientific activities of one of the main actors of Italian Physics, Antonino Zichichi, past president of the INFN and Centro Fermi, emeritus professor at the University of Bologna.

In this volume, two eminent physicists of the past are first recalled, namely Giampietro Puppi and Bruno Ferretti, whose vision in the 1960s opened up new horizons in Subnuclear Physics. The road to INFN and the history of the INFN Unit of Bologna at the Physics Department of the University are then nicely illustrated.

Zichichi's achievements are presented as an exhaustive suite of past, present and future experimental searches and projects implemented at CERN, Geneva, at DESY, Hamburg, at the INFN Frascati and Gran Sasso Laboratories, and on the International Space Station. Results about very advanced time-of-flight technologies and the forward-looking ELOISATRON collider design and feasibility studies are also part of this review of his endeavours. Highlights on the current outreach initiative EEE (Extreme Energy Events – Science in the heart of the young), conceived and led by Zichichi, and promoted by the Centro Fermi, are another interesting contribution included herein.

The birth and success of the Erice International School of Subnuclear Physics, established by Zichichi in 1963, and of the ever flourishing EMFCSC ("Ettore Majorana" Foundation and Centre for Scientific Culture) are also recalled in this book.

Finally, the last part of the proceedings consists in two deep reflections, by Gerard 't Hooft and Antonino Zichichi respectively, about the future of our science.

In addition to the above, this volume is enriched by a note by Gerard ('t Hooft) in honour of his friend Nino (Zichichi) to celebrate his 90th birthday. It is a very enjoyable tribute that we are very glad to publish here as a most special introduction.

Luisa Cifarelli
President of the Italian Physical Society

In honour of Antonino Zichichi

*Gerard 't Hooft**

Modern science is a relatively new way for humanity to communicate discoveries accurately as widely as possible. Until well in the middle ages, it was thought that all wisdom came from antiquity, in particular the Greek scientists from several centuries BC. There seemed to be no need to improve any of the elements of the deep wisdom that had been found. This changed gradually; it started, perhaps, with Galileo Galilei, who noticed that careful observations do not always confirm what was thought to be eternal truths, and this turned out to be the case not only in physics, but also in mathematics, chemistry, biology, medicine, and other subjects of advanced knowledge. When investigators started to specialise, the body of all existing published knowledge quickly expanded.

* Institute for Theoretical Physics, Utrecht University, Utrecht, the Netherlands.

Exactly as in the biological evolution of species, scientists also evolved into different species, all with their own subjects of expertise. There are now many sub-disciplines in theoretical physics and in experimental physics. Indeed, this specialisation continues up to this day, to such an extent that only few intellectuals can oversee what is happening, where all these fragments of scientific knowledge are leading, and how humanity as a whole can continue to profit from the fact that many former mysteries of the physical world have been clarified.

Antonino Zichichi is one of these intellectuals[1]. He not only introduced several elementary improvements for instruments to detect elementary particles, but also thoroughly investigated the existing theories that are needed to explain the observations.

This put him in a unique position to serve humanity in different ways, apart from being a first-rate scientist:

i As an influential and inspiring narrator, he manages to popularise science and explain the scientific method to the public. It is of utmost importance to emphasise the role played by science for the well-being of the human race, uniting us, enhancing our peaceful coexistence, and enabling us to communicate. Our industries depend totally on science.

ii He makes big efforts to promote the construction of a "strongest possible" elementary particle accelerator by advertising this idea both to the public at large and to as many politicians as he can reach. Machines such as the ones he is thinking of, demand the most advanced scientific knowledge that exists, leading to huge spin-offs for other sciences, for use in medicine, and in our demands for safe energy production, among others.

iii He realises that Planet Earth is endangered in several ways. He initiated meetings to address the "Planetary emergencies", focusing on the developing nations that may be the most vulnerable to natural and man-made disasters of global dimensions.

iv As a devoted catholic, he writes books and articles to explain how to combine scientific understanding with religious beliefs. In the eyes of some of his colleagues he goes rather far in this, but it enables him to reach out to many religious people for whom the scientific messages are often difficult to understand.

[1] I do know another one, my grand uncle Frits Zernike: he discovered not only how to make phase differences in light visible for human eyes, but also managed to construct single-handedly a microscope with which he could demonstrate this revolutionary effect. This earned him a Nobel Prize in 1953.

v To many scientists, young as well as senior, Antonino Zichichi is known most for having established the Ettore Majorana Foundation and Centre for Scientific Culture in 1963. Since then, throughout the year, scientific meetings, workshops and schools take place in the small historic town of Erice, near his birth place Trapani, on the sunny island of Sicily. In particular, each year the International School of Subnuclear Physics is held. It is a unique meeting where theoreticians and experimental physicists meet to discuss their methods and findings that help us to figure out the laws of Nature that govern the world of the very tiniest particles of matter, and as such also controlled the shape our universe has taken. Researchers, teachers, philosophers and students all come together, and discuss their interest during long working days. Antonino is known for modifying the days of the week to whatever is needed for the interests of the school, but this was no impediment for inviting his great friend, Pope John Paul II, in Erice.

Science

He made numerous important contributions to help us understand the physics of the sub-nuclear world; I here just name a few:

In the early days there were diffculties understanding the way a conserved quantum number called 'strangeness' acts in the heavy mesons now called K^0, $\overline{K^0}$, K_L and K_S , and the baryonic particles that were observed. Antonino Zichichi helped to clarify the situation by observing the production of pairs of particles with opposite strangeness. Paul Dirac, whom he much admired, had predicted that every particle comes with an associated antiparticle. Zichichi observed the first example of 'antimatter', the antiparticle of the deuteron.

In a number of ways, he contributed to improving experimental techniques needed for accurate detection and determination of energetic subnuclear particles. Examples are his invention of a new technology for obtaining much higher precision in magnetic fields, more efficiency in detecting lepton-antilepton pairs, and the measurement of the time of fight of particles in the pico-second range. High precision measurements were made possible for the electric dipole moment and the magnetic moment of muons, and for the determination of the weak coupling strength, The latter was important to find out how the fundamental interactions change with energy, and to establish what is needed to obtain a theory where the different fundamental interactions merge into one. He went into the theories with supersymmetry, that postulate the existence of gaugino particles, and he emphasised that supersymmetry will be needed if we believe in grand-unified theories.

He also advocated that the flavour multiplets of quarks and leptons need a third generation of particles, and this lead to the suspicion that a heavy counterpart of the electron and the muon should exist. It was unfortunate that his experiment for detecting these heavy leptons with masses beyond a GeV had been performed at an e^+e^- collider whose energy was not enough, so that the opportunity for doing a Nobel Prize level investigation was missed. A new lepton was waiting for him to discover it, but its mass was too high: 1.777 GeV.

The principle of 'effective energy' originated from an observation by Zichichi's group when they compared different high energy interactions that all resulted in a multi-particle final state. If one considers a $p\,p$ initial state, one should consider the energy of the leading hadron emerging from the interaction, and subtract its energy from the total energy of the final, multi-particle state. This defines the 'effective energy' of the interaction, and that appears to function as a decisive parameter, to be used in the comparison with other strong interaction events with the same 'effective energy'. The need to do this when comparing different processes, is now suspected to be an important feature of the strong interactions involved.

The Large Hadron Collider (LHC) is presently the most powerful particle accelerator of the world. Already before it was designed and constructed, physicists became aware of the need to detect particles at very high energies when thousands of particles are created at very high rates, and determine their energies and identities as fast and accurately as possible. For this, Zichichi initiated the LAA project[2]. Modern electronics is now applied to measure very accurately the time-of-flight for a particle, the nature of the magnetic field that it traverses, and the shape of its trajectory. The Multigap Resistive Plate Chambers (MRPC) developed within the LAA Project are the basic ingredients of the particle identification system of the ongoing ALICE experiment at LHC to study very high-energy ion collisions, and of the EEE experiment to detect extreme energy cosmic-ray showers on ground, which is actually based on a network of MRPC telescopes extended all over Italy.

As always, Zichichi is thinking far ahead, such as the design properties of a machine that could be as large as 100 km and generate particles in the range of 100 TeV. He named his idea the 'ELOISAtron', or 'Eurasian LOng Intersecting Storage Accelerator', as it should be a completely international endeavour.

Scientific knowledge advances through the relentless efforts of thousands of scientists. Most of them have learned how to do the hard work, consisting of long calculations, they teach the established theories and methods to their students, and they write proposals, recommendations and reports. It sometimes seems that only few of them have the brilliance of insight and ideas, which help us to overcome the numerous obstacles. These are the scientists who are glorified with Nobel Prizes and the like. Zichichi

[2] LAA originally stood for 'Lepton Asymmetry Analyser', but this is now rarely mentioned.

knows how important it is to emphasise this process, and to keep the memories alive, so as to inspire young people. In his Erice Schools, many Nobel Prize winners and other scientists whose roles have become evident, are invited, and put on pedestals, as one can see in pictures taken at Erice of Isidor I. Rabi, one of the founders of CERN and of the Ettore Majorana Foundation, Tsung-Dao Lee and Paul Dirac, Piotr Kapitza, Kenneth Wilson, Laura Fermi (the late Enrico Fermi's wife) and many others[3]. But we should not forget the others. Often it is by their efforts that the original ideas and discoveries are being streamlined and simplified to such an extent that they become easy to digest for large crowds of students, and indeed also for the next generations of scientists, who continue to build our edifice of knowledge.

Professor Zichichi has reached the age of 90 years. He still seems to be a youthful maverick expressing his strong ideas. Times are continuously changing, but Antonino has stayed as he was, a constant beacon defending pure and original scientific thinking.

[3] These pictures are also included in this volume (see pp. 143-148).

Ferretti, Puppi and the discovery which opened up new horizons in Subnuclear Physics

Antonino Zichichi[*]

Bruno FERRETTI	→	(Space-Time) → QED (J.A. Wheeler)
Giampietro PUPPI	→	Triangle → QFD Another Fundamental Force (E. Fermi)
Today	→	Gravitational Waves (7 = 6 + 1) Higgs boson
As celebrated in this Symposium promoted by Walter TEGA	→	The greatest discovery of the 20th Century: Subnuclear Physics.

1. Bruno Ferretti

Bruno Ferretti interest was on the problem of how a **Fundamental Force of Nature** (QED) "**comes into being**" from Space-Time. This problem, after many decades, is still **not solved**.

Let me quote **John A. Wheeler** (1977) [1]: On page 11 he writes: *"It is preposterous to think of the laws of physics as installed by a Swiss watchmaker to endure from everlasting to everlasting... The laws must have come into being".* The mechanism of how *The laws must have come into being* should indeed be studied. It was a problem in the discussions with Patrick Blackett and his friend Bertrand Russell [2], in the fifties. After many decades it

* University of Bologna and INFN, Bologna, Italy; CERN, Geneva, Switzerland; Enrico Fermi Centre, Rome, Italy; Pontifical Academy of Sciences, Vatican City; World Federation of Scientists, Beijing, Geneva, Moscow, New York; Ettore Majorana Foundation and Centre for Scientific Culture, Erice, Italy.

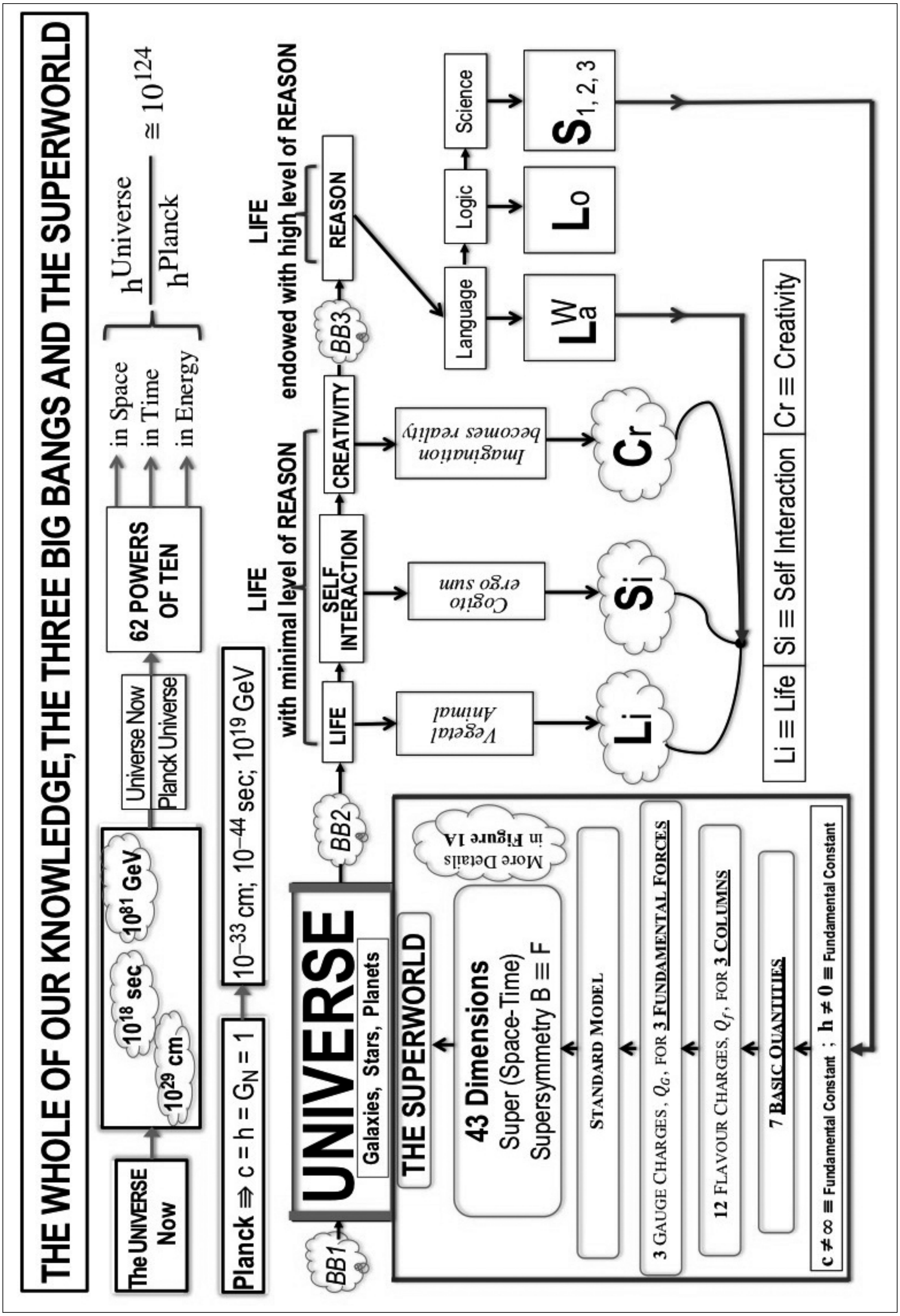

THE WHOLE OF OUR KNOWLEDGE, THE THREE BIG BANGS AND THE SUPERWORLD
The UNIVERSE Now
10^{29} cm
10^{18} sec
10^{81} GeV
Universe Now
Planck Universe
62 POWERS OF TEN
in Space
in Time
in Energy
$\frac{h^{Universe}}{h^{Planck}} \cong 10^{124}$
Planck ⇒ c = h = G_N = 1
10^{-33} cm; 10^{-44} sec; 10^{19} GeV
BB1
UNIVERSE
Galaxies, Stars, Planets
BB2
LIFE
with minimal level of REASON
LIFE
SELF INTERACTION
CREATIVITY
BB3
LIFE
endowed with high level of REASON
REASON
Vegetal
Animal
Cogito ergo sum
Imagination becomes reality
Language
Logic
Science
Li
Si
Cr
L_a^W
L_o
$S_{1, 2, 3}$
Li ≡ Life
Si ≡ Self Interaction
Cr ≡ Creativity
THE SUPERWORLD
More Details in Figure 1A
43 Dimensions
Super (Space-Time)
Supersymmetry B ≡ F
STANDARD MODEL
3 GAUGE CHARGES, Q_G, FOR 3 FUNDAMENTAL FORCES
12 FLAVOUR CHARGES, Q_f, FOR 3 COLUMNS
7 BASIC QUANTITIES
c ≠ ∞ ≡ Fundamental Constant ; h ≠ 0 ≡ Fundamental Constant

Figure 1

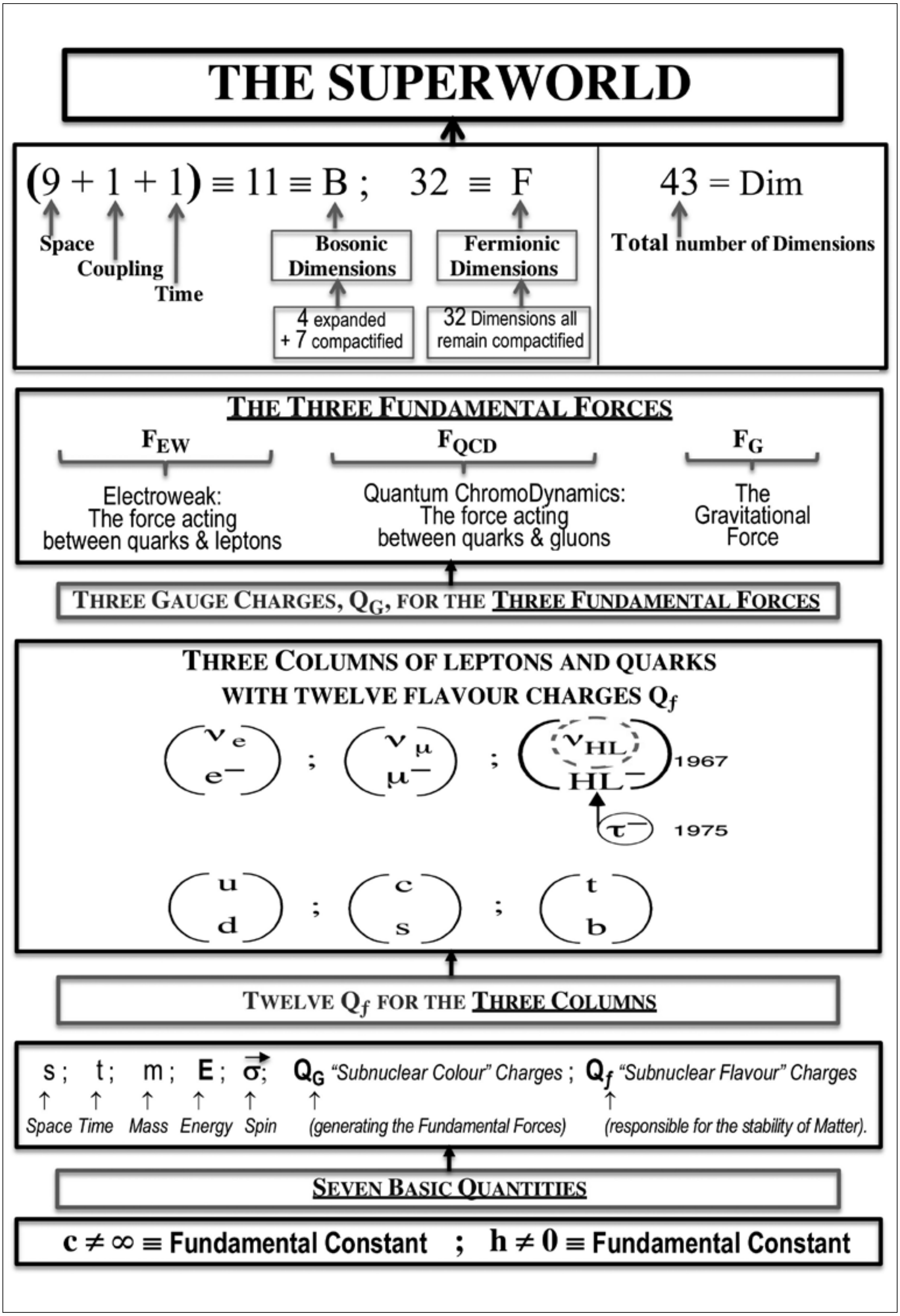

THE SUPERWORLD
(9 + 1 + 1) ≡ 11 ≡ B ; 32 ≡ F
Space
Coupling
Time
Bosonic Dimensions
4 expanded + 7 compactified
Fermionic Dimensions
32 Dimensions all remain compactified
43 = Dim
Total number of Dimensions
THE THREE FUNDAMENTAL FORCES
F_EW
Electroweak: The force acting between quarks & leptons
F_QCD
Quantum ChromoDynamics: The force acting between quarks & gluons
F_G
The Gravitational Force
THREE GAUGE CHARGES, Q_G, FOR THE THREE FUNDAMENTAL FORCES
THREE COLUMNS OF LEPTONS AND QUARKS
WITH TWELVE FLAVOUR CHARGES Q_f
ν_e e⁻ ; ν_μ μ⁻ ; ν_HL HL⁻
1967
τ⁻
1975
u d ; c s ; t b
TWELVE Q_f FOR THE THREE COLUMNS
s ; t ; m ; E ; σ ; Q_G "Subnuclear Colour" Charges ; Q_f "Subnuclear Flavour" Charges
Space Time Mass Energy Spin (generating the Fundamental Forces) (responsible for the stability of Matter).
SEVEN BASIC QUANTITIES
c ≠ ∞ ≡ Fundamental Constant ; h ≠ 0 ≡ Fundamental Constant

Figure 1A

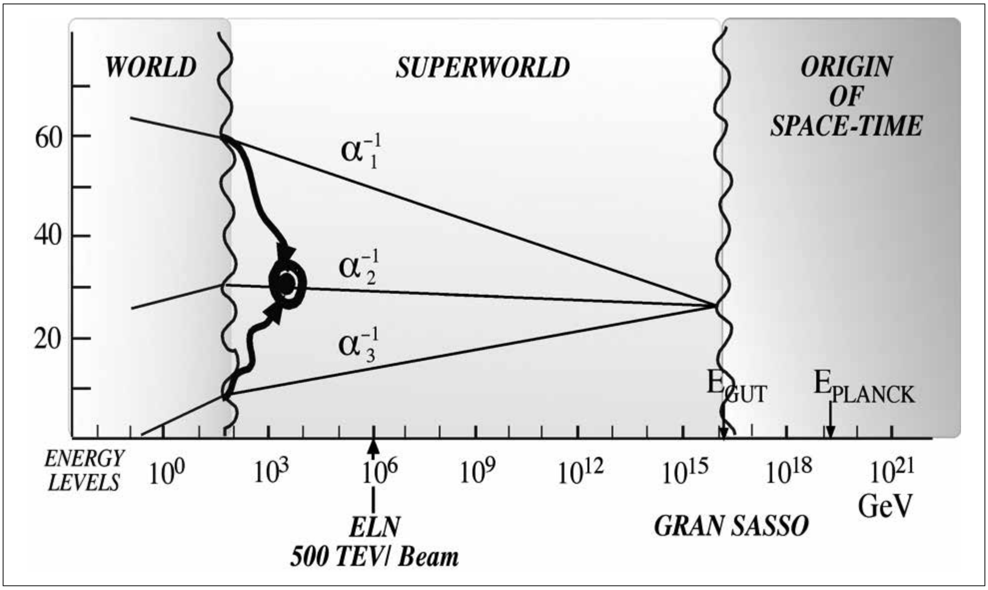


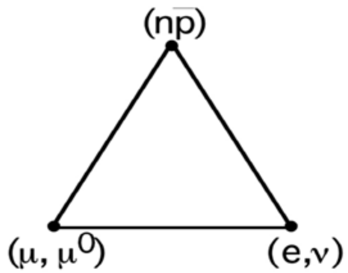
Figure 2

has been abandoned, since no one has been able to contribute towards a description of how the fundamental forces ***come into being***. On page 11 Wheeler continues: *"Therefore they could not have been always a hundred percent accurate. That means that they are derivative, not primary"*. And on page 44: *"Of all strange features of the Universe, none are stranger than these: time is transcended, laws are mutable, and observer-participancy matters"* [1].

Conclusion: The problem is now much more difficult: How QED + QFD + QCD *come into being* especially if Space-Time has 43 dimensions (**Superworld**).

2. Giampietro Puppi: The Puppi Triangle

In his paper "Sui Mesoni dei Raggi Cosmici" (*Nuovo Cimento*, 5, 1948, 587) G. Puppi suggests that all Fermi processes could be described by the same coupling. In fact the decay rates of three different processes (π decay), (μ capture) and (μ decay) were found to be "approximately" the same. This is the origin of the Puppi Triangle



where the three vertices allow, through their couplings, to describe all weak processes known at that time. Note that Puppi distinguishes the neutral counterpart of the muon, μ_0 (now known as ν_μ), from the neutral counterpart of the electron ν (now called ν_e). The existence of a second neutrino, *i.e.* $\nu_\mu \neq \nu_e$, was established in 1962 by L.M. Lederman, M. Schwartz, J. Steinberger and Collaborators at BNL [3]. The universality of the Fermi interactions attracted the interest of eminent physicists [4, 5, 6].

Enrico Fermi quoted the Puppi Triangle as a fundamental evidence for the existence of a new Fundamental Force: The Weak Interaction.

As celebrated in this Symposium promoted by Walter Tega: The greatest discovery in the 20th Century is QED, QFD, QCD.

QED → High precision $(g–2)_\mu$ (magnet)
QFD → High precision g_F
QCD → Confinement (no quarks at the highest energy (ISR))
Universality (Effective Energy)
Leading Effect.

Without QED, QFD, QCD → Subnuclear Physics neither the Gravitational Waves nor the Higgs Boson could have been discovered.

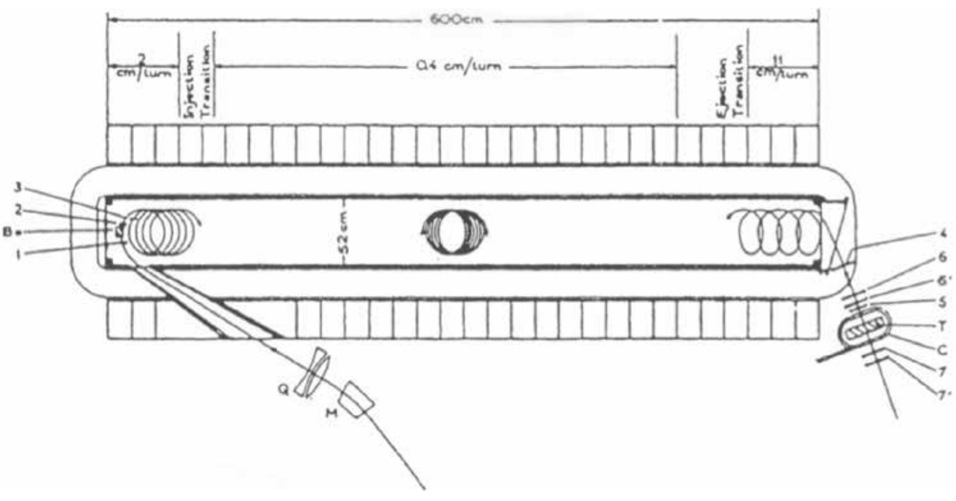


Figure 3: General plan of the 6-metre magnet. *M*: bending magnet; *Q*: pair of quadrupoles; 1, Be, 2, 3: injection assembly consisting of Be-moderator and counters 1, 2, 3; *T*: methylene-iodide target; counters 66′, 77′: "backward" and "forward" electron telescopes. A stored and ejected muon is registered as a coincidence 4, 5, 66′ $\bar{7}$, gated by a 1, 2, 3 and by either a forward or backward electron signal.

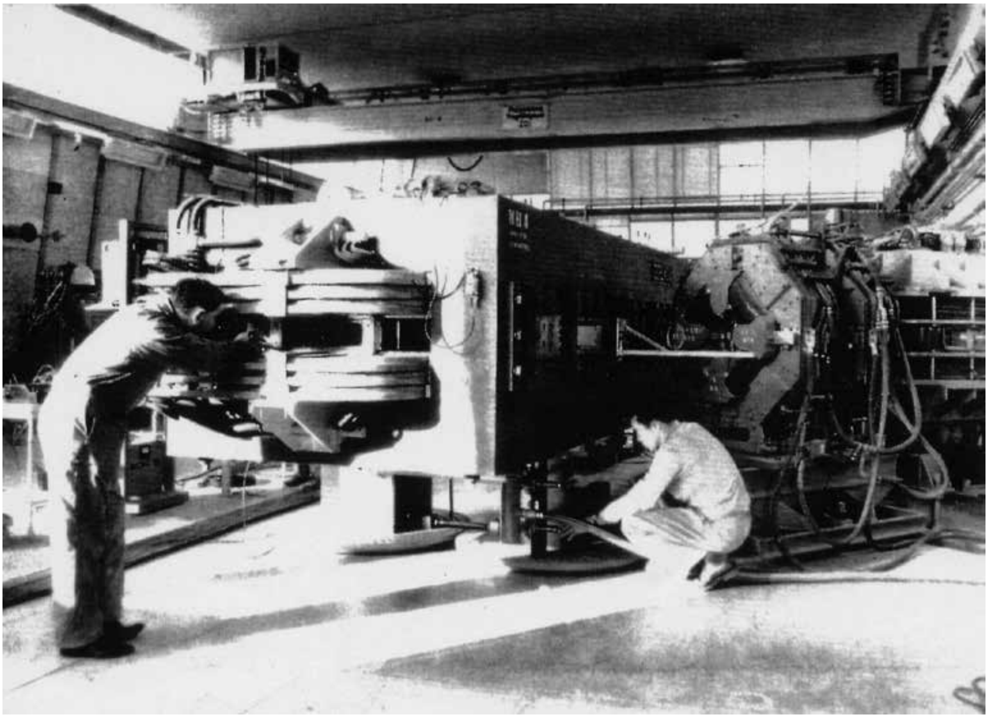
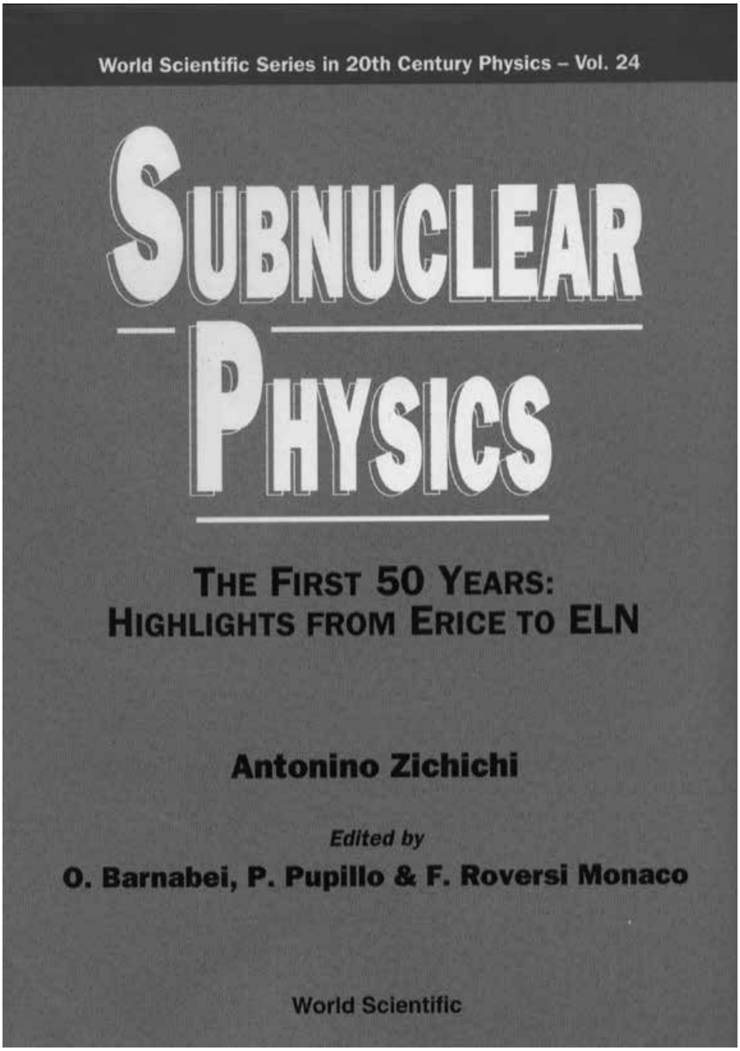


Figure 4: A photo of the six-metre "flat-magnet" where a sequence of high-precision magnetic fields has been implemented using what Feynman liked to call the "trick" of the "shimming technology".

Strong	EM	Weak
$\pi\, p$	$\gamma\, p$	$\nu\, p$
$K\, p$	$e\, p$	
$p\, p$	$\mu\, p$	
$p\, n$	e^+e^-	
$\bar{p}\, p$		



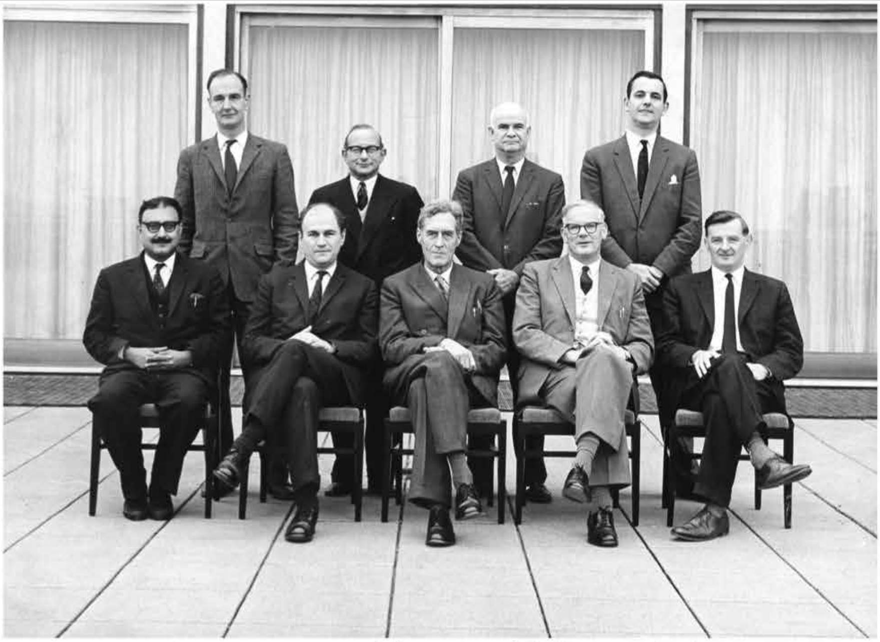
3. Ferretti and Puppi

Ferretti and Puppi were totally supporting the **idea** that a **New Universe** based on the "strange" quantum number **had to exist**.

What about **Enrico Fermi** criticism on the absence of ⊕ & ⊖ Strangeness for the same particle?

The answer had to be in the **experimental observation** of the same particle having

$$\left\{\begin{array}{c}\textbf{Positive}\\ \textbf{\&}\\ \textbf{Negative}\end{array}\right\} \qquad \left.\begin{array}{l}\textbf{Strangeness}\\ \textbf{Quantum}\\ \textbf{Number}\end{array}\right\}$$



(Picture courtesy of the Imperial College London)
Back row left:
Prof. P.T. Matthews, Prof. M. Blackman, Prof. J. McGee, Prof. Sir J. Mason
Front row left:
Prof. A. Salam, Prof. C.C. Butler, Lord P.M.S. Blackett, Prof. W.D. Wright, Prof. H. Eliott

Photo 4

G.D. James did not answer Gell-Mann's objection. In my broken English I said that at production $(10^{-23}\ \text{sec})$ the θ^0 has $s = \mathbf{+1}$ but, according to the most recent developments of our understanding of the physics of strange particles, the heavy meson θ^0, later becomes a mixture of a meson with $s = \mathbf{+1}$, θ^0, and an antimeson, $\bar{\theta}^0$, with $s = \mathbf{-1}$: $(\theta^0 \pm \bar{\theta}^0)$. Due to my broken English, no-one really understood what I was saying. The chairman realized that I was defending the "discovery" and said: "Could you please come to the blackboard." This gave me the chance to be understood by everybody since I was using equations not words, and the conclusion was me writing the correct reaction

$$\boxed{\bar{\theta}^0 + n \rightarrow \Lambda^0 + \pi\,,}$$

where the "strangeness" quantum number s was indeed conserved, since it was **–1** for the $\bar{\theta}^0$ and for Λ^0, and **zero** for the other two particles n and π.

In just a few minutes, from being a totally unknown fellow, I became the most famous physicist of the conference. Few words on the discussion. "The only difficulty" I said "is that there was no experimental evidence for the production of heavy mesons with positive and negative strangeness." This was a top-priority challenge in order to overcome the Enrico Fermi criticism against the "strangeness" quantum number. In fact, the introduction of this new quantum number in the description of the fundamental properties of the nucleon and of the meson (pion) was destroying their spectacular property: the nucleon is a fermion in Lorentz-Space-Time and is also a fermion in the intrinsic-space (isospin) (see "*Fermions and Bosons*", Appendix 4); the meson (pion) is a boson in Lorentz-Space-Time and also a boson in the intrinsic-space (isospin). The isospin-space was the new frontier of physics and its close link with the Lorentz-Space-Time was extremely interesting. This link gave the result that fermions must be isofermions and bosons must be isobosons.

This was the status of particle physics at that time, as recalled by Gell-Mann in his 80th Anniversary Celebration Lecture [6]. The physicists of that time really liked this spectacular property of mesons and nucleons, since it allowed the establishment of a very interesting connection between the intrinsic property (fermionic and bosonic) in Lorentz-Space-Time and in the isospin-space. No one had the slightest idea that many years later the "no-go" Theorem of Coleman and Mandula would have been discovered [7] and that with the discovery of Supersymmetry [8] (see "*Supersymmetry and Superworld*", Appendix 5), fermions and bosons would have been put on an equal basis, thus opening the new horizon for the existence of the Superworld [9]. Let me recall some of the theoretical achievements which originated in the discovery of Supersymmetry, i.e. the discovery of Supergravity [10] and of the M–theory [11]. Unfortunately, the Superworld is still missing direct experimental evidence for its existence [12].

Going back to 1947, in addition to the "destructive" power of the so much wanted connection between the Lorentz-Space-Time and the intrinsic space properties, there was another fundamental objection for the existence of the "strangeness" quantum number to be additively conserved. If a new quantum number, called "strangeness", really exists, it cannot be **+1** for the heavy meson θ^0 and **–1** for the neutral baryon Λ^0. The two opposite values of a quantum number **±1** must belong to the same particle/antiparticle state.

It cannot be (**+1**) for a particle which is a heavy meson, and (**–1**) for another particle which is a baryon. This assignment was based on the experimental discovery of the associated production of two V^0s, identified to be a baryonic event ($\Lambda^0 \rightarrow p\pi^-$) and a heavy mesonic event ($\theta^0 \rightarrow \pi^+\pi^-$).

What was needed was the experimental proof of pair production of heavy mesons with positive and negative strangeness, as it happens with the pair production of (e^+e^-) discovered by Blackett in 1932. This was my conclusion of the discussion session (**Photo 5**).

Photo 5: A.Z. and Murray Gell-Mann talking about heavy mesons with positive and negative strangeness.

After the 1955 conference, Professor Blackett asked me if I was interested in participating in a competition to join his group. This is how I became the youngest member of his group. My top priority was to study **the photos**, taken by the Blackett group at the Jungfraujoch Lab (3,580 meters a.s.l.).

II-2 – HOW IT COULD HAPPEN THAT – FEW YEARS AFTER CERN WAS ESTABLISHED – THE DISCOVERY NEEDED FOR THE EXISTENCE OF THE "STRANGE" CHARGE WAS OBTAINED

It took me two years (from 1955 to 1957) to find two photos, where the pair production of heavy mesons (whose name from θ became K), with positive and negative strangeness, was experimentally proved to exist [5]. This was the first discovery at CERN, founded in 1954.

The front page of the paper [5] is reproduced in **Figure 2**.

Examples of the Production of $(K^0, \overline{K}^0)$ and $(K^+, \overline{K}^0)$ Pairs of Heavy Mesons.

W. A. COOPER, H. FILTHUTH, J. A. NEWTH, G. PETRUCCI, R. A. SALMERON and A. ZICHICHI

C.E.R.N. - Geneva

(ricevuto il 14 Gennaio 1957)

Summary. — Two simple nuclear interactions that produce pairs of K-mesons are described and discussed. They are interpreted as examples of the processes $n + p \rightarrow K^0 + \overline{K}^0 + n + p$ and $n + p \rightarrow K^+ + \overline{K}^0 + n + n$ where $\overline{K}^0$ is the anti-particle of the K^0-meson.

Conclusion.

We interpret our observations, therefore, as being examples of $(K^0, \overline{K}^0)$ and $(K^+, \overline{K}^0)$ pairs produced in elementary neutron-proton interactions.

Figure 2

We will see in Chapter II-3 that Blackett was the first physicist who started to work with Wilson-chambers electronically triggered.

In the Jungfraujoch photos, there was a lot of physics to be found. In the photos taken at the Cervinia Lab (3,480 meters a.s.l.) it was very rare to find an interaction that produced many particles. How do you explain this?

Professor Blackett was the author of the *Electronic Trigger System with threshold Energy* at the level of at least ten GeV:

$$\boxed{E^{Cosmic}_{Rays}\ Interaction \quad \geq 10\ GeV.}$$

The Cervinia Trigger was at an energy level ten times lower E $\gtrsim$ 1 GeV.

This is why the photos taken at Cervinia had very little physics in. We will see in Chapter III-3.1 that at CERN also a discovery in the Physics of high precision was achieved thanks to the invention of a new technology able to allow the construction of a series of magnetic fields hundreds times cheaper and hundreds times faster to produce than all know technologies.

When a new laboratory is proposed the target is always along three lines of research: new physics, new high precision measurements of fundamental quantities, and new technological inventions.

This could be achieved in the new institution called CERN, in few years, thanks to Blackett, Bohr and Rabi. They are the authors of the fundamental actions in establishing CERN. They wanted to give this new institution a scientific component, in order to have, from the very beginning, a strong presence of Science in addition to administrative structures to avoid the invasion of bureaucratic powers in a scientific institution. Rabi, whose role was essential since he was the scientific advisor of the USA President, was convinced that this was a fundamental property (**Photo 6**). The official date for the existence of CERN is 1954 but the correct time should be one year before since it is in 1953 that Rabi convinced Dwight Eisenhower, the USA President, that the scientific activity of the new Europe emerging after the 2nd World War had to be encouraged by the USA.

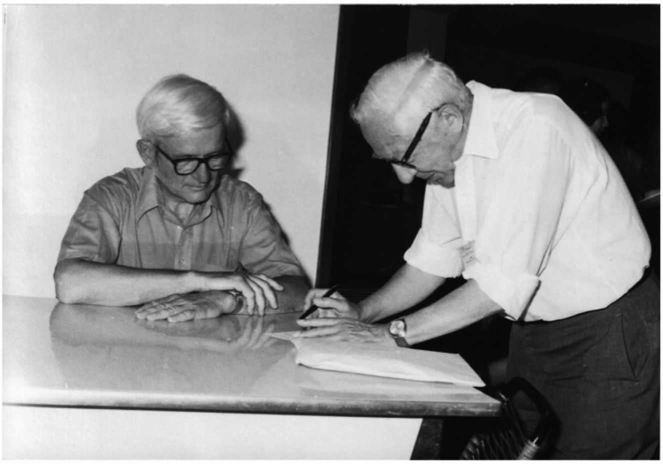


Photo 6: Rabi (Erice 1973) with his former student Norman Ramsey while preparing a lecture on the origin of CERN to celebrate the 20th anniversary.

Blackett offered his cosmic ray group, which was the most powerful in the world. Bohr who was responsible for getting the support of the Scandinavian Countries, considered the scientific activity for CERN a vital condition to start with. The results of the Blackett, Bohr and Rabi "*vital condition*" are in the Figure below (**Figure 3**).

THE RESULTS OF THE BLACKETT, BOHR AND RABI "*VITAL CONDITION*" FOR CERN

1 – **New Physics**: the discovery of pair production of heavy mesons with positive and negative "strangeness" (Chapter II-2).

2 – **High Precision Physics**: the anomalous magnetic moment of the muon (Chapter III-3.1).

3 – **The invention of a new technology** for the construction of polinomial magnetic fields (Chapter III-3.2).

4 – **The 1st proof that CERN could compete** with well established famous Labs and win (Chapter III-3.3).

Figure 3

Before going on to the next chapter a synthesis of the 1947 events, where from all started is given in **Figure 4**.

1947 – The end of my studies at the pre-university level.

1947 Great achievements in Physics

① **Virtual Physics** – Lamb–shift [13]: *unpredicted but needed since it was the simplest example of virtual phenomena discovered by Blackett* ***in 1932*** *with the "vacuum polarization"* [14, 15, 16]

② **The Nuclear glue** – π–meson [17]: *very much wanted as being the missing nuclear glue*

③ **The V–particles** [18]: *unpredicted with enormous consequences started with the new quantum number called strangeness*

Figure 4

1948 + **5** ≡> **1953** End of my university studies.

1955 ≡> The youngest member of the Blackett group.

1957 ≡> Discovery of pair production of heavy mesons with s = ±1.

Thanks to Blackett, the same research group was involved successfully in the three great achievements of **1947**: **Virtual Physics**, **Nuclear Glue and the V–particles**, the most spectacular **being the V–particles**, as we will see in Chapter III-1.

4. The role of Science in the Culture of our Time

This Culture was until the (3/4) of the 20th Century ***1% Modern and 99% Pre-Aristotelic.*** **Proof.** The Great Discovery of **Nuclear Fission** was given as the proof that **Science** produces weapons **10^6 times** more powerful than all known weapons.

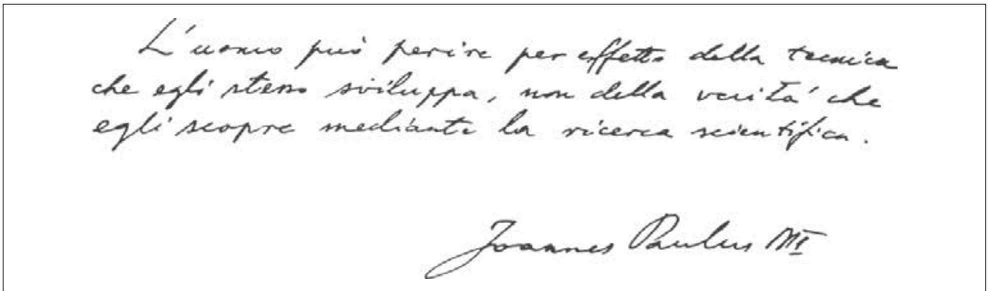
No Heads of State, No Political Leaders had the courage and the intellectual power of **defending Science**.

John Paul II is the Pope who **has *revived* Science** and **Scientific Culture**.

• Science ≠ Technology
• Hiroshima & Nagasaki

• Science and Faith Gift of God
• cm, gr, sec
• c, h, G_N

The **use** of Science **is no Science but Technology**.



L'uomo può perire per effetto della tecnica che egli stesso sviluppa, non della verità che egli scopre mediante la ricerca scientifica.

Joannes Paulus II

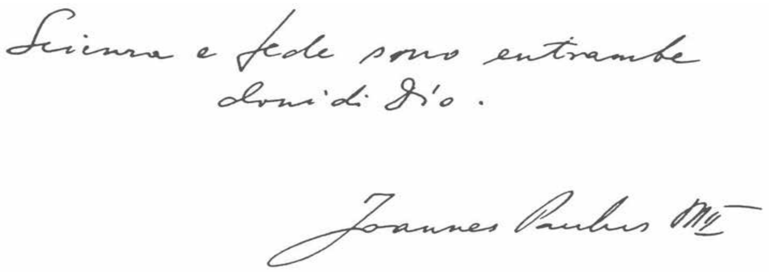
«Man could perish from the effects of technology
that he himself develops, not from the truth that he discovers
by means of scientific research».
To defend science from the attacks of prevailing culture.

The Modern Culture has to distinguish Science from Technology.

«The use of Science is not anymore Science; this is why Technology
could either be beneficial or harmful to life's values and human dignity».

SCIENCE AND TECHNOLOGY:
to distinguish between major scientific discoveries and military technologies, unbridled industrialisation and genetic manipulation.

What about the values of Science?


Scienza e fede sono entrambe doni di Dio.

Joannes Paulus PP II

«Science and Faith are both gifts of God».
To open the doors of the Church to Science.

John Paul II brought Science and its values to the same level as the Faith.
What about the Proof?

Before John Paul II the basic structure of **Fundamental Units** were:

cm	→	for Space (length)
gr	→	for mass-energy
second	→	for Time

After the *rebirth* of Science the Fundamental Units are:

$c \equiv$ The velocity of light
$h \equiv$ Planck's Constant
$G_N \equiv$ Newton's Constant

The three quantities which never change with Time. For these Units it is as if Time did not exist. These quantities govern the **Logic** of the Universe (from the Subnuclear to the one made of Stars and Galaxies). From this **Units** the following values come

10^{-33} *cm*
10^{-5} *gr*
10^{-44} *sec*

These values are in the **Evolution of the Universe** from the first instant to now.

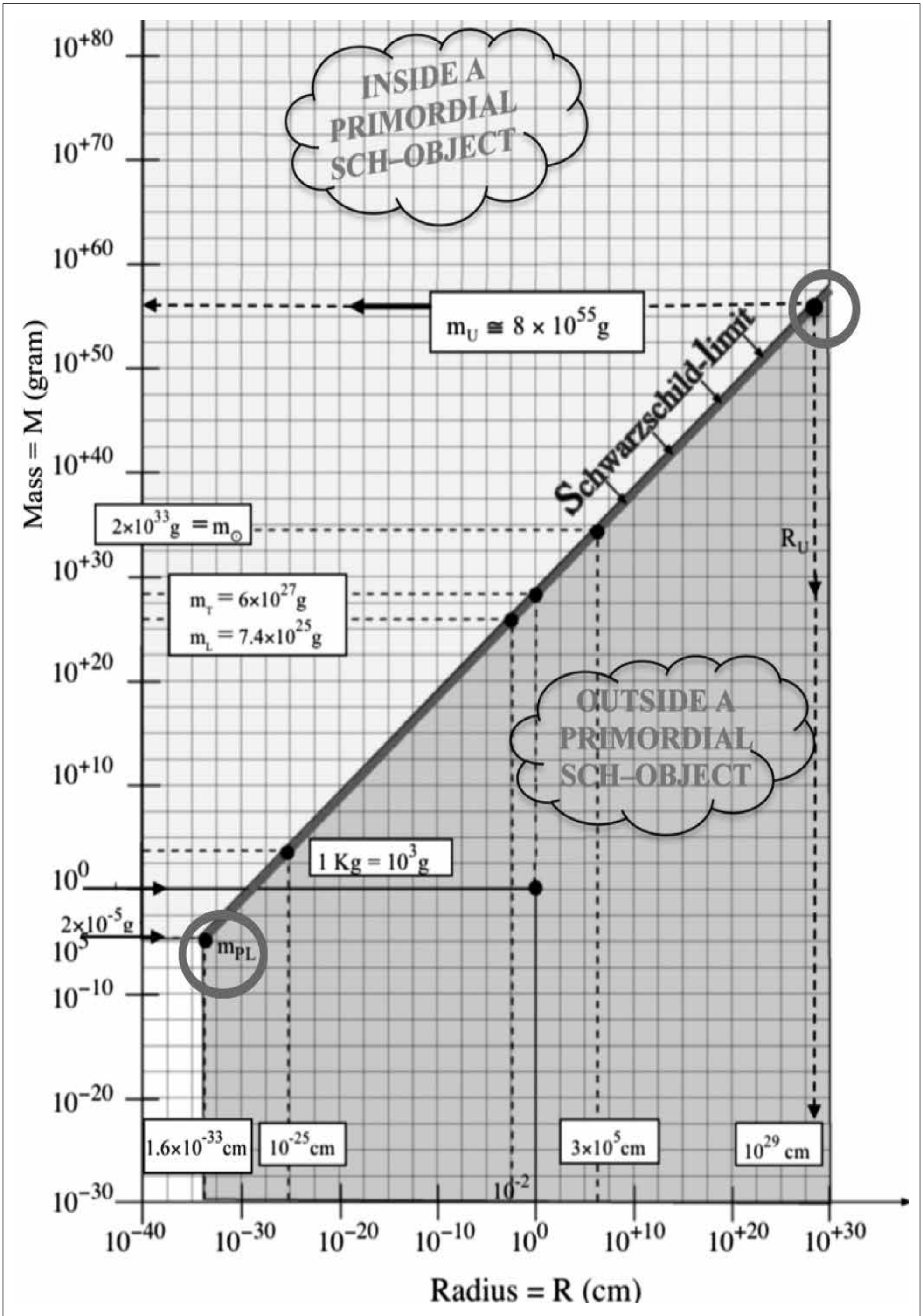


Figure 5: The Schwarzschild law between the radius of the gravitational horizon and the mass from the smallest to the largest SCH-object.

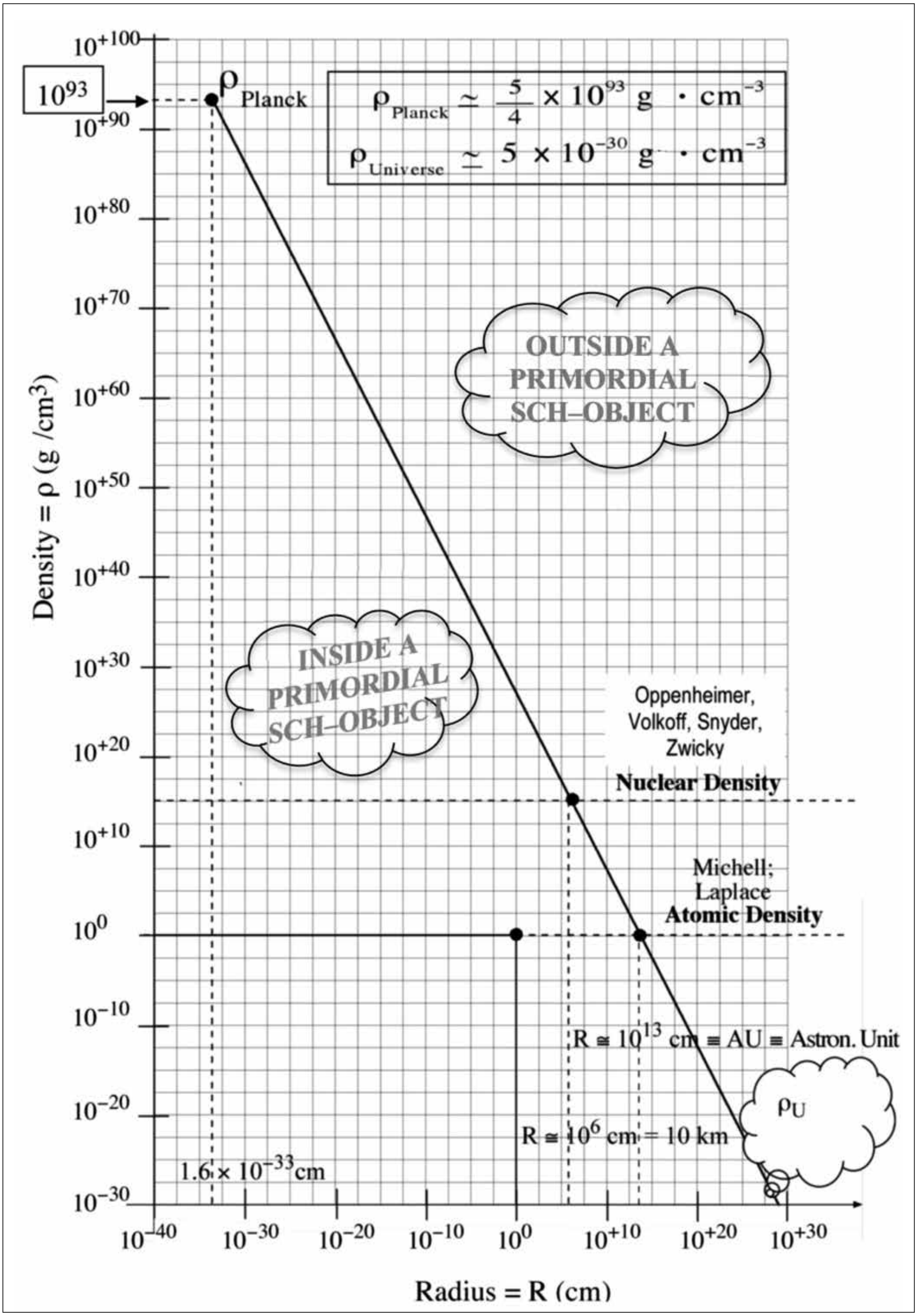


Figure 6: The relation which exists between the value of the SCH radius (R_{SCH}) and the corresponding density (ρ_{SCH}), from the smallest (the Planck Universe) to the largest SCH-object (the Universe now).

How did this happen? By an **act of Intellectual Humility**: The recognition that the **Author of the Logic of Nature is more intelligent than any of us** – philosophers, thinkers, mathematicians, logisticians, scientists.

These two graphs could not have been there without the great achievements of Galilean Science. **John Paul II** rehabilitated **Galileo Galilei** who wanted to search in the stones **the Imprints of the Creator**.

These graphs are the result of the fact that it is not enough to be Intelligent to discover the **Logic chosen by the One** who made the world. It is necessary **to ask Him** one question **at a time (Reductionism)**.

During **10^5 years** all Civilizations had sin of **intellectual arrogance: Just be smart** to understand the **Logic** that rules the world.

We scientists **cannot remain silent** when the great public is bombarded with topics such as:

- Complexity is the New Science
- The Reductionism is over. All Sciences must be Holistic
- The Artificial Intelligence will overcome the Human Intelligence
- Chaos is the origin of Life
- The global warming
- The energy crisis
- The information security
- The environment
- The Intelligent Design
- The Evolution
- and other Problems coming from the 'Whole of Our Knowledge'.

Now again the Culture of our Time remains silent.

The answer must be the **Whole of Our Knowledge** and the mathematical rigour needed to solve any problem. The **Whole of Our Knowledge** allows us to discover that we are the only form of living matter having the privilege of **Reason**. **And the Reason is a Gift of God**.

Gift of God

REASON

- Permanent Collective Memory **(Written Language)**
- Rigorous Theoretical Logic **(Mathematics)**
- Rigorous Experimental Logic **(Science)**

Thus confirming what Science has been able to discover asking to the Creator one question at a time.

Holism **is not a New Science** but the very old way of thinking that we could discover the Logic of Nature without asking questions to the **Fellow** who created the Universe.

The answer must be the **Whole of Our Knowledge** and the mathematical rigour needed to solve any problem (see Figs. 1 and 1A on pages 18, 19).

With Holism it would have been impossible to get **the Whole of Our Knowledge**, **the Superworld**.
Here is the Mathematics needed.

$$\mu \frac{d\alpha_i}{d\mu} = \frac{b_i}{2\pi}\alpha_i^2 + \sum_j \frac{b_{ij}}{8\pi^2}\alpha_i\alpha_j$$

α_i, α_j (with i = 1, 2, 3; and J = 1, 2, 3 but $i \neq j$).

μ is the fundamental variable such as Space, Time, Energy, etc.

This is a system of coupled non-linear differential equations in order to mathematically describe any phenomenon where quantities, **all functions of the variable μ**, play a fundamental role.

$$\underline{\textbf{MATHEMATICS}} \rightarrow \begin{cases} \rightarrow \boxed{\textbf{72 Planetary Emergencies}} \\ \rightarrow \boxed{\textbf{No Analytic Solutions for the Climate}} \end{cases}$$

5. A note on the mathematical difficulty of climatology

If the number of equations is more than two there is **no analytic solution**.

No one will be able to find an equation (for example like the Newton formula) to mathematically describe the **Climate**.

Those who claim that they are able to do this are like the famous theoretical physicist who, in the middle of the 20th Century, went to Enrico Fermi saying that he had a mathematical model which could explain all discoveries done in Nuclear Physics. Fermi asked him: *"How many free parameters are there in your model?"* The answer was: *"Many"*.

Fermi recalled him the von Neumann statement: *"If you allow me to have four free parameters I can build a model which describes an elephant. If you allow me a fifth free parameter my model will predict that the elephant will fly"*.

This was the end of the most exact mathematical model able to describe all known experimental features of the Nuclear Forces.

Nobody could imagine that the Nuclear Forces are secondary effects produced by the "Gauge Force" (Quantum Chromo Dynamics, QCD) which acts between quarks and gluons. If we switch off QCD, the Nuclear Forces disappear. The mathematical rigor and the needed experimental checks are the basis of all activities which can be called scientific.

Our Universe comes from the Planck Universe (solution of Einstein's equation).

Ratio of Gravitational to Electromagnetic attraction
between proton and electron

$$\simeq \frac{G_N \cdot m_P \cdot m_e}{e^2} \simeq 4 \cdot 4 \times 10^{-40}$$

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The road to INFN and the history of the INFN Unit of Bologna at the Physics Department of the University

*Graziano Bruni**

I review some of the main events that led to the birth of the INFN (National Institute of Nuclear Physics) and then to the INFN Unit of Bologna inside the Physics Department of the University. It is a personal view with several simplifications. Important additional information and details can be found in the specialised literature.

1. Augusto Righi and the new Institute of Physics at the dawn of the 21st Century

Augusto Righi (Bologna, 1850-1920) was one of the best experimental physicists of the time (Fig. 1). He became Professor of Experimental Physics in Palermo (1880-85), the same University where few years later also Mario Orso Corbino, whom we are going to meet shortly, was Professor. In 1886 Righi moved to Padua and then was back in Bologna in December 1889. During the modernization work started in connection with the celebrations of the 800th anniversary of the foundation of the University – conventionally set in the year 1088 – he had the initiative of the construction of the new Institute of Physics (1901-1907), now dedicated to him [1].

He did a lot of experimental work, in particular on the electromagnetic structure of matter. To cite but a few examples: discovery of the magnetic hysteresis [2], fundamental contributions to the comprehension of the photoelectric effect [3] ,foundation of the field of short and micro electromagnetic waves, and so on. In 1872 he built an electrostatic device corresponding to a small Van der Graaf accelerator [1], [4], today visible at the Museum of the old Institute of Physics. He guided Guglielmo Marconi (who was a free visitor at the University) to the birth of wireless telecommunications [1].

* INFN, Sezione di Bologna, Bologna, Italy.

Figure 1: Augusto Righi, the founder of the new Institute of Physics in Bologna at the beginning of the 20th Century (www.radiomarconi.com/marconi/augustorighi.html).

2. The "via Panisperna" boys

In 1908 Prof. Pietro Blaserna called Prof. Orso Mario Corbino to Rome from Messina (Sicily). It was the year in which the big earthquake destroyed almost the whole city of Messina. Ten years later Corbino became director of the Rome Physics Institute located in via Panisperna. He aimed to set up an Institute of international level and, being a "talent-scout", in a short time was able to create from nothing a top level group of physicists around Enrico Fermi, who went to the Institute in 1926 as Professor of Theoretical Physics. In fall 1927, at the initiative of Corbino, three students, Emilio Segrè, Edoardo Amaldi and Ettore Majorana moved from Engineering to Physics under Fermi's guidance. Until about 1929 the group worked mainly on Atomic Physics and Spectroscopy. In 1930 Franco Rasetti reached the Institute as Professor of Spectroscopy and in 1931 Bruno Pontecorvo joined the group as a student of Physics (coming from Pisa where he was studying Engineering) – see Fig. 2, left. Fermi and Rasetti decided to move the research interests on to the more challenging problems of the atomic nucleus, leaving behind them atomic physics, a field in which they thought that much was already done. During those years, Ettore Majorana developed a theory of the nuclear forces, that he refused to publish it in spite of Fermi's willings. In 1932 Heisenberg published a work about the atomic nucleus [5]. Majorana then moved to Leipzig to work with Heisenberg and finally published his work [6].

In 1931 Wolfgang Pauli hypothesized the emission of an almost non-interacting neutral particle together with the electron in the nuclear β-decay to explain the energy balance of the reaction. Enrico Fermi called it the "neutrino" (a kind of a joke with respect to the word "neutron"). Two years later, in 1933, Fermi published his theory of the weak-interaction nuclear β-decay. The seminal paper was published on the *Nuovo Cimento* and *Z. für Physik* [7] (Fig. 2, right) after it was refused by *Nature*. Fermi's theory

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TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (¹) di Enrico Fermi

Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del «neutrino» e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria dell'irradiazione per descrivere l'emissione di un quanto di luce da un atomo eccitato. Vengono dedotte delle formule per la vita media e per la forma dello spettro continuo dei raggi β, e le si confrontano coi dati sperimentali.*

Ipotesi fondamentali della teoria.

§ 1. Nel tentativo di costruire una teoria degli elettroni nucleari e dell'emissione dei raggi β, si incontrano, come è noto, due difficoltà principali. La prima dipende dal fatto che i raggi β primari vengono emessi dai nuclei con una distribuzione continua di velocità. Se non si vuole abbandonare il principio della conservazione dell'energia, si deve ammettere perciò che una frazione dell'energia che si libera nel processo di disintegrazione β sfugga alle nostre attuali possibilità di osservazione. Secondo la proposta di Pauli si può p. es. ammettere l'esistenza di una nuova particella, il così detto «neutrino», avente carica elettrica nulla e massa dell'ordine di grandezza di quella dell'elettrone o minore. Si ammette poi che in ogni processo β vengano emessi simultaneamente un elettrone, che si osserva come raggio β, e un neutrino che sfugge all'osservazione portando seco una parte dell'energia. Nella presente teoria ci baseremo sopra l'ipotesi del neutrino.

Una seconda difficoltà per la teoria degli elettroni nucleari, dipende dal fatto che le attuali teorie relativistiche delle particelle leggere (elettroni o neutrini) non danno una soddisfacente spiegazione della possibilità che tali particelle vengano legate in orbite di dimensioni nucleari.

(¹) Cfr. la nota preliminare in «La Ricerca Scientifica», 2, fasc. 12, 1933.

1

Figure 2: Left: from left to right: Oscar d'Agostino, Emilio Segrè, Edoardo Amaldi, Franco Rasetti and Enrico Fermi. Bruno Pontecorvo was taking the picture (Archivio Amaldi, Dipartimento di Fisica, Università La Sapienza, Roma). Right: 1934 Fermi's paper with his theory of beta decay.

paved the way to the modern description of the weak interactions. After the discovery by Frédéric and Irène Joliot-Curie of the radioactivity induced in atomic nuclei through their interaction with α particles in 1934, Fermi had the idea to use neutrons as projectiles against the atomic nucleus, instead of the α particles. Fermi and his group made then fundamental discoveries about the power of slow neutrons to break the nuclei, opening the door to the atomic energy era (see for example [8]).

3. The Arcetri group and the study of the "cosmic radiation"

Another group of physicists, led by Bruno Rossi, was active in Arcetri, a hill near Florence hosting the Institute of Physics [9]. Rossi, who got his degree in Physics at the University of Bologna in 1927, introduced a fundamental innovative coincidence circuit that was able to provide information comparable to that from Wilson chambers, giving a boost to the experimentation on the cosmic radiation discovered by Victor Hess in 1912.

In Rossi's group there were, among others, Giberto Bernardini (assistant of Enrico Persico), Giuseppe Occhialini, Daria Bocciarelli, Guglielmo Righini, Lorenzo Emo Capodilista and Giulio Racah. In 1929 the group defined a detailed research program for the investigation of the nature of the cosmic radiation. In 1932 Rossi and Fermi did a theoretical study about the influence of the Earth magnetic field on the cosmic radiation, that allowed them to conclude in favour of its corpuscular nature [10].

4. The idea of a dedicated Italian Institute

In the second half of the 30s of last century, Enrico Fermi had clear the point that it was needed a step forward the to compete with other Countries in the field of nuclear physics. He was convinced that a modern accelerator facility was compulsory: the era of the University-scale laboratories was setting. In 1936 he wrote to the directors of the main European laboratories to get information about devices, the staff needed for their operation and the budget level. The cyclotron was emerging as the best device to accelerate particles with respect to the older electrostatic devices. However, he only succeeded in getting the budget to build a conventional 200 kV Crocktrof-Walton accelerator in the Physics Institute of Rome (1937) and later a 1 MV accelerator located at the "Istituto di Sanità" (1939). He proposed to Italian authorities the institution of a *National Institute of Radioactivity*, to coordinate both fundamental physics research and applications in medicine and biology. The sudden death of Guglielmo Marconi, at that time President of the Italian National Research Council (CNR), who was an estimator of Enrico Fermi and the group of nuclear physicists, stopped the project.

5. The racial laws and the war

In 1938 the Italian cabinet deliberated the racial laws against the Jews, adding darkness to darkness. Bruno Rossi, who was professor at the University of Padua, lost the chair and the salary. He survived with a fellowship until he left Italy. He first went to the Niels Bohr Institute in Copenhagen, then to the United Kingdom and in June 1939 reached the United States. Enrico Fermi got the Nobel Prize in 1938 and then he left Europe too, by going directly to Chicago from Stockholm: Laura, Fermi's wife, was a Jewish.

In 1938 Gilberto Bernardini went to Bologna and then became Professor of Experimental Physics. Between 1942 and 1947 he was the Director of the Institute of Physics "Augusto Righi".

In 1940 Italy declared war to France and UK. The tragic event definitely broke the nuclear physicists group formerly led by Fermi, albeit the group had already started its downward trajectory. However, not everything went lost.

6. The rise of the National Institute of Nuclear Physics (INFN)

This section is mainly based on the research work published on the book [11] and the papers [12], [13]. After the conclusion of the second world war, in 1945 Giovanni Polvani, director of the Institute of Physics of the State University of Milan, organized a conference in Como to celebrate the 200 years of the birth of Alessandro Volta. It was an important meeting as it put together several scientists that discussed together about how to restore the physics research in Italy. A report, prepared by Edoardo Amaldi at the beginning of 1946, had the effect that the FIAT Industry of Turin gave a contribution for the “Testa Grigia” [14] laboratory that was setting up on the Plateau Rosà mountain group for research on cosmic rays. In addition, it sparked interest about the research on civil applications of nuclear technologies. The Testa Grigia Laboratory (officialy inaugurated on January 11, 1948) was built at 3505 m above sea level, under the guidance of Gilberto Bernardini [15], Claudio Longo and Ettore Pancini on behalf of the Physics Institute of Rome directed by Edoardo Amaldi (Fig. 3). It played an aggregation role of Italian physicists that was important for the future birth of INFN. It also favoured the contact between Italian and international groups that carried out researches at the laboratory.

In October, an agreement between the CNR (National Research Council) and the University of Rome established a Centre of Study on the nuclear and elementary particle physics, that was inspired to the old Fermi’s project. The background idea of the construction of an accelerator facility was present, but it was at the same time clear that the economic situation of the Country would have made it impossible it on a short time scale.

In the meantime, the research resumed also in other Institutes. Between 1945 and 1951 the CNR set up four Centres for Nuclear and Particle physic research, ruled by specific agreements with the single Universities:

- **1945: Centre of Rome – Nuclear and Particle Physics;** the Rome group carried on the work of the previous years that was slowed but never completely stopped by the war.
- **1947: Centre of Padua – Study of Fast Ions**; in spite of the name the Padua group tried to recover the experience on cosmic rays lost with Rossi’s departure, leaving opened the window for future research directions.
- **1951: Centre of Turin – Experimental and Theoretical Physics**; it was decided the construction of a synchrotron by a consortium among CNR, University and FIAT; the FIAT completed the civil engineering in 1953 while the machine was

Figure 3: From left to right Edoardo Amaldi, Gilberto Bernardini and Ettore Pancini at the Testa Grigia Laboratory and other images of instrumentation and installations at the laboratory (Archivio foto storiche, Sezione di Torino).

completed at the end of the fifties; the Turing group participated to the cosmic ray researches at the Testa Grigia laboratory.
- **1951: Centre of Milan – Cosmic Radiation Group**; in Milan there was a tradition on cosmic ray physics that restarted after the war with the study of extended showers and detectors.

Initially, the base research on nuclear physics went together with applied research. I mention the experience of the CISE (Centro Italiano Studi Esperienze, Italian Center of Study and Experiences). The Center was set up in Milan at the end of 1946, with the purpose to to drive the foundation of an electro-nuclear industry in Italy. Given the costs, public investment was needed to have any chance of success. After a long period of pressures on the Government, the CNR obtained a doubling of its budget (budget 1950-1951): it passed from 265 to 540 millions of Italian liras. After few years it became clear that nothing concrete was coming out. The President of CNR, Gustavo Colonnetti, in agreement with Edoardo Amaldi and a Physics Committee, decided to establish a dedicated Institute for the use of the future resources for fundamental research.

The decree of the President of CNR n. 599 of Agust 8, 1951 gave rise to **the Italian Institute of Nuclear Physics (INFN)**, with the task of the coordination of the Rome, Padua and Turin Centres and the possibility of further future additions. The directors of the Centres were members of the governing body of the Institute, the Board of Directors. In [11] it is defined as a "virtual organization" as it coordination power was indeed very limited.

7. The "new" INFN

In June 1952, the National Committee for Nuclear Research (CNRN), an organism that had to coordinate the CISE and INFN, was established with a decree of the Prime Minister. It had a very large budget, 1 billion of Italian Liras, larger than the budget of CNR. As a consequence, there was also an important reorganization of the INFN (Decree of the President of CNR n. 635, July 9, 1952). The main points were:

- the four CNR Centres became the first four Divisions (or units) of the INFN;
- the Testa Grigia Laboratory became a Laboratory of INFN;
- a President of INFN was introduced (Gilberto Bernardini was the first one);
- the Board of Directors had the real power of the coordination of the nuclear and particle physics research, as it had the power of distributing locally fractions of the overall budget (the budget was set to the large amount of 200 millions of Italian Liras);
- INFN was in charge of the relationships with other International Organizations;
- it was allowed to collaborate with external structures and researchers by funding them for specific research programs.

In September of the same year new "aggregate groups" or sub-units appeared, see Fig. 4. The group of Bologna was organized as sub-unit of Padua.

Before passing to the history of the INFN Unit of Bologna, I recall that in 1955 it was inaugurated the first INFN National Laboratory in Frascati, a small town on the hills near Rome. In 1957 the construction of the first electron-synchrotron started under the leadership of the young Giorgio Salvini. It was completed in 1959 and operated until 1975 (Fig. 5).

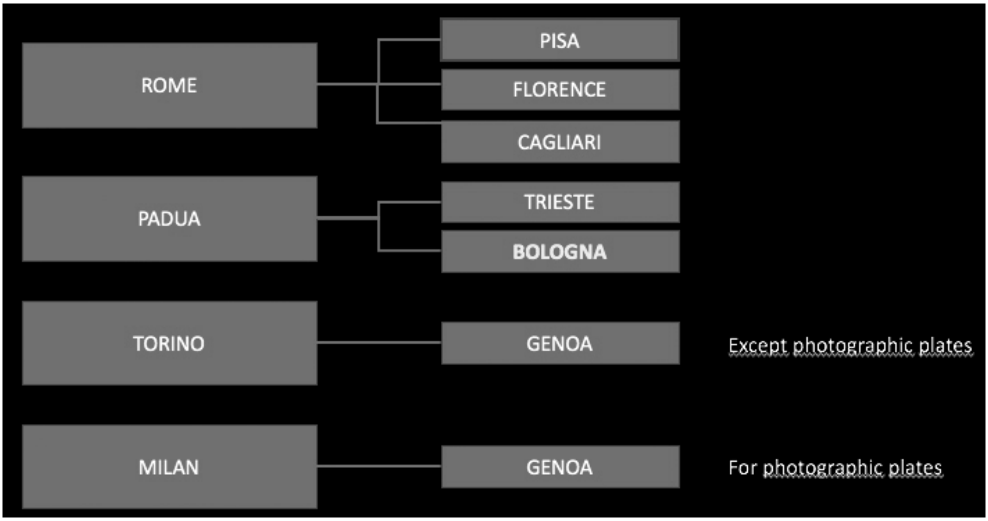

Figure 4: The first four divisions of INFN (left) and the aggregate groups introduced in September 1952 (right). Bologna appeared in 1952 as a sub-unit of Padua.

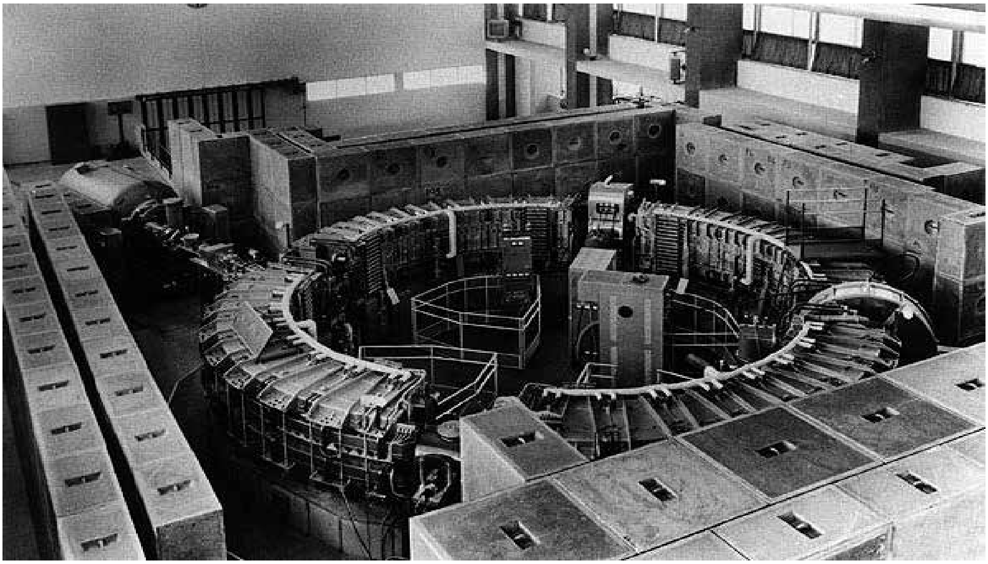

Figure 5: The Frascati electro-synchrotron, built in 1959 (Collezione Fermi, Museo di Fisica, Università La Sapienza, Roma).

8. Giampietro Puppi and the foundation of the INFN Unit of Bologna

The foundation of the INFN division of Bologna can be traced back to the actions of Giampietro Puppi [16]. Puppi (Fig. 6) became famous after a work published in 1948 [17] on the universality of the weak interactions, a very important step for their understanding. He demonstrated the approximate equality of the coupling constants of the nuclear β-decay, the muon β-decay and the muon nuclear capture (the "Puppi's triangle"). In 1951 Puppi became Professor of Theoretical Physics at the University of Bologna and 1954 he was the new director of the Institute of Physics. Between 1962 and 1965 he had international roles at CERN first as Director of Research (1962-63) and then as Chair of the CERN Experimental Committee (1964-65).

Bubble chambers, invented in 1952 by Donald Glaser, where the dominant experimental devices to study particle physics at that time. A large community of physicists operating at bubble chamber facilities grew in Bologna under Puppi's leadership. Thanks to him, bubble chamber data taken at the Brookhaven Cosmotron were sent to Bologna around 1955 and were analysed by Puppi's group. In 1957 the group published an important paper where from the analysis of the Cosmotron data parity non-conservation was established in hyperon decay (showing that parity non-conservation is a property of the interaction) [18]. In spite of that, during his Chair of the CERN Experimental Committee he encouraged the use of different techniques for the study of special topics (the "non-bubble chamber" techniques as they were named by A. Zichichi).

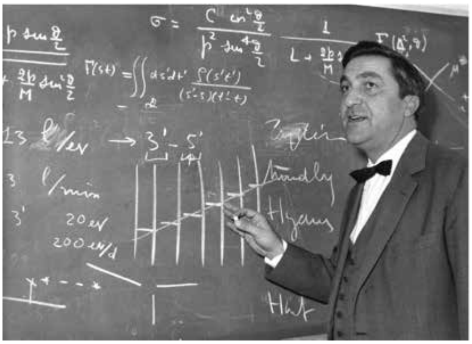

Figure 6: Giampietro Puppi relaunched physics research in Bologna after the 2nd World War and established the INFN unit at the Institute of Physics (*Suppl. Nuovo Saggiatore*, n. 5-6, 2007, p. 15).

Since 1955, Puppi established a strong relationship with the Municipality of Bologna, in particular with the Major Giuseppe Dozza. In 1956 the Municipality granted a 10 years funding of 500 million of Italian Liras (50 million per year) for the development of the nuclear research at the University. It was a crucial act for the rise of the INFN Unit in Bologna. In Fig. 7 it is reproduced the first page of the *Bulletin of information of the municipality activity*, supplement of the *Bologna magazine* of the year 1960 [19]. The monograph is about the funding and the actions of the Municipality in favour of the research and the University. It reports the speech about the event of the Major, of Puppi, of the Rector of the University and representatives of the Municipality Council.

BOLLETTINO D'INFORMAZIONE DELL'ATTIVITA' MUNICIPALE

IL COMUNE PER GLI STUDI NUCLEARI A BOLOGNA

supplemento a

BOLOGNA

RIVISTA DEL COMUNE

Il Centro di Studi Nucleari presso l'Istituto di Fisica «Augusto Righi» della Università di Bologna sorse per il contributo finanziario concesso dal Comune all'Istituto nel 1956. Il contributo fu fissato nella misura di 500 milioni, da corrispondersi in dieci quote annuali di cinquanta milioni ciascuna. Alla base dell'iniziativa era la riconosciuta necessità di potenziare un'attività di ricerca considerata, per unanime giudizio, fondamentale per lo sviluppo generale del Paese. Una serie di contatti fra la Direzione dell'Istituto e l'Amministrazione Comunale portò alla formulazione generale dei criteri secondo i quali il Centro doveva essere costituito e funzionare, e delle modalità dei rapporti fra Comune e Istituto. Dal 1951 fino all'atto della costituzione del Centro, l'Istituto «Augusto Righi» faceva parte dell'Istituto Nazionale di Fisica Nucleare (I. N. F. N.) come sottosezione della sezione di Padova. Il finanziamento del Comune ha permesso di completare varie attrezzature e di raggiungere una consistenza numerica e una produzione scientifica tali da ottenere l'elezione al rango di sezione dell'Istituto Nazionale di Fisica Nucleare, assieme con Roma, Milano, Torino e Pisa.

Figure 7: Cover of the 1960 addendum to the Magazine of the Municipality of Bologna in which it is celebrated the ten years funding of the Municipality to the Institute of Physics for the development of researches on Nuclear and Particle Physics at the University and the birth of the INFN unit.

The cover reports the following words (my free translation):

> *The Centre for nuclear studies at the Institute of Physics 'Augusto Righi' of the University of Bologna arose thanks to the financial contribution of the municipality of 1956. The contribution was set to 500 millions, to be paid in 10 years with shares of 50 millions per year. The initiative was motivated by the recognized need to strengthen a research activity that is considered, by overall judgement, as fundamental for the overall development of the Country.*

and then continues:

> *Since 1951 until the realization of the Centre, the Institute 'Augusto Righi' was part of the National Institute of Nuclear Physics (I.N.F.N.) as sub-unit of the unit of Padua. The funding of the Municipality allowed to complete the construction of scientific devices and to reach a size and a scientific production such to allow the promotion to Unit of the National Institute of Nuclear Physics, together with Rome, Milan, Turin and Pisa.*

The last part refers to the resolution of the INFN board of directors of July 19, 1956 that established the INFN Division of Bologna, where one reads:

> *Bernardini says the board of Directors of INFN judges that it is the right time to transform two aggregate groups into INFN Divisions due to their impressive degree of development. These are the groups of Bologna and Pisa.*

Giampietro Puppi was the first Director of the INFN unit of Bologna. The summary of Fig. 8 shows the evolution from the foundation of INFN in 1951 until the foundation of the Division of Bologna.

In Fig. 9 (adapted from [11]) there is the INFN organization chart as of December 31, 1957. The Bologna unit was one of the largest, as it is today, with a good degree of internationalisation.

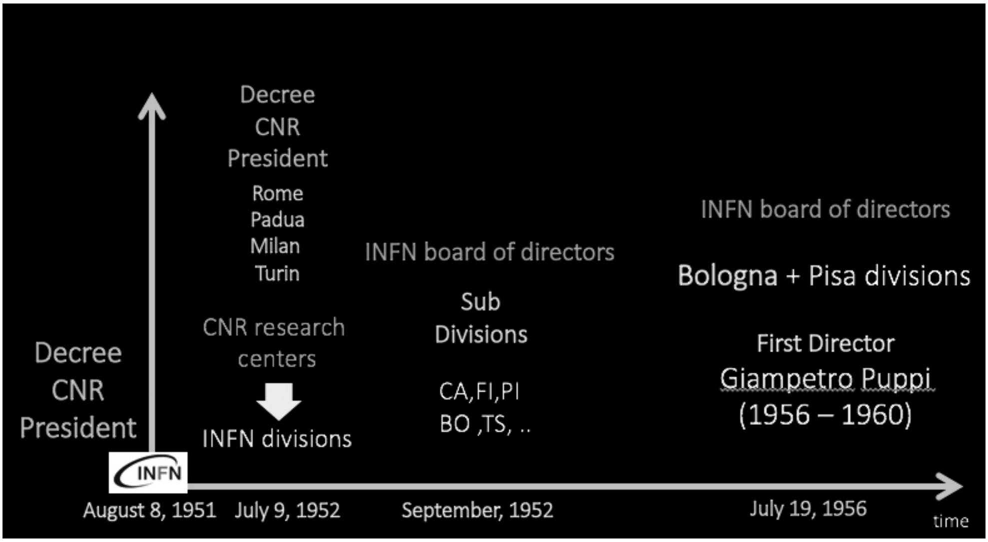

Figure 8: From the foundation of INFN in 1951 to the establishment of the unit of Bologna in 1956.

9. The National Hydrogen Bubble Chamber

During the same 1956 meeting of the INFN board of Directors that set the unit of Bologna, the three physicists Massimo Conversi (Pisa), Giampietro Puppi (Bologna) and Giorgio Salvini (Electro-synchrotron of Frascati) presented a project for the construction of a "National Hydrogen Bubble Chamber", that was approved and funded. It was an important project as it was the first example of collaboration among different units for a national-scale scientific project. In the project were involved groups of researchers of Trieste, Padua, Bologna, Pisa and Rome. Puppi called Professor Pietro Bassi to Bologna (from Messina) to lead the project. He was an expert of bubble chambers technologies since when he was in Padua. The device was built in Bologna between 1956 and 1958, and then carried to CERN to take data (Fig. 10).

The project set the beginning of a tradition of design and construction by the experimental groups of Bologna that never stopped, grew with the size of the unit and is continuing today.

Pietro Bassi directed the Division of Bologna (1960-1966) and then was member of the INFN Executive Board (1967-1970).

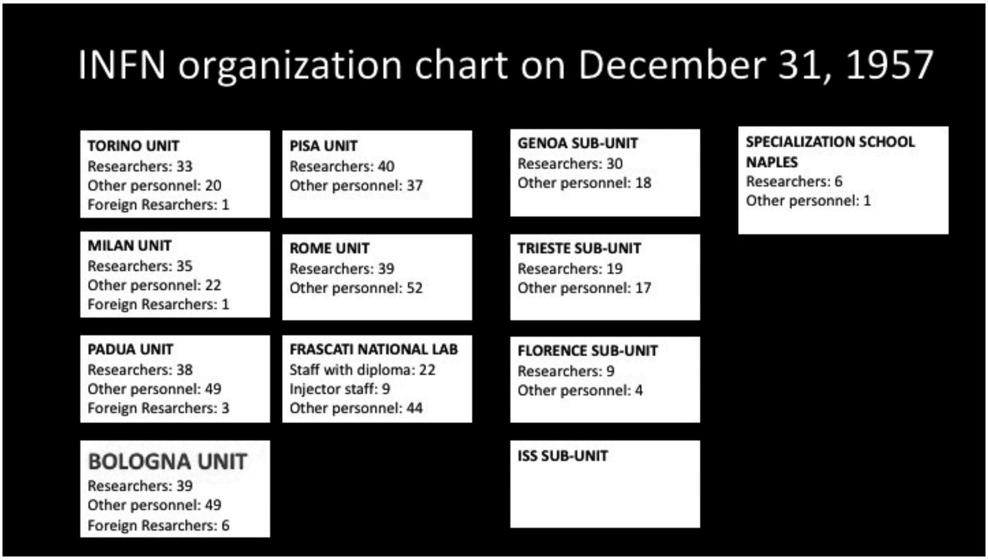

Figure 9: INFN organization chart on December 1957 (adapted from [11]). The Unit of Bologna was one of the largest.

10. Developments of the INFN unit and the Institute of Physics

Puppi's actions were not limited to nuclear and particle physics but he acted in several directions and under his initiative physics in Bologna expanded in different fields:

- Nuclear and particle physics;
- Electronic microscopy;
- Radioastronomy (Radiotelescope "Croce del Nord" in Medicina, a village near Bologna);
- Computing (CINECA – a consortium among different Italian universities equipped with modern computers for the research, located near Bologna; promotion of the foundation in Bologna, in 1962, of the INFN Centre CNAF (Centro Nazionale Analisi Fotogrammi – National Centre for the Analysis of Photographic

Films), originally devoted to the automation of the scanning and analysis of the photographic films taken at bubble chamber facilities, then evolved to become the INFN centre for the scientific computation);
- Theoretical Physics (by calling Bruno Ferretti to Bologna);
- Nuclear Engineering (set up, together with Bruno Ferretti, of Nuclear Engineering Laboratories in Monte Cuccolino − hills of Bologna).

Bruno Ferretti played an essential role in Bologna in the education and training of young theoreticians. He got his degree in Physics in Bologna in 1937 and then moved to Rome. In Rome he joined a group formed by Gilberto Bernardini, Oreste Piccioni and Gian Carlo Wick. The group was led by Enrico Fermi and had the task of studying cosmic rays. He took the leadership of the group after the departure of Fermi to Chicago in 1938. In 1956 he became Professor of Theoretical Physics in Bologna. He directed the CERN theoretical divisions between 1957 and 1959.

Antonino ("Nino") Zichichi, Professor Emeritus of the University of Bologna since 2006, was the third director of the INFN unit of Bologna (1967-1971). He led and is currently leading one of the largest research groups in Bologna. In 1977-1983 Zichichi was President of INFN. Thanks to him there was a transfer to the Italian industry of the superconducting magnet technology, initiated with the construction of the HERA $e^{\pm}p$ collider at DESY in Hamburg.

He also imagined and established the world-best laboratory for underground physics, the Gran Sasso National Laboratory of INFN (LNGS), located near L'Aquila in the centre of Italy. In addition, he wanted the experimental halls oriented along the axis Lab-CERN, picturing the future experiments with neutrinos sent from CERN to underground detectors.

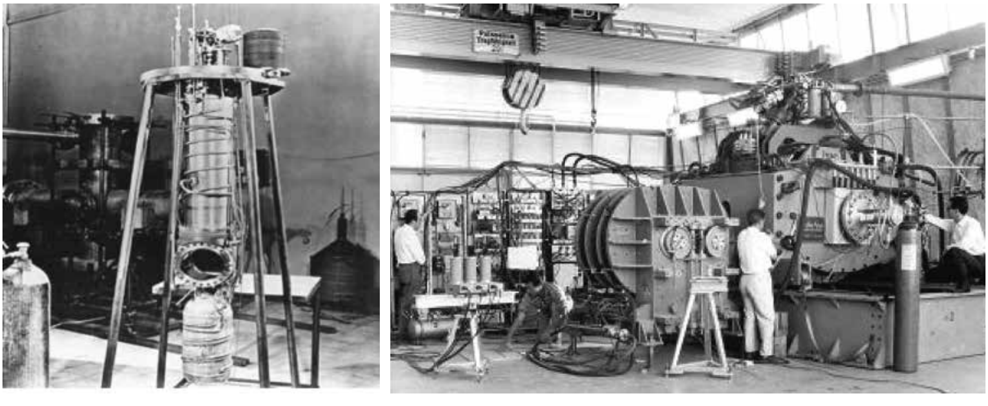

Figure 10: The National Hydrogen Bubble Chamber, built in Bologna (left) and at the 600 MeV CERN SC (Synchro Cyclotron) on the right (*Suppl. Nuovo Saggiatore*, n. 5-6, 2007, p. 28).

Other two large and "historical" groups of researchers grew under the leadership of Giorgio Giacomelli and Luigi ("Gigi") Monari. Giorgio Giacomelli, who trained many students and young researchers, was director of the Institute of Physics between 1975 and 1982 and of the Department of Physics from 1985 to 1988[1]. Gigi Monari was the sixth director of the INFN unit in Bologna (1976-1982) and then director of the Department of Physics from 1982 until his premature and sudden death in 1985. In the middle of the 70's of last Century he originated and led another group of researchers. Between 1978 and 1982 he represented Italy in the CERN Finance Committee.

The map of Fig. 11 represents the evolution of the University (left) and INFN (right) side of the research in nuclear and particle physics in Bologna. The division is a bit artificial as INFN and University in this field of research are different sides of the same coin. While the roots are in nuclear physics, particle (sub-nuclear) rapidly became the dominant field of research. In the picture there are the names of the directors of INFN and the Institute and Department of Physics from 1952 to today.

A rough and incomplete list of the main scientific enterprises is[2]:

- Hadron Physics with fixed target experiments – at the CERN PS and SPS and at the Fermilab National Accelerator Laboratory (FNAL);
- Energy frontier and precision physics at pp and $p\bar{p}$ and *p-Ion* colliders – at the CERN Intersection Storage Rings (ISR), at the Large Hadron Collider (LHC) and at the FNAL TeVatron collider;
- Deep Inelastic Scattering – at CERN with different (from the SPS) and beams and at the Deutsches Elektronen Synchrotron (DESY) with the HERA $e^{\pm}p$ collider;
- Physics at e^+e^- colliders (Frascati INFN National Laboratory at ADONE storage ring, CERN at LEP circular collider and at the Stanford Linear Accelerator Centre SLAC at the SLAC Linear Collider (SLC);
- Antimatter – pioneering production experiments at CERN, search in space on satellite with the Alpha Magnetic Spectrometer AMS;
- Astro-particle, Neutrino and Dark Matter underground (at the Gran Sasso INFN National Laboratory) and under sea water in the Mediterranean Sea near Marseille (France) and Capo Passero (Sicily) with the KM3 project.

In Fig. 12 a (somewhat complicated) picture gives a graphical representation of the evolution of the experimental sub-nuclear and astro-particle research after the bubble-chamber era. It is an approximation, not everything fits in. The horizontal upper and

[1] The Institute of Physics became the Department of Physics in 1982 and at the end of 2011 Department of Physics and Astronomy.

[2] For space reasons I cannot touch the early Bubble Chamber era of the 50s and 60s, low and intermediate energy Nuclear Physics, Technological, Applied and Interdisciplinary research and Theoretical Physics.

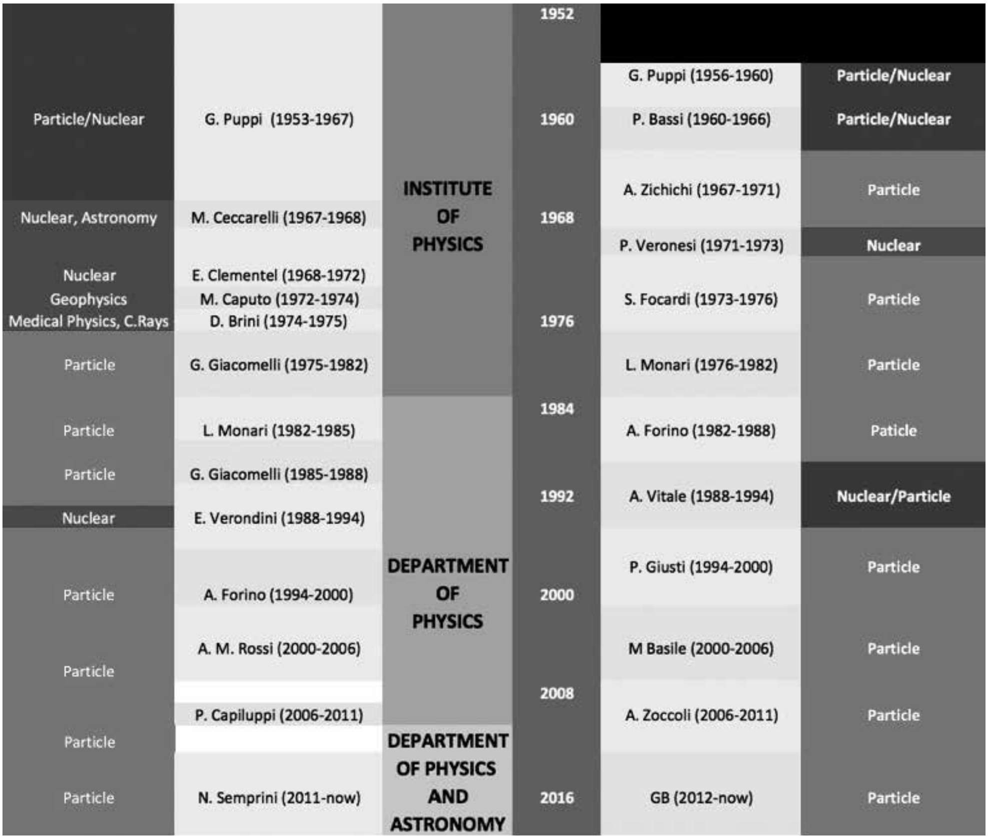

Figure 11: Snapshot of the evolution of the nuclear and particle physics research in Bologna: University side (left) and INFN unit side (right). Of course University and INFN are two sides of the same coin.

lower stripes represent the time axis. The vertical bands in the first column identify homogeneous research areas.

We see experiments on hadro-production at fixed target, at proton-proton and proton-antiproton colliders, deep-inelastic lepton-nucleon scattering, at the e^+e^- colliders, the recent neutrino-astronomy with detectors under the sea, the antimatter search chapter, and all the underground physics at Gran Sasso (magnetic monopole searches, neutrino-oscillations, search of supernovae events, search for the neutrino-less double-beta decay, search for dark matter).

The dashed areas of the picture represent preparatory phases, design, R&D and construction activities. Also are indicated the initials of the group leader that initiated the project.

At the bottom there is the origin of the underground Gran Sasso Laboratory idea, followed by the construction phase and then the "green light" when the Laboratory became ready to host experiments.

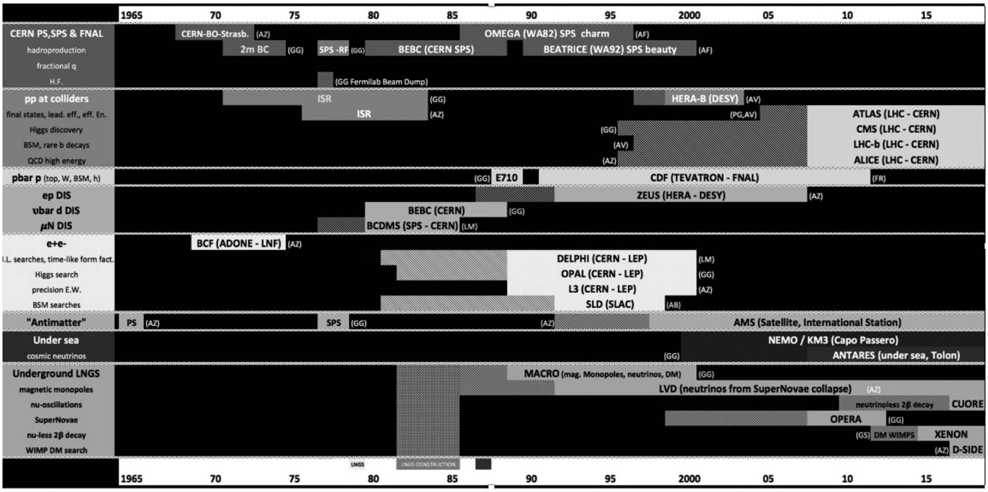

Figure 12: A representation of the sub-nuclear and astroparticle experimental physics in Bologna from mid 60s of 1900, after the Bubble Chambers era.

11. Conclusions: the INFN Bologna unit today

Nowadays INFN has 4 National Laboratories (Frascati, Gran Sasso, Legnaro and Catania), 20 Divisions located in Physics Departments of Italian Universities, 6 "linked groups" (associated personnel in Physics Departments where a formal INFN division does not exist that connected with a reference Division or Laboratory located elsewhere. Since its foundation INFN is strictly connected with the University. A large fraction of its researchers, engineers, technicians and administrative staff "live" within the University. The relationship between INFN Divisions and the relative Universities are ruled by specific conventions. INFN has also 3 Centres that support its activity: CNAF in Bologna (for the computing), TIFPA (Trento Institute for Fundamental Physics and Applications) in Trento, and GGI (Galileo Galilei Institute), in Arcetri a Centre of advanced studies for theoretical physics.

The Division of Bologna is on of the oldest. It became an independent INFN unit in 1956, 5 years after the foundation of INFN. It has a long tradition of design and construction of experiments in nuclear, particle and astroparticle physics. In January 2019 the total staff of the unit of Bologna was of 110 people (46 researchers, 10 technologists, 41 technicians and 13 administrative), to which one should add 8 post-doc positions and 174 users, almost entirely University professors, researchers, post-doc and students. Groups of Bologna have today important responsibilities in the four big experiments at the CERN Large Hadron Collider, in experiments for the search of Dark Matter at the INFN Gran Sasso Laboratory, search of antimatter with an experiment located in the International Space Station, a program for the study of cosmic neutrinos with detectors under sea water, a program for study of neutrino oscillations based at FNAL (Chicago) and many other fundamental and applied activities, without forgetting the research in theoretical physics and phenomenology.

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The search for heavy leptons from CERN to Frascati

*Federico Palmonari**

The years of QED and leptons, the 60s, are a very rich period of particle physics experimental research. To describe the back-story of the Bologna group one should recall the beautiful theoretical aspects of such interesting fields as the lepton family, high energy QED, lepton electromagnetic and weak interactions.

I will go through the really great experimental work done in few years (from 1965 to 1975) by enthusiastic people, physicists, engineers, electronics and mechanics technicians. The story starts in Geneva with the CERN-Bologna-Strasbourg (CBS) group engaged in a scientific program to study the time-like electromagnetic form factor of the proton, and to introduce new experimental techniques for particles identification.

Zichichi became professor at the Bologna University and formed there a second group, (Bologna-CERN-Frascati) to start a new research in the exciting field opened by the forefront (e^+e^-) storage ring ADONE in Frascati. At this moment, it was 1966, I entered the group and went to Frascati. In the second part of my talk I will describe the design in Bologna, the costruction of the apparatus and the program of research of the BCF group at the Frascati e^+e^- storage ring.

1. The back-story of the Bologna group

The experimental activity of the Bologna group was inspired by the two papers on the *Il Nuovo Cimento*. In 1962 Zichichi and Berman, at CERN at that time, and Cabibbo and Gatto, at Frascati to study the (e^+e^-) machine being built there, write a study "Proton-Antiproton Annihilation into Electrons, Muons and Vector Bosons" [1]. The Proton Syncrotron at CERN was infact at that time already able to produce relatively intense beams of antiprotons.

* INFN, Sezione di Bologna and Università di Bologna, Bologna, Italy.

The declared purpose was twofold: i) study the time-like electromagnetic structure of the proton; ii)compare the muon pair production to the electron pair one to investigate whether the muon behaves as a heavy electron. This paper gave the theoretical basis for the future research program of Zichichi after the completion of the (*g*-2) CERN experiment.

On the other end, the '61 paper by Cabibbo and Gatto, "Theoretical Discussion of Possible Experiments with Electron-Positron Colliding Beams" [2], shows that these two young and brilliant theorists had been called to work in the CNEN Laboratories of Frascati (Only later they became INFN laboratories) to prepare for the completion of the (e^+e^-) storage ring, en exciting idea put forward by B.Tuschek. This famous paper developed the fundamental theory to test the validity of QED at high energy. It will be used later when describing the Frascati experiment.

2. The CERN-Bologna-Strasbourg (CBS) group in Geneva

The formation of the CBS group started when the Director of the Bologna Physics Institute, G. Puppi, called Zichichi at the Bologna University to teach a course of Advanced Physics at the Science Faculty. He was already working at CERN, with researchers coming from Liverpool (T. Massam) and from Strasbourg (T. Muller, M. Schneegans). They studied experimentally how to optimize particle detectors able to separate electrons and muons from the background of hadrons in the intense proton beams of the CERN PS.

One paper "Range measurements for muons in the GeV region" [3], was studying the behavior of muons, distinguished by their property of being the most penetrating particles in any detector. The other paper, "A new electron detector with high rejection power against pions", [4] was really a new way of detecting high energy electrons in a abundant background of hadrons, mainly pions. In Fig. 1 the detector cross-section is shown: 5 elements consisting in a lead layer followed by a plastic scintillation counter and a two-gap spark chamber. On the right three spark chamber pictures showing the different behavior of muons, pions and electrons of this "earlier shower developement method". On the left a photo of the electron detectors apparatus, aside a tired technician (Berbiers) after a hard assembly work.

The most important characteristic of this electron detector was the achieved rejection power against pions, quoted in the paper as 4×10^{-4}, with an efficiency not lower than 75% and an energy resolution as good as 10% in the energy range 1.1 to 2.5 GeV. Those performances permitted to build a trigger selecting the wanted antip-p interaction events producing lepton pairs as a signature of the annihilation into Vector Bosons. The importance of this achievement was recognized by S. Ting, who had used this tecnique to discover the J/Ψ, in his Nobel Lecture of 11 december 1997: *"To my knowledge the Zichichi group was the first to use hadron-hadron collisions to study e^+e^- yields from the proton accelerators. This group was the first to develop the "Earlier Shower Development Method" so as to greatly increase the electron / pion rejection*".

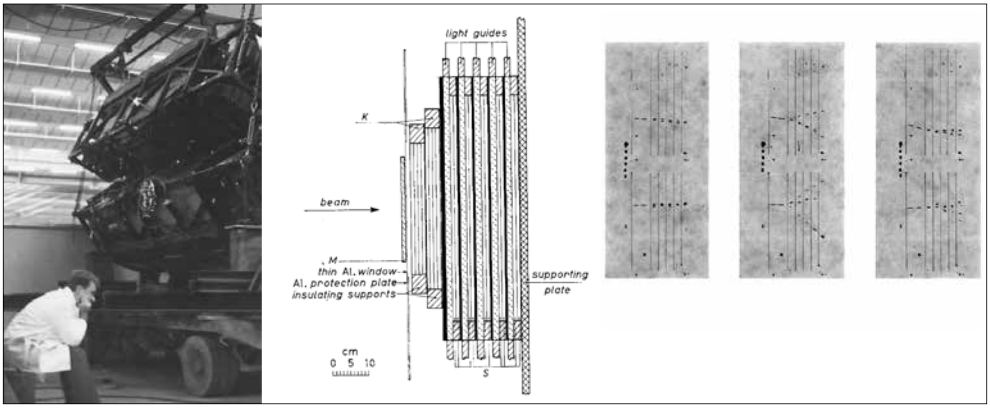


Figure 1

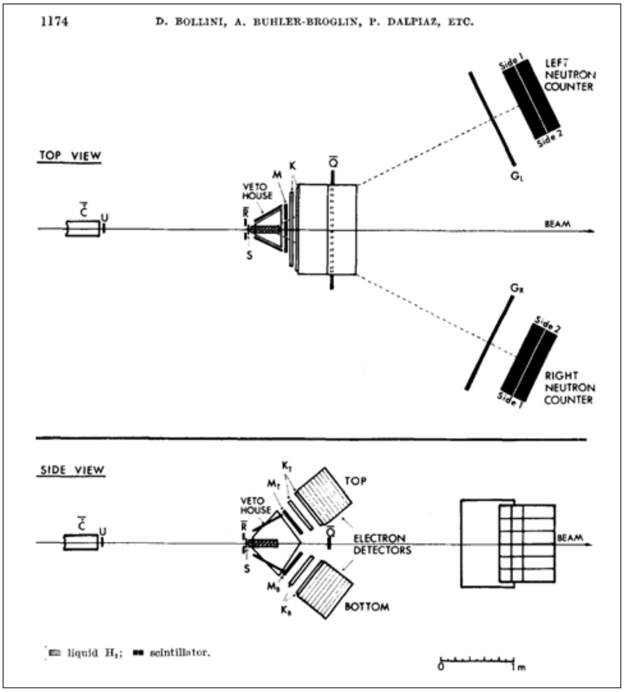


Figure 2: Schematic diagram of the experimental set-up.

New people from Bologna joined the CBS group to assembly the apparatus for the study of the time-like electromagnetic Proton Form Factor. In Fig. 2 lateral view, the two electron detectors are shown above and below the hydrogen target to detect the production of the Vector Bosons ρ, ω, and φ decaying into lepton pairs. In the top view the other fundamental piece of the apparatus is shown, the neutron detector.

The Neutron Counter was an original development of the CBS group, based on a

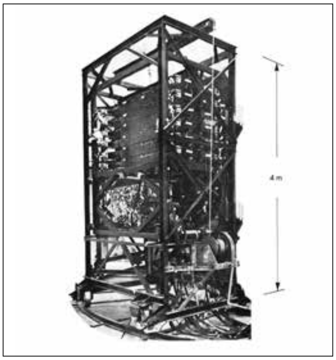


Figure 3a

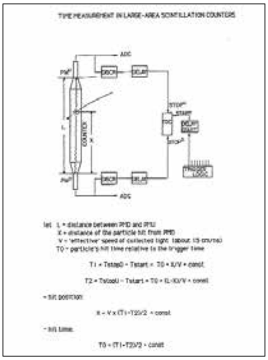


Figure 3b

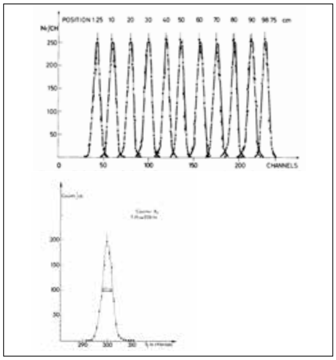


Figure 3c

novel idea, a plastic scintillation long bar seen at both ends by a fast photomultiplier (PMT). Taking advantage of the two PMT anode signals and measuring both the arrival time and the total charge collected one could measure the released energy, the particle arrival time and the hit position.

All performances of the Neutron Counter were published in "A new large-acceptance and high-efficiency neutron detector for missing-mass studies" [5]. The first author was D. Bollini, a young physicist expert of fast electronics arrived at the Bologna University from Pavia, and working later at Frascati. Fig. 3 shows: (a) a photo of the assembled counters; (b) the principle of the measurements; (c) above, the time difference giving the hit position X; (c, b) below, the times sum gives the hit time T0. This counter design was the same implemented later in the Frascati experiment. The performances of the Neutron Counter was an accuracy in locating the incident particle of $\pm$ 1.4 cm for charged particles and $\pm$ 2.5 for neutrons, and an accuracy for the time of flight measurement of $\pm$ 0.25 ns for charged particles and $\pm$ 0.7 ns for neutrons.

The CBS group made in the years 1965-67 an intensive series of measurements in the antiproton secondary beam of the CERN 30 GeV PS. Here we quote few papers describing fundamental studies (at that time) on the electromagnetic form factor of the proton and on the time-like processes producing the Neutral Vector Bosons. In the first paper on this subject, published in the year '65: "The leptonic annihilation modes of the proton anti-proton system at 6.8 $(\mathrm{GeV}/c)^2$ timelike four-momentum transfer" [6] there was yet no author from the Bologna group. The first CBS group papers appeared in the year '68: "Observation of the rare decay mode of the φ meson: $\varphi \to e^+e^-$" [7]; "The decay mode $\omega \to e^+e^-$ and a direct determination of the ω-φ mixing angle" [8]; "A measurement of the branching ratio $\omega \to$Neutrals/$\omega \to$total" [9]. The other results can be found in references [10-16], and starting from year '71, "Measurement of the X^0 cross-sections in π^-p interactions at 1.6 GeV/c ($X^0 \to$neutrals)/($X^0 \to$total)" [11], has as first author M. Basile, because Bollini was at that time fully engaged on the BCF experiment in Frascati.

3. The proposal to search for Heavy Leptons

Zichichi was leading the CBS experiment at CERN, but he wanted a group of physicists in Bologna to prepare an experiment for the Adone (e^+e^-) storage ring, which was supposed to start arond the end of the 60s at the Frascati Laboratories.

Let me quote (from https://www.sif.it/riviste/sif/sag/ricordo/gatto) a description of the Frascati laboratories ambient preparing the new machine.

Back to Italy, in 1960, Gatto became the director of the newly formed theory group at Frascati laboratories. He found there, as junior partner, Nicola Cabibbo. […]

Frascati was busy building an electron-positron collider, a big machine that followed the pioneering work done by Touschek and collaborators with the accumulation ring AdA (Anello di Accumulazione). A larger version of AdA, was called Adone (big AdA, in Italian) and it was the sensation of the moment.

Great expectations were raised about the results to be obtained in what was the first exploration of Electrodynamics at high energy. Raoul Gatto and Nicola Cabibbo wrote a long article that summarised the theoretical situation of the high-energy electron-positron collisions. It ***was called 'The Bible' by people in Frascati*** *and showed very clearly the potential for elementary particle physics of future experiments with Adone.*

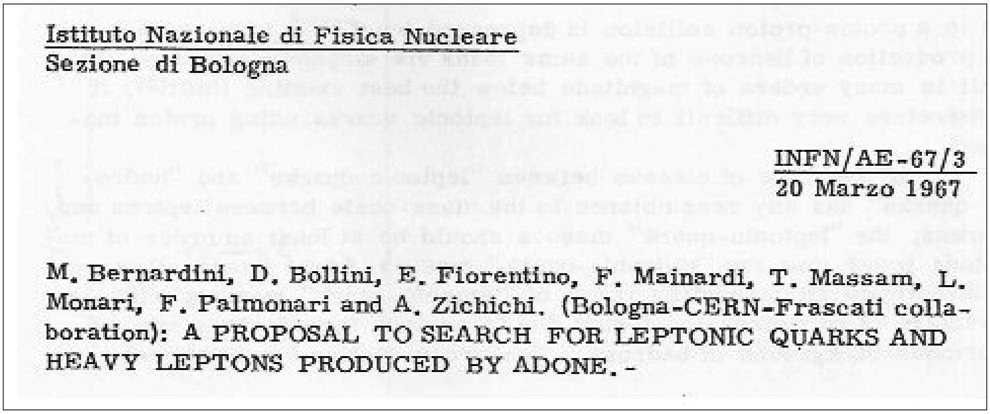
As later recalled by Cabibbo, writing this paper they had the exhilarating experience of expanding into a vacuum because for a few years the only theoretical papers on the physics of e^+e^- annihilations were those coming out of Rome and Frascati. […]

In 1960, independently of Schwinger and Lee and Yang, Cabibbo and Gatto formulated the hypothesis that there is a muon neutrino different from the electron neutrinos, noting that two massless neutrinos with exact muonic and electronic number conservation would make the amplitude of the decay $\mu \rightarrow e\,\gamma$ to vanish exactly, as suggested by data.

A first proposal based on a large-aperture magnet pointing to the interaction region of Adone, able to analyze completely the particles emerging from the interaction, and prepared essentially at CERN at the end of '66 with the help of experts in magnets, was soon abandoned for the times and cost of the magnet.

Meanwhile in Bologna a solid group of about ten physicists and technicians was formed to design and prepare the Adone experiment. Local group leader was Monari, particle physics expert grown in the Bubble Chamber group held by Puppi. Bollini having had already his training at CERN in the CBS experiment, was bringing the new experimental techniques, being expert in electronics, software and calculus. I was coming from the "Muon Capture in Hydrogen" experiment with some expertise in non-conventional particle detectors.The group was completed by external people like E. Fiorentino associated in Bologna and M. Bernardini, staff at the Frascati Laboratories, expert of vacuum and precious link between Bologna and the Laboratories where the experiment would have been assembled and run.

An intense period of work to design the experiment between 1966 and winter 1967, produced a completely new apparatus, where the analyzing power of a magnet was



Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

INFN/AE-67/3
20 Marzo 1967

M. Bernardini, D. Bollini, E. Fiorentino, F. Mainardi, T. Massam, L. Monari, F. Palmonari and A. Zichichi. (Bologna-CERN-Frascati collaboration): A PROPOSAL TO SEARCH FOR LEPTONIC QUARKS AND HEAVY LEPTONS PRODUCED BY ADONE.-

Figure 4

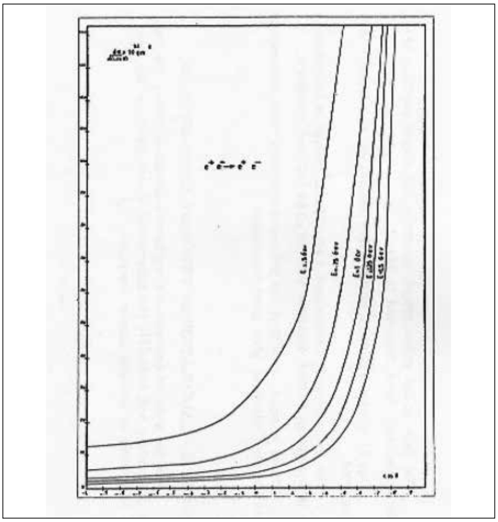


Figure 5a

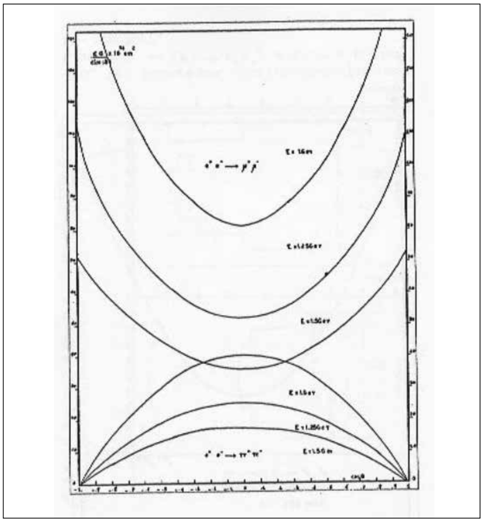


Figure 5b

replaced by a detector taking advantage of the techniques developed at CERN, the electron detector to distinguish electrons from muons and hadrons coming from the (e^+e^-) interaction, and scintillation counter bars like those of the CERN Neutron Counters, to measure their arrival time and angle.

Most important in the proposal, “A proposal to search for leptonic quarks and heavy leptons produced by ADONE” [17] (in Fig. 4 the original INFN report is shown), was the clear identification of the physics items to be studied: Leptonic Quarks (LQ), the fractional charge costituents of protons (the fresh Quark Model of Hadrons) being searched for but unobserved in high energy hadronic interactions; Heavy Leptons (HL), the possible existence of HLs being justified by the unexplained existence of the muon as partner of the electron. The proposal stated clearly the purpose to search for new phenomena not excluded by theoretically founded speculations, given that time-like processes at such High Q^2 could be studied for the first time with ADONE.

Furthermore the proposal was considering of utmost importance to study the lepton interactions expected in QED processes at such high energy , so all cross-section calculated in the "Cabibbo and Gatto Bible" should be tested and for this reason are plotted in the proposal (see for example Fig. 5).

The experimental apparatus described in the proposal was taking advantage of the two techniques developed at CERN : i) the electromagnetic sandwich detector to separate electrons from muons and pions; ii) the scintillation bars seen by two PMTs to measure the hit time of a charged particle. The performances of the scintillation bars (dimensions 5 × 5 × 76 cm^3) are reported in Fig. 6, compatible with a time resolution of 0.25 ns.

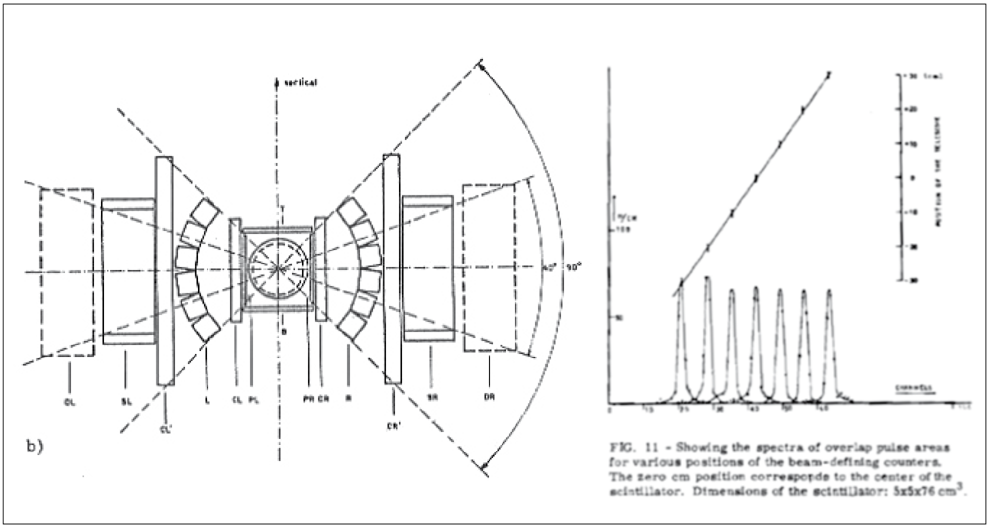


Figure 6

4. The BCF experiment at the (e^+e^-) storage ring ADONE in Frascati

The final set-up of the BCF experiment, realizing the apparatus designed in the proposal, is shown in a 3D view in Fig. 7. Starting from the interaction point of ADONE there are: small plastic scintillation counters for a fast coincidence trigger, spark chambers to reconstruct the interaction vertex, a layer of thick plastic scintillation bars seen by PMTs at both ends to measure the hit time and the position in the bar, then the spark chambers to distiguish electrons from muons and pions.

The only difference with the set-up design of the proposal, was a big improvement in the acceptance of the final electromagnetic sandwich detector which was possible using

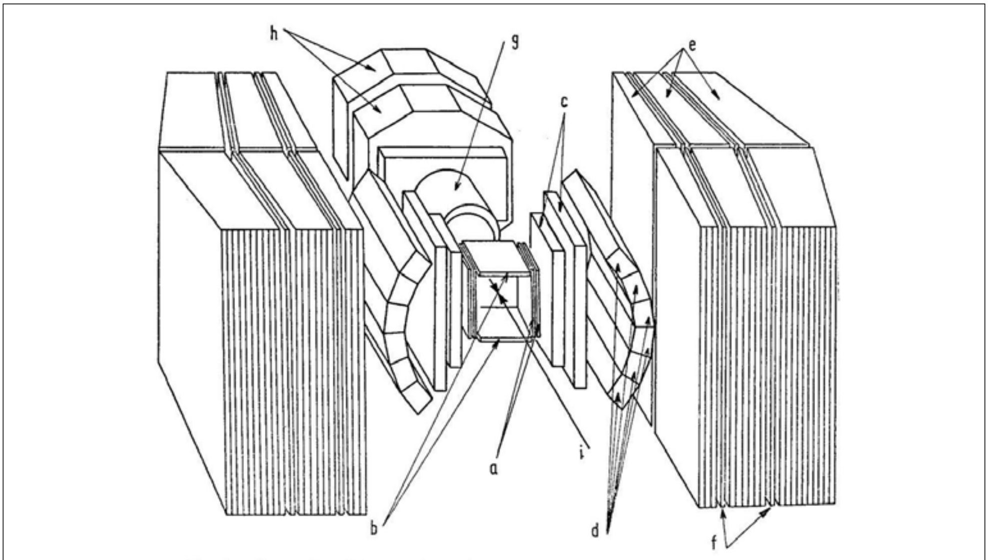


Figure 7

the large aluminum and brass spark chambers recycled on loan by the muon experiment at CERN.

Fig. 8 shows two photos of the BCF apparatus in the ADONE experimental hall: on the left, a view from the balcony of the interaction region with the apparatus, the system of mirrors and the recording cameras on each side; on the right, a general view of the electronics located close to the apparatus. Fiorentino is making calibration and tests of the trigger electronics.

The trigger was generated by the scintillation counters with a coincidence of both sides and the horizontal axis of the apparatus minimized the acceptance for Cosmic Rays (CR). At trigger level the rate of background was reduced by anticoincidence counters detecting vertical CR, and by a fast measure of the time of flight performed by the thick bar counters. In Fig. 9 the result of the fast measure of the time of flight performed by the thick bar counters is shown: the time-of-flight resolution of about 0.5 ns was sufficient to separate good ADONE events from background CR. Furthermore, thank to the thickness of the tof counters producing lot of light for ionizing particles, the trigger was able to detect Fractionally Charged Particles in the search for Quarks.

The other technique, the "earlier shower developement detector" used at CERN to distinguish the electron pairs from the overwhelming background of pions, was implemented in ADONE to have a good separation between the abundant electron pairs from Bahba scattering and the muon pairs and pions from the high energy annihilations. The electron detector was made of two thin wall spark chambers followed by thick wall spark chambers, so that the muon pairs gave a clear single traversing track in

Figure 8a

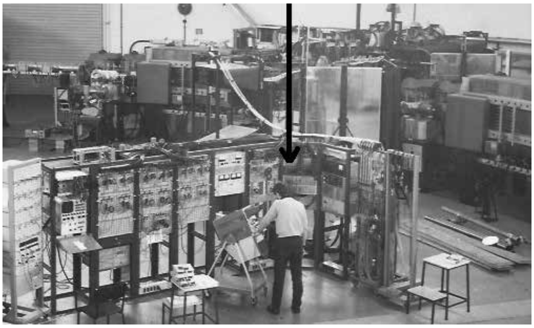


Figure 8b

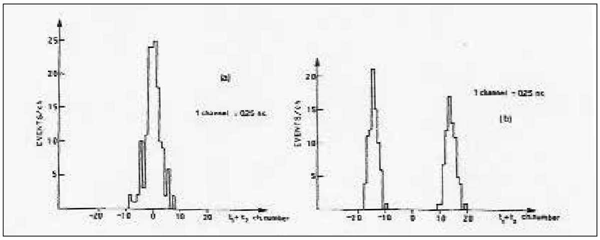


Figure 9

each telescope, and pion tracks had an high probability of making a hadronic shower , well distingued from the early electromagnetic compact shower. In Fig. 10 the camera records for a pair of electrons and a pair of muons are shown.

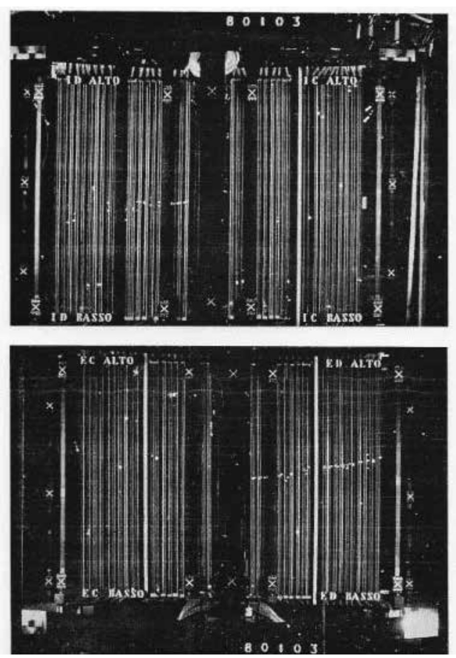


Figure 10a: an electron

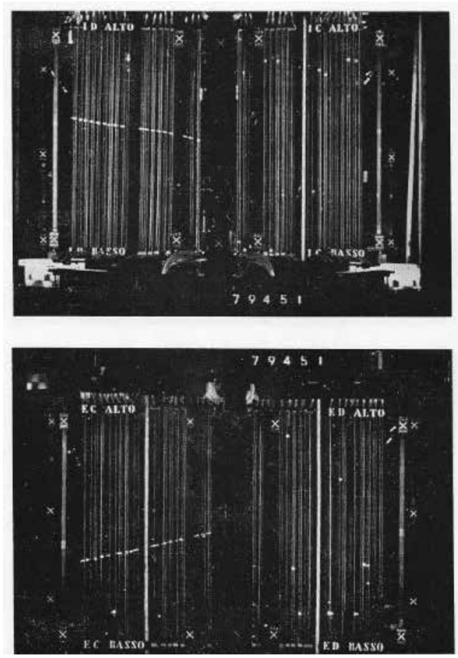


Figure 10b: a muon

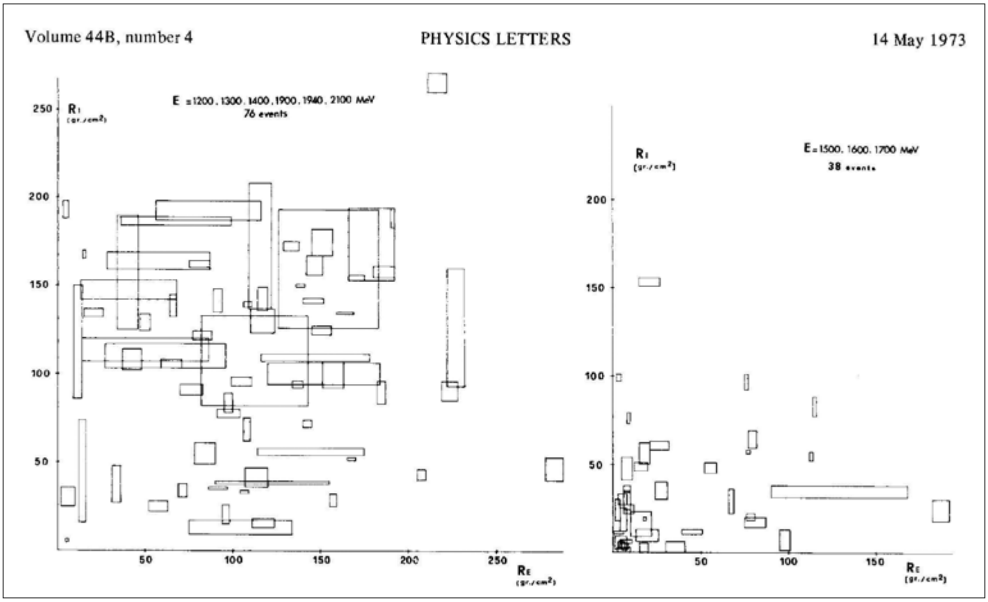


Figure 11

The photos were scanned systematically and all visible tracks characterized by 6 parameters. A Boosted Decision Tree (BDT) conceived by Bollini, for that time and available computer resources an advanced technique, was classifying events in three populations: electrons, muons, hadrons. A set of photos taken at CERN on a copy of the ADONE Spark Chamber Sandwich was used to tune the parameters. The photos were taken with a set-up assembled and run by Massam on a PS secondary hadron beam equipped to select pure samples of electrons, muons an hadrons. This calibration permitted to assign to each population a value for the detection efficiency and contamination.

Those parameters could also distinguish kaons from pions in the hadron selected population as one can see from Fig. 11, taken from the paper "Proof of comparable K-pair and π-pair production from time-like photons of 1.5, 1.6, and 1.7 GeV and determination of the K-meson electromagnetic form factor" [18]. Two scatterplots are shown, tracking the range, represented by parameters R_e and R_i, respectively, in the opposite Sandwiches. The Kaon population in the right plot is clearly distiguished from the left Pion population.

5. The search for (e^+e^-) annihilation into Heavy Lepton pairs

The BCF experiment produced in the years 1970-75, more than 20 papers, 11 published in Physics Letters and 10 in the Italian Physical Society journals. The first published result (1970) was, according to the main research item, "Limits on the Electromagnetic

Production of Heavy Leptons" [19]. In this paper the experimental method and the BCF apparatus characteristics for this purpose are stated, and the conclusion was that no HL had been seen of mass lower than 780 MeV/c^2 at 95% cl. Fig. 12 shows the page of that paper where the search method of HLs is stated and the detailed structure of one of the two symmetric arms of the experimentis shown. Here the thickness of the Sandwich

If the electromagnetic properties of the heavy lepton are assumed to be purely Dirac-like, as for other known leptons, then the cross-section may be calculated as a function of the heavy-lepton mass (3).

By analogy with muon decay, we may expect the predominant decay channel to be

$$\mathrm{HL}^{\pm} \begin{cases} \to e^{\pm}\nu_e\nu_H\,, \\ \to \mu^{\pm}\nu_\mu\nu_H \end{cases} \qquad (2)$$

where ν_H indicates the neutrino proper to the heavy lepton HL. If this is the case, and the two modes are, as expected, equally probable, then there is $\sim 50\%$ probability that the final state from reaction (1) consists of a noncollinear $e^{\pm}\mu^{\mp}$ pair.

An event of this type would have a very clear signature in our detection system which is shown schematically in Fig. 1 (4). The parts of the apparatus relevant to the present search are the four heavy-plate spark chamber telescopes, placed two on the

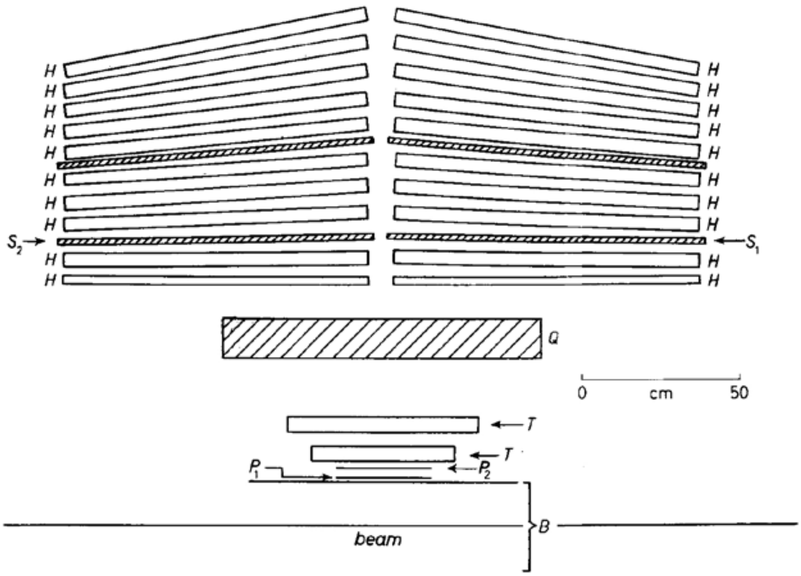


Fig. 1. – Plan view of one half of the apparatus. The part on the other side of the intersection region is the mirror image of this: *B* is the colliding-beam region; P_i are thin plastic scintillator counters ($i = 1, 2$); *T* are thin-plate spark chambers (6 gaps each); *Q* are 12 cm thick plastic scintillator counters. Six *Q*-counters are mounted on the surface of a cylinder about the beam line. They subtend an azimuthal angle of 90° and are used in an electronic OR configuration. *H* are brass and aluminium spark chambers with 0.5 cm thick plates. There is a total of 15 cm of brass and 9 cm of aluminium in the chambers. *S* are plastic scintillator counters with S_1 and S_2 in an electronic OR. The other two *S* counters shown in the drawing are not used for triggering.

Figure 12

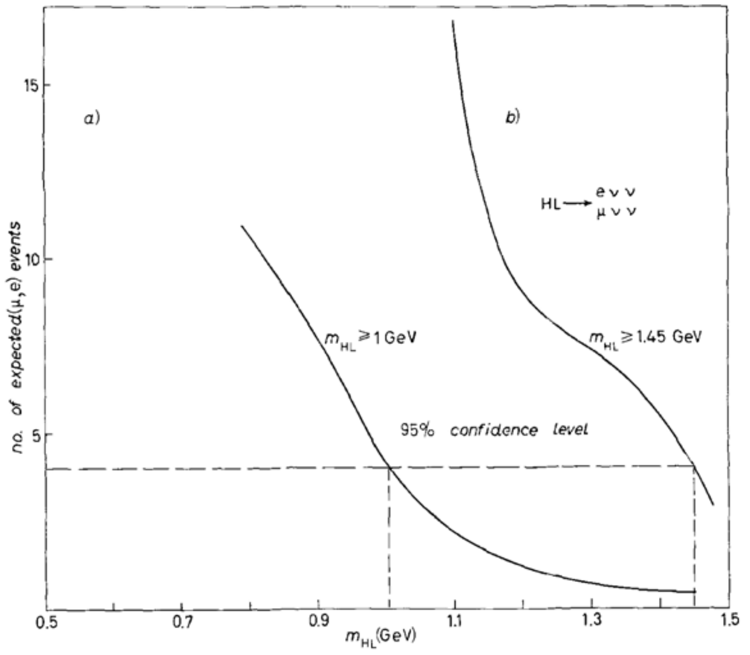


Figure 13

Spark Chamber was an adequate particle absorber, permitting a clear separation of electrons, muons and hadrons.

The best limits reached analyzing all ADONe data were published in 1973 in the paper "Limits of the Mass of Heavy Leptons" [20], and there the search was extended to HL that could decay also to hadrons. In Fig. 13 the limits, at 95% cl of 3 observed events, are plotted as a function of the HL mass for two possible types of HL, those coupled only to leptons (b) and those coupled also to hadrons (a).

The detection of the third lepton Tau, later discovered at SLAC, was missing simply because the maximum total cm energy of the ADONE storage ring, 3 GeV, was insufficient to recognize the production at threshold of the τ mass of about 1780 MeV/c^2. Most incredibly also the epocal discovery of the J/Ψ vector meson of mass 3096.9 MeV/c^2, was missed at ADONE, although pushing the machine at the limit of 3.1 GeV was detected in 1974, when the BCF experiment had been already dismantled.

6. Some results of the BCF esperiment at ADONE

The physics results obtained with the BCF apparatus have been however numerous and relevant at that time at least in three fields:

Experimental Check of Crossing Symmetry in the Electromagnetic Interaction of Leptons.

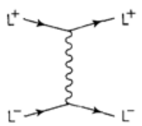
V. Alles Borelli, M. Bernardini, D. Bollini, P. L. Brunini, E. Fiorentino, T. Massam, L. Monari, F. Palmonari and A. Zichichi

CERN - Geneva
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna
Istituto di Fisica dell'Università - Bologna
Laboratori Nazionali - Frascati

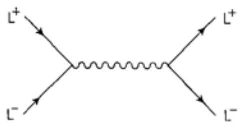
(ricevuto il 2 Luglio 1971)

A fundamental theorem of quantum field theory is crossing symmetry [1]. QED being the only working example of field theory, it is indeed crossing symmetric.

A straightforward check of QED crossing symmetry would be possible through a comparison between timelike and spacelike lepton-photon processes. In the one-photon approximation, this is shown in the diagrams below, where L stands for either electron or muon.



I) Timelike diagram.



II) Spacelike diagram.

If we call $F^{LL\gamma}(q^2)$ the vertex function which describes the electromagnetic interaction between the lepton and the photon, crossing symmetry says that this vertex function is the same analytic function for timelike and spacelike processes, the only change being the value of the variable q^2.

The experimental check we propose for this QED crossing symmetry is based on comparison of the following two leptonic processes:

(1) $$e^+e^- \to e^\pm e^\mp ,$$

(2) $$e^+e^- \to \mu^\pm\mu^\mp ,$$

which have been studied at Frascati using the colliding-beam facility Adone.

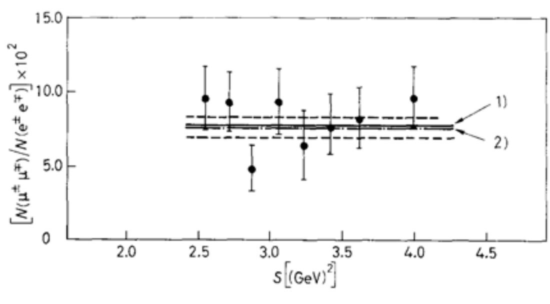
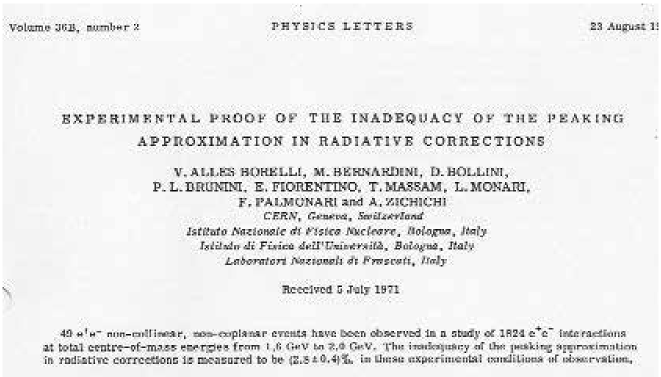


Fig. 1. – Experimental values of $R =$ (rate of $e^+e^- \to \mu^\pm\mu^\mp$)/(rate of $e^+e^- \to e^\pm e^\mp$) at various Adone energies. $S = (2E)^2$; E is the colliding-beam energy. 1) Theory (QED), 2) experiment.

Figure 14



Volume 36B, number 2 PHYSICS LETTERS 23 August 1

EXPERIMENTAL PROOF OF THE INADEQUACY OF THE PEAKING APPROXIMATION IN RADIATIVE CORRECTIONS

V. ALLES BORELLI, M. BERNARDINI, D. BOLLINI,
P. L. BRUNINI, E. FIORENTINO, T. MASSAM, L. MONARI,
F. PALMONARI and A. ZICHICHI
CERN, Geneva, Switzerland
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto di Fisica dell'Università, Bologna, Italy
Laboratori Nazionali di Frascati, Italy

Received 5 July 1971

49 e^+e^- non-collinear, non-coplanar events have been observed in a study of 1824 e^+e^- interactions at total centre-of-mass energies from 1.6 GeV to 2.0 GeV. The inadequacy of the peaking approximation in radiative corrections is measured to be $(2.8 \pm 0.4)\%$, in these experimental conditions of observation.

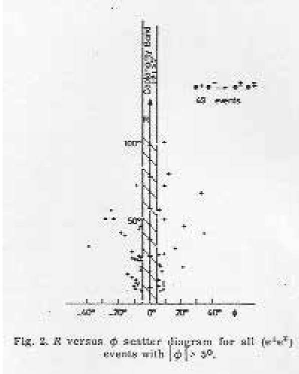


Figure 15a **Figure 15b**

i) Tests of QED at high Q^2, both in the electron pair and in the muon pair channels, the first of those tests was "Experimental check of crossing symmetry in the electromagnetic interaction of leptons" [21] The paper front page, explaining the QED test principle, and the graph showing the agreement between theory and the experimental values of the ratio $(\mu^+\mu^-)/(e^+e^-)$ are shown in Fig. 14. Other papers on the same subject can be found in references [22, 23].

ii) The first and original studies of radiative corrections in the final state leptonic two-body channels was "Experimental proof of the inadequacy of the peaking approximation in radiative corrections" [24], and Fig. 15 displays the front page of the paper published on Physics Letters and the scatterplot showing that radiative corrections in two-body (e^+e^-) final states produced slightly non-colinear and non-coplanar events. Further radiative corrections effects are discussed in references [25, 26].

iii) Measurements of hadron production processes in the annihilation of (e^+e^-) at all ADONE energies, and especially the precise identification of pions and kaons, possible with the techniques used in the BCF apparatus. This permitted to measure "The timelike electromagnetic form-factors of the charged pseudoscalar mesons from 1.44 GeV^2 to 9.0 GeV^2" [27], one of the most cited papers at that time. The other papers on hadronic physics are in references [28-34].

To conclude, the work done in the years 1965-75 by the CBS and BCF groups was starting the long tradition, at the Physics Institute and INFN in Bologna, of physicists conceiving, building, running and analyzing experiments at the forefront of particle physics fundamental research.

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The LAA Project

*Horst Wenninger**

Professor Antonino Zichichi initiated the LAA Project [1] in 1986 at CERN knowing that preparations for Large Scientific Projects needed long lead times such as Large Collider Projects. First discussions on the Large Electron Positron collider (LEP), planned for CERN, started around 1977. The White Book on LEP was published on 1979. It was evident that the ECFA LEP working group in 1979, chaired by A. Zichichi, had already the installation of a large Hadron Collider (LHC) in the same LEP tunnel in mind, when defining a tunnel circumference of 27 km, fitting between Jura mountain and Geneva airport.

The Large Electron-Positron collider was operated between July 1998 and November 2000. On 10 September 2008 a beam of protons was steered around the 27-kilometre Large Hadron Collider for the first time. At the end of 2018 the 2nd Run period (2015 to 2018) ended and an LHC (accelerator and experiments) upgrade is scheduled during the coming two years.

Considering the long lead times for large scientific projects the idea of the LAA project was to use this time effectively for the preparation of the next steps and projects by performing R&D as an independent research program with its own, independent funding. Considering the status of the particle physics detector developments in the 1980s and the challenges for the planning of future LHC collider experiments, the R&D project activities, funded by the LAA proposal, helped CERN in the right period when CERN's budget had to finance the large infrastructure related to the LEP collider tunnel and experimental caverns.

* CERN, Geneva, Switzerland.

LAA funds allowed to hire dedicated staff (physicist, engineers, technicians) and to form collaborations supported by LAA to prepare the future beyond LEP: 40 **LAA** staff and 80 unpaid scientist worked together over 10 years. LAA activities are published in over 350 papers and journals, only some examples are listed under ref. [1].

Topics of LAA R&D were the development of new particle detectors, such as the so-called "spaghetti" electromagnetic calorimeter, multi-drift chambers, scintillation fibre trackers, micro-strip detectors, precision tracking read-out electronics, IPSA tube, Ga-As crystals (Imaging Silicon Pixel Array), silicon pixels detectors, CMOS chips and ASIC/VLSI chips - Multi Resistive Plate Chambers and many more.

The LAA impact on LHC was i) through people with engineers, physicists, technicians, recruited for the LAA activities. They helped LHC experiments preparation, and participate in the experiments still today and ii) in addition to all the experiment detector R&D, through competences gained in micro-electronics. Working on CMOS chips, ASIC/VLSI chips, micro-strip-, silicon pixel development, data acquisition and software, excellent progress was made by the LAA staff and collaborators. It is fair to state that the LAA project propelled electronics at CERN into the era of microelectronics and of the silicon pixel technology [2].

A short list of examples is: 1988: the AMPLEX multiplexed read-out chip (UA2); 1990: hybrid pixel devices, with a read-out chip "bump bonded" to the detector (WA97 mid-1990s); 2002: CERN had developed a bump-bonded 8000-channel pixel for the LHC - ALICE silicon-pixel detector; 2004: NINO [3], the front-end amplifier / discriminator used for applications in many experiments and for training (EEE project) and for medical applications (see example below) as a CERN spin-off (Fig. 1).

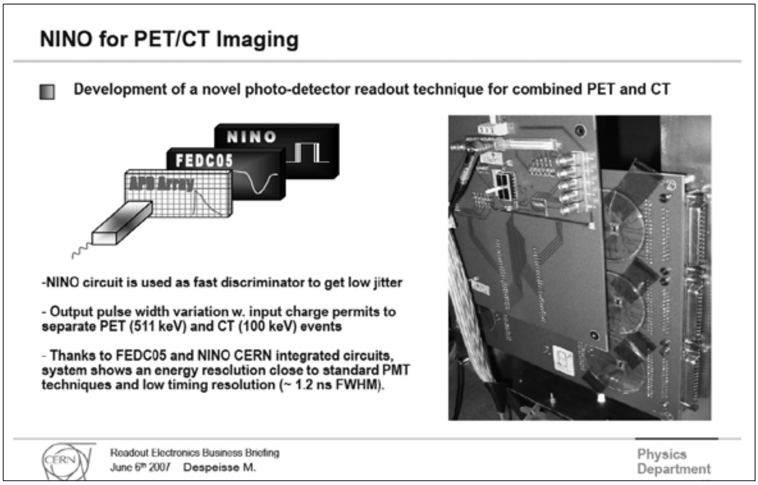

Figure 1: Contributions from LAA are also part of the spin-offs developed by the Medipix collaboration (© CERN).

An interesting example of an early LAA R&D work was the contribution of a detector for the Eloisatron (ELN) project (Fig. 2), developed and also published by George Charpak and by Fabio Sauli [4] with a link to more recent developments of gaseous detectors – namely of the Gas Electron Multiplier GEM and the Micro Mesh Gas Detectors MICROMEGAS which are important contributions for the actual LHC experiments (Fig. 3).

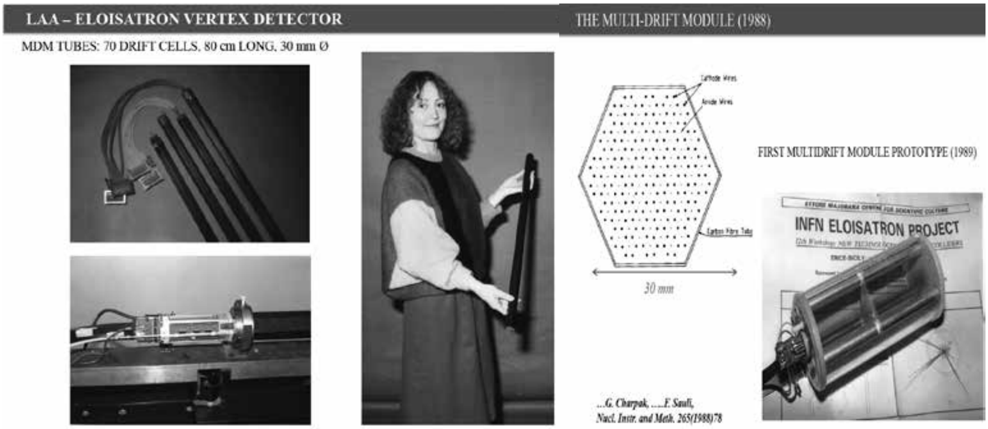

Figure 2: (© CERN).

Figure 3: Left: The GEM consists of a thin, metal-clad polymer foil, chemically pierced by a high density of holes. With a potential difference between the two electrodes, electrons released by radiation in the gas on one side of the structure drift into the holes multiply and transfer to a collection region. Right: Georges Charpak, a true man of science. In a Micromegas detector, the gas volume is divided in two by a metallic micro-mesh placed between 25 μm and 150 μm of the readout electrode. This allows for a high gain 104 and a fast signal 100 ns. (© CERN).

In the same context of R&D on Vertex detectors for LHC experiments, promoted by Erik Heijne and his group of engineers, resulted the work on Silicon detectors in the LAA project. The first publications appeared at the Institute of Electrical and Electronics Engineers Nuclear Science Symposium in 1989 and 1991. This meeting is widely regarded as the most important annual radiation instrumentation conference. In the LAA project, between 1989 and 2000 the development of pixel detectors continued.

The LAA project is also part of the New Manhattan Project as part of the Chapter "Science Culture needed in the III Millennium".

The present LHC shutdown and accelerator upgrade will of course require to start an important upgrade of the LHC detectors. As an example we are pointing to the ALICE Collaboration, which includes the Bologna group, responsible for the Time-of-Flight system based on MRPCs [5], presenting 5 Technical Design Reports for the detector upgrade following the spirit of the LAA R&D initiative started by Prof. A. Zichichi some 25 years ago.

The High-Luminosity LHC and future colliders call for more sophisticated experimental technologies. CERN has launched a process to define its R&D program on new experimental technologies from 2020 onwards [6].

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Progress towards the ultimate discovery machine: Eloisatron

*William Barletta**

The INFN ELOISATRON project has a long and fruitful history of driving forward both the physics and the technologies of proton accelerators and super-detectors aimed at investigating fundamental particle physics at the highest energies and highest luminosities.

1. Introduction

Ever since the first proton collisions at the CERN intersecting Storage Rings (ISR), *hadron colliders* have been the proven tools for fundamental discovery at the highest mass scales of the Energy Frontier. They will remain so, unchallenged[1] for the foreseeable future. Discoveries at hadron colliders have been essential to establish the Standard Model of particle physics. Discovery of the Higgs has opened a new era of particle physics

The next great challenge for particle physics using colliders is understanding of origins of electro-weak symmetry breaking (EWSB). This challenge can be expressed in terms of two questions:

1) Up to what precision does the Higgs boson behave as predicted by the Standard Model?
2) Where are the new particles that should solve the electroweak naturalness problem? Possibly they will offer insight into the origin of dark matter, matter-antimatter asymmetry, and neutrino masses?

To realize a vision for the future of high-energy physics will demand a deep insight in to both physics and the technology of accelerators plus detectors decades of per-

* Department of Physics, Massachusetts Institute of Technology, Cambridge MA, USA.

[1] The only possible competitor would be a $\mu+\mu-$ collider operating at 10 TeV_{cm}; however, it is completely unknown if and how such a machine could ever be built.

severance. Colliders with energy reach and luminosity much greater than LHC will determine progress of particle physics during the next 100 years. The questions are "what energy?" and "at what luminosity?" Extensive theoretical analysis plus Monte Carlo simulations show that the extension of discovery reach at high masses saturates quickly with increases in luminosity. After a while the incremental gain with increasing luminosity becomes minimal. What we can say with respect to the next European plan for high-energy physics is "High luminosity LHC is NOT enough." While the most recent report of CERN's Future Circular Collider (FCC) study show important practical (industrialization) and financial challenges, it confirms a conclusion reached in both the 1991 and 1992 ELOISATRON workshops that there are no technological showstoppers to building a 100 to 200 TeV proton collider at a luminosity of $10^{35}cm^{-2}s^{-1}$.

However, serious challenges for adequate detectors must be addressed. These challenges concern the geometrical acceptance of forward/backward jets as well as the ability to reconstruct them in presence of large pileup of underlying events. Over the past decades Antonino Zichichi has led two important efforts: the ELN and LAA projects that have pursued the science and technologies of accelerators and super-detectors to investigate particle physics at the highest possible energies. These projects recognize that Discovery science requires discovery technology. Hence, we have on the accelerator side the ELN project as shown in Fig. 1.

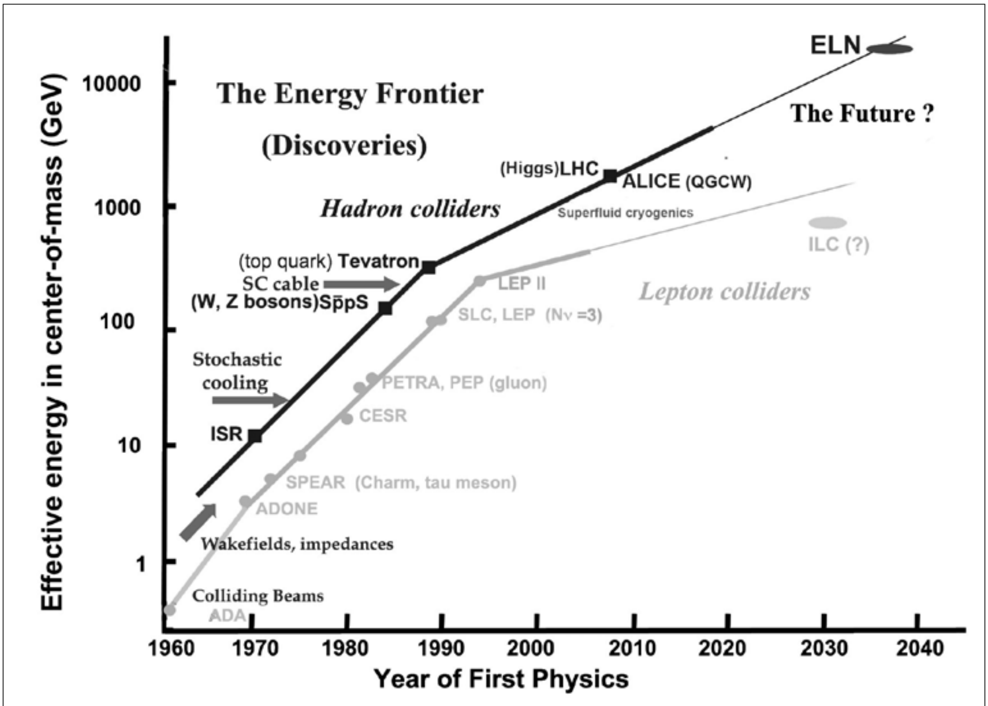

Figure 1: Discovery technology leads to discovery physics.

History from the 1970s and 1980s demonstrates that even the early steps toward ELN have lasting impact on high-energy and nuclear physics. In building the scientific workforce of the future, the earliest contribution (1976) has had the broadest impact. Zichichi's first International School of Accelerator Physics at Erice directed by Kjell Johnson directly inspired Dr. Mel Month of BNL and Dr. Phillip Bryant of CERN to establish the US Particle Accelerator School (USPAS) in 1981 and in 1982 the CERN Accelerator School (CAS) respectively. Their actions led to the blossoming of graduate education and training in accelerator physics and engineering. Soon afterward the project to build a superconducting cyclotron for the INFN Laboratorio del Sud in Catania resumed (1979). Two years later, Italian industry (Ansaldo-LMI-Zanon) started construction of the cyclotron at University of Milano. Once completed in Milano, the cyclotron was moved to Catania where it remains the mainstay of a successful research into nuclear physics. Thanks to the contributions of cyclotron experts from Catania cyclotrons are poised to play a strong role in neutrino physics.

At the same time as initiating cyclotron project, the INFN Council approved Italian participation in the HERA construction at the DESY, the German laboratory for high-energy physics. Italy's contribution to HERA embodied Zichichi's critical insight that industrial labs had to be engaged at the outset of magnet R&D for HERA. Italian industry began design and fabrication of the prototype superconducting magnets in 1985 and delivered the prototype for testing in 1988. The long-term result has been the large industrial production of magnets for the LHC plus an essential role in R&D related to superconducting magnets. The next ELN workshop will be exclusively devoted to this topic.

2. Progress to LHC and beyond

During the first years of the ELN project many high-energy physicists spoke pessimistically that between the high-energy colliders operating at CERN and at Fermilab and the grand unification energy scale, there was a vast desert devoid of new phenomena. Zichichi retort as, "If there is a desert, it is a desert of our imagination." We know that the relevant machines for proton colliders are proton synchrotrons with the major variables at the disposal of designers being size of the collider and its luminosity. For at least the next fifteen years, the energy frontier physics will be dominated by the LHC followed by its high luminosity upgrade (HL-LHC). That period provides enough time to complete the research in support of building the ELOISATRON and a suitable detector.

The present perspective from CERN FCC study is that ELN would represent several decades of forefront particle physics. The FCC study has driven a growing interest worldwide in a ≥100 TeV class proton-proton collider. That interest is represented by the participation of more than 530 individuals, 124 institutes and 30 commercial companies from 32 countries. Such a machine is recognized as the only sure way to the next energy scale. Consequently, it would be wisest if the site for the ELN does not constrain the peak energy to a value below 200 TeV_{cm}.

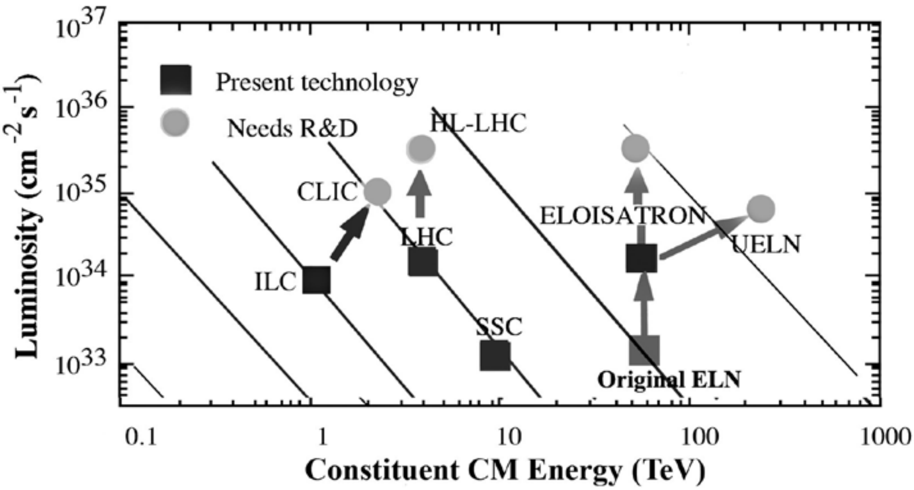

Figure 2: Lines of roughly "constant" discovery potential in energy-luminosity space.

As Zichichi counseled long ago, "The machine should be designed with the highest possible luminosity and energy." The relation is depicted in Fig. 2.

Mangano and Hinchliffe [1] have assessed the potential of a future hadron collider under the assumption that HL-LHC begins operation in 2026 to produce 1.5×10^6 Higgs per year. In that case the guaranteed physics of a 100 TeV class collider is a detailed program of study the properties of the Higgs and top quark together with an exploration of electroweak symmetry breaking *with an unmatchable precision and sensitivity.* The exploration potential is provided by enhancing the mass reach by ~ $E_{\text{collider}}/14$ TeV (that is a factor of 5 to 7 × at 100 TeV, depending on integrated luminosity. The collider would enhance statistics by several orders of magnitude with respect to beyond standard model (BSM) physics uncovered by the LHC. These explorations would benefit from direct (large Q^2) and indirect (precision) probes.

3. Technological challenges

The discovery potential of a collider is determined by the beam energy, the time averaged collider luminosity and the detector efficiency. The beam energy determines the energy scale of phenomena to be studied. The luminosity $\mathcal{L}$ (collision rate) determines rate of producing of "interesting" events. One can write the *peak luminosity* as

$$\mathcal{L} = \frac{N_1 \times N_2 \times \textit{frequency}}{\textit{Overlap Area}} = \frac{N_1 \times N_2 \times f}{4\pi\sigma_x\sigma_y} \times \text{Disruption} \times \text{ angle correction.}$$

Thus $\mathcal{L}$ is proportion to the beam power ($I_{\text{beam}} \bullet E_{\text{beam}}$).

For a signal *at a fixed mass scale* the cross section will scale as

$$\sigma(M,g) \propto \frac{g^2}{M^2} \times L(x), \text{ where } x = M / \sqrt{s} \text{ is the partonic luminosity}$$
$$\propto \sqrt{s}, \text{ where } L(x) \sim \log(1/x).$$

Then luminosity does not need to increase with accelerator energy. In contrast, scaling mass reach *M* with beam energy, E, means keeping *x* fixed; that implies that luminosity must scale as $E_{cm}{}^2$ to maximize discovery potential at a given energy. However, the scaling may have to be faster due to the energy dependence of the proton's parton distribution function.

The third determinant of the discovery potential of the collider is the dependence of detector efficiency on the luminosity of the collider. However, the relationship is not simple; detector efficiency is strongly coupled to collider design. One complication is driven strongly by the relation between luminosity, bunch spacing and event pile-up. As the inelastic p-p cross-section scales as ln ($\sqrt{s}$), at E_{cm} = 200 TeV and $\mathcal{L}$ =2×10^{35}cm^{-2}s^{-1}, one expects >100 events/cm per crossing in the luminous region at 20 MHz. The limits of handling pile-up at such high collision rates remain problematic.

One might decrease the bunch spacing to 5 ns and thereby reduce the pile-up by a factor of four. Experts in modern trigger electronics believe that practical designs could cope with this rate. However, putting the bunches in the storage rings so close together would increase the effects of parasitic near-collisions between bunches with insufficient separation after passing the collision point. The parasitic long-range tune shift in the collider would decrease the luminosity and increase backgrounds. One could reduce long-range effects by increasing the crossing angle of the two counter-rotating beams. However, doing so will decrease the luminosity somewhat and more importantly lessen the hermeticity of the detector.

For a giant project like the ELN, in-depth cost-benefit analysis of building for higher energy *vs*. providing higher luminosity is essential. Detailed physics studies will have generate important input to this analysis. Hinchliffe, Mangano *et al.* [1] have argued that at the 100 TeV$_{cm}$ scale, the peak discovery luminosity should be ~2×10^{35}. However, the luminosity lifetime at such a high luminosity in a 100 km collider is only 5 hours Unfortunately, while the time to load and accelerate the beams is ~1.5 hours. One must conclude that maximizing peak luminosity does not maximize integrated luminosity. Increasing the collider circumference to ~200 km would dramatically lessen this difficulty by increasing the luminosity lifetime.

Although an injector complex the size of LHC would be a 10% level component of a 100 TeV collider, the collider ring itself will dominate the cost and size of the collider as it has for the LHC itself. In the LNC collider ring, the cost of the 8 T arc diploes contribute ~50% of total cost of collider ring. The cost-efficient design of the collider is a balancing act embodying many compromises. Many choices can be modified as the design develops and even during the initial phases of construction. However, one decision is irreversible: the radius of the collider tunnel.

Thanks to the extensive engineering experience in industry for the many technologies embodied in the LHC, one can make credible estimates of the cost of a 100 TeV_{cm} collider. The LHC dipoles operate reliably at 8 T; hence the circumference of a 100 TeV class collider must be in the rage of 100 – 300 km in, depending on the dipole field. For dipole occupancy similar to LHC, a 100 TeV machine in a 100 km tunnel requires 16 T magnets, while 270 km tunnel requires 4.5 T dipoles. The energy stored in the beam scales to fifteen to fifty times the already large energy stored in the LHC beam. Magnets operating at greater than 9 T will require Nb_3Sn; dipoles operating at >16 T may also require insert of high temperature superconductor (HTS). To be affordable, ELN magnets should cost less than half the cost per Tesla-meter of the LHC magnets.

The relative cost scaling is illustrated in the Fig. 3 where breakpoints are introduced to account for the sharp differences in cost between NbTi, Nb_3Sn and high temperature superconductors (HTS). The CERN estimates cost ratios of NbTi::Nb_3Sn::HTS are [1::8::20 per kA-m]. Tunneling costs are highly geology dependent, varying by a factor of up to ~5 in areas that have been considered for a 100 TeV class collider.
Machine protection will be particularly challenging as multi-TeV proton colliders have enormous stored energy both in their dipole magnets and also in the circulating beams.

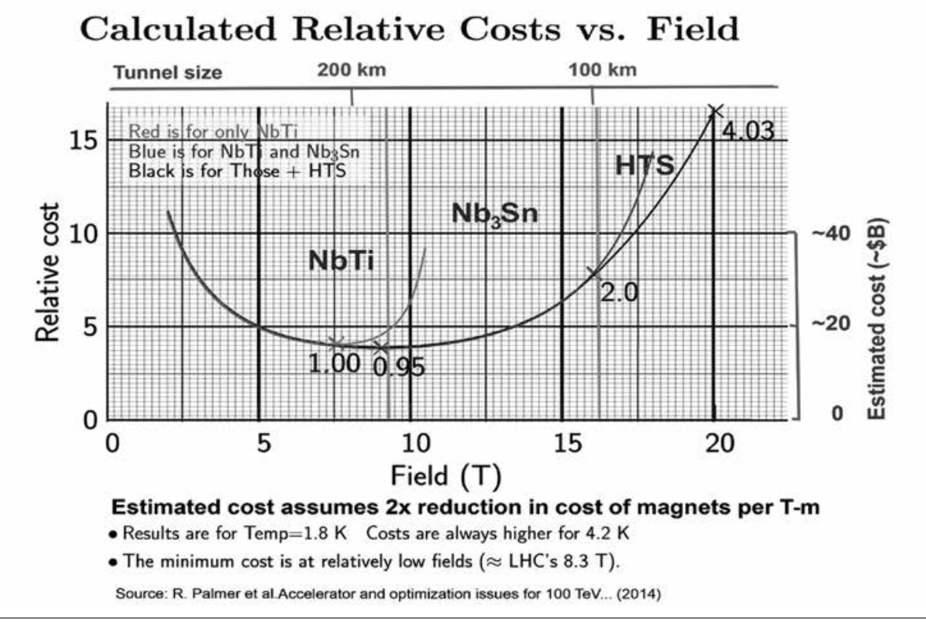

Figure 3: ELN cost trends *versus* dipole field as scaled by R. Palmer.

In addition, radiation damage of interaction region components severely limits maximum luminosity of the collider.

	E_{cm} (TeV)	Circumference (km)	Energy in beams (GJ)	Energy in dipoles (GJ)
LHC-14	14	27	~2 x 0.4	11
FCC-100 km*	100	100	~2 x 9	~180
ELN-300 km	100	300	~2 x 30	~ 60

4. "Go big or go home"

Previous studies including the very recent FCC study have reproted no insurmountable technical obstacles to building a high luminosity, 100 TeV_{cm} class proton collider. Nonetheless, considerable research is required for sufficient engineering and industrial readiness and to reduce the technical risks in such an ambitious project. A primary goal of this research program is to halve the cost per TeV that characterized the LHC. Since the arc dipoles of the collider represent ~50% of the cost of the collider ring, their cost per T-m must be slashed by a factor of 2 to 3.

We have proposed a continuation and enhancement of the ELOISATRON (ELN) project to maintain a clear international focus on a 100 TeV-class collider well after the CERN FCC study concludes. An enhanced ELN project would strongly leverage existing research activities in critical accelerator (magnets, vacuum systems, and machine protection) and detector technologies being conducted in Europe and in the U.S.

My interests and involvement in the ELN project began in August 1990 with a challenge from Nino Zichichi. I am grateful to Nino for his provocative question to me that year and for very many weeks of hospitality at Erice.

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The effective energy in QCD

*Francesco Noferini**

It the last 60 years it was demonstrated that particle production in high-energy collisions is mostly ruled by Quantum Chromo Dynamics (QCD). Since QCD at the hadronic scale acts in a non-perturbative regime, nobody was able so far to get a complete description of hadronization processes derived by a fundamental theory (QCD): we are dealing with plenty of models. In spite of that, experimental results at ISR in the 70s threw light on universal properties in particle production. It was shown that particle production in different collision systems behaves in the same way if the energy available for particle creation is the same, namely the "effective energy". Despite the big effort done in the past such a topic is still actual and open to further investigations in the current experiments at the LHC.

1. Introduction

In the last 60 years and still nowadays high-energy collisions are the most powerful tools to investigate the properties of the subnuclear world. Different accelerator techniques (e^+e^- and pp collisions, DIS processes, etc.) were explored so far to produce collision with center-of-mass energy up to several TeV and for different collision systems. The nature of the colliding particles normally plays an important role in the definition of the physics accessible in an experiment: for instance e^+e^- and pp collisions have very different features affecting both the accelerator design (*e.g.* different synchrotron radiations) and the evolution of a collision (e^+e^- are elementary particles, protons are formed by partons). Therefore, even if the same center-of-mass energy is taken the final product of collisions with different projectiles cannot be directly compared. For instance differently from the e^+e^- case, in pp collisions the quantum number flow conservation (from lead-

* INFN, Sezione di Bologna, Bologna, Italy.

ing baryons) doesn't allow the whole center-of-mass energy available in the interaction.

This kind of differences disappear once the "effective energy" is used to characterize the system as proved in the past at CERN ISR (Intersecting Storage Ring) [1-6]. In Fig. 1 a picture of the Split Field Magnet (SFM) taken during its construction phase at CERN is reported.

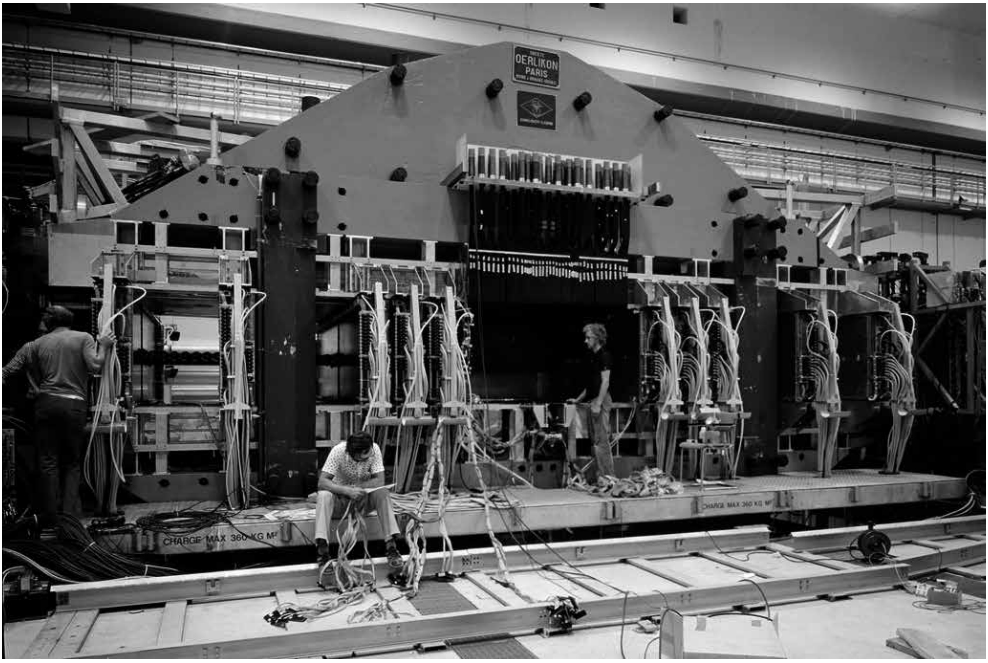

Figure 1: Split Field Magnet construction at CERN ISR.

ISR results were obtained after the construction of the first hadron (pp) accelerator which was able to provide proton beams up to few tens of GeV. Nowadays CERN still provides pp collisions but with an energy which is serval orders of magnitude higher, up to 13 TeV center-of-mass energy. In this respect we will show how LHC provides favorable conditions to continue the ISR physics programme. In particular, we will focus on some recent ALICE results and perspectives.

2. CERN ISR and quantum number flow in pp collisions

As mentioned since the beginning CERN was pioneering in developing facilities able to provide high energy collisions. On 27 January, 1971 two protons beams were injected in the ISR for the first time which ran until 1984 and held the luminosity record for hadron collider until 2004. The ISR was composed of two interlaced rings with a diameter of 300 meters each and reached a maximum center-of-mass energy of 62 GeV. At that time it was believed that the final states produced in high-energy collisions depended on the nature of the initial interacting particles. Such an idea was based on the observation that for a given center-of-mass energy several observables (average charged multiplicity, fractional momentum distribution, …) were measured to be different for different initial projectiles.

Thanks to the ISR the Bologna-CERN-Frascati (BCF) group proved that differences arose because of the assumption that the center-of-mass energy is considered as the total available energy for particle production. Such an assumption is in general wrong since in pp collisions the "effective" energy available is usually lower because of the initial quantum number flow carried out by leading baryons after the interaction. Indeed protons are not elementary particles and not all partons inside them participate to the collisions. In particular the spectators ones, responsible for the baryon number conservation, carry out a fraction of energy which is different event-by-event.

It was then demonstrated [5] that once the leading energy (the one carried out by leading baryons) is subtracted to the nominal one ($\sqrt{s}$) the final states in pp collisions are perfectly comparable with the ones measured in e^+e^- collisions. This is visible in Fig. 2, where the total charged multiplicity is reported as a function of the effective energy accordingly, for pp collisions, to the formula

$$q_{had}^{tot} = \sqrt{s\left(1-x_F^1\right)\left(1-x_F^2\right)},$$

where $x_F^{1,2}$ are the fractions of energy carried out by the leading baryons for both sides.

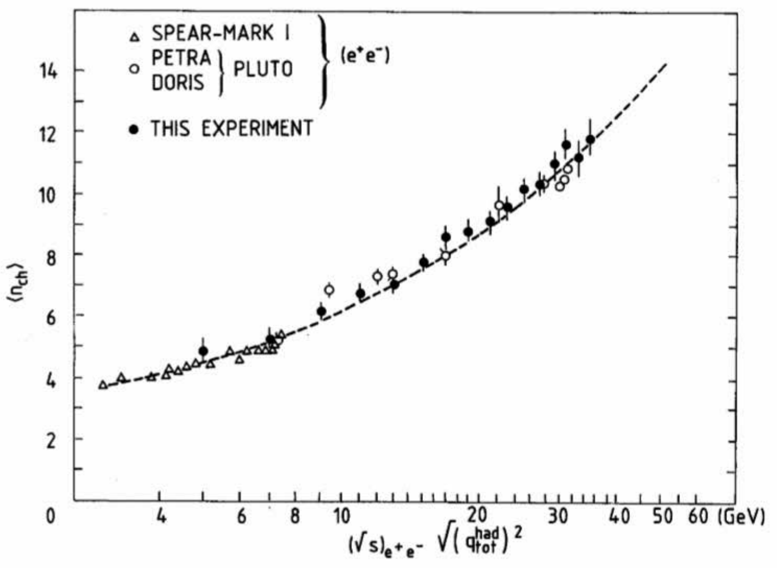

Figure 2: Average charged multiplicity (n_{ch}) as a function of the effective energy (q_{had}^{tot}), as measured in minimum bias pp collisions collected by the SFM experiment at the CERN ISR (full circles). The data from e^+e^- experiments are also shown (open circles and triangles) in terms of ($\sqrt{s}$). A fit to ISR pp data is superimposed. The plot is taken from [5].

Since the quantum number flow has to be conserved for both the incident protons, in each pp collisions there are two leading particles. The observation at ISR [6] (Fig. 3) that the two leading energies are totally uncorrelated is a non-trivial effect and proved the independency of the two hemispheres, *i.e.* the two final-state hemispheres are decoupled allowing to define also an effective energy in each of them.

These important results were recently reviewed on the occasion of the 40th anniversary of the ISR [7,8].

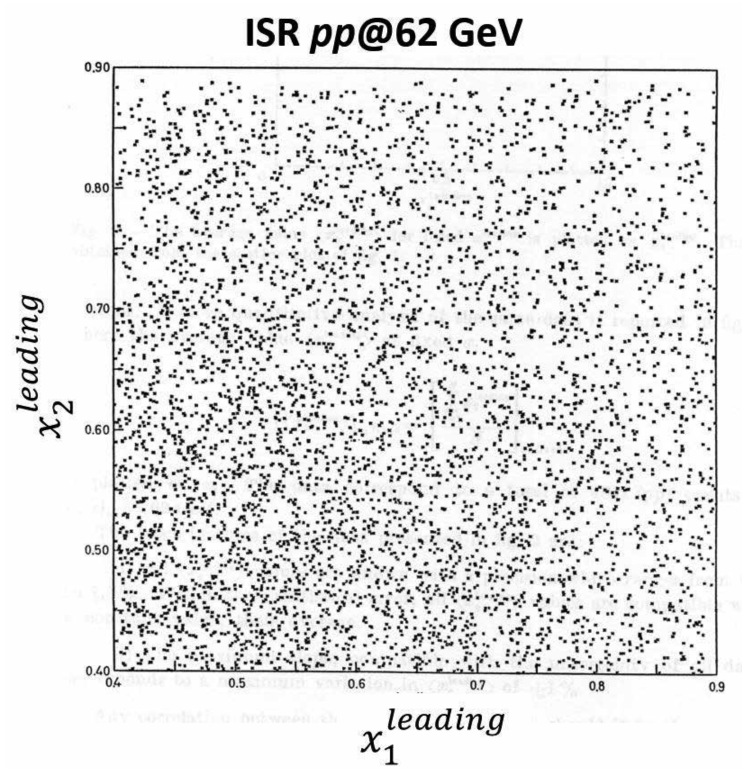

Figure 3: Independency of hemisphere as measured at ISR [6].

3. Effective energy at the LHC

In order to measure the effective energy available in each pp collisions the energies of the two leading baryons have to be measured, as done at ISR. The ALICE experiment at the LHC is able to perform such a measurement using the Zero Degree Calorimeters (ZDC) placed in the very forward region at 116 m from the interaction point [9]. The ZDCs are four hadronic calorimeters (two for each side) built to reconstruct the energy of proton and neutron spectators in heavy-ion collisions but they can be used for the same task in pp. While the neutron calorimeter has a full energy acceptance the proton ZDC is limited by the proton beam optics and therefore can see protons in the range $0.3 < x_F < 0.6$.

As shown in [10] ALICE ZDC features satisfy the requirement to repeat the ISR studies in a different energy regime.

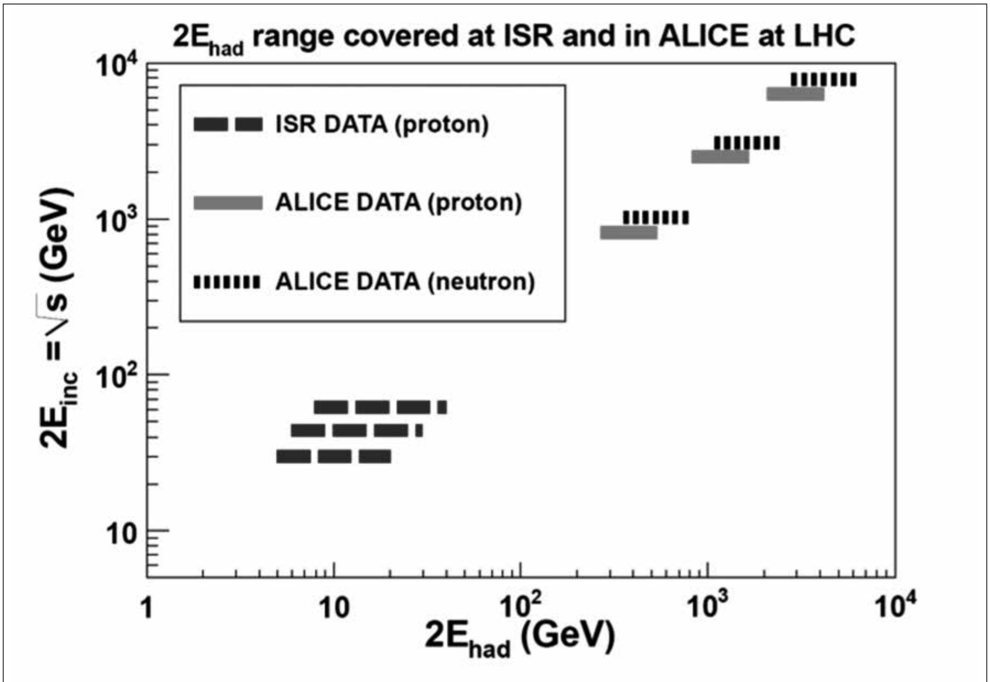

Figure 4: Effective energy range (ere indicated as $2E_{had}$) covered at ISR and LHC as a function of $\sqrt{s}$.

In Fig. 4 the different effective energy ranges explored at ISR and at the LHC are reported. As shown in [11] the preliminary observations of the quantum number flow in pp at the LHC are consistent with the picture emerged at ISR (*e.g.* independency of the hemispheres).

What we can learn from LHC in the new energy regime?
In a very recent paper [12] ALICE published very interesting results on strangeness production in pp and p–Pb collision systems. The main novelty of the ALICE results is the dependence of the strange and multi-strange baryon production on the particle multiplicity of the event.

The main interesting observation in [12] is that the strangeness production increases with the event multiplicity, no matter of the collision system considered. In particular the observed increase with multiplicity is stronger when increasing the strangeness content in the baryon composition (*i.e.* it is larger for Ω than for Ξ) as clearly visible in Fig. 5.

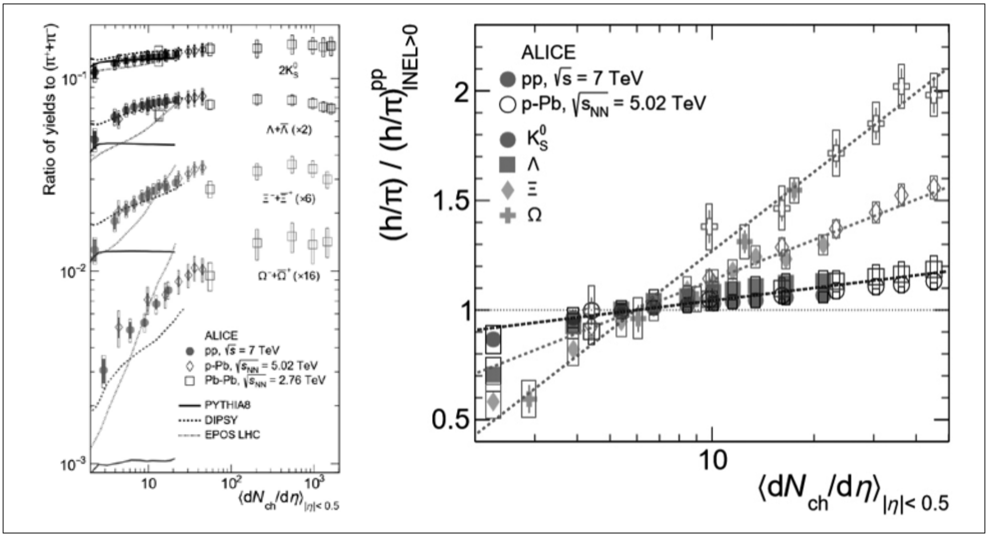

Figure 5: Particle yield ratios to pions normalized to the values measured in the inclusive INEL>0 pp sample. The results are shown for pp and p–Pb collisions, both normalized to the inclusive INEL>0 pp sample [12].

The observed strangeness production might point to some universal properties of QCD and, after the ALICE publication [12], a large discussion on the origin of such properties started in order to understand what is ruling the process.

There are many possible interpretations for such an effect. One of the main conclusions reported in the abstract of [12] is that "the measurements are in remarkable agreement with the p-Pb collision results, indicating that the phenomenon is related to the final system created in the collision".

From our point of view the mentioned conclusion of [12] may be not straightforward since the final system created is depending on the initial condition, namely the energy available in the collision, which is also fluctuating on event-by event basis.

Since charged particle multiplicity and effective energy are strongly correlated, the observed enhancement in strange production can be ascribed to an increase of strangeness with the energy available in the collision, therefore linked to the initial state.

In fact, it was observed at the ISR [8] that on average the event multiplicity in pp is strongly correlated with the initial effective energy of the collision, as shown in Fig. 2.

Therefore one of the open questions concerns the possibility to ascribe the observed effect to initial state effects, like Effective Energy, or to final state effects, namely particle density. The way to distinguish between the two scenarios is in reconstructing simultaneously both event multiplicity and effective energy. Such a double differential measurement is possible within the ALICE experiment since the ZDC information and we think this will represent the most natural perspective for ISR-like studies at the LHC.

4. Final remarks

As discussed the particle production mechanism is ruled by QCD in non-perturbative regime and for this reason many effective models are available in the market but not a complete theory.

Effective energy universality was demonstrated at ISR when two beams of protons collided for the first time (almost 50 years ago).

The lesson learned at the ISR is still actual, and effective energy in QCD represent a further interesting frontier of the LHC research programme.

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Advanced Time-Of-Flight detectors and ALICE at the LHC

*Gilda Scioli**

Time-Of-Fight (TOF) detectors have been used mainly for Particle IDentification (PID) since more than half a century now in particle physics, both at fixed-target and, later, at collider experiments. The development of more and more precise (and larger area) timing detectors has always been pursued with the aim to keep pace with the increasing requirements of the experiments in terms of PID capability even in very complex events, like those produced by the Large Hadron Collider (LHC) at CERN. In particular, the requirement of large-area TOF systems for collider experiments has shifted the R&D from the traditional detector based on plastic scintillators and PhotoMultipliers (PM) to gaseous detectors, in order to decrease the total cost, especially the PM's cost.

Before presenting the main features and performances of the TOF detector built by the Prof. Zichichi group in Bologna for the ALICE experiment at the LHC, let us see some examples of past experiments in which the group was involved and where a "traditional" TOF detector was used and played an important role.

The first example is the so-called "one-night experiment" (11 March 1965) [1] that showed evidence of the existence of anti-deuterons in proton-berillium collisions at the CERN Proton Synchrotron (PS). In this experiment (Fig. 1) the TOF was used to improve the mass resolution in order to detect particles produced at very low rates with respect to pions.

Another example is the experiment based on the Neutron Missing-Mass Spectrometer (Fig. 2) dedicated to study of neutral mesons decays between 1967 and 1970 at the CERN PS. The two TOF arrays [2] used to measure the neutron time of flight and to calculate the missing mass are shown on the left and right sides of the picture. These neutron counters were built at the "Istituto di Fisica" in Bologna and had a FWHM time resolution of ±0.70 ns for neutrons and of ±0.35 ns for charged particles.

* Department of Physics and Astronomy, Università di Bologna and INFN, Sezione di Bologna, Bologna, Italy.

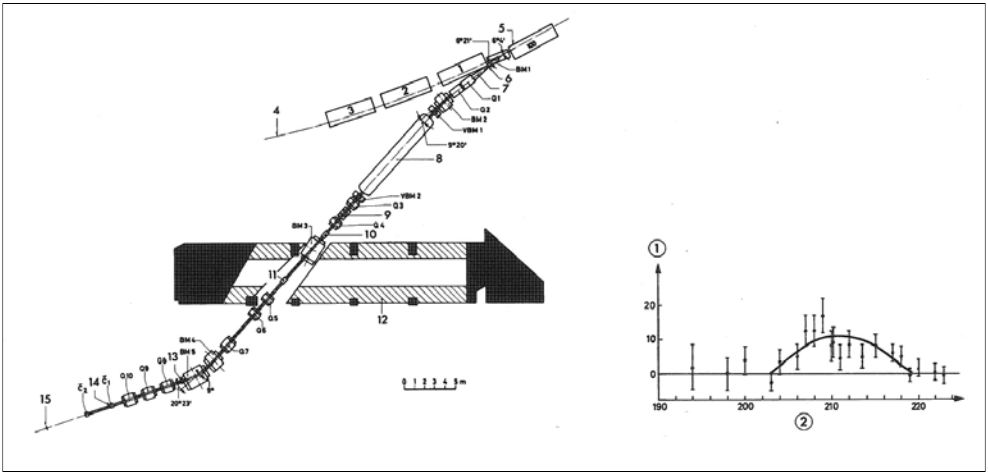

Figure 1: Experimental layout where, in particular, 1,2,3, are scintillation counters used for the time-of-flight measurements.

The last example is given by two experiments performed between 1976 and 1984 at the CERN ISR (Intersecting Storage Rings) [3] (Fig. 3) and dedicated to the study of charm and beauty production in p-p collisions where, for this purpose, the TOF was used to identify the decay products of the charm and beauty particles. One of the nine TOF arrays with vertical plastic scintillators is visible in the foreground on the picture; the intrinsic time resolution of these counters was about 0.3 ns. It is important to note that in this experiment there was the first implementation of a new statistical method used in the offline analysis for the TOF PID, the same method that is used today in the ALICE experiment at the LHC.

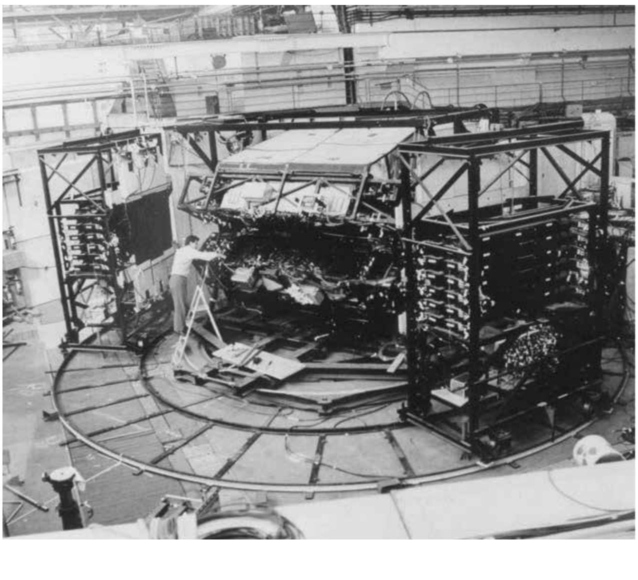

Figure 2: Picture of the experimental setup with the two Neutron Counter Arrays at the CERN PS.

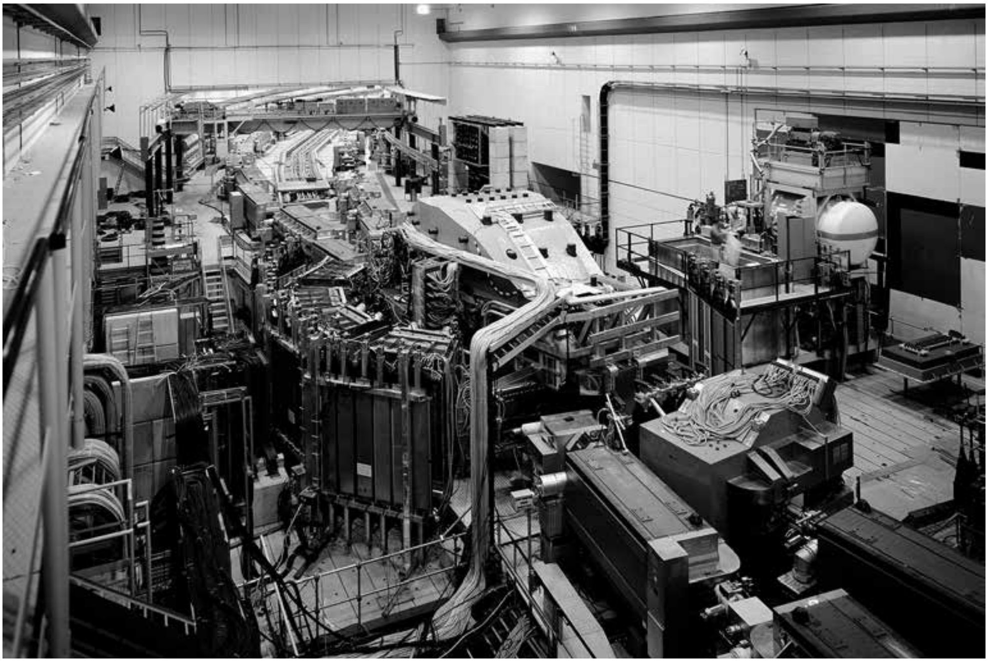

Figure 3: Picture of the experimental setup at the CERN ISR.

Turning now to the present with ALICE (A Large Ion Collider Experiment), it is important to underline that, unlike the other experiments at the LHC, it is a dedicated heavy-ion experiment. ALICE has 3 major features:

1. it was designed to cope with very high multiplicities, up to 8000 charged particles produced per unit of pseudo-rapidity, higher than what has been measured up to now in Pb-Pb collisions, with the biggest (at the time of its construction) gaseous TPC (Time Projection Chamber) for 3D tracking;
2. it has a unique capability of very low-p_t tracking (less than 100 MeV/c) thanks to the
   - moderate magnetic field (B) of 0.5 T
   - a thin silicon tracker around the beam pipe;
3. it uses all the known PID techniques, in particular ALICE has the largest area and most performing Time-Of-Flight system.

The TOF detector was designed to identify hadrons in heavy-ion collisions with the following requirements:

1. large coverage of 150 m^2;
2. high efficiency of 99%;
3. good global time resolution of 100 ps to assure a 3-sigma separation of π/K up to 2 GeV/c;

4. high granularity: 10^5 channels to keep the occupancy in Pb-Pb lower than 15% for few thousands of primary charged particles produced per unit of rapidity.

The final solution for the detector was the double-stack Multigap Resistive Plate Chamber (MRPC) with an efficiency of 99% and an intrinsic time resolution less than 50 ps.

But let us go by steps and let us see which was the idea of the MRPC [4] starting with the single-stack configuration with respect to the standard RPC.

To improve the time resolution it is fundamental to have thinner gas gaps and thus higher Towsend coefficient but still working in the avalanche mode. The brilliant idea was to divide the gas gaps in several micro gas gaps using internal commercial glass plates, electrically floating and equally spaced (Fig. 4, left side).

The internal plates get the right voltage by electrostatic effect and keep the voltage thanks to the electrons and ions flux. This is a detector that works in avalanche mode and the avalanches in the gas gaps are independent. The total induced signal is given by the sum over all the micro-avalanches.

Very good experimental results were obtained with the single-stack but it was not enough because the efficiency needed to be increased. How to do that? By increasing the number of gas gaps in order to increase the total gas volume. But using the single-stack configuration a higher High Voltage (HV) had to be applied. So the second brilliant idea was to divide the single stack into two different and independent stacks as shown on the right side in Fig. 4; in this way it is possible to keep a lower applied HV even by increasing the number of gaps. Moreover in this way the charge foot-print on the readout pads is smaller due to the fact that the distance between the two electrodes is smaller, and a smaller charge foot-print means to reduce the double-hit probability in two adjacent pads.

So the final geometry (Fig. 5) was the double-stack MRPC, with an active area of 120×7.4 cm^2, with 5 gas gaps each 250 micron thick, defined by the internal glasses equally spaced by using a common fishing line.

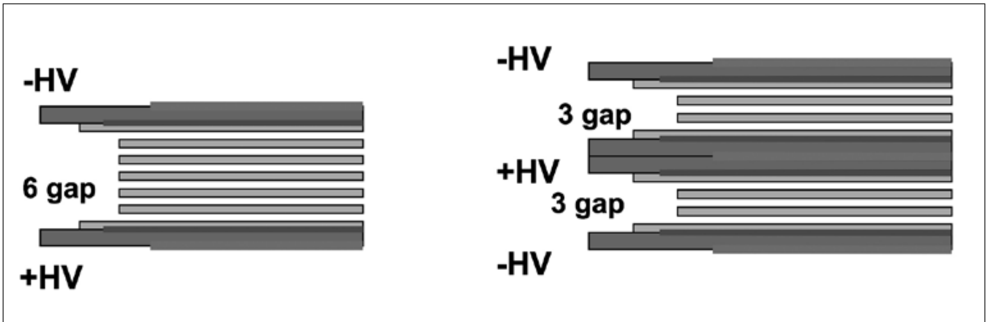

Figure 4: Single-stack (on the left) and double-stack (on the right) MRPCs.

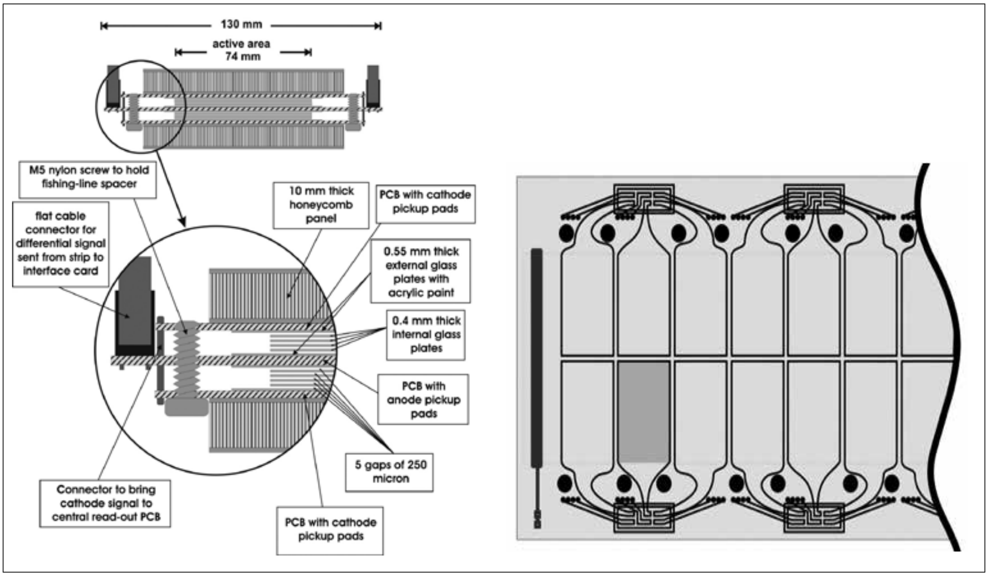

Figure 5: Final geometry layout of the MRPC used in ALICE TOF system.

The two stacks are kept closed by using several pins soldered on the 3 PCBs, pins that also bring the signals from the two cathodes to the anode and then, through the flat cable connectors to the front-end cards. The PCBs host the 96 (3.5×2.5 cm^2) readout pads (Fig. 5, right side) divided in 2 rows of 48.

Of course in parallel to the detector R&D there were the front-end and readout electronics R&D; in Fig. 6, on the left side, the final card used as front-end is shown. It is based on the NINO ASIC chip [5] that has the following features:

1. it is a low-power-consumption device;
2. it has a differential input and it is differential throughout to minimize the cross-talk;
3. it is fast to minimize the jitter;
4. the input charge measurement is done via the TOT (Time-Over-Threshold) technique.

On the right side of Fig. 6 the front-end control card is shown; it is used to:

1. monitor the applied voltage;
2. set the thresholds;
3. provide the OR signals (for triggering purposes).

The readout boards are housed in water-cooled custom VME crates (Fig. 7) where there are four types of boards:

1. the DRM (Data Readout Module) that is the master of the VME crate and the interface to the global ALICE DAQ;

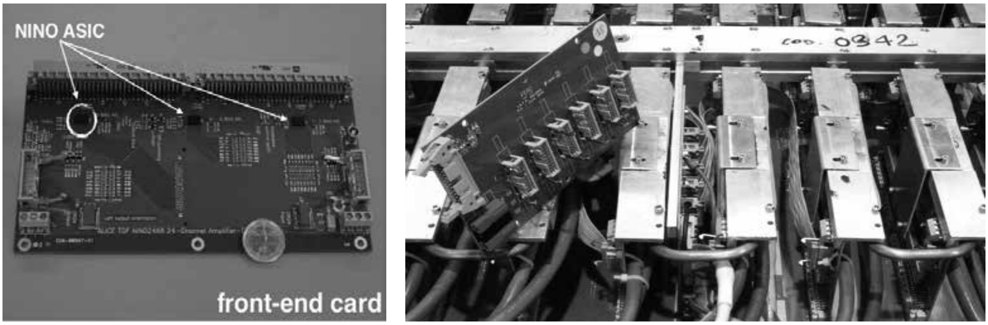

Figure 6: Last version of the front-end and control cards on the left and on the right respectively, used in the ALICE TOF system.

2. the TRM (TDC Readout Module) (there are 9 or 10 per crate) that has a multi-hit/multi-event design
   - it is based on the HPTDC chip [6] in the Very High Resolution Mode
   - it has the detection capability of the leading and trailing edges of the input signal;
3. the LTM (Local Trigger Module) that provides the TOF trigger;
4. the CPDM (Clock Distribution Module) used to distribute the high-quality clock from the LHC machine to the readout boards.

Figure 7: Custom VME crate with the readout electronics used in the ALICE TOF system.

The ALICE TOF detector covers a cylindrical surface at 3.7 m from the beam pipe, it has full azimuthal acceptance and it is divided in 18 sectors each equipped with one SuperModule (SM). A SM, more than 9 m long, inserted in the ALICE spaceframe is shown in Fig. 8 (right side). Each SM is made of 5 modules with, in total, 91 MPRCs.

The total number of MRPCs for the whole TOF is 1593 for a total of 152928 read-out channels; in fact, in three sectors the central modules (each with 15 MRPCs) were not installed in order not to affect the performance of the electromagnetic calorimeters placed outside the spaceframe.

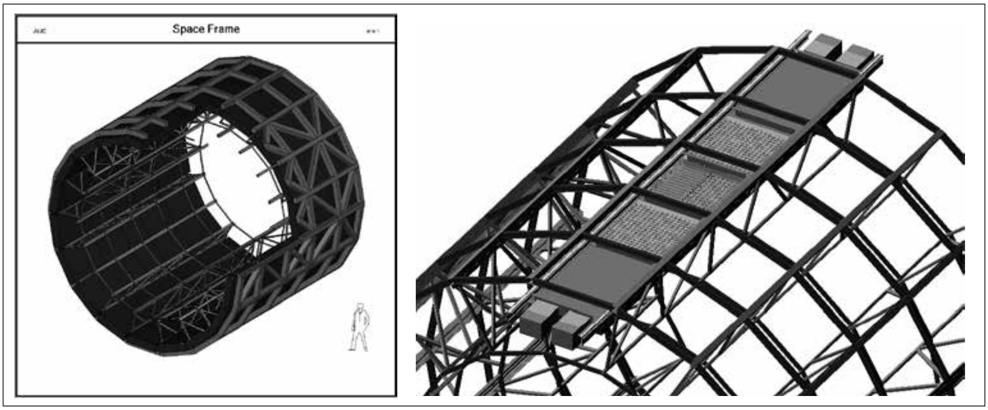

Figure 8: Left: drowing of the TOF detector in blu inside the sface frame in pink. Right: one TOF SM inside the Space frame with the 5 Modules visible.

Fig. 9 shows two photos of the construction, starting from the MRPC mass-production here in Bologna, that began in 2004. On the left there are the two parallel assembly lines and on the right the storage structures for the produced MRPCs.

Figure 9: The MRPCs assembly and storage in Bologna.

In 2006 a sample of 10 MRPCs, randomly chosen from the production, were tested at the CERN PS. Fig. 10 shows the results: on the left there is the HV scan in terms of efficiency and time resolution over 55 readout pads while on the right there is the result of the uniformity scan at fixed voltage over 159 pads. An excellent efficiency greater than 99% and excellent time resolution less than 50 ps were obtained.

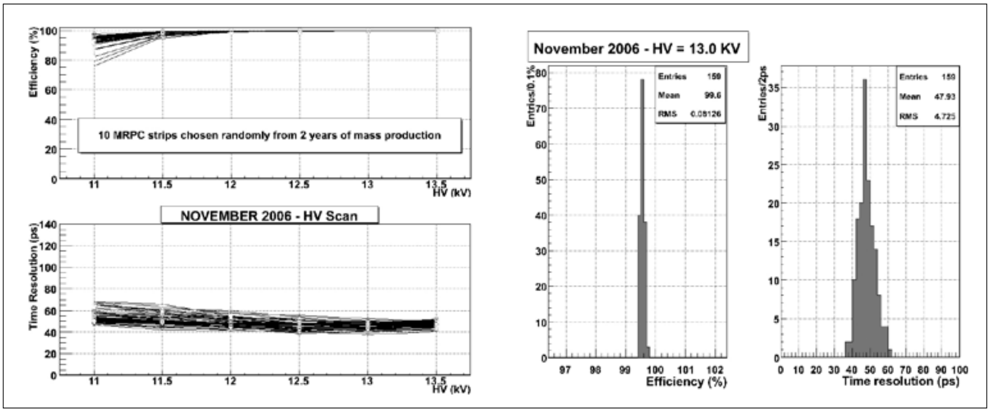

Figure 10: Left: HV scan over 10 MRPCs with the efficiency on the top and the time resolution on the bottom. Right: efficiency and time resolution distributions at fixed HV.

Let us go on with the production, Fig. 11 shows the assembling of the first module in Bologna on December 2005, in particular on the right one can see that all the MRPCs are superimposed to minimize the dead area and tilted with a projective geometry with respect to the interaction point.

Figure 11: Assembly of one TOF Module in Bologna.

The assembling of the SMs was done at CERN and started on May 2006; in Fig. 12 the two parallel assembly lines and two of the storage structures are shown.

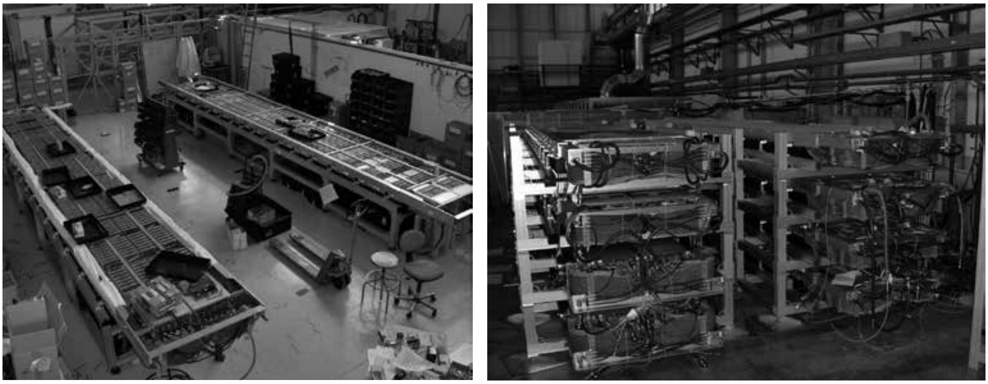

Figure 12: Assembly of the TOF SMs at CERN.

To have an idea of the big effort spent to build the TOF detector the following list summarizes the main milestones:

1. on December 2006 the MRPC production was completed;
2. on April 2008 the last SM was installed on the ALICE spaceframe; Fig. 13 shows the picture of the lowering of the SM in the ALICE cavern;
3. on May 2008 all the services like the cables, pipes (cooling and gas pipes) and fibers were connected;
4. on Summer 2008 the integration with the ALICE general systems (as DAQ, Trigger, DCS) and the commissioning with cosmic-rays were started.

Figure 13: Lowering of one TOF SM in the ALICE pit.

The 2018 marks the first decade of operation of the ALICE TOF detector, 10 years of results summarized in Fig. 14 with two plots, from the very first signals seen with the cosmic-rays (left side) to the full detector exploitation for Physics at the LHC with the PID capability given by TOF (right side).

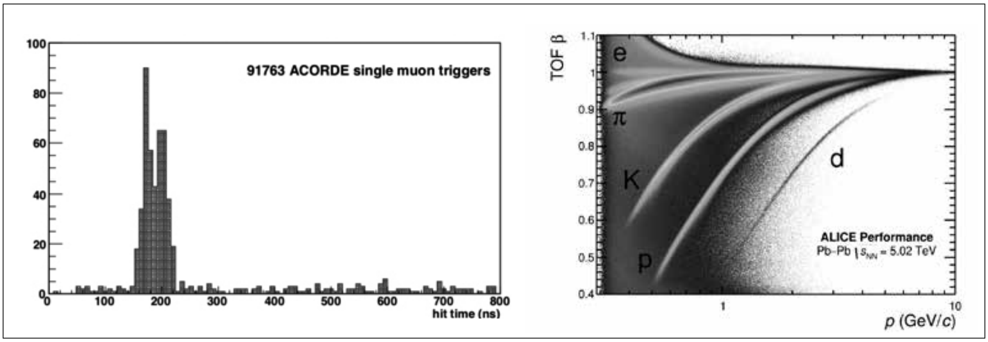

Figure 14: Left: first signals seen with the cosmic rays. Right: present PID performance with the TOF.

From the operational point of view there are two important features, excellent stability and excellent total time resolution.

The stability of the MRPCs as shown in Fig. 15. Here the total TOF current is plotted *versus* the luminosity in Pb-Pb, p-PB and pp scaled to equalize the detector load. The blu and the red points are respectively the current values recorded during the Pb-Pb data taking period in 2015 and the ones recorded during the p-Pb period in 2016. Very interesting are the green points that correspond to current values recorded during dedi-

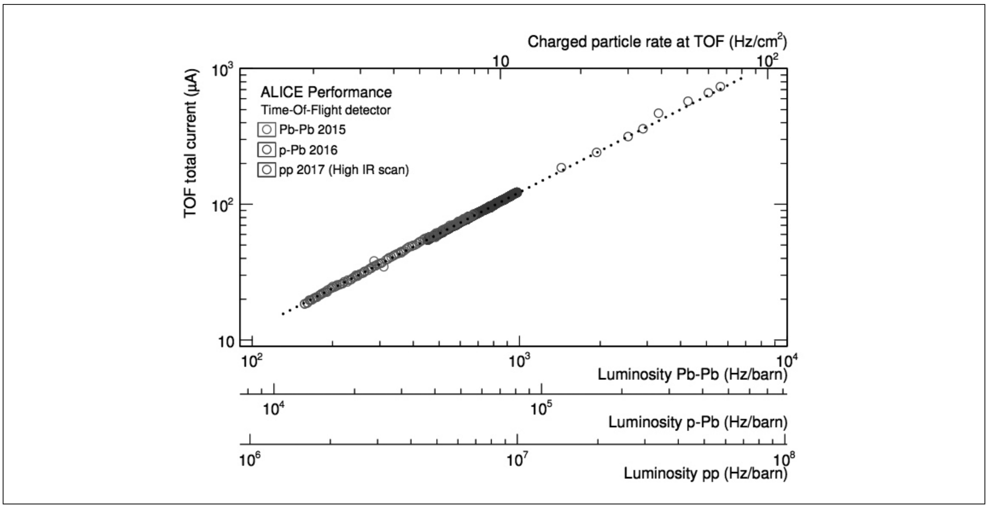

Figure 15: Total TOF-MRPC current *vs* luminosity in Pb-Pb, p-Pb, p-p collisions.

cated tests, done in 2017, to simulate the charged particle flux and thus the luminosity expected for the LHC RUN3. In 2018 there were other dedicated tests that confirmed the same behavior.

It must be underlined that the total current increases linearly with the rate, this means that no aging effects are observed. Therefore the MPRCs are working and will work in the next years as expected.

The total time resolution is shown in Fig. 16. For that purpose the improvement of the calibrations due to a fine tuning of the TOT correction for all the readout channels, improves the time resolution that now better than 60 ps.

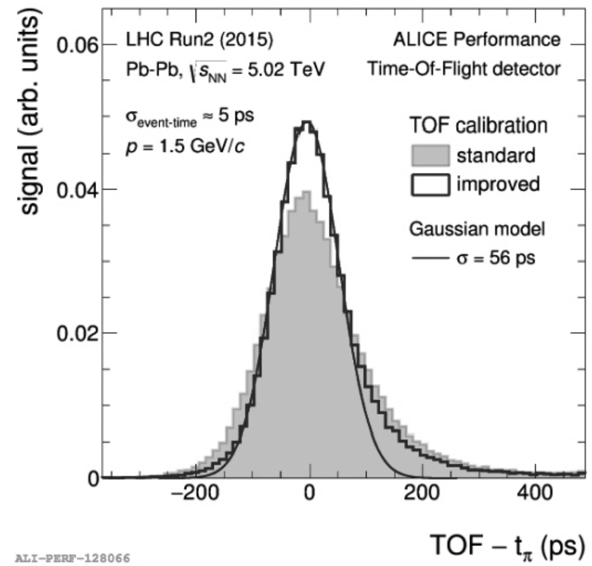

Figure 16: Total time resolution of the TOF detector.

In the framework of the ALICE experiment the TOF detector is used for a very large number and diverse set of physics measurements. Just a few examples: a) the transverse momentum distribution for pions, kaons and protons, light nuclei and anti-nuclei (Fig. 17), b) the study of the hadronic resonances and charmed mesons and baryons (Fig. 18), c) the precision measurement of anti-nuclei mass (Fig. 19), d) the study of the exclusive J/Ψ photo-production (Fig. 20) where the TOF trigger played a crucial role for the Ultra Peripheral Collisions (UPC) physics.

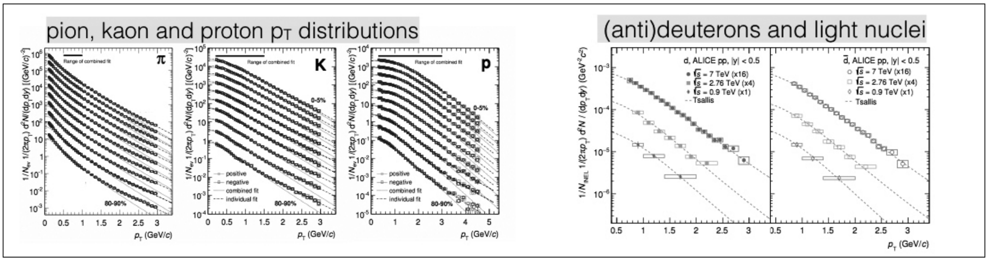

Figure 17: Transverse momentum distribution for pions, kaons and protons, light nuclei and anti-nuclei.

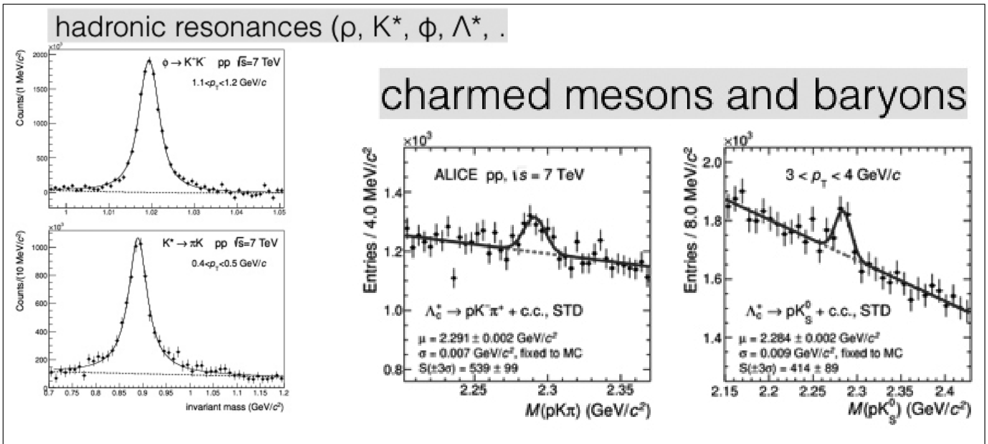

Figure 18: A few examples of Physics results obtained with the TOF crucial contribution.

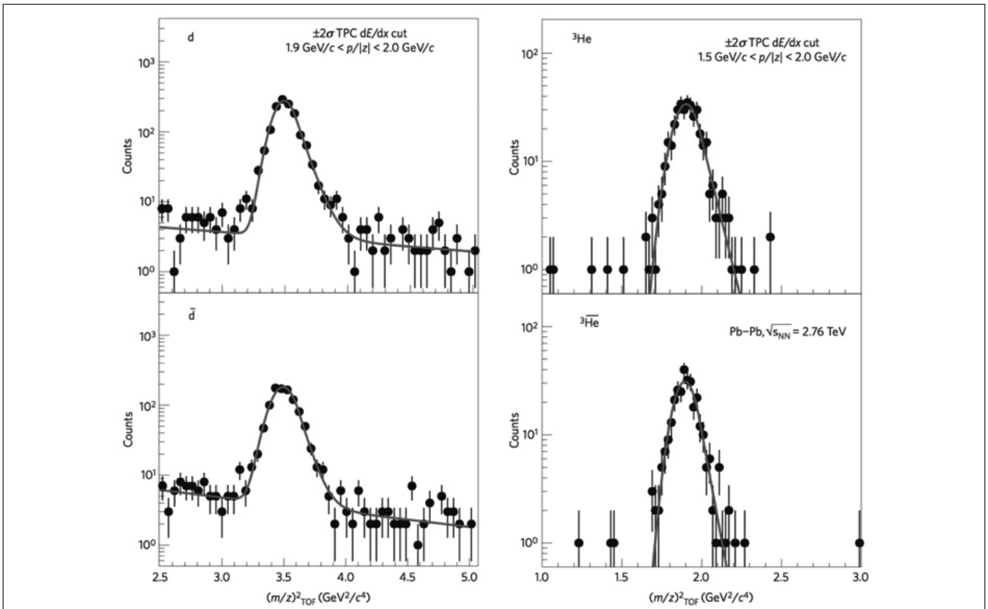

Figure 19: Precision measurement of the anti-nuclei mass with the TOF crucial contribution.

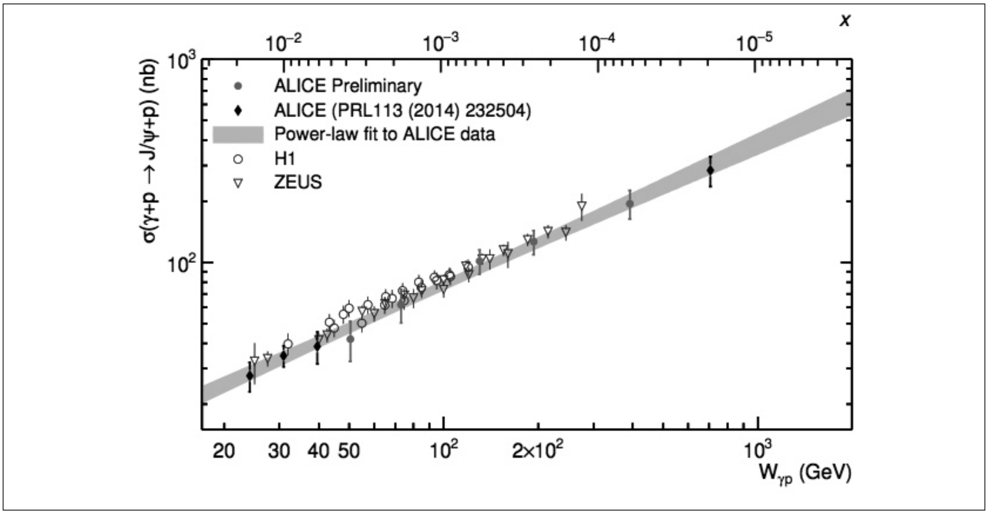

Figure 20: Exclusive J/Ψ photo-production; the TOF trigger played a crucial role for the Ultra Peripheral Collisions (UPC) physics.

However, the story of the MRPC is not finished with the ALICE TOF because the Bologna group is involved in a new R&D phase with the aim to improve the rate capability and the time resolution.

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The Alpha Magnetic Spectrometer experiment on ISS

*Andrea Contin** on behalf of the AMS-02 Collaboration

1. The AMS-02 detector

The Alpha Magnetic Spectrometer (AMS-02) is a general-purpose high-energy particle physics detector. It was installed on the International Space Station (ISS) on 19 May 2011 to conduct a unique long-duration mission (20 years) of fundamental physics research in space.

The layout of the AMS-02 detector [2] is shown in Fig. 1. It consists of nine planes of precision silicon Tracker, a transition radiation detector (TRD), four planes of time-of-flight counters (TOF), a permanent magnet, an array of anticoincidence counters (ACC), surrounding the inner tracker, a ring imaging Cherenkov detector (RICH), and an electromagnetic calorimeter (ECAL). The Tracker accurately determines the trajectory and absolute charge (Z) of cosmic rays by multiple measurements of the coordinates and energy loss. Three planes are equipped with one layer of silicon ladders. Plane 1 is located on top of the TRD, plane 2 is above the magnet, and plane 9 is between the RICH and the ECAL. Three planes are equipped with ladders on both sides of the plane. These double planes are numbered 3–8. Planes 2–8 constitute the inner tracker. Coordinate resolution of each plane is measured to be better than 10 μm in the bending direction, and the charge resolution is DZ=0.06 at Z=1. The total lever arm of the tracker from plane 1 to plane 9 is 3.0 m. The TRD is designed to use transition radiation to distinguish between electrons and protons, and energy release to independently identify nuclei. Two planes of TOF counters are located above and two planes below the magnet. Each plane contains eight or ten scintillating paddles. Each paddle is equipped with two or three photomultiplier tubes on each end for efficient detection of traversing particles. The coincidence of signals from all four planes provides a charged particle trigger. The TOF charge resolution, obtained from multiple measurements of the ionization energy

* University of Bologna and INFN Sezione di Bologna, Bologna, Italy.

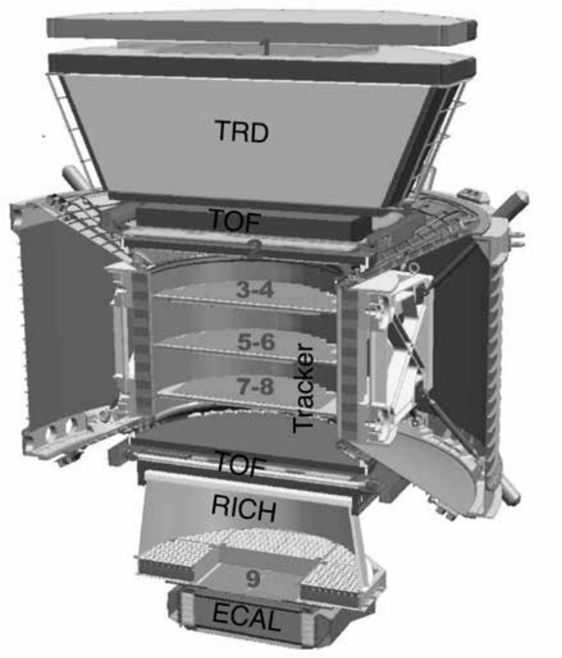

Figure 1: AMS detector. Tracker planes 1–9 measure the particle charge and momentum. The TRD identifies the particle as an electron or a proton. The TOF measures the charge and ensures that the particle is downward-going. The RICH independently measures the charge and velocity. The ECAL measures the 3D shower profile, independently identifies the particle as an electromagnetic particle, and measures its energy.

loss, is Z=0.05 at Z=1. The average time resolution of each counter has been measured to be 160 ps, and the overall velocity (b=v/c) resolution of the system has been measured to be 4% for Z=1 particles, which also discriminates between upward- and downward-going particles. The timing resolution improves with increasing magnitude of the charge to a limit of 50 ps for $Z > 5$ particles. The magnet is made of 64 high-grade Nd-Fe-B sectors assembled in a cylindrical shell structure 0.8 m long with an inner diameter of 1.1 m. This configuration produces a field of 1.4 kG in the x-direction at the center of the magnet and negligible dipole moment outside the magnet. This is important in order to eliminate the effect of torque on the Space Station. Together with the tracker, the magnet provides a maximum detectable rigidity of 2 TV on average, over tracker planes 1–9, where rigidity is the momentum divided by the charge. The ACC counters surround the inner tracker inside the magnet bore. Their purpose is to detect events with unwanted particles that enter or leave the inner tracker volume transversely. The RICH is designed to measure the magnitude of the charge of cosmic rays and their velocities with a precision of 1:1000. It consists of two non-overlapping dielectric radiators, one in the center with a refractive index of n=1.33, surrounded by a radiator with n=1.05. The Cherenkov photons are detected by an array of 10880 photosensors at an expansion distance of 45 cm. To reduce lateral losses, the expansion volume is surrounded by a high reflectivity mirror with the shape of a truncated cone. The ECAL consists of a multilayer sandwich of lead foils and scintillating fibers with a thickness of 17 radiation lengths. The AMS electronics consists of 650 microprocessors and about 300,000 readout channels. All components and circuits used in the electronics passed rigorous selection and space qualification tests, including irradiation with heavy ions at GSI, Germany and Catania, Italy and protons in Indiana, USA and at the SPS, CERN.

The AMS-02 detector has been developed by an International Collaboration composed of over 600 researchers from sixteen countries. To date, the total volume of data collected amounts to approximately 115 billion events. The experiment is monitored, with shifts of 24 h / 365 days, by a team of experts in the AMS Collaboration, in the Payload Operation Control Centre (POCC) at CERN (Geneva, Switzerland).

2. The AMS-02 scientific program

The scientific program of AMS-02 deals with the understanding of the origin, propagation and mechanisms of acceleration of cosmic rays by:

1. the measurement of the chemical composition of cosmic rays, electrons, positrons and nuclei up to iron, depending on the rigidity;
2. the measurement of the isotopic composition of light nuclei as a function of the kinetic energy per nucleon from 0.5 GeV/n up to a few tens of GeV/n;
3. the search for primordial antimatter in cosmic rays with a sensitivity of one part out of 10^9;
4. the search for non-standard sources of cosmic rays, such as the decay of dark matter;
5. the search for exotic components in cosmic rays, like new stable particles.

The first results, published in 2013, concerning the fraction of positrons [1] in the primary cosmic energy rays from 0.5 to 350 GeV, was followed by the publication in 2014 of the extension of the measurement up to 500 GeV [2], of the measurements of the individual electron and positron flows [3] and of their total flow [4]. In 2015 the proton flow measurements [5] from 1 GV to 1.8 TV and the flow of helium nuclei [6] from 1.9 GV to 3 TV were published. Measurements of the flow of antiprotons and of the ratio of proton flow [7] from 1 to 450 GV, and of the Boro / Carbon ratio [8] from 1.9 to 2.6 TV, were published in 2016. Finally, in 2017 the results were published on the flows of the primary nuclei [9] (He, C, O) and of the secondary nuclei [10] (Li, Be, B). Finally, a precision measurement of cosmic ray positrons up to 1 TeV, based on 1.9 million particles has been published at the beginning of 2019 [11].

3. Results

Some of the most significant results are illustrated below.

3.1. Electrons and positrons

The measurement of the positron fraction up to 1 TeV shows that above the ~ 200 GeV the positron fraction no longer shows an increase in energy and is therefore compatible with the annihilation of dark matter with a mass of about 1.2 TeV/c^2 [11]. The flow of electrons and the flow of positrons each require a description over a single power law. Both the flow of electrons and the flow of positrons change their behaviour to ~ 30 GeV, but the flows are significantly different in their energy dependence. Between 20 and 200 GeV the positron spectral index is significantly harder than the spectral index of the electrons. Determining the different behaviour of spectral indices with respect to energy is a new observation and provides important information on the origins of cosmic electrons and positrons (see Fig. 2).

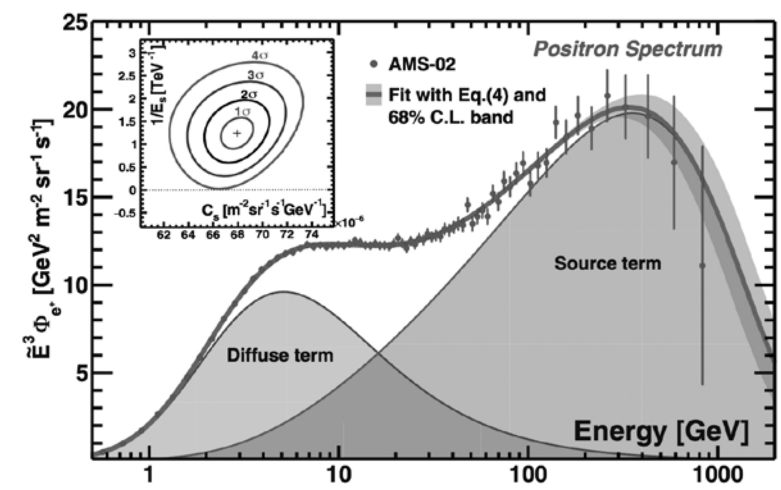

Figure 2: The positron spectrum (grey data points) scaled with E^{-3}. The light grey line is a fit with the sum of a diffuse term and a source term with a cut-off, together with the 68% C.L. interval (light grey band) (from [11]).

3.2. Protons and helium nuclei

For both protons and helium, the spectral index progressively hardens for rigidities above 100 GV (see Fig. 3). The dependence on the rigidity of the helium spectral index

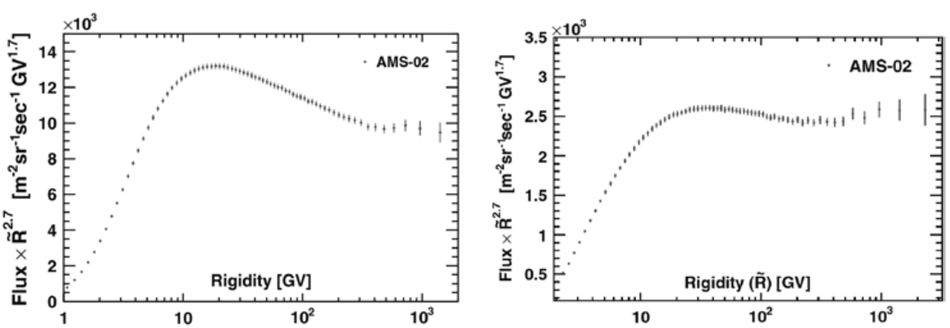

Figure 3: Proton (left [5]) and helium (right [6]) spectra.

is similar to that of the proton spectral index, although the absolute quantities of the flows are different. Surprisingly, the spectral index of the ratio between protons and helium increases with rigidity up to 45 GV and then becomes constant; the flow ratio above 45 GV is well described by a single power law.

3.3. Nuclei

The very high statistics of AMS-02 brought to light new properties of the primary cosmic rays He, C and O measured in the rigidity range from 2 GV to 3 TV. In total, 90×10^6 helium nuclei, 8.4×10^6 carbon and 7×10^6 oxygen nuclei were collected during the first six years of AMS activity. Above 60 GV, the spectra of the primary cosmic rays He, C and O have an identical dependence on rigidity. All differ, in an identical way, from a single power law for rigidities higher than 200 GV. The dependencies on the rigidity of the primary cosmic rays and of the secondary cosmic rays, however, are clearly different. Fig. 4 summarizes the results.

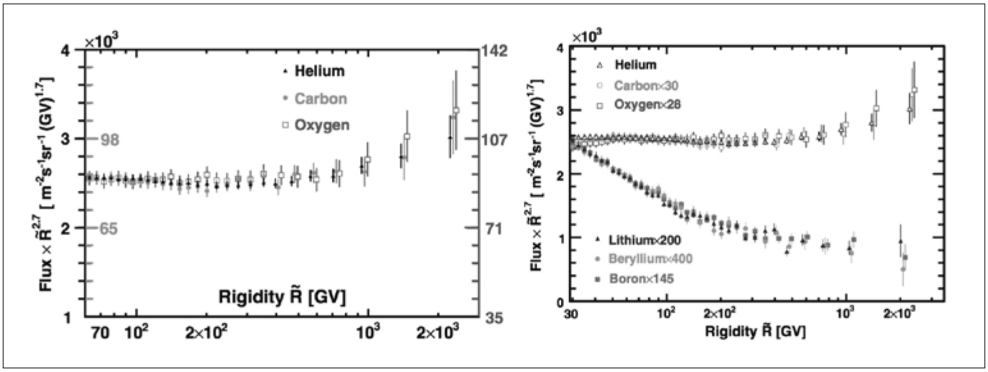

Figure 4: Primary (left [9]) and secondary (right [10]) nuclei spectra measured by AMS-02 in the first six years of operation.

4. The contribution of Bologna

Most of the AMS-02 TOF has been built in INFN Bologna and University of Bologna premises. The system has been designed for maximum redundancy to ensure the fast trigger to AMS even in the presence of HV, PMT or front-end electronics faults:

- Each counter is 4-fold redundant in PMTs.
- Each HV power supply is doubly redundant.
- Each coincidence signal for the fast trigger is doubly redundant.

The mechanical structure, shown in Fig. 5 for the Upper planes has been tested in Thermal Vacuum and for vibrations up to 13 g.

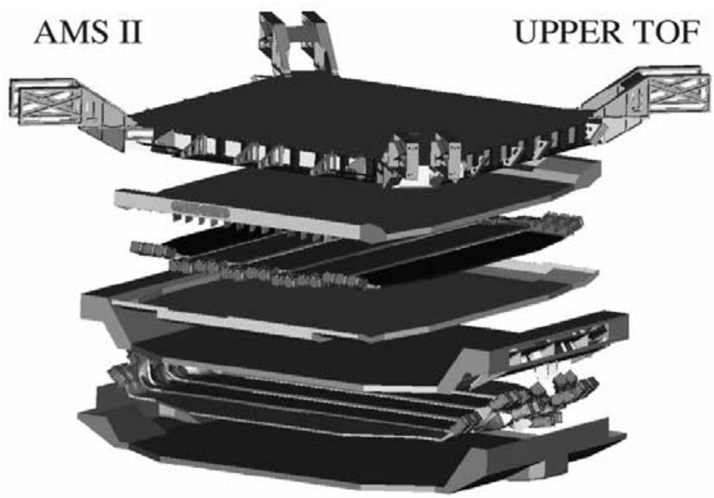

Figure 5: The Upper TOF mechanical structure, built in Bologna and space qualified in Terni.

In order to achieve the full potential of TOF in a constantly changing thermal environment, a dynamic TOF calibration method has been developed. High energy particles are used to calibrate the time response taking into account anode gain fluctuations, scintillator aging, and threshold setting fluctuation which are important issues in space extreme environment. Calibration is redone completely every 15days to dynamically follow any possible changes. After this precise calibration, the time resolution of TOF counter is 160 ps for proton (Z=1) and 48 ps for carbon (Z=6).

The charge calibration procedures include light attenuation calibration for each counter side every 15 days, anode gain and attenuation correction calibration for each counter every 3 days, correction for non-linear response using the full available statistics. Thanks to excellent charge resolution, TOF is able to identify nuclei up to charge Z=40 with a resolution of 2% (see Fig. 6).

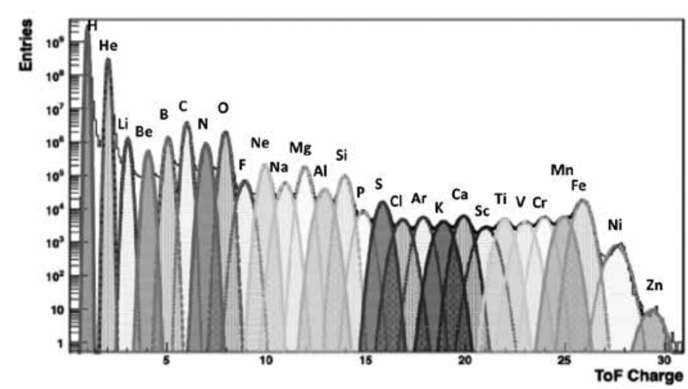

Figure 6: The TOF response to all nuclei up to Z=30.

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From LVD to DarkSide

*Eugenio Scapparone**

Supernova explosion and dark matter search are two of the most important research area in astro-particle physics. Although the Supernova scenario was validated by the observation of the neutrino burst from the SN1987A, the explosion mechanism is not fully understood: a detailed comprehension of this astrophysics event requires a large neutrino statistics, to reconstruct the time structure of the neutrino emission.

Understanding the nature of the Dark Matter is an urgent open question in astro-particle physics and cosmology. We infer the Dark Matter existence from its gravitational effects, but the nature of this elusive object, making-up the 27% of the universe, remains a mystery.

Both researches aim at the detection of rare events, and therefore require an underground laboratory that has to act like a shield, to protect the experiments from the cosmic ray showers, as Laboratori Nazionali del Gran Sasso (LNGS). In this talk, I will focus on two of the most important experiments designed to provide an answer to the above open questions.

The Large Volume Detector (LVD) experiment has been searching for Supernova neutrinos at LNGS since 1992; the DarkSide-50 detector makes use of 50 kg of liquid argon as Dark Matter active target. This is just the first step towards the construction of a 30 tonnes TPC (DarkSide-20k), that is expected to start the data taking at the end of 2022.

1. Introduction

Supernova explosion is one of the most terrific event in our Universe and is the outer brilliant sign of the catastrophe marking the end of the evolution of a massive star

* INFN, Sezione di Bologna, Bologna, Italy.

[1]. These events are associated with a neutron star or a black hole formation, that are copious sources of neutrinos, detectable in underground experiments. According with theoretical calculations, about 3×10^{53} erg are released to form a neutron star: most of this energy is carried by neutrinos.

Despite the huge energy release that characterizes this event, there is strong evidence from astronomical measurements that the visible fraction of the Universe does not exceed ~5%. Gravitational effects that cannot be explained by visible matter are well documented, though their source remains unknown. Unlike normal matter, dark matter does not interact with the electromagnetic force. This means it does not absorb, reflect or emit light, making it extremely hard to spot. There are several evidences for dark matter from astronomic observations. I report here just a couple of them. The study of the rotation curve of the spiral galaxies shows that the star velocity, when moving away from the galaxy centre, does not decrease as $1/\sqrt{r}$, as expected by the Newton laws; on the contrary, it remains flat or even increases, indicating the presence of extra mass in addition to the visible one.

Another compelling evidence comes from the observation of the cosmic microwave background (CMB), studied by several experiments (COBE, WMAP and PLANCK). The CMB is an almost uniform background of radio waves that fills the universe. It is the leftover heat of the Big Bang itself; it was released when the universe became cool enough to be transparent to light, about 400,000 years after its birth. At this time, the universe was filled with a hot, ionized gas. While the CMB is extraordinarily uniform in temperature (at the level of 1 part in 100,000), it is not perfectly uniform. These anisotropies reflect the initial density fluctuations of the universe, about 400,000 years after the Big Bang: The slight changes in the intensity of the CMB across the sky give us a map of the early universe. The analysis of the CMB anisotropy, in terms of multipole moments, indicates a dark matter fraction of about 27%.

Dark matter seems to outweigh visible matter roughly six to one, but what is dark matter? One idea is that it could be made of primordial black-holes [2]. Another possibility is given by "supersymmetric particles" – hypothesized particles that are partners to those already known in the Standard Model. A well-motivated leading candidate is as-yet undiscovered elementary Weakly Interacting Massive Particles (WIMPs). Motion of galactic halo WIMPs relative to a detector on Earth could result in WIMP-nucleus elastic collisions directly detectable by a low-background, low-threshold detector capable of unambiguously identifying a small number of nuclear recoils from a very large exposure. Elucidating the nature of Dark Matter is a key priority at the leading tip of astro-particle physics.

In 1998 and the Hubble Space Telescope (HST) observations of very distant supernovae showed that, a long time ago, the universe was actually expanding more slowly than it is today. Therefore, the expansion of the universe has not been slowing due to gravity, as everyone thought, but has been accelerating. No one expected this, no one knew how to explain it. But something was causing it. The accelerated expansion of the universe is driven by a kind of repulsive force generated by quantum fluctuations in otherwise "empty" space. The force seems to be growing stronger as the universe expands. For lack of a better name, this mysterious force was named "dark energy". At the moment there are no plausible explanations for dark energy, we just know it is a dominant component of the Universe, accounting for ~68% of its mass.

A common feature of the experiments aiming at the detection of neutrinos from stellar collapse or at the search for Dark Matter is the need of a low background environment. The cosmic ray flux at the earth surface would make these searches impossible.

In 1979 the President of the INFN, A. Zichichi, proposed to the Parliament to build a large underground laboratory close to the Gran Sasso freeway tunnel then under construction (an opportunity that reduced substantially the cost). In 1982 the Parliament approved the construction, which was completed by 1987. Fig. 1 shows the handmade original sketch of the LNGS by A. Zichichi. Today the underground area available is made of three main halls, each about 100×20×18 m^3, plus ancillary tunnels providing space for services and small-scale experiments. The total area is 17,300 m^2, and the total volume 180,000 m^3.

2. LVD

A massive star, at the end of its evolution, shows an onion-like structure: a central ion core surrounded by layers of Si, O, Ne, C, He and H. When the nuclear fuel has been consumed, the star cannot support itself against the gravity and the core begins to collapse.

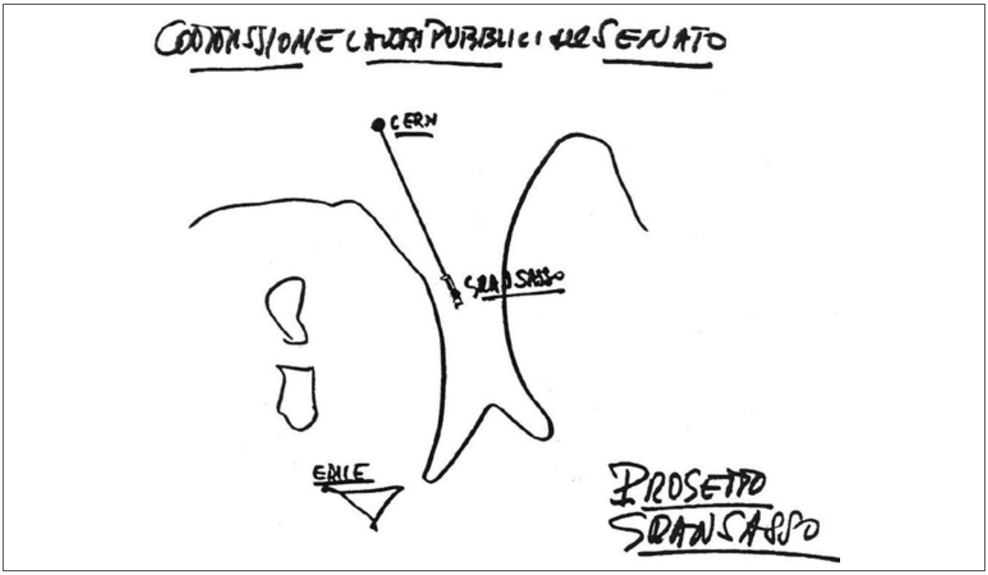

Figure 1: Handmade original sketch from Zichichi's presentation to the Commission on Public Works of the Italian Senate in a session organized by the Senate's President to discuss the proposed Gran Sasso project in 1979.

As soon as the density of the inner region of the core exceeds the nuclear density, the collapse of the core stops and a shock wave starts to move outwards. If the wave reaches the outer envelope with enough energy, the supernova explosion takes place.

According to theoretical calculations, about 3×10^{53}erg are released to form a neutron star: most of the energy is carried by neutrinos. Less than 10% of the neutrinos is radiated in the neutronization phase ($p + e^- \rightarrow n + \nu_e$) and the remainder in pair processes (deleptonization), $e^- + e^+ \rightarrow \bar{\nu}_i + \nu_i$, $i = e, \mu, \tau$. When the density is larger than 10^{11} g/cm^3, the inner core is no longer transparent to the neutrinos and they are in equilibrium with matter. The neutrino pairs are thermally radiated in a time scale of few seconds.

It is worth noting the general scenario of collapse is well understood, but the explosion mechanism still need clarification. The time structure of the neutrino luminosity is strictly related to the explosion mechanism: it is therefore crucial for any observatory aiming at supernova neutrino detection to provide a detailed time structure of the neutrino emission.

The Large Volume Detector (Fig. 2) is a 1000 t liquid-scintillator experiment optimized to detect neutrinos from supernova explosions. LVD consists of an array of 840 scintillator counters, 1.5 m^3 each, viewed from the top by three photomultipliers (PMTs). It is a modular detector. The detector is located underground at a depth of 1400 m under rock (3600 m water equivalent), in the Hall A of Laboratori Nazionali del Gran Sasso (LNGS). Neutrinos can be detected in LVD through charged current (CC) and neutral current (NC) interactions on proton, carbon nuclei and electrons of the liquid scintillator. The scintillator detector is supported by an iron structure, whose total mass is about 850 t. This can also act as a target for neutrinos and antineutrinos, as the product of interactions in iron can reach the scintillator and be detected.

Figure 2: The Large Volume Detector at LNGS. The liquid scintillator is contained in the blue tanks.

This modularity allows LVD to achieve a very high duty cycle that is essential in the search of unpredictable sporadic events. Three independent data acquisition systems, one per tower, minimize (in practice, nullify) the probability of a complete shutdown of the experiment.

The detector has been in operation since 9 June 1992, its mass increasing from 300 t (about one full "tower") to its final one, 1000 t, in January 2001.

LVD has been participating in the Supernovae Early Warning System (SNEWS) since July 2005 [3]. The goal of SNEWS is to provide the astronomical community with a prompt alert of the occurrence of a Galactic core-collapse event. The neutrino burst signal emerges promptly from a supernova's core, whereas it may take hours for the first photons to be visible. Therefore, the detection of the neutrino burst from the next Galactic supernova can provide an early warning for astronomers. Requiring a coincident signal from several detectors will provide the astronomical community with a very high confidence early warning of the supernova's occurrence. Currently, seven neutrino experiments are involved: Super-K(Japan), LVD (Italy), Ice Cube (South Pole), KamLand (Japan), Borexino (Italy), Daya Bay (China), and Halo (Canada).

The explosion of the supernova SN1987A provided few tens of events in few underground detectors, confirming the Supernova scenario, but the observed number of events was too small to reveal details of the explosion. For a galactic or near-extragalactic core-collapse *supernova* more than 500 neutrino interactions are expected in LVD. The experiment has been running since 25 years (uptime 99.8%). The analysis based on the data collected in this long period allowed to put a limit on the rate R of gravitational collapses out to 25 kpc R< 0.098/year at 90% C.L. [4].

These results showed that there is no experimental evidence of any stellar collapse in our Galaxy in the last 25 years. This result, obtained by LVD, sensitive with full efficiency to source up to 25 kpc, is the best experimental limit obtained by any detector studying this astrophysical event.

3. DarkSide

Direct WIMP searches look for the nuclear recoils (NR), resulting from collisions of galactic WIMPs with ordinary matter in the laboratory. The bulk of the region left open for discovery requires masses on the scale of TeV/c^2 and beyond: this is exactly the region where argon-based dark matter searches will perform at their best, thanks to their unique ability to strongly reject background from minimum ionizing events over an exposure as large as several hundred tonnes × year. That will leave the low-rate nuclear recoils induced by coherent scattering of atmospheric neutrinos as the sole residual background – the so-called "neutrino floor". Another possible discovery region for dark matter sits below 10 GeV/c^2. Indeed, argon detectors already lead the search for low mass WIMPs, thanks to their unique combination of very low background and threshold. Argon can deliver the ultimate background-free search for dark matter, but that comes with extensive technological development, as argon in the Earth's atmosphere is unsuitable owing to its high content of the radioactive isotope ^{39}Ar. The argon road to dark matter had therefore to solve the problem of procuring large batches of argon that are much more depleted in ^{39}Ar than atmospheric argon is. The solution came through an unlikely path: the discovery that underground sources of CO_2 originating from Earth's mantle carry sizable quantities of noble gases, in reservoirs where secondary production of ^{39}Ar is significantly suppressed. The use of underground argon (UAr) plays a key role in this search: while the general characteristics (including the high light yield) of the UAr remain similar when compared to the atmospheric argon, showing a radioactivity 1 Bq/kg, the reduction of the ^{39}Ar content gives for UAr a reduction factor of about 1400.

In early 2018 the DarkSide Collaboration reached the milestone of its DarkSide-50 program by publishing results from a 532.4 live-days campaign with a two-phase LAr time projection chamber (LAr TPC) in operation since 2013 in the underground Laboratori Nazionali del Gran Sasso (LNGS). The outcome of the high-mass WIMP dark matter search is a null result, delivering on the promise of zero-background [5]. The extremely low background, high stability, and low analysis threshold of DarlSide-50, enabled a study of very-low energy events, characterized by the presence of the sole ionization signal which resulted in the world-best limit (see Fig. 3), for low-mass dark matter searches in the mass range 1.8 GeV/c^2 to 6.0 GeV/c^2 [6]. The Global Argon Dark Matter Collaboration (GADMC), which was formed in September 2017, comprises more than 300 scientists from 15 countries and 60 institutions involved in four first-generation dark-matter experiments: ArDM at Laboratorio Subterráneo de Canfranc in Spain, DarkSide-50 at INFN, Laboratori Nazionali del Gran Sasso (LNGS), DEAP-3600 and MiniCLEAN at SNOLAB in Canada. GADMC is working towards the immediate deployment of a dark-matter detector called DarkSide-20k. This experiment would accumulate an exposure of 100 tonnes × year and will be followed by a much larger detector, named ARGO, to collect more than 1000 tonnes × year, both potentially with no instrumental background. These experiments promise the most complete exploration of the mass/parameter range of the present dark-matter paradigm.

The DarkSide-20k detector [7], a two-phase TPC filled with Underground Argon at Laboratori Nazionali del Gran Sasso (LNGS), has been approved by INFN and NSF. It will be located in the Hall C of the LNGS. It consists of two detectors: the inner detector and the veto detector, both hosted in a ProtoDUNE-like cryostat. The inner detector is a Liquid Argon Time Projection Chamber (LAr TPC) filled with UAr. The collaboration has developed a broad strategy to increase the production of UAr to procure the target required for DarkSide-20k. The Urania project will extract and purify the UAr from the CO_2 wells at the Kinder Morgan Doe Canyon Facility located in Cortez, Colorado (USA) at a production rate of 250 kg/day.

It will be necessary to make a final chemical purification of the UAr before deployment into the LAr TPC. Additionally, it would be beneficial to deplete further the UAr of ^{39}Ar, giving extended sensitivity to DarkSide-20k. The *Aria* project will serve to chemically purify the UAr using a cryogenic distillation column called Seruci-I. *Aria*

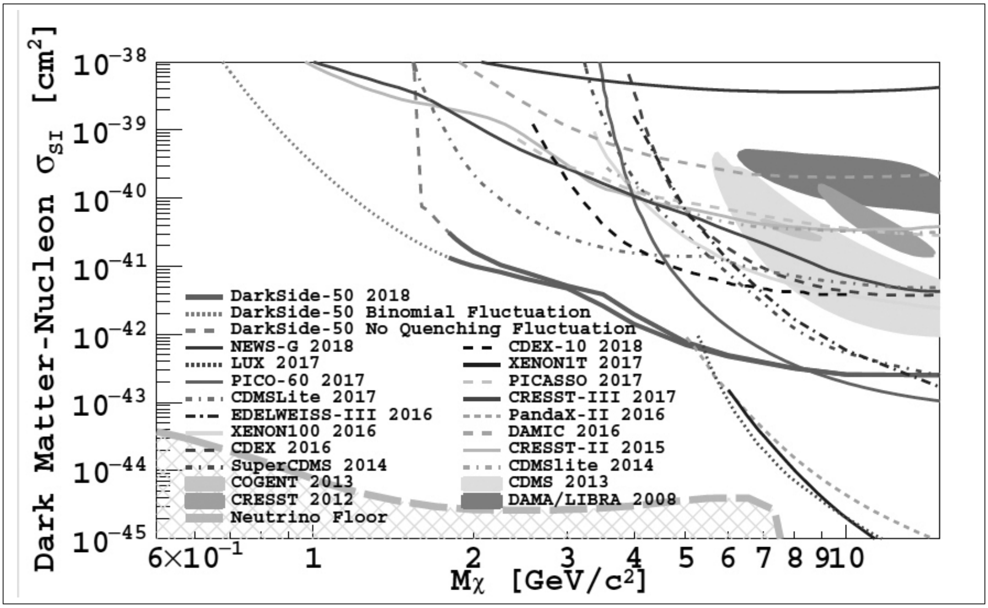

Figure 3: 90 % upper limits on spin-independent Dark Matter nucleon cross sections from DarkSide-50 in the range above 1.8 GeV/c^2.

could also potentially further deplete the UAr of ^{39}Ar by a second, and larger cryogenic distillation column called Seruci-II. The ultimate goal of the Aria project is to process about 250 kg/day of argon through Seruci-II to achieve an additional depletion factor between 10 and 100 (in addition to the reduction of ^{39}Ar already seen in the UAr).

The elusive signals produced in liquid argon by the scattering of a WIMP require efficient and reliable photo-sensors. Silicon photomultipliers (SiPMs) are one of the key enabling technologies for large-scale LAr-based dark matter experiments. SiPMs have a number of performance advantages over traditional PMTs, including higher photon detection efficiency (PDE) and much better single-photon resolution, all while operating at much lower bias voltage. SiPMs can also be efficiently integrated into tiles that cover large areas and feature better radio purity than PMTs. The DarkSide Collaboration committed to building the next detectors of its dark matter research programs with SiPM-based photosensors. These photo-sensors have unfortunately a large capacitance, about 50 pF/mm^2: when dealing with large area detectors, grouping as many as possible of them in a single readout channel is mandatory, to limit the number of electronic channels. As an example, the largest area SiPM produced up to know is 1 cm^2: instrumenting a 20 m^2 area with single SiPM readout would require 200,000 electronic channels, whose cost would exceed 30 M€. Grouping SiPMs together may result in a large total capacitance, limiting the bandwidth (and thus the time resolution) and increasing the noise. A long R&D made by the DarkSide Collaboration allowed to group 24 SiPMs, while preserving a SNR larger than 15 (Fig. 4) and a time resolution better than 5 ns [8]. For DarkSide-20k, the photo-sensing unit will be a “Photo-Detector Module”

(PDM), consisting of a large tile of SiPMs covering an area of 50 × 50 mm^2, operating as a single detector. Each PDM is made of 24 SiPMs with area 11.7 × 7.9 mm^2, designed by the Bruno Kessler Foundation (FBK) and produced by LFoundry. Besides the tile, each module will also contain a cryogenic preamplifier, which will amplify and shape the signal in the immediate proximity of the sensor.

On March 2018 the collaboration successfully built the first PDM (Fig. 5, left); shortly after the first Motherboard (Fig. 5, right), made of 25 PDMs was finalized. At the moment the Collaboration is building the photo-electronic system for the 1-ton prototype, under assembly at CERN. The light produced in the prototype TPC will be detected by 370 PDMs, made by 9,000 SiPMs. The DarkSide-20k detector requires a SiPM area of about 20 m^2. The packaging of the 12,000 PDMs is expected to start by the end of 2019 in a dedicated clean room, presently under refurbishing at Tecnopolo (AQ), equipped with cutting-edge technology equipment.

One of the most important classes of background in WIMP detectors are nuclear recoils. These can be produced by neutrons scattering off argon nuclei. Neutrons are neutral particle, therefore we cannot see them directly; on the contrary we can see the signal produced by the recoiling nucleus, which may look identical to the signal we expect from a WIMP.

Not all neutrons produce a “perfect” WIMP background; few of them scatter more than once in the detector to produce “multiple recoil” events, and others produce nuclear recoils with energies higher than we expect from WIMP interactions. Still, it is possible that an incoming neutron may only scatter once and produce a signal in the WIMP recoil energy range. This means that, especially in detectors like DarkSide, where events other

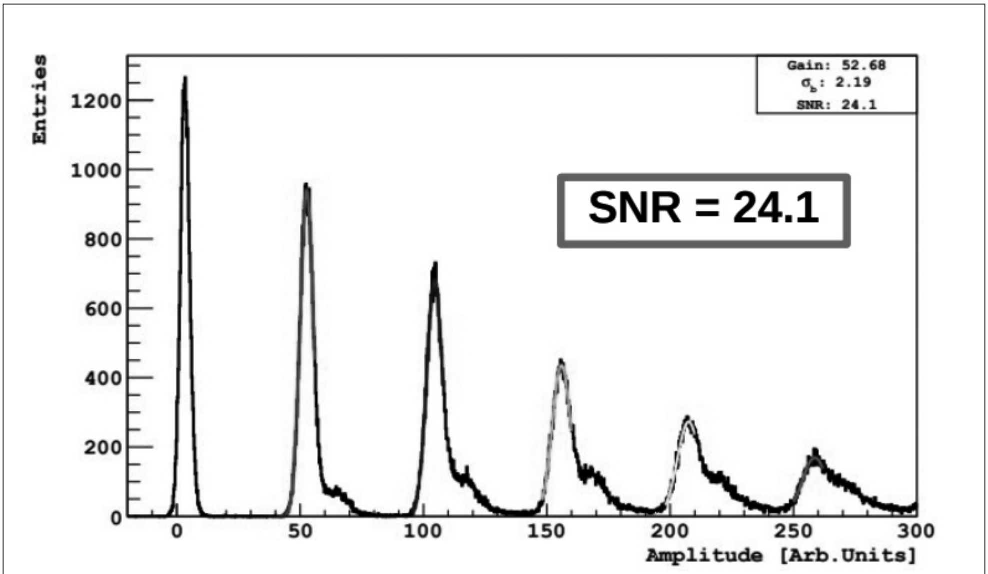

Figure 4: Amplitude spectrum of 24 SiPM tile at cryogenic temperature.

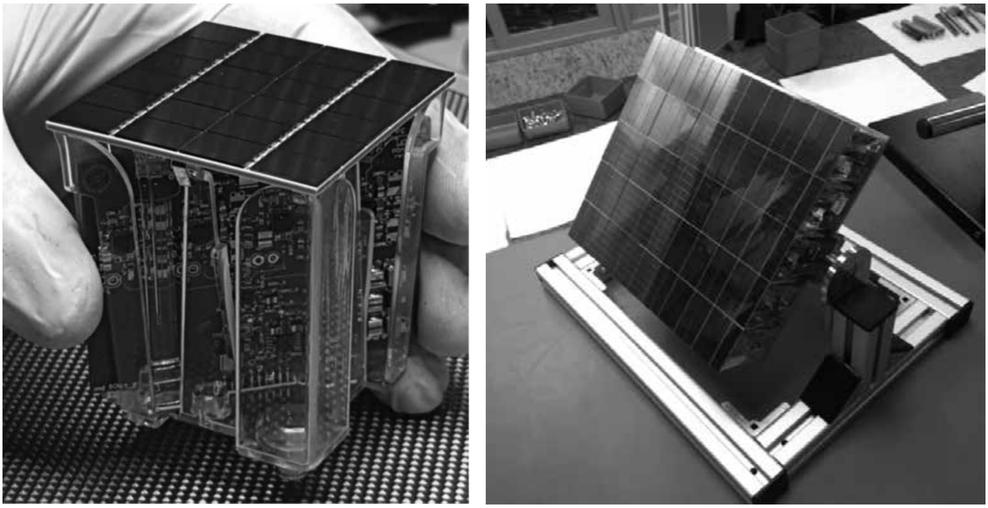

Figure 5: The first Photo-Detection module built by the DarkSide Collaboration (left) and the first Motherboard (right, 25 PDMs, 600 SiPMs).

than nuclear recoils can be very efficiently rejected neutron, induced nuclear recoils are typically the limiting background. There are two main classes of background-producing neutrons: radiogenic neutrons, which are produced from nuclear processes in the detector components, and cosmogenic neutrons, which are produced by the interactions of cosmic ray muons in the detector and surrounding materials. These different classes of neutrons are detected using two different suppression systems. DarkSide minimizes

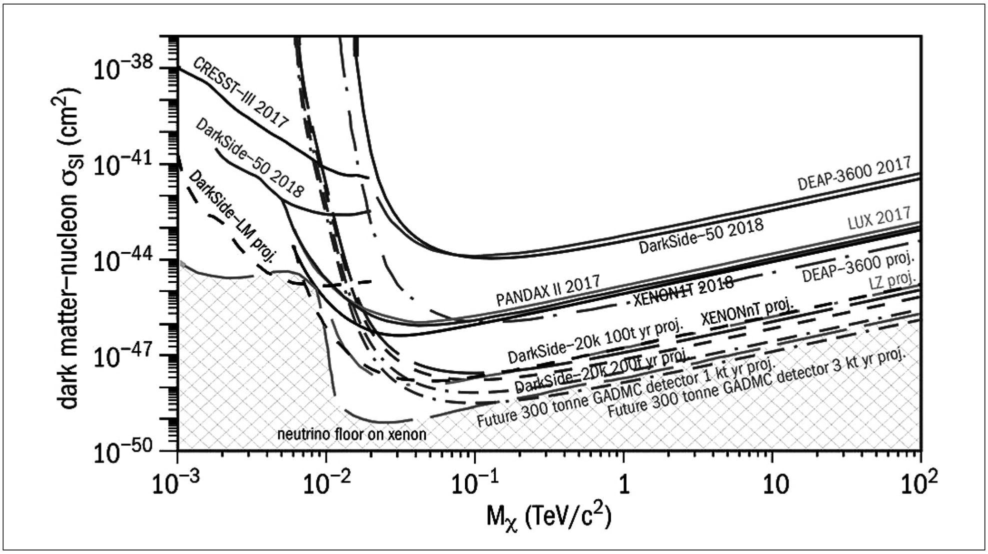

Figure 6: Current limits on WIMP dark matter, showing the expected sensitivity from the DarkSide programme.

radiogenic neutron production by selecting and developing detector materials with very low levels of intrinsic radioactivity. The DarkSide-20k detector reduces, identifies, and measures the rate of neutron-induced backgrounds using an active suppression system, named “Veto” detector. It is made of a plastic shell, loaded with Gadolinium, surrounding the inner detector, sandwiched between two active AAr layers.

DarkSide-20k is designed to collect an exposure of 100 tonnes × year (Fig. 6) in a period of five years (to be possibly extended to 200 tonnes × year in 10 years), completely free of any instrumental background. The start of data taking is foreseen by 2022. The second step of the program will involve building an argon detector that is able to collect an exposure of more than 1000 tonnes × year.

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The EEE – Extreme Energy Events project

Rosario Nania for the EEE Collaboration*

1. Introduction

Cosmic rays are still an unevaluable source of information to better understand astrophysical events like Supernovae explosions, stars evolution or search for exotic phenomena: their composition, energy distribution and direction are presently being actively studied with experiments on Earth and in space [1]. Secondary muons arriving on Earth are also widely used in schools and universities to perform simple experiments allowing the students to understand the basic principles of particle detectors, electronic readout, data analysis (including mathematical and statistical applications) and physics.

There is however a unique example of an experiment capable to combine both the research aspects and the dissemination of scientific culture among the students: the Extreme Energy Events - Science inside schools project [2].

In the following the project will be described both in the detector and outreach aspects and few recent results will be reported.

2. The EEE project

The EEE project was first proposed by Antonino Zichichi [3] in 2004 and is presently being coordinated by the *Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi* in Rome. The development of the detectors has been done in strict collaboration with researchers belonging to the Physics Department of the University of Bologna and INFN section, responsible for the Time-Of-Flight (TOF) system of the ALICE experiment at the CERN LHC accelerator.

The detector is made of three Multigap Resistive Plate Chambers (MRPCs) [4] (see

* See the Appendix for the complete list of authors and affiliations.

also G. Scioli in these proceedings), a modification of the detector used in the ALICE TOF system. Each chamber (220×110 cm^2) is made of a 6 gaps MRPC with dimensions as shown in Fig. 1. The signal produced is collected by copper strips, 2.5 cm wide, read on both sides by the NINO front-end ASIC amplifier/discriminator, specifically designed for MRPC operations [5]. Each detector unit, called "telescope", is made of three stacked chambers (Fig. 2) with completely independent control, trigger and read-out units with GPS information.

The chambers are built at CERN by groups of students under the supervision of expert researchers [6,7]. The chambers are then transported to their home institute, installed and commissioned. It is then responsibility of the students to verify every day the status of the apparatus (gas flow, rates, trigger, data quality) by means of tools which often are developed by the students themselves.

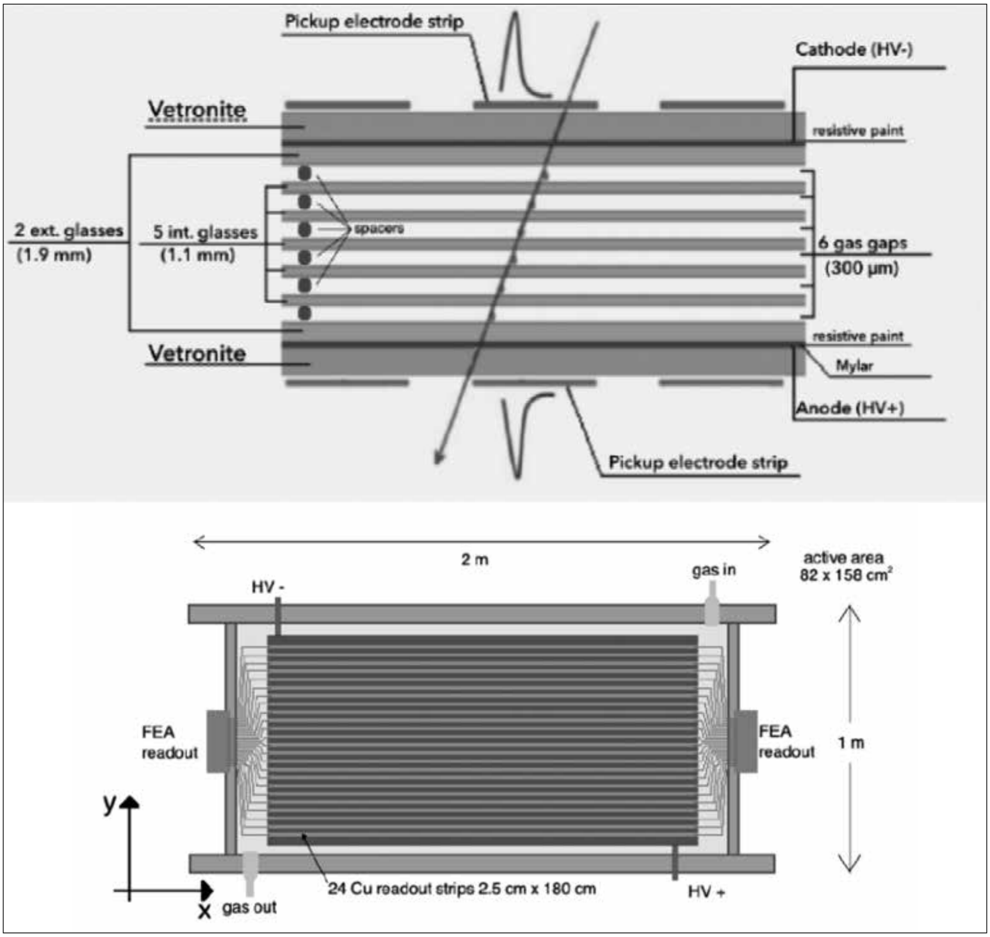


Figure 1: Side view and Top view of an EEE MRPC chamber [4].

Figure 2: One of the EEE telescopes installed inside a high-school institute.

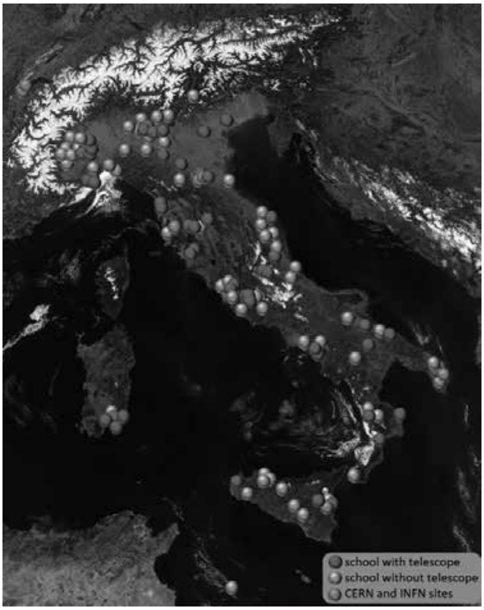


Figure 3: Map of participation to EEE: in dark grey schools with a telescope, in grey installations inside laboratories and in light grey institutes without a telescope.

Presently 51 telescopes are installed in high-school institutes spread all over Italy (Fig. 3). Eight telescopes are installed in research laboratories, including two at CERN. The total area covered is larger than 3×10^5 km^2, the largest coverage in the world for such kind of experiments. All data are sent in real time to INFN CNAF computing center (Bologna) for storage and reconstruction. A web-page interface and an automatic checker allows a continuous monitor of the data from the telescopes. Since 2014, more than 80 billion events have been recorded during four Run periods which extend from October until June (when the schools are open) and sometimes also during summer. Students or researchers can retrieve all data for analysis. The detector performances are extensively described in [4], where the analysis was performed over a large number of telescopes, demonstrating the reliability and good response uniformity of the telescopes of the network. In particular, the average time resolution is 238±40 ps and the average efficiency is 93%, as measured on the middle chambers using the external ones as trigger.

The outreach part of the project includes also Masterclasses (on Physics, detector performances and data analysis) prepared by the researchers, exchange of visits between schools, monthly video-conferences where students can present their work and yearly *Conferenze di Progetto* where students from many institutes are invited to a three days meeting on the project status and with special hands-on masterclasses.

Approximately 50 additional schools participate in the project without a telescope installed in their institutes. They can actively contribute in all activities of the project, from chamber construction till data analysis, making EEE a large collaboration with order of thousand students and teachers involved every year. It is important to notice that EEE is a long-term project and students are involved for a year-long (and sometimes several years) engagement which allows a full immersion in the scientific aspects of an experiment and stimulates their interest toward future university scientific disciplines.

As a unique example of this dissemination engagement, the EEE collaboration has recently made an official publication [8] based on the masterclass performed with more than 150 students during the VIII *Conferenza di Progetto 2018* in Erice (Ettore Majorana Center for Scientific Culture). The paper reports their measurements of the variation of the cosmic ray flux with altitude and, for the first time, includes the signatures of all the students participating.

3. EEE Physics results

A complete list of the EEE scientific publications can be found in [9]. Among the several studies performed, three examples will be mentioned in the following.

It is well known that cosmic rays fluxes are subject to a decrease associated to solar phenomena as Coronal Mass Emissions (the Forbush decreases), or solar flares. These events, *the galactic cosmic-ray flux decreases (GCRDs)*, take place over few hours and are generally detected via neutron monitor stations, much sensitive to the low energy component. The EEE network was capable to detect such events also from the muon flux and with detectors monitored by students.

Starting from the optical observations of strong solar activity, muon data were analyzed in the same time interval where the decrease was expected. After normalization via a barometric coefficient evaluated in each station, several telescopes detected the rapid variations due to GCRDs, as reported in Fig. 4 for two different flares [10]. Data are also compared with the OULU neutron monitor station.

The large area coverage of the EEE project is especially adapt to search for *long-range (order of hundreds of kilometers) correlation of individual Extensive Air Showers (EAS)*. These events can be related to different processes (like the photo-disintegration of a primary heavy nucleus in two lighter but highly energetic fragments by interaction with a solar photon, the Gerasimova-Zatsepin mechanism) but also new, more exotic possibilities have been proposed. The showers are detected by pairs of MRPC telescopes: the pairs belong to a cluster of nearby telescopes and the coincidence between them allows a reduction of the background. The search is performed studying the number of coincidences between two pairs in time slices going from ±10 s down to tens of microseconds and looking at a possible event excess with respect to the spurious rate [11]. Using 10 EEE cluster sites with a time exposure of 3968 days, few events with unusually small time difference and small p-values (< 0.05) were observed (Fig. 5). To increase the statistics, still having low background, the analysis is being extended to coincidences among

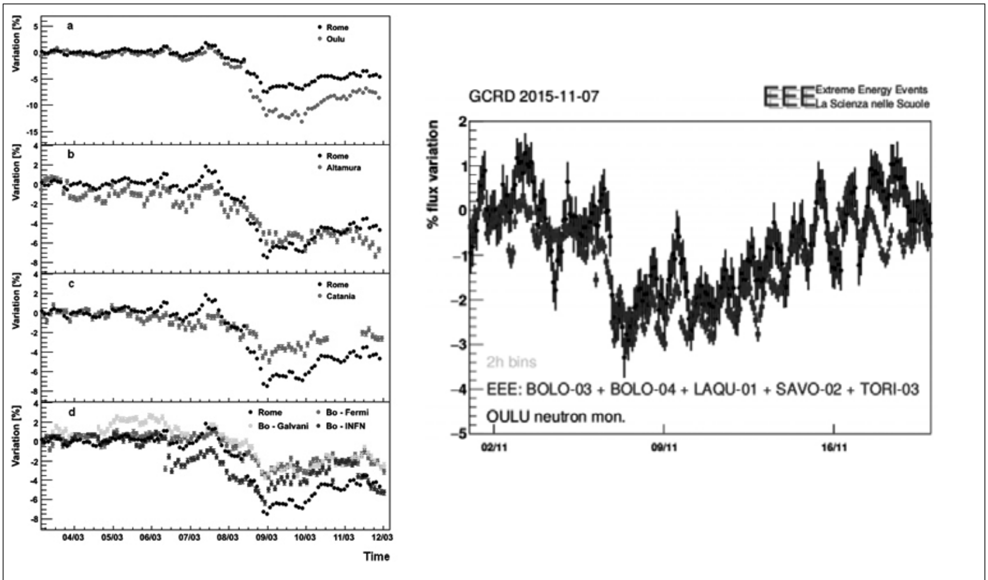
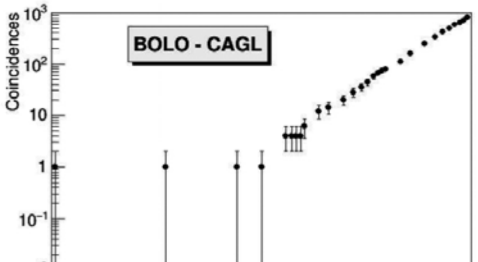


Figure 4: Variation of the muon flux detected by EEE telescopes in correspondance of the Forbush events of March 6th 2012 (left) and November 11th 2015 (right) [10].

single telescopes after requirement of a number of reconstructed tracks per telescope in excess of 4 with a distance of at least 5 km between the two telescopes. Preliminary results with 39 telescopes indicate 11 events with coincidences in the range $10^{-5} \div 10^{-4}$ s against an expectation of 5 events.



Event	EEE pairs	Distance (km)	$\lvert t_1 - t_2 \rvert$ (μs)	$\vartheta_{\rm rel}$ (deg)	Expected events	p-value	UTC time
(A)	BOLO-CAGL	614	86	27.1	0.0069 ± 0.0002	0.007	26.11.2015 19 h 07′ 16″
(B)	BOLO-LAQU	290	740	9.1	0.014 ± 0.001	0.014	25.03.2016 18 h 31′ 05″
(C)	CATA-TORI	1040	88	9.2	0.0265 ± 0.0005	0.026	09.01.2016 06 h 42′ 15″
(D)	GROS-TORI	377	297	14.4	0.032 ± 0.001	0.031	04.06.2016 02 h 31′ 08″
(E)	CERN-CATA	1200	248	9.3	0.049 ± 0.001	0.048	15.02.2016 01 h 28′ 29″

Figure 5: An example of the study of time correlations in time slices and the table of events characteristics with p-value < 0.05 [11].

During 2018, remembering the 90th anniversary of the unfortunate expedition of the airship Italia guided by Umberto Nobile, the Polarquest mission [12] organized a voyage toward the North Pole with Nanuq, a 60-feet Grand Integral eco-sustainable sailing boat. The mission, together with various events dedicated to Nobile's expedition, included also few scientific programs like *the PolarquEEEst detector for cosmic rays measurements near the North Pole* [13]. The goal was to perform measurements of the flux at sea level at latitudes till now with scarce data. PolarquEEEst is made of two planes of scintillator (each one divided into 4 tiles 30×20 cm^2), read with SiPMs (two per tile) and a low power consumption trigger/readout system (< 15 W as required by Nanuq) with time and charge information. A GPS time stamp and several control signals (temperature, pressure, orientation...) allowed a complete set of information to be used during the analysis.

The detectors were built at CERN by a group of researchers and students from Italy, Norway and Switzerland, as for all the chambers of EEE. Two additional twin detectors were built and installed in Norway and Italy as reference. During the mission, from 22nd July till 4th September, more than 100 million tracks have been recorded per detector and all data have been transferred to INFN CNAF for reconstruction and are now available for data analysis.

Preliminary measurements cover from 66° until 82° 07′ latitude, a unique result for such regions (Fig. 6). Although the Earth geo-magnetic field decreases at these latitudes,

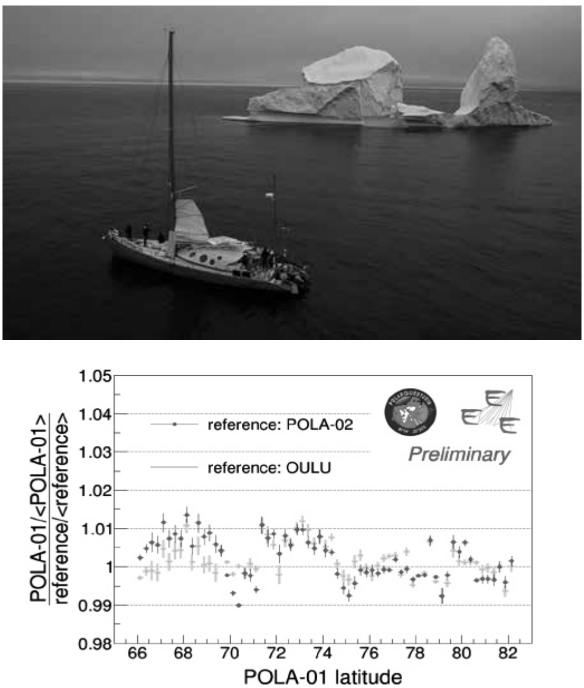


Figure 6: The Nanuq sailing-boat during the Polarquest2018 mission (top, courtesy by Mike Struik, Polarquest2018) and flux measurement at latitudes between 66 and 82.07 degrees [13] (bottom).

no variation in the flux was observed, confirming the suppression of the low energy cosmic rays due to the solar effects. PolarquEEEst is presently involved in a "on the road" program of measurements along the Italian peninsula, hosted in different schools of EEE, to perform a scan at different latitudes and obtain a complete map of measurements.

4. Summary

Started from the experience of a team of researchers from the INFN Section in Bologna and the Department of Physics of the University of Bologna, with Antonino Zichichi as group leader, the EEE project demonstrated the possibility to perform an advanced experiment on cosmic rays physics and a strong dissemination of scientific culture among the students of the high schools. On the one hand, the students participate in all phases of the experiment, from the construction of the detectors to their installation and monitoring, until the data analysis, both for performances checks and physics studies. On the other hand, several physics results have been published demonstrating the reliability of the detector and, profiting from the large area covered, the possibility to make unique studies.

The EEE project is still increasing the number of active telescopes and it is starting international collaborations in order to include also data from other European regions and further expand its physics capabilities.

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Appendix: The EEE Collaboration

M. Abbrescia[a,b], C. Avanzini[a,c], L. Baldini[a,c], R. Baldini Ferroli[a,d], G. Batignani[a,c], M. Battaglieri[a,q], S. Boi[a,e] E. Bossini[a,o,e], F. Carnesecch,[a,f], D. Cavazza[f], A. Chiavassa[a,g], C. Cicalo[a,h], L. Cifarelli[a,f], F. Coccetti[a], E. Coccia[a,i], A. Corvaglia[a,j], D. De Gruttola[a,k], M. Guerzoni[f], S. De Pasquale[a,k], F.L. Fabbri[a,d], D. Falchieri[f], S. Finelli[f], A. Flammini[f], V. Frolov[p], M. Furini[f], L. Galante[a,g], P. Galeotti[a,g], M. Garbini[a,f], G. Gemme[a,q], I. Gnesi[a,g], S. Grazzi[a], C. Gustavino[a,l], D. Hatzifotiadou[a,f,o], P. La Rocca[a,r], L. Lombardo[x], G. Mandaglio[a,s], O. Maragoto Rodriguez[n], A. Margotti[f], G. Maron[m], M.N. Mazziotta[a,t], S. Meneghini[f], S. Miozzi[a,d], R. Nania[a,f], F. Noferini[a,f], F. Nozzoli[a,u], F. Palmonari[a,f], M. Panareo[a,j], G. Pancaldi[f], M.P. Panetta[a,j], R. Paoletti[a,e], W. Park[n], C. Pellegrino[a], L. Perasso[a,q], F. Pilo[a,c], O. Pinazza[f], G. Piragino[a,g], S. Pisano[a,d], F. Riggi[a,r], G.C. Righini[a], C. Ripoli[a,k], M. Rizzi[a,b], G. Sartorelli[a, f], E. Scapparone[a,f], M. Schioppa[a,v], A. Scribano[a,c], M. Selvi[a,f], S. Serci[a,h], S. Squarcia[a,q], M. Taiuti[a,q], G. Terreni[a,c], G. Torromeo[f], R. Travaglini[f], A. Trifirò[a,w], M. Trimarchi[a,w], M.C. Vistoli[m], L. Votano[a,l], M.C.S. Williams[a,f,o], L. Zheng[a,n,o], A. Zichichi[a,f,o], A. Zucchini [f] and R. Zuyeuskia[n,o]

a. Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Roma, Italy
b. INFN and Dipartimento Inter-ateneo di Fisica, Università di Bari, Bari, Italy
c. INFN and Dipartimento di Fisica, Università di Pisa, Pisa, Italy
d. INFN, Laboratori Nazionali di Frascati, Frascati (RM), Italy
e. INFN Gruppo Collegato di Siena and Dipartimento di Fisica, Università di Siena, Siena, Italy
f. INFN and Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
g. INFN and Dipartimento di Fisica, Università di Torino, Torino, Italy
h. INFN and Dipartimento di Fisica, Università di Cagliari, Cagliari, Italy
i. INFN and Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
j. INFN and Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
k. INFN and Dipartimento di Fisica, Università di Salerno, Salerno, Italy
l. INFN, Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy
m. INFN CNAF, Bologna, Italy
n. ICSC World Laboratory, Geneva, Switzerland
o. CERN, Geneva, Switzerland
p. JINR Joint Institute for Nuclear Research, Dubna, Russia
q. INFN and Dipartimento di Fisica, Università di Genova, Genova, Italy
r. INFN and Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy

s. INFN Sezione di Catania and Dipartimento di Scienze Chimiche, Biologiche, Farmaceutiche e Ambientali, Università di Messina, Messina, Italy
t. INFN Sezione di Bari, Bari, Italy
u. INFN and ASI Science Data Center, Roma, Italy
v. INFN and Dipartimento di Fisica, Università della Calabria, Cosenza, Italy
w. INFN Sezione di Catania and Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, Università di Messina, Messina, Italy
x. Politecnico di Torino

The Erice International School of Subnuclear Physics

*Pierre Darriulat**

Fifty-five years ago, in 1963, Antonino Zichichi, together with John Bell, Robert Blackett, Isidor Rabi and Vicki Weisskopf, signed the charter constitution of the Ettore Majorana Foundation and Centre for Scientific Culture (EMFCSC) in Erice. That same year, the first Erice school of subnuclear physics was bringing together prestigious lecturers such as John Bell, Sid Drell, Dick Garwin, Giampietro Puppi, Val Telegdi and Vicki Weisskopf on the topic of *Present Problems in Weak, Electromagnetic and Strong Interactions*. It was the first in an uninterrupted series of fifty-six courses in particle physics, the first in an even much broader series of courses covering all fields of sciences: every year since then, authors of new discoveries or inventions come to Erice; 85 of them were awarded the Nobel Prize after their participation and 49 were already Nobel laureates. These scientific world leaders teach students from all over the world who are eager to receive the latest knowledge directly from the mouth of its authors, just as was done in the University of Bologna more than nine centuries ago. Erice has since become a shrine of science, by 2015 it had hosted over 120.000 scientists from 140 nations who came there to take part in post-university activities in the spirit of promoting a science without secrets and without borders. Together with Antonino Zichichi, Gabriele Veneziano and the late Guido Altarelli have briefly served as school directors and, since 2007, Gerard 't Hooft is in charge as co-director (Fig.1).

Soon after the creation of the school of subnuclear physics, the field entered an outstanding period of remarkable and rapid success. In less than two decades, the Standard Model of particle physics was constructed, based on group symmetries and gauge invariance. Contrary to the normal sequence of events in science, with experiments and observations preceding their description and synthesis in a well-rounded theory, theory came first, experiments followed. Major milestones were the quark model of Gell-Mann and

* Department of Astrophysics, Vietnam National Space Centre, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Hanoi, Vietnam

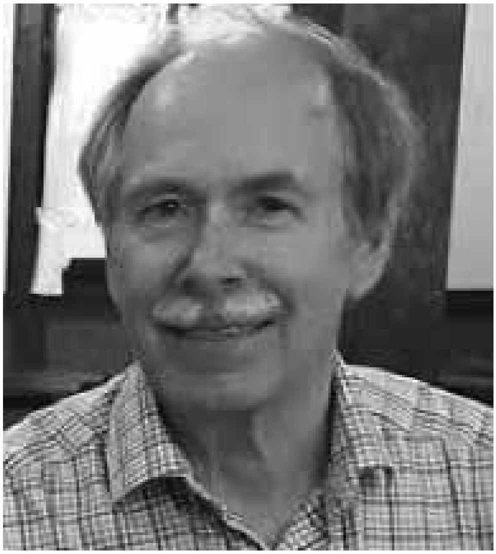


Figure 1: The directors of the school: Antonino Zichichi and Gerard 't Hooft.

Zweig (1964), the bases of electroweak unification by Glashow, Weinberg and Salam (1967), the parton model of Feynman following the measurements of deep inelastic electron scattering at SLAC (1969), the Glashow-Iliopoulos-Maiani (GIM) mechanism predicting the existence of charm (1970), the work of 't Hooft on the renormalization of Yang-Mill fields (1971) and, in 1973, quantumchromo-dynamics and asymptotic freedom with Gross, Wilczek and Politzer, colour with Fritzsch, Gell-Mann and Leutwyler. That same year neutral currents were discovered in Gargamelle, starting a series of discoveries that would superbly confirm the predictions of theory: 1974 was marked by the joint discovery of charmonium at SLAC and Brookhaven (Richter and Ting) and of the third lepton family at SLAC (Perl); the next quarkonium state was discovered at Fermilab in 1977 (Lederman) and the weak bosons in 1983 by the UA1 and UA2 collaborations at the CERN proton-antiproton collider (Rubbia). By then evidence for the validity of the Standard Model was broadly accepted; the missing piece of the fermion jigsaw was discovered in 1995 at Fermilab (top quark, CDS and D0); and in 2012 the Higgs boson (or a Higgs boson?) was discovered at the CERN Large Hadron Collider by the ATLAS and CMS collaborations, closing a glorious series of experiments that had considerably modified the particle physics landscape.

It is interesting to follow these developments through the few lines of introduction that we read on the posters announcing each year's edition of the school. The first decade stated the general spirit of the courses in the following terms: *The school is devoted to those physicists who are interested in having a much deeper theoretical understanding of the field of physics in which they are working. In order to exploit to the fullest extent the material presented at the school, three lectures will be given in the morning and at least two hours of* *the afternoon will be dedicated to clearing up in free, informal discussions the topics of the morning lectures.* But as soon as theoretical developments took off, it became necessary to limit the scope of the school to the most recent findings: *The emphasis of the program will be on the elucidation and discussion of the progress achieved in experimental and theoretical particle physics during the last year*. Year 1977 marked the start of a new era, that of *Beyond the Standard Model*: *We present this year's program in a provocative format based on a series of why's* and the years that follow are witnessing the concerns of the community, here expressed in the positive and optimistic way that is in order in such cases: *In spite of the spectacular results obtained in recent times subnuclear physics is far from reaching the asymptotic limit of a field without a future. This is testified by the large number of problems, which open up at a rate at least comparable with that of new results.*

Since 1979, the theme and the program of the school is specified each year separately. In the mid-nineties, the school started to promote programs aimed at supporting young new talents, the importance of which has kept growing over the years.

Detailed accounts of the achievements of the school are given in the web site of the EMFCSC and in a book authored by Professor Zichichi [1] to which the interested reader is referred. I shall instead limit the scope of the present article to a brief overview of where we stand today in particle physics and of how the school addresses it, and to a few words on the Erice spirit, which, I believe, plays an essential role in the success of the school.

Fig. 2 displays an overview of contemporary frontier physics. It uses natural units, with Planck constant $\hbar$, light velocity c and Newton gravity constant G taken as unity, and displays in logarithmic coordinates masses M as abscissa and sizes L as ordinate, covering respectively 150 and 120 orders of magnitude. Two lines, at 90° from each other mark the limits of the observable world: the quantum limit, associated with Heisenberg uncertainty relations, is for $ML=1$ and the black hole limit, associated with Schwarzschild metric, is for $M/L=1$.

The quantum limit hosts elementary massive particles, using Compton wave length as measure of their size; the lightest of these, the neutrino, has mass and size of, respectively, 10^{-30} and 10^{30}. The black hole limit hosts, in addition to stellar black holes and supermassive black holes at the centers of galaxies, the Universe itself, more precisely the visible Universe. The Universe is not a black hole, there is more of it behind its horizon, but it satisfies the Schwarzschild relation with escape velocity reaching velocity of light at the horizon. The line joining the Universe and the neutrino, corresponding to M proportional to L^3 is a line of constant density: Universe and neutrino share the same density of $\sim 10^{-120}$ in natural units. As the Universe is known to be dark energy dominated, and as dark energy is well described by a cosmological constant Λ, its density $\Lambda/8\pi$ is equal to the neutrino density, M_ν^4, thereby providing a relation between neutrino mass and cosmological constant. Quantum and black hole limits meet at the Planck scale where new physics is required: indeed, Heisenberg uncertainty relations prevent a wave packet of size L and mass M to contain a gravitation energy GM^2/L larger than $\hbar/(L/c)$, hence to have a mass in excess of $M_{Planck}=\sqrt{(\hbar c/G)}=10^{19}$ GeV/c^2.

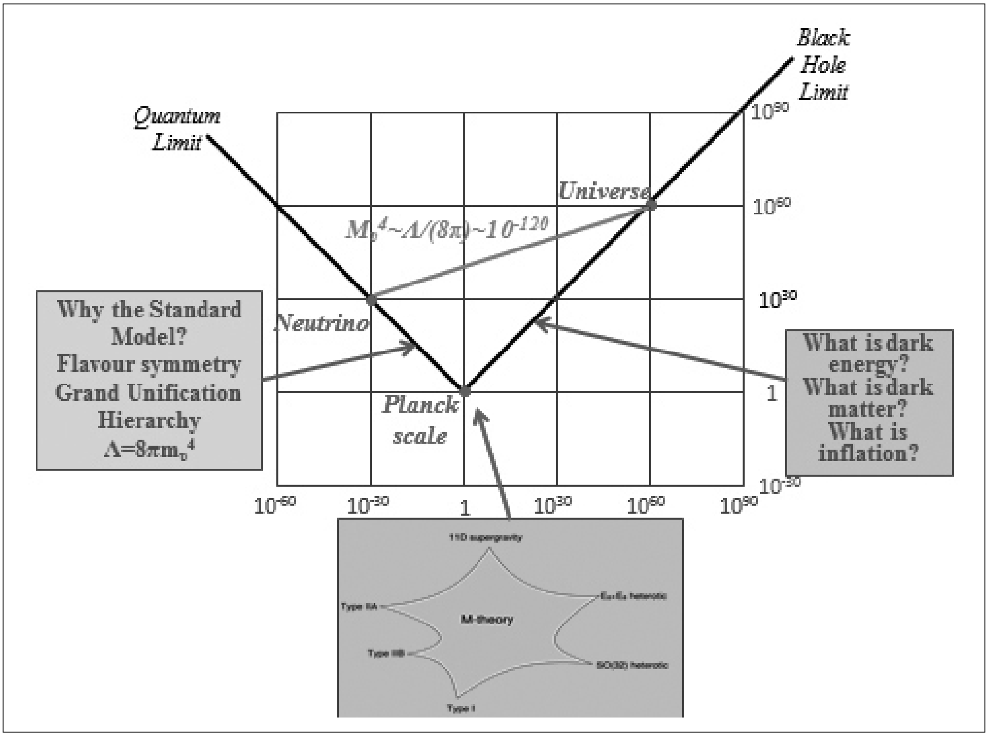


Figure 2: An overview of contemporary frontier physics.

Major unanswered questions of contemporary frontier physics can be identified on each of the quantum and black hole limits as well as at their intersection.

The quantum limit (Fig. 3) hosts open questions *beyond the Standard Model* of particle physics:

- Why do we have three lepton families, who ordered that? as Rabi said when the muon was discovered. What is the reason behind the observed flavor symmetry that relates them?
- The strong, electromagnetic and weak forces tend to converge to a common strength, suggesting some *Grand Unification* to take place some two orders of magnitude below the Planck mass; what does this hide?
- Particle masses cluster below 10^{12} eV/c^2, 16 orders of magnitude below the Planck mass, causing a difficulty referred to as the hierarchy problem. Moreover, neutrino masses stand out six orders of magnitude below the mass of the electron, the lightest charged lepton, suggesting that there may be something special about neutrinos (they might be Majorana rather than Dirac particles; is the observed relation between their mass and the cosmological constant a pure coincidence?).

The black hole limit (Fig. 4) hosts open questions *beyond the Standard Model* of cosmology:

- The model predicts an energy density of the Universe, based on three major observations: the abundance ratio of nuclides, strongly constrained by the fact that three minutes after Big Bang the Universe had no time, in the small window of opportunity offered by its cooling-down rate, to synthetize ^{12}C and more massive nuclei; the power spectrum of the Cosmic Microwave Background, the remnant of the photons hosted by the plasma that dominated the Universe in the first 400 thousand years after Big Bang, before entering into dark ages after atoms had formed; the evidence for a violation of Newton's gravity laws obtained from the rotation curve of galaxies, from gravitational lensing of clusters, from simulations of galaxy formation, etc.
- Hence the first major question: what is hiding behind what we call dark energy? Additional evidence from it has been obtained from the Hubble relation of distant standard-candle galaxies.

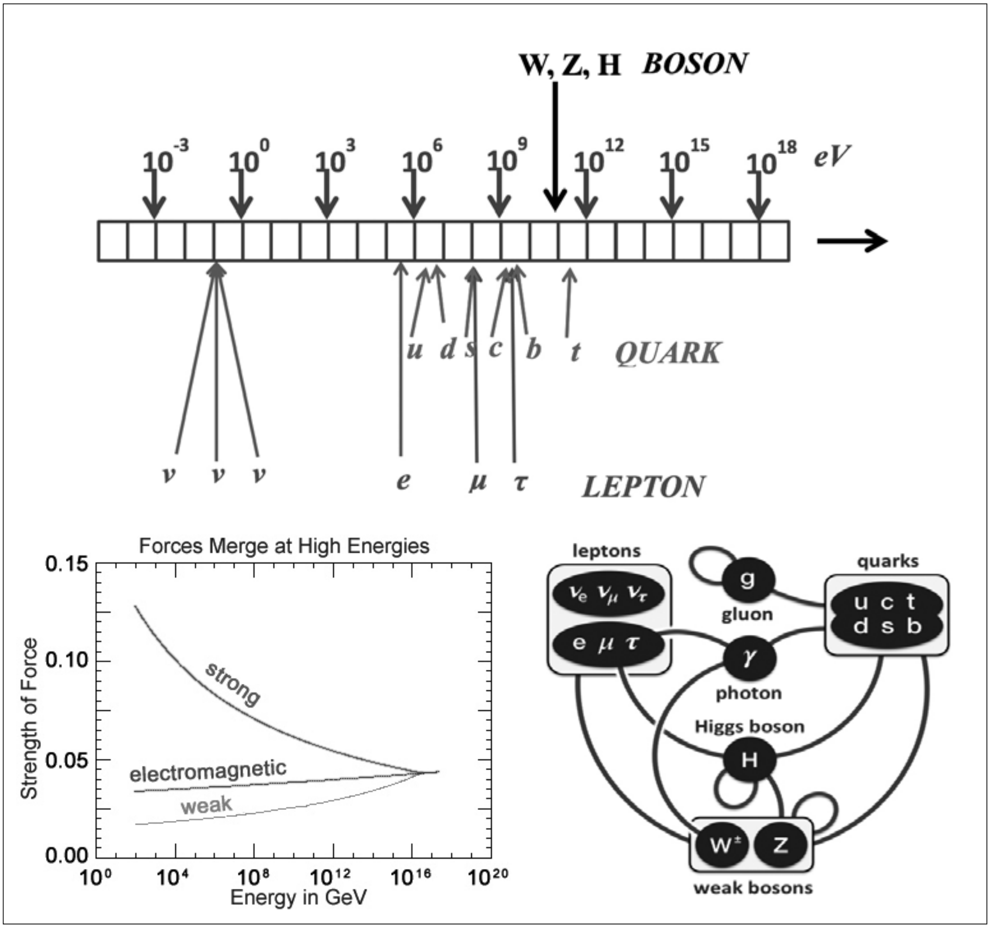


Figure 3: Open questions in particle physics. Upper panel: particle masses, the hierarchy problem and possible neutrino peculiarity. Lower panels: Grand unification (left) and ingredients of the Standard Model (right).

- What is dark matter? If caused by unknown particles having essentially no interactions other than gravity, they must be massive enough for their velocities to be non-relativistic (one speaks of Cold Dark Matter). Presently, all efforts to discover such particles have been vain.
- Another major question concerns the very first moments of the Universe, just above Planck scale. The Standard Model of Cosmology has no ambition to describe it but requires that this epoch was governed by an exponential expansion called inflation in order to dispose of puzzling observations such as the flatness of the Universe, the absence of Dirac magnetic monopoles, etc. But till now, no sensible understanding of the mechanism that caused inflation has been obtained.

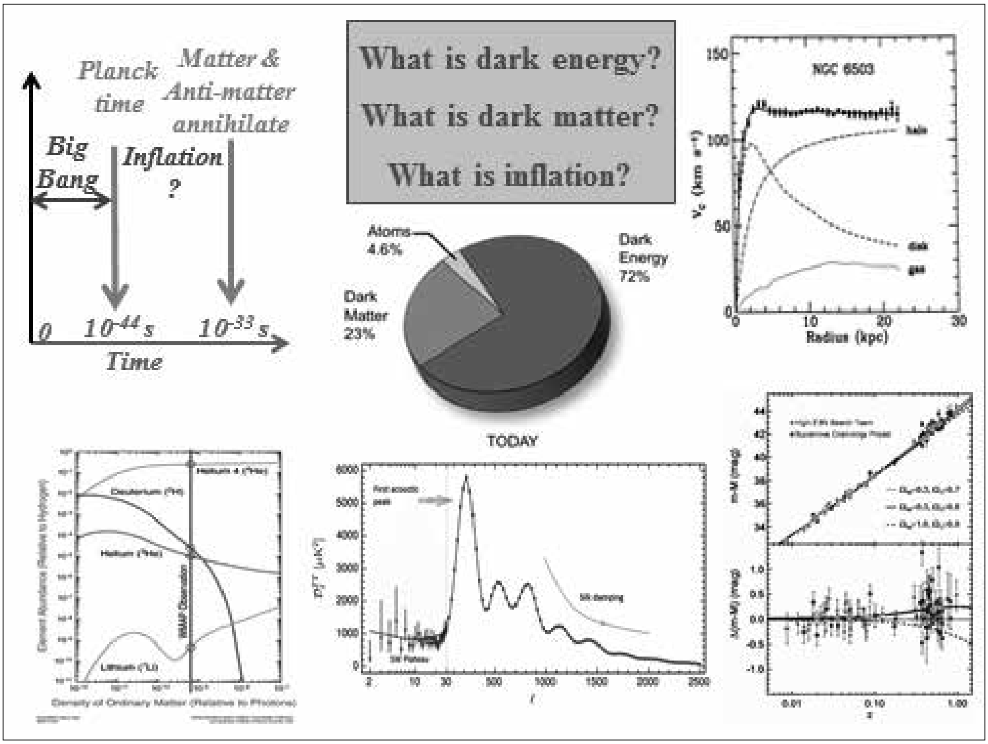


Figure 4: Open questions in cosmology. Upper left: the Universe near the Planck scale; upper middle: respective shares of baryons, dark matter and dark energy; upper right: evidence for dark matter; lower left: nucleosynthesis; lower middle: power spectrum of the Cosmic Microwave Background; lower right: Hubble relation and dark energy.

Finally, understanding physics at the Planck scale is undoubtedly, and by far, the most puzzling unanswered question of contemporary physics. Many think that its answer will bring with it an answer to all the other major questions of particle physics and cosmology. Till today, efforts in this direction have been dominated by Superstring Theories, where super stands for supersymmetry relating bosons to fermions and strings are, together with branes, the basic ingredients of the theory. To be viable, such theories have to live in 9+1 dimensions, of which 6 are compactified. The so-called M-theory, in 10+1 dimensions, is known to unify 11-D Supergravity with the five consistent versions of String Theory as limiting cases. Different versions of string theories are related this way by highly non-trivial duality relations. Yet, the extreme mathematical complexity of standard Superstring Theory and the experimental inaccessibility of the Planck Scale, together with the lack of encouraging signals, is causing a surge of different approaches based on the direct study of quantum size black holes without biasing influence of string prejudices. The Erice school of subnuclear physics is naturally focusing on Planck scale physics and is making for such theories the room that it deserves. An illustrative example is shown in Fig. 5 that displays the content of the lectures that were delivered at the 2017 school.

THEORY & PHENOMENOLOGY

The Black Holes Physics is a New Frontier
- G. 't HOOFT, Utrecht University, NL

Black Holes in String Theory
- S.D. MATHUR, Ohio State University, Columbus, OH, US

Status of Inflation
- A. GUTH, MIT, Cambridge, MA, US

Inflation and Neutrino Masses in NoScale Supergravity
- D. NANOPOULOS, Texas A&M University, College Station, TX, US

Updates on Brane Supersymmetry Breaking
- A. SAGNOTTI, Scuola Normale Pisa, IT

Thirty Years of Erice on the Brane
- M.J. DUFF, Imperial College London, UK

Gravity Amplitudes from Gauge
- Z. BERN, UCLA, Los Angeles, CA, US

Dark Matter and LHC
- H. FRITZSCH, Ludwig-Maximilians-Universitaet, Muenchen, DE; Nayang Technological University, Singapore, SG

Highlights in Supergravity
- S. FERRARA, CERN, Geneva, CH; LNF–INFN, Frascati, IT; UCLA, Los Angeles, CA, US
- P. VAN NIEUWENHUIZEN, State University of New York, Stony Brook, NY, US

The Early Universe as observed by Radio-Astronomy
- P. DARRIULAT, VATLY Laboratory, Hanoi, VN

Status of Neutrinos
- A. BETTINI, INFN & Padoa University, IT

QCD from its birth to its stubbornly unsolved problems
- A. DE RUJULA, CERN, Geneva, CH

The GAP between α_G and α_{GUT}
- A. ZICHICHI, CERN, Geneva, CH; University of Bologna & INFN, IT

Figure 5: Program of the 2017 Erice School of Subnuclear Physics.

The success of the Erice schools is in part the result of the Erice spirit that pervades all activities of the EMFCSC. Emblematic of such spirit is the famous Erice statement that was written in August 1982 by Dirac, Kapitza and Zichichi and has since been signed by nearly 100'000. It pleads for a free science without secret and without borders. Quoting from it "The choice between peace and war is not a scientific choice, it is a cultural one. The culture of love produces peaceful technology, the culture of hatred instruments of war. Love and hatred have existed forever. It is [now] imperative that the culture of love wins."

Also emblematic is the World Laboratory that is open to the best intellects, without racial, ideological, political, religious or geographical barriers, fruit of a promise that the scientific community has made for the sake of all those who love peace not only as a word, but also as something that they wish to construct day by day out of facts. The scientists of Erice have given life to a new way of conceiving international scientific collaboration based on voluntary scientific service with the aim of developing all of the poor countries that are far below the scientific and technological levels of today's industrialized countries. They realize projects that would require enormous sums if they could not rely on the work offered by thousands of scientists and specialists who ask nothing in terms of stipends or compensation for the work they put in. This voluntarism touches all levels, up to the highest, including protagonists of global prestige from Science, Technology and Medicine, among who are many Nobel Laureates.

I should like to close this brief presentation by mentioning two other manifestations of the Erice spirit, which are particularly close to my heart: Planetary Emergencies and Scholarship Program.

The International Seminars on Planetary Emergencies, Science for Peace the World over, have been analyzing and discussing threats to the planet for over 50 sessions. In order to mitigate such threats, Professor Zichichi has recently launched a new project: the Project for Mankind for the 21st century.

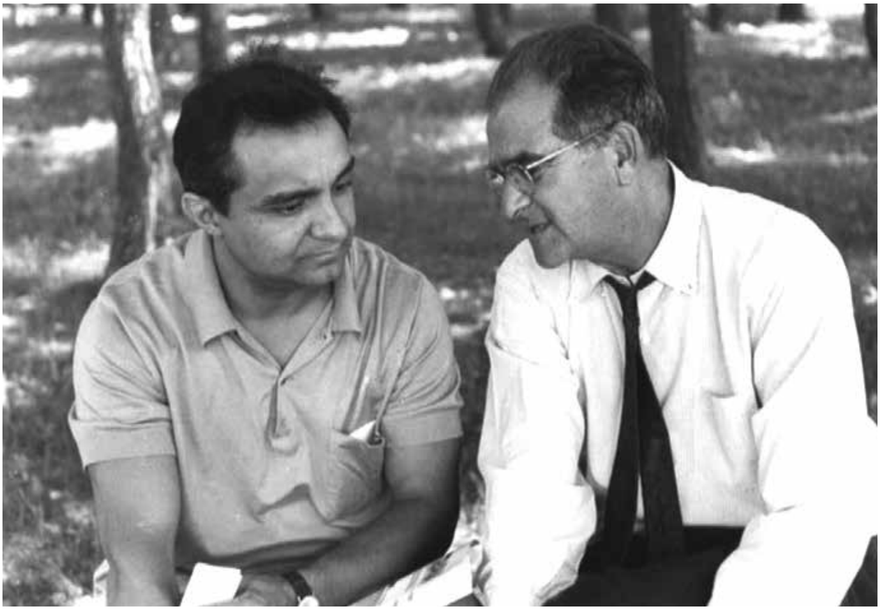
The World Federation of Scientists and the World Laboratory have instituted a National Scholarship Program for young graduates from developing and newly emergent countries to conduct scientific research activities in their own country under the supervision of the best and most experienced national scientists. The small research team of Vietnamese astrophysicists with which I am associated benefits of this program and I should like to take this opportunity to express our extreme gratitude to Professor Zichichi.

I conclude this presentation by displaying a picture gallery that evocates, not without some nostalgia, the glorious past of the school.

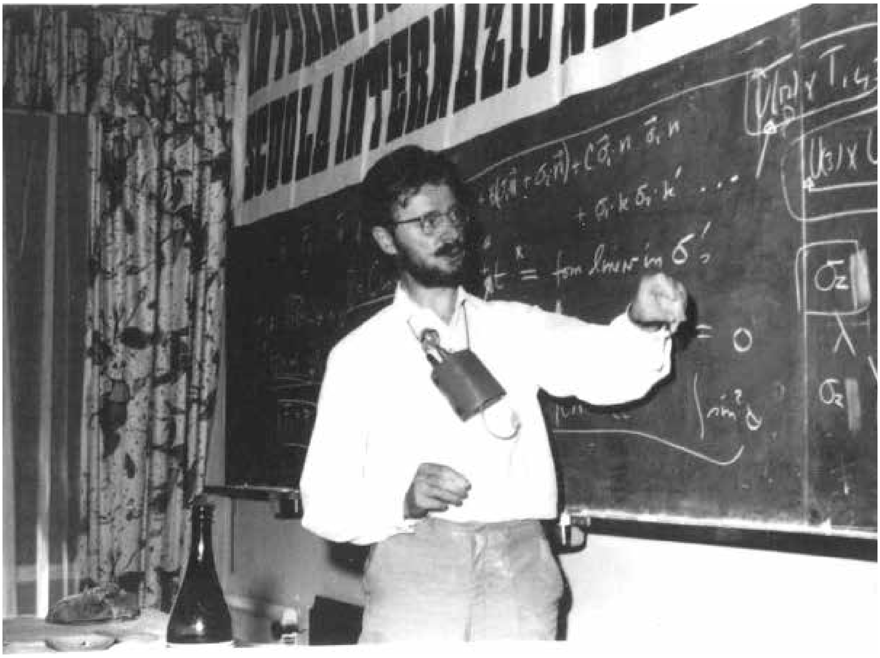
References

[1] A. Zichichi, *Subnuclear Physics: The First 50 Years, Highlights from Erice to ELN*, World Scientific Series in 20th century physics, edited by O. Barnabei, P. Pupillo and F. Roversi Monaco, Vol. 24 (World Scientific, Singapore 2000).

Photo gallery



Victor F. Weisskopf with Antonino Zichichi (1960).

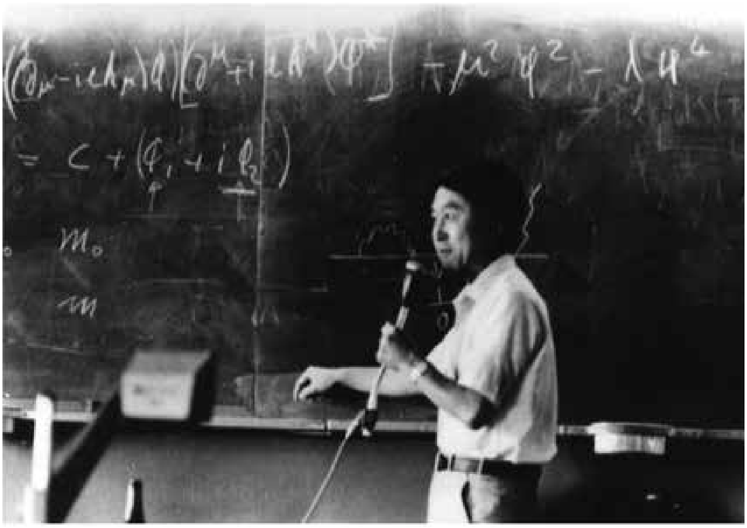


John Stewart Bell at Erice (1963) lecturing on Dirac and Majorana neutrinos.

Melvin Schwartz, Tsung Dao Lee, Antonino Zichichi and Isidor Isaac Rabi at Erice (1968).

Bruno Zumino lecturing at Erice (1969) on the PCT theorem.

Victor F. Weisskopf lecturing at Erice (1970).



Yoichiro Nambu at Erice (1972).

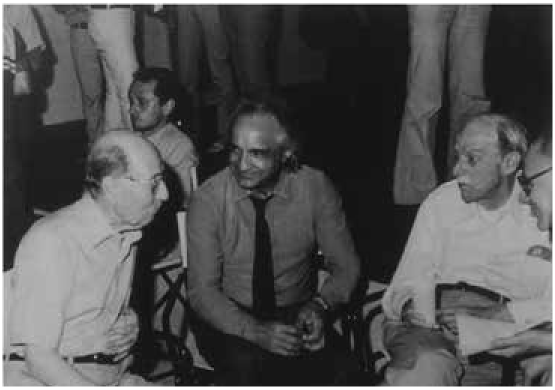
Julian Schwinger at Erice during a discussion session devoted to Anomalies in Quantum Field Theory.

Julian Schwinger celebrating his 70th birthday in Erice during the 26th Subnuclear Physics School. From left: Sheldon Glashow, Mrs Manci Dirac, Sergio Ferrara, Michael Duff (1988).

John Stewart Bell at Erice (1975).

Giancarlo Wick at Erice (1971).

Sergio Ferrara lecturing at Erice (1988).



The father of Time Reversal Invariance, Professor Eugene Wigner (on the left) and Professor Paul Dirac (on the right), father of the equation which sparked the existence of 'annihilation' and of antimatter, with Antonino Zichichi at Erice (1982).

Laura Fermi at the Subnuclear Physics School at Erice (1975), lecturing on her recollections of Ettore Majorana.

2016: Best student prize awarded to X. Fan.

Erice on the brane in 1987

*Michael J. Duff**

So are we quarks, strings, branes or what?
New York Times, September 22, 1998

After initially meeting with fierce resistance, *branes*, p-dimensional extended objects which go beyond particles ($p = 0$) and strings ($p = 1$), now occupy centre stage in theoretical physics as microscopic components of M-theory, as the seeds of the AdS/CFT correspondence, as a branch of particle phenomenology, as the higher-dimensional progenitors of black holes and, via the *brane-world*, as entire universes in their own right.

Notwithstanding this early opposition, Nino Zichichi invited me to talk about supermembranes and eleven dimensions at the 1987 School on Subnuclear Physics and has continued to keep Erice on the brane ever since. This is a shortened version of arXiv:1812.11658 [hep-th] where I provide a distillation of my Erice brane lectures 1987-2017 and some personal recollections.

1. Introduction

1.1. Geneva and Erice: a tale of two cities

In 1987 I was a staff member in the Theory Division at CERN, on leave of absence from Imperial College London. I spent the early 1980s advocating spacetime dimensions greater than four [1] and the late 1980s advocating worldvolume dimensions greater than two [2]. The latter struggle was by far the harder. See for example [3]. At this time CERN was playing a prominent part in the development of branes and the 11-dimensional foundations of what was later to be called M-theory. See, for example, CERN TH-4124-85 [4], CERN-TH-4664-87 [5], CERN-TH-4731-87 [6], CERN-TH-4749-87 [7], CERN-TH-4779-87 [8], CERN-TH-4797-87 [9], CERN-

* Institute for Quantum Science and Engineering and Hagler Institute for Advanced Study, Texas A&M University, College Station, TX, USA & Theoretical Physics, Blackett Laboratory, Imperial College London, UK & Mathematical Institute, Andrew Wiles Building, University of Oxford, UK.

TH-4818-87 [10], CERN-TH-4820/87 [11], CERN-TH-4924/87 [12]. As a matter of fact, the Oxford English Dictionary attributes first usage of the word *brane* to the May 1987 CERN preprint [6] by Duff, Inami, Pope, Sezgin and Stelle, published the following year in Nuclear Physics B[1]. See Fig. 1. Since then, according to INSPIRE there have been 46,192 papers on branes garnering 1,786,998 citations as of November 2018. According to [13], brane ranks 13th in the list of most frequent words in hep-th titles[2].

The 1987 Annual Report of the CERN Theory Division was upbeat:

> *Finally there were a few papers that are highly critical of string theory and its prospects, and a few that started a heroic study of more complicated objects, namely supermembranes. During 1987 the CERN theory group became the leading research centre for this subject, which is still in its infancy. The main goal is to understand why there exists an elegant and unique eleven dimensional supergravity, while string theory seems to be restricted to ten dimensions.*

brane, *n.*   Text size:

View as: Outline | Full entry   Quotations: Show all | Hide all Keywords: On | Off

Pronunciation: Brit. /breɪn/ , U.S. /breɪn/

Etymology: Shortened < MEMBRANE *n.*

Physics.

An extended object with any given number of dimensions, of which strings in string theory are examples with one dimension. Also with prefixed numbers, or symbols representing numbers, as *2-brane, p-brane*.   Categories »

Quot. 1988 is from a paper received for publication earlier (18 May 1987) than quot. 1987 (1 Aug.).

1987 *Physics Lett.* B. **198** 441 The extension of the spacetime supersymmetric Green–Schwarz covariant superstring action to *p*-dimensional extended objects (*p*-branes) is possible if and only if the on-shell *p*-dimensional Bose and Fermi degrees of freedom are equal.

1988 M. Duff et al. in *Nucl. Physics* B. **297** 516 We shall be concerned only with extended objects of one time and two space dimensions, i.e. '2-branes'... Possible '*p*-brane' theories exist whenever there is a closed *p* + 2 form in superspace.

1996 *Sci. Amer.* Jan. 75/2 He [sc. M. J. Duff] found that a five-dimensional membrane, or a 'five-brane', that moved through a 10-dimensional space could serve as an alternative description of string theory.

1997 *New Scientist* 18 Jan. 35/2 A string is a one-brane, an ordinary membrane like a soap bubble is a two-brane, and so on.

1998 *Independent on Sunday* 19 July (Rev. Suppl.) 56/2 With extra dimensions thrown in, strings turn into membranes..—and, to complicate things further, these membranes are also called 'p-branes', where 'p' is the number of dimensions.

2000 *Nature* 2 Mar. 28/3 One of the key ideas..is that the four-dimensional space–time we observe at everyday scales is actually the evolution in time of a three-brane moving through an ambient space–time of higher dimension.

(Hide quotations)

Figure 1: Oxford English Dictionary: the word *brane*.

That year I also co-authored an article for New Scientist with Christine Sutton, former editor of the *CERN Courier*, entitled "The Membrane at the End of the Universe" [14], describing conformal field theories arising from branes living on the boundary of anti-de Sitter space (AdS) [15], a theme later to play a part in the AdS/CFT correspondence [16, 17, 18]. See Fig 2. By the way, I apologized to Mike Green for the caption inserted by New Scientist without my knowledge. Mike reminded me recently that at the 1983

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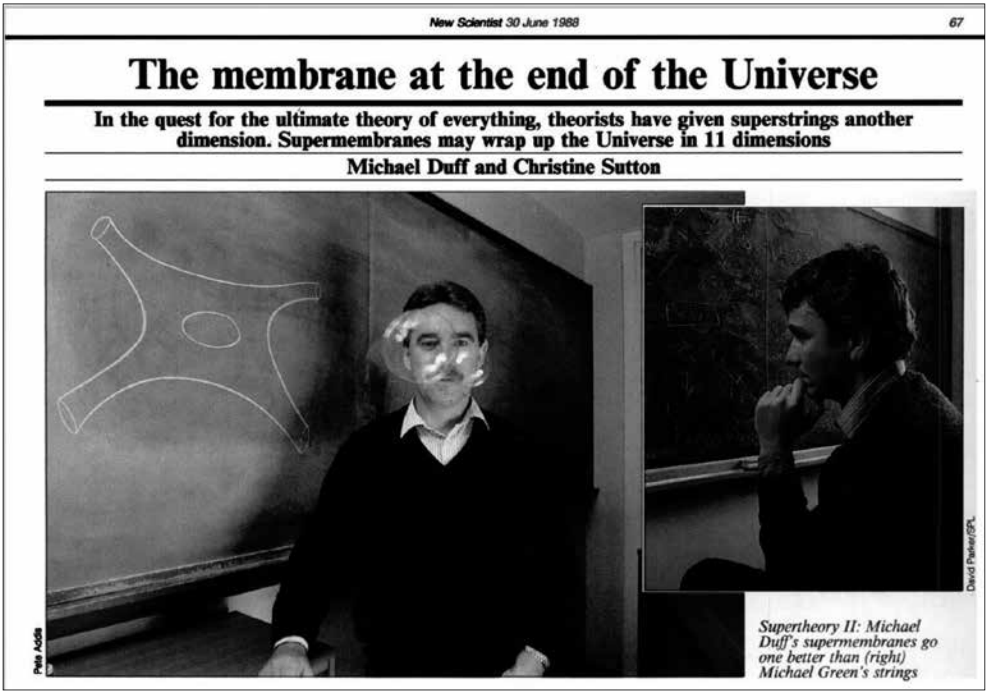
[1] Paul Townsend's lecture at the Trieste Spring School in April 1987 was intended to be entitled "P-branes for pea-brains", but organizer Ergin Sezgin baulked (at pea-brains, not p-branes).

[2] The top 20 are *model*, *theory*, *black-hole*, *quantum*, *gravity*, *string*, *susy*, *solution*, *field*, *equation*, *symmetry*, *brane*, *inflation*, *gauge-theory*, *system*, *geometry*, *sugra*, *new*, *generalized*.


New Scientist 30 June 1988 67

The membrane at the end of the Universe

In the quest for the ultimate theory of everything, theorists have given superstrings another dimension. Supermembranes may wrap up the Universe in 11 dimensions

Michael Duff and Christine Sutton

Supertheory II: Michael Duff's supermembranes go one better than (right) Michael Green's strings

Figure 2: 1987 article in *New Scientist*.

High Energy Physics Conference in Brighton, he and I played a game of crazy golf on the promenade in order to decide whether spacetime had ten or eleven dimensions. I won (the golf that is). My excuse for needing a reminder about the golf was that later that same evening I met my future wife.

There are no superstrings in eleven dimensions but there are supermembranes [19, 20, 21] which is why between the 1984 Superstring Revolution and the 1995 M-theory Revolution many string theorists were opposed to eleven dimensions. Membrane-related grant proposals tended to attract hostile referee reports during that period and papers with titles like *Supermembranes: a fond farewell* and *Eleven dimensions (Ugh!)* did not help. One string theorist announced that "I want to cover up my ears every time I hear the word membrane" and some organisers of the annual superstring conferences even banned the use of the M-word. My colleague Paul Townsend, one of the membrane pioneers, compared this with the theatrical superstition of calling Macbeth the M-Play. This opposition continued even after it was shown in 1987 that one of the five consistent ten-dimensional superstring theories, the Type IIA string, was just the limiting case of the eleven-dimensional supermembrane [5].

An exception to this negativity was Nino Zichichi and in 1987 he invited me to give two lectures on branes at the School on Subnuclear Physics in Erice. Ironically, an experimentalist could see what many theorists could not: since supermembranes are not forbidden by supersymmetry they must be compulsory. He has not only continued to welcome me and others to speak about branes at Erice in the intervening 30 years (together more recently with his co-organizer Gerard 't Hooft) but has also promoted them himself. See [22] for a recent example. I should also mention that another Erice visitor, CERN theorist Sergio Ferrara, was always very supportive [23].

This is a shortened version of arXiv:1812.11658 [hep-th] where I provide a distillation of my Erice brane lectures 1987-2017 and some personal recollections. Other Erice lectures devoted to branes include those of Khuri [24], Witten [25], Polchinski [26], Bachas [27], Antoniadis [28], Randall [29] and Sagnotti [30]. Two other historical accounts which are well worth reading are those of Witten [31] and Polchinski [32].

2. 1987 Not the Standard Superstring Review

1987 International School of Subnuclear Physics - Director: A. Zichichi, 25th Course: The Super World - II 6 - 14 August 1987 [7]

> *No talk at Texas A&M would be complete without mention of supermembranes. If one compactifies the Type I SO(32) superstring, which is unoriented, and sends r → 0, one obtains a theory with a super-D-brane...*
> J. Polchinski, *Strings 89*, Texas A&M, March 1989 [33].

The first of my lectures at the School on Subnuclear Physics, *Not the standard superstring review* [7], was an appraisal of the current state of superstrings which differed from the superstring orthodoxy in those heady days following the 1984 Superstring revolution. Specifically I focussed on the vacuum degeneracy problem and supermembranes. However, I tempered my scepticism by saying:

> *In order not to be misunderstood, let me say straight away that I share the conviction that superstrings are the most exciting development in theoretical physics for many years, and that they offer the best promise to date of achieving the twin goals of a consistent quantum gravity and a unification of all the forces and particles of Nature. Where I differ is the degree of emphasis that I would place on the unresolved problems of superstrings, and the likely time scales involved before superstrings (or something like superstrings) make contact with experimental reality.*

2.1 Vacuum degeneracy and the multiverse

> *In the absence of an exhaustive classification, we do not know how many (consistent compactifications to four-dimensions) there are[3] but it surely runs into billions [34].*

[3] It had already been noted in [1] that there are an infinite number of compact Einstein manifolds in seven dimensions and hence an infinite number of compactifications of $D = 11$ supergravity down to $D = 4$.

For the time being, therefore, the phrase "superstring-inspired phenomenology" can only mean sifting through these billions of heterotic models in the hope of finding one that is realistic. The trouble with this needle-in-a-haystack approach is that even if we found one with good phenomenology, we would be left wondering in what sense this could be called a "prediction" of string theory.

Some cosmologists, on the other hand, accept vacuum degeneracy as a fact of life. They argue that the Universe has billions of different vacua and we just happen to be living in one of them with $SU(3) \times SU(2) \times U(1)$, three families etc. In which case, as Murray Gell-Mann puts it, physics will have been reduced to an environmental science like botany.

2.2. Supermembranes

Membrane theory has a strange history which goes back even further than strings [35]. The idea that the elementary particles might correspond to modes of a vibrating membrane was put forward originally in 1962 by Dirac [36]. When string theory came along in the 1970s, there were some attempts to revive the membrane idea but things did not change much until 1986 when Hughes, Liu and Polchinski [37] showed that it was possible to combine membranes with supersymmetry: the *supermembrane* was born. Consequently, while all the progress in string theory was going on, a small splinter group was posing the question: Once you have given up 0-dimensional particles in favor of 1-dimensional strings, why not 2-dimensional membranes or in general p-dimensional objects (inevitably dubbed *p-branes*)? Just as a 0-dimensional particle sweeps out a 1-dimensional *worldline* as it evolves in time, so a 1-dimensional string sweeps out a 2-dimensional *worldsheet* and a p-brane sweeps out a d-dimensional *worldvolume*, where $d = p + 1$. See Fig. 3. Of course, there must be enough room for the p-brane to move about in spacetime, so d must be less than or equal to the number of spacetime dimensions D. In fact, as we shall see in Section 3, supersymmetry places further severe restrictions both on the dimension of the

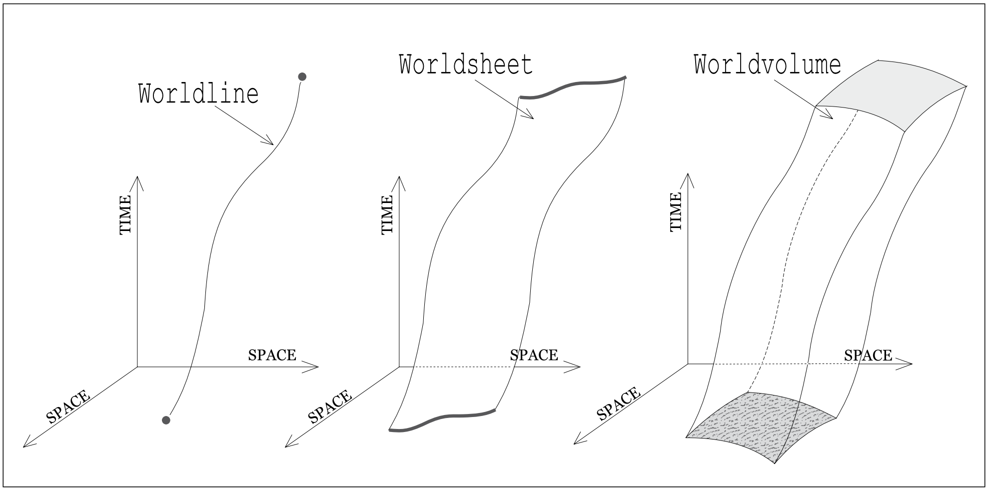


Figure 3: Particles, strings and membranes.

extended object and the dimension of spacetime in which it lives [38]. One can represent these as points on a graph where we plot spacetime dimension D vertically and the p-brane dimension $d = p+1$ horizontally. This graph is called the *brane-scan* [39]. See table 1. In the early eighties Green and Schwarz [40] had shown that spacetime supersymmetry allows classical superstrings moving in spacetime dimensions 3, 4, 6 and 10. (Quantum considerations rule out all but the ten-dimensional case as being truly fundamental. Of course some of these ten dimensions could be curled up to a very tiny size in the way suggested by Kaluza and Klein [41]. Ideally six would be compactified in this way so as to yield the four spacetime dimensions with which we are familiar.) It was now realized, however, that these 1-branes in $D = 3; 4; 6$ and 10 should now be viewed as but special cases of this more general class of supersymmetric extended object.

Curiously enough, the maximum spacetime dimension permitted is eleven, where Bergshoeff, Sezgin and Townsend found their supermembrane [19, 21] which couples to eleven-dimensional supergravity [42]. (The 3-form gauge field of $D = 11$ supergravity had long been suggestive of a membrane interpretation [43]). Moreover, it was then possible to show [5] by simultaneous dimensional reduction of the spacetime and worldvolume that the membrane looks like a string in ten dimensions. In fact, it yields precisely the Type *IIA* superstring:

> *We do not yet know whether this "supermembrane" is consistent at the quantum level but the orthodox claim that only strings can be quantum consistent now looks much less certain.*

$D\uparrow$												
11	.			s			t					
10	.	v	s/v	v	v	v	s/v	v	v	v	v	
9	.	s				s						
8	.				s							
7	.			s			t					
6	.	v	s/v	v	s/v	v	v					
5	.	s		s								
4	.	v	s/v	s/v	v							
3	.	s/v	s/v	v								
2	.	s										
1	.											
0	.	.	.	.	.	.	.	.	.	.	.	.
	0	1	2	3	4	5	6	7	8	9	10	11 $d\rightarrow$

Table 1: The old brane-scan involves only scalar multiplets *s* on the worldvolume; the new one includes vector multiplets *v* and antisymmetric tensor multiplets *t*.

Figure 4: Nino and the author.

3. 1987 From super-spaghetti to super-ravioli

1987 International School of Subnuclear Physics - Director: A. Zichichi 25th Course: The Super World - II 6 - 14 August 1987 [39]

Since my second lecture attempted to justify this passage from strings to membranes and bearing in mind its location, I called it *From super-spaghetti*[4] *to super-ravioli*. It began:

> *Many of the supergravity theories that we used to study a few years ago are now known to be merely the field theory limit of an underlying string theory. For example, N=2a supergravity in 10 dimensions is just the field theory limit of the Type IIA superstring. What are we to make, therefore, of supergravity theories which cannot be obtained from strings such as N = 1 supergravity in eleven dimensions? This is a particularly puzzling example since it is well known that upon dimensional reduction to 10 dimensions, it yields the above-mentioned N = 2a theory. Indeed, if supersymmetry allows D ≤ 11, why do strings stop at D = 10?*

[4] What better place to recall this than Bologna?

3.1 The old brane-scan

It is ironic that although one of the motivations for the original supermembrane paper [37] was precisely to find the superthreebrane as a *topological defect* of a supersymmetric field theory in $D = 6$; the discovery of the other supermembranes proceeded in the opposite direction. Hughes *et al.* showed that kappa symmetry could be generalized to $d > 2$ and proceeded to construct a threebrane displaying an explicit $D = 6$, $N = 1$ spacetime supersymmetry and kappa invariance on the worldvolume. It was these kappa symmetric Green-Schwarz actions, rather than the soliton interpretation which was to dominate the early work on the subject. First of all, Bergshoeff, Sezgin and Townsend [19] found corresponding Green-Schwarz actions for other values of d and D, in particular the eleven-dimensional supermembrane.

Let us introduce the coordinates Z^M of a curved superspace:

$$Z^M = (x^\mu, \theta^\alpha) \tag{3.1}$$

and the supervielbein $E_M{}^A(Z)$, where $M = \mu$, α are world indices and $A = a$, α are tangent space indices. We also define the pull-back

$$E_i{}^A = \partial_i Z^M E_M{}^A. \tag{3.2}$$

We also need the super-d-form $B_{A_d \cdots A_1}(Z)$. Then the supermembrane action has a kinetic term, a worldvolume cosmological term, and a Wess-Zumino term

$$S = T_d \int d^d\xi \left[-\frac{1}{2}\sqrt{-\gamma}\gamma^{ij} E_i{}^a E_j{}^b \eta_{ab} + \frac{1}{2}(d-2)\sqrt{-\gamma} + \frac{1}{d!}\varepsilon^{i_1 \cdots i_d} E_{i_1}{}^{A_1} \cdots E_{i_d}{}^{A_d} B_{A_d \cdots A_1} \right]. \tag{3.3}$$

This action has the virtue that it reduces to the Green-Schwarz superstring action when $d = 2$.

The target-space symmetries are superdiffeomorphisms, Lorentz invariance and d-form gauge invariance. The worldvolume symmetries are ordinary diffeomorphisms and kappa invariance referred to earlier which is known to be crucial for superstrings, so let us examine it in more detail. The transformation rules are

$$\partial Z^M E^a{}_M = 0, \quad \partial Z^M E^\alpha{}_M = \kappa^\beta (1 + \Gamma)^\alpha{}_\beta, \tag{3.4}$$

where $\kappa^\beta(\xi)$ is an anticommuting spacetime spinor but worldvolume scalar, and where

$$\Gamma^\alpha{}_\beta = \frac{(-1)^{d(d-3)/4}}{d!\sqrt{-\gamma}} \varepsilon^{i_1 \cdots i_d} E_{i_1}{}^{a_1} E_{i_2}{}^{a_2} \cdots E_{i_d}{}^{a_d} \Gamma_{a_1 \cdots a_d}. \tag{3.5}$$

Here Γ_a are the Dirac matrices in spacetime and

$$\Gamma_{a_1 \ldots a_d} = \Gamma_{[a_1 \ldots a_d]}. \tag{3.6}$$

This kappa symmetry has the following important consequences:

1) The symmetry is achieved only if certain constraints on the antisymmetric ten-

sor field strength $F_{MNP..Q}(Z)$ and the supertorsion are satisfied. In particular the Bianchi identity $dF = 0$ then requires the Γ matrix identity

$$\left(d\bar{\theta}\Gamma_a d\theta\right)\left(d\bar{\theta}\Gamma^{ab_1\cdots b_{d-2}}d\theta\right)=0 \tag{3.7}$$

for a commuting spinor $d\theta$. As shown by Achucarro, Evans, Townsend and Wiltshire [38] this is satisfied only for certain values of d and D. Specifically, for $d \geq 2$

$$\begin{aligned} d=2:&\quad D=3,4,6,10\\ d=3:&\quad D=4,5,7,11\\ d=4:&\quad D=6,8\\ d=5:&\quad D=9\\ d=6:&\quad D=10\,. \end{aligned} \tag{3.8}$$

Note that we recover as a special case the well-known result that Green-Schwarz superstrings exist *classically* only for $D = 3, 4, 6$, and 10. Note also $d_{max} = 6$ and $D_{max} = 11$. The upper limit of $D = 11$ is already known in supergravity but there it is necessary to make extra assumptions concerning the absence of consistent higher spin interactions. In this formulation of supermembranes, it follows automatically.

2) The matrix Γ of (3.5) is traceless and satisfies

$$\Gamma^2 = 1 \tag{3.9}$$

when the equations of motion are satisfied and hence the matrices $(1\pm\Gamma)/2$ act as projection operators. The transformation rule (3.4) therefore permits us to gauge away one half on the fermion degrees of freedom. As described below, this gives rise to a matching of physical boson and fermion degrees of freedom on the worldvolume.

3) In the case of the eleven-dimensional supermembrane, it has been shown [16] that the constraints on the background fields $E_M{}^A$ and B_{MNP} are nothing but the equations of motion of eleven-dimensional supergravity [19, 21].

3.2. Type *IIA* superstring in *D* = 10 from supermembrane in *D* = 11

We begin with the bosonic sector of the $d = 3$ worldvolume of the $D = 11$ supermembrane:

$$\begin{aligned} S_3 = T_3\int d^3\xi\Big[&-\frac{1}{2}\sqrt{-\gamma}\gamma^{ij}\,\partial_i X^M\,\partial_j X^N G_{MN}(X)+\frac{1}{2}\sqrt{-\gamma}\\ &+\frac{1}{3!}\varepsilon^{ijk}\,\partial_i X^M\,\partial_j X^N\,\partial_k X^P A_{MNP}(X)\Big], \end{aligned} \tag{3.10}$$

where T_3 is the membrane tension, ξ^i ($i = 1, 2, 3$) are the worldvolume coordinates, γ^{ij} is the worldvolume metric and $X^M(\xi)$ are the spacetime coordinates ($M = 0, 1, \ldots, 10$). Kappa symmetry [19, 21] then demands that the background metric G_{MN} and background 3-form potential A_{MNP} obey the classical field equations of $D = 11$ supergravity, whose bosonic action is

$$I_{11} = \frac{1}{2\kappa_{11}^{\ 2}} \int d^{11}x\sqrt{-G}\left[R_G - \frac{1}{2\cdot 4!} F_{MNPQ}^2 \right] - \frac{1}{12\kappa_{11}^{\ 2}} \int A_3 \wedge F_4 \wedge F_4, \qquad (3.11)$$

where $F_4 = dA_3$ is the 4-form field strength. In particular, F_4 obeys the field equation

$$d * F_4 = -\frac{1}{2} F_4^2 \qquad (3.12)$$

and the Bianchi identity

$$dF_4 = 0 \qquad (3.13)$$

To see how a double worldvolume/spacetime compactification of the D = 11 supermembrane theory on S^1 leads to the Type *IIA* string in D = 10 [5], let us denote all (d = 3, D = 11) quantities by a hat and all (d = 2, D = 10) quantities without. We then make a ten-one split of the spacetime coordinates

$$\hat{X}^{\hat{M}} = \left(X^M, Y\right) \qquad M = 0,1,\ldots,9 \qquad (3.14)$$

and a two-one split of the worldvolume coordinates

$$\hat{\xi}^{\hat{i}} = \left(\xi^i, \rho\right) \qquad i = 1,2 \qquad (3.15)$$

in order to make the partial gauge choice

$$\rho = Y, \qquad (3.16)$$

which identifies the eleventh dimension of spacetime with the third dimension of the worldvolume. In other words, the membrane is wrapped around the S^1 (See [58] for subtleties concerning zero modes). The dimensional reduction is then effected by taking the background fields $\hat{G}_{\hat{M}\hat{N}}$ and $\hat{A}_{\hat{M}\hat{N}\hat{P}}$ to be independent of Y. The string backgrounds of dilaton Φ, string σ-model metric G_{MN}, 1-form A_M, 2-form B_{MN} and 3-form A_{MNP} are given by[5]

$$\begin{aligned}
\hat{G}_{MN} &= e^{-\Phi/3} \begin{pmatrix} G_{MN} + e^{\Phi} A_M A_N & e^{\Phi} A_M \\ e^{\Phi} A_M & e^{\Phi} \end{pmatrix}, \\
\hat{A}_{MNP} &= A_{MNP}, \\
\hat{A}_{MNY} &= B_{MN}.
\end{aligned} \qquad (3.17)$$

5 The choice of dilaton prefactor, $e^{-\Phi/3}$, is dictated by the requirement that G_{MN} be the D = 10 string σ-model metric. To obtain the D = 10 fivebrane σ-model metric, the prefactor is unity because the reduction is then spacetime only and not simultaneous worldvolume/spacetime. This explains the remarkable "coincidence" [44] between $\hat{G}_{MN}$ and the D = 10 fivebrane σ-model metric.

The actions (3.10) and (3.11) now reduce to

$$S_2 = T_2 \int d^2\xi \left[-\frac{1}{2}\sqrt{-\gamma}\gamma^{ij}\partial_i X^M \partial_j X^N G_{MN}(X) - \frac{1}{2!}\varepsilon^{ij}\partial_i X^M \partial_j X^N B_{MN}(X) + \cdots \right] \quad (3.18)$$

and

$$I_{10} = \frac{1}{2\kappa_{10}{}^2}\int d^{10}x\sqrt{-G}e^{-\Phi}\left[R_G + \left(\partial_M \Phi\right)^2 - \frac{1}{2\cdot 3!}H^2_{MNP} - \frac{1}{2\cdot 2!}e^{\Phi}F^2_{MN} - \frac{1}{2\cdot 4!}e^{\Phi}J^2_{MNPQ} \right] - \frac{1}{2\kappa_{10}{}^2}\int \frac{1}{2}F_4 \wedge F_4 \wedge B_2, \quad (3.19)$$

where the field strengths are given by $J_4 = F_4 + A_1 \wedge H_3$, $H_3 = dB_2$ and $F_2 = dA_1$.
One may repeat the procedure in superspace to obtain

$$S_2 = T_2 \int d^2\xi \left[-\frac{1}{2}\sqrt{-\gamma}\gamma^{ij}E_i^a E_j^b \eta_{ab} + \frac{1}{2!}\varepsilon^{ij}\partial_i X^M \partial_j X^N B_{MN}(Z) \right], \quad (3.20)$$

which is just the action of the Type *IIA* superstring.

3.3. Bose-fermi matching on the worldvolume

The matching of physical bose and fermi degrees of freedom on the *worldvolume* may, at first sight, seem puzzling since we began with only spacetime supersymmetry. The explanation is as follows. As the p-brane moves through spacetime, its trajectory is described by the functions $X^M(\xi)$ where X^M are the spacetime coordinates ($M = 0, 1, \ldots, D - 1$) and ξ^i are the worldvolume coordinates ($i = 0, 1, \ldots, d - 1$). It is often convenient to make the so-called *static gauge choice* by making the $D = d + (D - d)$ split

$$X^M(\xi) = \left(X^\mu(\xi), Y^m(\xi)\right), \quad (3.21)$$

where $\mu = 0, 1, \ldots, d - 1$ and $m = d, \ldots, D - 1$, and then setting

$$X^\mu(\xi) = \xi^\mu. \quad (3.22)$$

Thus the only physical worldvolume degrees of freedom are given by the $(D - d)$ $Y^m(\xi)$. So the number of on-shell bosonic degrees of freedom is

$$N_B = D - d. \quad (3.23)$$

To describe the super p-brane we augment the D bosonic coordinates $X^M(\xi)$ with anticommuting fermionic coordinates $\theta^\alpha(\xi)$. Depending on D, this spinor could be Dirac, Weyl, Majorana or Majorana-Weyl. The fermionic kappa symmetry means that half of the spinor degrees of freedom are redundant and may be eliminated by a physical gauge choice. The net result is that the theory exhibits a *d-dimensional worldvolume supersymmetry* [38] where the number of fermionic generators is exactly half of the generators in the original spacetime supersymmetry. This partial breaking of supersymmetry is a key idea. Let M be the number of real components of the minimal spinor and N the number of supersymmetries in D spacetime dimensions and let m and n be the corresponding quantities in d worldvolume dimensions. Let us first consider $d > 2$. Since kappa symmetry always halves the number of fermionic degrees of freedom and going on-shell halves it again, the number of on-shell fermionic degrees of freedom is

$$N_F = \frac{1}{2}mn = \frac{1}{4}MN. \tag{3.24}$$

Worldvolume supersymmetry demands $N_B = N_F$ and hence

$$D - d = \frac{1}{2}mn = \frac{1}{4}MN. \tag{3.25}$$

A list of dimensions, number of real dimensions of the minimal spinor and possible supersymmetries is given in table 2, from which we see that there are only 8 solutions of (3.25) all with $N = 1$, as shown in table 1. We note in particular that $D_{max} = 11$ since $M \geq 64$ for $D \geq 12$ and hence (3.25) cannot be satisfied. Similarly $d_{max} = 6$ since $m \geq 16$ for $d \geq 7$. The case $d = 2$ is special because of the ability to treat left and right moving modes independently. If we require the sum of both left and right moving bosons and fermions to be equal, then we again find the condition (3.25). This provides a further 4 solutions all with $N = 2$, corresponding to Type *II* superstrings in $D = 3, 4, 6$ and 10 (or 8 solutions in all if we treat Type *IIA* and Type *IIB* separately). Both the gauge-fixed Type *IIA* and Type *IIB* superstrings will display (8, 8) supersymmetry on the worldsheet. If we require only left (or right) matching, then (3.25) replaced by

$$D - 2 = n = \frac{1}{2}MN, \tag{3.26}$$

which allows another 4 solutions in $D = 3, 4, 6$ and 10, all with $N = 1$. The gauge-fixed theory will display (8, 0) worldsheet supersymmetry. The heterotic string falls into this category. The results [38] are indicated by the points labelled *s* in table 1. Point particles with $d = 1$ are usually omitted from the brane-scan [38, 45, 2], but in table 1 we have included them.

An equivalent way to arrive at the above conclusions is to list all scalar supermultiplets and to interpret the dimension of the target space, D, by

$$D - d = \text{number of scalars}. \tag{3.27}$$

Indeed, these scalars are the Goldstone bosons associated with the spontaneous breaking of the $D - d$ translations. A useful reference is [46] which provides an exhaustive classification of all unitary representations of supersymmetry with maximum spin 2. In particular, we can understand $d_{max} = 6$ from this point of view since this is the upper limit for scalar supermultiplets.

There are four types of solution with 8+8, 4+4, 2+2 or 1+1 degrees of freedom respectively. Since the numbers 1, 2, 4 and 8 are also the dimension of the four division algebras, these four types of solution are referred to as real, complex, quaternion and octonion respectively. The connection with the division algebras can in fact be made more precise [47, 48, 49, 50, 51].

Dimension (D or d)	Minimal Spinor (M or m)	Supersymmetry (N or n)
1	32	1
2, 1	16	2, 1
2, 1	16	2, 1
2, 1	16	2, 1
2, 1	16	2, 1
4, 3, 2, 1	8	4, 3, 2, 1
4, 3, 2, 1	8	4, 3, 2, 1
8, . . ., 1	4	8, . . ., 1
16, . . ., 1	2	16, . . ., 1
32, . . ., 1	1	32, . . ., 1

Table 2: Minimal spinor components and supersymmetries.

3.4 A heterotic 5-brane?

Of particular interest was the $D = 10$ fivebrane, whose Wess-Zumino term coupled to a rank six antisymmetric tensor potential A_{MNPQRS} just as the Wess-Zumino term of the string coupled to a rank two potential B_{MN}. Spacetime supersymmetry therefore demanded that the fivebrane coupled to the 7-form field strength formulation of $D = 10$ supergravity [52] just as the string coupled to the 3-form version [53, 54]. These dual formulations of $D = 10$ supergravity have long been something of an enigma from the point of view of superstrings. As field theories, each seems equally valid. In particular, provided we couple them to $E_8 \times E_8$ or $SO(32)$ super-Yang-Mills [40], then both are anomaly free [55]. Since the 3-form version corresponds to the field theory limit of the heterotic string, we conjectured [9] that there ought to exist a *heterotic fivebrane* which could be viewed as a fundamental anomaly-free theory in its own right and whose field theory limit corresponds to the dual 7-form version. We shall refer to this as the *string/fivebrane duality conjecture*. At this stage, however, the solitonic element had not yet been introduced.

3.5. E(8) × SO(16) in D=11?

It is interesting to note that the three-eight split

$$SO(1,10) \supset SO(1,2) \times SO(8) \tag{3.28}$$

implied by the embedding of the three-dimensional worldvolume of the supermembrane in eleven-dimensional space-time had previously been invoked in [4] to exhibit the hidden $SO(16)$ symmetry of $D = 11$ supergravity, where the 128 bosonic degrees of freedom may be assigned to the coset $E_8{=}SO(16)$. We wondered what role E_8, the Kac-Moody extension E_9 and the Lorentzian algebra E_{10} will play for the supermembrane.

3.6. Branes on the boundary of AdS

Compactification of $D = 11$ supergravity: $d = 4$ anti-de Sitter space-time $\times S^7$ yields four-dimensional supergravity with maximum ($N = 8$) supersymmetry and local $SO(8)$ invariance [1]. The vacuum symmetry is the AdS supergroup OSp(4/8) which admits the strange "singleton" which have no analogue in the Poincaré group and no immediate field theory interpretation. Owing to the $N = 8$ supersymmetry they form an ultrashort $N = 8$ supermultiplet consisting of eight spin-1/2 fermions and eight spin-0 bosons which transform according to the 8_s and 8_v representations of $SO(8)$. Although we are dealing with the four-dimensional anti de Sitter group $SO(2, 3)$, we cannot write down an action for these singletons living in AdS_4. However, as discussed by Fronsdal [56], we can write down an action living on its three-dimensional boundary $S^1 \times S^2$ with signature (–,+, +).

But 8_s spin-1/2 and 8_v spin-0 on a 3-dimensional worldvolume with signature (–,+, +) is just what we get from gauge-fixing the supermembrane! We noted that relativistic membranes and singletons have one more thing in common: they were both invented by Dirac at about the same time [36, 57].

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Is science in a crisis?

*Gerard 't Hooft**

If we compare the developments of physics as a science at the beginning of the 20th century, with what we are seeing today, more than a century later, it seems as if progress is now slowing down. We bring forward however, that scientific developments never form a linear pattern, advances come in irregular and unexpected spirts. The biggest advances come when researchers turn to different fundamental logical procedures. This is what happened a century ago, it does not happen often, but it can happen again.

1. Introduction

The entire 20th century has been a brilliant success for fundamental sciences in practically all fields. Landslides took place in physics, astronomy, chemistry, biology, medicine, and many more doctrines. In theoretical physics alone, we had revolutionary advances in our understanding of relativity theory, quantum mechanics, condensed matter physics, molecules, atoms and the sub-atomic world. The Standard Model of the sub-atomic particles was first launched as a simple model that could serve as a summary of our understanding at the time, but it quickly grew to become a fundamental stepping stone from which further refinements were expected to illuminate our paths forward.

During the last decades, many researchers assumed that we have gained so much momentum in our ongoing research that these developments would be difficult to stop – we simply proceed further and further until the last dark spots in our understanding will have disappeared. Is this true?

* Institute for Theoretical Physics, Utrecht University, Utrecht, the Netherlands.

Some uprising did take place. Various observers, both from inside these sciences and from outside[1, 2, 3, 4], gave air to their complaints concerning the direction science is taking: could it be that we have become so addicted to success that our methods are suffering from sloppiness? Is it by using dubious arguments, that outrageous claims are passed as valid "conjectures" that are assumed to be true only because they could not be falsified? Is continuation through murky material preferred as opposed to more assiduous procedure, merely since the latter is promising less spectacular successes, if any?

A theoretical physicist well-known for his precision and reliability in performing and presenting his science, N.G. van Kampen [5], can be cited as stating:

> "The history books of the future will recount: *The scientific period lasted from 1500 to 2000"*.

He noted that more and more people call themselves scientists as soon as they performed a superficial survey on how customers appreciate some brand of toothpaste. Real scientific findings are no longer receiving much apprehension. We live in a post-scientific society. Scientists did their jobs; no more real knowledge is wanted.

In the 20th century alone, high quality science made more progress that the rest of that millennium. It is fair to ask the question: *Will the 21st century match that?* Will the next 100 years of science once again thoroughly modify our understanding of the universe, and with that, our world view? Or is science in a crisis?

2. Trying to be fair

Indeed, 20th century science started with a bang. The year 1900 was marked by its first great discovery:

> It was noted by Max Planck *that light is emitted and absorbed with well-defined units of energy, the light quanta.*

Only soon afterwards, Einstein would mark the full implications of this:

> *light is associated with particles;* they were to be called "photons".

In 1905, Einstein succeeded to prove the existence of atoms, using Brownian motion. Again, the implications of this were momentous. Atoms may be considered to be *the quanta of matter*. Even though these atoms can formally further be broken in parts, it is clear that they imply the end of the idea that matter could be essentially continuously dividable.

The same year marked Einstein's discovery of the theory of *Special Relativity*, followed, less than 10 years afterwards, by *General Relativity*.

Both theories had a big impact on the way we look at space and time; the latter theory implied that space and time have dynamical properties, features that left the public in awe and little understanding. His findings, however, were soon embraced by the physics community, since the mathematics is accurate and transparent. They inspired many lay physicists to try to outsmart Einstein by tossing "alternative theories" around, with no avail.

For the professional scientists, these developments were the beginning, not the end of a new era. For them what happened there-after was even more spectacular. We note the discoveries of

- quantum mechanics,
- nuclear physics,
- the Dirac equation (as a start towards combining quantum mechanics with special relativity),
- a whole plethora of elementary particles,
- superconductivity,

and all this was followed by spectacular advances in technologies: radio and television, the first computers, new telescopes and microscopes, numerous new findings in medicine, and so on.

And what is happening now?

New discoveries are still being made. Using spectacular new technologies, *exoplanets* are found, planets orbiting nearby stars other than the Sun. More and more details are uncovered concerning the early universe. The Higgs particle, the one jig-saw piece of the Standard Model that had stayed undetected during the turn of the century, was finally identified. Gravitational waves were finally detected, yielding a new window on distant parts of our universe. Technology brought us the smart phones. Autonomous cars are soon expected. Artificial intelligence is developing slower than expected, but it makes progress. Also, the *quantum computer* is expected to revolutionise computation, in a somewhat more distant future.

Do these advances allow for any comparison with what happened in the first two decades of the 20th century? This we think not. Without exception, the advances just mentioned were foreseen long ago, nothing came entirely unexpected. And today, we do hear complaints:

"Students, young scientists, postdocs, are meekly following their teachers and peers, they hesitate to pioneer in new directions, and if they do, little progress is made."

"Many of today's most significant theories rely on speculations that seem to be disconnected from any possibility of experimental verification …"

"Little real progress is made today, especially in elementary particle physics. The latest particle accelerators were supposed to make elementary new discoveries. This does not seem to be happening."

An awful reality seems to surface here: if we go back more than one or two centuries, we see that progress was also slow. Almost two centuries passed between Isaac Newton's fundamental publication of his *Principia*, in 1687, and the next giant leap for mankind, James Clerk Maxwell, who published his results in 1865.[1] Should we conclude that the 20th century was an anomaly? The natural progress in science has always been slower than its surge in the 20th century.

One may suspect that the great advances of the 20th century might be explained by the uniqueness of some circumstances. Perhaps they are due to just one major discovery, not many. The one discovery that was made, was that the tremendous shortcomings of the "existing lore" were unveiled. This dates back all the way to antiquity. Greek philosophers had caused a boom in *their* understanding of the world. Their wisdom was so powerful that it was mistaken for the eternal truth, not to be questioned by trying to be smarter. The discovery scientists made, a century ago, is that questions can be posed in a smarter way, appearances may be not what they seem, an *observer* registering observed events, may, subconsciously, interpret his findings differently from another observer, who may be using different instruments, at a different velocity, or in an altogether different setting. These realisations underpin both theories of relativity, as well as quantum mechanics. Even of these theories are only indirectly related, they have this in common: what you see may not necessarily be the completely correct interpretation of what happens 'in reality'.

Perhaps, today, the lack of fundamental advances can be due to a similar phenomenon: investigators have not yet realised that philosophies that were useful as well as revolutionary 100 years ago, may have to be refreshed and adapted, so as to reveil new avenues for facing the problems that are still wide open today.

Notably, in physics, new obstacles have come along, and they, again, require new ways of thinking. Examples are:

1. String theory. This seems to be a spectacular idea that came up in the 1970s and 1980s, during the height of the developments in elementary particle physics. The theory is promising indeed, and at first it evolved quickly, carrying its own kind of logic and world view. But a problem emerged. In the past, theoretical ideas could

[1] It would be wrong to say that there were no major advances at all in the intermediate period; electricity and magnetism were gradually understood better and better, but today we tend to see Maxwell's result as a culmination that really shifted the existing views.

always be subject to experimental tests. It was relatively easy to select viable arguments from dead alleys.
String theory is deprived from such important test possibilities. This was considered to be a minor setback. One could still design toy models and investigate these. Toy models however, did not reveal the serious absence of strong theoretical foundations. This problem was not recognised as being a very serious one, since one still could investigate the internal coherence of the new ideas. Mathematical proofs were often lacking, but, as was proclaimed at numerous occasions: *The theory is so beautiful, it must be true*. As if only minor details had to be sorted out. We suspect however, that to really make progress without the necessary experimental tests, internal, logical accuracy is much more decisive than ever before. Such internal, logical accuracy is lacking in our toys. It is also lacking in the foundations of string theory. This is much more of a problem than often admitted.

2. Quantum mechanics. This was a splendid achievement of the previous century. Now, we reached the stage of asking further questions concerning this theory. Dogmatic approaches convinced investigators that "hidden variables" are not the way. They do not see the analogy with bygone years, when quantised field theories (QFT) were being dismissed. The logic in these rejections turned out to contain demonstrable aws. The idea of extreme and absolute rigor in Nature's laws is not yet embraced; we are still allowing for magic and mysticism, even in the most modern theories, and emphatically in quantum mechanics. One must understand that successful theories often seem to radiate with magic and mysticism, while in reality these are due to some deeper internal logic that may not yet be quite understood. Turning this around, not understanding the internal logic while counting on magic and mysticism, will more often than not lead to failures. It is this author's opinion that only fully deterministic underlying theories will contain sufficiently precise logic to explain the quantum mechanical nature of the mechanical laws of tiny objects.

The above is a personal view; not everyone agrees, to put it mildly. One may merely suspect that irrational conservatism is holding us back today.

Imagine a biologist investigating the intelligence of rats. Rats are held in a large cage, filled with gadgets. These gadgets are intelligence tests. By pulling strings, pressing buttons, moving handles and switches, the rats can get access to food that tastes a lot better than what they normally get. They can see how the strings, the switches, buttons and handles work. By logical deduction, they can obtain the food they want. The rats still remember how successful they have been, many times in the past.

And then, they see a delicious peanut. It should be obtainable, provided they argue correctly. Unfortunately, the test is too difficult. The rats know that they are too stupid. This time, none of them manage to get hold of the delicacy.

The story is a metaphor. The rats, that is us. The peanut stands for the theory of general relativity, modified to be compatible with the laws of quantum mechanics. We are trying one gadget after the next, but we fail. Previous experiences encourage us to persevere; that there must be a way, but alas, we are too stupid. The peanut is still lying there, untouched. There is only one way to get hold of it: improve our logic.

3. Is science in a crisis?

Science is not in a crisis. One has to remember that, often, breakthroughs are not immediately recognised as such. There are enough examples of this.

Ludwig Boltzmann made brilliant observations on how to combine Newton's laws of mechanics with the laws of statistics. His work is now widely recognised as a real breakthrough, but during his entire life Boltzman did not receive much recognition. He was severely depressed. Today, breakthroughs also take place, but, as yet, we have not become aware of this.

21st century science will differ from the science of the 20th century. Problems that now appear to be exceptionally diffcult are left over. It will take longer to unravel these, but new tools will become available. *Artificial intelligence* is not yet at a level that it can be applied to address the problem of quantising gravity, but it will be. In the near future, *AI* can be improved in such a way that extremely precise logic can be maintained. It will be possible to address questions such as:

- In cosmology, what can observations *really* tell us about the origin of the universe, and the laws of physics beyond the Planck scale?
- What else will be needed to quantise gravity?
- What role will ("quantum") black holes play?
- Which principles should be applied in solid state physics to obtain *room temperature superconductivity*?
- How do biological organisms respond to the DNA code?
- What are the laws for complex organic molecules?
- What do we need technically for the colonisation of outer space?

It is not obvious whether artificial intelligence will or will not be able to largely surpass − or even compete with − human intelligence, but it is reasonable to sustain hope, and very high expectations for the near future of AI.

In some branches of science, we seem to be held back by obstacles. Some of these, today, seem to be unsurmountable. This by itself is not a sign for crisis. We had such moments at numerous occasions in the past. The way these obstacles are overcome often manifests itself later. In practice, what happens is the the *hot spots* in science are continuously moving around. One may observe cycles of trends:

- Until around 1960, a hot topic in physics was the spectral lines of atoms, their measured values and comparisons with calculations according to the most recent theories. From there, attention shifted to:
- Nuclear physics, the determination of masses and cross sections of nuclei, their excited states, and their behaviour in nuclear reactions, with an eye on what were thought to be very promising possibilities in numerous applications.
- The availability of high energy particle accelerators then shifted the focus to the subnuclear particles. From around 1960 and 1970 this science underwent an enormous boost, from being mainly phenomenological to the highly accurate theories culminating in the Standard Model.
- Then, observations became available to study the early phases of the universe and the associated laws of cosmology. Many advances are experienced in this science up to today.
- At the same time, other sciences are going through their own cycles. Biologists are searching for the laws controlling the very origin of life on this planet and possibly elsewhere. We are still at the beginning of understanding how life can form spontaneously [6].
- Deciphering the DNA code is an important subject now. The basic principles are known, but generating entire new organisms is still a dream that is associated with numerous complications.
- And as explained above, perhaps the development of the foundations of quantum mechanics and quantum gravity can prosper in a symbiosis with artificial intelligence. Adding machine intelligence to our scientific tools will certainly resolve temporary setbacks, and so, we conclude that there is no reason for worry.

Only if one is not prepared to move along with the changing trends of the most important developments, one might experience the new situation we are in as a crisis. Progress is non-linear, and surprises will always await us in the near or more distant future.

And finally: the 21st century is not over yet.

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The future of our science –
From the evolution of the electron to the evolution of the Universe

*Antonino Zichichi**

Preamble on the Evolution of the Universe
From 1897→ to →2018

The Dirac Equation, describes the evolution of the first elementary particle (the smallest piece of electricity) discovered by J.J. Thomson in 1897.

This object, the great Thomson thought it was like a "ball". No. It was spinning. Why? Nobody knew.

More than 30 years were need, and the great Dirac, to find how to describe the evolution of the first elementary particle (**1928**).

In 1964 Dick Feynman told me that the next step had to be to describe the evolution of the most complex object we know: our Universe. You are the youngest fellow and should do it.

This is why I have encouraged great fellows of the International School of Astrophysics, such as John Archibald Wheeler, Peter Bergmann and Nathan Rosen to think about the **Evolution of the Universe.**

Purpose of this lecture is to encourage all of you to devote some time to this problem.

* University of Bologna and INFN, Bologna, Italy; CERN, Geneva, Switzerland; Enrico Fermi Centre, Rome, Italy; Pontifical Academy of Sciences, Vatican City; World Federation of Scientists, Beijing, Geneva, Moscow, New York; Ettore Majorana Foundation and Centre for Scientific Culture, Erice, Italy.

The first step in the Evolution of the Universe must be to explain the values for the mass and the vacuum of our Universe.

The second step has to be related to the Gap between the Gravitational Force and the other Forces [QED, QFD, QCD].

QED → *All Electromagnetic Phenomena (Quantum ElectroDynamics).*
QFD → *All Phenomena generated by the Weak Forces (Quantum FlavourDynamics).*
QCD → *All Phenomena generated by quarks, gluons with their strong subnuclear "colour" charge.*

1. The first step

1.1. The mass and the vacuum of our Universe

We would like to understand the origin of the mass and of the vacua of our Universe on the basis of the Planck fundamental constants and the Schwarzschild solution of the Einstein equation.

The fact that the Schwarzschild equation [1] allows to get the value for the mass and the vacua of our Universe **when**, starting from the Planck Universe, its radius increases by 62 powers of ten, cannot be a casual coincidence, but the result coming from the Evolution of the Universe.

We know that the structure of our Universe has the Galaxies concentrated along lines and planes immersed in very large amount of empty spaces.

The first of these empty spaces was discovered in 1981 in the Boöte constellation.

It is estimated that about 98% of the Universe volume is empty.

The reason why these empty spaces must exist is the consequences of its evolution.

We find that the evolution is described by the Schwarzschild equation [1] which predicts that the density of the Universe must decrease with the square of its mass.

The evolution of the Universe is illustrated in Figs. 1 and 2 whose origin is in the intellectual venture whose author is Max Planck [2].

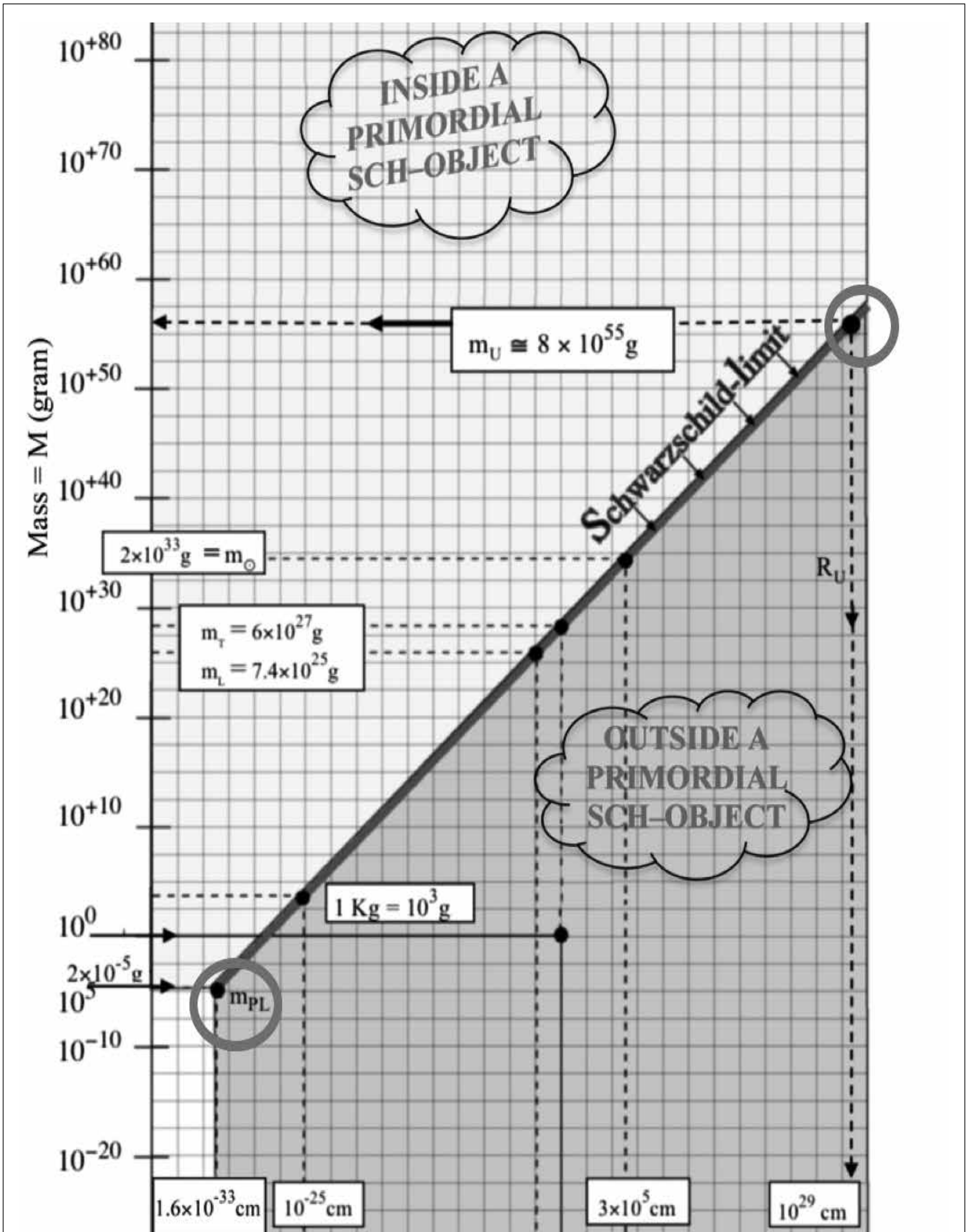

Figure 1: The Schwarzschild law between the radius of the gravitational horizon and the mass from the smallest to the largest SCH-object.

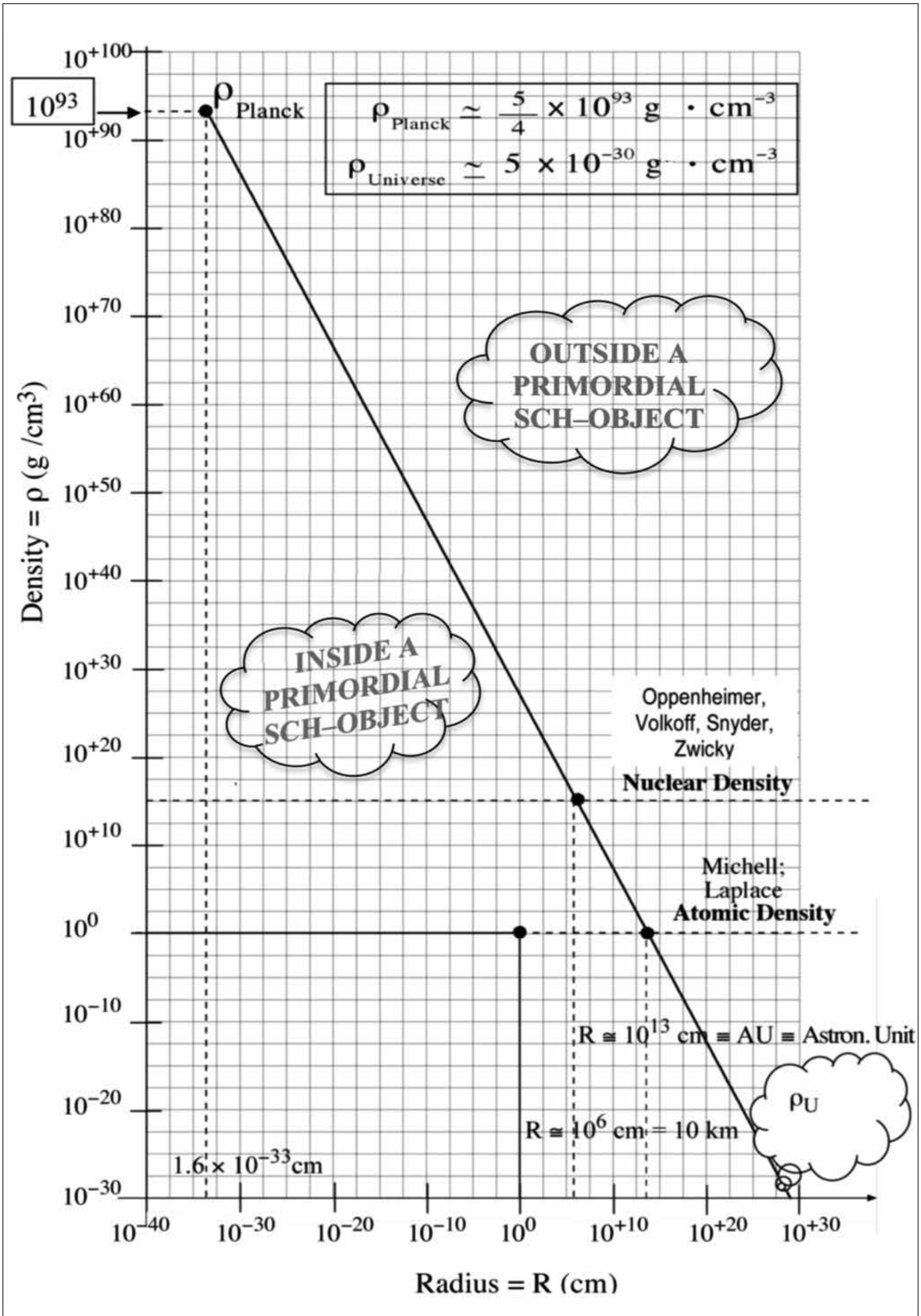

Figure 2: The relation which exists between the value of the SCH radius (R_{SCH}) and the corresponding density (ρ_{SCH}), from the smallest (the Planck Universe) to the largest SCH-object (the Universe now).

In his universal outlook of the world – independent of our restricted environment – Planck in 1899 wanted that the fundamental units of mass, length and time to depend only on the values of the fundamental constants of Nature:

c (the speed of light),
h (the Planck constant) and
G_N (the Newton gravitational coupling).

These quantities had a special meaning for Planck [2]: *"These quantities retain their natural significance as long as the Law of Gravitation and that of the propagation of light in a vacuum and the two principles of thermodynamics remain valid; they therefore must be found always to be the same, when measured by the most widely differing intelligence according to the most widely differing methods"*. The way Planck considered these quantities it is remarkable: *"In the new system of measurement each of the four preceding constants of Nature (G, h, c, k) has the value one"*.

This is the meaning of measuring lengths, times, masses and temperatures in Planck's units. Planck included the Boltzmann constant k which converts the units of energy into units of temperature. This allowed Planck to have a fundamental value also for the temperature, 3.5×10^{32} kelvins (K). Here are the orders of magnitude of Planck's units in the "Planck Universe":

Length	$= (G \cdot h / c^3)^{1/2}$	$\simeq 10^{-33}$ cm
Time	$= (G \cdot h / c^5)^{1/2}$	$\simeq 10^{-44}$ s
Mass	$= (h \cdot c / G)^{1/2}$	$\simeq 10^{-5}$ g
Temperature	$= k^{-1} \cdot (hc^5/G)^{1/2}$	$\simeq 10^{32}$ K.

When Planck was expressing his ideas on the meaning of his fundamental natural units there was neither the Big Bang nor the Einstein equation. And no one knew that the Einstein equation had a solution, discovered by Karl Schwarzschild [1], which describes the gravitational field of a massive point-like particle. John Wheeler in 1967 gave to this solution the name of "black hole", the reason being that even the light cannot escape the gravitational attraction. This extremely successful name given to the Schwarzschild solution of the Einstein equation produced the effect of neglecting the fundamental meaning of the Schwarzschild formula which establishes between the radius of the gravitational horizon (R^{PM}) of a point-like massive (PM) object and its mass (M^{PM}) a very important coupling:

$$R^{PM} = \frac{2G\ M^{PM}}{c^2} \cong 1.5 \cdot 10^{-28} \cdot \mathrm{cm} \cdot \mathrm{g}^{-1} \cdot M^{PM} \tag{1}$$

The radius of the gravitational horizon increases with the mass, as shown in Fig. 1. The Schwarzschild formula remains as it is despite all developments [3, 4] in the physics of black holes including what has been discovered by RQST (Relativistic Quantum String Theory, see later).

The remarkable fact is however that if we look in Fig. 1 at the point where the radius of the horizon is that of the world where we leave (about 10^{29} cm) the mass turns out to be $\simeq 10^{56}$ g, which is the mass of our Universe (without dark matter and dark energy, see later).
Let us now assume that M^{PM} is not concentrated in a point, as in the Schwarzschild solution of the Einstein equation, but distributed inside the volume defined by the sphere of the black hole gravitational horizon.
We assume that the black hole horizon [5] is the surface of a sphere where M^{PM} is distributed. We define as "primordial Schwarzschild object" (primordial SCH–object) the sphere whose mass is M^{PM}.
We neglect details like [(4/3) π] in front of R^{PM} to have the volume. Since the density is given by the mass over the volume

$$\rho_{PM} = \frac{M^{PM}}{V^{PM}} = \frac{M^{PM}}{\left(K \cdot M^{PM}\right)^3},$$

the result – following the Schwarzschild equation (1) – is that the density decreases with the square of the mass

$$\rho = K^{-3} \cdot M^{-2} \qquad (2)$$

with

$$K = \frac{2G}{c^2} \cong 1.5 \cdot 10^{-28} \ \ \mathrm{cm} \cdot \mathrm{g}^{-1}.$$

In Fig. 2 the density of our Universe,

$$\rho_{\mathrm{Universe}},$$

and the Planck density,

$$\rho_{\mathrm{Planck}},$$

are given as a function of the radius of all possible horizons produced by all possible masses allowed by the Schwarzschild solution of the Einstein equation. It is interesting to see (Fig. 2) the different values of densities which can go from the minimum,

$$\rho_{\mathrm{Universe}},$$

to the maximum,

$$\rho_{\mathrm{Planck}}.$$

The density which has attracted the interest of John Michell in 1783 and independently of Pierre-Simon de Laplace in 1796 is the "atomic" density.

It took more than a century for the "nuclear" density to come in the game and attract in 1939 the interest of Robert Oppenheimer, George Volkoff, Hartland Snyder and Fritz Zwicky.

For both forms of matter, atomic and nuclear, the density does not change when the amount of matter increases: one ton of lead has the same density as one kilogram of lead.

For matter where the binding force is gravitational (without any other forces being involved) – following the Schwarzschild equation – **the density decreases with the square of the mass** (2). This is the great novelty derivable from the Schwarzschild equation [1].

On many occasions, during the activities of the International School of Cosmology and Gravitation, in Erice, I have been discussing with friends and colleagues (including John Wheeler [6, 7], Nathan Rosen [8] and Peter Bergmann [9-17]) how it happens that no one has been able so far to derive the **mass** and the **vacua** of our Universe.

For example the number of protons, neutrons and electrons that our Universe is made of, which is about

$$N_{(p\ n\ e)} \simeq 10^{80}.$$

Despite the enormous work devoted to understand the physics of black holes [3, 4] including the study of Quantum Gravity [18] and the Relativistic Quantum String Theory (RQST) [19] with the interesting discovery of the "landscape" [20], no one has been able to get the easier goal, namely the Universe mass and vacuum.

The mass is about 10^{56} grams, if we ignore the problem of dark matter and dark energy.

The dark matter and dark energy will bring the mass to $\simeq 10^{58}$ grams but will not contribute to increase the number of $N_{(p\,n\,e)}$.

Our Universe has a number of galaxies of about 2×10^{11} ; each galaxy has, on the average, a number of stars of about the same order of magnitude, $2\cdot10^{11}$.

The average mass of each star is in the range of the mass of our Sun

$$\simeq 2 \times 10^{33}\,\mathrm{g}.$$

The total mass of the Universe turns out to be about

$$m^{\mathrm{Universe}} \simeq 8 \times 10^{55}\ \mathrm{g} \simeq 10^{56}\,\mathrm{g}.$$

c* ≡ *The velocity of light
h* ≡ *Planck's Constant
G_N* ≡ *Newton's Constant

From these **Units** the following values come

10^{-33} cm
10^{-5} gr
10^{-44} sec

An interesting point is to know if the primordial SCH-objects are scale invariant: *i.e.* if the laws of Physics remain valid inside small and big primordial SCH-objects. We know that there are information problems in the black hole physics [21].

What we are sure of is that the law of Physics remains valid inside a primordial SCH-object, provided that this "object" is as large as our Universe. This finding could be related – applying the time-reversal invariant operator T [22, 23] – to the problem theoretically studied by Gerardus 't Hooft [24].

He says on p. 77: *"If the original amount of material was big enough, the contraction will proceed, and, in the limit of zero pressure and purely radial, spherically symmetric motion, the equations can easily be solved exactly. We obtain flat Space-Time inside, and a pure Schwarzschild metric outside. As the ball contracts, a moment will arrive when the Schwarzschild horizon appears. From that moment on, an outside observer will no-longer detect any radiation from the shell, but a black hole instead"*.

The Universe where we have life and knowledge is an example of a very large primordial SCH-object. Sooner or later the mass and the vacua of our Universe should come out from RQST.

Meanwhile their origin remains in the three fundamental constants of Planck and in the Schwarzschild solution of the Einstein equation if the point-like massive objects are replaced by the primordial SCH-objects.

2. The second step

2.1. The Gap between the Gravitational Force and the other Forces [QED, QFD, QCD]

The energy level where the best values of the three fundamental gauge couplings (α_1, α_2, α_3) converge is at least two orders of magnitude below the Planck energy level. The existence of this Gap could imply that the gravitational force *"comes into being"* before QED, QFD and QCD.

The most interesting consequence of the Gap would then be the existence of matter whose charge is only the gravitational charge. If this is so, events should be detected where only gravitational waves are produced.

Primordial black holes (PBHs) would be produced much more frequently than the standard black holes (SBHs) since SBHs would be *derivative* effects produced later, after matter made of protons, electrons, neutrons, and stars can exist. Collisions between PBHs generating only gravitational waves would be more frequent than SBHs collisions.

2.2. The Gap and the origin of the Fundamental Forces

We would like to call attention on the energy Gap which exists between the energy level E_{GUT} (where the three gauge couplings α_1 (QED), α_2 (QFD) and α_3 (QCD) converge towards a common origin, α_{GUT}) and the Planck energy level, E_{Planck}.

This Gap could be the first evidence for the origin of the fundamental forces to be at two different energy levels.

The first energy level being the one where the gravitational force *comes into being*: in 1977 John Wheeler recalled [25] that we should care to study how *the laws come into* *being*. Since no one has been able to solve this problem, the solution has been given for granted: all fundamental forces start at the same instant with a Big Bang. In this case the Gap should not exist, due to the fact that all forces start at the same energy level.

The existence of the Gap opens new problems on the study of the gravitational forces. For example the study of the spectrum of the primordial black holes (PBHs) produced before QED, QFD and QCD *come into being*.

These PBHs possess only the gravitational charge. The first PBH is the smallest object in the Universe, with mass 10^{-5} g and radius 10^{-33} cm: the Planck PBH.

During the existence of the Gap no other forces could be active. **Only gravitational waves and particles with gravitational charge exist**.

The mass spectrum of the PBHs cannot be derived from fundamental principles but described by models [26].

Let us not forget that the masses of all particles of the Standard Model of Subnuclear Physics [27] are not predicted but experimentally measured. This is why we should be prepared to experimentally determine the masses of the PBHs, as already started to be done by the LIGO-VIRGO collaboration [28].

The existence of the Gap is illustrated in Fig. 3.

The present value of E_{GUT} is based on the most exact study of the evolution with energy of the three gauge couplings (α_1, α_2, α_3) [29, 30].

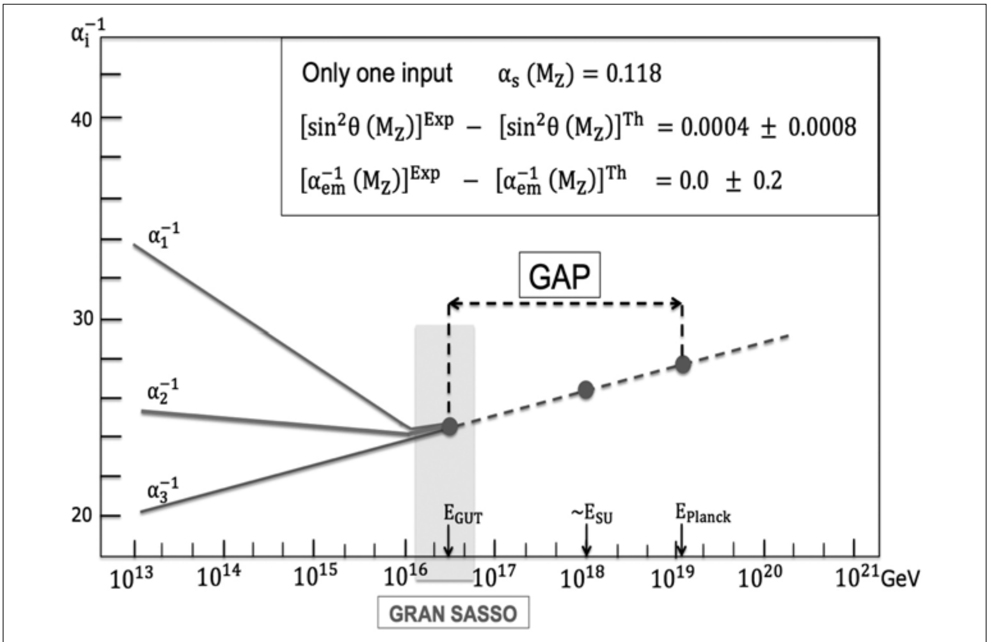

Figure 3: The Gaps between the Planck energy, E_{Planck}, and the two energy levels, E_{GUT}, where the three gauge couplings converge, and E_{SU}, where the RQST (Relativistic Quantum String Theory) [19] puts the origin of the gravitational forces [29-30]. The Gran Sasso label indicates the biggest underground laboratory to study neutrinos and cosmic energies of extremely high values.

It should not be forgotten that **during more than ten years** (from 1979 to 1992), no one realized that the energy threshold for the existence of the superworld (i.e. the threshold for supersymmetry breaking $E^{(\neq)}_{\mathrm{SUSY}}$) was strongly dependent on the **running of the masses**.

Until 1992 it was so. The **then best theoretical** prediction [19] for the energy threshold of the superworld,

$$E^{(\neq)}_{\mathrm{SUSY}}\ ,$$

was calculated to be **21 TeV**. The authors of this prediction computed, as everybody else, **the energy threshold**

$$\boldsymbol{E^{(\neq)}_{\mathrm{SUSY}}}$$

using only the running of the gauge couplings

$$(\alpha_1,\ \alpha_2,\ \alpha_3)$$

which corresponds to **neglecting** [31] nearly **three orders** of magnitude in the energy threshold for the discovery of the lightest particle of the superworld (LPS), **as proved in ref. [32]**.

The running of the masses is now called the **EGM effect** (from the initials of **E**volution of **G**augino **M**asses). Since then many other measurements of the gauge couplings at higher energies have been obtained; the values of α_1, α_2, α_3 have been confirmed [33] and the Gap, reported in Fig. 3, remains as it was in **1992** [29-30].

The **consequences of the Gap** in understanding **the origin of our Universe and its evolution** is one of the most interesting problems in front of us.

The first question is how the Universe would be if only gravitational forces were active. There would be neither stars nor standard black holes (SBHs).

In this Universe **only gravitational waves could exist** and **masses with only one type of charge**: the **gravitational one**.

Between the two extreme levels, E_{GUT} and E_{Planck}, there is the energy level E_{SU}, where the Relativistic Quantum String Theory (RQST) [19] puts the origin of the gravitational forces, *i.e.* **the string unification scale** $\boldsymbol{E_{\mathrm{SU}}}$.

Superstring theory **does not provide** the fundamental length. This is derived from the Planck length.

The string unification coupling, α_{SU}, where all gauge interactions join with gravity rather than being an arbitrary parameter, is determined by the vacuum expectation value (**VEV**) of a scalar field, the so-called **dilaton** $\phi(t)$ (for a review see ref. [34]).

Superstring theory **does not** provide the VEV of the dilaton. This is taken to be equal to α_{GUT} at the E_{GUT} scale. Taking into account the RQST it is necessary to multiply

$$E_{\mathrm{Planck}}\ \text{by}\ \sqrt{\alpha_{\mathrm{SU}}}\,.$$

The result goes down to

$$E_{\mathrm{SU}} \simeq 10^{18}\,\mathrm{GeV}$$

and the energy interval of the Gap becomes

$$(10^{-16} \div 10^{-18}) \text{ GeV.}$$

The conclusion is that E_{SU} is not a spectacular result of RQST. It is very strongly related to E_{Planck}.

Few words on the study of the pre-Big Bang.

Gabriele Veneziano and collaborators [35] proposed the existence of a **stochastic background of gravitational waves**.

These waves are coming from **the Universe which** existed long before the *quantum of time* in what they call a pre-Big Bang phase. The stochastic background has a characteristic frequency spectrum [36], several orders of magnitude **higher** than that of **standard inflationary cosmology**.

This *gravitational light* would be the effective radiation emitted at times of the order of the Planck time $(\simeq \mathbf{10^{-44}\ s})$

Another interesting effect is the amplification of electromagnetic fluctuations, due to the drastic variation of α_{SU}, which could provide the long-sought explanation for the observed **galactic magnetic fields** [37].

All these ideas have no effects on the existence of the Gap.

The only effect is the production of a background of gravitational waves. End of the few words on the Pre-Big Bang.

And **now back** at the time of the 1979 EPS Geneva Conference, when the three gauge couplings, $(\alpha_1, \alpha_2, \alpha_3)$, *were not converging in a point but in a sort of triangle* (Fig. 4).

These words are of Rudolf Mössbauer [38]. The three gauge couplings

$$(\alpha_1, \alpha_2, \alpha_3)$$

do converge towards a unique value

$$\alpha_{GUT} \simeq \frac{1}{25}$$

at the energy **if the existence of supersymmetry** is introduced [39] in the evolution equations of

$$\alpha_1, \alpha_2, \alpha_3.$$

As mentioned before the energy evolution of the three couplings

$$\left.\begin{array}{c} \alpha_1(q^2) \\ \alpha_2(q^2) \\ \alpha_3(q^2) \end{array}\right\} \qquad (1)$$

had never been performed before with the **new condition** [32, 40] based on the energy dependence, not only of the gauge couplings themselves, but also of the masses: *i.e.* the **EGM** (Evolution of Gaugino Masses) effect [32, 40-42] mentioned before. The EGM

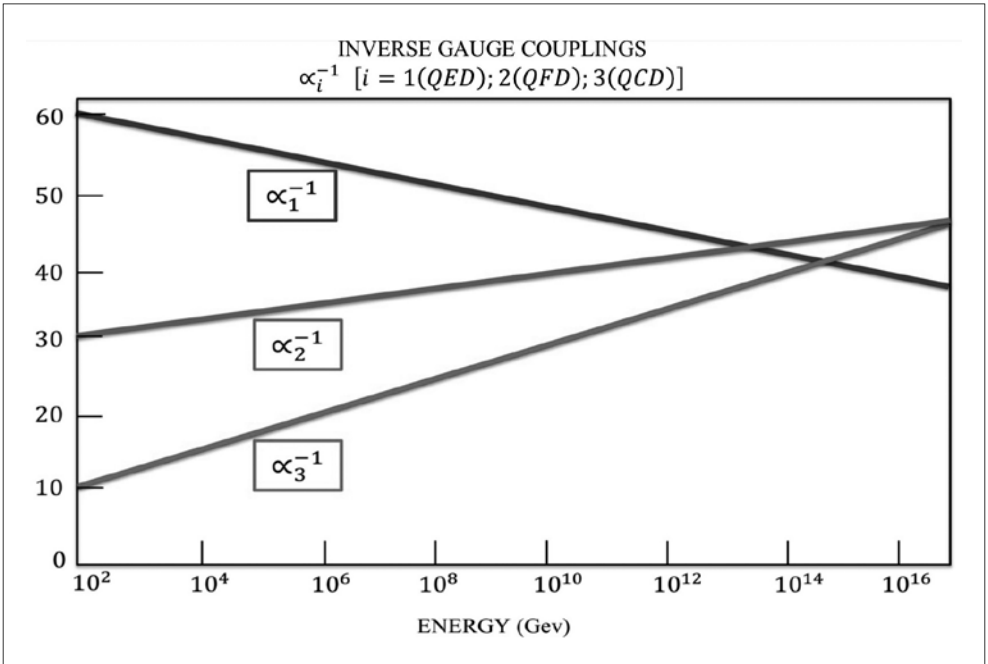

Figure 4

effect produces nearly three orders of magnitude (a factor **(700)**$^{-1}$), for the threshold of supersymmetry breaking,

$$E_{\text{SUSY}}^{(\neq)} \quad [42].$$

Suppose the convergence of the three couplings (α_1, α_2, α_3) is computed taking into account the evolution of each coupling with q^2, neglecting the variation of the masses associated with the physics of the given gauge group, *i.e.* $U(1)$ for α_1, $SU(2)$ for α_2 and $SU(3)$ for α_3.

Suppose the prediction is

$$E_{\text{SUSY}}^{(\neq)} = \mathbf{700\ TeV}.$$

Using the same model this prediction becomes **1 TeV**, if the EGM effect [32, 40-42] is included: the search for the lightest supersymmetric particle becomes possible at LHC.

The EGM effect is important for the lowest limit of the Gap, while the upper limit is given by the Planck energy level. In the energy interval

$$(10^{16} \div 10^{18})\ \text{GeV}$$

the Universe consists only of what the gravitational forces can do in terms of ***primary* effects** [25], not ***derivative***.

The primary effects are the “primordial Schwarzschild objects” **(P-SCH-objects)** previously discussed.

We have pointed out that our Universe seems to be the proof that a P-SCH-object, starting from the **Planck Universe**, can expand its radius by something like **62 orders** of magnitude following the conditions dictated by the Schwarzschild solution of the Einstein equation. The Einstein equation and the Schwarzschild solution ignore the existence of $SU(3) \times SU(2) \times U(1)$. The convergence of the three gauge couplings (α_1, α_2, α_3) at E_{GUT} is nearly two orders of magnitude below E_{SU}. In this energy Gap the P-SCH-objects are produced, which could indeed be the seeds of all galaxies.

If we could see the inner structure of these objects we would find that the matter they are made of is not the one familiar to us, i.e. a matter made of protons, electrons and neutrons (p, e, n).

The **P-SCH-objects**, as said before, are made **of matter whose charge is only the gravitational charge**.

Their size is not necessarily confined within the **cosmological horizon**. Inflationary scenarios allow for even larger PBHs, the so-called super horizon PBHs [43].

Standard black holes (SBHs) [3-4] are produced later, when QED, QFD and QCD are switched on. SBHs are actually due to ***derivative*** **effects produced** by matter made of (p, e, n). All we can do is to study the collisions of two black holes, as done by Riccardo De Salvo, Walter Del Pozzo and Collaborators. If they are P-SCH-objects [44], these collisions would generate **only gravitational waves**. If these gravitational waves are not accompanied by electromagnetic waves and/or neutrinos, this would be evidence that **P-SCH-objects exist**.

These **P-SCH-objects** could solve the problem of the missing mass in the Universe, for the very simple reason that P-SCH-objects are directly produced at extremely high energy when only the gravitational forces are active [44].

Their number should be much larger than the number of SBHs since the production mechanism of the latter is not *primary* but *derivative* [25]. SBHs are the result of a succession of secondary processes at much lower energies, occurring **after matter** made of protons and electrons, including the subsequently produced neutrons and stars, can exist.

The problem is to find out if the origin of the fundamental forces is all at once in the Big Bang or if the origin is in **two steps**.

The existence of the Gap is a result which implies that the gravitational force *comes into being* before QED, QFD and QCD.

The ***comes into being*** brings us back to **1977** when John Wheeler, after many discussions, was invited to give a series of lectures in Italy.

In the **lecture notes** [25] on page **11** he writes: *"It is preposterous to think of the laws of physics as installed by a Swiss watchmaker to endure from everlasting to everlasting…* ***The laws must have come into being****"*.

The mechanism of how *The laws must have come into being* **should indeed be studied**; it was a problem in the discussions with **Patrick Blackett** and his friend **Bertrand Russell** [45], in the fifties.

After many decades it has been **abandoned**, since **no one has been able to contribute towards a description of how the Fundamental Forces** ***come into being***. On page 11 Wheeler continues: *"Therefore they could not have been always a hundred percent accurate. That means that they are **derivative, not primary**"*. And on page 44: *"Of all strange features of the Universe, none are stranger than these: time is transcended, laws are mutable, and observer-participancy matters"* [25]. These notes allow to understand what John Wheeler elaborated after many successful decades of activities in physics.

Here is a synthesis of our discussions [25]: *"When a new idea comes in, we physicists should not start writing formulae but translate the new idea in terms of effects to be first imagined in terms of known facts. Formulae must come later*". The wording is not exact: **the conceptual meaning is exact**.

This is the reason why we have to go on with effects to be imagined, before a mathematical formalism can be worked out.

Following John Archibald Wheeler [25], the starting point is the new idea (the gravitational force comes into being before the other fundamental forces) first imagined in terms of known facts: the existence of the Gap.

The mathematics needed to describe **how the Gap can be connected** with the P-SCH-objects [44] and how **the mass spectrum of PBHs** can be derived and connected with other effects, like the origin of the dark matter [26] must come later [46]. All possible Einstein equations are represented by the function

$$\left(R=\frac{1}{M}\right)$$

in Fig. 5.

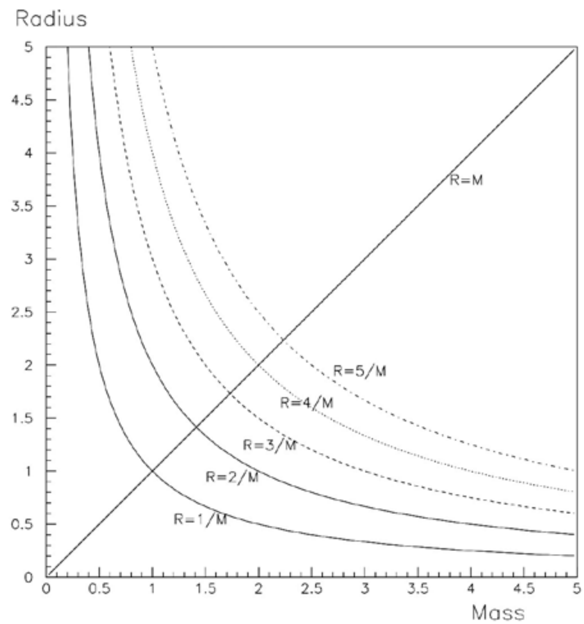

Figure 5

What is needed is the function ψ^U (R, M) which evolves with Time (3) along the line $(R = M)$ given by the Schwarzschild equation (1) [27, 31].

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