2016

# LNF Highlights


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# One year of Research at LNF: 2016

# Foreword

Year 2016 has been an exciting year for physics, being highlighted by the first observation of gravitational waves generated by the sudden collapse of two giant black holes. Our community has followed these events very closely. Frascati Lab has been historically involved in searches with bar antennas. This discovery has made the running of NAUTILUS, the cryogenic antenna hosted in Frascati, which was shut down in October, obsolete.
DAΦNE has continued to provide excellent performances, not only in terms of peak of luminosity (up to 2.2 $10^{32}$ $cm^{-2}s^{-1}$) but also in reliability. KLOE-2 experiment is profiting from the data, willing to achieve the goal of 5 $fb^{-1}$ on tape by March 2018. INFN and LNF managements set a clear path of DAΦNE activities until late 2019, where PADME and SIDDHARTA-2 experiments will manage to acquire the desired amount of data. In the meantime, the Beam Test Facility will undergo an important upgrade to double its beam lines. In the future DAΦNE can be possibly used as an accelerator research facility, or to deliver single beams. A detailed program to guarantee the survival of both infrastructure and of technical competences will be sorted out in 2017.
In parallel, the Laboratory is preparing his long-term future, which has been identified toward a European-class accelerator facility devoted to R&D in acceleration techniques, notably in plasma acceleration. Within the EUPRAXIA H2020 design study, INFN and the Laboratory is planning a large investment in the upgrade of the SPARC_LAB installation, where in the meantime, a long series of very important experiments have been performed.
In addition to taking care of detectors at DAΦNE, the Research Division has continued its intense activity in the experimental apparatus at CERN, Fermilab, JLAB, KEK and in other large laboratories. LHC Phase 1 upgrades prepared their production sites and will be ready to take off by the end of 2017.
A long list of activities has characterized 2016 not only in dissemination (Open Day, Researchers' Night, public lectures, training of High School students, etc...), but also in Technological Transfer, showing the strong will of the Laboratory to contribute, not only to basic science and to academic training, but also to the Third Mission of INFN.
All this, and much more not reported in this summary, would not have been possible without the efforts of our staff and of our hosts. I am happy to send everybody, and especially to the youngest collaborators, my deepest and warmest regards.

Pierluigi Campana
LNF Director

# KLOE measured the "variable" constant

One of the most fascinating predictions of Quantum Electro-Dynamics (QED), is the existence of a state of minimum energy, the vacuum state, which is full of particles, namely the particle-antiparticle pairs, that exist for a very short time and for this reason they are called "virtual". These pairs, which are formed in vacuum the same way air bubbles in a pot of water on the stove, are mainly composed of light particles such as electron and anti-electron (positron). However, occasionally, other types of heavier particle pairs can be formed, such as muon- antimuon or quark-antiquark, or possibly pairs of still unknown particles. As the bubbles forming at the bottom of the pot and rising to the water surface, these virtual particles produce tangible effects to the physical processes involving real elementary particles.

Concerning electrical properties, vacuum behaves in the same way as a common insulating material. In the presence of an electric charge, the spatial distribution of particles and antiparticles warps due to the electric field of the charge. Particles with opposite charge will be attracted, while those with the same charge will be repelled.

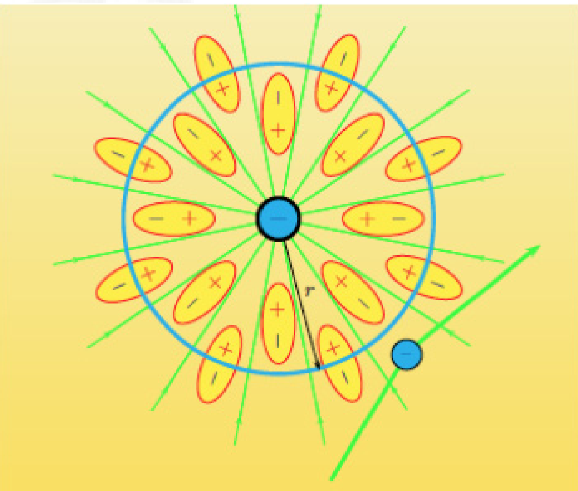


Figure 1 Representation of the vacuum polarization phenomenon causing charge screening by a virtual pairs.

This vacuum polarization effect has an important implication. If we design an experiment to measure the electric charge of a particle, the result of the experiment is a function of how close our probe is to the charge: the effective charge decreases at a great distance, while it increases as we get closer to the position of the original charge. In technical terms, this is called "running" of the electromagnetic field coupling constant α, also known as the fine structure constant. This behavior is responsible for the fact that the value of α, corresponding to the mass of the vector boson $Z_0$ (about 90 GeV), is 1/128, instead of about 1/137, which is the usual value when the energy involved is very small.

Inside the quantum vacuum there are all kinds of particles, so we should wonder about its properties in the context of other interactions of Nature. We found out that things can be different from the electromagnetic interaction. For example, with regard to the color interaction, experienced by quarks and responsible for the nuclear force, this kind of screening effect works in the opposite way: an elementary charge of color, for example a quark, attracts virtual charges of the same color, repelling those of the opposite color.

Such behavior of the quantum vacuum means that, contrary to the electromagnetic constant, the strong coupling constant grows as the distance increases and vanishes when quarks are in contact with each other. This phenomenon, known as asymptotic freedom, was predicted in 1972 by David Gross, David Politzer and Frank Wilczek, who were awarded with the Nobel Prize in 2004.

Going back to the evolution of the electromagnetic coupling constant, there is another important aspect to take into account. In fact, while the screening effect due to leptons (electrons, muons and taunos) is known with high precision, the same cannot be said of the contribution of the quark-antiquark pairs. In particular, this contribution cannot be calculated in the range of energies of the order of GeV, therefore, indirect determinations must be used.

The KLOE-2 collaboration, analyzing data of the electron-positron conversion process into muon pairs, measured for the first time the running of α in the energy region below 1 GeV, highlighting in a spectacular way (with a statistical significance larger than five standard deviations) the contribution of virtual quark-antiquark pairs to the vacuum polarization.

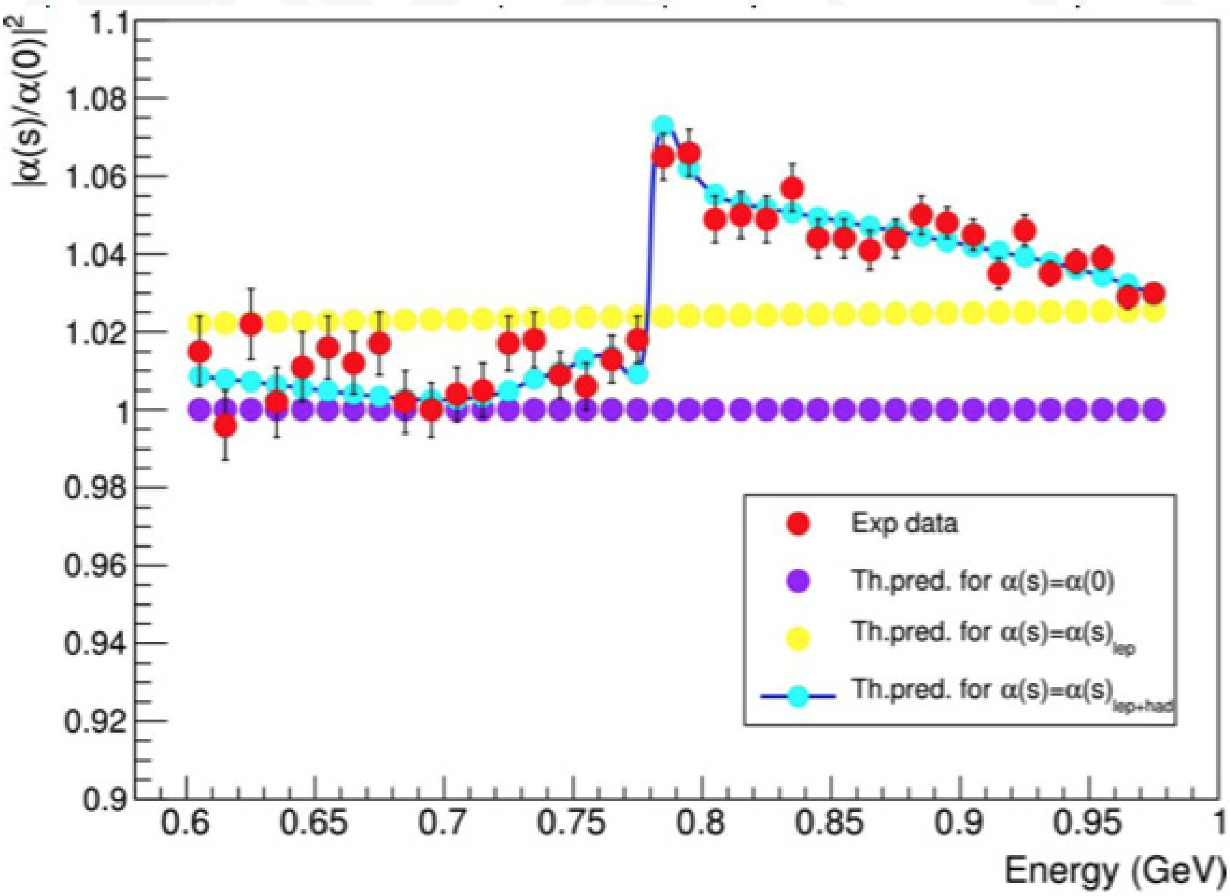



Figure 2 Running of the square of electromagnetic coupling constant as a function of the energy (see text for more details).

The results of this analysis, performed in 2016, have been recently published on Physics Letters B, one of the most prestigious journal for particle physicists.
Figure 2 shows the main result of this work: namely the running of the square electromagnetic coupling constant, normalized at its value at zero energy (α (0) ≈1/137), as a function of the muon pair's invariant mass. Red dots represent experimental data; turquoise and yellow dots represent, respectively, the expected behavior when considering quarks and leptons, and when considering leptons only. Purple dots represent the case of no contributions from the vacuum polarization.


References:
[1] A. Anastasi et al., "Measurement of the running of the fine structure constant below 1 GeV with the KLOE Detector", Phys. Lett. B 767, 485 (2017).

# A history of one hundred years

It was 1908 when Ernest Rutherford, Hans Geiger and Ernest Madsen started a series of experiments to study radioactivity, using the first gaseous detectors and opening a road on which we are still traveling. This road has many milestones: Charpak 1968, Iarocci 1978, Oed 1987, Giomataris 1996, Sauli 1997, Bellazzini 1999. Each name is connected to a new type of detector that allowed a step forward in particle detection. The most recent one is represented by Micro-Pattern Gaseous Detectors (MPGD). This new kind of detector concentrates the amplification and the development of the electrical signal produced by a charged particle in a space of hundredths of a millimeter. In this way, also the response time of the detector is reduced, since the positive ions do not have to travel long paths and the detector can be immediately ready for a new detection. In the first decade of the 2000's, the attention has been centered on MicroMegas (Micro-mesh gaseous structure) and GEM (Gas Electron Multiplier) which were used for the first time in a real experiment by the COMPASS collaboration at CERN. The difference between the two classes of detectors is mainly in the layout of the amplification stage: a metallic mesh with size 50 μm for the MicroMegas, an etched kapton foil, aluminized on both sides with a few microns of copper, for the GEM (see Fig. 4).
The development of these detectors, on one side has exploited the new technologies developed by industries, on the other, it has pushed industries toward innovation for new materials and for the production of new printed circuit board. In particular, the need to protect the electronic components of the detector from discharges, has opened a new way: the resistive MPGD.

When a huge number of electrons is present, a resistive coating material is locally charged and the electric field in the hole is reduced stopping the amplification mechanism and then quenching the discharge. The use of resistive coatings dates back to the end of the 1970's, but only recently it has become widely used.

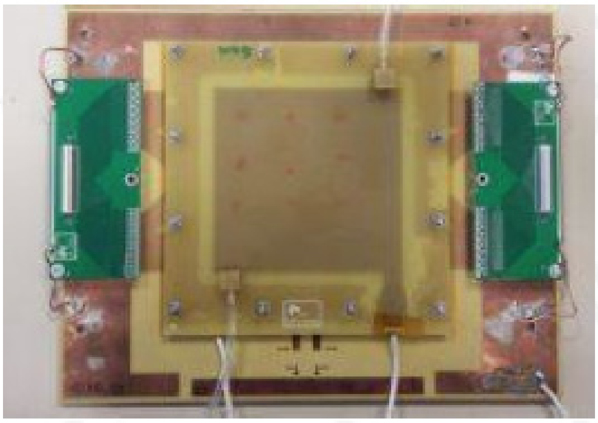


Figure 3 Prototype of a M-RWell.

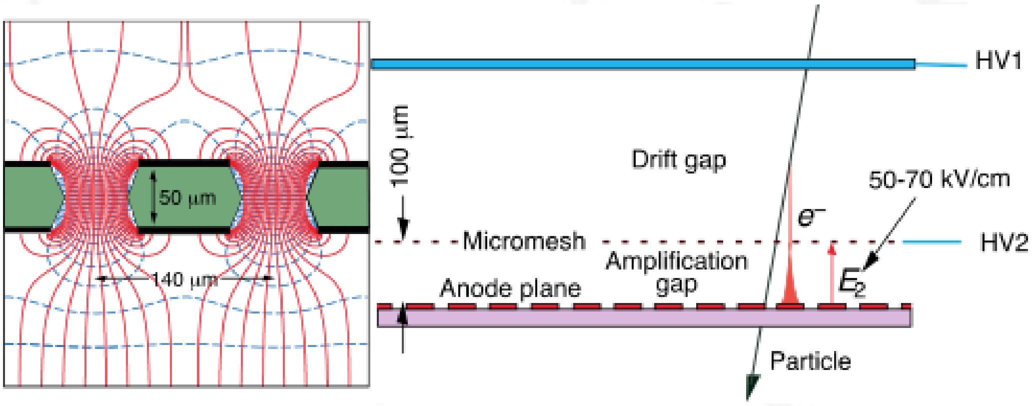



Figure 4 (left) Detailed view of the field lines in a GEM kapton foil; (right) layout of a MicroMegas (from Ref [1]).

At LNF, characterized by a long tradition of gaseous detector development, many new, large size detectors have been realized: in the 80's Plastic Streamer Tubes (PST) that made the history of the apparatuses installed on the Large Electron-Positron Collider (LEP) at CERN; in the 90's RPC with glass electrodes, also known as Glass Electrode Spark Counter (GSC, developed within the LNF Detector Development Group – DDG), from which Multi-gap Resistive Plate Counters (MRPC) were derived, and that have been extensively installed on the ALICE experiment at CERN LHC; in year 2012, the first cylindrical GEM (CGEM, produced by the DGG) has been built. It was designed to become the internal tracking system of KLOE experiment at DAΦNE, in order to complement the tracking information obtained from the largest drift chamber ever built, again designed and constructed at LNF.
This long-standing tradition is nowadays kept alive be the Detector Development Group – DDG, that, starting from the year 2000, has become expert on detectors based on GEM technology, and has recently developed a new MPGD. The main characteristics of this new device, named micro-Resistive WELL (μ-RWELL), are compactness, easiness of assembly and intrinsic protection from discharges. The inspiration came from the two more common MPGD: it takes from GEM detectors the amplification stage (an etched kapton foil) directly superimposed to a readout board covered by a resistive layer, taken from MicroMegas. The cathode, few millimeters from the amplification zone (hold by a glass-fiber frame), closes the entire detector (see Fig. 5)

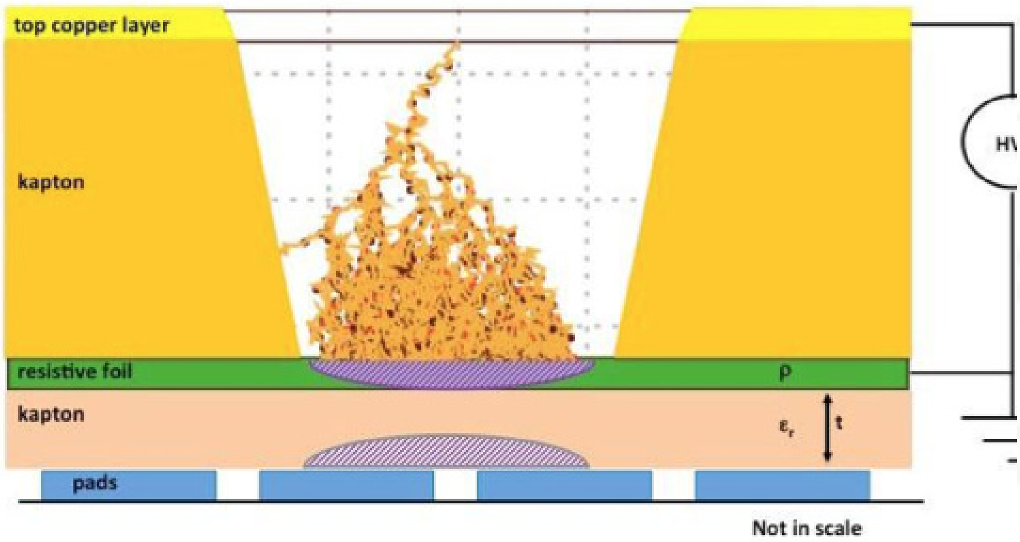



Figure 5 Cross-section of a M-RWELL.

The absence of complicated mechanical workaround makes the detector easy and fast to be assembled. Another point of strength of this kind of detector, with respect to other similar ones, is represented by the uniformity of the amplification stage. This is due to the fact that the production technique of the etched kapton foils, after 20 years of GEM development, has become very robust. This permits to use μ-RWELL to build large area detectors like those installed at the CERN Large Hadron Collider (i.e. CMS, LHCb). The μ-RWELL detectors, like many other MPGD, can be used also in other fields: neutron detection for industrial tomography, detection of X and gamma rays for medical applications, muon tomography for homeland security and archaeological uses.

References:
[1] C.Patrignani et al., "The Review of Particle Physics", Chin. Phys. C 40, 100001 (2016).

# Search for Physics beyond the Standard Model: muon to electron conversion experiment

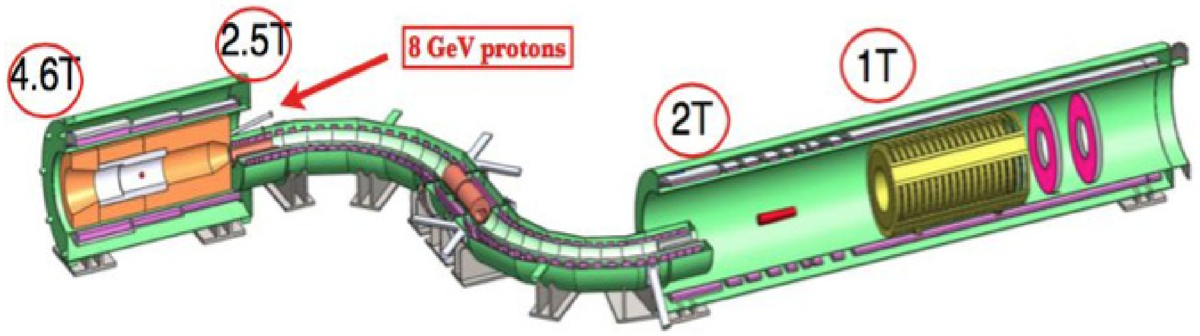



Figure 6 Layout of the Mu2e experiment solenoidal system: from left to right Production Solenoid, Transport Solenoid and Detector Solenoid. The total lenght of the experiment is around 25 m.

The muon to electron conversion is one of the forbidden processes in the Standard Model (SM) belonging to the so called Charged Lepton Flavour Violating (CLFV) category, together with complementary channels of muon decays in flight such as $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$. Nature does not allow leptons of the "fat-families" to transform into the lighter species without emitting neutrinos. Even when extending the SM to include neutrino oscillation in the calculation, the branching fraction (BR) of such CLFV muonic processes is negligible ($BR=10^{-54}$) making all this business very interesting. Theories beyond the Standard Model, such as Supersimmetry, foresee BR that can be accessible to nowadays or next generation CLFV experiments. Any experimental observation of such events would be a clear indication of new physics.

The MEG experiment at PSI (Zurich) has set the most stringent limit on $BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ at 90% C.L. [1] and it is now concluding the preparation of its upgrade aiming to a further sensitivity increase of ten times in the next four years. This experiment is shooting for a discovery or for posing a serious threat to the existence of the Supersimmetry model that estimates BR ~ $O(10^{-15})$. The next step forward is in the hands of the muon-to-electron conversion experiments: Mu2e [2] at Fermilab (USA) (Fig. 6) and the twin experiment (Comet) at JPARC (Japan). Mu2e proposes to improve the single event sensitivity on the conversion process of four order of magnitude in order to reach $2.5 \times 10^{-17}$ or, in other words, to discover processes with BR as low as few $10^{-16}$. The interplay and complementarity between MEG, Mu2e and other experiments in this field are shown in Fig. 7, where their sensitivity reach is shown in the $\lambda$-k plane. $\lambda$ indicates the mass scale, while k indicates if the loop or the contact interactions are dominant.

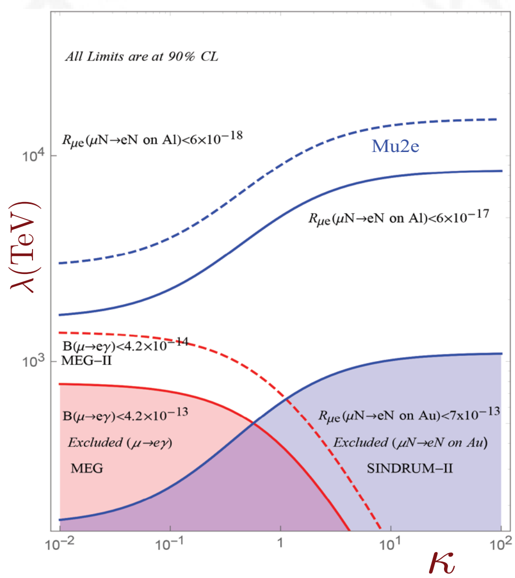



Figure 7 The CLFV sensitivity reach for MEG, MEG-upgrade, Sindrum-II, Mu2e and Mu2e-II. Mu2e-II foresees an intensity that is higher than Mu2e by a factor of 10.

The contours in the plane indicate that Mu2e/Mu2e-II have a better reach with respect to MEG experiments and they are sensitive to more physics that MEG. The mass reach extends up to thousands of TeV i.e. much further than any other existing or planned high-energy collider experiment.

In Mu2e, the muon beam is stopped on an aluminum target and a muonic atom is formed. The muon quickly proceeds to the 1S state circulating in an orbit very close to the nucleus so that: 40% of the muons Decay In Orbit (DIO) while the remaining 60% are captured by the nucleus. The nuclear capture creates low energy neutrons, photons and protons that constitute a nasty background and a strong radiation environment (100 krad, $10^{12}$ n/cm$^2$) for the detector. The Conversion Event (CE) has a clear distinctive signature: a mono-energetic electron with energy very close to the muon rest mass (104,97 MeV).

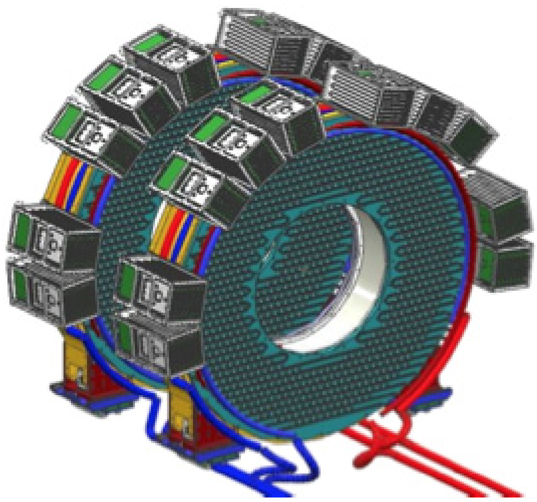
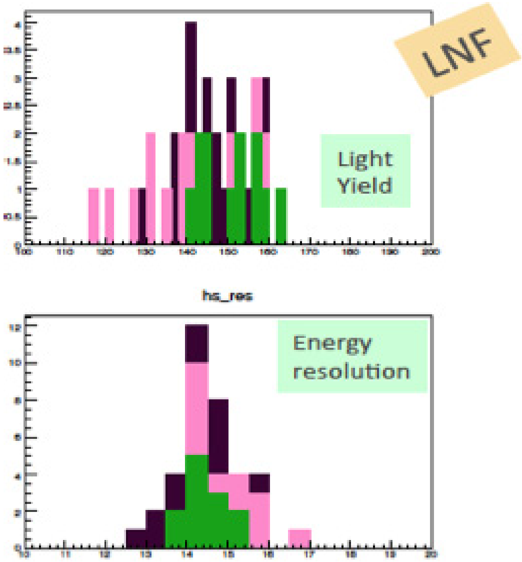


Figure 8 CAD drawing of the calorimeter system.

To reach its goal, Mu2e needs to stop $6\times10^{17}$ low momentum muons in 3 years of running and to distinguish the CE line from the falling slope of the decay in orbit (DIO) events. To improve 10000 times with respect to the previous experiments, Mu2e needs three basic ingredients: (1) a pure high intensity negative muon beam (c.f.r. $10^7$ μ /sec at PSI vs $10^{10}$ μ /sec at Fermilab); (2) a pulsed beam with micro-bunches interleaved of 1.7 μs, to allow all prompts signal to decay with respect to the slow decaying muons, τ(μ) = 826 ns, and (3) a performant detector. The detector is composed of a high precision tracking system, with 20000 straw tubes of 15 μm thickness, designed to reconstruct the particle momenta with a precision of 120 keV. The tracker is assisted by an electromagnetic CsI crystal calorimeter (Fig. 8), readout with Silicon Photomultipliers (SiPM) that should provide a clear particle identification, support and seed the tracking particle recognition and provide a track independent trigger.

LNF group has a strong responsibility in the design, prototyping and construction of the Mu2e calorimeter [3] covering the project leadership and coordinating the activities of all the INFN groups. It consists of 14 researchers, engineers and PhD students with a large technical support. The experiment was approved in July 2016, providing, this way, the start for the construction of the calorimeter. INFN has signed an agreement with Fermilab for a financial support of around 3 MEuro on the "core-material" and a commitment on: (i) providing Quality Assurance (QA) for crystals and SiPMs and (ii) delivering in-kind the mechanical system, the front-end and digitizer electronics and the laser calibration system. The pre-production phase for crystals and SiPMs has been concluded at the end of 2016. Left panel of Fig. 9 shows results of the tests performed. The right panel shows a prototype of the custom Mu2e SiPMs. Each Mu2e SiPM consists of a 2x3 array of 6x6 mm$^2$ UV- extended sensors thus allowing a good light collection from the crystal surface. In the same picture the pre-production front-end electronics boards can also be seen. These have been fully designed by the LNF electronics service.



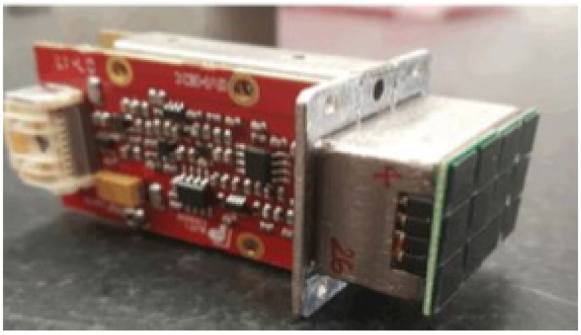



Figure 9 (left) QA plots for pre-production crystals. (right) SiPMs and FEE amplifiers

During 2016, other important steps have been reached by the Mu2e collaboration: (i) the 75 thousand km of superconducting cables have all been produced and some samples of those have been tested and characterized by the INFN group of Genova, (ii) the construction of the three large solenoids is started, with ASG superconducting of Genova working on the Transport Solenoid, (iii) the civil construction of the experimental hall has been completed and (iv) all the sub-detectors are entering in the construction phase. The experiment schedule foresees the conclusion of the construction phase for the end of 2019, with commissioning with cosmic rays and beam expected for the end of 2020.

References:
[1] A.M. Baldini et al., "Search for the Lepton Flavour Violating Decay $\mu^+ \rightarrow e^+ \gamma$ with the Full Dataset of the MEG Experiment", Eur. Phys. J. C 76 no.8, 434 (2016).
[2] MU2E TDR: ArXiv:1501.05241v2.
[3] FTDR: Mu2e-Docdb.fnal.gov # 8429.

# NAUTILUS the end of a program to discover Gravitational Waves

On October the 7th, 2016, the gravitational wave antenna NAUTILUS (Nuova Antenna a Ultra bassa Temperatura per esplorare In Lontano Universo le Supernovae) has ended its long data collection started in February 2003. In all this time, the 2300 kg aluminum bar was kept at a 2 K temperature despite the many problems due to the helium recovery and liquefaction.
The gravitational wave experiments started with Joseph Weber at the University of Maryland in the early sixties. Although during the following years his initial results were not confirmed by other experiments using essentially the same technique (resonant bars at room temperature), the search for gravitational waves has been pursued by many experimental groups all over the world. It is interesting to remember that the first prototype of an interferometric gravitational wave detector was built in the late 1960s by Robert L. Forward, a student of Weber.
In Italy this search started in September 1970 with a group led by G. Pizzella and E. Amaldi [1]. They decided quite soon to aim at the construction of bar detectors at very low temperature to reduce the thermal noise. After several detectors operating at room temperature and at liquid helium temperature, they proposed to build NAUTILUS, the first antenna cooled at 0.1 K (see Fig. 10). This proposal was at the end of 1980s and the INFN group name was ROG (Ricerca Onde Gravitazionali). NAUTILUS and its twin AURIGA (at the INFN Laboratory of Legnaro) held the record for sensitivity until the introduction of gravitational waves interferometers, such as Virgo and LIGO. After the first cryogenic tests NAUTILUS was moved from CERN to Frascati in the spring of 1992. The antenna EXPLORER, operated by the ROG group remained at CERN running until 2010.

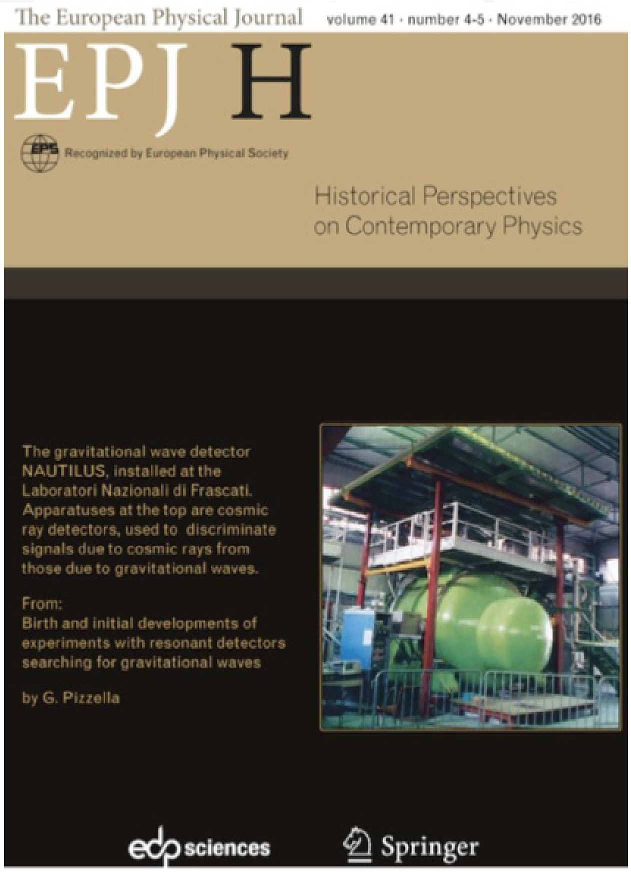



Figure 10 Cover of the European Physical Journal section H (Historical) dedicated to NAUTILUS.

NAUTILUS, cooled down at 0.1 K, had its first scientific run in 1998, when cosmic ray signals were also detected. Indeed, the detector was also used for research on certain hypothetical kinds of dark matter and it has been the coldest solid body in the Universe for a long time. The signals due to cosmic ray showers (Fig. 11) were larger than expected.
To understand this result, a dedicated experiment (RAP) was done at the Frascati BTF. The result was that this amplification was due to the transition from superconductive to normal Aluminum, induced by ionizing particles. The acceptance of the bar detectors is smaller than that of other detectors used for strongly interacting dark matter searches. However, the detection mechanism is completely different and is more straightforward than in other detectors.

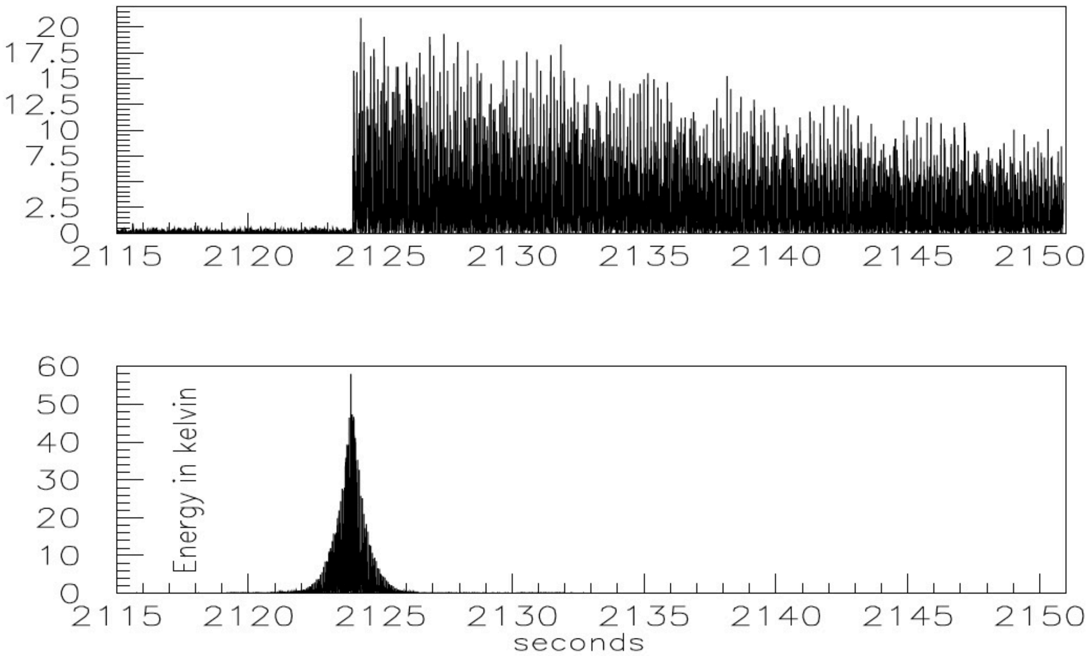



Figure 11 One of the first cosmic ray shower detected in the 1998 run with the antenna cooled at 0.1 K. The signal (Volt square) before optimum filtering versus the time expressed in seconds from the preceding midnight. From the decay, the merit factor of the apparatus, Q = 1.7 x $10^{5}$ is evaluated. The lower figure shows the data after filtering, in unit of kelvin. Here the inverse of the decay time gives the detector bandwidth equal to 0.34 Hz. The amplitude of this signal was an order of magnitude larger than expected.

Later in 2001, to reduce the consumption of liquid helium, it was decided to keep the bar at a 2 K temperature. The long run, which came to an end in October 2016, was mainly devoted to detecting signals from supernovae within our galaxy. Unfortunately, no cosmic event of this kind was registered after the 1987 supernova explosion.
The main results in the search of coincidences among bars are summarized in Fig. 12, and compared to the interferometer results until 2015. Those results apply to short bursts having a significant Fourier component at the bar resonant frequencies (900 Hz). The IGEC limits were obtained by a combined analysis of several bars (ALLEGRO, AURIGA, EXPLORER, NAUTILUS, NIOBE) until 2006.

From these figures considering also that the IGEC and the EXPLORER-NAUTILUS limits are in different years, it is interesting to note that for very strong signals the bar limits are still better than the limit obtained by the interferometers. This is due to the longer data taking.

Last year, the interferometer LIGO detected for the first time the gravitational waves originated from black holes' coalescence and started a new chapter in physics: gravitational waves astronomy, as wonderfully predicted in a short visionary video by E. Amaldi [2]. This detection ends this pioneer stage of the search.

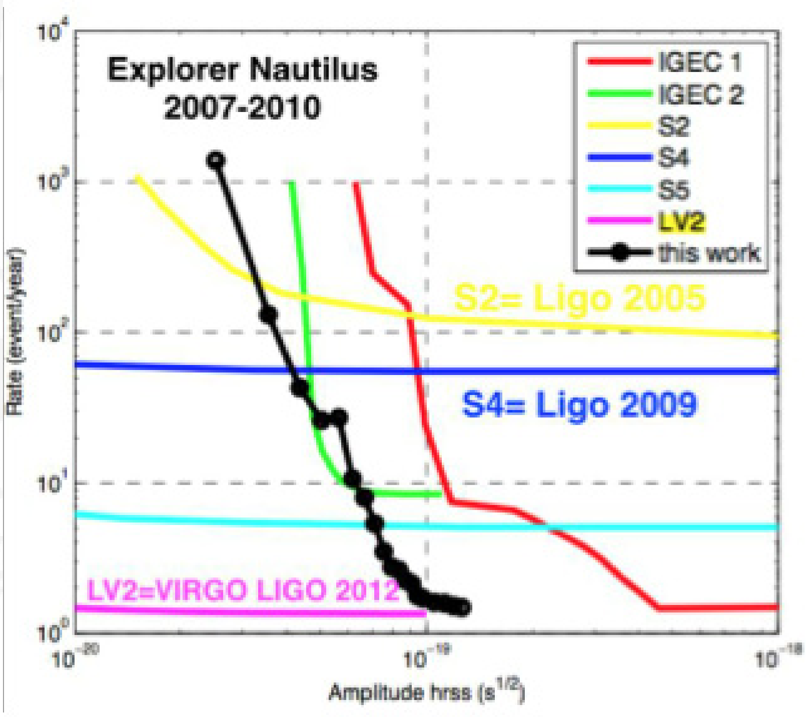



Figure 12 Comparison between upper limits of the rate of short burst of gravitational waves obtained by bar detectors (IGEC1, IGEC2 up to 2006), and EXPLORER-NAUTILUS from 2007 to 2010, with limits at 95% C.L., and the interferometers limits S2, S4, S5, LV2 (90% C.L.) before 2015. The two events detected by LIGO in 2015 have an amplitude roughly one order of magnitude smaller than the origin of the x a axis and a negligible component at 900 Hz. Note that an amplitude hrss of $10^{-19}$ in NAUTILUS corresponds very roughly to a measurement of oscillations of $10^{-17}$ meters between the bar ends in 1 ms burst.


References:
[1] G.Pizzella, "Birth and initial developments of experiments with resonant detectors searching for gravitational waves", Eur. Phys. J. H 41 no. 4-5, 267 (2016).
[2] E. Amaldi, "Amaldi e le nuove astronomie", https://youtu.be/sGjkxQF4ckQ.

# Where should we search to find the Axion?

During the past decades, a plethora of experimental results has firmly established that strong interaction phenomena in particle physics are correctly described by a fundamental theory wich is commonly known as Quantum Chromo Dynamics (QCD). While to date there are no experimental results contradicting QCD predictions, this beautiful theory, together with a deep understanding of many fundamental issues, also brings in one theoretical conundrum. The QCD sector, which describes the strong forces, depends on two dimensionless fundamental parameters whose values are not predicted by the theory, but must be determined experimentally. The first one $\alpha_s$, determines the strength of the QCD interactions, and its experimental value is a natural one $\alpha_s$, for a dimensionless quantity (roughly speaking it is of order unity, although the precise number depends on the energy scale at which $\alpha_s$ is measured). The second one, $\theta$, gives the amount of violation of the charge-parity (CP) symmetry in strong interactions. The theory only dictates that the value of $\theta$, which is an angular parameter, must range within the interval $[-\pi, \pi]$, and also in this case it would be natural to expect a value roughly of order unity. Surprisingly, it is found instead that the absolute value $|\theta|$ must be smaller than $10^{-10}$. This upper bound, follows from the stringent experimental limits on the neutron electric dipole moment, which is a CP violating quantity. Such a tiny value is regarded as highly unnatural for a dimensionless parameter, and QCD would definitely be more natural if, for some reason, $\theta = 0$. This would straightforwardly imply that QCD is a CP conserving theory, in agreement with observations.

An elegant mechanism to guarantee the vanishing of $\theta$ was proposed in 1977 by Roberto Peccei and Helen Quinn [1].

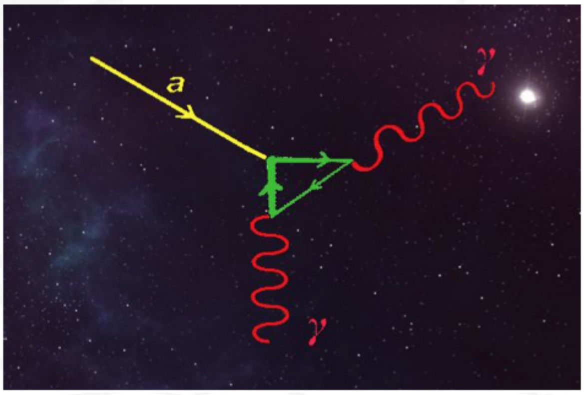



Figure 13 Axion-photons interaction mechanism.

A crucial ingredient of the Peccei-Quinn (PQ) mechanism is the introduction of a new symmetry governing particles interactions. However, the physical state of lowest energy, commonly referred to as the vacuum, does not respect this symmetry. According to a general theorem (the Goldstone theorem) this implies the existence of a physical particle of zero mass and zero spin. In PQ scenarios, this particle is known as the axion. The axion, however, is not exactly massless, and this is because also a class of subtle QCD effects does not respect the PQ symmetry. Although the overall effect is quite small, this explicit breaking of the PQ symmetry induces a tiny mass $m_a$ for the axion, presumably even smaller than the mass of the neutrinos.

Soon after the PQ mechanism was proposed, it was realised that the same dynamical phenomenon which drives $\theta \rightarrow 0$, also implies that a population of zero momentum axions is generated from the vacuum. These axions would pervade today the whole observable Universe. Noteworthy, for a certain range of axion masses, well compatible with theoretical expectations, this "sea" of axions could provide the cosmological dark matter.

Clearly, the fact that axion models can naturally provide a dark matter candidate, enhances the theoretical appealing of the PQ mechanism, and justifies the several ongoing axion search experiments, and the many more that are being planned for the next future.
One of the most peculiar property of axions is that they couple to a pair of photons (see Fig. 13). While the strength of the axion-photon coupling $g_{a\gamma\gamma}$ is model dependent, virtually all ongoing search experiments rely on the conversion of axions into photons, which is mediated by this coupling. Clearly, the goal of axion searches is to reach inside the parameter space region (in the $g_{a\gamma\gamma}$ - $m_a$ plane) where realistic axion models live. Currently, however, the boundaries of this region are fixed on the basis of somewhat arbitrary criteria. The problem of defining on a solid phenomenological basis the region inside which axion searches should focus, has been recently pointed out by a team of three researchers respectively from the theory groups of the Durham University in the UK, Barcellona University in Spain, and Frascati National Laboratories. The results of this research have been published on one of the most prestigious scientific journals: Physical Review Letters.

The authors proceed to classify axion models selecting as phenomenologically preferred those that do not give rise to cosmological issues (in the form of cosmologically stable strongly interacting relics, which are not observed) and further requiring that the strength of the interactions between the known particles (for example the leptons and the quarks) does not become infinite in the energy range of validity of Quantum Filed Theory, that is below the Planck scale. Fifteen cases satisfy these two criteria, and define a phenomenologically preferred axion window. The window is delimited with the two continuous lines in Fig. 14, labeled E/N=44/3 and E/N=5/3, where E/N is a theoretical quantity that determines the strength of the axion-photon coupling, and which assumes different values in different axion models. (For comparison, the region that was so far considered is also depicted, enclosed between the two dashed lines). By combining among them the fifteen models, other possibilities that still satisfy the two phenomenological requirements can be constructed. They span the larger region colored in the figure in light yellow, delimited from above by the dot-dashed line labeled E/N=170/3. Within this enlarged region, axion-photon couplings enhanced by almost one order of magnitude are possible. However, in a few cases it can also happen that the axion decouples almost completely from the photon, so that the region has no lower boundary.
It is expected that this analysis will contribute to focus ongoing and future experimental efforts for axion searches towards the parameter space region encompassing the phenomenologically most appealing axion models.

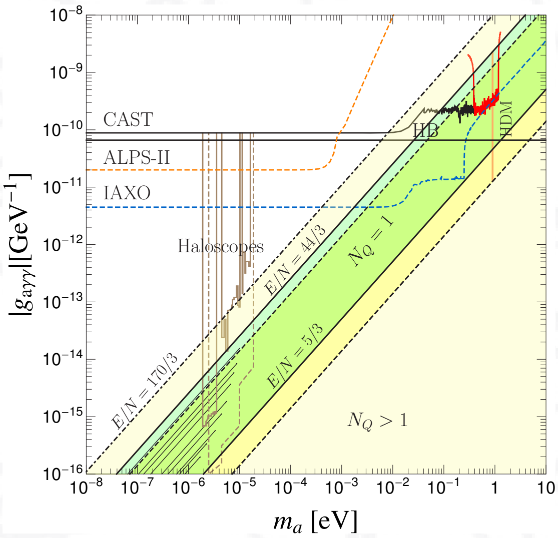



Figure 14 The window for preferred axion models (see text for more details). From Ref. [2].

References:
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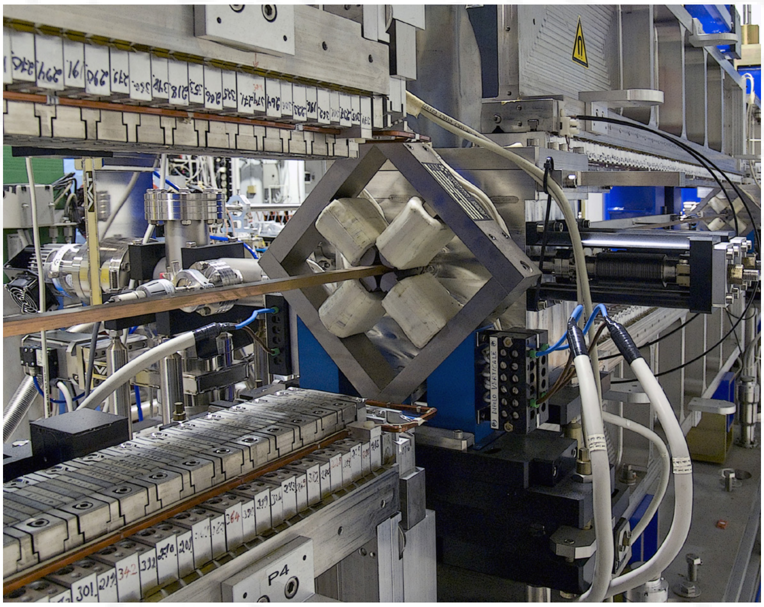
# Characterization of Active Plasma Lenses at SPARC_LAB



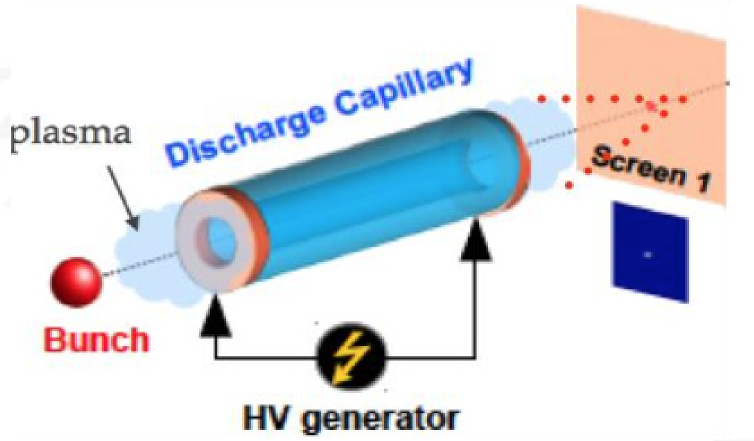



Figure 15 Layout of a set up to realize an active plasma lens within the SL_COMB experiment at the SPARC_LAB (see text for more details).

The Holy Grail of particle accelerator physics is nowadays represented by the possibility to use plasmas to accelerate and focus charged particles [1]. This will allow the building of new generations of compact machines that could reach higher energies in smaller spaces [2]. This ultimate goal still requires some efforts to guarantee high brightness, stability and reliability of the beams, but important steps forward have been already achieved.

At the SPARC_LAB test facility [3] is ongoing an experiment called SL_COMB that aims at accelerating high brightness electron beams by resonant plasma wakefields (PWFA) [4]. Within this experiment plasma based lenses [5] are under test, these innovative devices give the possibility to achieve focusing gradients of about kT/m, much stronger than conventional quadrupole magnets.

An active plasma lens is a current-carrying conductor transparent to the electron beam, realized shaping an arc inside a capillary [6]. The beam goes through the capillary filled with gas, while a current is flowing in it. Therefore, the bunch is focused by the azimuthal magnetic field generated by the discharge current, according to Ampére's law.

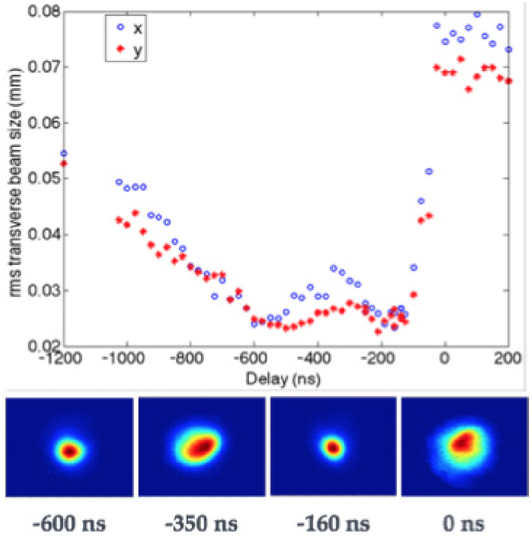



Figure 16 Transverse beam size evolution as a function of the delay of the bunch with respect to the discharge begin. At positive delays the discharge is off; -550 ns is when the discharge current produces a waist on the screen.

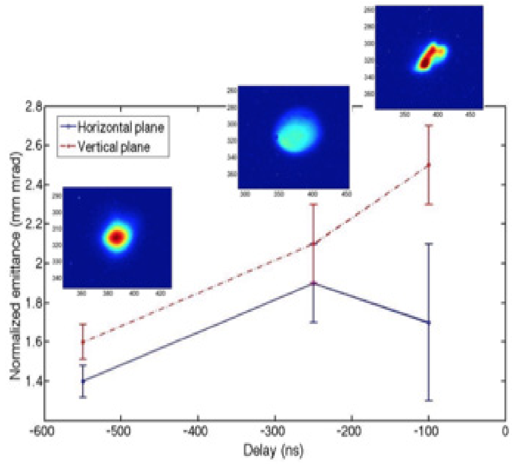



Figure 17 Beam emittance evolution as a function of the relative time of the discharge.

Fig. 15 illustrates the layout of the plasma lens setup at the SPARC_LAB test facility to focus the electron bunch produced by the high brightness photo-injector. This bunch has a charge of 50 pC, an energy spread of 50 keV at 126 MeV, 1 mm mrad normalized emittance and 1.1 ps rms duration. The capillary consists in a sapphire hollow tube of 1 mm diameter, 10 mm long, filled at 1 Hz rate by $H_2$ gas through a central inlet. Two electrodes, placed on each end of the capillary, are connected to a 20 kV generator producing up to 200 A peak discharge current.

The focusing field produced by the active plasma lens, strongly depends on the discharge dynamics along the capillary. The arrival time of the electron beam is scanned with respect to the discharge pulse in order to change the active plasma lens focusing as shown in Fig. 16. With the discharge turned off at 0 ns, the unperturbed beam has a spot size of 75 μm. Its normalized transverse projected emittance is $\varepsilon_{nr}$ = 0.95 mm mrad, measured by quadrupole scan on the last screen. By turning the discharge on (at delays less than 0 ns), the beam is focused down to 24 μm at -550 ns, but due to the nonlinear magnetic field in the capillary, its emittance becomes less than a factor of 2 larger, as shown in Fig. 17. Indeed, Fig. 17 reports the emittance evolution as function of the delay from the beginning of the discharge: at -550 ns delay the measured emittance is 1.4 mm mrad in the horizontal plane and 1.6 mm mrad in the vertical one. The estimated focusing gradient for this case is about 100 T/m.

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# INFN2016: States-General of nuclear physics took place at LNF


Figure 18 Poster of the meeting INFN2016.

The meeting Incontro Nazionale di Fisica Nucleare (INFN2016) is the third of a series of nuclear physics workshops, whose aim is to foster the interplay within theoretical and experimental activities in the field. The trigger, that initiated this tradition, came in 2011 by the understanding, within the Italian nuclear physics community, that stronger synergies among all researchers would have been necessary. Nowadays, the level of specialization is becoming extreme, and this implies that often it is hard to deeply understand or contribute to the work of the colleagues. The goal of this workshop is to cross-fertilize the field giving the community the possibility to show the progresses and the critical points of all the ongoing activities, and to launch new projects.

Special attentions are also given to the aspects that are borderline with other communities such as interdisciplinary applications. Nuclear physics has been for many years, not only a subject of fundamental research, but it has become a powerful tool for medical applications (i.e. medical imaging, radioactive tracers, particle therapies) cultural heritage studies, homeland security. The first two meetings of the series took place in Catania LNS in 2012, and in Padua in 2014, organized by the Padua and LNL colleagues. The 2016 edition moved away from the traditional sites of INFN devoted to nuclear physics studies, with the ultimate goal to widening the audience.

The topics addressed during these meetings, that are supported by all the national scientific commissions of INFN, foresee general review talks given by affirmed specialists, who depict the status of their sector, and since this edition, some focused presentations, given by young researchers.

The subjects addressed are:
· hadrons and quarks dynamics;
· phase transitions and quark-gluon plasma;
· nuclear structure and dynamics;
·nuclear astrophysics;
·interdisciplinary applications of nuclear physics.


Figure 19 Award of the three best young speakers.

The workshop that was held in Frascati over three days (14-16 November 2016) was attended by 131 participants. The spirit of these events is that the audience is actively involved during the discussions that accompany each session. Furthermore, in the afternoon of the third day, an open round table on the perspectives of the nuclear physics was organized. The directors of five INFN laboratories (Frascati, Gran Sasso, Legnaro, Catania and Trento) were lively debating the subject with the attendance.
"The organization of the event was though", said Alessandra Fantoni member of the Scientific Advisory Committee and chair of the local one. New rules for the public administration, that are also applied to the research field, impose a lot of paperwork. But conferences and workshops are an integral part of the research activity. Without a continuous exchange of ideas and a peer-review of each work, no results can be affirmed.

# LNF Outreach activities

The detection of signals of gravitational waves has been the fundamental discovery of the year 2016. Thanks to the measurements made with the twin LIGO interferometers, that were able to detect the gravitational waves produced by the collision of two black holes, the LIGO and Virgo scientific cooperation opened up a new window on the universe.
The Frascati National Laboratory has played a pioneering role in this type of research, hosting NAUTILUS one of the first-generation experiments that constituted the starting point for the development and construction of modern interferometers.
Most of the 2016 LNF outreach programs have been dedicated to this theme: seminars, public lectures, courses for students and teachers were organized for explaining the importance of this discovery of the international research community both inside LNF and at school.
Also the traditional open day of the laboratory to the general public has been centered on this subject. It has been titled OpenLabs2016 ...follow the wave! About 2500 visitors entered the site, participating to guided tours to the experimental sites, conferences and special programs for kids. High school teachers from all over Italy, could attend the XVI edition of Incontri di Fisica (IdF 2.0 – 2016), a refresher course on Modern Physics. This year the course presented a brand- new approach; the 200 enrolling teachers had the chance to choose between two different paths:
– the new IDF course 2.0, consisting of an e-learning package combined to the attendance at LNF;
– the traditional IDF course including only the attendance at LNF.
During the three days at LNF, the participants worked together with LNF staff: researchers, technologists and technicians.


Figure 20 Poster of the 2016 Open lab event.

68 high school students of 8 different nationalities attended for one week the 6th edition of INSPYRE 2016 (INternational School on modern PhYsics and Research). It consists in a full immersion in the modern and contemporary physics for younger in English language.
An important activity carried out in 2016, has been the restyling of LNF website which now shows new graphics, new contents and insights at http://w3.lnf.infn.it./
The LNF researchers regularly publish contents, both in Italian and English, to explain their experiments and technologies to the general public. A whole section of the website is dedicated to the rich event program, concerning both scientific research and science dissemination.
Special contents and press materials are constantly updated, with pictures, videos and useful links.


Figure 21 Picture of the participants to the INSPYRE 2016 edition.

| | Participants |
|---|---|
| Visits | 3000 |
| OpenLabs | 2000 |
| Seminars and Public Lectures (at the LNF and outside) | 3900 |
| European Researchers' Night | 450 |
| "Incontri di Fisica" for high school teachers | 200 |
| Stages for high school students | 411 |
| "Matinées di scienza" for high school students | 800 |

Table 1 Number of participants to the different events organized during at LNF 2016.

# LNF in numbers

The LNF personnel, at the end of 2016, consists of 326 units, including 57 with a fixed term contract, plus 226 associate members. Among these, there are university and PhD students, young post-Docs and employees from universities or other research institutions. Associate members work alongside staff members and likewise take part in the laboratory's activities. Tab. 2 shows the division of the LNF personnel among the different profiles.

| | Staff | Temp. | Tot. |
|---|---|---|---|
| Researchers | 74 | 9 | 83 |
| Engineers | 40 | 20 | 60 |
| Administrative employees | 31 | 10 | 41 |
| Technicians | 124 | 17 | 141 |
| Tot. | 269 | 57 | 326 |

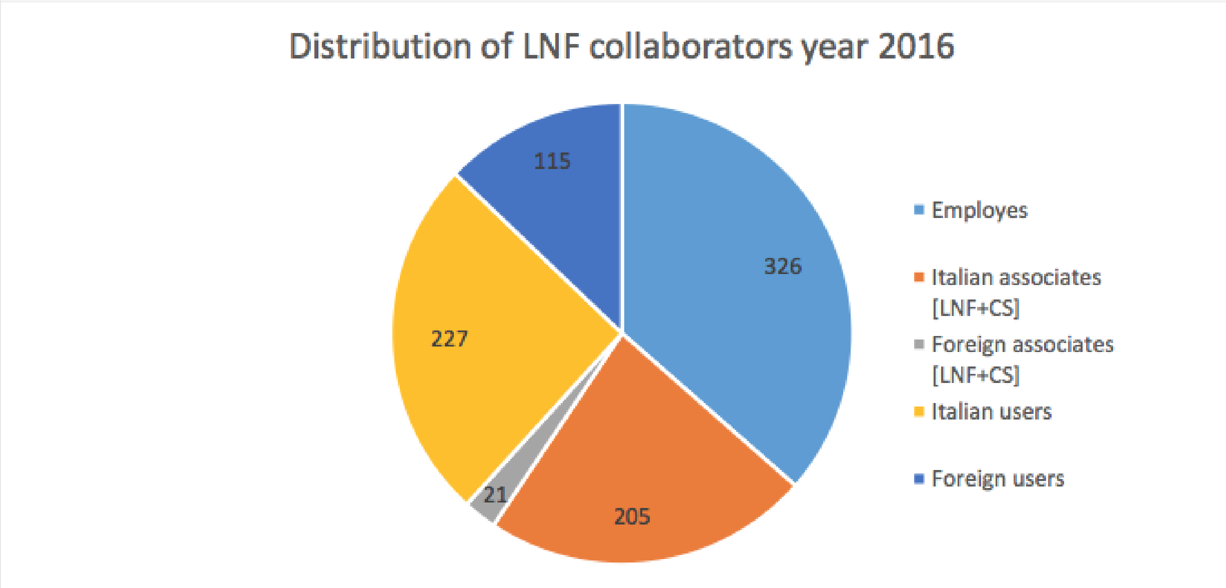


Table 2 LNF personnel at December 2016

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