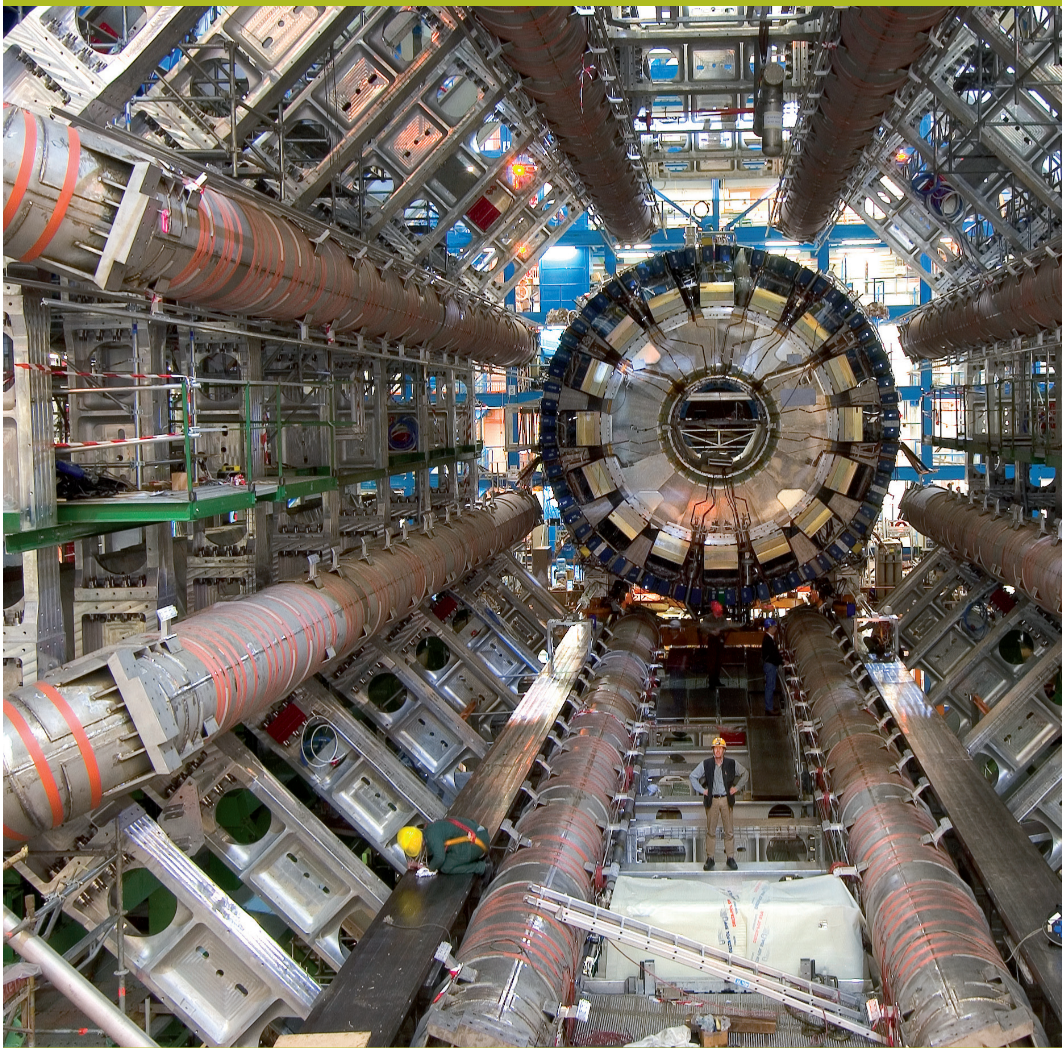
Particle physics division

Institute of research into the fundamental laws of the Universe

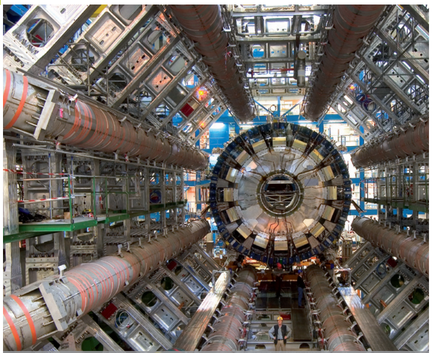


SPP report

2011-2013

Irfu

Preface



The eight supraconducting coils of the ATLAS toroidal magnet.

What amazing years! It is rare to see so much effort leading to extraordinary results in such a short time. Any particle physicist remembers July 4th, 2012. This day, at a special seminar at CERN, the ATLAS and CMS experiments announced the discovery of the Higgs boson. The 2013 Nobel Prize in physics attributed to Englert and Higgs rewarded the whole community. SPP physicists have contributed to this discovery as front-liners in the analyses but also in the technical effort, without forgetting the precursor works at the Tevatron. The discovery of the Higgs boson belongs to them all.

LHC is providing data to address a wide variety of physics topics. At SPP, two ERC junior grants support researches on the production of dibosons and on the precise measurement of the W boson mass and several physicists are strongly involved in top quark studies. The main purpose is testing the consistency of the Standard Model and searching for manifestations of new physics.

In light of the Higgs boson discovery, the development of the European strategy has been completed in May 2013. IN2P3-Irfu joint prospective, featured in Giens in April 2012, was an important contribution. The division was highly involved through these exercises, which provide guidance for programmatic priorities for the coming years. The pursuit of a significant interest in the LHC physics program is reflected by our contributions to detector upgrades. For the first phase, these include for the ATLAS experiment the construction of Micromegas detectors for the "New Small Wheels" – the muon forward detectors – as well as the upgrade of the calorimeter trigger system. For the second phase, the so-called high luminosity phase planned in the 2020s, the reflections in the two collaborations are underway. To prepare a more distant future, CERN will initiate preliminary studies for a 100 km hadron collider, VHE-LHC, with optional $e^+ e^-$ and e p collisions in the same tunnel.

Beyond LHC, the possibility of building ILC in Japan has sparked interest in the divison. The delivery of the TDR in June 2013 was an important milestone in the consolidation of R&D efforts. A participation of the division to the future ILD collaboration is currently considered. The decision to build ILC should be taken in the next 2-3 years.

In 2012, "La Recherche" magazine has awarded the prize for the best publication in physics to the T2K collaboration, for their observation of the appearance of electronic neutrinos in a muon neutrino beam, a first indication for a value of the θ_{13} mixing angle around 10°. This result was obtained with the data taken before the March 2011 earthquake. The management of this difficult period by our Japanese colleagues has been exemplary and data taking resumed in 2012. After being the first reactor experiment giving indications on the θ_{13} value, Double Chooz is progressing with the construction of the near laboratory. Although the accuracy of the Daya Bay final results cannot be reached, Double Chooz will be able to provide an independent measurement of θ_{13} with a 10% accuracy.

After the measurement of θ_{13}, the determination of the mass hierarchy and the search of a possible CP violation in the lepton sector remain major issues. Projects for long baseline experiments are under discussion and the European strategy explicitly mentioned a possible participation in experiments in Japan or the United States. At first, the SPP team contributes to the construction of a prototype liquid Argon detector at CERN, in following its participation in Laguna and Laguna-LBNO. The development of a "PMNS–fitter" software in collaboration with other laboratories comes along with technical projects.

This spring 2013, the Nucifer experiment observed its first neutrinos, a premiere in Saclay. Installed at the Osiris reactor in order to develop new tools for monitoring nuclear reactors within the frame of non-proliferation, Nucifer also has sensitivity to sterile neutrinos. Searching for such neutrinos is supported *as well by an ERC junior grant, which funds the preparation of an experiment based on a Cerium source.*

The advent of observational cosmology is continuing, as shown by the Nobel Prize in physics awarded in 2011 to Adam, Riess, and Perlmutter for the observation of the accelerating expansion of the Universe through type Ia supernovæ. The SNLS project has confirmed with a high accuracy these first observations and should present its final results within two years. A good example of synergy between cosmology and accelerator particle physics is the search for manifestations of scaler fields performed with the SNLS and CMS data.

In 2013, the Planck collaboration reached the era of precision measurements in cosmology with its results based on fifteen months of data taken since the satellite launch in 2009. Planck detected new galaxy clusters using the Sunyaev-Zel'dovich effect, a result which the SPP contributed to in collaboration with SAp and APC.

The emblematic result of cosmology in 2013 is the observation of the deceleration of the expansion of the Universe as it was 11 billion years ago. For this result the SPP team has received the award for the best publication in astrophysics by "La Recherche" magazine. This result was achieved by observing the effect of baryon acoustic oscillations (BAO) in the distribution of quasars observed by the BOSS experiment. The division's strategy in cosmology for the years to come is based on BAO as a probe, with participation at short term to the e-BOSS project and at longer term, with a data taking around 2020, to the DESI project.

Direct search for dark matter is going on with phase III of the EDELWEISS experiment, which is being installed in the Modane underground laboratory to achieve a better sensitivity than Xenon100. A particular emphasis is placed on the lower masses reachable with the use of HEMTs, low noise and high gain transistors. The present EDELWEISS setup also hosts some $ZnMoO_4$ crystals developed at CSNSM to study double beta decay. This is a possible axis for future use of bolometric techniques.

The inauguration of the new telescope, a 28 meter-high giant, was certainly a spectacular moment for the HESS collaboration. This new phase of the observatory, HESS 2, should lead to gamma astronomy observations with higher sensitivity and lower energy threshold. While analysing HESS data, the team prepares the community flagship project in gamma-ray astronomy, CTA. This is a global project, with a hundred telescopes of three different sizes on two different sites. SPP leads developments on technical solutions, being evaluated by the collaboration, for the medium size telescope camera and the mirrors.

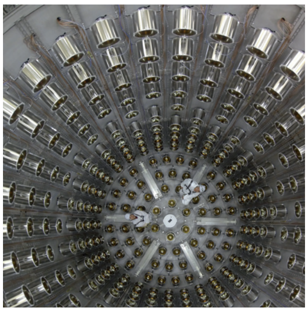
The development in Saclay of a positron source based on an electron accelerator allowed, the first time this year, producing of a positron beam with an intensity comparable to that from a radiation source. An accelerator based source shows potential benefits: an increased flexibility in handling the beam, a stable operation for years, and a simplified security management compared to an intense radioactive source. The GBAR experiment managed to store these positrons in a Penning trap and to cool them down with an electron plasma. This is an important milestone for this experiment which aims to be set up at CERN in 2016. The SPP group at the origin of project succeeded in building an international collaboration, supporting the experiment.

The development of the organometallic liquid calorimeter CaLIPSO is part of basic science societal spinoffs. Its primary purpose is for use in very high space and time resolution PET devices. A patent has been filed on this novel concept. Studies with an optical demonstrator helped to validate the concept and will be followed by the study of ionising properties with another demonstrator.

All these activities are carried out in a moving research landscape: the national budget issues that impact research organisations, the site policy implemented by the government and our positioning within the Paris-Saclay campus, the debate on our internal structuration related to the role of basic research at CEA. The discussions we have had on these issues were passionate, sometimes difficult, but show the particle physics division keen to find the means matching its ambitions.

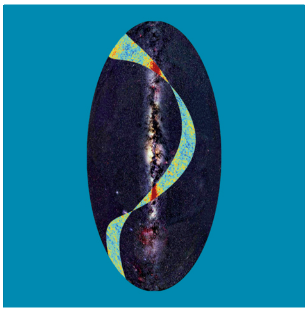
Ursula Bassler

Contents



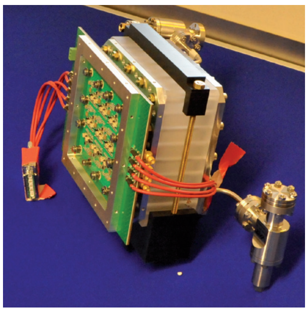
Fundamental laws of the Universe 7

- T2K 9
- DOUBLE CHOOZ 11
- GBAR 13
- DO 15
- CMS 17
- ATLAS 21
- ILC 25



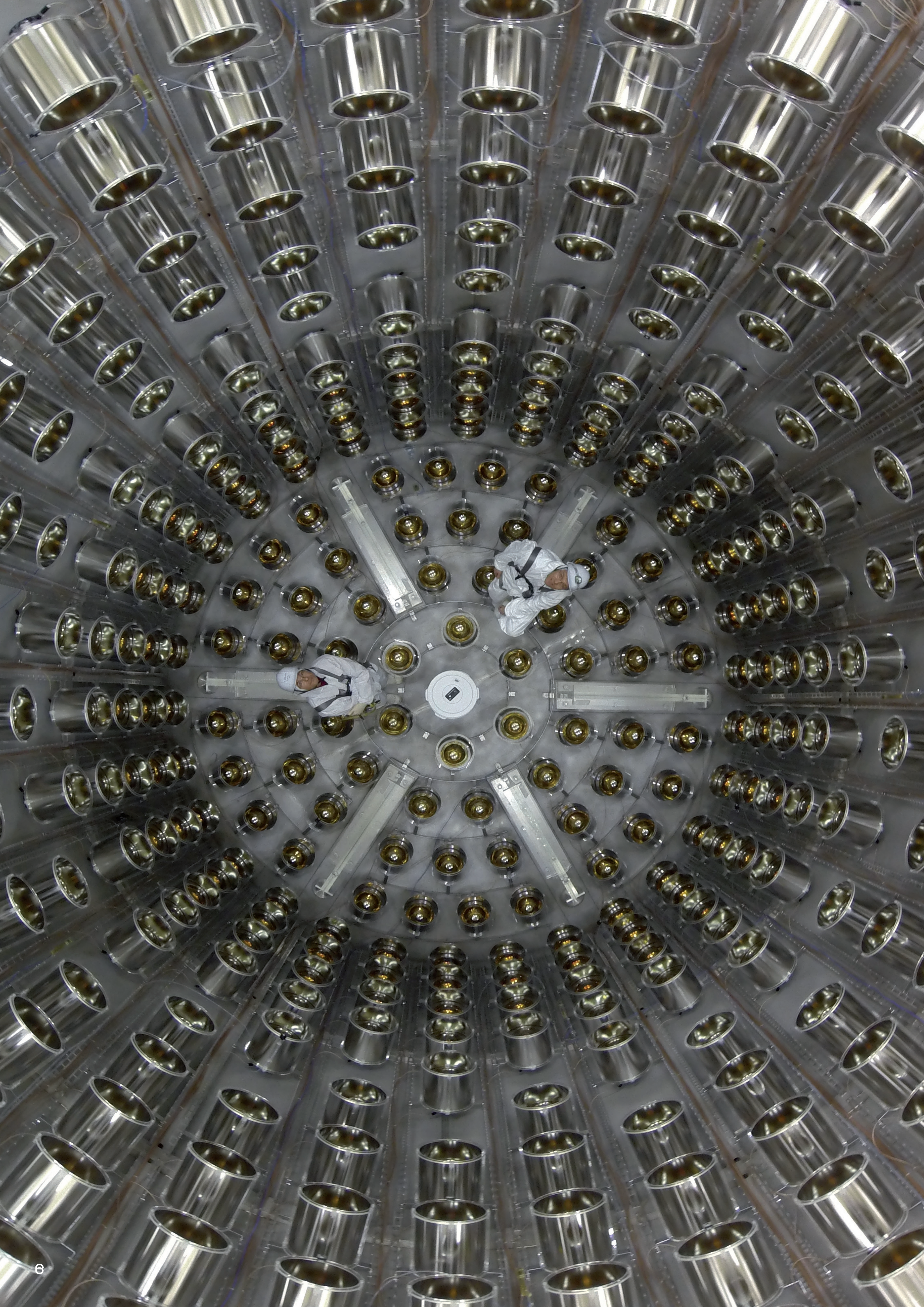
Content of the Universe 27

- COSMOLOGY 29
- EDELWEISS 31
- ANTARES AND KM3NET 33
- HESS AND CTA 35



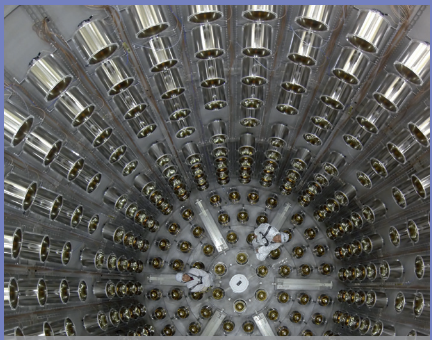
Applications 39

- CALIPSO 41
- NUCIFER 43



Fundamental laws of the Universe

- T2K
- DOUBLE CHOOZ
- GBAR
- D0
- CMS
- ATLAS
- ILC



Vessel and photomultipliers of the Double Chooz near detector.

The years 2011-2013 witnessed the triumph of the Standard Model of particle physics. This model developed since the 1960s coherently describes the elementary constituents of matter as well as the fundamental forces.

Indeed in 2012, the ATLAS and CMS experiments discovered a new particle, which shows, at the moment, all the properties of the Higgs boson predicted by the Standard Model. In 2013, the Nobel Prize in physics to Peter Higgs and François Englert rewarded this discovery. An evidence for this particle was also observed at the Tevatron in a complementary channel. In parallel, the Standard Model has been scrutinised by studies of electroweak bosons and of the top quark both at the Tevatron and at the LHC.

In the neutrino sector, the neutrino oscillation model was consolidated by the measurements of the mixing angle θ_{13} by the T2K and Double Chooz experiments, clearly establishing a non-zero value of this angle.

Despite all these successes, the story is not over. The study of the properties of the new discovered particle is of course a priority. In addition, search for signs of physics beyond the Standard Model is continuing looking, for instance, for supersymmetric Higgs bosons, new resonances at large mass or composite particles. The possible existence of a sterile neutrino to explain the anomaly in the antineutrino flux of nuclear reactions is also to be explored as an intriguing path, as well as the possibility of measuring the effect of gravity on antimatter.

The next steps in Standard Model understanding require new tools. Several developments are already going on in order to improve the LHC detectors for the high-luminosity phase or in order to build a future e^+e^- collider. In neutrino physics, new ideas are arising like measuring neutrino flux close to a radioactive source or studying the feasibility of new long baseline experiments.

Frédéric Déliot

T2K

The T2K collaboration studies neutrino oscillations with a beam produced at J-Parc and sent to Super Kamiokande. It has produced the first observation of muonic neutrino to electronic neutrino transition. Its main goals are to measure the θ_{13} mixing angle and to obtain information on CP violation in the leptonic sector.

Group meeting for the T2K experiment.

The T2K experiment

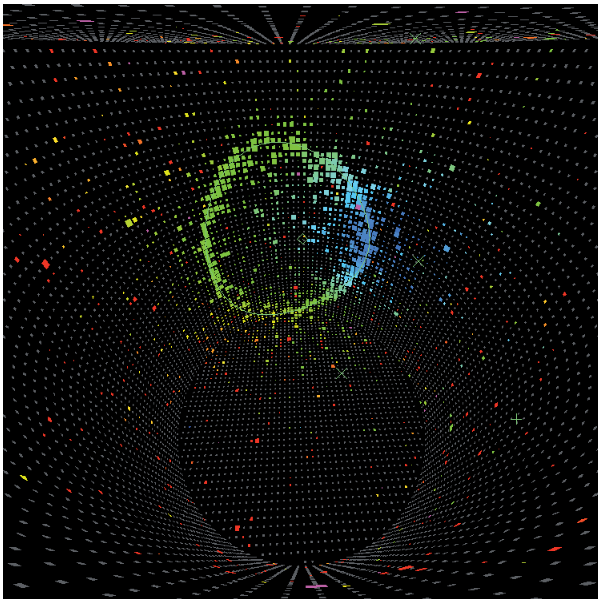
The T2K (Tokai to Kamioka) experiment, based in Japan, is an international collaboration, with a strong contribution from Europe (half of the 500 collaborators). It is a neutrino oscillation experiment measuring a muonic neutrino beam at short (280 m) and long distance (295 km). The J-Parc accelerator complex, based at Tokai near Tokyo, produces the beam which points to a near detector and the far detector, Super Kamiokande, a huge 50 kt water Cherenkov detector. The main goal of T2K is to measure the oscillation from muonic neutrinos into electronic neutrinos, dependent upon the θ_{13} mixing angle of the PMNS matrix proposed by Pontecorvo, Maki, Nakagawa, and Sakata to account for the difference between the neutrino flavour eigenstates and mass eigenstates. The appearance of electronic neutrinos also depends on CP violation in the leptonic sector. The study of muonic neutrino disappearance allows the precise measurement of the θ_{23} mixing angle and the Δm^2_{31} square mass difference.

The “accelerator neutrino” group from SPP has been active in T2K collaboration from the beginning. It strongly contributed to the design and construction of the TPC for the near detector, which played a central role in the physics analyses. We designed and tested the 72 Micromegas modules for this first large TPC instrumented with micro-pattern detectors with a total active area of 9 m^2. The Micromegas modules were made with the “bulk Micromegas” technology, which provides robust and large detectors. Each detector, covering an area of 35 x 36 cm^2, contains 1726 pads, 6.9 x 9.7 mm^2, and can reach gains of 10^4 with an energy resolution of 9% for a deposit of 5.9 keV. Besides Irfu has designed and produced all the front-end electronics, equipped with the AFTER chip specially designed for this use.

Results and perspectives

T2K data taking started in December 2009. A data sample corresponding to 6.63×10^{20} protons on target has been recorded as of summer 2013. That corresponds to several tens of thousands neutrino interactions at the near detector and several hundreds at the far detector. The experiment presented in July 2011 its first results, which showed strong evidence for a non-null θ_{13} angle. In 2013, the collaboration announced that the statistical significance of this signal exceeded seven standard deviations. This is the first clear observation of the appearance of neutrinos with a different kind than the one originally produced. This corresponds to a sample of 28 events which are compatible with an electronic neutrino hypothesis in Super Kamiokande while the expected background for a null θ_{13} is 4.64 events.

Combining a precise measurement of θ_{13} by the reactor experiments with T2K data will enable to constraint the CP violation parameter in the leptonic sector. In 2013, T2K also showed by studying the disapearance of ν_μ that the mixing angle θ_{23} is compatible with the maximum value, i.e. $\pi/4$, which suggests the existence of a symmetry between ν_μ and ν_τ. T2K data taking will start again in the beginning of 2014 with the goal to accumulate 8×10^{21} protons on target until the end of the decade.

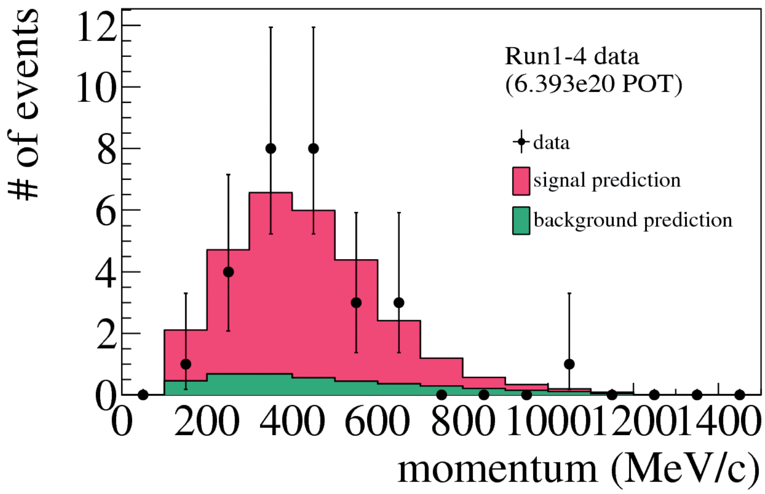


ν_e *candidate seen by the Super Kamiokande detector.*

LBNO

Along with these activities in T2K, the group is strongly involved in the definition of the European strategy for the next generation of long baseline experiments, whose goals are to determine the neutrino mass hierarchy and study CP violation in the leptonic sector. We are active within the LAGUNA-LBNO design study, financed by the FP7 European programme, which studies an underground laboratory for neutrino physics and astrophysics, in combination with a new beam from CERN. We are also part of the WA105 experiment, for the construction of a large liquid argon TPC prototype, scheduled at CERN in 2014-2018. In this framework we pursue R&D to optimise a Micromegas detector for the charge readout with amplification in pure argon. ■

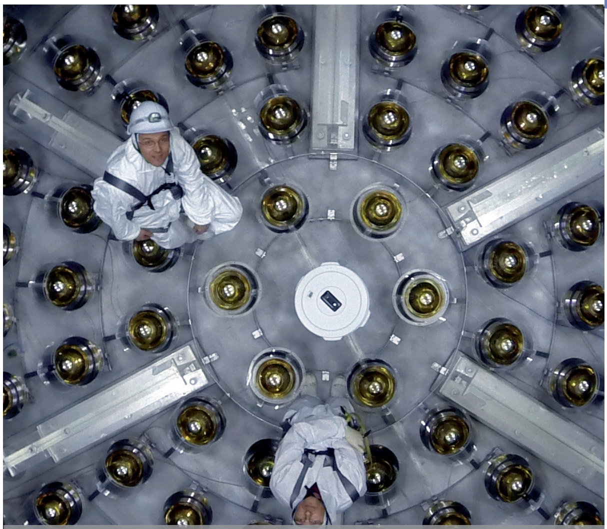
Marco Zito, Olivier Bésida, Sara Bolognesi,
Sandrine Emery, Edoardo Mazzucato, Georges Vasseur



Momentum distribution of ν_e *candidates selected with Super Kamiokande. The green histogram shows the prediction for the background, i.e. for* $\sin^2(2\theta_{13}) = 0$*, the pink one for a value of* $\sin^2(2\theta_{13}) = 0.150$*, which corresponds to the best fit to the data.*

DOUBLE CHOOZ

The Double Chooz experiment, in the French Ardennes, has contributed to the recent demonstration of a new mode of neutrino oscillation and helps to measure precisely the θ_{13} mixing angle. Moreover, the re-analysis of neutrino experiments around nuclear reactors by the Irfu group revives the hypothesis of a fourth type of neutrino.

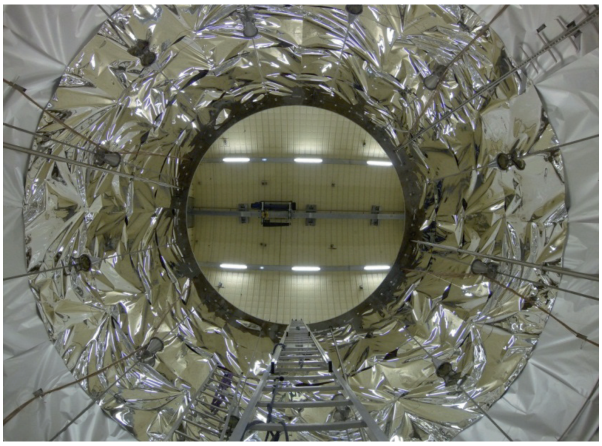


At the bottom of the tank of the Double Chooz near detector.

Neutrinos are neutral elementary particles, which the Standard Model described in three different species. Because of their weak interactions, matter is virtually transparent to them. Their main feature is the ability to transform from one species to another. These oscillations are described by three "mixing angles", including the θ_{13} parameter whose measurement is the main objective of the Double Chooz experiment.

Double Chooz

The Double Chooz experiment will consist of two identical detectors, conceptually conceived largely by the SPP. The first one, located 1 km away from the nuclear reactors, was built between 2008 and 2011 under the technical coordination of Irfu. It has taken data since 2011. The detector target contains 10 m^3 of liquid scintillator to identify the interaction of electronic antineutrinos (denoted "neutrinos" in the following) by their capture on gadolinium nuclei generating electron-neutron pairs. The target is observed by 390 photomultipliers, immersed in a high-purity oil, which translate the interactions into electronic signals.



Construction of the near detector for the Double Chooz experiment.

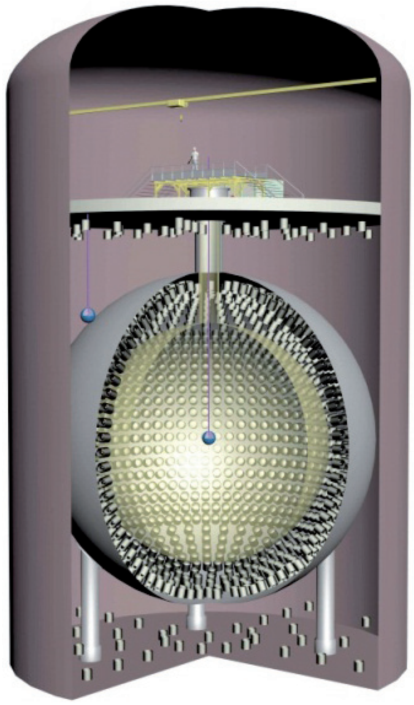
The comparison between the number of neutrinos measured by the detector at 1 km of the reactors and the expected flux allowed observing, for the first time with a reactor, neutrino disappearance interpreted as a new type of oscillation. In 2011, the first analysis allowed to obtain a value of $\sin^2(2\theta_{13}) = 0.109 \pm 0.030$ (stat) $\pm$ 0.025 (sys). Moreover, thanks to the low background rate, the identification of the interactions not signed by gadolinium has expanded the fiducial volume by a factor of three to provide an independent measurement of $\sin^2(2\theta_{13})$ increasing the significance of the first result. These results were strengthened by unambiguous measurements of the backgrounds, which are sources of systematic errors limiting the accuracy of the measurement, when the two Chooz nuclear reactors are shut down for maintenance. In addition, the Double Chooz experiment conducted the first test of Lorentz invariance with a source of reactor neutrinos. A second detector is being assembled in a new cavity excavated on the site of Chooz, 400 m away from the cores. This new detector will come into operation in 2014. This is the comparison between the results of the two detectors which will improve the precision on $\sin^2(2\theta_{13})$ to eventually reach 10%. SPP plays a significant role in the experiment. In addition to proposing the original idea in 2002, the division is involved in the construction of acrylic vessels constituting the heart of the detector and vessels supporting the photomultipliers, as well as measuring the number of target protons with an accuracy of 0.2 %. It is also in charge of the qualification of materials and the analysis coordination for the entire collaboration (until 2011).

Reactor anomaly

In 2011, our group of physicists from SPhN and SPP published surprising results on the flux of antineutrinos produced by fission of uranium and plutonium in nuclear reactors. Using a better estimate of this flux, a shift of 3.5 % compared to predictions which had been the reference for 25 years has been found. If one interprets with this new flux the results of neutrino oscillation experiments performed so far at reactors, then it reveals a significant "anomaly" in all past measurements. The lack of measured antineutrinos almost reaches 7 % since the revision of the theoretical flux reinforces the effect of a slight deficit in all measurements. The explanation for this anomaly may result in the existence of a new particle, a "sterile" neutrino. This fourth neutrino which would be sensitive only to gravitation would be added to the bestiary of the Standard Model of particle physics. Its existence would also have cosmological consequences that must be confronted with observations.

The irrefutable verification of the existence of this new particle will pass through measurements of neutrino flux at less than ten meters from a source of radioactive nature. Two projects have been proposed by Irfu to decide on the existence of a new oscillation at short distance: the Stereo experiment, 10 m away from the ILL nuclear reactor, and the CeLAND experiment using a source of antineutrinos (cerium-144) deployed near a large liquid scintillator detector.

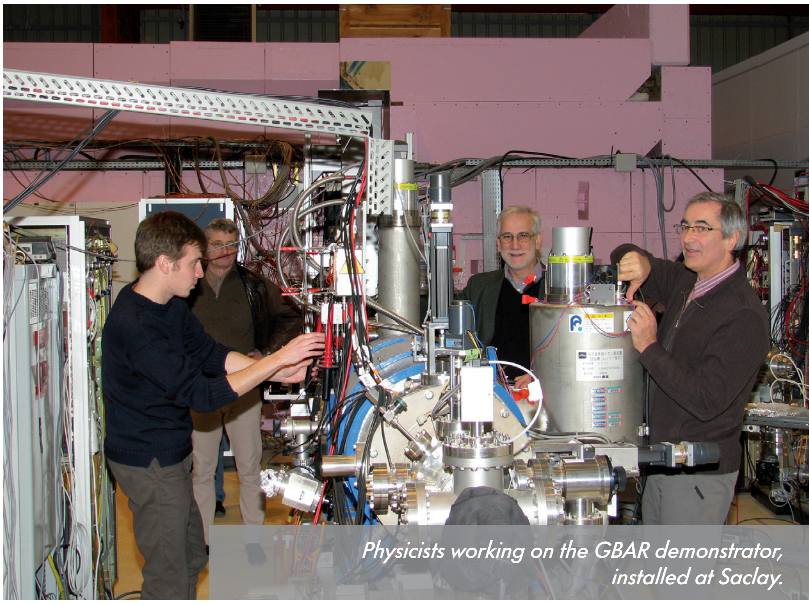
Through the Double Chooz, Nucifer, Stereo, and CeLAND experiments, and in line with the Gallex experiment, the work conducted by the Irfu group rethinks the nuclear fuel cycle through neutrinos. ■



^{144}Ce-^{144}Pr source of antineutrinos deployed in a big liquid scintillator detector, such as KamLAND or Borexino.

Thierry Lasserre, Michel Cribier, Guillaume Mention, Jean-Luc Sida, Matthieu Vivier

GBAR



Physicists working on the GBAR demonstrator, installed at Saclay.

Although Einstein's equivalence principle has never been directly verified with antimatter, the recent trapping of antihydrogen atoms at CERN shows that such an experiment is becoming increasingly feasible. Such a test is important since the standard cosmological model makes use of unknown ingredients, dark matter and dark energy, in order to explain an increased gravity and an acceleration of Universe's expansion. The requirement of these components could be a hint that our understanding of gravitation is incomplete; alternate theories have been proposed that predict antimatter may behave gravitationally differently to matter, hence the importance of such a test.

Principle

The GBAR experiment, initiated at Irfu, will measure the gravitational acceleration imparted to a free falling antihydrogen atom in the Earth's gravitational field. The primary difficulty of such an experiment lies in the cooling of antihydrogen atoms, which are produced at keV kinetic energies, and are required to be just a few tens of nano-eV for the measurement to be performed. To overcome this problem, the GBAR collaboration aims to create of an intermediary state, the $\overline{H}^+$ ion, made with one antiproton ($\overline{p}$) and two positrons (e^+). These ions can be prepared such that their thermal energy corresponds to speeds of the order of one meter per second, an achievement impossible to obtain with neutral atoms. These ultra-cold ions are then stripped of their excess positron leaving ultra-cold neutral atoms. The production of antihydrogen ions will be done using a positronium target (Ps, e^+ e^- bound state) through successive reactions:

$$\overline{p} + Ps \rightarrow \overline{H} + e^-, \text{ followed by } \overline{H} + Ps \rightarrow \overline{H}^+ + e^-.$$

The antiprotons will be provided by the Antiproton Decelerator (AD) at CERN, supplemented by a new ring under construction, ELENA.

View of the positron line at Saclay outside of the linac bunker (in pink). The positron trap is visible at the end of the line to the left (in blue).

Positron Production

The production of the $\overline{H}^+$ ion requires the production of a very dense cloud of positronium. This cloud is achieved by sending an intense positron pulse on a nano-porous substrate. The design and development of such a positron source was undertaken at Saclay using a test facility based on an electrons linear accelerator (linac).

In this facility, positrons are produced through the interaction of an intense electron beam, provided by a compact 4.3 MeV linac, with a tungsten target. Positrons then proceed through a "moderation" phase which re-emits them at a few eV energy. This positron source, dubbed SOPHI, began to operate in 2011.

This source has been supplemented by a positron transport line, which splits to guide positrons either into a trap where they are stored or to a spectrometer where the positronium production is studied. This source is now operational and provides 3×10^6 e^+/s with a good stability and reliability condition. A study of industrialisation of such a facility is underway, as a start-up project, POSITHOT.

Positronium production

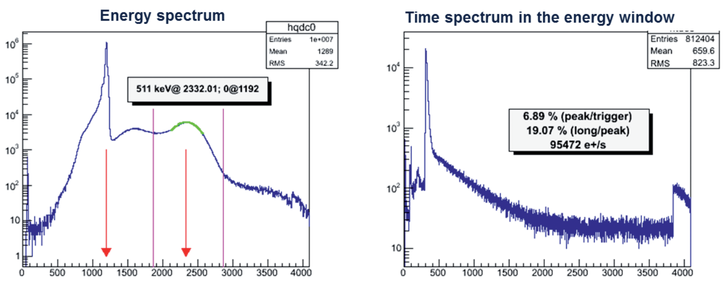
Characterisation of substrates, for positronium production, began on a positron beam of ETH Zurich and continues now with the Saclay positrons line. A spectrometer was developed using BGO crystals for this purpose and is now operational. The positronium annihilation time spectrum indicates the creation of ortho-positronium.

Positron trapping

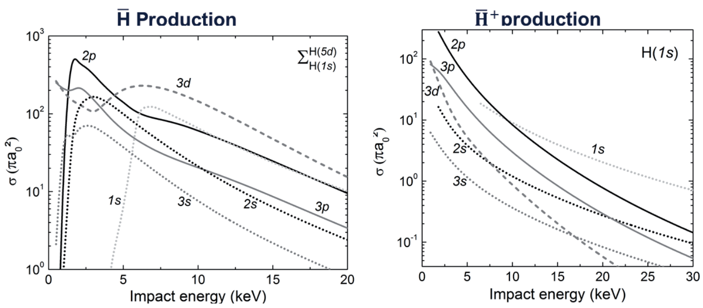
In order to achieve the required positronium density, it is necessary to accumulate and trap the positrons during the 110 s period separating each bunch of antiprotons provided by the CERN ELENA ring. The Multi-Ring Trap (MRT) created by the Atomic Physics Laboratory of RIKEN, near Tokyo, is a Penning-Malmberg trap which has been transported to Saclay and connected to the positron beam line and used to store large numbers of positrons. The device must be synchronised to the frequency of the linac (200 Hz) in order to let a bunch of positrons enter but prevent them from exiting by raising a trapping potential. Once captured, the cloud of positrons interacts with an electron plasma and loses energy before the arrival of the following pulse, allowing the trapping potential to be lowered for a subsequent cloud. In 2013 the first evidence of this accumulation process was obtained. This new and innovative trapping method should allow the capture of the record number of positrons required for the experiment. The first results on positron accumulation have been the subject of a thesis.

Antihydrogen production

Calculations show that the cross sections for production of antihydrogen and of $\overline{H}^+$ ion are greatly increased when the positronium is in an excited state and the aim is to produce one of these states in the experiment to increase the number of ions produced. Theoretical calculations have been made at Irfu (thesis pending) in collaboration with the IPCMS (Strasbourg) using new methods of approximation. A laser for the excitation of the positronium clouds to the 3d state is under development at the Kastler-Brossel Laboratory (ENS-Paris 6).



Results obtained with the spectrometer. On the left, energy spectrum of gamma rays; right, time spectrum for gamma rays selected in a window around 511 keV, showing a production of ortho-positronium.



Calculated cross section values for production of antihydrogen atoms and of $\overline{H}^+$ ions versus antiproton incident energy, for different excitation states of the positronium target.

Progress of the project

In the period between 2011 and 2013 a number of important steps have occurred. The GBAR experiment was approved by Cern (May 2012), and an international collaboration, with in France CSNSM, the Kastler-Brossel Laboratory, the Institut de Physique et Chimie des Matériaux (Strasbourg), and the Laue-Langevin Institute (Grenoble) was formed. The Collaboration includes 50 members from 15 institutes.

At Saclay, the positron source was commissioned and connected to the Penning-Malmberg trap. Trapping procedures and studies of converters for the production of positronium are underway. Laser excitation studies should begin in 2014. The installation at CERN will start in 2015; the first tests are planned in 2016, in line with the commissioning of the ELENA Antiproton Decelerator ring. The first antiprotons beams are planned for 2017. ■

Patrice Perez, Pascal Debu, Yves Sacquin, Bertrand Vallage

DO

The D0 experiment is one of the two experiments located at the Tevatron at Fermilab near Chicago. The Tevatron has completed its data taking on September 30th 2011 and provided a luminosity of the order of 12 fb^{-1}. Between 2011 and 2013, the highlights of the D0 experiment concern the search for the Standard Model Higgs boson, top quark and W boson physics. The Tevatron has been able to show an indication for a Higgs boson produced in association with a W or Z boson and decaying into a pair of b-quarks. The combination of D0 and CDF allows to reach an accuracy of less than 1 GeV (0.5%) on the top quark mass measurement and to obtain the current world most accurate measurement of the mass of the W boson, i.e. 15 MeV.

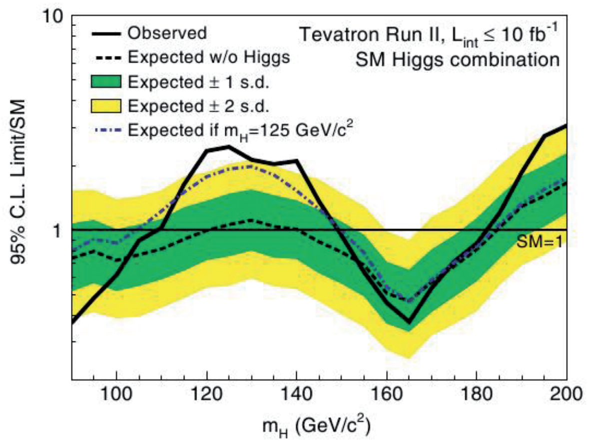
Discussion between two physicists from the D0 group.

Between 2011 and 2013, the D0 group of SPP has been in charge of several technical projects such as: τ leptons identification, reconstruction algorithms concerning the liquid argon calorimeter, and the global comparison of data and simulation for D0. The group has also been deeply involved in data analyses. Between 2011 and 2013, it has been involved, on the one hand, in the search for Higgs bosons either the Standard Model one or those of its supersymmetric extensions as well as on the top quark physics in the dilepton channels on the other hand. Between 2011 and 2013, the D0 collaboration published more than 110 articles. In addition to their contributions and the 18 publications specific to the D0 group of SPP, the group members also benefited from more than 20 talks in conferences and workshops.

Higgs boson physics

The D0 group of SPP led the search for supersymmetric Higgs bosons produced in association with one or two b-quarks and decaying into two τ leptons, one of which further decaying into a muon (and two neutrinos) and the other decaying hadronically. The results have been interpreted in the framework of the MSSM and allowed to exclude a large domain of the parameter space. The combination of the searches for supersymmetric Higgs bosons in all the production and decay channels explored by D0 has also been performed by the D0 group of SPP and interpreted in the framework of the MSSM.

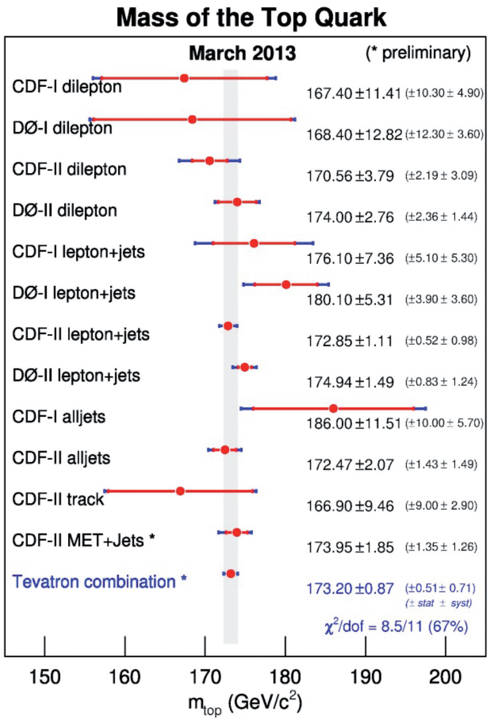
The group also led the search for Standard Model Higgs boson in the two τ leptons channel as well as the two W bosons channel where the two W bosons decay leptonically. These searches allowed the exclusion of mass domains for the Standard Model Higgs boson. They have been included in the final combination of all channels explored by D0 and in the combination with CDF. The search performed in the WW channel in the ee final state has been extended to search for anomalous quartic couplings WW$\gamma\gamma$ thus allowing constraining the coupling parameters in a competitive way with the results from the LHC. These searches concern three theses and the contribution of one post-doc. They all have published between 2011 and 2013.



Search for the Standard Model Higgs boson at the Tevatron.

Top quark physics

In 2011-2013, the D0 group of SPP has extended its commitment in the physics of top quark pair production and dilepton final states. The group performed the measurement of the production cross section extending it to include up to half of the data sample. It contributed to the cross section measurement in the lepton+jet channel. It participated to the combination of the measurement performed in all the channels as well as the combination with CDF. The group continued its very strong and leading contribution in measuring the top quark mass with the matrix element method and has been strongly involved in the combination of measurements in other channels and with CDF. The mass measurement concerned one thesis and benefited from the contribution of one post-doc. The D0 group of SPP has further extended its commitment in top quark physics with the measurement of the ratio of two top quark branching ratios, of spin correlations and forward backward asymmetries. This spin correlation measurement combined with the one performed in the lepton+jets channels allowed to give evidence for spin correlation for the first time. This work benefited from the contribution of one post-doc. The ratio measurement concerned one thesis. Finally the asymmetry measurement concern two theses and benefited from the contribution of a visitor from LPT Orsay.



Summary of the top quark mass measurements at the Tevatron.

Responsabilities

The D0 group of SPP has been in charge of the top quark physics group of D0 since 2008, the sub-group on top quark pair production (2009-2011), and the Higgs boson physics group of D0 since 2011. The Higgs boson and top quark physics groups merged in 2013 and the convenorship is ensured by two members of the D0 group of the SPP. The D0 group of the SPP also ensured the convenorship of the V+jets physics group (2008-2011) as well as the lepton identification group since 2007. The D0 group of SPP is involved in the Tevatron combination group for top quark physics. In addition several members are in charge of various general (data quality control software, authorship Committee). Finally several members of the group were in charge and involved in various D0 Editorial Boards (EB) i.e. Higgs, top, new physics, luminosity. These EB were involved in more than 10 publications of the D0 collaboration between 2011 and 2013. ■

Marc Besançon, Ursula Bassler, Fabrice Couderc, Frédéric Deliot, Christophe Royon, Viatcheslav Sharyy, Maxim Titov, Boris Tuchming, Didier Vilanova

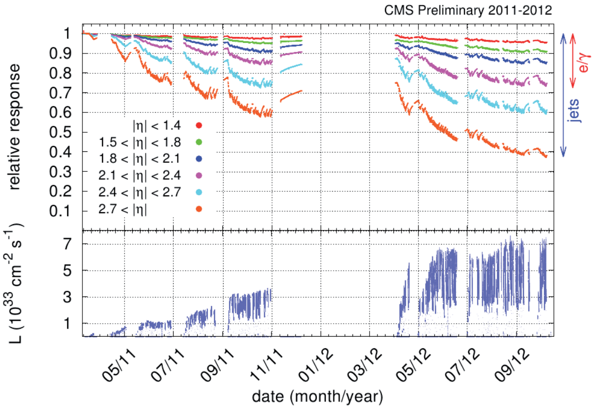
CMS

The objective of the CMS experiment is to exploit the discovery potential of the LHC by running a multi-purpose detector which has been designed to obtain physics results of the highest scientific quality.

Control room of the CMS experiment at CERN.

The Compact Muon Solenoid (CMS) collaboration

The CMS collaboration involves more than 2500 physicists and engineers from more than 180 laboratories in 43 countries. The high performance compact detector is built around a superconducting solenoid magnet, 13 meters in length and 6 meters in diameter, designed in collaboration with the SACM. In the central part of the solenoid, where a uniform magnetic field of an unprecedented intensity of 3.8 Tesla is present, a silicon tracker, electromagnetic and hadronic calorimeters have been installed. The return coil, consisting of 11,000 tons of steel, is equipped with a set of muons chambers.



Top: evolution of the crystal transparency of the CMS electromagnetic calorimeter in 2011 and 2012, as measured by the laser monitoring system developed at Saclay. Bottom: LHC luminosity during the same period.

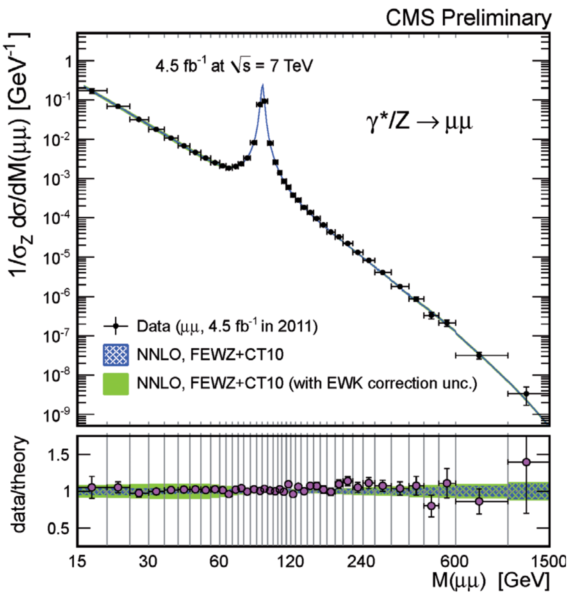
After the incident at the LHC in 2008, during the first commissioning, and one year off to make necessary repairs, data taking began in late 2010 with collisions at 7 TeV in the centre of mass. The collaboration recorded 35 pb^{-1} that year. In 2011, 4.4 fb^{-1} have been recorded and finally, in 2012, 21.8 fb^{-1} of 8 TeV collisions have been added. In 2013, the machine was stopped to allow a consolidation of magnets in order to achieve the nominal energy of 13 TeV when restarting in 2015.

Knowledge and calibration of the detector

The Saclay group has been present from the very beginning of the collaboration in the design and the optimisation of CMS and very active in the construction of the detector, mainly in the electromagnetic calorimeter (ECAL). It contributes to the proper functioning of the experiment through tasks of general interest and also participates in the studies necessary to define the necessary upgrades for the HL- LHC.

From 2011 to 2013, the group was heavily invested in the understanding and the calibration of the ECAL. Outstanding performances of this calorimeter are essential to the discovery of a Higgs boson with a mass below 140 GeV in its decay into two photons since the signal to noise ratio for this mode is low (~ 1/20 at 120 GeV). These performances are closely related to the stability of the detector response, itself dependent on the proper functioning of the monitoring system of the transparency of the crystals, for which the group is responsible. The response of each ECAL crystal is measured continuously by injecting a calibrated laser light and used to calculate the corrections to be applied to the measurements of the energy of incident particles.

The group also participates in the analysis of π^0 and η events recorded at a rate of a few kilohertz through a parallel DAQ line and analysed immediately on the online farm of CMS. These massive data allow, on the one hand, the calorimeter calibration, and on the other hand, the online tracking of the crystal transparency losses and the validation of the energy corrections determined by our group. A physicist from the SPP is convener in CMS of the group responsible for the optimisation of the performance of the detector (DPG).



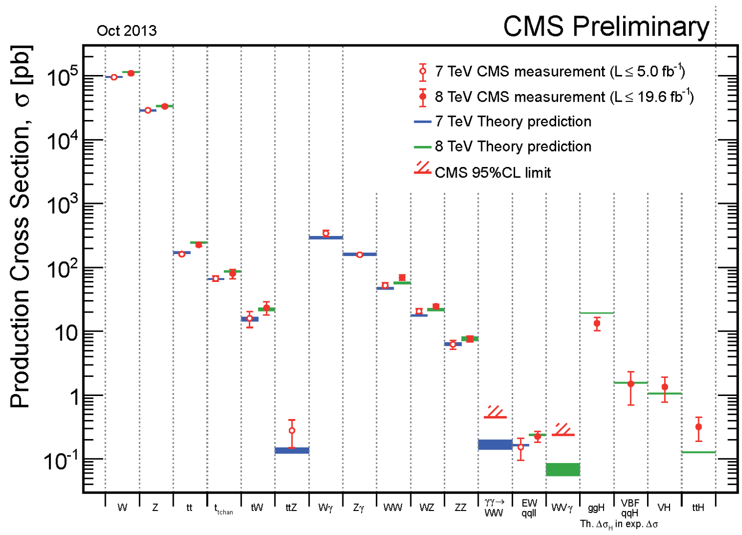
Mass spectrum of muon pairs between 15 GeV and 1500 GeV. The CMS data (black dots with error bars) are compared to a theoretical prediction (blue curve).

Physics analysis

The physics analyses conducted in the group are organised in three main areas: the electroweak physics and multiple production of gauge bosons, the search for the Higgs boson decays into two photons, and the search for the Higgs boson decays into two τ leptons.

Standard Model study

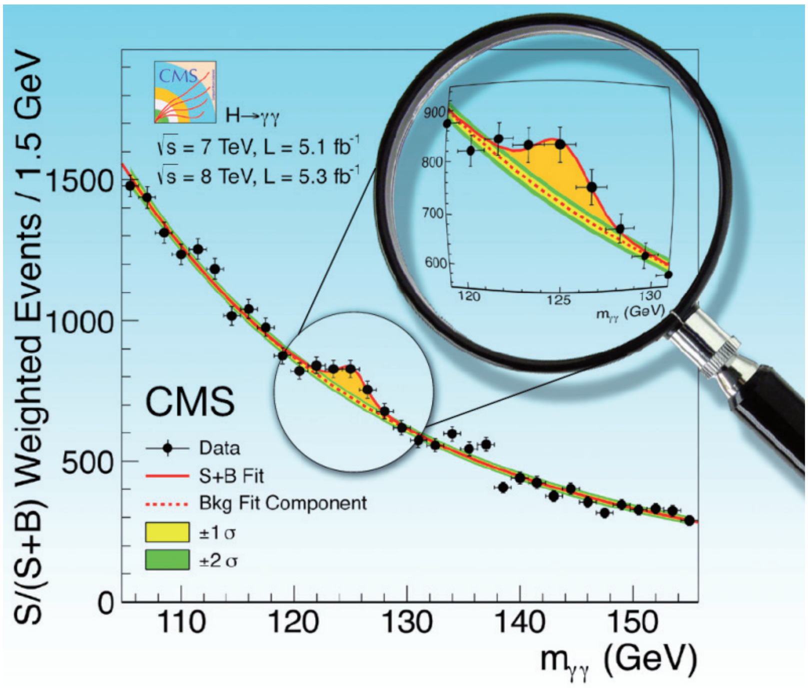
From 2010 to 2013, the LHC has provided the CMS experiment with about 30 million of Z bosons and ten times more W bosons in leptonic channels (electron or muon). These samples have been exploited to produce electroweak precision measurements which are direct tests of the Standard Model. A member of our group was responsible for the gauge bosons physics in CMS between 2010 and 2013.



Summary of the production cross sections measured by CMS in the domain of electroweak physics, top quark, and Higgs boson. CMS measurements (red dots with error bars) are compared with theoretical predictions (blue and green lines).

The data recorded at low luminosity in 2010 at 7 TeV were used to measure accurately the cross sections of inclusive production of W and Z bosons, as well as differential cross sections, charge asymmetries, polarisation of bosons, the mass spectrum between 15 and 1500 GeV and forward-backward asymmetry in the di-lepton events (Drell - Yan) and a measurement of the Weinberg mixing angle.

The data recorded at higher luminosity at 7 TeV in 2011 gave access to rare production processes of multiple gauge bosons that allow to test the predictions of the Standard Model in the gauge sector, and in particular the intensity of direct interactions between bosons. These measurements can provide constraints on anomalous contributions (i.e. due to new physics) to three gauge bosons couplings.



Mass spectrum of photon pairs selected in the search for the Higgs boson, which was used for the announcement of the discovery of the particle in July 2012.

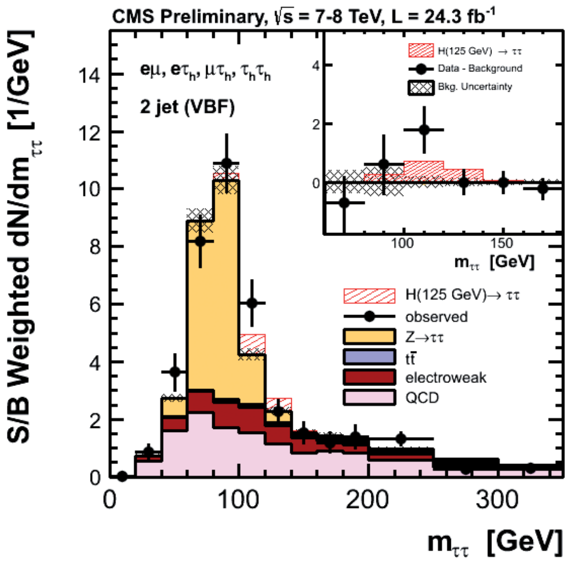
The study of the production of multiple gauge bosons, γγ, Wγ, Zγ, WW, WZ, and ZZ, is essential to control the electroweak background in the search for new particles, including the Higgs boson. A student in our group measured the differential cross sections of the production of pairs of isolated photons using the 2010 data. Another student wrote his thesis on the measurement of ZZ production where one Z decays into a pair of leptons (electrons or muons) and the other in a pair of neutrinos, based on a portion of data recorded in 2011.

Search for the Higgs boson decays in two photons

One of the key analyses of CMS for the first three years of data taking was the search for the Higgs boson in the decay into two photons. Despite having a low branching ratio, this channel is interesting because it allows the extraction of a clear signature in case of presence of signal (narrow peak in the invariant mass distribution of two photons). This analysis is ideally linked to activity of the calorimeter calibration for which the group is responsible. Indeed, the important ingredients for this analysis are: reduction and knowledge of the di-photon background and optimisation of the resolution of the measurement of the photon energy. In addition to working on the optimisation of the resolution of the ECAL, the group was strongly involved in the development and the optimisation of the algorithms of this analysis, which ended in July 2012 with the announcement of the discovery of a new particle with a mass of 125 GeV by CMS. This particle has all the characteristics of the Higgs boson. The distribution of the invariant mass of two photons in CMS, alone, can highlight an excess of events at 3 standard deviations. Coupled with the study of the decays in two Z bosons, CMS was able to announce a discovery with 5 standard deviations in July 2012.

Search for the Higgs boson decays in two τ leptons

The CMS group in SPP was also involved in the search for the Higgs boson of the Standard Model as well as its supersymmetric extensions (SUSY) in the process of disintegration into two τ leptons with one decaying into a muon or electron (and two neutrinos) and the other in hadronic channels. This search requires excellent reconstruction of τ leptons in hadronic decays and a good understanding of the production of gauge bosons Z decaying into τ lepton pair which represents the main physical background. Concerning the search for SUSY Higgs bosons with data from the LHC at 7 TeV, results have been interpreted within the MSSM and allowed to exclude a large area of the parameter space. The search for SUSY Higgs bosons in this decay channel was



Mass spectrum of the τ lepton pairs selected in the search for the Higgs boson. A significant excess (3 standard deviations) is compatible with the presence of a Higgs boson at 125 GeV.

continued with data from the LHC at 8 TeV. Concerning the search for the Standard Model Higgs boson, the SPP physicists contributed to the preliminary observation of an excess of events over a wide range of invariant mass with data at 7 and 8 TeV with an observed local significance of 2.93 σ for a Higgs boson mass of 120 GeV, compatible with the presence of a Higgs boson with a mass of 125 GeV. Searches of Higgs bosons in decay channels with τ leptons permitted two theses as well as the contribution of a post- doc.

Marc Dejardin, Marc Besançon, Fabrice Couderc, Daniel Denegri, Bernard Fabbro, Jean-Louis Faure, Federico Ferri, Serguei Ganjour, Alain Givernaud, Gautier Hamel de Monchenault, Patrick Jarry, Elisabeth Locci, Julie Malclès, André Rosowsky, Maxim Titov

ATLAS

For the ATLAS collaboration, which runs a detector installed at the LHC at CERN, the years 2011 to 2013 have been marked by the analysis of the data taken from the proton-proton collisions at 7 TeV centre of mass energy in 2010 and 2011 and at 8 TeV in 2012. The high point has been the announcement on the 4th of July 2012 of the discovery of a particle, the measurable characteristics of which are compatible with the ones of the Higgs boson, keystone of the Standard Model of particle physics, which has been predicted more than 45 years ago and intensely sought-after since then. During this period, the ATLAS group of the SPP took an active part in this discovery, as well as in other searches leading to precise tests of the Standard Model.

Part of the SPP group on the ATLAS experiment.

The ATLAS experiment

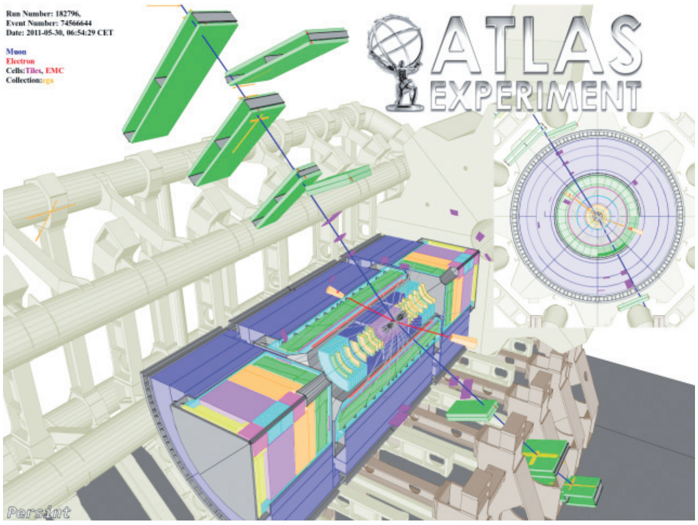
The ATLAS collaboration gathers about 3000 physicists from 174 laboratories of 38 countries. It aims at making the most of the discovery potential of the LHC operating at the nominal energy of 14 TeV in the centre of mass of the proton-proton collision with an instantaneous luminosity which will reach progressively 10^{34} cm^{-2} s^{-1}. The Saclay group has contributed from the start to the design of the ATLAS detector and took important responsibilities in the construction and the commissioning of the electromagnetic calorimeter and of the muon spectrometer. It also made significant contributions to the development of software programs for events reconstruction and to the preparation of physics analyses.

Data taking in 2011 and 2012

After the technical hitch caused by faulty junctions between superconducting magnets in September 2008, the LHC has worked at a centre of mass energy of 7 TeV in 2010 and 2011, and 8 TeV in 2012. The progresses in luminosity have been much faster than expected. They have allowed, as early as the end of 2011, to accumulate enough data to provide the first hints of the production of a particle decaying in the channels $\gamma\gamma$ (photon-photon) and ZZ with rates compatible with those expected for the production and decay of the Higgs boson of the Standard Model. In 2012, the instantaneous luminosity of the LHC reached 7.7x10^{33} cm^{-2}s^{-1}, already close to the nominal value. A member of the Irfu group is co-convener of the group in charge of the measurement of the luminosity at the ATLAS interaction point, which is essential for the measurement of production cross-sections of various final states.

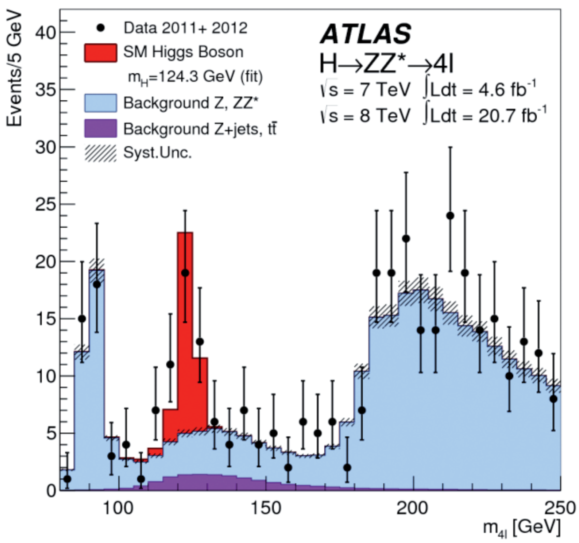
Higgs boson discovery

Benefiting from its competences in the muon and electron reconstruction that have been developed over many years, the Irfu group has been very active in the search of the Higgs boson in the decay channel into two Z bosons, each of them decaying into a $\mu^+\mu^-$ or e^+e^- pair. In particular, the Irfu group devoted itself to the determination of the level of some backgrounds originating from Standard Model phenomena leading to a final state with four charged leptons, like the associated



Display (using the PERSINT software developed at Irfu) of an event from the 2011 data set, which is a candidate for being a Higgs boson decaying into two Z bosons, one Z decaying into a muon-antimuon pair ($\mu^- \mu^+$) and the other Z decaying into an electron-positron pair ($e^- e^+$). The invariant mass of the four leptons is about 125 GeV.

production of a Z boson and a $b\bar{b}$ quark-antiquark pair decaying in semileptonic mode. It also set out to study measurement biases like the one coming from the possible radiation of a photon by one of the muons from the Z decays. The historic announcement of the discovery of a particle with characteristics compatible with those of the Higgs boson in term of production and decay rates in the modes $\gamma\gamma$ and ZZ took place on the 4th of July 2012 at CERN. Since then, with the increase of integrated luminosity, the significance of the signal has increased for these channels whereas news decay modes became accessible. This allowed the confirmation, within the experimental errors, that the couplings of the Higgs boson with a Standard Model particle are proportional to the mass of this particle. The Irfu group also contributed to the analysis of the tensor properties (spin/parity) of this newly discovered particle, rejecting with a probability in excess of 95.5% the possibility that this particle has spin 1 or 2. All the measurements done so far tend to confirm that this particle is indeed a Higgs boson with properties very close to the ones predicted by the Standard Model.



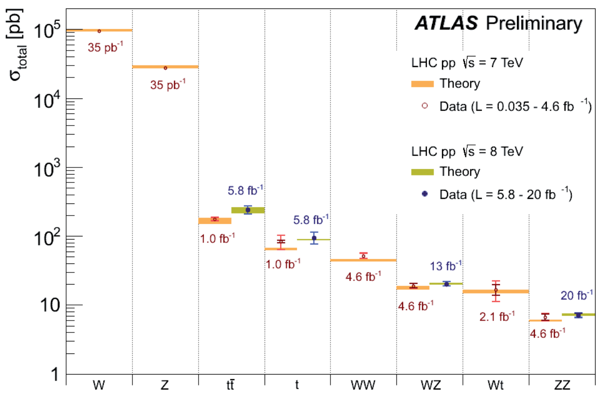
Distribution of the invariant mass of the four charged leptons for the events selected by the analysis searching for final states with two Z bosons. The black points correspond to the 2011 and 2012 data. The histogram in blue corresponds to the expected background from Standard Model phenomena (except Higgs boson). The one in red corresponds to the expected signal from a Standard Model Higgs boson with a mass of 125 GeV.

Standard Model tests

At the same time as the search for the Higgs boson, the Irfu group has contributed very significantly to the measurements of several production cross-sections for final states containing one or several gauge bosons (W, Z, or γ), or a pair of top-antitop quarks. These measurements lead to tests of the theoretical predictions of the Standard Model and possibly to signs of new physics in case of disagreement. In particular, the ATLAS Irfu group has performed a systematic study of final states with two gauge bosons which has provided limits on the possible deviations of the values of triple gauge couplings with respect to the Standard Model predictions.

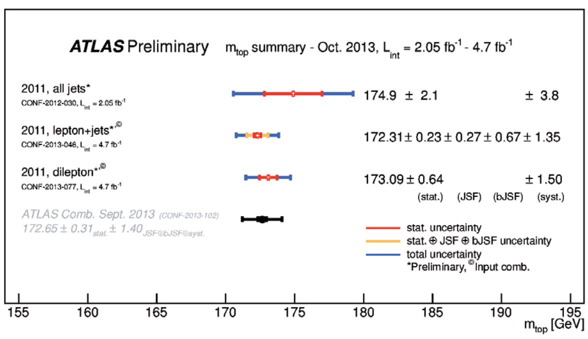
One of the group's objectives is also the very precise measurement of the W boson mass m_W, which will provide a powerful test of the Standard Model consistency when it is connected with other precise measurements like the ones of the top mass and the Higgs boson mass. In order to achieve a better precision level than the one reached by the Tevatron experiments at Fermilab, it is mandatory to control the gauge bosons production processes. Specific studies have been pursued in 2011-2013 along these lines, waiting for the first m_W measurements at the LHC expected in 2014.

Another team of the ATLAS Irfu group put itself into the studies of the top quark properties. The value of the top quark coupling to the Higgs boson, close to 1, tends



Summary of several measurements of production cross-section of Standard Model particles (or pair of particles) in proton-proton collisions at 7 TeV (and at 8 TeV for $t\bar{t}$, WZ, and ZZ productions) centre of mass energy. The measured values are compared to the theoretical predictions. The integrated luminosity used for each measurement is indicated.

to indicate that it probably plays a special role in the phenomena of spontaneous electroweak symmetry breaking. In particular, the precise measurement of its mass with the LHC data is complementary to the one obtained at the Tevatron, with a similar precision (and possibly better with the 2012 data) and different systematic uncertainties. Another research theme of the top group is the study of the production asymmetry in rapidity between top and antitop. The Tevatron experiments have reported the observation of such an asymmetry. A confirmation of this anomaly would be a sign of new physics beyond the Standard Model.



Top quark mass measurements performed in different types of decay channels, classified according to the number of charged leptons (muons or electrons) in the final state. The final measurement combines the data from the three channels. The dominant systematic errors come from the uncertainties on the jet energy calibration (JSF) and from the calibration of jets from b quarks (bJSF).

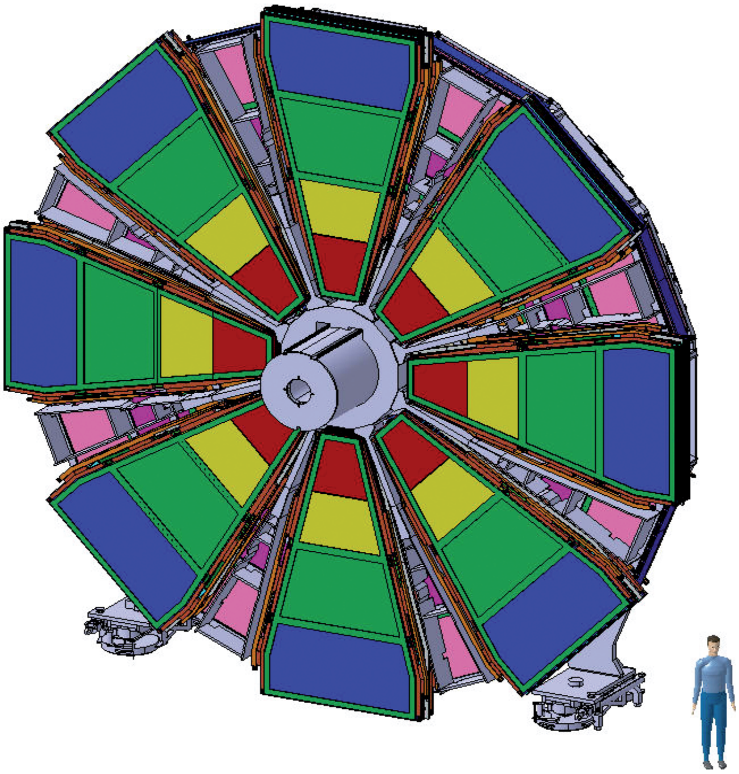
Direct search for physics beyond the Standard Model

This type of search is complementary to precise Standard Model tests, which only provide indications on the possible presence of new physics at a higher energy scale. The ATLAS Irfu group has been involved in the search for heavy resonances (beyond 1 TeV) decaying into two charged leptons. Such resonances are predicted by Grand Unification Theories and by models with additional space dimensions. It also looked for “exotic” partners of the top quark, with an electric charge of 5/3, and more generally for non-chiral heavy quarks (called “vector like”), predicted by composite Higgs models. It also contributed to the search of a possible decay of the Higgs boson into invisible particles, with no interaction with the matter of the detector, which may provide a candidate for the dark matter of the Universe. None of these searches has so far led to a significant signal of new particles beyond the Standard Model. Nevertheless, these studies have allowed setting limits on the mass and the production cross-section of these particles if they exist. The group is eagerly waiting for the data at 13 TeV in 2015 to possibly find such particles or to improve these limits.

Upgrade of the ATLAS detector

In order to improve the precision in the study of the Higgs boson properties and the discovery potential of new physics beyond the Standard Model, it is necessary to significantly increase the luminosity of the LHC, which is foreseen with a first phase in 2018 and a second one around 2023 (HL-LHC project). The detectors will have to be upgraded in order to cope with these new conditions, with pile-up in excess of 150 collisions per beam crossing. This will affect in particular the trigger systems based on the presence of high energy electrons or muons.

The Irfu group is involved in the upgrade program of the muon spectrometer, which aims at replacing the chambers of the first layer of the forward part (“small wheel” located upstream of the end-cap toroid) by detectors of the Micromegas (MM) type. Irfu has been the instigator and developer of this technology for many years. The choice by the ATLAS collaboration of this type of chamber in 2012 is largely a consequence of the work of the Irfu physicists to convince their peers that it is particularity well suited to the harsh conditions expected at the HL-LHC and that it will be possible to build large areas at an acceptable cost. Irfu will be in charge of the construction of about one quarter of the MM chambers of these New Small Wheels. The group is also involved in the development and the production of a new electronic chip to improve the quality of the first level of the electromagnetic calorimeter trigger. This study, performed in collaboration with the LAL at Orsay, makes use of the Irfu competence in analogical electronics and is in line with its involvement in the ATLAS calorimeter trigger system at the time of the ATLAS construction. At last, let us mention the studies of the Irfu group on the development of electronics chips for the readout of very fast (<10 ps) detectors, located closed to the beam at about 200 m from the interaction point. These detectors are intended to tag the passage of elastically scattered (without being destroyed) protons, which occur in so-called “diffractive” phenomena that are going to be studied in the regime of the very high LHC energies. ■

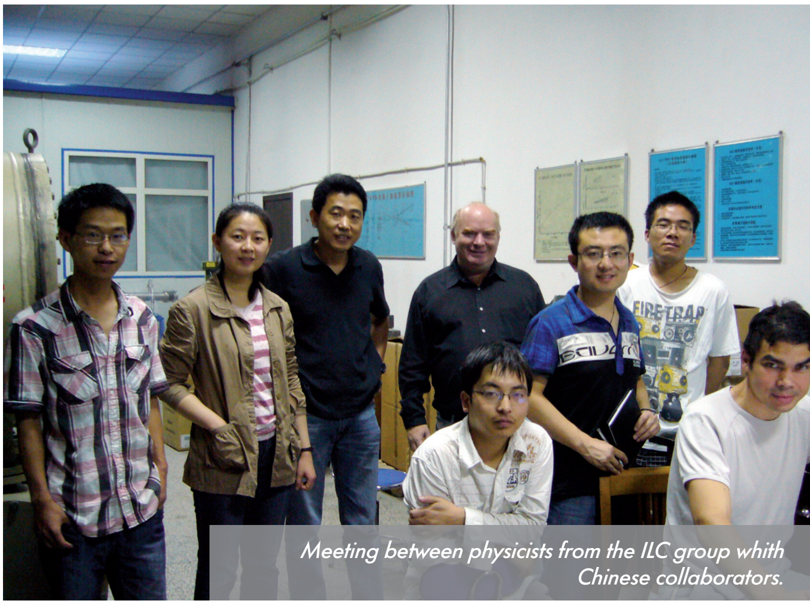


General view of one of the two « New Small Wheels» which make up the first layer of chambers for the measurement of the particles momenta in the forward part of the muon spectrometer. Irfu is responsible for the construction of Micromegas type detectors covering the lower half (at small radius) of each of the eight sectors.

Claude Guyot, Henri Bachacou, Florian Bauer, Nathalie Besson, Maarten Boonekamp, Laurent Chevalier, Frédéric Deliot, Jean Ernwein, Anne-Isabelle Etienvre, Pierre-François Giraud, Samira Hassani, Gertraud Kozanecki, Witold Kozanecki, Eric Lançon, Jean-François Laporte, Bruno Mansoulié, Jean-Pierre Meyer, Rodanthi Nikolaidou, Ahmimed Ouraou, Christophe Royon, Laurent Schoeffel, Philippe Schune, Philippe Schwenling, Jérome Schwindling

ILC

Studies conducted at Irfu for a future detector on ILC, $e^+ e^-$ international linear collider, focus on the development of a TPC.

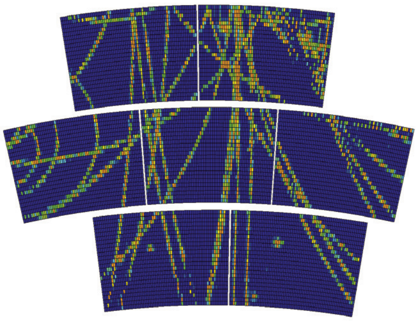


Meeting between physicists from the ILC group whith Chinese collaborators.

TPC R&D

The years 2000-2007 were devoted to the proof of principle and understanding of the operation of the Micromegas TPC. During the years 2008-2010, beam tests have been made using a large prototype. They have led to develop a charge-spreading technique to bring the resolution to 60 microns by pad row, with 3 mm wide pads.

The next step in the period 2011-2013 was to test a multi-module prototype. The T2K experiment electronics had to be miniaturised to fit in the small place assigned to a module, and thus be able to cover the endplate of the TPC with detectors, by completing all seven slots. This multi-module prototype beam study was the subject of a thesis. It allowed distortions to be studied, due to inhomogeneities of fields (edges of modules, edges of the magnet, …). The mitigation and correction of these distortions will be subject of a new thesis.



A cosmic shower seen in the detector.

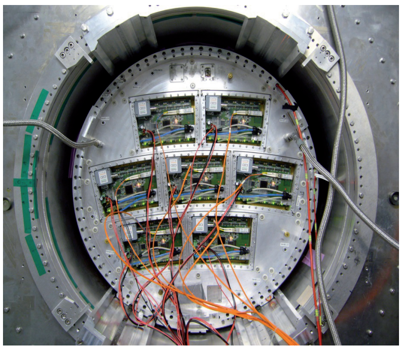
Another way is still under study: the digital TPC, in which each ionisation electron is reconstructed with efficiency close to 100% and positioned on a canvas with 55 micron pitch. Devices with eight adjacent chips (two rows of four) have been studied in beam and are the subject of a thesis.

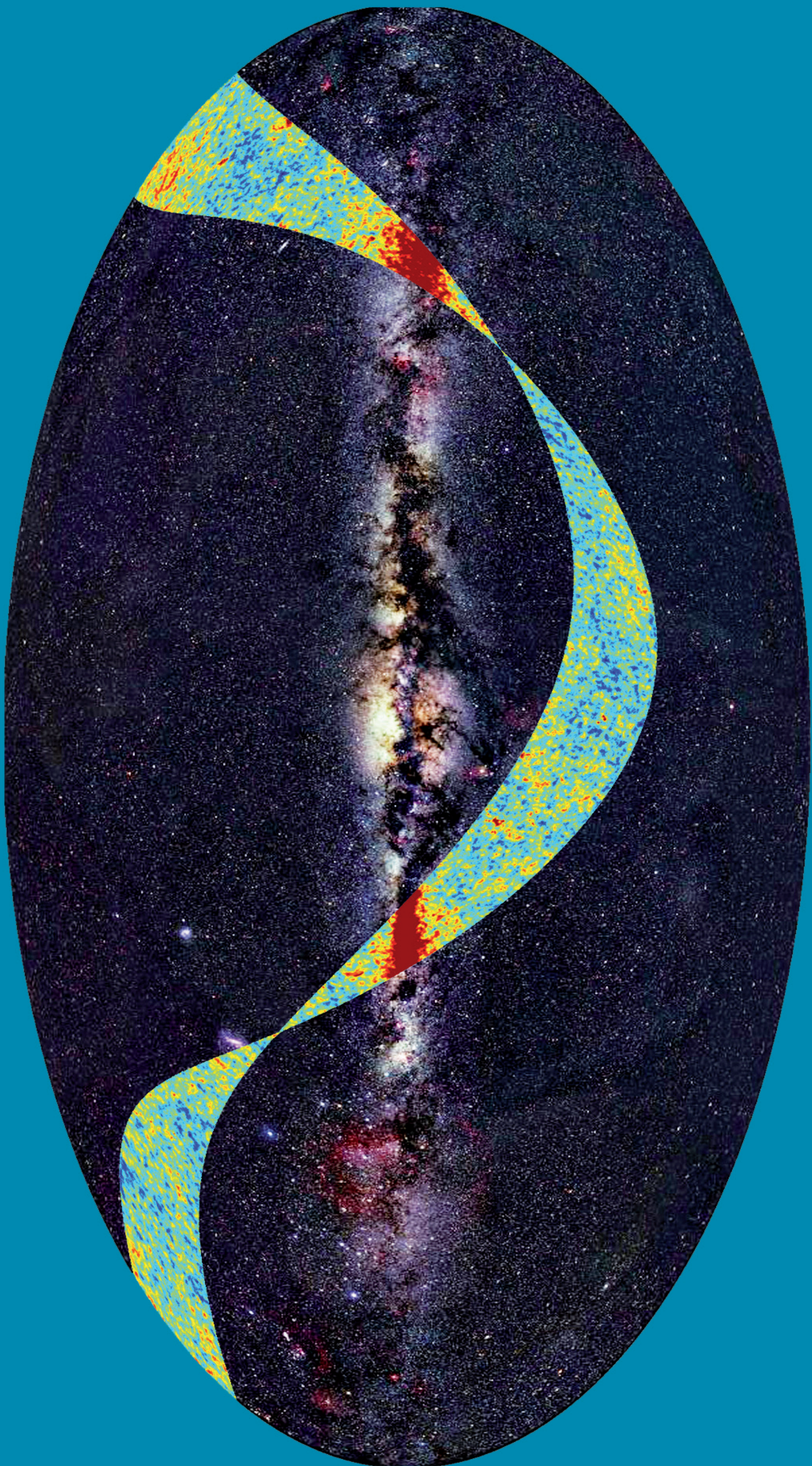
International context

In this period happened the discovery of the Higgs boson with a mass of 125 GeV. Although expected, this discovery has brought back to the forefront the construction of a $e^+ e^-$ collider in a range of energy beginning at 250 GeV. The high energy physics community in Japan, supported by a significant part of the political class, supports the construction of such a machine in this country. Our group has reacted strongly to this historic opportunity to build finally this machine and its detectors by undertaking a reflection on the physics potential of such a machine, revised according to the results of the LHC and direct dark matter searches, and through late 2013 information and prospective days. The “physics analysis” parts of the theses being prepared concern possible manifestations of dark matter at the ILC. In addition, the TPC offers the possibility of measurements without reference to a model of the couplings of the Higgs, in view of comparison with the Standard Model.

Paul Colas, Marc Besançon, Maxim Titov

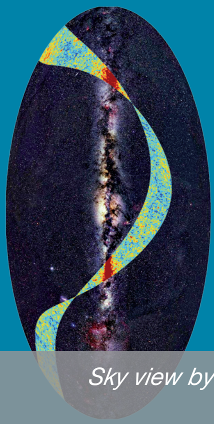
The TPC equipped with its seven fully integrated modules.





Content of the Universe

- COSMOLOGY
- EDELWEISS
- ANTARES AND KM3NET
- HESS AND CTA



Sky view by Planck.

The standard model of cosmology is a great success. It allows a coherent description of the origin and evolution of the expanding universe from a denser and hotter phase in the past. Nevertheless the model raises two major questions of contemporary physics: the nature of dark matter and dark energy. At the interface of particle physics and cosmology developed astroparticle physics which emerged about a century ago with the discovery of cosmic rays. High-energy cosmic phenomena are examined through detectors initially designed for particle colliders to unveil the origin of cosmic rays. The particle physics division plays a significant role within international collaborations in the experiments seeking to answer to these questions.

Universe is a unique laboratory to test fundamental physics, from gravity at large scale to laws of microscopic physics. The two infinites are scrutinised, from the infinitesimal large with cosmological probes for dark energy to the infinitesimal small with searches for dark matter particles predicted in extensions of the Standard Model of particle physics and actively hunted at LHC.

The cosmic messengers, high-energy neutrinos and photons, testify of the most violent phenomena in the Universe and are unique probes to reveal the origin of cosmic rays. Despite the absence of cosmic neutrino sources to date, ANTARES is accumulating neutrinos. HESS is continuing its harvest of results and provides the most detailed view of the Galactic Centre in high-energy gamma-ray astronomy.

WIMPs colliding on germanium nuclei are searched in the EDELWEISS experiment with bolometric detectors in the underground laboratory of Modane. These bolometers are employed for axion searches showing their flexibility for rare event searches. Dark matter particles captured in astrophysical objects may annihilate producing high energy photons actively hunted by the HESS experiment towards the Galactic Centre region, dwarf galaxies, and galaxy clusters. Axion-like particles are also tracked via the detection of distant active galactic nuclei with HESS.

The years 2011-2013 witnessed the first set of Planck results, the commissioning of the EDELWEISS phase 3, the start-up of HESS phase 2 and the successful preparatory phase of CTA. The detection of galaxy clusters with Planck allows the determination of the cosmological parameters and the deceleration of the expansion of the primordial universe has been observed through distance of galaxies as standard ruler with the BOSS experiment. High accuracy cosmological observations (CMB, SNIa, BAO, structure growth) are now faced to models of modified gravity.

Emmanuel Moulin

COSMOLOGY

Impressive results were obtained by the SPP cosmology group on both the expansion of the Universe and the formation of structures. Probes encompassed distant type Ia supernovae, baryonic acoustic oscillations observed for the first time in intergalactic hydrogen clouds, and galaxy clusters detected by the Planck satellite.

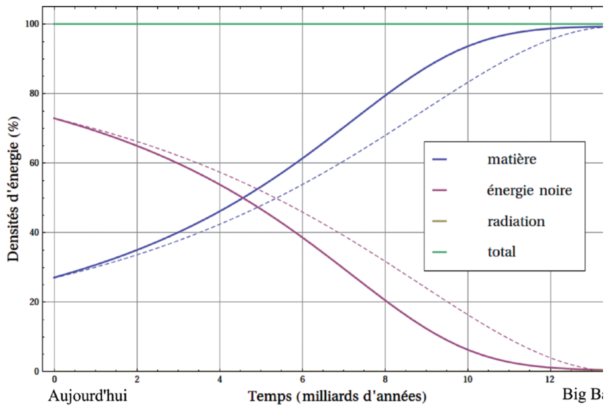
Attending a talk at the "cosmo-club".

SNLS

In 2011, the SNLS collaboration published the most precise Hubble diagram of type Ia supernovae, confirming the acceleration of the Universe expansion at the 99% C.L. Combining this result with other measurements, the SNLS team of Irfu showed that this acceleration can be explained by a modified gravity theory called the Galileon model. The Galileon is a scalar field mediating a fifth force that is negligible with respect to gravitation close to massive objects, but becomes dominant at cosmological scales. This model is not plagued by any theoretical default, fulfills all local tests of General Relativity, and proposes an explanation for the accelerated expansion of the Universe.

The Irfu team developed an analysis code to predict values of all cosmological observables for millions of possible combinations of the model parameters and confronted these predictions to data. Their publication (2013) proved that the Galileon model is as consistent with present data as the standard ΛCDM model and derives the first constraints on the model that use the most recent cosmological measurements in a rigorous way. This result shows that data favor a universe scenario which resembles that of the ΛCDM model with a matter density of 27% but with a stronger growth of structures.

In parallel, the team works on the final analysis of the whole data set of SNLS with their method of photometric SN classification published in 2011.



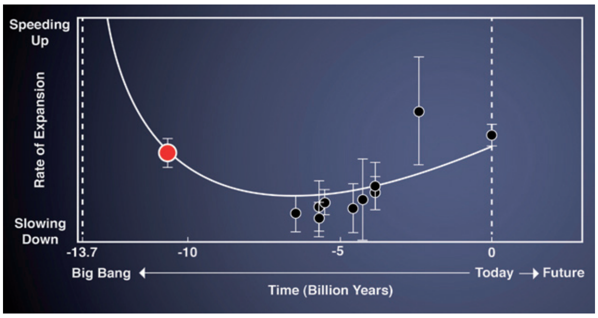
Evolution of energy densities in the ΛCDM (dashed line) and Galileon (solid line) models: the two models have similar evolutions.

BAO

The Universe expansion can also be studied with baryonic acoustic oscillations (BAO) whose characteristic scale, imprinted in the matter distribution since recombination, was measured for the first time in 2005 in the distribution of red luminous galaxies.

The Boss group at Irfu developed an original method to extend this measurement at higher redshift, i.e. further back in the past of the Universe. They used quasars which are far and extremely bright objects. Their spectra are extremely rich since they contain Ly-α absorption lines from clouds of intergalactic gas present between the quasars and the Earth. Clouds of intergalactic hydrogen can thus be detected and their distribution measured.

The team set up the selection of 150,000 quasars with the help of statistical tools which discriminate quasars from stars based on their colors and variability. Using all lines of sight, correlations between hydrogen clouds were measured and the cloud relative velocities were derived. This allowed the group to establish the first detection of the BAO scale in the intergalactic gas and the first measurement of the intergalactic gas expansion rate 11 billions of years ago, right in the matter-dominated era.



Expansion rate of the Universe as a function of its age. The BOSS measurement (red point) probes the Universe when the expansion was still decelerating.

This analysis, which was mostly led by Irfu, translated into the direct observation of the decelerated expansion of the Universe 11 billions of years ago, when gravity was still counteracting expansion, before the present phase of accelerated expansion due to dark energy. This work was published at the end of 2012 and was well received by the scientific community.

In parallel, the group is actively involved in preparing the e-BOSS and DESI surveys, both on target selection and instrument design.

Planck

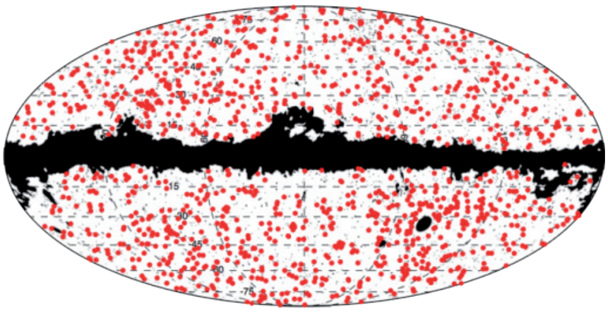
Studying the distribution of galaxy clusters is a complementary way to constrain cosmology, through the history of structure formation. Irfu got involved in cluster studies with Planck in 2002 and played a key role in this field since the satellite was launched in 2009.

Planck observations led to the most precise map of CMB anisotropies but also provided a large catalogue of clusters detected by the Sunyaev-Zel'dovich effect, the inverse Compton scattering of CMB photons by hot gas inside clusters. The Planck researchers from SPP and SAp worked together to produce and validate the cluster catalogue, and to use it for cosmology.

The Irfu team developed one of the three cluster extraction algorithms used to obtain the deepest full-sky catalogue ever made. They were also leaders in the validation of the detected sources. They compared these to known clusters and followed the new sources with other instruments. Irfu coordinated the follow-up of Planck clusters with the XMM satellite, whose sensitivity and excellent resolution allowed them to characterise these objects. Finally, Irfu led two studies that provided more precise cluster scaling laws (flux vs mass relation) as well as the catalogue selection function (detection efficiency, statistically determined), two major ingredients of the use of clusters for cosmology.

All of this work allowed Irfu to have a key role in several of the Planck publications, both on cluster physics (2011, 2012) and the use of clusters for cosmology (2013) that includes a first estimate of neutrino masses. The team is now heavily involved in the next series of Planck papers in 2014.

Vanina Ruhlmann-Kleider, Christophe Yèche,
Eric Armengaud, Eric Aubourg, Jean-Marc Le Goff, Christophe Magneville, Jean-Baptiste Melin, Nathalie Palanque-Delabrouille, James Rich



Galactic distribution of the 1227 Planck detections, published in 2013 (red). In black, the Milky Way, the Magellanic Clouds and the point sources masked by the extraction algorithm.

EDELWEISS

A wide effort is currently ongoing in order to detect the hypothetical "WIMPs" which could make up dark matter. Thanks to the development of groundbreaking bolometric detectors, the EDELWEISS-II experiment brought a crucial contribution and also carried out an original search for axion particles. The ongoing EDELWEISS-III project aims at improving the bolometer sensitivity to new physics.

The EDELWEISS detector.

Astronomical and cosmological observations have demonstrated the existence of a non-baryonic dark matter probably made up of new particles with respect to the Standard Model of particle physics. Among the candidates suggested by theoreticians, the WIMPs, Weakly Interacting Massive Particles, have a typical mass of 100 GeV and are coupled to the nucleus through weak interactions. They are the subject of most active researches. In particular, direct detection experiments aim at measuring nuclear recoils produced by the diffusion of WIMPs from the Milky Way halo with a target nucleus. To reach this goal, massive detectors are needed with a low energy threshold (less than 10 keV), and the ability to discriminate WIMP-induced recoils from other radioactive backgrounds such as gamma or beta-rays.

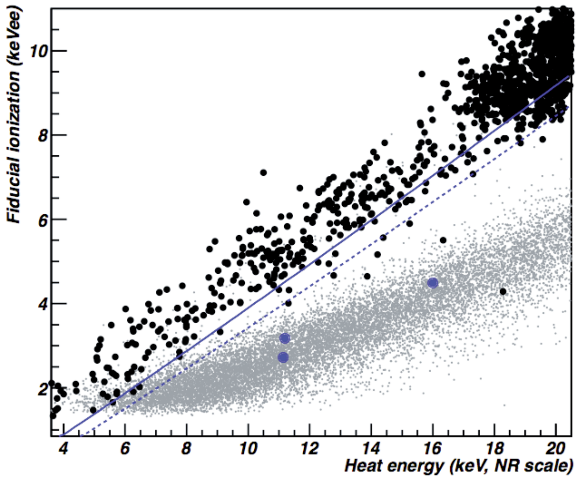
WIMP search with EDELWEISS-II

The EDELWEISS collaboration gathers CEA, CNRS laboratories, as well as German, Russian and English laboratories. The detectors, specially designed by the collaboration, are massive bolometers able to measure two parameters. The first one is the temperature rise induced in a Germanium crystal by an interaction. This measurement is made possible by cooling the detector down to few tens of millikelvin in a dilution cryostat. The second one consists in the charge generated by each interaction, collected by electrodes deposited on the crystal. For each interaction, a measurement of the ionisation yield is therefore possible, allowing the discrimination of WIMP-induced nuclear recoils against gamma-ray radioactivity. In addition, the detectors used for EDELWEISS-II are equipped with segmented, ring-shaped electrodes. These “InterDigit” or ID bolometers are then able to discriminate interactions taking place close to the surface of the detector, generated by beta radioactivity or low-energy X-rays.

The EDELWEISS-II experiment is located at the Laboratoire Souterrain de Modane in order to reduce the background contribution from cosmic rays. It consists in a 50-liter dilution fridge able to host few tens of detectors. A set of lead and polyethylen shields, together with a cover of scintillators which identifies residual muons, allows a remarkably low radioactive background reaching the detectors. Physics data taking with EDELWEISS-II took place in 2009-2010. The results of a search for “standard WIMPs” with these data, published in 2011, excluded a WIMP-nucleon cross-section of 4×10^{-8} pb for 85 GeV WIMPs, placing EDELWEISS among the most sensitive experiments worldwide. The implication of Irfu, and SPP in particular, in the EDELWEISS-II project was major, at the level of scientific coordination, detector fabrication, electronics, DAQ, and data analysis.

Other physics results: low-mass WIMPs and axions

Between 2011 and 2013, the SPP group lead other searches for new physics using EDELWEISS-II data. On one hand, several WIMP-search experiments claimed the observation of WIMP signals with a particularly low mass (around 10 GeV): DAMA historically, then from 2010 on, CoGeNT, CRESST, and CDMS. The signals induced by such low-mass WIMPs are very weak, therefore a



Low-mass WIMP search with EDELWEISS-II: grey dots (neutron calibration) indicate the WIMP signal area; black and blue points are the recorded events, compatible with the expected backgrounds.

dedicated «low threshold» analysis was carried out with a subsample of the EDELWEISS-II dataset, reaching a sensitivity to recoil energy depositions down to 5 keV. No hint for WIMPs was found and the obtained results strongly constrain - but do not exclude completely - the potential signals from other experiments.

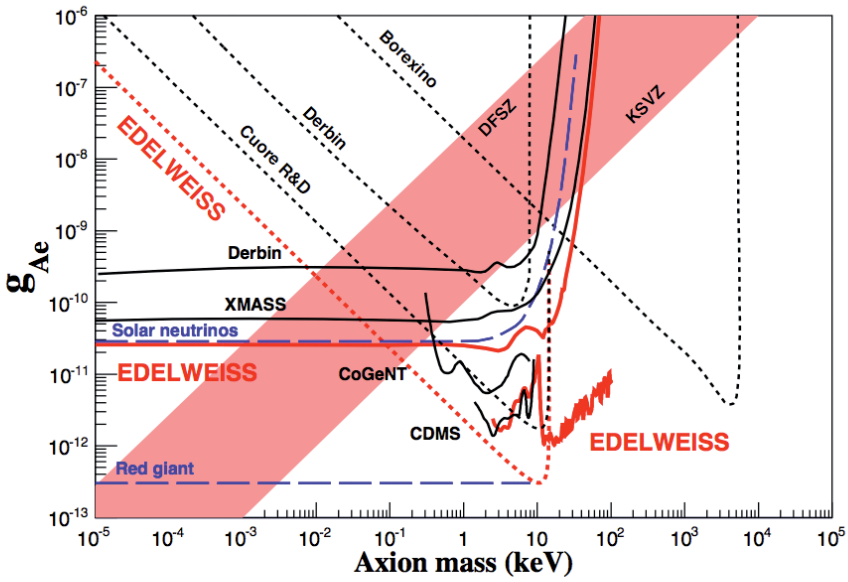
On the other hand, thanks to its good sensitivity to low energy electron recoils, EDELWEISS is an ideal tool to search for axions, these hypothetical particles which are the most promising solution to the CP violation problem in the strong interaction sector. Not less than four axion search channels could be explored with EDELWEISS-II data, while considering different hypotheses on the origin of observed axions (solar axions or dark matter), and on their couplings (to the photons or the electrons). Several competitive limits could therefore be set, and we excluded for example the whole mass range 0.91 eV < m < 80 keV for the so-called DFSZ axions

EDELWEISS-III

The ongoing EDELWEISS-III project is deploying around forty so-called FID detectors in the Modane installation with improved performances. These FID bolometers have a fiducial mass four times larger than ID detectors, and better gamma rejection capabilities. The search for standard WIMPs with EDELWEISS-III will allow reaching a sensitivity of few 10^{-9} pb on the WIMP cross-section for a WIMP mass of 100 GeV. On the other hand, the situation is still open concerning low-mass WIMPs. Developments are ongoing, in particular at SPP, in order to explore as much as possible this physics window within EDELWEISS-III: improved thresholds will be obtained thanks to innovative electronics based on HEMTs (HARD project), and the sensitivity of heat sensors will increase thanks to the amplification of the Joule effect in the detectors.

Finally, the SPP took part to the writing of a Conceptual Design Report in order to define the EURECA project of ton-scale bolometric detectors. In the competitive context generated by the emergence of the xenon TPC technology, a collaboration is also considered with the SuperCDMS project.

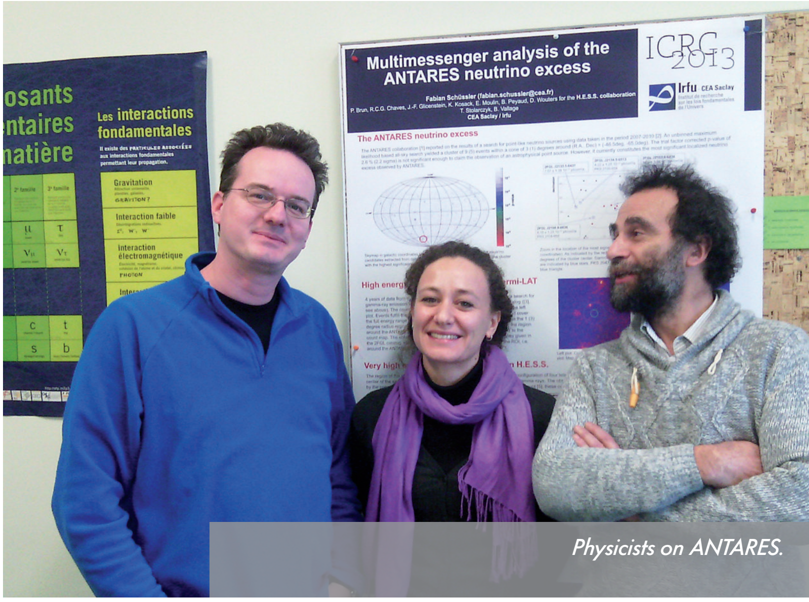
Gilles Gerbier, Eric Armengaud, Claudia Nones



Summary of constraints on the axion-electron coupling. Red: upper bounds obtained by EDELWEISS using three distinct analysis channels. Black: constraints from other experiments. Blue: indirect (astrophysical) constraints. The pink band shows standard axion models.

ANTARES AND KM3NET

The primary aim of ANTARES experiment is to use neutrinos as a tool to study particle acceleration mechanisms in energetic astrophysical objects such as supernova remnants, active galactic nuclei, or gamma-ray bursts, and shed light on the origin of ultra-high-energy cosmic rays.



Physicists on ANTARES.

Cosmic rays consist essentially of protons and heavier nuclei which have been observed up to very high energies. Neutrinos, produced in all objects where protons are accelerated, appear as unique messengers for astronomy since they are insensitive to magnetic fields and do not interact with the cosmic microwave background (CMB): they can carry information from very distant sources. The observation of cosmic neutrinos will allow a better understanding of the violent phenomena occurring in the Universe.

A neutrino telescope consists of a 3D array of photomultipliers detecting the Cherenkov light emitted by muons crossing a transparent natural medium. The muon trajectory reconstruction gives access to the incoming neutrino direction. Muons from cosmic ray showers in the atmosphere (atmospheric muons) or from the interaction of neutrinos coming from these showers (atmospheric neutrinos) are backgrounds for the experiment. Atmospheric neutrinos cannot be distinguished from cosmic neutrinos, but the ratio of the two species gets smaller at higher energies.

ANTARES

The ANTARES neutrino telescope houses 12 flexible 450 m high lines, anchored on the seabed at 2475 m depth and separated by 65 m, covering a 30,000 m^2 area. Each line comprises 25 floors holding 3 photomultipliers spaced every 14.5 m, and is connected to a junction box transmitting the data in real-time through a 40 km cable to the La Seyne-sur-Mer shore station, close to Toulon.

The detector is fully deployed since June 2008 and records data continuously since then, signing about five neutrino interactions per day. It is currently the largest neutrino telescope in the Northern hemisphere, complementary to the IceCube detector located at the South Pole.

Using data from 2007 to 2012, the search for a high energy excess in the region where the atmospheric neutrino flux is negligible allowed to set an upper limit on the presence of a cosmic neutrino diffuse flux. The search for a stacking in the sky map in the same dataset led to a limit on the presence of cosmic neutrino emitters. Limits on the crossing of the detector by magnetic monopoles and nuclearites (very heavy particles made of strange quarks) have also been determined. The indirect search for the accumulation in the center of the Sun of weakly interacting massive particles and the study of atmospheric neutrino oscillations are among the high priority physics topics.

The Irfu team is still involved in the data acquisition, calibration, and tuning of the detector, to ensure a good quality data taking. They led a study on the stability and ageing of photomultipliers exposed to intense illumination. They contribute to the operation of the multi-messenger Tatoo alert system, sending alerts to a network of robotic optical telescopes able to point with very short latency in the direction of high neutrino events detected by ANTARES.

The physicists have also been involved in the data analysis and physics event reconstruction, in particular in the muon energy estimation, as well as in the coordination of the development of the analysis tools. They participate to the various steering committees of the collaboration.

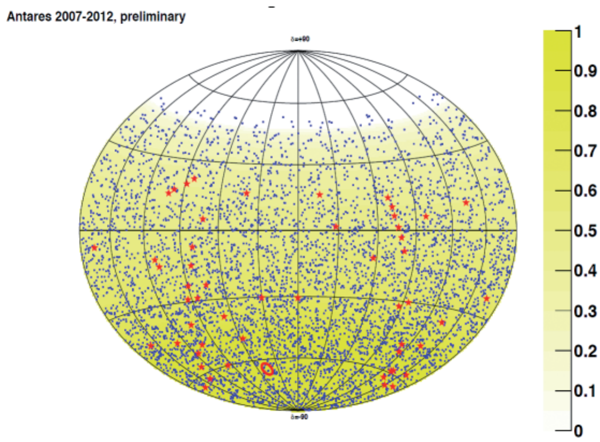
KM3NeT

The future of neutrino astronomy requires very large instrumented volumes, of the order of several km^3. The IceCube collaboration, whose detector is 50 times larger than the ANTARES one, has not detected any significant excess in the search for point sources with 2 years of data, even though they recently observed a diffuse flux of neutrinos from extra-terrestrial origin.

From 2006 to 2012, the Irfu team got involved in the design study and preparatory phase of KM3NeT, a next generation telescope, planned to be larger than IceCube, with leading responsibilities in system engineering, prototyping, and physics studies. A first outcome was the construction of an ASIC allowing the sampling at several thresholds of large size photomultipliers signals. Following the decision of the collaboration to use multi-photomultipliers based optical modules, the engineers and physicists took the responsibility to realise a full readout system for the Digital Optical Module comprising 31 photomultipliers.

As one of the result of an extended R&D, in April 2013, a prototype of an innovative optical module was deployed undersea on the ANTARES site. Since then it has provided continuous data to shore and proved the validity of the acquisition and clock distribution systems. Despite these successes, recent results in high energy gamma ray astrophysics and the lack of technological breakthrough for instrumenting a multi km^3 detector at an affordable cost motivated the decision of the Irfu team to not pursue the KM3NeT activity after the preparatory phase.

Bertrand Vallage, Sotiris Loucatos, Fabian Schüssler, Thierry Stolarczyk, Pascal Vernin

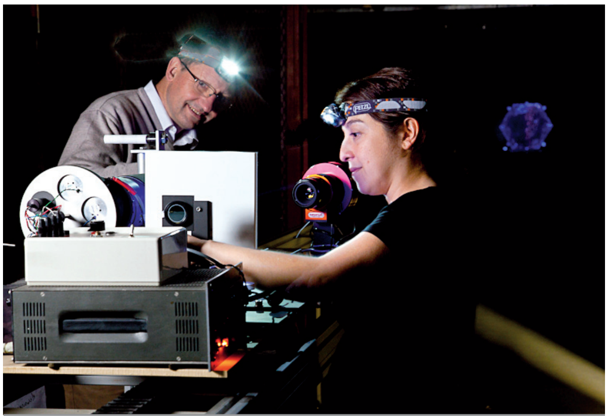


Representation in equatorial coordinates of the arrival directions of the 5516 up-going muons detected by ANTARES from 2007 to 2012.

Picture of the digital optical module prototype during deployment in April 2013. For this occasion, the prototype was connected to the ANTARES instrumental line.

HESS AND CTA

The HESS experiment covers the field of high-energy gamma-ray astronomy. The array of four Cherenkov telescopes on the ground, installed in Namibia, has been completed in the HESS 2 phase with a large telescope, 28 meters in diameter, placed in the centre of the array. The future of gamma-ray astronomy is based on the CTA project, which provides an extensive network of about one hundred telescopes in three different sizes.

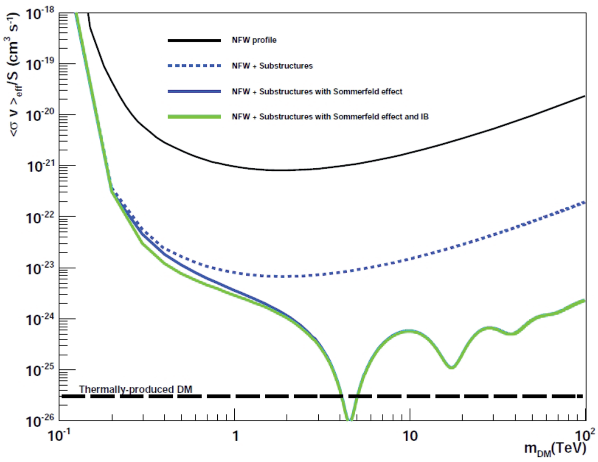


Test bench for CTA.

HESS

Physics analyses by the HESS group at Irfu in the period 2011-2013 mainly concerned astroparticle subjects: search for dark matter in the form of WIMPs, search for axions, but also some more astrophysical topics such as the study of the Galactic Centre or the study of the emission of blazars.

Particles of non-baryonic dark matter interacting weakly with ordinary matter can annihilate into Standard Model particles in dense regions of the Universe. Motivated candidates for dark matter are WIMPs. WIMP candidates are naturally available in extensions of the Standard Model such as supersymmetry or extra dimensions models. Among the annihilation products are neutrinos, charged cosmic rays, and photons. The search for high-energy photons with the HESS array of Cherenkov telescopes on the ground was conducted towards globular clusters (NGC6388 and M15) and clusters of galaxies (Fornax). The data analysis yielded robust constraints on the annihilation cross section of dark matter in the mass range around 1 TeV, complementary to those obtained with the Fermi satellite. In the context of blind searches for which the position of the objects was not known a priori, studies have focused on galactic dark matter sub halos. The first constraints with a network of Cherenkov telescopes on the ground were obtained on data from the Galactic plane taken by HESS. As part of the definition of the sensitivity of CTA for the detection of dark matter, the studies are concentrated on the dwarf satellite galaxies of the Milky Way (Sagittarius, Sculptor, and Carina) and clusters of galaxies (Fornax).



Constraints in the plane (M_{DM}, $<\sigma v>$) obtained with the HESS data to the Fornax cluster of galaxies. The curves give upper limits at 95% confidence level on the effective annihilation cross section of the dark matter particle as a function of its mass, taking into account various effects.

A thorough study of the Galactic Center region on all the data from the phase 1 of HESS confirmed the presence of a break in the spectrum of the central source HESS J1745-290 and showed that the break is intrinsic to the central source. This break is crucial to determine the nature of the emission of HESS J1745-290, which could be associated with the central black hole in our galaxy Sgr A*. The detailed study of the close diffuse emission shows photon emission up to several tens of TeV involving the presence of a proton accelerator at the PeV range in the Galactic Centre.

The HESS team at Irfu is also interested in the physics of extragalactic gamma-ray emitters such as blazars. These studies constrain the properties of the diffuse extragalactic light with the blazar PKS0301-243 and search for axion-like particles with the blazar PKS

2155-304. For this latest study, a novel method has been proposed by the team and published upstream of the analysis with HESS.

CTA

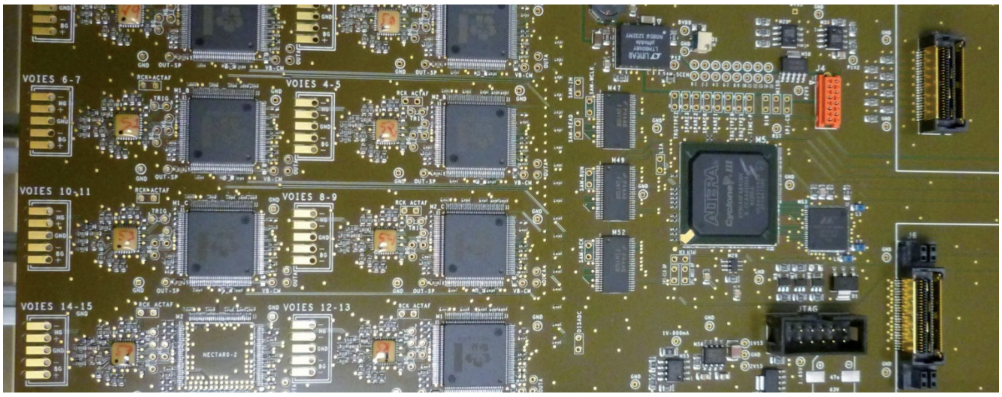
Irfu is involved in the project of gamma-ray observatory CTA planned for the second half of the 2010s. The SPP team is engaged in two technical projects for CTA: the NectarCAM camera and the manufacture of mirrors. These projects are carried out in collaboration with SEDI and SIS.

NectarCAM

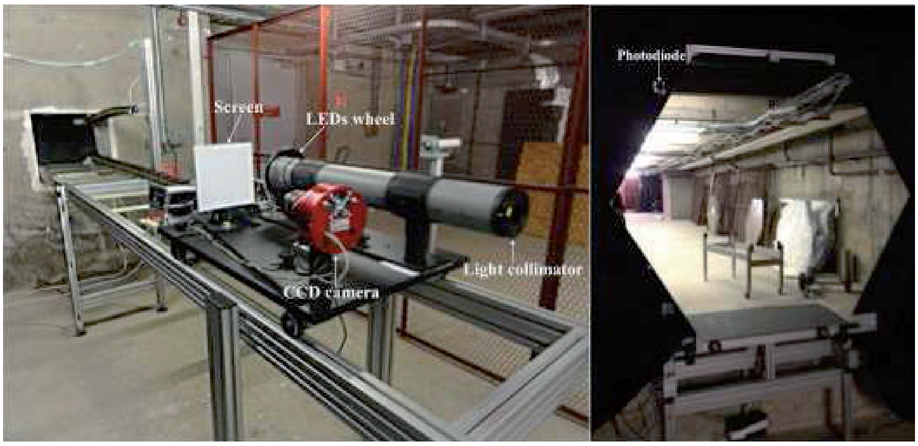
NectarCAM is a camera designed for the medium-sized telescopes (MST), which are Davies-Cotton type telescopes including a reflector with a diameter of 12 meters. The cameras of the MSTs, weighing two tons, will be placed at the telescope focal point, 16 meters away from the reflector. They will be equipped with about 1800 pixels, which will provide a field of view larger than seven degrees. The NectarCAM includes about 250 modules. Each of these modules consists of seven photomultipliers and an electronic card for reading, triggering the acquisition, and digitising data from these photomultipliers. Storage and digitisation of data is carried out by the electronic chip NECTAr designed by SEDI. The development of NectarCAM is studied by a consortium of fifteen French, Spanish, and German laboratories. Irfu provides the design and manufacture of the NECTAr chips, the design of the cooling system of the camera, the integration of the different components, the test of the full camera, and the production test benches. The scientific advisor for the camera and the system engineer belong to Irfu. Forty cameras could be built at Saclay in 2016. A test bench for the NECTAr chips was installed in late 2012. The installation of an electronic demonstrator, consisting of several modules designed to test the trigger system, began in late 2013. That of a thermal demonstrator should start in early 2014.

Mirrors for CTA

Since 2008, the Irfu teams work on the development of composite aluminum / glass mirrors to equip the medium-sized telescopes of the CTA network. These are innovative mirrors, whose optical characteristics are halfway between solar concentrators and astronomical mirrors. The need for a large number of mirrors, representing more than 4,000 m^2 just for the medium-sized telescopes, requires high production efficiency and cost content. The technique proposed by the engineers at Saclay involves the use of a mould which will see its shape replicated for the manufacture of mirrors. The process has been the subject of a technology transfer between Irfu and the Kerdry company in Lannion, which positions itself as a reliable partner for the manufacture of mirrors for CTA. A series of 20 mirrors produced by industry has shown the industrial feasibility of the project and refined cost estimates for mass production. This is essential in the selection process of the technology for the mirrors by the consortium. In parallel, a laboratory to test mirrors exhaustively was installed on site in Saclay. It allows the characterisation of mirrors from



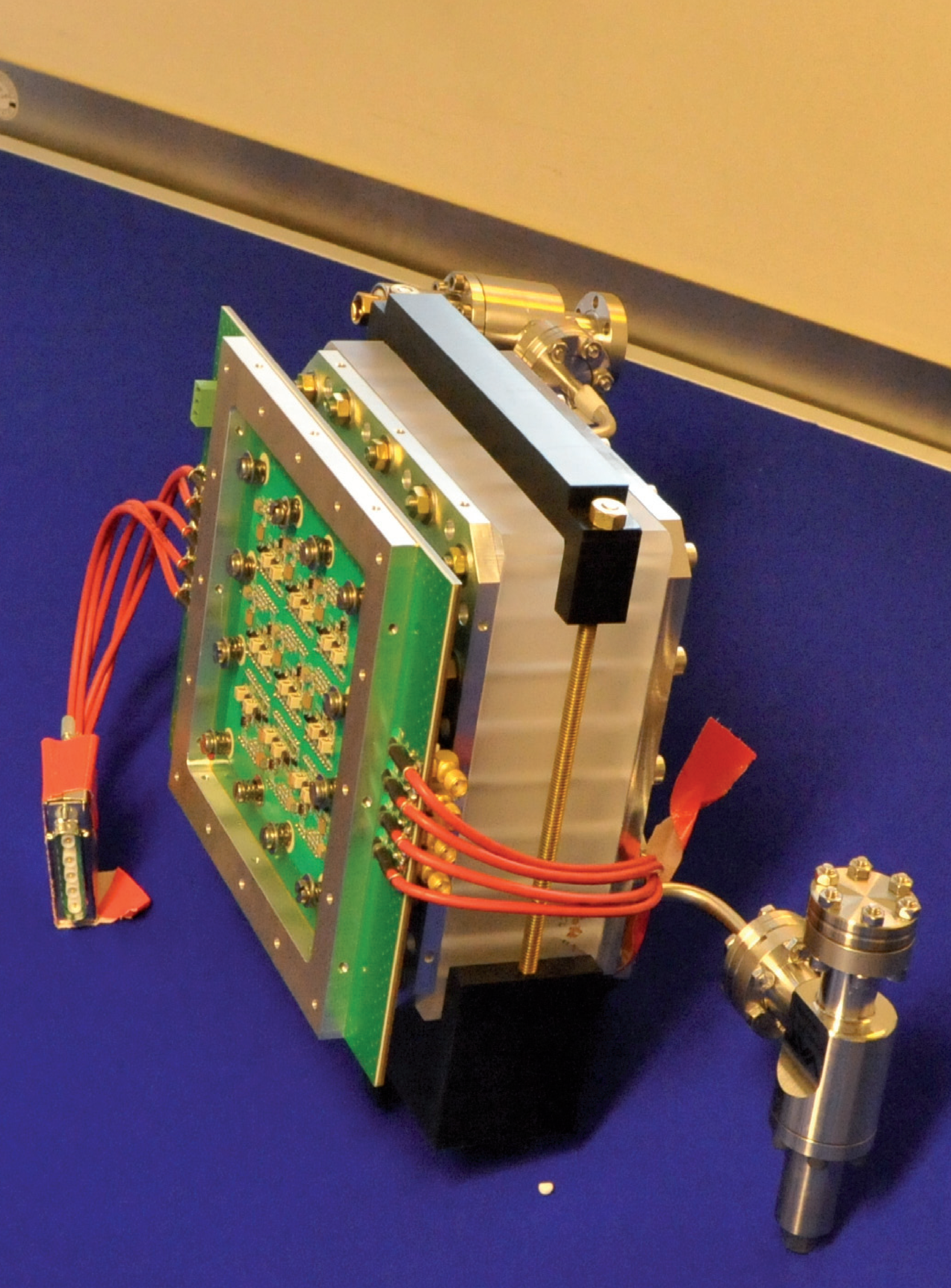
Front-end electronic card Nectar V1, designed at Irfu to achieve the capture and digitisation of signals from the NectarCAM camera.



Test bench for CTA mirors at Irfu.

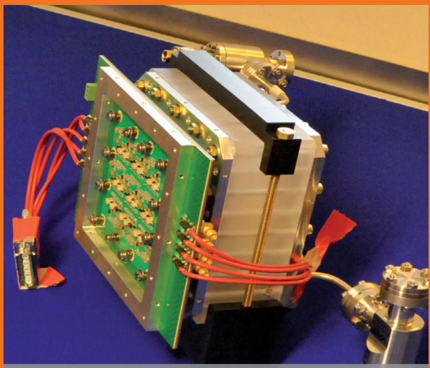
Kerdry as well as mirrors from partners and competitors within CTA. Additional tests are conducted in European laboratories participating in the consortium and the decision on the technologies adopted should occur in 2014. In the meantime, a second set of 50 mirrors will be produced by Kerdry in order to further investigate the reliability of mirrors. ■

Jean-François Glicenstein, Pierre Brun, Emmanuel Moulin, Bernard Peyaud, Fabian Schüssler



Applications

- CALIPSO
- NUCIFER



First optical detector prototype for CaLIPSO.

Although fundamental research is its primary motivation, the particle physics division is not limited only to it, but it is also pursuing societal applications of the fruit of its research.

This is particularly true in the field of medical applications, following a long tradition in our discipline. Currently, the CaLIPSO project develops a new imaging concept, especially suitable in neuroscience. It is a calorimeter using a heavy organometallic liquid, TriMethyl Bismuth, whose purpose is to detect energetic photons through their conversion by photoelectric effect. This detector aims for a high efficiency, very good spatial resolution, and excellent temporal resolution. To achieve the desired performance, the technologies developed in the laboratories of fundamental research are essential. Launched in 2009, the project led to the successive construction of two prototypes, to establish the optical characteristics of the detector and to study the ionisation properties. The ultimate goal is to use this new technology for medical imaging based on positron emission tomography.

Another field of application has emerged more recently. This is related to the non-proliferation of fissile materials. For this purpose, neutrinos are an ideal probe. Using the technology developed for the Double Chooz experiment, the Nucifer detector is a demonstrator for real-time monitoring of the activity of nuclear reactors and assessment of the isotopic composition of nuclear fuel using neutrinos detected in the vicinity of the reactors. It is currently installed near the Osiris research reactor in Saclay. Thus in 2013, neutrinos have been detected there for the first time at the expected rate. Future deployment near a nuclear power plant is under consideration.

Georges Vasseur

CALIPSO

The aim of the CaLIPSO project is to develop the proof of concept of a fast response high efficiency gamma detector. This innovative calorimeter could be used in medical imaging.


Connecting the CaLIPSO prototype.

Motivations for CaLIPSO

The CaLIPSO project (French acronym for Calorimètre Liquide Ionisation Position Scintillation Organométallique) is based on the recent developments of the TriMéthyl Bismuth (TMBi). This innovative liquid allows a very efficient and accurate detection of positron annihilation. Once fully developed and integrated with an acquisition system, it may become a key element of PET (positron emission tomography) imagers. In particular, the detector performances would allow efficient 1 mm^3 resolution PET imaging of the whole human brain, thus being an excellent complement of magnetic resonance imagers for diagnosis and research on neurodegenerative diseases. The development of such detector is a long-term effort pursued at Irfu since 2009, partially funded by the Neuropôle de Recherche Francilien (NeRF), LabEx P2IO, and CEA interdisciplinary program TechnoSanté. This innovation is patent protected.

The CaLIPSO detector uses the TriMethyl Bismuth to efficiently convert photons of energy less than 1 MeV, through the photoelectric effect. The photoelectric electron is relativistic in the liquid TMBi. Thus it produces a quasi-instantaneous flash of few tens of Cerenkov photons, as well as free charges in the liquid. Light produced is detected by an efficient photodetector and charges released drift along a strong electric field, pass through a Frisch grid, and are collected by a pixelated charge detector.

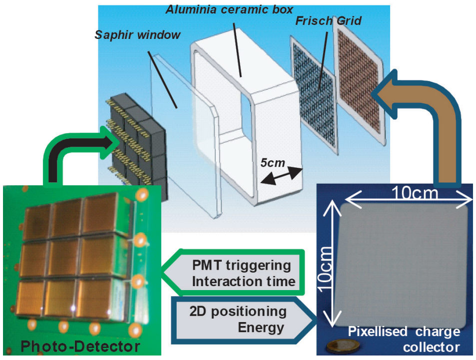
The simultaneous detection of light and charge signals leads to very promising performances when positron-annihilation detection is needed. We anticipate a gamma conversion positioning in detector volume down to 1 mm^3, 100 ps timing (FWHM), 10% photon energy measurement (FWHM), and a single-interaction (photoelectric) conversion probability above 47%. These detector performances can be achieved simultaneously. This is why the CaLIPSO detector has the potential to outperform the other detector technologies proposed for PET imaging (scintillating crystals, high-Z semiconductors, and liquid Xenon).

Scientific and technological challenges

The CaLIPSO project is very ambitious. At the project start, little was known about liquid TMBi for particle detection. Key science and technological issues were listed as:

- TMBi physical properties: namely light production yield, light absorption length at optical and UV wavelength, charge mobility in TMBi. We measured these properties using tailored devices designed for handling our mildly-pyrophoric liquid.
- The low light production efficiency does require careful optimisation of the optical couplings. The first optical demonstrator, along with its detailed Monte Carlo simulation, allowed us to quantify the issue. The next optical demonstrator should demonstrate efficient triggering on 511 keV photons.

- The electronic readout density: Integrating an electronic density approaching one preamplifier per mm^2, has already been achieved in the laboratory (ASIC and 3D electronics), in the context of a spaceborne experiment. We have chosen to limit the resolution of our demonstrator to 2 x 2 mm^2, in the charge collection plane, in order to avoid having to use 3D electronics and to focus in the short term our efforts on the detector development.
- The TMBi must be ultra-purified to allow the charge drift and the measurement of gamma energies. We organised the detector cleaning and mounting work at the SEDI clean rooms. The materials, from which the detector is made, shall be carefully chosen to be compatible with ultra-high vacuum technologies.



Principle of the CaLIPSO detector.

Preliminary work on the ionisation detector

This work confirmed the feasability of the proposed detector. Ions do drift in TMBi. The free ion yield (Gfi) for TMBi is (78.8 ± 1.7)% of the free ion yield of the TMSi at zero fields for liquids with the same purity (but not ultrapurified). The TMBi dielectric constant value is 2.65. We built a free electron lifetime measurement cell, which is a single pixel charge detector.

Collaborations

Collaboration work is ongoing with the CSNSM and IPNO on the charge detector and timing measurements technologies. Discussions are engaged with the XEMIS project team, and on the longer term with Sherbrooke University on ASICS charge readout electronics. Finally, we are looking for international collaborators within the HEPTech network.

Work on optical detection is well advanced

Optical properties of the TMBi have been measured. A first prototype has been constructed and tested. A second prototype, optimised using a GEANT4 simulation, was just assembled at the end of 2013 and will soon be characterised.

Technologies for pixelated charge detector

R&D on the ceramics technologies needed to build the densely pixelated CaLIPSO ionisation detector has been funded by P2IO LabEx R&D program (collaboration between CSNSM, IPNO, and Irfu). We recently achieved to produce ceramic boards of controlled surface resistivity. Scaling of the method at detector size is foreseen this winter 2014.

Ultrapurification of TMBi

We need to extract electronegative molecules that trap free electrons in order to achieve free electron lifetime larger than 10 µs. This will ensure effective charge drift toward the Frish grid and collection of the ionisation signal, thus single photon detection in the CaLIPSO charge detector.

We use molecular sieves for purification because it is known to achieve an impurity level lower than 0.1 ppb O_2 equivalent. We monitored TMBi purity level by measuring macroscopic ionisation current yields, and measured significant increase of the ionisation yields with purification. Big efforts are starting to improve the efficiency of this molecular sieve and to upgrade all the systems: vacuum system, distillation system, and purification system. And keep them clean. ■

Dominique Yvon, Viatcheslav Sharyy, Patrice Verrecchia

Full features TMBi purification bench for the CaLIPSO project.

NUCIFER

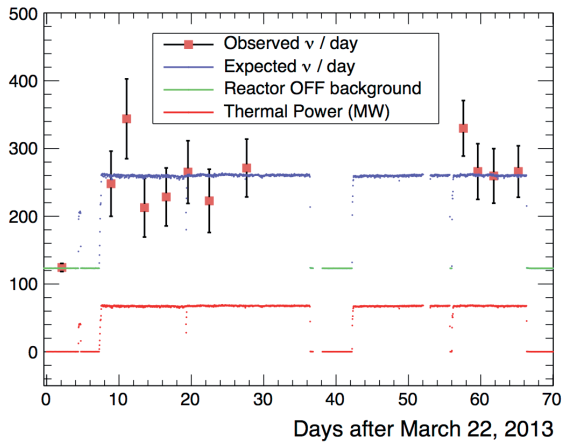
In 2013, the Nucifer experiment detected its first neutrinos from the Osiris reactor in Saclay. It is the closest "neutrino" experiment to a compact nuclear reactor core ever made.

Receiving part of the detector.

Placed ten meters away from a nuclear reactor, such as Osiris in Saclay, the Nucifer detector allows real-time monitoring of the fuel composition, particularly the amount of plutonium produced in the core. It is considered by the IAEA as a demonstrator for monitoring future civilian nuclear facilities.

Neutrino detection

The detector design dates from 2006 and its implementation started in 2008. The detector, which uses as a detection medium a liquid scintillator doped with gadolinium, is the fruit of a collaboration of technical and physics divisions of Irfu, DAM, DEN, IN2P3, and Max-Planck-Institut für Kernphysik. Nucifer deployment at Osiris began in 2011. But it had to be endorsed by the Nuclear Safety Authority to be put into operation in 2012. After a first filling, the detector was calibrated using radioactive sources. An upgrade of Nucifer was conducted between 2012 and 2013. The scintillating liquid was changed to increase transparency. An additional lead shielding was also added. Thus better protected against external backgrounds, Nucifer could begin his quest for neutrinos during the cycles of reactor operation in April 2013. This allowed extracting the signal in agreement with the expected rate, i.e. 250 neutrinos per day. Nevertheless work of accidental background noise reduction is underway to carry out more precise measurements, in 2014. It will be achieved through the addition of a new lead shield between the reactor core and Nucifer.



First detection of neutrinos in Saclay. The red line represents the evolution of the thermal power of the Osiris reactor as a function of time. The measurement points represent the daily rate of detected neutrino candidates, averaged over periods of about two days. When the reactor is shut down, we measure the background noise induced by cosmic rays (green line). In operation, the neutrino signal follows the evolution of power. We measure a rate compatible with the prediction, 250 per day (blue line). Error bars demonstrate the existence of a big enough background induced by the reactor.

Reactor anomaly

Beyond the application to the monitoring of nuclear power plants, the first objective of this project, Nucifer could also provide a first test of the reactor antineutrino anomaly. In fact, no experiment has ever detected neutrinos in such a short distance of a compact core (only 7 m!). This configuration is suitable for the detection of a new hypothetical fourth type of neutrino with a mass close to an eV/c ^{2}. It could bring new elements in response to the antineutrinos deficit observed by twenty experiments or so for several decades.

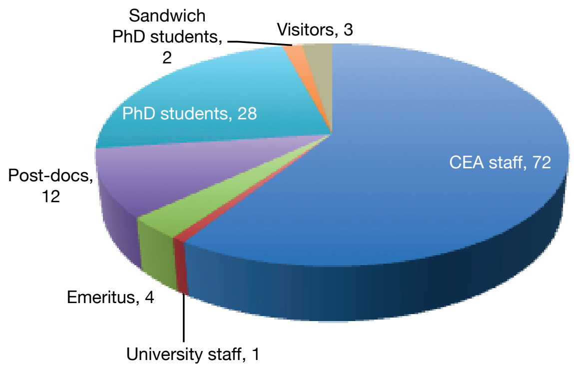
Thierry Lasserre, Michel Cribier, Guillaume Mention, Jean-Luc Sida, Matthieu Vivier

SPP

The particle physics division is part of the Institute of Research into the Fundamental Laws of the Universe (Irfu) within the Physical Sciences Division (DSM) of the Atomic Energy and Alternative Energies Commission (CEA). Its activities are carried out in close collaboration with the technical divisions (accelerators, cryogenics, and magnetism division - SACM; electronics detectors, and computing division – SEDI; systems engineering division - SIS) as well as the other physics divisions of Irfu (astrophysics division - SAp; nuclear physics division - SPhN).

Staff

At the end of 2013, the particle physics division comprises 72 CEA permanent staff, including 70 physicists and two secretaries, as well as one university professor, who arrived during the period 2011-2013. Two physicists were hired over the same period. Four retired physicists perform as emeritus. The division has 12 postdocs and 30 PhD students, including two sandwich PhD students. Finally, 12 physicists are currently based elsewhere, mainly at CERN.



International links

To strengthen collaborations between institutes, the division participates in two international laboratories associated with Japan (FJJPL) and China (FCPPL). For the latter, Irfu has organised the annual meeting in 2012. In addition, thanks to external funding, about half of PhD students and the vast majority of postdocs are foreigners.

Funding

Primary funding for the division comes from the CEA subsidy. Nevertheless, over the period 2011 to 2013, diversification of funding sources continued. The division has won three European ERC grants and participates in seven FP7 European programmes and seven ANR programmes.

Scientific production

The following table summarises the number of publications in scientific journals as well as thesis and HDR defenses, year by year.

	2011	2012	2013
Publications	264	360	280
Theses	12	10	10
HDR	4	2	2

Scientific events

In one or two sessions per year, the scientific and technical evaluation committee of the division discusses new projects and current experiments. The themes for the period 2011-2013 are given in the table below.

November	2011	Atlas upgrade, CMS upgrade
June	2012	GBAR, eBOSS, CAST
June	2013	Laguna, CTA
November	2013	Atlas upgrade, CMS upgrade

Publication Director: Ursula Bassler

Technical and editorial coordination: Georges Vasseur

Design and Production: Reor

Photo credits: © CEA

Service de physique des particules
CEA, Irfu, SPP
Centre de Saclay
91191 Gif-sur-Yvette Cedex
Phone: +33 (0) 1 69 08 23 50
Fax: +33 (0) 1 69 08 50 13
http://irfu.cea.fr/Spp/