2015

// ANNUAL REPORT

30 anos LIP

LIP

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

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// ABOUT LIP

Introducing LIP

LIP was created to exploit the unique opportunities created for fundamental research in Portugal by the country's accession to CERN. LIP brought experimental particle physics in Portugal to a truly international ground and shall continue to lead and develop this effort, ensuring the full participation of the national scientific community in the experimental discovery of the fundamental laws of the Universe. Current challenges include the detailed investigation of the origin of mass and the search for new laws of physics at the LHC, the re-creation of conditions that existed just after the Big Bang, or the discovery of dark matter particles. LIP has the mission to enhance the direct access of the national scientific community to international research facilities and collaborations in particle physics. We aim to inspire the younger generations to pursue careers in S&T, through international collaboration, excellence in research and training, and opportunities for engaging with society.

LIP is the reference institution for experimental particle physics and associated technologies in Portugal. We are present in Lisbon, Coimbra and Braga, in close collaboration with the local universities. The geographically-distributed nature of LIP reflects the need to articulate strategies at national level, in an area of research often conducted within large international collaborations or using large scientific infrastructures.

LIP is devoted to research and development in experimental particle physics, new instruments and methods and advanced computing. Also central to our mission are advanced training, supporting education in science and technology and the promotion of the public engagement in this field of science. LIP further aims at strengthening the links between academia and industry, fostering technology transfer, and promoting the participation of Portuguese industry at CERN and other international scientific organizations. LIP distributed computing infrastructures are used by many other research institutions.

LIP was founded in 1986, in the event of Portugal's accession to CERN, the European particle physics laboratory. The inter-university and geographically distributed nature of the Laboratory was present from its birth, as LIP was created simultaneously in Lisbon and Coimbra, joining researchers from the University of Coimbra and from the two universities that today constitute the University of Lisbon. In 2001, LIP was recognized as "Laboratório Associado" (Associated Laboratory).

LIP's members are the Portuguese Foundation for Science and Technology (FCT), the Universities of Lisbon, Coimbra and Minho, Instituto Superior Técnico (IST) and ANIMEE (Electrical and electronics business association). The participation in experiments at CERN remains central in the activities of LIP, which today are developed also in collaboration with the European Space Agency and international scientific infrastructures such as the Sudbury Neutrino Observatory, the Pierre Auger Observatory, SURF(LUX) and the GSI research center in Darmstadt. LIP further participates in numerous international infrastructures of distributed scientific computing.

Directorates Report

Prof.
Mário Pimenta
Directorates President

In the beginning of 2015 we were all shocked by the dramatic illness, and soon after the death of José Mariano Gago. In a few decades, Mariano Gago was able to build in Portugal a modern scientific community deeply rooted in society; implementing his vision that science is a source of both technical and human progress. Mariano Gago was a founder of LIP, and its president for many years. His death was an enormous loss for Portugal and for all of us at LIP.

This year LIP celebrates its 30th anniversary, and we have many reasons to be proud. We are proud of having been able to participate, as full partners, in some of the most significant scientific and technical enterprises of our times. We are proud of the many students who passed through LIP, and found here the right environment to complete their formative years and dream up their future.

We are proud of our achievements, but we are also conscious of the main scientific, technical and political challenges which lie ahead of us. LIP is an unconventional institution. It is a private non-profit association that has a national mission: to fully exploit the opportunities opened by the Portuguese participation in CERN and in other large international scientific infrastructures, in the domain of particle and astroparticle physics.

We celebrate thus the 30th anniversary of LIP looking forward. We organized a public exhibition which we named "Particles: from the Higgs boson to Dark Matter". Its main goal is to put in evidence, for students, teachers and the general public, the main scientific and technological challenges in our area in the next decades. The exhibition was held in Braga in February/March and will be held in April in Coimbra and in May in Lisbon. We hope that many of those who have or will visit this exhibition will get curious about the Universe we are living in, and the methods that science has to try to understand it. And, who knows, some of them may join us later, in this great adventure.

The last years were not easy for Portugal, for science in Portugal, or for LIP. We were able, nevertheless, to keep most of our main activities and human resources and even, in a few areas, to increase them: the LIP section in Minho, born in 2010, had in these years a fast and consistent development; the nuclear reaction, instrumentation and astrophysics group (a small but very active group) has recently joined LIP; a framework, the National Distributed Computing Infrastructure (INCD), able to ensure the renewal and the management of the Portuguese computing infrastructure, was created in a partnership with the Portuguese Science and Technology Funding Agency (FCT) and with the National Laboratory of Civil Engineering (LNEC). We hope that, in the near future, the stability of science funding and the perspective that there is a scientific future in Portugal for brilliant students and young researchers may be reestablished.

From time to time it is good to see our activity publically recognized. After the impact that the 2012 discovery of the Higgs boson by the experiments ATLAS and CMS at CERN (we are member of both experiments) had in the public, media and in the scientific community, particle physics was again in the front pages. The Nobel Committee decided to attribute the 2015 Nobel Prize in Physics to Arthur McDonald and Takaaki Kajita, leaders of the two collaborations which contributed to solve the solar neutrino puzzle: T2K and SNO, of which LIP is a member. The Breakthrough Prize in Fundamental Physics was shared by the participants in these collaborations, including some of our colleagues at LIP, for the discovery of the neutrinos oscillations.

A last word about this report, the LIP annual report. It comes for the first time in this format, which aims to give in a fast but precise way the global picture of LIP, its research lines, last year's main achievements, and plans for the near future. More specific information on each of LIP's research groups and research facilities, as well as on our activities in advanced training, education, outreach and technology transfer, can be found in a second report, the 2015 detailed report. We hope that this new format, together with the new web site that will be available soon, will help us to improve our communication with all that are (or will be) interested in LIP and/or its scientific and technological domains.

(Mário Pimenta - LIP Directorates President)

Report from the International Advisory Board

LIP Management met with the recently enlarged International Advisory Committee on April 6th and 7th, 2016.

In addition to summary reports distributed ahead of the meeting, detailed information was provided by project leaders about the full scope of LIP activities, covering three main areas: Experimental Particle and Astroparticle Physics, Development of new Instruments and Methods and Computing.

In Experimental Particle and Astroparticle Physics LIP researchers are addressing some of the most topical questions, such as new laws of fundamental physics, origin of dark matter, which represents approximately 80% of the matter content of the Universe, and studies of particle collisions at the highest energies ever recorded. The programme of Experimental Particle and Astroparticle physics is of world class quality and LIP researchers make significant contributions to the leading experiments in the field.

Over many years members of LIP have made major contributions in the area of 'Development of new Instruments and Methods'. Particularly noteworthy are recent developments in medical imaging. Efforts in Positron Emission Tomography (PET) instrumentation have led to instruments, presently evaluated in clinical trials and resulted in contacts with industries which have the potential of developing instrumentation with major impact in the field of medical imaging.

For a long time LIP has recognized the importance of scientific computing for science in Portugal. LIP has developed and is operating three major computer centres which are part of a world- wide computing network. They provide the computing infrastructure and are vital for science in the country.

One very positive development is the increasing strength of research outside the traditional sites at Coimbra and Lisbon. The development in Braga is particularly noteworthy, where in a few years a strong research activity was built up, including fruitful collaboration with other university departments and with local industry. In parallel, collaborations between the various LIP sites have been strengthening with a clear impact on the quality and efficiency of the research.

LIP is well aware of the importance of communicating their research activities to the general public. Their efforts are an inspiring example for many groups around the world. LIP, however, also recognizes that the (under)standing of fundamental particle physics within the universities needs further and continued exchange of information.

The Committee noted the impressively wide range of activities in the area of Development of new Instruments and Methods. It is recognized that further synergies and consolidations of activities should be encouraged with the aim to further strengthen the impact and visibility of these LIP activities in the medium term.

One concern expressed repeatedly and shared by the Committee is the lack of clear career prospects for scientists. Many researchers in their early forties are still employed on temporary contracts with no obvious perspectives of pursuing their scientific career. For a fruitful prospect of LIP research, the Committee considers it essential to establish mechanisms for the long term career development.

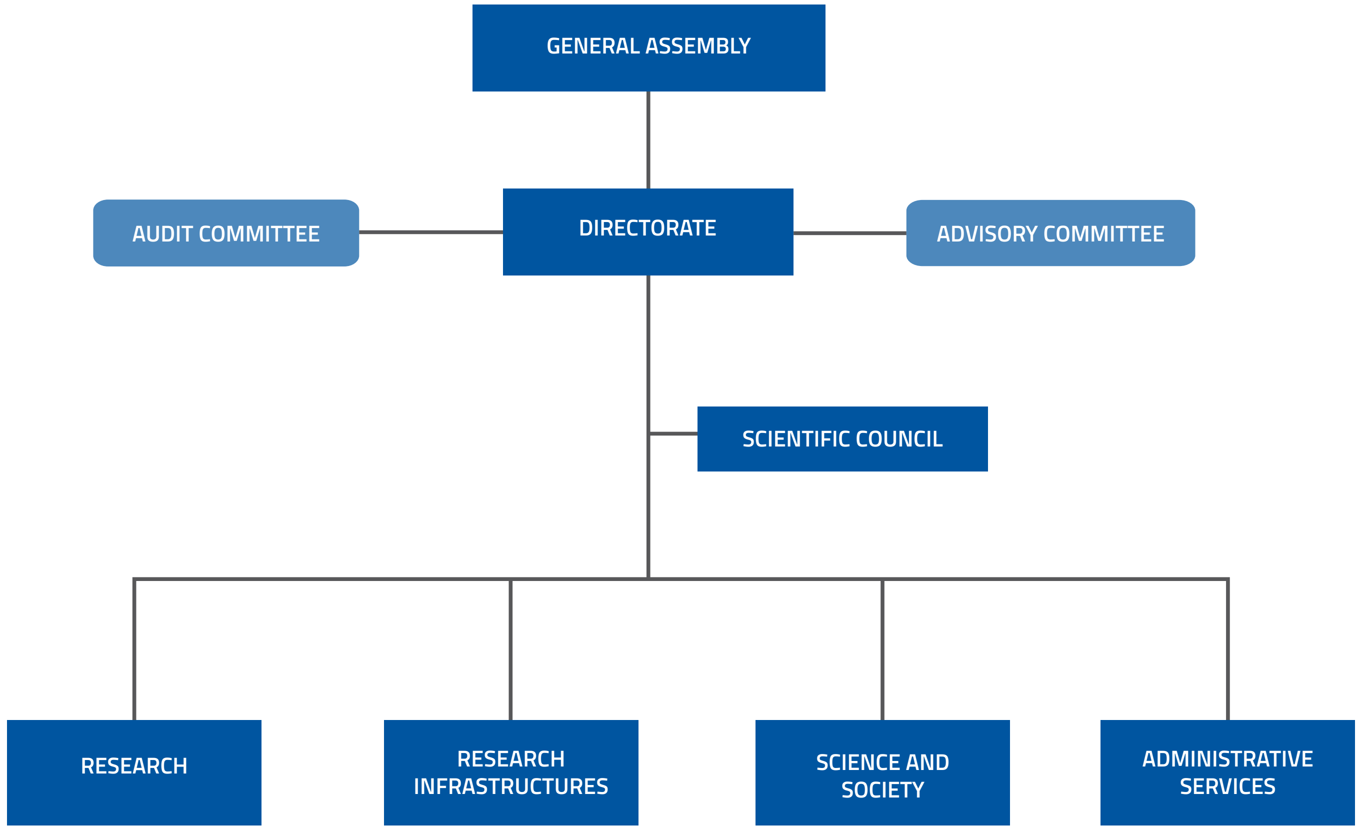
A related problem is the lack of a mechanism to provide a roadmap for the funding profiles needed for scientific research which extends frequently over ten to twenty years. This makes planning of experiments very hazardous and has prevented some of the LIP groups to accept major scientific responsibilities in international collaborations, with detrimental impact on the scientific output of the country.

The Committee understands that the last years have been quite difficult because of funding uncertainties, lack of support for students and lack of career prospects for young scientists. Nevertheless, LIP has managed to carry out their research program at the highest level with the potential to continue to be a major actor at the forefront of science. The Committee congratulates LIP to these achievements.

P.G. Innocenti, K. Parodi, C.W. Fabjan,

L. Rolandi, M. Teshima

Structure and governance



The organizational structure of LIP is designed to support a program with a coordinated strategy at national level, in an area of research often conducted within large international collaborations or using large scientific infrastructures. The structure is designed to be efficient and flexible.

In accordance with its legal structure, LIP is managed by a Board of Directors nominated by and accountable to its General Assembly, composed by the top representatives of LIP associated institutions. An internal Scientific Council endows LIP with the required structure of internal communication, participation and support to management. An External Advisory Committee, holding regular meetings with Directors and group leaders, provides strategic advice to the Laboratory. LIP administrative and financial operations are systematically audited by external auditors and reviewed by a top level independent Fiscal and Auditing Authority.

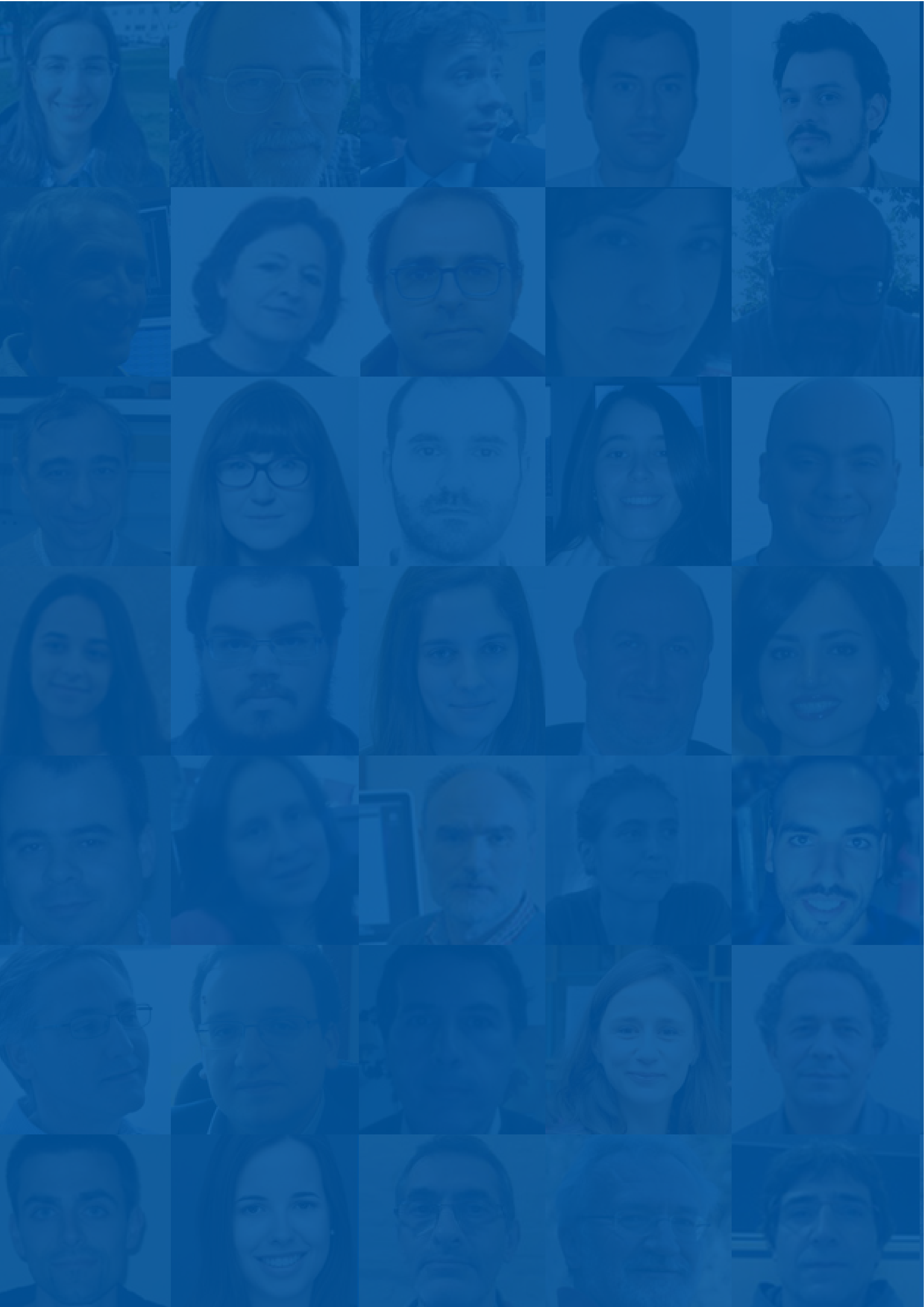
The different nodes of LIP are represented in the Board of Directors, which meets on a monthly basis and issues brief reports of its deliberations to the scientific council.

The scientific council includes all PhD holders, the heads of LIP's research facilities and a representative of the students from each LIP node. The scientific council has ordinary meetings four times per year and extraordinary meetings whenever necessary.

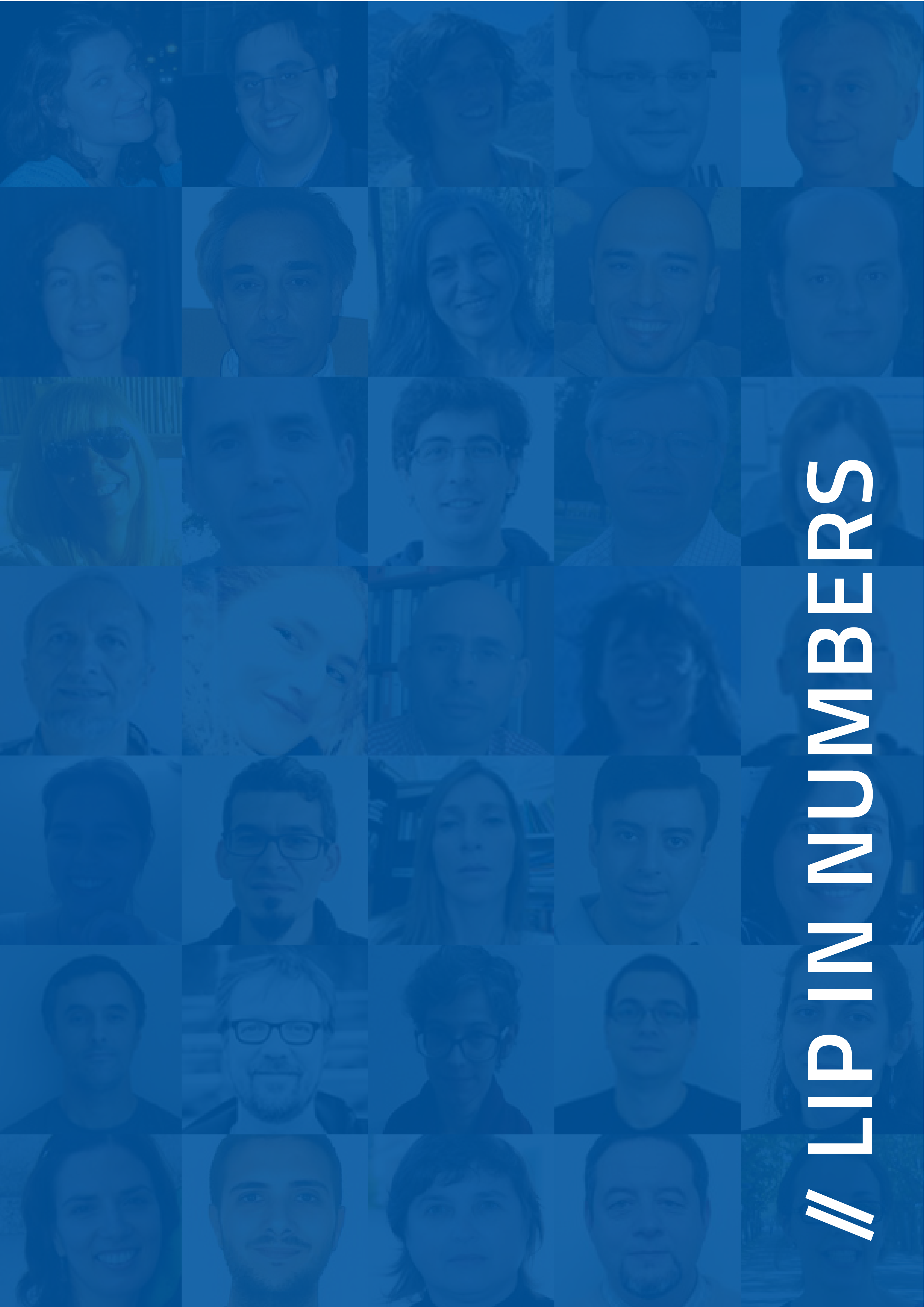
Once every two years, a lab meeting takes place. In these "Jornadas científicas" the scientific work of all groups is presented and discussed. Group leaders are encouraged to foster the participation of younger and senior members, and of students.

Highlights of the year

04 April 2015	LHC run 2 start at a new energy record.
15-17 April 2015 AMS Days at CERN	Results from AMS presented on the "AMS Days at CERN" meeting in April. In particular, the measured antiproton to proton ratio cannot be explained by existing models.
26 April 2015	30 Years of Portugal's accession to CERN celebrated on the 26th of April.
15-16 May 2015 Physics Dept., University of Coimbra	Visit to Portugal of the Restricted Eureopean Committee for Future Accelerators.
18-22 May 2015 ISCTE-IUL University, Lisbon	European Grid Initiative annual conference in Lisbon.
June 2015	Observation of the rare $B_s^0 \rightarrow \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data published in Nature. An X-Ray polarimeter developed at LIP is part of the planned XIPE mission, pre-selected for ESA's medium-class science missions programme.
September 2015	Combination of the ATLAS and CMS Higgs Run 1 results presented.
06 October 2015	Nobel prize of physics 2015 to A. McDonald and T. Kajita and Breakthrough prize 2016 to all scientists participating in the discovery of neutrino oscillations, including 4 LIP collaborators.
28 Sept - 02 Oct 2015 IST, Instituto Superior Técnico Lisbon	TWEPP 2015 - Topical Workshop on Electronics for Particle Physics, organised by CMS LIP Group.
17 November 2015	International agreeement AugerPrime signed to run the Observatory for the next 10 years.
14 December 2015	re-analysis of the LUX 2013 data, with improved limits! http://arxiv.org/abs/1512.03506 submitted to PRL in December

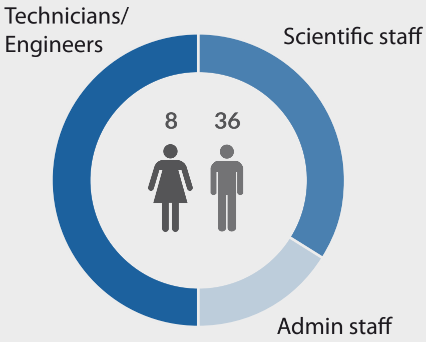


// LIP IN NUMBERS



HUMAN RESOURCES

STAFF



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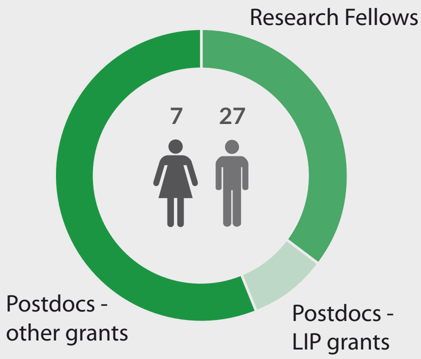
44
TOTAL

	Women	Men
Technicians/ Engineers	0	22
Scientific staff	3	12
Admin staff	5	2

FIXED-TERM RESEARCHERS



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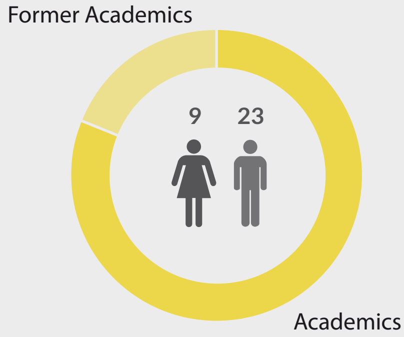
34
TOTAL

	Women	Men
Postdocs other grants	3	16
Research Fellows	4	8
Postdocs LIP grants	0	3

UNPAID



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32
TOTAL

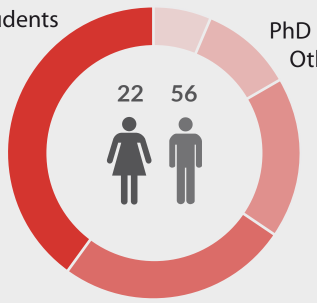
	Women	Men
Academics	5	21
Former Academics	4	2

TOTAL

188

Women: 46 Men: 142

STUDENTS



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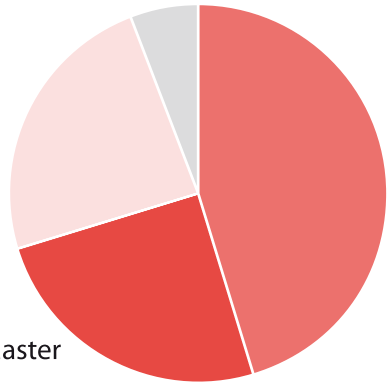
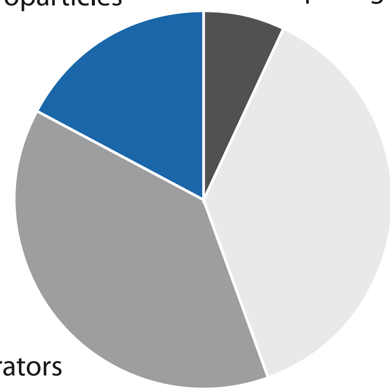
78
TOTAL

	Women	Men
Master students	10	21
PhD students FCT grants	5	15
PhD students LIP grants	3	11
PhD students Other grants	2	6
Undergraduates	2	3

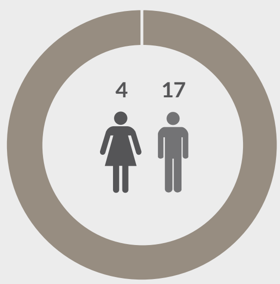
DISTRIBUTION BY ACADEMIC DEGREE



DISTRIBUTION BY RESEARCH AREA



EXTERNAL COLLABORATORS



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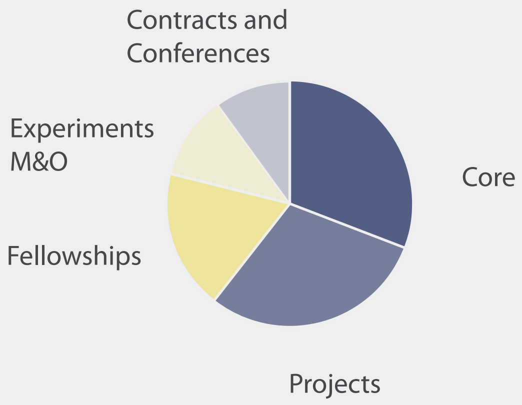
21
TOTAL

GENERAL FUNDING



1.9M
CORE FUNDING

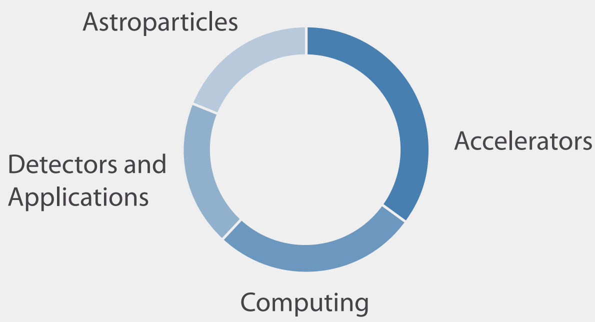
1.4M
PROJECT-BASED

0.64M
FELLOWSHIPS

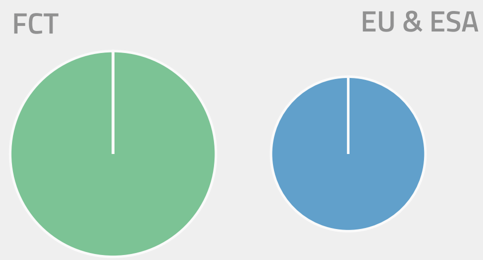
0.4M
EXPERIMENTS M&O

0.34M
CONTRACTS AND CONFERENCES

PROJECT-BASED FUNDING BY RESEARCH AREA



FUNDING BY ORIGIN

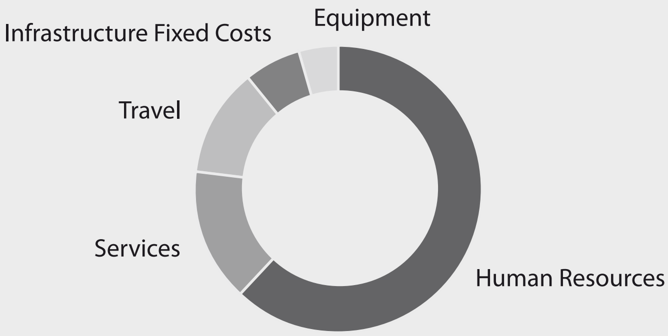


TOTAL
1.4M €

TOTAL
4.7M €

FINANCES

COSTS



HUMAN RESOURCES

STAFF 1.5M

FIXED-TERM RESEARCHERS 1.0M

SERVICES AND OTHER EXPENSES

0.6M

TRAVEL

0.5M

EXPERIMENTS M&O

0.4M

INFRASTRUCTURE FIXED COSTS

0.3M

EQUIPMENT

0.2M

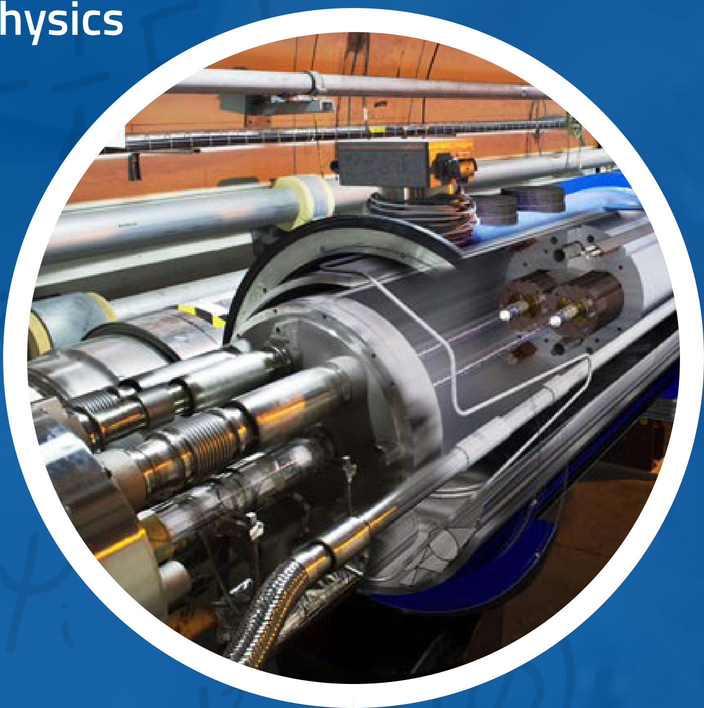
SCIENTIFIC OUTPUT

	Astroparticles	Accelerators	Detectors and Applications	Computing	TOTAL
Books, Reports and Proposals	3	6		5	14
Completed Theses	3	2	2	1	8
Proceedings	6	16	1	1	24
Notes	20	16	1	1	38
Presentations	16	23	8	2	49
Papers in refereed journals	16	200	13		229

Astroparticles
Accelerators
Detectors and Applications
Computing

// RESEARCH

Experimental particle
and **astroparticle**
physics



Developme
new instru
and **method**

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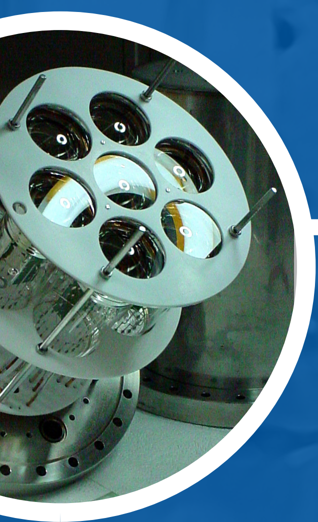
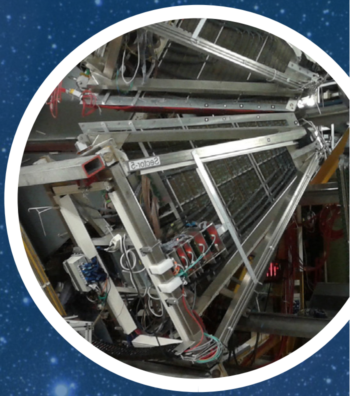


Computing

RESE

Experimental particle and astroparticle physics

Development of new instruments and methods

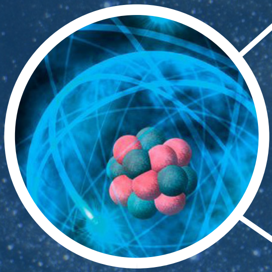


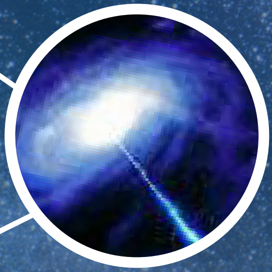
LHC experiments and phenomenology

- ATLAS
- CMS
- LHC phenomenology

Structure of matter

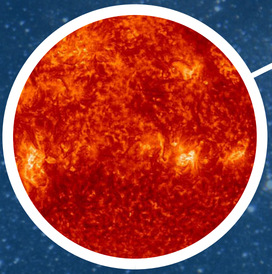
- COMPASS
- HADES





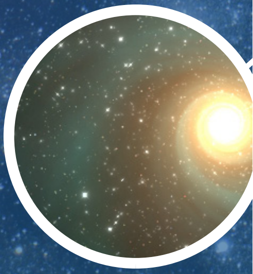
Cosmic rays

- AMS
- Auger



Dark matter and neutrinos

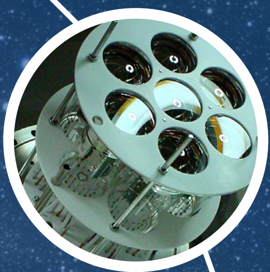
- LUX/LZ
- SNO+



ARCH

Computing

- GRID
- Advanced Computing



Detector development for **particle** and **nuclear physics**

- Neutron detectors
- RPC R&D
- NEXT
- Liquid Xenon R&D
- NUC-RIA

Instruments and **methods** for **biomedical applications**

- RPC-PET
- OR Imaging
- Gamma Cameras
- Dosimetry
- STCD TagusLIP

Radiation environment studies and **applications** for **space missions**

- Space
- A-HEAD

Experimental particle and astroparticle physics

- LHC experiments and phenomenology
- Structure of matter
- Cosmic rays
- Dark matter and neutrinos

Experimental particle physics seeks always deeper into the universe – its constituents and workings at the most elementary level, its origin and evolution.

LIP is deeply involved in the CERN LHC endeavor, contributing from the very beginning to the two largest LHC experiments, ATLAS and CMS. With these fantastic scientific instruments we are studying Nature in many ways, from deepening our understanding of the Higgs boson, to searching for new physics or recreating the conditions that existed just after the Big Bang. To do this in an optimal way we established an LHC phenomenology group, which created crucial links between experimental and theoretical particle physics. At the same time, we are very actively improving our experiments, to respond to the future challenges of running at higher LHC luminosities.

The LIP structure of matter group is currently involved in the COMPASS experiment, designed to study hadron structure, and in the HADES experiment at GSI, studying cold nuclear matter at high densities.

Experimental particle physics is conducted in ever more powerful accelerators, but also in astroparticle physics experiments, detecting particles that come to us from the cosmos. The quest for dark matter, a deeper understanding of the elusive neutrinos, or the origin and nature of cosmic rays are among the great challenges of particle physics for the next decades. LIP is deeply involved in these challenges through its engagement in the Auger, AMS, SNO+ and LUX/LZ collaborations.

EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

LHC experiments and phenomenology

Physics at the energy frontier

Together with its four experiments, the Large Hadron Collider (LHC) is the largest and most complex experimental facility in the world. The highlight of the LHC scientific achievements so far was the discovery of the Higgs boson in the ATLAS and CMS experiments in 2012, a crucial missing piece of the Standard Model (SM) of particle physics. This great discovery resulted in the 2013 Nobel Prize for Physics being awarded to François Englert and Peter Higgs who first proposed the existence of this particle.

After the very successful first data-taking run, the LHC went into a long shutdown in 2013, to increase the beam energy. It resumed operations during 2015 for its second run (LHC run 2) at a much higher centre of mass energy and with a larger reach for discovering new physics. This was the first of three long shutdowns to upgrade the accelerator and detectors, after which the LHC will enter a high luminosity phase (HL-LHC). During this year, the LHC groups at LIP were very active in finalizing the analysis of the data already collected, in commissioning their experiments for the new LHC run, and in studying the phenomenology of relevant theoretical models of new physics in view of the new run.

The heavy weights – Higgs and W bosons and the top quark

During 2015, many Higgs boson related analyses, using data collected before the LHC shutdown, were completed and published. Both the ATLAS and CMS teams at LIP had a strong involvement in this. In addition, phenomenological and experimental studies performed during this year are improving the sensitivity of future analyses.

Currently, the focus of the ATLAS team at LIP is on the Higgs boson interactions with quarks. Contrary to the boson channels, which are already quite well explored, the experimental knowledge of the Higgs couplings to quarks is still poor. The ATLAS search for the Higgs boson produced together with a W or a Z boson and decaying to b quarks was published early in the year [1]. This had important contributions from the LIP ATLAS team, most notably in improving the jet calibration [2] and the resolution of the $b\bar{b}$ di-jet mass peak, which is a crucial variable in the analysis. This analysis resulted in a lower number of Higgs candidates than expected (albeit with a large uncertainties).

Studies at LIP during 2015 focused on the use of new variables to improve the sensitivity in this channel, to increase the reach of future searches.

In collaboration with the LHC Phenomenology group at LIP, the ATLAS team published a study [3] of a novel method to increase the separation between the Higgs signal and the main irreducible background in ttH associated production. In this analysis, a top-quark pair and a Higgs boson are produced together and the Higgs decays to b quarks. The main irreducible background contains events where a b quark-antiquark pair is produced, mainly through gluon splitting, together with a top pair. The new method takes advantage of the different spins of the Higgs boson and the gluon, leading to differences in angular discriminating variables.

The CMS team at LIP had a leading role in the analysis and publication of a search for a charged Higgs boson, $H^{\pm}$ [4]. The existence of this particle is a prediction of several models of physics beyond the SM, and so its discovery would herald a new era in particle physics research. The analysis used proton-proton data collected at a centre of mass energy of 8 TeV and searched for the charged Higgs in top quark decays (in the mass range from 80 to 160 GeV) or produced in association with a top or b quark (for masses between 180 and 600 GeV). The data was examined in search of the $H^{\pm}$ decaying to a tau lepton plus a neutrino or to a top and bottom quark pair. No evidence for this particle was found, and upper limits were determined for the product of its production cross-section and branching ratio. These limits were also interpreted as exclusion limits for the $H^{\pm}$ in several benchmark supersymmetric models which extend the SM.

In connection to this work, the CMS team is strongly involved in the analysis of top-quark events where the top decay products include a tau lepton, which itself decays into hadrons. This builds upon the team's experience with the reconstruction of final states containing taus and is the subject of an ongoing PhD thesis.

Finally, the CMS team has made important contributions to the re-analysis of the W^+W^- production cross section [5] using LHC run 1 data collected at 8 TeV centre of mass energy. The measured value was found to be consistent with the SM expectation, solving a puzzling discrepancy found in a previous measurement.

In 2015 the LHC Phenomenology group continued to work on theoretical models and Monte Carlo generator development on Flavour Changing Neutral Currents (FCNC) and top anomalous couplings. The project allowed to bring together the experimental communities under a common research goal, with the long term objective of exploring in an efficient way the data collected at the LHC. Particularly relevant is the fact that a new branch of LIP was developed at the University of Minho bringing the field of particle physics to the northern universities in Portugal.

The ATLAS team has much experience of searching for FCNC decays of the top quark. An observation of this process, forbidden at leading order in the SM, would give strong indications on the nature of new physics beyond the SM. The team led the search for FCNC decays of top quarks to a u or c quark plus a Z boson, with the Z decaying to charged leptons. The search used data collected in 2012 and its results were published in a paper [6]. No evidence for signal was found and a 95% confidence level upper limit on the branching ratio was established: $BR(t \rightarrow qZ)<7\times10^{-4}$

Into the unknown – Supersymmetry

The supersymmetric extensions of the SM provide natural candidates for new physics, whose existence is heralded by e.g. astrophysical measurements of the mysterious dark matter and dark energy. The CMS team at LIP is deeply involved in searching for signs of supersymmetric partners of the known particles.

The team contributed to the search for the lighter of two supersymmetric partners of the top quark, the *stop*, in data collected by CMS in 2012. This search targeted final states where the stop decays include the lightest chargino and neutralino predicted by the model, and allowed to determine new lower limits for the masses of the *stop* (700 GeV) and neutralino (250 GeV). The corresponding paper was published in early 2016 [7].

Another paper exploring supersymmetric final states in a compressed mass spectrum scenario was concluded and submitted to publication [8]. In this case, events with soft leptons, low jet multiplicity, and missing transverse momentum were targeted. The search used data collected in 2012 and established a lower limit on the stop mass of 316 GeV, at 95% confidence level. This assumes a stop at least 25 GeV more massive than the lightest supersymmetric particle, and a 100% branching ratio for its 4-body decay into a b quark, fermions and a neutralino. The group is also involved in the continuation of this analysis using LHC run 2 data.

The CMS team is also involved in the search for stau and chargino pair production in di-tau final states, notably in the development of new background estimation methods, which were the object of an internal note. This analysis was internally approved by the Analysis Review Committee [9] but not yet made public.

A new generation? – Vector-like quarks

The ATLAS team contributed strongly to searches for new, heavy, vector-like quarks, leading the effort on the Zt/b+X topology and contributing to the global combination effort. Previous searches were updated to the full 8 TeV ATLAS dataset, resulting in several publications.

The team was involved in a search [10] for a new down-type quark, named B, using data from 2012. In the absence of a signal, and depending on assumptions, it arrived at lower B mass limits ranging from 640 GeV to 810 GeV at 95% confidence level. The same analysis can also be re-interpreted as a search for pair production of a hypothetical $T_{5/3}$ exotic fermion with charge 5/3 leading to a lower $T_{5/3}$ mass limit of 840 GeV at 95% confidence level.

Both the B and a corresponding u-like quark, the T, were also searched in 2012 ATLAS data [11] targeting three cases: a T quark with significant branching ratio to a W boson and a b-quark ($TT \rightarrow Wb+X$), and both a T and a B quark with significant branching ratios to a Higgs boson and a third-generation quark ($TT \rightarrow Ht+X$ and $BB \rightarrow Hb+X$, respectively). Lower limits were derived for the masses of the vector-like T and B quarks under several branching ratio hypotheses. The T mass limits, ranging from 715 GeV to 950 GeV, are the most stringent constraints to date.

The ATLAS team was involved in a third analysis searching for a new heavy quark (Q) that decays to a W and a light quark, which is complementary to searches for vector-like quarks that decay to third- generation quarks. The search results are interpreted both in the context of vector-like quarks and a chiral fourth-generation quark, where the latter are excluded at the 95% confidence level for masses below 690 GeV.

Finally, members of the ATLAS team published a paper [13] discussing the interpretation of vector-like quark searches in the case that QCD is not the only relevant production mechanism. It was found that the effects on event topology and kinematics of a new massive color-octet vector boson are washed out at the reconstruction level. Importantly, this indicates that the existing experimental results on vector-like quarks can be reinterpreted in models with heavy gluons by simply rescaling the production cross section.

A needle in a haystack – rare decays

One of the physics highlights in 2015 was the joint observation by the CMS and LHCb collaborations of the extremely rare decays $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$, and the best measurement so far of its branching fraction [14]. The branching ratios in these decays are very sensitive to the existence and nature of new physics beyond the SM. The CMS team at LIP was deeply involved in this analysis, with a member of the group being the main author of one of the two parallel analyses.

The hot universe – hadronic matter and Heavy Ion collisions

Apart from its p-p programme, the LHC is a unique place to study heavy-ion collisions at the highest energies achieved in laboratory conditions. In particular the LHC experiments have confirmed the existence of the quark-gluon plasma.

Hadronic jets in very energetic heavy ion collisions signal the presence of quarks, which cross the quark-gluon plasma medium, and so are invaluable probes for its study. The ATLAS team is deeply involved in these studies, and is preparing a publication summarizing the di-jet asymmetry measurements performed using LHC run 1 heavy ion collisions.

The CMS team has a long history of studies of heavy quarkonium production. The team contributed to the measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons polarization versus the charged particle multiplicity using data collected in 2011 [15]. The corresponding paper was submitted to publication early in 2016.

Tools of the trade - Detector operation and upgrade

In addition to the physics analysis activity during 2015, the ATLAS and CMS teams at LIP were very actively involved in implementing or commissioning several crucial improvements to the experiments. Later, they were involved in detector operations and data quality control. The increased LHC beam energy and expected luminosity in run 2, together with the shorter 25ns bunch-crossing interval, dictated the need for some of the changes. Others are motivated by the longer-term needs of the LHC upgrade.

The ATLAS team has important responsabilities in the TileCal calorimeter, a major subsystem of the detector. The TileCal control software was migrated to a new system and improved, to allow easier replacement of faulty modules and support for future upgrades. A new calibration laser system was installed and commissioned, including a new laser box made in Portugal. This allowed detailed studies of calorimeter linearity and stability to be initiated. The team made a strong contribution to a new hardware trigger system, built to provide muon detection capabilities using the last layer of the TileCal in a pseudo rapidity region poorly covered by the muon spectrometer trigger. This included the production of electronic boards, to act as the interface to the central trigger processor. For the longer term, new electronic boards are being designed for the distribution of high-voltage in the TileCal, to be used during the future high-luminosity phase of the LHC.

The team participated in the beam tests of the Tilecal upgrade prototype and the ATLAS Forward Proton tagging detector, installed around the beampipe in 2016. The team also has important responsabilities on the detector control of the ALFA and AFP forward detectors.

The ATLAS High-Level Trigger was re-commissioned after undergoing deep modifications. It changed from two processing levels running in different CPUs to a single processing level, leading to the re-writing of the jet trigger software. LIP made important contributions to this upgrade, including a strong input to the new system design and organization, the new trigger menu, the system commissioning and operations. The team has also made an important R&D effort on the parallelization of trigger algorithms to be run on Graphic Processing Units (GPU) for the first phase of the LHC upgrade.

The CMS team is a long-standing contributor to the electromagnetic calorimeter (ECAL) data acquisition system and the trigger, and has made leading contributions to its operation and upgrade in the last year. It installed and commissioned the optical serial link boards (oSLB) that interface the ECAL electronics to the trigger system.

The LIP group is a leading contributor to the new CMS-TOTEM Precision Proton Spectrometer detector (CT-PPS), to be installed around the beampipe near the CMS experiment. In 2015, three electronic boards have designed for the readout of this detector, two of these under LIP's responsability. LIP also contributed to the CT-PPS testbeam activities and leads the development of its data acquisition system.

Finally, the ATLAS and CMS teams were responsible for the operation of the Portuguese Federated Tier2 in the Iberian Cloud, which delivered a capacity in excess of expectations, with very good reliability and availability metrics.

Event organization

In 2016, the LIP LHC teams organized the following events in Portugal:

TWEPP 2015 - Topical Workshop on Electronics for Particle Physics, in Lisbon.

Workshop on New Physics Search in the Top Quark Sector, in Braga.

ATLAS Trigger GPU Demonstrator Sprint, in Lisbon.

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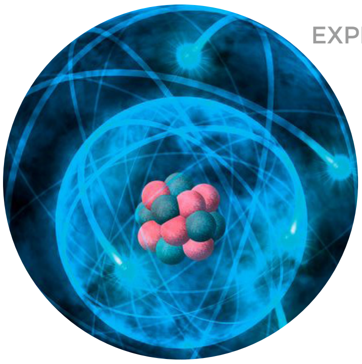

EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

Structure of matter

Looking inside hadronic matter

Knowing the properties of the elementary particles and the way in which they interact is knowing what we are made of. The properties of quarks and gluons must determine the properties of protons and neutrons and, as a consequence, of the atoms themselves. And we still have a lot to discover about the ways in which elementary quarks and gluons work together to form the particles we observe, from the proton to a variety of more exotic hadrons. The LIP structure of matter group is currently involved in the COMPASS experiment, designed to study hadron structure, and in the HADES experiment at GSI, studying cold nuclear matter at high densities.

COMPASS

Researchers at LIP study how quarks and gluons group together to form nucleons and other known hadrons in the COMPASS experiment at CERN.

Major aims of the experiment are to discover how quarks and gluons contribute to the spin of the proton and to investigate the spectrum of particles that quarks and gluons can form.

To do so, they collide high intensity muons or π meson beams and a fixed polarized target at a temperature of -273 °C, very close to the absolute zero, and observe the particles that result from these collisions. These experiments use beams from the SPS accelerator (super proton synchrotron). The target is followed by a two stage spectrometer: a first stage with a large angular acceptance, and downstream a second one with a reduced acceptance, designed to detect particles up to more than 100 GeV/c.

Detector Control System

The LIP group is fully responsible for the Detector Control System (DCS). Over the years, the COMPASS DCS has continuously evolved, in order to accommodate the required complexity while promoting flexibility, reliability and speed.

In 2015, the DCS integrated new and refurbished COMPASS detectors, in view of the long polarized Drell-Yan data taking run. This included the developments concerning the new polarized ammonia target. The DCS system must be in operation practically 12 months per year. Even during the no-beam part of the year, in order to control devices like the detectors gas systems.

Data Analysis and Offline Studies

The previous COMPASS programme, which lasted untill 2011, focused on the measurement of the gluon polarization, of the longitudinal and the transverse quark spin structure, and of fragmentation functions. The LIP group strongly contributes to key data analysis subjects of this programme. Results concerning these matters have been published in much cited international reviews [1,2,3]. New analysis methods were also developed, in order to increase the measured precision. With a hadron beam, COMPASS studied the pion polarizabilities and various spectroscopy issues, such as the production of new mesons and baryons, namely exotics or hybrids.

In the context of the present COMPASS programme, the analysis subjects carried out by LIP members are among the top priority analysis channels of the experiment. In 2015 the subjects addressed included detailed and refined studies of spin asymmetries, fragmentation functions, transversity (namely transverse momentum dependent parton distribution functions) and gluon polarization studies.

The Drell-Yan run

In the Drell-Yan process, a pair of leptons is created from the anihiliation of a quark and an antiquark, in hadron-hadron collisions. The process provides valuable information, on parton distribution functions - the sharing of the hadron momentum among its constituent quarks and gluons.

In 2015, a COMPASS data taking period lasting several months was dedicated to Drell-Yan. The LIP group has developed studies concerning the preparation of the experiment, namely the optimization of the reconstruction programme, preparation of data production and analysis, dimuon trigger design and optimization, performance and timing, detector alignment and calibrations. Presently, LIP coordinates the data reconstruction and the data analysis of the Drell-Yan physics run. The polarized Drell-Yan process measurement was a world first.

HADES

The HADES high acceptance spectrometer at GSI is design to study cold nuclear matter at high densities [4,5]. It is is a versatile detector for the precise spectroscopy of e+e- pairs (dielectrons) and charged hadrons produced in proton, pion and heavy ion induced reactions in a 1-3.5 AGeV kinetic beam energy region. Dielectron pairs originating from in-medium hadron decays, and rare strange hadrons (kaons, hyperons), are the main probes measured in the experiment.

After several successful data taking campaigns, including the heavy system Au + Au run in 2012 and pion induced reactions in 2014, the accelerator infrastructure has been shut down for a complete upgrade. This upgrade will put into operation the future SIS100 in the framework of the FAIR facilities, providing higher beam energies and intensities. HADES will be one of the first experiments to be operative in the new infrastructure, with the mission of providing high-quality di-electron data at baryon densities and temperatures not accessible to other detectors, neither in the past nor in the foreseeable future.

Hardware responsibilities

The main contribution of the LIP team was the design and construction of a high granularity, high resolution Time of Flight (TOF) wall based on timing Resistive Plate Chambers (RPC). This new system reduced the limitations imposed to the spectrometer by the old scintillator based TOF, that prevent HADES from doing measurements with heavy systems, a fundamental part of the physics program. The RPC-TOF wall has been running within specifications and flawlessly during all campaigns and it is, most probably, the detector of this kind with best performance in the world. LIP team has the responsibility of the RPC operation and optimization in HADES. Even during the 2015 shutdown, the detector was kept powered and running, due to its intrinsic characteristics. This required its continuous operation and maintenance. The team is also collaborating actively with the ECAL group on the installation of the new electromagnetic calorimeter of HADES, which will have a huge impact on the RPC detector since it will be supported on the ECAL frame.

Data analysis

The LIP team is involved in the electron identification, where a new method based on a dynamic neural network has been proposed. This algorithm achieved an identification purity of 97% while keeping a reasonable lepton efficiency of 75%. Furthermore, detailed studies of the efficiency and acceptance corrections were performed. These corrections will be applied to the di-lepton mass spectrum. Concerning the physical background, several simulation studies were performed with the purpose of removing the di-lepton contamination resulting from photon conversion in the spectrometer.

Event organization

Concerning management and organization, the group organized in October 2015 one of the collaboration meetings of the year, held in Estoril.

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EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

Cosmic rays

Messenger from outer space

Planet Earth is constantly being struck by cosmic rays - particles expelled by distant stars and galaxies. Most of these particles have very low energies. But, very rarely, once per km² per century, particles reach us with energies thousands of times greater than that of the most powerful accelerators. When these particle collide with atoms in the atmosphere they produce showers of billions of new particles. These messengers from outer space bring much information about the history and composition of the Universe.

Cosmic ray physics is an active field of research, with many ongoing experimental projects addressing some of the most compelling questions in science today. The very wide range of energies of cosmic rays implies that different detection methods are used, from space-based experiments in the GeV-TeV, range to ground-based giant air shower detectors in the EeV range. The LIP cosmic ray group covers much of this range as it is committed to both the Pierre Auger Observatory and to the Alpha Magnetic Spectrometer (AMS) experiments. These address the origin, nature, acceleration and propagation of cosmic rays. The LIP group is deeply involved in data analysis in both experiments and has unique conditions to play a leading role in R&D of cosmic ray detectors.

AMS: A complex particle detector in space

The AMS Spectrometer is installed in the International Space Station, orbiting the Earth since 2011. This detector can identify cosmic ray particles before these interact with the earth's atmosphere. AMS studies cosmic ray fluxes in detail, but it also searches for antimatter nuclei and dark matter in the universe [1,2].

LIP is part of this project from its start and contributed to the construction of the RICH sub-detector. Today, the team is involved in the performance improvements, detector monitoring, reconstruction algorithms, and in the exploitation of the huge physics potential of the AMS data. The experiment is expected to continue up to at least 2024.

RICH performance and reconstruction

The LIP group took part in the design, construction, simulation and data reconstruction activities of the RICH subdetector. Today, the group has responsibilities in its monitoring and operation, from the payload operation control center at CERN, and cares for the RICH - specific reconstruction (velocity resolution studies and reconstruction performance monitoring)

AMS data analysis and phenomenology

The LIP team is involved in analysing the time variability of the low-energy fluxes in AMS, and their interpretation under solar modulation models. In fact, AMS was launched during a minimum of solar activity, and a maximum has already been reached. The LIP team conducted phenomenological studies of cosmic ray propagation, and developed an algorithm for deuteron/proton separation based on the response of the different AMS detectors.

Auger: the most energetic particles in the Universe

The Pierre Auger Observatory consists of 1600 detectors, spread across and area of 3 000 km², and 27 telescopes that detect the ultraviolet light emitted by cosmic ray induced showers.

The Observatory is taking data since 2004, and a number of breakthroughs have been achieved. In particular, a suppression of the cosmic ray flux above shower energies of 5×10^{18} eV has been firmly established, and there are indications of an anisotropy in the cosmic ray arrival directions at the highest energies. Nevertheless, several open questions remain concerning the nature and origin of the highest energy cosmic rays.

In November 2015 the science funding agencies and the main laboratories signed, at Malargue, Argentina, the renewal of the international agreement of the Pierre Auger Observatory, assuring its continued operation until 2025. For Portugal, both FCT and LIP signed the agreement, in the presence of the Portuguese ambassador in Argentina.

Data analysis & phenomenology

The LIP group is mainly focused on the full exploitation of the particle physics potential of the Observatory, namely on the efforts to understand hadronic interactions at high energies through a window that is largely complementary to the LHC. The team has acquired a deep knowledge of shower physics and has developed innovative analysis methods and tools. This will allow us to give relevant contributions to the analysis of the new Auger data. In particular, the team is involved in the measurement of the fluctuations on the number of muons in inclined showers and of the mean shape of the lateral density function of the high energy cosmic ray data. The first measurement of the average longitudinal profile shapes of the showers (described by two new independent parameters sensitive to the primary shower composition) was presented at the 2015 International Cosmic Rays Conference. A new method to interpret the number of muons measured in extensive air shower experiments was developed. This method is able to verify mass composition scenarios almost independently of the absolute energy scale and the standard high energy hadronic interaction models [3,4].

Detector upgrade and R&D

A minimal upgrade plan for Auger has been approved by the collaboration, with the goal of enabling a better understanding of the electromagnetic and muonic shower components. It foresees the installation of scintillators on top of the present surface detectors and the replacement of their readout electronics.

In the last few years, LIP has been deeply involved in the development of autonomous low gas flux, low cost, large surface RPC detectors, in a project called MARTA. More than 20 such detectors were produced at LIP-Coimbra and 6 are working successfully in Malargue. The MARTA concept (combining the Auger surface detectors with RPC) was not selected for the full Auger upgrade, but will be used to obtained a deeper understanding of the surface detectors, for the validation and in situ test of the scintillation detectors and for detailed shower studies at lower energies (10^{18} eV). A MARTA engineering array of 8 surface detectors (and 36 RPC) will be built in a close collaboration between Portugal and Brazil. MARTA detectors are also being installed at the CBPF in Rio de Janeiro. Their use in a future large field of view gamma-ray observatory at very high altitude in South America (the LATTES project) is under study.

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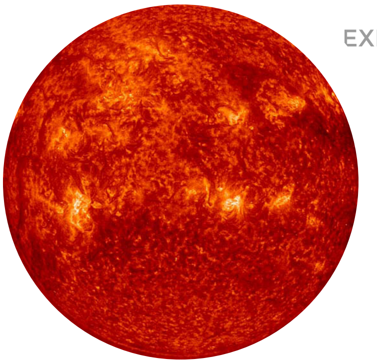

EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

Dark matter and neutrinos

Hunting for the most elusive particles

What do neutrinos and dark matter have in common? They are searched for in deep underground detectors that other particles can't reach. Only in such clean, background-free environments one can try to better understand the properties of the elusive neutrinos, which interact only through the weak force, or look for direct hints of the still undetected dark matter particle. In the present generation of highly sensitive detectors, neutrinos also become a relevant background for dark matter searches.

Through its engagement in the LUX/LZ and SNO+ collaborations, LIP is deeply involved in quest for dark matter and for a deeper understanding of the elusive neutrinos, two of the great challenges in particle physics for the next decades.

Search for dark matter

According to the most recent experimental evidence, dark matter makes up 27% of the total density of the Universe. We have strong clues that dark matter is made of particles that interact very weakly. One of the ways to search for it is to use super-sensitive underground detectors to identify very rare interactions between dark matter particles that cross Earth and normal matter particles.

LIP is part of the LUX collaboration, which operates the Large Underground Xenon detector.We also work on the preparation of the LZ (LUX-ZEPLIN) experiment, which will be the most sensitive dark matter detector in the world.

LUX

After having obtained a world-leading limit for the spin-independent WIMP-nucleon elastic scattering cross-section, which has received enormous interest from the scientific community, LUX started a new science-data acquisition period in September 2014. Since then, LUX has been collecting science data, with periodic calibrations. An improvement in sensitivity by a factor of 2 to 3 is expected from this run. Prior to the start of this run, several improvements in the calibration of the photomultipliers and detector, as well as various advances in modeling the background, have motivated a reanalysis of the data from the previous run. The result was accepted for publication in Physics Review Letters [1].

LZ

The LZ project [2] proposes a 7-ton xenon detector using the same technology as LUX. The LZ Concept Design was approved by the U.S. Department of Energy in April 2015. This triggered the procurement of xenon, photomultipliers and titanium for the detector, and the preparation of the Technical Design Report that is expected in April 2016. After that, the fabrication of the detector and auxiliary systems will be started. The underground deployment of LZ is scheduled to begin in July 2018. We hope that LZ will be able to identify the recoil of xenon nuclei, when struck by WIMPs. The detector will be sensitive enough to identify the movement of xenon nuclei caused by neutrino collisions. It uses simultaneously liquid and gaseous xenon to obtain two different dark matter signatures, so that it can be distinguished from background noise.

2015 activities

The main responsibilities of the LIP team are the LUX and LZ detector control systems, the LUX data processing framework, the vertex reconstruction methods, data analysis tools for LUX and LZ, and the modelling and GEANT4 based simulation of the background in LZ.

In 2015, the architecture of the slow-control system for LZ was chosen and the implementation started. The inner-surface reflectivity is strongly dependent on the manufacturing process and the ultimate sensitivity of the LZ detector critically depends on its value. The LIP team has world-wide recognized experience in liquid Xenon detectors and is involved in reflectivity measurements for selecting the best materials for the LZ detector. During the second LUX science run we made key contributions to the modeling of the background events and to the position reconstruction of the recoil events [3]. This was crucial to achieve the improved limit on the WIMP-nucleon cross-section. The team was part of a task force dedicated to studying the LZ sensitivity to detect neutrinoless double-beta decays.

Detecting neutrinos

After photons, neutrinos are the second most abundant particle in the Universe. Neutrinos practically don't interact with matter and, for this reason, are extremely difficult to detect. They can easily cross the Earth and stars without being disturbed, and so can travel enormous distances, bringing important information about the Universe.

SNO+

The Sudbury Neutrino Observatory (SNO) was an experiment that measured the oscillations of solar neutrinos, i.e., their transformations from one type to another. The detector is located 2 km deep underground, in SNOLAB, Canada. An acrylic sphere with 12 m diameter and 5 cm thickness, that contained 1000 tons of heavy water, is surrounded by 9500 light sensors. The SNO+ experiment follows from SNO, by replacing the heavy water with liquid scintillator, increasing the sensitivity to other neutrino physics signals.

The LIP Neutrino Physics group joined the SNO experiment in 2005, and is a founding member of the SNO+ international collaboration. The main goal of the experiment is the search for neutrino-less double-beta decay, by loading the scintillator with large quantities of Tellurium. Several other low-energy, low-background, physics topics are also part of its program: antineutrinos from nuclear reactors and the Earth's natural radioactivity, solar and supernova neutrinos, and searches for new physics.

2015 activities

In 2015 The LIP team was deeply involved in the detector calibration, having responsibility for the optical fiber-based system used for photomultiplier calibration and a part of the internal calibration source insertion system. The main design work for this system was finalized in 2015, and production and testing started. Among the tasks related to optical calibration [4,6], work proceeded in the preparation of the water phase data taking. Concerning detector and data-taking performance, the LIP team was particularly dedicated to data quality and detector modeling algorithms. Finally, the team contributed to the preparation of the analysis of physics data, namely studying backgrounds for double-beta decay, both internal and external, and also antineutrino signatures.

In terms of detector installation, SNO+ activities in 2015 were strongly affected by a severe water leak in the detector cavity, found in November 2014. A large-scale search campaign for the location of the leak was undertaken by the collaboration, and our group participated in that effort in August. By the end of 2015 the leak was identified and repaired, and water filling has resumed. In 2016, installation activities will continue in the spring, and the water data taking phase is expected in Summer/ Autumn. The liquid scintillator phase is planned for 2017. During this year the group's activities will correspondingly change focus, from construction and preparation of calibration systems and analysis software to the deployment of sources, and commissioning data analysis [5,7].

Awards

2015 was a remarkable year for Neutrino Physics. The Nobel prize in Physics was awarded to Arthur McDonald and Takaaki Kajita, for the discovery of neutrino oscillations. LIP is proud to have been collaborating with Arthur McDonald since 2005, through the participation in the SNO and SNO+ experiments. The Nobel prize was followed soon after by the 2016 Breakthrough Prize in Fundamental Physics, that was shared by all members of several collaborations, again for the discovery of neutrino oscillations. Three current members and a former member of the LIP group were among the recipients. These awards are very important in raising awareness of Particle Physics in the general public: a dedicated web page was prepared, and members of LIP gave interviews to several mass media – TV, radio, newspapers, websites – and gave 8 seminars in different Universities in the whole country.

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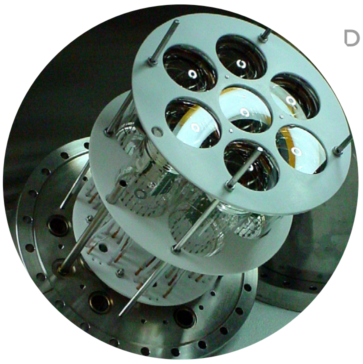
Development of new instruments and methods

- Detector development for particle and nuclear physics
- Instruments and methods for biomedical applications
- Radiation environment studies and applications for space missions

Radiation detectors are sensitive to the passage of particles and able to measure some of its characteristics. Throughout the history of particle physics, the development of ever more powerful detection technologies has played a crucial role in fostering new discoveries. Detector development involves not only the detecting device itself but the associated data acquisition and readout electronic system, as well as trigger and data processing tools.

The development of new instruments and methods related to experimental particle physics has been from its inception one of the main pillars of activity at LIP. Over the years, LIP has built a high level of expertise in key radiation detection technologies, supported by research on the fundamental processes involved. Our current activities can be divided into research on fundamental detection processes and on applications of radiation detectors, where the latter include our specialities in Resistive Plate Chambers (RPC), Patterned Gas Detectors (PGD) and Xenon-based detectors, as well as the development and operation of radiation detection systems for medical and space applications.



DEVELOPMENT OF NEW INSTRUMENTS AND METHODS

Detector development for particle and nuclear physics

Technologies to see the invisible

The development of new instruments and methods related to experimental particle physics has been, from its inception, one of the main pillars of activity at LIP. Over the years LIP has built a high level of expertise in key radiation detection technologies, supported by research on the fundamental processes involved.

RPC R&D

Due to their fast response, intrinsic radiation hardness and relative low cost per unit area, Resistive Plate Chambers (RPC) feature in many nuclear and particle physics experiments. This is a flexible technology, easily adaptable to many types of applications. It is also a speciality of LIP's detector development group. Besides the development of RPC-based detectors, the team keeps an interest in the physical modelling of RPCs and in fundamental issues such as gas mixture properties and detector aging.

During 2015, the team was involved in the construction of a large area (2 m^2) 3-layer cosmic-ray telescope, the TOFtracker. The system was built and tested, showing encouraging performance. A commercial application of this system is being envisaged, in the inspection of cargo containers in sea ports.

Other RPC based systems were installed in CBPF in Rio de Janeiro, Brasil, and at the Santiago de Compostela University in Spain, for the TRAGABALDAS collaboration [1]. The team also continued to support the operation of several chambers [2] in harsh field conditions at the site of the Auger experiment in Argentina, and performed several beam tests of large scale prototypes [3,4].

The LIP team has developed several other activities, such as high-rate studies within the AIDA2020 project, developments for thermal neutron detection, and studies in view of the development of RPC-based Positron Emission Tomography (RPC-PET) for human use and for medical research.

Neutron Detectors

There is a widespread need for ^{3}He free Position Sensitive Neutron Detectors (PSNDs) with enhanced performance for applications ranging from neutron scattering science (NSS) to homeland security and well logging. The European Spallation Source (ESS), currently under construction, is a prime example and a driver of such need for high performance PSNDs to fully explore all its potential. Neutrons as a non-ionizing radiation cannot be detected directly, but only through the reaction products in converter materials. Only a few isotopes can be used for this purpose, with ^{3}He being the most commonly used. Nowadays, however, the ^{3}He crisis resulted in a change of paradigm which poses demanding challenges to develop new types of ^{3}He free neutron detectors, capable of satisfying high performance standards.

Boron-10, with a thermal neutron capture cross section close to the ^{3}He one, and with an occurrence in natural boron of ~20%, which has an average abundance on Earth, is one of the most promising alternative candidates to ^{3}He. However the maximum detection efficiency achieved with a single layer of a solid neutron converter such as $^{10}B_4C$, is only ~5%. To surpass this limitation one option is to cascade the converter layers. A considerably high number of thin layers is needed to attain high detection efficiency. As a solution to face this challenge the LIP team proposed a new detector concept based on $^{10}B_4C$ coated RPCs, which takes advantage of the naturally layered configuration of RPCs.

After a first round of preliminary tests on the operation of RPCs with B_4C coatings [5], and having demonstrated that and adequate B_4C layer can be introduced into a thin-gap RPC, the LIP team has designed and built a detector prototype with optimized layers of $^{10}B_4C$ (enriched in ^{10}B) deposited by DC sputtering onto the RPC electrodes [6]. The feasibility of the proposed concept was successfully demonstrated in a monochromatic thermal neutron beam at ILL, Grenoble, which has shown e.g. sub-millimeter resolution capability. The work developed at LIP is now integrated into the Horizon-2020 EU research project, Science & Innovation with Neutrons in Europe in 2020 (SINE2020).

High-pressure Xenon doped mixtures for the NEXT collaboration

LIP collaborates in the NEXT neutrinoless double-beta decay experiment [6], whose observation would establish neutrinos to be Majorana particles. After decades of fruitless search for this process, a competitive experiment now needs a significant amount of double-beta emitting isotope, in addition to a very low background. Besides the obvious physics interest, our team is dedicated to study the optimal gas mixture for use in the NEXT detector: a large electroluminescence time projection chamber containing $\beta\beta$-emitting 136Xe and using both the charge and light signals produced during charge multiplication.

In the past year, the team has studied several aspects of the behavior of Xe/TMA mixtures, namely charge multiplication, scintillation yields and mobility of the ions in the parent gas. The main challenge consists of finding a Xe-based gaseous detection medium that will have low diffusion coefficients and high drift velocities, while maintaining a very good energy resolution. Several additives were targeted (CF4,CH4,TMA,TEA) and studied experimentally and with Monte Carlo simulation, focusing on charge multiplication and electroluminescence yield. The challenging experimental measurements using TMA, which was thought to be particularly promising, showed some degradation in electroluminescence yield [6-9], and so the search for the optimal solution continues.

Simulation studies of the detector gain, efficiency and energy resolution were made using the GEANT4 and Maxwell codes, and the results of this simulation used to optimize the design of the prototype detector. An experimental system was also projected, designed and constructed to study the dependence of the photocathode quantum efficiency on gas pressure and on the angle of incidence of light, important factors in the detector performance.

Liquid Xenon R&D

Another speciality of LIP are detectors based on the use of liquid xenon (LXe) as the active material. The high density of LXe and its high interaction cross sections with ionizing radiation make it an ideal detection medium for many applications, such as gamma radiation and dark matter searches. Although the energy ranges of interest of these experiments are different, from the detection point of view they have very much in common.

During the past year, the LIP team has studied the possibility of using wavelength shifting materials in contact with liquid xenon, in particular tetraphenylbutadien (TPB). Although xenon scintillation light can be detected using photomultiplier tubes with quartz windows, the use of wavelength shifters would widen the possible choice of photon detectors (for example silicon photomultipliers). However, stability of organic wavelength shifters in contact with liquid xenon has long been questioned.

Three main methods have been used to characterize the exposed samples and compare them with the control ones: electron microscopy (for possible structural changes), XPS (for chemical degradation) and UV-visible light transmission measurements (to detect possible layer by layer removal of the material). The first two methods gave negative results but the increase in transmission of the exposed samples allowed to conclude that there is indeed dissolution of TPB molecules in liquid xenon. This was the first direct proof of the degradation of organic films in contact with liquid xenon, and shows that the use of TPB in direct contact with liquid xenon must be avoided in detectors.

Scintillating Detectors and Optical Fibres

LIP has expertise in detectors based on radiation hard scintillators and scintillating or wavelength-shifting (WLS) optical fibres. In the past we have contributed to the ATLAS Tilecal calorimeter and we are now involved in R&D for its upgrade, in which a set of special scintillators located in the calorimeter gap and crack areas, and the respective WLS fibres, will be replaced. In addition, we contributed to the STIC luminosity detector of the DELPHI experiment, to the ALPHA ATLAS luminosity detector, and to the RD52/DREAM fibre calorimeter project.

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DEVELOPMENT OF NEW INSTRUMENTS AND METHODS

Instruments and methods for biomedical applications

From physics labs to the hospital

LIP's expertise in planning, building and operating detectors for particle physics finds a natural application area in the fields of medical imaging, radiotherapy instrumentation and dosimetry. In fact, particles have been used in medicine ever since the discovery of X-rays. Today, particle accelerators and detectors are used in clinical treatments and to look inside the human body. These applications require truly multidisciplinary collaborations, combining the skills of physicists, doctors, radiologists, engineers and programmers.

Ongoing projects include the development of RPC-based PET scanners, adaptive algorithms for gamma-camera image reconstruction, a new system for dosimetry in mammography tests, a method to produce an image of a tumor's morphology in real time for patients undergoing radiotherapy, and a spin-off company dedicated to the development of a PET scanner based in scintillating crystals.

RPC-PET

Positron emission tomography, or PET, is an extremely sensitive technique of medical diagnosis. A marker containing a radioactive substance is injected in the patient's body, releasing positrons by radioactive decay in the zone to study. When the positrons encounter electrons from neighboring molecules, they annihilate, producing two very energetic gamma photons travelling in opposite directions. These photons are identified by a ring of detectors, to create detailed images of the organism and to monitor dynamic processes. The detectors, electronics and algorithms for image reconstruction used in PET are similar to those developed by particle physicists for their experiments.

RPCs, with their good uniformity, excellent spatial and time resolution and low cost per unit area, offer a radically different alternative to the usual crystal-based gamma detection systems, and a dramatic increase in the field of view [1]. Already two avenues of development were identified: high-sensitivity, whole-body human PET, and high-resolution animal PET.

The first RPC-PET scanner for mice has been installed at the site of our collaborators at ICNAS (an institute of the University of Coimbra dedicated to Nuclear Medicine) since August 2014. Dozens of examinations of mice and rats have been performed by the ICNAS team for clinical research. The scanner installed at ICNAS was continuously upgraded, driven by the user demands, and is already in use for the study of the molecular mechanisms subjacent to the Alzheimer, Parkinson and Huntington neurodegenerative deseases in mice models. The radiopharmaceuticals include FDG (metabolism) PK11195 (inflammation), PiB (beta-amiloide deposition) and Cu-ASTM (oxidative stress).

On the human PET front, the basic structure of the scanner was long ago designed and simulated and a general test of the readout system is now under way. The LIP group, in conjunction with its partners, has the necessary competences to develop all elements of the RPC-PET scanners, including evaluation.

Gamma cameras: from dark matter to the hospital

Adaptative algorithms developed at LIP for position-sensitive neutron and dark matter detectors have been used in medical imaging devices. They were used to improved the calibration of gamma cameras, used for instance in cardiology tests. During the past year, the LIP team has shown that the detailed photomultiplier response functions required by the method can be obtained automatically from a flood irradiation of the camera area [2].

The prototype of a compact gamma camera with silicon photomultiplier readout was built and its performance was studied. Machine learning algorithms for position and response reconstruction was focused on two methods: artificial neural networks (ANN) and k-nearest neighbour (k-NN). Both methods were incorporated into the LIP ANTS2 software package.

The next step will be the development of the working prototype with characteristics comparable with the industrial standards. In a parallel line of work, we are performing R&D in a view of developing a compact high-resolution gamma camera for small animal imaging. We collaborate with medical imaging units of Coimbra University (ICNAS and AIBILI) and Coimbra University Hospital.

Orthogonal ray imaging

A LIP project developed in partnership with two Portuguese Oncology Institutes and several medical centers aims to improve traditional radiotherapy by optimizing the treatment in near real time, so that the irradiation can better accommodate the tumor and spare surrounding healthy tissue. To do this, we make use of X-rays emitted orthogonally to the treatment beam and detected by a multi-slice scintillating detector, which is currently in construction. Preliminary simulation studies have shown that 4 to 10% dose deviations can be prevented in head or lung tumor treatments depending on conditions like edema, tumor progression/regression, or the patient having a cold [3].

The project is moving forward in two fronts at LIP Coimbra: adaptation of the simulation code in Geant4 to the DICOM medical imaging data format, to enable the computation of real treatment plans; and measurements of dose values in treatment conditions obtained so far. Finally, a third working front is the construction at the precision mechanical workshop of LIP of an OrthoCT prototype made of 200 GSO crystals for the imaging of a heterogenous phantom. This imaging experiment should occur in the next 1 to 1.5 years. The rotation-free and low-dose imaging capability of OrthoCT are two of its more promising strengths.

Dosimetry

Researchers at LIP have develop dosimeters to measure the amount of radiation that patients are subject to in clinical examinations. This monitoring is essential to protect the patient from over-exposure due to repeated exams or faults in the equipment.

During 2015 the project had two main tasks: the development of scintillation detectors for medical applications; and the development of radon detection techniques and environmental radon survey. A plastic scintillator connected to a PMMA optical fiber, read by a photomultiplier was tested in a PMMA phantom under the X-ray beam produced by a Siemens Mammomat tomograph (Hospital da Luz, Lisbon) used for Tomosynthesis. The device showed a linear response with dose for beams of 26 and 36 kV and no relevant energy dependence [4].

Finally, in an environmental radon survey conducted by LIP's dosimetry group, the radon concentration in water sources of public drinking of Covilhã's County was assessed. In this study 30/33 assessed samples had radon concentration levels above the safe limit of 11.1 Bq/L recommended by the United States Environmental Protection Agency.

STCD – Spin-off technology for cancer diagnosis

The STCD group was created in 2004 around the development of a new Positron Emission Tomography scanner (ClearPEM) for breast cancer diagnosis, exploiting technologies developed at LIP for the CMS experiment at the LHC. Scientific research, technological development and laboratory testing of new PET scanners is pursued at the laboratory infrastructure TagusLIP. The ClearPEM project was developed by a national consortium of research institutes and clinical centers under LIP's leadership. The consortium collaborated with institutes of the international Crystal Clear Collaboration, namely CERN Switzerland, INFN-Milano Italy, Univ. Hospital Nord Marseille France, Hospital San Gerardo Monza Italy.

In 2011-15 the LIP/STCD group was part of the EndoTOFPET project and the associated Marie Curie Training Network PICOSEC funded by the European Union. This project developed a PET detector for detection of prostate and pancreatic cancer. LIP coordinated Work Package 4, responsible for the electronics and data acquisition systems. In this context, LIP developed innovative electronics with good time resolution for Time-of-Flight PET. This technology was licensed to the spin-off PETsys. The laboratory infrastructure TagusLIP at the science park Taguspark is shared by the PETSys and STCD.

The research lines pursued by the LIP/STCD group are: the development of new gamma ray detectors with improved performance for PET Time-of-Flight; development of new front-end and data acquisition systems, including electronics, firmware and software; construction and exploitation of demonstration PET scanners based on the above technologies, associated calibration and image reconstruction software; and the development of detectors for other medical imaging applications [4,5].

The group continues to give technical support to the operation of two ClearPEM scanners (installed at ICNAS Coimbra and Hospital S. Gerardo Monza), and two EndoTOFPET detectors (installed in Cerimed Marseille and TUM Munich) which are being used in clinical research.

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DEVELOPMENT OF NEW INSTRUMENTS AND METHODS

Radiation Environment Studies and Space applications

Into outer space

The line of activity, "Radiation Environment Studies and Applications for Space Missions", has two groups, one based in Lisbon and another based in Coimbra. Both groups have strong competences in the development of tools and studies based on the Geant4 simulation toolkit for space applications, and in instrumentation for space. The "Space Radiation Environment and Effects" group, based in Lisbon, has been developing tools and detector concepts concerning mostly the charged particle environment in heliosphere missions, both planetary and orbital. It has also studied the damage that radiation sources can cause in electronic circuits, through modelling and tests. The group has mainly worked in the framework of contracts with the European Space Agency (ESA). The "LIP Coimbra Astrophysics Instrumentation Group" has strong competences in the development of detector concepts for polarized x- and gamma-rays. It is now part of the AHEAD consortium for the promotion of the domain of high energy astrophysics at the European level, assuring that the high energy astrophysics community will present solid proposals to future ESA mission calls.

LIP also collaborates with the EFACEC company in the contract for the data analysis of MFS, the Multi-Functional Spectrometer, a radiation monitor aboard the AlphaSAT, the largest ESA telecommunications satellite, in Geostationary Orbit since July 2013. During 2015, the data analysis methods for extracting charged particle spectra from the MFS data were finalized and presented for the first time at the 2015 International Cosmic Ray Conference.

LIP leads the work in the ECo-60 contract for validating tests of several types of electronic components for the JUICE mission, where they will be exposed to the hard Jovian electron radiation environment. During 2015 the system for irradiating components was developed at LIP, and the irradiation with electrons and ^{60}Co gammas will be performed in 2016.

The development of the CODES integrated framework for ESA, a top level web based engineering tool, which uses GEANT4 to predict Single Event Effects in electronic devices, was finished in 2015. The framework will be made available to the community in the first semester of 2016.

The exploitation of dMEREM, the detailed Martian Energetic Radiation Environment Model, based in Geant4, which was developed by LIP for ESA, continued with studies of the radiation environment in the Martian sub-soil and of the radiation exposure of crews in possible scenarios for future manned missions to Mars.

Within the Horizon-2020 AHEAD project, started in September 2015, the LIP team focuses on instrument simulations, to determine the optimal configuration of future high-energy space telescopes.

The Coimbra team is also involved in the XIPE (X-ray Imaging Polarimetry Explorer) mission proposal, which was one of three pre-selected for further study by ESA in 2015. One mission will be selected in June 2017, to be launched by 2026. In 2015 the team analyzed the effects of proton irradiation on a pixelated CdTe detector matrix, at the ICNAS facility. In addition to the main activation products, the team established that radiation damage did not affect detector performances for a satellite life-time dose equivalent. Multi-pixel polarimetric analysis methods and techniques were implemented for a CdZnTe prototype and were validated both by simulation and experimental methods.

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Computing

Computer science is a fundamental tool in modern research. LIP develops novel ICT technologies and operates advanced services to support demanding scientific applications. As an example the LHC experiments have to process about 8000 Terabytes of data per year, this data must be analyzed by researchers in many different locations. A worldwide distributed computing infrastructure had to be developed to overcome this challenge. LIP has been participating in several projects for the development, deployment and operation of the computing infrastructure for the LHC experiments, and also for generic use. These activities are mainly focused on grid computing and cloud computing technologies.

Grid computing has the goal of integrating, in a transparent way, resources which may belong to independent organizations; hiding their specific features and presenting an homogeneous interface to users. In this way, large computing infrastructures can be created from spread resources, appearing to users as a unique system. LIP is working on combining Grid computing with Cloud computing, to enable federated access to distributed virtualized computing resources. Cloud computing is gaining momentum in industry and science as a flexible way to access computing and storage capacity. LIP participates in some of the largest R&D projects in this field.

LIP operates the largest scientific computing facility in Portugal. The facility is part of the Worldwide LHC Computing Grid (WLCG) and delivers computing and storage capacity to high energy physics experiments and to the research community in a large ensemble of scientific domains. In this context, LIP in partnership with FCCN and LNEC is promoting the National Distributed computing Infrastructure (INCD), an e-infrastructure that is part of the Portuguese Science Foundation Roadmap of Research Infrastructures of strategic relevance.

COMPUTING

Computing

Enabling Compute Intensive and Data Intensive Science

The LIP distributed computing and digital infrastructure activities encompass the support to scientific research through the provisioning of computing and support services, complemented by a component of innovation, aimed at staying at the forefront of computing technologies.

Distributed Computing

The activities of the LIP computing group are developed in the context of national and international projects. At national level the activities are now focused on ramping-up the National Distributed Computing Infrastructure (INCD), in the context of the FCT infrastructures roadmap, and on the LIP Tier-2 facility, part of the Worldwide LHC Computing Grid (WLCG). At international level the activities are shaped by the participation in European ICT projects which currently include the H2020 projects EGI-ENGAGE and INDIGO-DATACLOUD, and by the participation in international e-infrastructures such as the European Grid Infrastructure (EGI) and Iberian Grid Infrastructure (IBERGRID).

The group's main line of work is the research, development and provisioning of services and infrastructures for scientific computing. The group is especially focused on distributed computing technologies including grid, cloud, high throughput and high performance computing (HPC). The LIP Tier-2 has delivered 51,646,727 normalized hours to ATLAS and CMS corresponding to 104% of the pledged capacity.

Our activities cover a wide range of areas including federation of computing and storage resources across networks and organizations, technologies for massive data processing and analysis, databases and information systems, computing, storage and networking technologies, systems and network design, implementation and management, systems and network security, authentication and authorization, virtualization technologies, datacenter design and operation, resilient systems, IT management. The group also operates many core IT services for LIP.

A contract with FCT for the creation of a pilot cloud service finished in December 2015 with very good results. LIP deployed cloud services based on Openstack which were tested by several user communities and demonstrated good potential. The pilot cloud activities included several research projects and organizations such as: INESC-ID, IGC, IPMA, LNEC, ISCTE, FCCN and roadmap infrastructures such as PORBIOTA and BIODATA. The cloud pilot constitutes the basis for a future service to be delivered by the National Distributed Computing Infrastructure (INCD). The INCD association was formaly established in December 2015 having as members LIP, FCT and LNEC. LIP coordinates the infrastructure and pilot services work-package.

In 2015 LIP continued to participate in the European Grid Infrastructure (EGI) and in IBERGRID. The EGI Conference 2015 was organized by LIP in Lisbon and joined about 300 participants from Europe and elsewhere.

Advanced Computing

The Minho advanced computing group joined LIP in 2014. Without abandoning research in Computer Science and Engineering, the team has been directing its activity to areas more related to the general interests of LIP. In particular, it has been supporting the development and optimization of code applications related to particle physics, with some emphasis on the optimization of distribution strategies for access to large volumes of data, in order to improve efficiency and execution time. Another focus of our activity has been on advanced training in Scientific Computing. Finally, the group is also responsible for the administration of a local HPC cluster that supports the running of the data analysis applications developed by other groups in LIP. Worth mentioning is the start of the participation in ATLAS.

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Research facilities

- Mechanical workshop and Detectors laboratory
- e-CRLab (Cosmic rays electronics laboratory)
- LOMaC (Laboratory of Optics and Scintillating Materials)
- TagusLIP laboratory

RESEARCH FACILITIES

Mechanical workshop and Detector laboratory

The Mechanical Workshop (MW) of LIP was established in 1986, to support the experimental activities performed in collaboration with CERN. The workshop's capabilities were recently improved with high performing machine tools and CAD-CAM software. The highly qualified staff of the MW performs a large spectrum of mechanical services, from project design to production and testing. Nowadays, the MW provides services not only to CERN related projects but also to research groups inside and outside LIP, and external companies.

In parallel, the detector laboratory (DL) was also created at LIP's foundation, with the main aim of supporting the experimental activities developed at LIP. The laboratory has been continuously updated according to general and specific needs of research groups. The available equipment and technical staff, allow a variety of services, including the design, construction and repair of electronic circuits and vacuum systems, and the design, construction and testing of particle detectors.

During 2015 there were two main projects that required an important share of the available resources: the construction, assembly and test of Resistive Plate Chambers (RPC) detectors and related instrumentation for the LIP-Auger group, and the construction, assembly and test of the Umbilical Retrieval Mechanism (URM) for photomultiplier calibration in the SNO+ experiment. In addition to these other activities were carried out in support of several LIP projects and others: RPC-PET, LUX/LZ, SPACE/ESA, Neutron detectors, the construction of a spark chamber for CBPF, Brazil, the development of a cryostat for the Chemistry Department, etc. In 2015, the main external clients were Active Space Technologies (AST), Centro de Neuro--Ciências (CNC), the Physics and Chemistry Departments of the University of Coimbra and the Institute of Systems and Robotics (ISR).

TagusLIP laboratory

TagusLIP was created in 2004 at the Lisbon Science and Technology Park (Taguspark) as a generic infrastructure for the development of nuclear medicine imaging technologies. It is installed in the modular building with a total of 400 m^2 which includes office space for about 15 people, a meeting room for 20 people, two large laboratory spaces, electronics workshop, and a bunker for work with high activity sources. The TagusLIP laboratories are well equipped with general purpose equipment needed in the development and validation of large electronics and data acquisition systems. The PETsys start-up company has recently been using the TagusLIP infrastructure for the development and validation of Time-of-Flight PET technology. The company has assembled a TOF-PET demonstrator ring and performed the validation of the system using radiation sources.

e-CRLab

(Cosmic rays electronics laboratory)

The e-CRLab is mainly dedicated to the development of electronics for Cosmic Ray experiments. The main focus is given to fast digital electronics implemented in FPGAs. The laboratory has the capability to design complex printed circuit boards and to produce simple printed circuit board (PCB) prototypes. The production of complex PCB and its assembly is outsourced. There is capability to do rework in PCB boards. A small set of mechanical tools allows the production of simple detector prototypes mainly for proofs of concept.

In 2015 the e-CRLab had two main activity lines: The first one was developed within the Auger MARTA project to operate RPCs outdoors in the Argentine Pampa, and consisted in the development of the engineering prototype of the MARTA front-end electronics, based in the MAROC ASIC. The second activity line, in the framework of the SPACE project, was the development of the test procedure and test system for Co-60 irradiation in different conditions of several components, in the context of the preparation of the ESA mission to Jupiter.

The e-CRLab also contributed to outreach and teaching. In the outreach context it has been involved in the development of AMU – A ver MUões, a small Cosmic Ray Telescope to be deployed in high schools. The e-CRLab also participated in the installation of experimental setups at IST for the Advanced Experimental Physics Laboratory.

LOMaC

(Laboratory of Optics and Scintillating Materials)

The laboratory of scintillating materials was established in the framework of the ATLAS experiment, to provide support for detector R&D and construction. It focuses on the characterization of plastic scintillators and clear, scintillating and wavelength shifting (WLS) optical fibres. The laboratory was set up in collaboration with CFNCUL (Centro de Física Nuclear da Universidade de Lisboa), where it was located. The laboratory was used to select radiation hard scintillators and WLS fibres for the ATLAS Tilecal calorimeter, and for the massive preparation and quality control of the WLS fibre sets used in the calorimeter. By the time of the selection of the WLS fibres for the Tilecal, the laboratory contributed also to the construction of the DELPHI luminosity monitor STIC, with the selection, aluminization and quality control of its WLS fibres. The team was later requested to contribute to the ATLAS Luminosity detector ALFA with the preparation of scintillating fibres with a square cross section at a smaller scale and to the RD52/DREAM fibre calorimeter project, including also clear/non-scintillating optical fibers. Clear fibres for the calibration systems of Tilecal and SNO+ were also tested in this laboratory.

The laboratory is equipped for testing and preparation of scintillators, optical fibres, photomultipliers and related electronics. The main test setup is used for the characterization of plastic WLS or scintillating optical fibres in large numbers, using holders for the scan of up to 32 fibres at a time. It can use both direct radiation from a ^{90}Sr radioactive source to produce light in the fibres or use an additional scintillator as light source. There are additional setups to test scintillators and PMTs. There are facilities for the preparation and aluminization of plastic optical fibres. The aluminization is done by magnetron sputtering technique and the facility allows the deposition of aluminium mirrors in the top of fibres with variable length up to 3 m.

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// SCIENCE AND SOCIETY

Communication, outreach and education

To engage society with particle physics and related technologies, and to give support to education in science and technology, are key aspects of our mission at LIP.

The LIP Communication & Outreach team cares for two fundamental aspects: communication, both internal and external; and science outreach and public education.

While outreach concerns every group and every researcher in the lab, the Communication & Outreach team fosters such efforts and leads its own activity lines. Flagship projects are IPPOG's International Masterclasses in particle physics and the CERN Portuguese language teachers programme. These and other projects and events developed in 2015 are illustrated below. LIP is an associate of the Ciência Viva Agency for the promotion of scientific and technological culture, our partners in several education and outreach projects.

LIP is part of international communication and outreach groups, namely the International Particle Physics International Group (IPPOG) and the European Particle Physics Communication Network (EPPCN). In the context of EPPCN, LIP works in close contact with the CERN press office, locally spreading, translating and adding the national angle to the CERN press releases. In addition, LIP increasingly spreads its own news, via press releases send to our media contacts but also via the lab's web site and social media.

2015 was a special year, with the preparation for the 30 years of LIP, celebrated in 2016. An exhibition about the big challenges of particle physics for the next decades will be presented in university venues in Braga, Coimbra and Lisboa, the towns where LIP is present, and public sessions will be organized. A new LIP web site will be launched.

IPPOG International Masterclasses students are invited to be particle physicists for one day, analyzing real data collected by the ATLAS and CMS experiments at the LHC. The results are presented and discussed in a video-conference with scientists at CERN and participants in other locations around the world. The Masterclasses are held in 47 countries every year and are present in Portugal since their first edition in 2005. In 2015, about 2000 students participated in Masterclass sessions all across the country, from Bragança to Faro, from Covilhã to Ponta Delgada, Azores. The plan for 2016 is to reach the Island of Madeira.

CERN Portuguese language teachers programme was held in the first week of September and hosted high school teachers from Portugal (24), Brazil (20), Mozambique (2), Cabo Verde (1), S. Tomé e Príncipe (1) and East Timor (1). This school has been held since 2010 with the support of CERN and Agência Ciência Viva.

The **Environmental radiation project**, and more recently the **LabLEDs project**, have the goal of bringing to the classroom simple experiments on particles, radiation, and their detection. Over the years, a consolidated network of teachers has been built.

In the context of the **Science in the Summer programme** of Agência Ciência Viva (OCJF - Ocupação Científica de Jovens em Férias), LIP offers 2-week internships every summer to about 20 high-schools students.

The **LIP-News bulletin** is an internal communication instrument. It also plays a role in the links with the school community and our partners institutions, namely universities.

The **LIP spark chamber** is a successful example of a detector for outreach built at LIP. It has been used to demonstrate cosmic rays and particle detection in a variety of events.
LIP spark chambers now exists in Austria, Argentina, Brazil, Italy, Spain, at CERN, and in several locations in Portugal.
Other detectors development projects are ongoing, both for demonstration and for school projects.

Every year, LIP researchers take part in dozens of **seminars in schools** and other **public sessions** on all topics related to their research: particle physics, astroparticles, particle detectors and their application, computing, etc. In 2015, the Nobel Prize for neutrino Physics brought a lot of attention from the media and much interest from schools and universities.

// CONTACTS

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Advanced training

The advanced training of new researchers is one of the priorities of LIP. The laboratory permanently hosts tens of Bachelor, Master and PhD students, who actively work within research groups. LIP has a long standing experience in advanced training, and offers scientific excellence, appropriate infrastructures, careful guidance, a stimulating atmosphere, and students integration both in its local research groups and in the framework of international collaborations.

LIP can offer research subjects in a range of areas, covering broadly the subject of experimental particle and astroparticle physics, but also related technologies and computing. LIP has specific laboratories for detector development, electronics and nuclear medical physics, in cooperation with hospitals and other entities. It also has a high precision mechanical workshop and distributed computing infrastructures used by many other research institutions. The role of LIP in the training of teachers and engineers, via schools and internships at CERN, is also widely recognized.

In 2015, LIP hosted 42 PhD students, 31 Master students and 5 bachelor students. The number of students per research line and information on grants is given in the LIP in Numbers chapter of this report. The universities of Lisbon, Coimbra and Minho are LIP associates. In each of its three nodes, LIP works in close relation and cooperation with the local university, and the strengthening of these bounds is one of our clear goals.

LIP coordinates two national doctorate programmes (FCT PhD programmes):

- **DAEPHYS Applied Physics and Physical Engineering**, at the Universities of Coimbra, Aveiro and Lisbon (both ULisboa and UNL);
- **IDPASC-Portugal: Particle Physics, Astrophysics and Cosmology**, involving the Universities of Minho, Porto, Coimbra, Lisboa and Évora.

We are also a partner in two other programmes: MAPFIS, with the universities of Minho, Porto and Aveiro; and DPMPI, Physics and Mathematics for future information technologies, involving IST and several research centers.

LIP belongs to international doctorate networks that bring together universities and research centres, including the IDPASC international network, coordinated by LIP, and several International Training Network (ITN) sponsored by the European Commission.

During 2015, LIP participated in several active ITN sponsored by the European Commission: The PicoSECMCNet network, "Picosecond Silicon photomultiplier Electronics & Crystal research Marie Curie Network" had two Early Stage Researchers (ESR) with 36 month contracts at LIP, both of which ended during 2015. The project finished at the end of 2015. The network INFIERI, "INtelligent Fast Interconnected and Efficient Devices for Frontier Exploitation in Research and Industry" is ongoing, with one ESR at LIP. The AMVA4NewPhysics network, "Advanced MultiVariate Analysis for New Physics Searches at LHC" started last September.

A variety of short duration training events were proposed to 1st cycle students by LIP in collaboration with the local Universities.

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Technology transfer, industry and spin-offs

LIP's activities provide various sets of opportunities for knowledge transfer to the economy.

Directly, the areas of application, namely in the biomedical field and in the space sector, are potential sources for the generation of new industrial property rights to be transferred to existing or new companies. Knowledge transfer opportunities may also be expected across the whole spectrum of LIP experimental activities, especially by research leading to new instruments and methods, or in advances in computing applied to other fields. Two examples of direct technology transfer in the 2015 activities are highlighted below.

Indirectly, LIP's involvement with CERN has triggered technological transfer to Portuguese industry through the training of Portuguese engineers at CERN and through industrial contracts awarded to Portuguese firms by CERN, in the context of its industrial procurement rules. In this respect, LIP has been operative in the coaching and in some cases in the technical support to Portuguese firms in their networking with CERN. Industrial contracts with ESA shared by LIP and by Portuguese industry are also important sources of technology transfer induced or facilitated by LIP in specific areas.

The Portuguese Industrial Liaison Officer (ILO) is a member of LIP's staff and his activities are developed under the framework of FCT, by agreement with LIP.

STCD – Spin-off technology for cancer diagnosis

The STCD group was created in 2004 around the development of a new Positron Emission Tomography scanner (ClearPEM) for breast cancer diagnosis, exploiting technologies developed at LIP for the CMS experiment at LHC. Scientific research, technological development and laboratory testing of new PET scanners is pursued at the laboratory infrastructure TagusLIP. The ClearPEM project was developed by a national consortium of research institutes and clinical centers under the LIP leadership. The consortium collaborated with institutes of the international Crystal Clear Collaboration, namely CERN Switzerland, INFN-Milano Italy, Univ. Hospital Nord Marseille France, Hospital San Gerardo Monza Italy.

In 2011-15 the LIP/STCD group was part of the EndoTOFPET project and the associated Marie Curie Training Network PICOSEC funded by the European Union. This project developed a a PET detector for detection of prostate and pancreatic cancer. LIP coordinated Work Package 4, responsible for the electronics and data acquisition systems. In this context LIP developed innovative electronics with good time resolution for Time-of-Flight PET. The technology was licensed to the spin-off PETsys. The activities of the group are done in coordination with the start-up PETsys. The laboratory infrastructure TagusLIP at the science park Taguspark is shared by the two entities.

RPC production in the Brazilian industry

LIP is a recognized world leader in RPC (Resistive Plate Chamber) detectors. MARTA is an RPC-based cosmic ray detector thought for an upgrade of the Pierre Auger Observatory but with many other possible applications. The installation at the Observatory of an engineering array of MARTA was recently approved in a very competitive joint FCT/FAPESP. This project will run for three years in a close collaboration between Portugal and Brazil, and foresees the transfer of the RPC production technology to the Brazilian industry.

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// LOOKING FORWARD

Looking forward

In this report we provided an overview of LIP's work in its main areas of activity: particle and astroparticle physics, new instruments and methods, and computing. Our main achievements in 2015 were presented, as well as the links of the lab to society: through outreach, advanced training, and relations to industry. Before concluding, it is now time to look into the future, identifying the key aspects of LIP's roadmap, and unveiling what to expect in 2016.

As a starting point, it is useful to mention a few boundary conditions, or key aspects that set the scene for the defining LIP's roadmap. And we start with time. Timescales are an issue in particle physics and associated technologies. Cycles are long in this field. Experiments are planned, built, operated, and their data are analyzed in a process that can easily take one decade or more. Even for the smaller projects a year is a rather short timescale, for which only very partial goals can be set, and stability in the framework and resources is important.

Another issue is internationalization. When introducing the lab, we stated that LIP was created to exploit the unique opportunities to the fundamental research in Portugal by our country's accession to CERN. Our participation in international scientific infrastructures and collaborations is a fundamental aspect in LIP's activities. Their roadmaps for the future do have a strong impact in our planning.

As a third aspect, internationalization often brings the need to work in large collaborations. It also requires the ability to conquer a certain domain of expertise, and to put together a team with the required competence and critical mass.
It is within this framework that LIP defines its strategic options, which are expressed in the following:

- In the choice of the experiments in which the lab participates, and within each of these experiments, the choice of well-defined areas of scientific specialization;
- In the development, within the lab, of areas of technological expertise which cuts across different contexts, experiments, scientific areas and applications;
- In the strong bet in advanced training, and in outreach, for the promotion of the public engagement in this field of science.

Let's now take a walk through the different research lines of LIP and find key aspects of what to expect in 2016.

In what concerns **LHC physics**, after a successful year of data taking at 13 TeV in 2015, this year's run will bring an important increase in the accumulated luminosity. Enough to improve the precision in many Higgs and top physics studies and the sensitivity in new physics searches. This will bring many data analysis opportunities for the LIP teams in ATLAS and CMS, as well as for the construction of theoretical models and Monte Carlo generators in the LHC phenomenology group. And indeed there are good reasons to believe that the near future may bring important results, hinted at by recent measurements.
The investment in the very forward detectors ALFA and AFP (ATLAS) and CT-PPS (CMS) open very interesting opportunities for the future, in particular the study of exclusive photon-photon processes and of diffractive physics. Besides the participation in the maintenance and operation of the sub-detectors of their expertise, the TileCal for the ATLAS team and the ECAL for the CMS team, upgrade activities are already ongoing. In the medium-term, both the LHC and the experiments will be upgraded. In 2016, the ATLAS team will continue to invest in the upgrade of the TileCal calorimeter and on the high-level trigger, whereas the CMS team will continue its involvement with the ECAL readout.

In the **structure of matter** research line, the two experiments are in particular moments that offer great opportunities for data analysis: in COMPASS, the analysis of the 2015 Drell-Yan long data taking is starting; in HADES, strangeness studies are at the top of the list. Besides that, general commitments and strong responsibilities in the collaborations will be kept. The COMPASS group has the responsibility of the DCS, of a variety of offline tasks, and of the several of the most relevant physics analysis.
A member of the LIP team has top responsibilities in the Drell-Yan physics programme. In the time scale of a few years, the present and future polarized Drell-Yan physics programme will allow to deepen the understanding on the spin structure of the nucleon, namely the study of its transverse components. At GSI, the accelerator infrastructure will be inoperative during 2016, in view of its full upgrade. Nevertheless, the LIP team will as usual guarantee the continuous operation and maintenance of the RPC TOF. Furthermore, the collaboration with the ECAL group will continue, and the excellent work developed during past years leads now with the opportunity to build a new detector for the collaboration, the new TOF-FW.

Also in **cosmic rays**, opportunities for data analysis are at present very appealing, given the impressive data sets collected by both AMS and Auger over the years and the interesting results and puzzles that have been found. AMS is a unique observatory in space, and the interest of the scientific community in topics such as dark matter and cosmic anti-matter brings AMS to the spotlight as being an extraordinary source of knowledge. The LIP team maintains its commitments in the RICH detector operation and event reconstruction, and is particularly interested in low energy proton, helium and electron flux variability with solar cycles, as well as in anti-proton identification. In Auger, the team will continue to exploit the particle physics potential of the observatory, studying hadronic interactions at the highest energies, investigating in detail the electromagnetic and muon components of air showers, and in particular addressing the puzzle of the large number of muons observed in air showers

with respect to the expectations. In parallel, our ambitious R&D programme for future cosmic ray detectors based on RPC will be pursued, mainly with the installation at the observatory of a MARTA engineering array, combining water Cherenkov tanks and robust RPCs, able to operate outdoors under harsh conditions. MARTA detectors are also being installed at the CBPF in Rio de Janeiro and their possible use in a possible future large field of view gamma-ray observatory at very high altitude in South America (the LATTES project) is under study.
Rather soon, important steps forward are expected in the **dark matter and neutrino** experiments in which LIP is involved. In SNO+, after a few years of preparation, and some delays due to a water leak in 2015, water phase data should arrive in 2016. This will be a great opportunity to use and commission the hardware and software tools developed in calibration, data quality and data analysis preparation tasks, to attempt some physics measurements, and further prepare the upcoming scintillator phase. Several opportunities for growth exist, with new senior members and students in the team. In 2016 the dark matter team will continue sharing the focus between LUX and LZ. After having obtained in 2013 a world-leading limit for the spin-independent WIMP-nucleon elastic scattering cross-section, LUX started a new science-data acquisition period in September 2014. The run is expected to be completed in May 2016. An improvement of the sensitivity by a 2 to 3 factor is expected from this run, and an extremely detailed calibration, background modeling and analysis work is ongoing, with key contributions from the LIP team. The approval of the LZ Technical Design Report is expected in April 2016. After that, the fabrication of the detector and auxiliary systems will be started. The underground deployment of LZ is scheduled to begin in September 2018 and operations are expected to start in Spring 2020.

The development of **detectors for particle and nuclear physics** has been from its inception one of the main pillars of activity at LIP. In this research line, our focus will be two-fold: on the one hand, to keep the high level of expertise developed over the years in key technologies, namely Resistive Plate Chambers (RPC), Patterned Gas Detectors (PGD) and liquid Xenon detectors (LXe) and, on the other hand, to actively look for opportunities which can be either specific experiments or topical application of these technologies, to solve concrete issues in a variety of related fields. In 2016, LIP welcomes warmly the Nuclear Reactions, Instrumentation and Astrophysics group.

The **development of instruments and methods for biomedical applications** stems from LIP's detectors R&D expertise, and a strong inter-connection obviously remain. Nevertheless, it has since long become a research line on its own right. The ongoing research activities will continue to be pursued, to attain the full promise shown by existing performance results and by added value with respect to existing technologies. In the last few years, partnerships with hospitals and biomedical institutions represent important steps forward in the development and testing of such proposals. The focus now lies in moving further along this path, moving closer to clinical testing and industry.

Space applications is another research lines stemming from LIP's expertise in radiation detection and process simulation. The participation in ESA mission, ESA contracts and European Union funded H2020 programmes, together with the recent growth of the teams, makes this research line a rather active one. Highlights for 2016 surely include the participation in the preparation of JUICE, ESA's future mission to the Jovian system, and the XIPE (X-ray mission Polarimetry Explorer) mission, recently pre-selected by ESA.

The LIP distributed **computing** and digital infrastructure activities encompass the support to scientific research through the provisioning of computing and support services, complemented by a component of innovation, aimed at staying in the forefront of computing technologies. In 2016 the work will continue to focus on the operation and improvement of LIP's computing services, the participation in the Worldwide LHC Computing Grid (WLCG), European H2020 projects, and in the national and international initiatives: National Distributed Computing Infrastructure (INCD), European Grid Infrastructure (EGI) and Iberian Grid Infrastructure (IBERGRID). Looking further into the future, opportunities include to use the strategic know-how accumulated over the last 10 years to maintain and improve LIP's computing infrastructure in partnership with FCCN and LNEC, to consolidate and optimize scientific computing resources distributed across several organizations under a single well defined infrastructure, and to enable future policies for scientific computing by creating a structure for the sharing and open access to publicly funded computing capacity.

Before concluding, it is useful to leave for a moment the fascinating investigation into the laws of physics, to re-connect with other aspects of reality. The last few years were difficult for Portugal and for the scientific research system in particular. At the start of a new political cycle, external aspects will play a critical role, such as scientific careers, PhD grants, evaluation and funding of research centres, and their relations with universities.

Regardless of this, LIP has to pursue its way to fully accomplish its scientific, technical and public role. Key aspects are the construction of stronger synergies between its research groups, and the capability to construct and exploit new development opportunities. To diversify the sources of funding, and in particular to attract European funding more effectively, are mandatory short term goals. A reinforced, and more effective internal organization, and the ability to communicate with its partners in society, are important aspects on the table for 2016. Premises are always an important issue. In Minho, there are good perspectives to obtain new premises. A new space to install our mechanical workshop was made available by the University of Coimbra. In Lisbon, an agreement was established to relocate LIP to a University of Lisbon central building. This will provide us with very good conditions to install laboratories and with approximately twice our current available office area.

Last but not least, LIP is celebrating 30 years in 2016, and we hope you can all enjoy this celebration by coming onboard for a journey to the big challenges of particle physics for next decades, starting from the latest discoveries towards the unknown!

EXPOSIÇÃO

PARTÍCULAS

do bosão de Higgs à matéria escura

Universidade do Minho
17 Fev - 09 Mar 2016

Universidade de Coimbra
05-23 Abril 2016

Universidade de Lisboa
02-25 Maio 2016

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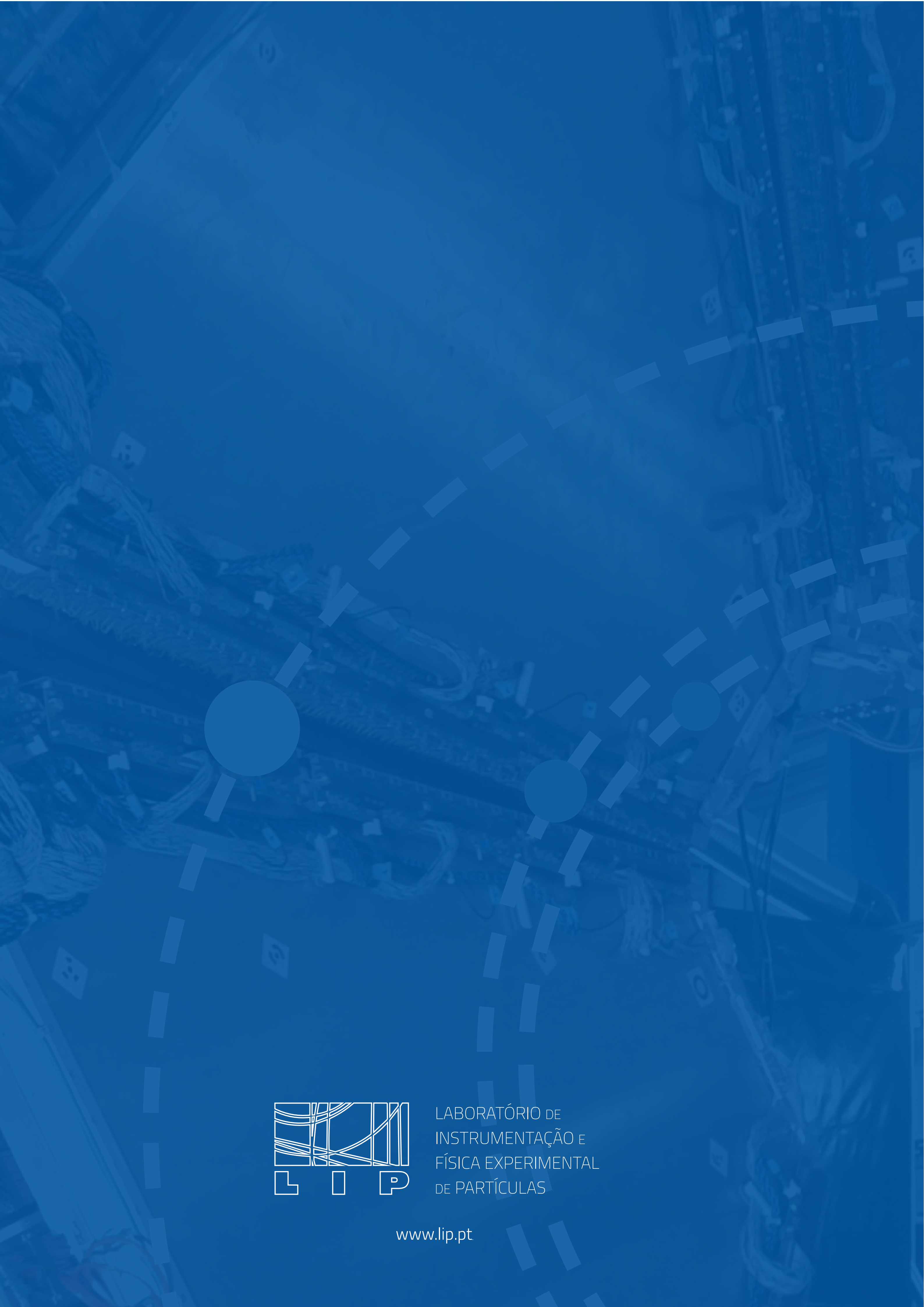

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