annual report

2023/2024

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

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LIP is about Particles, Technology and People

LIP, Laboratory of Instrumentation and Experimental Particle Physics, is the reference institution for experimental particle physics and associated technologies in Portugal. It was founded in May 1986 to exploit the unique opportunities created by the country's accession to CERN, the European particle physics laboratory. LIP brought experimental particle physics in Portugal to a truly international ground and will continue leading this challenge.

LIP is devoted to research in experimental particle physics and associated technologies, enhancing the direct access of the Portuguese scientific community to international infrastructures and collaborations. At the centre of our mission are also scientific computing, advanced scientific and technical training and the engagement of society with science. Opportunities of knowledge and technology transfer to society are also explored, in domains such as health, space exploration and information technologies.

LIP

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about

LIP

LIP is the reference laboratory for experimental particle physics and associated technologies in Portugal

LIP is the reference laboratory for research in particle physics and related technologies in Portugal, and the Portuguese reference partner of CERN. The laboratory is nation-wide, with nodes in Lisbon, Coimbra, and Braga, closely collaborating with the local universities. LIP has about 100 PhD researchers, 40 technical and administrative staff, and permanently hosts over 80 graduate students. Founded in May 1986 to exploit the unique opportunities created by the country's accession to CERN, LIP is an Associate Laboratory since 2001, and was rated as "Excellent" in the latest independent evaluation promoted by FCT.

The three pillars of LIP's mission are:

- Discovery through science: LIP's program in particle and astroparticle physics is international, has world-class quality and addresses some of the most topical questions of our time
- Innovation through technology: basic science drives innovation in the long term. LIP is a key player in the application of particle physics technologies to health care, space exploration, information technologies, and big data analytics
- Community development: LIP works to engage science and society and to address societal challenges through science — promoting scientific culture and education, inspiring the younger generations to pursue careers in science and technology, contributing to the qualification of the Portuguese innovation sector, promoting digital competences and technology accessibility.

Under the supervision of FCT, LIP defines the national policy for the participation at CERN, leading particle-physics related science and innovation, ensuring the involvement of the national academic and business communities, promoting advanced training, and sharing knowledge with society.

LIP is also a partner of ESA, the GSI research centre in Germany, SNOLAB in Canada, the Pierre Auger Observatory in Argentina, Fermilab and the Sanford Underground Research Facility (SURF) in the USA and represents Portugal in European digital infrastructures and in science and society international forums. The associates of LIP are FCT, the Universities of Lisbon, Coimbra, and Minho, Instituto Superior Técnico (IST), the Faculty of Sciences of the University of Lisbon (FCUL) and the Electrical and Electronics Business Association (ANIMEE).

Growing increasingly multidisciplinary, LIP's research includes three main areas:

- Particle and astroparticle physics
- Development of new instruments and methods for nuclear and particle physics and of technology applications to health care and space exploration
- Information technologies, scientific computing, and big data analytics.

LIP is engaged in CERN's Large Hadron Collider (LHC), contributing from the very beginning to the two largest LHC experiments, ATLAS and CMS. LIP is also involved in the fixed target programs at CERN and GSI, probing the strong nuclear force and dense nuclear matter. The quest for dark matter, a deeper understanding of the elusive neutrinos, or the exploration of the Universe with charged and neutral cosmic rays are among the great challenges of particle physics for the next decades and are part of our agenda. LIP's experimental program is complemented and supported by the high-quality work of LIP's phenomenology and theory research groups.

The development of new instruments and methods for particle physics has been from its inception one of the main strengths of LIP. Current activities include research in fundamental detection processes and applications of particle detectors. LIP is a world leader in Resistive Plate Chambers (RPC) and liquid xenon detectors, and has strong expertise in other gaseous detectors, scintillator/fibre calorimetry, and fast electronics for data acquisition systems. Specific R&D lines are dedicated to health care and space exploration applications.

The LIP Computing Groups have extensive knowledge and experience in scientific computing, focusing on grid, cloud, high performance and high throughput computing, artificial intelligence and big data analytics. They have excellent international relations and integration in the main R&D projects and scientific e-infrastructures at European level. LIP co-leads the National Infrastructure for Distributed Computing (INCD), participating in the enabling of future policies for scientific computing and open access, and serving the Portuguese scientific community at large. The fast-growing expertise in data science and big data in the laboratory creates the potential for engaging with other communities in addressing a number of societal challenges.

Our vision for the future is to make sure that LIP will be present in the next great scientific discoveries of humankind, and lead science and innovation in Portugal in close connection with the academic and business communities, and strongly engaged with community development.

prof.
Mário Pimenta
President

Foreword
Past and Future

LIP was created in May 1986, almost 40 years ago. Science in Portugal was almost a curiosity, and Fundamental Science was generally considered as superfluous luxury for the small and poor country we had. The gap to other European countries was tremendous. Normalizing to the population, four time less researchers, five time less research spending. Then, in a few years with Mariano Gago as the science minister and Portugal joining International Science Organizations, the derivative changed dramatically.

The first mission of LIP was, and still is, to coordinate the Portuguese participation at CERN. Bringing together researchers and students of diverse Portuguese institutions. Forming research teams, and guaranteeing the necessary scientific and technical critical mass and medium-term stability to be able to assume responsibilities over many years. In a country known for the individualism of its people and its institutions, and for short-term reactive policies, it was not (and it is not) a minor job. The legal status of LIP, was that of a private non-profit association, whose main members were the Portuguese scientific funding agencies and also, from 2010 on, reference Portuguese Universities and Faculties. This original format has the merit of efficiency, flexibility and pragmatism. Regrettably, it is also fragile to sudden changes in the public funding policies.

Meanwhile, LIP has grown in people, scope and ambition. Nowadays, we are at CERN, but also at ESA and in several other important international scientific experiments in Europe and in North and South America. Nowadays, we have experimentalists but also theorists, particle physicists but also astro-particle and nuclear physicists. Computing, detectors and instrumentation, present at LIP since the first days, have considerably expanded, driving now also their own projects. Interdisciplinarity, is a growing word at LIP, embracing space, health, environmental and social applications. Education, communication and outreach have always been a priority.

In 2023, the model in which the "Associated Laboratories" would become a third pole (together with the Universities and State Laboratories) of stable scientific employment and scientific careers, supported partially by long-term public funding, was clearly over. The majority of the present 40 Associated Laboratories are not legal entities; most of them depend legally on the Universities. In this way, the capability to assure, each month, the salaries of their permanent researchers is not determinant for their own survival. The recently created FCT tenure mechanism, being short-term, is mainly designed to boost/renew the scientific employment at Public Institutions and not for independent research institutions. It was not at all enough, in a year where thousands (more than ten at LIP alone...) of medium-term research contracts were about to end.

The paradigm we were aiming for, of having 1/3 of LIP researchers with permanent position at the Universities, 1/3 with permanent positions at LIP, and 1/3 with three to five-year contracts at LIP, is nowadays a chimera. The way out was to try to increase the number of LIP members with permanent positions at Universities, opening a new position in the LIP scientific career only whenever there the possibility exists of long-term specific funding to sustain it. At the same time, a new scientific-technical research career was created at LIP, which formalizes and clarifies the career of researchers working in some specific sectors at LIP, namely research infrastructures and competence centres, funded namely by European funding or other external public or private contracts.

Also in 2023, the "Fundo CERN", that supports the Portuguese participation at CERN and in CERN recognized activities, was seriously questioned, even though no one was asking for Portugal to leave CERN and being "Fundo CERN" a relatively small fraction (~ 10%) of the value of the quota Portugal pays (~ 1% of the CERN budget, about 14 M €/year). Thus, 2023 was not a very easy year for LIP. In Portugal, there is nowadays a large amount of European funding, but Fundamental Science is not at all a priority. Furthermore, the role of CERN as a booster of science, technology and education is no longer widely recognized by the Portuguese scientific community. We were slow in recognizing that and in changing our public communication targets accordingly…

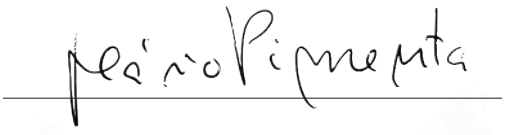
We had then to mobilize many that still had the memory of the History of the last decades, of the scientific development in Portugal. Many that were or are witness of our activities. Thanks, to them all and to the commitment of many LIP members we succeed in mitigating the losses: although late and with a smaller total budget, Fundo CERN will now open; six to eight new professor positions will open this year at Universities, with profiles compatible with LIP areas. However, the suspension of the relatively small but rather important quota (200k euros – equivalent to the annual salary of four auxiliary researchers …), that FCT has paid to LIP since 1986 in the quality of LIP founding associated member, was not yet reverted. Flagship initiatives were: in May, the re-edition of the "Manifesto para a Ciência em Portugal" by Jose Mariano Gago, first published in 1990; in September, the organization of the restricted ECFA meeting in Lisboa, and of public seminar also at Lisbon by Fabiola Gianotti, the Director General of CERN; in October, the publication of a dossier on the impact of the Portuguese participation at CERN and the organization of a public seminar by Francis Halzen, founder and principal investigator of IceCube Neutrino Observatory at the South Pole. In all these actions we never used negative arguments, just the opposite: we tried to demonstrate that the support to LIP and CERN is not some kind historical privilege. On the contrary, it is an efficient and cheap way to be consequent with a National political and scientific option.

Meanwhile, in 2023 the World was not getting better: the unthinkable war in Ukraine pursued its bloody course; a devastating war has broken out in Palestine, many tens of thousands of people, many Jews and even many more Palestinians, were brutally killed.

Let´s however end with good news: the Science Gateway, the new CERN flagship centre for education and outreach was inaugurated in October, and the feasibility study for the future CERN collider (FCC) is in good progress. We must not give up the ideal of CERN, of looking for knowledge with all and for all. It is the contribution we can make to a better World.

After so many years serving in the LIP director´s board, and nine as president, it´s more than the time to step down. What LIP has accomplished in all these years, thanks to the work and dedication of so many present and past LIP members, was far more than I could ever have imagined. Now, the way to proceed is to look forward, confident in the capacity of LIP and its members to integrate new competences, face new challenges, secure new national and international funding and contracts. Helping the scientific development of Portugal and increasing its scientific culture, but being more resilient to moods, wind changes and small powers. LIP should be able to increase its connection to Society and to increase the number of its associates. New management structures and organization schemes may be needed in the future, keeping however always in mind that fragmentation, sooner rather than later, would put in great danger the future of all.

Long and successful life to LIP!
Long and happy life to all!



(Mário Pimenta)
Lisbon, 2024

REPORT FROM THE

International Advisory Committee

LIP's international advisory committee members: Jorgen D'Hondt, José Miguel Jimenez, Karoline Wiesner, Katia Parodi, Masahiro Teshima, Sergio Bertolucci, Werner Riegler.

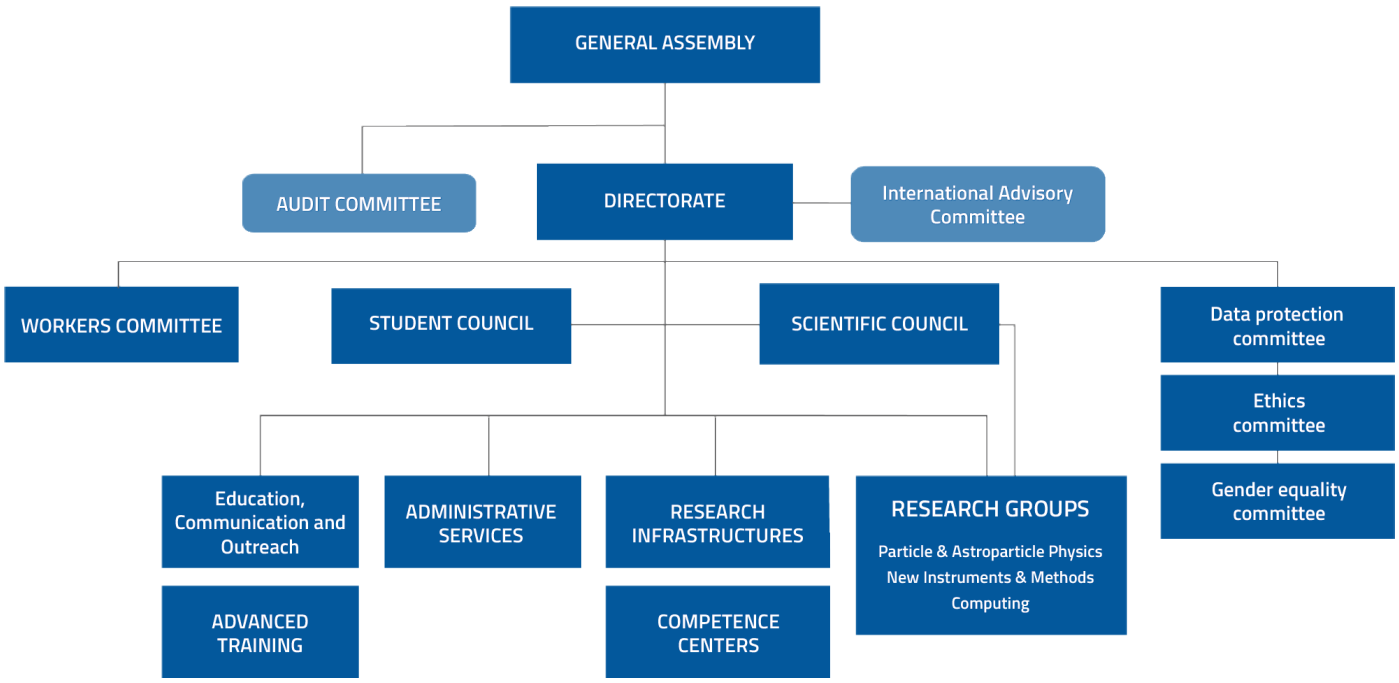
Structure & governance

Research in experimental particle physics and associated areas and technologies is often conducted within large international collaborations, by multidisciplinary teams, or using large scientific infrastructures. This requires adequate critical mass and a solid organizational support infrastructure.

The structure of LIP was designed from its inception to be efficient and flexible, and to ensure a coordinated strategy at national level. The growth of the laboratory over nearly four decades called for an increasingly structured and participated organization and management approach.

The basic scientific units of LIP are the research groups, which are organized in eight research lines gathered in three research areas: particle and astroparticle physics; development of new instruments and methods; computing and information technologies.

The research groups have the technical support of LIP's research infrastructures and competence centres. The LIP management and community have the support of a number of administration and management support services split in: Accounting and financial management; Users Support and Project Office, including Grant's office (pre-award); Knowledge transfer and societal projects; ECO and advanced training.



General Assembly

LIP is an Associated Laboratory of the Ministry of Science, Technology and Higher Education. The associates of LIP are the Portuguese Foundation for Science and Technology (FCT, president), the Universities of Lisbon, Coimbra and Minho, Instituto Superior Técnico (IST), the Faculty of Sciences of the University of Lisbon (FCUL) and the Electrical and Electronics Business Association (ANIMEE).

International Advisory Committee

An External Advisory Committee provides strategic advice to the Laboratory. The Committee is formed by world recognized experts in the areas of activity of LIP and holds regular meetings with the directors and group leaders. In 2023, the members of the IAC were: Jorgen D'Hondt, Eamonn Daly, Katia Parodi, Masahiro Teshima, José Miguel Jimenez, Karoline Wiesner, Sergio Bertolucci and Werner Riegler.

Audit Committee

LIP administrative and financial operations are systematically audited by external auditors and reviewed by a top level independent finances council and auditing authority. Members are: João Sentieiro (president), António Morão Dias, Vera Martins.

Directorate

LIP is governed by a Board of Directors nominated by its General Assembly, after consultation of LIP members. 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 LIP community. At present the national directorate is formed by Mário Pimenta (president), Isabel Lopes, Nuno Castro, Patrícia Gonçalves and Ricardo Gonçalo.

Scientific Council

The Scientific Council is LIP's scientific management body. Its members are all PhD holders, a representative of the technical staff and a representative of the students from each LIP node. The SC participates in the definition of the scientific strategy of the laboratory, namely in the creation of research groups and in the decision to participate in international collaborations, as well as in the evaluation of LIP's researchers. The SC delegates some of its authority to a committee where all research groups are represented. Up to December of 2023, the SC board is formed by José Maneira (president Lisboa), Raúl Sarmento (Minho) and Alexandre Lindote (Coimbra).

Workers Committee

The LIP Workers' Council has been legally constituted in 2021 as LIP workers' interlocutor for the institution's management. Its effective members for the mandate from 2021 to 2024 are Américo Pereira, Rui Alves (coordinator) and Sofia Andringa.

Student Council

LIP's Student Council promotes the communication between students from different LIP nodes, encouraging the exchange of ideas, interests and mutual aid between students. It also suggests and assists in the preparation of advanced training activities.

For more details on the role and composition of the different structures and committees please refer to the LIP web site.

Selected news of the year 2023

JANUARY | FEBRUARY

- CERN celebrated the completion of the civil engineering work for the high-luminosity LHC.
- UN's Day of Girls and Women in Science, with SPF and UFPLP, "Invisibilidade feminina na ciência - vamos reverter? Débora Peres Menezes (president of the Brazilian Physical Society).
- Article published by the LIP Gaseous Detectors Group in Coimbra highlighted in the newsletter of the company Hidden Analytical.
- Official start of EuroCC 2 gathered in Germany the 34 countries that are part of the project.
- LIP became a member of the Ibero American Network of Nuclear Astrophysics, which recently become part of the International Research Network for Nuclear Astrophysics.

MAY | JUNE

- AMBER collects its first physics data, measuring the antiproton-production cross section in proton-helium collisions.
- LIP and Gradiva relaunched "Manifesto para a Ciência em Portugal" by José Mariano Gago, with a simultaneous event in Lisbon, Coimbra and Braga.
- Portugal and Galicia signed a cooperation agreement for the development of medical technologies.
- World Environment Day: sustainability in particle physics highlighted by CERN and EPPCN in a social media campaign.
- ATLAS published the search for vector-like quarks conducted by the LIP group at Minho.
- CMS published a search for top squarks, with LIP PhD student Diogo Bastos as main author.
- Jornadas FCCN 2023 gathered the computing and digital infrastructures community.

SEPTEMBER | OCTOBER

- Restricted European Committee for Future Accelerators (R-ECFA) visit to Portugal for a day-long meeting with the community. CERN's director-general Fabiola Gianotti was in a public session co-organized by LIP and CV.
- LIP's SPAC paper on Nature Human Behaviour, highlighted in a Research Briefing in Nature, presents compelling evidence that both overconfidence and negative attitudes towards science peak at intermediate knowledge levels.
- 15th CERN School for Teachers in Portuguese, with 48 teachers from all Portuguese-speaking countries.
- Heavy ion season at CERN's LHC, with stable beams of lead nuclei circulating for the first time in five years, and at a record energy.
- 2023 European Researchers' Night: LIP was in Braga, Coimbra and in three venues in Lisbon.
- Conference IBERGRID 23 in Benasque (Spain).
- CERN inaugurates Science Gateway.

MARCH | APRIL

- PRL Editor's Suggestion: SNO+ observed antineutrinos from nuclear reactors using a water-filled detector.
- IPPOG's Particle Physics Masterclasses marked by the introduction of the Pierre Auger Observatory Masterclass, fully developed at LIP.
- ESA's JUICE mission to the Jupiter moons was launched. It carries the LIP-developed RADEM radiation monitor and has the participation of Portuguese companies.
- First LHC stable beams at 13.6 TeV of 2023 declared on Friday, April 21, the restart of Run 3 after the winter break.
- 4th Joint LIP/IGFAE Workshop continues the long-standing collaboration between the leading institutions in Portugal and Galicia.

JULY | AUGUST

- PRL Editor's Suggestion: The new LHC experiments SND@LHC and FASER reported the first-ever observation of neutrinos produced in a particle collider.
- 2023 LIP Summer Internship Programme starts.
- INCD was on focus in the Ciência 2023 summit. It was presented by LIP's head of computing and IT Jorge Gomes in the session devoted to RNCA - National Network for Advanced Computing.
- Ciência Viva in the Lab internship programme: nine secondary school students spent two weeks at LIP in Lisbon, "hunting for elementary particles in nature".
- Lousal science center held an activity dedicated to the LouMu project.
- ATLAS reported at the Lepton Photon Conference the most precise measurement yet of the Higgs boson mass: 125.11 GeV with an uncertainty of 0.11 GeV.

NOVEMBER | DECEMBER

- 3rd RNCA Meeting and inauguration of the new INCD operational center at UTAD, Vila Real.
- The first LIP Open Day took place in Lisbon, associated to the inauguration of TTC@ULisboa.
- Duarte Guerreiro and João Gentil, from LIP's RADART group, were at HollandPTC (Delft, the Netherlands) testing the prototype device for the study of radiation on biological tissues.
- Cristóvão Vilela, member of the LIP group in SND@LHC, has been appointed "Deputy Physics Coordinator" of the experiment.
- Study published in PLoS Digital Health by LIP's SPAC group uses the shock caused by the COVID-19 pandemic as an opportunity to learn more about the dynamics of other respiratory viruses.
- LIP's plenary scientific council meeting and Christmas lunch held on 19 December 2023.

Main organised events and Awards of 2023

2023-02-13
"Invisibilidade feminina na ciência"
Lisbon, Portugal

2023-05-16
Essay reprint "Manifesto para a ciência em Portugal", Lisbon, Coimbra and Minho, Portugal

2023-09-11 / 2023-09-14
"IDTM"
Lisboa, Portugal

2023-12-23
"Uma viagem ao mundo do LIP"
Lisboa, Portugal

Awards to LIP Members

Sara Mesquita

Fulbright Grant 2023 (FLAD/FCT) - Visiting researcher at MIT for 9 months

Matteo Pisano

Third prize in the first edition of ULisboa's 3 Minute Thesis Competition, Winner of the TecInnov Jerónimo Martins competition, IST

Beatriz Amorim

Marie Sklodowska-Curie Fellowship Programme Grant from the International Atomic Energy Agency for a one-year project at GSI

Joana Antunes

Awarded a Short-term Research Internship at the University of Texas at Austin 2023

Simão Cardoso

UMinho Award for Initiation in Scientific Research 2023

Gonçalo Ribeiro

JEF Award for the best presentation (category undegrad) Jornadas da Engenharia Física, IST

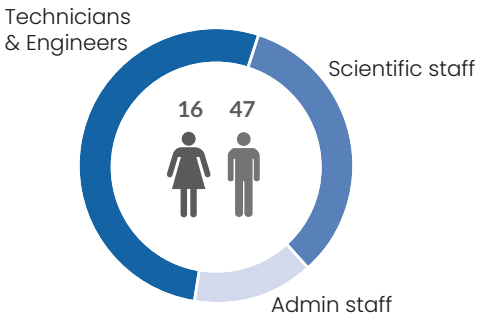
The CMS collaboration at CERN has attributed the CMS industry award to the LIP spin-off company PETsys Electronics for the challenging development of the TOFHIR2 front-end ASIC of the barrel MTD detector, performed in collaboration with the LIP - CMS group.

LIP

in numbers

Human Resources

STAFF



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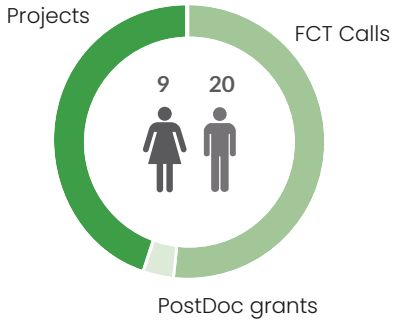
63
TOTAL

Technicians/ Engineers	3	30
Scientific staff	5	16
Admin staff	8	1

FIXED-TERM RESEARCHERS



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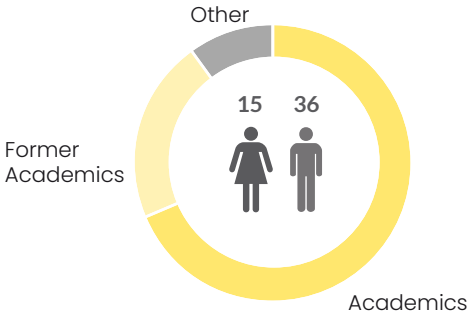
29
TOTAL

Projects	4	9
FCT Calls	4	11
PostDoc grants	1	0

UNPAID



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51
TOTAL

Academics	10	25
Former Academics	4	7
Other	1	4

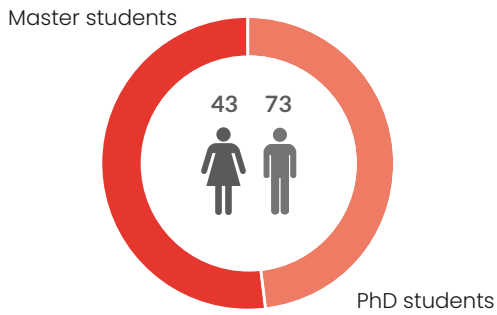
TOTAL
259
83 176

101
RESEARCHERS
29 72

42
TECH & ADMIN
11 31

116
GRAD STUDENTS
43 73

STUDENTS



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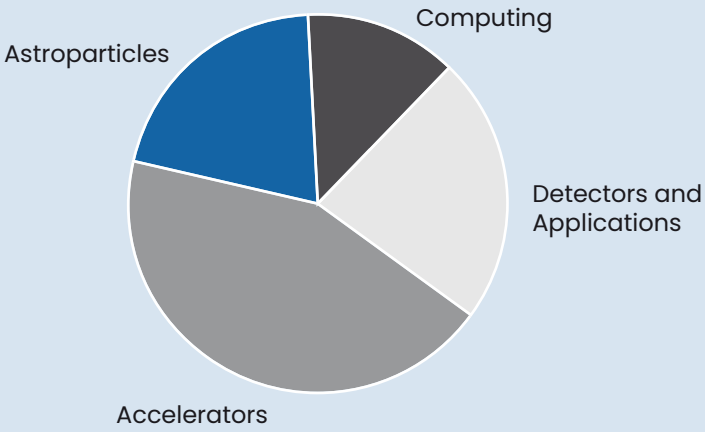
116
TOTAL

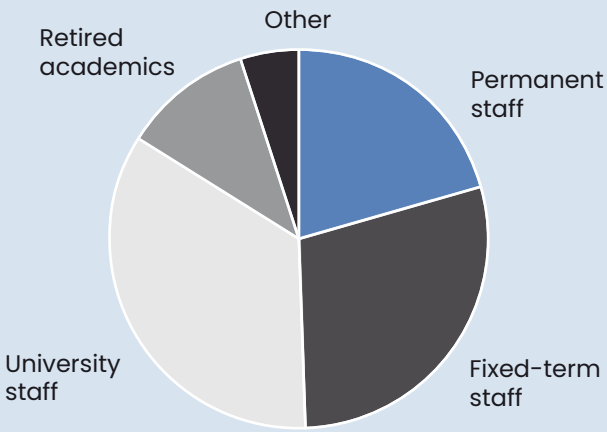
Master students	24	36
PhD students	19	37

LIP RESEARCHERS

DISTRIBUTION BY RESEARCH AREA



DISTRIBUTION BY CONTRACT STATUS

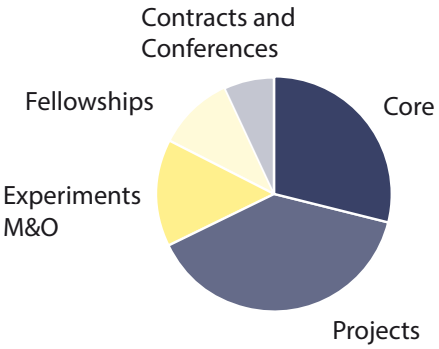


INVITED PROFESSORS AT UNIVERSITIES (UNPAID)

6	LIP permanent staff
11	LIP fixed-term staff

Finances

GENERAL FUNDING



2M
CORE FUNDING

2.7M
PROJECT-BASED

1M
FELLOWSHIPS

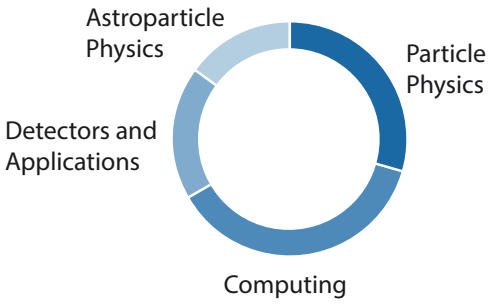
0.7M
EXPERIMENTS M&O

0.5M
CONTRACTS AND CONFERENCES

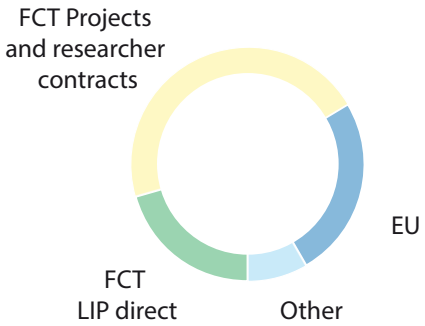
TOTAL
6.9M €

PROJECT AND CONTRACT-BASED FUNDING

BY RESEARCH AREA

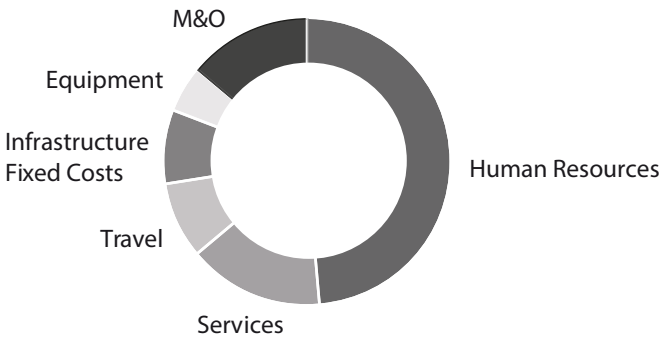


BY ORIGIN



TOTAL
2.7M €

COSTS



HUMAN RESOURCES

STAFF 2.5M

FIXED-TERM RESEARCHERS 1.7M

SERVICES AND OTHER EXPENSES

0.8M

MISSIONS

0.5M

EXPERIMENTS M&O

0.7M

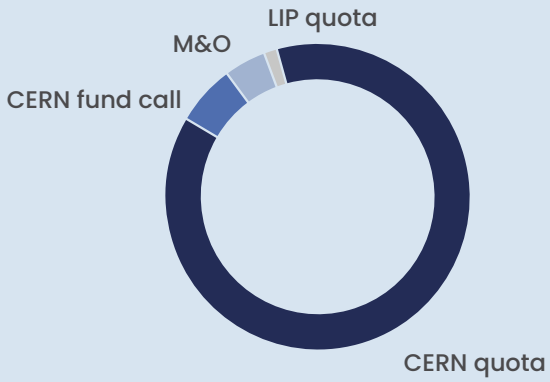
INFRASTRUCTURE FIXED COSTS

0.4M

EQUIPMENT

0.3M

PARTICLE PHYSICS FUNDING IN PORTUGAL



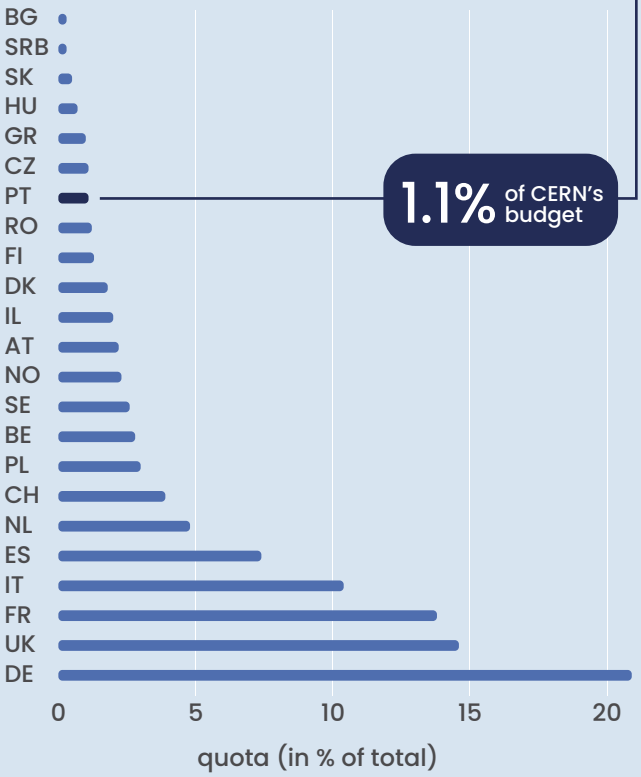
LIP quota — 0.2M

Experiments M&O — 0.7M

CERN fund call — 1.0M

CERN quota — 13.7M

CONTRIBUTION TO CERN'S BUDGET PER COUNTRY



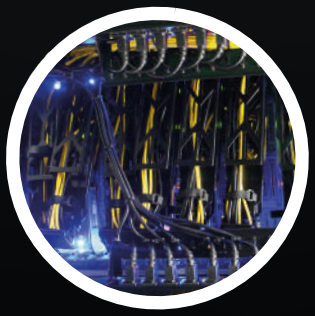
Scientific output 2023

	Particle Physics	Astroparticle Physics
Papers in refereed journals	242	49
Proceedings Preprints and Notes	54	30
Books, Reports, Proposals, SW tools, Exhibition materials	2	1
Presentations in International Conferences	33	17
Other Presentations	78	50
Master Theses	18	2
PhD Theses	4	2

Detectors and Applications	Computing	TOTAL
36	16	333
13	10	107
0	7	10
17	18	85
40	42	205
19	3	40
2	0	8

Experimental particle and **astroparticle physics**

Development of **new instruments** and **methods**



Computing

research at

LIP

Experimental particle and astroparticle physics

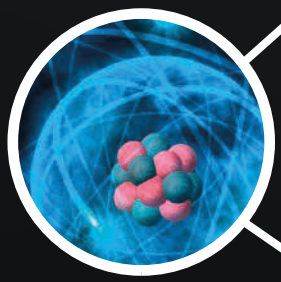
Development of new instruments and methods

LHC experiments and phenomenology

- ATLAS
- CMS
- Pheno
- FCC

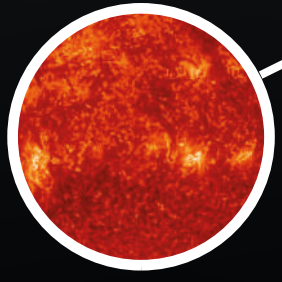
Structure of matter

- pQCD
- HADES
- NUC-RIA
- NPstrong



Cosmic rays

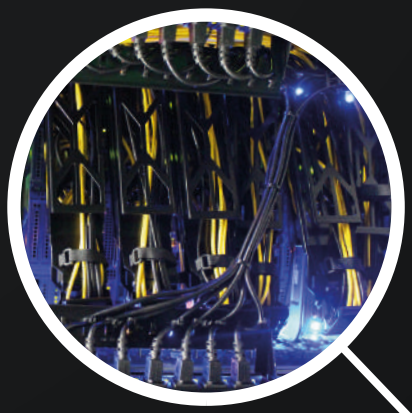
- AMS
- Auger
- SWGO

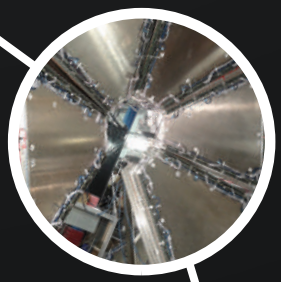


Dark matter and neutrinos

- DARK MATTER
- NEUTRINO
- SHiP/ SND@LHC

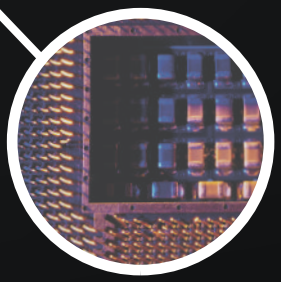
Computing





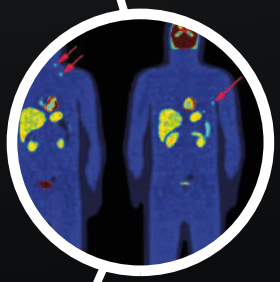
Detectors for particle and nuclear physics

- RPC R&D
- Neutron detectors
- Gaseous Detectors R&D
- Liquid Xenon R&D



Scientific computing

- GRID – Distributed Computing and Digital Infrastructures
- SPAC – Social Physics and Complexity



Health and biomedical applications

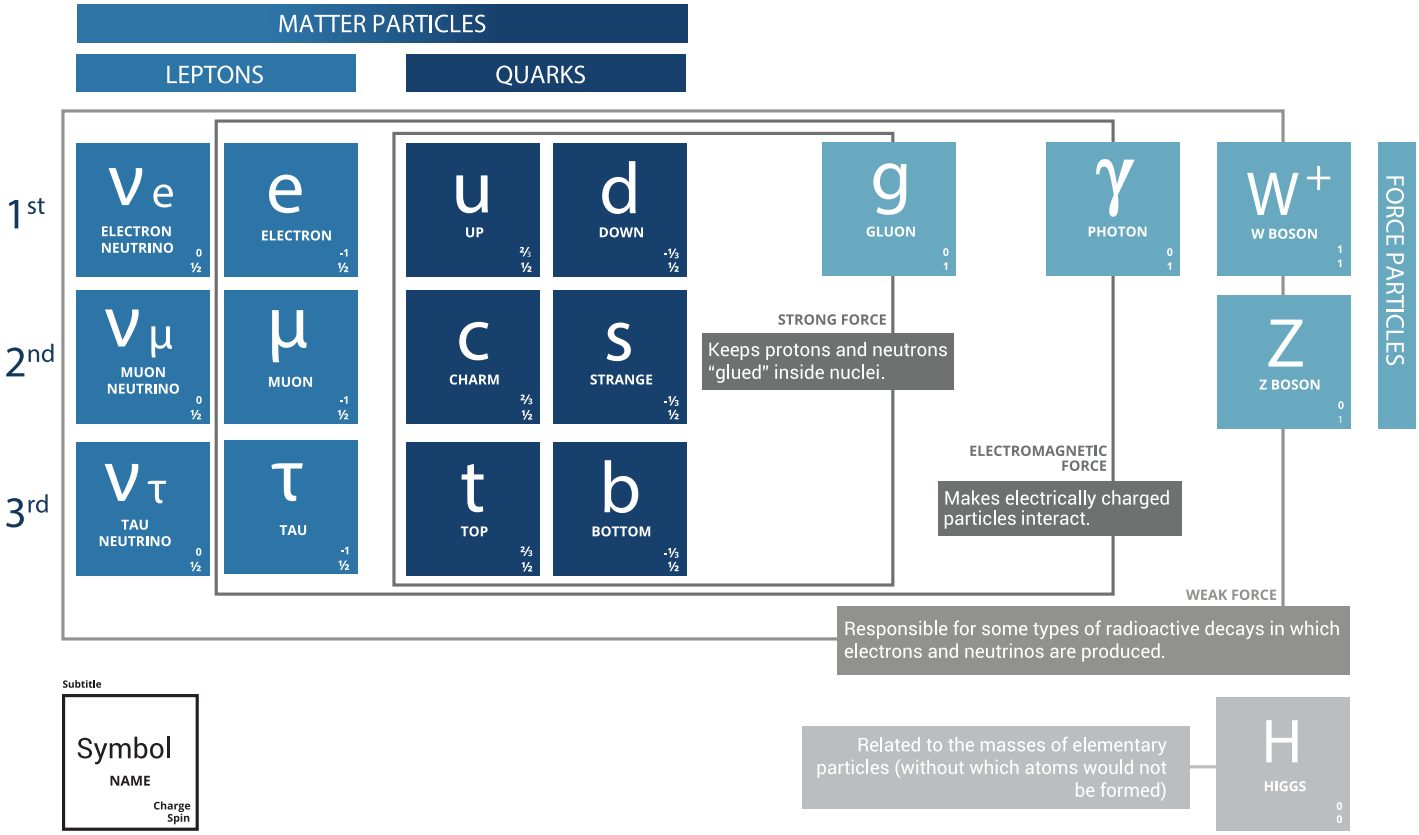
- RPC-PET
- Proton Therapy
- OR Imaging
- RADART

Space applications

- Space Rad
- i-Astro

In a nutshell...

All matter we see around us is made of only three elementary particles: electron (e), up quark (u) and down quark (d). These particles are pieces of a larger puzzle, the Standard Model of Particle Physics (SM). In the SM there are three families of elementary matter particles, successively heavier and with shorter lifetimes. In each family there is also a neutrino. Neutrinos are very light, weakly interacting particles which arrive, for example, from the Sun. Particles interact with each other through forces, which in fact result from the exchange of other particles (called force particles) between them. For each type of matter particle there is a matter anti-particle, which is exactly the same but with opposite charges.



The Standard Model is one of the most successful theories in the history of physics.

Still, it leaves many unanswered questions:

- Why three families of particles?
- What happened to all the anti-matter created in the big bang?
- How to include gravity in the theory?
- What is dark matter, which we know is 5/6 of all matter in the Universe?

At LIP we seek to answer these and other questions about our Universe!

To do that, we accelerate and collide particles at high energies, creating new particles ($E = mc^2$). We also study particles that come from outer space, bringing information about the history and composition of the Universe. To "see" particles we develop and operate detectors that can register the passage of particles and measure some of their properties. Particle detectors can be rather complex devices. Particle physics technologies are useful for other purposes too.

Experimental particle & astroparticle physics

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

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. At the same time, we are very actively improving our experiments, to respond to future challenges of running at higher LHC luminosities, and we are starting to prepare the far-future with LIP's recent involvement in the Future Circular Collider (FCC) feasibility study. LIP's Phenomenology group conducts research bridging theory and experiment. Its research, while independent, is centered in areas in which LIP has active experimental activities. Its purpose is to strengthen impact through the provision of excellent directed phenomenological research.

We still have a lot to discover about the ways in which quarks and gluons work together to form the particles we observe. That is the focus of our Structure of Matter line of research. The Partons and QCD group is currently involved in the analyses of the data collected in the final years of the COMPASS experiment, and in running its successor AMBER. LIP has the only Portuguese experimental team preparing to explore the frontier between nuclear and particle physics at the new FAIR facility at the GSI and is deeply involved in the HADES and R3B experiments. The NPstrong group brings remarkable theoretical consistency to this research line, as well as opportunities for collaborations between different groups.

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 charged and neutral cosmic rays are among the great challenges of particle physics for the next decades. LIP is part of these challenges through its engagement in some of the main international collaborations, including SNO+ at SNOLAB in Canada, LZ at the SURF Laboratory in the USA, the Pierre Auger Observatory in Argentina, and the Alpha Magnetic Spectrometer in the ISS.

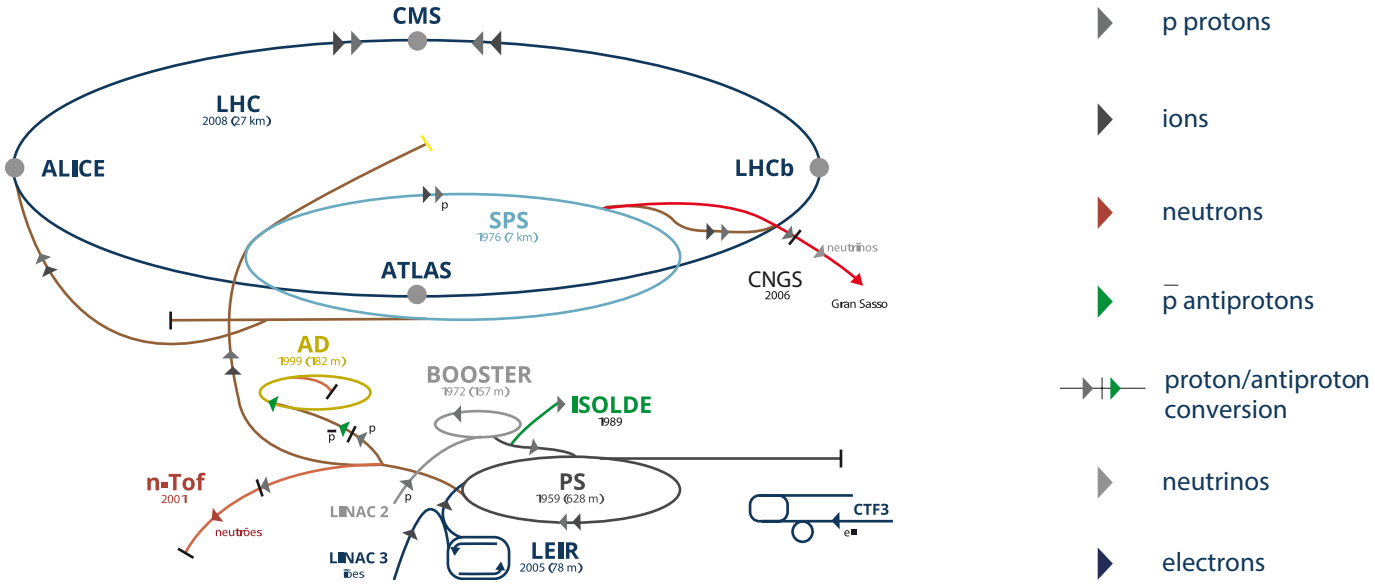
More recently embraced projects are the participation in DUNE, one of the two flagship neutrino experiments for the next decade; the SWGO project for the installation of a wide field-of-view gamma ray-observatory in the Southern hemisphere; and SHiP, an experiment proposed to be installed in a beam dump facility at the SPS. The first step was the installation of its neutrino detector (SND) at the LHC for its Run 3 (SND@LHC) providing first observations of collider neutrinos.

EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

LHC experiments and phenomenology

Physics at the energy frontier

In 2023 the LHC's Run 3 went on, successfully completing its second year. In parallel, analyses of the full Run 2 (2015-2018) data set are still being concluded, as well as the preparation of both accelerator and experiment for the high luminosity phase HL-LHC scheduled to start in 2029. The new detectors and upgrades will be installed during the long shutdown from 2026 to 2028. LIP is also very much engaged in the most recent LHC experiment, SND@LHC, which is taking data since the start of Run 3, and the publication of the observation of the first collider-produced neutrinos is certainly one of the highlights of the year. The LIP Phenomenology group is now a large team with consolidated research programmes in both QCD and new physics searches. Last but not least, we are also preparing the far-future. The LIP FCC group was created in late 2021 to contribute to the ongoing Future Circular Collider (FCC) feasibility study. The group starts from a core of members from LIP's ATLAS, CMS and Pheno groups, who were involved in the production of the FCC Conceptual Design Review.



LIP at the LHC

Research at CERN's Large Hadron Collider (LHC) is central to the quest for the fundamental physics laws of Nature. LIP is member of the ATLAS and CMS collaborations at the LHC since their creation in 1992 and had a leading role in the design and construction of important components of the detectors: the data acquisition system of the CMS ECAL sub-detector, used to measure the energy of electrons and photons; the ATLAS TileCal sub-detector, used to measure the energy of hadrons, and the trigger systems that performs the online selection of the interesting collisions in each of the experiments. After the LHC start-up in 2010 LIP made major contributions to the physics program of both ATLAS and CMS. Both groups were involved in the discovery of the Higgs bosons, and are now measuring its properties. LIP is also involved in top quark physics, B mesons and QCD studies, heavy ion collisions and a wide spectrum of searches for hints of precise standart model measurements including particles or phenomena beyond the Standard Model of particle physics.

Precision measurements: Higgs boson and top quark

Higgs and top physics have for long been a particular specialty of LIP's ATLAS, CMS and Phenomenology groups. The experimental teams focus on the accurate measurement of the Higgs boson properties, namely on Higgs bosons decaying to a pair of b quarks in the associated production of the Higgs boson both with a W or Z boson (VH channel, V=Z, W) and with a top-quark pair (ttH channel). In 2023 the LIP team in ATLAS contributed to two Run 2 Legacy papers on the Higgs boson properties: measurement H→bb decays in VH production; and measurement of ttH(H→bb). Furthermore, the team published the CP-sensitive analysis of ttH production and started the ATLAS analysis of the spin/CP properties of the HWW vertex in the WH channel, with H→ bb. The LIP-CMS group has been leading the search for the rare Higgs boson pair (HH) production process in the "tautaubb" final state using Machine Learning tools. This process gives access to the Higgs self-coupling parameters, and new physics processes can significantly alter the expected production mechanism. Studies with Run2 data and a first look at Run3 are ongoing. Projections of the expected sensitivity were updated for different HL-LHC conditions.

The LHC is a top quark factory, providing opportunities for detailed measurements of the heaviest of fundamental particles. The large mass of the top quark makes it a likely window to observe subtle effects of physics beyond the SM. The LIP CMS team led the data analysis and publication of the first Run 2 measurement of the top-quark pair-production cross section with the top decaying to tau leptons. Studies are continuing to assess the lepton flavour universality in W leptonic decays of the W boson. In a similar final state, a study of vector boson scattering processes including a tau lepton using the full Run 2 data was presented at the European Physics Society particle physics conference EPS2023. Studies using the first Run 3 data are also being conducted.

The group is also pursuing analyses of exclusive production (of top, tau, W/Z pairs) through two-photon exclusive processes, only made possible through the use of the Precision Proton Spectrometer (PPS), located very close to the LHC beam. The LIP CMS team has since long a leading role in the PPS detector.

The higher luminosity and the upgraded detectors open new possibilities for Run 3. The analysis of exclusive W and Z boson pairs was published in 2023 and the paper searching for the exclusive top quark pair production was submitted for publication. The related analysis of two-photon production of tau lepton pairs is ongoing. The LIP ATLAS team leads the effective field theory interpretation of different precision measurements in the top quark sector, aiming to constrain the possible forms of new physics theories that may be at the basis of the SM. In 2023, another leading contribution was on the measurement of the ttc production cross section.

Searching everywhere

LHC experiments are searching everywhere and in every way for hints of particles or phenomena beyond the SM of particle physics. This includes looking for tiny deviations in precision measurements, searching for new particles or phenomena predicted in proposed theories and models, and performing wide searches employing powerful analysis methods to search for any anomalies in data.

In 2023 both the ATLAS and CMS LIP teams were busy concluding search analyses in variety of models and channels using the full Run 2 dataset. Several papers with leading or important contributions of the LIP groups were published during the year or are undergoing final reviews. The ATLAS team has published the anomaly search (Y→XH channel), the first application of fully unsupervised ML to ATLAS data, the search for pair-production of vector-like quarks in the multilepton channel and the search for Ztq flavour changing neutral currents. Undergoing review are the searches for single vector-like quarks production, monotop (t+MET) events and the combination of heavy resonance searches. Still, the exploitation of the Run 2 data does not end here. As an example, the search for axion-like particles using forward detectors (AFP) data was formally initiated by the collaboration, co-coordinated by the LIP team.

The LIP CMS group had a leading role in the search for the 4-body decay of the lightest scalar top (stop) in the Run 2 data. This search, also motivated by dark matter searches, is very challenging because the reconstructed particles can be extremely soft. The legacy analysis with the full Run 2 sample was published in a peer-reviewed journal in 2023. Dark matter production in association with a Higgs boson is also considered. On the other hand the exclusive production in a photon fusion process mentioned above allows probing several BSM processes.

Secrets of the strong force

Hadrons containing heavie quarks (c, b, usually referred to as heavy flavors) are a likely window to observe subtle effects of physics beyond the SM. The interest is reinforced by the so-called flavor anomalies, consisting of different hints of deviation of SM's expected flavor universality, and by the large accumulated data sets. The LIP CMS group is keeping a focus on b→sll transitions, at the core of the flavor anomalies. The group has been exploring FCNC decays realizing the b→sll transition, namely B→μμ and B→K*μμ. The internal CMS review of the results on the angular observables and rates with the full Run 2 data is being finalized. Studies in additional datasets have been performed by undergraduate students in 2023.

The LIP CMS team performed the first measurement of the polarizations of χ_{c1} and χ_{c2} states. Precise measurements of the polarizations of several quarkonium states are being pursued using the larger Run 2 data samples. They are presently undergoing CMS internal review and will have an important impact in the understanding of quarkonium production.

The LHC provides unique opportunities to study heavy-ion collisions and observe the Quark Gluon Plasma (QGP), which existed in the hot and dense medium of the very early Universe. The LIP CMS group is bringing its unique expertise on B physics into the heavy-ion realm, and it has been playing a leading role in the investigation of B mesons in PbPb collisions data. The measurement of the nuclear modification factors was developed and approved. The measurement of B mesons production cross-sections at 5 TeV pp collisions is advanced. Complementary work was performed by LIP internship students. A study of the dependence of the B_s/B^+ hadronization ratio has been performed, and the effect of the environment in b quark hadronization has been explored for the first time in CMS. The exploration of the first Run 3 PbPb data collected in Fall 2023 started. The LIP ATLAS team is also involved in QGP studies, focusing on the use of hadronic jets initiated by heavy quarks, and has been developing b-tagging algorithms adapted to this very special environment.

The work of the experimental teams is well matched by the expertise in LIP's Phenomenology group, that leads groundbreaking research in collider physics. Its diverse portfolio of activities includes precision QCD studies, forward physics, heavy-ion, quarkonia studies, top physics, Higgs, and BSM physics. While autonomous, its research strategically aligns with LIP's experimental activities. Research is often conducted in collaboration with LIP groups that actively participate in the analysis done at the LHC and helps shaping LIP's broader program, anticipating future initiatives such as the FCC. The Phenomenology group has established a close synergy with the Competence Centre on Simulation and Big Data. An AI and ML-based approach to improve sampling efficiency in highly constrained Beyond the Standard Model (BSM) theories has been developed. Other recent work include the contribution to evaluate the physics potential of the proposed Forward Physics Facility (FPF) at the High-Luminosity LHC, highlighting synergies between QCD at colliders (namely forward particle production and QGP formation) and astroparticle physics (namely extensive air shower physics).

Tools of the trade - Detector Upgrades

In 2023, the ATLAS and CMS teams at LIP got ready for the restart of Run 3 after the winter break and operated their detectors and tools, performing expert shifts, data quality monitoring, calibrations, and other operation activities. In parallel, they performed detector development activities in view of future upgrades. Also, both teams contribute to the LHC Grid computing maintenance and operations. The CMS group has been mainly involved in the preparation of the PPS and ECAL detectors. The ATLAS team coordinates the maintenance, control system, operation, and calibration of the TileCal calorimeter, forward detectors, and parts of the trigger system.

In the High-Luminosity phase of the LHC physics program starting in 2029, the accelerator will provide an additional integrated luminosity of 3000 fb-1 over 10 years of operation. The LIP group is responsible for the design and construction of the readout system of the Barrel Timing Layer (BTL), including a high-performance TOF ASIC for time measurement. Dedicated ASIC electronics (TOFHIR) will be used to readout the SiPM arrays. The TOFHIR ASIC is being developed in the framework of the Collaboration Agreement KN436/EP between LIP and CERN. The microelectronics design of the TOFHIR circuits is sub-contracted to the Portuguese company PETsys Electronics. In 2023 samples of the production version (TOFHIR2C) were assembled in test boards coupled to sensor modules for evaluation in test beams at CERN. The results confirmed the predicted timing performance of the BTL detector. An additional irradiation campaign with heavy-ion beam was carried-out with TOFHIR2C to confirm the radiation tolerance of the chip. LIP is also involved in the upgrade of the barrel and endcap calorimeters. In collaboration with industry, LIP will provide a radiation resistant high-performance ADC ASIC for the ECAL front-end electronics. The CMS upgrade includes also the complete replacement of the end-cap calorimeters with a new high-granularity sampling calorimeter. LIP collaborates with industry to supply a high-current low voltage regulator (LVR) resistant to radiation for the High-Granularity Calorimeter (HGCAL) front-end system.

The LIP group is involved in the upgrade of the PPS detector for HL-LHC Phase2, specifically in the area of precision timing detectors. The large number of "pile-up" interactions foreseen at the HL-LHC (up to 200) makes it necessary to precisely measure the longitudinal coordinate of the vertex via time-of-flight and sensors with a single plane time resolution of 40-50 ps are adequate. The LIP group is pursuing R&D studies of LGAD silicon sensors and associated electronics for timing measurements.

The LIP ATLAS team is deeply involved in the upgrade of the TileCal and of the Trigger and Data Acquisition (TDAQ). LIP has full responsibility for the new TileCal high voltage distribution, to be produced mainly in Portuguese industry. Sensitive electronics components will be placed in a service cavern and power distribution will be through thin cables to the front end, thus allowing much greater accessibility for maintenance. The team has designed, produced, and tested prototypes of different types of electronics boards. In 2023 boards for the test benches for the quality control of the HV distribution boards and cables were produced. Tests of the controls of the HV Remote crates were successfully done. In collaboration with LIP's infrastructures (eCRLab and Detectors Lab) the team is also involved in the High Granularity Timing Detector (HGTD), with responsibilities in the DCS system and electronics system (front-end ASIC tests). In 2023 we tested version 3 of the front-end ASIC in view of pre-production, including performance characterization and irradiation tests.

Looking into the future

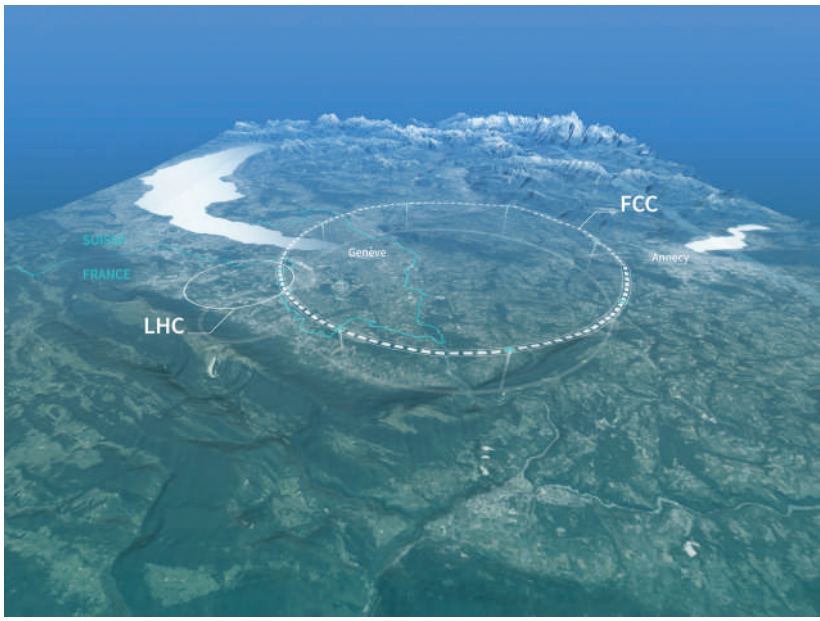
Following the 2020 update of the European Particle Physics Strategy (EPPS), a global collaboration was established to produce a feasibility study for a Future Circular Collider (FCC) facility located in Geneva. If approved, this facility will represent the future high-energy frontier in accelerator physics and will succeed the High Luminosity LHC from around 2040 onwards. It will include an e^+e^- collider (FCC-ee) devoted to a broad physics programme with highlights in Higgs, top and electroweak precision measurements. This will later be replaced by a hadron machine (FCC-hh), which will share most of the infrastructure of the previous collider and repeat the virtuous cycle represented by LEP and the LHC (which, in sequence, used in same tunnel and accelerator chain). It will enhance the current energy frontier by an order of magnitude, allowing a future generation of physicists to explore the limits of the SM and possibly reach beyond, to a more fundamental theory.

The FCC-ee experiments will require a totally new level of detector precision, with instrumental uncertainties well understood to the per-mille level. Experiments for the FCC-hh, on the other hand, will demand extremely radiation-hard but very highly granular detectors. In both cases, opportunities are created for new ideas in instrumentation R&D, which LIP should profit from. These opportunities are mirrored by the ECFA detector development roadmap, which will foster and support technological developments for future colliders. The detailed definition of the FCC-ee/-hh physics case, and the careful assessment of the reach of these colliders, also creates ample avenues for theoretical and experimental physics research.

The recent European Accelerator R&D roadmap includes the Muon Collider as a novel project with renewed interest in the future of Particle Physics. This is based on the physics potential of a lepton collider with a center of mass energy of 10 TeV and on the recent advances in technology that make the realization of a muon collider possible.

Muons are much heavier than electrons resulting in much reduced synchrotron radiation thus allowing acceleration and collision in compact dimensions. In this context, LIP members, together with colleagues at other Institutions, prepared the MuCol EU proposal that was recently approved, to address the key challenges, develop a baseline design and assess the physics performance.

In 2023, activity grew along a few lines of development: detector R&D, Higgs studies at the FCC-ee, and QCD observable calculations. The scintillator work continued at LIP's LOMaC in collaboration with IPC/UMinho with the production and characterization of different samples and the submission of a paper summarizing the results. Concerning calorimeter simulations, we contributed to a proposal of a hadronic calorimeter design for the FCC-ee/hh under the scope of a new international collaboration in Calorimetry resulting from the implementation of the ECFA Detector R&D Roadmap. Sensitivity studies in the Higgs sector at the FCC-ee were developed in di-Higgs production. It became clear that second order effects and precision cross section measurements will be essential to achieve some sensitivity. On the QCD theory side, work is ongoing with the aim of performing comprehensive QCD studies for the FCC-ee physics program. This project is particularly relevant to the ongoing feasibility study of the physics potential of the future circular collider. Some activity has also been developed around the Muon Collider project.



Neutrinos at the LHC

LIP is a founding member of the Scattering and Neutrino Detector at the LHC, SND@LHC, which is taking data since the start of Run 3 to exploit the LHC potential as a neutrino factory. The detector is installed in the TI18 tunnel next to the LHC ring and about 500 m from the ATLAS collision point. The highlight of 2023 was the first observation of collider neutrinos, a milestone physics result achieved under the leadership of the LIP group and published by SND@LHC. This first observation marks the dawn of the era of neutrino physics at colliders. For more information, please go the Dark Matter and Neutrinos Section in this report.

// CONTACTS

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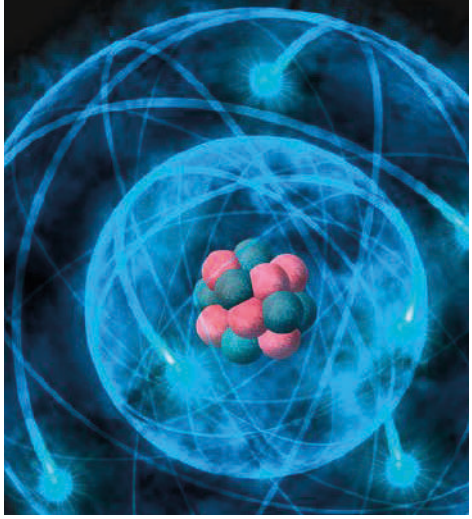


Structure of matter

Looking inside hadronic matter

We still have a lot to discover about the ways in which quarks and gluons work together to form the particles we observe, and that's the focus of LIP's structure of matter research line. The Partons and QCD group is currently involved in the analyses of the data collected in the final years of the COMPASS experiment, and in running its successor AMBER, which collected its first physics data in 2023. FAIR (Facility for Antiproton and Ion Research) will be the next step at GSI and LIP is part of the HADES and R3B experiments. NPstrong, the Nuclear Physics and Strong Interactions group, brings remarkable theoretical consistency to this research line, as well as opportunities for collaborations between the different groups.

The workings of nucleons

The LIP PQCD group is heir to a long tradition in CERN's fixed target experimental programme, starting in the 1980s with the heavy ion experiments NA38 and later NA50. The group is now focused on the completion of COMPASS and in the starting AMBER experiment. During its first phase COMPASS achieved the world's most direct and precise measurement of the gluon contribution to the nucleon spin. A second phase devoted to understanding the tridimensional nucleon structure started in 2012. The experiment used beams from CERN's SPS accelerator, colliding high intensity muon or hadron beams with a polarized target at a temperature only 0.1 degree above absolute zero. The target is followed by a two-stage spectrometer that observes the particles resulting from the collision. The successor experiment AMBER inherited several components of COMPASS.

The COMPASS experiment concluded data-taking in November 2022 and now fully focuses on data analysis. The LIP group has special responsibility in Drell-Yan (high-mass lepton- pair production in a hadron-hadron collision, a powerful tool for probing the partonic structures of hadrons) and charmonium. A major physics result of COMPASS in 2023 was the release of pion-induced Drell-Yan cross sections from measurement with three different targets. This was one main goal of the Drell-Yan program, and provides new direct input, after nearly 40 years, to the extraction of the pion PDFs. Both the analysis and preparation of the paper were coordinated by the PI of the LIP group. Two other publications on Drell-Yan transverse spin asymmetries are being finalized; the results of the analysis of charged hadron multiplicity ratios and sums from semi-inclusive DIS on proton target have been presented and are also being prepared for publication.

The physics goals of AMBER evolved from those addressed by COMPASS: the measurements of the proton (spin) structure lead to increasing interest in understanding its counterpart on the meson sector, now explored at AMBER. The LIP group is among the first and main proponents of the new experiment, approved in 2020. After two short beam tests in 2022, physics data taking in AMBER started in April 2023 with a two-month run for the measurement of the antiproton production cross section in collision of protons on helium-4 nuclei. This is a fundamental input value for the interpretation of the antiproton fluxes observed by cosmic ray experiments in search for signs of Dark Matter or cosmic antimatter. A second data taking period was devoted to a pilot run for the proton radius measurement program planned for 2025. Finally, there was a four-day beam test in which the CEDAR detectors (Cherenkov Differential Counter with Achromatic Ring Focus, used for beam particle identification) were read-out at the high intensities required for the future Drell-Yan measurement. This beam test took place under the coordination of the LIP group, who are presently analysing the collected data.

Stars and Nuclei

The GSI Helmholtz Centre for Heavy Ion Research in Darmstadt (Germany) operates the only facility allowing to accelerate nuclei of all chemical elements occurring on Earth. The facility has been closed for a few years and is slowly coming back to life. The performed upgrades will allow to put into operation the 1.1 km ring accelerator SIS100, the key component of the new Facility for Antiproton and Ion Research (FAIR) currently under construction. At FAIR scientists will produce matter under extreme conditions (of pressure, density, temperature) such as those existing in giant planets, stars, or during stellar explosions and collisions.

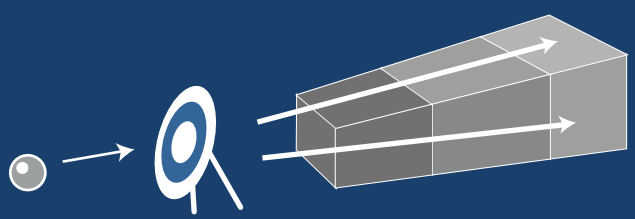
Stars and stellar explosions create the chemical elements everything is made of. To understand stars, we first need to understand atomic nuclei. This is the goal of NUSTAR (Nuclear Structure, Astrophysics and Reactions), one of the four research pillars of FAIR. It will use the unprecedented range of radioactive ion beams, with all kinds of exotic isotopes, to study the complex stellar nuclear reaction chains.

LIP's Nuclear Astrophysics and Instrumentation Group (NUC-RIA) is part of NUSTAR's R3B (Reactions with Relativistic Radioactive Beams). Another pillar of FAIR is CBM (Compressed Baryonic Matter). The collision of atomic nuclei at high speeds can reproduce for a split second the conditions inside supermassive objects such as neutron stars. This is where sits the HADES experiment, in which LIP is involved. Scientists want to find out how matter changes at such densities.

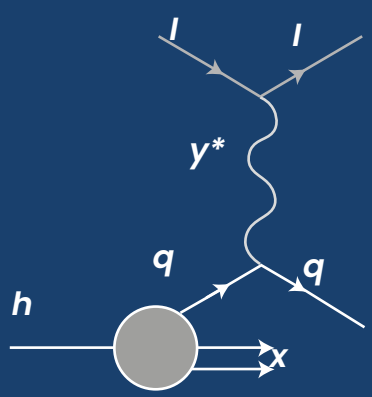
The LIP HADES group designed, built, and operates an essential component of the spectrometer, the RPC-TOF-W: a wall (W) of 3 m x 3 m of resistive plate chambers (RPCs) that accurately measures the crossing time of particles (TOF, time-of-flight). The group extended TOF measurements to the region closer to the beam direction with the new RPC-TOF-FD, and a paper on its performance has been published in 2023. Unfortunately, the current global political and economical situation severely affected FAIR's phase-0 program and casts uncertainty over its schedule.

Jumping into theory

NPstrong, the Nuclear Physics and strong Interaction group, joined LIP in 2020. The group works on a variety of topics in nuclear and hadron physics, addressing non-perturbative phenomena in QCD with computational methods. This includes the internal structure of hadrons and their interactions with photons, their production mechanisms, and properties of exotic hadrons, which are not yet understood from first principles and challenge our understanding of the strong force. The fundamental and still open questions behind are the origin of confinement of quarks in hadrons and in nuclei, the origin of the mass of hadrons, and the properties of matter in extreme conditions such as heavy-ion collisions and neutron stars.



Fixed-target experiment

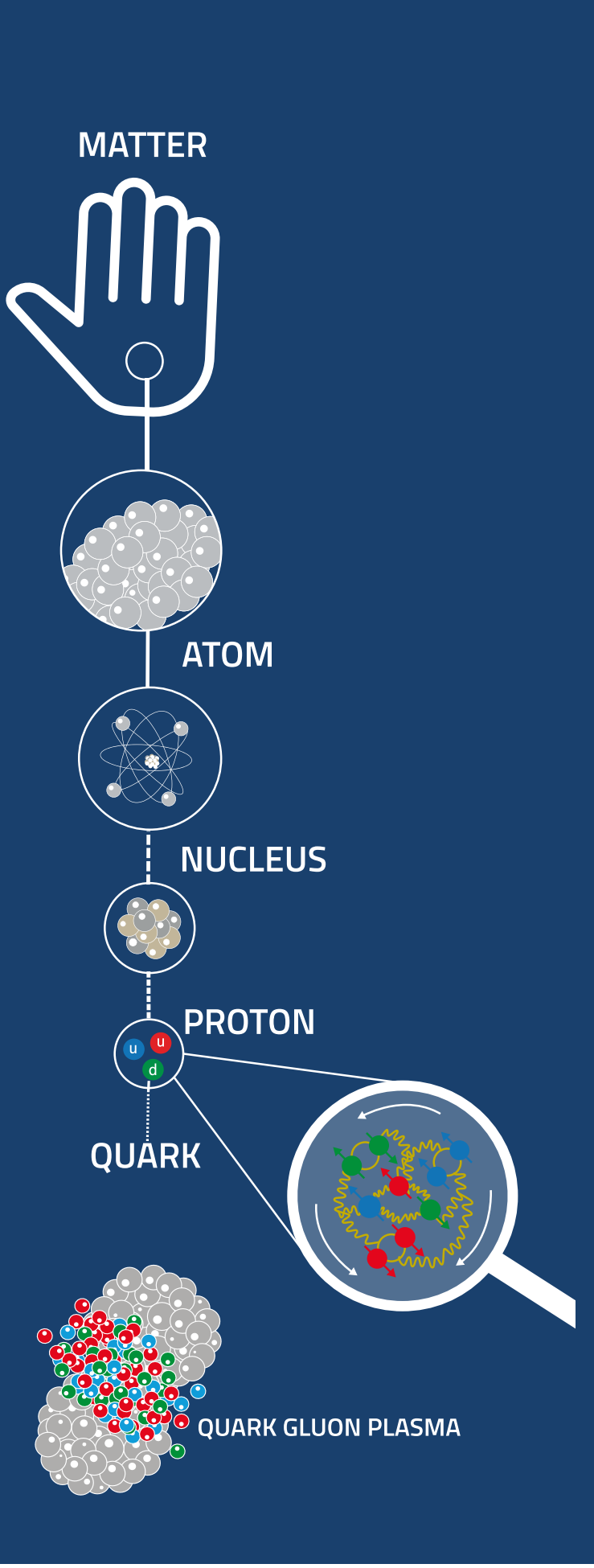


Deep inelastic scattering probes the insides of hadrons using electrons, muons and neutrinos. It provided the first convincing evidence of quarks. The higher the energy, the finer the resolution on the components of the nucleus.

According to the quark model, mesons are made of a quark-antiquark pair and baryons are made of three quarks. While the quark model can be derived from QCD, the structure of hadrons is more complicated than this model allows. The full quantum mechanical description of any hadron must include, besides the dominant (valence) quarks, a "sea" of underlying quark pairs and gluons and allows for a variety of mixings. To describe bound systems of quarks and gluons, we use non-perturbative functional methods (complementary to lattice QCD simulations) that provide ab-initio solutions for QCD's correlation functions. These subsequently enter in the calculation of hadron properties and allow us to make predictions for hadronic observables.

The 2023 highlights build up on ongoing research work and explore new directions. We performed calculations of the structure of heavy-light baryons Δ_c and Σ_c, obtaining an unexpectedly large contribution (around 60%) from the heavy-light diquarks. Importantly, it was clear from our findings that a scalar diquark component alone would not be sufficient to describe these baryons. The group led the first realistic calculation of the deuteron as a multiquark system from first principles of QCD. The calculation was based on quark, diquark and meson exchange between the quark structure of a proton and a neutron used as input; a large contribution of p-waves which is totally suppressed within a non-relativistic framework was found. No other two-nucleon bound state is found.

By invitation of the editor of "Progress in Particle and Nuclear Physics", we prepared and submitted a comprehensive review on recent experimental and theoretical advancements in our understanding of the electromagnetic structure of baryons. One main conclusion is the necessity of linking complementary theoretical approaches, for more model independence and uncertainty control. In addition, connecting Lattice QCD and the quark phenomenological picture can leverage the strengths of both.



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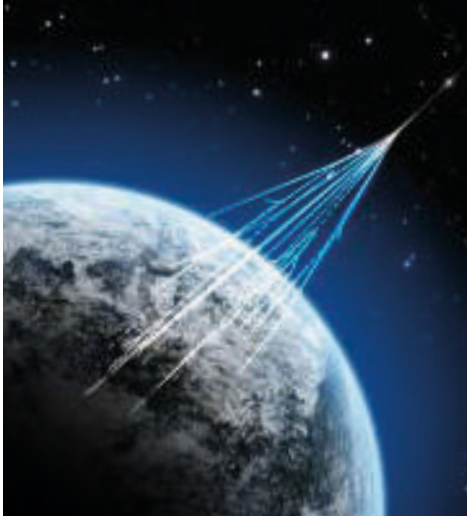


EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

Cosmic Rays

Messengers from outer space

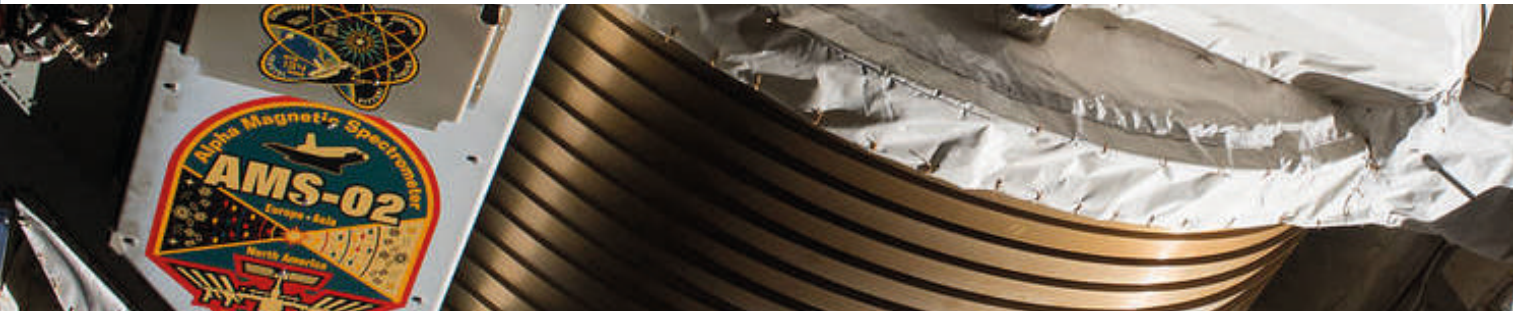
Planet Earth is constantly being struck by charged particles (electrons, protons atomic nuclei) and energetic photons (gamma rays) expelled by distant stars and galaxies. These messengers from outer space bring information about the history and composition of the Universe. The very wide energy range of cosmic rays implies that different detection methods are used, from space-based experiments range to ground-based giant air shower detectors at the highest energies. LIP is committed to the Alpha Magnetic Spectrometer, the Pierre Auger Observatory, and the SWGO.

A unique detector in space

Since 1998 LIP is part of the international collaboration that designed and operates the Alpha Magnetic Spectrometer (AMS). The AMS-I prototype was flown aboard the space shuttle in 1998, and the final detector was installed in the International Space Station (ISS) in May 2011. Since then, a huge set of data has been gathered at a continuous rate of over 45 million events per day. AMS catches cosmic ray particles directly, before they interact in Earth's atmosphere. The detector has different layers that measure different particle properties, and a magnetic field causing particles to bend according to the sign of their electric charge. AMS allows to study in detail the fluxes of different types of cosmic particles, but also to search for antimatter nuclei and dark matter in the Universe.

LIP had an important role in the design and construction of AMS's Ring Imaging Cherenkov sub-detector (RICH). RICH detectors allow to identify charged particle types through Cherenkov radiation, emitted when a particle crosses a medium at a velocity larger than the velocity of light in that medium. Identification is achieved by measuring the Cherenkov radiation emission angle, which is related to the particle's velocity. If the particle momentum is measured by another sub-detector, the particle mass can be derived. LIP holds responsibilities in the RICH operations and monitoring, and in reconstruction algorithms. The magnetic activity of the Sun varies in 11-year cycles, affecting cosmic ray fluxes arriving to Earth in a way that depends on the particle charge, mass and rigidity, while presenting complex time signatures that provide insight into cosmic ray transport mechanisms. The LIP group has for long been involved in the study of solar modulation effects and their interpretation under solar modulation models.

Observations of isotopes of the same nuclear species provide information on galactic matter distribution and cosmic-ray propagation, as their intrinsically different cross-section can be used to probe different space depths. Over the last years, the group has deepened its involvement in deuteron-proton separation and isotope flux analysis. The analysis of deuterons and protons with AMS data from May 2011 to May 2021 has been concluded in 2023. The LIP/ Groningen approach included parametric mass templates, Bayesian data unfolding, and a machine learning method based on RICH observables to reject badly reconstructed events.



The most energetic particles in the Universe

While at low and moderate energy cosmic rays are quite abundant, the flux decreases steeply as we go up in energy. The highest energy cosmic rays ever detected have energies of a few times 10^{20} eV. This corresponds to a macroscopic energy of tens of Joules and is well above the energy available at any human-made accelerator. The highest energy cosmic rays are thus messengers from the most energetic phenomena in the Universe and a window to particle interactions at energies above accelerators.

The Pierre Auger Observatory is the largest cosmic ray detector on Earth, covering an area of 3000 km² in the Pampa Amarilla, (Argentina). It consists of 1660 water Cherenkov detectors (WCD) separated by 1.5 km that sample the showers of millions of particles produced when the highest energy cosmic rays hit the atmosphere. In dark nights, telescopes detect the UV light emitted by showers. Running since 2004, the Observatory has confirmed that highest energy cosmic rays are of extra-galactic origin and most likely accelerated in yet unknown astrophysical source. Still, several open questions remain. The observatory is currently completing the upgrade to Auger Prime. Scintillator detectors (SSD) have been installed on top of the working WCD, which were also equipped with faster electronics. This will enable a better measurement (and disentangling) of the electromagnetic and muonic components of shower at ground.

In recent years, the LIP team has been involved in R&D projects on the use of RPC detectors to directly measure the muon component of showers, and for calibration studies of WCD, in collaboration with the Auger groups in Brazil. The commissioning of the MARTA WCD-RPC unit (a layer of RPCs placed underneath the WCD) was successfully concluded. Control data was acquired to study the performance of the system.

RPC show a remarkable performance stability over the long field deployment period. A first set of shower data was also acquired. The potential of a single MARTA station for specific shower physics investigations is being evaluated.

The studies performed with the WCD calibration setup became an important tool for the collaboration. The WCD calibration hodoscope has been upgraded to the Auger Prime configuration. The effective area was increased and data acquisition efficiency enhanced, reducing the collection time. The system's integrity was validated and analysis is ongoing.

In parallel the LIP group has been exploring the Auger data, mainly pursuing the detailed understanding of air showers, in collaboration with the Auger group in Santiago de Compostela (Galicia, Spain). We focused on the energy spectrum of shower particles and on further exploring the properties of the muon number distribution. We have demonstrated the possibility of jointly analysing SSD, WCD and RPC data to evaluate the previously unaccessible energy spectrum of the electromagnetic shower component at ground. This analysis demonstrates sensitivity to muon energies below 1 GeV. Despite higher muon energy thresholds, AMIGA, (a set of buried scintillators within the SD array) confirmed the muon puzzle and lowered Auger's photon flux limits. Simulation studies conducted by the LIP group revealed that AMIGA has the potential to distinguish between different hadronic interaction models at energies comparable to the LHC's.

The Auger masterclass fully developed by the LIP group was part of the official IPPOG International Masterclass in 2023. The activity was conducted with high-school students in national and international institutes with remarkable success. Continued support was given to the Auger 3D visualizer and virtual reality tools developed at LIP and now used also at the Auger visitor center in Malargue.

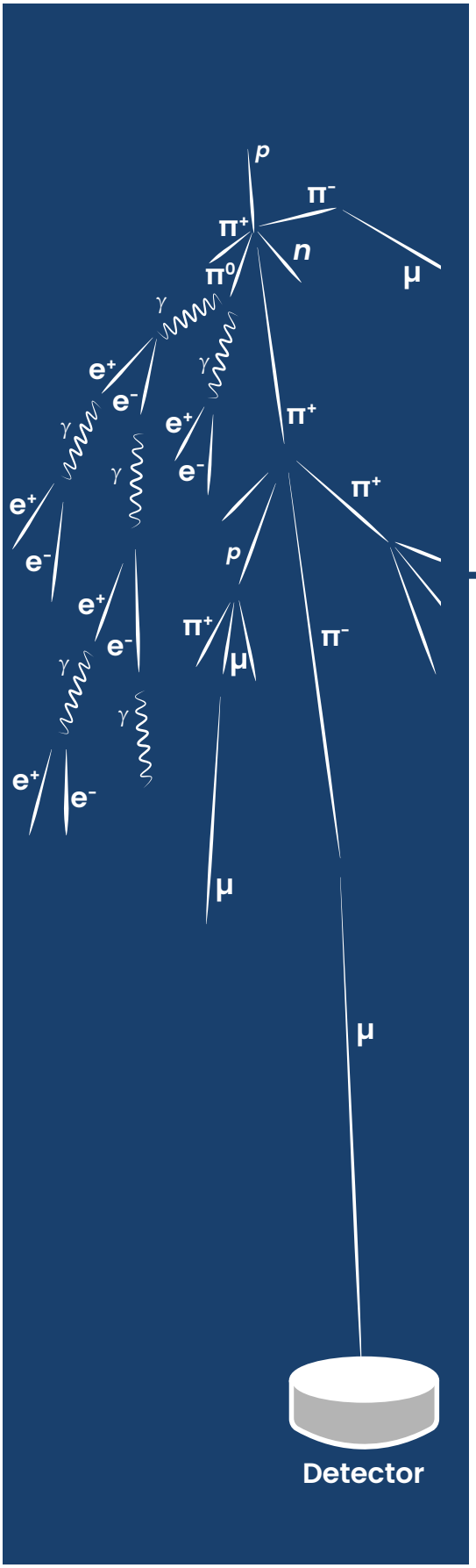
At the top of mountains

The Southern Wide-field Gamma-ray Observatory (SWGO) collaboration was formed in 2019 after a workshop in Lisbon where different groups developing similar projects decided to joint efforts. Today, SWGO comprises 80 research institutions from 14 countries, plus 10 scientists from other countries individually collaborating in SWGO. The main goal of SWGO is to pave the way for the construction of the next wide field-of-view gamma-ray observatory to be installed at high altitude (4500 m) in South America. The new observatory will cover an extended energy range and address a rich science program. Moreover, SWGO will be the only wide-field observatory surveying the Southern sky and thus the centre of the galaxy region. The collaboration aims at producing a complete proposal by the end of 2024, including the physics goal, location, observatory layout, detector design, and cost.

The Portuguese participation in SWGO is focused on specific goals spanning different areas: science requirements, detector design, analysis development, outreach. In 2023, two priorities were defined. The first was to finalize the detailed design and performance studies of the "Mercedes station", a single-layered small Water Cherenkov detector (WCD) proposed by the LIP group as candidate to be the SWGO detector unit. The second priority was to complete the development of discriminator-based methods to separate gamma-initiated showers from the largely dominant background of charged cosmic rays showers (initiated by protons and nuclei).

In collaboration with CBPF, a consolidated and detailed end-to-end proposal of the Mercedes WCD station was elaborated, with two versions depending on thermal isolation requirements. In a partnership with Brazilian companies, the industrial design of both versions was finalized and the funding to produce a small number of tanks was obtained. The LIP team also presented the detailed unit thermal simulation model and contributed to the completion of the site characteristics matrix.

Gamma/hadron discrimination is paramount in any gamma ray observatory. The LIP team developed gamma/hadron discriminant algorithms for two energy ranges. At lower energies (100 GeV - 10 TeV), a machine learning algorithm based on muon identification in each Mercedes station (using PMT signal time structure); at higher energies (10 TeV – few PeV), two discriminant variables based on the signals collected in the stations (and introduced by the group): LCm quantifies the azimuthal fluctuations of the particle distributions at ground; and Ptail identifies the stations with signals well above the mean signal measured in the stations located at similar distances to the core. Within the limited statistics available, both variables demonstrated a discriminant power similar to the number of muons at ground. Both reconstruction algorithms are now part of the SWGO reconstruction framework.



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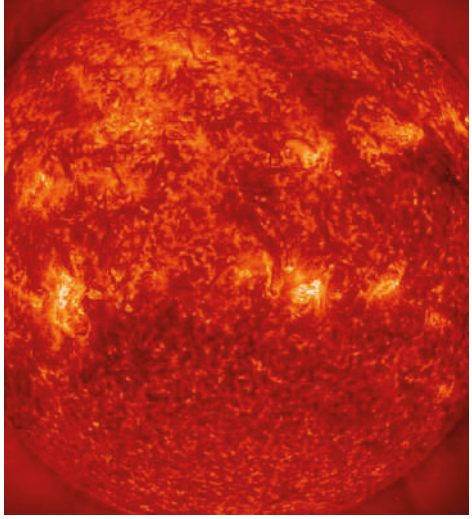


Dark matter and neutrinos

Hunting for the most elusive particles

The quest for dark matter and a deeper understanding of the elusive neutrinos are among the great challenges of particle physics for the next decades. LIP takes part in these challenges through its engagement in some of the main international collaborations in this area: the neutrino physics experiment SNO+ at the SNOLAB (Canada), LZ dark matter detector at the SURF Laboratory (USA), and the more recently embraced participations in DUNE, one of the leading neutrino physics experiment for the next decades; in SHiP, proposed for CERN's SPS (Super Proton Synchrotron) and its predecessor SND@LHC; and in the preparation for third generation dark matter search experiments in XLZD.

Searching for the dark side

Although we cannot see dark matter, we can see the effects of its gravitational interaction. According to the most recent experimental evidence, dark matter makes up 27% of the Universe. And we have strong clues that dark matter is made of particles that interact very weakly. One of the ways to search for dark matter is to use super-sensitive underground detectors to identify very rare interactions between dark matter particles crossing the Earth and normal matter nuclei in our detector.

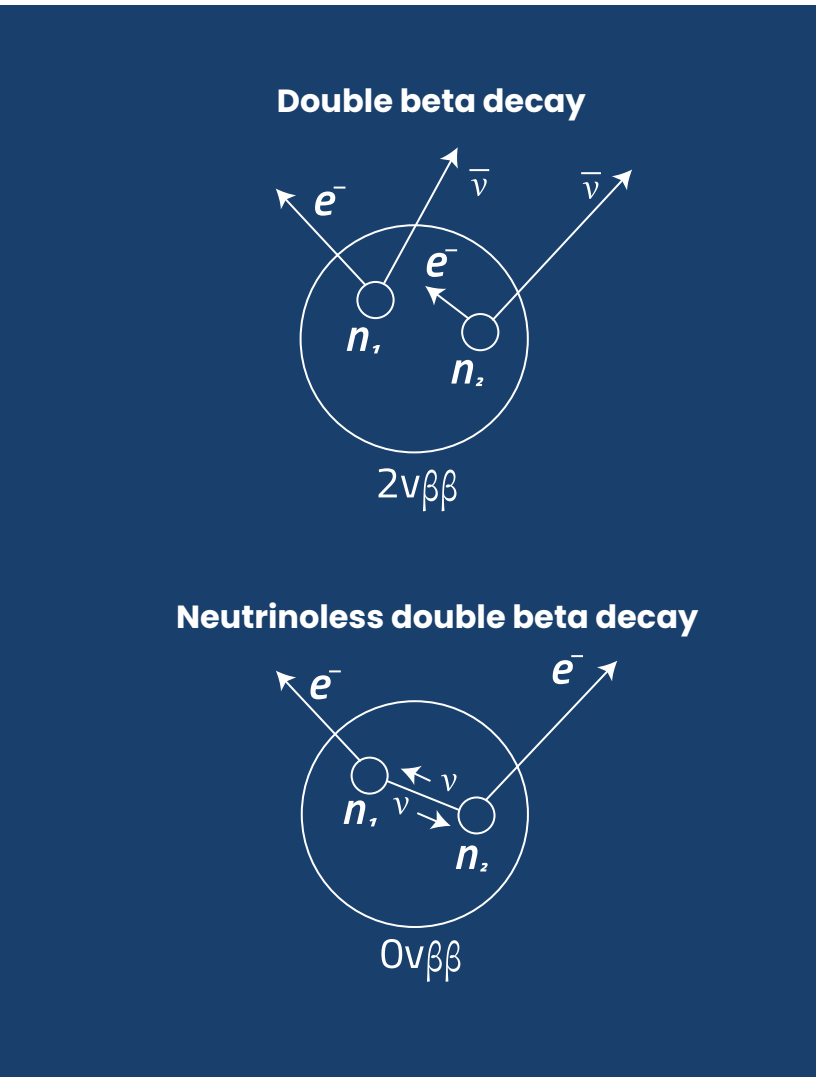
The LIP Dark Matter group is a founding member of the LUX-ZEPLIN (LZ) experiment at the Sanford Underground Research Facility (SURF). LZ uses 7 tonnes of liquid xenon as active medium in a dual phase TPC to search for dark matter signals. The interaction of a dark matter particle with a xenon nucleus would cause a nuclear recoil and produce a detectable photon signal. A TPC is a detector able to measure the 3D position of each spot where an interaction occurs. To improve the rejection of background (cosmic rays and natural radioactivity) the detector is placed 1480 m underground inside a double vessel of radio-pure titanium, and there are auxiliary veto detectors. Due to the extremely low background, LZ can be used for other studies such as the search for Xe rare and forbidden decay.

LZ had its first science run in early 2022, with an exposure of 60 live days. The corresponding analysis was published in 2023. It showed that the data are consistent with a background-only hypothesis and crosssection limits have been derived for WIMP masses above 9 GeV/c^2, proving LZ as the world most sensitive WIMP search experiment. After a six month long calibration campaign, a second period of data acquisition dedicated to WIMP search started in early 2023 and continues to the present day. The LIP group is contributing to many areas of the LZ experiment. It has a leading role in the studies of the LZ sensitivity to Xe neutrinoless double beta decay, is responsible for the detector control system and online underground performance monitor, and also for the development of data analysis tools.

Since 2020, the group is part of a UK-based project aiming to observe the Migdal effect: nuclear recoil interactions can be accompanied by atomic ionisation, and this would extend the sensitivity of WIMP direct detection detectors to lower (sub-GeV) WIMPs masses. From June to August 2023 the detector collected data at the ISIS Neutron and Muon Source (UK) and analysis is currently ongoing. On the other hand, the LIP team is now part of the XLZD consortium, a joint venture of the LZ, DARWIN and XENON collaborations towards a next-generation direct detection WIMP search experiment employing a double phase xenon TPC with about 100 tonnes of xenon. Working groups were formed towards achieving a final design of the detector and planning the experiment. LIP has coordination responsibilities in the $0\nu\beta\beta$ and calibration groups. The LIP team is leading the preliminary sensitivity study of XLZD to $0\nu\beta\beta$.

Understanding the elusive neutrinos

Neutrinos are the second most abundant particle in the Universe, after photons. They are constantly being produced in nuclear reactions inside stars. On Earth, radioactive decays and cosmic rays interactions in the atmosphere also produce neutrinos. Neutrinos interact only weakly with matter and are thus extremely hard to detect. They can go through the Sun and the Earth undisturbed, bringing important information about the Universe. There are three neutrino types, or flavours: electron, muon, and tau neutrino. Neutrinos alternate between the three flavors while propagating — we say they oscillate. For that, neutrinos must have a non-zero (although tiny, and as yet unknown) mass, which was not foreseen in the Standard Model of Particle Physics. The discovery of neutrino oscillations gave the 2015 Nobel Prize to Takaaki Kajita, from the SuperKamiokande experiment, and Arthur B. McDonald, from the SNO experiment. Another open question about neutrinos is whether they are Majorana particles, i.e., if they are their own antiparticle.



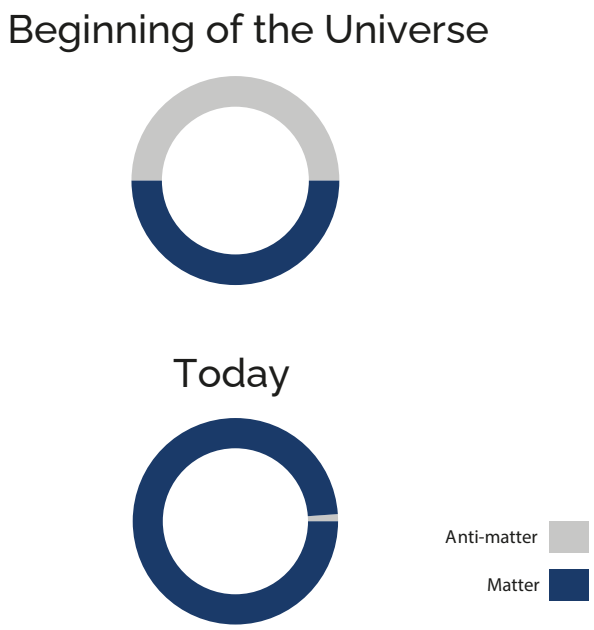
SNO+

The LIP Neutrino Physics group joined the SNO experiment in 2005 and is a founding member of the SNO+ international collaboration. The detector is located 2 km deep underground, at SNOLAB (Canada). An acrylic sphere with 12 m diameter and 6 cm thickness is surrounded by 9500 light sensors. The SNO+ experiment followed from SNO, replacing the active medium inside the sphere: from heavy water to water and then to liquid scintillator. The main goal of the experiment is the search for neutrinoless double-beta decay, by loading the scintillator with large quantities of Tellurium. The observation of this process would be a breakthrough in the understanding of the nature of neutrinos, revealing that they are Majorana particles. Several other low-energy, low-background, physics topics are also part of the SNO+ program: antineutrinos from nuclear reactors and the Earth's natural radioactivity, solar and Supernova neutrinos, and searches for new physics.

The filling of the detector with LAB scintillator was completed in April 2022, and since then SNO+ has been taking high-quality data. A secondary wavelength shifter to boost the light output is being added, in preparation for the tellurium loading phase in 2025. Tellurium purification and loading systems are currently being commissioned. LIP has been very much involved in the construction of the SNO+ calibration systems and is currently active in the data analysis of the water and scintillator fill phases, namely in backgrounds and antineutrino physics analyses and in calibrations. The group had a large contribution in evaluating the background ingress (U and Th) and the correlation with the recirculation of the scintillator, crucial for preparing the tellurium loading. We actively monitored the scintillator purity and optical quality during the addition of the secondary wavelength shifter. Besides the observation of antineutrinos from nuclear reactors with the water-filled detector — a first for such a device, published in PRL in early 2023 and selected as Editor's Suggestion — we highlight the paper about scintillation directionality, submitted to PRL, and two others undergoing final review in the collaboration: antineutrino analysis in partial-fill, and solar neutrinos in the water phase. The group further participated in the technical meeting on the requirements for (alpha,n) data organized by the IAEA.

DUNE

DUNE is a long baseline experiment: neutrino and antineutrino beams will be produced at Fermilab and detected 1300 km away at SURF, in large Liquid Argon (LAr) TPCs (the far detector). DUNE will certainly be one of the great projects of the next decades, studying in particular the mass hierarchy of neutrinos and investigating wether neutrinos can contribute to explain the matter-antimatter asymmetry in the Universe.



LIP joined the DUNE collaboration in 2018. The team focused on the design and construction of the far detector calibration systems, both mechanics and electronics. LIP also leads the Calibration and Cryogenic Instrumentation Consortium (one of eleven consortia) and plans to contribute to the Near Detector. In 2023, the group completed the development of the custom electronics that control the laser calibration system and implement the interfaces with the other subsystems, such as DUNE DAQ and SC. Furthermore, the team completed the production and test of most mechanical parts under its responsibility for the ProtoDUNE-VD detector at LIP's Mechanical Workshop and Detectors Lab, and coordinated the installation of the two mirror-based alignment targets. We also participated in the assembly, alignment and installation of the two periscopes at ProtoDUNE-HD at CERN, following adjustments made after the initial 2022 deployment. Finally, the group implemented the calibration control software, and progressed in the developed software for simulation, processing and analysis.

SHIP and SND@LHC

A LIP team is currently involved in the SND@LHC experiment operating at the LHC, and is a proponent of SHiP at CERN, a general-purpose intensity-frontier experimental infrastructure being proposed at CERN for operation during the upcoming decade. LIP is responsible for RPC-based detector systems for SHiP.

SND@LHC is the most recent CERN experiment. It has been designed to exploit the potential of the LHC as a neutrino factory, and to perform measurements with all neutrino flavours, in the unexplored TeV energy range. The detector is installed in the TI18 tunnel next to the LHC ring and about 500 m from the ATLAS collision point. LIP is a founding member of the SND@LHC collaboration, which was established in 2021. In a close collaboration between the Lisbon and Coimbra nodes of LIP, the group took part in the construction of the muon and hadronic calorimeter systems and in the commissioning of the detector, as well as in data taking, which started in 2022 with LHC's Run 3.

The highlight of 2023 was the first observation of collider neutrinos, a milestone physics result achieved under the leadership of the LIP group and published by SND@LHC. This first observation marks the dawn of the era of neutrino physics at colliders. Larger data sets continue to be accumulated will allow for more detailed investigations. A very successful calibration campaign has been conducted in 2023, with LIP's leading involvement. Calibration is a crucial ingredient for the next step: measuring the energy of the detected neutrinos.

In 2023, a novel muon telescope, based on the sealed RPC technology, was assembled and tested, towards installation in the LHC tunnel in 2024 to monitor the muon flux in different angular regions. Planning for an upgraded (AdvancedSND) detector for the high-luminosity LHC phase was initiated.

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Development of new instruments & methods

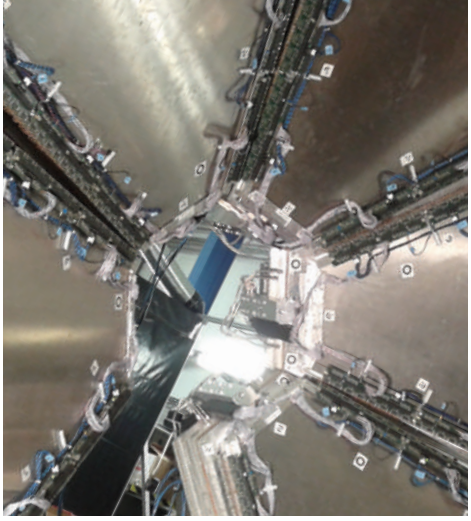
• Detectors for particle and nuclear physics • Health and biomedical applications • Space applications

Radiation detectors are sensitive to the passage of particles and able to measure some of their 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 also the associated data acquisition and readout electronic system, trigger and data processing tools, control and other ancillary systems.

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. The laboratory holds a high level of expertise in key radiation detection technologies, supported by research on the fundamental processes involved.

LIP's expertise in planning, building and operating detectors for particle physics finds natural application in the fields of radiation and particle therapy instrumentation, dosimetry, and medical imaging. These areas are covered in multidisciplinary projects developed in collaboration with partners such as ICNAS, the institute for nuclear health applications at the University of Coimbra, CTN/IST, the centre for nuclear technology at the University of Lisbon, and several hospitals, medical research centres, and companies.

Space exploration is another natural area of application of particle physics technologies, especially in what concerns radiation detection instrumentation and the modeling of complex processes involving the interaction of radiation with matter. Over the last decades, LIP became a recognized player in the space community. LIP is a partner of the European Space Agency (ESA) in several planetary missions and consortia for the development of scientific instruments, and also a partner of the Portuguese Space Agency.



DEVELOPMENT OF NEW INSTRUMENTS AND METHODS

Detectors for particle and nuclear physics

Technology to see the invisible

The development of particle detectors and related instrumentation has been, from the start, one of the 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 specialties include Resistive Plate Chambers (RPC), neutron detectors, gaseous and Xenon-based detectors, optical fibre calorimeters and fast electronics for data acquisition systems. Both applications to other fields and the preparation for future experiments open great opportunities for detector R&D.

RPC R&D: pushing the limits of performance and versatility

Resistive Plate Chambers (RPC) are versatile detectors with a fast response, intrinsically radiation hard, and relatively low cost. Over the last years, LIP's RPC R&D group developed a set of coherent and ambitious lines of work that took the performance and the flexibility of RPCs to a new level. This expanded the range of RPC applications to several areas addressing societal challenges, from nuclear and particle physics to medical physics, from rugged outdoor muon detection systems to helium-free neutron detectors, confirming LIP as a world leader in the development, design, and construction of RPCs. The group presently works in a number of research directions.

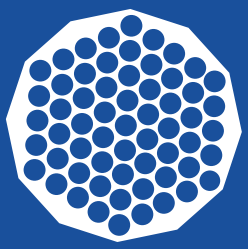
RPC-PET: medical imaging

The development of RPC-based devices for medical imaging through Positron Emission Tomography (PET) is a priority for LIP. The group is currently focused on HiRezBrainPET, the human-brain PET device developed in collaboration with the company ICNAS Produção. The project for the production of a full prototype was completed in 2022. Tests demonstrated a sub-millimeter spatial precision and the ability to create images of small brain structures in phantoms. For further details, see the Health and Biomedical Applications research line.

Detectors at LIP

Resistive Plate Chambers (RPC)

Flexible and robust gas detectors with very good time and space resolution and a wide range of applications.



Liquid Xenon detectors

Very sensitive detectors in which dark matter particles would cause nuclei to recoil producing a light and charge signal.

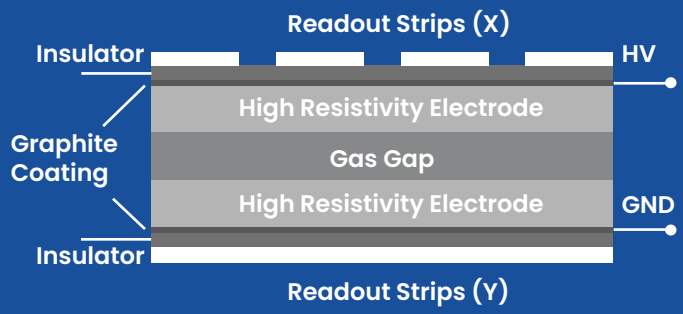
Patterned Gas Detectors (PDG)

In modern gas detectors, instead of wires one uses electrodes deposited in a electronics board.

Time & position sensitive RPC

Many large particle physics experiment use RPC-based detectors: their very good time precision is ideal for trigger or timing, and it continues to be one of the main technologies for particle identification (using the time of flight technique, TOF), specially when implementation in large areas is needed. The LIP RPC group develops and builds RPC detectors for particle and nuclear physics experiments using an innovative technology that allows for 98% efficiency and 50 ps time precision. In 2021 and 2022 two such systems were installed at GSI for the FAIR phase-0 runs. In 2022, the new HADES forward TOF detector run for six weeks. In 2023, the preliminary calibration of the new TOF detector for R3B has been carried out. For further details, go to the Structure of Matter research line.

The precise measurement of position in combination with time is also of interest for TOF-based particle identification. In addition, it finds direct application in muon tomography. Cargo container muon scanners STRATOS were developed and built at LIP for company HIDRONAV (Spain). Each unit is a 2 m x 2 m telescope (four RPC planes) with 98% efficiency and 1 cm 2D spatial precision. Preliminary tests in scattering tomography mode showed the capability to identify high Z materials (e.g., tungsten and lead) within a few minutes of data acquisition. MUTOM, a muon telescope for the tomography of geological structures, was fully integrated in 2021 and successfully operated at the Lousal mine in 2022 and 2023, demonstrating its ability to perform tomographic imaging. The first paper on the detector performance has been published in 2023. For further details, see the Muon Tomography report. Position information depends on readout strips configuration and data acquisition channels. In 2023, the LIP RPC group developed a readout capable of extracting both timing and spatial information (below 100 ps and 1 mm respectively) scalable in area without the need to incorporate new electronics channels. Results will be presented and published in early 2024.



Resistive Plate Chamber (RPC)

RPC are gaseous particle detector with two parallel electrode plates made of a high resistivity material (glass). The gap between them is filled with a gas mixture. As a charged particle travels through the detector, it will ionize the gas between the plates. High voltage applied to the plates creates a uniform electric field, and a localized electron avalanche is instantaneously produced directly on the particle's trajectory and drifts towards the anode plate. Due to the high resistivity of the plates, only a very small portion of the plate is discharged. The signal is collected by pickup strips. Multi-layer RPC improve efficiency and provide trajectory information.

Autonomous RPC

The development of autonomous and reliable RPCs, able to operate under harsh conditions and/or with little maintenance, is of great interest for several applications and the LIP team has a strong record in this domain. In 2020, chambers have been successfully tested at pressures down to 400 mB (about 6000 m altitude). After several tests operating chambers at a reduced gas flow, in 2022 a 1 m x 1 m double gap sealed (no gas flux) chamber has been assembled, fully instrumented and setup for characterization: measurement of time resolution, efficiency and charge spectrum over time, showing a stable performance after a several months of operation. The first paper on the sealed RPC technology (sRPC) was published in 2023. Also in 2023, a portable sRPC telescope was built as characterised. It will be installed close to the SND@LHC apparatus in 2024. For further details, see the Dark Matter and Neutrinos section.

RPC-based neutron detectors

Neutrons are a unique probe for revealing the structure and functioning of matter from the microscopic to the atomic level. Neutron-based techniques can be applied to a wide range of scientific domains, including physics, chemistry, material and life sciences. These techniques rely on neutron sources equipped with advanced instrumentation available only in global research infrastructures used by academia and industry. The gold standard for neutron detection was based on ^{3}He, a stable helium isotope with a high thermal neutron capture cross section. The forbidding cost of this rare isotope motivated the development of alternative neutron detection technologies meeting the requirements of a new generation of instruments. LIP's Neutron Detectors group has a long record of participating in EU-funded R&D projects dedicated to neutron detection technologies.

Currently the group is focused on the development of a neutron detection technology based on RPCs and solid neutron converters ($^{10}B_4C$), aiming at high resolution and high count rate position sensitive detectors for cold and thermal neutrons. The first stages of the development were conducted in partnership with the ESS and FRMII in the framework of the SINE2020 project, and characterization studies in neutron beam lines have demonstrated the potential of this technology. Recently, we designed and build a proof-of-concept demonstrator in the framework of the FCT-funded project "Fast timing high resolution nRPC-4D detector concept for neutron science". The goal is to demonstrate that this type of detector can provide 4-dimensional readout capability (XYZ and time). The prototype has been tested at two neutron facilities, the PSI (in late 2022) and the ILL (in late 2023) and the analysis of the results is ongoing. Application of this technology is foreseen in ToF neutron diffraction/reflectometry, energy- and time-resolved neutron imaging, as well as in other applications requiring readout of position and time. As a spin-off project, the group is developing a fast neutron detector concept based on the ^{10}B-RPC technology. A potential application is the measurement of beta-delayed neutron emission probabilities of exotic neutron-rich nuclei (e.g., in ISOLDE at CERN).

Gaseous detectors and RD51 collaboration

The main focus is currently on application of MPGDs (Micropattern Gaseous Detectors) in double phase xenon (liquid/gas) and the development of novel methods for their readout according to the programme of the RD51 Collaboration at CERN. In 2023 we continued the study of a novel method of electron extraction from liquid xenon proposed by our group. The method is based on using a multihole two-electrode structure freely floating on the liquid surface (Floating Hole Multiplier, FHM). Two setups have been completed, at LIP in Coimbra and at Weizmann Institute of Science (Israel) that allowed us to prove the principle and to study the behaviour of liquid xenon in contact with a floating THick Gaseous Multiplier structure at sub-millimetric level. A set of microscopic images has been acquired and the electrons drifting in the liquid were observed to be collected from the liquid into the THGEM holes, extracted to the gas (in the hole), and to induce secondary scintillation in the gas thus providing the typical S1/S2 event signature. The electroluminescence of liquid xenon has been observed with a standard microstrip plate.

The main investigation areas of the Gaseous Detectors R&D group are the study (simulations and experimental measurements) of the drift parameters of electrons and ions (positive and negative) in noble gases and mixtures with the aim of finding the more suitable active medium for each application. Recent studies include the electroluminescence xenon TPC used by the NEXT collaboration and ion mobility measurements in mixtures of interest for the RD51 collaboration. The use of negative ions as charge carriers (from the addition of electronegative dopants to a main gas) is being considered in high volume experiments, as ion diffusion during drift is much smaller than electron diffusion, allowing for more accurate path reconstruction. The study of negative ion mobilities but also of other parameters in electronegative mixtures are thus very important. We intend to fully investigate such parameters. Due to the implementation of ECFA's Detector R&D (DRD) roadmap, the coming year will be marked by the transition from RD51 (development of micro-pattern gas detectors technologies) to DRD1 and the start of recently approved DRD2 on particle detectors based on liquid media.

DEVELOPMENT OF NEW INSTRUMENTS AND METHODS

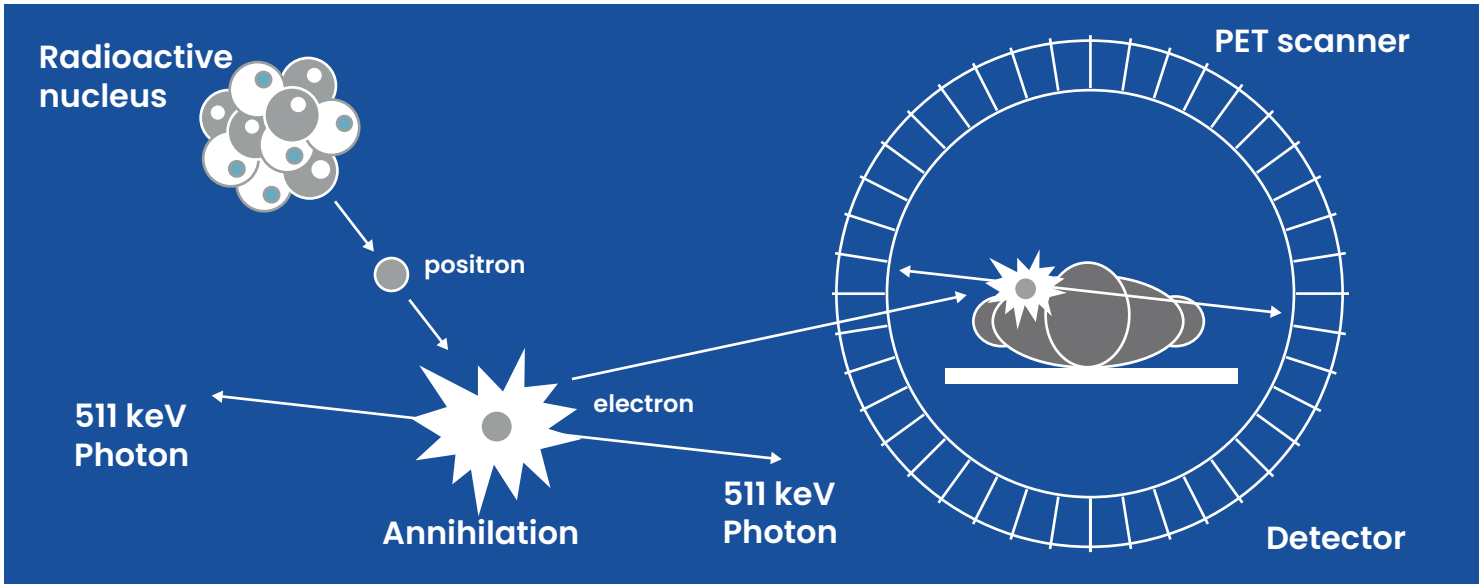
Health and biomedical applications

Interdisciplinary projects for healthcare instrumentation

LIP's expertise in planning, building and operating detectors for particle physics finds natural application in radiation and particle therapy instrumentation, dosimetry, and medical imaging. These areas are covered in multidisciplinary projects developed in collaboration with partners such as the ICNAS institute for nuclear health applications, the CTN/IST campus for nuclear technology, and several hospitals and medical research centres in several countries in Europe and in the USA.

RPC for medical imaging

Positron emission tomography (PET) is an extremely sensitive medical diagnosis technique. A radioactive marker is injected in the patient's body, releasing positrons in the zone to study. When the positrons encounter electrons from neighboring molecules, they annihilate, producing two energetic photons traveling in opposite directions. These photons are identified by the surrounding detectors to create detailed images of the organism and to monitor dynamic processes. This line of work has been pursued by the RPC team at LIP for a number of years. A high-resolution, small animal RPC-PET scanner developed at LIP is installed at ICNAS since 2014. Hundreds of tests have been performed in mice, with goals such as studying degenerative diseases or testing new drugs. This technology is now being applied for human brain PET. In the framework of the project HiRezBrainPET, a prototype RPC-BrainPET scanner has been developed and constructed. This equipment has the potential to change the paradigm in the diagnosis and investigation of central nervous system diseases, for example by allowing to see small brain structures involved in neuropsychiatric diseases. The high spatial resolution of the system may play an important role in the characterization of vascular injury or tumors, allowing for better treatment planning. The evaluation of RPC-BrainPET started in 2022, showing a spatial resolution better than 1 mm FWHM. In a phantom of a human brain with an average activity concentration of 6 kBq/ml and 50 kBq/ml in the striatum, it was possible to resolve the striatum chambers. The scanner shows a sensitivity of 0.09%, equipped with less than half of the detectors it can accommodate. The first paper on the scanner performance has been published in 2023. The RPC-BrainPET scanner will be tested at ICNAS (on a volunteer basis) with patients that are taking a scan with a commercial PET/CT device installed in the same room.



Advanced Radiotherapy and Charged Particle Therapy Applications

During the past decade LIP has been strongly engaged in fostering the creation of a charged particle therapy facility for the treatment of cancer in Portugal. In this context, LIP played a pivotal role in creating the Prototera association, along with Técnico, CTN, Universidade de Coimbra, and the Portuguese network of Oncology Institute.

In this context, it was necessary to increase the expertise in this domain in Portugal, a LIP has been engaged in providing advanced training in the field of radiation and particle therapy applications. In addition, LIP's research groups in health and biomedical applications have been working in a synergetic way towards developing devices and tools that could lead to technology transfer from particle and detector physics towards clinical applications. Unfortunately, the future of such a facility for cancer therapy in Portugal is presently undefined.

LIP is thus redefining its strategy in a two-fold way:

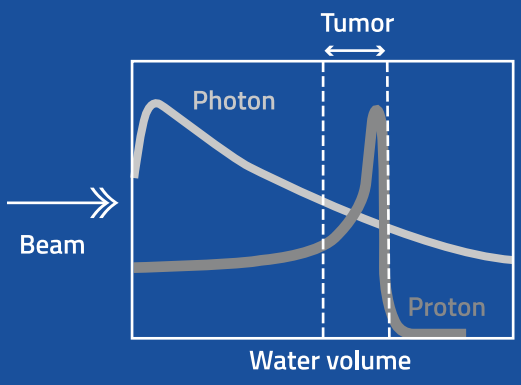
- Pushing forward an International Network for Advanced Radiotherapy, in which LIP and its partners will promote the advanced training of physicists, medical physicists, and clinicians at Iberian and European level, exploring the opportunities that arise from the planned installation of 13 proton therapy facilities in Spain in the next few years (besides the two facilities already existing in Madrid) and the collaborations that have been put in place throughout Europe, in particular.

- Creating at LIP a Radiation Engineering Learning Centre for advanced training in the applications of ionizing radiations to different fields (health, materials, and space). This will bring together the expertise existing in the laboratory in different application fields of particle and nuclear physics, thus consolidating LIP's research in charged particle therapy applications and enhancing the laboratory's contribution to advancements in the field

The interest of students in advanced radiotherapy, charged particle therapy and related domains has been remarkable in the last few years. The Prototera doctoral programme, an FCT doctoral programme active between 2020 and 2023 and coordinated by LIP, awarded 30 PhD grants, in co-supervision with external collaborators from recognized national and international research and therapy institutions in this domain, namey C2TN, IBEB, BioISI, ICNAS, and the Portuguese Oncology Institute at the Hospital of the University of Coimbra, and international research centers, including ICPO, DKFZ, and CMAM.

Proton-therapy

Comparison betwen a photon and a proton beam in what concerns energy deposition as a function of depth (J. Seco , 2019).



In 2023...

- Construction of a small-scale prototype of a full system for assisting head irradiation developed at LIP (four slats of tungsten interleaved with three rows of YAP scintillators). The device has been tested in a clinical proton cyclotron at HollandPTC (Delft, The Netherlands).

- SPOF array for high-resolution dosimetry: development of a detector for radiobiology and quality assurance applications in charged particle RT, able to measure energy depositions at the sub-millimeter scale using scintillating plastic optical fibres. The campaign with clinical protons at the HollandPTC took place in early December. Preliminary results indicate that we successfully measured the Bragg-peak profile accurately.

Real-time beam monitoring and imagiology

Since several years researchers at LIP are committed to the development of instrumentation for radiotherapy. The aim is to optimize treatments in near-real time, so that the irradiation can better accommodate the tumor and spare surrounding healthy tissue. In orthogonal ray (OR) Imaging techniques, this is done using x- or gamma-rays emitted orthogonally to the treatment beam. The rotation-free, low-dose imaging capabilities of such techniques are two of their strengths. In the last few years, the OR imaging for radiotherapy improvement group (OR-imag) team at LIP developed both experimental work and ever more realistic simulations, focusing mainly in orthogonal prompt-gamma imaging (O-PGI) for proton therapy monitoring in a variety of situations (head-and-neck, pelvis, lung, total-body irradiation in pediatric tumors, among others) in a collaboration between LIP and the University of Coimbra.

Radiation dosimetry and applications for advanced radiotherapy

Knowledge of the biological efficiency of ionizing radiation in organs and tissues is essential to obtain more precise parameters for radiotherapy planning. This efficiency depends on physical properties, such as linear energy transfer and dose, chemical effects, and biological factors. This can be studied through in vitro and in vivo irradiation experiments of various cell types. Knowledge of spatial distributions and dose at the sub-cellular scale is particularly important in the case of charged particle therapy. LIP has a long experience in the development of instrumentation, simulations, and calculations of fundamental physical parameters relevant in dosimetry. Currently, the main goal of the LIP dosimetry applications group (RADART) is to contribute to the analysis and interpretation of research studies in forefront radiotherapy modalities. Activities are divided in two main areas: New detectors and materials for high-resolution dosimetry (i.e., capable of measuring energy depositions at micro and nanometer scales); New modalities and applications in radiotherapy (RT) (using simulation tools extensively to study the physical and physicochemical effects of radiation and from these infer biological effects).

Synergy projects

In the past years the OR-Imag and RADART groups participated in synergy in two funded projects. ImprovingPT is a CERN fund project aiming at the optimization, construction and first in-beam tests of range monitoring and quality assurance systems for the improvement of proton therapy. The TPPT project is a consortium led by company PETSys electronics and involving several other institutions in Portugal and in Texas, in the framework of the Portugal-Austin collaborative projects, with the objective of establishing the in-beam TOF-PET technique. In these projects the OR-Imag group has been developing instruments and methods for beam range monitoring in near real time, such as Orthogonal Prompt Gamma Imaging and associated instrumentation, and in the use of Time-of-Flight Positron Emission Tomography for the same purpose. The RADART group contributes, from a dosimetry perspective, to the analysis and interpretation of pre-clinical and clinical studies within cutting-edge radiotherapy (RT) modalities.

- PhD student Joana Antunes was awarded a Short-term Research Internship at the University of Texas at Austin 2023. She will focus on finding ways to predict the response of pancreatic cancer cells to radiotherapy.

- Gonçalo Ribeiro received prize of the Jornadas da Engenharia Física at Técnico in the undergraduate category for his presentation on a device for beam monitoring in innovative radiotherapy techniques

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Space applications

Into outer space

Space exploration is a natural area of application of particle physics technologies, especially in what concerns radiation detection instrumentation and the modeling of complex processes involving the interaction of radiation with matter. Over the last decades, LIP became a recognized partner in the space community. LIP is today a partner of the European Space Agency (ESA) in several planetary missions and consortia for the development of scientific instruments, and of the Portuguese Space Agency (PT Space).

Radiation environments and effects

Radiation environment in space is the combination of several sources. In addition to solar wind particles and cosmic radiation coming from outside the solar system, the Sun emits sporadically but intensely electrons, protons, and ions with energies up to 1 GeV. On top of that, planets with magnetosphere are surrounded by belts of trapped charged particles. The radiation environment affects spacecraft instrumentation and is one of the main constraints for future crewed missions. The detailed knowledge of the radiation environment is essential to establish radiation hazard mitigation strategies. The LIP SpaceRad group addresses questions posed by ionizing radiation in space. Its competences include all the areas on ESA's roadmap for this domain: radiation environment analysis and modeling; radiation effects analysis tools; radiation measurement technologies; radiation hardness assurance of EEE (Electrical, Electronic and Electromechanical components).

Currently LIP's SpaceRad group leads a project supporting data quality assurance, calibration and in-flight analysis for two radiation monitors flown in ESA Planetary Missions: the BERM instrument on board of the BepiColombo mission to Mercury and RADEM on board of the JUICE mission to the Jovian System successfully launched in April 2023. These monitors will provide unique data sets and consequently are being used as windows to the Heliosphere for multi- observation of Solar Particle Events and for energetic particle propagation studies. The group joined diverse science working teams both for the BepiColombo and the JUICE missions.

SpaceRad is also preparing for future Mars and Lunar missions, for which it can contribute with the predictions of dMEREM, the detailed Geant4 Martian Energetic Radiation Environment Model, which will be adapted to the description of the Lunar and Cislunar radiation environments. dMEREM was developed at LIP and is available to the community in the Space Environment Information System SPENVIS. In 2023 the work continued towards the assessment of the Martian underground radiation environment and with the development of PlanetRAD Virtual lab - a Geant4-Python tool for the demonstration of different planetary radiation environments.

The proposal "SpaceRAD - An Integrated Framework for the Radiation Environment in Space, on Mars and on the Moon and its Implications for Human Space Flight " was selected for funding in the 2023 PROSSE – PRODEX call. The project is expected to have its kick-off in early 2024.

Astrophysics instrumentation in space

LIP's Instrumentation for Astrophysics (i-Astro) group develops its research activities in the framework of mission proposals to ESA and NASA, in the domains of x- and gamma-ray space astrophysics and terrestrial gamma-ray flashes (TGFs, bursts of gamma rays produced in Earth's atmosphere). The group develops gamma-ray and particle detection space instrumentation based on semiconductor detector planes (CdTe, CzT, Si, Ge), scintillators (CsI) or gas-filled detectors with polarimetric capabilities, including front and back-end electronics.

i-Astro is currently part of the EU project consortium "Activities in the High Energy Astrophysics Domain" (AHEAD2020) as well as of the NASA mission proposal consortium "All-sky Medium Energy Gamma-ray Observatory" (AMEGO). These are long term projects whose technology and science case are validated and improved in previous small-size space- and balloon-borne missions. i-Astro is currently leading two small-size ESA funded projects: "Gamma-ray Laue Optics and Solid State detectors experiment (GLOSS)" onboard the ISS; and "TGF and High-energy astrophysics Observatory for gamma-Rays" on board the Space Rider (THOR-SR).

In the framework of AHEAD2020, i-Astro is developing a demonstrator for a 4U CubeSat Compton Telescope (COMCUBE) with GRB polarimetric capability in the few hundred keV range. In 2023, we took part in the COMCUBE scientific payload prototype integration task, prior to the prototype launch in a CNES high-altitude balloon. In the framework of AMEGO, i-Astro performed polarimetric performance evaluations for GRBs and blazars simulations.

The GLOSS project onboard the ISS Bartolomeo platform started in July 2021. It is led by LIP in collaboration with Active Space, UBI, and several Italian institutions. The goal is to assess the effects of orbit radiation environment on a CZT-based instrument of the type that could be used in a future gamma-ray observatory for a Low-Earth Orbit (LEO) mission. In 2023, performance tests to assess Ge and Si crystals detection parameters degradation after 1 year exposed to the ISS orbit environment were conducted at ICNAS (Coimbra) proton beam. Samples are scheduled for launch to the ISS in June-July 2024.

The THOR-SR mission is a high-energy astrophysics pathfinder mission designed to explore a range of phenomena that includes gamma-ray astrophysics' emissions (such as the Crab Nebula or GRB emissions), space weather and terrestrial gamma-ray flashes, addressing a major aviation safety concern. 2023 activities included both simulation work, payload instrument design and experimental testing. A CdTe detector model was tested. An Onboard Computer test model was programmed and preliminary tests were performed. The Space Rider launch is foreseen for late 2025.

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Computing

• Scientific computing

Scientific research requires increasingly higher data storage and processing capacities that stress the limits of information systems and related technologies. The LIP computing groups have extensive knowledge and experience in scientific computing, excellent international relations, and integration in scientific e-infrastructures with users from multiple disciplines and organizations, participating in the FCT infrastructures and in the enabling of future policies for scientific computing, data science and open access.

LIP participates in some of the largest European R&D projects in this field and 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.

LIP leads the National Distributed Computing Infrastructure (INCD) and is part of the National Advanced Computing Network (RNCA), both in the Portuguese Science Foundation Roadmap of Research Infrastructures of strategic relevance. Scientific computing is certainly one of the areas placing LIP at the forefront of innovation.

LIP's expertise in large scale computational tools and data science opens up opportunities for knowledge transfer and for addressing societal changes. The SPAC group has very much strengthened this domain and opened new research lines in disease forecasting, human behaviour and public policy.

COMPUTING

Scientific Computing

Enabling compute intensive and data intensive science

The LIP computing groups have extensive knowledge and experience in scientific computing, excellent international relations, and integration in scientific e-infrastructures, with users from multiple disciplines and organizations, participate in the FCT infrastructures (namely INCD and RNCA) and in the enabling of future policies for scientific computing and open access. LIP's expertise in large scale computational tools and data science opens up opportunities for knowledge transfer, fostering innovation, addressing societal changes and informing public policies.

Distributed computing and digital infrastructures (GRID)

The Distributed Computing and Digital Infrastructures Group provides the information and communication technology (ICT) services that support research, innovation, education, outreach and administrative activities at LIP. The group has extensive experience in delivering compute and data oriented services for research, including the operation of the Portuguese Tier-2 facility integrated in the CERN Worldwide LHC Computing Grid (WLCG), a global collaboration of more than 170 computing centres in 42 countries, linking up national and international e-infrastructures to serve the LHC experiments. In 2023 the LIP Tier-2 in the WLCG executed more than 886,000 jobs and delivered more than 162,000,000 HEPscore23 normalized processing hours.

The group activities bridge at international level with science related e-infrastructures and initiatives such as the European Grid Infrastructure (EGI), Iberian Grid Infrastructure (IBERGRID), European Open Science Cloud (EOSC) and EuroHPC. In this context the group collaborates with several research communities beyond high-energy physics. In the framework of IBERGRID and EGI, LIP ensured the national liaison and coordinated the operations of the Iberian distributed computing infrastructure and its integration in the pan-European EGI infrastructure. IBERGRID delivers federated cloud, HPC and HTC to support international projects and initiatives of common interest to Portugal and Spain. LIP participated in the organization of the 12th IBERGRID conference that in September 2023 joined Iberian researchers, developers and infrastructure managers in Benasque, Spain. The development of the group competences and capabilities is backed by the participation in R&D&I projects on the development and exploitation of digital technologies applied to both compute and data intensive science. Ongoing activities focus on data processing using cloud computing, High Throughput Computing (HTC), High Performance Computing (HPC), and machine learning (ML).

During 2023 the LIP group was part of several European projects, namely: DT-Geo, providing solutions for containerization, integration and software quality for a digital twin on geophysical extremes (earthquakes, volcanoes and tsunamis); interTwin, delivering quality and software management for a generic framework to support interdisciplinary digital twins; AI4EOSC working in the development, provisioning and quality assurance of the DEEP AI platform; iMagine, providing support to the use of the DEEP AI platform for aquatic science; and EOSC-Future, coordinating the software management activities. A new European project EuroCC-2 started in 2023 to continue boosting the knowledge and opportunities in the domain of HPC in Europe. Furthermore, the group finalized the European project EGI-ACE, focused on delivering the middleware management for the EGI infrastructure, supporting cloud applications and working on solutions for high performance computing integration; and also the

BigHPC project in the framework of the UT-Austin-Portugal program, where we contributed to the quality assurance and integration of a platform for big data applications. Two new European projects were submitted and approved to start in 2024: ENVRI-hub-NEXT and EOSC-Beyond; where LIP will be again contributing in the areas of software management and quality assurance.

The group leverages its expertise to deliver scientific computing services to the wider Portuguese scientific and academic communities via the Portuguese National Distributed Computing Infrastructure, of which LIP is the main technological partner.

LIP coordinated INCD's participation in R&D&I projects such as: the implementation of a catch-all repository for research data in collaboration with FCT, whose pilot usage has started; implementation of Earth observation services exploiting Copernicus data in the C-Scale project; delivery of cloud services to support thematic services in biodiversity and coastal engineering in the EGI-ACE project; and hosting of deep learning services in the iMagine project. Collaboration in the context of the European Partnership Agriculture of Data is ongoing with relevant stakeholders in this domain.

Under LIP's coordination, in 2023, INCD delivered 40,000,000 CPU hours to computing projects in all domains. Partial migration of the Bob supercomputer from Minho to Lisbon was completed in the beginning of the year. Also in Lisbon a new HPC cluster partition with 2000 CPU cores started operation. In Vila Real a new operations centre with 5000 CPU cores for HPC and cloud computing was deployed and inaugurated. Tape-based storage was deployed in Coimbra.

Through INCD, the group is also engaged in national activities related to HPC in the context of RNCA LIP represented INCD in the national advanced computing network RNCA council and related work-groups.

LIP provided support to INCD users within the scope of the 3rd FCT Call for Advanced Computing projects (CPCA). LIP also participated in the preparation of the 4th CPCA, to start in 2024. In collaboration with FCT, the group is also involved in the development and implementation of a catch-all repository for research data, whose pilot usage has started;

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Social Physics and Complexity (SPAC)

Understanding complexity has always been a hallmark of physics research and, right now, the Digital Revolution is offering radically new ways to study complex human behaviors. There is a growing perception that physics will be fundamental to study sociology and even psychology. Leading scientists are calling this new science "Social Physics" and arguing that, in some ways, complexity science will study the physics of human interactions.

SPAC uses large scale computational tools to study societal challenges, especially in disease forecasting, human behavior, and public policy, using a complex systems approach. It is a very multidisciplinary team with members having backgrounds in Physics, Mathematics and Computer Sciences, but also in Biology, Neurosciences, Psychology, and Law. Together, the group takes advantage of the so-called "Big-Data Revolution" and aims at understanding how individual behavior impacts on society. SPAC also focuses on the risks that these upcoming technologies might entail, from privacy to biases, and works to establish guidelines for ethical uses of data science and artificial intelligence.

SPAC's work is mainly funded by two European Research Council (ERC) grants to the group's PI: a Starting Grant to conduct the research project "Fake News and Real People – Using Big Data to Understand Human Behaviour (FARE)" and a Proof-of-Concept grant (FARE_Audit) to develop an auditing tool for websites and search engines. In previous years, the group established the required computational and data support infrastructure. In 2023 SPAC started the analysis for the FARE project, most notably piloting the large survey, completing the collection of the Twitter and Fake News databases, and initiating the theoretical framework required to bring everything together. A high-profile paper in Nature Human Behaviour was accepted for publication. A system of web-crawlers, previously piloted during the Brazilian elections of 2022, has been step up and is being used to study misinformation during the ongoing Israel/Palestine conflict.

In parallel, SPAC continued to contribute to health research and policy design, in collaboration with different entities. As part of these efforts, SPAC set the groundwork for a long-term collaboration with the Portuguese National Health service, to begin in January 2024. A large-scale analysis of the impact of the pandemic on respiratory viral research has been completed. This work led to a manuscript already published in PLOS Digital Health, another currently under review, and a third one to be submitted in early 2024.

SPAC is strongly involved in science communication, outreach and citizen engagement. Our work led to two book chapters aimed at general audiences: one analysing the last 20 years of Portuguese Science, and another explaining the effects of confidence in fake news spreading. SPAC members participated in different outreach activities, including 4 round tables, 3 television appearances, more than 10 articles in print media and radio interviews and 2 podcasts. SPAC's work received wide national and international media attention, particularly our article in Nature Human Behaviour. SPAC members also designed a large stand to showcase our work during the European Researchers Night (currently placed in LIP's main entrance). It serves the double purpose of collecting data and raising awareness of the importance of reducing overconfidence for limiting fake news spread and has received ~400 participants in less than 3 months.

- PhD student Sara Mesquita was awarded a Fulbright Grant 2023 (FLAD/FCT) and will spend 9 months as visiting researcher at MIT.
- PhD student Íris Damião was selected for the competitive Women in Network Science Colabathon.
- PI Joana Gonçalves de Sá was selected as one of the 50 people who will "define the future" by the leading Portuguese newspaper Expresso.

Research Infrastructures & Competence Centres

Reasearch Infrastructures • Computing • LOMaC • Mechanical workshop • Detectors laboratory • e-CRLab • TagusLIP laboratory

Competence Centres • Monitoring and Control • Simulation and Big Data

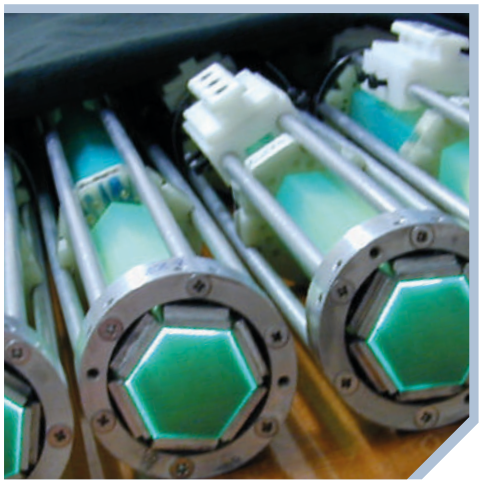
LIP's **Research Infrastructures** are central in the laboratory's activities. They provide support to the R&D activities of the LIP research groups and services to external entities. Just like the Computing Infrastructures, the Mechanical Workshop (MW) and the Detectors Laboratory (DL) in Coimbra were created at LIP's foundation in 1986 to support research activities and provide LIP with the necessary conditions to give effective contributions to detector development and construction in CERN collaborations, using the existing high-level expertise. The research infrastructures in Lisbon, initially linked to specific projects or groups, became wider in competences and use: LOMaC (optics and scintillating materials lab), created in 1992 in the context of R&D for the ATLAS TileCal calorimeter; and the electronics labs TagusLIP and e-CRLab, initially linked to medical physics and cosmic ray experiment instrumentation, and continuing the instrumentation lab created at LIP's foundation for the development of front-end electronics and data acquisition systems for the CERN experiments in which LIP was involved.

Competence Centres at LIP are designed to be light and flexible horizontal structures joining LIP members that share the same tools and technologies. Competence Centres have a positive impact both internally, increasing the synergies between groups, and externally, promoting advanced training and boosting LIP's collaboration with other research centres and with industry.

REASEARCH INFRASTRUCTURES

Computing

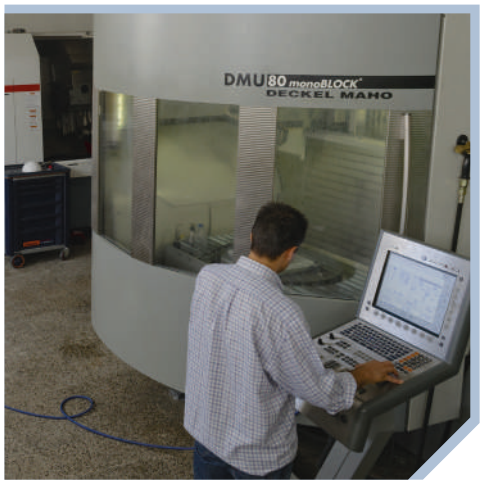
The LIP Computing Infrastructures provide scientific computing services to LIP and to the wider Portuguese scientific and academic communities in the context of the national multidisciplinary digital infrastructure INCD. Through INCD, LIP is engaged in national activities related to HPC in the context of the National Advanced Computing Network (RNCA). LIP operates the Portuguese Tier-2 facility integrated in the CERN Worldwide LHC Computing Grid (WLCG). LIP Computing bridges at international level with science related e-infrastructures and initiatives such as the European Grid Infrastructure (EGI), Iberian Grid Infrastructure (IBERGRID), European Open Science Cloud (EOSC) and EuroHPC. In the framework of IBERGRID and EGI, LIP ensures the national liaison and coordinated the operations of the Iberian distributed computing infrastructure and its integration in the pan-European EGI infrastructure. IBERGRID delivers federated cloud, HPC and HTC to support international projects and initiatives of common interest to Portugal and Spain. Under LIP's coordination, in 2023 INCD delivered 40,000,000 CPU hours to computing projects in all domains. Partial migration of the Bob supercomputer from Minho to Lisbon was completed in the beginning of the year. Also in Lisbon a new HPC cluster partition with 2000 CPU cores started operation. A new operations centre with 5000 CPU cores for HPC and cloud computing was deployed and inaugurated in Vila Real. Tape-based storage was deployed in Coimbra. The LIP Tier-2 in the WLCG executed more than 886,000 jobs and delivered more than 162,000,000 HEPscore23 normalized processing hours. For details, please go to the LIP Computing and Digital Infrastructures (GRID) group report above.



REASEARCH INFRASTRUCTURES

Laboratory of Optics and Scintillating Materials (LOMaC)

LOMaC 's expertise is centered on the characterization of plastic optical fibres (clear, WLS and scintillating), scintillator plates, and related devices for particle and nuclear physics applications. LOMaC has unique capacity in the preparation of optical fibres, including cut, polish and mirroring with magnetron sputtering. The activities developed at LOMaC are currently centered on the following lines: upgrade for HL-LHC of the ATLAS TileCal calorimeter; development of materials for next-generation detectors in future accelerators (in the context of the ECFA Detector R&D Roadmap implementation in calorimetry, DRD6); preparation of sets of fibres for the NEXT experiment; applications to microdosimetry. Collaboration with other LIP infrastructures is frequent. In the last year, we have acquired new photosensors for the testing setups, an optomechanical set, and a 3D printer for flexible and easy fabrication of custom made parts. The new TileCal HV distribution system is being developed at LOMaC. In 2023, several boards have been designed and tested, including in a setup with the cables that are being developed by General Cable. Research in new scintillating materials is ongoing through the FCT-funded DLight project in collaboration with IPC/UMinho and in the context of the LIP FCC group. Results were published in 2023. We complement scintillator R&D with radiation hardness studies using TileCal data. This is important both for HL-LHC and for future collider experiments. We are developing a dosimeter with sub-millimetric resolution in collaboration with the LIP RADART group. A prototype has been tested at HollandPTC proton therapy centre (Delft, the Netherlands).

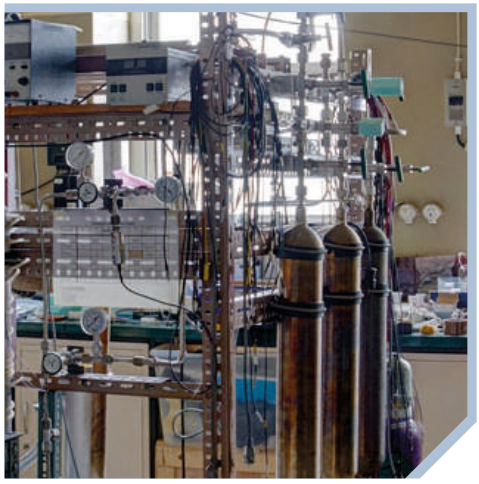


REASEARCH INFRASTRUCTURES

Mechanical Workshop (MW)

LIP's Mechanical Workshop was established in 1986 to support the experimental activities performed in collaboration with CERN. The available equipment and highly qualified staff allow for the MW to offer a large spectrum of mechanical services, from project design to production and testing. In particular modern CNC (Computer Numerical Control) machines (including a large area 3 x 2 m^2 machine) allow for complex jobs to be performed. Today the MW provides services to research groups both inside and outside LIP and also to companies. The work is often developed in close collaboration with the Detectors Laboratory (DL).

2023 highlights were the contribution to the construction of two RPC-based detector systems for the Neutron Detectors group, a muon telescope and mechanical frames for the SND@LHC detector, mechanical parts for the ProtoDune-II calibration system, systems for extracellular measurements and a diversity of small equipment for UC's Bioelectronics & Bioenergy Research Lab, and contributions to experimental devices and setups to be mounted at LIP in the framework of projects conducted by different groups. The MW also contributed to the construction of two spark chambers and one cloud chamber for outreach purposes. The MW significantly increased the number of external orders, especially among universities and national research centers. Some of the external clients in 2023 were: CNC-Centro de Neurociências e Biologia Celular, ITAV-Instituto do Ambiente, Tecnologia e Vida, SerQ-Centro de Inovação e Competências da Floresta, IT-Instituto de Telecomunicações, UC-Biotech, Bioelectronics & Bioenergy Research Lab, ICNAS-Produção, Biophysics group, LIBPhysGian, FireLab, CERN workshops, among others.

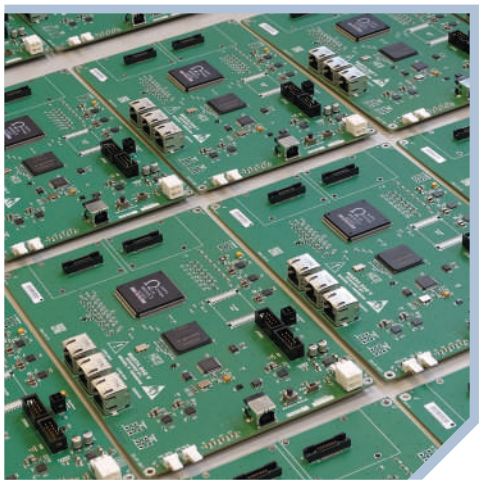


REASEARCH INFRASTRUCTURES

Detectors laboratory (DL)

The Detectors Laboratory was created at LIP's foundation in 1986 with the aim of supporting the experimental activities developed by the laboratory's research groups. Along the years the DL has been continuously updated considering both general and more specific needs. Today the available equipment and technical staff allow for a variety of services, including the design, construction and repair of electronics circuits and vacuum systems, and the design, construction and testing of particle detectors. DL's services span from the project design phase to installation and maintenance, following a procedure similar to industry's. In 2023 an ISO 6 Clean Room has been installed, increasing the capacity of the DL to fulfill the requirements to be a partner/collaborator/supplier in new collaborations.

2023 highlights were: the production of an RPC- based prototype neutron detector for the Neutron Detectors group; R&D and assembly of a prototype detector (based on scintillators and SiPMs) for the Health Applications groups (within the projects ImprovePT); R&D and assembly of two portable telescopes based on RPCs for cosmic ray monitoring (MINGO project); systems for extracellular measurements for UC's Bioelectronics & Bioenergy Research Lab and and a diversity of small equipment for the same Lab and for the UC Biophysics center. The work on sealed RPC had important progress and a full detection system will be deployed in SND@LHC in 2024. Three spark chambers were assembled to be sold to external clients. The DL also contributed with technical work and added value to many other LIP groups and collaborated with external R&D groups, mainly from UC but also from other universities and research centers.



REASEARCH INFRASTRUCTURES

Cosmic-rays electronics laboratory (e-CRLab)

The e-CRLab started as a facility dedicated to the development of electronics for cosmic ray experiments and is progressively widening its activities. The focus is put on fast digital electronics implemented in FPGAs (field-programmable gate array integrated circuits). The laboratory has the capability to design complex printed circuit boards (PCB) and to produce simple PCB prototypes. The production and assembly of complex PCB is outsourced. There is also the capability to do rework in PCB boards. A small set of mechanical tools allows for the production of simple detector prototypes mainly for proofs of concept.

MARTA is an RPC-based R&D project within the Pierre Auger Observatory. e-CRLab developed the electronics and has the responsibility of operations. In 2022 it was finally possible to organize campaigns in Argentina to complete deployment and commission the setups: a hodoscope for precision calibration of the response of the Auger detectors to muons; and a detector station of the Auger array equipped with RPCs underneath. In 2023 the MARTA front-end electronics based in the MAROC ASIC was deployed and the slow control and central unit were developed and are being tested. The systems are expected to become online during 2024.

The eCRLab has been deeply involved in the ATLAS upgrade, in particular in the development of electronics for the High Granularity Timing Detector (HGTD): testing the front-end electronics for fast timing and developing auxiliary systems such as DCS and interlock. The laboratory supports the development of electronics and instrumentation for several LIP groups and is involved in outreach and training.

REASEARCH INFRASTRUCTURES

TagusLIP Laboratory

TagusLIP was conceived as a generic infrastructure for the development of radiation detectors with emphasis on nuclear medicine imaging technologies, open to external entities. The laboratory is equipped with the necessary instrumentation for R&D on radiation detectors and associated electronics and data acquisition and is licensed for the use of radiation sources needed to develop and test instruments in nuclear medicine. The development of TOFPET1 ASICs for positron emission tomography (PET) time-of-flight (TOF) applications was at the origin of the creation of the startup company PETsys Electronics in 2013.

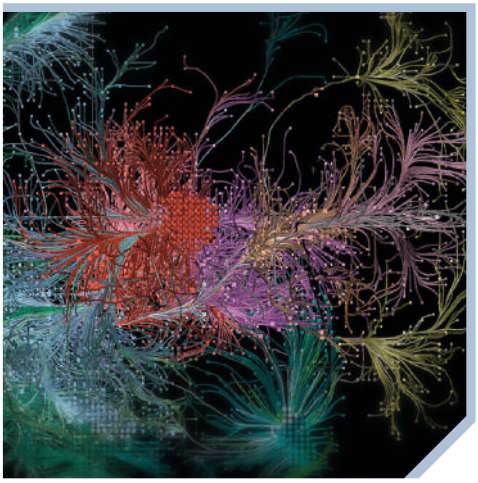
In 2023 the main users of TagusLIP were the LIP CMS group and PETsys. On the LIP side the activities concern the Phase-2 Upgrade of CMS. PETsys leads the consortium time-of-flight PET for Proton Therapy, in which LIP is involved, and has the responsibility of developing the readout system. In addition, the TOFPET ASIC is being used in the DAQ system of SND@LHC detector elements. Characterization and calibration studies carried out by the collaboration in 2023 employed an acquisition kit developed by PETsys in collaboration with TagusLIP.

The CMS collaboration has attributed the CMS industry award to PETsys Electronics for the challenging development of the TOFHIR2 front-end ASIC of the barrel MTD detector, performed in collaboration with the LIP-CMS group. A protocol between LIP and PETsys regarding future collaboration and the TagusLIP facility is being prepared and will soon be signed.

COMPETENCE CENTRES

Monitoring and Control (CCMC)

The main purpose of the CCMC is to gather the expertise in the design, implementation and operation of monitoring and control systems accumulated by LIP groups in their research activities. Besides facilitating the sharing of this body of knowledge (including sensors, electronics and software) among LIP members, the CCMC aims to establish partnerships or contracts with third parties (e.g., other research laboratories or companies) as a means to transfer knowledge and solutions to the community, including the training of human resources and development of outreach tools. In 2023 the CCMC continued its partnership with the ECOTOP group from MARE (UC). The project MonNest, funded by the Technology Transfer Office of UC has been completed. We developed and built a kit for environmental, physiological and behavior monitoring of nesting birds, to better understand and quantify the impact of climate change and anthropogenic pressure on bird populations. The team then re-focused on the development of Machine Learning tools to analyze the data collected in previous seagull's breeding seasons using the electronic egg develop by the CCMS. The aim was to improve the heart rate measurement and to associate it with bird behavior features. A paper describing these studies was submitted to a peer review journal. Additional research was developed in the context of master student projects, one of them in collaboration with company TheLOOP (Coimbra) on the detection and localization of leaks in water distribution systems using a hydraulic model simulator and deep learning. Furthermore, the CCMS delivered one cloud chamber for outreach activities at LIP-Minho, designed and constructed by the CCMC with the support of LIP's MW&DL. In collaboration with LIP-ECO, we created a portfolio of the CCMC activities and capabilities to assist us in the task of reaching new partners and clients.



COMPETENCE CENTRES

Simulation and Big Data (SimBigData)

The purpose of the SimBigData CC is to foster an effective collaboration between the different LIP groups working on such domains and to boost the capability to exploit the existing expertise both internally and externally, towards the academia and industry. The different LIP groups hold a vast range of competences in data science and simulation tools, including physics models, Monte Carlo generators, detector simulation, advanced data analysis and data mining. The ability to fully benefit from such competences requires critical mass, a coordinated training program, the exploitation of synergies and a clear identification of key areas where we can be competitive. For the Simulation part, advanced teaching/training and support to the simulation production needs of the LIP groups, researchers and graduate students remain as central tasks. The solid expertise in GEANT4 is complemented by the specific contributions to the GEANT4 collaboration, which will be continued and expanded. The core activity of the Big Data part continues to be the use of Machine Learning techniques for the different data analyses performed by different groups. The study of anomaly detection techniques is becoming a key effort and different applications are being explored. A close collaboration with the LIP Computing Group and with INCD has been pivotal for our activities. The use of containers and the corresponding training of the different teams has gained relevance in the context of data preservation and reproducibility. A paper on the development of quantum machine learning models has been published, tackling the challenges of large datasets for the current quantum computers. A second paper dealing with the use of machine learning in condensed matter physics is already accepted for publication.

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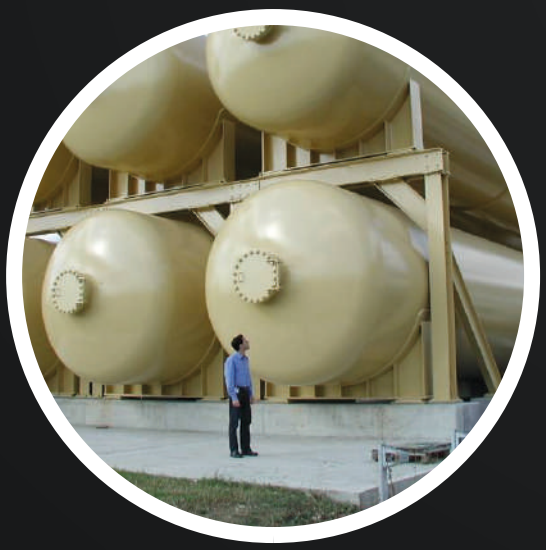

Knowledge transfer and **societal impact**

Radiation, health and **environment**

Muon tomography

Advanced training

Education, communication and **outreach**

LIP

science and society

Knowledge transfer and societal impact

Fundamental science drives innovation in the long term. Particle physics technologies have a wide range of applications and the potential to respond to societal challenges. In the last few years, LIP has made impactful contributions by developing excellent fundamental and applied research; attracting talent; bridging scientific knowledge and business innovation; developing diagnosis and therapy methods; focusing on science and technology culture and education; promoting digital competences and technology accessibility towards social inclusion; and contributing to increase computing power and expertise in the scientific community at large.

KT at LIP

As CERN's reference institution in Portugal and a recognised partner of ESA, LIP has a special role in promoting the internationalization of Portuguese companies and to help creating opportunities to increase the industrial return to Portugal. More than three decades of high impact contribution to international collaborations at CERN and in other international scientific infrastructures have proven a successful way to achieve these goals — by proposing partnerships, providing support or facilitating a first contact. Strategic areas for LIP's KT are healthcare, space application, data science and digital technologies.

LIP keeps a close connection with the representative of Portugal in the CERN KT forum (José Antão, ANI), with ESA's Industrial Policy Committee representative at PT Space, and represents Portugal in the CERN KT forum for medical applications, in HEPTech, a European Network devoted to KT from large scale HEP science projects and research facilities, and in several European computing infrastructures and initiatives. LIP is a member of PERIN.

LIP directly involves graduate students in collaborative, multidisciplinary, innovation projects with companies and other external entities, through internships, technology-oriented advanced training and the inclusion of an applied research component in their projects. This enhances their level of employability in the private sector and contributes to increase the qualification of the human resources in Portuguese companies.

- LIP spin-off company PETsys Electronics has been awarded the CMS industry award for the challenging development of the TOFHIR2 front-end ASIC of the barrel MTD detector, performed in collaboration with the LIP-CMS group.
- The first "Big Science Portugal - strategy and networking" event was organised by ANI in collaboration with FCT. The events are part of the agency's strategy to provide more robust support to the Big Science ecosystem in Portugal.
- Portugal and Galicia signed a cooperation agreement on technology for medical imaging.
- The list of companies the LIP groups have collaborated with in the last 5 years includes: Adductio, Bosch, Cabelte, Dialog Semiconductors, EFACEC, EVOELEO, General Cable, Grupo ASSEC, HIDRONAV (Spain), ICNAS-Produção, Ideas (Norway), Kinetic (UK), Nielsen, NuRise, PETsys, Siemens, Silicon Gate, Systion, Tellspec, TheLOOP and Wavecom.
- Some of the Portuguese research units and other public institutions we collaborated were: CEFITEC/ NOVA, CFTC/FCUL, CFTP/IST, Champalimaud Foundation, CHUC, CTN/IST, FCCN/FCT, GHIPOFG, Hospital de Santa Maria, IBEB/FCUL, ICNAS, ICT/U. Évora, INCD, INESC-ID, INESC-TEC, LNEC, MACC, MARE, ISCTE, NOVA SBE.

Radiation, health and environment

Radon, abundant in granitic areas, is signaled by the World Health Organization as the second leading cause of lung cancer after tobacco smoke. According to European Directive 2013/59/Euratom, house-building materials must be analyzed for the possibility of exhaling radon gas. In addition, Radon is the largest contributor for underground water radioactive pollution. In the past few years, we focused on the measurement of radon in the air and water. At UBI, the group operates LabExpoRad, a laboratory dedicated to the detection and study of radon. At FCUL the development of instrumentation for radon detection is carried out. In 2023 we completed the development of an active Radon detector prototype designed to measure Radon exhalation from building materials. The detector is modular, low-noise, and capable of accurately resolving the peaks from radon daughter alpha emitters. The group is also actively involved in training on environmental radiation at different levels. Work on the effect of radon-containing aerosols on plants is in progress with further experimental measurements at UBI.

Muon Tomography

Muon tomography is a non-destructive imaging technique using the natural flux of atmospheric muons. LIP has the expertise to contribute to develop the technique and establish it as a standard worldwide. LouMu was a short-term project funded by FCT in 2021 to conducted an exploratory muography subsurface geophysical survey demonstrating the potential of the technique while testing the capabilities of the detector and analyses. The responsibilities were shared between LIP and ICT/UÉvora with the support of Ciência Viva science centre at Lousal. The detector is a muon telescope with four (1 m²) RPC planes mounted horizontally in a movable structure that can be tilted up to 30°. We started by testing the detector and developing the methods while muographing known structures in the LIP Coimbra building. The telescope was moved to Lousal in mid 2022 to muograph the geological layer above the mining gallery. In 2023 we took data from a second position inside the gallery. The combination of muography data with data from other techniques is ongoing to retrieve 3D density maps. In parallel, we developed and tested innovative reconstruction methods for 3D imaging from a single or several telescope positions and for incorporating external knowledge in the final density maps. We now have the tools to predict sensitivities and to optimize telescope configurations, survey designs and data analysis methods for different scenarios and goals. This is being used to search for relevant applications of muon tomography in follow-up projects.

Advanced Training

The ability of LIP to attract, engage, train and support university students in its fields of activity is paramount for the future of the laboratory. The advanced training (AT) team coordinates and promotes actions dedicated to university students at the several levels (undergraduate, master, doctoral), providing high-quality training and ensuring LIP's capability to attract, engage and retain research students.

Graduate students

LIP permanently hosts tens of PhD, master, and bachelor students, who actively work within its research groups. In 2023, LIP hosted over 120 graduate students mainly from the Universities of Lisboa (IST and FCUL), Coimbra and UMinho, but also from the universities of Évora, Beira Interior, Aveiro e Porto, from UNL/NOVA and USC (Spain).

During the year, 8 PhD theses and more than 30 Msc theses were defended. FCT and LIP promoted two calls within the PhD programme PT-CERN. Six grants have been awarded in the first call and eight grants in the second one.

LIP is a founder of the IDPASC international PhD network. The 2023 edition of the IDPASC school in particle physics, astrophysics, and cosmology took place in Granada, Spain, gathering 24 students. The LHC physics course consists of around 20 lectures covering introduction to the standard model, detectors, statistics, and overall research. It is held from March through May and has a final evaluation valid for ECTS credits at IST.

Student awards

PhD

Sara Mesquita
Fulbright Grant 2023 (FLAD/FCT) - Visiting researcher at MIT for 9 months

Joana Antunes
Awarded a Short-term Research Internship at the University of Texas at Austin

Matteo Pisano
Third prize in the first edition of ULisboa's 3 Minute Thesis Competition, Winner of the TecInnov Jerónimo Martins competition, IST

Master

Beatriz Amorim
Marie Sklodowska-Curie Fellowship Programme Grant from the International Atomic Energy Agency for a one-year project at GSI

Undergrad

Simão Cardoso
UMinho Award for Initiation in Scientific Research 2023

Gonçalo Ribeiro
JEF Award for the best presentation Jornadas da Engenharia Física, IST

Undergraduate students

LIP is involved in several regular school and workshop series directed at undergraduate students, which include lectures, hands-on exercises, and introductory overviews of ongoing research activity at LIP and in particle physics and its application in general.

Besides training events, LIP conducts a number of initiatives with the goal of making LIP and particle physics known and attractive among undergraduate students. In particular, LIP regularly participates in events organized by physics departments and physics student associations at the different universities.

LIP Internship Program

The Lab's flagship Internship Program remains active and attractive, benefitting from the ability to systematically improve at each edition. In 2023, the programme's 7th edition counted as always on the broad participation of LIP researchers through the three LIP nodes, who served as project supervisors, delivered tutorials and lectures, guided topical discussions, and attended and contributed to the discussion at the final workshop. A total of 67 students completed the program. The overall structure was kept starting with an introduction week in July (lectures and hands-on tutorials) and ending with a two-day workshop in September in which the students presented their work. Common activities were held in hybrid mode. In between, the participants carried out their projects, integrated in LIP's research groups.

The LIP Internship Programme in numbers

75 positions in 54 projects (all LIP groups). 116 applications received.

TOTAL
67

students concluded the internship*

Students from: FCUL, IST, UMinho, UC, UA, FCT-NOVA, Univ Complutense de Madrid (Spain), Liverpool (UK). Univ Extremadura (Spain), Univ. Bordeaux (France).

*presented at the final workshop or delivered a final paper

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Education, communication and outreach

Education, Communication and Outreach (ECO) are an inseparable part of LIP's societal role. They are also essential for the recognition of the laboratory's impact and for the construction of its future. The ECO team plans, implements, coordinates, and facilitates the laboratory's activities in these domains, encompassing all three LIP nodes. LIP also develops equipment for exhibition and demonstration purposes, with the collaboration of its scientific infrastructures and competence centres.

2023 communication highlights

Reedition of Gago's "Manifesto"

On the 75th anniversary of LIP's founder and former science minister José Mariano Gago, LIP and Gradiva partnered for the reedition of his influential essay "Manifesto para a Ciência em Portugal", with a foreword by Mário Pimenta and a new preface. The book was launched in a national event with simultaneous panel debates in Braga, Coimbra, Lisbon involving the wide scientific community, followed by an online session on the conclusions of the three panels moderated by Joana G. Sá.

R-ECFA & CERN DG in portugal

The visit to Portugal of R-ECFA was organised by R-ECFA and LIP and had a strong participation of the national scientific community. On the event, a public session with CERN's DG Fabiola Gianotti was organised by LIP at CV's "Pavilion of knowledge". The DG's talk "The Higgs boson and our life" was followed by a panel discussion and questions from the public.

LIP Open Day

On the inauguration of the renewed TTC@ULisboa building where LIP is installed, we opened the doors to the community and the public. The concept of the Open Day was to give visitors the opportunity to see LIP from the inside but also travel to the places where our daily work takes us: where the data we analyse come from, where the experiments are run, where the detectors we build are being installed. Multimedia tools developed by the ECO group in LIP-Minho played a very important role. SPAC's exhibit can now be visited in the TTC@ULisboa entrance hall. The Open Day took place on 7 December (4-8 pm) and gathered around 200 visitors. This was only possible with the strong participation of the LIP community: over 50 researchers, students and technicians were present during the visits or/and in the preparation.

Public session with Fabiola Gianotti in Lisbon moderated by journalist Sara Sá with the participation of José Antão (ANI) and Ricardo Barrué (LIP).

Open Day at LIP

LIP's programme for the school community

At LIP a comprehensive programme for the school community has been put in place along the years. Each year, LIP researchers deliver over 50 outreach talks for students in schools and other settings and schools visit the three nodes of LIP. LIP is the scientific partner of around 20 Ciência Viva and other science clubs all around the country, providing support and activities along the year. The Ciência Viva "Science in the Lab" summer internship programme hosted 9 high-school students at LIP Lisboa for two weeks in 2023. Flagship initiatives are IPPOG's Masterclasses and the Teachers Programme at CERN.

IPPOG's International Masterclasses in Particle Physics

At research centres and universities in over 50 countries, high-school students analyse real data from particle physics experiments and discuss their results with scientists at CERN or another lab and with participants in other institutions in a videoconference. LIP is the national coordinator of the Masterclasses in Portugal since their start in 2005. Every year the event is held in around a dozen cities all over the country gathering over 1000 participants.

During 2022 a new masterclass based on data from the Pierre Auger Observatory was fully developed at LIP. It became an official IPPOG Masterclass in December and was used for the first time in the 2023 edition — in Lisbon, Braga and Funchal (Madeira), but also at the Institute of Space Science in Bucharest (Romania), INFN sections of Lecce and Naples (Italy) and in two universities in Czechia.

CERN Teachers Programme in Portuguese Language

Over the last decade, more than 800 teachers attended the programme, coordinated by LIP with the support of CERN and Ciência Viva. In 2023 the program hosted 48 participants: 20 Portuguese teachers, 20 Brazilian teachers, and 8 teachers from all the Portuguese language countries in Africa and Asia, with the support of Instituto Camões, CGD, Agência Ciência Viva, CA, Santander and, for Brazilian teachers, RENAFAE, CBPF, SPRACE and SBF.

LIP developed IPPOG masterclass on Pierre Auger Observatory data.

Partnerships

LIP has several national and international partners in communication, outreach, and support to education. At national level we are partners of Agência Ciência Viva and of the Portuguese Physical Society. LIP is a member of the International Particle Physics Outreach Collaboration, the European Particle Physics Communication Network and the CERN high-school students and teacher forum.

// CONTACTS

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Glossary

AGN - Active Galactic Nuclei
AMS - Alpha Magnetic Spectrometer (particle physics experiment in the ISS)
AEEF - Alphasat Environment and Effects Facility (ESA)
AHEAD - Integrated Activities for the High Energy Astrophysics Domain (H2020)
AI - Artificial intelligence
Alphasat - the largest European telecom satellite (ESA)
AMBER - Apparatus for Meson and Baryon Experimental (CERN)
AMEGO - All-sky Medium Energy Gamma-ray Observatory (NASA)
ANIMEE - Associação Portuguesa das Empresas do Sector Elétrico e Electrónico
ASIC - Application Specific Integrated Circuit
AT - Advanced Training
ATLAS - A Toroidal LHC ApparatuS (general-purpose experiment at the LHC
Auger - Pierre Auger Observatory (Argentina)
BEXUS - Balloon Experiments for University Students
biodata.pt - Portuguese distributed e-infrastructure for biological data
BioISI - Instituto de Biossistemas e Ciências Integrativas
BTL - Barrel Timing Layer (CMS)
BSM - Beyond the Standard Model
CBM - Compressed Baryonic Matter (one of the pillars of FAIR)
CBPF - Brazilian Centre for Research in Physics (Centro Brasileiro de Pesquisas Físicas)
CC - Competence Centre
CCMC - Monitoring and Control Competence Centre (LIP)
CEFITEC - Centre for Physics and Technological Research, NOVA (Centro de Física e Investigação Tecnológica)
CERN- European Laboratory for Particle Physics, Geneva, Switzerland
CFTC - Centre for Theoretical and Computational Physics, FCUL (Centro de Física Teórica e Computacional)
CFTP - Centre for Theoretical Particle Physics, IST (Centro de Física Teórica de Partículas)
CHUC - Coimbra University Hospital Centre (Centro Hospitalar e Universitário de Coimbra)
CMS - Compact Muon Solenoid (general-purpose experiment at the LHC)
CNC - Computer Numerical Control (refers to computer controlled machine or tool)
CNES - French Space Agency (Centre National d'Études Spatulas)
CoastNet - Portuguese Coastal Monitoring Network
COMPASS - Common Muon and Proton Apparatus for Structure and spectroscopy (CERN experiment)
COVID-19 - Disease caused by the coronavirus SARS-CoV-2
CPCA - FCT Call for Advanced Computing Projects (2020)
CS -Control System
CTA - Cherenkov Telescope Array
CTN - Nuclear Technology Campus, IST (Campus Tecnológico e Nuclear)
CTTB - Component Technology Test Bed
CV - Agência Ciência Viva
DCS - Detector Control System
DELPHI - Detector with Electron, Photons and Hadron Identification, experiment at LEP (CERN)
DIS - Deep Inelastic scattering
DL - Detectors Laboratory (LIP)

DQM - Data Quality Manager
DUNE - Deep Underground Neutrino Experiment (CERN/FermiLab)
ECAL - Electromagnetic Calorimeter (CMS)
ECO - Education, Communication and Outreach
ECOTOP - Ecology and Conservation of Top Predators group (MARE)
eCRLab - Cosmic Rays Electronics Laboratory (LIP)
EEE - Electronic and Electric Engineering
EFACEC - Portuguese company, operating in the energy and transportation sector
EGI - European Grid Infrastructure
EGI-ACE - European Open Science Cloud implementation project
EOSC - European Open Science Cloud
ERC - European Research Council
ESA - European Space Agency
ESPP - European Strategy for Particle Physics
ESPPU - European Strategy for Particle Physics Update
ESS - European Spallation Source
EU - European Union
EuroCC - H2020 EU project for HPC coordination
EuroHPC - European High Performance Computing Joint Undertaking
eV - electron-Volt (unit of energy; the energy of an electron under 1 Volt; multiples are: keV, MeV, GeV, TeV, PeV, EeV)
EVOLEO - Portuguese company, operating in the electronic engineering sector
FAIR - Facility for Antiproton and Ion Research (GSI)
FARE - Fake News and Real People (ERC project at LIP)
FCC - Future Circular Collider
FCCN - Fundação para o Cálculo Científico Nacional
FCT - Foundation for Science and Technology, Portugal (Fundação para a Ciência e a Tecnologia)
FCUL - Faculdade de Ciências, Univ. de Lisboa
Fermilab - Fermi National Accelerator Laboratory, USA
FOV - Field of View
FPGA - Field-programmable gate array (integrated circuit)
FRMII - Research Neutron Source Heinz Maier-Leibnitz
GBIF - Global Biodiversity Network
GHIPOFG - Portuguese Institute of Oncology (Grupo Hospitalar Instituto Português de Oncologia Francisco Gentil)
GEO - Geostationary orbit
GPU - Graphics processing unit
GRB - Gamma-Ray Burst
GSI - Helmholtz Centre for heavy ion research, in Darmstadt, Germany
H2020 - EC Framework Program for Research & Innovation 2014-2020
HADES - High Acceptance Di-Electron Spectrometer (experiment at GSI)
HEP - High Energy Physics (or Particle Physics)
HiRezBrainPET - Project for Brain imaging by high resolution PET (LIP participation)
HL-LHC - High-Luminosity LHC
Horizon Europe - EC Framework Program for Research & Innovation 2021-2027
HPC - High Performance Computing
HTC - High Throughput Computing
IAEA - International Atomic Agency
IBEB - Institute for Biophysics and Biomedical Engineering, FCUL
IBERGRID - Iberian Computing Grid Infrastructure
ICNAS - Institute for Nuclear Sciences Applied to Health

ICT - Information and Communications Technologies
IDPASC - International Doctorate Network on Particle Physics, Astrophysics and Cosmology
ILL - Institut Laue-Langevin
ILO - Industrial Liaisons Officer
INAF - Istituto Nazionale di Astrofisica (Italy)
IMEM - Istituto dei Materiali per l'Elettronica e il Magnetismo (Parma, Italy)
INCD - National Infrastructure for Distributed Computing (Infraestrutura Nacional de Computação Distribuída)
INESC - Institute for Systems and Computer Engineering (Instituto de Engenharia de Sistemas e Computadores)
IPC - Industrial Policy Committee
IPPOG - International Particle Physics Outreach Collaboration
ISS - International Space Station
IST - Instituto Superior Técnico, Universidade de Lisboa
ITQB - Instituto de Tecnologia Química e Biológica (NOVA)
JUICE - Jupiter Icy Moons Explorer (ESA)
KT - Knowledge Transfer
LAr - Liquid argon
LEO - Low Earth Orbit
LHC - Large Hadron Collider (at CERN)
LHCb - LHC experiment
LHCC - LHC experiments Committee
LIP - Laboratory for Instrumentation and Particle Physics
LNEC - Laboratório Nacional de Engenharia Civil
LOMaC - Laboratório de Óptica e Materiais Cintilantes (Optics and Scintillating materials lab)
LUX - Large Underground Xenon (dark matter experiment, at SURF)
LZ - Dark Matter experiment at SURF (merge of LUX and ZEPLIN experiments)
MACC - Minho Advanced Computing Centre
MARE - Marine and Environmental Sciences Centre
MFS - MultiFunctional Spectrometer
MSc - 'Master of Science' (M.Sc.) degree
MW - Mechanical Workshop (LIP)
M&O - Maintenance and Operations
NA38 - CERN SPS experiment
NA50 - CERN SPS experiment
NASA - National Aeronautics and Space Administration (USA)
NEI - European Researchers Night (Noite Europeia dos Investigadores)
NEXT - Neutrino Experiment with a Xenon TPC
NOVA - Universidade Nova de Lisboa
NPstrong - Nuclear Physics and strong interactions (LIP)
NREN - National Research and Educational Network
NUC-RIA - Nuclear reactions and Astrophysics experimental group (LIP)
NUSTAR - Nuclear Structure, Astrophysics and Reactions (one of the pillar of FAIR)
O-PGI - Orthogonal Prompt-Gamma Imaging
OR-imaging - Ortogonal Ray imaging
Ortho-CT - Orthogonal Computer Tomography
PANDA - experiment at FAIR, GSI
PCB - Printed Circuit Board
PERIN - Portugal-Europe R&I Network (ANI)
PET - Positron Emission Tomography
PhD - 'Doctor of Philosophy' (Ph.D.) degree
Pheno - Phenomenology group (LIP)
PI - Principal Investigator
PORBIOTA - Portuguese Infrastructure for Information and Research on Biodiversity
ProtoDUNE - Prototype of the DUNE detector, installed at CERN

PPS - Precision Proton Spectrometer
PQCD - Partons and QCD (LIP)
ProtoTera - Association for Proton Therapy and Advanced Technologies for the Prevention and Treatment of Cancer
PT Space - Portuguese Space Agency
QCD - Quantum Chromodynamics
QGP - Quark Gluon Plasma
R3B - Reactions with Relativistic Radioactive Beams (GSI experiment)
RADART - Radiation Dosimetry Applications to Advance RadioTherapy
RADEM - RADiation hard Electron Monitor for ESA's JUICE mission
RD51 - CERN collaboration of detector R&D
RICH - Ring Imaging Cherenkov detector
RNCA - National Network for Advanced Computing (Rede Nacional de Computação Avançada)
RPC - Resistive Plate Chamber (gaseous detector)
RPC-TOF-FD - RPC TOF Forward Detector (HADES)
RPC-TOF-W - RPC TOF Wall (HADES)
R&D - Research and Development
R&D&I - Research, Development and Innovation
R&I - Research and Innovation
SARS - Severe Acute Respiratory Syndrome
SHiP - Search for Hidden Particles (CERN)
SM - Standard Model (of particle physics)
SND - Scattering and Neutrino Detector (SHiP)
SNO+ - Sudbury Neutrino Observatory, at SNOLAB. SNO+ is the successor of SNO
SNOLAB - Underground science laboratory, Ontario, Canada
SPAC - Social Physics and Complexity (LIP)
SPENVIS - Space Environment Information System (ESA)
SPF - Portuguese Physical Society
SPS - Super Proton Synchrotron STEM - Science, Technology, Engineering and Mathematics
STRATOSPOLCA- BEXUS Stratospheric Polarimetry with Cadmium Telluride Array experiment
SURF - Sanford Underground Research Facility (USA)
SWGO - Southern Wide-field Gamma-ray Observatory
TACC - Texas Advanced Computing Centre
TagusLIP - LIP laboratory at the Tagus Park business campus
TDAQ - Trigger and Data Acquisition System
TileCal - ATLAS Tile Calorimeter (ATLAS hadron calorimeter)
TOF - Time-of-Flight
TPC - Time Projection Chamber (detector)
TRISTAN - name of a specific RPC-based detector
UA - Universidade de Aveiro
UC - Universidade de Coimbra
WLCG - Worldwide LHC Computing Grid
WLS - Wavelength Shifter (referring to optical fibres)
ZEPLIN - Zoned Proportional scintillation in Liquid Noble gases, series of dark matter experiments (UK)

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