annual report

2024/2025

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 particle physics and related technologies in Portugal, and the primary Portuguese partner of CERN.

The laboratory is nation-wide, with nodes in Lisbon, Coimbra and Braga, closely collaborating with the local universities. LIP has over 100 PhD researchers, about 40 technical and administrative staff, and permanently hosts over 100 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 again rated as "Excellent" in the latest independent evaluation promoted by FCT in 2025.

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, the Faculty of Sciences of the University of Lisbon 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 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.

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.

They have excellent international relations and integration in the main R&D projects and scientific e-infrastructures at European level. LIP is a key technical partner of the National Advanced Computing Centre (CNCA), formerly INCD, participating in the enabling of 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 potentiates collaboration with several research communities for 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.
Patrícia Gonçalves
President
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Foreword

In 2024, we celebrated 50 years of the Carnation Revolution. This historic event, on the 25th April 1974, opened the door to democracy, education, and scientific progress in Portugal. Before 1974, one in four Portuguese citizens was illiterate, and for most, a scientific career was little more than a dream. At the time, the seeds of a national scientific community were just beginning to be sown by a few academics working in universities or abroad, with very limited support for PhD training. LIP was founded 12 years later by a group of scientists inspired by José Mariano Gago's vision for bringing Portuguese science into international scientific collaborations, with Portugal's accession to CERN 40 years ago, in 1985, marking a pivotal first step.

From the start, LIP brought together researchers working in CERN experiments and developing instrumentation and detectors. As the national reference laboratory for particle physics and associated technologies, our scope evolved to include particle and astroparticle physics, and their many applications, and in 2024 our research reflected both the long-term commitment required by frontier science and the agility needed to respond to new challenges and opportunities — from CERN's LHC to space missions with ESA, from dark matter searches to multi-messenger astrophysics, from neutrino studies to probing the structure of matter itself. Additionally, we continue to broaden the application of our knowledge, contributing to the development of new instruments for health, space, and interdisciplinary research, particularly where physics intersects with data science and pressing societal challenges. LIP also maintains a strong connection with society as part of its mission. We are deeply committed to education, science communication, and open science. We collaborate closely with schools, universities, and industry, helping to build trust and foster a vibrant scientific culture. Our infrastructures, competence centres, and computing resources support not only LIP's projects, but also other national and international research teams.

2024 was a year of transition at LIP. For the first time, none of our founding members were part of the Board of Directors, which began its mandate in June. And for the first time, I take on the task of writing this foreword, which was for so many years written by Mario Pimenta, whose wisdom and enthusiasm led LIP through so many challenges, for whom the construction of LIP as a national institution was more than part of his job - it was a life objective. We now share the great responsibility of maintaining the scientific integrity and strategic vision that has defined LIP over the decades.

And to fulfil that role, keeping pace with the events in the international particle physics community, LIP is following and participating in the European Strategy for Particle Physics (ESPP) third update, launched by the CERN Council in 2024, in a process that will be concluded in January 2026. We have thus hosted, in January 2025, a national discussion of the ESPP to identify priorities and gather input from the national scientific community.

Another major focus in 2024 was preparing LIP's application for the national research unit evaluation, a competitive process led by FCT every five years. The outcome of this evaluation determines base and programmatic funding for 2025–2029. In April 2025, we were proud to learn that LIP received the highest possible rating: "Excellent" with a score of 5/5, ensuring continued support at approximately the same level as for the 2020–2024 cycle.

LIP has also been an Associate Laboratory since 2001 — a designation now granted to 40 Portuguese research institutions for supporting public policy and contributing to qualified human resources hiring capacity. However, the present LIP's Associated Laboratory status and funding were granted for the period between 2021 and 2025, subject to re-evaluation in 2025. As I write, LIP status as an Associated Laboratory for 2026 and beyond remains uncertain, since no dedicated evaluation process has been announced so far by FCT.

In terms of project funding - and while LIP's core mission is fundamental research, largely supported directly by FCT - in the last years we have diversified funding sources, especially in applied research and computing. As a consequence of this effort, between 2018 and 2023, direct project funding from FCT grew by less than 20%, while international funding more than doubled, reflecting our growing competitiveness in European and global initiatives.

LIP's integrated research team includes university faculty, researchers on fixed-term FCT contracts, tenured LIP researchers, and those hired through specific projects. While only a portion is directly funded by LIP, human resources represent the largest share of our budget, accounting for 55% of total expenses. Managing such a diverse and dynamic team is both a responsibility and our greatest asset. In 2024, professorship positions opened at some of our associate Universities within the scope of the FCT-tenure programme, and in 2025, a few more are expected, contributing to the consolidation of the LIP team and of our connection with our associates. It is our people — researchers, technicians, students, and staff — who drive innovation, secure competitive funding, and bring ideas to life across disciplines. Their dedication to collaboration, scientific excellence, and public service is at the core of LIP's mission.

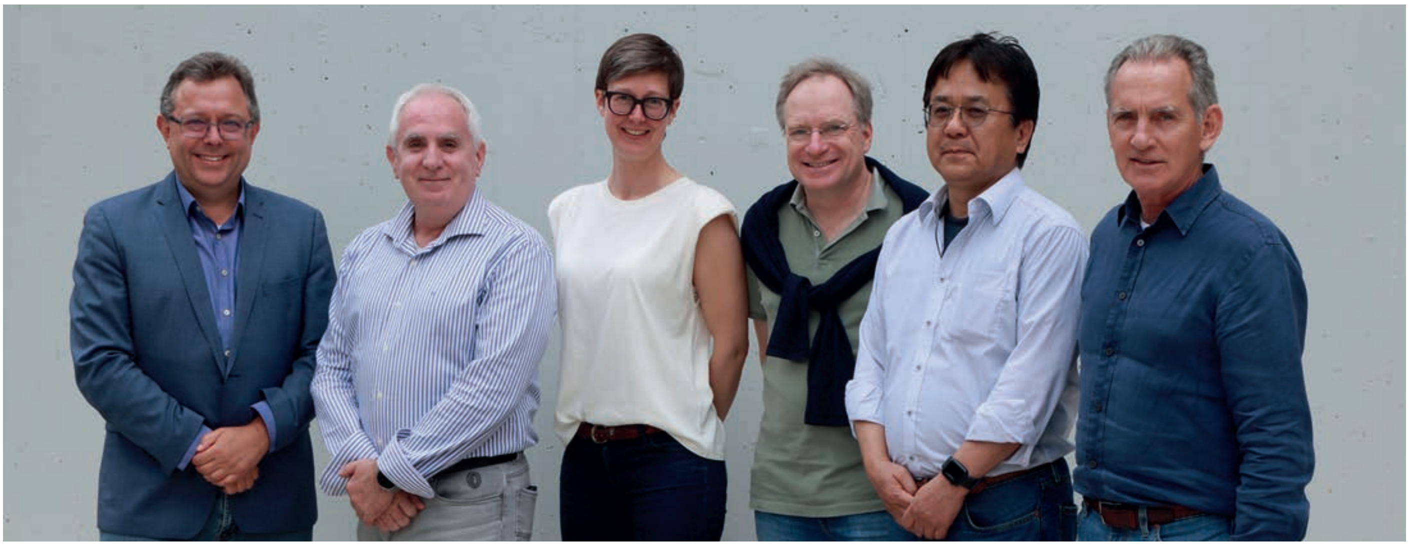
As we look ahead, even in uncertain times, such as those we are experiencing at the beginning of 2025, we remain committed to building an inclusive, dynamic organisation — open to talent from Portugal and around the world. This report reflects our collective work over the past year and outlines our vision for the future. It is a testament to what can be achieved when fundamental research, technological development, and societal engagement are pursued together, as inseparable parts of the same mission.

This year we celebrate 40 years of the adhesion of Portugal to CERN, next year, in 2026, we will be celebrating LIP's 40th anniversary, until then, as always, let´s keep working together towards a stronger and shared institution.

Lisbon, 2025

REPORT FROM THE

International Advisory Committee



LIP's international advisory committee members meeting in Lisbon: Jorgen D'Hondt, José Miguel Jiménez, Karoline Wiesner, Werner Riegler, Masahiro Teshima, Eammon Daly (left to right), Katia Parodi joined the meeting online.

The meeting of the LIP International Advisory Committee took place on April 23 and 24, 2025. This was the first gathering of the committee called by the new LIP Directorate. Before the meeting, extensive documents informed committee members about LIP's status and achievements. It was our greatest pleasure to learn that LIP has been assessed as the best physics research unit in Portugal with the maximum score. The committee congratulates the LIP directorate for the award of the 5-year excellence grant, which secures a substantial part of LIP's base funding. Although LIP has significantly increased its funding from external (international) programs, securing this quasi-flat base funding over the years remains essential for the institute. This remarkable quality label is an outstanding opportunity to exploit when applying for additional funding in various programs.

To even further enhance LIP's success in supporting its mission, the committee advises the directorate to consider especially the following four dimensions when continuously developing its organization.

Coherence & strengths

LIP is a great family of researchers and technologists, and the committee feels that everyone is strongly engaged in realizing its core mission. LIP's main scientific drivers are focused on developing a deep understanding of both the largest cosmological and smallest quantum structures in the universe. Maintaining coherence between the various research programs will contribute to strengthening LIP. The committee encourages the new LIP directorate to identify LIP's most impactful research programs in physics, technology and applications, and to build the organization around LIP's main strengths. It remains important to rally everyone at LIP behind a coherent shortlist of strong programs, to appreciate their interdependence and to organize around these core programs accordingly.

Internal focus

LIP has several recognized strengths. The committee encourages LIP to leverage these unique assets by fostering internal collaborations along these clearly defined core research directions. Combining forces and scope across LIP groups could unlock new opportunities when applying for funding, for example at FCT. Furthermore, LIP's local laboratory capacity is relevant for evaluations in Portugal and therefore an incentive to continue investing in it. In order to consolidate LIP's local laboratory infrastructures, the committee recommends developing an overall strategy with considerations for alignment within the LIP and Portuguese landscape.

External dissemination

It remains important to inform the national and international landscape and stakeholders about LIP's strength and impact. The committee recommends continuing developing strategic actions for national policy makers with a view to inform them about the broad impact of fundamental physics, and to strengthen the LIP communication group to reach this goal. At the international level, the committee recommends establishing formal partnerships with European institutions, for example to join in supervising PhD students on LIP's core strengths and to consolidate the position of LIP as a valuable partner in European project applications for training and developments.

Strategy

With the achievement of the excellence grant, it is advisable to look ahead and to consolidate. The committee recommends that the LIP directorate develops an overall LIP strategy for science and technology, with considerations for both the short term and the long term, and on that basis further develops its organization for effective implementation. This vision is to embrace a sustainable strategy to generate revenues, but with a focus on a limited number of priority directions and a monitoring methodology to verify effectiveness and impact in relation to the LIP core mission in fundamental physics. Also here, coherence of the portfolio of activities is essential. LIP could consider establishing a steering board to assist the directorate in setting strategic priorities.

The committee is pleased to learn that LIP continues to achieve impact in the international landscape of particle, astroparticle and nuclear physics.

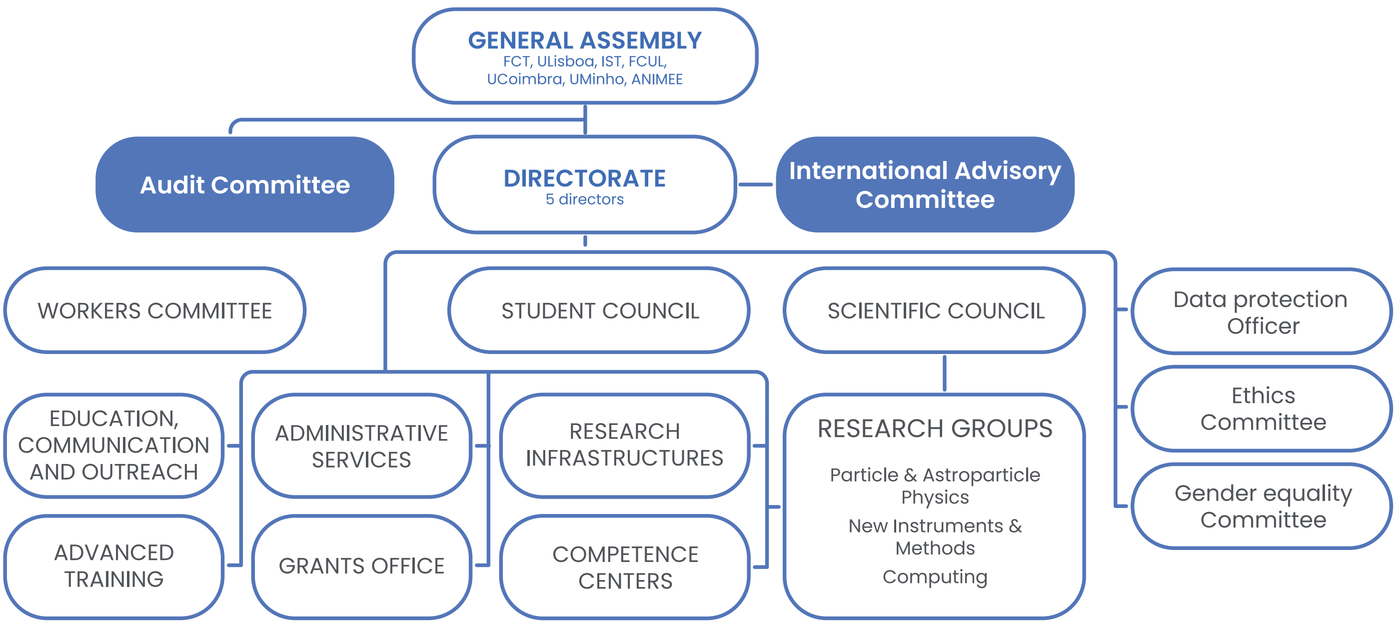
Structure & governance

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 2024/2025, 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: Isabel Ribeiro (president), José Carmelo e 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. A new board was nominated at the end of May, and is formed by Patrícia Gonçalves (President), Guilherme Milhano, Alberto Blanco, Ricardo Gonçalo and Nuno Castro. The directorate co-opted Pedro Assis, to help in local matters in the Lisbon node.

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. The present board is formed by Alexandre Lindote (president, Coimbra), Raúl Sarmento (Minho) and Ruben Conceição (Lisboa).

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 2024

JANUARY | FEBRUARY

- Fermilab completed the excavation of the colossal caverns that will host the DUNE experiment.
- Portuguese ministers for the Economy and Maritime Affairs and Science, Technology and Higher Education, visited CERN.
- As part of LIP's partnership with the Clube Ciência Viva at Agrupamento de Escolas Mães D'Água, 60 students visited LIP.
- LIP's ATLAS group submitted a paper on the Tile Calorimeter's operation and performance during LHC Run 2, highlighting their leading role in calibration, control systems, radiation studies and detector maintenance.
- LIP supported the celebrations of the 120th anniversary of physicist Manuel Valadares, contributing to the exhibition "Ver o Invisível" .

MAY | JUNE

- Following internal elections, LIP's General Assembly appointed the new Board of Directors.
- The European Particle Physics Communication Network (EPPCN) visited LIP's facilities in Lisbon.
- The United States and CERN signed a joint statement of intent to collaborate on the Future Circular Collider (FCC) project.
- LIP hosted the SND@LHC Collaboration Meeting.
- The LIP Neutrino Physics Group took part in Neutrino 2024, the XXXI International Conference on Neutrino Physics and Astrophysics in Milan.
- LIP organized its first Kubernetes Hackathon, in partnership with Google Cloud Infrastructure.
- NUC-RIA group carried out an experimental campaign at HUN-REN ATOMKI, Debrecen, Hungary.

SEPTEMBER | OCTOBER

- CERN celebrated its 70th Anniversary.
- LIP hosted the IBERGRID 2024 Conference in Porto, gathering the Iberian computing community.
- The LUX-ZEPLIN experiment announced a new dark matter search result nearly five times better than the previous global benchmark.
- LIP PhD students participated in interdisciplinary research discusssions in the ProtoTera and in the LIP/IDPASC Stydent Workshops.
- LIP's biennial Scientific Meeting took place in Braga, Portugal.
- An atmospheric balloon carrying the THOR Mission subsystem, developed at LIP, was launched.
- The CMS collaboration, with a leading contribution from LIP researchers, published a major study on rare B meson decays.
- The ATLAS experiment reported the first observation of top quarks in lead-lead collisions.

MARCH | APRIL

- Brazil became CERN's first Associate Member State in the Americas, a historic step for international scientific cooperation.
- A new LIP-built detector—a muon telescope based on sealed RPC technology—was installed in the LHC tunnel near the SND@LHC experiment.
- LIP researchers played a leading role in two nuclear physics experiments (S118 and S091) at the R3B collaboration's at GSI.
- The 2024 edition of the International Masterclasses in Particle Physics, coordinated by LIP, expanded globally.
- The LIP GRID Group joined three major international initiatives: LHCONE, the EOSC-Beyond consortium for advancing the European Open Science Cloud, and AlmaLinux's HPC/AI Special Interest Group.

JULY | AUGUST

- The Atacama Astronomical Park in Chile was officially announced as the site of the future Southern Wide-field Gamma-ray Observatory (SWGO).
- LIP researchers participated in ICHEP 2024, held in Prague, contributing to sessions on heavy-ion physics, detector technologies, and science outreach.
- LIP Internship Programme welcomed over 60 students from Portuguese and international universities.
- The AMBER experiment at CERN carried out antiproton-production runs in proton-helium collisions.
- LIP hosted the annual meeting of the international CompAS collaboration in Lisbon.

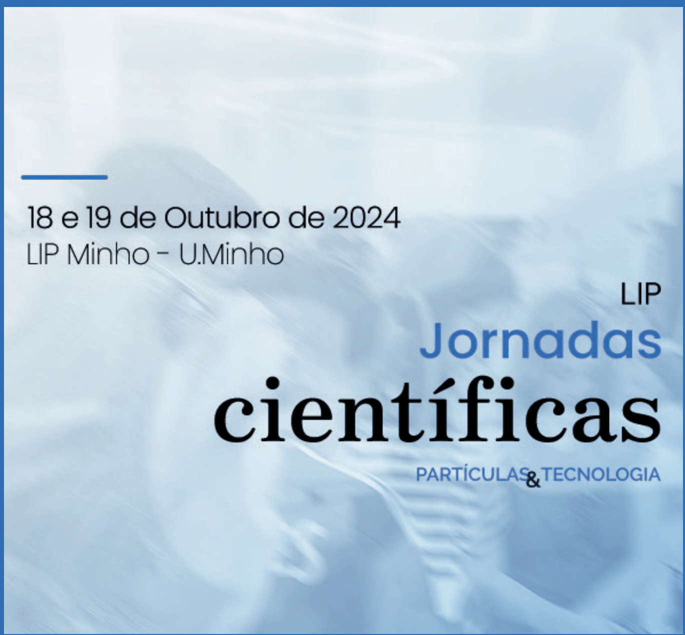
NOVEMBER | DECEMBER

- The TGF Monitor experiment, led by LIP's i-Astro group, was selected for launch aboard ESA's Space Rider vehicle.
- The LHC celebrated a decade of operations, achieving record data collection and advancing preparations for its high-luminosity upgrade scheduled for 2026.
- ProtoDUNE detectors were calibrated using high-intensity UV laser, testing a system jointly developed and built by LIP and LANL, USA.
- The second edition of LIP's Open Day was held in Lisbon.
- The Pierre Auger Observatory announced the extension of its scientific operations for another ten years.
- The BoneOscopy project was officially launched.

Main organised events & Awards of 2024

2024-03-15
"LIP Into the Future"
Lisbon, Portugal

2024-06-11/14
"SND@LHC Collaboration Meeting "
Lisbon, Portugal



2024-10-18/19
"LIP Scientific Meeting"
Braga, Portugal

2024-11-22
"Uma viagem ao mundo do LIP - LIP Open Day"
Lisboa, Portugal

Awards to LIP Members

Conceição Abreu and Teresa Peña

Awarded the title of Honorary Members of the Portuguese Society of Physics

Miguel Amorim Lacerda

UMinho Scientific Research Initiation Award

Cristiana Rodrigues

SCTE's Best Student Presentation Award

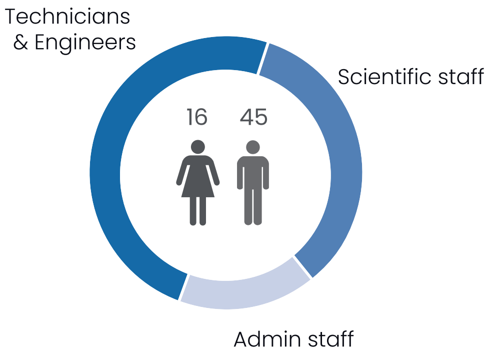
Rúben Inácio

2nd place of the Jerónimo Martins Merit Award in Computer Science and Engineering

LIP in numbers

Human Resources

STAFF



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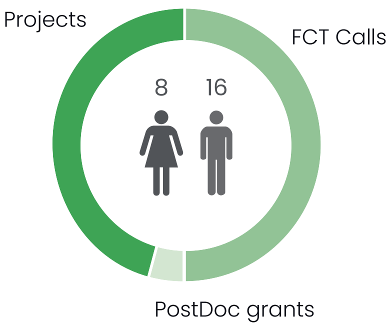
61 TOTAL

	Women	Men
Technicians/ Engineers	3	27
Scientific staff	4	17
Admin staff	9	1

FIXED-TERM RESEARCHERS



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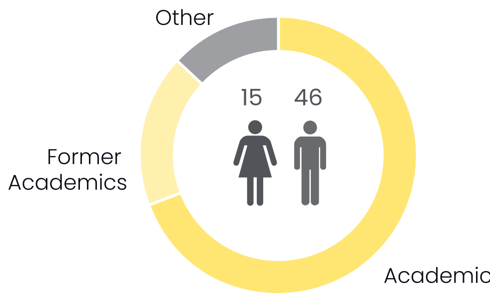
24 TOTAL

	Women	Men
Projects	3	8
FCT Calls	4	8
PostDoc grants	1	0

UNPAID



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61 TOTAL

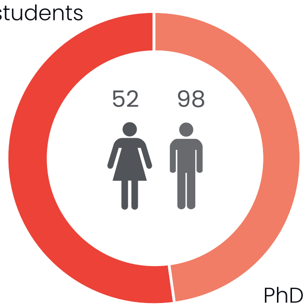
	Women	Men
Academics	11	32
Former Academics	4	7
Other	0	8

TOTAL 297

91 206

107 RESEARCHERS	40 TECH & ADMIN	150 GRAD STUDENTS
27 80	12 28	52 98

STUDENTS



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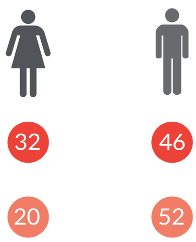
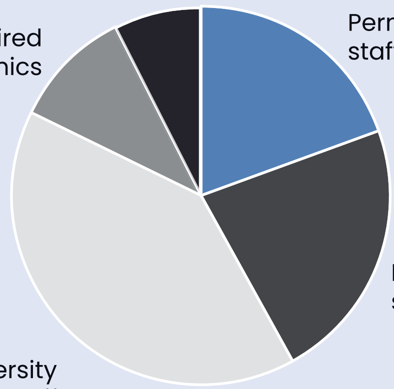
150
TOTAL

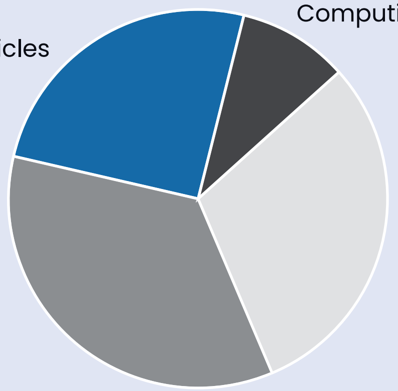


LIP RESEARCHERS

DISTRIBUTION BY CONTRACT STATUS



DISTRIBUTION BY RESEARCH AREA



Finances

GENERAL FUNDING

2.5M
PROJECT-BASED

1.9M
CORE FUNDING

0.9M
RESEARCHERS

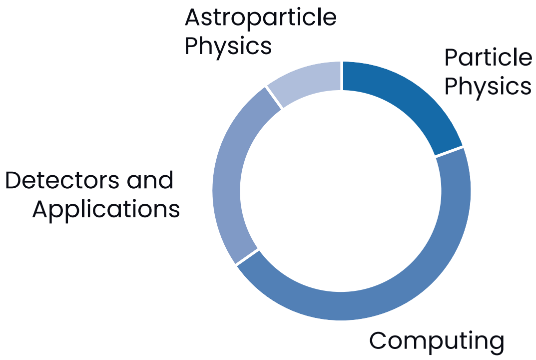
0.4M
EXPERIMENTS M&O

0.2M
CONTRACTS & CONFERENCES

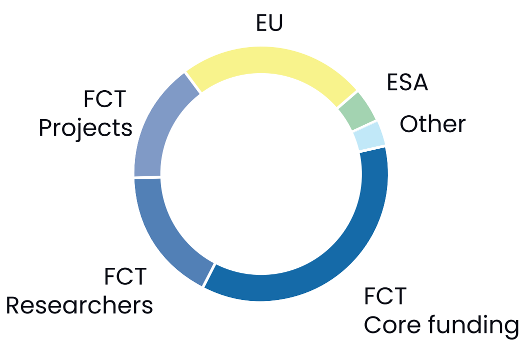
TOTAL
5.9M €

PROJECT FUNDING

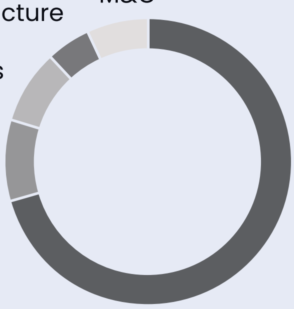
BY RESEARCH AREA



BY ORIGIN



COSTS



HUMAN RESOURCES

STAFF 2.5M

FIXED TERM RESEARCHERS 1.6M

SERVICES AND OTHER EXPENSES

0.6M

MISSIONS

0.5M

EXPERIMENTS M&O

0.4M

INFRASTRUCTURE AND EQUIPMENT

0.3M

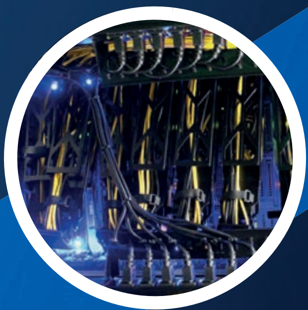
Scientific output for 2024

	Particle Physics	Astroparticle Physics
Papers in refereed journals	193	56
Proceedings Preprints and Notes	40	15
Books, Reports, Proposals, SW tools, Exhibition materials	2	1
Presentations in International Conferences	50	22
Other Presentations	117	64
Master & PhD Theses	17	4

Detectors and Applications	Computing	TOTAL
53	13	303
30	1	84
1	6	9
29	25	118
50	34	255
14	7	38

Experimental particle and **astroparticle physics**

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



Computing

Research at LIP

Experimental particle and astroparticle physics

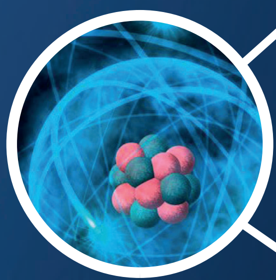
Development of new instruments and methods

LHC experiments and phenomenology

- ATLAS
- CMS
- Pheno
- FCC

Structure of matter

- pQCD
- NUC-RIA
- NPstrong



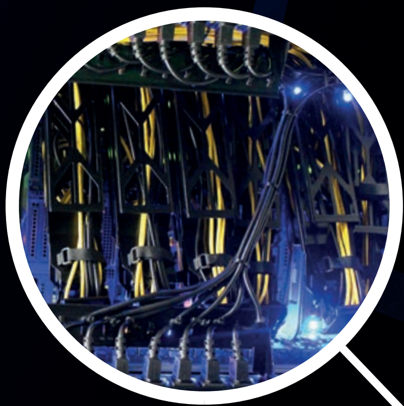
Cosmic rays

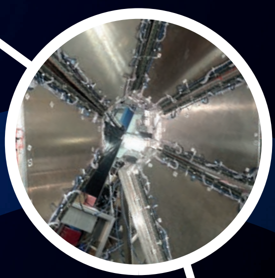
- AMS
- Auger
- SWGO

Dark matter and neutrinos

- DARK MATTER
- NEUTRINO
- SHiP/ SND@LHC

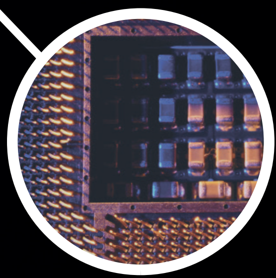
Computing





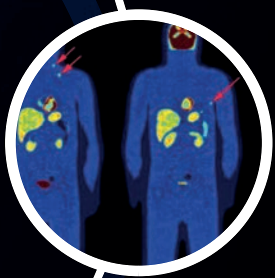
Detectors for **particle** and **nuclear physics**

- 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**

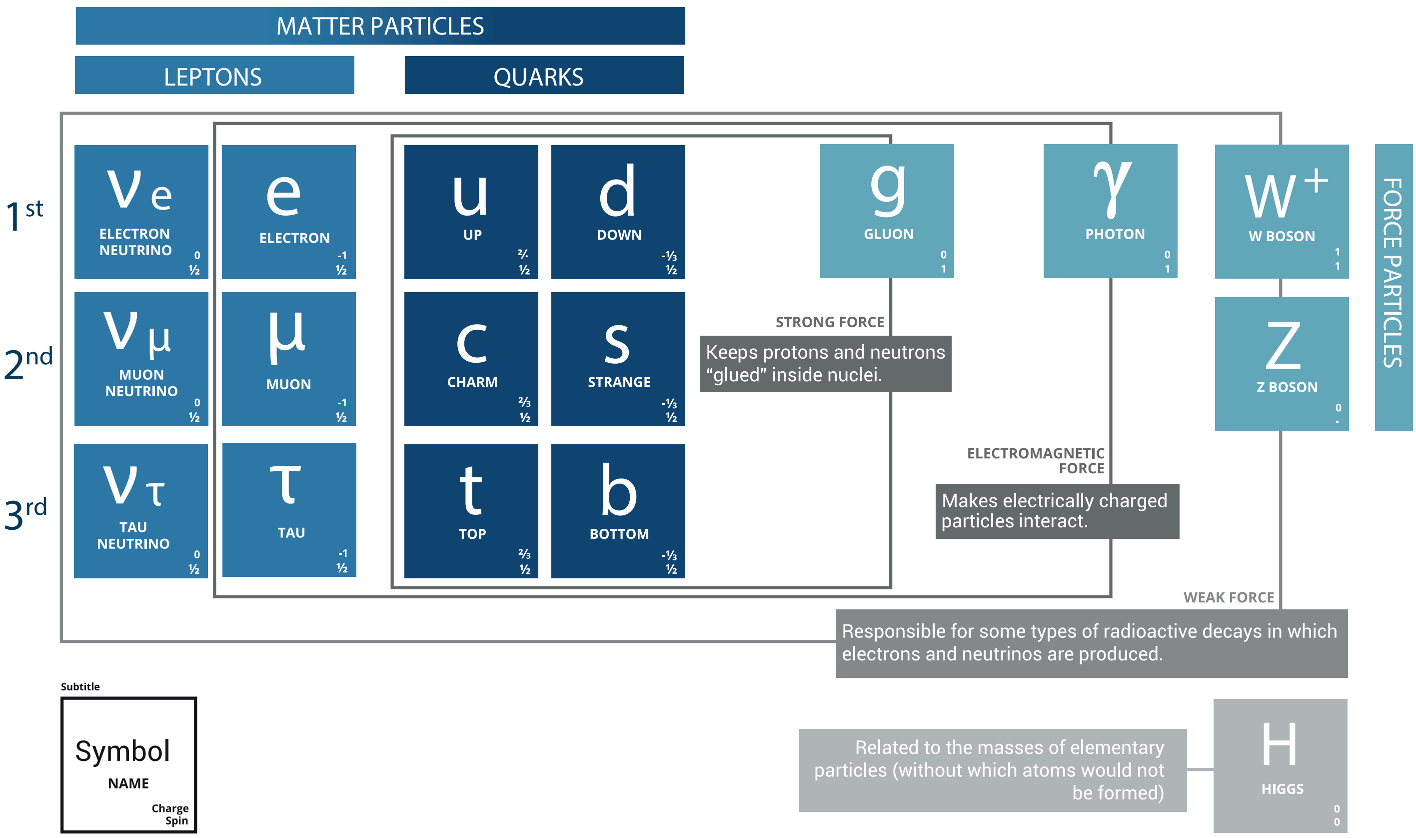
- RPC-PET
- Proton Therapy
- OR Imaging
- RADART

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?
- How did matter behave in the first miliseconds after the big bang?
- What happened to all the anti-matter?
- 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, we are preparing the far-future, namely by participating in the Future Circular Collider (FCC) feasibility study. Theoretical insight is crucial to interpret these phenomena. The LIP Phenomenology group develops innovative frameworks that bridge experiment and theory, with a strong focus on QCD and the Quark-Gluon Plasma. It also contributes to guide searches and interpret data. The synergy with LIP's experimental teams, strongly enhances the scientific reach of the LHC programme.

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, namely in the R3B experiment. 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.

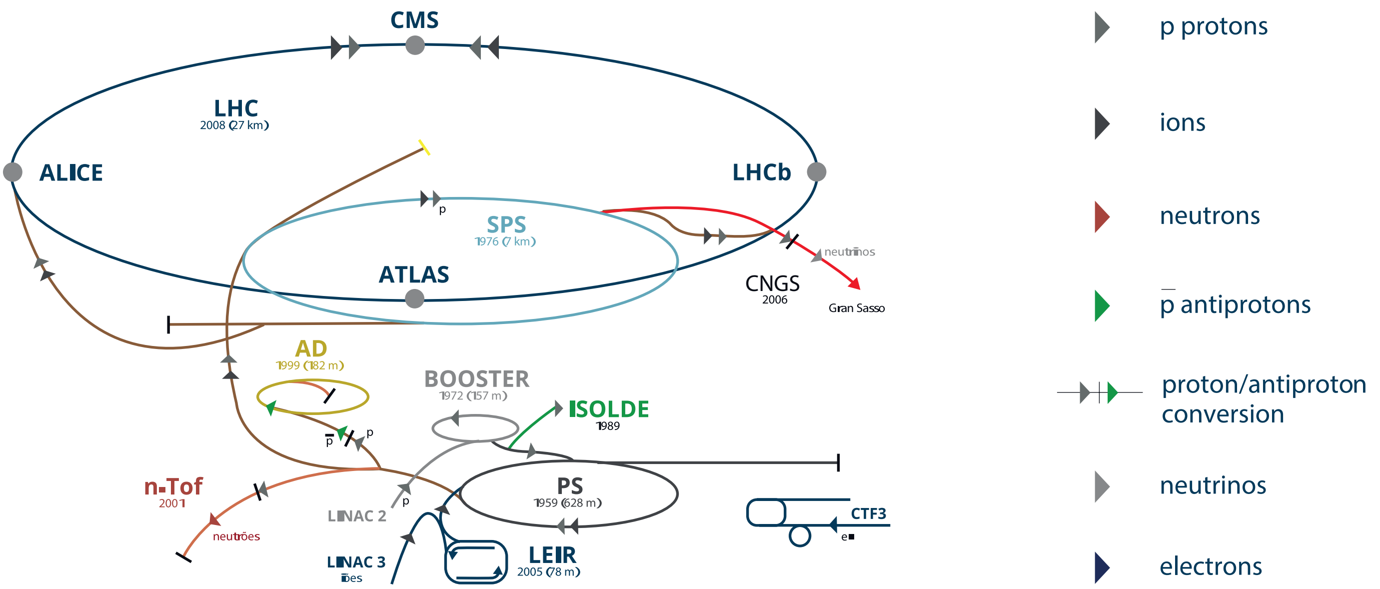
More recently embraced projects are the participation in DUNE, one of the two flagship neutrino experiments for the next decade; the SWGO for the installation of a wide field-of-view gamma ray-observatory in the Southern hemisphere; and SHiP, an experiment proposed to be installed in a beam dump facility 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

LHC's Run 3 continued in 2024, successfully completing its third 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 2030. The new detectors and upgrades will be installed during the long shutdown from 2026 to 2029. LIP is also very much engaged in the most recent LHC experiment, SND@LHC, which has been taking data since the start of Run 3. The LIP Phenomenology group consolidates research programmes in both QCD and new physics searches. Last but not least, we are also preparing for 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 Phenomenology 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 perform 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 boson, 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 precise standard model measurements, searching for hints of new physics including particles or phenomena beyond the Standard Model of particle physics.

Precision measurements: Higgs boson and top quark

Higgs and top physics have long been a particular specialty of LIP's ATLAS, CMS and Phenomenology groups. The LIP-ATLAS team focus on the accurate measurement of the Higgs boson production with either a W or a Z boson (VH channel, V=Z, W) or a top-quark pair (ttH channel), to access the Higgs properties. In 2024, the team contributed to the Run 2 Legacy paper on the measurement of H→bb decays in VH production, and is leading the ATLAS analysis of the spin/CP properties in WH. The team published the results of the CP-sensitive analysis of ttH production, and the measurement of one of its main backgrounds (ttcc). 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. The results for nonresonant HH production in Run 2 were published, search for resonant HH production is being finalized. This process gives access to the Higgs self-coupling parameters and can be significantly changed by new physics. 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 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 ongoing to measure the ratio of the decays into other leptons to test lepton flavor universality. The group is also pursuing analyses of exclusive production (of top, tau, W/Z pairs) through two-photon processes. These are only made possible by the Precision Proton Spectrometer (PPS), located very close to the LHC beam, in which the LIP team has long played a leading role.

The higher luminosity and the upgraded detectors open new possibilities for Run 3. The CMS analysis searching for the exclusive top quark pair production was published in 2024 and the related analysis of two-photon production of tau lepton pairs is ongoing.

The ATLAS group continues to work on interpretation of precision top quark measurements in effective field theory, aiming to constrain the possible forms of new physics at the basis of the SM.

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 different theories and models, and performing wide searches employing powerful analysis methods to search for any anomalies in data. In 2024 both the ATLAS and CMS LIP teams were busy concluding search analyses in a variety of models and channels using the full Run 2 dataset.

Several papers with leading or important contributions of the LIP ATLAS group were published during the year, such as the combination of heavy resonance searches, monotop and the single vector-like quarks production. Still, the exploration of the Run 2 data does not end here. As an example, the search for axion-like particles using forward detectors data continues, as does the analysis of mono-jet events with anomaly detection techniques. The LIP CMS group's efforts in analysis of exclusive production in photon fusion processes allows probing several BSM scenarios. In addition to directly searching for tt and tautau resonances, the team contributed also to a comprehensive report reviewing the CMS searches in the context of the dark sector and its mediators.

The LIP Phenomenology group is also exploring how artificial inteligence and machine learning can help uncover new physics. With algorithms that spot unusual patterns in the data, these tools make it possible to search for signs of new particles or interactions without knowing in advance what they look like; similar tools can be used to match the patterns to beyond the Standard Model theories. Results using the full Run 2 data were published this year.

Hadrons containing heavy 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 groups is focusing on the b->sll transitions, at the core of these anomalies, namely exploring Flavour Changing Neutral Currents in $B \to \mu\mu$ and $B \to K^*\mu\mu$. Results on the angular observables with the full Run 2 data were published.

Secrets of the strong force

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 using the large Run 2 data samples were published and will have an important impact in the understanding of quarkonium production.

The LHC provides unique opportunities to study heavy-ion collisions and recreate the Quark-Gluon Plasma (QGP), a state of matter that existed in the hot and dense environment of the early Universe.

LIP's Phenomenology group plays a central role in advancing our understanding of this exotic phase by developing theoretical and computational tools to describe how energetic quarks and gluons lose energy and evolve as they traverse the medium. Their research focuses on the internal structure of QCD jets and their use as tomographic probes of the QGP, offering insight into its time evolution, transport properties, and microscopic dynamics. Recent contributions include new algorithms to extract information about QGP evolution from experimental data, analytical studies of the role of coherence in QCD radiation inside a medium, and model-based comparisons to identify hadronization mechanisms through jet substructure observables.

These theoretical efforts go hand in hand with LIP's participation in the CMS and ATLAS heavy-ion programs, which provide high-precision experimental data on jet quenching and other QGP signatures. 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 LIP CMS group is bringing its unique expertise on B physics into the heavy-ion realm, and playing a leading role in the investigation of B mesons in PbPb collisions data. The measurement of the nuclear modification factors was published. The measurement

of B mesons production cross-sections at 5 TeV pp collisions is advanced. The team performed the first measurement of the polarizations of χ_{c1} and χ_{c2} states. Precise measurements of the polarizations of several quarkonium states using the large Run 2 data samples were published and will have an important impact in the understanding of quarkonium production.

Tools of the trade - Detector Upgrades

In 2024, 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 detector. The ATLAS team coordinates the maintenance, control system, operation and calibration of the TileCal calorimeter, forward detectors and parts of the trigger system. It contributed significantly to publications on the ATLAS configuration for Run 3 and its trigger system, and lead the publication on operation and performance of the TileCal calorimeter.

In the High-Luminosity phase of the LHC physics program starting in 2030, the accelerator will provide an additional integrated luminosity of 3000 fb^{-1} over 10 years of operation.

The LIP CMS group is responsible for the design and construction of the readout system of the Barrel Timing Layer, including a high-performance TOF ASIC. A dedicated circuit (TOFHIR) to readout the Silicon Photo Multiplier array is developed in the framework of a Collaboration Agreement between LIP and CERN, with its microelectronics design subcontracted to PETsys Electronics.

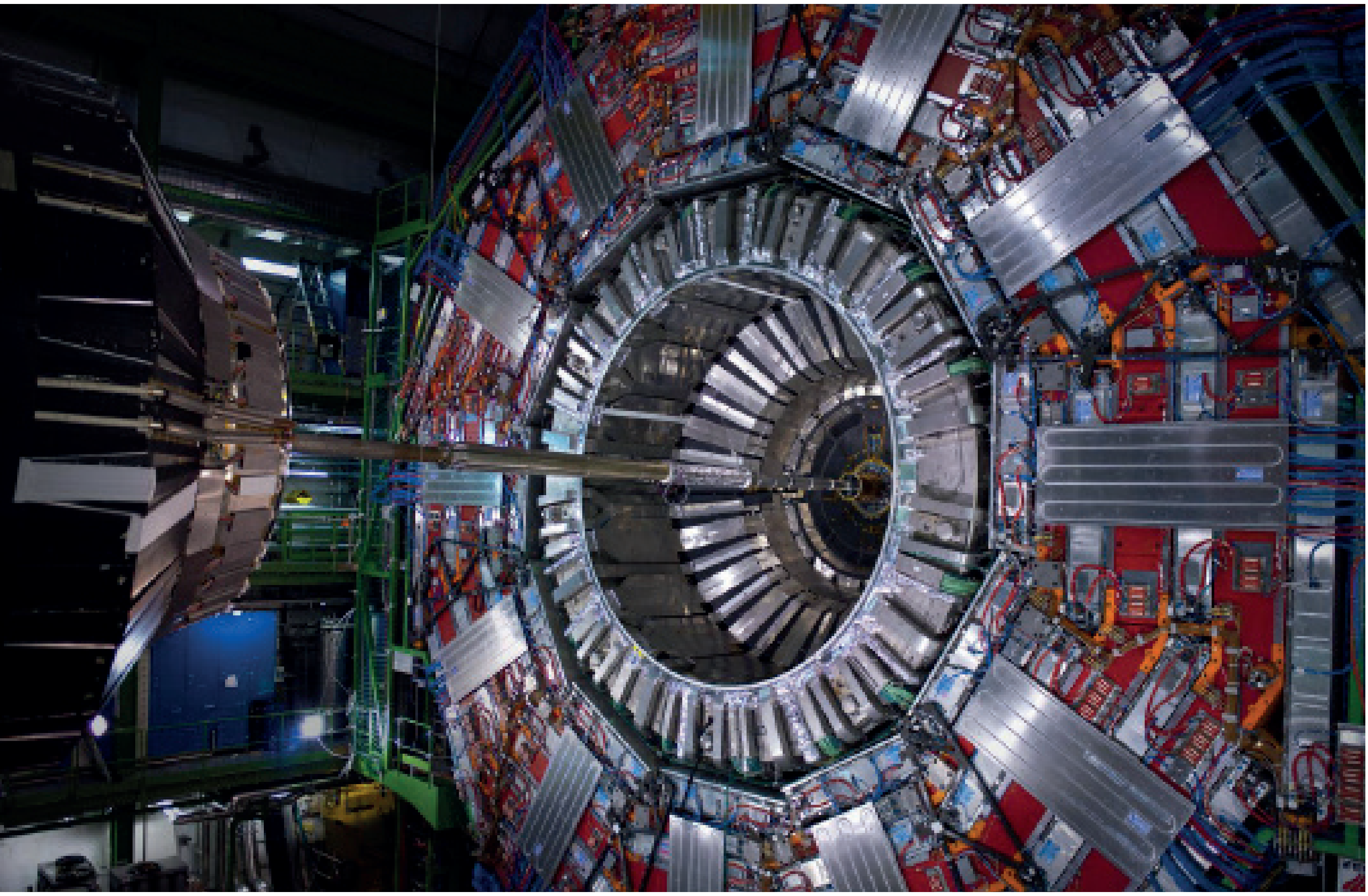
In 2024 the packaging of the TOFHIR2C was contracted to ASE, Taiwan, and the assembly of 19,000 units was concluded in June 2024. LIP had developed and validated a test system in 2023, that was now automated by a Portuguese company, and concluded in 2024.

The CMS upgrade also includes the calorimeters, which will be completely replaced in the end-cap with a new high-granularity sampling calorimeter. In collaboration with industry, LIP provided a radiation resistant high-performance ADC ASIC for the ECAL front-end electronics, and will supply a high-current low voltage regulator resistant to radiation for the High-Granularity Calorimeter 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. Sensors with a single plane time resolution of 40-50 ps are adequate for time-of-flight measurements. The LIP group is pursuing R&D studies of LGAD (low gain avalanche) silicon sensors and associated electronics for these timing measurements.

The LIP ATLAS team is deeply involved in the upgrade of the TileCal and of the Trigger and Data Acquisition. LIP has full responsibility for the new TileCal high voltage distribution, to be produced mainly by 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, and in 2024 high voltage cable prototypes were also produced and tested.

The quality control of the HV distribution boards and cables was done, together with tests of the controls of the HV Remote crates. In collaboration with LIP's infrastructures (Electronics and Detectors Lab) the team is also involved in the High Granularity Timing Detector (HGTD), with responsibilities in the DCS and electronics system (front-end ASIC tests). In 2024 prototype boards of the high voltage patch panels and interlock safety system were produced and integrated in the HGTD demonstrator module at CERN.



Looking into the future

Following the 2020 update of the European Particle Physics Strategy (EPPS), a global collaboration was established to deliever 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), repeating the virtuous cycle represented by LEP and the LHC (which, in sequence, used the same tunnel and accelerator chain).

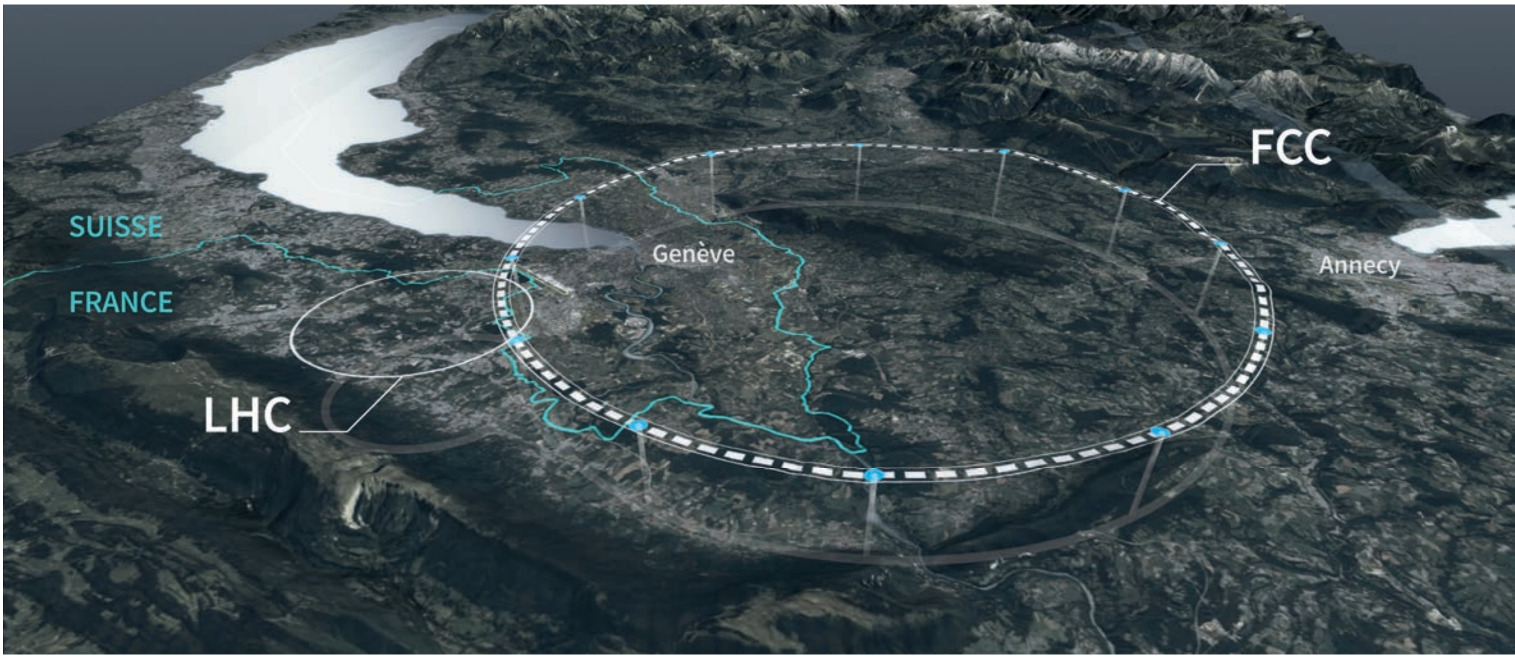
The FCC will enhance the current energy frontier by an order of magnitude, allowing a future generation of physicists to explore the limits of the SM and possibly reach beyond, to a more fundamental theory.

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. Muons are much heavier than electrons resulting in much reduced synchrotron radiation thus allowing acceleration and collision of leptons at a higher energy in compact dimensions.

In 2024, activity grew along several lines, from detector R&D to theoretical calculations. The R&D work on new scintillators continued at LOMaC, with the characterization of different samples summarized in a publication. We also contributed to a proposal of a hadronic calorimeter design for the FCC-ee/hh and are exploring calorimeter design optimization using machine learning. On the theory side, work is focused on comprehensive QCD studies for the FCC-ee physics program, with impact on the feasibility study of the physics potential of the future circular collider. The sensitivity of other accelerators is also being considered, with simulation and optimization of identification algorithms for W-pair production at the ILC at 250 GeV and 500 GeV; and detailed studies of the Higgs decay to tautau, and its sensitivity to new physics, considering a 3 TeV center-of-mass energy Muon Collider.



Neutrinos at the LHC

LIP is a founding member of the Scattering and Neutrino Detector at the LHC, SND@LHC, which has been 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 first observation of collider neutrinos, in 2023, was made under leadership of the LIP group, and marked the dawn of the era of neutrino physics at colliders. In 2024, separate results in muon and non-muon events, give a first demonstration of flavour classification possibilities. More information is given in the Dark Matter and Neutrinos Section of this report

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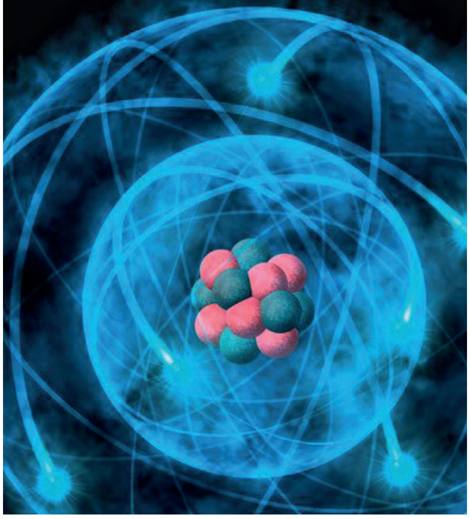


Structure of matter

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 are 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 participates in one of its experiments, R3B. NPstrong, the Nuclear Physics and Strong Interactions group, brings remarkable theoretical consistency to this research line, as well as opportunities for collaboration 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 analyses and in the running 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 proton beam from the CERN's SPS accelerator, colliding on primary targets, originates high intensity muon or hadron beams that impinged on the COMPASS polarized target at a temperature lower than 0.1 degree above the 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 responsibilities in Drell-Yan (high-mass lepton-pair production in a hadron-hadron collision), as well as in deep inelastic scattering of muon beams off protons. Both types of processes are powerful in probing the partonic structure of hadrons.

A major physics result of COMPASS in 2024 was the release of the positive and negative pions, kaons and unidentified hadron multiplicities produced in deep inelastic collisions. They tell us about the probabilities that the originated quarks reorganize to appear in the final state as a specific hadron species, the so-called fragmentation functions. A publication on this analysis was prepared by a member of the LIP group and is already submitted and accepted.

The physics goals of AMBER evolved from those addressed by COMPASS: the measurements of the proton (spin) structure led 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 AMBER experiment, that started physics data taking in April 2023, with the measurement of the antiproton production cross section in collision of protons on helium-4 nuclei.

Another series of antiproton production measurements was done in 2024, on hydrogen and on deuterium targets. These cross sections are fundamental inputs for the interpretation of the antiproton fluxes observed by cosmic ray experiments, like AMS, in search for indirect signs of Dark Matter.

In a future measurement planned to happen after the Long CERN shutdown (LS3, 2026-2028) AMBER proposes to study the pion and kaon structure using the Drell-Yan process induced by these mesons. In such studies, the beam particle identification is essential but challenging, given the very high beam intensity required. CEDAR detectors (Cherenkov Differential Counter with Achromatic Ring Focus) are used for identifying event-by-event the beam particles. Beam tests have been done in 2023 and in 2024 to read-out the CEDARs at high intensity. The data analysis is still ongoing, but the tested hardware and software improvements already allowed to separate the pion and kaon peaks at the highest intensities for the first time.

Stars and Nuclei

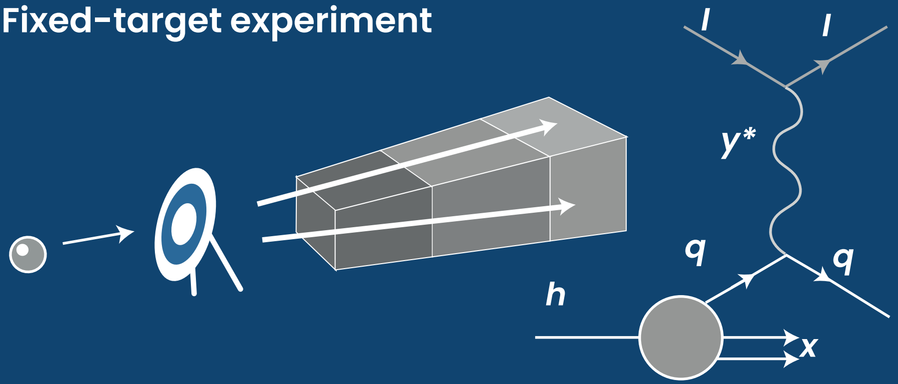
The GSI Helmholtz Centre for Heavy Ion Research in Darmstadt (Germany) operates the only facility allowing to accelerate nuclei of all chemical elements occurring on Earth. The facility has been closed for a few years and is slowly coming back to life. The performed upgrades will allow to put into operation 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). An RPC (Resistive Plate Chamber) detector, responsibility of the LIP group, was used in two short experimental campaigns during 2024, as part of the FAIR phase-0 program.

NUC-RIA pursues measurements of nuclear reaction cross sections at low energies, in various laboratories across Europe, including ISOLDE (On-Line Isotope Mass Separator) at CERN.

A complementary activity, developed by another branch of the NUC-RIA group, concerns systematic calculations of multiple atomic parameters of heavy elements. Such calculations are relevant for the understanding of Kilonovae, catastrophic events that occur when two compact stellar objects collide.

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.

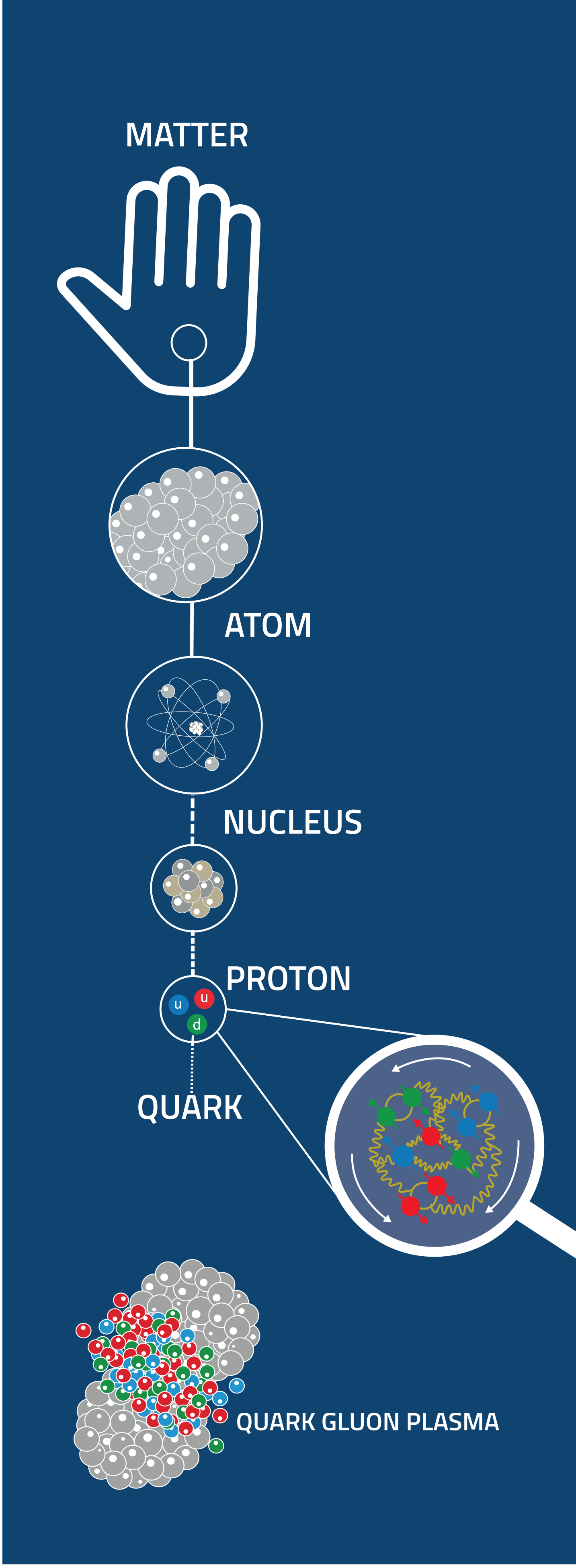
Jumping into theory

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.

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.

In 2024 the group finished the first theoretical results in the literature for hyperon form factors in the time-like kinematic region and defined its uncertainties and domain of validity. Studies of the deuteron as a six-quark state have shown a cancellation between quark and diquark exchanges, providing first evidence from QCD that effectively the active degrees of freedom of low energy nuclear physics are mesons and nucleons. The NPStrong group developed a novel approach to calculating PDFs (Parton distribution functions) and TMDs (transverse momentum distributions) that involves constructing hadronic matrix elements from a set of self-consistent non-perturbative Dyson-Schwinger/Bethe-Salpeter Equations (DSE/BSE) by directly performing the projection to the light-front.

Another interest of the group is the pentaquark functional QCD spectroscopic calculation. Both the ground and excited states of a bound system of five scalar particles interacting by exchange of scalar-bosons are studied, in a ladder truncation approach. The results were systematically compared with the two-, three-, and four-body system ones. We concluded that all multi-body systems have ground and excited states coexisting for a certain range of coupling.



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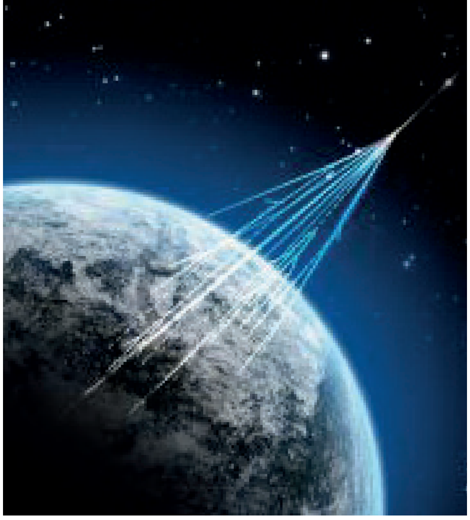


EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

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 energy. LIP is committed to the Alpha Magnetic Spectrometer, the Pierre Auger Observatory, and the Southern Wide-field Gamma-ray Observatory.

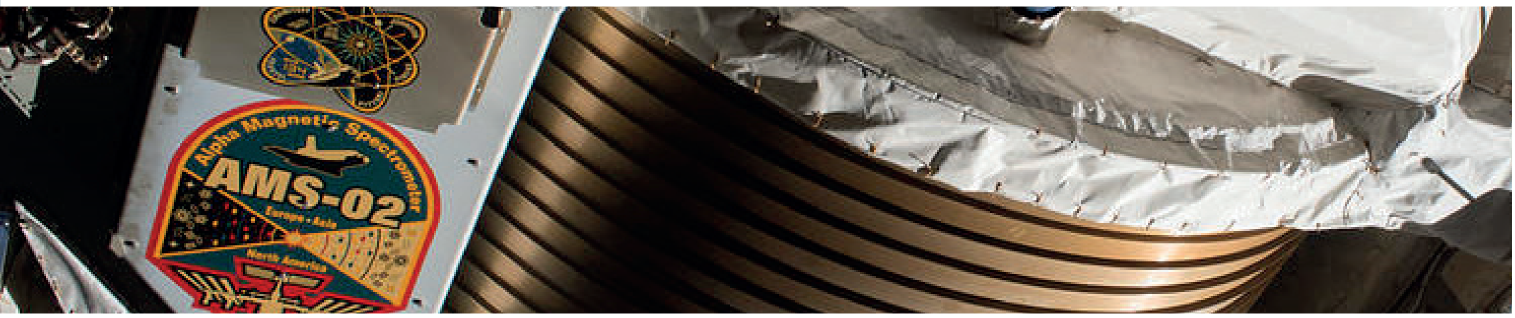
A unique detector in space

Since 1998, LIP has been part of the international collaboration that designed and operates the Alpha Magnetic Spectrometer (AMS). The AMS-I prototype flowed 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.

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. The group is mainly focused on the separation and analysis of the deuteron flux.

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. It is now exploring models to predict the variability of particle fluxes reaching the Earth a few months in advance.



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 the 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 now entering a new phase, Auger Prime, with significant upgrades and an operational extension through 2035. Scintillator detectors (SSD) have been installed on top of the working WCD, which were also equipped with faster electronics. Auger Prime will enable a better measurement (and disentangling) of the electromagnetic and muonic components of the air-shower at ground.

The LIP team has long standing expertise in the use of RPC detectors for WCD calibration studies and for directly measuring the muon component of air showers using the MARTA WCD-RPC unit (a layer of RPCs placed beneath the WCD). Analysis of calibration data from an upgraded RPC hodoscope at the Observatory confirmed the compatibility between the old and new surface detector electronics, and provided the first SSD calibration constants, in equivalent vertical muon units. Simulation studies identified particle trajectories within the WCD that could help improve the understanding of aging effects in the detector. The MARTA station was fully commissioned, and initial data demonstrated the RPC's performance and stability.

In parallel the LIP group has been exploring the Auger data, mainly pursuing the detailed understanding of air showers, partly in collaboration with the Auger group in Santiago de Compostela (Galicia, Spain). The group advanced studies on the energy spectrum of shower particles and the muon distribution. New observables were introduced to quantify spectral modifications.

A Geant4-based surface detector simulation was developed to support a proof-of-principle analysis of electromagnetic shower spectrum measurements using data from MARTA and SSD. Work on Auger's Underground Muon Detectors focused on systematic uncertainties in the tail of the muon number distribution, a quantity never accessed before. Progress was made in extracting the muon energy spectrum by combining MARTA data with the Muon Production Depth algorithm, supported by a toy Monte Carlo simulation and a machine-learning approach for muon arrival direction reconstruction. In searches for neutral particles, efforts were made to improve the resilience of gamma/hadron discrimination to real shower events. The neutrino identification method was extended to include muon-neutrinos, demonstrating effectiveness despite their lower detection sensitivity compared to electron-neutrinos.

In outreach, the LIP team successfully coordinated the organization of the Auger International Masterclass 2024, expanding its reach to students in Asia and North America. The Auger virtual reality goggles and 3D visualizer developed at LIP were updated and further improved. In particular, the VR goggles now feature a balloon-flight tour built from 360-degree drone videos, which is available also at the Auger visitor center in Argentina.

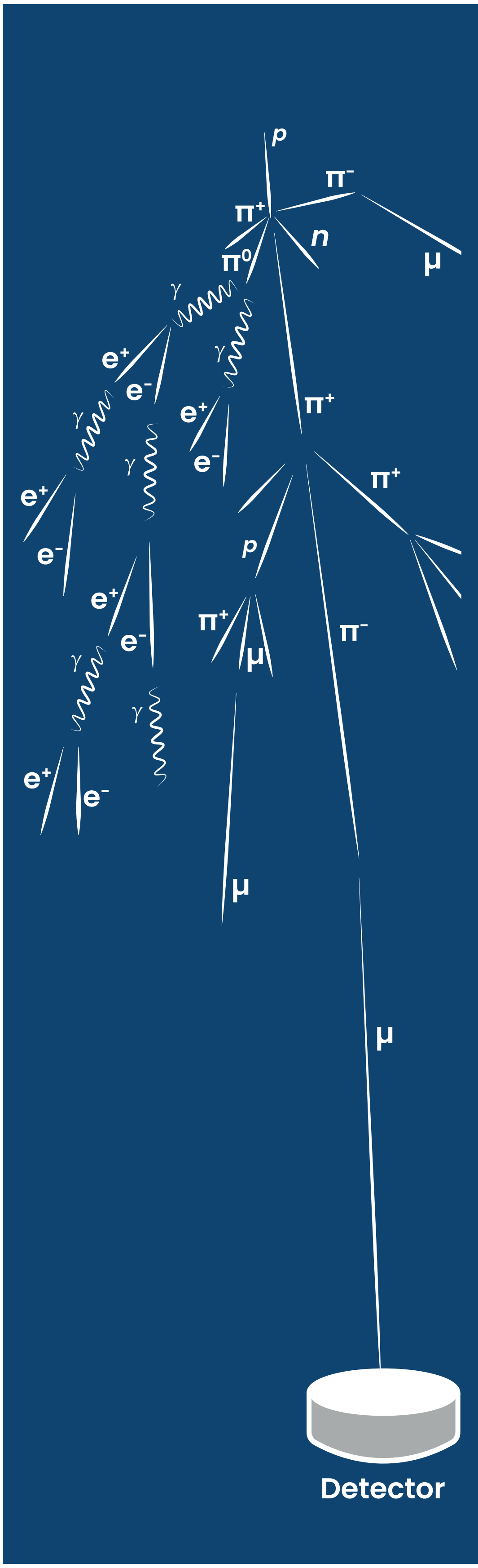
At the top of mountains

The Southern Wide-field Gamma-ray Observatory (SWGO) collaboration was formed in 2019 after a workshop in Lisbon where several groups developing similar projects decided to joint efforts. The collaboration now includes 90 research institutions from 15 countries, with additional support from scientists in 10 other countries. SWGO will be the only wide field-of-view gamma-ray observatory surveying the Southern sky and thus the centre of the galaxy. In 2024, two major milestones were achieved: finalizing the observatory design and selecting Pampa la Bola (Chile) as the future SWGO site at 4,770 meters altitude. The first prototype installations are expected already in 2025, while full observatory deployment is planned by the end of the decade.

The Portuguese participation in SWGO, led by LIP, spanns over different areas: science requirements, detector design, analysis development, outreach. In 2024, key contributions included the development of the Mercedes station, a single-layered Water Cherenkov Detector (WCD) proposed by the LIP group and the leading candidate for the sparse array detector unit; the development of new methods to separate gamma-initiated showers from the largely dominant background of charged cosmic rays showers (initiated by protons and nuclei); and the assessment of the potential of SWGO in the emerging field of Multimessengers. The first full-scale Mercedes prototypes were successfully produced in Brazil. Two prototypes are set for installation in early 2025 at a test site in Chile, near the future Observatory, including one with an innovative reflective inner layer to reduce production costs and simplify maintenance. Another prototype at CBPF in Rio de Janeiro was equipped with a novel photosensor multiPMT unit developed by INFN Napoli, with seven small photomultipliers.

The LIP team has also been actively engaged in the development of innovative algorithms for gamma/hadron discrimination and playing a pivotal role in the advancement of state-of-the-art techniques. These target low-energy showers (100 GeV–10 TeV) and high-energy showers (10 TeV–few PeV) with distinct approaches. At low energies, machine-learning techniques are used for identifying muons crossing the Mercedes stations, by analyzing the time structure of photomultiplier signals, and for distinguishing gamma from proton-induced showers, by analyzing the ground-level footprints of shower particles. For high energies, the LIP group introduced two novel observables: one quantifying the azimuthaç fluctuations of the particle distributions at ground; the other identifying stations with signals which significantly exceed the average as measured in stations located at similar distances to the shower core.

Finally, in the context of multimessenger observations, studies were conducted on the feasibility of tagging upward-going neutrinos by leveraging the large total target mass of the water in the WCDs and the Earth beneath. Additionally, we began to access the impact of using multiPMT photosensors.



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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 these areas. LIP's involvement in neutrino experiments includes SNO+ at SNOLAB (Canada), DUNE at the SURF Laboratory (USA), as well as SND@LHC and its upgrade at CERN. LIP participates in the LZ direct dark matter search experiment at the SURF Laboratory (USA) and in the preparation of the third generation experiment XLZD, as well as the SHiP experiment, which will search for the production of dark matter candidate particles in CERN's SPS (Super Proton Synchrotron).

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. 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 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 time-projection chamber (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. TPC detectors are able to measure the 3D position of dark matter interactions with nuclei. To improve the rejection of backgrounds due to 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 rare and forbidden decays of xenon.

LZ had a first science run in early 2022. After a six-month calibration campaign in early 2023, a second period of data acquisition accumulated an exposure of 220 live days. These data yielded the most stringent constraint on the cross section for the interaction of dark matter particles with masses above 9 GeV/c^2.

The LIP group contributes to many areas of the LZ experiment, including a leading role in studies of the sensitivity to the neutrinoless double-beta decay of xenon, responsibility for the detector control system and online performance monitor, and the development of data analysis tools.

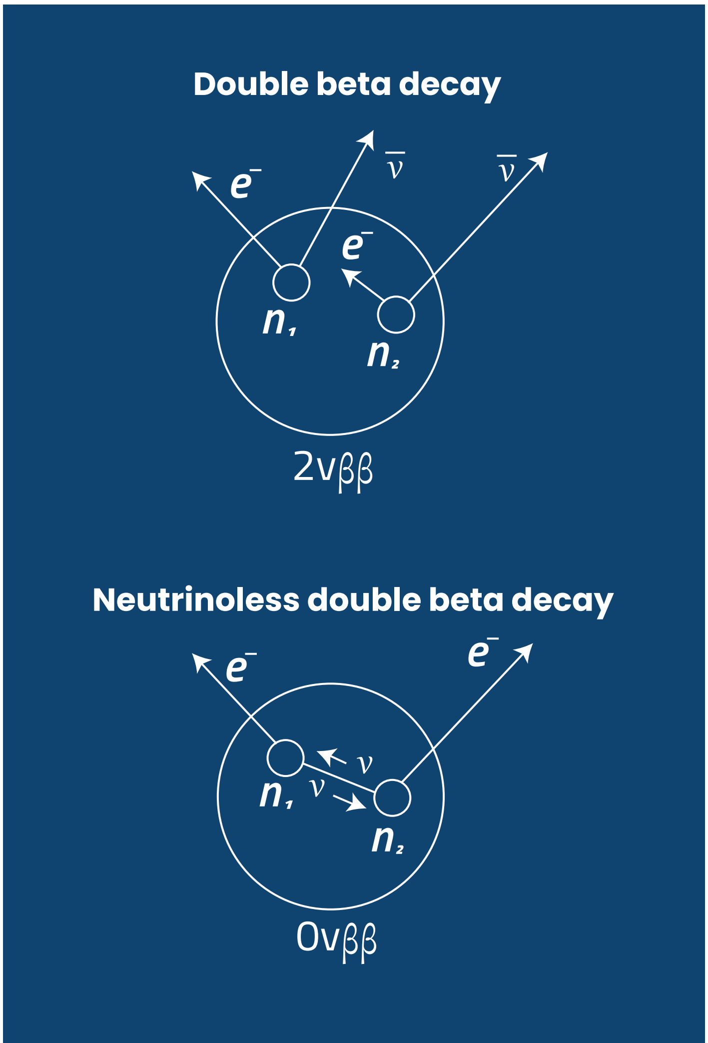
To prepare the next-generation experiment using a dual phase TPC with ~100 tonnes of xenon, the LZ, DARWIN and XENON collaborations created the XLZD consortium. A study led by the LIP group demonstrated that XLZD can be one of the leading experiments in this search.

Since 2020, the group has joined a UK-based project aiming to observe the Migdal effect: nuclear recoil interactions may be accompanied by atomic ionisation, extending the sensitivity of xenon TPCs to dark matter masses below 1 GeV/c2. In 2023 and 2024, the Migdal experiment collected data at the ISIS Neutron and Muon Source (UK), which is now under analysis, and the detector is being upgraded for a third run in 2025.

Understanding the elusive neutrinos

Produced in vast numbers shortly after the big-bang, neutrinos are the second most abundant particle in the Universe, after photons. They are constantly being produced in nuclear reactions inside stars. On Earth, neutrinos are also produced in radioactive decays and cosmic ray interactions in the atmosphere, as well as in human-made particle accelerators. 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 flavours while propagating — we say they oscillate. For that, neutrinos must have a non-zero (although tiny, and 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 Super-Kamiokande 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.



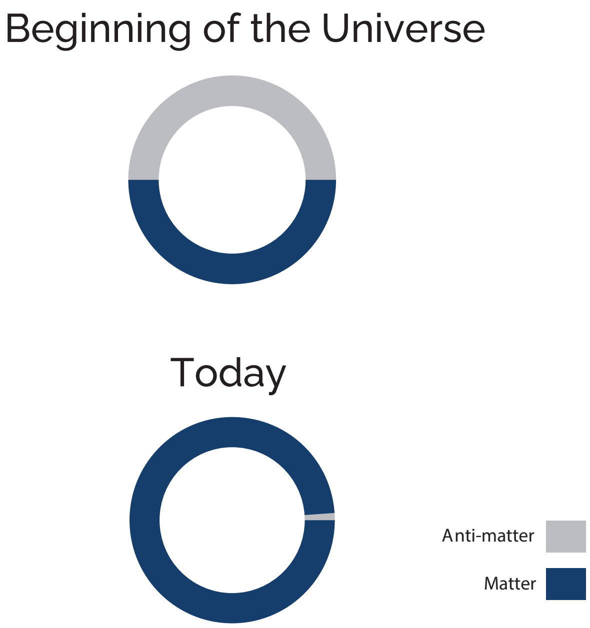
SNO+

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) and consists of 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 to light water and then to liquid scintillator. The main goal of the experiment is to 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 linear alkylbenzene (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 was added in 2023 in preparation for the tellurium loading phase in 2025. The 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, focusing on backgrounds, antineutrino physics and calibrations. The group had a large contribution in evaluating the background ingress and its correlation with the recirculation of the scintillator, a crucial step in preparing the tellurium loading. We actively monitored the scintillator purity and optical quality during the addition of the secondary wavelength shifter. The group had leading roles in high-profile publications on diverse topics over the last year including directional reconstruction of neutrinos with a scintillator detector; and analysis of solar neutrinos with the water-filled detector. A paper on the analysis of antineutrino data in the partial-fill phase of the detector was published and the following one, with the full scintillator phase, is undergoing final review in the collaboration. 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 is one of the largest particle physics projects of the next decades, studying in particular the ordering of neutrino masses and investigating wether neutrinos can contribute to our understanding of 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. LIP leads the Calibration and Cryogenic Instrumentation Consortium (one of eleven consortia) and plans to later contribute to the Near Detector, on the Fermilab site.

In 2023, the group completed the development of the custom electronics that control the laser calibration system and implement the interfaces with the DUNE data acquisition and slow control systems. In 2024, it was already operated in the DUNE horizontal-drift prototype at CERN, and the analysis of the calibration data is starting. The corresponding systems for the vertical-drift prototype, under responsibility of LIP, were tested at LIP's mechanical workshop and installed at CERN, together with two mirror based alignment targets. Finally, the group implemented the calibration control software, and progressed in the development of simulation and processing software, as well as data analysis, including a new study of the impact of electron-ion recombination models on the physics reach of the DUNE.

SHIP and SND@LHC

LIP is involved in the SND@LHC experiment operating at the LHC, and is a proponent of SHiP, 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. In 2024, the group led the preparation of the technical proposal for the upgrade of SND for the high-luminosity LHC, which uses silicon microstrip detectors for the first time in a neutrino detector.

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, 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 detector commissioning, as well as in data taking, which started in 2022 with LHC's Run 3. A novel muon telescope, based on the sealed RPC technology, was installed in the LHC tunnel since early 2024 and collected one year of data, which will result in the precise measurement of the muon flux in different angular regions.

In 2023, the SND@LHC collaboration published the first observation of collider muon neutrinos, a milestone physics result achieved under the leadership of the LIP group. This first observation marks the dawn of the era of neutrino physics at colliders. This was followed in 2024 with the observation of neutrinos of different flavours, a result that demonstrates the experiment's ability to scrutinise the Standard Model's flavour puzzle. Larger data sets continue to be accumulated and will allow for more detailed investigations. Very successful calibration campaigns were conducted in 2023 and 2024, with LIP's leading involvement. These resulted in the measurement of the hadron jet energy in muon neutrino interactions reported in 2024, a milestone for the experiment. The group has also initiated a first search for new particles using SND@LHC data.

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Development of new instruments & methods

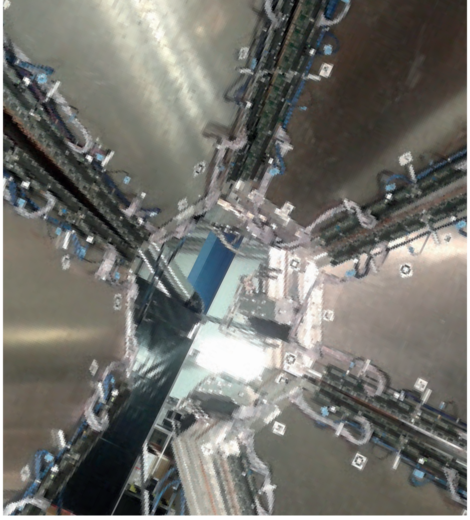
• Detectors for particle and nuclear physics • Health and biomedical applications • Space applications

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.



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 hardness, 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.

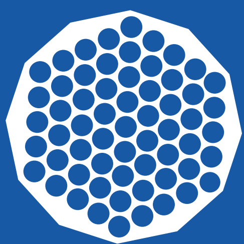
RPC-PET: medical imaging

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/Pharma. 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

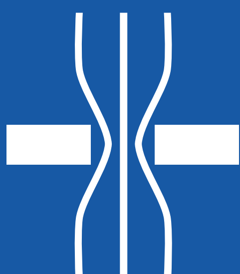
Resistive Plate Chambers (RPC)

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.

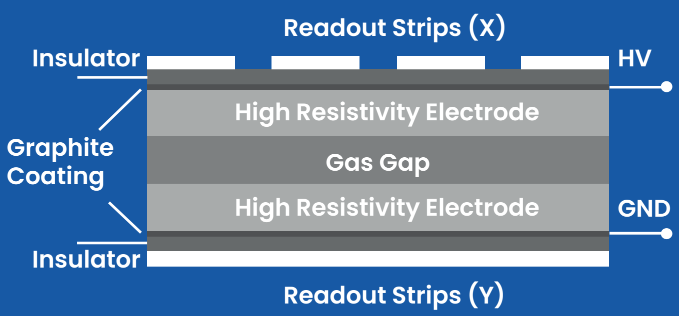


Patterned Gas Detectors (PDG)

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, which can reach 98% efficiency and a time precission of 50 ps.



Resistive Plate Chamber (RPC)

RPC are gaseous particle detector with at least 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.

LIP delivered and supports the operation of large RPC TOF detectors in the HADES and the R3B/FAIR experiments at GSI. The lessons learned in each project being then exported to new projects. The use of the R3B proton TOF arm is detailed in the Structure of Matter Section.

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. Both modalities, of muon transmission (e.g. for imaging volcanoes and mines) and muon scattering (e.g. for container scanning) are of interest for the group.

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. In 2024, the results have been presented in several conferences and published.

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 the last years, tests were conducted reducing the gas flow in the chambers, until they could be sealed and operated with no gas flow.

The first paper on the sealed RPC technology (sRPC) was published in 2023. In 2024, a successful demonstration of the technology was achieved in a real experiment: a sRPC telescope was installed at the LHC tunnel, next to SND@LHC, and monitored and studied while collecting a large data set for measuring the muon flux. Details are given in 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 3He, a stable helium isotope with a high thermal neutron capture cross section. The prohibitive cost and scarcity 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, and characterization studies have demonstrated the potential of this technology. A proof-of-concept nRPC-4D detector was then designed and built, and tests in neutron beam lines have now shown cutting-edge performance in spatial resolution, neutron time-of-flight measurement, as well as potential for high detection efficiency and high count rate operation. These capabilities indicate that the nRPC-4D detector is well-suited for TOF neutron scattering and wavelength- and time-resolved neutron experiments. The possibility to extend the use of nRPC for detection of epithermal and fast neutrons is being evaluated. Three prototypes were already tested at a neutron source, analysis and validation of the simulation models is ongoing so that the detector configuration can be optimized for this use. The sensitivity to gamma rays is also being characterized to further increase the potential uses of the new technology.

Gaseous and Liquid Detectors

Following the implementation of ECFA's Detector R&D (DRD) roadmap, these several lines of work are now organized within the DRD1 and DRD2 international collaborations, dedicated to fundamental R&D in gas and liquid detectors.

The Gaseous Detectors R&D group at LIP studies the drift parameters of electrons and ions (positive and negative) in noble gases and mixtures with the aim of optimizing the active medium for each application. This is achieved with dedicated simulations and measurements performed locally and considering general requirement set forward in DRD1 or specific needs, like those of the NEXT collaboration, using an electroluminescence xenon TPC for neutrino physics, or dark matter experiments using mixtures of noble and molecular gases.

The Liquid Xenon R&D group is currently focused on the application of MPGDs (Micropattern Gaseous Detectors) in double phase xenon (liquid/gas) and the development of novel methods for their readout. Previously, the novel concept of a Floating Hole Multiplier has been proven by measuring primary and secondary scintillation signals in liquid xenon, optimization now ongoing with different sizes of the holes and different dielectric materials and thicknesses for the floating plate. In 2024, a new cryogenic setup has been developed and is being manufactured at the LIP mechanical workshop to allow for future experiments with liquid xenon and possibly also liquid argon.

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DEVELOPMENT OF NEW INSTRUMENTS AND METHODS

Health and biomedical applications

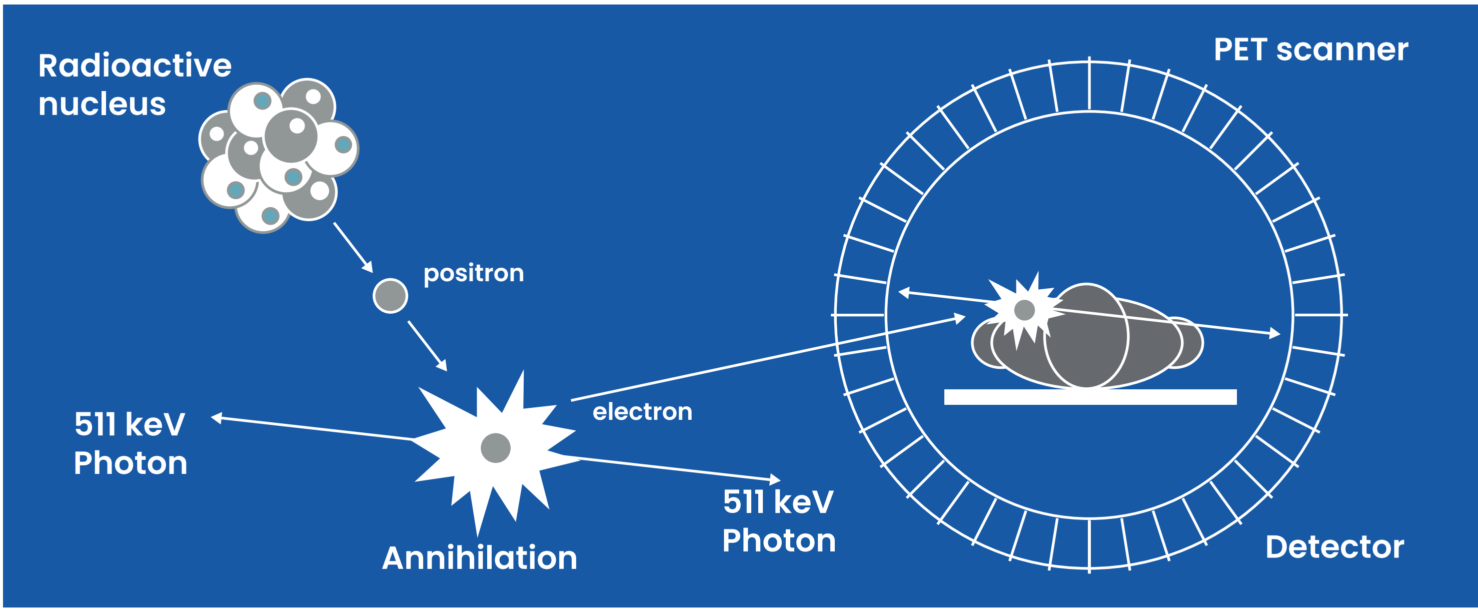
Interdisciplinary projects for healthcare instrumentation

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 into 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 several years. A high-resolution, small animal RPC-PET scanner developed at LIP has been 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 next step will be to test the RPC-BrainPET scanner 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, 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. This facility has been somewhat undefined in recent years, but the recent decision to build the first facility in Portugal will undoubtedly bring new opportunities.

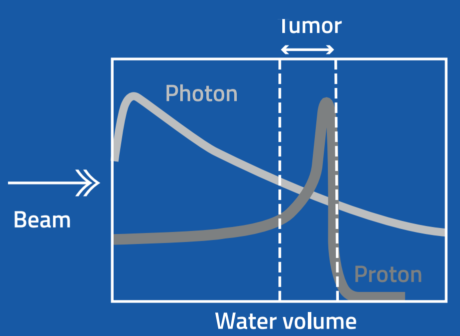
LIP is thus redefining its strategy in a two-fold way:

- 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 radiation 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, namely 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 of the energy deposition as a function of depth for a photon or a proton beam.

(J. Seco , 2019)

In 2024

PhD student Duarte Gurreiro submitted to University of Lisbon his Doctoral thesis on Scintillating Array for Real-Time High-Resolution Dosimetry. The thesis details the conception, simulation and construction of the device, and its test with the clinical proton beam at HollandTPC.

PhD Student Cristiana Rodrigues was in an Internship shared between DKFZ and PSI for 3 months learning methodologies and good practices in dosimetry using passive dosimeters.

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. In 2024, analysis of data acquired at HollandTPC resulted in first time measurement of the microbunched structure of the proton beam (2 ns in a 13 ns repetition RF cycle) and of the longitudinal profile of the Bragg peak, using LIP's device to detect prompt--gammas from the proton beam interactions.

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.

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 lot of 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 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;
- New detectors and materials for high-resolution dosimetry, i.e., capable of measuring energy depositions at micro and nanometer scales. A project to develop new sapphire based passive detectors was funded in 2024.

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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. 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 and joined diverse science working teams both for the BepiColombo and the JUICE missions.

The monitors provide unique data sets and are windows to the Heliosphere, for multi- observation of Solar Particle Events and for energetic particle propagation studies. The group issues monthly RADEM activity reports to ESA and is responsible for ongoing data archiving in collaboration with ESA's Science Operations Centre (SOC), ensuring public release of the detector's data.

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. The group developed also PlanetRAD, for simulating the Martian, Lunar, and Earth atmospheres, further refined in 2024.

In 2024, a team of researchers from the former FCUL-SIM/CENTRA joined the LIP SpaceRad group. Their projects include instrument development for astrophysics space missions and ESO, and image reconstruction for the ESA Gaia mission, aiming at a 3D dynamic reconstruction of the Milky Way using measurements of nearly two billion stars.

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 contributes with simulation of polarimetry for two consortia proposing Gamma-ray Universe Observatories. The EU-funded AHEAD, "Activities in the High Energy Astrophysics Domain", proposes a cubesat constellation; the NASA's AMEGO, "All-sky Medium Energy Gamma-ray Observatory", a probe-class satellite. The group is also 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).

The GLOSS project 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, tests were conducted at ICNAS (Coimbra) proton beam. to assess the degradation of Ge and Si crystals detection parameters with exposure to radiation. At the end of 2024 the samples were successfully launched and installed at the ISS, in the Bartolomeo platform outside ESA Columbus module. They will be there for one year, exposed to radiation and thermal stress during the sun/shadow exposure cycles of the ISS.

The THOR-SR mission is a high-energy astrophysics pathfinder mission to explore a range of phenomena that includes gamma-ray astrophysics' emissions, space weather and terrestrial gamma-ray flashes, addressing a major aviation safety concern. 2024 activities included simulation work, payload instrument design and experimental testing. AI particle identification algorithms were developed and trained with data from the ICNAS proton beam and alpha particles. The Space Rider launch was postponed to 2027, but first tests of the Onboard Computer subsystems were conducted in low vacuum and temperature-controlled chamber and in a 3-hour flight of a Meteorological balloon at an altitude of 22 km.

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Computing

• Scientific computing

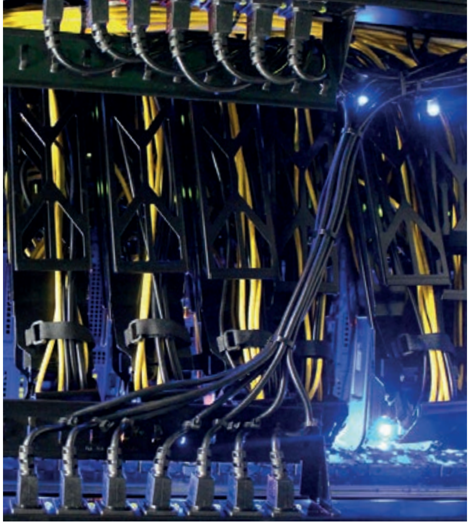
Scientific research requires increasingly higher data storage and processing capacities that stress the limits of information systems and related technologies. The LIP computing groups have extensive knowledge and experience in scientific computing, excellent international relations, and integration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

LIP participates in major European R&D projects in this field and operates a large scientific computing facility. This 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 established the National Distributed Computing Infrastructure (INCD), which has been recently renamed and promoted to National Advanced Computing Centre (CNCA). In this framework, LIP has leading coordination and technical roles in the management, development, support and operation of this national infrastructure.

CNCA is currently being enlarged in terms of scope, membership and resources. CNCA is part of the National Advanced Computing Network (RNCA) and continues the participation in the Portuguese Science Foundation roadmap of research Infrastructures of strategic interest. 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 opportunities for knowledge transfer and for addressing societal changes. The SPAC group has very much strengthened this domain bridging with computing and social physics and opened new research lines in disease forecasting, human behavior 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 CNCA previously known as 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 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 long-standing 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 2024, this infrastructure executed 579,797 jobs and delivered over 169 million HEPscore23 normalized processing hours, a 4% increase compared to 2023. The Tier-2 was upgraded with new token-based authentication, extended IPv6 connectivity, and deployed a new dedicated 100Gbps link connected to the LHC Open Network Environment (LHCONE).

The group activities bridge at international level with major science-related e-infrastructures and initiatives such as the European Grid Infrastructure (EGI), the Iberian Grid Infrastructure (IBERGRID), the European Open Science Cloud (EOSC), and EuroHPC. In this context, the group collaborates with several research communities beyond high-energy physics, including life sciences, environmental sciences, health and engineering. In the framework of both 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 hosted the 13th IBERGRID conference in Porto, gathering developers, infrastructure managers and researchers from Portugal and Spain. During the event, a survey was conducted, allowing attendees to evaluate their experience. IBERGRID received a rating of 4.76 out of 5 stars, confirming the success of the conference and the relevance of the discussions held.

The development of the group's competences is sustained through participation in R&D&I projects on the development and exploitation of digital technologies applied to both computing 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).

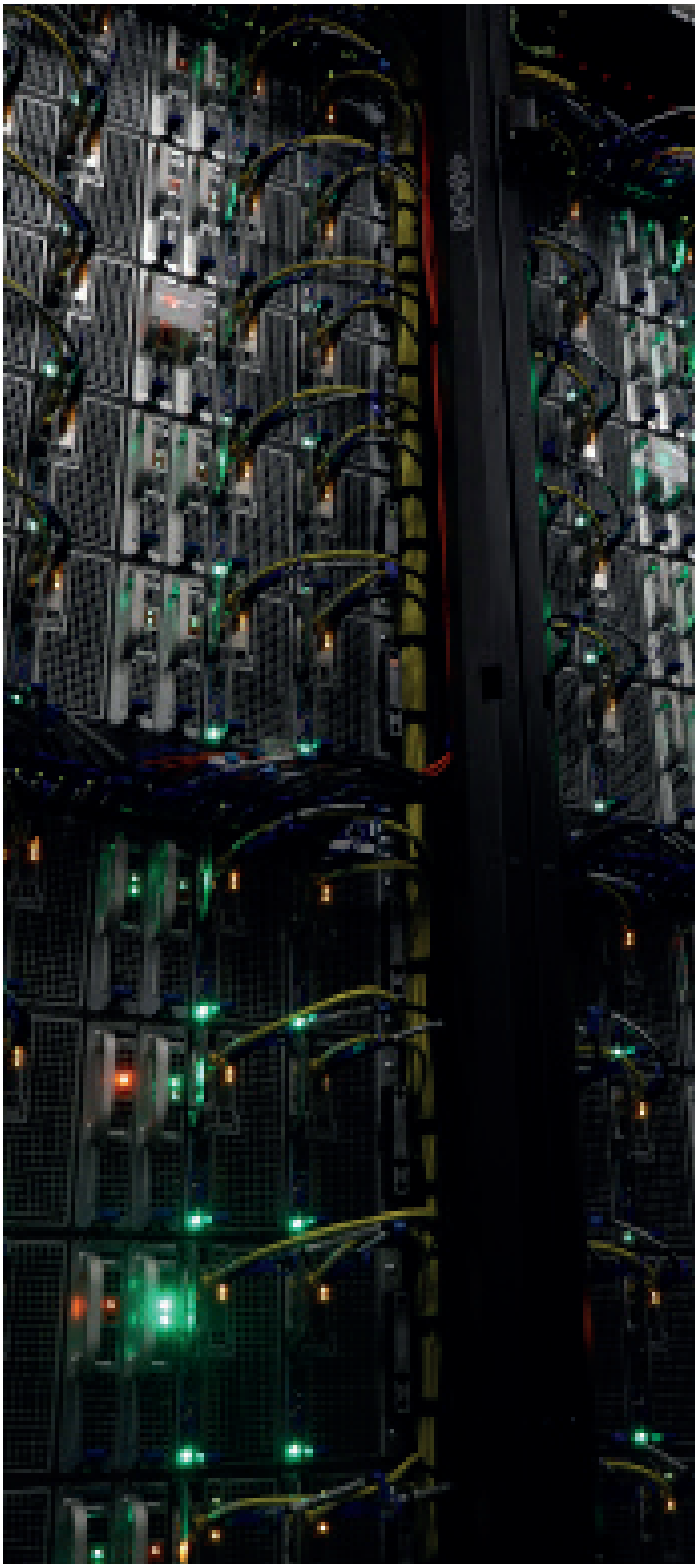
During 2024, the group concluded the EOSC-Future project and contributed to several ongoing European projects, namely: DT-GEO, providing solutions for containerization, integration and software quality in digital twins of geophysical extremes (earthquakes, volcanoes and tsunamis); interTwin, delivering 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 EuroCC-2, promoting knowledge and opportunities in the domain of HPC in Europe. Furthermore, two new projects, EOSC-Beyond and ENVRI-Hub-Next, were launched with LIP leading the software management and quality assurance areas.

The group also played a key role in the evolution of the Portuguese National Distributed Computing Infrastructure (INCD) into the National Advanced Computing Centre (CNCA). LIP led CNCA's technical operations and supported its expanded mission in advanced computing and research data. In 2024, this infrastructure delivered over 40 million CPU hours through the FCT Calls for Advanced Computing Projects (CPCA). New services were deployed across its sites: a second OpenStack cloud, Ceph and MinIO storage, tape archival systems, and Kubernetes orchestration.

LIP coordinated CNCA's contributions to several strategic initiatives, including the implementation of a national research data repository in collaboration with FCT, the hosting of thematic cloud services for EOSC and EGI, and the deployment of deep learning infrastructure for iMagine. Work also continued a data lake pilot for the EU Partnership "Agriculture of Data" and the processing of Earth observation data in cooperation with public sector institutions.

At the national level, LIP remained active in the RNCA network, holding coordination and access roles. The group supported user onboarding for the 4th CPCA call and participated in the preparation of the 5th call, to be allocated in 2025.

Institutionally, the group maintained and improved LIP's core IT services. In Lisbon, computing and storage hardware was renewed. In Coimbra, the planning of infrastructure upgrades began. Additionally, the development of a new internal platform for administrative services was initiated.
Overall, in 2024, the group continued to reinforce its strategic role in enabling science through advanced computing, leading national infrastructures and contributing to international initiatives that shape Europe's digital research landscape.



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Social Physics and Complexity (SPAC)

Understanding complexity has always been a hallmark of physics research and, today, the Digital Revolution is offering radically new ways to study complex human behaviours. There is a growing perception that physics will be fundamental to the study of sociology and even psychology. Leading scientists are calling this emerging field “Social Physics” and argue that, in many ways, complexity science is becoming the physics of human interactions.

SPAC uses large-scale computational tools to address societal challenges, particularly in disease forecasting, human behaviour, and public policy, through a complex systems approach. It is a strongly multidisciplinary team, with members from diverse backgrounds including Physics, Mathematics, Computer Science, Biology, Neurosciences, Psychology, and Law. The group takes advantage of the “Big-Data Revolution” to better understand how individual behaviours shape society. SPAC also focuses on the ethical dimensions of data science and artificial intelligence, including privacy, transparency, and algorithmic bias.

SPAC’s work is primarily funded by two European Research Council (ERC) grants awarded to the group’s PI: a Starting Grant supporting the project “Fake News and Real People – Using Big Data to Understand Human Behaviour (FARE)”, and a Proof-of-Concept Grant (FARE_Audit), which concluded in 2024 and focused on developing tools to audit search engines and websites. The group advanced its work on misinformation and algorithmic bias, piloting large-scale behavioural surveys, refining its datasets on Twitter and fake news, and building an auditing pipeline now applied to several real-world cases, including recent electoral processes and international conflicts. Two peer-reviewed papers were accepted for publication in 2024, and a white paper on ethical practices in computational social science is underway, following a workshop co-organized with the Complexity Science Hub in Vienna, where the group’s PI spent a research sabbatical.

In parallel, SPAC continued its contributions to health research and public policy, including a collaboration with the Portuguese National Health Service beginning in 2024. The group published work on the post-pandemic impact on respiratory research, with additional manuscripts nearing submission. Group member Lília Perfeito was awarded an FCT-funded project (HealthDisrupt) to further develop this research line.

SPAC remained deeply involved in science communication and outreach. Highlights include a chapter on science and science policy in the book Portugal in the 21st Century, participation in EU-level working groups supporting the Digital Services Act, and visibility in national and international media. SPAC members contributed to public debates through television, print and radio, and ran interactive outreach activities at LIP and during the European Researchers’ Night.

SPAC continues to establish itself as a leading research group in the international computational social science community. Its team of 11–14 members work collaboratively across three focus areas: health and disease modelling, misinformation and algorithmic bias, and data ethics. The group is planning to support new PhD and MSc candidates in 2025, while maintaining a strong presence in national and international research discussions. With new funding secured, publications submitted and accepted, and increasing international partnerships, SPAC is well-positioned to further its mission in the years ahead.

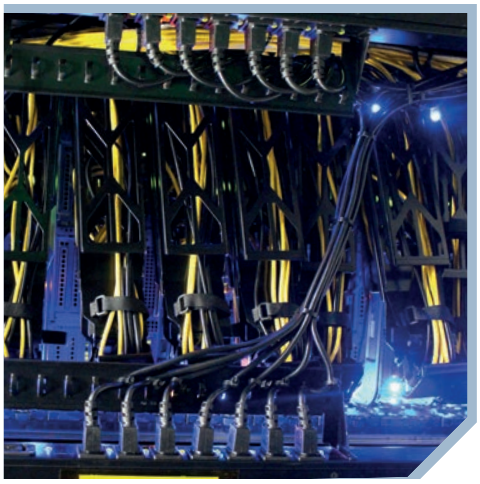
Research Infrastructures & Competence Centres

Reasearch Infrastructures • Computing • Mechanical workshop • Detectors laboratory • E-Lab • LOMaC

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. In 1986 also an instrumentation lab was created for the development of front-end electronics and data acquisition systems for the CERN experiments, and later evolved to two more specific electronics labs TagusLIP and e-CRLab, respectively linked to medical physics and cosmic ray experiment instrumentation. The first gave rise to the PetSys Electronics a spin-off that is now an independent company, with which LIP maintains close collaboration. The second diversified its activities and in 2024 was renamed to E-Lab. The LOMaC (optics and scintillating materials lab) was created in 1992 in the context of R&D for the ATLAS TileCal calorimeter, it maintains a strong link to the TileCal, but as also diversify into more general R&D in scintillating materials and calorimetry.

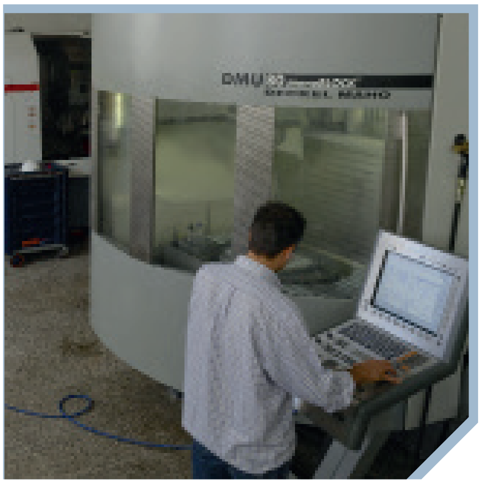
Competence Centres at LIP are designed to be light and flexible horizontal structures joining LIP members that share the same tools and technologies. Competence Centres have a positive impact both internally, increasing the synergies between groups, and externally, promoting advanced training and boosting LIP's collaboration with other research centres and with industry. In addition to the existing Competence Centers on Monitoring and Control and on Simulation and Big data, a new RAD LIP Competence Centre in Radiation Engineering is being established.



REASEARCH INFRASTRUCTURES

Computing

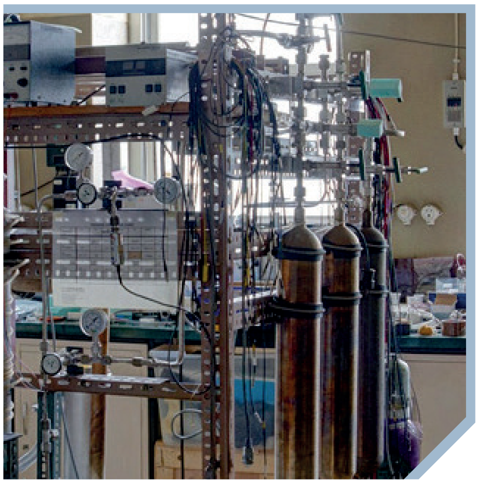
The LIP Computing Infrastructures provide scientific computing services to LIP and to the wider Portuguese scientific and academic communities in the context of the National Advanced Computing Centre (CNCA). The national activities include both distributed computing, formerly in INCD and high performance computing. LIP operates the Portuguese Tier-2 facility integrated in the CERN Worldwide LHC Computing Grid (WLCG), and bridges at international level with science related e-infrastructures and initiatives such as the Iberian Grid Infrastructure (IBERGRID), European Grid Infrastructure (EGI), European Open Science Cloud (EOSC) and EuroHPC. More details are given in the Computing Section.



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.

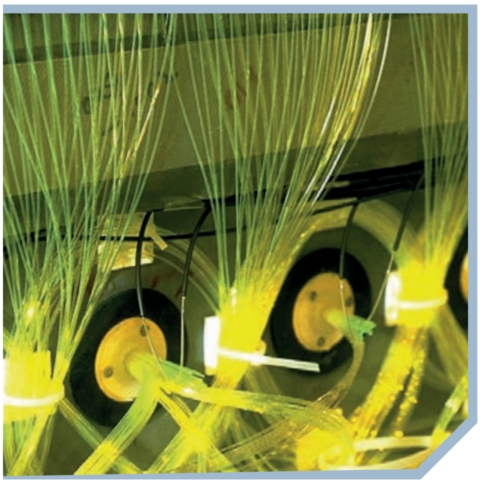


REASEARCH INFRASTRUCTURES

Detectors laboratory (DL)

The Detectors Laboratory was created to support the experimental activities developed by the LIP's research groups. Along the years the DL has been continuously updated considering both general and more specific needs. Today, the 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.

Main activities of MW & DL in 2024 were the construction and testing of RPC muon telescopes, including the first one with sealed RPC technology; of Cloud and Spark Chambers for outreach; and the construction of parts for DUNE and the Gas and Liquid DRD groups. Support was also given to the maintenance of an RPC installed in HADES at GSI. The two infrastructures 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.

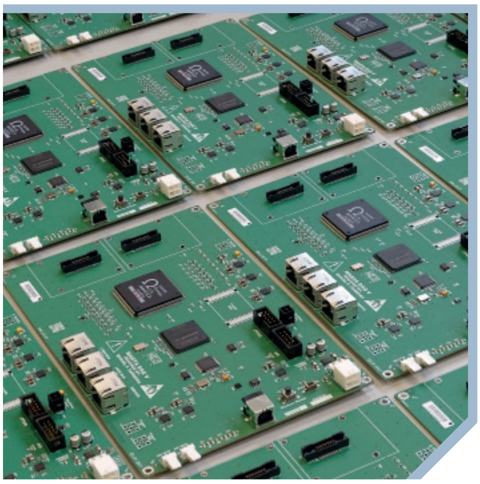


REASEARCH INFRASTRUCTURES

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 DRD6 Collaboration on Calorimetry); preparation of sets of aluminized fibres for the NEXT experiment; and applications to microdosimetry.

The new TileCal HV distribution system is being developed at LOMaC, and tests continued in 2024. Ageing studies of TileCal, focusing on scintillator and fibres were also continued, and a paper with results of the study in Run 2 was submitted for publication. A TileCal-like detector is being proposed for FCC-ee, and is being simulated in the framework of DRD6. The exploratory project on R&D of new scintillators concluded, and a follow-up project is expected. The work on development of a micro-dosimeter with the RADART group is also leading to scientific papers, and new projects are agreed to start in 2025.



REASEARCH INFRASTRUCTURES

Electronics laboratory (E-Lab)

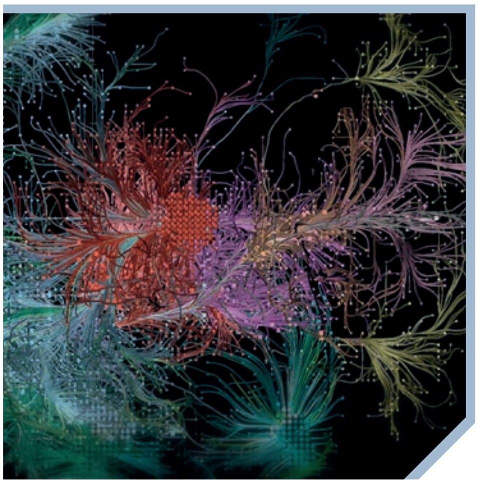
The E-Lab started as a facility dedicated to the development of electronics for cosmic rays, but has expanded its scope to general particle and astroparticle physics experiments, as well as applications. The focus is put on fast digital electronics implemented in FPGAs (field-programmable gate array 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.

Activities in 2024 were concentrated on the operation of the MARTA setup at the Pierre Auger Observatory, for which stable versions of the slow control and acquisition systems were developed and on support to the development of the High Granularity Timing Detector (HGTD) detector for the ATLAS. Furthermore, the laboratory contributes to developments in space and medical technologies, through experimental setups and electronics development. These were primarily centered on the instrumentation of photodetectors and the exploration of novel silicon devices for particle identification in medical beams.

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 2024, the available resources of the CCMC were fully committed to a project to develop a digital nuclear Multi-Channel Analyzer (MCA) suitable for High Purity Germanium (HPGe) gamma spectroscopy, contracted by an external company. In addition, the CCMC supported master's student projects connected to this initiative and collaborated with another external company on the development of artificial intelligence solutions for steering control and an industrial drying system.



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. Master projects in different groups have been concluded with this support .

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Knowledge transfer and **societal impact**

Radiation, health and **environment**

Muon tomography

Advanced training

Education, communication and **outreach**

LIP science & 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.

BoneOscopy: Real-time Monitoring for Cancer Radiotherapy

LIP coordinates the Boneoscopy project, developing a novel scintillating timing tracker to monitor radiotherapy in bone cancer in real-time. Funded by PT2020, this medical physics innovation brings together LIP, IPO-Porto, and the Centre for Minimally Invasive Surgery in Cáceres. It applies high-energy physics technology to enhance precision and safety in clinical treatment — a breakthrough example of particle physics know-how entering the healthcare arena.

Gallaecia-PET: Cross-border Innovation in Medical Imaging

LIP is part of the Gallaecia-PET network, a public-private initiative from Portugal and Galicia to boost innovation in Positron Emission Tomography. The goal is to advance non-invasive, high-resolution imaging for earlier and more precise diagnosis of diseases like cancer and neurodegenerative conditions. The network fosters collaboration between scientists, health professionals, and industry, accelerating the development of next-generation imaging systems and radiopharmaceuticals.

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. The region around UBI has significant geological diversity, with variable concentrations of uranium and thorium. During 2024 the group has conducted a survey to map their distribution, dispersed by mining activities and natural erosion. It is studying also the effect of radon-containing aerosols in plants.

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/U.Évora with the support from Ciência Viva science centre at Lousal. The detector is a muon telescope with four (1 m^2) 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, allowing to obtain 3D density maps. These measurements inspired a new seismic tomography setup, with which muography can be more directly compared. The developed tools can now be used to predict and optimize muography surveys in other setups. In 2024, the group studied the feasibility of getting a first image of a city seen from below, by deploying muography in the full 5 km drainage tunnel being built in Lisbon. The survey is on-hold awaiting the end of the main construction works.

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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, MSc and bachelor students, actively working within its research groups. In 2024, LIP hosted a record of 150 graduate students. During 2024, a total of 38 MSc thesis were defended, and 19 students started their PhD work.

PhD students are integrated in more general networks, founded by LIP to bridge to close-by areas, namely the International Doctoral Network on Particle Physics, Astrophysics and Cosmology (IDPASC) and the national Association for the Proton Therapy and Advanced Technologies for the Prevention and Treatment of Cancer (ProtoTera). These networks are meant to facilitate and promote the exchange of ideas and direct contacts between the future specialists in related areas. In October 2024, most of the PhD students at LIP participated in either the ProtoTera or LIP/IDPASC PhD Student workshops, or both.

8th student workshop, UMinho

Undergraduate students

LIP regularly organizes and participates in events and workshops aimed at undergraduate students, introducing them to the research carried out at LIP and its applications in particle and astroparticle physics. These activities include lectures, hands-on tutorials, and outreach initiatives, often in collaboration with student associations and university departments. In 2024, LIP participated in the National Meeting of Physics Students (ENEF), organized a Mini-School in Particle and Astroparticle Physics in partnership with CFTP, and co-organized visits to LIP's infrastructures such as the LNEC computing centre.

LIP Internship Program

The Lab's flagship Internship Program remains one of its most visible training initiatives. In 2024, over 60 students participated in the program, which brings together students and LIP researchers from all three nodes. The format included a one-week introductory school in July—featuring lectures and tutorials—and a final workshop in September, where students presented the results of their summer projects. In between, students were integrated into LIP research groups and carried out hands-on work under supervision.

The Internship Program continues to draw participants from across Portugal and abroad, including France, Spain and the UK, reinforcing LIP's role as a welcoming and dynamic environment for training the scientists of tomorrow.

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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.

2024 communication highlights

LIP into the Future

On May 9, to mark LIP's 38th anniversary, the ECO group organized a special event under the theme "LIP into the Future". The program included presentations by PhD students, a session on science and technology challenges, and a gathering of partners to reflect on long-term strategic goals. This celebration was also the occasion to introduce LIP's first line of branded merchandise.

CERN at 70

In June, LIP hosted the spring meeting of the European Particle Physics Communication Network (EPPCN), coinciding with CERN's 70th anniversary. Members from across Europe visited LIP and explored opportunities for improved communication across CERN's member states.

LIP Open Day

The second edition of LIP's Open Day took place during the National Science & Technology Week, offering the public a chance to visit LIP's facilities in Lisbon and engage directly with researchers. Interactive activities, lab visits and a guided game introduced topics from CERN experiments to medical applications of particle physics.

Online and Social Media

Despite limited staffing in 2024, LIP's communication presence grew stronger. With 97 news articles published and a growing community on social media (reaching 9,300 followers), LIP expanded its visibility through new Instagram series and visual materials tailored for specific audiences.

For 2025

We are preparing to celebrate the membership of CERN, 40 years after the negotiations that led to Portugal becoming a member. LIP was created just after, in May 9th 1986.

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.

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.

In 2024, LIP organized, in coordination with local Universities, sessions in 13 locations in Portugal and 4 in other portuguese speaking countries, mostly on ATLAS and Auger data. The Auger Masterclasses, created and maintained by LIP, spread over four continents, reaching a total of 550 students.

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. The 16th edition of the programme hosted 47 participants from Portugal, Brazil, and several African and Asian Portuguese-speaking countries. Teachers visited LIP in Lisbon before heading to CERN. Many also attended the 5th Conference of Physics for Portuguese-Speaking Countries in Coimbra.

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 highschool students and teacher forum. In 2024, these partnerships remained key to the success of ECO's mission.

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Glossary

AMS - Alpha Magnetic Spectrometer (particle physics experiment in the ISS)
AHEAD - Integrated Activities for the High Energy Astrophysics Domain (H2020)
AI - Artificial intelligence
AMBER - Apparatus for Meson and Baryon Experimental (CERN)
AMEGO - All-sky Medium Energy Gamma-ray Observatory (NASA)
ANI – Agência Nacional de Inovação
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)
CERN - European Laboratory for Particle Physics
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)

DRD – Detector R&D Collaborations (CERN)
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
E-Lab – Electronics Laboratory (LIP)
EPPCN – European Particle Physics Communication Network
EOSC - European Open Science Cloud
ERC - European Research Council
ESA - European Space Agency
ESO – European Southern Observatory
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)
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)
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
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

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
SNO+ - Sudbury Neutrino Observatory, at SNOLAB. SNO+ is the successor of SNO
SNOLAB - Underground science laboratory, 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
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
ZEPLIN - Zoned Proportional scintillation in Liquid Noble gases, series of dark matter experiments (UK)


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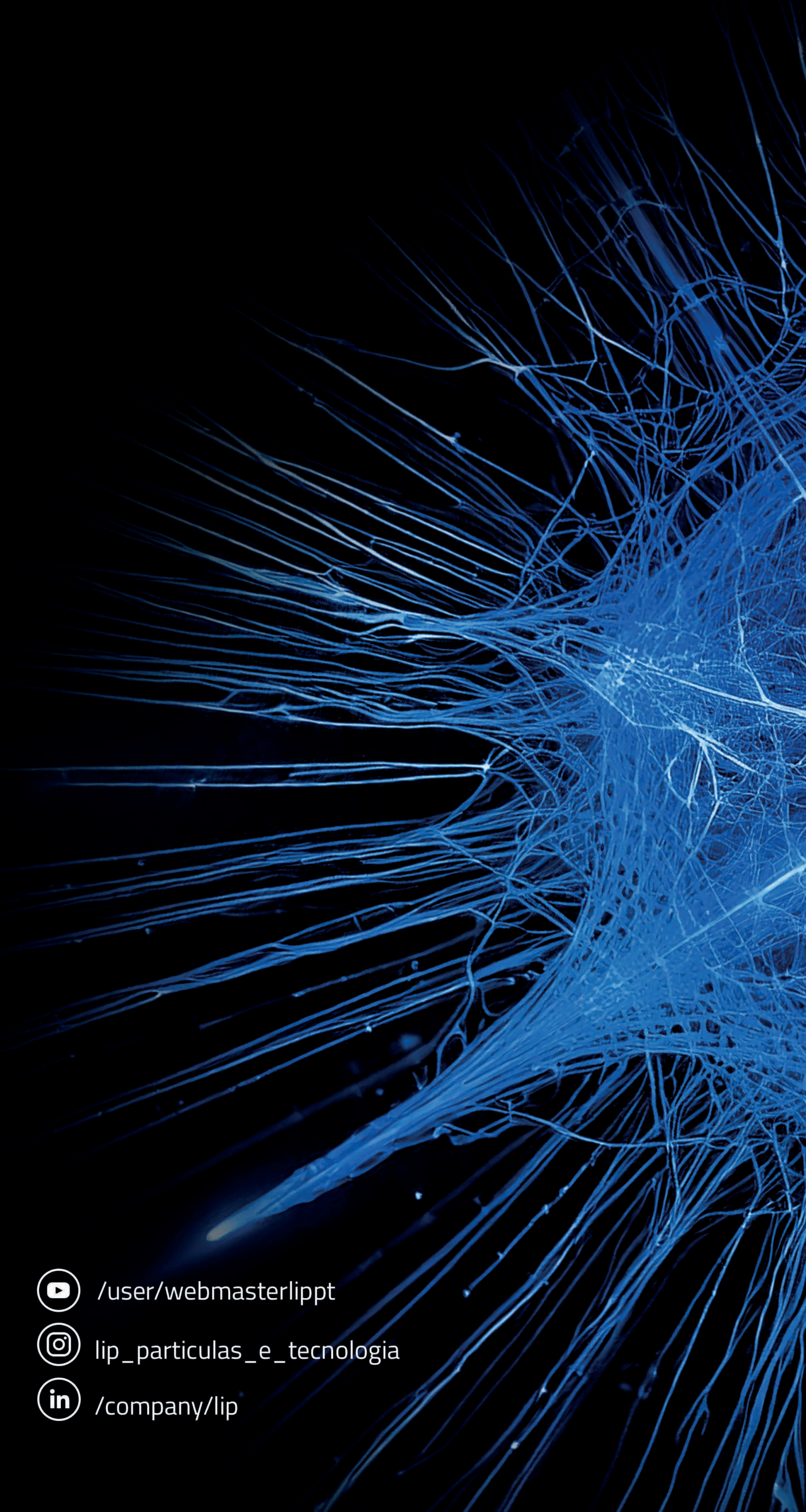

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