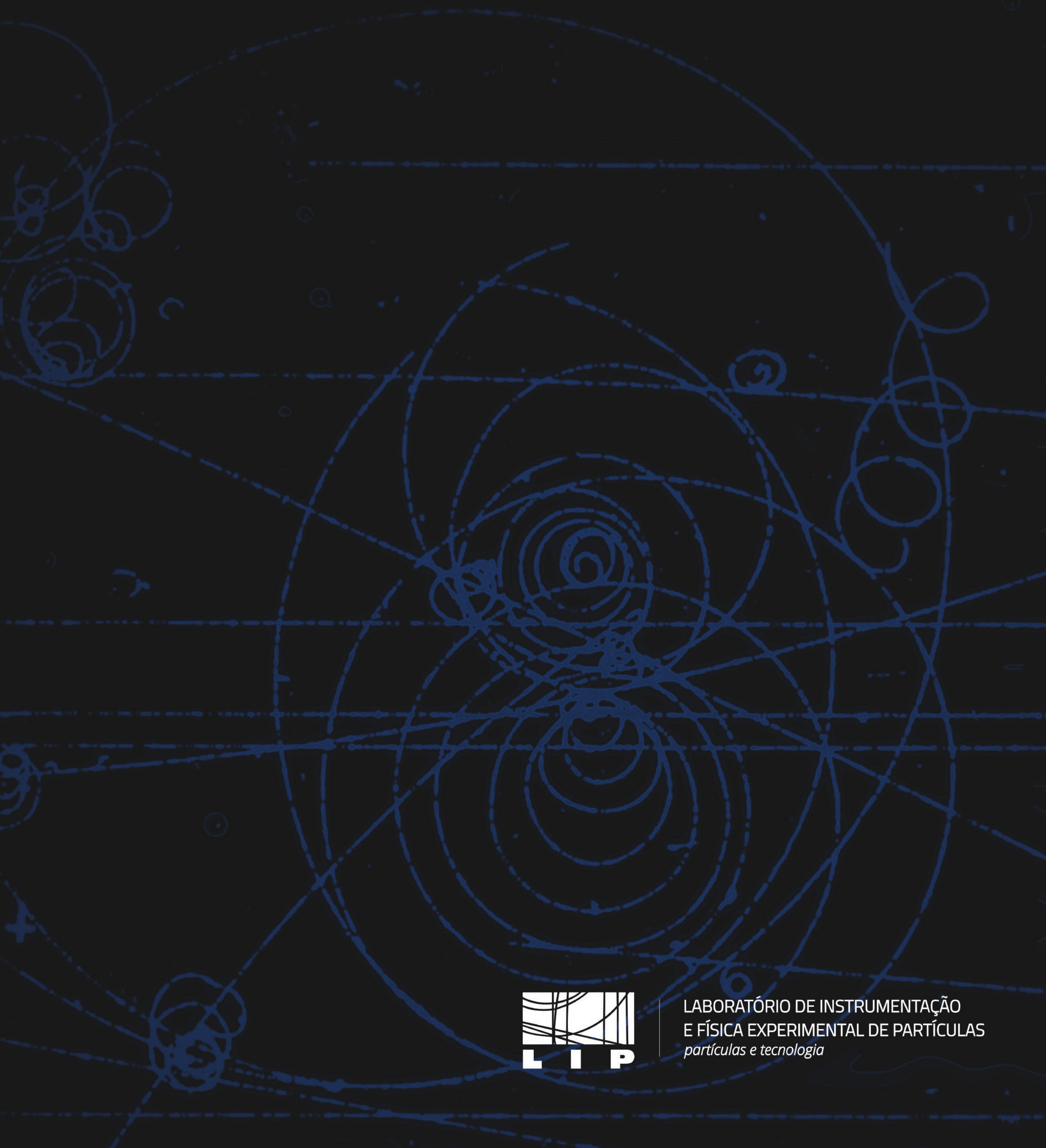
annual report

2021/2022



LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Editors
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LIP is about Particles, Technology and People

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

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

LIP

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about

LIP

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

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

The three pillars of LIP's mission are:

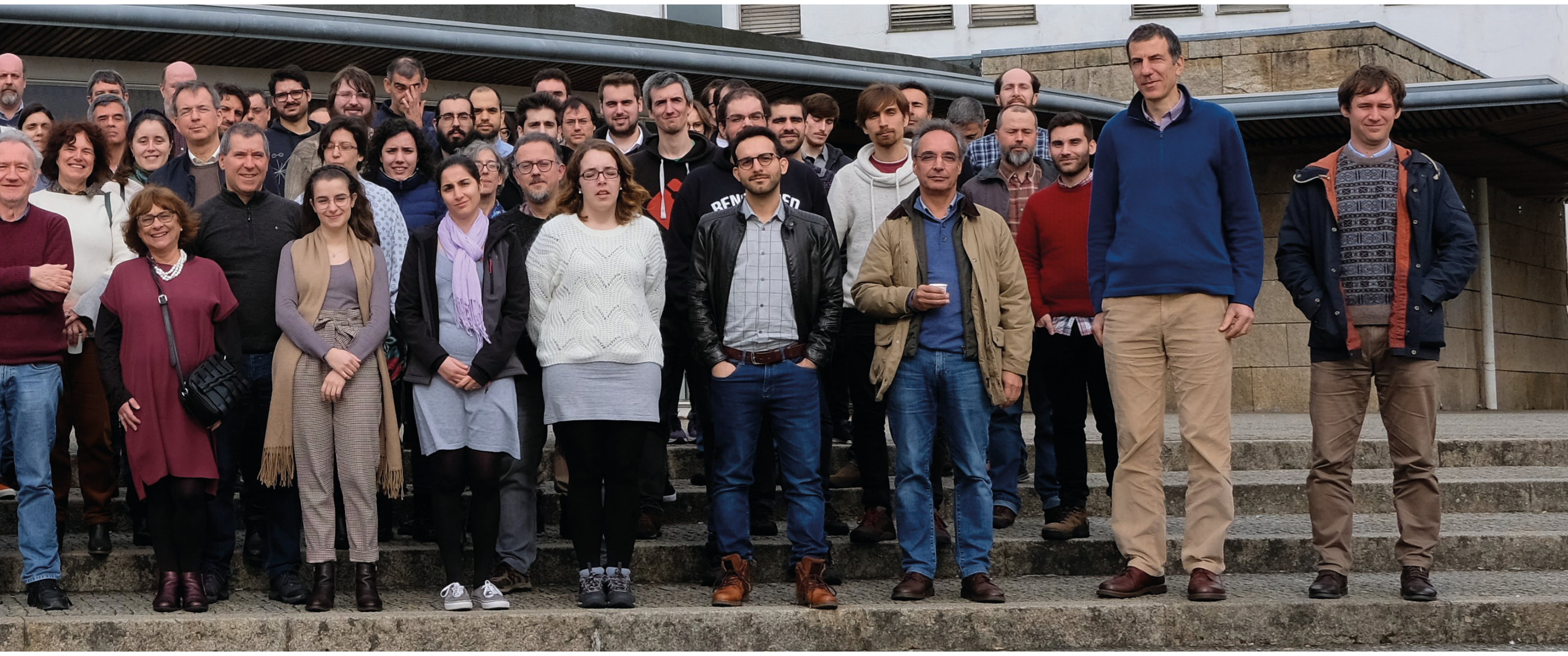
- Discovery through science: LIP's program in particle and astroparticle physics is international, has world-class quality and addresses some of the most topical questions of our time
- Innovation through technology: basic science drives innovation in the long term. LIP is a key player in the application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

Under the supervision of FCT, LIP defines the national policy for the participation at CERN, leading particle-physics related science and innovation, ensuring the involvement of the national academic and business communities, promoting advanced training, and sharing knowledge with society. LIP is also a partner of ESA, the GSI research centre in Germany, SNOLAB in Canada, the Pierre Auger Observatory in Argentina, Fermilab and the Sanford Underground Research Facility (SURF) in the USA and represents Portugal in European digital infrastructures and in science and society international forums. The associates of LIP are FCT, the Universities of Lisbon, Coimbra, and Minho, Instituto Superior Técnico (IST), the Faculty of Sciences of the University of Lisbon (FCUL) and the Electrical and Electronics Business Association (ANIMEE).

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

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

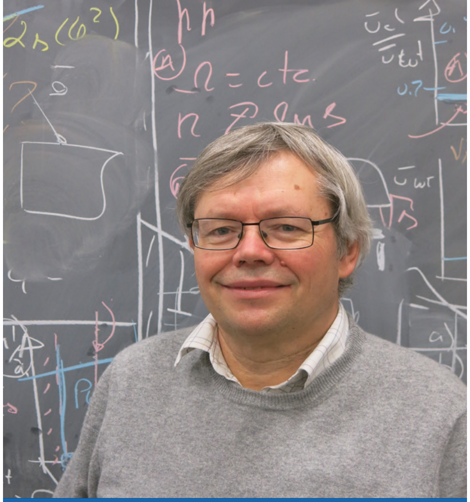
LIP is engaged in CERN's Large Hadron Collider (LHC), contributing from the very beginning to the two largest LHC experiments, ATLAS and CMS. LIP is also involved in the fixed target programs at CERN and GSI, probing the strong nuclear force and dense nuclear matter. The quest for dark matter, a deeper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



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

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

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



prof.
Mário Pimenta
President

Foreword

Sailing through troubled **waters**

We are navigating, since many years, through troubled waters. Storm after storm has surged: after the financial and the economic crisis, the COVID-19 crisis and now the war in Europe.

Also during these years we lost several LIP founders, José Mariano Gago already in 2015, Gaspar Barreira in 2019, and Armando Policarpo in April 2021. Armando Policarpo was decisive in the creation, consolidation and development of LIP by bringing in, at the very beginning, his high scientific and academic credibility, and throughout the years his clairvoyance and wisdom.

In 2010, the financial/economic crisis hit the Portuguese scientific system in a moment of growth, with many young scientists eager to engage in competitive but sound scientific and academic careers. LIP was not an exception but, for better or worse, we succeeded to keep on track many of our young scientists, although being forced to use in excess the precarious resource of project-funded post-doc positions, as many other institutions had to do.

In 2016/2019, the role of Science, including Fundamental Science, as key factor for Portuguese societal and economic development was again recognized. However, strong financial constrains were still present and, on the other hand, a mid- and long-term agreement between the universities, the scientific institutions, and the government, was not reached. In fact, even among the main scientific institutions, the Associate Laboratories, there wasn't, and there is still not a common vision on how the system should be organized, or on what should be the responsibilities of each peer. The only basic agreement is on the need for increasing the public funding for science, which is clear but not at all enough. Nevertheless, the replacement of the vast majority of the post-doc grants by 5/6-years contracts was a clear improvement. At LIP we have fully used all the possible opportunities to secure scientific employment, and several critical situations were mitigated.

Anyhow, by the end of 2019, some encouraging perspectives were on the horizon, namely:

- The LIP classification as "Excellent" in the evaluation of the Portuguese Research Units.
- The announcement of the opening of the new call for the attribution (renewal) of the status of Associate Laboratory.
- The steady growth of LIP in previous years, by the inclusion of new groups on phenomenology, nuclear physics, social physics and complexity, enlarging and enriching the LIP scientific scope and increasing the potential of collaboration with other Portuguese institutions.
- The positive signs of a consistent economic growth in Portugal.

But then, suddenly, COVID-19 emerged, imposing enormous challenges on the sanitary safety of the population in general and, in particular, forcing the work paradigm to change to remote interchanges whenever possible, since access to the experimental sites became severely constrained. Nevertheless, LIP was able to adapt and re-invent its procedures, trying to help society and being able to keep our scientific production standards, as detailed in the previous and present reports. There was even an increase on the number of MSc and PhD students and on the offer of academic training opportunities,

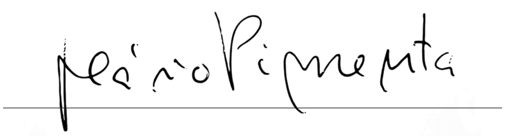
such as the LIP Summer Internship Program, where a record of almost one hundred first-cycle university students were engaged last summer.
Simultaneously, in dialog with the relevant LIP internal bodies, namely the Scientific Council Board and, after its creation, the workers council, new organizational steps have been pursued:

- The first internal evaluation of all members of the Scientific Council thare are LIP integrated researchers, and of all LIP staff was done, leading to a well-deserved salary progression of the majority of the LIP administrative and technical employees and a better articulation of some of the technical and administrative LIP services.
- A Grants Office was created to support applications to European projects.
- A new Scientific-Technical Career was created aiming to better frame the work of the physicists and top technical staff engaged in central scientific and service tasks.
- The plans and procedures for the opening of new permanent research positions and for the career evolution of the present permanent researchers were proposed.
- New regulations on the composition of the jury of mid-term research positions were approved.
- New regulations on the organization of the staff training programs were proposed.
- A Code of Conduct to be observed at LIP was proposed.
- An Ethics Committee was created to monitor scientific projects and proposals, whenever needed, and to respond to questions raised in the course of research activities.

These steps aim to better prepare LIP for the challenges of its growth in terms of the number of groups and members, projects and activities, and to potentiate the necessary growth in funding, namely from European sources.
A piece of recent and very good news was the approval of four new European projects submitted by the LIP Distributed Computing and Digital Infrastructures Group.

And now, when COVID-19 started to be hopefully under control, and signs of economic growth were back, the unthinkable war in Europe broke out. Our first word is of a clear and strong condemnation of the Ukraine's brutal invasion by Russia, and of solidarity with the suffering Ukrainian people. LIP will use all possible Portuguese and/or European funding programs to support the temporary integration at LIP of Ukrainian scientists, that were forced to abandon their country. But also of Russian scientists who, not agreeing with the Russian invasion, have to face exile. War is back, and, once again, the future became more uncertain and every scientific institution, including CERN, will have to adapt to the new reality.

On a small note of optimism, let´s really hope that finally we will be able to meet in July in Coimbra, for the 2022 Jornadas do LIP.



(Mário Pimenta)
Lisbon, March 2022

REPORT FROM THE

International Advisory Committee

Sergio Bertolucci (former Director of Research and Scientific Computing at CERN), Eamonn Daly (former Head of Space Environment and Effects Section of ESA), Katia Parodi (Medical Physics Chair at LMU, Munich), Pier Giorgio Innocenti (former CERN Electronics and Computing for Physics Division Leader), Christian W. Fabjan (Austrian Academy of Sciences), Luigi Rolandi (Scuola Normale Superiore - Pisa), Masahiro Teshima (Director of the Max Planck Institute of Physics)

The LIP International Advisory Committee and representatives of LIP held their annual meeting on 20th and 21st April 2022 in Lisbon; some participants joined the meeting by videoconferencing. Prior to the meeting, the Committee had received extensive and well-prepared documentation about the LIP activities. Oral presentations and discussions during the meeting provided further clarifying information.

LIP's primary mission is the study of the fundamental laws of particle physics. Presently, this research is carried out with accelerators at CERN, where LIP has an important role in the two large experiments, ATLAS and CMS at the LHC and in COMPASS at the SPS. Neutrinos are investigated with SNO+ in Canada. Research on cosmic rays and their astrophysics implications is carried out with the world's largest array of earth-based detectors (Auger in Argentina) and on the International Space Station (AMS). Search for Dark Matter in our Universe is pursued with the LUX-ZEPLIN (LZ) experiment in the US. LIP contributes to these research programmes as a partner in large international scientific collaborations, with many leading positions, major responsibilities and new initiatives. LIP's scientific achievements within the collaborations are outstanding. The LIP theory groups are remarkably productive and complement with the interpretation of the results the research of the experimental groups.

LIP is strongly engaged in preparing future experiments at the frontier of particle and astro-physics. LIP teams have made a significant contribution with equipment for the High-Luminosity LHC upgrade of ATLAS and CMS detectors and are now finishing the installation of the upgrades planned for Run 3. LIP participates to the studies for the Future Circular Collider FCC. R&D, design, prototyping and testing are pursued for the DUNE neutrino experiment planned in the US and for its preparatory phase, proto-DUNE at CERN. LIP is a leading partner in AMBER, a fixed target experiment at the CERN SPS. LIP is among the proponents of the new SHiP facility at CERN and is prototyping some components of the proposed detector. It also participates in the SHiP-inspired neutrino experiment SND at the LHC, which is being installed and commissioned, aiming at taking first data already in 2022. LIP is a key promoter of SWGO, a ground-based array for high-energy gamma ray astronomy in the Southern hemisphere, which is now evaluating possible designs and sites. The LIP LZ team is among the promoters of the next generation dark matter experiment G3.

LIP pursues an impressive number of “smaller” research efforts: Nuclear Physics, Space and Astrophysics, Simulation activities and various detector R&D programmes. The Committee noted with satisfaction the focus and determination of the groups in making valuable contributions and achieving outstanding results.

LIP’s development of novel medical imaging and high-resolution dosimetry instrumentation for applications in diagnostics, image-guided radiation therapy and radiobiology is expanding and is increasingly successful. The Committee is however quite concerned by the delays of the Proto-Tera initiative which risks slowing down the interdisciplinary effort to bridge physics and biology and to establish working connections with clinical and biologist end-users.

LIP has a continuing and growing engagement in activities with a direct and positive impact on society, relying on the competence of individuals and teams, such as particle detector R&D and construction techniques, electronics and computing. Knowledge transfer in relation with these technologies is increasing.
LIP is maintaining its outstanding leadership in scientific computing, both within Portugal and internationally. Software developments, advanced algorithms and techniques and an excellent record of system management, performance and availability have made LIP the leader in the deployment and operation of the Portuguese scientific computing infrastructure. The Committee shares the concerns expressed about meeting the major new demands on computing resources required for the HL-LHC exploitation.

Last year LIP launched very successfully a fascinating novel line of research: SPAC, Social Sciences and Complexity. This interdisciplinary effort uses approaches familiar to particle physics to explore a variety of societal topics, such as the risk of new technologies, the impact of social networks or spread of diseases. Its research is based on extracting information from “Big Data”, a very familiar topic to LIP.

The Committee acknowledges the success of the Competence Centers, not only as a means of increasing competence and cohesion of LIP staff but also as an opening to other fields of science and to industry. The Committee sees clear potential for further progress and encourages the groups to actively pursue their missions.

LIP has been outstandingly successful in presenting science to society and attracting students to science and particle physics in particular, notwithstanding the restrictions imposed by the pandemics, which heavily limited communications, meetings and personal contacts. One measure of the success is the marked increase of students joining the LIP research programmes during the past year.

With regard to the employment situation the Committee was pleased to learn of the further progress in consolidating some staff positions during last year. It also noticed the success of the staff career monitoring and follow-up implemented by the Management.

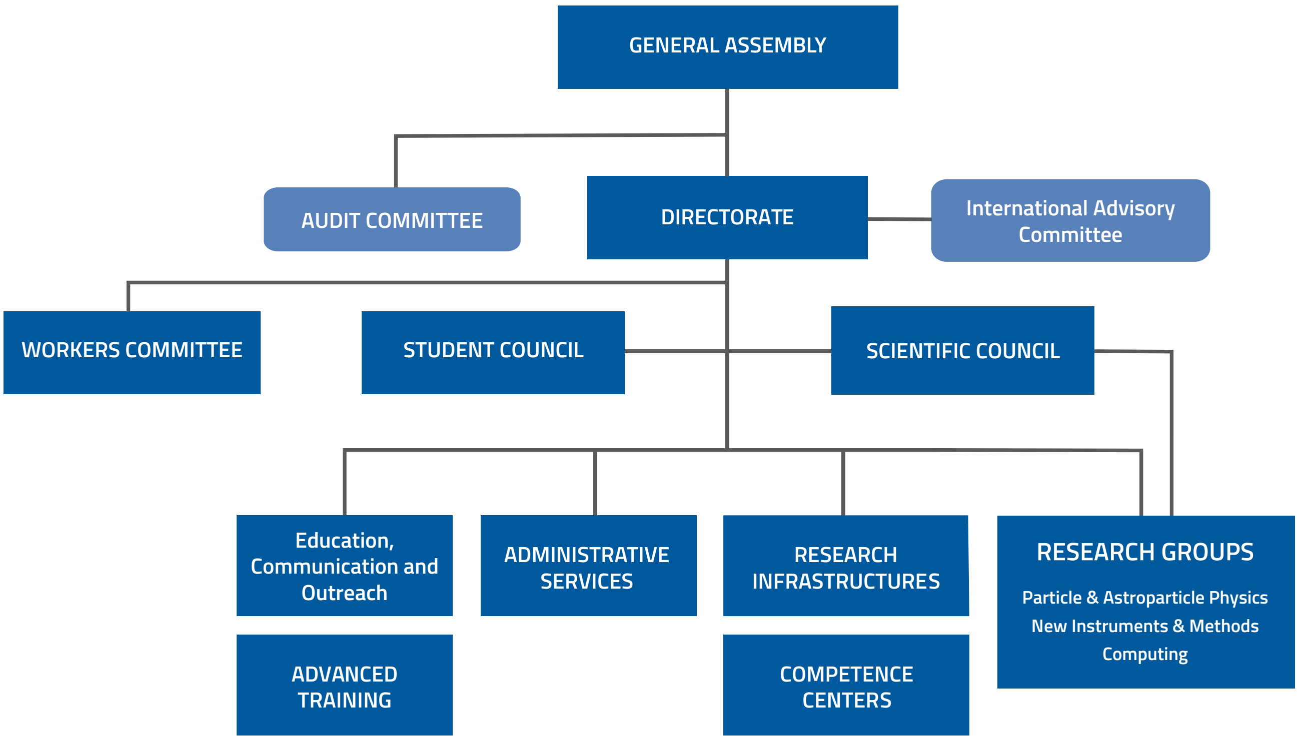
The increased number of students is an occasion for the Committee to encourage LIP to further improve formal mentoring and supervising procedures for all students and supervisors.

The Committee wishes to emphasize that, despite the continuing constraints and obstacles brought about by the pandemic, the performance of LIP in the past year has been excellent. It congratulates the LIP Management and the LIP staff for their achievements.

S. Bertolucci E. Daly C. W. Fabjan P. G. Innocenti K. Parodi L. Rolandi M. Teshima

Structure & governance

Research in experimental particle physics and associated technologies is often conducted within large international collaborations or using large scientific infrastructures. This requires research teams large enough to have the required critical mass and adequate support infrastructures. The organizational structure of LIP ensures a coordinated strategy at national level and is designed to be efficient and flexible.



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 ANIMEE (Electrical and Electronics Business Association).

International Advisory Committee

An External Advisory Committee provides strategic advice to the Laboratory. The Committee is formed by seven worldwide recognized experts in the areas of activity of LIP and holds regular meetings with the directors and the group leaders. Presently, the members of the International Advisory Committee are: Christian W. Fabjan (Austrian Academy of Sciences), Eamonn Daly (former Head of Space Environment and Effects Section of ESA), Katia Parodi (Medical Physics Chair at LMU, Munich), Luigi Rolandi (CERN), Masahiro Teshima (Director of the Max Planck Institute of Physics), Pier Giorgio Innocenti (former CERN ECP Division Leader), Sergio Bertolucci (former Director of Research and Scientific Computing at CERN).

Audit Committee

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

Directorate

LIP is governed by a Board of Directors nominated by its General Assembly, after consultation of LIP members.

The different nodes of LIP are represented in the Board of Directors, which meets on a monthly basis and issues brief reports of its deliberations to the scientific council. At present the national directorate is formed by Mário Pimenta (president), Isabel Lopes, Nuno Castro, Patrícia Gonçalves and Ricardo Gonçalo.

Scientific Council

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

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 Rui Alves (coordinator), Lina Barata and Sofia Andringa.

Student Council

The goals of the recently created LIP Student Council are: to promote communication between students from different LIP nodes; to encourage the exchange of ideas, interests and mutual aid between students; to promote teamwork and to suggest and assist in the preparation of advanced training activities.

The main elements of the working structure of LIP are:

Research Areas, Lines and Groups

Research Groups are the fundamental organizational units of LIP. The research groups are organized in eight Research Lines gathered in three Research Areas: particle and astroparticle physics; development of new instruments and methods; computing.

Research Infrastructures

Research infrastructures are central in the laboratory's activities. They provide support to R&D activities at LIP and services to external entities. The existing infrastructures are: the precision mechanical workshop and the detector laboratory in Coimbra, the scintillating materials laboratory and the electronics laboratories in Lisbon.

Competence Centres

The Competence Centres cluster related expertise from the different research groups and infrastructures of LIP to create a pool of knowledge that eases R&D and can provide services to external entities and foster knowledge transfer into the non-academic sector. They are designed to be light and flexible horizontal structures joining all the LIP members that share the same tools and technologies.

Administrative services

The LIP community has the support of a small but effective group of administrative staff (seven elements in Lisbon and two in Coimbra) split in the following services: Users Support and Project Office; Accounting and Financial Management. The Project Office has recently been reinforced with a new member dedicated particularly to assisting researchers with preparation of proposals (pre-award). The goal is to strengthen LIP's capacity to attract international funding.

Science and Society

The Education, Communication and Outreach (ECO), Advanced Training (AT) and Knowledge Transfer (KT) groups are dedicated support structures reinforcing the link to society. The ECO group deals both with institutional communication, both internal and external, and with LIP's broad programme for the school community. The AT group engages with undergraduate and graduate students through the organization of schools, workshops, internships and other events, and oversees the hosting and training condition of PhD and master students at LIP. The KT group maintains a close connection with CERN-related KT bodies, FCT and ANI.

Highlights of the year 2021

JANUARY

- LIP researcher Lorenzo Cazón was nominated as one of the two Physics Coordinators of the Pierre Auger Observatory
- An ATLAS PhD grant was officially awarded to Ana Luísa Carvalho, PhD student in the LIP ATLAS group

FEBRUARY

- LIP researcher Jonathan Hollar received the 2021 CMS Award
- LIP's online debate celebrating UN's Day of Women and Girls in Science gathered close to 100 people. The secretary of state for Science and the president of FCT were among the participants.
- The Pierre Auger Observatory publicly released a large open data set, including analysis tools

MAY

- LIP's 35th Anniversary is celebrated on 9 May
- LIP researcher Valentina Lozza was nominated Analysis Coordinator of the SNO+ experiment
- Patricia Conde Muiño, PI of the LIP ATLAS group, was nominated scientific secretary of ECFA
- A collaboration agreement between Portugal and Brazil was signed, specifically including the area of particle physics

JUNE

- LIP researcher Inês Ochoa presented the ATLAS results at the LHC Committee open session
- Liliana Apolinário, from the LIP Pheno group, was appointed theory co-convener of the Heavy-Ion Working group of the LHC Physics Centre at CERN (LPCC)

SEPTEMBER

- Nuno Leonardo, from the LIP CMS group, was appointed co-coordinator of the LHC Physics Centre at CERN (LPCC) for the area of "heavy flavours"
- The PANIC 2020 conference, organised by LIP, was held online
- All three nodes of LIP were present in the European Researchers' Night, held in hybrid mode

OCTOBER

- The MPI at LHC conference, organised by LIP, was held in hybrid mode
- CERN and LIP were present at the first edition of the FIC.A science festival, in Oeiras
- The National Scientific Computing Meeting was held in Coimbra, with the participation of LIP

MARCH

- CERN's LHCb experiment announced new results which, if confirmed, suggest hints of something beyond the Standard Model of particle physics
- First IPPOG Masterclass in Particle Therapy in Portugal

APRIL

- g-2 Fermilab result Fermilab published a measurement of the muon g-2 coefficient that deviates from the value predicted by the Standard Model of particle physics
- UMinho's 2020 Initiation to Research Prize given to LIP Summer Internship student Luís Amorim

JULY

- Start of the 2021 LIP Internship Programme, with the participation of close to 90 students in all LIP nodes
- Ciência Viva internships for high-school students were held at LIP

AUGUST

- LIP and INCD demonstrated the capabilities of the new submarine optical cable EllaLink connecting Europe to Latin America using data from the CMS experiment

NOVEMBER

- UMinho's 2021 Initiation to Research Prizes given to LIP Summer Internship students Magda Duarte and Miguel Peixoto
- Online advanced schools for physics teachers in Portuguese language
- National Day of Scientific and Technological Culture: LIP's muon tomography project was highlighted at the national public radio station Antena 1

DECEMBER

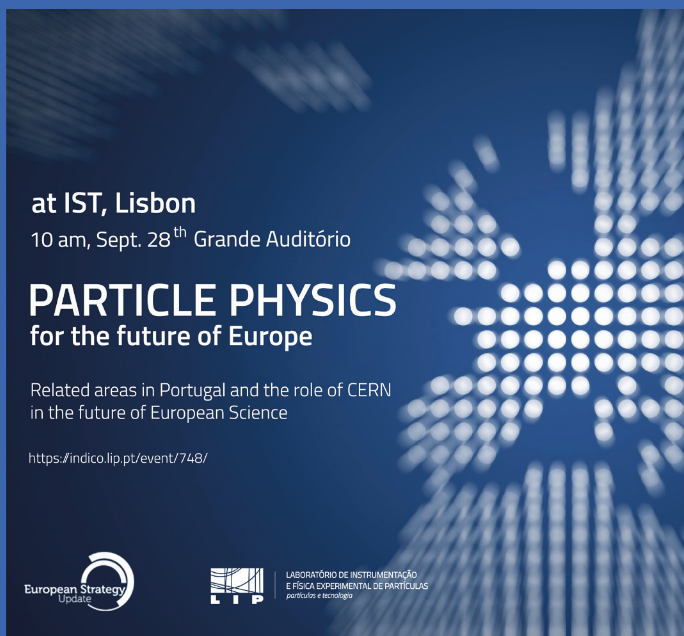
- First LIP Mini-School on Charged Particle Therapy Applications
- The RPC-TOF-FD detector developed and built at LIP in Coimbra detector was installed in HADES at the GSI

Organized events and Awards of 2021

2021-07-01 / 2021-09-30
"LIP Internship Program 2021"
All LIP nodes

2021-09-05 / 2021-09-10
"PANIC - Particles an Nuclei International Conference", Lisbon, Portugal (online)

2021-09-11 / 2021-09-15
"12th International workshop on Multiple Partonic Interactions at the LHC", Lisbon, Portugal (hybrid online+presential)



2021-09-28 / 2021-09-28
"Particle Physics for the Future of Europe"
IST, Lisbon

Awards to LIP Members

Jonathan Hollar

"CMS 2021 Award"

Luis Amorim

"UMinho Scientific Research Initiation Award 2020"

Joana Gonçalves-Sá

"Inspiring Women" Award - Science category

Marco Alves Pinto

"RADECS 2020 Best Data Workshop Paper Award"

Magda Duarte

"UMinho Award for Initiation in Scientific Research 2021"

Miguel Peixoto

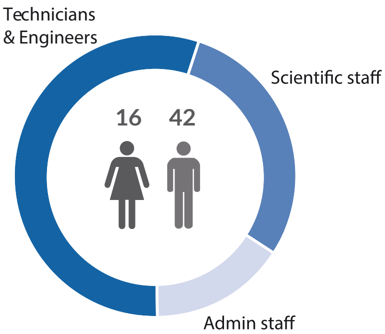
"UMinho Award for Initiation in Scientific Research 2021"

LIP

in numbers

Human Resources

STAFF



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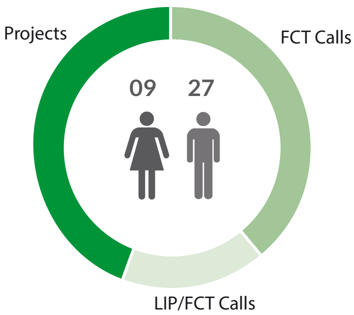
58 TOTAL

	Women	Men
Technicians/ Engineers	3	29
Scientific staff	5	12
Admin staff	8	1

FIXED-TERM RESEARCHERS



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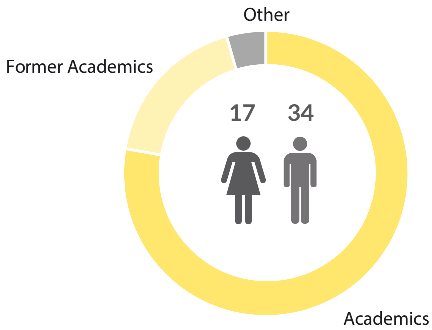
36 TOTAL

	Women	Men
Projects	06	10
FCT Calls	2	12
LIP/ FCT Calls	1	5

UNPAID



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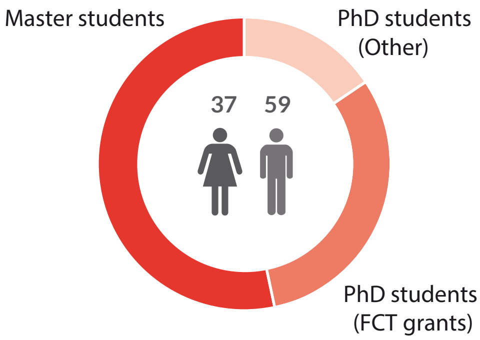
51 TOTAL

	Women	Men
Academics	10	25
Former Academics	4	4
Other	3	5

TOTAL 241

79 (women) 162 (men)

STUDENTS



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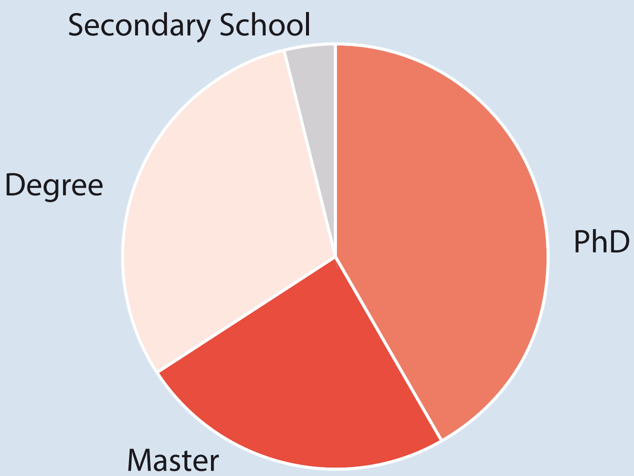
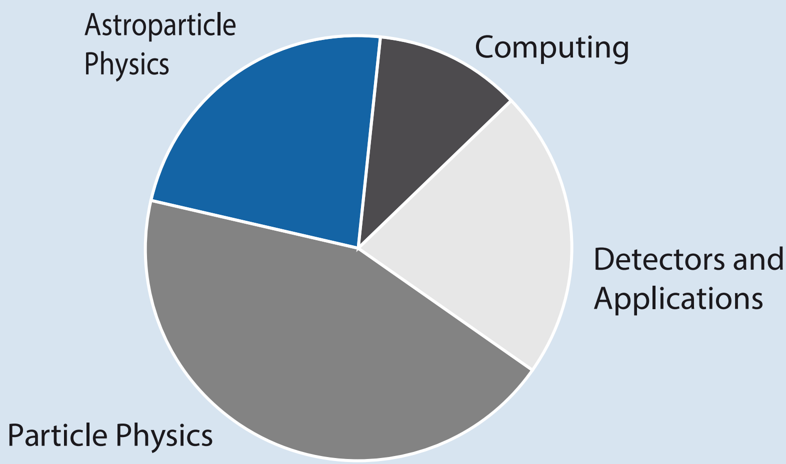
96
TOTAL

Master students	18	33
PhD students FCT grants	13	17
PhD students (Other)	6	9

DISTRIBUTION BY ACADEMIC QUALIFICATION

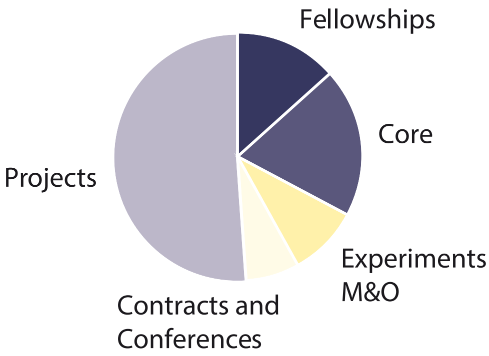


DISTRIBUTION BY RESEARCH AREA



Finances

GENERAL FUNDING



1.5M
CORE FUNDING

2.2M
PROJECT-BASED

1M
FELLOWSHIPS

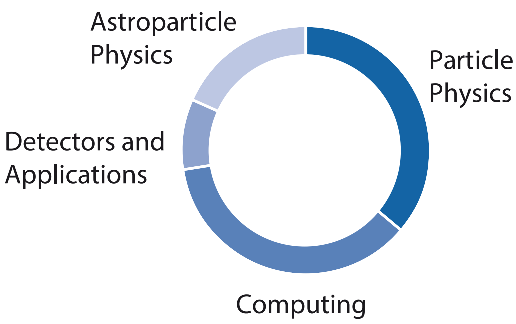
0.8M
EXPERIMENTS M&O

0.2M
CONTRACTS AND CONFERENCES

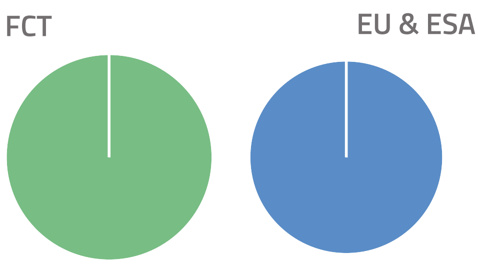
TOTAL
5.7M €

PROJECT AND CONTRACT-BASED FUNDING

BY RESEARCH AREA

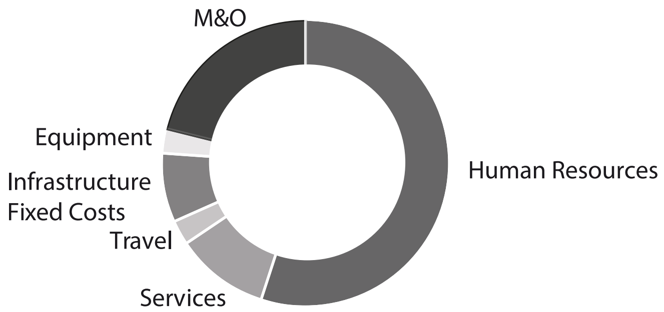


BY ORIGIN



TOTAL
2.2M €

COSTS



HUMAN RESOURCES

STAFF 2.1M

FIXED-TERM RESEARCHERS 1.9M

SERVICES AND OTHER EXPENSES

0.4M

TRAVEL

0.1M

EXPERIMENTS M&O

0.8M

INFRASTRUCTURE FIXED COSTS

0.3M

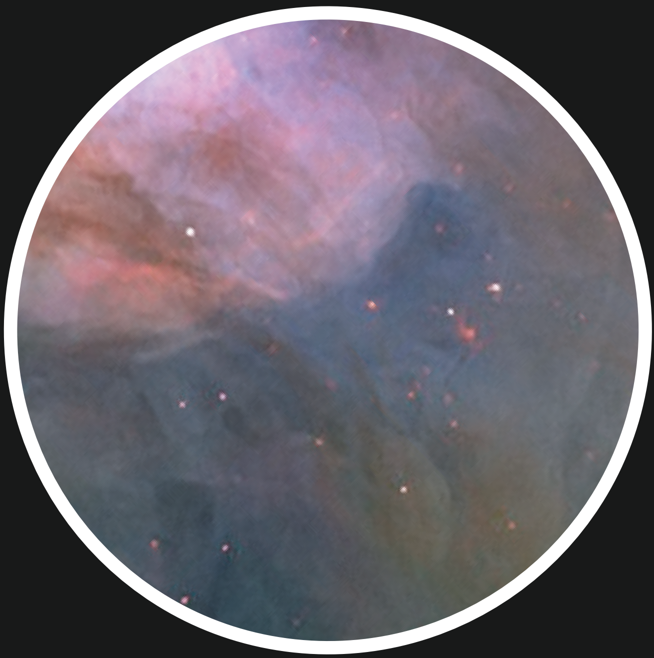
EQUIPMENT

0.1M

Scientific output 2021

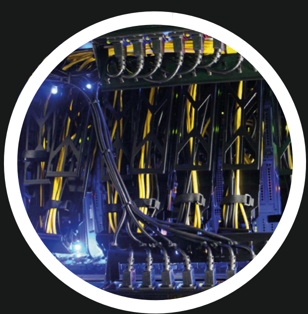
	Particle Physics	Astroparticle Physics
Papers in refereed journals	175	33
Proceedings Preprints and Notes	62	17
Books, Reports and Proposals	1	3
Presentations in International Conferences	34	12
Other Presentations	77	27
Master Theses	13	8
PhD Theses	4	1

Detectors and Applications	Computing	TOTAL
18	6	232
8	9	96
2	3	9
21	13	80
27	31	162
6	2	29
2	2	9



Experimental particle
and astroparticle
physics

Development of
new instruments
and methods



Computing

research at

LIP

Experimental particle and astroparticle physics

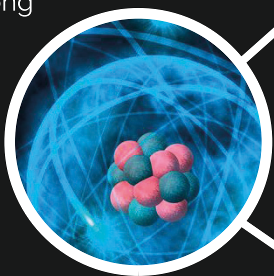
Development of new instruments and methods

LHC experiments and phenomenology

- ATLAS
- CMS
- Pheno
- FCC

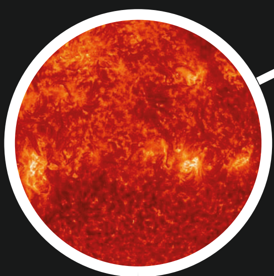
Structure of matter

- pQCD
- HADES
- NUC-RIA
- NPstrong



Cosmic rays

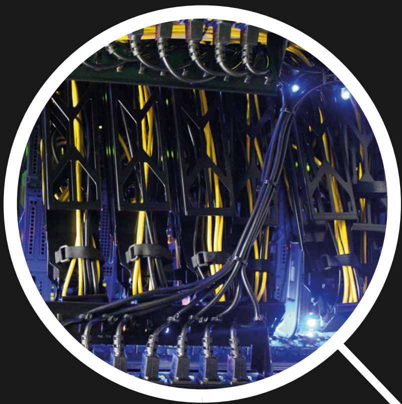
- AMS
- Auger
- SWGO

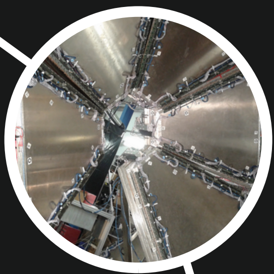


Dark matter and neutrinos

- DARK MATTER
- NEUTRINO
- SHiP

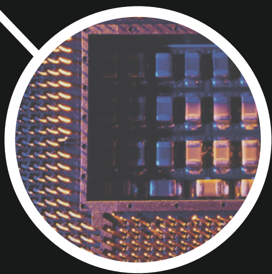
Computing





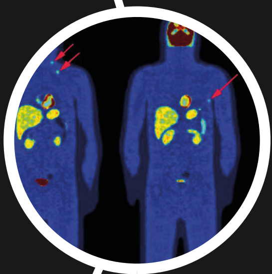
Detectors for particle and nuclear physics

- 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

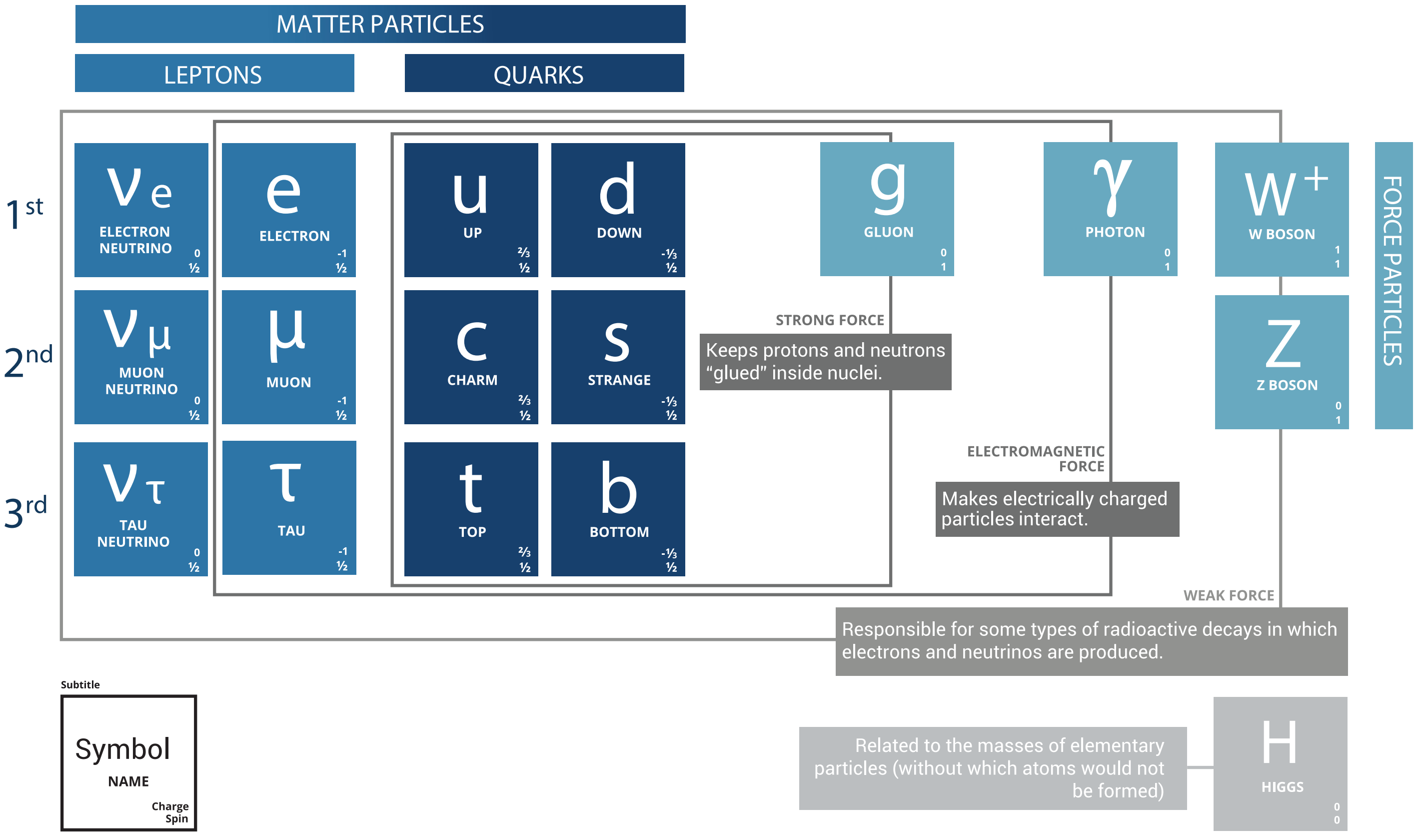
- RPC-PET
- Proton Therapy
- OR Imaging
- Dosimetry

Space applications

- Space Rad
- i-Astro

In a **nutshell...**

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



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

Still, it leaves many unanswered questions:

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

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

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

Experimental particle & astroparticle physics

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

Particle physics seeks always deeper into the universe — its constituents and workings at the most elementary level, its origin and evolution. LIP is deeply involved in the CERN LHC endeavor, contributing from the very beginning to the two largest LHC experiments, ATLAS, and CMS. With these fantastic scientific instruments, we are studying Nature in many ways, from deepening our understanding of the Higgs boson to searching for new physics or recreating the conditions that existed just after the big bang. At the same time, we are very actively improving our experiments, to respond to future challenges of running at higher LHC luminosities, and we are starting to prepare the far-future with LIP's recent involvement in the Future Circular Collider (FCC) feasibility study. LIP's Phenomenology group conducts research bridging theory and experiment. Its research, while independent, is centered in areas in which LIP has active experimental activities. Its purpose is to strengthen impact through the provision of excellent directed phenomenological research.

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

Experimental particle physics is conducted in ever more powerful accelerators, but also in astroparticle physics experiments, detecting particles that come to us from the cosmos. The quest for dark matter, a deeper understanding of the elusive neutrinos, or the origin and nature of charged and neutral cosmic rays are among the great challenges of particle physics for the next decades. LIP is part of these challenges through its engagement in some of the main international collaborations, including SNO+ at SNOLAB in Canada, LZ at the SURF Laboratory in the USA, the Pierre Auger Observatory in Argentina, and the Alpha Magnetic Spectrometer in the ISS.

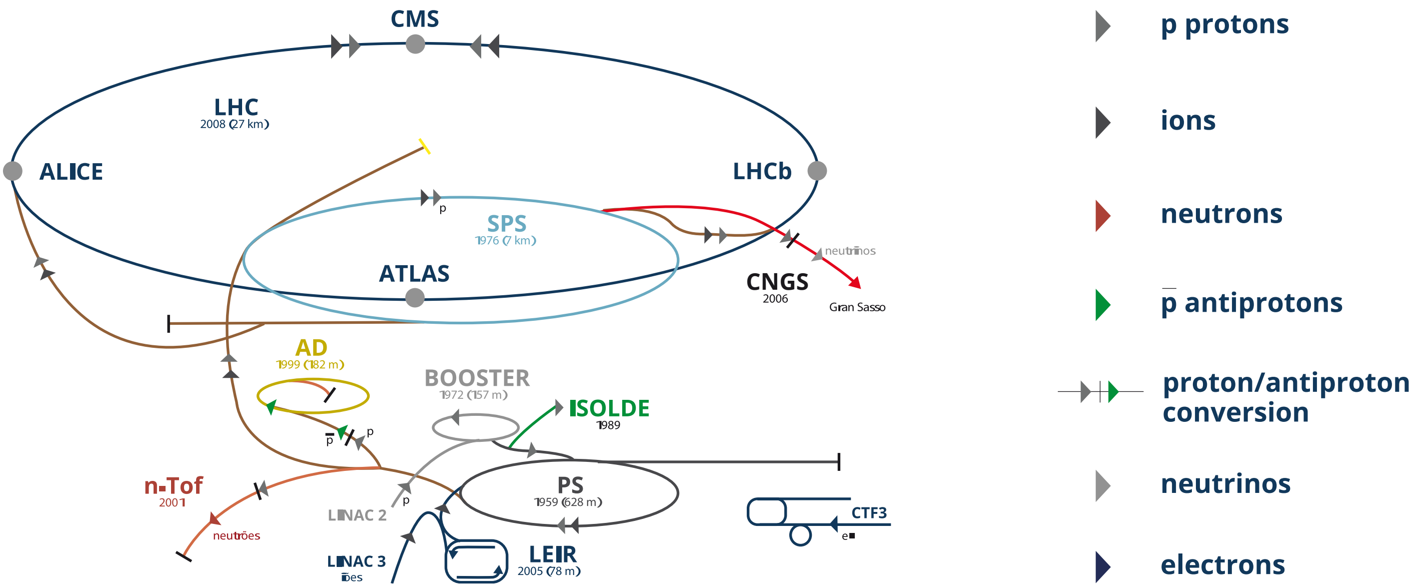
More recently embraced projects are the participation in DUNE, one of the two flagship neutrino experiments for the next decade; the SWGO project for the installation of a wide field-of-view gamma ray-observatory in the Southern hemisphere; and SHiP, an experiment proposed to be installed in a beam dump facility at the SPS. Its first step will be the installation of its neutrino detector (SND) at the LHC already in the run staring in 2022 (SND@LHC), providing first observations of collider neutrinos.

EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

LHC experiments and phenomenology

Physics at the energy frontier

With the LHC Run 3 starting in the summer of 2022, the year 2021 was used to complete analyses, many using the full Run 2 (2015-2018) accumulated data set, and to prepare both for the coming restart and for the LHC Phase 2 upgrade. The new sub-detectors and upgrades will be installed during the long shutdown from 2025 to 2027, and the High-Luminosity LHC (HL-LHC) commissioning will start at the end of 2027. In addition, LIP is actively participating in the most recent LHC experiment, SND@LHC, built and installed in 2021, for studying neutrinos at the LHC, from the start of its Run 3. The LIP Phenomenology group, now a large team with consolidated research programmes in both QCD and New Physics Searches. The successful synergies with the Simulation and Big Data Competence Centre continue as, increasingly, machine and deep learning techniques become ubiquitous in our work. Last but not least, we are also starting to prepare the far-future. The LIP FCC group was recently created to contribute to the ongoing Future Circular Collider (FCC) feasibility study. The group started from a core of members from the ATLAS, CMS and Pheno groups at LIP, who were involved in the production of the FCC Conceptual Design Review.



LIP at the LHC

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

Precision measurements: Higgs boson and top quark

Higgs and Top physics have for long been a particular specialty of LIP's ATLAS, CMS and Phenomenology groups. The experimental teams first focused on the accurate measurement of the Higgs boson properties, namely on Higgs bosons decaying to a pair of b quarks in both the associated production of the Higgs boson with a W or a Z boson (VH, V=Z, W) and with a top-quark pair (ttH). In 2021, the LIP ATLAS team strongly contributed to the measurement of ttH associated production with full Run 2 data set, submitted for publication in December. Both the ATLAS and CMS teams also focused on the Higgs as a window to physics beyond the SM. The LIP-CMS group has been leading the search for the rare Higgs boson pair (HH) production process with developed Machine Learning tools. This process gives access to the Higgs self-coupling parameters, and New Physics processes can significantly alter the expected production mechanism through a resonant production. Results have recently been approved for publication. While any deviations from the expectations of the SM of particle physics may have far-reaching implications, getting enough sensitivity to reach clear conclusions will be a long and challenging process.

The LHC is a top quark factory, providing the best opportunity for detailed measurements of the heaviest of fundamental particles. The huge mass of the top quark makes it a likely window to observe subtle effects of physics beyond the SM. In 2020 the LIP CMS team had a leading role in the data analysis and publication of the first Run 2 results on the measurement of the top-quark pair production cross section with the top quark decaying to tau leptons. Studies are continuing to assess the lepton flavour universality in the leptonic decays of the W boson. The group is also pursuing a search for top-quark pairs through two-photon exclusive processes, only made possible through the use of the Precision Proton Spectrometer (PPS), located very close to the LHC beam. The LIP CMS team has since long a leading role in the PPS detector, which collected over 100 fb of data in Run 2. The higher luminosity and the upgraded detector open new possibilities for Run 3. The LIP ATLAS team is playing a leading role in the effective field theory interpretation of top quark precision measurements, aiming to constrain the possible forms of new physics theories that may be 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 proposed theories and models, and performing wide searches employing powerful analysis methods to search for any anomalies in data. Both the ATLAS and CMS LIP teams were busy concluding search analyses using the full Run 2 data set in variety of models and channels: exotic heavy quarks, whose existence could account for the unexpectedly low value of the Higgs mass; forbidden or rare quark flavour changes; final states with multiple bosons and/or Higgs bosons; single-top final states and other events with a large missing energy, which is a signature for particles escaping detection and may also indicate the presence of a dark matter particle; supersymmetry, according to which each known particle is expected to have a supersymmetric partner (sparticle) with different spin and could include the perfect candidate to explain dark matter. However, showing that this is realized in Nature has so far proved a difficult task.

After the analyses, other tasks include the interpretation within different possible models or the combination of different contributing channels. Several searches are on track for publication in 2022. Another focus was the development of approaches that maximise the physics information extracted from the upcoming Run 3 data. Examples are topology-based approaches and heavy resonance searches using sophisticated anomaly detection methods.

The work of the two experimental teams is well matched to the expertise in the Phenomenology group, whose core portfolio of activities includes, among other, top-quark, Higgs, and BSM physics. The Phenomenology group has established a close synergy with the Competence Centre on Simulation and Big Data, with studies addressing in particular putative New Physics signals in collider searches. The effort to explore physics opportunities in future collider facilities contributed significantly to the creation within LIP of a dedicated group to the Future Circular Collider studies.

Secrets of the strong force

Hadrons containing one of the heaviest quarks (c, b, t, usually referred to as heavy flavours) are a likely window to observe subtle effects of physics beyond the SM. The interest is reinforced by the so-called flavour anomalies, consisting of different hints of deviation of SM's expected flavour universality, and by the large, accumulated data sets. The LIP CMS group is keeping a focus on b–›sll transitions, at the core of the flavour anomalies, and has carried out measurements of b-quark production and fragmentation, a crucial ingredient for the measurement of rare B decays, esp. B–›μμ. Another important decay realizing the b–›sll transition is B–›K*μμ. The group is completing the analyses of the angular observables and rates with the full Run 2 data.

The LIP CMS group is bringing its unique expertise on B physics into the heavy-ion realm. The observation of B meson signals in heavy ion collisions, achieved for the first time by CMS, provides novel probes of the QGP. This work is pursued in collaboration with MIT. The measurement of Bs and B+ production in lead ions collision data was accomplished and will soon be published. The analyses have been extended to the reference proton-proton data set. In fact, the LHC provides unique opportunities to study heavy-ion collisions and observe the Quark Gluon Plasma (QGP), which existed in the hot and dense medium of the very early Universe. The LIP 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.

Again, the work of the two experimental teams is very well matched to the expertise in the Phenomenology group. The scope of the group's QCD work has expanded over the years, encompassing at present heavy-ion phenomenology, forward physics, precision collider predictions, and quarkonic studies. The group has accumulated extensive expertise in the development of event-generators and has pioneered studies for extracting the time evolution of QGP, including its formation stages, through analysis of jet properties. Phenomenological studies of quarkonic, to better understand the mechanisms of hadron formation in QCD, have also been pursued in collaboration between the CMS and Phenomenology groups.

Tools of the trade - Detector Upgrades

During 2021, the ATLAS and CMS teams at LIP worked on their detectors and tools tin order to get ready for Run 3, and 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 the ECAL detectors. The ATLAS team coordinates the maintenance, operation and calibration of the TileCal calorimeter, as well as in the optimisation of jet triggers for the starting run.

In the High-Luminosity phase of the LHC physics program starting in 2027, the accelerator will provide an additional integrated luminosity of 3000 fb-1 over 10 years of operation. The LIP CMS group participates in the construction of a new Timing Detector and in the upgrade of the barrel and endcap Calorimeters. The LIP group is responsible for the design and construction of the readout system of the Barrel Timing Layer (BTL), including a high-performance TOF ASIC for time measurement. In collaboration with industry, LIP provides a high-performance ADC ASIC for the ECAL front-end electronics resistant to radiation. The CMS upgrade includes also the complete replacement of the end-cap calorimeters with a new high-granularity sampling calorimeter. LIP collaborates with industry to supply a high-current low voltage regulator (LVR) resistant to radiation for the High-Granularity Calorimeter (HGCAL) front-end system.

The LIP ATLAS team is deeply involved in the upgrade of the TileCal and of the Trigger and Data Acquisition (TDAQ). LIP has full responsibility for the new TileCal high voltage distribution, to be produced mainly in Portuguese industry. Sensitive electronics components will be placed in a service cavern and power distribution will be through thin cables to the front end, thus allowing much greater accessibility for maintenance. The team has designed, produced, and tested prototypes of different types of electronics boards in collaboration with LIP's e-CRLab. The team is also involved in the High Granularity Timing Detector (HGTD), with responsibilities in the DCS system and front-end ASIC tests.

Looking into the future

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

The LIP FCC group was recently created to contribute to the ongoing Future Circular Collider (FCC) feasibility study. We hope it will be the seed to the long-term participation of LIP in the FCC endeavor. The group's activities range from detector R&D to theoretical contributions to FCC physics. The group grew from a core of members from the ATLAS, CMS, and Phenomenology groups at LIP, who were involved in the production of the FCC Conceptual Design Review, one of the inputs to the latest EPPSU. Current research directions include R&D on new radiation-hard scintillators, detector simulation, and Standard Model parameter calculations relevant for the FCC-ee programme.

Neutrinos at the LHC

LIP is a founding member of the Scattering and Neutrino Detector at the LHC, SND@LHC. LIP has been involved in the construction and ensuing commissioning of the detector since it was approved in 2021. The most recent LHC experiment, installed 480 m away from the ATLAS interaction point, aims at observing collider neutrinos and providing unique studies of all three neutrino flavours and of heavy flavour production as well as searching for FIPs (see p.44).

Nominations and awards

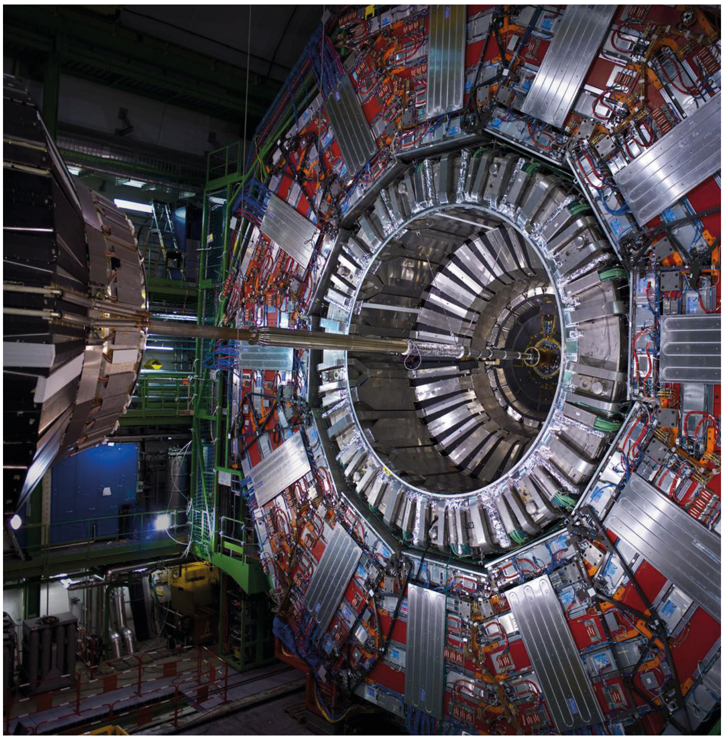
Patricia Conde Muiño, PI of the LIP ATLAS group, was nominated scientific secretary of ECFA

LIP researcher Jonathan Hollar received the 2021 CMS Award

Liliana Apolinário, from the LIP Pheno group, was appointed theory co-convener of the Heavy-Ion Working group of the LHC Physics Centre at CERN (LPCC)

Nuno Leonardo, from the LIP CMS group, was appointed co-coordinator of the LPCC for the area of "heavy flavours"

LIP researcher Inês Ochoa presented the ATLAS results at the LHC Committee open session



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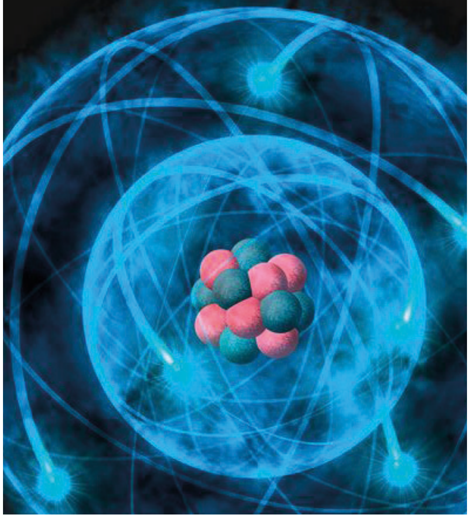


Structure of matter

Looking inside hadronic matter

We still have a lot to discover about the ways in which quarks and gluons work together to form the particles we observe, and that's the focus of LIP's structure of matter research line. The Partons and QCD group is currently involved in studying hadron structure in the final runs the COMPASS experiment, and in preparing its successor AMBER; FAIR (Facility for Antiproton and Ion Research) will be the new step at GSI and LIP is part of the HADES and R3B experiments. NPstrong, the Nuclear Physics and Strong Interactions group brings remarkable theoretical consistency to this research line, as well as opportunities for collaborations between 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 now concentrates on the final run of the COMPASS and in the preparation of AMBER. During its first phase COMPASS achieved the world's most direct and precise measurement of the gluon contribution to the nucleon spin. A second phase devoted to understanding the tridimensional nucleon structure started in 2012. The experiment uses beams from the SPS accelerator, colliding high intensity muon or hadron beams with a polarized target at a temperature only 0.1 degree above absolute zero. The target is followed by a two-stage spectrometer that observes the particles resulting from the collision. The successor experiment AMBER inherits several components of COMPASS.

COMPASS will have in 2022 its last data taking period, completing the measurement of Deep Inelastic Scattering (DIS) of a muon beam off a transversely polarized deuteron target, which shall lead to an accurate determination of the spin dependent transverse momentum distribution of the d-quark in the nucleon. The 2021 COMPASS data taking was followed by the pilot Run for the proton radius measurement of AMBER. Despite travel restrictions, the group ensured a permanent presence and expert support to the Detector Control System (DCS), for which it has full responsibility, and contributed very significantly to the target system and to data taking.

The LIP group has always been deeply involved in the analysis of COMPASS data, with special responsibility in Drell-Yan: high-mass lepton-pair production in a hadron-hadron collision, a powerful tool for probing the partonic structures of hadrons. The first COMPASS study on the unpolarized Drell-Yan angular dependence was released in April 2021. These results show good compatibility with those published by past experiments, confirming an angular modulation stronger than expected from perturbative QCD. This may be interpreted as a hint for the presence of non-negligible non-perturbative effects. The results were presented at several international conferences during 2021. Several other analyses are still ongoing.

As AMBER became a recognized and approved CERN experiment (NA66), during 2021 the Collaboration was established. The main responsibilities of the group in AMBER are on Drell-Yan, namely on physics simulations including the new detectors and setup modifications, and in developing new approaches for beam particle identification. The group is also adapting the COMPASS DCS to the AMBER conditions. A proposal for the AMBER second phase (after the next long shutdown at CERN) is in preparation.

Stars and Nuclei

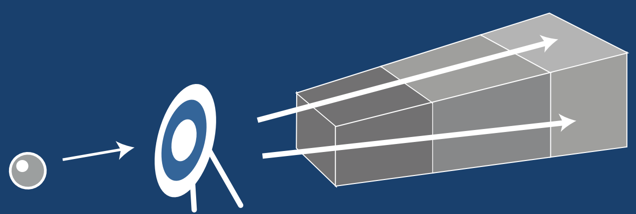
The GSI Helmholtz Centre for Heavy Ion Research in Darmstadt (Germany) operates the only facility allowing to accelerate nuclei of all chemical elements occurring on Earth. The facility has been closed for a few years and is slowly coming back to life. The performed upgrades will allow to put into operation the SIS100 1.1 km ring accelerator, 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 Group (NUC-RIA) is part of NUSTAR's R3B (Reactions with Relativistic Radioactive Beams).

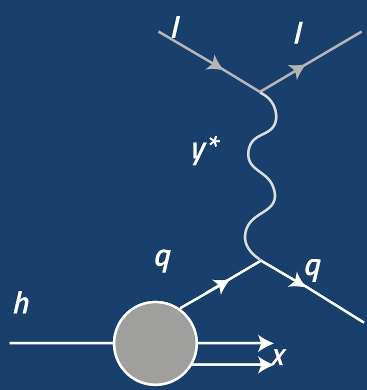
Another pillar of FAIR is CBM (Compressed Baryonic Matter). The collision of atomic nuclei at high speeds can reproduce for a split second the conditions inside supermassive objects such as neutron stars. This is where sits the HADES experiment, in which LIP is involved. Scientists want to find out how matter changes at such densities. The LIP HADES group designed, built, and operates an essential component of the spectrometer, the RPC-TOF-W: a wall (W) of 3 m x 3 m of resistive plate chambers (RPCs) that accurately measures the crossing time of particles (TOF, time-of-flight).

The group is extending TOF measurements to the forward region of the detector (closer to the beam direction) with the new RPC-TOF-FD. A beam test took place in February, confirming the excellent performance of the RPC-TOF-W equipped with a new DAQ system designed to handle the high particle rate expected in FAIR (200 kHz). In addition, two RPC-TOF-FD modules were exposed to proton collision at 4.5 GeV. A heating system based on circulating water was built to increase the temperature of the detector by 15°, providing extra rate capability (due to the decreased glass resistivity). The two remaining FD modules were built at LIP-Coimbra, tested, and shipped. Commissioning of the full system at GSI took place at the end of the year.

As for NUC-RIA, during Spring 2021 the group remotely contributed to R3B experiments in the framework of the Phase-0 campaign at FAIR. Later in the year, a new RPC-based detector was installed at the R3B setup to measure with high precision (about 1%) the momentum of protons emitted in reactions. The group also expanded its research activities in experimental nuclear astrophysics. NUC-RIA led the preparation and defense of a successful proposal for an experiment measuring for the first time the elastic scattering reaction of alpha particles with radioactive nuclei, to be scheduled at CERN's ISOLDE facility in the near future. The group also continued and expanded its work on the systematic calculation of atomic parameters needed to model the light-curves of the kilonova electromagnetic transient associated with neutron star mergers. Finally, they are working towards providing a research tool that allows for the identification of nuclear properties relevant for stellar nucleosynthesis.



Fixed-target experiment



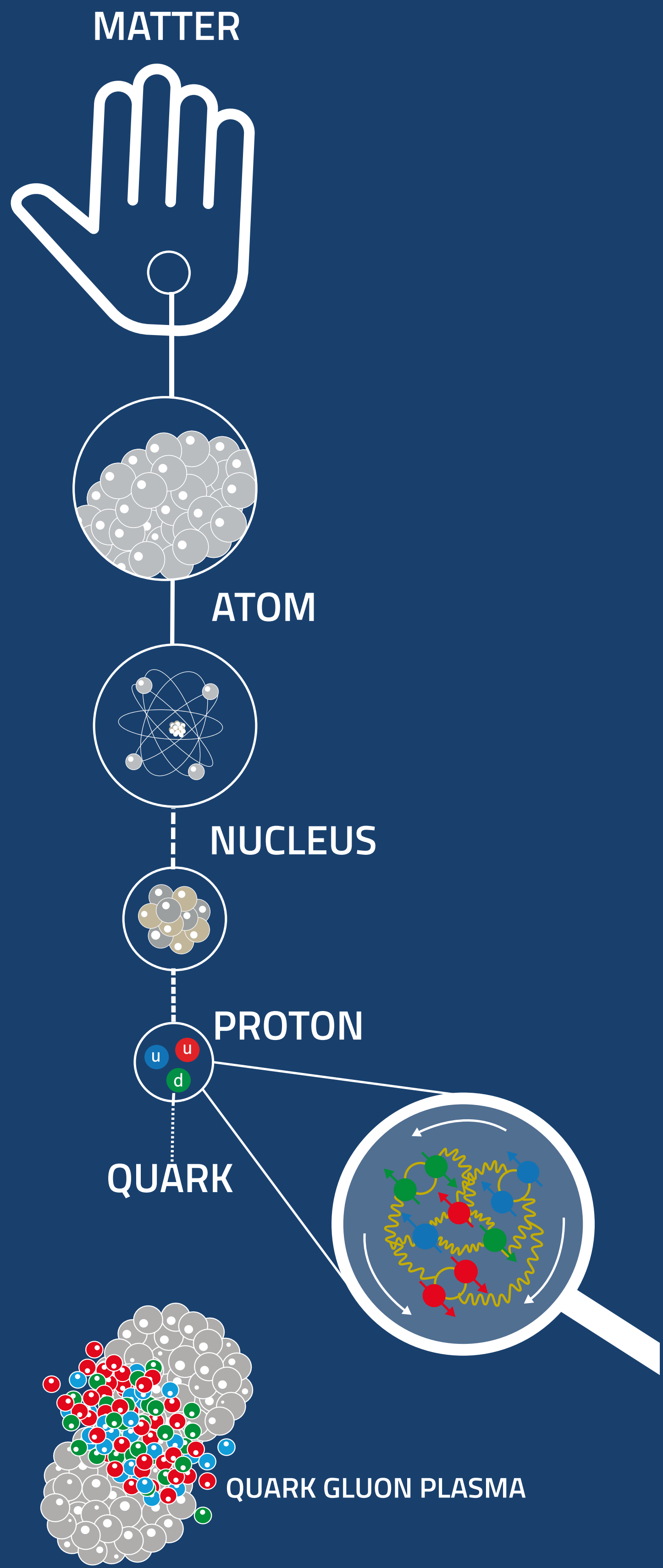
Deep inelastic scattering probes the insides of hadrons using electrons, muons and neutrinos. It provided the first convincing evidence of quarks. The higher the energy, the finer the resolution on the components of the nucleus.

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, the 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 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. Thus, there may be exotic hadrons, which lie outside the quark model. Among these are glueballs, hybrids (with valence quarks and gluons) and exotic hadrons such as tetraquarks or pentaquarks.

In 2021 NPstrong explored new research directions, considerably expanding the portfolio of the group. A novel method to compute hadron properties on the light front was developed and applied to calculate light-front wave functions; the next step is to compute parton distributions with functional methods, establishing close ties with experimental efforts at the future Electron Ion Collider. There was substantial progress in ab-initio solutions of the Yang-Mills sector of QCD, i.e., QCD with gluons but without quarks. This provides a glimpse into the underlying mechanisms of confinement and dynamical mass generation for gluons and will serve as the starting point for genuine ab-initio calculations of hadron properties also with dynamical quarks. The group improved and extended the calculation of the heavy-light pentaquarks spectrum, in view of the LHCb pentaquark observations. In addition, computed the spectrum of heavy baryons using functional methods. The goal of this work is to shed light on the newly discovered states at LHCb, in particular those with different flavors.



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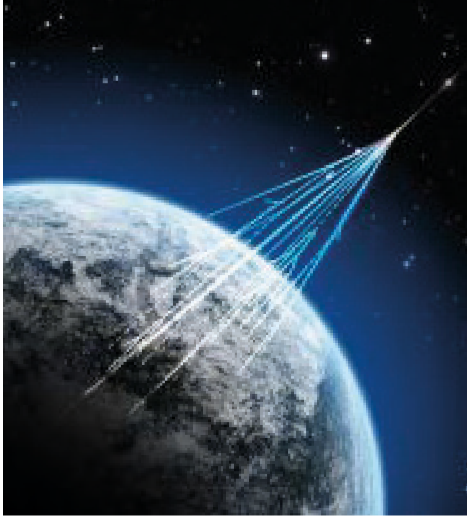


EXPERIMENTAL PARTICLE AND ASTROPARTICLE PHYSICS

Cosmic Rays

Messengers from outer space

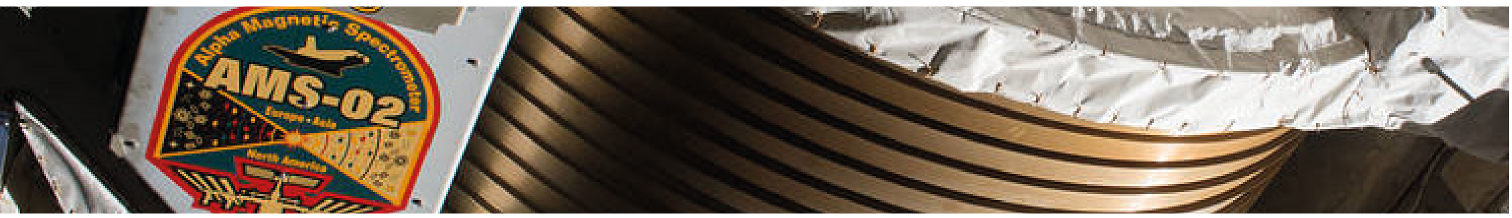
Planet Earth is constantly being struck by cosmic rays: particles (electrons, protons atomic nuclei) expelled by distant stars and galaxies. These messengers from outer space bring information about the history and composition of the Universe. The very wide range of energies of cosmic rays implies that different detection methods are used, from space-based experiments in the GeV/TeV range to ground-based giant air shower detectors at the highest energies. LIP is committed to the Alpha Magnetic Spectrometer, the Pierre Auger Observatory, and the SWGO project for the installation of a wide field-of-view gamma ray observatory in the Southern hemisphere.

A unique particle detector in space

Since 1998 LIP is part of the international collaboration that designed and operates the Alpha Magnetic Spectrometer (AMS). The AMS-I prototype was flown aboard the space shuttle in 1998, and the final detector was installed in the International Space Station (ISS) in May 2011. Since then, a large 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 is rather complex, with different sub-detector layers that measure different particle properties, and a magnetic field causing particles to bend according to the sign of their electric charge. With its powerful particle identification capabilities, 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 the detection of Cherenkov radiation, emitted when a particle crosses a medium at a velocity above the velocity of light in that medium. Identification is achieved by measuring the emission angle of Cherenkov radiation, which is related to the particle velocity. If the particle momentum is measured by another sub-detector, the particle mass can thus be derived. The LIP group holds responsibilities in the RICH operations, monitoring and in the algorithms used to reconstruct the properties of particles from the raw data recorded by the RICH.

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. The north-south magnetic field component of the Sun also flips every 11 years, at the minimum between two cycles. AMS observed the 24th solar cycle almost from the beginning, through the reversal of the magnetic dipole in 2013, and will continue operating at least until the magnetic reversal of the 25th cycle in 2023, observing the phenomenon with unprecedented detail. The LIP group is involved in the study of solar modulation effects, their interpretation under solar modulation models, and the study of associated propagation mechanisms. Observations of isotopes of the same nuclear species provide information on galactic matter distribution and cosmic-ray propagation, taking advantage of the change in velocity and interaction probability for the same charge. The mass separation capabilities of the RICH are key in such studies. The LIP group started from the lightest case, proton/deuteron separation, and will proceed with isotope flux analyses in collaboration with other AMS groups.



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 1020 eV. This corresponds to a macroscopic energy of tens of Joules and is well above the energy available at any human-made accelerator. In addition, several open questions remain on the nature and origin of such particles. The highest energy cosmic rays are thus both 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 km^2 in the Pampa Amarilla, (Argentina). It consists of over1600 detectors 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 ultraviolet light emitted by the showers. The observatory will continue operations until 2025 and is currently completing an upgrade to become AugerPrime, with the installation of scintillators on top of each of the existing detectors and the use of faster electronics. This should enable a better understanding of the electromagnetic and muon components of the shower. Muons play a big role in unveiling the nature of the highest energy cosmic rays, as they may come directly from the first few, high-energy interactions. They are indirectly accessible in AugerPrime, and the development of powerful methods to separate them from the dominant electromagnetic signals is of the utmost importance.

MARTA is a joint Portugal-Brazil R&D project to directly measure the muon content of cosmic showers using low gas flux RPC installed beneath a small set of Auger ground detectors. Again in 2021, MARTA activities were severely impacted by the pandemics. The most significant impact was still on the commissioning of the first MARTA station. The installed hardware requires recabling, and part of the electronics has to be updates. Solutions were found in the laboratory, and we are waiting for a mission to Argentina for fieldwork. The development of MARTAos simulation and reconstruction framework was concluded. This is now part of the official Auger Software, with maintenance ensured by the LIP group.

In parallel the LIP group is thoroughly exploring the Auger data and contributing to several analyses. The team holds great expertise in shower physics and is co-coordinating the collaboration efforts in this field. Previous work on model development and innovative analysis methods will allow for a central contribution to the analysis of AugerPrime data. In 2021 the team remained focused on the relation between the first few interactions, and the observables at the ground. One such observable is the muon content, and the group is establishing a direct relationship between muons content and pion production properties. Efforts will continue to measure the pion production at the highest energies.

Auger open data

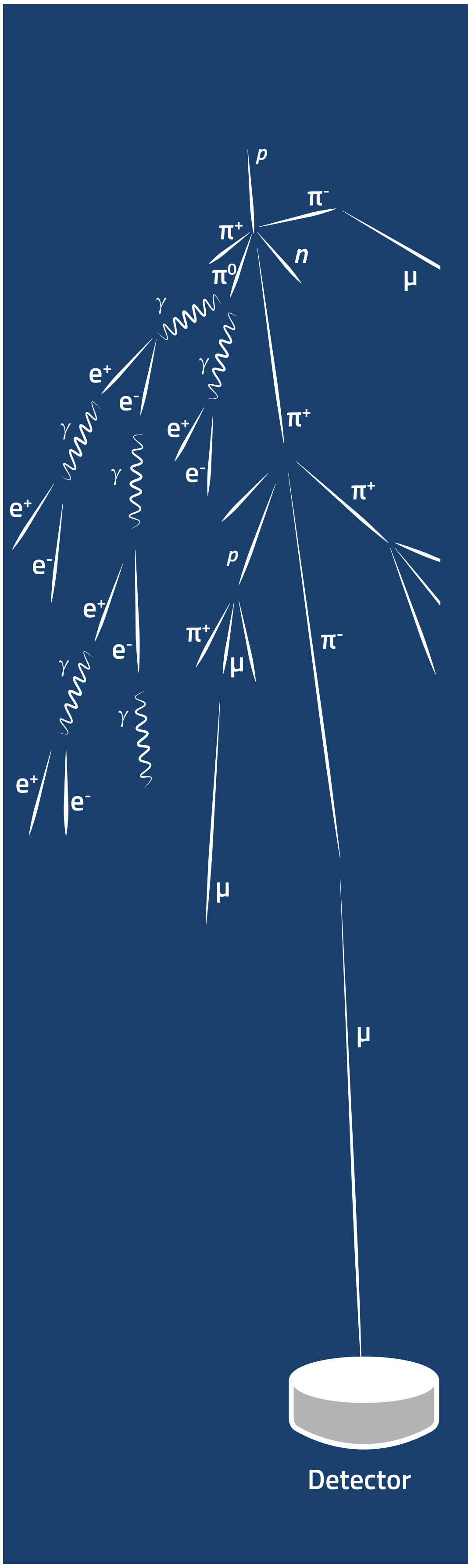
The Auger Collaboration has publicly released about 10% of the collected data, together with analyses tools. Several activities were organized in this context.

At the top of mountains

High-energy gamma rays provide an excellent window to the most extreme phenomena in the Universe. They are not deflected by magnetic fields, thus pointing to their sources, and they probe supernovae, black holes in active galactic nuclei (AGN) and the origin of gamma-ray bursts (GRB). Gamma-ray emission is associated to charged cosmic-ray acceleration, the production of cosmogenic neutrinos and gravitational waves. Gamma-ray astrophysics could also provide indirect hints of dark matter. The observations of gamma-ray telescopes in the last decade changed radically our perception of the Universe. High-intensity flares with an energy spectrum extending beyond the GeV have been observed. Direct detection of primary gamma-rays is only possible with satellite-based detectors. However, the cost of space technology limits their size, and thus their sensitivity at higher energies. In the atmosphere, gammas interact creating a shower of particles. These showers can be studied in imaging atmospheric Cherenkov telescopes, highly sensitive pointing instruments (such as CTA) or in high altitude air shower arrays. These have a wide field-of-view and are ideal to search for transient sources.

The Southern Wide-field Gamma-ray Observatory (SWGO) collaboration was formed in 2019 after a workshop held in Lisbon where different groups developing similar projects decided to joint efforts. Today, SWGO comprises 52 research institutions from 12 countries. The main goal of SWGO is to pave the way for the construction of the next wide field-of-view gamma-ray observatory to be installed at high altitude (4500 m) in South America. The new observatory will cover an extended energy range and address a rich science program. Moreover, SWGO will be the only wide-field observatory surveying the Southern sky and thus the centre of the galaxy region. The collaboration aims at producing a complete proposal, including the physics goal, location, observatory layout, detector design, and cost.

The Portuguese participation in SWGO is focused on specific goals spanning different areas: from the science requirements to the detector design, from the development of new analysis methods to the design of innovative calibration systems. In 2021, studies on the ability to detect transient phenomena in SWGO have been pursued, originating two peer-reviewed publications. The evaluation of SWGO's capability to measure neutrino-induced showers has been initiated. An algorithm to improve shower energy reconstruction in gamma-ray experiments has been developed and published. The LIP group proposed a novel concept for a small, single-layer water Cherenkov detector (WCD) with three light sensors placed at the bottom, in a 120° star configuration (Mercedes WCD). In collaboration with the company Rotoplastyc and with CBPF, in Brazil, an engineering design was developed, and a prototype was acquired and installed. The group was also strongly committed to the development and validation of SWGO's simulation and reconstruction tools. The Mercedes station was implemented and machine learning based analysis for the discrimination of muons using small-WCDs has been developed and published.



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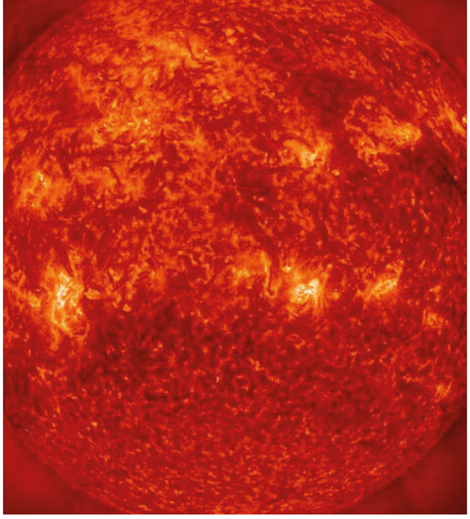


Dark matter and neutrinos

Hunting for the most elusive particles

The quest for dark matter and a deeper understanding of the elusive neutrinos are among the great challenges of particle physics for the next decades. LIP takes part in these challenges through its engagement in some of the main international collaborations in this area: the neutrino physics experiment SNO+ at the SNOLAB (Canada), LZ dark matter detector at the SURF Laboratory (USA), and the more recently embraced participations in DUNE, one of the two leading neutrino physics experiment of the next decade, SHiP, proposed for CERN's SPS (Super Proton Synchrotron), and R&D for third generation dark matter search experiments. Furthermore, LIP is actively participating in the most recent LHC experiment, SND@LHC, built and installed in 2021, for studying neutrinos at the LHC, from the start of its Run 3.

Searching for the dark side

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

The LIP Dark Matter group is a founding member of the LUX-ZEPLIN (LZ) experiment at the Sanford Underground Research Facility (SURF). The LZ detector utilizes 7 tonnes of liquid xenon as active medium in a dual phase TPC to search for potential dark matter signals. The interaction of a dark matter particle with a xenon nucleus would cause a nuclear recoil and produce a detectable photon signal. A TPC is a detector able to measure the 3D position of each spot where an interaction occurs.

LZ has been designed to improve on the sensitivity of the prior generation of experiments by a factor 50 or more. All efforts were made to improve rejection of unwanted background events, namely from cosmic rays and natural radioactivity. In particular, the detector is placed 1480 m underground; there are auxiliary veto detectors, including a liquid scintillator outer detector; the detector is inside a double vessel of radio-pure titanium.

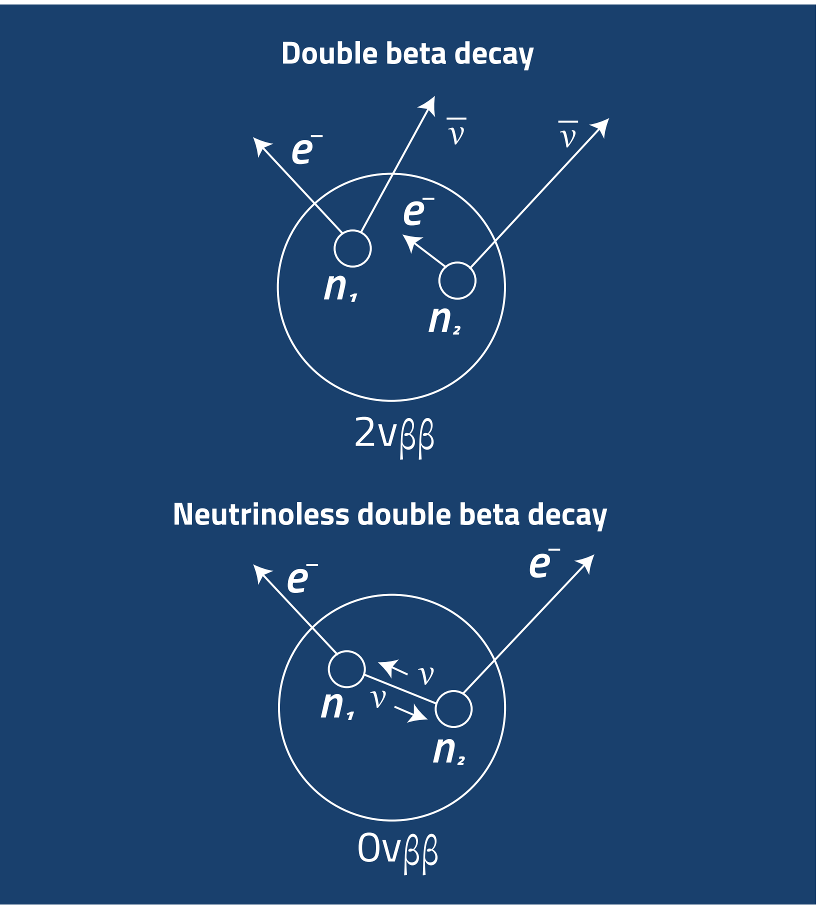
Due to the extremely low background, LZ can also be used forvother studies such as the search for Xe rare and forbidden decay modes.

The first LZ science run started in the last days of 2021, lasting for about 2 months. During the year, the LIP group contributed to the preparation for commissioning of the Control System (CS) and online Data Quality Manager (DQM), the two elements of the experiment infrastructure under LIP's responsibility. The group also made multiple contributions to the development of data analysis tools for pulse identification and characterization, as well as position and energy reconstruction, and to the modeling, simulation, and accounting of backgrounds. The search for the neutrinoless double beta decay (0ν2β) of 136Xe is the second most important goal of LZ, and the LIP group has a leading role in this analysis.

The group recently joined a proposal for a UK-based project aiming to observe the Migdal effect, theoretically predicted but never confirmed experimentally, which would allow extending the sensitivity of direct detection experiments to the sub-GeV mass region. The experimental set-up assembly is currently being completed. Finally, the group was involved in R&D projects for the preparation of a next generation dark matter direct search experiments, specifically concerning the measurement of optical properties of reflecting surfaces.

Understanding the elusive neutrinos

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



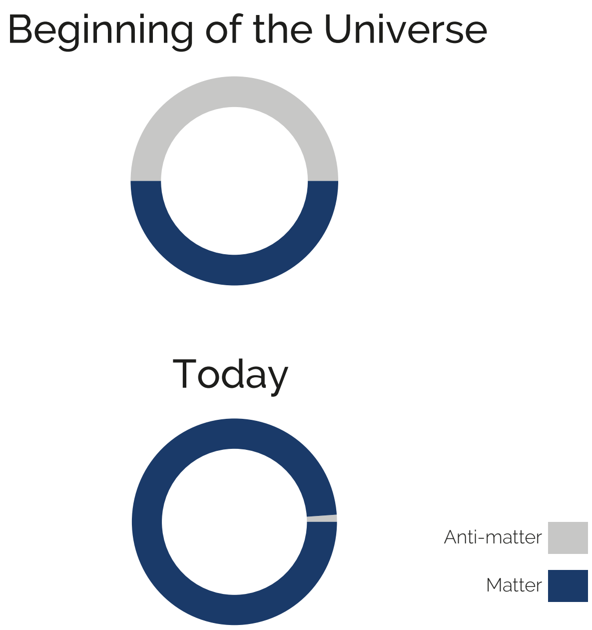
SNO+

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

The LIP group has participated in the construction of calibration systems and is currently very active in the data analysis of the water and scintillator fill (half-full and full) phases, with leadership or strong contributions to background studies, antineutrino analyses and calibrations. As highlights of the water phase, the group published a paper on optical calibrations, the antineutrino analysis in water is nearly completed and the paper is in preparation; the search for nucleon decay into invisible channels was improved using the more recent low background dataset and the corresponding paper is in internal review; the analysis of solar neutrinos in the water low background dataset is nearly completed and a paper is in preparation. The group had a large contribution in the data analysis of the partial fill data. In particular, they completed the 8B solar neutrino analysis in the partial fill phase (365 t of scintillator) and the results have been presented at the conference PANIC2021; the first antineutrino measurement in partial fill was completed and a paper is currently being written. The scintillator fill was completed in 2021 and preparations are ongoing for the Tellurium loading, expected to start later in 2022.

DUNE

DUNE is a long baseline experiment: neutrino and anti-neutrino beams will be produced at Fermilab and detected 1300 km away at SURF, in large Liquid Argon (LAr) TPCs (the far detector). Beam is expected in 2026, and the first detector installation in 2025. DUNE will certainly be one of the great projects of the next decades, studying in particular the mass hierarchy of neutrinos and investigating wether neutrinos can contribute to explain the matter-antimatter asymmetry in the Universe.



The LIP Neutrino Physics group joined DUNE in 2018. The activities are focusing on the design and construction of the far detector calibration systems and in the operation and analysis of the ProtoDUNE prototype detectors at CERN. Testing the designs of the calibration systems at ProtoDUNE-II is a priority for the next few years. After having completed the main aspects of the design for the ionization laser calibration system for the DUNE far detector, in 2021 we proceeded towards the demonstration of that design in ProtoDUNE. Some system parts were produced and tested at LIP's Mechanical Workshop and Detectors Lab. Most components were then shipped to LANL for the full system assembly. The group also progressed on the design of the interface electronics between the laser system and the DUNE DAQ and SC and initiated the implementation of the calibration control software.

SHIP and SND@LHC

The SHiP experiment at CERN is being designed to search for extremely feebly interacting particles (FIPs) and to measure neutrinos. It is planned to be located in a new beam dump facility using the high-intensity, 400 GeV/c protons beams from the SPS accelerator. SHiP constitutes a long-term, general-purpose facility offering high sensitivity for the discovery of FIPs, which arise in various models as mediators between the SM and hypothetical "dark sectors". The physics program of SHiP encompasses a SM precision component involving heavy flavour and neutrino physics, specially allowing for a unique study of the tau neutrino. The involvement of the LIP group in SHiP includes detector development, with focus on RPC technology, and physics studies, with focus on machine learning. With the SHiP timeline delays, activities were refocused in the shorter-term to the SND@LHC project. SND@LHC is the most recent LHC experiment. It stems from the SHiP neutrino detector and is located in the LHC tunnel away from collision points and near the beam-line direction. It shall utilize the potential of the LHC as a neutrino factory to perform measurements with all three neutrino flavours, providing first observations of collider neutrinos. The new experiment is being installed and commissioned, aiming at taking first data already in 2022, with the start of Run 3 of the LHC.

The LIP group is involved in the construction of the SND@LHC experiment. The year 2021 has been a determining one. Following submission of the Technical Proposal at the beginning of the year, the SND@LHC experiment was readily approved by CERN. The MoU for construction followed, having LIP as a founding institution with responsibility for the muon system of the experiment. The mechanical parts of the system were produced almost entirely by LIP's Mechanical Workshop. Design optimizations were implemented with our collaborators in Berlin, Bologna, Mainz, and Zurich. Following intensive production and test assembling in Coimbra, the detector structures were shipped to CERN, assembled, and tested. The commissioning phase followed, including data taking with two test beams. The system was installed in the LHC tunnel. The LIP group was very actively involved in all phases of the process. A member of the group presented first SND@LHC beam test data analysis results to the collaboration.

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Development of new instruments & methods

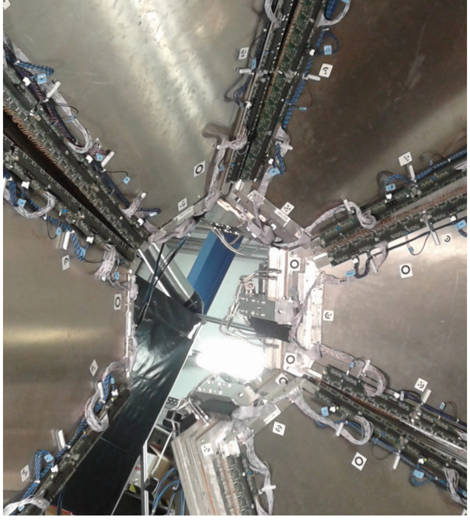
▪ Detectors for particle and nuclear physics ▪ Health and biomedical applications ▪ Space applications

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 systems 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. Over the years, LIP has built 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 the ICNAS institute for nuclear health applications, the CTN/IST centre for nuclear technology, 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.



Detectors for particle and nuclear physics

Technology to see the invisible

The development of particle detectors and related instrumentation has been, from the start, one of the pillars of activity at LIP. Over the years LIP has built a high level of expertise in key radiation detection technologies, supported by research on the fundamental processes involved. Our specialties include Resistive Plate Chambers (RPC), neutron detectors, gaseous and Xenon-based detectors, optical fibre calorimeters and fast electronics for data acquisition systems. Both applications to other fields and the preparation for future experiments open great opportunities for detector R&D.

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

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

RPC-PET: medical imaging

The development of RPC-based devices for medical imaging through Positron Emission Tomography (PET) is a priority for LIP. The group is currently focused on HiRezBrainPET, human-brain PET device developed in collaboration with the company ICNAS Produção. In 2021 all components of the HiRezBrainPET system (designed almost entirely by LIP) have been built, the system has been fully assembled, and is now ready to start performance evaluation tests. For further details, please go to the Health and Biomedical Applications research line.

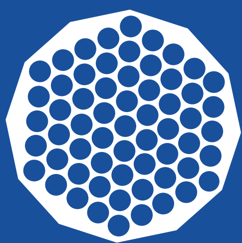
Time and position sensitive RPC

Many large particle physics experiment presently use RPC-based detectors: their very good time precision is

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.



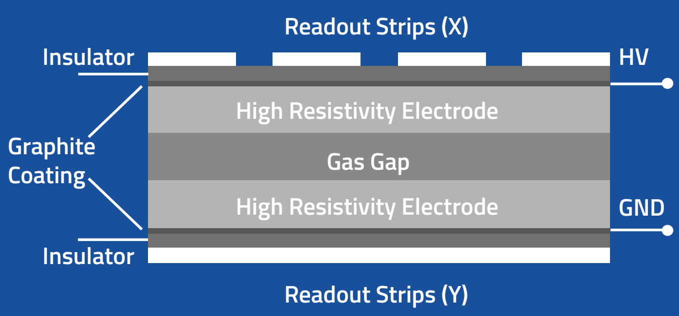
Liquid Xenon detectors

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.

ideal for trigger or timing, and they can cover large areas. The LIP RPC group develops and builds RPC detectors for particle and nuclear physics experiments using an innovative technology that allows for 98% efficiency and 50 ps time precision. In 2021 and early 2022 two such systems were installed at GSI, in the two experiments in which LIP participates. The construction and testing with cosmic rays of the third and fourth sectors of the RPC-TOF-FD detector for HADES were completed before the end of 2021 and the two sectors were installed and tested in the beginning of 2022. An RPC detector has been installed in R3B and is currently in the calibration phase.



Resistive Plate Chamber (RPC)

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

Both experiments will operate during the 2022 phase 0 campaign of FAIR. For further details, please go to the Structure of Matter research line.

As for position information, it depends essentially on the chosen configuration for the readout strips and data acquisition channels. The precise measurement of position in combination with time is of interest for particle identification, based on the measurement of the time-of-flight of particles. In addition, it finds direct application in muon tomography. Cargo container muon scanner units (STRATOS) were developed, prototyped and built at LIP for the company HIDRONAV. The first unit was transferred to the company in 2021 and is operational; the second one is close to completion. Each STRATOS unit is a four-plane telescope. Planes have a homogeneous efficiency around 98%, 2D spatial precision better than 1 cm and an industrial design that facilitate deployment. In the framework of an exploratory project on muon tomography of geological structures to be developed in the Lousal mine (Alentejo), a muon telescope was fully integrated at the beginning of the year. Field operation started by muographing the Physics Department building in Coimbra. For further details, please go to the Muon Tomography report, in the Science and Society section.

Autonomous RPC

Cosmic-ray experiments often require operating detector arrays in remote locations, with little maintenance and under harsh conditions. The development of RPCs able to operate outdoors in a reliable and performant way, solar powered and with very low gas consumption is thus of great interest. In particular, sealed RPCs will be a breakthrough in the field, and LIP is close to achieving this goal. In 2020 sealed RPC (0.5 x 0.5 m^2) have been in operation for eight months with no performance degradation. In the context of R&D for the gamma ray observatory SWGO, RPCs are being pushed to another limit: operation at an altitude close to 5000 m, under very low atmospheric pressure. In 2020, chambers have been successfully tested at pressures from 1000 mB down to 400 mB (about 6000 m altitude). These topics are part of a recently approved project and will have high priority in 2022.

RPC-based neutron detectors

Neutrons are a unique probe for revealing the structure and function of matter from the microscopic to the atomic level. Neutron scattering can be applied to a wide range of scientific domains, including physics, chemistry, material science, geology, heritage, and life sciences. Neutron scattering instruments, and in particular the future European Spallation Source (ESS), will be prominent global research infrastructures useful to academia and Industry. Helium-3, a stable and rare isotope of helium, has a high absorption cross section for neutrons and is used as a converter in neutron detectors. The shortage of ^{3}He during the last decade and the ongoing construction of new high intensity neutron spallation sources motivated the development of alternative neutron detection technologies meeting the requirements of a new generation of instruments: high-rate capability, good space, and time resolution. The LIP group has introduced and is developing a pioneering concept of a position sensitive thermal neutron detector based on RPC lined with 10B4C as neutron converter. This technology offers very good space and time resolution, modularity, robustness, scalability, and low cost. We demonstrated that it could provide detection efficiencies above 60% and is well suited for neutron imaging (spatial resolution of 0.25 mm).

Our next aim was to design, optimize and construct a prototype of a 10B-RPC detector, demonstrating their ability to operate above 100 kHz/cm2 with the same efficiency and spatial resolution. Prototype design and simulation-based optimization were completed, construction materials were carefully selected and purchase. Combining all the results and knowledge acquired, we are now building a new neutron detector optimized for high rate, which will be tested in Spring 2022. Two papers have been published. Another goal was to investigate the capabilities of applications of 10B-RPCs for the characterization of delayed neutron emission in very exotic nuclei beta decay experiments. Based on simulation results, the best design was selected, and the expected performance fully characterized. Detection efficiency and flatness are quite similar to the ones of the best fast neutron detector for delayed neutron emission experiments operating today, while cost can be reduced by an order of magnitude. A paper has been submitted for publication in collaboration with the NUC-RIA Group.

Scintillating Detectors and Optical Fibres

LIP has expertise in detectors based on radiation-hard scintillators and scintillating or wavelength-shifting optical fibers. We decisively contributed to the ATLAS TileCal calorimeter and to a number of other projects. LIP has an experimental lab in Lisbon (LOMaC), dedicated to instrumentation for processing and characterization of optical wavelength shifting and scintillating fibres, plastic scintillators, and photomultipliers. Ongoing projects include collaborations with the LIP ATLAS, FCC, and Dosimetry teams. For further details please go see the LOMaC report, in the Research Infrastructures section, or the relevant group reports.

Gaseous detectors and RD51 collaboration

The Gaseous Detectors R&D group develops research in the performance of gas detectors. Its main investigation areas are the study of the drift parameters of electrons and ions (both positive and negative) in noble gases and mixtures, with the aim of finding the more suitable active medium for each application. Both simulation studies and experimental measurements are conducted. Recent or ongoing studies include: the electroluminescence xenon TPC used by the NEXT collaboration to search for neutrinoless double beta decay; the measurement of negative ion mobilities, as the use of electronegative dopants in the gas mixture is being considered in several experiments; the identification of ions and measurement of their mobility in mixtures of interest for the RD51 collaboration, that aims at developing novel gaseous detectors with microstructure. Another line of work within CERN's RD51 collaboration concerns R&D on liquid xenon detectors.

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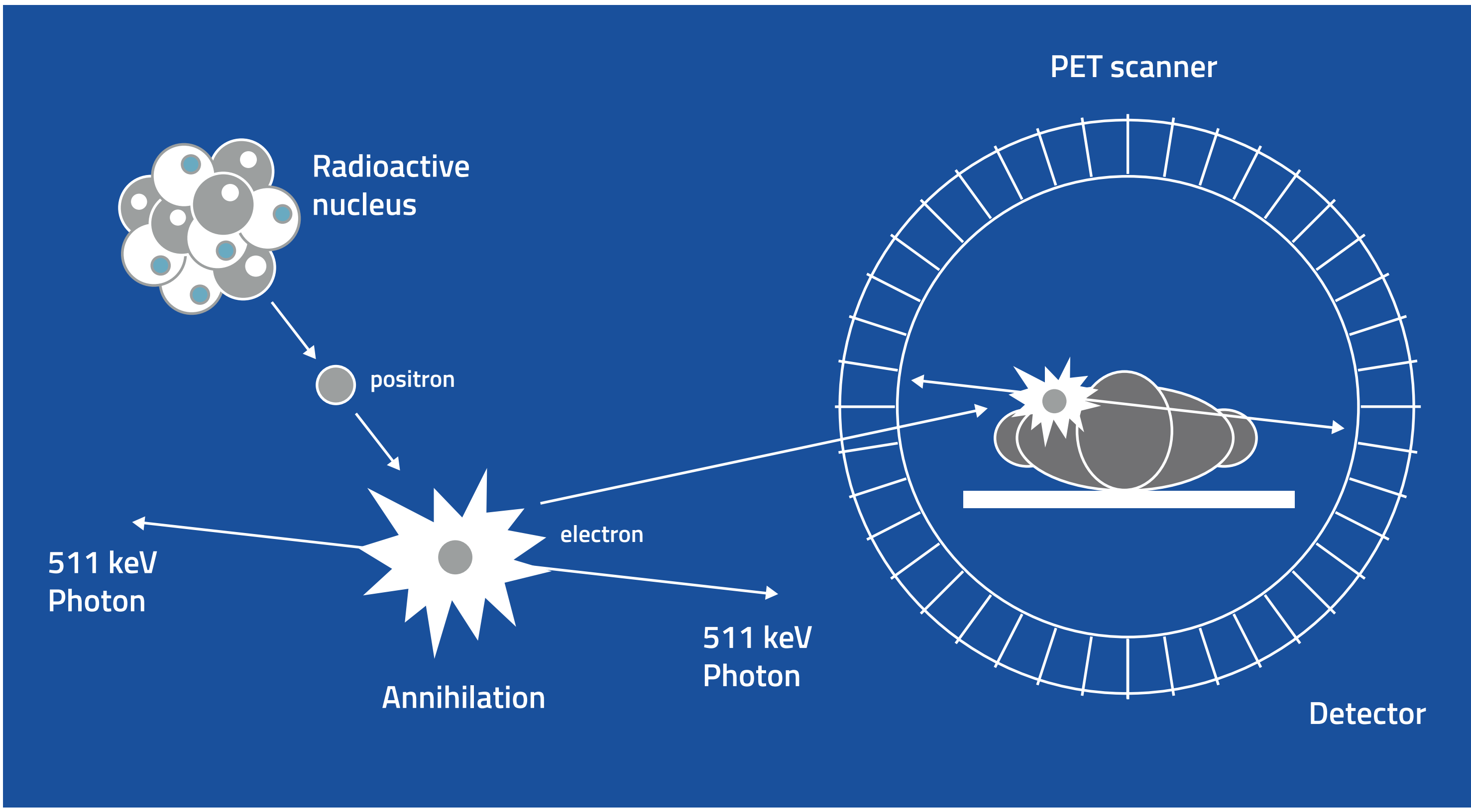
DEVELOPMENT OF NEW INSTRUMENTS AND METHODS

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. A centre for proton therapy will be installed in Portugal in the near future. LIP is a founding member of the Portuguese Network of Infrastructures for Proton Therapy and Advanced Technologies for Cancer Prevention and Treatment (ProtoTera), jointly with the Portuguese Institute of Oncology Hospital Group, Instituto Superior Técnico, and the University of Coimbra (Resolution of the Council of Ministers n. 28/2018). ProtoTera will promote and develop a national network for research, education and treatment of cancer using advanced technologies, such as proton therapy. The first two nodes are expected to be operating by 2026: a 250 MeV proton accelerator coupled to two treatment rooms and one research room in Sacavém, Lisbon; plus, a 70 MeV accelerator for the treatment of ocular melanoma and radioisotope production in Coimbra. Several research lines and technologies are core to the success of this interdisciplinary infrastructure: improvement in dose distribution, in vivo dosimetry and dose estimation, organ mobility, toxicity, imaging, computing technologies. On the other hand, R&D activities with good cross-fertilization prospects include radiation detectors, imaging techniques and devices, radiobiology, radiation effects on electronic devices, among others. These lists match the competences of several research groups at LIP with already secured funding in collaborative projects with companies. Close collaborations with international reference centres have been established, namely CERN, GSI, Heidelberg University Hospital (Germany), MD Anderson Cancer Centre (USA) and Trento Proton Therapy Centre (Italy). A PhD grant's programme was created in 2020, under an agreement between FCT and ProtoTera. 13 grants have been awarded.



RPC for medical imaging

Positron emission tomography (PET) is an extremely sensitive technique of medical diagnosis. A radioactive marker is injected in the patient's body, releasing positrons in the zone to study. When the positrons encounter electrons from neighboring molecules, they annihilate, producing two energetic photons traveling in opposite directions. These photons are identified by the surrounding detectors to create detailed images of the organism and to monitor dynamic processes. This line of work has been pursued by the RPC team at LIP for a number of years. A high-resolution, small animal RPC-PET scanner developed at LIP is installed at ICNAS since 2014. Hundreds of tests have been performed in mice, with goals such as studying degenerative diseases or testing new drugs.

This technology is now being applied for human brain PET, in the framework of the project HiRezBrainPET. This equipment has the potential to change the paradigm in the diagnosis and investigation of diseases of the central nervous system by allowing, for example, 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. In 2021 all components of the HiRezBrainPET, mostly designed at LIP, have been built. The main parts are individual head mechanics and head support structure, 300x300 mm^2 five-gap RPC detectors, signal pickup electrodes and interface PCBs, charge and time amplifiers, digital data acquisition system, low and high voltage power supplies, I2C based control system and gas distribution system. The system has been fully assembled and is ready to start performance evaluation tests. Tests with cosmic rays indicate a spatial precision well below 100 us and a timing precision better than 200 ps, perfectly suitable for Brain PET tomography. The next ambitious R&D project would be a full body human PET system, increasing the overall sensitivity as much as 10-fold, with a spatial resolution of 2 mm across the entire field of view. This requires a considerably higher level of funding which is yet to be secured

Collaborations & partnerships

HiRezBrainPET: neurofunctional cerebral imaging by high resolution positron emission tomography, led by ICNAS-Produção, LIP is main R&D partner

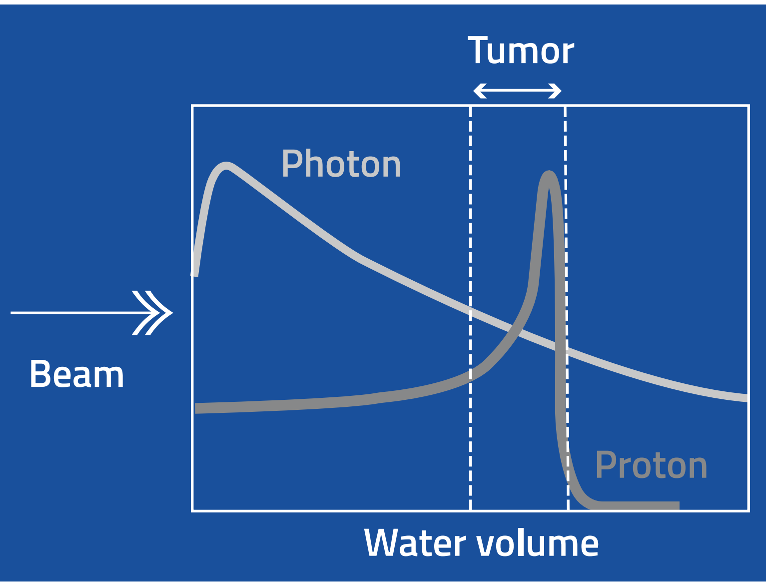
TPPT: TOF-PET for Proton Therapy, led by LIP's spin-off PETsys, PT-Austin collaborative project

PrototerapiaPT+: real-time prompt gamma imaging and microdosimetry, led by LIP, CERN fund.

FCT Strategic Infrastructures Roadmap 2020: LIP is a partner in ProtoTera and Brain imaging network (BIN)

CERN medical physics KT forum: contact person in Portugal is Paulo Crespo (LIP)

Advanced training partnership: co-supervision of PhD and MSc students with J.Seco (DKFZ and Univ. Heidelberg)



Proton-therapy

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

Proton-therapy Instrumentation

Real-time beam monitoring and imagiology

Since several years researchers at LIP are committed to R&D in instrumentation for radiation and particle therapy. The aim is to optimize the treatment in near-real time, so that the irradiation can better accommodate the tumor and spare surrounding healthy tissue. To do this, we make use of x- or gamma-rays emitted orthogonally to the treatment beam. The orthogonal ray (OR) Imaging technique can be divided into two main branches: OrthoCT (orthogonal computer tomography) for monitoring radiotherapy (high-energy x-rays); and O-PGI (orthogonal prompt-gamma imaging) for monitoring proton therapy. The rotation-free, low-dose imaging capability of such techniques are two of their strengths. On the last few years, both experimental work and ever more realistic simulations have been performed. The goal is to demonstrate beyond doubt to the medical community the usefulness of such techniques in a variety of cases: head-and-neck, pelvis, lung, total-body irradiation in pediatric tumors, among others.

In 2021 a full O-PGI simulation with a clinical proton beam of 200 MeV (prostate and pelvic irradiation with bone tumor very close to the spinal cord) was performed, and the results were accepted for presentation at the 2022 International Conference on Monte Carlo Techniques for Medical Applications. The experiment to be performed at the clinical proton therapy facility TU-Delft site, HollandPTC was postponed due to the restrictions imposed by the pandemic. In what concerns our simulation engagement with the TPPT consortium, the goal is to adapt one or more DICOM-based (Digital Imaging and Communications in Medicine) computed tomograms and proton therapy treatment plans into the GEANT4 simulation framework, so that both O-PGI and PET simulations can be conducted based on this information. This has been accomplished for the computed tomograms of the head of a pediatric patient lent by the MDACC. Adapting a treatment plan onto GEANT4 is still ongoing, with results expected by mid 2022.

Dosimetry

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

The first area includes the development of a new detector capable of measuring energy depositions at the sub-millimeter scale using scintillating plastic optical fibres (SPOFs). The surface of the detector's sensitive area will act as a support for the growth of cell cultures or biological tissues to be irradiated. This project is being developed with the collaboration of the Biosystems and Integrative Sciences Institute (BioISI) at FCUL, ULisboa. In the second area we are using simulation tools to study the physicochemical effects of radiation and from these infer biological effects. The group has been acquiring skills in the TOPAS code and its extension TOPAS-nBio that allows simulating point-to-point energy deposition processes as well as reactive oxygen species production. Applications include different types of emerging modalities in radiotherapy: nanoparticle radiosensitizing RT, minibeam RT, ultrahigh dose rate RT (FLASH-RT), among others. This research is being carried out in collaboration with national and international research centers, namely C2TN-IST, ICNAS, Champalimaud Foundation, German Cancer Research Center (DKFZ) and Institut Curie (IC-CNRS).

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

The JUICE ESA mission to the Jovian system has launch foreseen in 2022. JUICE's radiation monitor RADEM (RADiation hard Electron Monitor) was developed by a consortium including LIP and EFACEC SA in Portugal, Paul Scherrer Institute in Switzerland, and IDEAS in Norway. LIP worked on the RADEM detector design, response and calibration, radiation analysis, and testing of the radiation effects on the electronics. The beam tests and calibration of the RADEM Flight Model finished in November 2021.

LIP is also contributing to the Juice Science Working Team for future analysis of cruise data and cross analysis of RADEM data with other instruments on board of JUICE.

LIP has developed dMEREM — detailed Martian Energetic Radiation Environment Model in 2009 within ESA's contract Martian Radiation Environment Models. dMEREM is available to the community in the Space Environment Information System SPENVIS. The validation of the dMEREM upgrade with data from Mars Curiosity Rover radiation detector on the Martian surface was performed and the corresponding paper was accepted for publication. The upgraded model be used in assessing radiation hazards in future crewed missions to Mars and in astrobiology studies.

AlphaSAT is the largest ESA telecom satellite, in geostationary orbit (GEO) since July 2013. LIP has been collaborating with EFACEC SA and EVOLEO SA in different contracts regarding the AlphaSAT radiation Environment and Effects Facility (AEEF) and is responsible for the analysis of the in-flight data of AEEF's particle spectrometer and radiation monitor MFS (Multifunctional Spectrometer), and also of its CTTB (Component Technology Test Bed). Valuable scientific data acquired during five years are being analyzed. LIP developed an unfolding method to obtain the MFS measured fluxes. Correlations of CTTB data with solar activity were presented at RADECS2020 and received the award of the Best data analysis Workshop paper, given during RADECS2021, and a paper was published.

Astrophysics instrumentation in space

Knowledge of the polarization state of radiation provides much astrophysical information that cannot be obtained from intensity alone. In fact, polarimetry provided insight into physical processes occurring in a diversity of systems, from our own solar system to distant galaxies.
However, in what concerns high-energy astrophysics (x- and gamma-ray astrophysics) polarimetry has known very few developments, despite its great potential to open a new scientific observational window. LIP's Astrophysics instrumentation (i-Astro) group holds high-level competences in instrumentation for astrophysics with emphasis in x- and gamma-ray polarimetry. The group contributes to the development of space instrumentation based on semiconductor detector planes (CdTe, CzT, Si, Ge), scintillators (CsI) or gas-filled detectors with polarimetric capabilities. More recently, the competences of the group have been applied to the study of the effects of Terrestrial Gamma-ray Flashes (TGFs), which are bursts of gamma rays produced in Earth's atmosphere, which may affect the health of aircraft crews and passengers.

The group develops its research activities in the framework of mission proposals to ESA, NASA and EU, in the domains of X- and gamma-ray space astrophysics and Terrestrial Gamma-ray Flashes emission effects. i-Astro is currently part of the EU project consortium "Activities in the High Energy Astrophysics Domain" (AHEAD2020) as well as of the NASA mission proposal consortium "All-sky Medium Energy Gamma-ray Observatory" (AMEGO). In these projects, our group develops detection space instruments based in CdTe, CZT, CsI, Si solid-state detectors. The project "Gamma-ray Laue Optics and Solid State detectors experiment" (GLOSS) onboard the ISS started in July 2021. It is led by LIP in collaboration with University of Beira Interior and several Italian research institutions, namely INAF, University of Ferrara, Active Space, and Istituto dei Materiali per l'Elettronica e il Magnetismo (IMEM, Parma). GLOSS will test and characterize CZT samples onboard the ISS Bartolomeo platform. 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.

Within ESA's program BEXUS (Balloon EXperiments for University Students), and under the guidance of LIP researchers, a group of students from the University of Coimbra proposed the experiment STRATOSPOLCA — BEXUS STRATOSpheric POLarimetry with Cadmium Telluride Array experiment, with the goal of measuring the stratospheric background noise for space Compton astrophysics polarimeters. After some delays caused by the pandemic, STRATOSPOLCA was launched on 29 September 2021. The instrument, based on a small CdTe 5×5 pixels (each 2×2×10 mm3) prototype that, was accommodated in the balloon gondola and flew four 3 hours up to a maximal altitude of 27.7 km.

The project "Terrestrial Gamma-ray Flash Science and Monitoring for Aviation Safety" (TGF Monitor) address a major aviation safety concern and may have a real impact on the aircraft safety standards. A solution for TGF onboard monitoring is also proposed and a CdTe laboratory monitor prototype will be developed and tested.

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Computing

▪ Scientific computing

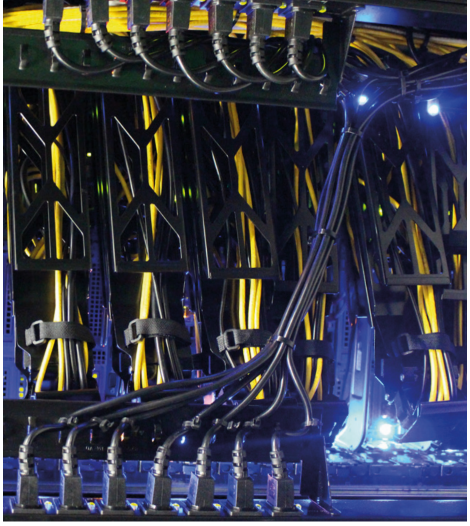
Scientific research requires increasingly higher data storage and processing capacities that stress the limits of information systems and related technologies.

LIP participates in some of the largest European R&D projects in this field and operates the largest scientific computing facility in Portugal. The facility is part of the Worldwide LHC Computing Grid (WLCG) and delivers computing and storage capacity to high energy physics experiments and to the research community in a large ensemble of scientific domains.

In partnership with FCCN and LNEC, LIP leads the National Distributed Computing Infrastructure (INCD), which is part of the Portuguese Science Foundation Roadmap of Research Infrastructures of strategic relevance. Scientific computing is certainly one of the areas placing LIP at the forefront of innovation.

LIP has growing expertise in data science and big data analytics that open opportunities for knowledge transfer and for addressing societal changes. The arrival of the SPAC group very much strengthened this domain and opened new research lines in social physics and complexity.

The LIP computing groups have extensive knowledge and experience in scientific computing, excellent international relations, and integration in scientific e-infrastructures with users from multiple disciplines and organizations, participating in the FCT infrastructures and in the enabling of future policies for scientific computing, data science and open access.



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, and in the enabling of future policies for scientific computing and open access. LIP has growing expertise in data science and big data analytics that open opportunities for knowledge transfer and for addressing societal changes. The arrival of the SPAC group very much strengthened this domain and opened new research lines in social physics and complexity.

Distributed computing and digital infrastructures (GRID)

The LIP Distributed Computing and Digital Infrastructures The LIP Distributed Computing and Digital Infrastructures group provides information and communications technology (ICT) services to LIP. These services support research, innovation, education and outreach, and administrative activities. The group has extensive experience in delivering compute and data-oriented services for simulation, data processing and analysis. In particular, the group operates the Portuguese Tier-2 facility integrated in the CERN Worldwide LHC Computing Grid (WLCG). WLCG is 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 2021 the LIP Tier-2 in the WLCG executed more than 486,000 jobs and delivered more than 111,000,000 HEP Spec06 normalized processing hours, corresponding to 110% of the pledged capacity. Overall, the reliability was 97%.

The group activities bridge at international level with science related infrastructures and initiatives such as the European Grid Infrastructure (EGI), Iberian Grid Infrastructure (IBERGRID), European Open Science Cloud (EOSC) and EuroHPC. In this context the group collaborates with several international research communities beyond particle physics. In the framework of IBERGRID and EGI, LIP ensured the national liaison and coordinated the operations of the Iberian distributed computing infrastructure and its integration in the pan-European EGI infrastructure. IBERGRID delivers federated cloud, HPC and HTC to support international projects and initiatives of common interest to Portugal and Spain.

The development of the group competences and capabilities is backed by the participation in R&D&I projects at national and international level. The group participates in European projects related to the development and exploitation of digital technologies applied to both compute and data intensive science. The current activities are focused on data processing using cloud computing, High Throughput Computing (HTC), High Performance Computing (HPC), and machine learning.

The LIP Computing group is currently participating in the following H2020 projects: in EOSC-Synergy, which aims at aligning national infrastructures and policies in Spain, Portugal, UK, Czech Republic, Germany, Slovakia, Poland and The Netherlands, developing a platform for quality assurance on-demand for software, services and data; in EOSC-Future, providing software and IT service management for the EOSC core; in EGI-ACE, delivering the middleware management for the EGI international federation, supporting Cloud applications and working on solutions for wider high performance computing (HPC) integration; In the context of the EuroHPC initiative for a world class supercomputing ecosystem in Europe, LIP participated in the EuroCC project to establish a national advanced computing competence centre. LIP coordinated the awareness creation and communication task and participated in the support, consulting, technology transfer and training activities. LIP also participated in the BigHPC project that is developing a framework to support Big Data applications in HPC environments; the contributions were mainly focused on quality assurance, monitoring and containers support.

Based on its accumulated experience the group is also delivering scientific computing services to the wider Portuguese scientific and academic communities in the context of the national multidisciplinary digital infrastructure INCD (National Distributed Computing Infrastructure). The group is also engaged in national activities related to high performance computing in the context of the National Advanced Computing Network (RNCA). Both INCD and RNCA are part of FCT's roadmap of research infrastructures of strategic interest.

LIP participates in the management bodies of the INCD Association and coordinates all technical activities. In 2021 the INCD infrastructure has delivered more than 33 323 114 CPU hours. LIP is also managing the participation of the INCD Association in several projects. These include the implementation of a national catch-all repository for scientific data in partnership with FCT, implementation of Earth observation services exploiting Copernicus data in the C-Scale project, delivery of cloud computing services to support thematic services in biodiversity and coastal engineering in the EGI-ACE project, and integration of compute and data services in the framework of the EOSC-Synergy project.

LIP collaborates with FCT also in the framework of RNCA as part of the group that is establishing the foundations for this FCT network joining scientific computing centres in the country. The joint LIP/INCD team supported more than 40 computing projects from the first FCT call for advanced computing projects. The team also participated in the preparation of the second FCT call for advanced computing projects launched in the Summer.

The formal accession of INCD to the RNCA network as an operational centre was signed.

Finally four proposals to Horizon Europe were approved and the projects will start in 2022. AI4EOSC and iMAGINE focus on the support to artificial intelligence (AI) applications. DT-GEO and interTwin focus on digital twins in multiple domains, from Earth sciences to particle physics and climate research.

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Social Physics and Complexity (SPAC)

SPAC uses large scale computational tools to study societal challenges, especially in disease forecasting, human behavior, and public policy, using a complex systems approach. SPAC joined LIP during the second half of 2020. Its work is mainly funded by a European Research Council (ERC) Starting Grant to the group's PI to conduct the research project "Fake News and Real People – Using Big Data to Understand Human Behaviour (FARE)".

Understanding complexity has always been a hallmark of physics research and, right now, the Digital Revolution is offering radically new ways to study complex human behaviours. There is a growing perception that physics will be fundamental to study sociology and even psychology. Leading scientists are calling this new science "Social Physics" and arguing that, in some ways, complexity science will study the physics of human interactions. SPAC is very multidisciplinary with members having backgrounds in Physics, Mathematics and Computer Sciences, but also in Biology, Neurosciences, Psychology, and Law. Together, the group takes advantage of the so-called "Big-Data Revolution" and aims at understanding how individual behaviour impacts on society. SPAC also focuses on the risks that these upcoming technologies might entail, from privacy to biases, and works to establish guidelines for ethical uses of data science and artificial intelligence.

In 2021, SPAC set the cornerstones of the FARE project, namely designing the large-scale survey, and designing the databases. Two manuscripts are in the last stages of preparation and the team is actively collecting "big" data. In parallel, SPAC participated in the pandemic control efforts, in collaboration with different entities. The group finished a long-term project on analyzing 40 years of Portuguese political discourse. This work has led to a large corpus of the parliamentary debates (published in November 2021), one searchable repository, open and of free access to journalists and the scientific community, one in-depth report, sponsored by the Calouste Gulbenkian Foundation, on the public salience of "Intergenerational Justice" as a political concept, and one manuscript submitted during 2021. Research on the current pandemic has led to two working papers, both on medrxiv. Several group members actively collaborate with national health authorities on mitigation and information capacity building and participated in a broad effort to produce a roadmap for pandemic control, made publicly available in March 2021. In parallel, all group members received full training in GDPR and compliance with the EU privacy standards and SPAC should become officially certified during 2022.

SPAC intends to internationally cement its position in social physics research and help improve the current national research capacity, mostly through infrastructure creation and postdoctoral training. In a broad way, the development of the field of "Social Physics" will rely strongly on applying theoretical models from physics (e.g., diffusion, statistical physics) and simulation techniques to human interactions. Therefore, it is expected that strong collaborations will arise with different LIP group, which can expand to international partners, including CERN, that are strongly growing their DS&AI resources. Finally, the group accepts its strong social responsibility and, parallel to scientific output, consistent efforts will be developed to improve public understanding of science and of the current risks brought about by the digital revolution.

SPAC is strongly involved in science communication and outreach.

Joana Gonçalves de Sá was distinguished with the "Mulher Activa" award in the Science category.

During 2021, she participated in 8 round tables, both in Portuguese and English, wrote 2 newspaper opinion articles and gave 5 interviews to the media, both on disinformation and COVID-19 control.

Research Infrastructures & Competence Centres

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

Competence Centres ▪ Monitoring and Control ▪ Simulation and Big Data

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

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

REASEARCH INFRASTRUCTURES

Computing

LIP Computing Infrastructures provide scientific computing services to LIP and to a wider community in the context of the national multidisciplinary digital infrastructure INCD (National Distributed Computing Infrastructure). LIP participates in the management bodies of the INCD Association and coordinates all technical activities. INCD provides advanced computing and data-oriented services to the Portuguese scientific and academic communities. It supports all scientific and technological domains enabling computing and data intensive research. INCD also supports the use of international resources through the connection to European digital infrastructures such as EGI, IBERGRID and WLCG. In 2021 INCD operated and made available computational and data services, providing more than 33 323 114 CPU hours. The INCD resources were also used to support teaching and advanced training. In the European project EOSC-Synergy, INCD contributed to policy harmonization and federation of thematic services,
data and computing resources within the scope of the European Open Science Cloud (EOSC). As member of the National Advanced Computing Network (RNCA), a joint LIP/INCD team supported more than 40 projects from the first FCT call for advanced computing projects. The team also participated in the preparation of the second FCT call for advanced computing projects launched in the Summer. For further details please see the LIP Computing group report above.

REASEARCH INFRASTRUCTURES

Laboratory of Optics and Scintillating Materials (LOMaC)

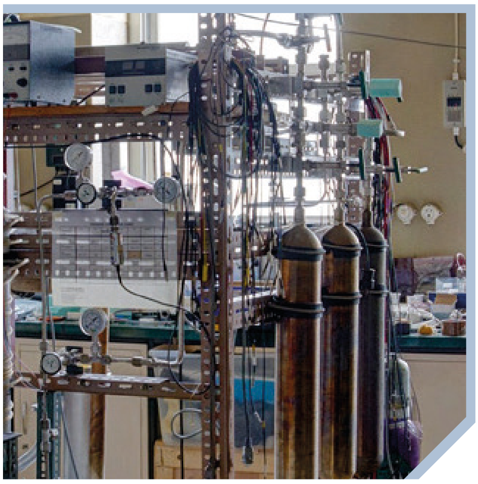
LOMaC was created in the context of the ATLAS TileCal project in the 1990s. The entire set of plastic wavelength shifter (WLS) fibres for the TileCal has been polished, aluminized and quality controlled at LOMaC. Along the years, LOMaC selected and/or prepared optical fibres and scintillators for several experiments, including DELPHI, SNO+ and the ATLAS ALFA luminosity monitor. LOMaC's expertise is centered on the preparation and test of plastic WLS and scintillating optical fibres, scintillators and related devices for particle and nuclear physics detectors. LOMaC has facilities for cutting, polishing, and aluminizing (by magnetron sputtering) bundles of optical fibres; automated devices for the characterisation and test of optical fibres, scintillators, and light sensors, and equipment to measure absolute light yield.
In 2021 LOMaC focused mostly in three projects: i) development of a high-resolution dosimeter prototype (submillimetric resolution), in collaboration with the Dosimetry group and e-CRLab. The first set of modules of scintillating fibres arrays was prepared and polished. A first prototype is expected to be concluded in 2022; ii) radiation hardness studies of TileCal scintillators and WLS fibres, focusing on HL-LHC as well as on future detectors. The study uses data from the TileCal calibration systems collected along the years of LHC runs; iii) support to the development of the high-voltage boards for the TileCal upgrade, in collaboration with the e-CRLab and the LIP ATLAS group. Research of new scintillating materials for future detectors started in a collaboration with the Institute for Polymers and Composites (IPC) of UMinho.

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 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 3x2 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 external companies.

The main projects schedule for 2021 were completed respecting the pre-defined delivery times, even if work that was not foreseen was required in all cases. Highlights were the construction of the mechanical parts for HirezBrainPET, protoDune and HADES RPC-FD. New internal projects arised during the year, in particular the production (including design checking) of the mechanics for the upstream and downstream modules of the SND@LHC detector. Some of the MW's external clients in 2021 were: CNC-Centro de Neurociências e Biologia Celular, TEandM-Tecnologia e Engenharia de Materiais S.A., ITAV-Instituto do Ambiente, Tecnologia e Vida, Universidade de Santiago de Compostela, SerQ-Centro de Inovação e Competências da Floresta, IT-Instituto de Telecomunicações, HIDRONAV Technologies SL, ICNAS-Produção, MARE-UC, among others.



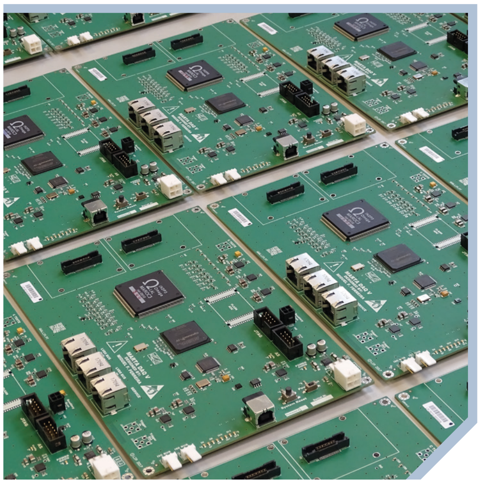
REASEARCH INFRASTRUCTURES

Detectors laboratory (DL)

The Detectors Laboratory was created at LIP's foundation in 1986 with the aim of supporting the experimental activities developed by the research groups. Along the years the DL has been continuously updated considering both general and more specific needs. Today the available equipment and technical staff allow for a variety of services, including the design, construction and repair of electronic circuits and vacuum systems, and the design, construction and testing of particle detectors. DL services span from the project design phase to installation and maintenance, following a procedure similar to industries.

In 2021 the main activities of the DL concerned the R&D and production of different types of large area Resistive Plate Chambers (RPC) used in experiments and projects in which LIP is involved, the support to LIP groups in their R&D activities, and products and services delivered to external institutions through contracts. Highlights were the production of the HiRezBrainPET scanner in collaboration with the MW and also the production and installation at GSI of the second half of the HADES-FD detector. The DL also contributed with technical work and added value to many other LIP groups, including: NUC-RIA, SND@LHC, RPC R&D, Gaseous Detectors, ORimaging, Dark Matter, i-Astro and the CCMC.

LIP's Detectors Laboratory and Mechanical Workshop have complementary competences, and many projects at LIP require the services of both facilities. MW and DL now share the same coordination, which is an important step to achieve optimal efficiency.



REASEARCH INFRASTRUCTURES

Cosmic-rays electronics laboratory (e-CRLab)

The e-CRLab is mainly dedicated to the development of electronics for cosmic ray experiments. 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.

The e-CRLab has the responsibility of the development, deployment, and commissioning of the electronics for the MARTA detectors to be installed at the Pierre Auger Observatory. During 2021 solutions for the issues previously found in the field were developed at the e-CRLab. The system for MARTA is now mature and tested, waiting for a possibility for deployment in Argentina. The developments in the MARTA front-end electronics were adopted for other projects. A new hodoscope setup consisting of two MARTA RPC planes separated by 3 m has been installed in the lab and will be used has a detector test bench. The e-CRLab has been involved in the development of the high-voltage (HV) system for the ATLAS TileCal upgrade, namely the HVsupplies board, and in identifying and proposing solutions for the several test setups and interconnects. A new project on the ATLAS High Granularity Timing Detector (HGTD) has been started. The expected contributions are two-fold: on the DCS, and on the testing and development of the ALTIROC ASIC for fast timing. This will be part of the in-kind contribution of Portugal to the experiment. There is also the opportunity to develop electronics and instrumentation for LIP's medical physics projects.

REASEARCH INFRASTRUCTURES

TagusLIP Laboratory

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

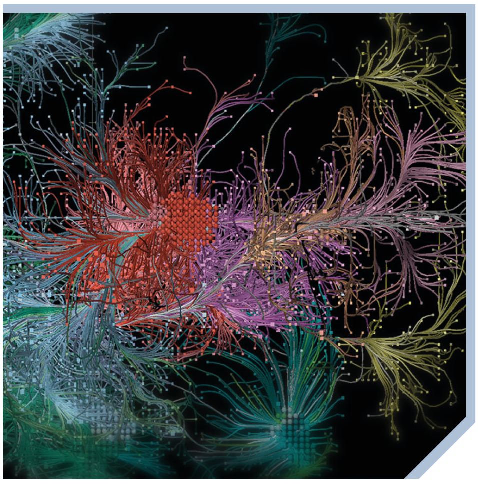
In 2021 the main users of TagusLIP were the LIP CMS group and PETsys. On the LIP side the activities concern the Phase-2 Upgrade of CMS. The development of the new ASIC TOFHIR2 board for the new CMS Barrel Timing Detector (BTL) was pursued. PETsys is responsible for the ASIC design and LIP develops the integration of the chip in detector modules (LIP-CERN Collaboration Agreement KN436/EP). Testing of the second version with improved performance (TOFHIR2X) started in July 2021. TOFHIR2X was integrated with sensor modules and tested successfully in a proton beam at CERN in October. PETsys concluded the design of the final version (TOFHIR2B) and submitted it for fabrication in November. The LIP CMS group pursued the development, fabrication, and test of the second prototype (FE_v2) of the BTL front-end board. In the end of 2021, the new boards have been integrated in the prototype of the BTL Readout Unit at CERN. PETsys leads the consortium Timeof-Flight PET for Proton Therapy, in which LIP is involved, and has the responsibility of developing the readout system.

COMPETENCE CENTRES

Monitoring and Control (CCMC)

The CCMC gathers expertise in design, implementation and operation of monitoring and control systems accumulated by LIP groups. Besides facilitating knowledge sharing, the CCMC aims at establishing partnerships and contracts with other research laboratories and companies as a means to transfer knowledge and solutions to the community. In 2021 the CCMC continued the development of the end-user software framework meant to be the basis solution when deploying its products. It is designed to be easy to adapt to the client's needs and to interface with virtually any monitoring and control hardware, while supplying a user friendly front-end for data handling. The CCMC has also implemented the temperature control software for the RPC modules installed in the HADES experiment at GSI.

Additional research concerned non-invasive temperature monitoring devices, embedded systems for heating, ventilating, and air conditioning (HAVAC) and machine learning in micro-controllers. The main external client in 2021 was the ECOTOP group from MARE (Univ. Coimbra), on the ongoing project to monitor physiological and environmental parameters in the natural habitat of birds. After the development of the electronic eggs for measuring the heart rate and temperature of nesting seagulls in 2020, Machine Learning tools for the extraction of such parameters were developedin 2021. The CCMC participated in the project outreach with a live presentation at the European Researchers' Night of the electronic eggs and of an interactive card game (adaptable to other topics). The CCMC is supervising three master students, one of them in collaboration with industry (Bosch Aveiro).



COMPETENCE CENTRES

Simulation and Big Data (SimBigData)

At LIP there is a wide range of competences in data analysis and simulation tools, including physics models, Monte Carlo generators, detector simulation tools, big-data analytics, and data mining. The ability to fully benefit from such competences requires exploiting synergies between groups and identifying key areas in which we can contribute in a competitive way. This is the purpose of the SimBigData CC. Concerning Simulation, the vast know-how in the GEANT4 toolkit and the contributions to the GEANT4 collaboration play a central role, while in Big Data the team is consolidating experience in anomaly detection in contexts where uncertainties play an important role. Training and knowledge sharing are additional goals.

Concerning simulation, several developments were undertaken in 2021 in the context of the specific activities of the LIP groups: training on advanced detector simulation at undergraduate and graduate levels; active participation in the GEANT4 collaboration, with development and support responsibilities by LIP members; support to the specific needs of LIP research groups; simulation of space radiation environments, in the context of the LIP SpaceRad group. On the Big Data side, in 2021 the BigDataHEP project was successfully concluded with several publications and theses completed. A follow-up project is being prepared. A new exploratory project on quantum machine learning started, as well as a new collaboration with the Centre of Physics of UMinho on to the use of machine learning techniques in condensed matter physics. The collaboration with Tellspec on the use of portable, near infrared spectrometers for quality control in industrial production lines continued, in collaboration with the Centre of Chemistry of UMinho.

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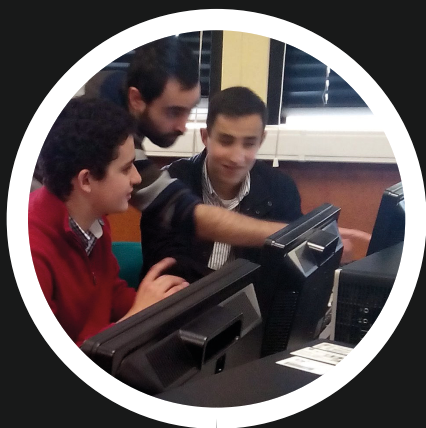
Knowledge transfer and **societal impact**

Radiation, health and **environment**

Muon tomography



Advanced training

Education, communication and **outreach**

LIP

science and society

Knowledge transfer and societal impact

Fundamental science drives innovation in the long term, and particle physics technologies have a wide range of applications, and the potential to respond to societal challenges. LIP is engaged on specific objectives that support public policies in the science, health, economy, social and environmental sectors. 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,supporting the school community; 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

Strategic areas for LIP's KT are healthcare, space application, data science and digital technologies. The list of companies the LIP groups have collaborated with in the last 5 years includes Adductio, Bosch, Cabelte, Dialog Semiconductors, EFACEC, EVOELEO, Grupo ASSEC, HIDRONAV (Spain), ICNAS-Produção, Ideas (Norway), Kinetic (UK), Nielsen, NuRise, PETsys, Siemens, Silicon Gate, Systion, Tellspec and Wavecom. Some of the main Portuguese research units and other public institutions we collaborated were CEFITEC/ NOVA, CFTC/FCUL, CFTP/IST, Champalimaud Foundation, CHUC, CTN/IST, FCCN/FCT, GHIPOFG, Hospital de Santa Maria, IBEB/ FCUL, ICNAS, ICT/U. Évora, INCD, INESC-ID, INESC-TEC, LNEC, MACC, MARE.

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 infrastructureshave proven a successful way to achieve these goals — by proposing partnerships, providing support or facilitating a first contact.

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 and will actively develop efforts to strengthen the collaborations with this network.

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.

National Roadmap of Scientific Infrastructures of Strategic Interest

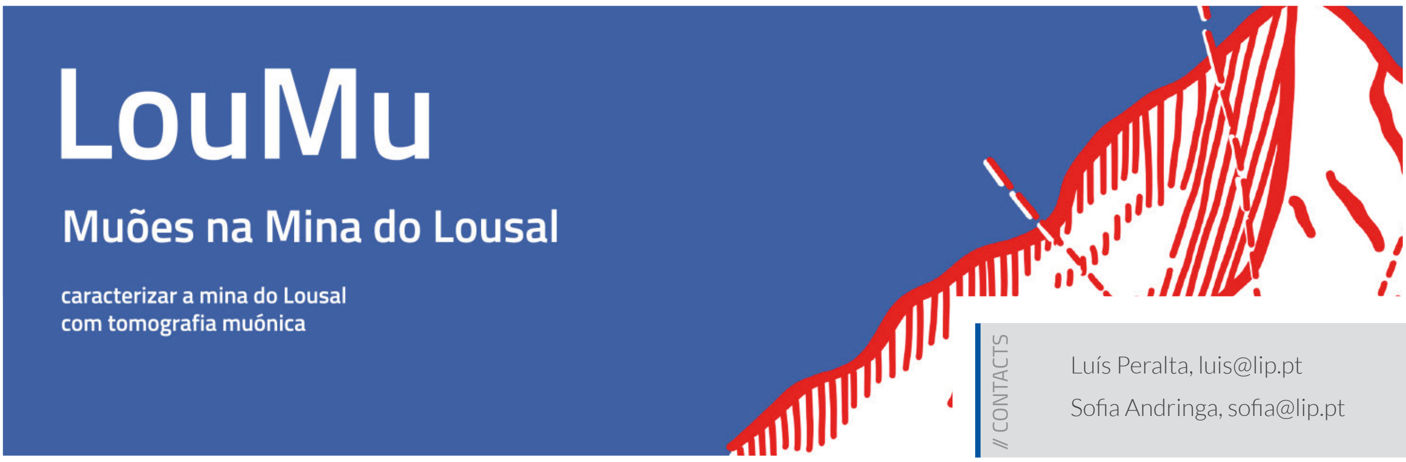
LIP is the technical coordinator of the National Distributed Computing Infrastructure (INCD); a member of the Nacional Advanced Computing Network (RNCA); founding member of ProtoTera; the main technological partner in several projects of the National Brain Imaging Network (BIN); a close partner of the Portuguese Space Agency (PT Space)

Radiation, health and environment

Radon measurements are currently the focus of activity of LIP's Radiation, Health, and environment group. This radioactive gas, abundant in granitic areas, is recognized as a carcinogenic agent, and is signaled by the World Health Organization as the second leading cause of lung cancer after tobacco smoke. Knowing its concentration inside houses is thus important from the point of view of radiological protection. In addition, Radon is the largest contributor for underground water radioactive pollution. The group's main laboratory for the radon study is the LabExpoRad. The facility is integrated in UBIMedical, the University of Beira Interior health technology park. The laboratory is equipped for the detection of radon in water and air. In the past few years, the work focus was on the measurement of radon in the air and water in Angola and the study of radon exhalation from building materials.

Muon Tomography

Muon tomography, a non-destructive imaging technique using the natural flux of atmospheric muons, has had a growing number of applications worldwide in the last decade. LIP has the expertise to contribute to the generalization of the technique locally and to help to establish it as a standard tool worldwide. The ongoing LouMu project conducts an exploratory muography subsurface geophysical survey to demonstrate the potential of the technique with a well-known target. We explore an existing muon telescope developed at LIP. LouMu is a partnersip with the Earth Science Institute (ICT) of the University of Évora and the Ciência Viva science centre at Lousal (CCVL), that houses an underground mining gallery. The telescope is made of 4-RPC planes of 1 m^2, mounted horizontally in a movable structure, that can be tilted up to 30º. A few percent accuracy is achieved in the contrast of the muon transmission images. In 2021 the telescope was optimized in the Laboratory and a campaign was started to muograph a part of the building where it was located in Coimbra. In 2022, the telescope will be moved to the underground gallery in the Lousal mine, and the geophysical survey will be started. The first surveys will guide us in the search for applications of muon transmission tomography in follow-up projects, and in the upgrade of telescopes, analyses tools and methods for new requirements.



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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) group 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. The onset of the pandemic two years ago led to disruption of several training activities. Some of the regular actions, that were in essence built upon in-person activities, have been delayed or canceled. Others have been adapted to a remote or mixed mode of operation and have successfully explored offline collaborating resources and novel opportunities. For 2022, it is anticipated, and hoped, that several activities can resume in in-person or mixed modes. Priorities include the LIP Internship Programme, Data Science school and workshop, IDPASC and LIP student workshop. Below we give an overview of what are the main advanced training event series at LIP, stating in particular what happened in 2021.

Graduate students

LIP permanently hosts tens of PhD, master, and bachelor students, who actively work within its research groups. This enhances the close connection between LIP and associated universities, namely in Lisbon, Coimbra, and Minho. Various actions are directed towards the PhD and master students working at LIP, and also in the framework of international PhD networks. During 2021, LIP hosted about 100 graduate students (about 35 PhD and 65 MSC). In 2021 FCT and LIP promoted calls within the PhD programmes PT-CERN and ProtoTera. In 2021, 19 fellowships were awarded within the two programmes.

IDPASC school

LIP coordinated the IDPASC international network. The 10th edition of the school of the IDPASC network, which aim is to train a new generation of high-level experts in the fields of particle physics, astrophysics, and cosmology, took place online, involving 22 students.

Student awards

UMinho's Initiation to Research Prizes given to LIP Summer Internship students Luís Amorim, Magda Duarte and Miguel Peixoto

LIP/IDPASC Students Workshops

Two-day meetings in which all PhD students present the status of their work to an audience of graduate students and researchers. Keynote lectures on selected topics (including some suggested by the students) are also part of the program. As an event in which the possibility of more direct social interaction and spontaneous discussions was considered a fundamental element the LIP/IDPASC student workshop was postponed and shall take place in 2022.

LHC Physics Course

Consists of close to 20 lectures covering introduction to the standard model, detectors, statistics, and overall research, held from March through May/June. The course has a final evaluation valid for ECTS credits at IST. In 2021 the course was given online. Eight students gave a final presentation followed by discussion that served as final evaluation, valid for ECTS credits at IST.

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Undergraduate students

LIP Internship Program

The Lab's flagship Internship Program remains active and attractive, benefitting from the ability to systematically improve at each edition. In 2021, the programme 5th edition counted as always on the broad participation of LIP researchers through the three LIP nodes, who served as project supervisors, delivered tutorials and lectures, guided topical discussions, and attended and contributed to the discussion at the final workshop. Over 50 project proposals were submitted, and a record number of student applications was received. The effort was made to accept a larger number of participants, about 100. Of those, 87 successfully completed the programme. The overall structure was kept starting with an introduction week in July (lectures and hands-on tutorials) and ending with a two-day workshop in September in which the students presented their work. Common activities were fully held online. In between, the participants carried out their projects, integrated in LIP's research groups. Mid-term activities involved social get togethers for participants.

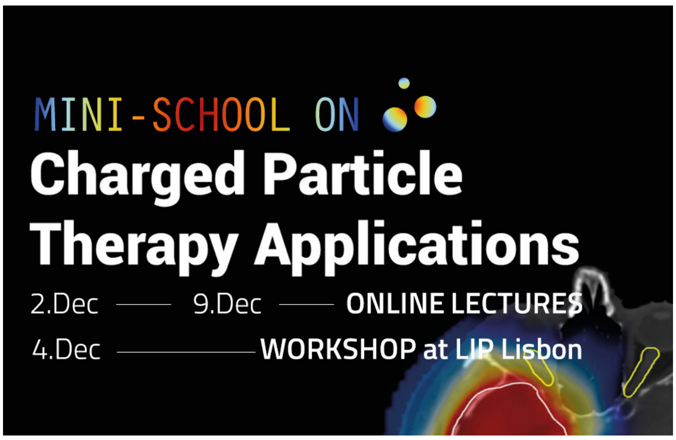
Outreach for undergraduates

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

Schools & workshops

LIP is involved in several regular school and workshop series directed at undergraduate students, which include lectures, hands-on exercises, and introductory overviews of ongoing research activity at LIP and in particle physics and its application in general.
In 2021, the following schools and workshops were held:

- 6th edition of the school, co-organized by LIP and CFTP: held exceptionally in a remote format in July, it gathered 25 undergraduate students from several universities.
- Mini-school on charged particle therapy applications: consisted of a combination of student talks and invited talks by experts, in a hybrid event that included a one-say in-person workshop at LIP, involving about 40 participants.



Education, communication and outreach

Education, Communication and Outreach (ECO) are part of LIP's societal role and essential for the recognition of its work. The LIP-ECO group exists to boost, integrate, and coordinate the laboratory's activities in this domain. The activities of LIP-ECO involve all three LIP nodes. The group activities are divided in two interconnected and partly overlapping branches: 1) LIP's institutional communication and outreach; 2) LIP's programme for the school community - support to education and outreach. Below, highlights of the 2021 communication activities are given below, and LIP programme for schools is outlined. LIP also develops equipment for exhibition and demonstration purposes, with the collaboration of its scientific infrastructures and competence centres.

2021 communication highlights

In what concerns LIP's institutional communications, the activities developed in 2021 covered mainly the following lines of action: routine management of LIP's communication channels and tools (site news, social media, reports, newsletters, public sessions), support to LIP's groups communication needs (preparation of posters, banners or merchandising items; advertising among LIP's contacts, help with participant surveys), and relations with the media; revision of LIP's communication strategy; continued development of LIP's basic set of communication materials and resources — following the renovation of LIP's visual identity, we proceeded with the design of a minimal set of merchandising items to be distributed in events or to new members. Production will happen in 2022. A minimal communication kit was also produced for the participation in several events: set of three roll-ups introducing LIP; updated institutional flyer; new flyer with a short introduction to particle physics. In the context of EPPCN, we participated in the preparation of the ESPPU communication strategy, in a collaboration with the CERN-ECO group.

Media - FIC.A

The first edition of the FIC.a science festival, in Oeiras, was held in October 2021. LIP was fully responsible for the stand representing LIP and CERN, which featured the demonstration equipment LHC Interactive Tunnel, LIP's spark chamber, the "CERN in Images" exhibition, and a small set of roll-ups about LIP. The LIP/CERN stand was highlighted in two national TV channels.

UN's International Day of Women and Girls in Science

On 11 February 2021 we organised an online debate on gender issues in science, with a panel including the secretary of state for science, the president of FCT, the president of the national physics student's association, a science journalist and a science teacher. Close to 100 people followed the very lively and interesting discussion.

European Researcher's Night

On the last Friday of September 2021, we celebrated both online (with a talk on FCC and a virtual visit to CMS) and in-person in all the three towns where LIP has premises. Although there were still restrictions on number of people and distancing, the enthusiasm for "real" interactions was clear and much larger than expected.

LIP's programme for the school community

At LIP a comprehensive programme for the school community has been put in place along the years. Flagship initiatives are IPPOG's Masterclasses and the Teachers Programme at CERN. LIP also provides support to the participants in the international beamline for Schools (BL4S) competition.

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 Fermilab 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 more than 1500 participants. In 2021 the masterclasses were held online. On the positive side, a new activity was introduced, the Proton Therapy Masterclass.

CERN Teachers Programme in Portuguese Language

Training program in national languages of CERN member states started in 2006, and the first Portuguese-language training at CERN was held in 2007. Two years later, the program became the first to host teachers from non-member countries with the same language. Over the last decade, more than 700 teachers attended the programme, coordinated by LIP with the support of CERN and Ciência Viva. In 2021 the regular programme was cancelled due to the restrictions imposed by the pandemic. An advanced online school for a limited number of past participants was held, featuring updates in particle physics and other fields.

Ciência Viva Summer Internships

The Ciência Viva Science in the Summer internship programme hosted 12 high-school students at LIP Lisboa for one week full time.

Seminars and other activities in schools

LIP goes to school in several different occasions. Each year, LIP researchers deliver over 50 outreach talks for students in schools and other settings. LIP maintained its participation on the CV "Space goes to school" event, with 14 talks about space, cosmic rays and particle physics. LIP is the scientific partner of several Clubes Ciência Viva and other science clubs, providing support and activities along the year. In particular, cloud chamber construction sessions are also held.

Partnerships

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

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Glossary

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

DUNE - Deep Underground Neutrino Experiment (CERN/FermiLab)
ECAL - Electromagnetic Calorimeter (CMS)
ECO - Education, Communication and Outreach
ECOTOP - Ecology and Conservation of Top Predators group (MARE)
eCRLab - Cosmic Rays Electronics Laboratory (LIP)
EEE - Electronic and Electric Engineering
EFACEC - Portuguese company, operating in the energy and transportation sector
EGI - European Grid Infrastructure
EGI-ACE - European Open Science Cloud implementation project
EOSC - European Open Science Cloud
ERC - European Research Council
ESA - European Space Agency
ESPP - European Strategy for Particle Physics
ESPPU - European Strategy for Particle Physics Update
ESS - European Spallation Source
EU - European Union
EuroCC - H2020 EU project for HPC coordination
EuroHPC - European High Performance Computing Joint Undertaking
eV - electron-Volt (unit of energy; the energy of an electron under 1 Volt; multiples are: keV, MeV, GeV, TeV, PeV, EeV)
EVOLEO - Portuguese company, operating in the electronic engineering sector
FAIR - Facility for Antiproton and Ion Research (GSI)
FARE - Fake News and Real People (ERC project at LIP)
FCC - Future Circular Collider
FCCN - Fundação para o Cálculo Científico Nacional
FCT - Foundation for Science and Technology, Portugal (Fundação para a Ciência e a Tecnologia)
FCUL - Faculdade de Ciências, Universidade de Lisboa
Fermilab - Fermi National Accelerator Laboratory, Illinois, USA
FOV - Field of View
FPGA - Field-programmable gate array (integrated circuit)
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
IBEB - Institute for Biophysics and Biomedical Engineering, FCUL
IBERGRID - Iberian Computing Grid Infrastructure
ICNAS - Institute for Nuclear Sciences Applied to Health (Instituto de Ciências Nucleares Aplicadas à Saúde)
ICT - Information and Communications Technologies
IDPASC - International Doctorate Network on Particle Physics, Astrophysics and Cosmology
INAF - Istituto Nazionale di Astrofisica (Italy)
ILO - Industrial Liaisons Officer

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

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

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