# European Strategy for Particle Physics

AC-FPFN (IST-Univ. Lisbon) contribution

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The Scientific Area of Particle Physic and Nuclear Physics (AC-FPFN in the Portuguese acronym) of the Physics Department of Instituto Superior Técnico of the University of Lisbon is a structure combining all professors and researchers teaching at the Physics Department that have indicated this as their primary scientific area. It encompasses a wide range of activities with members actively participating in large Particle Physics experiments, such as ATLAS, Auger, CMS, DUNE, among others. AC-FPFN is also devoted to the interplay with Medical Physics, Public Outreach, Quantum Computing, and Space Physics. For many decades, there has also been a very strong theoretical component, devoted to Nuclear Physics, the phenomenology of QCD and electroweak phenomena, including more recent activity concerning Dark Matter.

Over the past 10 years, AC-FPFN has yielded over 30 PhD theses and close to 100 MSc theses. In addition, several introductory research projects have been performed by younger students. This is a very salient feature of this group; we have prepared many young physicists who went on to highly successful international careers. As CERN embarks on a vision for the long term (which could culminate with the FCC start at best in the mid 2040's) a continued effort must be placed on attracting the best students to this field and maintain its momentum.

We believe that maintaining consistent support for groups with a strong track record in attracting and training talented students is essential for the future of the field. Ensuring opportunities for early-career researchers, including grants for introductory research projects, MSc, and PhD programs, will sustain the momentum of talent development across Europe. ECFA and the international community in this area should use their influence on granting agencies of member states in order to guarantee dedicated funds for these actions, in regular application calls.

We also recognize the importance of sustained efforts in Public Awareness, to highlight the value of a thriving Particle Physics community. This will help in attracting students, but also in securing the support of public opinion in an endeavor which will be costly and require sustainable funding over several decades.

In general, we recommend: i) that the High-Luminosity Large Hadron Collider (HL-LHC) begin operations around 2030 and that its full program be executed; ii) that the Neutrino Platform continue operation at CERN; iii) that FCC-ee be operated as a first stage into FCC-hh. Other possibilities, especially concerning an electron-positron collider, have been considered, but FCC-ee's large luminosities combined with FCC-hh's 100TeV energy likely provide the best chances for new discoveries at colliders. Further recommendations are included below, organized by research topic.

* Scalar sector

As mentioned in CERN's Deliberation Document on the 2020 update of the European Strategy for Particle Physics (ESPP), "Nearly all the unsatisfactory aspects of the Standard Model (SM) and many of the open questions Beyond the Standard Model (BSM) are related to the scalar sector. The study of the scalar sector is therefore of central importance". Portuguese scientists have been part of this theoretical and experimental effort since the 1980's, many through the AC-FPFN.

Portugal has a leading expertise in experimental physics at particle colliders, including members of the ATLAS and CMS experiments, with leading contributions both in the data analysis efforts and in the detector operation and preparation. Portugal was among the founders of the ATLAS and the CMS experiment with strong contributions to detector design, operations and upgrades as well as to the physics programme. Through AC-FPFN, Portugal directly contributed to several key measurements of SM parameters and searches for new physics, thus limiting the phase space of new physics.

The understanding of the Higgs boson, the only elementary scalar particle observed in Nature, is limited. During the HL-LHC, the experiments will be able to collect larger (approximately ten-fold) event samples. This will allow further study of the Higgs boson properties. During the High HL-LHC, the search will continue for extra fundamental scalars (both neutral and charged) as well as deviations of the 125GeV Higgs boson couplings to fermions and gauge bosons. These may enable the indirect detection of heavier states, or even dark matter, through loop effects. The combination of the measurements in the FCC(ee+hh) will result in an ultimate precision of less than a per cent level in all the Higgs couplings, while a sub-per-mil precision is possible on the Higgs invisible branching fraction, thus constraining Higgs portal models. An important objective is the determination of the Higgs self-coupling, as it is the only parameter sensitive to the shape of the Higgs potential in the SM. It will be marginally accessible at the HL-LHC, after combining the results from both ATLAS and CMS experiments, with increased precision requiring a new collider. The combination of FCC-ee with a 100 TeV FCC-hh collider provides the best chance to uncover physics beyond the SM, both through virtual effects and through direct searches at the energy frontier.

The requirements of maximum precision in these measurements have several experimental consequences. The first is that the HL-LHC is the next future collider project, and, as such, the success of the HL-LHC physics programme should continue to be the highest priority in Europe. Considering the ultimate precision achievable in the measurements of the scalar sector, as well as the ambition that Europe continues to be at the forefront of research in High Energy Physics, the AC-FPFN supports the construction of the FCC-ee followed by FCC-hh at CERN. The ultimate precision highlights the need for advanced detector technologies, similar to the role the LHC physics programme played in guiding past R&D efforts. Key focus areas include leveraging

Europe's expertise in particle detection technologies, energy measurement, and particle identification. Cutting-edge developments in microelectronics, real-time data processing, engineering, and computing are also critical. Adequate resources and investments in these technologies are essential, alongside fostering a skilled workforce, as detailed in the ECFA Detectors R&D Roadmap.

* Neutrino Physics

Neutrino physics is crucial for exploring fundamental aspects of the Universe that are otherwise inaccessible. This research field can lead to significant breakthroughs in understanding how Nature works on both the smallest and largest scales, by exploring synergies among the energy, intensity and cosmic frontiers of particle physics. In this sense, the CERN Neutrino Platform has been crucial in fostering and contributing to worldwide fundamental research in neutrino physics.

The contributions of the AC-FPFN to the International Neutrino Physics Programme have been twofold:

Experimental Contributions:
The Deep Underground Neutrino Experiment (DUNE) is designed to address some of the most fundamental questions about our Universe. At its core, DUNE seeks to investigate neutrino oscillations with unprecedented precision, providing critical insights into the ordering of neutrino masses and the potential violation of charge-parity (CP) symmetry in the lepton sector—both of which are key to understanding the matter-antimatter asymmetry of the Universe. At DUNE our efforts are focused on activities related to the experimental developments at CERN (protoDUNE) to define the final design of the detectors to be installed in DUNE in the following years. There is Portuguese participation in the calibration systems of the detectors involving ultraviolet lasers and radioactive sources, both in the construction and analysis of data. Since construction and installation are completed, the current activities include modelling the liquid argon ionization by the laser, analysis of the laser beam data taken with protoDUNE and simulation and data analysis of the Bi207 radioactive sources deployed inside protoDUNE to simulate known energy depositions. The calibration systems are fundamental to ensure the experiment's unprecedented precision and reliability by minimizing systematic uncertainties and validating the detector's performance over its long operational lifetime.
The Scattering and Neutrino Detector (SND) experiment at the LHC (SND@LHC) is an experiment built for the detection of collider neutrinos. The primary goal of SND is to measure the $p+p\rightarrow\nu+X$ process and search for feebly interacting particles. SND@LHC is a newcomer to the field that has arrived since the last ESPPU (2020), with founding members from AC-FPFN. Exploiting the potential of the HL-LHC with some key detector improvements will largely extend the physics reach of the experiment both in neutrino physics and in BSM searches. We strongly support the upgrade of the SND@LHC detector which will allow the exploration of neutrino physics during the HL phase of the LHC. It will further extend the scope of direct BSM

searches along with unique heavy flavour measurements in the forward region that are not accessible by other experiments. Collaboration with the ATLAS and CMS general-purpose experiments is foreseen. Significant synergy exists in detector R&D, particularly for the SHiP experiment, with a highly complementary physics case.

Theoretical Contributions:
At the theoretical level, our efforts focus on exploring neutrino phenomena as a gateway to BSM physics, offering opportunities to uncover new particles or interactions within the framework of well-motivated extensions of the SM. Specifically, we aim to use the results of neutrino experiments like DUNE, SND@LHC, SHiP and others as a testing ground for theoretical frameworks addressing three major open problems in Particle Physics: the nature of dark matter, the excess of matter over antimatter in the Universe, and the origin of neutrino masses. In particular, we will focus on approaching these matters in a complementary way by performing combined phenomenological analyses of BSM models in light of the forthcoming results provided by different neutrino experiments. For instance, in the case of DUNE, future results are expected to severely constrain the parameter space of flavour models and of theoretical frameworks where heavy neutral leptons are predicted. Furthermore, exotic physics phenomena, such as Lorentz and CPT violation, quantum decoherence, and the existence of extra dimensions, can also be probed and constrained. The relevance of these activities aligns strongly with the objectives of the European Strategy for Particle Physics, and we recommend that the CERN Neutrino Platform keeps promoting activities that foster the interaction between the experimental and theoretical neutrino community to maximise the potential of neutrino experiments in the search for BSM physics.

* Dark Matter

The quest to understand the nature of the elusive dark matter (DM) in the context of a complete model of particle physics persists as one of the paramount challenges in modern physics. It is embarrassing that a very precise SM has been developed in order to explain around 15% of matter in the Universe, while the 85% DM component remains unexplained. AC-FPFN has been, and will continue to be, involved in two aspects of this effort. On the one hand, the theoretical construction of models of particle DM subject to all experimental constraints, and which provide solutions to other open questions in particle physics. On the other hand, on the search for DM from cosmic particle detectors such as AMS and the Pierre Auger Observatory, as well as constraints arising from LHC searches for missing energy.

Collider explorations are complementary to direct DM detection, and are more efficient for lighter DM masses. At HL-LHC and FCC there will be greatly improved probes for DM pair production with one or more of gluon/photon/Z/W/h. In particular, mono-jet searches are expected to probe axial-vector and pseudoscalar mediators up to around 1TeV already at HL-LHC. Several dedicated SUSY searches can be turned into DM constraints, but this is usually very difficult to perform without access to the full data. Thus, we recommend that such experimental results be presented also in a more model independent fashion, using simplified DM models as a testing ground.

The exploration of the Dark Sector is also performed through searches for long-lived particles. At the LHC, these are performed with the general-purpose detectors as well as dedicated detectors such as FASER, SND@LHC, MoEDAL-MAPP. SHiP has been selected by CERN as the beam-dump apparatus to explore the high-intensity upgrade of SPS. Portugal has a longstanding involvement in the preparation of the SHiP experiment, which will enable a wide search program for feebly interacting GeV-scale particles. Our physics and detector activities in SHiP benefit from and significantly extend our current involvement in the SND@LHC experiment. We strongly support the effort of the SHiP collaboration to ensure the detector can be constructed in a timely manner, to be ready for data-taking in 2032, and delivering a successful and impactful physics program over the ensuing 15 years (i.e. beyond HL-LHC).

Given the complementarity between direct, indirect and collider searches for DM, a robust encompassing European progamme is required. Thus, we also propose a reinforcement of the 2020 recommendations "A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world."

* Astroparticle

For over twenty years, Portugal has actively contributed to advancing experimental astroparticle physics through the Laboratory of Instrumentation and Experimental Particle Physics (LIP). The country's efforts are centered around three major international collaborations: the Alpha Magnetic Spectrometer (AMS), the Pierre Auger Observatory, and the upcoming Southern Wide-field Gamma-ray Observatory (SWGO). Notably, the first two are experiments recognized by CERN.

These collaborations explore cosmic and gamma rays across a vast energy spectrum, ranging from less than 1 GeV to 10^{20} eV. This broad energy range complements particle physics research at CERN, providing unique insights across different scales of energy, time, and space. For instance, the stringent limits now placed on Lorentz Invariance Violation—several orders of magnitude above the Planck energy scale—underscore the importance of this synergy.

Astroparticle physics experiments have greatly benefited from the wealth of particle physics knowledge generated by the Large Hadron Collider and will continue to leverage future findings. One significant contribution lies in understanding hadronic interactions, which are essential for modeling cosmic ray propagation through the interstellar medium. These models are also crucial for interpreting extensive air showers, enabling the indirect detection of high-energy cosmic rays when their flux becomes too low for direct measurement by satellite-based experiments.

* Flavour Physics

Flavor physics is a cornerstone for probing the SM and search for the physics that lies BSM. Outstanding puzzles include the hierarchies in mass and couplings, in the lepton and quark sectors, the number of generations, and the insufficient CP violation needed to generate baryogenesis. The search for BSM physics ought to be pursued in complementary ways. Direct searches at the LHC, while resulting in extended exclusions, did not yet reveal BSM. While direct sensitivity to TeV-scale particles will increase only slowly, the high-luminosity phase of the LHC will provide much increased sensitivity for direct searches at GeV scales and for indirect searches through virtual contributions of new heavier particles.

AC-FPFN members have a longstanding involvement in Flavor Physics — both in theory and experimental fronts. Experimentally this has been achieved with CDF at the Tevatron, CMS at the LHC, more recently complemented in the forward region by SND@LHC. Interests of the group that will be facilitated by the HL-LHC phase involve the exploration of rare heavy flavor processes along with precision measurements. For example, rare b to s quark-level transitions and precise CP violation measurements offer high sensitivity to BSM physics. Extensive tests of lepton flavor violation (LFV) and lepton university violation (LUV) will be enabled. Heavy flavor probes in pp and ion collisions at HL-LHC shall shed light on underlying QCD mechanisms, the nature of exotic hadrons and the deconfined medium, and provide novel avenues for BSM searches.

We strongly recommend support for theorists working on flavor, a main topic of Portuguese Particle Theory groups. Members from AC-FPFN have leading contributions in CP violation and in flavor symmetries. We recommend strong support for experiments probing flavor at the LHC, specifically for their upgrades for the HL-LHC phase, including ATLAS, CMS, LHCb, SND@LHC. Outside Europe, we recommend support for Belle II and Mu2e.

* QCD

The HL-LHC presents unprecedented opportunities for QCD studies in exotic hadrons, states that do not fit into the conventional scheme of quark-antiquark mesons or three quark baryons, such as tetraquarks, pentaquarks, hexaquarks, hybrids or glueballs.

Tetraquarks were first proposed by Jaffe within the bag model in 1977. In the early eighties, Richard and colleagues proposed tetraquarks with some heavy quarks would most likely form boundstates. After many decades, finally multiquark resonances have been confirmed in more than forty different experiments, mostly at LHC, and lattice QCD computations. LHCb is perfect, as a high luminosity B factory, utilizing the decays of B mesons, to study the spectrum of exotics, for instance X(3872) and Tcc including a charm and anti-charm pair. Moreover, all the LHC experiments produce abundantly exotics during the final hadronization resulting from the heavy ion collision. We expect HL-LHC to produce the Tbc and the Tccs and possibly new tetraquarks of the Zb family. Besides the large multiplicity of HL-LHC should finally allow us to detect glueballs, hybrids and hexaquarks, beyond the presently detected tetraquarks and pentaquarks. This is crucial for a deeper understanding of hadronic physics, with an important technological impact in our understanding of the fundamental interactions in nuclear physics. The new spectroscopic findings will motivate detailed structure studies (as measurements of electromagnetic form factors giving information on size and charge distributions) in other facilities, namely FAIR-GSI and BESIII, which will impact our understanding of the effective nuclear interactions, by accessing for example the role of diquarks in baryon structure.

The exploration of ion collisions further unlocks a better understanding of the properties of the Quark-Gluon Plasma (QGP) by enabling access to rare hard probes, such as heavy-flavour and boosted particles. These provide tomographic insight into the QGP, with semi-leptonic decays of boosted top quarks probing timescales corresponding to roughly half the QGP's lifetime. Such studies complement soft probes, which infer the QGP's time evolution through hydrodynamic modelling. Hadronic W-boson decays, while sensitive to shorter timescales, compensate with significantly larger production cross-sections.

The use of lighter ion species, such as Kr, offers notable advantages by reducing geometric and background biases. Building on RHIC results for Cu (which has a similar mass number), these lighter systems are known to produce sizeable QGP-induced effects. They allow for the exploration of identical geometries at varying nuclear densities, independent of centrality-based initial anisotropies, and complement the existing Pb program as well as the upcoming Oxygen runs. This capability is essential for disentangling the effects of initial spatial anisotropies on QGP formation and evolution, providing a robust baseline for comparison. Achieving the target Pb-Pb luminosity by the mid-term of the LHC program will open the door to lighter ion collisions during Run 5, enabling systematic investigations into the QGP's initial conditions and evolution, while also supporting rare probe studies.

Looking ahead, FCC-ee's higher center-of-mass energy compared to LEP presents a unique opportunity to establish a critical baseline for understanding collective effects observed in p-Pb and high-multiplicity pp collisions. These studies will bridge the gap between small and large systems, advance our understanding of QCD dynamics in dense environments, and foster deeper synergy between theory and experiment.

* New computation techniques

In the last decade, due to the complexity and the amount of data of present day machines and detectors, machine learning and artificial intelligence became mandatory tools for any meaningful data processing and analysis. Advanced statistical techniques and neural networks became common tools for the Large Hadron Collider experiments and clearly are going to become even more so in future facilities. In what concerns experimental and phenomenological studies, neural networks are essential to look for extremely rare events corresponding, in particular, to Physics beyond the Standard Model, not to mention their use in the determination of parton distribution functions.

A newcomer to High Energy Physics are Quantum Technologies. Their influence will occur in two areas, quantum sensing and quantum computation. Quantum sensing uses quantum phenomena to measure quantities with unprecedented precision. As for quantum computing, the purpose is to use quantum processes to perform the calculation of quantities in a time expected to be exponentially faster than its classical counterparts. There are basically two universal quantum computing models: adiabatic and digital. In both of them the basic unit in the qubit, a quantum superposition of states |0> and |1> (for instance, the two states of a quantum two-level system). Adiabatic computing is best suited for optimization problems and uses the quantum adiabatic theorem to make a definite quantum system (typically of the Ising type) converge to the ground state of a system corresponding to the desired solution of the problem at hand. It has been used in HEP for tracking and for jet reconstruction. A complexity analysis of the quantum algorithms has shown that they will outperform their classical counterparts once the number of available qubits will be sufficient large in future quantum computers.

In what concerns quantum digital algorithms, qubits are acted upon by quantum gates which are represented by unitary operators or combination of unitaries. They have been applied in HEP to both theoretical and experimental problems. One of the major theoretical breakthroughs has occurred in Lattice Gauge Theories where, in particular, quantum algorithms have been able to tackle the sign problem in a particularly efficient way. In experimental HEP the digital model has been successfully been applied to jet clustering and several problems with quantum neural networks. The major difficulty at present with the use of quantum computers is the limited number of usable qubits and the difficulties in error correction in the available quantum circuits. There is an ongoing discussion concerning the interplay between real quantum data coming from quantum sensors in experiments and the processing by quantum algorithms in quantum hardware. At present there is no obvious solution for this question, but we expect that this issue will be solved as quantum hardware is developed and optimized in the next decades. It is important that CERN reinforces its Quantum Technology Initiative (CERN QTI).

* Physics Outreach

1. Training of students in Particle Physics with a broad view of the HEP field, which should include a component about public engagement and outreach, achievable by revising/proposing new curricular units at the corresponding levels, or providing specialized “training schools”.

2. High-schools teachers and students engagement through activities training teachers and creating large multiplication factors, and activities for students at the University or at the schools, also in support of science clubs at the schools (such as “Ciência Viva Science Clubs”).

The CERN Portuguese Language Teachers Programme is recognized as one of the most important CERN Teachers Programmes, receiving yearly 48 teachers from Portugal, Brazil, and the other Portuguese speaking countries in Africa and East Timor. It is thus a unique and very important tool to reach diverse communities with Modern Physics and Technologies, especially from our field, and allows to get us in touch with many different communities.
Activities for students like the IPPOG's International Masterclasses in Particle Physics, reaching more than 15000 participants worldwide, of which 1600 from Portugal, should be organized at all Universities/Institutes, to carry the excitement of the discovery with real data to students from all places, enhancing the motivation of the high-schools students to follow Physics and Engineering Physics.

3. Public Engagement and Outreach in High Energy and Particle Physics, and associated methods and technologies, should be a mandatory component of the activity of every Researcher in the field, with an appropriate level of commitment. This level depends on many factors, but a minimum level of 1% should be required (roughly 2 working days per year), and higher levels should be encouraged/recognized. Actions related to public engagement and outreach should be carried out by the relevant institutions, involving the scientists and engineers connected with the field.

4. Recognition of the efforts in public engagement and outreach should be a mandatory criterium in the assessment of researchers (and faculty), in equal footing as technology developments, software tools and methods, published papers, etc.

5. Scientific Diplomacy should be encouraged in our colleagues, so that multiplying factors can be achieved, as they become ambassadors of our field to their peers (especially outside the field), their family and friends, and general audiences at public events.

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The Scientific Area of Particle Physic and Nuclear Physics of the Physics Departament of Instituto Superior Técnico of the University of Lisbon emphasizes the critical importance of consistent public funding for the activities of this scientific area, including, but not exclusively, the following aspects:
* Yearly openings by the Portuguese Fundação para a Ciência e Tecnologia (FCT) for grants for projects in this area, under the auspices of the collaboration with CERN;
* Yearly openings by FCT of PhD grants in this area, under the auspices of the collaboration with CERN, possibly with a revival of the "Programa de Doutoramento IDPASC" or "PT-CERN Programme";
* Establishing predictable funding timelines, with calls occurring on consistent dates annually, enabling long-term planning for researchers and institutions involved in High Energy Physics.
Such measures will ensure the sustainability of long-range projects, attract and retain top talent, and reinforce Portugal's contributions to the European Particle Physics Strategy.