# Position for the 2025 European Strategy on Particle Physics Update

## *Spanish LHC network - Red Española para el LHC*

### INTRODUCTION

Particle Physics at the Large Hadron Collider at CERN is one of the main research areas of the Spanish Particle, Astroparticle and Nuclear Physics community. More than 30% of the research personnel working in experimental physics activities participate in the LHC program; a strong community of theorists contribute to theoretical developments directly related with LHC Physics. Participation in the LHC project is fully aligned with the Spanish membership of CERN. Enormous efforts are invested to maximise the scientific, technological and industrial returns.

### HISTORICAL CONTRIBUTION TO LHC

Spanish HEP groups have made substantial contributions to the LHC experiments since their conceptual phase (back to the 1990's), participating in the R&D activities for the development of the experimental techniques, to the detector technical design and also to evaluate the Physics potential of the experiments. Since then, members of our community have taken important roles & assumed responsibilities in the construction, installation, commissioning and operation of the detectors, as well as in the computing and the data preparation. We have also led many of the physics groups as well as the data analysis groups, which translated as the main authors of many of the experiments publications. Also, members of the Spanish LHC community have been appointed for managerial roles in the different collaborations.

The LHC project has proven to be a successful one as its research at the Run 1 and Run 2 LHC operation periods have been extremely fruitful. The discovery of the Higgs boson was a major breakthrough in particle physics in the XXI century and thousands of new physics results scrutinising the SM (with more and more precision measurements) and its possible extensions were performed. The experimental and theoretical Spanish LHC researchers have been key players in many of these forefront results.

### LHC RUN 3 & HL-LHC

LHC is currently operating with twice the design instantaneous luminosity and an increased collision energy of 13.6 TeV in Run 3. A total integrated luminosity of 300 $fb^{-1}$ per experiment (ATLAS and CMS, while 23 $fb^{-1}$ for LHCb) is expected to be collected up to the end of the Run 3 which is scheduled in July 2026.

Following a major upgrade (2026-2030), a completely new regime will be in place with expected peak luminosities of 5 to 7.5 x $10^{34}$ $cm^{-2}$ $s^{-1}$. This will mark the start of a new, revolutionary, phase of the LHC program, the high luminosity phase, referred to as HL-LHC, aiming to collect 3000-4000 $fb^{-1}$ of data at 14 TeV by ATLAS and CMS, and 300 $fb^{-1}$ by LHCb.

In order to face the experimental challenges that HL-LHC will impose on the detectors, a major upgrade of their equipment is required. Therefore, major upgrades in tracking detectors, electronics of the calorimeter and muon systems, as well as improved trigger and data acquisition systems have been designed. The projects are now moving towards the

production phase of the required new components. The LHC experiments and their Physics potential will benefit from extensions to larger pseudorapidity range, particularly in tracking and muon systems, plus the new precise timing layers.

Depending on the upgrade schedule of the individual experiments, some of these activities already took place during the first and second Long Shutdown periods (2013-2014 and 2019-2022) of the LHC or during the end-of-year maintenance periods. In any case, the bulk of the work for the general purpose detectors, ATLAS and CMS, remains to be done during the Long Shutdown period 3 (2026-2030) for the installation and commissioning. In what concerns the LHCb upgrade, phase I was already installed prior to the start of Run 3 and only in 2024 has collected more data than in Run 1 & Run 2 together. The Spanish groups are strongly committed to the LHCb upgrade detector (vertexing, tracking system and calorimeter) and to data physics exploitation. To further exploit the potential of the HL-LHC, the LHCb collaboration is planning a second upgrade that will enable it to collect data reaching a total integrated luminosity collected by the end of the HL-LHC of 300 $fb^{-1}$. There is also a Spanish involvement in Belle II to which it has made significant contributions. Belle II is regarded as a vital complement to the European flavour physics agenda.

**SPANISH CONTRIBUTION TO LHC UPGRADE (HL-LHC)**

The HL-LHC is a critical project for the immediate future of CERN and the Spanish LHC groups have been participating in detector upgrade activities in ATLAS, CMS and LHCb experiments since day one. The community is strongly committed to the HL-LHC project and a substantial fraction of their human and financial resources has already been dedicated to it.

The Spanish community participates in the upgrade of the ATLAS Pixel Inner Tracker and the end-cap Strip Tracker, as well as in the upgrade of the electronics for the Tile Calorimeter. Our community also contributes to the upgrade of the CMS L1 trigger and electronics of the DT-muon spectrometer, the inner tracker detector, and the end-cap layer of MTD. With respect to LHCb, Spanish groups have participated in the upgrade of the vertex detector, tracker and calorimeter, and are already working towards the upgrade phase II. The theory community is actively providing improved projections and predictions for the HL-LHC physics program.

**POSITION ABOUT COMPLETION OF THE LHC PROGRAM**

We firmly support the HL-LHC program (detector upgrades and Physics exploitation) will guarantee a unique (and the best) opportunity to improve our knowledge of the known and explore the limits of the unknown. Studying as accurately as possible the Higgs sector (including Higgs potential via its self-coupling) is a fundamental and crucial point for the future of the Particle Physics field. Moreover, the LHC in the most favourable scenario is the last hadron collider for the next two decades. We should exploit it to the last $pb^{-1}$ of data, taking full benefit from the large investment already made into the HL-LHC project.

The HL-LHC is expected to deliver high luminosity collision samples exceeding 3000 $fb^{-1}$. This will enable us to extensively characterise the Higgs boson, and allow us to fully exploit the capabilities of the upgraded detectors for the most precise SM measurements, and to explore BSM physics scrutinising the most remote corners of the available phase space. Priority should be given to provide sufficient statistics to investigate any intriguing anomalies observed in previous analysis in order to confirm or discard any hints of new Physics. Many

measurements and searches are still statistically limited. We should make sure to profit from the opportunity of taking the full 3000-4000 $fb^{-1}$ per detector.

Regarding flavour physics, there are still tensions with the SM in branching fractions and angular distributions, which could indicate BSM physics. Moreover, precision measurements of SM parameters with the HL-LHC sample of 300fb-1 could point towards deviations from the SM indirectly induced by particles that can not be probed directly on the current accelerators.

The whole Spanish LHC community reiterates its decision to have a strong participation in the HL-LHC program, in the maintenance, operation, and consolidation of the upgraded detectors, in the physics exploitation of the full potential of the data to be taken, and providing new or improved theoretical predictions and performing novel theoretical and phenomenological analysis.

**PRIORITY OF THE LHC & HL-LHC FOR NEXT ESPPU**

The Spanish LHC community reaffirms that the LHC and HL-LHC should remain central to the European Strategy for Particle Physics Update (ESPPU) in the coming years, in alignment with the 2020 ESPPU mandate: *"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"*.

The full exploitation of the Run 3 data and the success of the HL-LHC project: detectors, computing, data preparation and physics analysis (to reach its ambitious physics goals) have to be guaranteed. The LHC program should deserve our highest priority receiving the corresponding human and financial resources. The progress of the program should be closely followed-up should any signal for new physics or unexpected findings be observed.

**COMPUTING AT THE LHC**

The Worldwide LHC Computing Grid (WLCG) is the global infrastructure developed and operated over the past two decades to provide the computing power and storage capacity necessary for processing and analysing the LHC experiments' data. WLCG has been instrumental in enabling the remarkable scientific achievements of the LHC. This essential technology, which integrates globally distributed exascale-level resources with advanced services and software, will face critical challenges in scaling, technology, funding, and sustainability to meet the High-Luminosity phase of the LHC (HL-LHC) and beyond (2030+). The HL-LHC phase will require close to an order-of-magnitude increase in resources, and further demands are anticipated as new collider projects emerge.

Over the next decade, meeting the computational needs of LHC experiments will require sustained funding, technological innovation, and resource optimization, especially as the HL-LHC phase amplifies data demands. The integration of High-Performance Computing (HPC) and cloud resources will be essential, though it presents challenges due to diverse hardware architectures and policies. Environmental sustainability should be a strategic priority, with investments in energy-efficient hardware and improved data centre power usage. Developing expertise in these areas requires significant human resources, underscoring the importance of attracting and retaining skilled computing professionals through clear career paths and competitive recognition. Expanding WLCG's role beyond high-energy physics to support multiple scientific fields will enhance its value proposition for

funding agencies and build a larger contributor base, fostering a more sustainable, collaborative computing infrastructure for the global scientific community.

**R&D IN DETECTORS**

The Spanish contribution to the LHC and HL-LHC detectors has been based on an extensive R&D program. In view of new proposed HEP facilities/colliders and experiments, the R&D program in new detector technologies should be a priority, in particular the development of new tracking devices, very highly segmented calorimeters or more compact electronics. The LHC Spanish groups are already participating in several Detector R&D collaborations recently set up as a result of the implementation of the European Detector R&D Roadmap.

The Detector R&D Collaborations that have materialised from the European Detector R&D Roadmap should be consolidated and the active participation of the research groups has to be stimulated, facilitated and funded. These technological developments also have the potential for sizable industrial return.

In a very interconnected research environment nowadays, efforts have to be made to seize common developments and synergies with other research fields like Nuclear, Medical, or Photon Sciences which also have a very strong need and R&D on instrumentation. In this sense, interdisciplinarity in instrumentation developments has to be promoted and strengthened.

In the coming years, the construction of the different subsystems of the HL-LHC experiments will be progressively completed. As this happens more and more, researchers and engineers will reduce their participation in construction. It is very important for the Spanish and European Particle Physics community that this expertise and person-power is not lost. The community should make sure and encourage that the people working on instrumentation for the HL-LHC, get gradually involved in instrumentation developments for the proposed future experiments as they have an invaluable expertise on developing and constructing a large experiment, which will be needed in the future.

**THEORY AND PHENOMENOLOGY**

From the theory and phenomenology side, the Spanish HEP community is strongly involved in providing new and accurate theory predictions for current ATLAS, CMS and LHCb precision SM measurements and searches. This concerns higher-order corrections for SM processes (e.g. Higgs boson and top quark) as well as for BSM physics (Higgs, SUSY, new gauge bosons, vector-like fermions etc.), flavour phenomenology concerning quark and leptons, as well as for heavy ion physics (PbPb and pPb). Furthermore, the Spanish theory community takes a vital role in the planning and the evaluation of the physics potential of future facilities. These efforts ensure that the Spanish theory community will continue its strong involvement also in the future in the ongoing efforts to discover BSM physics. Theory efforts aligned with experimental analysis should be seen as an integral part of high-energy physics.

**INPUT FOR THE NEXT ESPPU**

The Spanish LHC community recognizes that a lot of time (measured in tens of years) and efforts are needed to design and develop a plan for the future of the Particle Physics field

which is scientifically ambitious and achievable. In this sense, beyond the HL-LHC, a new large collider can be decisive in shedding light on many fundamental questions that still remain unresolved and to which the HL-LHC may not be able to provide a definite answer.

Designing well ahead the path for the future of Particle Physics in Europe, gathering the community around the next flagship project at CERN, will allow maintaining existing European leadership in the field, both in scientific and technological developments.

It must be also mentioned that: in order to avoid the dispersion of the community and its know-how, it is desirable that the next large collider at CERN must become operational within a few years after the completion of the HL-LHC.

THE PHYSICS QUESTIONS TO BE ADDRESSED

The origin of the electroweak symmetry breaking mechanism in the SM, the origin of CP violation, the origin of the neutrino masses, what is the nature of dark matter and dark energy, why are there three families... are still among the most relevant physics questions that should be addressed.

A deep characterization of the Higgs boson, including the determination of the Higgs potential, as well as performing ultra precise measurements of the top quark and the electroweak sector, and indirect searches exploiting the high intensity frontier which can pave the way by narrowing down our options in new physics searches are among the prioritised physics goals of the community. On the other hand, direct searches for new physics in an extended (higher) energy regime are also of the utmost interest in the community.

A HIGGS FACTORY (2020 ESPPU)

In this respect, and as already stated in the 2020 ESPPU, an $e^+e^-$ Higgs factory is the preferred option as the next big project the HEP community should tackle. Such a collider should provide high precision and (as far as possible) model independent measurements of the Higgs boson properties and couplings (including its self-coupling), of electroweak precision observables as well as of the top quark properties.

B-FACTORY AT THE Z-POLE

Having a scenario where the $e^+e^-$ collisions can be run at the Z pole is of paramount importance for flavour physics. It will bring the benefits of having an enormous amount of data for the entire family of b-hadrons that a hadronic machine has, together with the low level of background characteristic of a B-factory. At this machine, B decay modes that are impossible at LHCb (even with the HL-LHC statistics) and very limited statistically at Belle-II will become a reality reaching precision measurements of SM observables today unexplored. This will help both the precision measurements of CKM parameters to check inconsistencies with the SM, as well as with measuring rare loop-dominated processes.

FCC-ee AS HIGGS/TOP/ELECTROWEAK FACTORY

We acknowledge the current feasibility study being worked out by CERN for the realisation of the 2020 ESPPU, through an FCC integrated programme with a Higgs/top/electroweak factory (ZH, ttbar, Z and WW processes) in a circular machine with about 90 km circumference (FCC-ee) followed by a hadron collider of at least 100 TeV (FCC-hh). Several

Spanish institutions have signed the FCC MOU with contributions to the development of the accelerator for the hadron-hadron phase and participation in physics studies.

In our view, the FCC-ee should be designed in such a way that it has to be flexible enough to be able to operate with a new collision energy (for Z, WW and ZH) without requiring to undergo a major upgrade. We also are in favour of running several experiments at the FCC-ee based on different detection technologies depending on specific physics targets, and/or for a thorough cross-check and confirmation of the results.

IN SUPPORT OF THE FCC-ee

Should the final FCC-ee Feasibility Study establish that the realisation of the project is achievable in a timely way and financially affordable, the Spanish LHC community firmly supports the construction of the FCC-ee as the next major project/flagship collider at CERN. This support is grounded in the technical feasibility and maturity of the enabling technologies necessary for the realisation of this collider. Our community is eager to participate in the future at the FCC-ee project, gradually increasing our engagement as our HL-LHC commitments will be fulfilled.

On a longer timescale, and planning for the exploration of the 100 TeV energy regime, the second phase of the FCC program, with a hadron-hadron collider in the FCC-ee tunnel, the so called FCC-hh, will provide opportunities to produce new states with higher masses (>10 TeV) as well as to identify new Physics phenomena or particles which may be hinted at previous experiments. We support the idea of a vigorous and continued R&D for such a high-energy pp collider (FCC-hh) to be materialised in the future, succeeding the FCC-ee.

Other proposals have been presented at worldwide level: the linear collider ILC (with an already mature design, starting at a center-of-mass energy of 250 GeV) and CLIC (starting at 380 GeV), as well as new proposals, still in a preliminary stage, as the Cool Copper Collider or the HALHF concept. Another $e^+e^-$ circular machine, the CEPC in China (starting at 250 GeV) has also been proposed.

ALTERNATIVES FOR A NON FEASIBLE FCC-ee:

If the FCC-ee Feasibility Study would indicate that that project cannot be realised for technological or financial reasons, an alternative must be found. There is a preference for a linear e+e− machine at CERN.

OTHER SCENARIOS

Of course, a reassessment of the priorities would be necessary should any of the other proposed facilities/accelerators with similar Physics objectives as FCC-ee be built elsewhere on an earlier time scale.

If it were indeed the case, it would be more interesting to explore the high energy frontier (either with a high energy $e^+e^-$ linear collider or pushing the FCC-hh program). New input showing the evolution of the different proposals is expected to be received during 2025. Therefore our community will be observant to any new information and developments.

In what concerns the participation of the Spanish LHC community in facilities that may stem in the far east countries. On one hand, as part of our community has been also involved in

the R&D tasks for the ILC, if it were to be built in Japan, then our community considers the ILC a very interesting option. On the other hand, our interest in a CEPC collider in China is limited.

Other developments such as a high energy muon collider, have also an interesting physics case. The development of technologies needed by a muon collider should be pursued.

Physics potential is the main driver in either case, but also financial and human resources requirements, long-term perspective, timing, careers and training, industrial return, technology development and sustainability are important rationale for the choices.

CONNECTION TO NUCLEAR, ASTROPARTICLE OR OTHER AREAS OF SCIENCE:

CERN has achieved a unique worldwide position as the reference laboratory for High Energy Physics. Contribution to key projects in Nuclear and Astroparticle physics has also now become part of its portfolio of activities. CERN should indeed continue participating in Nuclear, Astroparticle or other fields of science in those areas where scientific or technological synergies are identified. However, the main focus should be Particle Physics in accelerators, pursuing a flagship project at the energy frontier to maintain and reinforce its leading position at the forefront of High Energy Physics.