Input to the update of the European Strategy on Particle Physics provided by the Spanish Scientific Particle Physics community

Addendum

Submitted to the ESPP Physics Preparatory Group - December 2018

Abstract

This addendum provides more detailed information on the topics addressed in the main document. In particular, it summarizes the contribution of the Spanish groups to the different research areas and the vision of the thematic networks on scientific strategy for the coming years/decades. The document is organized in 6 sections. Section 1 is devoted to the LHC and HL-LHC physics program. Flavour Physics is briefly highlighted in Section 2. In Section 3 we include the vision, and activities related with Future Facilities, and R&D in accelerator and detector technologies. Section 4 concentrates on the different areas of activity of the Spanish community in Astroparticles, Neutrinos, Multi-messengers and Cosmological surveys. Nuclear Physics and its interface with Particle Physics are addressed in Section 5. Finally, Section 6 briefly describes the scope and status of those mid- and large-size national scientific infrastructures with specific relation to the European Strategy for Particle Physics. A glossary with the acronyms of the Spanish groups used along the text is given at the end of the document.

Editorial Board:
Caterina Biscari, Martine Bosman, Antonio Bueno, Luis M. Fraile, Juan Fuster, María José García-Borge, Inés Gil, Luis Ibáñez, Mario Martínez, Sergio Pastor, Antonio Pich, Teresa Rodrigo

Contact persons:
Antonio Pich (pich@ific.uv.es) and Teresa Rodrigo (rodrigo@ifca.unican.es)

1 Physics at the High-Energy Frontier. The role of the LHC and its upgrade HL-LHC.

Following the main line of the strategy approved in 2006 and its update in 2013, an optimum Spanish participation in the LHC program and its upgrade HL-LHC has been so far, and will continue to be for the next years, our highest priority.

With the discovery of the Higgs boson in 2012 Particle Physics has entered a new era. The Higgs boson could be the closing piece of the Standard Model (SM), but more likely it opens up the door to physics beyond the Standard Model (BSM), that is known to exist. Consequently, it is of utmost importance to learn as much as possible about the Higgs boson, its interaction with SM particles and with (so far undiscovered) particles beyond the SM. The LHC will remain as the energy frontier machine for many years. We must exploit its potential of discovery of new particles produced in pp interactions. The first priority of the Spanish groups collaborating in the LHC experiments is the full exploitation of the data provided by the LHC collider and the participation in the coming upgrade phases of the project.

The Spanish participation at LHC during the last decades included an important contribution to the design, construction, operation, and since 2010 scientific exploitation of the pp collision data at 7 and 8 and 13 TeV, of three detectors: ATLAS (IFAE, IFIC, UAM), CMS (CIEMAT, IFCA, UAM, UO), and LHCb (IFIC, IGFAE, UB, URL). There has been as well a participation in ALICE (CIEMAT, IGFAE) that was terminated in 2015. In 2012 a group of theoretical and experimental researchers from IFIC joined the MoEDAL collaboration, aiming for the observation of magnetic monopoles experimental signatures.

The contribution to ATLAS and CMS represents 2.5% to 4.6% (depending on the experiment) of the total capital cost and manpower. The Spanish contribution to the WLCG (LHC Computing Grid) project has been slightly higher (about 4%). Spain hosts one of the 12 Tier1 centers of the GRID worldwide structure for the LHC. This Tier1 is located at PIC, a centre for massive storage and data processing created through a joint venture of IFAE and CIEMAT at the campus of the UAB. In addition, there are three Tier2 centers, one for each large LHC experiment with Spanish participation. Finally, Spain also contributed with the participation of IMB-CNM, a microelectronics center with a microfabrication Clean Room, which made an important contribution to LHC experiments proposing and fabricating new detectors technologies for tracking and timing applications.

When the LHC started, in November 2009, all detectors with Spanish responsibility (Silicon Tracker and LAr and TileCal Calorimeters of ATLAS, Muon System and First Level Trigger of CMS, Silicon Tracker and SPD calorimeter of LHCb) were ready. They have been operating extremely well, contributing to the smooth data taking process all along these years. They have also adapted well to the rapidly varying LHC running conditions, especially the large increase in pile-up in the case of ATLAS and CMS. Spanish groups assumed important responsibilities in the commissioning, maintenance and operation of those detectors, ensuring their smooth operation, and are also playing a major role in the analysis work leading to many relevant results associated to Flavour, QCD, Electroweak, top quark, Higgs and BSM physics, obtaining good visibility in the exploitation of the huge amount of data delivered by the LHC.

The participation in the LHC project is also well aligned with the Spanish membership of CERN (8% contribution to the global budget) and will help to maximize the scientific, technological and industrial returns.

In the short term, LHC will continue operation with Run 3 starting in 2021, at already twice the design instantaneous luminosity and a foreseen increase of the energy of the collisions to 14 TeV. Spanish groups have participated with leading responsibilities in the ATLAS (IFAE and CNM) and CMS (CIEMAT, UAM and UO) Phase-I upgrade programs to operate at twice the design LHC instantaneous luminosity: the ATLAS Forward Proton (AFP) upgrade, the addition of a pixel layer IBL (ATLAS Insertable B-layer) and the relocation and replacement of the trigger and readout backend electronics of the CMS Muon System, are examples of these contributions.

In the medium term, the already approved high-luminosity phase (HL-LHC), which is expected to start by 2026-2027, will bring a major increase in the luminosity, aiming to collect 3000-4000 fb^{-1} of data at 14 TeV by ATLAS and CMS, and 50 fb^{-1} by LHCb. The physics program includes more precise measurements of the Higgs boson properties, SM parameters, physics of the flavour sector of the SM, as well as the direct searches for new phenomena. The expected improvements at the LHC and the HL-LHC in both, precision measurements and searches for BSM physics are significant and will improve our knowledge of nature substantially. They deserve our highest priority now and the corresponding human effort and financial resources.

In order to face the experimental challenges that HL-LHC will impose on the detectors, a major upgrade of their equipment is required. The aim is to cope with the extremely high HL-LHC instantaneous and integrated luminosity, along with the associated radiation levels. There will be major upgrades in tracking detectors, electronics of the calorimeter and muon systems, as well as improved triggers and data acquisition systems. The experiments and their physics potential will benefit of extensions to larger pseudorapidity, particularly in tracking and muon systems. Depending on the upgrade schedule of the individual experiments, some of these activities already took place during the first Long Shutdown period (2013-2014) of the LHC or during the end-of-year maintenance periods, as mentioned above. In any case, the bulk of the work is still to be done during the Long Shutdown periods LS2 (2019-2020) and LS3 (2023-2024).

The Spanish LHC community is strongly committed to the upgrade project and a substantial fraction of their human and financial resources is already dedicated to it. To withstand an instantaneous luminosity of 10^{35} cm^{-2} s^{-1} and having to stand very high doses, ATLAS needs to replace its Inner Tracker. IFIC and IMB-CNM designed many components of the end-cap strip tracker and will produce part of the modules. IFAE and IMB-CNM developed the radiation-hard 3D-pixel technology that has been selected for the innermost layer, and will produce part of the modules. There is also a contribution to the upgrade of the readout electronics and the mechanics of the TileCal ATLAS hadronic calorimeter (IFIC and IFAE, respectively). In the case of CMS, IFCA, ITA and US, together with IMB-CNM, are also involved in activities related to the tracker system upgrade for HL-LHC, in particular in the silicon 3D sensors assessment, powering schemes integration and monitoring of stability. In addition, CIEMAT, UAM, and UO are actively working in the upgrade of the muon and trigger systems which needs, on the one hand insure the capability of the gaseous detectors to operate under the expected integrated charge and also to redesign the on-detector readout and trigger electronics to adapt it to the high luminosity scenarios and to improve its performance. In both experiments increasing attention is devoted to the development of precise timing detectors based on the LGAD technology where the Spanish groups (IFAE in ATLAS and IFCA in CMS, both led by IMB-CNM) have special interest. IFAE and IMB-CNM will provide such sensors for the new High Granularity Timing Detector (HGTD) of ATLAS. In CMS, its use is being considered to be implemented in endcap dedicated detectors. In LHCb the contribution of Spanish groups (IFIC, IGFAE, UB, and URL) is centered on a new calorimeter front-end electronics, which needs to be developed in order to handle the 40 MHz readout, and the upgrade of the forward vertex locator, VELO, to a new detector aiming at unprecedented time resolution. Another important area of interest is a novel concept of tracking consisting of a thin scintillating fiber detector and its readout electronics.

Computing activities for HEP are crucial in the next years to cope with the HL-LHC data processing requirements. Spanish ATLAS, CMS and LHCb Tier-1 and Tier-2 infrastructures will need 20 times more resources for HL-LHC with respect to current ones, being storage the main challenge to address. The Spanish LHC computing community is establishing the main guidelines for the next years, moving towards common implementations: Integrated High Performance Computing, Grid resources and increasing network bandwidth. The development of a new computing model and investment in the computing resources is a strategic effort towards the successful exploitation of the LHC data.

From the theory side, the Spanish HEP community is strongly involved in providing theory predictions for current ALICE, ATLAS, CMS, LHCb, and MoEDAL precision measurements and searches. This concerns higher-order corrections for SM processes (e.g. Higgs and top) as well as for BSM physics (Higgs, SUSY, new gauge bosons, vector-like fermions, magnetic monopoles, 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 also in the future will continue its strong involvement in the on-going efforts to discover BSM physics.

In summary, The LHC Spanish community believes that the new phase of the LHC project at CERN (LHC Run 3, detector upgrades and HL-LHC physics exploitation) will be a unique (and the best) opportunity to improve our knowledge of the known and explore the limits of the unknown. We consider LHC should constitute the main path in the European Strategy for Particle Physics for the coming years. Therefore, the full LHC/HL-LHC operation and the exploitation of its physics programme are fully supported by the community. From the Spanish side it is then essential to guarantee an adequate support to LHC/HL-LHC activities, and the successful exploitation of its physics program.

Going beyond HL-LHC, the way to higher energies in pp colliders has to be paved (see Section 3). Our contribution to LHC and HL-LHC detectors has been based on an extensive R&D program. To maintain and strengthen our position at international level, the R&D program in new detector technologies should be one of our priorities, in particular the development of new tracking devices, precise timing detectors, and very highly segmented calorimeters or more compact electronics for their use at future facilities are the main lines of activity.

2 Flavour Physics

The understanding of flavour is, together with the electroweak symmetry breaking mechanism and the dark matter origin, one of the fundamental problems of today's particle physics. Since Rabbi asked who ordered the muon, the formulation of the flavour problem has evolved to the origin of the number of generations of quarks and leptons, to the origin of the mixing among different flavours and to the origin of CP violation. The large amount of data collected in kaon experiments, hadron colliders (D0, CDF, LHCb) and the B factories (BaBar and Belle) have established the SM Cabibbo-Kobayashi-Maskawa (CKM) paradigm as the dominant mechanism responsible for CP violation (and flavour mixing). The discovery of the neutrino masses and the improved knowledge of the Pontecorvo, Maki, Nakawa and Sakata (PMNS) mixing matrix are other achievements of paramount importance towards the understanding of the origin of flavour.

Recently, several observables in the flavour sector of the SM have shown anomalies concerning heavy quarks, which can be pointing out BSM physics. The LHCb experiment, which will be upgraded in the coming years to be operative during Run 3, and the Belle-II experiment at KEKB, which is at present starting to take data, are of high interest to confirm or refute those possible hints of new physics. ATLAS and CMS experiments are expected to contribute in the flavour physics program.

The Spanish groups are strongly committed to the LHCb upgrade detector (tracking system and calorimeter) and to the data physics exploitation (see Section 1). The Experimental Physics community, whose origins go back to BaBar and CDF, has grown and its current major experimental activities are related to the LHC experiments and especially to LHCb. Despite the enormous interest of the physics of Belle II, the b-physics Spanish scientific community prioritizes the participation in the LHCb experiment. In Spain there is an important Theoretical Physics community working in flavour phenomenology that closely collaborates with the experimental groups, being deeply involved in the physics exploitation of the data.

Since many important open questions in the SM are related with Flavour Physics, we believe that special attention should be given to ensure that the LHC detectors, analysis techniques, and physics program of the LHC experiments could optimally exploit their potential for flavour physics. B-physics should represent an important ingredient of the LHC and HL-LHC physics program. The new physics energy scale, which can be explored by indirect measurements in the flavour sector, goes well beyond the direct searches at ATLAS and CMS experiments. Therefore, the LHCb upgrade program that will allow the detector to operate with increased luminosity is considered relevant in the overall HL-LHC program.

3 Physics at the High-Energy Frontier: future Linear and Circular Colliders

In this section, we focus on future circular and linear colliders apart from HL-LHC as this has been discussed previously. Several proposals have been developed. The ILC project, a linear collider using superconducting acceleration technology, is by far the most robust and mature technology and already developed its Technical Design Report proposal (ILC-TDR, arXiv:1306.6327). An alternative approach to the ILC, the CLIC concept based on normal conducting technology, is developed under the CERN leadership (Conceptual Design Report and Updates: arXiv:1202.5940 and arXiv:1608.07537). Other proposals for future colliders are the energy upgrade of LHC to 27 TeV (HE-LHC), the Circular electron-positron Collider (CepC) (Conceptual Design Report: arXiv:1809.00285 and arXiv:1811.10545) and the Circular proton-proton Collider (SppC) in China, and a Future Circular Collider at CERN which could operate initially as an e^+e^- collider (FCC-ee) and later as a hadron collider (FCC-hh) or/and as an ep collider (FCC-he) (Machine Parameters of proposed Future Colliders at CERN: arXiv:1810:13022).

The extension of the physics programme beyond the LHC will thus require the construction of a new generation of colliders and the development of new cutting-edge detectors, using much improved detector technologies than those existing at present. In Spain, starting in the mid 2000's, a continuous effort has been made in this direction. As a result of this, in 2006 the Spanish Network for Future Colliders was created, including experimental groups (CIEMAT, IFCA, and IFIC), technological centres and departments (IMP-CNM, INTA, ITAINNOVA, NTC, UB, and US), accelerator groups (ALBA, CIEMAT, and IFIC), and theoretical groups (IFCA, IFIC, IFT, and UGR). Despite other punctual developments, this network concentrates the bulk of the activity in R&D for future facilities.

3.1 Considerations on the physics case for future machines

The **International Linear Collider (ILC)** with center-of-mass energies between 250 GeV and 1000 GeV has a mature technical design that is ready for construction. The ILC will be a Higgs boson factory where the clean operating environment, low backgrounds, adjustable beam energies and polarizations will allow model-independent measurements of the Higgs-boson absolute couplings to SM fermions and gauge bosons, most of them to better than 1% precision, as well as determining their CP properties. ILC can make precision measurements of the Higgs boson self-coupling to an accuracy of typically 10-20%. The ILC will be also a precision top-quark factory. The adjustable beam energy and clean operating environment will allow determining the top quark mass to a precision of 50 MeV or better. Also, the ILC will be able to produce new BSM particles up to half its centre-of-mass energy, and sensitive to new force particles Z' with masses ranging up to 7-12 TeV.

The ILC250 with its high luminosity and the possibility to polarize both beams offers great opportunities to measure with high precision the couplings of the Higgs and gauge bosons (where roughly similar precisions are expected at CLIC/FCC-ee). This will allow discriminating between the SM and many different BSM models, e.g. through exotic/invisible Higgs decays. This includes in particular Dark-Matter discoveries. Going to lower energies, high-precision measurements of SM processes can be performed (GigaZ, WW threshold), offering a high potential for the indirect discovery of BSM physics. Extended to higher energies, the ILC will give access to the top quark properties and in particular to the Higgs self-coupling.

The Compact Linear Collider (CLIC) project may open the possibility of multi-TeV e^+e^- collisions. A first, low-energy phase collecting 500 fb^{-1} at a centre-of-mass energy of 380 GeV (CLIC staging document: CERN-2016-004, arXiv:1608.07537) which would allow the two main Higgs-boson production mechanisms, through Higgs-strahlung and vector-boson-fusion. The Higgs-boson couplings to W bosons can be determined to excellent precision, as well as competitive measurements of electroweak couplings of the top quark. After that, the machine will be upgraded to reach centre-of-mass energies in the multi-TeV regime, where it can study associated production of Higgs bosons and top quarks, vector-boson scattering and di-Higgs boson production. Its unique multi-TeV reach is key to fingerprint new massive particles and search for new phenomena that escaped detection at the LHC. While the CLIC design is somewhat less mature than that of the ILC, the low-energy stage forms a realistic and affordable option for the period following the LHC.

With the discovery of a relatively light Higgs boson, the interest in **Circular e^+e^- colliders (FCC-ee, CepC)** has revived. Groups in Europe (First Look at the Physics Case of TLEP, arXiv:1308.6176) and China (CEPC-SPPC Preliminary Conceptual Design, IHEP-CEPC-DR-2015-01) are investigating a circular e^+e^- collider, with high luminosity at centre-of-mass energies up to 250 GeV. Its main target is the measurement of Higgs boson couplings at or below the per-cent level. Eventually it could reach the top-quark pair production threshold. The top-quark Yukawa coupling to the Higgs boson and the Higgs-boson self-coupling could only be accessed indirectly due to the limited centre-of-mass energy. Synchrotron energy loss of the beams effectively prevents reaching higher energies.

A 100 TeV pp **Circular hadron collider (FCC-hh)** is under consideration following the completion of the LHC and high-luminosity LHC physics programs, to probe new energy scales, allowing us to hunt for new fundamental particles roughly an order of magnitude heavier than we can possibly produce with the LHC, and new particles the LHC may produce in small numbers will be produced with up to a thousand times higher rate (arXiv:1607.01831 [hep-ph], arXiv:1606.09408 [hep-ph], arXiv:1606.00947 [hep-ph]). Many years of intensive work are still needed to arrive at a complete description. Operating the FCC-hh with heavy ions is also an option that is being considered (arXiv: 1605.01389 [hep-ph]). A design study by the Chinese community for a similar machine but with smaller centre-of-mass energy (20-30 TeV) is also ongoing (arXiv:1510.05754).

Studies on the physics program of a **proton-electron collider (FCC-he)** at the FCC facility are also taking place, although results have only been documented for a Large Hadron Electron Collider (LHeC) (arXiv:1206.2913 [physics.acc-ph], where the IGFAE group has made important contributions), a possible precursor of the FCC-he. The physics program is centred in the exploration of high precision measurements of deep inelastic scattering (DIS) measurements at the energy frontier.

The High Energy LHC (HE-LHC) is a study aimed at exploring the possibility to upgrade the present LHC ring to reach 27 TeV centre-of-mass collision energy, substituting the present LHC superconducting magnets with ones with much higher fields, of up to 20 Tesla. (https://cdsweb.cern.ch/record/1344820/files/cern-2011-003.pdf). The physics case of a high-energy upgrade of the LHC is similar to that of the FCC-hh, although with a smaller energy reach.

3.2 Spanish detector R&D activities related to future colliders

The main R&D activities of the Spanish groups in relation to the above described future facilities are related to two aspects. On one side in the tracking systems, pixel and strip semi-conductor detectors, with excellent space-point resolution in systems of extremely low mass and low power consumption. The activity focuses on the sensor performance and quality tests, module assembly, connectivity, powering, system engineering, alignment and data extraction. On the other, in highly segmented calorimetry inside the CALICE Collaboration, the mechanics of the semi-digital hadron calorimeter and its final detector interface readout electronics are the challenges.

Spanish groups (IFCA, IFIC, ITANNOVA, NTC, IFCA, and UB) are involved in several aspects of the Belle II using DEPFET technology for the vertex detector, including passive components, digital handling processor, critical temperature controller, environmental monitoring system, noise propagation effect of power cables and the electromagnetic susceptibility of the electronics. DEPFET remains one of the main candidates for the vertex detector of future energy-frontier electron-positron colliders (ILC, FCC-ee, and CEPC). Further DEPFET applications include X-ray imaging on satellites and in the X-ray Free Electron Laser.

IFAE, IFCA, IMB-CNM, UB, and US, have also worked on microstrip sensors, which combines signal amplification –allowing the thinning of the sensor's substrate– and resistive electrodes –allowing the implementation of the charge-division method for the determination of the hit position along the strip direction (LGAD, and a new concept called i-LGAD still under study). The application of LGAD devices to the Linear Colliders (LC) tracking is a spin-off of its original aim as timing devices for high radiation environments, this technology is being proposed as vertex locator technology for the LHC experiments: AFP2 and HGTD (ATLAS); and CT-PPS (CMS). UB has worked on Geiger-mode avalanche photo-diodes (GAPDs) fabricated in a conventional CMOS process with internal gain and ultra-high speed, which constitute the basic cells of Silicon Photomultipliers (SiPMs). The group analysed and proposed methods to limit that noise for application in ILC and CLIC. Apart from LC uses, since the apparition of GAPDs in CMOS in 2003 most of the applications were bioassays in which labels are identified by the emission of fluorescence light. Furthermore, a collaboration of Spanish Institutes (IFCA, IGFAE, IMB-CNM) is also starting a new R&D on radiation hard 4D-tracking detectors for the HL-LHC (CMS, LHCb Upgrade-II). This technology will be used in many proposed projects for the post-LHC era (FCC at CERN or SppC in China).

HV-CMOS is assuredly emerging as the prime candidate technology for future tracking sensors for ionising radiation for particle physics and numerous other applications. It is a priority to study these types of devices in view of future high-luminosity collider applications (HL-LHC and beyond, e.g. FCC). IFAE, IFCA, and UB, among others, are involved in the CERN RD50-HV-CMOS design which includes several types of test structures, from diode arrays for TCT studies, amplified structures with different pitches for resolution studies and assessment of S/N and other parameters (e.g. cross talk) and time resolution enhanced matrices.

CIEMAT is part of the CALICE Collaboration since 2007. The group has worked in the tests of Silicon-ECAL and Scintillator-HCAL prototypes but its main contribution is related to the SDHCAL (Semi Digital Hadronic Calorimeter) been one of the major contributors to the collaboration. A ~1 m^3 prototype has been build and the results obtained in beam tests shows a good energy resolution, linearity and an extraordinary tracking capability, making it an excellent option for future experiments. The SDHCAL is one of the two options considered for the hadron calorimeter of the ILD experiment at ILC and for the Chinese CEPC-SppC detector. The group is facing now some specific challenges associated to the ILD calorimetry, both in mechanics (as the use of electron beam welding technologies) and electronics (due to the huge number of channels to deal with) that can be applied to the CEPC-SppC.

ITAINNOVA group works in collaboration with the other Spanish groups, both for tracking and calorimetry, in a power supply system based on supercapacitors compatible with the power pulsing technology.

IFCA and IFIC groups, with support from the technological institutes, are deeply involved in the design of the experiments for the ILC and CLIC.

The Spanish community is heavily engaged and participates in the design/performance studies of the ILD detector concept of ILC and on physics studies for both ILC and CLIC. Most of the groups are members of the ILD and CLICdp collaborations. Several groups (IFCA, IFIC, IMB-CNM, INTA) contribute to the design and benchmarking of the ILD forward tracking system. In addition, IFIC also keeps contact and collaborates in activities related with FCC-ee and CepC like the production of its Concept Design Report, CDR.

3.3 Accelerator R&D

On Accelerator Technology, during the past 20 years there has been a significant activity in Spain for developing and constructing accelerator components as contributions to major International Projects and Facilities like LHC, HL-LHC, CLIC and its test facility CTF3 at CERN, ILC and its test facility ATF2 in KEK, XFEL at DESY, FAIR at GSI, IFIMIF and others; and even for a complete accelerator complex as the Spanish Synchrotron Radiation Source, ALBA-CELLS in Barcelona.

In particular, the ALBA accelerator division has a consolidated experience, acquired during the design and construction phases of the ALBA machine. More specifically in the design and fabrication of resistive and special magnets (including magnetic measurements), beam instrumentation, vacuum or Radio Frequency (RF). Furthermore, the ALBA workshops and the magnetic and RF laboratories have been made available for own and exterior use. The ALBA accelerator group is participating in the CLIC project for the beam test of the Stripline Kicker Damping Rings (DR) prototype, Beam Instrumentation and RF systems and in the FCC project in the FCC-hh Vacuum activities (EuroCirCol H2020) (see Section 6).

The Electrical Engineering Division of CIEMAT expertise is basically focussed on Superconductivity (SC) and RF and it includes an experimental facility for manufacturing and testing superconducting magnets based on NbTi technology and also for assembling accelerator components. The group has collaborated in the ILC SC magnets R&D, in the construction and industrialization of XFEL components (SC magnets, Movers, Phase Shifters and Control Systems) and also for the CLIC-CTF3 (Resistive magnets, Ultrafast Stripline Kickers, Ultra Precise Moving Tables, and Power Extraction Structures (PETS)). Currently the group is involved in the CLIC project, particularly in the development of Permanent Magnet based Gradient Dipoles for CLIC DRs and in the fabrication of Accelerating Structures Prototypes; in the HL-LHC developing a superconducting nested dipole as part of the Spanish contribution; and in EuroCirCol and the FCC project in the joint R&D effort for High Field Superconducting Magnets (16Tesla) for HE-LHC or FCC-hh. Furthermore, the group has developed during these years a unique experience in the industrialization process of accelerator components that could be crucial in the participation in Future Accelerator projects.

The Accelerator group of IFIC has actively contributed to study the beam dynamics for LHC collimation system and the Beam Delivery Systems (BDS) of CLIC and ILC-ATF2. The group has also designed and constructed Beam Position Monitors and a Stripline DR Kicker prototype (in collaboration with CIEMAT) for CLIC-CTF3 project and Optical Transition Radiation (OTR) Beam Size Monitors and a halo Collimator for ATF2-ILC project. Currently the group is involved in the High-Gradient (HG) Normal Conducting CLIC RF R&D effort, more specifically in extending the CLIC HG RF technology for medical applications. To consolidate this effort, the group is constructing an S-Band high-power test stand, which will be capable of performing high-power tests and a complete breakdown analysis of RF components up to 30 MW.

Future Spanish contributions to Particle Physics Accelerators will be probably conditioned by a number of factors like:

- From the point of view of participants, it is very likely that the actors that are now involved in international collaborations will continue to participate in future accelerators projects contributing with their experience, expertise, and facilities, which have been developed over the last 10 to 20 years. Other actors may join, as the ESS Bilbao with a strong potential either in know-how and experimental facilities, as well as other smaller university groups in the UPC and UH.

- From the point of view of technological choices, some strategies are now under consideration. As a significant example, CIEMAT has decided to be deeply involved in the technology of High Field SC magnets based on Nb_3Sn for applications in future accelerators projects as HE-LHC or FCC-hh. In general, we could conclude that the Spanish accelerator groups involved in the Future Accelerator network have a solid programme that has a strong potential not only from the scientific and technological point of view, but also strategically, and industrially.

- From the industrial point of view, participation of national companies in this sector is becoming more and more relevant when deciding the corresponding in-kind contributions. In this regard and in parallel with the scientific and technological development in the Public Institutions, an interesting industrial fabric related to accelerator technologies has been established in our country, part of them framed by the INDUCIENCIA-INEUSTAR federation (Spanish Industry for Science Association), which is able to compete successfully in technologies such as SC and resistive magnets, normal conducting RF, power converters, beam instrumentation and others.

3.4 Further remarks

The Spanish community is concerned of having a long-time gap between the end of HL-LHC programme and the start in operation of a future machine following. This is felt as a high-risk period with negative impacts to the field and as such it should be reduced as much as possible. Realistic plans for a future collider should consider seriously this fact.

Beyond the LHC physics programme, the choices of the community can be summarized following:

- Given the latest LHC physics results and those of the field, in general our priority is for an e^+e^- collider extendable in energy and capable to reach at least 550 GeV. At this level both e^+e^- linear collider proposals, ILC and CLIC should be considered. ILC offers a more mature technology and a faster implementation. The present ILC proposal, conceived as a Higgs factory at 250 GeV centre-of-mass energy with potential upgrades to higher energies, is positively seen to make the project realistic and feasible. If the Japanese government proposes to construct and to host the ILC250, the Spanish community is committed to participate in this new endeavour. Having more labs in addition to CERN, which have central roles in the development of collider High-Energy physics, is noticed as a very positive feature to pursue that reinforces the strength of the field. Circular e^+e^- machines (FCC-ee and CepC) are supported as a Higgs factory and should be considered mainly in case the linear collider projects fail to materialize.

- A possible future contribution from Spain to ILC250 should be negotiated in close collaboration with the rest of interested European countries, including the participation of the CERN lab to this possible European contribution in technology and science as well as logistics. A structure similar to the already existing one for the DUNE neutrino programme at FERMILAB could be considered.

- A strong R&D programme to develop the needed technologies for the future CERN projects following LHC is mandatory and fully supported by the Spanish community. This includes detector and accelerator R&D. In the case of Spain, the development of high-field superconducting magnets for either HE-LHC or FCC-hh is our main line of activity in the area of accelerator physics and magnet development.

- For the HE-LHC and FCC-hh proposals the Spanish community understands that at this stage both projects need to develop a common technology, mainly for high-field magnets. For the period of the next 4-5 years no urgent need is felt to decide on which project to prioritize. Hence both are supported expecting for results from HL-LHC which may also help finding the best way to go.

- Future developments on accelerator technologies like plasma acceleration or muon colliders are also supported, and in particular the CERN program of AWAKE should be continued.

- Any of the above future activities should be compatible with the successful completion of the LHC and HL-LHC physics program. Therefore, any future activity should have a realistic plan to accommodate resources accordingly.

4 Astroparticles, multi-messengers, and cosmological surveys

Lying at the intersection of astronomy, particle physics and cosmology, astroparticle physics is well placed to search for signs of physics beyond the standard models of particle physics and cosmology.

Here we summarize the input received from the Spanish community, whose main interests match those included in the topics in astroparticle physics set to take priority in Europe in the coming years, according to a recent report by the Astroparticle Physics European Consortium (APPEC): neutrino physics, dark matter and multi-messenger astronomy. Many research lines related to these topics are studied by the Spanish groups working in astroparticle physics, either through their contributions to the international experimental collaborations or via their theory activities.

The existence of massive neutrinos confirms that there exists new physics beyond the Standard Model of Particle Physics, and the discovery of the neutrino mass through neutrino oscillations was a major breakthrough (Nobel prize in physics in 2015). However, neutrino physics will still be an active area of research in the near future. Oscillation studies and neutrinoless double beta decay searches are thriving with new experiments, performing precise determinations of the absolute mass scale and oscillation parameters or unveiling whether neutrinos are their own anti-particles.

Non-accelerator experiments, such as searches for proton decay, neutrinoless double beta decay and dark matter, as well as the study of high-energy cosmic rays, are key to address fundamental questions of particle physics beyond the standard model. This kind of experiments requires extremely low levels of background, both from cosmic rays and from the natural radioactivity of the materials used in their construction. Spain hosts one of the few underground sites in Europe to carry out this kind of physics: the Canfranc Underground Laboratory (LSC), a singular scientific and technical infrastructure (ICTS), (see Section 6). The LSC should be a central objective in the Spanish scientific strategy, reinforcing experiments ongoing in its facilities and fostering collaborations with international partners, and leading to increase the role of the LSC in the European Strategy and to exploit maximally its capabilities.

The recent detection of gravitational waves from the merger of two neutron stars (Nobel Prize in Physics 2017) and the identification of the gamma-ray counterpart to an astronomical neutrino detection highlight the rise of "Multi-messenger Astronomy": a discipline that exploits the complementary power of charged cosmic rays, electromagnetic waves, neutrinos and gravitational waves to study extreme events such as supernovae, black-hole mergers and the Big Bang itself. Spain is involved in detectors for cosmic rays (Auger and AMS), gamma rays (MAGIC and CTA), astronomical neutrinos (Antares and KM3Net) and gravitational waves (LIGO-Virgo and LISA). Spain will host a key infrastructure for gamma-ray detection: the CTA North observatory, located at another ICTS, the Roque de los Muchachos observatory in La Palma (see Section 6).

4.1 Neutrino physics

Neutrino oscillation experiments led to the historical discovery of neutrino mass through flavour oscillations, and they will continue to provide answers to key questions in particle physics (CP violation in the lepton sector, mass hierarchy, sterile neutrinos, violation of unitarity of the neutrino mixing matrix, etc.). In addition, deep underground detectors offer powerful physics synergies with e.g. proton decay searches, detection of geophysical, solar, atmospheric and supernova neutrinos.

As described in the main document (ESPP2020-ES, Section 2) the Spanish community has an active program in neutrino acelerator-based experiments for more than 20 years, providing very relevant results to improve our understanding of neutrino properties. Moreover a group at CIEMAT is participating in the Double Chooz reactor neutrino experiment in France.

Beyond neutrino oscillations' physics, the IFIC and IGFAE groups carry out an active program on double beta decay research. NEXT (Neutrino Experiment with a Xenon TPC, https://next.ific.uv.es/next/) is a neutrinoless double-beta decay experiment that operates at the Canfranc Underground Laboratory. It is based on a novel detection concept for neutrinoless double-beta decay searches, consisting in a Time Projection Chamber (TPC) filled with high-pressure gaseous xenon and with separated-function capabilities for calorimetry and tracking. NEXT, the flagship experiment at LSC, aims to lead the search for neutrinoless double beta decay worldwide by demonstrating the best scaling needed to reach half-life sensitivity better than 10^{27} years.

Besides the experimental effort, the theoretical contribution to neutrino physics has in Spain a long tradition; with many and strong groups making significant contributions to this field.

4.2 Dark Matter

Playing a leading role in future dark matter (DM) experiments requires the development of new detectors and technologies. It is crucial to support R&D in detectors based in noble elements (Ar, Xe), silicon technologies, or superheated fluids (C_3F_8, CF_3I, Ar, etc.) among others. Spanish groups currently participate in experiments that search for hypothetical DM particles in two well-defined mass regions: WIMPS (high mass, above 1 GeV) and axions (low mass, below meV).

Concerning WIMPs, the Spanish DM community is involved in direct detection experiments, based on several technologies, such as DarkSide-20k (a large liquid argon TPC), ANAIS (using NaI(Tl) scintillating crystals), TREX-DM (a high-pressure Micromegas-read TPC), superheated fluids (PICO, MOSCA-B), and scientific CCDs (DAMIC - Dark Matter in CCDs).

Recently, all the experiments using liquid argon (LAr) detectors joined in the Global Argon Dark Matter Collaboration, including members from the DarkSide-50, DEAP-3600, ArDM and MiniClean collaborations. The membership totals 350 scientists from 68 institutions in 12 countries and has an immediate objective of a 20,000-kilogram detector called DarkSide-20k to be sited at the Gran Sasso Laboratory in Italy, using argon from an underground source in Colorado. ArDM and the LSC, where it is located, will play an important role in this Collaboration. ArDM will be used to host a small detector that will measure the content of radioactive ^{39}Ar in the underground argon to be used in DarkSide-20k. LSC is a reference laboratory for the precise measurement of radioactivity in the materials to be used in the construction of DarkSide-20k. Support to the activities in DarkSide-20k should be secured in the next 10 years. The upgrade of this detector to a 300-tonne LAr TPC, which will have the sensitivity to search for high mass WIMPs down to the level of the so-called neutrino floor (neutrino background from coherent scattering with nuclei), should be supported as a natural continuation of the DM search using LAr TPCs.

ANAIS is a Spanish DM direct detection experiment at the LSC using 112.5 kg of NaI(Tl) detectors, which has finished construction in 2017. It is essential to secure its operation in the five years required to test DAMA/LIBRA annual modulation signal at the three-sigma level and the scientific exploitation of its data. It would be also important to support the study for an experiment upgrading, if considered convenient after results from the present experimental setup are released.

TREX-DM is a relatively recent project looking for low-mass WIMPs with a high-pressure Micromegas-read TPC, mostly driven by Spanish scientists. It exploits amplification in gas and low background capabilities from recent R&D on microbulk Micromegas. Approved in 2017 and now being installed at the LSC, the first background measurements should come soon. If current prospects from simulation studies are confirmed, the experiment could attain sensitivity surpassing current bounds on low mass WIMPs.

Superheated fluids have been proven to be good DM detectors due to the intrinsic electronic recoil rejection. The use of acoustic technique to background discrimination has improved their capability significantly and PICO detectors provide the most constraining limits for proton-WIMP spin-dependent interaction. Ongoing R&D studies for scaling detectors, for increasing background discrimination and for extending to other targets are very promising. Spain, that has been contributing in this area through the Multidark project, and Europe should not abandon this line.

Finally, the DAMIC experiment employs a novel detection technique, it has pioneered the detection of nuclear and electronic recoils induced by dark matter particles in the silicon bulk of charge-coupled devices, the CCDs that have been used for many years in digital cameras and in the focal plane of astronomical telescopes. Thick CCDs, almost a mm compared with the typical tens of microns, used by DAMIC are extremely sensitive: they can detect signals as low as few electrons, as those expected from light dark matter interactions. In addition, the spatial resolution of these devices (the pixel size is 15 micron x 15 micron) results in the unique capability to characterize and reject backgrounds from radiogenic sources. A next generation detector (kg-size, DAMIC-M), mostly funded by ERC and NSF funds, will be installed at the Laboratoire Souterrain de Modane in France. With unprecedented sensitivity DAMIC-M will take a leap forward of several orders of magnitude in the exploration of the dark matter particle hypothesis, in particular of candidates pertaining to the so-called “hidden sector” which may have so far escaped detection. An extensive R&D program is being developed in collaboration with LSC.

The physics case of axions as DM candidates has been considerably developed in recent times. Experiments to detect them are quickly increasing in number and size. Axion helioscopes, aiming at detecting axions from the Sun, occupy an outstanding place in the wider axion experimental landscape. During the last 15 years, CAST at CERN has been the leading experiment in this category, with a relevant Spanish participation since its beginning. Since few years, Spain leads the project for a next generation axion helioscope, IAXO, aiming an important step forward in sensitivity, by substantially scaling concepts introduced in CAST. The current goal is the realisation of an intermediate experimental stage, called BabyIAXO, as prototype of all IAXO subsystems but that will already produce physics results with sensitivity beyond CAST. IAXO is the largest experimental collaboration on axions, with 17 institutions from all over the world, including CERN and DESY (where it will be likely hosted). Having attracted ERC funding, BabyIAXO is expected to be built in 2-3 years with first physics data in 3-4 years. IAXO has a unique physics case, in particular being able to probe QCD axion models in the meV to eV mass range. It has a central role in the European axion community, and is increasingly supported by European institutions and agencies. It is also an important activity with large visibility for the Spanish community and important synergies with current expertise and trajectory of the groups involved. A particularly noteworthy synergy is the one existing with the underground physics community and LSC (already exploited in CAST) due to the low-background requirements of the X-ray detectors of IAXO.

An independent avenue to investigate DM is the production and analysis at high-energy particle colliders, and the search for DM is one of the main tasks of the ongoing and upcoming LHC runs. In the most favourable case the mass and the couplings of the DM particle can be measured precisely, its relic density calculated and compared with astrophysical measurements. Such a high precision can only be reached in the clean environment of e^+e^- colliders. The possibility to extend the reach to higher center-of-mass energies (if required) and the availability of polarised beams are crucial for the desired high-precision measurements.

4.3 Multi-messenger observatories

Neutrino telescopes

After the discovery of the existence of a flux of high-energy cosmic neutrinos by the IceCube Collaboration, a rich harvest of new results is rapidly increasing our knowledge about the high-energy Universe, including those of the current ANTARES telescope, which have shown the feasibility of undersea detectors. Also located in the Mediterranean Sea and included in the ESFRI, KM3NeT is a research infrastructure housing the next generation neutrino telescopes (with contributions from Spanish groups at IFIC, UPC, UPV and UGR). It will have two configurations in their intermediate phase, called ORCA and ARCA, which reflects the double nature of its scientific scopes: fundamental particle physics and astroparticle physics.

The ORCA configuration, denser and located in the French coast, will contribute to two fundamental physics questions. Its low-energy threshold (of a few GeV) will allow for the measurement of neutrino mass ordering due to the matter effect in the propagation of atmospheric neutrinos, in an unbeatable scale of time (completed in 2020) and cost. With a detector as ORCA, three years will suffice to reach a 3-sigma significance for neutrino mass ordering, while competitors like PINGU, in the South Pole, will not be ready in a so short time scale. Other neutrino properties, such as non-standard interactions and sterile species, can be potentially studied with ORCA. In addition, another fundamental goal is the indirect search for dark matter, for instance from the Sun or the Galactic Centre. On the other hand, the ARCA configuration, of a larger volume and located in the Italian coast, will focus on the search for cosmic neutrino sources in the context of the new multi-messenger era. In addition to its geographical location, that allows the observation of the Galactic Centre and most of the Galactic Plane, another critical advantage of ARCA is that water offers better optical properties than ice, which translates into a better angular resolution, a key parameter for this kind of searches.

The construction of KM3NeT has already started. The first lines of Phase 1, completely funded, have been installed. In the meantime, the construction and integration of lines continues at a briskly path across the several sites in the Collaboration. On the budget side, more than 60% of the project required funding is already approved, with good prospects for additional contributions from the core countries (France, Italy and the Netherlands), while only a small part is needed from the rest of partners (including Spain) to complete ORCA and the first building block of ARCA.

Gravitational waves

Since the first discovery of gravitational waves (GW), the Spanish participation in the LIGO/Virgo collaboration grew from one research group to an expected five by the end of 2018 (IFAE, IGFAE, UB, UIB, UV). To date, the main direct contributions have concerned the computational challenges of GW astronomy: searches for gravitational wave events, Bayesian inference to identify sources, source modelling based on high-performance computing, mostly at European Tier-0 facilities, and characterisation of the detector noise, including works at the detector sites. Nowadays, hardware contributions, in the area of stray light control, have been also recently planned for the mid-term upgrade of the interferometers. Many observational astronomers and astroparticle physicists joined the Spanish GW community, organised in the thematic network REDONGRA (part of the FPA National Program), with groups at eight universities and research centres. Significant contributions were made to follow-up activities of electromagnetic and possible neutrino counterparts as a result of the detection of the BNS merger GW170817 and new agreements have been reached to boost these activities during the upcoming LIGO/Virgo observing runs.

In parallel to preparations for LIGO/Virgo design sensitivity and the next possible discoveries (including black-hole neutron star mergers or isolated neutron stars), members of the Spanish GW community are also involved in the ongoing efforts towards third-generation GW detectors (the design projects Cosmic Explorer and the Einstein Telescope). In particular, we recently signed the Letter of Intent that constitutes the basis of the newly created ET Collaboration and is aimed to develop the necessary structure by early 2019 to submit the ET proposal for the 2020 update of the ESFRI Roadmap. Activities focused on ground-based detectors are complemented by the developments for the LISA space mission selected by ESA as its third large-class mission and several groups joined the LISA consortium (ICE, IFT, UIB). The ICE (CSIC & IEEC) group has led the Spanish contribution in hardware and software for the LISA Pathfinder mission and its currently doing the same for the Phase A of LISA.

Further improvements of the existing LIGO/Virgo installations are foreseen, in parallel to the planning for third generation detectors and detectors based on atom interferometry. The participation of Spanish groups to observations with the existing network of GW detectors and multi-messenger observations is expected to expand further and take full advantage of synergies between the field of GW astronomy and the existing community in cosmology, astroparticle and theoretical physics.

Gamma-ray observatories

The Cherenkov Telescope Array (CTA) is the leading project among all current designs of future Very High Energy (VHE) gamma-ray observatories. CTA is ranked as one of the top priorities by the European Astroparticle roadmap (ASPERA) and the European AstroPhysics Roadmap (Astronet). In early July, the European Forum on Research Infrastructures (ESFRI) made the decision to promote CTA to Landmark status on its 2018 ESFRI Roadmap. CTA was one of 8 projects promoted to the current list of 37 Landmarks. CTA is also a High Priority Project in the Spanish Strategy for the participation in Scientific Infrastructures.

CTA will consist of two sites, one in each hemisphere, holding large arrays of Cherenkov telescopes made up of small-, medium-, and large-sized reflector dishes that will help face different scientific problems within a single observatory. The improvement in sensitivity is expected to match the development achieved by X-ray and low-energy (20 MeV-50 GeV) gamma-ray space-borne telescopes in recent decades. With an initial expectation of a thousand source detections over the lifetime of the array, CTA is poised to make a significant impact on fundamental questions of Physics and Astrophysics.

CTA is completing the pre-construction phase, in which a comprehensive Technical Design Report was completed, a Critical Design Review was successfully passed, the CTA North and South observatory sites were downselected to be the Observatorio del Roque de los Muchachos (ORM) located at La Palma and ESO-Paranal respectively, and the CTA Project Office (PO) site was downselected to be in Bologna while for the Science Data Management Centre (SDMC) was chosen DESY-Zeuthen in Berlin.

The CTA North site at ORM will become a key infrastructure of Astroparticle Physics inside the European territory and will benefit with synergies with optical, infrared and radio astronomical facilities in La Palma and Tenerife (see Section 6).

All the efforts are currently focused in starting the pre-production phase in the two CTA observatories. Furthermore, the prototype of the Large-Size Telescope (LST1), co-led by the Spanish community, has finish installation in October 2018, and the first Mid-Size Telescope equipped with an analogue camera (MSTN1 where the N stands for NeCTArCam, where the Spanish groups are also involved), a pre-production telescope that should start installation at ORM.

The VHE gamma-ray Spanish community had already a high impact in projects such as HEGRA and MAGIC and is playing a key role in CTA. The Spanish groups at CIEMAT, IAA, IAC, ICCUB, ICE, IFAE, IFT, PIC, UAB, UCM, and UJA, act in a coordinated way ("CTA-Spain"). The Spanish government supports CTA-Spain through its R&D programs and also committed a significant amount of development funds ("ERDF" or "FEDER") to the infrastructure of CTA North, the construction of the next 3 LSTs and a significant fraction of the MSTs at ORM.

5 Interface with Nuclear Physics

The understanding of the Universe from basic principles is an ambitious goal that involves many physics disciplines. Nuclear, particle and astroparticle physics play a key role in this context. The main objective of nuclear physics is the understanding of the fundamental properties of nuclei starting from their building blocks, the nucleons, and eventually from the quark and gluon degrees of freedom of QCD. To this aim, detailed knowledge about the structure of hadrons, the residual forces between nucleons stemming from their constituents, and the limits of the existence of the nuclei and of the hadrons themselves, is required.

Nuclei form an exceptional laboratory for fundamental physics, in many cases complementary to particle physics and astroparticle physics.

The Spanish Nuclear Physics community plays an important role in advanced research at the European and World scales. The main goals are in line with those defined by the recent Long Range Plan drawn up in 2017 by NuPECC, the Nuclear Physics European Collaboration Committee. The research topics addressed by Spanish groups include experimental research, theoretical activities and applications. Concerted efforts with other countries are co-ordinated within European-wide projects and integrating activities.

There are strong synergies between nuclear and particle physics that can be exploited both inside and outside CERN, mainly related to accelerator facilities and instrumentation, neutrino physics, astrophysics and applications.

Accelerator facilities

NuPECC urges for the completion and exploitation of the ESFRI flagship facility FAIR, a unique assembly of accelerators and experimental facilities that will allow for forefront research in physics and applied sciences. NUSTAR (Nuclear Structure, Astrophysics and Reactions) is the collaboration where the Spanish experimental nuclear physics community is strongly involved, concentrated in decay and in-flight spectroscopy at DESPEC/HISPEC, mass measurements at MATS and the study of reactions with high-energy secondary beams with R^3B. Spain has played a leading role in the definition of the NUSTAR Physics case and in the design, R&D, and construction of advanced instrumentation. Spanish scientists occupy relevant positions in the NUSTAR management and in several of the experimental collaborations.

CERN infrastructures are of extraordinary importance in shaping nuclear research. The ISOL facility ISOLDE can take full advantage of the recent LHC Injector Upgrade at CERN, specifically the higher proton current provided by the new Linac4 and the increased proton beam energy from the PS Booster. These upgrades will allow for higher radioactive beam intensities and for the simultaneous operation of two target stations to deliver beams to the many low energy and post-accelerated beam experiments. The construction of a storage ring behind the HIE-ISOLDE post-accelerator will open up new possibilities in the fields of fundamental symmetry studies, atomic and nuclear physics. Spanish scientists have contributed to the success of the physics research at ISOLDE using both low- and high-energy beams and they have played a key role in the upgrade of the facility. The future ISOL facilities in Europe, specially the ESFRI SPIRAL2 facility, will complement the scientific scope.

n_TOF, the CERN neutron time of flight facility, is designed to investigate neutron-induced reactions for neutron kinetic energies from a few meV to several GeV. These are of interest in research fields ranging from stellar nucleosynthesis, symmetry breaking effects in compound nuclei to applications of nuclear technology, i.e. the transmutation of nuclear waste. There is a strong contribution from Spanish research groups and several of them have proposed key measurements at n_TOF, and continue to develop instrumentation and analysis methods to fully exploit the facility, also in the EAR2 beam line.

Instrumentation

Advanced instrumentation is a key element leading to progress in nuclear physics. While nuclear physics experiments have increased in scope and complexity over time, their relatively small size makes it possible for the nuclear physics groups to work in small or medium size collaborations and to transfer easily technologies to applications and industry.

Strong efforts have been devoted by Spanish research groups to the development of state-of-the-art equipment for the full exploitation of FAIR, including the coordination of the BELEN, DTAS, FATIMA and MONSTER instruments for DESPEC and several contributions to the HISPEC detectors. Spanish groups participating in R^3B have focused their main interest on the design and construction of the CALIFA detector. Part of this equipment can already be employed at present facilities such as LNL (Italy), GANIL (France), Jyväskylä JYFL (Finland), ISOLDE and other. AGATA, the next generation γ-ray tracking array, with a strong Spanish contribution, will have unprecedented resolving power that will help reshape experimental studies. Small-scale facilities play and important role in detector tests and calibrations. Two small accelerators, in

Madrid (CMAM) and Seville (CNA), have dedicated beam lines for this purpose.

Nuclear theory

Several nuclear models have been developed over time to describe nuclear properties. Their predictive power has steadily increased in the last decade. Spanish theory groups have been in the forefront of nuclei theory in Europe for decades, and are involved in the main approaches to address the properties of nuclei (bound states and continuum) as well as the properties of nuclear matter: *ab initio* methods, shell model approaches, and models based on density functional theory. Reaction theory groups are working on the understanding of reaction mechanisms, the simultaneous treatment of the reaction dynamics and underlying structure and effective interactions, and on features that appear at threshold regimes, such as the coupling to breakup channels in reactions involving weakly bound nuclei.

Neutrino physics, nuclear astrophysics and applications

The precise measurement of neutrino properties is one of the highest priorities in fundamental particle physics. Such endeavour requires the collaboration of specialists in strong interactions and electroweak physics, including both theorists and experimentalists from the nuclear, particle and astroparticle physics communities. Nuclear theory has an impact on the direct detection of neutrinos since the experiments depend on the interactions of neutrinos with bound nucleons inside atomic nuclei. The existence of sterile neutrinos that could explain the deficit of reactor antineutrinos at very short distances can be also tested with the improvement of experimental decay data of fission products.

Nuclear physics results have an impact on our understanding of the chemical element production in astrophysical environments. Complementary information from charged particles, signals in the electromagnetic spectrum, neutrino winds and gravitational waves help understand events under extreme conditions, such as supernovae, or neutron star mergers. Fundamental nuclear properties and reactions using radioactive beams at large-scale facilities provide fundamental input to nuclear astrophysics.

Applications derived from basic nuclear physics research have a large impact in many aspects of everyday life, including areas as diverse as nuclear medicine, energy and security. These applications are only possible thanks to a solid basic knowledge on nuclear structure and decay, nuclear reactions and nuclear properties, and to the developments of associated technologies. The Spanish Nuclear Physics community continues to build on its strong record of accomplishments to answer fundamental societal needs, specifically on nuclear data for energy, environmental applications, medical imaging, dosimetry and radiotherapy.

6 National Scientific and Technical Infrastructures

The so-called Singular Scientific and Technical Infrastructures (ICTS) are large installations, resources, facilities and services, unique in its kind, that are dedicated to cutting-edge and high-quality research and technological development, as well as to promote exchange, transmission and preservation of knowledge, technology transfer and innovation. The Spanish ICTS are aligned with the European Strategy Forum on Research Infrastructures (ESFRI) and with other international plans of specific application.

The ICTS are located throughout the country and are displayed on the “Map of Unique Scientific and Technical Infrastructures (ICTS)” (http://www.ciencia.gob.es/stfls/MICINN/Innovacion/FICHEROS/ICTS_ing.pdf). The current Map is composed of 29 ICTS that bring together a total of 59 facilities. In this section a brief description of those infrastructures which activity is related with the European Strategy for Particle Physics is given.

ALBA Synchrotron

The ALBA synchrotron light source is an instrument that provides solutions to societal challenges, from health to energy production and storage, from environmental challenges to advances in communication, from understanding to preserving our cultural heritage. It is a Spanish public entity in which the national and regional governments play an equal role. It has been in operation since 2012.

The core of the infrastructure is the accelerator system, which includes a Linac that produces a 100 MeV electron beam, a booster that accelerates the beam to 3 GeV and the low-emittance storage ring, working in top-up mode, where synchrotron radiation is produced with photon energies ranging from infrared to the hard X-ray regime up to 60 keV, using dipoles and different kinds of insertion devices as photon sources.

The beamlines (BLs), located around the synchrotron, are the experimental stations where the synchrotron light is exploited. Currently, eight BLs are in operation and four more in construction, each specializing in a different technique covering the needs of diverse scientific communities. These specialisms include the X-ray magnetic circular dichroism capacity of the BOREAS BL, a key tool for magnetic studies on thin layers and nanostructures, and the high-resolution 3D imaging of biological cells available at the cryo-soft X-ray microscope of the MISTRAL BL, whose penetration power makes imaging possible at the level of 30 nm full cells, without altering their morphology by slicing.

ALBA serves more than 4000 users from the academic and industrial world. It has contributed to the increase in the Spanish user community by one order of magnitude since it came into operation, and attracts competitive international users, hailing from as many as 40 different countries. As an example, in 2017, more than 1700 researchers visited the facility, two thirds national and one third international.

ALBA fosters technology transfer to high-technology companies and the development of a previously non-existent Spanish industrial user community. All key performance indicators are competitive with those of sister facilities, for example the number and impact factor of peer-reviewed publications based on beamtime, operation availability and stability, data management, user support and industrial usage.

ALBA has created a network of international links and fruitful collaborations with national research facilities, also through the use of ancillary laboratories. A good example is the measurement of dipoles for the storage ring of the SESAME project, carried out through a collaboration with CERN as part of the H2020 CeSsaMag project. The ALBA accelerator team, whose priority is the operation and development of the synchrotron, is also involved in several projects that go beyond the synchrotron radiation community, an example being its participation on the two main future colliders being designed by CERN: FCC and CLIC with participation in the preparation of the corresponding Conceptual Design Reports.

For CLIC ALBA has been and is developing technologies and tools for the CLIC damping ring, including novel diagnostics, the RF system, tools for simulations of beam instabilities, and testing of the fast kickers.

For the FCC design, ALBA is leading a Work Package on the H2020 EuroCirCol project, aimed to develop the design and the critical technologies for this future collider. In concrete ALBA is leading the group designing the FCC vacuum system, but also doing studies for the incorporation of High Temperature Superconductors in the vacuum screen as well as developing new image techniques for determining the beam dimensions using the Speckles interferometry technique.

Other participations in H2020 projects, involving international collaboration for new developments in accelerators, are the ARIES project, which is an Integrating Activity project aiming to develop European particle accelerator infrastructures; and the XLS-CompactLight Project, the key objective being to demonstrate, through a conceptual design, the feasibility of an innovative, compact and cost effective FEL facility.

So, in summary, the ALBA team is the first group within Spain which has dealt with the design, construction and operation of a complex accelerator infrastructure and has built up experience in all its technologies: magnets, radiofrequency, diagnostics, vacuum, control systems, fast electronics, precise mechanical engineering design and integrated infrastructures for complex accelerators and experiment systems. It is now an active member of international collaborations for state of the art accelerator physics and technology, offering key contributions to new synchrotron light facilities and Particle Physics accelerator projects. In addition, the infrastructures and laboratories developed during the ALBA construction, like magnetic measurements, RF power, vacuum and metrology laboratories, are now available for future developments, and for collaborations with other institutions.

ALBA is a member of the recently created League of European Accelerator-based Photon Sources (LEAPS), within which it contributes to the general European scientific and technological strategy. The aim of LEAPS is to enhance European science, innovation and integration through closer cooperation and coherence in developing and implementing new technologies, better engagement with industry, broadening its user community and improving outreach and training programs.

CNA (Centro Nacional de Aceleradores)

The Centro Nacional de Aceleradores (CNA), located at Seville, is one of the Spanish ICTS, which are user-oriented facilities, characterized by an open access, which are unique in their respective domains. About 100 proposed experiments are carried out per year at CNA, selected by an external scientific committee. About 10% of these experiments are proposed by foreign researchers and companies.

CNA has six major facilities: A 3MV Tandem Accelerator, an 18 MeV Cyclotron, a 1MV Tandetron, a compact accelerator for 14C, a 60Co Irradiator, and a PET-CT scanner. The scientific objectives of the centre are defined in its strategic plans, and include Ion Beam Analysis Techniques, Nuclear Physics and Technology, Accelerator Mass Spectrometry, Irradiation, Radiopharmacy and Nuclear Imaging, Proton therapy and Fusion-related research.

CNA has an international orientation, and it participates in several European projects: The Nuclear Physics European project ENSAR2, the radioecology project COMET, the medical accelerator ITN network OMA, the EUROFUSION program, H2020 contracts and ITER contracts. Recently, a CNA researcher (E. Viezzer) obtained an ERC project.

CNA is a suitable environment for the test of detectors and electronics, under a radiation environment. Irradiation experiments using photons, from the ^{60}Co sources, as well as protons, up to 18 MeV from the tandem and the Cyclotron, and neutrons form the recently installed neutron beam line, have been used to see the response of detectors and electronic equipment under controlled conditions.

Of particular interest for the European strategy of particle physics, is the collaboration of CNA, along with IFCA, IFIC and IMB-CNM, in the CERN RD-50 collaboration. This collaboration aims to study in detail the effect of irradiation on Si detectors, with the objective of having ready the most adequate detector equipment for the High Luminosity LHC, in which the detectors will be subject to high irradiation dose. CNA contributes with its capabilities associated to the IBIC (Ion Beam Induced Current) technique, which has been applied to investigate, with a resolution of a few microns, the change produced by irradiation on detectors. Thus, CNA, along with IFCA, IFIC and IMB-CNM, can contribute as a cluster of Spanish centres to develop and test detector and electronic equipment to be used in the harsh radiation environment of future particle physics facilities.

CNA strategy for the future relies in increasing its internationalization. CNA sees itself as a middle size, cross disciplinary accelerator facility that is complementary to large, international accelerator facilities with a focus on basic research, both in nuclear and in particle physics. CNA aims to increase its international visibility, the exchange of personnel with larger facilities, and the number of international research proposal carried out in its facilities. This complementarity of CNA to larger facilities is not limited to the development of instrumentation. CNA can provide hands-on training on accelerator and detector techniques, which would be useful to young researchers aiming to participate in experiments at larger facilities. Also, through the strong collaborations that CNA has with Spanish high-technology companies (Alter Technology, AVS), it can facilitate the access of these companies to the larger facilities.

LSC (Laboratorio Subterráneo de Canfranc)

The Laboratorio Subterráneo de Canfranc (LSC), located in the Pyrenees, belongs to the Spanish ICTS and has strong connections with the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. The possibility to establish an Underground Global Research Infrastructures organization between the underground laboratories [LSC(Spain), LNGS (Italy), SNOlab (Canada), Boulby (UK), LSM (France), Kamioka (Japan), and CallioLab (Finland)] is under consideration. Current and near-future generation experiments require share of workload and facilities between underground laboratories.

The instrumented 1600 m^2 below 800 m of limestone rocks mainly host double beta decay and dark matter experiments and a number of facilities to support the research activities carried out by experimental collaborations. Radon-free air delivered by a radon abatement system (220 m^3/h) is monitored with a radon detector system with mBq/m^3 sensitivity. The Ultra-Low Background Service includes seven very low background HPGe detectors for gamma spectroscopy and the BiPo detector for radio-purity assay on planar geometry samples which uses the Bi-Po $\beta-\alpha$ sequence in the ^{238}U and ^{232}Th radioactive chains to measure the contamination at ultra-low level, complemented with an ICP_MS instrument with ppt sensitivities for specific isotopes. Very low radioactivity shielding materials provided by the lab are improved with the Copper Electroforming Service, a unique facility among operating underground laboratories, that produces radio-pure copper parts using the electroforming technique.

The LSC has an active program on double beta decay and dark matter searches. At the LSC, double beta decay experiments make use of two different techniques: searches with pressured Xenon gas and R&D with oxide bolometers. NEXT is the flagship experiment in the LSC, which aims to lead the search for neutrino-less double beta decay worldwide by demonstrating the best scaling needed to reach a half-life sensitivity better than 10^{27} years. The CROSS demonstrator consists on a composite bolometer with pulse-shape sensitivity to the surface interaction by using a superconducting thin film temperature sensor. It is recognized as part of the CUPID R&D activities towards a ton-scale DBD detector based on bolometers. The LSC program on direct dark matter detection includes ANAIS, the first experiment that can directly verify the DAMA/LIBRA annual modulation, ArDM/DarkSide-20k, contributing to the international effort on next generation massive liquid argon detectors, and TREX, a high pressure gas TPC demonstrator filled with argon or neon to search for low mass WIMPs. The LSC is support new opportunities, such as DAMIC, dark matter in the silicon bulk of charged-coupled devices and the Global Argon Program.

ORM (Observatorio del Roque de los Muchachos)

The Observatory of Roque de los Muchachos (ORM) houses for the last 15 years the telescopes of the international collaboration MAGIC, formed by researchers from 12 countries. The first one came into operation in 2003 and the second one in 2008. Together with the experiments HESS (Namibia) and VERITAS (USA) they are the most advanced current observatories for the observation of very high-energy gamma rays. MAGIC, in particular, is now working in a stable and reliable mode and generates a huge scientific output (more than 10 articles a year in journals of the first quartile, including Science).

However, the community working in this field understood more than a decade ago that it was essential to take a step forward that would involve a jump of at least an order of magnitude in sensitivity and angular resolution. Hence the concept of CTA (Cherenkov Telescope Array), which is conceived as the global observatory of very high energy gamma rays. It is, in particular, an ESFRI infrastructure. During the 12 years of the project, a collaboration of more than 1400 people from 31 countries has been built, with the aim of building two observatories (one in the Northern Hemisphere and one in the South), capable of observing the whole sky and focusing its energy ranges to the type of objects visible from each hemisphere.

CTA is currently an umbrella that encompasses the scientific consortium (CTAC) and the observatory (CTAO). The consortium is made up of the researchers and engineers participating in the project, and the observatory is the entity in charge of the construction and operation of the infrastructures.

The ORM was chosen in September 2016 as the place to host the CTA-North observatory. Prior to this decision, in 2015, it was agreed to build there the prototype of the CTA large diameter telescopes (23 m), which is called to be the first telescope in the network, once accepted by CTAO. That telescope, inaugurated in October 2018, is currently a reality, and is in the testing phase.

Currently, and under the umbrella of an agreement, signed in April 2016, with the Institute for the Study of Cosmic Rays of the University of Tokyo, we are in the construction phase of three other telescopes of this type. We expect them to become operational by the end of 2022. The Spanish contribution to this phase of the project is funded through FEDER funds (approximately half the cost of the 4 telescopes). The Spanish participation in CTA has about 100 researchers from 11 institutions.

The installation of the CTA-North Observatory in the ORM is a boost and recognition of ORM within the framework of the Singular Scientific-Technical Facilities (ICTS) in Spain. In this sense, the investment in CTA-North (as well as the participation of Spanish researchers in the operation of CTA-South) is a fundamental piece of the Spanish strategy in the field of Astrophysics of Very High Energies.

The presence in the ORM, as well as in the Teide Observatory (OT, Tenerife) of telescopes operating at other wavelengths is an additional advantage for CTA because it will allow simultaneous observations in different ranges, thus providing complementary physical information.

MICRONANOFABS (Spanish Network of Micro and Nano Fabrication Clean Room Facilities)

MICRONANOFABS is a networked Singular Facility (ICTS) composed of three nodes:

- Clean Room of the National Microelectronics Center in Barcelona (IMB-CNM)
- Institute of Optoelectronic Systems and Microtechnologies in Madrid (ISOM-UPM)
- Nanophotonics Technology Center in Valencia (NTC-UPVLC)

The mission of MICRONANOFABS network is to support the Spanish and European Research groups and industries in their research in the fields of Micro and Nano Fabrication and Photonics, three areas of activity which have been considered Key Enabling Technologies (KET's) by the European Commission. KET's are expected to help on finding new solutions for the different societal challenges identified within the Framework Programme Horizon-2020 and may find a place in the development of innovative products for our everyday life.

Among the three nodes, the one that has active participation in particle physics is the first one, the Clean Room of the IMB-CNM. It is dedicated to the development and application of innovative technologies in the field of Microelectronics together with other emerging Micro/Nanotechnologies. It is embedded administratively in the Instituto de Microelectrónica de Barcelona - Centro Nacional de Microelectrónica (IMB-CNM), a research centre belonging to the Spanish Council of Scientific Research (CSIC). Not only the Clean-Room facilities are part of the institute building complex, but also the scientific support for the Clean-Room activities lies mainly on the human resources of the IMB-CNM research groups.

Thus, the SBCSIC-CNM aims at helping national and international research groups to carry out R&D activities thanks to the availability of a set of complete micro and nanotechnologies and processes housed in a highly specialized Clean-Room environment devoted to R&D&i of excellence, conducted by an expert team. Thanks to the operational procedures in place and to the reliability and repetitiveness of the processes offered, the Clean Room also supports industrial partners. Such support ranges from technology awareness to the development of basic demonstrators, or small series of prototypes. Such activities have been open to external access by being a Spanish ICTS, and also a labeled reference European Infrastructure, in past and present EC Framework INFRA Programmes.

Because of the transversal nature of the technologies developed, the range of applications that can be covered in the facility is very broad, i.e., biomedical applications, environment, food, energy and mobility, safety and security, communications, consumer electronics, space, big science, etc. For all these applications the most outstanding results of last years have been in the following families of devices: Semiconductor devices including power devices and radiation detectors; Integrated circuits; Sensors, actuators and MEMS; Nanoscale devices and actuators; and Lab-on chip systems; and devices polymer.

The main capabilities are:

- Processing Techniques: Metallization (Evaporation - Sputtering); Thermal Processes and CVD; Ionic Implantation; Photolithography; Nanolithography; Dry and Wet etching; and Microsystems MEMS Post Processing
- Packaging and Integration: Wafer Dicing; Packaging: Wire Bonding, Flip-Chip..; Reverse Engineering and Reliability; Electronic Circuits and Systems Integration;
- Device, circuit and system characterization: Electrical and Physics Characterization

Spanish Research Groups’ Acronyms

CIEMAT: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas)
CNM-IMB: Barcelona Microelectronics Institute of the National Microelectronics Centre
CSIC: Consejo Superior de Investigaciones Científicas
IAA: Instituto de Astrofísica de Andalucía
IAC: Instituto de Astrofísica de Canarias
ICE: Institut de Ciencies de l’Espai
ICCUB: Institut de Ciències del Cosmos
IEM: Instituto de Estructura de la Materia
IFAE: Institut de Física d’Altes Energies
IFCA: Instituto de Física de Cantabria
IFIC: Instituto de Física Corpuscular
IFF: Instituto de Física Fundamental
IFT: Instituto de Física Teórica
IGFAE: Instituto Galego de Física das Altas Enerxias
INTA: Instituto Nacional de Técnica Aeroespacial
ITA/ITAINNOVA: Instituto Tecnológico de Aragón
NTC: Centro de Tecnología Nanofotónica
UAB: Universidad Autónoma de Barcelona
UAM: Universidad Autónoma de Madrid
UB: Universidad de Barcelona
UCM: Universidad Complutense de Madrid
UIB: Universitat de les Illes Balears
UGR: Universidad de Granada
UJA: Universidad de Jaen
UH: Universidad de Huelva
UM: Universidad de Murcia
UO: Universidad de Oviedo
UPC: Universitat Politècnica de Catalunya
UPV: Universitat Politècnica de València
UPV/EHU: Universidad del País Vasco
URL: Universitat Ramon Llull
US: Universidad de Sevilla
USAL: Universidad de Salamanca
UZ: Universidad de Zaragoza