1st December 2018

Submission to the European Strategy from University of Liverpool Experimental Particle Physics Group

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Introduction

The Particle Physics Group at the University of Liverpool has prepared this submission to the European Strategy Update. This was performed as a consultation process across the whole group including academics, research scientists, engineers, and research associates. The views were collected separately between the early career/junior staff and the senior academics. Every care has been taken to ensure the voice of those whose future is vested in the long-term decisions of the European Strategy is heard whilst, at the same time, building on the experience of experimental group leaders and those with international influence. Staff were consulted on facilities and experiments round the world, physics drivers and priorities, and which areas of research and development were considered critical. The results have been combined and reconciled into a series of ranked prioritizations in each area (1 being highest priority). These are presented below in simple format. In all cases the world-wide perspective, not simply a CERN-centric "slice" was sought. This forms the basis of an accompanying narrative and for a series of recommendations.

Current and Future Experiments and Facilities

1	ATLAS, CMS, LHCb (upgrades and operation at HL-LHC)
2	DUNE
3	T2K followed by HK
4	LZ (Wimp search)
5	g-2 and dedicated lepton flavour violation experiments (mu2e, mu3e)
6	Large Hadron Electron Collider (LHeC)
7	EDM experiments
8	Astro & Astro-Particle Particle experiments (CTA and LSST)
9	MAGIS-100 (Atom Interferometer @ FNAL)
10	HE-LHC

Science Drivers

1	Dark matter
2	Nature of neutrinos and leptogenesis
3	Properties of the Higgs
4	SM tests at LHC
5	Precision tests for new physics (e.g. g-2, LFV, EDMs)
6=	Dark energy
6=	Exotics at colliders
8	Antimatter nature
9=	Axions
9=	Early universe & physics at the Planck scale

R&D

1	Next generation tracking sensors inc. monolithic, high speed & ultra-low noise
2	Fast electronics and DAQ
3	Machine Learning
4	Quantum Sensors
5=	New accelerator technology
5=	Liquid detectors for ν and DM searches
7	Advanced mechanics for detectors
8	Magnet technology for colliders
9	Quantum Computing
10	Ultra-fine calorimetry

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Narrative

Our view is that one of the most important physics drivers is the search for **dark matter (DM)** whether this be **at the LHC** or at dedicated experiments such as LZ. This is a discovery rather than an incremental measurement theme, and (at a lower priority) new technologies such as atom interferometric quantum sensors should be developed to build highly sensitive experiments such as MAGIS to study DM. There is, for many, a pessimism that negative results will be obtained by WIMP searches and that many consider that **axionic searches** will become more pressing. The second biggest theme is that of **the nature of neutrinos**, and this is matched by the importance of the current and future neutrino experiments. This follows a large investment by the UK in neutrinos. The next highest priority, and one that belongs exclusively to the energy frontier experiments, is the measurement of the **properties of the Higgs at the LHC**. There remains a broad consensus that **using the LHC to continue to test the SM**, in "standard" and "exotic" searches, remains a high priority. This, of course, forms a large fraction of the group's scientific output and embeds interests in the high-luminosity (HL)-LHC programme as well as the complementarities offered by the LHeC electron-proton facility. Dedicated studies of **lepton flavour violation and precision muon physics** are seen as an important addition to the landscape.

These mainstream scientific drivers are then accompanied by more futuristic and speculative ideas e.g. probing physics at PeV or Planck scale, relic neutrinos etc. The low ranking (page 1) of study the nature of quark anti-matter (CP) at LHCb was surprising and reflects the idea that leptogenesis is more likely to explain the matter anti-matter imbalance in the Universe than was thought two decades ago. Nonetheless, studying CP for sources of NP is part of the (high ranked) programme of SM tests at the LHC.

Our prioritization of the international experimental and facilities environment is consistent with our scientific drivers: a high priority on running (HL)-LHC experiments, neutrino facilities, dark matter, and near-term precision experiments. These are clearly attractive to our early career scientists. Future facilities and experiments are more interesting to senior scientists who tend to have a long-term view of the field.

FCC & future accelerators: there is a substantial debate about the medium (10+ years) and long term (20+ years) accelerator facilities. We have no absolute certainty about what forms the "best route" but we present two requirements, based on the sustainability and the broad health of the field, which we believe must be met and propose realistic solutions:

i) That a physics-driven, mid-term solution that is fiscally possible, low-risk to act as training ground for new physicists and maintaining our capabilities must be found. **LHeC** provides a strong physics programme that extends the physics reach capability of HL-LHC and provides its own programme including heavy neutrinos and Higgs. When combined, HL-LHC and LHeC provide excellent opportunities to improve our understanding of the Higgs and to extend our coverage for new physics searches.

ii) That early career researchers are well-served by ensuring the health and diversity of the field with more smaller experiments being built (Physics Beyond Collider, PBC-like).

These are both seen as providing stability and health to the field. These should happen prior to a decision regarding investment in long-term, expensive next generation facilities such as FCC ee, FCC hh+he, CLIC, ILC or CepC. There are few advocates for CLIC/ILC and there is no enthusiasm for turning now to the FCC (based on physics arguments) other than the vision of retaining a multi-TeV capacity. In the longer-term (20+ years) projects there is support for energy frontier development of an HE-LHC although the complexities and the need for many years of magnet development are recognized.

Our views on R&D and detector and accelerator development are consistent with our scientific priorities and our research strengths (e.g. tracking, DAQ, LAr). We note that the need to invest in machine learning, with the aim of reducing the existing CPU load (and cost of IT) is a priority. The development of novel sensor and accelerator technologies for fundamental physics, **notably quantum sensors,** is viewed as important for the immediate and long-term future of the field.

Recommendations

1. *The (HL)-LHC remains as the cornerstone of our physics programme for the next 20 years. It should continue to*
    a. *Search for dark matter*
    b. *Make measurements of the properties of the Higgs*
    c. *Continue to make detailed measurements of the properties of the SM*
    d. *Look for evidence of new physics through direct and indirect measurements*
    e. *Investigate LFV and lepton universality to complement dedicated flavour experiments*
2. *The international neutrino programme is a vital part of the European Strategy and there should be continued investment in US and Asian facilities.*
3. *Dedicated searches for dark matter, from the WIMP scale to ultra-low mass, should be undertaken and invested in. New technologies should be developed to help explore possible hidden dark sectors.*
4. *There is substantial risk involved in a large-scale commitment to the long-term programmes being proposed which are currently not matched by the potential scientific goals and technical and political feasibility. These risks include starving the field of funds for other projects and lack of evidence that the investment will sufficiently progress the field to avoid long-term damage to fundamental science. We propose that a pragmatic intermediate solution is the construction of an LHeC at CERN. This should be the next large project at CERN and complement the HL-LHC programme.*
5. *Europe continues to build an ambitious, strong and diverse programme of high-quality fundamental experiments at a smaller scale (compared to LHC) and establish world leadership and excellence in these at CERN, and other laboratories. This should be prioritized over the construction of an "iconic", very long term, large-scale facility that would prematurely bind a large fraction of European resources.*
6. *The interests of early career researchers should be protected and nurtured, providing them with the possibility to work on smaller but dedicated ones as well as large-scale, multi-purpose experiments. Some junior scientists report the concerns and difficulties of working in large collaborations whilst some senior scientist profoundly disagree. We urge the community to look carefully at the system as a whole from the perspective of ECR researchers and to evaluate the benefits of different size experiments for researchers staying and leaving the field.*
7. *A new and diverse experimental programme of fundamental physics requires an investment and R&D in new technologies such as Quantum Sensors as well as continuing to develop "traditional" strengths. The developments of Quantum Sensors is required for Europe to play a significant role in the "2nd Quantum Revolution".*
8. *We strongly urge additional investment in career paths for computing experts within the experiments. Developments to find a solution to the ever-increasing burden of the huge quantities of data being generated (and the load that these place on the financing of fundamental physics) are important. We believe that machine learning plays a critical role in this as well as other technologies.*
9. *We support the development of new accelerator technologies (including: high field superconducting magnets, high quality SRF, energy recovery technology, and more novel techniques) to prepare new routes to the future of energy frontier accelerator physics.*
10. *It is noted that theoretical physics and phenomenology plays a critical role in shaping and providing support for Europe's future experimental programme. Where new techniques and experiments are being developed there is a clear need for investment, particularly in early career researchers in theory.*