European Strategy Workshop, IPPP 16-18th April 2018: Meeting Summary (v1.1)

Overview (J. Evans, S. Farrington, E. Goudzovski, M. Patel, M. Spannowsky)

1.Introduction

A workshop was held at, and sponsored by, IPPP, titled “UK Input to the European Strategy” on 16-18th April 2018. The European Strategy on Particle Physics is due to be updated in 2020. Submissions to the European Strategy (ES) process are invited by 18th December 2018. The intention of the workshop was to set out the scientific status and the scientific reach of particle physics experiments and technologies and to help to identify relevant questions in the ES process for further discussion, seeking convergence at future national PPAP and town meetings. In particular, our brief for this IPPP workshop was *to engage a cross-section of mid-career UK Particle Physicists* in the ES process and so a number of them nominated by their institutes were invited. In addition, an open registration phase invited anyone from the community who wanted to join.

Talks on a wide range of current and future Particle Physics (PP) topics were given. Speakers were given a brief to focus on the science cases and technological capabilities; key measurements and sensitivities of current and future experiments. The sessions are summarised in this document; discussions were energetic and thought-provoking. The sessions were: Theory/Motivation; Technical topics (Accelerator, Detector and Computing); Neutrino and Lepton Flavour; Dark Matter; Quark flavour; Resonance Searches; Higgs Physics; Gravity/Astroparticle physics and Standard Model and Top Quark physics. The talks can be viewed here: https://conference.ippp.dur.ac.uk/event/661

This report is intended to summarise the IPPP workshop and to serve as a *briefing document* for the UK ES submission. It is not intended as a draft document for ES submission. Here we suggest some points that may be useful input to discussions at the upcoming PPAP and town meetings.

The organisation of this report is as follows. In section 2 we attempt to summarise the outcomes of the workshop as they relate to possible input to the European Strategy update (ES) and we highlight where further discussion could start, based on those topics which did not find an easy convergence at this meeting, as well as those topics which were omitted in the workshop. In section 3 we provide summaries, put together by meeting participants, on the sessions. These are intended as scientific briefing documents that may give a helpful snapshot to non-experts in a given area.

2. Meeting Outcomes

Below we summarise the meeting outcomes, first relating to the bigger questions (part A); then we list some specific practical suggestions (part B) which were gathered during the workshop discussions, regarding organisational aspects of PP in Europe that could be flagged up for discussion in a wider forum.

A) On the bigger questions:

There was consensus that a future collider for particle physics is desirable from many theoretical motivations. A clear consensus was not reached on a preferred solution among the workshop participants. The science cases for the various future colliders were brought out well by the speakers in each of their sessions. Here we list some talking points which we suggest could be useful as a starting point for future discussions. The main talking points were:

1) It was a clear outcome from the talks that the extensions to current sensitivities provided by the High Luminosity LHC (HL-LHC) provide important constraints to many SM parameters and search capability for BSM physics. The commissioning and exploitation of the HL-LHC should therefore be one of the highest priorities for European Particle Physics in the 2020s.

2) What is the possible scale of new physics? To what extent could insights be delivered by flavour physics anomalies on the timescale of the ES update? While some hints will be available it is not clear if an energy scale could be identified, such that it could inform a choice of future collider.

3) Related to (2) Is there a consensus among theorists on a collider CoM energy at which null observations would definitively tell us something about the way in which the SM is broken?

4) The physics cases for FCC and CLIC are clearly both strong but there are resource implications in pushing both R&D programs forward during the 2020s. The last UK ES submission said that *“a timely decision should be taken on optimal next-generation collider facilities for exploitation of LHC discoveries”*. The final 2013 ES update document said *"to stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available".* It is the recommendation of the organisers of this workshop that it should be considered, in a UK community meeting, whether a decision can now be made on a definitive UK recommendation. If a consensus cannot be reached, then it could be debated in the community meeting whether to put forward to the ES process that its committee makes a definitive recommendation by 2020.

5) Which program(s) can best engage a generation of physicists over the next decades such that expertise is retained in operating experiments/accelerators and analysing data, rather than witnessing a brain drain while waiting for the next large project?

6) In relation to (5) the importance of smaller, non-collider experiments was agreed both for their own strong science objectives and as training grounds for the field in general.

Some topics were raised in addition to the program of the meeting, and these could be addressed at the UK community meetings:

1) Should a deep-underground-facility be part of a future ES?
2) Axion experiments, in the context of dark matter, were not discussed but this was noted as an omission. There is a small UK involvement in these experiments.
3) Availability of satellite data for astroparticle physics - it has been so far fortuitous that this is public, can we rely on this in future?
4) Contact should be increased between collider experiment efforts to search for dark matter and direct detection experiments
5) The SHIP experiment was not discussed and should be addressed in future discussions.

B) Practical/organisational suggestions:

— Technical:

1) The positive benefits of RD collaborations were discussed and it was suggested that these could be extended to cover more areas and to have a more open structure, for example envisaging RD's on Trigger and DAQ; silicon work across Europe on producing wafers/dicing.

2) It was noted that the role of physicist programmer underpins experimental particle physics and should be supported appropriately with a better defined career path across European institutes and labs.

— Theory:

1) A concerted approach to theory combinations may be of use e.g. to combine EDM's;

2) global fits with neutrinos were suggested;

3) greater engagement of nuclear theorists with neutrino research would be of benefit. This could be developed for example by the CERN theory division as part of the CERN Neutrino Platform, the existence of which was strongly appreciated by the workshop attendees.

3. Session Summaries

It should be noted that the text below is intended to summarise the sessions and talks as they happened at the workshop, rather than providing exhaustive surveys of the field. For complete reviews of, for example, Physics Beyond Colliders, see the work of the group here https://indico.cern.ch/category/7885/; for the latest HL-LHC projections, see the upcoming yellow report; for CLIC see https://indico.cern.ch/event/668147/ and upcoming studies for ES, for ILC see https://arxiv.org/abs/1710.07621 and for FCC see the upcoming CDR that will be released on the ES timescale, and references in the Higgs section below.

Theory (A.Banfi, S. Jaeger)

Theoretical arguments for new physics at or near the TeV scale were reviewed. There are no guarantees of a particular model framework to be realised as long as the SM agrees with data: the cutoff scales suggested by vacuum stability, neutrino masses, etc., are many orders of magnitude beyond the TeV scale. A variety of possible BSM signatures were reviewed and an argument for an energy-frontier 'exploratory' machine made. This received support in the following discussion. It was also pointed out in the discussions that a departure from the SM in the form of contact interactions, as suggested by several lepton-universality tests and other measurements in b-physics, would in fact imply upper bounds on the new physics scale in the tens to hundreds of TeV and a resulting no-lose theorem.

So far, direct searches have not shown signals of new physics beyond the SM. However, only conventional scenarios have been explored so far, so more exotic signatures should be investigated. Although there seem to be no guaranteed discoveries, constraining the Higgs sector provides a set of well defined goals for present and future colliders. Deviations from the SM can be interpreted in terms of new operators in an effective field theory. The potential of various colliders was discussed. In particular, the increase of the cross section for ttH at FCC-hh provides a precise determination of the top Yukawa couplings. The complementarity of hadron and lepton colliders in the measurements of Higgs couplings was also discussed. Access to the Higgs potential is an important asset for any collider. Measurement of the Higgs tri-linear coupling lies in a difficult corner of parameter space for the LHC experiments, so future hadron or lepton colliders will play a crucial role in its determination.

Another important aspect that was discussed was that at future hadron colliders, parton distribution functions will enter an unexplored regime. Therefore, it is important to keep in mind the benefits of an electron-positron machine for pdf determinations, though it was also suggested that these would be to some extent constrained at the hadron collider itself. In addition, high luminosity and energy gives us access to Higgs production plus one jet, which can be used as an indirect probe of Higgs couplings through quantum corrections.

Technical

Silicon Detectors R&D: future needs and opportunities for European collaboration (J. Vossebelt)

Along with the R&D on accelerator technologies, the technology development work to achieve ever more performant detectors systems is probably one of the most critical ingredients to enable the next generation of frontier experiments in particle physics.

In 2017, representatives of several UK PP institutes considered the priorities for R&D on CMOS silicon detectors to ensure it serves the needs of future experiments. Although their report focused on depleted CMOS technology, a set of key performance aspects were identified that apply independently of the chosen technology. Improvements in granularity & radiation hardness and timing resolution were identified as essential to address the challenge of ever increasing collision rates and particle densities. Position resolution, power consumption and radiation length improvement would benefit in particular the highest precision experiments. Finally, cost-per-area is a critical parameter for large tracking or high granularity calorimetry systems. The full report that was produced can be found in ref. [1]. Today, across Europe, a broad programme of R&D on different sensor technologies as well as development work on suitable interconnect technologies, to integrate these sensors into fully operational detector systems, are pursued to meet the above challenges.

The successful R&D towards future silicon detector technologies relies critically on: having an active and open R&D environment; collaborative developments; and excellent access to (often commercial) providers of these technologies. Access to commercial partners is also critical for the development of spin-off applications of the technologies that are developed for fundamental science. The latter is more-and-more a strong focus of national funding agencies. For this reason European collaboration in the field should have knowledge exchange as one of its key areas of focus. By training many students and young postdocs, who often then end up working in the commercial or other sectors, the community also provides an essential service to the wider economy. European collaboration on education and training is therefore also of high value. Successful R&D on silicon sensors also relies critically on access to a wide range of advanced commercial technologies and services, including: software for integrated circuit design and device simulation and the associated training; access to foundries; access to custom wafer processing such as implantation or metallisation, wafer dicing and thinning; access to advanced interconnection techniques such as solder bump deposition and flip-chip bonding. Access to these technologies and services is critical and in many cases provided, at academic rates, through the EuroPractice project. The continuation of this or an equivalent service is highly critical to the R&D in this area. Similarly, access to irradiation facilities, with neutrons, protons, other particles, and to beam facilities for test beam studies are further critical ingredients for successful silicon sensor R&D. The arrangements for access to the above facilities, technologies and services, cannot be achieved without strong and open collaboration between research labs and universities. Collaboration at the European level has been highly valuable to create a currently very strong research environment, in the widest sense.

[1]https://conference.ippp.dur.ac.uk/event/542/contributions/3021/attachments/2568/2808/Statement_to_PPAP_on_CMOS_RD.pdf)

Perspectives from Trigger & DAQ (V. Boisvert)

Although ATLAS and CMS chose very different approaches to the implementation of their respective TDAQ systems, they have both performed very well and managed to adapt to the increasing pile-up of the LHC collisions. By and large the philosophies of the Phase-I and Phase-II TDAQ upgrades will be similar to the current detectors.

The prospect of a future lepton collider is not considered to be very challenging for trigger & DAQ systems, although the factor of ten larger number of channels compared to LHC detectors, as well as the power pulsing feature of the CLIC detector systems, might bring novel challenges. Recently, discussions and studies have started regarding the possibility of a hadron Future Circular Collider (FCC-hh). The incredibly large data rates foreseen for a detector operating at such a machine are definitely a challenging feature for a TDAQ system and it might only be possible to operate the system with very high object momentum trigger thresholds, with a direct impact on the physics outputs. Finally, the future neutrino experiments (e.g. DUNE, HyperK) also bring in interesting challenges for a TDAQ system, due to their very versatile physics programme.

We can identify two main strategies being considered to deal with future challenges of TDAQ systems: one is to process a lot of the data directly on-detector, such that the data transfer offline is done with a very light trigger layer, while another approach is to have a sophisticated multi-layer trigger architecture which uses the latest, fastest hardware components to handle the very high data rates.

In order to meet the challenges being faced by future TDAQ systems, different initiatives could be implemented. For example more collaboration and discussion among current and future projects are needed in order to exchange information and ideas, so TDAQ-specific conferences could be envisaged at both international and UK level. In addition, more collaboration with industry would help in many ways: the particle physics community would stay abreast of latest developments and it would improve the employability of PhD students. The UK could help with this last point by initiating a call for a CDT on detector technologies. Finally, although there are pros and cons with whether a CERN RD collaboration would be flexible enough to allow for R&D on TDAQ technologies, it is widely acknowledged that the OpenLab project from CERN is very useful and could be more widely communicated and expanded.

Particle ID (excluding calorimetry) (A. Papanestis)

The current experimental trend in collider experiments for higher energy and higher luminosity is presenting a new set of challenges for particle identification, especially hadron identification. The dE/dx technique, used very successfully in the past with information from the tracking detectors can be used only for particle energies up to a few GeV/c. The time of flight technique is also applicable below 10 GeV/c. Currently the most promising detectors for particle ID up to (and possibly beyond) 100 GeV/c are Ring Imaging Cherenkov detectors (RICH).

A good example of a RICH system providing pion-kaon separation from 2 to 100 GeV/c is the LHCb RICH system. With two Cherenkov radiators, accurate optics, efficient photon detectors and working mainly in the visible part of the Cherenkov spectrum, it can provide accurate particle ID in a very challenging environment with hundreds of particle tracks.

The challenges for experiments searching for rare decays are similar. The number of tracks is usually smaller, but the misidentification requirements are much stricter, generally of the order of 10^{-3} or better.

Currently the limiting factor is the availability of high granularity, efficient single photon detectors that can work in a high radiation environment at an affordable price to cover multiple square metres. The intrinsic Cherenkov angle resolution of a RICH detector can improve by working in the green part of the spectrum, away from the UV. Fast photon detectors (order 100 ps) can also help reduce the complexity of each event by separating particles using the time dimension.
The characteristics of the ideal photon detector for a RICH based particle ID system are:

- High granularity (pixel size 1mm^2)
- Radiation hard
- Good quantum efficiency in the visible
- Low dark count rate
- Durability
- Inexpensive

Many of these characteristics are shared with the photon detector requirements for medical applications like PET scanners. Synergies with industry should be exploited whenever possible.

Software and computing (T. Scanlon, D. Costanzo)

Software and computing will be central to all current and future High Energy Physics experiments. In addition, the demands on computing will also increase with time, with future experiments producing significantly more data which will also have greater complexity. For instance, the HL-LHC will run at a much higher luminosity (x10) than the LHC, with a corresponding increase in the event complexity, which will be accompanied by an increased trigger rate and event throughput, resulting in an order of magnitude more events being collected than in Phase I. It has been estimated that the computing resources needed will exceed a “flat budget” scenario by a factor of 4 to 5 [1]. It should be noted that similar challenges are also faced in other areas of fundamental physics, most notably in large scale astronomy surveys.

Given these challenges, a coordinated effort is needed to ensure the enhanced hardware/software solutions and computing facilities that will become available in the future are fully exploited [2]. To benefit from such enhancements, a large-scale ‘software upgrade’ is required that will need significant effort and expertise over the coming decades. Such an effort would be best coordinated at a larger scale (e.g. at the European level across the field of High Energy Physics, but potentially also incorporating the fields of astronomy/space), to benefit from large-scale synergies, efficient development, to encourage wider-ranging take-up and to ensure the engagement of scientists with the necessary skills/expertise. Steps that could be taken include:

- The establishment of pan-European “software institute” to provide an overarching structure to coordinated such an effort;
- Expanded CERN support for software experts, by supporting a co-fund scheme for physicist programmers with partner institutes. This will promote a more stable funding source and career progression for a critical element of all future experiments, ensuring the field is able to fully exploit the latest computing/software developments;
- European-wide computing/software support for the theoretical community. To aid the development and improvement of simulation/generator code. This will enable such programmes to profit from enhanced hardware/software capabilities, saving significant

computing resources in the production of simulated events. Small investments in such schemes could produce considerable savings in production/storage costs for experiments;

- Encourage greater engagement with industry partners, via such initiatives as CERN Openlab and other joint training programmes, which will enable the field to benefit from industry experience, additional funding opportunities and could help attract/retain individuals with the necessary software/computing skills to the field;
- Greater interoperability between CERN software and external libraries, to allow experiments using CERN data formats/libraries easier access the cutting-edge libraries developed by external bodies.

[1] http://wlcg-docs.web.cern.ch/wlcg-docs/technical_documents/WLCG%20Strategy%20towards%20HL-LHC.pdf

[2] https://arxiv.org/abs/1803.04165

Accelerators (S. Gibson)

The energy and luminosity requirements for future lepton and hadron colliders, continue to challenge accelerator physicists. The next flagship facility will be the HL-LHC, which already has the advanced technical design necessary to increase the luminosity by a factor ten, targeting 3000 fb-1. The UK is a leading contributor to the accelerator and detectors for the HL-LHC and a near term focus is to optimize the accelerator design and deliver the technology required (crab cavities, collimation, beam diagnostics and superconducting links). Exploitation of the LHC in Run III and the HL-LHC from 2026 – 2036 should be Europe's top priority.

In the intermediate future, which collider to build next depends on several factors, including innovation, physics, price and politics. There is a strong scientific case to build an e+e- Higgs factory for precision measurements, with an upgradable energy to study any new physics that may emerge from the (HL-)LHC. A decision on whether to build a first stage 250 GeV CoM International Linear Collider in Japan is expected by the end of 2018, based on mature superconducting technology, similar to XFEL at DESY, and has the support of ICFA. Alternatively, drive beam technology with gradients up to 150 MV/m has been demonstrated for a multi-TeV (380 GeV, 1.5 TeV 3.0TeV) Compact Linear Collider (CLIC) at CERN. Design studies for Future Circular Colliders are well advanced, with multiple options including the High Energy-LHC, FCC-hh, FCC-ee and FCC-eh/ LHeC (e- from ERL) at CERN, and Chinese developments for CePC/ SppC. Various build order scenarios were presented driven mainly by Japan's imminent decision on ILC, and whether to build a new 100km tunnel at CERN and/or solely reuse the existing LHC tunnel. Continued balanced R&D on FCC and other options is required so a decision can be taken, as results emerge from the LHC.

Near term R&D is necessary to prepare for far future colliders that can access >100TeV in a feasibly sized underground ring. Pushing acceleration gradients to multi GV/m requires novel accelerator technologies, such as laser plasma, beam-driven plasma wakefield, THz, dielectrics, or new concepts in muon acceleration; such R&D efforts could be increased. Accelerator R&D is also required to generate high-intensity beams to support physics beyond colliders and long baseline neutrino programmes. The UK should seek both scientific and economic return on investment in major colliders.

Leptons (S.Peeters)

Neutrino oscillation physics

The physics of understanding neutrino oscillations still has many important questions to answer and, in the context of this review, answering the question whether neutrinos violate CP dominates. The neutrino platform has served the community extremely well, and it was felt that this should be used to strengthen further the EU involvement on the accelerator involvement (and add the non-accelerator part).

Experimental challenges facing neutrino physics: cross sections are vital for the next generation of neutrino accelerator experiments, but it was felt that this is currently not addressed sufficiently by the theoretical community. Getting theorists interested in the neutrino nuclear cross-section issues is important, and greater involvement from the CERN theory division could be helpful to stimulate research. With the increase in the size of future experiments, it is crucial to ensure the breadth of the physics at these facilities so they can look for the unknowns and do not become a one-horse race.

Neutrinoless double-beta decay

This search is crucial for the understanding of the nature of neutrinos and is sensitive to new physics. The current (and imminent) experiment will advance the search significantly - even if neutrinos follow the normal mass hierarchy. In the discussion it was pointed out that the usual depiction of the available parameter space is unfavourable for normal mass hierarchy; however, this depends on the assumptions made. The EU strategy should align with international efforts and contribute to a global next-generation experiment.

Muon physics

Muon physics presently encompasses charged lepton violation, g-2 and EDM experiments, all of which will achieve significant increases in sensitivity in the next five years. The programme has a strong UK involvement, and a (proton) EDM experiment is being proposed at CERN. The measurements probe a wide range of physics phenomena with significant synergy with the neutrino measurements, e.g. those probing leptogenesis.

Overall

1) It was felt that the non-accelerator neutrino experiments would be better served by being under the CERN neutrino platform than under APPEC.
2) Given the lack of observation of new physics from the LHC, the design of a future collider may benefit from input from the results of non-accelerator experiments. It is therefore vital that there is room in the overall EU programme for a significant breadth of neutrino and lepton experiments that could provide new information. As the scale of the collaborations is increasing, a stronger alignment of the EU programme with the international effort is required.

Dark Matter (D.G. Cerdeno, P. Chadwick, C. Chag, A.S. Murphy)

Motivation

Astrophysical and cosmological observations have provided substantial evidence for the existence of a new type of matter, which constitutes the 85% of all the matter in the Universe that does not emit or absorb light. The detection and identification of this dark matter (DM) constitutes one of the greatest challenges in modern Physics.

From the particle physics point of view, there is a very diverse landscape of viable models for DM, with masses and couplings ranging over many orders of magnitude. Weakly-interacting massive particles (WIMPs) stand out for their simplicity, and the fact that particles with electroweak-scale interactions can be thermally produced in the early universe with an abundance that naturally fits the observed relic density today. However, other production mechanisms are possible and DM production could also be linked to baryon production, in asymmetric DM scenarios. In the last few years, there has been a renewed interest in exploring light-DM models, with masses significantly below 1 GeV. Axions and axion-like particles provide yet another well-motivated scenario in which the new-physics might be related to fundamental aspects of QCD.

Direct Dark Matter searches

Numerous experiments are attempting to detect DM directly or indirectly with increasing sensitivities. A variety of search strategies allow a broad coverage of the wide range of the aforementioned particle physics models, and experiments are also becoming increasingly versatile, exploring less conventional DM scenarios. The remarkable experimental advances of the last decade raise the hope that DM detection could take place in the next years.

Liquid xenon (Xe) experiments, such as LUX, XENON1T, or PandaX dominate the search for WIMP masses above 10 GeV. The next-generation Xe experiments, LZ and XENONnT, presently under construction, will extend the reach for WIMPs by another order of magnitude over the current state of the art. The successors to liquid argon (Ar) experiments such as DarkSide and DEAP will target complementary sensitivities in the coming decade.

The low-mass window (0.5-10 GeV approximately) is currently being explored by a wide range of experiments, SuperCDMS (Ge), CRESST, DAMIC and low- mass Spherical Proportional Counter, SPCs (which employ light targets such as Ne). Searches in this mass window require a very low-threshold.

Experiments that employ liquid noble gases can also probe the low mass window if they only make use of the ionisation signal, at the expense of losing discrimination between electron and nuclear recoils. The DarkSide collaboration have also used this technique, first demonstrated in liquid xenon by the XENON10 collaboration, to set the most stringent upper bounds for particles with masses above 2 GeV.

Direct detection experiments can also probe DM-electron interactions, although this in general implies dealing with a larger background. This type of search sets constraints on sub-GeV scenarios, such as dark photon models, as well as on various freeze-in DM models and axion-like particles.

In the event of a future observation, direct detection experiments would attempt to extract the DM properties (mass and couplings) using the information from the recoil spectrum (and, if available, from the modulated data). Direct detection experiments will eventually reach the sensitivity to observe coherent neutrino-nucleus scattering which can be a source of background for DM searches.

Indirect dark matter searches

Indirect dark matter searches focus on the detection of DM particles which are expected to annihilate or decay to SM particles, and also the effects of axions. They therefore primarily involve astroparticle experiments designed to detect neutrinos, cosmic rays or gamma rays. For such experiments, a major concern is the astrophysical background and the choice of target is motivated by the need to maximise the potential signal and minimise signal produced from astrophysical sources, such as the supermassive black hole at the centre of the Galaxy.

The search concept for DM in neutrino experiments is that DM particles accumulate in massive objects and annihilate inside them, resulting in pairs of SM particles. Further decays of these particles then produce neutrinos. Dark matter searches towards the Galactic centre have been conducted with both ANTARES and IceCube. It is also possible to use neutrinos to probe DM annihilations in the Sun, despite the considerable background caused by cosmic ray interactions. Forthcoming experiments include PINGU, KM3NeT, Baikal-GVD and Hyper-Kamiokande.

There are many cosmic ray experiments currently in operation, none of which have any UK involvement (although the UK was a founding member of the Auger Observatory). Measurements of the rising positron fraction with energy from PAMELA, later confirmed by other experiments, have been interpreted as evidence for dark matter decay products in the cosmic rays. However, this interpretation has been questioned, since astrophysical sources could be responsible.

None of the current gamma-ray observatories have a UK collaborator, although the UK was involved in the construction several experiments. The next spaced-based gamma-ray observatory is GAMMA-400, a Russian-led mission which will have electron/positron capability. Launch is expected in the early 2020s. On the ground, the dominant instrument for the next decades will be the Cherenkov Telescope Array (CTA) which will consist of two arrays of telescopes, one in the northern hemisphere (La Palma) and one in the southern hemisphere (Chile).

Future

There is a very solid physics case for a third generation (G3) xenon-based WIMP dark matter experiment, that will also extend dark matter searches well beyond the WIMP-only paradigm and to BSM physics. Such a G3 rare-event search observatory will have unprecedented sensitivity to well motivated alternative DM models involving electron scattering, axions and axion-like-particles, and low-mass thermal relic candidates, and neutrino physics such as neutrinoless double beta decay, solar neutrino scattering and supernovae neutrino detection. The world-wide argon based community of direct searches has now consolidated a future programme around DarkSide20k, and this could form a successor to the present DEAP3600 activity.

For indirect searches, the community is agreed that bigger and better instruments as well as deeper and wider searches are needed. The experimental opportunities for the next ten years are clear, and the advent of more sensitive neutrino and gamma ray experiments is notable.

Flavour Physics (K. A. Petridis, M. Vesterinen)

The quark flavour sector is that part of the Standard Model which arises through the interplay of the electroweak gauge couplings and the Higgs couplings to quarks. Studying the decays of beauty, charm and strange hadrons can help us understand: the origin of the hierarchical structure of fermion masses and mixings; what gives rise to three generations of quarks and leptons; and the reason behind the observed baryon asymmetry in the universe. Quark flavour phenomena such as mixing and rare decays are mediated by loop processes, and are therefore sensitive to heavy new particles beyond the reach of both current and future colliders. The energy reach of these processes is driven by two factors: the experimental precision of the measurements, and the theoretical precision of the predictions. Observables related to rare decays or quark flavour mixing can be cleanly predicted in the SM. Therefore, it is these observables that it is worth measuring with exquisite precision. The first generation B-factory experiments paved the way for these measurements, followed more recently by the LHCb experiment which capitalised with its vast samples of beauty and charm hadrons.

CP violation in B and D decays

In the SM, quark flavour mixing is governed by the strongly hierarchical 3×3 unitary CKM matrix. The single irreducible complex phase is the sole source of CP-violation in the SM. Following the huge success of the first generation Y(4S) B-factory experiments, and Run-I results from LHCb, the current status is that the CKM picture accounts for most of quark flavour mixing and CP-violation. However we are far from exhausting the capability of this sector to probe BSM physics at higher mass scales. In the charm hadron sector we have now firmly established D−Dbar mixing, but BSM sensitive CP-violating phenomena have evaded discovery thus far.

In the near term, LHCb will produce new results including the full Run2 dataset but the 2020s will see roughly an order of magnitude improvement in the precision of flavour observables thanks to Belle II and LHCb Upgrade I. Furthermore, Phase II upgrades of ATLAS and CMS will greatly enhance their B physics reach. However, we will still be far from any theoretical uncertainty floor in a wide range of observables sensitive to beyond the SM processes. LHCb Upgrade II is proposed to increase the luminosity by a factor of 5−10 compared to Upgrade I and requires increased granularity, radiation hardness and fast-timing capabilities. During the 2030s the LHCb Upgrade II experiment would target an increase from the 50 fb−1 Upgrade I dataset to at least 300 fb−1.

In the following, a few examples are presented on the physics reach of this experiment. The phase γ will be determined with a precision of around 0.3°, while the related ratio |Vub|/|Vcb| will be determined to the percent level with a range of b hadron species. Semileptonic b hadron decays currently indicate anomalous lepton universality violation via the R(D(∗)) observables, at the level of around 4σ. This picture is exciting but inconclusive. Upgrade II will have the capability to measure differential observables, which could distinguish between BSM explanations. In B−Bbar mixing the phase φs would be measured with a precision of a few mrad, while the asymmetries asls,d would be measured to a few part in 10-4. Upgrade II has the capability to discover and characterise patterns of CP-violation in charm hadron decays.

Rare B decays

Rare B decays are highly sensitive probes of new physics as they are loop-, GIM- and helicity-suppressed in the SM. Sources of new physics can violate any of these principles giving rise to large measurable effects. Run-1 of the LHCb experiment has vastly improved the experimental precision of the properties of rare B decays. These measurements, combined with recent theoretical advances including those in Lattice QCD, are now probing energy scales up to $O(10)$ TeV. This reach is expected to be modestly extended in the near term with the analysis of Run-2 data from LHCb and the upcoming Belle II experiment.

More intriguingly, global analyses of the measurements of rare B decays indicate tensions with SM predictions at the level of 5σ, pointing towards an anomalous non-universal dilepton-vector coupling that favours muons over electrons. Concrete models that can produce such an anomalous couplings involve leptoquarks or new massive gauge bosons. This anomaly arises through two types of measurements. Ones that involve measurements of branching fractions and angular distributions of $b \to s\mu^+\mu^-$ processes and ones that test universality between electrons muons and τ-leptons such as ratios of branching fractions between $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ decays. Although theoretical predictions for the former might suffer from large unaccounted QCD effects, the latter observables are theoretically pristine. In the next few years these anomalies will be confirmed or refuted through further tests of lepton universality in $b \to sl^+l^-$ and semileptonic B decays, as discussed above. A 5σ tension with the SM using only such observables is a smoking gun for physics beyond the SM. Measurements by Belle II will be crucial to corroborate large tensions seen by LHCb and rare Kaon measurements at the NA62 experiment at CERN will contribute to the understanding of flavour anomalies by providing independent SM tests. In particular, assuming the SM rate, 30% precision on BR(K+ ->pi+nunu) is expected with the data collected by LS2 and the NA62 collaboration is working on a strategy to reach 10% precision with the data collected by LS3. A precision measurement of the K+ ->pi+mu+mu- decay and searches for lepton flavour and number violating processes will also be made.

If the aforementioned anomaly persists, even larger datasets will be required in order to pin down the Lorentz and flavour structure of the new physics. Upgrade II of LHCb will be the only experiment capable of delivering the required precision. If the hints of new physics dissipate, measurements of Rare B decays with Upgrade II of LHCb will provide the next benchmark constraints of models beyond the SM capable of reaching well beyond the $O(100)$ TeV energy scale.

Summary

In the next five years, Runs 2&3 of LHCb as well as Belle II in Japan and NA62 at CERN will perform a host of measurements that will improve our sensitivity to new physics. Beyond this time, the LHCb collaboration sees the exciting potential to exploit HL-LHC throughout the 2030s assuming a number of detector developments are addressed in the medium term. The LHCb Upgrade 1b (2025) and Upgrade 2 (2029) could provide a definitive dataset for exploring the new physics structure, even if the mass scales are beyond the direct reach of the LHC. Furthermore, the improvements to the CERN accelerator complex for HL-LHC strongly motivates a new generation of beam-dump experiments (e.g. SHIP) to search for the production of weakly interacting particles in a manner that is orthogonal but complementary to LHCb. There is extensive UK interest in the LHCb Upgrades and the new beam-dump experiments; the UK holds defining roles in both initiatives.

Exotics (M. D’Onofrio, N. Rompotis)

The quest for New Physics (NP) beyond the SM is clearly one of the main objectives for the UK and the international community as a whole. There is no single experiment or facility, in place or foreseen, which can guarantee discoveries in the next decades. Currently, the LHC offers a unique environment to look directly for NP. A new particle could manifest itself as an excess in one of the many accessible kinematic regions or as a resonance. New particles with small production cross-sections might also be seen as deviations from precision measurements of SM parameters.

With the High-Luminosity LHC, the upgraded experiments will collect more than 3000/fb (300/fb for LHCb) of data, providing an unprecedented sensitivity to any new physics at the TeV scale. Direct searches for NP will include, among others, lepto-quarks (LQ), new gauge bosons, supersymmetric (SUSY) particles, extended Higgs sectors, dark matter candidates, long-lived or other exotics particles. Particles coupling to LQ or new gauge bosons might explain some of the anomalies in the b-physics sector observed by various experiments (LHCb, Belle, Babar). Any SUSY particles, and in particular those arising from electroweak production, will be produced at a much larger rate than now. Together with extended Higgs sector models, SUSY could still provide a valuable solution for many of the open questions left by the SM. Dark matter models targeted by HL-LHC will offer excellent complementarities to the direct DM experiments and a more synergistic effort should be encouraged. Scenarios with challenging signatures (long-lived, low missing transverse momentum) will be fully explored thanks to the improvements in the experimental apparatus. In all cases, increases by hundreds of GeV or even by 1 TeV in NP particle mass reach are expected.

Future pp colliders (HE-LHC at 27 TeV c.o.m. energy, FCC-hh at 100 TeV c.o.m. energy) would provide a huge enhancement in NP reach, i.e. the discovery potential for heavy resonances would increase by a factor of 10 with 30/ab collected at the FCC-hh (factor of 2 with 10/ab at the HE-LHC). Indirect constraints on NP particles can also be inferred by precision measurements i.e. in the Drell-Yan process there is sensitivity to Z’ resonances with mass up to 30 TeV with HL-LHC data.

The possibility to complement proton colliders with electron-positron and electron-proton facilities is the subject of wide discussions. Electron-positron colliders as proposed to the international community include circular and linear options. The low centre of mass energy foreseen for most of these facilities (at least in its first phase for ILC and CLIC) reduces the discovery potential of direct searches, whilst the clean environment would boost the potential to constraint NP via precision measurements, in particular in the Higgs sector. Electron-proton colliders (LHeC and, later, FCC-eh) would exploit the LHC(FCC) proton beam making it collide with a 60 GeV electron beam concurrently. It would allow measurements of the sub-structure of matter with unmatchable precision and would enhance the potential of discovery for lepto-quarks, long-lived particles and extended Higgs sectors. The possibility of establishing once again a set of complementary and concurrent HEP facilities e+e-/ep/pp as it was at the time of the LEP/HERA/Tevatron should be considered as a possible target for the next decade(s), with the aim of discovering NP but also retaining a community of experimental particle physicists able to work on an active, data-taking experiment in their lifetime.

Higgs (N. Wardle, C. Englert, V. Martin, T. Scanlon)

The potential for Higgs boson physics is a major consideration for the European strategy update. Projections of existing Higgs boson measurements suggests that the Higgs boson couplings will be known within a 5% uncertainty for the couplings to massive bosons and less than 10% uncertainty for the 3rd generation fermions and the muon coupling, using the HL-LHC data. Using constraints from off-shell Higgs boson production, the total width will be measured with an uncertainty around 50%. Additionally, upper limits on the branching fraction of invisible Higgs boson decays could reach 3% at the 95% CL. Rare processes such as double Higgs boson production will be limited by small event yields at the HL-LHC. Limits on double Higgs boson production are expected to constrain the Higgs boson self-coupling (λ3) at the level of 1.5x SM with 3ab-1 of data. The potential upgrade of the LHC to run at a COM of 27 TeV (HE-LHC) would provide increased sensitivity to the double Higgs boson production and ttH production processes, due to the large increase in cross-section at higher COMs for these. This would increase the precision of the Higgs boson self-couplings and the top Yukawa coupling.

Electron-positron colliders, such as the linear ILC, or circular CepC and FCC-ee, can provide precision measurements of the Higgs boson mass and width when running with a COM of 250 GeV, which produces the Higgs boson predominantly in the ZH channel. The precision of the Higgs boson mass and total width measurements are expected to reach ~14 MeV (1 per mille) and 2.5-4% using this production channel and spectrum of the missing mass [3]. Furthermore, the branching fraction of invisible decays of the Higgs boson can be measured with a precision of around 1%. When combined with an additional 1.5 fb-1 of data at a COM of 350 GeV (both at FCC-ee and CLIC), at which the cross-section for WW->H becomes more relevant, the Higgs boson couplings to the Z, W, b and tau particles and effective coupling to the photon can be measured with uncertainties at the percent level or below. For rarer decays, such as H->mumu and 1st generation fermions, the precision will be limited due to smaller event rates. The upgrade of CLIC to 1.5 and 3 TeV will additionally provide sensitivity to the top Yukawa and Higgs boson self coupling through the ttH and ZHH production modes, respectively. Using the combined data at both upgrade COM energies at CLIC, the top Yukawa coupling is expected to be measured with an uncertainty of 1.9%, while the Higgs boson self coupling will be measured with an uncertainty of 16%, assuming 3ab-1 at 3TeV.

Electron-hadron colliders, such as (HE)LH-eC or Fcc-eh, will extend studies designed to probe the CP structure of Higgs boson production through the WW->H and ttH modes. Furthermore, e-p colliders will also offer strong constraints on PDF uncertainties which enter the theoretical uncertainties for pp->H processes.

A high energy (O 100 TeV) hadron-hadron collider, such as the FCC-hh or SppC, will provide the best sensitivity to both the ttH production and double Higgs boson production, as well as providing the largest rate of Higgs boson production overall. At such a collider the top Yukawa, and Higgs boson self coupling can be measured within 1% and 6% uncertainties, respectively, with 20ab-1 of data. Furthermore, additional constraints can be placed on the other Higgs boson couplings, including to the 2nd and 1st generation fermions, due to the increased rates of Higgs bosons expected for the relevant production processes at 100 TeV. Moreover, the increased energies available at a 100 TeV collider will allow for extended measurements of differential Higgs boson cross sections at large transverse momenta. These measurements will also be important for constraining BSM Higgs physics at higher energy scales.

The table below gives the expected uncertainty (in %) in key Higgs boson measurements from the various future collider options. Where a range is given, this covers different assumptions used to extract the results. The numbers given for the HL-LHC are given for a single experiment. The HE-LHC sensitivities have been omitted as these are expected to be provided in the coming year. For the branching fraction of invisible Higgs boson decays (B(inv)), upper limits are given in %. The SppC numbers are not shown but are expected to be of similar sensitivity to those of FCC-hh. A “-” indicates that either little to no sensitivity is expected in that case, or that no additional sensitivity is expected over previous stages or other colliders (e.g. in the case of CLIC (HE)). Model-dependent couplings from e+e- colliders are shown, except for the ILC couplings, which result from EFT fits.

	HL-LHC	**LH-eC**	**ILC**	**CLIC**	**CLIC (HE)**[§]	**FCC-ee**	**FCC-eh**	**CepC**	**FCC-hh / SppC**
E	13 TeV	e(60 GeV) p(7 TeV) / p(14 TeV)	250 GeV	350 GeV	1.4 / 3 TeV	240 (+350) GeV	e(60GeV) p(50TeV)	240-250 GeV	100 TeV
L	3 ab^{-1}	1 / 2 ab^{-1}	2 ab^{-1}	0.5 ab^{-1}	1.5 / 2 ab^{-1}	5 (+1.5) ab^{-1}	2 ab^{-1}	5 ab^{-1}	20 ab^{-1}
m_H	?	-	0.01	0.09	0.04 / 0.04	?	-	0.005	-
Couplings are ‘model-dependent’, except for ILC EFT fits see remark % below									
Γ_H	50*	-	2.5-4	6.7	3.7 / 3.5 ✢	1.55	-	2.8	-
κ Z	3.8-4.4	1.2 / 0.6	0.68	0.6	0.4 / 0.3 ✢	0.16	0.43	0.16	1-2
κ W	4.2-5.1	0.6 / 0.33	0.67	1.1	0.2 / 0.1 ✢	0.41	0.26	1.2	-
κ g	5-9	3 / 1.6	1.7	3.0	1.5 / 1.1 ✢	1.23	1.17	1.5	-
κ γ	4-5	7.1 / 3.2	1.2	-	5.6 / 3.1 ✢	2.18	2.35	4.7	1-2
κ τ	8.8-9.7	2.8 / 1.5	1.2	3.9	1.5 / 1.1 ✢	0.78	1.1	1.2	-
κ b	10-12	1.5 / 0.9	1.1	1.8	0.4 / 0.2 ✢	0.58	0.7	1.3	-
κ c	< 2.2**	3.8 / 1.9	1.9	5.8	2.1 / 1.7 ✢	1.05	1.35	1.6	-
κ t	7.6-11	- / 5.5	-	-	4.1 / -	-	1.9	-	1
κ μ	~10	-	5.6[#]	-	14.1 / 7.8 ✢	9.6	-	8.6	1-2
B(inv)	< 2.8 - 20 **	-	< 0.32 **	< 0.97 ^	-	< 0.63-0.92**	-	< 0.28 **	-
λ_3	< 1.37 - 1.44 **	-	-	-	40-54 / 19-26 ✢	28***	-	35***	5

Colour code : e+e- , electron-proton, proton-proton

* From off-shell couplings measurement

** 95% CL upper limit

^ 90% CL upper limit

*** Indirect constraint from radiative corrections

✢ Sequential improvement in combination with previous column

[#] fit includes ratios from HL-LHC: BR(gg)/BR(ZZ) and BR(mm)/BR(gg)

[§] The CLIC staging baseline has changed since these sensitivities were determined

% 'Model-independent' sensitivities essentially allow the total Higgs width to float in the fit, which allows for BSM Higgs->invisible; 'model-dependent' sensitivities essentially allow BSM Higgs->invisible, and sometimes also impose constraints on relations between couplings e.g. kappa_b = kappa_c. 'Model-independent' measurements rely on the Higgs recoil measurement to get the total width, which is possible only at lepton colliders. Adding extra constraints increases the sensitivity to the parameters that are left. And so the e+e- colliders provide 'model-dependent' fits to provide sensitivities that are a fair comparison to hadron-hadron and lepton-hadron machines. Thanks to Aidan Robson and Heather Gray for assistance with the table.

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Standard Model/Top Physics (A.Buckley, C. Englert, K. Lohwasser)

Standard Model and top-quark (SMT) physics provides a distinct and complementary view of collider physics to that of dedicated BSM searches. They test the (perturbative) consistency of the SM through precision measurements of EWSB parameters; test the predictive power of SM calculations and MC simulations against differential observables in increasingly high-multiplicity phase-spaces; and place generic and model-independent constraints on BSM through EFT/anomalous coupling fits and more recently reinterpretations against explicit new physics models. A defining characteristic of SMT measurements is their “gold standard” nature, preserving in perpetuity observables from which detector biases and inefficiencies have been “unfolded” to the best of the experiments’ abilities.

SMT measurements of precision EW parameters focus on mW, sin2θW, and mt. HL-LHC will give handles on all three, mainly through lepton-acceptance extension for the EWSB parameters, and via high statistics and the t→b→J/ψ+X channel for mt — high statistics alone gives little improvement as all measurements are currently systematics-limited. Combination of GPD measurements with LHCb’s forward acceptance (which does require high statistics) will also benefit the first two quantities through PDF correlations, as would high-precision PDFs from an LHeC programme. Linear colliders should impact precision measurements with, due to complementary operational proposals, the ILC delivering precision measurements of the W/Z parameters and the early CLIC programme providing an order-of-magnitude precision increase on mt via mass threshold scans. The clean e+e- environment would boost the potential to constrain NP via precision measurements, in particular in the Higgs sector (and in the top sector for higher centre of mass energies).

HL- and HE-LHC/FCC operation are of particular interest to measurements of unfolded kinematic distributions, by providing greater reach along the tails of steeply falling mass and pT distributions; doubly and triply differential measurements; and differential characterisation of rare SM processes such as diboson and t-channel single top state-of-the-art SM calculations and MC modelling. This will test and validate state-of-the-art SM calculations and MC modelling where the UK has a phenomenology leadership role (noting that computing strategy needs to include the high CPU cost of such simulations), and will provide further generic sensitivity for BSM reinterpretations such as the UK TopFitter and Contur efforts. Top-quark differential observables such as dileptonic tt spin correlations will benefit from high statistics. An FCC or LHeC machine would test PDFs in new regimes of x and Q2, and may finally probe a qualitatively different regime at very low x.

High statistics will provide tests of the SM via observation of rare processes: triboson production, 4t, s-channel single-top, ttV, and VBS. The latter has a distinctive topology requiring dedicated forward detector instrumentation at hadron colliders, plus a complementary form accessible at CLIC. HE-LHC/FCC offers less, since the LHC already has kinematic access to the “elementary” rare processes.

Finally, we note that some of the hardest theoretical problems in particle physics are at low energies or require a low instantaneous luminosity, e.g. non-perturbative hadron dynamics, and diffractive processes. While community priorities understandably focus on the energy and luminosity frontiers, we should not forget that important questions remain unsolved in less rarified regimes.