WG2 - Accelerator Particle Physics

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1 Introduction

Accelerators are essential tools for the study of particle physics. They create high-energy beams of particles, which can then either be collided together, or directed onto a fixed target. Both of these methods allow the generation of secondary particles, whose properties can then be studied. In this section we discuss colliding beam experiments such as the ATLAS and LHCb experiments at the CERN Large Hadron Collider and Belle II, as well as fixed target and single-beam experiments such as COMET, DUNE and Hyper-Kamiokande. Non-accelerator based particle physics, covering topics such as precision measurements of the Standard Model, nuclear physics, and other non-collider based methods detecting dark matter, is described more fully in the report of Working Group 3.

The main aim of particle colliders is probing the unknown at short distance scales and the exploration of physics Beyond the Standard Model (BSM). Whilst the SM has done an excellent job of explaining all physics up to (and including) LHC energies so far, it is far from perfect. In this context, the most important development in particle physics in the past decade was the discovery of the Higgs boson. The Higgs boson is a unique particle within the Standard Model, responsible for the breaking of electroweak symmetry and generating the masses of the matter fields in the SM. A major question about the Higgs boson is why its mass has the relatively low value it is observed to have. This is related to one of the most important theoretical problems in the field, the hierarchy problem. Solving the hierarchy problem requires the introduction of BSM physics, which in many models is within the reach of the LHC and related to the Higgs boson.

Astrophysical and cosmological observations provide abundant evidence that most of the matter in the universe is in the form of "dark matter", which cannot be comprised of any of the particles in the SM. The most popular explanation is that there is at least one new massive particle in Nature, which in many scenarios could be produced and studied at colliders. One of the primary goals of the particle physics community is therefore the precision characterisation of the properties of the Higgs boson, and the search for BSM physics.

This program of precision measurement of Higgs physics requires a firm quantitative understanding of the backgrounds to these measurements, and in particular the ability to make highly precise predictions in Quantum Chromodynamics (QCD), the theory of the strong interactions. This requires its own detailed program of theoretical calculations and measurements. These calculations can take the form of analytical calculations through a perturbative expansion, through numerical evaluation of cross-sections and simulations of particle collisions with Monte Carlo event generators, and via simulating the dynamics of QCD on a discretised lattice using high-performance computers.

The observed masses of the quarks and leptons of the Standard Model are spread over five orders of magnitude. Why this should be the case, and its possible relationship with the Higgs boson which gives these particles masses, is unknown. The SM also does not explain why there are three generations of matter. However, the flavour sector allows for some of the most precise measurements of the Standard Model possible. Consequently, flavour measurements can have exceptional sensitivity to the presence of many kinds of BSM physics at scales which cannot currently be probed at the LHC. CP violation in the flavour sector may also provide a means towards understanding the origin of the matter-antimatter asymmetry of the universe.

There are a number of outstanding issues in neutrino physics that may be resolved within the next decade. First among these is the issue of neutrino masses. Within the Standard Model neutrinos are massless particles. However, the discovery of neutrino oscillations conclusively established that neutrinos are massive, providing *prima facie* evidence for BSM physics. However, these masses are orders of magnitude lighter than those of the other particles in the Standard Model. There are many proposals capable of explaining this that are amenable to testing at colliders and in precision measurements of the Standard Model. The discovery of neutrino oscillations established that different kinds of neutrinos can mix with one another. However, this mixing looks very different in the neutrino sector compared with the quark sector of the Standard Model. Neutrino physics is thus intimately related to flavour physics. Finally, neutrinos may also play a role in explaining the matter-antimatter asymmetry of the universe.

We address these questions below in the separate areas of flavour physics, high-energy physics and neutrino physics. However they, along with dark matter physics discussed in WG3, may be intertwined and a solution or a hint towards a problem in one area may lead to rapid progress and understanding in another. Consequently, any particle physics community must have active involvement in all major areas of research to maintain international significance.

The needs of high-energy physics have historically acted as a driver for the development of new technologies in accelerator physics. Efforts and issues in accelerator science are covered in Working Group 4. Accelerator-based experiments such as the Large Hadron Collider generate vast amounts of data, shared among researchers around the world. The requirements of particle physics have thus also been a strong motivating factor in the development of areas such as advanced instrumentation and grid computation, which are discussed further in the reports of Working Group 5 and 6, respectively.

The current particle physics landscape is dominated by three large-scale experimental facilities, the Large Hadron Collider at the CERN laboratory on the Franco-Swiss border, the KEK laboratory in Japan, and FermiLab National Laboratory in Illinois, USA. The LHC is host to the ATLAS and LHCb experiments described below, which probe high-energy and flavour physics using proton-proton collisions. The LHC is also host to the CMS and ALICE experiments. CMS is a general purpose experiment with similar capability to ATLAS, and ALICE is a dedicated experiment for probing the structure of high-density and temperature matter produced in heavy-ion collisions. CMS and ALICE do not currently have Australian involvement, and so we focus on ATLAS and LHCb in our discussion below.

The KEK facility in Tsukuba is host to the Belle II experiment, a flavour physics experiment and detector which uses electron-positron collisions. KEK also runs the J-PARC facility which generates the beam for the long baseline neutrino experiment T2K, and will do the same for the its successor, which will operate in conjunction with the Hyper-Kamiokande neutrino detector currently under construction, and also hosted in Japan. KEK will also host the COMET muon decay experiment which is currently under construction.

The FermiLab laboratory is hosting the DUNE long-baseline neutrino experiment, the Muon $g-2$ experiment whose purpose is to measure the anomalous magnetic moment of the muon and NOνa, another neutrino experiment. Also in the United States, the CEBAF accelerator at Thomas Jefferson National Accelerator Facility and the proposed Electron-Ion Collider (EIC) at Brookhaven National Laboratory will study the nuclear and sub-nuclear structure. These experiments do not currently have Australian involvement.

There are a number of different proposals for future collider experiments which are currently being discussed among the particle physics community. The desire to precisely measure the properties of the Higgs motivates the construction of an electron-positron collider with a centre of mass energy around 250 GeV. This includes proposals such as the International Linear Collider (ILC) which would be located in Japan, the Future Circular Collider (FCC(e)) and Compact Linear Collider (CLIC, both at CERN) and the Chinese Electron Positron Collider (CEPC, in China). Another possibility (which could follow the construction of one of the above lepton colliders) is a high-energy hadron collider, such as FCC(h) which would follow FCC(e) at CERN, or a similar machine located in China which would follow CEPC. These would have centre of mass energies 80-100 TeV. A final possibility is an electron-hadron collider located either in the current LHC storage ring (LHeC) or in the proposed FCC ring (FCC-eh).

In the following sections we present overviews of the current experimental status and main problems in flavour physics, high energy physics and neutrino physics which can be probed using particle colliders. Following this we provide a brief timeline of future facilities, and outline pathways to impact relevant for the Australian physics community along with the commitments required in order to do so.

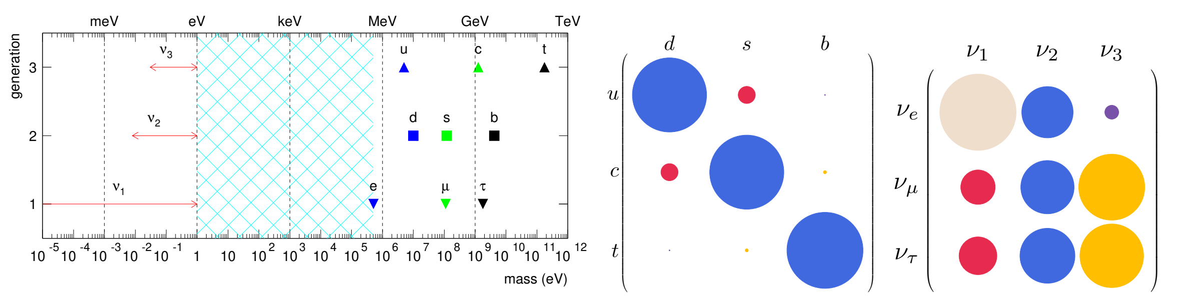
- Add References.

2 Flavour physics

2.1 Overview

Our current understanding of flavour in the SM has two large gaps usually referred to as the flavour problem. The first one is that the known fermion masses span five orders of magnitude between the lightest charged lepton, the electron, and the heaviest quark, the top quark. This range is even larger, by about eight orders of magnitude, if one includes the neutrinos. The SM offers no explanation for this extreme hierarchy. Related to this there is currently no explanation why there is small mixing between generations of particles in the quark sector and large mixing in the lepton sector. The second one, also known as the new physics (NP) puzzle, arises from comparing results of flavour physics and very high energy physics. The flavour measurements in kaons and B-mesons agree very precisely with the SM, leaving little room for new physics. Quantitatively, generic new physics is restricted to enter at a scale of hundreds or even thousands of TeV and current experiments are pushing this scale even higher with more precise measurements of SM predictions. On the other hand, solutions to the hierarchy problem or flavour anomalies discussed below require the introduction of new physics around the TeV scale. Consequently, flavour physics severely constrains the form which BSM physics can take, lest it produce much larger flavour changing neutral currents than what is observed. The flavour problem can be broken down into a number of questions:

- How does the hierarchical pattern of quark and lepton masses arise? Why are the neutrino masses so tiny compared to the charged fermions? This conundrum is illustrated in Fig. 1a.
- The unitary CKM matrix displays a very different pattern from the PMNS matrix, as illustrated in Fig. 1b. Is there any deep reason for it, and if so what is it?
- Is there an explanation of the family replication?
- Is there CP violation in the lepton sector, and is it related to the one observed in the quark sector?
- Are there new symmetries that enforce something like minimal flavour violation?



(a) Fermion mass hierarchies. Taken from Ref. [1]

(b) Magnitude of the CKM (left) and PMNS (right) matrix elements.

Figure 1: Parameters in the flavour sector.

Current experimental anomalies

In spite of the big picture just described, flavour physics experiments occasionally exhibit large deviations from the SM, referred to as anomalies. These often disappear with more precise measurements, but some remain and point to new physics. One prime example are massive neutrinos which will be discussed in a later section. Hence these anomalies are worthy of a thorough investigation. Currently there are several flavour anomalies that may indicate BSM physics.

- *Muon and electron $g-2$.* The anomalous magnetic moment $(g-2)$ of the muon shows a long-standing discrepancy between the SM theory prediction and the experimental measurement. The latest measurements [2] show a 3.7σ discrepancy of $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.74 \pm 0.73) \times 10^{-9}$ compared to the SM prediction [3,4]. Similarly, a recent new measurement of the fine structure constant [5] resulted in a 2.4σ discrepancy between for the anomalous magnetic moment of the electron $\Delta a_e = (-0.88 \pm 0.36) \times 10^{-12}$.

- *Charged B anomalies.* These refer to deviations from SM expectations in the ratios $R_{D^{(\star)}} = \Gamma(B \to D^{(\star)}\tau\nu)/\Gamma(B \to D^{(\star)}\mu/e\nu)$ which, if confirmed, would constitute the first evidence for lepton universality violation. Interestingly, they single out the tau-lepton thus suggesting a possible connection between the NP and the heavier particles/generations. The significance of this anomaly has decreased with recent measurements and currently sits at about 3σ.

- *Neutral B anomalies.* These are harder to quantify as they arise as an aggregate over many measurements. The measurements refer to processes with an underlying quark transition $b \to s\mu^+\mu^-$. There are multiple modes within this family that have shown small deviations from the SM since 2009 and none of them is particularly noteworthy on its own. Global fits that include hundreds of these observables, on the other hand, suggest a deviation from the SM of nearly 5σ. The largest individual contributors to this anomaly appear in subtle details of the angular distribution in $B \to K^\star\mu\mu$ contained in the P_5' observable. Out of these hundreds of measurements, the ones that could directly challenge the SM are $R_{K^{(\star)}}$ which would imply violations of lepton universality, this time distinguishing between muons and electrons.

- *The KOTO anomaly.* In kaon decays there are two "golden" modes that can be predicted very precisely, $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$. The first one has been measured by BNL-787/949 and more recently by NA62 and is in agreement with the SM although the statistics are still too low for a precise comparison. The second one is being studied by the KOTO experiment at KEK, which recently reported observing a few events, which indicate a branching ratio several orders of magnitude above the SM prediction. If these events survive further scrutiny they would imply not only a disagreement with the SM but also with all its most common extensions.

- *The Cabibbo angle anomaly.* There are several methods to determine the CKM matrix elements V_{ud} and V_{us}. The most precise measurements today are from $K \to \pi l\nu$ (K_{l3}) , from $K \to \mu\nu$ $(K_{\mu 2})$ and nuclear $0^+ \to 0^+$ β decays which determine $|V_{us}|$, $|V_{us}/V_{ud}|$ and $|V_{ud}|$, respectively. These three measurements disagree with each other which may particularly imply a violation of CKM unitarity.

Theory Efforts

The open questions in flavour physics and the experimental anomalies motivate many theoretical studies. In particular, there are well-motivated theory efforts to place the anomalies in the context of the flavour problem and to connect them with possible observables at the colliders. They include

- *Leptoquarks.* Models with leptoquarks naturally violate lepton flavour universality and can accommodate the charged and neutral B anomalies. These same models will also generally produce charged lepton flavour violation which is of interest to many experiments. They can be arranged to single out the third generation leading to testable consequences in top-quark physics. Finally, there may be a close connection to neutrino masses within radiative neutrino mass models.

- *Exotic gauge bosons.* Most extensions of the SM contain additional gauge symmetries and thus predict new gauge bosons. Generically, the neutral ones (Z'), will change flavour at tree-level (the new physics puzzle mentioned above) and models must minimise these effects. On the flip side, they can be arranged to accommodate unexpected results such as the neutral B anomalies. To accomplish this, the models have features that show up in the few TeV regime and thus make them easy to study at the LHC.

- *Non-SM neutrinos.* Both the charged B anomalies and the KOTO anomaly occur in processes with neutrinos and encourage the study of the neutrino sector. Enhancements in the respective rates could be correlated with non-SM behaviour of the neutrino or even with the existence of additional neutrino species.

Experimental Program

Quark and lepton flavour physics is currently being probed through a number of different experiments. The experiments with Australian involvement will be discussed in the following sections: These are the LHCb experiment [6] at CERN and the recently commenced Belle II experiment [7] at KEK with a rich flavour physics program and the μ to e conversion experiment COMET [8] in Japan. One important development to highlight is the 10^4 increase in experimental sensitivity to μ to e conversion expected from the COMET experiment [8] and the Mu2e experiment [9] at Fermilab. A similar sensitivity increase in the charged lepton-flavour-violating process $\mu \to eee$ is expected from the Mu3e experiment [10] in Switzerland. The search for muon decays is complemented by tau physics at the LHCb and Belle II experiments.

2.2 Belle II

The Belle II experiment at KEK in Japan is the successor experiment to the Belle experiment, which along with the BaBar experiment at SLAC, formed the highly successful B-Factory program which operated in the late 1990s and through the first decade of this century. Australian involvement with Belle has been through the Melbourne and Sydney experimental particle physics groups, and these groups are also part of Belle II along with the Adelaide group which joined the experiment several years ago. Belle has published in excess of 500 papers mostly on flavour physics, with notable highlights including the initial discovery of CP-violation in the B-meson system (along with BaBar) in 2001, observation of direct CP-violation in B-meson decays, the first observation of a purely leptonic decay of the B meson, $B^+ \to \tau^+\nu_\tau$, and the observation of a number of new and potentially exotic hadronic states.

Belle II exploits the newly constructed and commissioned SuperKEKB accelerator with a design luminosity of 8×10^{35} cm^{2}s^{-1} which is some 40 times larger than KEKB employed by Belle. SuperKEKB collides 7 GeV electrons with 4 GeV positrons, tuned to the $\Upsilon(4S)$ $b\bar{b}$ resonance which decays to produce pairs of charged and neutral B mesons. The target data sample for Belle II, which will be collected by 2029, is of order 50 billion pairs of B-meson decays, compared to the approximately 1.2 billion combined accumulated by Belle and BaBar. Elements of the previous Belle detector have been retained for Belle II, but much of the detector has been upgraded to both cope with the harsher environment and higher collision rates that come with SuperKEKB's much higher luminosity, and to provide performance improvements in, for example, vertex and timing resolution and particle identification.

Whilst the primary motivation for Belle was the study of CP violation, which will also be a very important component of the Belle II physics program, Belle II will have a broader focus on new physics searches. New physics can manifest itself through producing large effects on the rates of rare decays, or time dependent asymmetries, or via the observation of lepton flavor violating decays. A B-Factory experiment, despite not operating at the highest of energies, can be sensitive in this way to a large new physics scale, as well as to phases and sizes of new physics coupling constants.

Some of the areas of focus for Belle II will be:

- precision measurements of CKM-related quantities such as the angles of the Unitarity Triangle, and side-related parameters such as V_{ub} and V_{cb}, in order to test for deviations from unitarity
- studies of flavour anomalies such as the ratios $R_{D^{(\star)}} = \Gamma(B \to D^{(\star)}\tau\nu)/\Gamma(B \to D^{(\star)}\mu/e\nu)$ discussed above, or equivalent ratios involving $b \to u$ transitions
- studies of decays involving electroweak penguins, for example $b \to s$ transitions such as $B \to K^{(*)}\nu\bar{\nu}$
- studies of purely leptonic B-meson decays, for example increased precision for $B \to \tau\nu$ and discovery of $B \to \mu\nu$
- analogues of the $K \to \pi\nu\bar{\nu}$ investigations described above where one investigates $B \to K\pi\nu\bar{\nu}$ anf $B \to \pi\nu\bar{\nu}$
- dark sector searches, through the coupling of dark photons to other dark matter particles and Standard Model photons.

- complementary investigations of CP-violation B and D mesons to two and three-body final states, particularly for time-dependent measurements and measurements involving neutrals where the improved flavour-tagging capability of Belle II and improved neutral acceptance provides advantages over of the more copious production of the heavy flavour mesons at LHC experiments.

- searches for lepton flavour violation in the decays of tau leptons

The Belle II physics program complements that of LHCb, described below. For example, Belle II has the advantages of a cleaner experimental environment, a much larger and more uniform acceptance, open trigger, better flavour tagging and fixed initial collision state, which can help when studying decays with missing particles such as neutrinos. However it has significantly fewer B mesons in total to study and at the $\Upsilon(4S)$ resonance can only access B_d and B_u decays.

In addition to the mainline Physics program, which will see the experiment run to 2029, there are now working groups from Belle II, KEK and the international accelerator community, studying the implementation of polarized beams and a further factor of 5 upgrade in luminosity. With these updates, the Belle II program will stretch well beyond 2030.

The goal of the polarized beam working group is to provide the capability sometime in the mid-2020's after SuperKEKB reaches it's design luminosity. The initial physics goals of the program are:

- Precision measurements of left-right asymmetries (A_{LR}) to yield high precision measurements of the neutral current vector couplings (g_V) to each of five fermion flavours, $f \in \{b(B - mesons), c(D - mesons), \tau, \mu, e\}$ and their attendant measurements of $sin(\theta_W)$. The projected precision is at least as good as the combined LEP measurements and significantly exceeds them in the case of b,c and μ fermions.

- sensitivity to parity-violating Dark sector light neutral gauge bosons.

- measurement of the EDM and $g - 2$ for the tau lepton

- improved precision for LFV τ leptons

The polarized beam program at SuperKEKB has a significant possibility for involvement of the Australian accelerator physics community. Potential collaboration points include beam dynamics simulations, design of polarization rotation magnets and low-emmittance, high current polarized electron sources.

The collaboration for polarized beams at SuperKEKB is forming now and is actively seeking new members.

Discussions with the KEK accelerator physics team have identified a pathway to upgrade the luminosity of SuperKEKB to $5 \times 10^{36} cm^2 s^{-1}$, a factor of 6 increase on the projected design luminosity of SuperKEKB. Working groups have already formed to investigate the required detector upgrades. The initial focus is on improved vertex detector technologies. Several meetings have been held and working groups provide regular updates the Belle II General Meetings, held three times per year.

The combination of polarized-beams and luminosity upgrades will see the physics program of Belle II extend well into the mid-2030's. The collaboration is very welcome to new applicants and there are many opportunities for early and mid-career scientists in accelerator and particle physics within the program.

2.3 LHCb

The LHCb experiment is one of the four main experiments at the LHC. The main purpose of the experiment is to study the production of hadrons containing the heavy beauty and charm quarks and their subsequent decays. The experiment is designed as a cone around the beam pipe radiating out from one of the proton-proton interaction points of the LHC. This design allows for a very high resolution detector to be placed in the direction from the collision point where the production of heavy hadrons is the largest. During the first two run periods of the LHC, the experiment has exceeded its original design goals and has made a number of ground-breaking measurements such as:

- Discovery of CP violation in charm hadron decays.
- Discovery of the rare penguin decay $B^0_s \to \mu^+\mu^-$.
- Full kinematic analysis of the $b \to s\ell^+\ell^-$ decays like $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$.
- Test of lepton-flavour violation in penguin decays.
- Discovery of pentaquark hadrons as a third way for quarks to form bound states.

During the current shutdown of the LHC between Run 2 and Run 3, the LHCb detector is undergoing Upgrade I. The upgrade will enable the experiment to collect data at a rate ten times higher than what has been possible until now. The vertex detector and the Cherenkov detectors used for particle identification of hadrons will be completely replaced. The data acquisition system will be updated to read out the full detector at the 25 MHz bunch crossing rate such that the trigger can be implemented purely in software. The detector will be ready to take data from the end of the shutdown in the middle of 2021. Depending on how the identification of different decays benefit from the changes to the trigger, the expectation is to increase datasets by a factor 5 to 10 by 2031.

For LHCb Upgrade II, the plan is to increase the luminosity by a further factor ten with respect to Upgrade I. With the current dataset of LHCb, BSM effects that are of the order of 20% of the SM amplitudes are probed. By the end of Upgrade II, this will have moved to just a few percent. If the current anomalies are a sign of BSM physics, this will lead to precision measurements of them; if not, the mass scale of BSM physics that affects heavy flavour decays can be pushed up to the 100 TeV range.

The Monash group joined the LHCb experiment in 2019 with the purpose to be part of the upgrade of the electromagnetic calorimeter for LHCb Upgrade II. The upgraded calorimeter has to be able to perform in an environment with fifty times more simultaneous proton-proton collisions than what the original calorimeter was designed for and with radiation doses that are up to 100 MRad in the parts of the calorimeter closest to the beam pipe. To achieve this requires significant R&D in areas like:

- Radiation-hard scintillation materials to create a signal from the showering electrons and photons in the calorimeter.
- The development of timing information at the picosecond level that will allow for showers arising from different particles in the same bunch crossing to be separated.
- The wavelength-shifting fibres that transfer light from the scintillator to the photon detectors.
- Algorithms implemented in firmware that can identify showers in real-time to limit the required bandwidth in the data acquisition.

There will be an Australian involvement in all of these areas. For the physics exploitation during LHCb Upgrade II, these developments are essential for having reconstruction of electrons, and thus for future measurements of lepton flavour (non)-universality. The LHCb collaboration welcomes new groups interested in joining the experiment and becoming of the construction of the detector for Upgrade II and the subsequent data analysis.

After the submission of the Expression of Interest [11] and the Physics Case report [12] for LHCb Upgrade II, the CERN Scientific Policy Committee stated its support for the upgrade programme and requested that a Technical Design Report should be submitted in 2021. This report will include the overall design, specific technology options and a costing. A formal decision to support Upgrade II will be based on this report. The plan is to finish the installation of the upgrade in 2031.

2.4 COMET

The purpose of the COMET experiment is to search for charged lepton flavour violation (cLFV). In particular it will look for the neutrinoless conversion of a muon into an electron in the presence of the electromagnetic field of a nuclei. Within the SM all lepton family quantum numbers are conserved. In the decay of the muon this means that the muon decays to a muon neutrino, and electron and an anti electron neutrino. In this way the net muon number stays at one and the net electron number stays at zero. The addition of massive neutrinos to the SM does allow for cLFV but only at the 10^{-50} level compared to the normal muon decay. On the other hand, many BSM models introduce muon conversion rates that are much higher. These include many of the same type of theories that can explain the anomalies described above and a discovery would thus be able to cast much new information on those. As the expected conversion rate with just massive neutrinos beyond the SM is so low, a discovery at any level would be a clean sign of BSM physics.

In Australia, the Monash group is involved in the experiment. Phase 1 of the experiment is currently under construction and with data taking starting in 2021, it will be able to set limits a factor 100 better that current limits. The second phase of the experiment to follow a few years later will enable the upper limit on muon conversion to go down by a further factor 100 to a level of 10^{-17}. To reach such level requires a huge number of muons to be stopped in a target and their decays analysed. One of the main challenges in the experiment is to identify a possible conversion signal among the overwhelming background of normal muon decays. The Australian group is developing part of the trigger for this which will be a novel tracking algorithm implemented in firmware on FPGAs.

3 High energy

3.1 Overview

The previous sections have described the process of measuring rare processes in the Standard Model with very high precision in flavour physics experiments. Other low energy measurements (such as electric dipole moments) also allow the opportunity to conduct precision tests of the SM. Any deviation would indicate a discovery of new particle physics, but without telling us exactly what it is. It would, however, indicate that there are new particles with high masses that are disturbing the low energy measurements via quantum effects.

An alternative way to make new discoveries is to perform experiments at *high energy*, by building large particle accelerators. Such experiments can directly produce new particles, allowing us to extract much more information about their properties. The same experiments can measure a much wider range of Standard Model processes than is possible with low-energy experiments, since they can directly produce the heaviest particles of the Standard Model such as the newly discovered Higgs boson and the top quark.

MJD: Add some Higgs physics and QCD

Each of the main problems mentioned in the introduction to this section has many hypothesised solutions in the particle physics literature, some of which overlap. An incomplete list of ideas relevant to the next decade of collider physics is the following:

- *Grand unified theories*: The strengths of the forces in the SM are observed to change with energy, and for very high energy interactions the strengths come out to be very similar. This suggests that perhaps there is only one, unified force at high energies, which manifests as different forces at lower energies as the universe cools. A grand unified theory would produce several new particles to hunt for in high energy colliders.

- *Composite scenarios*: It transpires that the Higgs boson can be made naturally light if it is not in fact a fundamental particle, but is comprised of smaller constituents. The same logic can in principle be extended to other SM particles. Much as we observe bound states of quarks in Nature (of which the proton is only one example), such a theory would give us many new bound states comprised of these new fundamental particles, which would appear in high energy colliders.

- *Supersymmetry*: Recall that the matter in the universe is comprised of fermions, and the force particles are all bosons. Supersymmetry is a hypothesised symmetry of Nature that adds fermion partners for each boson, and vice versa, leading to a doubling of the particle content of the SM. Miraculously, this simple symmetry can resolve the hierarchy problem, whilst also giving ideal candidates for the dark matter in the universe. Supersymmetry gives us lots of particles to hunt for at the high energy colliders, including four extra Higgs bosons and the partners for the quarks, leptons and force particles.

- *Extra space dimensions*: A variety of scenarios exist in which there are more than four spatial dimensions. If gravity sees all of these dimensions but the fields of the SM are confined to a 4D structure, then the weakness of gravity relative to the other forces can be made natural. These theories can be used to predict signatures at the LHC that are not dissimilar to those of supersymmetry, albeit from a completely different fundamental framework.

Faced with the problems of the SM, there is a broad consensus within the community that the big unknown is not whether there are new particles beyond those of the SM, but how heavy they are. Any connection between the lightness of the Higgs mass and the new physics suggests that the new particles should have masses near the TeV range that will be probed extensively at the Large Hadron Collider over the next decade, with future experiments able to provide more detailed measurements or to go to even higher energies for further exploration.

There are two basic types of high energy collider:

- *Hadron colliders:* These collide hadrons (such as protons in the case of CERN's Large Hadron Collider), which are composite objects. That is, each hadron is made of other particles, and each collision involves a constituent of one hadron interacting with a constituent of another hadron. This can happen at any energy up to the energy at which the experiment is run, meaning that successive collisions effectively scan over lots of different energies. This makes hadron colliders excellent for discovery if we do not know the exact energy at which new particles must be produced.
- *Electron-positron colliders:* These collide electrons and positrons together, which are fundamental particles (i.e. they have no other particles inside them). The energy at which the experiment is run dictates what will be produced. Electron-positron colliders are able to measure new particle properties with much higher precision, with the caveat that one must know which energy to run at in order to produce the particles of interest.

Particle physics typically proceeds by making new discoveries at hadron colliders, then building electron-positron colliders to measure the new discovery with higher precision. We will now briefly summarise the key experiments that will define the international high energy collider programme in the next 30 years.

3.2 ATLAS

We pursue a comprehensive program of research designed to explore questions related to scale through measurements with the ATLAS detector at the CERN Large Hadron Collider (LHC), involving studies of the Higgs mechanism, the production and decay of the top quark and searches for new physics featuring dark matter candidates and/or additional symmetries, such as supersymmetry, which stabilise the mass of Higgs boson. The ATLAS experiment requires the coordinated operation of multiple sub-detectors to extract physics objects from the proton-proton collisions of the LHC. Crucial to the success of the physics studies of the collaboration is the efficient operation of these devices and their ability to work in unison to extract a coherent picture of the events created during the high energy collisions. Our task is to ensure that we collect and accurately record the events of interest, and create samples of simulated events to catalogue our expectations of what should occur in our detectors. Through accumulating vast samples of data we can then study the Standard Model objects present in the highest energy collisions to scrutinise their properties and search for as-yet-unseen new particles.

The physics program of the ATLAS experiment can be separated into key pillars, related to some of the most fundamental questions in modern particle physics:

- *Measurements of the Higgs boson*: While the discovery of the Higgs boson was a great triumph, with its existence confirmed, it is of paramount importance that we accurately measure its production and decay mechanisms. Precise measurements of the Higgs boson through its decays to pairs of photons, Z bosons and W bosons are complemented by the measurement of decays to fermions (b-jets and τ leptons). In upcoming runs at the LHC we expect to increase sensitivity to Higgs decays to muons and to pairs of charm quarks, hence directly probing the Higgs coupling to second generation particles. Beyond these studies are the efforts to measure the production of pairs of Higgs bosons.

- *Detailed studies of the Standard Model particles*: In order to understand the Standard Model in detail, the energy frontier has an extensive program of studying the heaviest particles in nature and how they decay and interact with one another. Measurements of the top quark, W boson and Z boson continue to provide a crucial window into our understanding of nature. As they become accessible, processes where these particles are produced in the same event such as ttW, ttZ, ttH and $tttt$ represent the heaviest Standard Model processes measured to date. We are also interested in the fundamental workings of QCD through understanding of jet production at the LHC.
- *Searches for Supersymmetry*: placeholder
- *Dark Matter and other exotic new physics*: placeholder

The High Luminosity LHC era

The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) is expected to begin operations in the second half of 2026, with an ultimate instantaneous luminosity of $L = 7.5 \times 10^{34}$ cm^{-2}s^{-1} corresponding to roughly 200 inelastic proton proton collisions per bunch crossing. The HL-LHC will enable the ATLAS experiment to increase the collected integrated luminosity by approximately an order of magnitude throughout its operation, reaching an integrated luminosity of about 3000 fb^{-1} by 2035.

This dataset holds tremendous potential for advances to precision measurements of Standard Model (SM) processes, with particular emphasis on probing the Higgs and electroweak sectors, and to searches for physics Beyond the Standard Model (BSM). Realising this potential requires upgrades to the ATLAS experiment in the form of the Phase-II upgrade to enable sufficient performance in the face of the more challenging experimental conditions expected at the HL-LHC while also increasing radiation hardness and replacing ageing detector components. We are playing key roles in preparation of new detector components for this upgrade and in designing the physics program to be undertaken during this period.

While many properties of the Higgs boson can be studied with the current LHC dataset, other properties, such as the Higgs self-coupling cannot be extracted from the existing dataset. Even with the large dataset expected at the HL-LHC, measurements of the Higgs self-coupling are expected to be extremely challenging. A direct measurement of the Higgs trilinear self-coupling λ_{HHH} requires the study of the Higgs boson pair production. For a centre-of-mass energy of 14 TeV, the production cross section of pairs of 125 GeV Higgs bosons is estimated to be 39.6 fb. It is anticipated that the combination of the $HH \to b\bar{b}b\bar{b}$, $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}\tau^+\tau^-$ during the lifetime of the HL-LHC will provide a statistically significant measurement of di-Higgs production. A combination of ATLAS and CMS will enhance the significance of such a measurement.

Beyond just the Higgs precision studies of rare SM processes will become commonplace. For instance, we expect a first evidence for the production of four top quarks at the LHC to be plausible with the Run2 LHC data. However, once we are producing datasets expected at the HL-LHC details property measurements of this SM process will be possible. This represents the most massive SM production channel probed and it's detailed study could unveil hints of BSM physics.

3.3 Future e^+e^-

3.4 Future pp

4 Neutrino physics

4.1 Overview

A heroic series of experiments over several decades has established that the three known flavours of neutrino – ν_e, ν_μ and ν_τ – transform in an oscillatory manner amongst themselves as they propagate. The discovery of neutrino oscillations was recognised through the 2015 Nobel Prize for Physics. While there are *a priori* several mechanisms that can give rise to this phenomenon, experiments have established that the dominant (and probably sole) mechanism is the most obvious one: neutrino-mass driven oscillations that arise when the flavour basis is misaligned from the neutrino mass basis. This misalignment is quantified through a 3×3 mixing matrix called U_{PMNS}, named after Pontecorvo, Maki, Nakagawa and Sakata. In the standard three-flavour scenario, this matrix is unitary, and it is the precise leptonic analogue of the CKM matrix of the quark sector. The neutrino oscillation probabilities in vacuum are governed by the parameters in this matrix as well as the quantities $\Delta m^2_{ij}/E \equiv (m_i^2 - m_j^2)/E$, where the $m_i,\ i = 1, 2, 3$ are the neutrino mass eigenvalues and E is energy. The PMNS parameters set the oscillation amplitudes, while the $\Delta m^2_{ij}/E$ set the oscillation (inverse-)lengths. The discovery of neutrino oscillations, and hence nonzero neutrino masses and mixings, is a discovery of physics Beyond the Standard Model (BSM), and is thus of the utmost importance. For reviews, summaries and citations to the large original literature, see Ref. [13].

Neutrinos are also crucial ingredients for particle or high-energy astrophysics and for cosmology, and these considerations inform aspects of the accelerator-based program. The first evidence for neutrino oscillations came from solar neutrinos. These measurements have now determined both the magnitude and sign of Δm^2_{21}. Similarly, $|\Delta m^2_{32}|$ was first measured using atmospheric neutrinos, which then informed the first generation of long-baseline accelerator experiments. As we discuss below, determining the sign of Δm^2_{32} is a major goal of future accelerator experiments. The cosmological matter-antimatter asymmetry requires a new source of CP-violation, which may well reside in the neutrino sector, as also discussed below.

4.2 The big issues in neutrino oscillation physics

Ultimately, the goal has to be the discovery of how neutrino masses and mixings are dynamically generated. This is a very ambitious and technically-challenging goal, and may be impossible to reach in practice. Even if so, there is much of great importance that can be learned through a practical program of experimental and theoretical research. We now list the main subproblems being addressed by the global neutrino oscillation physics program, even if they require non-accelerator input. The following subsection will then provide more detail on the subset of problems that can be investigated through neutrino beams from accelerators, and other accelerator measurements.

- *Why are neutrino masses so tiny?* Kinematic measurements of the tritium beta-decay spectrum endpoint limit the neutrino mass scale to be no larger than about 1 eV [14–16], while cosmological observations limit the sum of neutrino masses to be less than about $0.15 - 0.2$ eV [17]. Thus the neutrino mass scale is at least six orders of magnitude smaller than the lowest charged-fermion mass, that of the electron. Different neutrino mass generation mechanisms can be classified according to how they deal with the fundamental mystery of why neutrino masses are so tiny. The most widely studied theories are the various tree-level seesaw models [18–29], and models where the masses are generated radiatively at loop level [30].

- *Can the form of the PMNS matrix be explained by a deeper theory, or are its parameters random?* This is an important aspect of the flavour problem, as discussed in an earlier section. Detailed theoretical investigations of flavour symmetry models have been and continue to be carried out, while a purely random origin also cannot be ruled out at this stage.

- *Dirac versus Majorana?* Being electrically neutral fermions, neutrinos may be Majorana, meaning that they are their own antiparticles. Since neutrinos have lepton number $L = 1$, and antineutrinos have $L = -1$, Majorana neutrinos necessarily require NP that violates lepton number conservation by two units ($\Delta L = 2$). Whether or not this is the case is crucial for neutrino-mass model building. Experimentally, the main approach for probing this issue is the search for neutrinoless double-beta decay in non-accelerator experiments. If the scale of NP is low enough, there is also the chance to observe spectacular $\Delta L = 2$ processes at high-energy colliders. The alternative to Majorana neutrinos is Dirac neutrinos, which would see neutrinos as more similar in nature to the charged fermions, though the mechanism of mass generation could still be very different.

- *Measuring the absolute neutrino mass scale.* Since neutrino oscillations are only sensitive to the Δm^2_{ij} parameters, the only information they provide on the absolute scale is the lower bound from the square root of $|\Delta m^2_{32}|$, the largest of the two measured squared-mass difference parameters, giving 0.05 eV. Given the upper bounds quoted earlier, the absolute mass scale most likely lies between 0.05 and 0.2 eV.

The KATRIN tritium beta-decay experiment has an ultimate sensitivity at the top of this range [14]. Future astronomical measurements have potential sensitivities down to the lower bound.

- *Normal or inverted mass hierarchy?* The sign of Δm^2_{21} is positive, whereas the sign of Δm^2_{32} is unknown. There are thus two possible mass orderings: $m_1 < m_2 < m_3$ (normal ordering or hierarchy) and $m_3 < m_1 < m_2$ (inverted ordering or hierarchy). Determining which one holds is a major goal of the global program, including experiments using accelerator neutrino beams. Recently hints have emerged which favour the normal mass ordering.

- *Leptonic CP-violation.* If neutrinos are Dirac, then there is one physical CP-violating phase in the PMNS matrix, in exact analogy to the CKM phase. If neutrinos are Majorana, there are two additional phases. Oscillation probabilities are sensitive to the Dirac phase but insensitive to the Majorana phases (neutrinoless double-beta decay rates, however, do depend on the latter). Establishing the existence of CP violation in the lepton sector would be an important step in garnering evidence for "leptogenesis", a leading paradigm for explaining the cosmological matter-antimatter asymmetry. Measuring the Dirac phase is another major goal of accelerator-based neutrino experiments. Current global fits favour a large value for this parameter, though zero is still permitted given the statistical uncertainties.

- θ_{23} *octant.* The PMNS matrix is parameterised by three Euler mixing angles – θ_{12}, θ_{23} and θ_{13} – as well as the CP-violating phase(s). The θ_{23} parameter, often called the "atmospheric" mixing angle because of how it was first measured, is observed to be close to the maximal value of $\pi/4$. Determining if it is less than or greater than $\pi/4$ is a key goal, important for flavour symmetry theories.

- *Do sterile neutrinos exist?* Many neutrino mass generation mechanisms use sterile fermions, meaning they have no SM gauge interactions. Right-handed neutrinos are the simplest examples of this class of fermion. If such states have masses near $m_{1,2,3}$ then they are called "light sterile neutrinos", and if they are much more massive then they are more often termed "heavy neutral leptons". Searches for both types are on-going, with several experimental anomalies currently under investigation as possible evidence for light sterile neutrinos. Note also that heavy neutral leptons in the several keV mass regime are warm dark matter candidates.

4.3 Future accelerator-based neutrino experiments

4.3.1 Hyper-K and DUNE

The Deep Underground Neutrino Experiment (DUNE) will detect a high-intensity neutrino beam sent from the Long-Baseline Neutrino Facility (LBNF) at Fermilab towards DUNE's massive liquid argon detectors to be located 1.5 km underground at the Sanford Underground Research Facility (SURF) 1300 km away in South Dakota [31]. The beam will be alternately composed of ν_μ or $\overline{\nu}_\mu$. The Hyper-Kamiokande (Hyper-K) experiment will consist of megaton-scale water Cherenkov detectors located at Kamioka in Japan [32], or alternatively feature one detector at Kamioka and another in South Korea [33]. The neutrino beam will originate from the J-PARC accelerator laboratory located 295 km from Kamioka. The science goals of these complementary projects are very similar. Both aim to search for CP-violation in neutrino oscillations, establish the neutrino mass ordering, and determine the θ_{23} octant. Additional goals include the observation of supernova neutrinos and the search for proton decay. Both experiments are expected to be operational in the second half of the 2020s.

4.3.2 Searches for light sterile neutrinos

There are three classes of experimental anomalies that suggest the possible existence of light sterile neutrinos at the eV mass scale that participate in oscillations with the three active neutrinos: (i) the LSND/MiniBooNE anomaly which consists of the observation of ν_e or $\overline{\nu}_e$ events in beams that originated as ν_μ and $\overline{\nu}_\mu$, respectively; (ii) the reactor anomaly, which is evidence for $\overline{\nu}_e$ disappearance from nuclear-reactor produced neutrinos; and (iii) the gallium anomaly, which provides evidence for ν_e disappearance using intense radioactive neutrino sources that were used to calibrate gallium-based solar neutrino detectors. (For a review, see

Experiment	Start	End
Belle II	2019	2029
Belle II upgrades	2025	2035
LHCb Upgrade I	2021	2031
LHCb Upgrade II	2032	2036
COMET	2021	2032
ATLAS	2010	2027
ATLAS upgrade	2027	2036
Future e^+e^-		
Future pp		
Hyper-K / Dune	2024?	

Table 1: The expected data taking periods of current and future experiments.

Ref. [34].) In addition to very short-baseline non-accelerator experiments on reactor neutrinos, there is also an accelerator-based program at Fermilab that aims to resolve the anomalies: the Short-Baseline Neutrino (SBN) program [35]. The neutrinos originate from the Booster Neutrino Beam and are detected by three instruments located at different distances from the neutrino source. The detectors, in increasing distance from the source, are the SBN Near Detector, the MicroBooNE detector, and the SBN Far Detector, the last of which is a refurbishment of ICARUS-T600. MicroBooNE has been running for some time, with the SBN Far Detector to come online in 2020 and the SBN Near Detector in 2021.

4.3.3 Searches for heavy neutral leptons

Heavy neutral lepton production in the GeV-TeV mass range is being searched for at the ATLAS and CMS high-energy frontier detectors. The NA62 experiment at CERN is also searching for such states in the 100s of MeV mass range through charged-kaon decays [36]. The Forward Search Experiment (FASER) [37] was approved by CERN in 2019, while the main future experimental proposals are the Search for Hidden Particles (SHiP) [38] and MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles) [39] detectors, both to be sited at CERN. The former is a beam-dump type of experiment using the Super-Proton Synchrotron (SPS), while the latter is a surface detector that could be located above either ATLAS or CMS to search for long-lived particles including heavy neutral leptons.

4.3.4 Searches for other exotica

Radiative neutrino mass models, which number in the thousands in principle, feature exotic particles such as scalar leptoquarks, scalar diquarks, massive vector-like Dirac fermions, and massive Majorana fermions. Thus, the general search for such exotica also constitutes one aspect of the search for the origin of neutrino mass generation. The effect of such particles on other observables in the flavour sector (see earlier section) is also a pertinent consideration.

5 Summary

5.1 Time lines

The time lines of the data taking periods of the different experiments and their upgrades are shown in Table 2. To ensure a leading role in an experiment, it is important to be part of it at an early stage, often many years before the actual data taking starts.

5.2 Effort required to make impact

5.3 Discussion of committed/desired/possible/aspirational status

To be part of a particle physics experiment requires a significant involvement. Larger teams are the ones that have an influence on decisions and get larger exposure from the overall results of the collaboration. On the other hand, it is hard to say in which area the next big discovery might be and thus ensuring that Australian groups are part of that.

Text below is just a starting point of discussion.

- The Adelaide, Melbourne and Sydney groups are committed to the ATLAS experiment and its upgrades. The current academic effort is X FTE. (Sydney effort is currently 2.8 FTE: Varvell 0.2 FTE, Yabsley 0.2 FTE, Suster (postdoc) 0.4 FTE, Balaji (PhD) 1.0 FTE, Nommensen (PhD) 1.0 FTE). (Adelaide effort is currently 7.5 FTE: Jackson (academic) 0.5 FTE, White (academic) 0.2 FTE, Oliver (postdoc) 1.0 FTE, Sharma (postdoc) 1.0 FTE, Duvnjak (PhD) 0.4 FTE, Filmer (MPhil) 0.5 FTE, Kong (PhD) 1.0 FTE, Ruggeri (PhD) 1.0 FTE, Ting (PhD) 1.0 FTE, Mullin (MPhil) 0.5 FTE, Grant (honours) 0.4 FTE.) It would be desired for this to ...

- The Adelaide, Melbourne and Sydney groups are committed to the Belle II experiment for its lifetime. The current academic effort is 16.75 FTE. (Sydney effort is currently 2.4 FTE: Varvell 0.2 FTE, Yabsley 0.2 FTE, Hsu (postdoc) 1.0 FTE, Toutounji (PhD) 1.0 FTE). (Adelaide effort is currently 2.1 FTE: Jackson (academic) 0.1 FTE, De La Motte (PhD) 1.0 FTE, Grace (PhD) 1.0 FTE.) (Melbourne effort is currently 11.75 FTE Urquijo 0.25 FTE, Sevior 0.25 FTE, Barberio 0.05 FTE, Taylor 0.1 FTE, Dossett (post-doc) 1.0 FTE, Milesi (post-doc) 1.0 FTE, Krohn (Ph.D) 1.0 FTE, MacQueen (Ph.D.) 1.0 FTE, Ferlewicz (Ph.D.) 1.0 FTE, Hohmann (Ph.D.) 1.0 FTE, Webb (Ph.D.) 1.0 FTE, Smith (Ph.D.) 1.0 FTE, Pham (Ph.D.) 1.0 FTE plus 4 M.Sc. students at 0.5 FTE). While the experiment is scheduled to stop taking data in 2029, there will be a continued academic effort after that. We welcome other groups to join to accelerator physics and detector upgrade projects with our aspirational polarized-beam and accelerator upgrade program.

- The Monash group is committed to the LHCb experiment and its Upgrade II. The current academic effort is 2.6 FTE (Egede 0.6, Williams 1.0, Hadavizadeh (postdoc) 1.0 FTE and one PhD student). In addition there is currently funding for a further post-doc. It is desired to see this effort grow in LHCb Upgrade II by other group(s) joining within the next five years.

- The Monash group is committed to phase 1 of the COMET experiment. The current effort is Nash 0.2 FTE, Fuji (post-doc) 1.0 FTE and two PhD students. There is currently funding for a further post-doc.

- It is aspirational for Australia to become involved in either the Hyper-K or the Dune experiment. To make an impact, would require a commitment of X FTE and a decision to be made by 202X.

- It is desired or indeed essential for Australian particle physics to become involved in the experiments at a future e^+e^- or pp collider. With the long timelines involved this will be with effort from academics that are involved in running experiments at the same time.

- The Australian theory community is involved in...

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Experiment	Academic	Post-doc	PhD
Belle II	1.15	3.0	10.0
LHCb	1.6	1.0	1.0
COMET	0.2	1.0	2.0
ATLAS	1.1+X	2.4+X	5.4+X
Future e^+e^-			
Future pp			
Hyper-K / Dune			

Table 2: A summary of the current effort, the effort expected in 2023 and the aspirational effort in 2025. This includes academics and postdocs but not PhD students. Melbourne numbers missing for ATLAS.

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