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Charged Lepton Flavour Violation using Intense Muon Beams at Future Facilities

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Abstract

Charged-lepton flavour-violating (cLFV) processes offer deep probes for new physics with discovery sensitivity to a broad array of new physics models — SUSY, Higgs Doublets, Extra Dimensions, and, particularly, models explaining the neutrino mass hierarchy and the matter-antimatter asymmetry of the universe via leptogenesis. The most sensitive probes of cLFV utilize high-intensity muon beams to search for $\mu \to e$ transitions.

We summarize the status of muon-cLFV experiments currently under construction at PSI, Fermilab, and J-PARC. These experiments offer sensitivity to effective new physics mass scales approaching $\mathcal{O}(10^4)$ TeV/c^2. Further improvements are possible and next-generation experiments, using upgraded accelerator facilities at PSI, Fermilab, and J-PARC, could begin data taking within the next decade. In the case of discoveries at the LHC, they could distinguish among alternative models; even in the absence of direct discoveries, they could establish new physics. These experiments both complement and extend the searches at the LHC.

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Executive Summary

- Charged-lepton flavour-violating (cLFV) processes provide an unique discovery potential for physics beyond the Standard Model (BSM). These cLFV processes explore new physics parameter space in a manner complementary to the collider, dark matter, dark energy, and neutrino physics programmes.

- The global programme includes searches for $\mu \to e$, $\tau \to e$, and $\tau \to \mu$ transitions at experiments hosted in Europe, the US, and Asia. The relative rates among the various transitions are model dependent and comparisons among these transitions offer powerful model discrimination. A full exploration of cLFV parameter space requires the pursuit of all available $\mu \to e$ and $\tau \to e$, μ transitions.

- The most sensitive exploration of cLFV is provided by experiments that utilize high-intensity muon beams to search for cLFV $\mu \to e$ transitions: a muon decaying into an electron and a photon, $\mu^+ \to e^+\gamma$ (`MEG` experiment at PSI); a muon decaying into three electrons $\mu^+ \to e^+e^-e^+$ (`Mu3e` experiment at PSI); and the coherent neutrinoless conversion of a muon into an electron in the field of a nucleus, $\mu^-N \to e^-N$ (`Mu2e` experiment at Fermilab and `COMET` experiment at J-PARC).

- These "golden" search channels provide complementary sensitivity to new sources of cLFV since the relative rates depend on the details of the underlying new physics model. Thus, it is important to pursue a programme with experiments exploring all three $\mu \to e$ cLFV transitions to maximize discovery potential, and, in the event of discovery, to help differentiate the various BSM models through a comparison of the rates.

- Current limits for cLFV $\mu \to e$ transitions are in the $10^{-12} - 10^{-13}$ range and probe effective new physics mass scales above 10^3 TeV/c^2. Next-generation experiments at `MEG`, `Mu3e`, `Mu2e`, and `COMET` expect to improve these sensitivities by as much as four orders of magnitude on the timescale of the mid–2020s. This dramatic improvement in sensitivity offers genuine discovery possibilities in a wide range of new physics models with SUSY, Extra Dimensions, an extended Higgs sector, lepto-quarks, or those arising from GUT models.

- European contributions are vital to the success of all four of these experiments. Europe hosts two of them (`MEG`, `Mu3e`) and provides significant detector components for the others (`Mu2e`, `COMET`).

- Beginning in the latter half of the next decade, upgrades to the beamlines at PSI, Fermilab, and J-PARC offer the possibility to further explore this parameter space. Improvements in sensitivity by an additional factor of 10–100 are possible with: a High intensity Muon Beamline (HiMB) at PSI to enable an upgraded `Mu3e` (`Phase-II`); the PIP-II linac at Fermilab to enable an upgraded `Mu2e` (`Mu2e-II`); an increased intensity at J-PARC to enable an upgraded `COMET` (`Phase-II`). A next-generation `MEG` experiment is also being explored. Like their predecessors, significant European participation in the design, construction, data taking, and analysis will be important to the success of these future endeavors and represents a prudent investment complementary to searches at colliders.

- We urge the committee to strongly support the continued participation of European institutions in experiments searching for cLFV $\mu \to e$ transitions using high-intensity muon beams at facilities in Europe, the US, and Asia, including possible upgraded experiments at next-generation facilities available in the latter half of the next decade at PSI, Fermilab, and J-PARC.

Objectives

Historically, flavour-changing neutral currents have played a significant role in revealing details of the underlying symmetries at the foundation of the SM. In the SM there is no known global symmetry that conserves lepton flavour. The discoveries of quark mixing and neutrino mixing, each awarded Nobel Prizes, provided profound insights to the underlying physics. Motivated by these past successes, there exists a global programme to explore cLFV processes providing deep, broad probes of BSM physics.

The objective of our programme is to search for evidence of new physics beyond the SM using cLFV processes in the muon sector. These processes offer powerful probes of BSM physics and are sensitive to effective new physics mass scales of $10^3 - 10^4$ TeV/c^2, well beyond what can be directly probed at colliders. Over the next five years, currently planned experiments in Europe, the US, and Asia will begin taking data and will extend the sensitivity to cLFV interactions by orders of magnitude. The current experiments each benefit from significant contributions by European institutions. Further improvements are possible and new or upgraded experiments are being considered that would utilize upgraded accelerator facilities at PSI, Fermilab, and J-PARC and could begin taking data in the 2025–2030 timeframe. Strong European participation will be important for the success of these next-generation muon cLFV experiments.

Scientific Context

Flavour violation has been observed in quarks and neutrinos, so it is natural to expect flavour violating effects among the charged leptons as well. In fact, once neutrino mass is introduced, the SM provides a mechanism for cLFV via lepton mixing in loops. However, the rate is suppressed by factors of $\left(\Delta m_{ij}^2/M_W^2\right)^2$, where Δm_{ij}^2 is the mass-squared difference between the i^{th} and j^{th} neutrino mass eigenstates, and is estimated to be extremely small, for example $BF\left(\mu \to e\gamma\right) \sim 10^{-54}$ [1]. Many extensions to the standard model predict large cLFV effects that could be observed as new experiments begin data taking over the next five years. Significant improvements are expected across a wide variety of cLFV processes (e.g. $\tau \to \mu\mu\mu$, $\mu\gamma$, or $e\gamma$; $\mu \to e\gamma$, eee; $\mu N \to eN$; Z or $H^0 \to e\mu$, $e\tau$, or $\mu\tau$; $K_L \to e\mu$). The largest improvements are expected in experiments that search for cLFV transitions using muons.

Experimentally, there are three primary muon-to-electron transitions used to search for cLFV[1]: a muon decaying into an electron plus a photon, $\mu^+ \to e^+\gamma$; a muon decaying into three electrons, $\mu^+ \to e^+e^-e^+$; and direct muon-to-electron conversion via an interaction with a nucleus, $\mu^- N \to e^- N$. These three $\mu \to e$ transitions provide complementary sensitivity to new sources of cLFV since the observed rates will depend on the details of the underlying new physics model. For example, for models in which cLFV rates are dominated by γ-penguin diagrams, the $\mu \to e\gamma$ transition rate is expected to be $\sim 10^2$ times larger than the $\mu \to eee$ and $\mu N \to eN$ rates. On the other hand, if the cLFV rates are dominated by Z- or H-penguin diagrams, or if tree level contributions are allowed (e.g. as in some lepto-quark or Z' models), then the $\mu \to e\gamma$ rate is suppressed and $\mu \to eee$ and $\mu N \to eN$ rates can instead be largest. Thus, a programme with experiments exploring all three muon cLFV transitions maximizes the discovery potential and offers the possibility of differentiating among various BSM models by comparing the rates of the three transitions. This is discussed extensively in the literature, see for example references [3] and [4].

Searches for $\mu \to e$ transitions have been pursued since 1947 when Pontecorvo first searched for the $\mu \to e\gamma$ process. Since then, the sensitivity has improved by eleven orders of magnitude via a series of increasingly challenging experiments. The current best limits for the three $\mu \to e$

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[1] Muonium oscillations, $\mu^+e^- \to \mu^-e^+$, in which the muon and electron form a bound state, can also be used to set limits on cLFV interactions [2] but are not discussed here.

transitions are $BF\left(\mu^+ \rightarrow e^+\gamma\right) < 4.2{\times}10^{-13}$ [5], $BF\left(\mu^+ \rightarrow e^+e^-e^+\right) < 1{\times}10^{-12}$ [6], $R_{\mu e}\,(\mathrm{Au}) < 7 \times 10^{-13}$ [7] at 90% CL, where $R_{\mu e}$ is the $\mu \rightarrow e$ conversion rate normalized to the rate of ordinary muon nuclear capture. Currently planned experiments in Europe, the US, and Asia will provide sensitivities well beyond these existing limits. The `MEG` experiment at PSI has recently completed an upgrade and expects to extend the $\mu^+ \rightarrow e^+\gamma$ sensitivity by about an order of magnitude with physics data taking beginning in 2019. Further improvements will require a new approach and/or advances in instrumentation. The first phase of the `Mu3e` experiment is under construction at PSI and with about 300 days of data taking is expected to improve the $\mu^+ \rightarrow e^+e^-e^+$ sensitivity by over two orders of magnitude. A second-phase experiment with additional instrumentation could offer a further one order of magnitude improvement with an upgraded muon beam providing $> 2 \times 10^9$ stop-μ^+/s (e.g. a high-intensity muon beam, HiMB, at PSI; or a dedicated μ^+ beamline from PIP-II at Fermilab). The `COMET` experiment under construction at J-PARC will extend the sensitivity to $\mu^- N \rightarrow e^- N$ by about two orders of magnitude by the early-2020s, while the `Mu2e` experiment under construction at Fermilab will extend the sensitivity by about four orders of magnitude by the mid-2020s. On a longer timescale, upgrades in proton intensity offer the possibility of additional improvements. An upgrade to `Mu2e` that extends the sensitivity by another factor of ten or more, `Mu2e-II`, is proposed and would utilize about 100 kW of 0.8 GeV protons from the Fermilab PIP-II linac. An upgrade to `COMET`, `COMET Phase-II`, is proposed and would utilize about 56 kW of 8 GeV protons to reach a comparable sensitivity. The status of the currently planned experiments and their potential for further improvement is discussed in more detail in the next sections.

The outstanding sensitivities that can be achieved by the muon cLFV experiments provide access to new physics mass scales in the $10^3 - 10^4$ TeV/c^2 range, well beyond what can be directly probed at colliders. In general, these experiments explore the BSM parameter space in a manner complementary to the rest of the HEP experimental programme.

The search for muon-cLFV explicitly probes for flavour-violation in either CP-conserving or CP-violating BSM interactions; in contrast, for instance, to muon g-2 which is sensitive to flavour conserving (and chirality-flipping) interactions. If the Fermilab `Muon g-2` experiment confirms the BNL measurement [8] and hence an a_μ value at odds with the SM beyond 5σ, it will establish the presence of a BSM muon interaction which has obvious ramifications for muon-cLFV, since, in many BSM scenarios, the two are closely related [9]. If the a_μ anomaly disappears, the muon-cLFV experiments are still compelling since they probe effective mass scales well beyond the TeV scale probed by `Muon g-2`.

As the charged counterpart of neutrino oscillations, cLFV plays a significant role in most of the BSM models seeking to explain the neutrino mass hierarchy and the universe's matter anti-matter asymmetry generated through leptogenesis. The cLFV measurements thus have considerable synergy with the neutrinoless double beta decay and neutrino oscillation research programmes. For example, there is a large class of models (see e.g. [10]) proposed to explain the smallness of the neutrino mass. These typically involve extensions to the Higgs sector and the existence of heavier neutrino partners, the properties of which — sterile or non-sterile, Dirac or Majorana, and the mass-scale of the neutrino partners — depend on the model. These heavy neutrino partners typically also play a role in generating a matter anti-matter asymmetry. The majority of these models predict large cLFV effects, and the comparison of cLFV and neutrino measurements together becomes a strong constraint on the model type and its parameters. Indeed, in the most natural models, where the neutrino partners are extremely massive, these measurements are one of the few portals into GUT-scale physics. In the Inverse Seesaw models [11], right-handed neutrinos with masses in the TeV-scale are produced that are potentially observable at the LHC. The present LHC limits are below 1 TeV whereas `Mu2e`, `COMET`, and `Mu3e` will extend this sensitivity to 2 TeV. More generally `Mu2e`, `COMET`, and `Mu3e` still have a sensitivity for RH neutrinos up to masses of a few PeV, well beyond the direct detection limit of the LHC.

The $\mu \to e$ experiments also provide complementary information regarding the Majorana nature of neutrinos via the $\mu^- \to e^+$ transition: $\mu^- N(Z,A) \to e^+ N(Z-2,A)$. This transition violates both lepton number and lepton flavour and can only proceed if neutrinos are Majorana. This search channel comes for "free" in the `Mu2e` and `COMET Phase-I` experiments. The `Mu2e` and `COMET` sensitivity to Majorana neutrinos will significantly extend beyond the current best limit [12] with a $\langle m_{e\mu} \rangle$ effective Majoarna neutrino mass scale sensitivity down to the MeV region surpassing the $\langle m_{\mu\mu} \rangle$ sensitivity in the kaon sector which is limited to the GeV region [13].

The anomalies in B decays reported by the B-factories and `LHCb` and the `E821` a_μ anomaly have promoted a renewed interest in leptoquarks [14] and Z's [15]. These models can generate large cLFV effects via tree-level contributions. Direct searches for leptoquarks at `ATLAS` and `CMS` place limits in the 400–800 GeV/c^2 range which will ultimately increase to approximately 1 TeV/c^2 with HL-LHC. While there are model-dependencies, the limits from muon cLFV experiments [16] are much stronger with sensitivities up to masses of 300 TeV/c^2 beyond the present limit (120 TeV/c^2) established from lepton-flavour violating B-decays [17].

Many experiments will search for the cLFV $\tau \to \mu$ and $\tau \to e$ transitions including `ATLAS`, `Belle-II`, `BES-II`, `CMS`, and `LHCb`. In general the existing limits will be extended by about an order of magnitude to the $10^{-9} - 10^{-10}$ range. The proposed `tauFV` experiment [18] may offer another order of magnitude improvement. Thus, the ultimate sensitivity offered by the tau-cLFV searches is several orders of magnitude below the sensitivity offered by the muon cLFV experiments. The relationship between tau-cLFV and muon-cLFV processes is model dependent. The large, close-to maximal, mixing in the neutrino sector favours scenarios in which the rates of cLFV are similar in the two sectors, but other scenarios are also possible in which tau-cLFV rates are significantly enhanced. A comparison of all the transitions: $\mu \to e$, $\tau \to e$ and $\tau \to \mu$ is a very important probe of flavour models. All measurements should be pursued.

In summary, experiments sensitive to violations of lepton flavour, lepton number, and lepton universality play a significant role in the search for BSM physics. It will be necessary to make as broad an array of measurements as possible in order to maximally probe the available parameter space. The muon-cLFV experiments explore cLFV transition rates that are many orders of magnitude beyond what is explored by other experiments and offer sensitivity to new phenomena with mass scales in the few PeV/c^2 region. Over the next several years, the `MEG`, `Mu3e`, `Mu2e`, and `COMET` experiments have the best reach in their respective channels. Future upgrades could extend the sensitivity another one to two orders of magnitude by utilizing improved accelerator beamlines, and could begin data taking in the 2025–2030 timescale. These future experiments (e.g. `Mu3e Phase-II`, `Mu2e-II`, `COMET Phase-II`, `PRISM`) would offer the most sensitive probes of cLFV for the foreseeable future.

Beam Facilities

The muon-cLFV experiments rely on facilities with high-power proton beams capable of delivering high-intensity muon beams. The experimental infrastructure costs range from €5–50M with additional substantial facility costs. For example the `Mu2e` experiment has a total project cost of $274M. Several facilities exist with proton beams and transport channels capable of providing muon beams at high intensities. The PSI laboratory utilizes 1.4 MW of 590 MeV protons to provide high-intensity beams of secondary particles, including the most intense low-energy muon beams in the world. The πE5 channel serves the particle physics community and provides positively charged muons with a momentum of 28 MeV/c, a momentum bite of $5-7\%$ FWHM, and rates up to 10^8 stop-μ^+/s. At Fermilab 700 kW of 8.9 GeV/c protons are available for various experiments, of which about 8 kW will be utilized to produce about

10^{10} stop-μ^-/s for `Mu2e`. Similarly, at J-PARC about 500 kW of up to 30 GeV protons are available for various experiments, of which about 3 kW (at 8 GeV/c) will be utilized to produce 10^9 stop-μ^-/s for `COMET Phase-I`. The Fermilab and J-PARC muon beamlines are expected to become operational in the next few years.

Future facilities, capable of providing stopped muon rates a factor of 10–100 larger, are being planned and could become available as early as 2025. These future facilities would enable next-generation muon-cLFV experiments with improved sensitivities. At PSI, strong requests from both the particle physics and material science communities have motivated studies to upgrade the existing muon beamlines (HiMB study). By optimizing the existing M target station and improving the transport efficiency, a new beamline could deliver over 10^{10} stop-μ^+/s for `Mu3e Phase-II` or a future extension of the `MEG` experiment. At Fermilab, the long-baseline neutrino programme motivates the need for a significant upgrade of the proton beam intensity. The PIP-II linac will be CW capable and will use superconducting RF technology to provide 1.6 MW of 0.8 GeV protons available for a variety of experiments [19]. Conceptual designs exist to provide about 100 kW of protons to an upgraded `Mu2e` experiment, `Mu2e-II`, with over 10^{11} stop-μ^-/s. At J-PARC, plans exist to provide 56 kW to produce 2×10^{11} stop-μ^-/s for `COMET Phase-II`. Further future, in conjunction with a 1.3 MW upgrade to the Main Ring at J-PARC, the PRISM project would utilize a fixed-field alternating gradient (FFAG) muon storage ring to produce a very intense, very high purity, monochromatic muon beam with the potential to make a whole programme of muon-based measurements at world-class sensitivities.

Methodology

The same basic experimental methodology is employed in searches for all three cLFV $\mu \to e$ processes. The experiment beamline begins by colliding protons onto a production target to produce low momentum pions. The resulting pions are either transported through a decay volume or directly stopped inside the target, and their decay muons are collected. These experiments require low momentum muons, typically with momenta less than 50 MeV/c, in order to stop them in thin targets at the center of the experimental apparatus. At these low momenta, muons stop in a few mm or less of material. To reach the target sensitivities requires high-intensity muon beams, $> 10^8$ stop-μ/s. The detector apparatus is designed to precisely determine the energy, momentum, and timing of particles originating from the muon stopping target. Because these experiments aim for such extreme sensitivities, their apparatus are customized to the final state of interest.

The $\mu^+ \to e^+\gamma$ process

The $\mu^+ \to e^+\gamma$ process is sensitive to new physics mass scales around 10^3 TeV/c^2 and primarily tests cLFV dipole couplings where new physics appears in loops. The most stringent limit on this process was established by the `MEG` experiment using data collected from 2009–2013, $BF\left(\mu^+ \to e^+\gamma\right) < 4.2 \times 10^{-13}$ at 90% CL [5]. The `MEG II` experiment has recently completed construction and aims to improve the sensitivity by an order of magnitude.

The experimental signature of a $\mu^+ \to e^+\gamma$ decay at rest is given by a back-to-back, photon-positron pair coincident in time and each with an energy of half the mass of the muon. Each event can be described by four observables: the photon and positron energies (E_γ, E_e), their relative direction ($\Theta_{e\gamma}$), and their relative emission time ($\mathrm{t}_{\mathrm{e}\gamma}$).

The background has two components: an intrinsic physics background coming from the radiative muon decay (RMD), $\mu \to e\nu\bar{\nu}\gamma$, when the neutrinos carry a small fraction of the available energy; and an accidental background that arises when an energetic positron from a standard muon decay overlaps with an energetic photon from RMD, e^+e^- annihilation-in-flight, or bremsstrahlung. The effective branching fraction for the accidental background is a strong function of the muon beam intensity, I_μ, and the detector resolutions associated with the four observables, $\Delta\mathrm{E}_\gamma$, $\Delta\mathrm{E}_\mathrm{e}$, $\Delta\Theta_{e\gamma}$, and $\Delta\mathrm{t}_{\mathrm{e}\gamma}$:

$$BF_{\mathrm{eff}} \propto I_\mu^2 \times (\Delta E_\gamma)^2 \times \Delta E_e \times (\Delta\Theta_{e\gamma})^2 \times \Delta t_{e\gamma}. \quad (1)$$

In the `MEG` experiment, which used $I_\mu \sim 3 \times 10^7$ stop-μ^+/s, the accidental background accounted for over 90% of the events near the signal region ($\mathrm{E}_\gamma > 48$ MeV). To achieve an improved sensitivity, `MEG II` will utilize a higher muon beam intensity. Mitigating the accidental background requires `MEG II` to upgrade its detector components to achieve the required, improved resolutions.

Status and Plans of the `MEG II` experiment

The `MEG II` experiment [20] is depicted in Fig. 1 of the Addendum. The main features are an e^+ spectrometer formed by a new cylindrical drift chamber plus precision pixelated timing counters, located inside a superconducting solenoid with a graded magnetic field along the beam axis, and a γ detector, located outside the solenoid, made up of a homogeneous volume of 900 liters of liquid xenon readout in the central region by silicon photomultipliers and in the forward and background region by photomultiplier tubes. The finer granularity of the silicon photomultipliers provides improved γ angular and energy resolution. Additional systems are used to further reduce RMD background, and to monitor the beam quality and stopping target *in situ*. The detector construction is complete and commissioning has begun. Physics data taking is expected to begin in 2019 and to last for a few years. The upgraded detector is expected to provide resolutions roughly a factor of two better than `MEG`, thus allowing `MEG II` to utilize the full muon beam intensity available at PSI, $I_\mu \sim 10^8$ stop-μ^+/s, to achieve a factor of ten improvement in expected sensitivity.

Search for $\mu^+ \to e^+\gamma$ at future facilities

Improvements in sensitivity to the $\mu^+ \to e^+\gamma$ process beyond the `MEG II` projection may be possible by utilizing the increased muon intensities that could be available from future facilities at PSI, Fermilab, and J-PARC. However, future experiments would have to devise ways to reduce the accidental background below the 10^{-15} level in order to fully exploit the discovery potential offered by the increased muon intensities.

The use of an active or segmented target could allow a determination of the muon decay vertex, which, in principle, should lead to a strong suppression of the accidental background. Initial studies [21] made for the `MEG II` project indicated that this additional suppression would be required but this idea could be more effective if different schemes (see below) are adopted. Improvements to $\Delta\mathrm{E}_\gamma$ and $\Delta\Theta_{e\gamma}$ resolutions should be the most effective given their quadratic effect on the accidental background. Feasibility studies have been performed for two very different experimental concepts. One is based on a calorimetric detection of the photon, like `MEG II`, but with improved energy and timing resolutions [22]. The other is based on converting the photon and precisely measuring the trajectories of the resulting e^+e^- pair with a tracking spectrometer [22, 23]. The photon conversion concept is also being studied by `Mu3e` as a potential extension to its physics programme. These studies promise sensitivities around 10^{-15} at 90% CL after a few years running, but additional studies are required to verify the efficacy of these concepts.

The $\mu^+ \to e^+e^-e^+$ process

The $\mu^+ \to e^+e^-e^+$ process is sensitive to new physics at mass scales beyond 10^3 TeV/c^2 and probes cLFV couplings that arise from dipole interactions where new physics appears in loop diagrams and from μeee contact interactions. The most stringent limit on this process was established by the `SINDRUM` experiment using data collected from 1983–1986, $BF\,(\mu^+ \to e^+e^-e^+) < 1 \times 10^{-12}$ at 90% CL [6]. Any improvement in the sensitivity beyond this has a significant impact on models predicting cLFV, especially the associated four-fermion couplings. The `Mu3e` collaboration aims for a sensitivity of $BF\left(\mu^+ \to e^+e^-e^+\right) < 5 \times 10^{-15}$ at 90% CL in a first phase, `Mu3e Phase-I`, using the existing πE5 beamline at PSI. A further improvement is possible in a second phase, `Mu3e Phase-II`, with upgrades to the muon beam (HiMB project) and detector to reach a sensitivity that is four orders of magnitude better than the current experimental limit.

The experimental signature of a $\mu^+ \to e^+e^-e^+$ decay at rest is given by three charged particle tracks, corresponding to the $e^+e^-e^+$ decay products, coincident in time, originating from a common vertex, and with a total energy consistent with the mass of the muon. Since this is a three-body decay, the energy of the decay products ranges from < 1 MeV up to a maximum of about half the mass of the muon.

The background has two main components: an intrinsic physics background coming from radiative muon decays (RMD) when the photon converts to an e^+e^- pair; and an accidental background from the random combination of electrons and positrons from separate decays. The RMD background can be kept sufficiently small if the resolution on the $e^+e^+e^-$ energy sum can be kept below about 1 MeV, while the suppression of the accidental background additionally relies on excellent timing and vertex resolution.

Status and Plans of the `Mu3e` experiment

The `Mu3e Phase-I` experiment [24] is depicted in Fig. 2 of the Addendum. The main features include precision particle tracking with ultra-light, monolithic, silicon pixel tracking layers based on the HV-MAPS technology [25] cooled in an innovative manner using helium gas, plus a system of scintillating fibers and tiles to provide a time resolution below the sub-nanosecond level, all located inside a superconducting solenoid providing a constant 1 T field along the beam axis. A farm of GPUs will use a highly parallel track-fitting algorithm to perform full online tracking of all data as it streams continuously from the detector front-ends. The detector is capable of handling very high rates and the `Mu3e Phase-I` sensitivity will be limited by the muon rate that PSI can deliver. A new Compact Muon Beamline has been installed for `Mu3e` and will deliver a continuous high-purity beam of 28 MeV/c muons at a rate of about 10^8 stop-μ/s. The detector design is advanced and prototypes of all the main components have been built and successfully tested. Construction of the `Mu3e Phase-I` experiment will begin in 2019 and a first commissioning run is expected in 2020. After three years of operation the projected `Phase-I` sensitivity is $BF\left(\mu^+ \to e^+e^-e^+\right) < 5 \times 10^{-15}$ at 90% CL. However, the `Mu3e` experimental concept allows for further significant improvements in sensitivity.

Search for $\mu^+ \to e^+e^-e^+$ at future facilities

The sensitivity of `Mu3e Phase-I` is largely limited by the muon rate. The sensitivity to $\mu^+ \to e^+e^-e^+$ could be improved by more than an order of magnitude with a modest extension of the detector and access to a higher intensity muon beam. Roughly a factor two improvement in experimental acceptance is expected by extending the instrumentation in the forward and backward directions using the same pixel and scintillator technologies planned for `Phase-I`. At PSI, concepts for a new High Intensity Muon Beamline, HiMB, have been investigated. Recent studies indicate that by refurbishing target M, and by installing a new capture solenoid the muon rate could be increase up to 1.3×10^{10} stop-μ^+/s [26], which is more than sufficient for `Phase-II`. Future facilities at Fermilab and J-PARC could in principle provide similar muon intensities. If approved, the earliest HiMB could be installed is 2024. After three years of data taking at the increased muon intensity the projected `Phase-II` sensitivity is $BF\left(\mu^+ \to e^+e^-e^+\right) < 1 \times 10^{-16}$ at 90% CL.

Detector R&D should also continue to further improve the time resolution and to reduce the amount of detector material, both being important requirements for suppressing accidental backgrounds at higher rates. Silicon pixel detectors with picosecond timing represent a very promising technology for future `Mu3e` upgrades.

The $\mu^- N \to e^- N$ process

The $\mu^- N \to e^- N$ process is sensitive to new physics at mass scales up to 10^4 TeV/c^2 and probes cLFV couplings that arise from interactions where new physics appears in loop diagrams as well as from μeqq contact interactions. The most stringent limit on this process was established by the `SINDRUM-II` experiment using data collected in 2000, $R_{\mu e}\,(\mathrm{Au}) < 7 \times 10^{-13}$ at 90% CL [7], where, by convention, $R_{\mu e}$ is the rate of the $\mu^- N \to e^- N$ conversion process normalized to the normal muon nuclear capture process, $\mu^- N\,(\mathrm{A,Z}) \to \nu N^*\,(\mathrm{A,Z}-1)$. Significant improvements in sensitivity offer genuine discovery possibilities across many new physics models, including several to which it is uniquely sensitive. The `COMET Phase-I` experiment is currently under construction and aims to improve sensitivity by a factor of 100 starting in the next few years. The `Mu2e` experiment is under construction and aims to improve the sensitivity by four orders of magnitude by the mid 2020s, while `COMET Phase-II` is a proposed upgrade to `COMET Phase-I` that would achieve a similar sensitivity or better. Further improvements are possible for both experiments with upgrades to the beamline and detectors.

The direct conversion process, $\mu^- N \to e^- N$, is dominated by coherent interactions with the nucleus to provide a two-body final state yielding a clean experimental signature: an outgoing electron with an energy near the muon mass (the recoil nucleus is not directly observed). The time distribution of signal electrons should be consistent with the characteristic lifetime of the muonic atoms formed as the initial μ^- beam comes to rest in a stopping target.

Significant sources of background events can arise from muons that decay-in-orbit (DIO) — that is, decay while captured in the atomic orbit around a nucleus in the stopping target, from pions that survive to the stopping target, and from cosmic ray muons that decay-in-flight or interact in material to produce an electron with an energy near the muon mass. If the energy of the initial proton beam is above the anti-proton production threshold, then annihilations of the anti-protons can contribute an additional source of background. The steeply falling DIO background can be mitigated with excellent momentum resolution; the pion background can be suppressed by using a pulsed proton beam and employing a delayed live gate; the cosmic ray background can be removed using a high-efficiency cosmic veto system; and anti-proton backgrounds can be kept small by using absorbers to range out the anti-protons far away from the stopping target.

Both the `COMET` and the `Mu2e` experiments are based on a very clever idea first proposed by Lobashov and Djilkabaev in 1989 [27]. A system of three solenoids — a pion capture solenoid, a muon transport solenoid, and a detector solenoid — with graded magnetic fields which provide a significantly improved muon beam intensity to enable dramatic improvements in sensitivity relative to `SINDRUM-II`. The feasibility of this method has been demonstrated at low intensity at the MuSIC facility at the Research Center for Nuclear Physics in Osaka [28].

Status and Plans of the `COMET` experiment

The `COMET Phase-I` experiment [29] is depicted in Fig. 4 of the Addendum. The apparatus begins with a pion-production target made of graphite located inside the pion capture solenoid, which provides a graded magnetic field to collect low-momentum pions by reflecting them backwards with respect to the incoming proton beam. The muon transport solenoid is a curved 90-degree magnet that, together with a set of dipole coils, serves as a tranport and charge- and momentum-selection channel for $\pi^- \to \mu^- \nu$ decays. The muon transport solenoid delivers a high-intensity μ^- beam to the detector solenoid, which houses an aluminum stopping target and active detector elements, including a cylindrical drift chamber (CDC) for the $\mu^- N \to e^- N$ search and low-mass straw chambers and a fast LYSO crystal calorimeter for beam measurements. An active cosmic-ray veto system shadows the detector and stopping target regions outside the solenoid volume. Additional instrumentation monitors the proton and muon beams. The construction of the entire apparatus is at an advanced stage, with two of the magnets and the CDC complete, including significant European contributions to the cosmic-veto, muon stopping target and beam monitoring systems, the trigger and DAQ, and computing and software. Beam commissioning is expected to begin in 2020. The `COMET Phase-I` experiment will utilize about 3 kW of 8 GeV protons from the J-PARC Main Ring, delivered in pulses spaced by 1.17 μs, to first make important measurements of the muon yield and determine rates for various background processes before concentrating on a search for cLFV. After 150 days of operation the projected `COMET Phase-I` sensitivity is $R_{\mu e} < 7 \times 10^{-15}$ at 90% CL [29]. This sensitivity can be significantly improved using a higher intensity proton beam and extending the `COMET Phase-I` apparatus.

Status and Plans of the `Mu2e` experiment

The `Mu2e` experiment [30] is depicted in Fig. 6 of the Addendum. The graded high-field pion production solenoid collects and focuses low-momentum pions towards the muon transport solenoid, which is an “S”-shaped magnet with a total path length of about 13 meters. The muon transport solenoid includes a set of collimators for momentum and charge-selection to provide $\sim 10^{10}$ stop-μ^-/s using 8 kW of 8 GeV protons from the Fermilab Booster delivered in pulses spaced 1.7 μs apart. The detector solenoid provides a graded magnetic field in the upstream region, which houses the stopping target, and a near constant magnetic field in the downstream region, which houses the active detector elements. A low-mass tracking system consisting of approximately 21k thin aluminized-mylar straws [31] and a calorimeter consisting of two annular disks of pure CsI crystals [32] precisely measure the timing, energy, and momenta of particles originating from the stopping target. The apparatus is shadowed on the outside by a large, scintillator-based cosmic-veto system. Ancillary systems are used to monitor the quality and intensity of the proton and muon beams. Construction of the solenoids and all the detector sub-systems has begun, with significant European contributions to the muon transport solenoid, the calorimeter, and the muon beam monitoring system. Commissioning is expected to begin in 2022. After 690 days of operation the projected sensitivity is $R_{\mu e} < 8 \times 10^{-17}$ at 90% CL [30]. This sensitivity can be improved by at least a factor of 10 using a higher intensity proton beam and upgrading the `Mu2e` apparatus.

Search for $\mu^- N \to e^- N$ at future facilities

The `COMET Phase-I` experiment can be extended, as depicted in Fig. 5 of the Addendum, and utilize 56 kW of 8 GeV protons from the J-PARC Main Ring, delivered in pulses spaced by 1.17 μs, to reach a sensitivity of $R_{\mu e} < 2.6 \times 10^{-17}$ at 90% CL with about 230 days of operation. Further improvements by one order of magnitude from refinements to the experimental design and operation are being considered, within the beam power and the beam time as originally assumed [33]. These improvements include dipole steering fields in the curved muon transport and electron spectrometer sections to allow a more fine-tuned momentum selection which is important to optimize the acceptance and background rejection. The detailed measurements from `Phase-I` will provide important input to the final `Phase-II` design and construction. Data taking could begin in the mid-2020s.

The `Mu2e` experiment can be upgraded, `Mu2e-II`, to take advantage of the increased proton beam intensity available from the PIP-II project, currently in the design phase at Fermilab. The PIP-II linac is expected to become operational in the latter half of the 2020s and will provide 1.6 MW of 0.8 GeV protons with a programmable time structure. An Expression of Interest for `Mu2e-II` [34] was recently submitted to the Fermilab Physics Advisory Committee, which concluded that the science case was compelling and recommended that funding for high-priority R&D be identified. The Expression of Interest included signatures from 130 scientists from 36 institutions in six countries, including Italy, Germany, and the UK. Using 100 kW of protons from PIP-II, the `Mu2e-II` projected sensitivity is a factor ten or more better than the `Mu2e` sensitivity. Data taking could begin in the late 2020s.

The `COMET` collaboration is also heavily involved in R&D towards the `PRISM` project, which combines `COMET Phase-II` with an FFAG muon storage ring to potentially provide muon beam intensities of $> 10^{12}$ stop-μ/s with a narrow momentum bite allowing the use of very thin stopping targets, and significantly reduced pion contamination owing to the increased transport path length. In conjunction with an upgrade to the J-PARC proton source to achieve 1.3 MW and to the detector systems to accomodate the higher rates, `PRISM` offers the potential to achieve sensitivies to $\mu^- N \to e^- N$ of the order of 10^{-19}. The monochromatic, pion-suppressed, high-intensity muon beam provided by `PRISM` will allow the use of stopping targets comprised of heavy elements, such as gold or lead, that can be important in understanding the underlying new physics operators in the event of a discovery [33].

Summary

The `MEG`, `Mu3e`, `Mu2e`, and `COMET` experiments use intense muon beams to provide the broadest, deepest, most sensitive probes of charged-lepton flavour violating interactions and to explore the BSM parameter space with sensitivity to new physics mass scales of $10^3 - 10^4$ TeV$/c^2$, well beyond what can be directly probed at colliders. Over the next five years, currently planned experiments in Europe, the US, and Asia will begin taking data and will extend the sensitivity to $\mu \to e$ charged-lepton flavour violating transitions by orders of magnitude. Further improvements are possible and new or upgraded experiments are being considered that would utilize upgraded accelerator facilities at PSI, Fermilab, and J-PARC. The schedule of planned and proposed experiments is summarized in the figure below. Strong European participation in the design, construction, data taking, and analysis will be important for the success of these future endeavors and represents a prudent investment complementary to searches at colliders.

We urge the committee to strongly support the continued participation of European institutions in experiments searching for charged-lepton flavour violating $\mu \to e$ transitions using high-intensity beams at facilities in Europe, the US, and Asia, including possible upgraded experiments at next-generation facilities available the latter half of the next decade at PSI, Fermilab, and J-PARC.

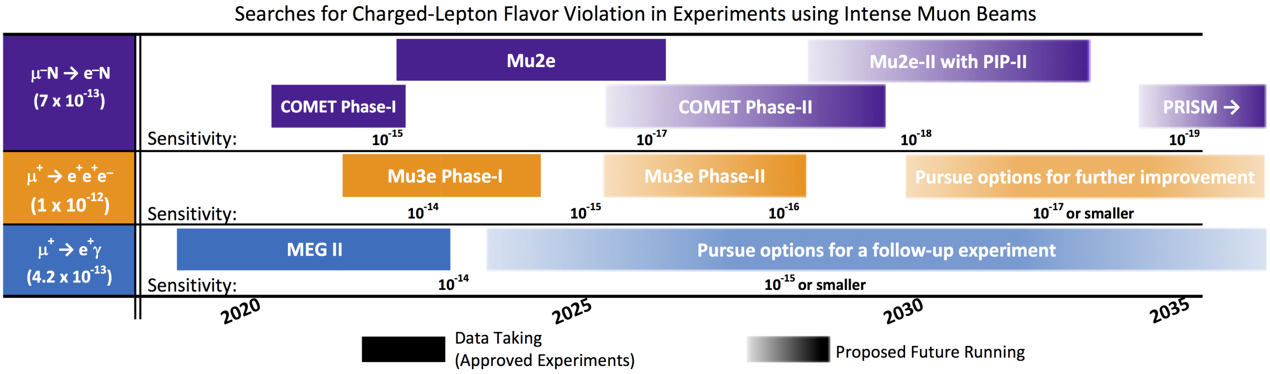

Figure 1: *Planned data taking schedules for current experiments that search for charged-lepton flavor violating $\mu \to e$ transitions. Also shown are possible schedules for future proposed upgrades to these experiments. The current best limits for each process are shown on the left in parentheses, while expected future sensitivities are indicated by order of magnitude along the bottom of each row.*

References

[1] S.T. Petcov, Sov. J. Nucl. Phys. 25 (1977) 340.

[2] L. Willmann, *et al.*, Phys.Rev.Lett. 82 (1999) 49.

[3] L. Calibbi and G. Signorelli, Riv. Nuovo. Cimento, 41 (2018) 71.

[4] V. Cirigliano, *et al.*, Phys. Rev. D80 (2009) 013002.

[5] A. Baldini, *et al.* (`MEG` Collaboration), Eur. Phys. J. C76 (2016) 434.

[6] U. Bellgardt, *et al.* (`SINDRUM` Collaboration), Nucl. Phys. B299 (1988) 1.

[7] W. Bertl, *et al.* (`SINDRUM-II` Collaboration), Eur. Phys. J. C47 (2006) 337.

[8] G.W. Bennett, *et al.* (`E821` Collaboration), Phys. Rev. Lett. 92 (2004) 161802.

[9] G. F. Giudice, P. Paradisi and M. Passera, JHEP11 (2012) 113.

[10] T. Hambye, Proc. Nucl. Phys. B248 (2014) 13.

[11] A. Abada, *et al.*, JHEP 11 (2014) 048.

[12] J. Kaulard, *et al.* (`SINDRUM-II` Collaboration), Phys. Lett. B422 (1998) 334.

[13] B. Yeo, Y. Kuno, M. Lee and K. Zuber, Phys.Rev. D96, no. 7 (2017) 075027.

[14] B. Gripaios, *et al.*, JHEP (2015) 6; B. Dumont, *et al.*, arXiv:1603.05248 (2016); M. Bauer and M. Neubert, Phys. Rev.Lett. 116 (2016) 141802; S. Baek and K. Nishiwaki, Phys. Rev. D93 (2016) 015002.

[15] A. Crivellin, *et al.*, Phys. Rev. D92 (2015) 050413.

[16] J. Arnold, *et al.*, Phys. Rev. D88 (2013) 035009.

[17] R. Aaij, *et al.* (`LHCb` Collaboration), Phys.Rev.Lett. 111 (2013) 141801.

[18] G. Wilkinson *et al.*, `https://indico.cern.ch/event/706741/contributions/3017537`

[19] M.Ball, *et al.* (PIP-II Accelerator Facility),
`http://pip2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=113 (2018).`

[20] A. Baldini, *et al.* (`MEG II` Collaboration), Eur. Phys. J. C78 (2018) 380.

[21] A. Papa, *et al.*, Nucl. Phys. Proc. Suppl. 248 (2014) 121.

[22] G. Cavoto, *et al.*, Eur.Phys.J. C78 (2018) 37.

[23] C. Cheng, B. Echenard, D.G. Hitlin, arXiv:1309.7679 (2013).

[24] A. Blondel, *et al.* (`Mu3e` Collaboration), arXiv:1301.6113 (2013).

[25] I. Peric, Nucl. Instrum. Meth. A582, 876 (2007).

[26] A. Papa, NuFact 2018, Blacksburg, Virginia USA,
`https://indico.phys.vt.edu/event/34/contributions/701`

[27] R.M. Dzhilkibaev and V.M. Lobashev, Sov.J.Nucl.Phys. 49(2), (1989) 384.

[28] S. Cook, *et al.*, Phys. Rev. Accel. Beams 20(3), (2017) 030101.

[29] R. Abramishvili, *et al.* (`COMET` Collaboration),
`http://comet.kek.jp/Documents_files/PAC-TDR-2016/COMET-TDR-2016_v2.pdf`

[30] L. Bartoszek, *et al.* (`Mu2e` Collaboration), arXiv:1501.05241 (2015).

[31] M. Lee (on behalf of `Mu2e` Collaboration), Nucl. Part. Phys. Proc., 273 (2016) 2530.

[32] N. Atanov, *et al.*, IEEE Trans. Nucl. Sci., Vol 65, N. 8, (2018) 2073.

[33] COMET submission to the European Strategy for Particle Physics 2020, and references therein.

[34] F. Abusalma, *et al.* (`Mu2e-II` Experiment), arXiv:1802.02599 (2018).

Addendum:

Charged Lepton Flavour Violation using Intense Muon Beams at Future Facilities

A. Baldini, D. Glenzinski, F. Kapusta, Y. Kuno, M. Lancaster,
J. Miller, S. Miscetti, T. Mori, A. Papa, A. Schöning, Y. Uchida

A submission to the 2020 update of the European Strategy for Particle Physics on behalf of the COMET, MEG, Mu2e and Mu3e collaborations.

Abstract

In this Addendum additional information is provided about the MEG, Mu3e, Mu2e, and COMET experiments and their associated collaborations. The contributions from Europe are emphasized.

Contact: André Schöning [schoning@physi.uni-heidelberg.de]

Addendum for the MEG Experiment

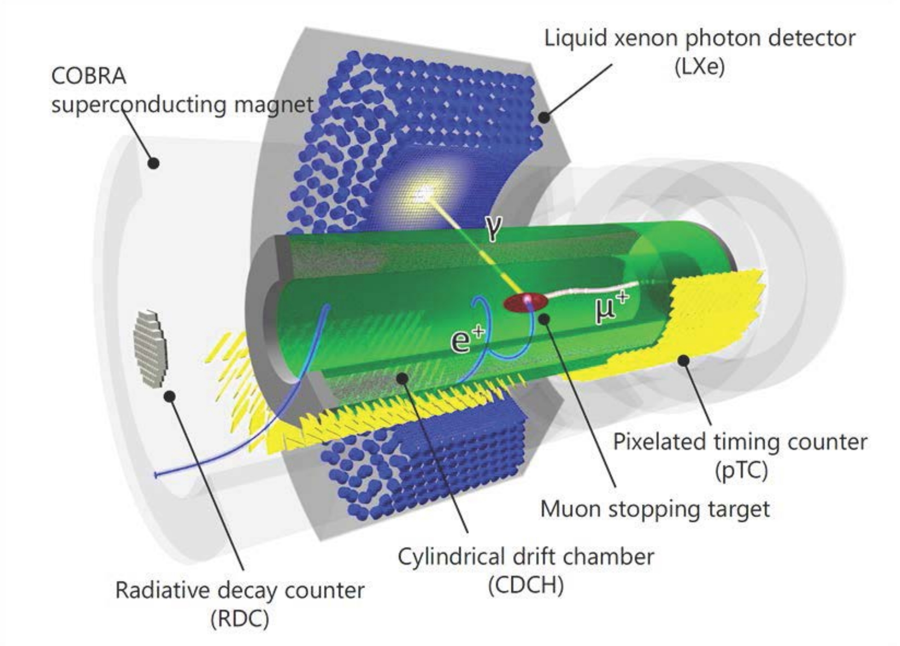

Figure 1: *Schematic of the* `MEG II` *experiment.*

Experiment Website and Contact Information

Website: http://meg.web.psi.ch
Co-spokespersons: A. Baldini (University of Pisa) and T. Mori (University of Tokyo)
(alessandro.baldini@pi.infn.it, mori@icepp.s.u-tokyo.ac.jp)

Interested Community

The `MEG II` Collaboration consists of about 75 participants from Japanese, Italian, Swiss, Russian and US institutions. Scientists and students from Europe account for 50% of the collaboration. The experiment is hosted at the PSI laboratory in Switzerland.

Timeline

The `MEG II` experiment has recently completed construction and first commissioning data was collected in 2018. A three year physics run is expected to begin in 2019.

European Contributions

The European contributions to `MEG II` spanned all the major sub-sytems of the experiment including:

- Data acquisition software
- Construction of trigger and read-out electronics
- Procurement of silicon photomultipliers for the positron timing counter
- Mechanical structure of the positron timing counter
- Construction of the new cylindrical drift chamber

- Construction of the liquid xenon detector cryostat
- Calibration devices for the liquid xenon detector

The European groups also play a significant role in the leadership, commissioning, operations, analysis, and publication activities of the experiment.

Computing Requirements

The computing system of `MEG II` consists in about 320 CPU cores and 1300/2000 TB of disk/tape space. Computing expenses are equally subdivided among Japanese, Italian and Swiss institutions.

Addendum for the Mu3e Experiment

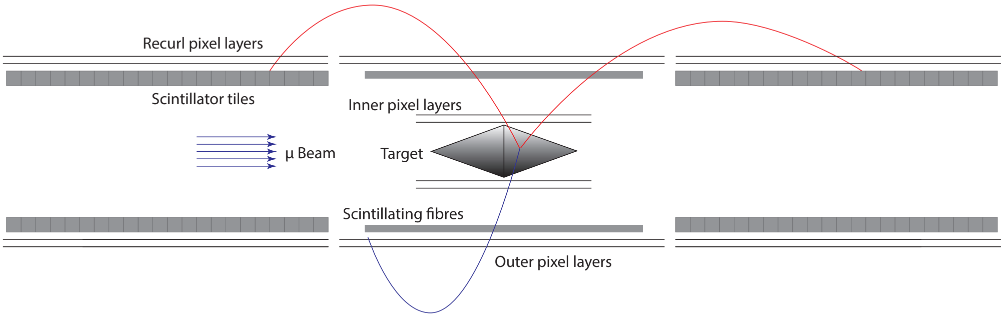

Figure 2: *Schematic of the* `Mu3e` *experiment.*

Experiment Website and Contact Information

Website: https://www.psi.ch/mu3e/mu3e
Co-spokespersons: S. Ritt (PSI Laboratory) and A. Schöning (Heidelberg University)
(stefan.ritt@psi.ch, schoning@physi.uni-heidelberg.de)

Interested Community

The `Mu3e` Collaboration consists of about 70 participants, from eleven European institutions in Germany, Switzerland and United Kingdom. Scientists and Europe account for 100% of the collaboration. The experiment is hosted at the PSI laboratory in Switzerland.

Timeline

The experiment will be performed in two phases. The R&D programme is nearly complete and construction has begun for various components. Commissioning with beam for `Mu3e Phase-I` is expected to start in 2020. Three years of physics data taking is required to reach the design sensitivity.

The `Mu3e Phase-II` experiment requires an upgraded detector with an extended geometrical acceptance and the construction of a new high intensity muon beamline, HiMB, at PSI. The proposal requires refurbishing target M of the proton beamline and installation of a new capture solenoid followed by a solenoidal beamline, using a design similar to existing μE4 beamline, see Fig. 3. Ongoing studies are investigating whether, with modest modifications, the `Phase-II` experiment may also allow searches for $\mu^+ \to e^+\gamma$ decays or muonium-anitmuonium oscillations. Design studies for HiMB are underway and installation, if approved, could start at the earliest in 2024 after the completion of the `Phase-I` programme.

European Contributions

The entire `Mu3e Phase-I` experiment is designed and built by European institutions. The main components of the experiment are:

- Superconducting solenoid with a homogeneous magnetic field of $B = 1$ Tesla (up to B=2.6 Tesla).
- Ultra-light pixel tracker based on high voltage monolithic active pixel sensors (HV-MAPS).

- Two scintillating detector systems for sub-nanosecond timing, based on scintillating fibers and tiles.
- Trigger-less data acquisition system with continuous readout.
- Filter farm based on graphical processing units.

The European groups also play a significant role in all aspects of the experiment including leadership, operations, analysis and publication activities.

Most groups of the `Mu3e` collaboration `Phase-I` have expressed interest to contribute to `Phase-II`. Also new groups are invited to contribute to the planned `Mu3e Phase-II` upgrade, and to investigate further extensions of the `Mu3e` physics programme, for example a search for $\mu^+ \to e^+\gamma$ with a photon conversion layer or muonium-antimuonium oscillations with an upgraded `Mu3e` detector.

Computing Requirements

The computing system and needs will be similar to those of the MEG experiment. Expenses for computing will be shared among the contributing institutes. Additional GRID computing resources will be required to fully exploit the physics potential of the experiment.

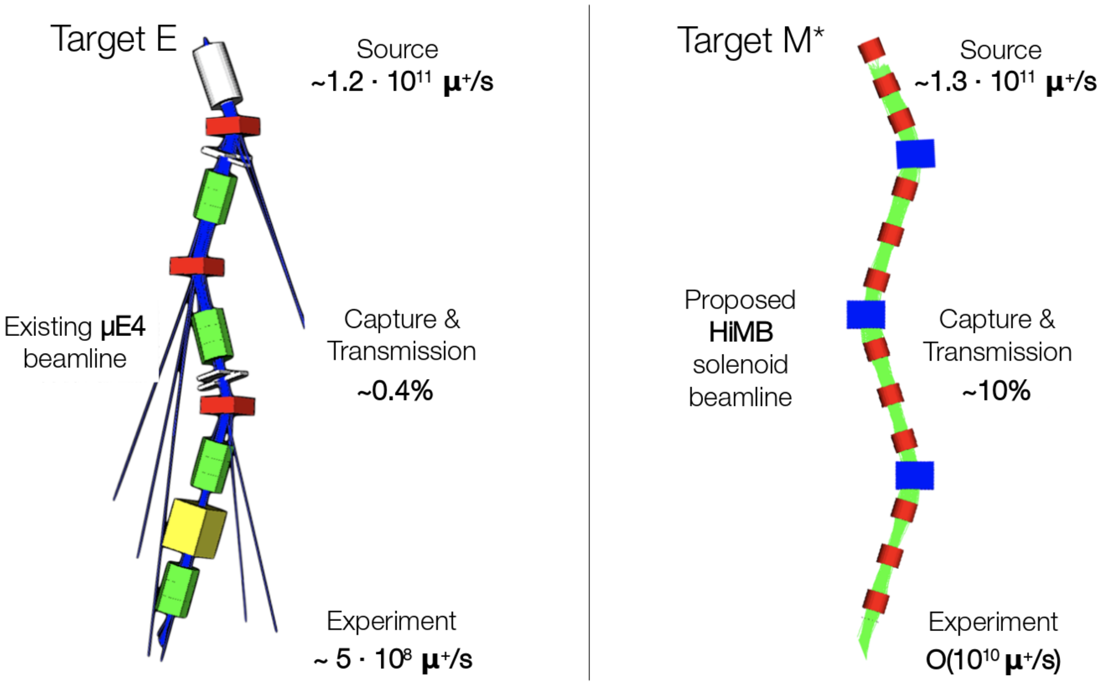

Figure 3: The new proposed solenoidal beamline for HiMB (right) compared to the current hybrid μE4 beamline (left).

Addendum for the COMET Experiment

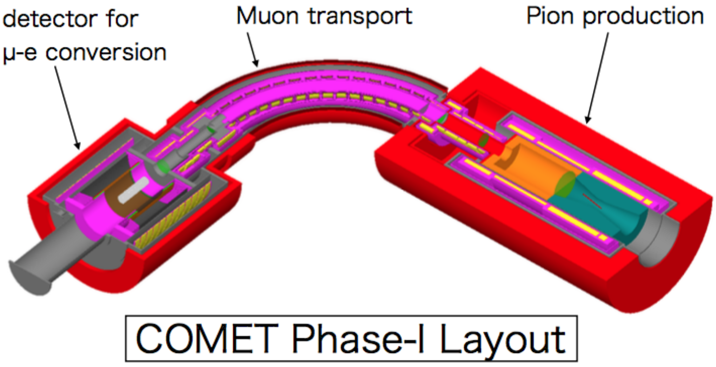

Figure 4: *A schematic of the* `COMET Phase-I` *experiment. A cosmic-ray veto system and monitors for the proton beam and muon beam are not shown.*

Experiment Website and Contact Information

Website: http://comet.kek.jp/Introduction.html
Spokesperson: Y. Kuno (Osaka University)
(kuno@phys.sci.osaka-u.ac.jp)

Interested Community

The `COMET` Collaboration consists of about 200 participants from 35 institutions from Australia, Belarus, China, Czech Republic, France, Georgia, Germany, India, Japan, Kazakhstan, South Korea, Malaysia, Russia, United Kingdom, and Vietnam. Scientists and students from Europe account for about 30% of the collaboration. The experiment is hosted at the J-PARC laboratory in Japan.

Timeline

The experiment will be performed in two phases. Construction of `COMET Phase-I` is at and advanced stage. The J-PARC proton beam will arrive at the `COMET` experimental area in early 2020, when `Phase-I` beam studies and integration will commence. The `Phase-I` physics data-taking and analysis will follow.

The `COMET Phase-II` experiment requires the construction of an extended solenoid system as depicted in Fig. 5. that, if approved, could be ready in the mid–2020s. The completed `COMET Phase-II` configuration can be adapted to search for and measure several charged-lepton flavour- and number-violating (cLNV) processes other than the main $\mu^- N \to e^- N$ channel, and a broad programme of study is expected to continue well beyond 2025 and into the 2030s, with a specific path that is dependent on the observations that have been made by that time. Some of these additional measurements will require the beamline to run in dedicated positive-muon mode, which will produce an extremely high-quality beam in the `Phase-II` configuration.

In the longer term (2030 and beyond), the `COMET` collaboration is also closely engaged with the next-generation PRISM experiment through the PRISM Task Force, which makes use of an FFAG muon storage ring to pursue detailed measurements of cLFV and LNV processes. This is a relatively long-term project which would be expected in the latter stages of the period relevant to the present strategy exercise.

European Contributions

The European contributions to `COMET` include:

- Cosmic Ray Veto detector (Belarus, France, Georgia, Russia)
- Electromagnetic calorimeter (Belarus, Russia)
- Muon target monitor (Germany)
- Data-acquisition and detector triggering systems (UK, Czech Republic)
- Straw-tube tracking detector (Georgia, Russia)
- Muon stopping targetry (Germany)

The European groups also play a significant role in the leadership, analysis, and publication activities and are expected to play a significant role in the commissioning and operation of the experiment beginning in 2020. The international PRISM task force also benefits from significant European contributions, including leadership.

Computing Requirements

Controlling and monitoring the beam composition and the various backgrounds for this rare-decay experiment requires very large simulated data samples. Single- and multi-bunch simulations have involved significant contributions in terms of CPU (France, UK and Germany), storage and data sharing (France). Software developments related to the analysis, track finding and track fitting optimization lead also to intensive software tests and improvements (UK, France, Germany). In particular, much effort has been focused on introducing simulation strategies that allow for high-statistics background and signal estimates without requiring a proportional increase in computational resources. Combining such strategies with increasing international resource contributions will allow the computational challenges of `COMET` to be met.

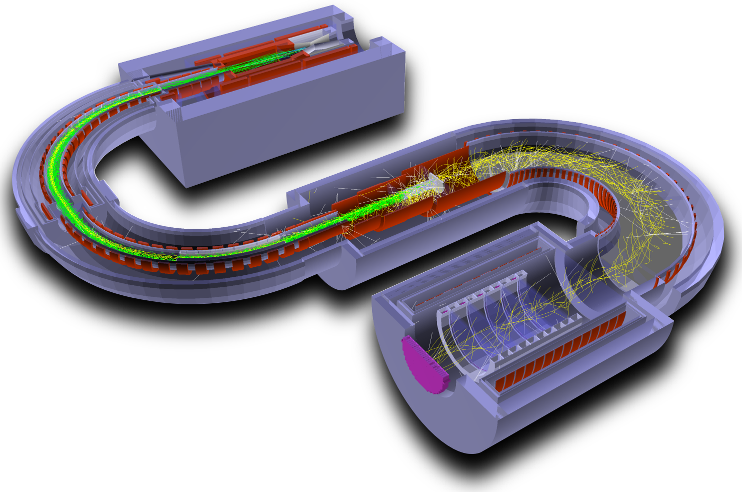

Figure 5: *Schematic of the* `COMET Phase-II` *experiment.*

Addendum for the Mu2e and Mu2e-II Experiment

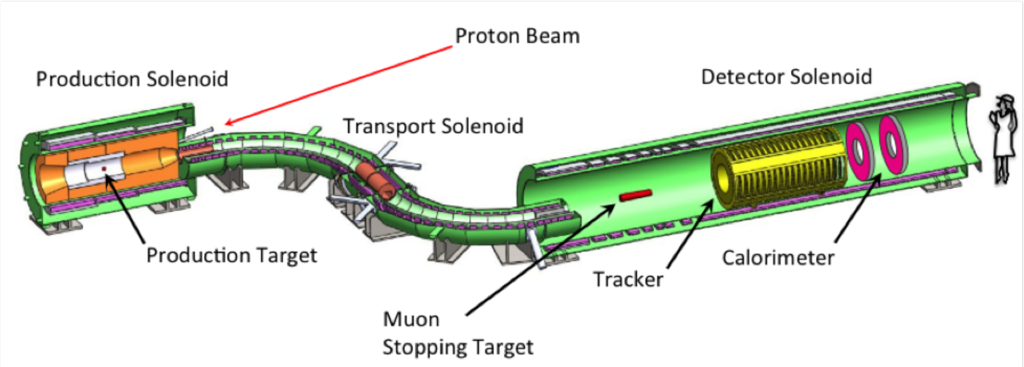

Figure 6: *Schematic of the* `Mu2e` *experiment. A cosmic-ray veto system, and monitors for the proton beam and muon beam are not shown.*

Experiment Website and Contact Information

Website: https://mu2e.fnal.gov
Co-spokespersons: D. Glenzinski (Fermilab) and J. Miller (Boston University)
(mu2e-spokespersons@fnal.gov)

Interested Community

The `Mu2e` Collaboration consists of 242 members from 40 institutions in China, Germany, Italy, Russia, the United Kingdom, and the United States. Scientists and students from European institutions account for 26% of the collaboration. The experiment is hosted by Fermilab in the US.

Timeline

The `Mu2e` experiment is currently under construction. In 2021 commissioning of the proton beamline, and cosmic-ray commissioning of the detector systems are scheduled to begin. Commissioning of the detector systems with beam is expected in 2022 and a four-year physics run is planned starting in 2023.

In parallel to `Mu2e` construction and commissioning, R&D for `Mu2e-II` will begin in order to develop a conceptual design for the detectors and a new proton beamline to accommodate the new beam energy provided by the PIP-II linac. There are challenging issues associated with the increased rate and radiation environment for the production solenoid, the production target, and the detector systems and their associated read-out electronics. The timeline for `Mu2e-II` will be driven by the completion of `Mu2e` as well as the construction of the PIP-II linac, which, if approved, is expected to become available in the mid-2020 timescale. To achieve another factor of ten or more improvement in sensitivity will require about three years of physics data taking with 100 kW of protons from PIP-II. The flexibility of PIP-II provides an opportunity to deliver customized muon beams for the exploration of other `Mu2e-II` stopping target materials as well as for next-generation $\mu^+ \to e^+e^-e^+$ or $\mu^+ \to e^+\gamma$ experiments.

European Contributions

The European contributions to `Mu2e` spanned several important sub-systems of the experiment including:

- Calorimeter: the design and construction is lead by Italy with additional contributions from Germany, Russia, and the US. Italy (INFN) is contributing $\mathcal{O}$(3M Euro) for core construction costs and provided support for $\mathcal{O}(30)$ people.
- Muon Target Monitor: the final design and construction of the muon target monitor is driven by the UK in collaboration with the US. The UK (STFC) is contributing $\mathcal{O}$(1M Euro) for core construction costs and provided support for $\mathcal{O}(15)$ people.
- Transport Solenoid: Italy made very significant contributions to the design, prototyping, and fabrication of the superconductor and coils of the transport solenoid.
- Irradiation facilities: Germany provides support for $\mathcal{O}(2)$ people plus in-kind access to the EPOS and G-ELBE irradiation facilities at HZDR for tests of the rate capabilities and radiation tolerance of various detector sub-systems.

European groups also play a significant role in the leaderhip, analysis, and publication activities and are expected to play a significant role in the commissioning and operation of the experiment beginning in 2021.

For `Mu2e-II`, European groups have expressed interest in contributing to the development and design of an upgraded calorimeter (e.g. using BaF_2 crystals and optimized photosensors), of upgraded read-out electronics using next-generation FPGAs or custom ASICs, and of an upgraded tracker potentially using micro-RWell or MPGD technologies.

Computing Requirements

The computing resources required for `Mu2e` data processing, reconstruction, and analysis are estimated to be about 1000 CPU cores and 30/60 PB of disk/tape space. Significant additional CPU resources ($\sim$ 30M CPU-hours per year) from the WLCG and high performance computing systems (e.g. NERSC) are utilized annually to produce high-statistics simulation samples.