Addendum:

Charged Lepton Flavour Violation using Intense Muon Beams at Future Facilities

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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.

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Addendum for the MEG Experiment

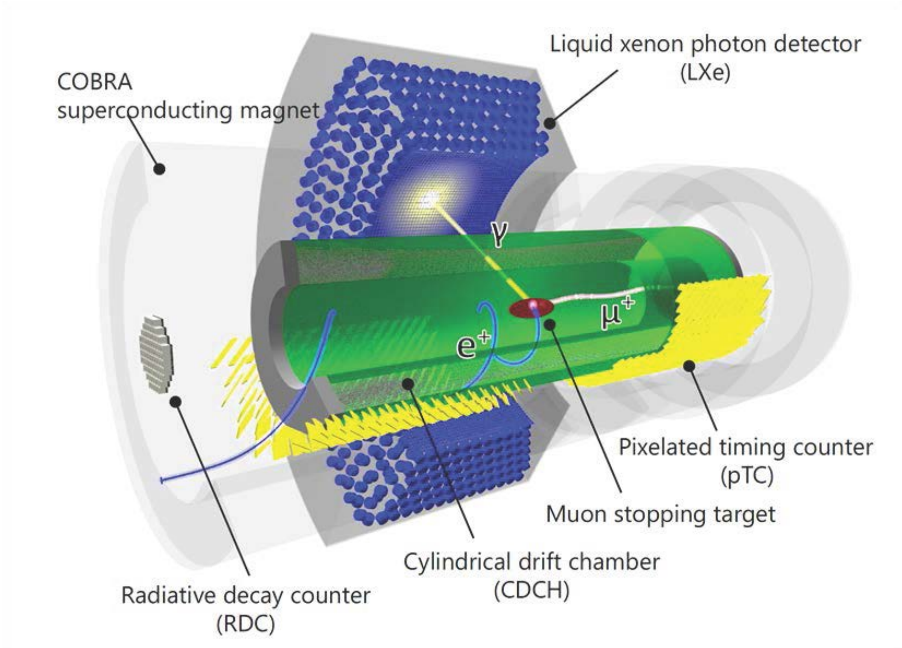

Figure 1: *Schematic of the* MEG II *experiment.*

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

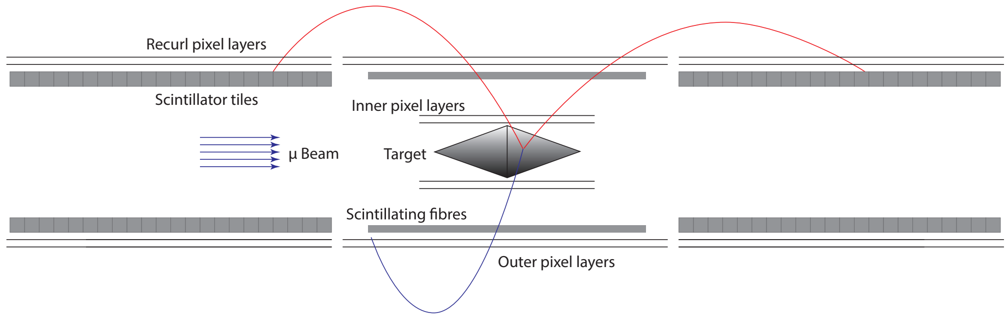

Figure 2: *Schematic of the* `Mu3e` *experiment.*

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.

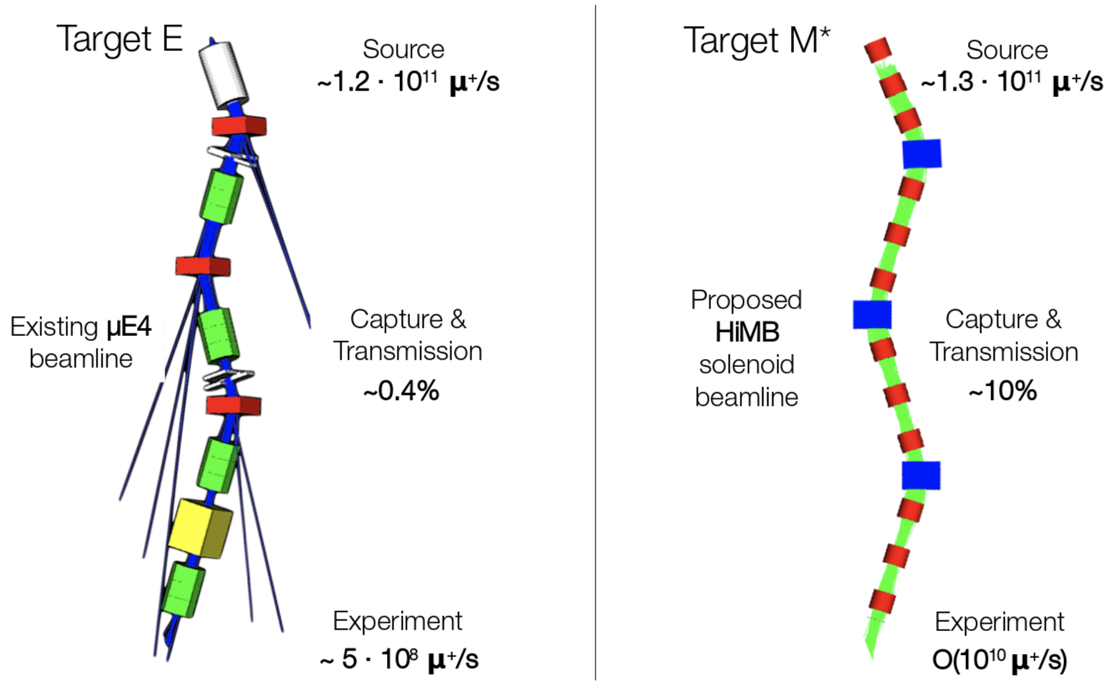

Figure 3: The new proposed solenoidal beamline for HiMB (right) compared to the current hybrid μE4 beamline (left).

Addendum for the COMET Experiment

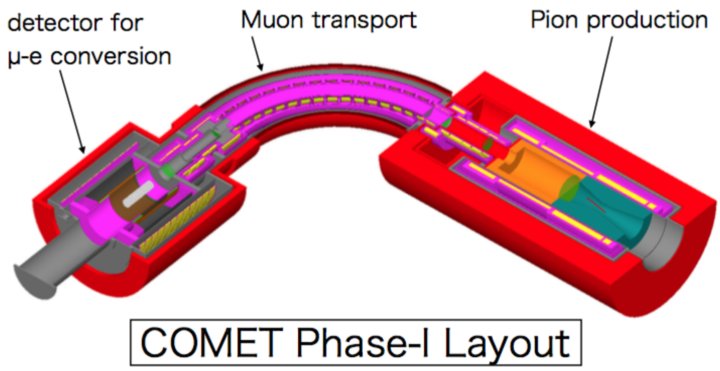

Figure 4: *A schematic of the* `COMET Phase-I` *experiment. A cosmic-ray veto system and monitors for the proton beam and muon beam are not shown.*

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.

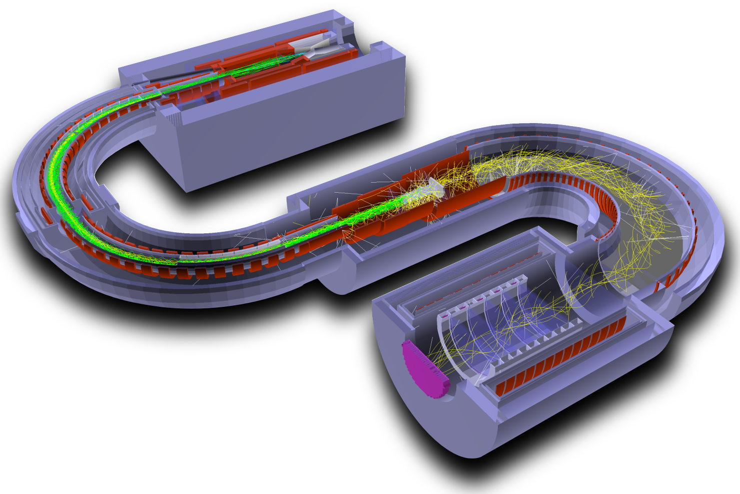

Figure 5: *Schematic of the* COMET Phase-II *experiment.*

Addendum for the Mu2e and Mu2e-II Experiment

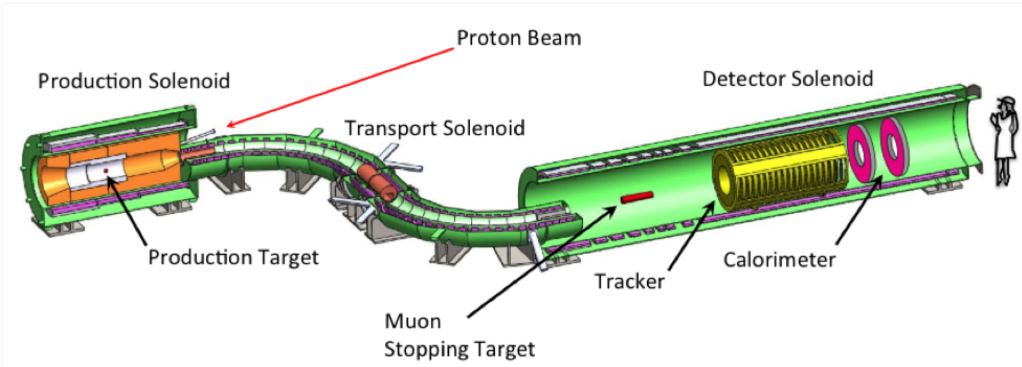

Figure 6: *Schematic of the* `Mu2e` *experiment. A cosmic-ray veto system, and monitors for the proton beam and muon beam are not shown.*

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.