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Search for the lepton flavor violating decay $\mu^+ \to e^+e^-e^+$ with the Mu3e experiment at PSI

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Abstract: Mu3e is an experiment under construction at the Paul Scherrer Institute (Switzerland) aiming to find or exclude the charged lepton flavor violating decay $\mu^+ \to e^+e^-e^+$ at branching fractions above 10^{-16}. A first running phase using an existing beamline targets a single event sensitivity of $2 \cdot 10^{-15}$, while the ultimate sensitivity is reached in a second phase with a new high intensity muon beamline. Achieving such sensitivity requires a high muon rate along with a detector of large kinematic acceptance able to reconstruct the low momenta of the decay positrons and electrons with minimal material budget. The Mu3e experiment is mounted with ultra thin tracking detectors based on high-voltage monolithic active pixel sensors, combined with scintillating fibers and tiles for precise timing. This paper presents an overview of the experimental requirements, the technical design, and the construction readiness of Mu3e.

Keywords: Front-end electronics for detector readout; Online farms and online filtering; Particle tracking detectors; Timing detectors

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Contents

1 Physics motivation

Mu3e [1] is a dedicated experiment under construction at the Paul Scherrer Institute (PSI) in Switzerland in the search for the charged lepton flavor violating (cLFV) decay $\mu^+ \to e^+e^-e^+$.[1] In the Standard Model contemplating neutrino masses (νSM), the decay can only occur via neutrino mixing; as the process is heavily suppressed (branching fraction $\mathcal{B} < 10^{-54}$ [2]), it is not reachable at experimental level, and its observation would be a clear indication of the new physics beyond the νSM. A new generation of experiments searching for the so-called muon golden channels (MEG II [3] for $\mu \to e\gamma$; Mu2e [4] and COMET [5] for $\mu \to e$ conversion; Mu3e for $\mu \to eee$) will potentially unveil the underlying physics in a complementary manner [6].

The Mu3e experiment is unique in addressing the $\mu \to eee$ decay: with a two-stage approach, it is expected to reach an ultimate sensitivity of 10^{-16} on its branching ratio, improving on the latest measurements by the SINDRUM experiment [7] by four orders of magnitude. In the first stage (phase I), Mu3e will use the existent πE5 beamline at PSI providing up to 10^8 muon stops per second to reach a sensitivity of 2×10^{-15}. An upgraded detector for the second stage (phase II) will benefit from the higher muon rates of the future High Intensity Muon Beamline [8] (HIMB) at PSI (2×10^9 muon stops per second) to target the Mu3e ultimate sensitivity of 10^{-16}.

2 Signal and backgrounds

The Mu3e signal is sketched in figure 1a. It is defined by the presence of two positrons and one electron that emerge coincident in time from a common vertex from a muon decaying at rest. The vectorial sum of the momenta of the three decay particles vanishes, while their invariant mass equals the muon rest mass. The energies of the outgoing particles range from the electron mass up to half the muon mass (53 MeV). At these energies, multiple scattering is the dominant factor limiting momentum resolution, thus detector material must be minimized – a key input that drives the Mu3e design. In addition, as the underlying cLFV kinematics are unknown, the detector acceptance must be maximized to capture new physics in all possible regions of phase-space.

[1]In this document the decay is refered to as $\mu \to eee$, but the charge of the muon is always positive.

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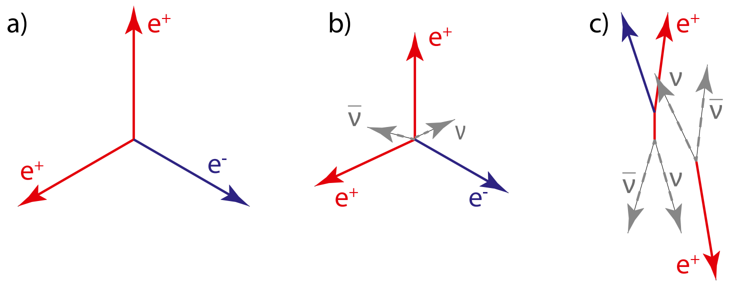

Figure 1. Sketch of (a) Mu3e signal, (b) internal conversion background, and (c) accidental background processes. Reprinted from [1], Copyright (2021), with permission from Elsevier.

Another critical requirement to the Mu3e design is the ability to suppress the backgrounds, which fall into two categories: the internal conversion (figure 1b) and the accidental background (figure 1c). The former corresponds to the $\mu^+ \rightarrow e^+e^-e^+\nu_e\bar{\nu}_\mu$ decay, separated from the signal by making use of energy and momentum conservation to infer the presence of neutrinos, for which a momentum resolution better than 1 MeV is needed. The latter arises from the coincidence of one or more standard Michel decays ($\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$) along with an electron from Bhabha scattering or radiative decays ($\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu\gamma$) with conversion inside the detector. In this case, the outgoing particles are not coincident in time nor share the same vertex; precise vertex reconstruction (< 0.5 mm) and timing (< 100 ps) are needed to reduce this background towards the target sensitivity.

3 Experimental design

The reconstruction of the signal against the backgrounds poses challenging requirements to the Mu3e design. Excellent momentum, timing and vertex resolutions must be achieved along with a large solid angle and kinematic acceptance. In addition, very thin detector material should be used to minimize multiple scattering. At the same time, the detector must present high granularity and very fast readout electronics to cope with the high occupancy expected from the large muon rates.

A sketch of the Mu3e detector[2] for phase I is shown in figure 2. The beam is delivered to a double-cone hollow stopping target at the center, where muons decay at rest. Optimal momentum resolution is reached by letting the outgoing particles “recurl”, i.e. pass through the detector a second time under the effect of a 1 T magnetic field. Vertices and tracks are reconstructed with four (two) layers of light-weight silicon pixel trackers in the central (outer) detector regions, cooled down with an innovative gaseous helium system [9]. Two timing detectors based on scintillating fibers and tiles are placed in between the tracking layers in the central and outer regions, respectively, aimed at complementary precise timing and charge identification.

The Mu3e tracker is mounted with 2844 pixel sensors, each containing 250×256 pixels which are 80×80 μm^2 large. The sensors, called MuPiX [10], are High Voltage Monlithic Active Pixel Sensors (HV-MAPS) developed specifically for the Mu3e experiment based on HV-CMOS 180 nm technology. Being fully monolithic, they do not require front-end chips for readout, hence they can be thinned down to 50 μm, resulting in a total layer thickness of $X/X_0 = 0.1\%$. The readout electronics is embedded inside a deep n-well; this way, a high negative bias voltage can be applied without compromising the electronics, increasing the signal size and the charge collection speed.

[2]A brief description of the Mu3e detector is provided in this paper; for more information the reader can refer to [1].

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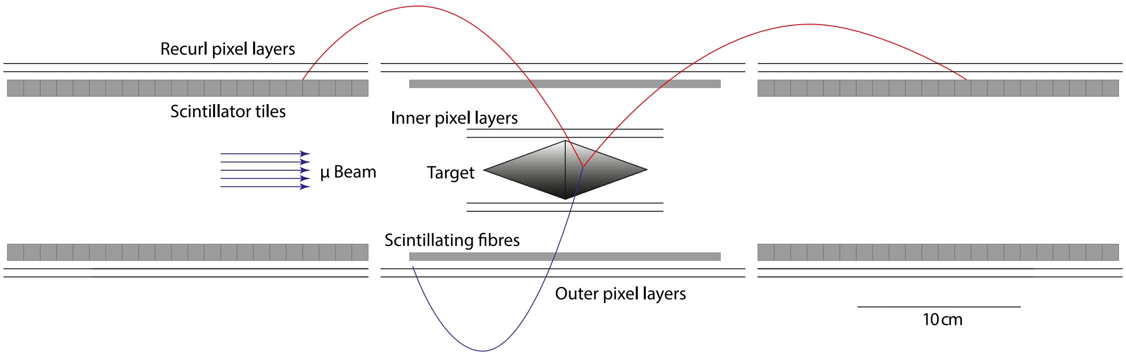

Figure 2. Sketch of the Mu3e detector. The central station surrounds the target and consists of four tracking layers and one layer of scintillating fibers for precision timing. The outer stations upstream and downstream have two tracking layers and one layer of scintillating tiles for complementary timing. Reprinted from [1], Copyright (2021), with permission from Elsevier.

These features allow to meet the experimental requirements and reach an efficiency higher than 99% with a time resolution of less than 20 ns.

The Scintillating Fiber (SciFi) timing detector is installed around the tracker's innermost layers in the central region to allow for an easy association between track and timestamp. It is composed of very thin (250 µm) round fibers (Kuraray model SCSF-78MJ) grouped in twelve 3-layer ribbons with an overall thickness of $X/X_0 = 0.2\%$. The ribbons are coupled to SiPM arrays (Hamamatsu model S13552-HQR) on both sides for optimal time resolution. The signals are read out with a custom-made mixed-mode ASIC, the so-called MuTRiG, able to digitize the crossing time information at single photon level at very high rates. Excellent time resolution is granted by a fully differential analog front-end and a 50 ps binning time-to-digital converter (TDC). Test beam campaigns show a SciFi performance of more than 95% efficiency and ∼250 ps time resolution [11].

A second timing detector, the Scintillating Tiles (SciTile), is installed inside of the outer tracking layers in the recurl stations. The space constraints in this region are less stringent and multiple scattering is not relevant, as only the pixel hits before reaching the tiles are used in track fitting. Hence, SciTile is composed of plastic scintillator (Eljen technology EJ-228) segmented into high-granularity tiles of size 6×6×5 mm^3. Seven modules of 416 tiles each provide full azimuthal coverage in each recurl station. Each tile is read out by a SiPM (Hamamatsu model S13360-3050VE), and the signals are digitized with the MuTRiG as in the SciFi case. A detection efficiency of more than 99% with a time resolution of 45 ps has been measured for SciTile [12].

4 Data processing

The Mu3e data acquisition system [13] operates in a continuous, triggerless readout mode. A series of custom FPGA front-end boards inside the magnet collect and sort the data from the systems before sending it via optical link outside the experimental area. In the counting house the data is aggregated and synchronized using PCIe40 boards [14]. It is then passed to the GPU filter farm for online event selection based on track and vertex reconstruction. A full offline tracking and signal selection, based on longer recurling (6 or 8 hit) tracks for optimal resolution, is then carried out on the recorded data. Figure 3 (left) shows the expected reconstructed invariant mass distribution based on full offline selection.

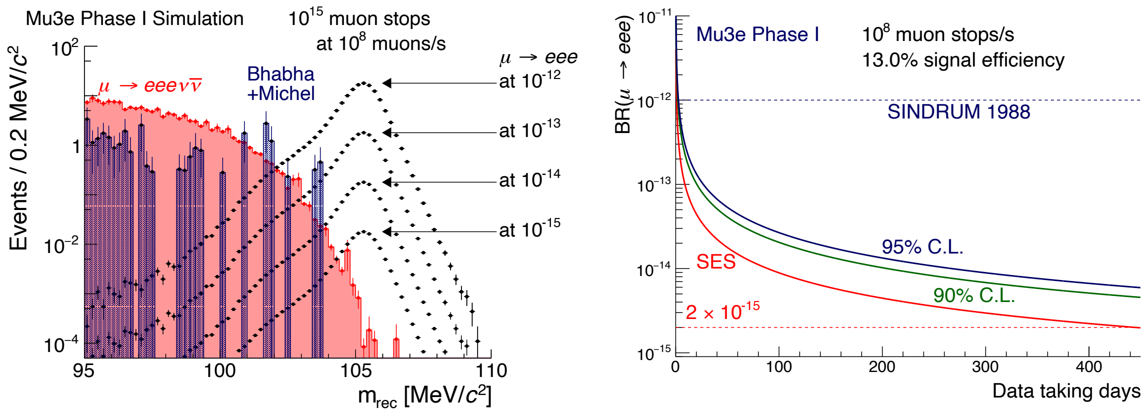

Figure 3. (Left) Reconstructed invariant mass for signal events at various branching fractions, and events from internal conversion and accidental backgrounds. (Right) Single event sensitivity and the corresponding 90% and 95% C.L. upper limits as a function of data-taking days for phase I. Results are derived based on simple cut-based signal regions and uncertainties are statistical [1]. Reprinted from [1], Copyright (2021), with permission from Elsevier.

5 Schedule

Extensive detector integration efforts in the past years have lead to a successful simultaneous operation of demonstrator sub-detectors. In particular, during the so-called Integration Run and Cosmic Run in 2021–22 at PSI, such demonstrators have been operated in a helium atmosphere within the Mu3e magnet with the beam turned on. Pictures of the setup can be seen in figure 4. First combined sub-detector correlations were observed and preliminary cosmic and recurl electron tracks were reconstructed. This important milestone served to validate the final hardware and probe the production readiness: the final subdetectors are currently being produced towards installation and commissioning in 2024. Phase I data-taking is expected to take place in 2025–26. Figure 3 (right) shows the expected evolution of sensitivity versus running time; existing limits on $\mu \to eee$ will be superseded within days, and the target sensitivity will be reached after around 400 days of data-taking. A two-year shutdown is foreseen after phase I in view of installing the new HIMB beamline and performing the necessary Mu3e detector upgrades. Phase II data-taking is expected to begin in 2029.

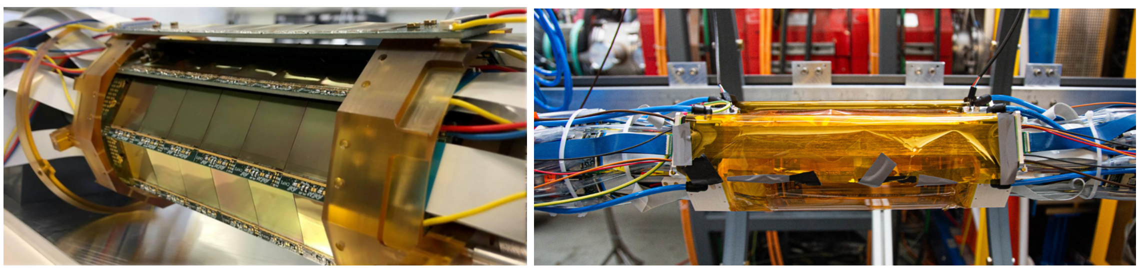

Figure 4. Demonstrator pixel tracker (left) and SciFi (right) installed along with the powering and cooling services during the Integration Run at PSI in 2021.

Acknowledgments

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References

[1] Mu3e collaboration, *Technical design of the phase I Mu3e experiment*, *Nucl. Instrum. Meth. A* **1014** (2021) 165679 [arXiv:2009.11690].

[2] L. Calibbi and G. Signorelli, *Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction*, *Riv. Nuovo Cim.* **41** (2018) 71 [arXiv:1709.00294].

[3] MEG II collaboration, *The design of the MEG II experiment*, *Eur. Phys. J. C* **78** (2018) 380 [arXiv:1801.04688].

[4] Mu2e collaboration, *Mu2e Technical Design Report*, arXiv:1501.05241 [DOI:10.2172/1172555].

[5] R. Akhmetshin et al., *Experimental Proposal for Phase-I of the COMET Experiment at J-PARC*, KEK/J-PARC-PAC 2012-10 (2012).

[6] Y. Kuno and Y. Okada, *Muon decay and physics beyond the standard model*, *Rev. Mod. Phys.* **73** (2001) 151 [hep-ph/9909265].

[7] SINDRUM collaboration, *Search for the Decay $\mu^+ \to e^+e^-e^+$*, *Nucl. Phys. B* **299** (1988) 1.

[8] M. Aiba et al., *Science Case for the new High-Intensity Muon Beams HIMB at PSI*, arXiv:2111.05788.

[9] T.T. Rudzki, F.M. Aeschbacher, M. Deflorin and N. Flucher, *Successful cooling of a pixel tracker using gaseous helium: studies with a mock-up and a detector prototype*, arXiv:2301.13813.

[10] I. Perić, *A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology*, *Nucl. Instrum. Meth. A* **582** (2007) 876.

[11] A. Bravar et al., *Development of the Scintillating Fiber Timing Detector for the Mu3e Experiment*, arXiv:2208.09906.

[12] H. Klingenmeyer et al., *Measurements with the technical prototype for the Mu3e tile detector*, *Nucl. Instrum. Meth. A* **958** (2020) 162852.

[13] Mu3e collaboration, *The Mu3e Data Acquisition*, *IEEE Trans. Nucl. Sci.* **68** (2021) 1833 [arXiv:2010.15648].

[14] J.P. Cachemiche et al., *The PCIe-based readout system for the LHCb experiment*, 2016 *JINST* **11** P02013.

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