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# The Mu3e Experiment at PSI

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The Mu3e experiment will search for lepton flavor violation in the neutrinoless muon decay $\mu^+ \to e^+e^-e^+$ with a sensitivity down to $10^{-16}$ (90% C.L.) using the world most intense muon beam at the Paul Scherrer Institute. This represents a four order of magnitude improvement w.r.t. previous measurements. The $\mu^+ \to e^+e^-e^+$ decay is strongly suppressed in the Standard Model whilst several Beyond the SM models predict observable effects accessible to the new generation of LFV experiments.
The search for the $\mu^+ \to e^+e^-e^+$ decay requires a large acceptance detector capable of measuring up to $2 \times 10^9$ decays of stopped muons per second with excellent momentum, space, and time resolution to suppress backgrounds below the $10^{16}$ level. The required Mu3e detector performance is possible thanks to tracking detectors based on thin monolithic active silicon pixel sensors (HV-MAPS) and very precise timing measurements using scintillating fibers and tiles both coupled to silicon photo-multipliers. The first phase of the Mu3e experiment aiming to a sensitivity of $10^{-15}$ has been recently approved. Following an intense R&D program the collaboration is preparing for detector construction. First data taking is expected in 2019.

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## 1. Introduction

Since the discovery of the muon and the realization that the muon is the electron's *big brother*, the origin of flavor stems as one of the outstanding puzzles in elementary particle physics. In the Standard Model (SM), in the absence of interactions that lead to nonzero neutrino masses, lepton flavor is strictly conserved. The discovery of neutrino oscillations, however, has shown that lepton flavor conservation is not a symmetry of Nature. This discovery implies that also charged lepton flavor violation (cLFV) processes are allowed in extensions of the SM with massive neutrinos. Loop diagrams involving massive neutrinos (Figure 2a), however, are strongly suppressed with branching ratios $\mathcal{O} \sim 10^{-54}$ and thus giving potentially high sensitivity to cLFV processes because of the absence of SM backgrounds. The search for cLFV has started back in the 50's, however processes like the $\mu^+ \to e^+e^-e^+$ or the $\mu^+ \to e^+\gamma$ decays, or the $\mu^\pm A \to e^\pm A$ conversion have not yet been detected. Figure 1 illustrates the evolution of upper limits (90% C.L.) on cLFV processes set by various experiments over more than 60 years. The study of LFV in the charged lepton sector is of big interest as LFV is connected to neutrino mass generation, CP violation, and new physics Beyond the Standard Model. In several models [1, 2] sizable LFV effects, accessible to the new generation of high sensitivity experiments are predicted.

The Mu3e experiment will search for cLFV in the neutrinoless $\mu^+ \to e^+e^+e^-$ decay using the world most intense continuous muon beam at the Paul Scherrer Institute (PSI). With a projected sensitivity of $10^{-16}$ (90% C.L. in the absence of a signal), Mu3e has the potential of probing new physics at the PeV scale. The cLFV decay $\mu^+ \to e^+e^-e^+$ is complementary to the $\mu^+ \to e^+\gamma$ decay and $\mu^-A \to e^-A$ conversion, since it probes different mechanisms for cLFV. It is also complementary to direct searches of Beyond the SM physics at the LHC.

Lepton flavor conservation is naturally violated in many extensions of the Standard Model [3]. Several models, such as grand unified theories (GUTs), supersymmetric models (Figure 2b), compositness, leptoquarks, left-right symmetric models, seesaw models, etc. predict an experimentally

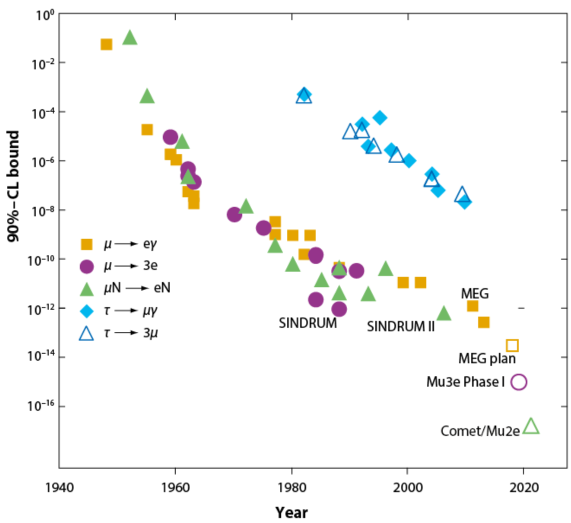


**Figure 1:** Evolution of upper limits (90% C.L.) for cLFV processes set by various experiments over more than 60 years including projections for the next generation of cLFV experiments (Figure adapted from [2]).

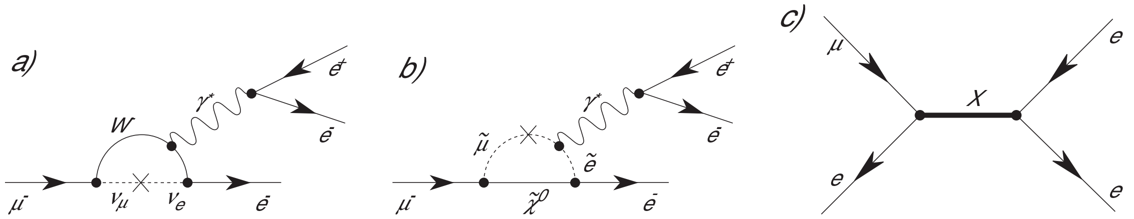


**Figure 2:** *Left to right:* a) SM Feynman diagram for the neutrinoless $\mu^+ \to e^+ e^+ e^-$ process via neutrino mixing, b) Diagram for LFV involving supersymmetric particles, c) Diagram for LFV at tree level involving new particles.

accessible amount of LFV in a large region of the parameter space. LFV can also be mediated by tree couplings involving new particles (Figure 2c) like new Higgs bosons, R-parity violating scalar neutrinos, or new heavy vector bosons, which are for example motivated by models with extra dimensions. Depending on the underlying mechanism, LFV effects might not be visible in some rare muon channels. For example, the $\mu^+ \to e^+\gamma$ decay is not sensitive to LFV four-fermion contact interactions (i.e. to diagrams like the one in Figure 2c), while the $\mu^+ \to e^+e^+e^-$ decay is sensitive to both, loop diagrams and contact interactions. The observation of LFV in the charged lepton sector will be a sign for new physics at scales far beyond the reach of direct observation, up to several PeV, while the absence of a signal would impose new and very stringent constraints on extensions of the SM.

## 2. The experiment

A new experiment to search for the cLFV neutrinoless muon $\mu^+ \to e^+e^+e^-$ decay has been proposed at the Paul Scherrer Institute [4] using the world most intense surface muon beamline. The

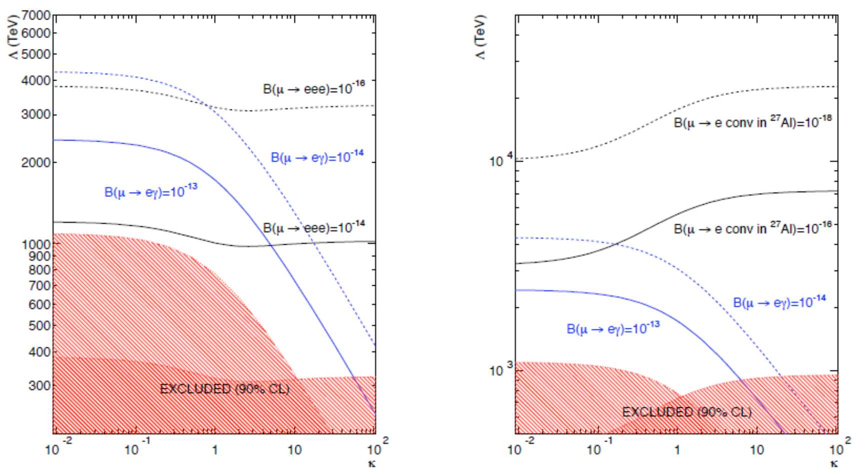


**Figure 3:** Comparison of the reach in effective mass scale $\Lambda$ of new physics theories in searches of decays $\mu \to e\gamma$ and $\mu \to eee$ (left), and decay $\mu \to e\gamma$ and conversion $\mu A \to eA$. Low values of $\kappa$ represent a dominating dipole contribution whereas high $\kappa$ values represent dominating four-fermion contact interactions [3]. Strictly speaking only $\kappa = 0$ and $\kappa \to \infty$ are of interest, since it is very unlikely that different mechanisms will contribute at similar scales.

proposed experiment aims at a sensitivity of $BR(\mu^+ \to e^+e^-e^+) \leq 10^{-16}$ at 90% C.L. in absence of a signal. This represents a four orders of magnitude improvement w.r.t. previous searches performed at PSI by the SINDRUM experiment [5]. Reaching this sensitivity requires:
(i) a detector with a large geometrical acceptance,
(ii) the ability to detect around $10^{17}$ $\mu^+$ decays over the lifetime of the experiment,
(iii) the ability to suppress any possible background (from physics, accidentals, and reinteractions) to a level below $10^{-16}$, and
(iv) a very high intensity continuous muon beam of $10^9 - 10^{10} \mu/s$.

The Mu3e detector geometry is optimized to reach the highest possible momentum resolution in a multiple Coulomb scattering environment, which is needed to suppress the dominating background from the $\mu^+ \to e^+e^+e^- \bar{\nu}_\mu \nu_e$ radiative decays. This source of background can be controlled by optimized momentum resolution. Another source of background can arise from the accidental combination of any two positrons and an electron that within the detector resolution shows the characteristics of the decay signal. As an example, this could be a positron from the dominant muon Michel decay $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ in combination with a positron and electron from a Bhabha scattering event or photon conversion. The rate of the accidental background depends on the beam intensity and muon stopping rate. This source of background can be controlled by optimized time and vertex resolution in addition to momentum resolution.

The first phase (phase I) of the experiment has been already approved and the experiment is prepring for the construction of the detector after an intense R&D program. In phase I (2019 – 2022) the sensitivity goal is set at $BR(\mu^+ \to e^+e^+e^-) \leq 2 \times 10^{-15}$. This sensitivity can be achieved with a muon beam intensity of $10^8$ $\mu^+$ per second, which can be provided already now by the existing PSI muon beamline. Reaching the sensitivity goal of $BR(\mu^+ \to e^+e^+e^-) \leq 10^{-16}$ requires a muon stopping rate of $2 \times 10^9$ $\mu^+$ per second. A new high intensity muon beamline HiMB is currently under investigation at PSI.

Minimizing the material within the acceptance of the detector is crucial to achieve these goals. Gas detectors cannot stand the required rates due to aging or occupancy or do not deliver the required precision. Solid state detectors until recently were either too thick or too slow. The high-voltage monolithic active pixel sensors (HV-MAPS) technology [6] providing sensors that can be

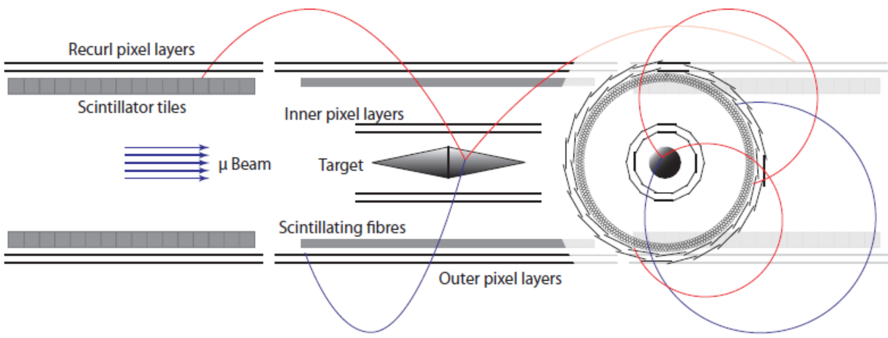


**Figure 4:** Schematic view of Mu3e detector in phase I configuration. Two additional recurling stations will be added in phase II. The total length of the full detector is about 200 cm and the transverse size is about 15 cm. The detector is inserted into a 100 cm diameter 250 cm long superconducting solenoid providing a uniform magnetic field of 1 T.

thinned down to 50 $\mu$m thickness and ran at frame rates above 10 MHz thanks to fast charge collection and built-in zero-suppression offers the right solution and has been adopted for Mu3e. With a pixel size of $80 \times 80$ $\mu\text{m}^2$ the HV-MAPS tracker will consists of 300 million pixels.

Figure 4 illustrates the Mu3e detector. The key elements are:
(i) a high precision tracker based on thin monolithic active silicon pixel sensors with high granularity (HV-MAPS) [6], providing high spatial resolution, and
(ii) a time-of-flight (ToF) system, consisting of scintillating fibers in the central region coupled to silicon photomultipliers arrays [7] and scintillating tails also coupled to Si-PMs in the outer regions, providing very precise timing information at very high particle rates.

By combining both detector technologies all backgrounds can be reduced below the aimed sensitivity of $BR(\mu^+ \to e^+e^+e^-) \sim 10^{-16}$ (see Figure 5). All detector elements are placed in a 250 cm long homogeneous solenoidal magnetic field of 1 Tesla. Surface muons of 28 MeV/$c$ produced by the PSI beamline are stopped on a hollow double cone aluminum target. The design of the target maximizes the surface where muons stop and then decay in order to maximize the separation of decay verteces.

Electrons from muon decays are detected by two cylindrical double layer silicon pixel detectors (HV-MAPS), one double layer just above the target, the second at a $\sim 7.5$ cm radius. Curling tracks are measured by a second cylindrical double layer silicon pixel detector, also at a $\sim 7.5$ cm radius, upstream and downstream of the central detector, for a total of at least 6 measured space points per track. By also measuring the curling part of the track one achieves a large lever arm. The Mu3e tracking detector is designed such to be sensitive for a transverse momentum range from 10 to 53 MeV/$c$ and to provide a momentum resolution of better than 0.5 MeV/$c$ over the same range. This kinematical coverage corresponds to an acceptances of 50% or more for all considered LFV models (70% for most LFV models).

The silicon tracker is complemented by a cylindrical time of flight (ToF) detector consisting of a scintillating fiber tracker in the central region with an expected time resolution of few hundred ps. In the current design, the Sci-Fi tracker is made of 12 ribbons, 30 cm long and 32 mm wide, composed of 4 staggered layers of 250 $\mu$m diameter fibers. The ribbons are arranged cylindrically at a $\sim 6$ cm radius. The curling tracks are measured a second time with scintillating tiles with an expected time resolution better than 100 ps. The main role of the ToF system is to measure very precisely the time of production of various tracks in order to reject pile-up events (accidental backgrounds) with very high efficiency. The ToF will operate at very high particle rates in excess of few MHz per channel.

## 3. Detector performance

The final sensitivity of the Mu3e experiment will depend on the ability to reduce accidental backgrounds, which scale with the square of the beam intensity, and irreducible backgrounds (physics) such as the $\mu^+ \to e^+e^+e^- \bar{\nu}_\mu \nu_e$ radiative decays. In addition, one has to also identify and reject reinteractions in the detector materials. The reconstructed kinematics of candidate events is mainly deteriorated by the multiple scattering of the low energy electrons. Therefore, the material budget of the target and detector, which will be operated in a helium atmosphere, will be kept to a minimum. Accidental backgrounds can be efficiently suppressed by excellent timing ($\sim 100$ ps)

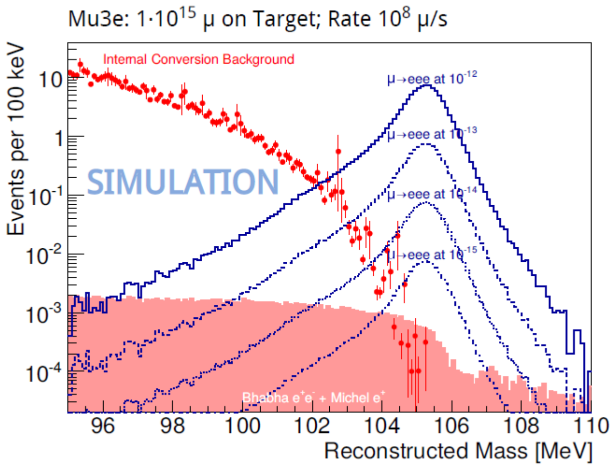


**Figure 5:** Reconstructed mass of three electrons from simulated internal conversion events, accidental combinations of Bhabha scattering events and Michel decays. In comparison, the ($\mu^+ \to e^+e^+e^-$ decay at various branching ratios is shown.

and vertex resolution. The suppression of physics backgrounds requires high momentum resolution ($\sigma_E < 0.5$ MeV) in order to reconstruct precisely the $\mu^+$ decay kinematics. The following criteria will be exploited:
(i) energy and momentum conservation (all 3 outgoing electrons are coplanar and the total energy reproduces the parent muon mass),
(ii) vertex reconstruction (all 3 tracks originate from the same point), and
(iii) timing (all 3 tracks are produced in a very narrow time window).

Figure 5 illustrates the ability of the proposed detector to separate the $\mu^+ \to e^+e^+e^-$ signal at different branching ratios from the radiative decay with internal conversion and accidental combinations of electrons from Bhabha scattering and Michel decays. The detector performs well enough to separate signal $\mu^+ \to e^+e^+e^-$ decays from background even at a branching ratio of $10^{-15}$.

In summary, the sensitivity goal of $10^{-15}$ for the phase I of the experiment represents already a significant improvement (3 orders of magnitude) w.r.t. existing limits on the LFV $\mu^+ \to e^+e^+e^-$ decay [5] and in absence of a LFV signal will set new stringent limits on new physics models.

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