The Mu3e Experiment

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Abstract:

The Mu3e experiment at the Paul Scherrer Institut will search for the lepton-number-violating decay $\mu^+ \to e^+e^-e^+$, extending the sensitivity by four orders of magnitude compared to existing limits. This probe of new physics is complementary to the existing collider, dark matter and neutrino particle physics programmes, and part of a global programme investigating the charged lepton flavour sector. As well as the main $\mu^+ \to e^+e^-e^+$ search, Mu3e will also extend the sensitivity to low-mass dark photons, and additional flavour-violating decays involving long-lived or stable particles.

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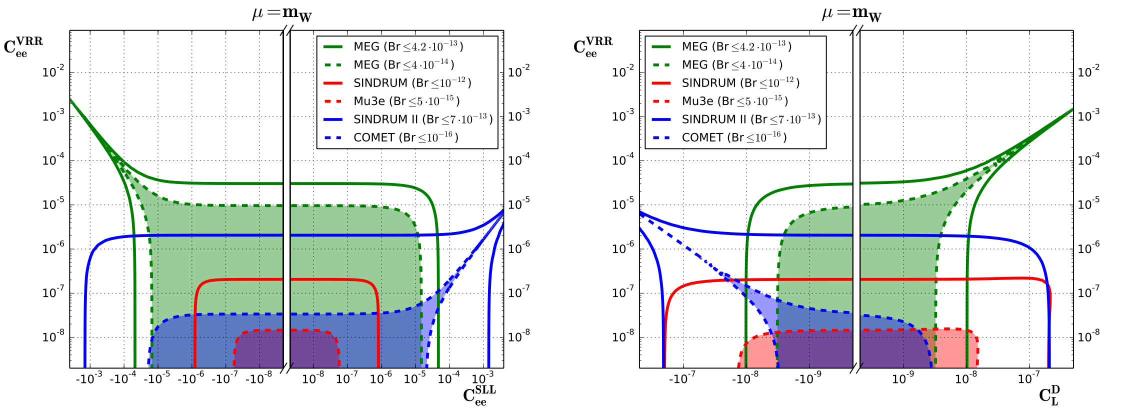
1 The search for $\mu^+ \to e^+e^-e^+$

Flavour violation is a known feature of the quark and neutrino sectors of the Standard Model. And while charged lepton flavour appears to be conserved, it is not protected by any known global symmetry and occurs at the 1-loop level via neutrino oscillation - though suppressed in the Standard Model to an unobservably small rate $\mathcal{O}(10^{-50})$ [1, 2]. However, significant enhancements to this rate are predicted by many BSM scenarios, and the observation of any charged lepton flavour violating (CLFV) processes would be the unambiguous observation of new physics. CLFV processes offer unique discovery potential, complementary to the existing collider, dark matter and neutrino particle physics programmes.

The Mu3e experiment [3] at the Paul Scherrer Institut (PSI) is part of a global programme of experiments searching for the "golden channels" of CLFV in the muon sector: $\mu^+ \to e^+e^-e^+$ (Mu3e), $\mu^+ \to e^+\gamma$ (MEG-II [4, 5]), $\mu^- N \to e^- N$ (Mu2e [6], COMET [7] and DeeMe [8]). This programme will bring a significant increase in sensitivity compared to previous searches, probing new physics mass scales up to 10^3 - 10^4 TeV. The nature of any CLFV signal will depend on the underlying physics. For example, in processes dominated by γ-penguin diagrams, $\mu^+ \to e^+\gamma$ is the most sensitive. If Z or H-penguin diagrams, tree level Z', or lepto-quark models dominate, sensitivity is best for $\mu^+ \to e^+e^-e^+$ and $\mu^- N \to e^- N$. There is an extensive and growing literature exploring these different scenarios, for example [9], which can be parameterised with a general effective operator approach, for example that proposed by Kuno and Okada [10]. The expected constraints on these effective operators have been studied in detail in, for example, [11]. Figure 1 (from [11]) shows the allowed regions in two planes, defined by Wilson coefficients C_{ee}^{VRR} (vector-type contact interaction), C_{ee}^{SLL} (scalar-type contact interaction), and C_L^D (dipole coupling). For the purely leptonic contact-type interactions (Fig. 1a), Mu3e is the most sensitive, and other channels ($\mu^+ \to e^+\gamma$ and $\mu^- N \to e^- N$) are even "blind" to certain regions of the parameter space due to cancellations. The different channels are more complementary for the dipole-type interaction (Fig. 1b). These studies highlight the degeneracy between different terms and the conclusion is clear: exploring all three "golden" muon channels is essential to resolve such degeneracy.

The current best limit on $\mu^+ \to e^+e^-e^+$ was set by the SINDRUM collaboration [12], excluding a branching fraction over 1.0×10^{-12} at 90% confidence level (CL). With a two-phase approach, Mu3e will extend this sensitivity to 10^{-16}. Phase-1, currently under construction, will utilise the πE5 beam-line at PSI will reach a sensitivity of 2×10^{-15} on the branching fraction. An upgraded detector for Phase-2 plans will utilise the High-Intensity Muon Beam upgrades at PSI to study 2×10^9 muon stops per second and reach the target sensitivity of 10^{-16} on the branching fraction.

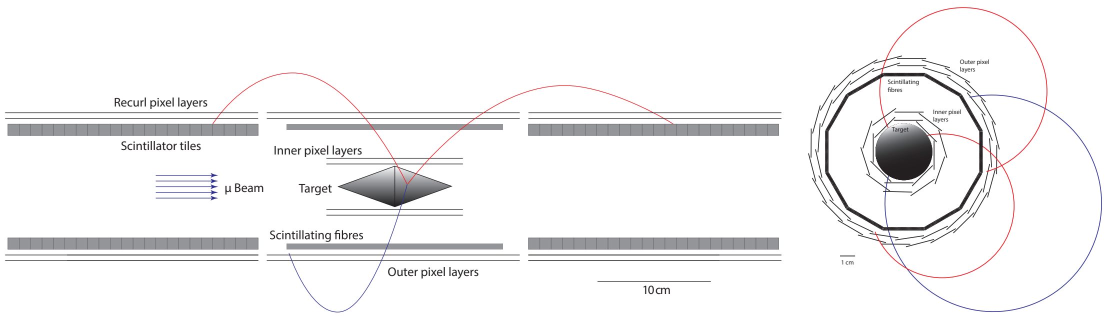
Mu3e uses an innovative design to obtain optimal momentum and vertexing resolution on low energy ($< m_\mu/2$) electrons. Four layers of High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) thinned to 50 μm surround the muon stopping target. Scintillating fibre and tile detectors providing sub-ns timing resolution. The detector is surrounded by a solenoid magnet providing a 1 T field; electrons from muon decays can pass through the



(a) (b)

Figure 1. Allowed regions (given at the scale m_W) in the 1a C_{ee}^{VRR} - C_{ee}^{SLL} plane, and the 1b C_{ee}^{VRR} - C_L^D plane. Existing (solid lines) and projected (dashed lines) are shown for $\mu^+ \to e^+\gamma$ (green), $\mu^+ \to e^+e^-e^+$ (red) and $\mu^- N \to e^- N$ (blue). Figures from [11].

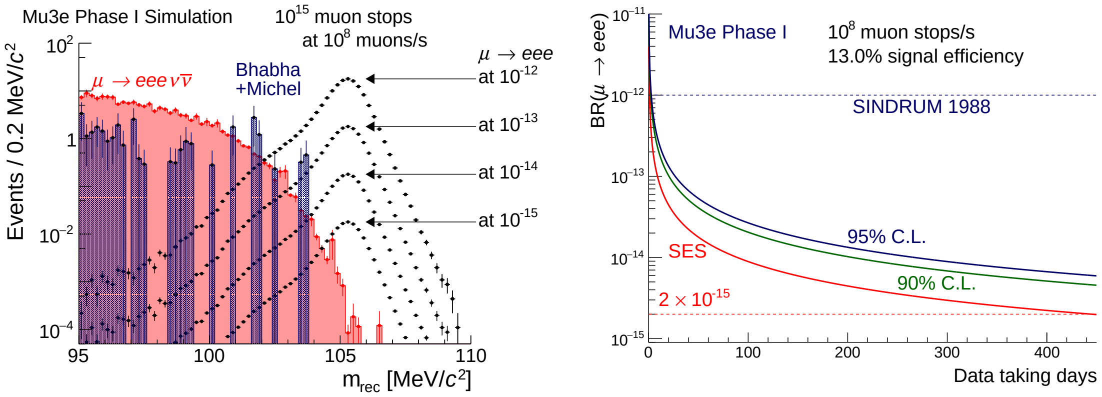
detector several times as they follow helical paths in this field. This significantly extends the lever-arm for measurement, and hence improves the momentum resolution. To increase the acceptance for such tracks, upstream and downstream *recurl stations*, consisting of two further layers of pixel sensors surrounding a layer of plastic scintillator tiles are installed. Figure 2 shows the layout of the Phase-1 Mu3e detector, with full details in [3].



(a) (b)

Figure 2. The layout of the Phase-1 Mu3e detector. Figures from [3].

Backgrounds are dominated by internal conversion ($\mu^+ \to e^+e^-e^+\nu_e\overline{\nu}_\mu$), and combinatorics (one or more Michel decays with an e^- arising primarily from Bhabha scattering or photon conversion). All backgrounds can be controlled using vertexing, kinematic are timing requirements to select three tracks from a common origin and no missing momentum (neutrinos). Mu3e will operate with a continuous, triggerless readout, with a fast online track reconstruction on GPUs used to select events containing three tracks consistent with a common vertex and reduce the high rate of combinatorics. The full offline tracking and signal selection will then deliver the optimal resolution, show in Figure 3a. Figure 3b shows the expected evolution of sensitivity with running time; existing limits will be superseded within days, and the target sensitivity reached with around 400 days of data taking with a muon stopping rate of 1×10^8 s^{-1}.



(a) (b)

Figure 3. 3a Simulation of the reconstructed vertex mass showing backgrounds and possible signal contributions. 3b the evolution of the Mu3e Phase 1 signal sensitivity with time. Figures from [3]

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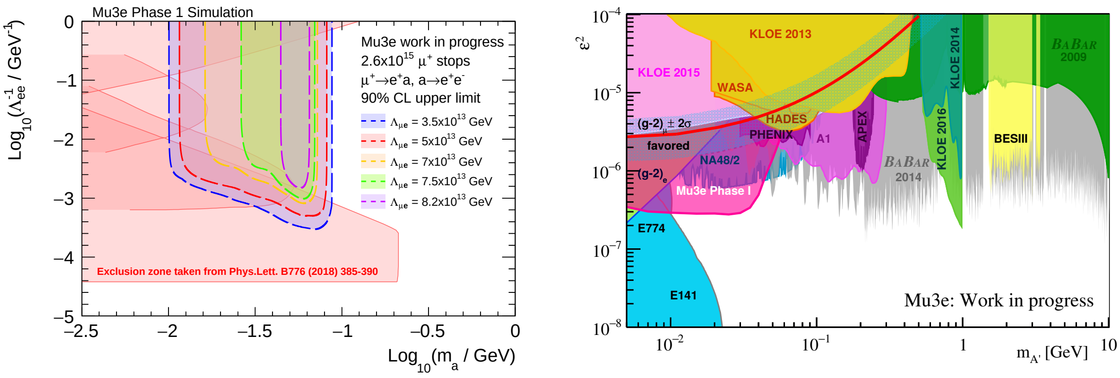
To reach the final target sensitivity of 10^{-16} on the branching fraction for $\mu^+ \to e^+e^-e^+$, a higher rate of muon stops is required. The High Intensity Muon Beam (HiMB) currently under study at PSI would deliver a stopping rate of 2×10^9 s^{-1}, but is not expected to be available before 2028. In order to deal with this higher stopping rate and resultant higher occupancy and rate of coincident backgrounds, upgrades to the Mu3e timing detectors are necessary, as well as possible improvements to the pixel sensors to improve time resolution, and extensions to the detector stations to increase the acceptance. Such upgrades are currently under study.

2 Other searches at Mu3e

As well as the main $\mu^+ \to e^+e^-e^+$ search, Mu3e can search for a number of other signature muon decays. For example, $\mu^+ \to e^+X$, where X denotes a neutral light particle that escapes the experiment undetected. An example of such a particle is the familon, a pseudo-Goldstone boson from an additional broken flavour symmetry [13]. The current strongest limits on familons are $\mathcal{B}(\mu^+ \to e^+X) < 2.6 \times 10^{-6}$ at 90% CL (massless X) [14], and for $13\,\text{MeV} < m_X < 80\,\text{MeV}$ with $\mathcal{B}(\mu^+ \to e^+X) < 9 \times 10^{-6}$ at 90% CL on average [15]. The characteristic signature is a mono-energetic positron whose energy is determined by the mass m_X of the undetected particle X. Such a signal would not pass the Mu3e online vertexing requirements, and therefore the analysis will be performed online. Although limited to the online track resolution, an unprecedented data-set of the order of 10^{15} μ^+ decays will allow Mu3e to test branching rations of 10^{-8}, an improvement in sensitivity by a factor of around 600 with respect the TWIST experiment [15]. Increased statistics in



(a) (b)

Figure 4. 4a: expected limits on long lived particles a in terms of the a mass and energy scale Λ. Adapted from [16]. 4b: expected limits on the dark photon kinetic mixing parameter ϵ at 90%CL. Adapted from [17].

Phase 2, along with possible improvements to online momentum resolution, will increase sensitivity further.

The Mu3e data-set will allow searches for muon decays to light, long-lived pseudoscalar particles that decay (to e^+e^-) within the first silicon layer. In this case the full resolution of offline tracking will be available, and a preliminary analysis shows the complementary of Mu3e to exclusions from beam dump experiments and electron $g-2$ (see Fig. 4a).

Finally, the Mu3e experiment will also search for resonances in $\mu^+ \to e^+e^-e^+\nu_e\overline{\nu}_\mu$. One example is dark photon A$'$ decays into e^+e^- pairs, where the dark photon is the messenger of a vector portal to the dark sector which interacts with Standard Model particles via kinetic mixing with the photon and Z boson, i.e. via coupling to the electro-magnetic current. If the dark photon is light enough, it can be radiated in muon decays: $\mu^+ \to \mathrm{A}'e^+\nu_e\overline{\nu}_\mu$. At low $m_{\mathrm{A}'}$, branching fractions of 5×10^{-9} at 90% CL can be investigated, while at higher $m_{\mathrm{A}'}$, branching fraction of 3×10^{-12} at 90% CL can be reached. These limits can be translated into limits on the kinetic mixing parameter ϵ, and the Phase 1 Mu3e experiment will extend current sensitivities (see Figure 4b).

3 Conclusion

The Mu3e experiment will search for the lepton-number-violating decay $\mu^+ \to e^+e^-e^+$. Using a two-phase approach and innovative design, it will extend the sensitivity to the branching ratio for this process to 10^{-16}, four orders of magnitude beyond current limits. In the context of the global programme covering $\mu^+ \to e^+e^-e^+$, $\mu^+ \to e^+\gamma$ and $\mu^-N \to e^-N$, Mu3e provides unique and complementary sensitivity to flavour-violating new physics.

The Mu3e experimental design also allows the search for a range of other processes, including familons, dark photons, axion-like particles and long-lived particles. In each case, Mu3e can extend existing sensitivities in the accessible range of parameter space for such models.

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