Prospects for Dark Photon Searches in the Mu3e Experiment

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The Mu3e experiment will search for the lepton-flavour violating decay $\mu^+ \to e^+e^-e^+$ with an unprecedented sensitivity of one in up to 10^{16} muon decays. The recorded data set will also be suited to search for e^+e^- resonances in $\mu^+ \to e^+e^-e^+\nu\nu$. In the following, a sensitivity study of the phase I Mu3e experiment to dark photons emitted in muon decays with prompt decay to e^+e^- pairs is presented.

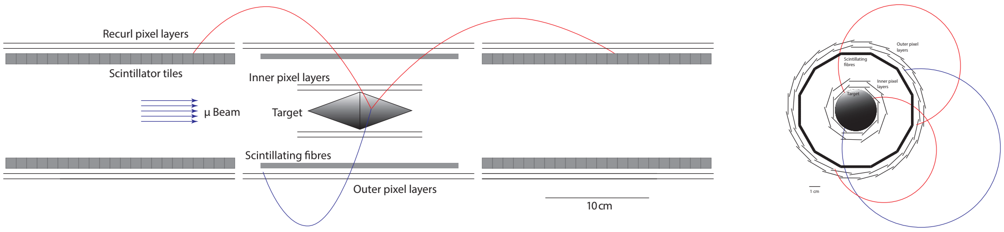
1 The Mu3e Experiment

In the Standard Model (SM), lepton flavour is conserved in all interactions. As there is no underlying global symmetry for this conservation, lepton flavour is violated in many extensions of the SM. While indeed the existance of lepton flavour violation (LFV) has already been proven by the observation of neutrino oscillations, in the charged lepton sector LFV has evaded observation so far.

The signature searched for by the Mu3e experiment [1] is the LFV decay $\mu^+ \to e^+e^-e^+$. Even if neutrino mixing is integrated in the SM, this decay is suppressed to unobservable branching fractions of $\mathcal{O}(10^{-54})$, and thus any observation of $\mu^+ \to e^+e^-e^+$ would be an unambiguous sign of physics beyond the SM.

The Mu3e experiment aims to search for $\mu^+ \to e^+e^-e^+$ down to branching fractions of 2×10^{-15} in the first and below 10^{-16} in the second and final phase of the experiment. The phase I experiment is currently being built at the Paul Scherrer Institute (PSI). It will be operated at muon stopping rates of $10^8\,\mu$/s at an existing beamline. The phase II experiment will require rates in excess of $10^9\,\mu$/s which will become available at the planned high intensity muon beamline at PSI. In the following, only the phase I experiment is discussed.

The main backgrounds in Mu3e are the rare muon decay $\mu^+ \to e^+e^-e^+\nu\nu$ as well as accidental combinations mainly of Bhabha scattering events with positrons from another Michel decay. The first can only be distinguished from signal by the missing energy that



(a) Longitudinal view.

(b) Transverse view.

Figure 1: Schematic of the phase I Mu3e detector [1] as seen (a) longitudinal and (b) transverse to the beamline with a potential $\mu^+ \to e^+e^-e^+$ signal decay.

is carried by the undetected neutrinos, and thus requires an excellent momentum measurement. The latter can be suppressed by precise tracking and timing measurements.

The Mu3e detector is constructed as a lightweight tracking detector in order to minimize uncertainties from multiple Coulomb scattering and to reduce the occurence of accidental background. A schematic of the Mu3e experiment is shown in Figure 1. The detector is placed in a 1 T solenoidal magnetic field. The incoming muons are stopped on the hollow target in the center of the experiment and decay at rest. The central tracking detector is constructed from four layers of ultra-thin pixel sensors with an additional scintillating fibre detector. In the large magnet bore, the electrons curl back to the detector and are measured again in the recurl stations up- and downstream of the central detector which are built from pixel sensors and scintillating tiles. Due to the increased lever arm, the momentum resolution of these recurling tracks is significantly improved. The detector is continuously read out. All events are reconstructed in the online filter farm but only events containing a potential $\mu \to eee$ candidate are kept for offline analysis.

It has been shown in simulation studies that the phase I Mu3e experiment can be operated free of background. A single-event sensitivity on the branching fraction of $\mathcal{B}(\mu^+ \to e^+e^-e^+) \approx 2 \times 10^{-15}$ can be achieved – pushing the current best limits obtained by SINDRUM [2] by three orders of magnitude.

2 Dark Photon Searches

The Mu3e experiment will record an unprecedented data set of $\mathcal{O}(10^{15})$ muon decays with three electrons in the final state in phase I. As there is a priori no selection on the kinematics of $\mu \to eee$ candidates during data taking, this data set can be exploited for other BSM searches, e.g. on e^+e^--resonances in $\mu^+ \to e^+e^-e^+\nu\nu$.

The sensitivity to such processes has been estimated with a dark photon model [3]. The dark photon A' interacts through kinetic mixing with the photon and Z boson and thus couples to the electro-magnetic current. In Mu3e, this decay can only be detected if the dark photon subsequently decays into an e^+e^- pair. The respective Feynman diagrams are shown in Figure 2.

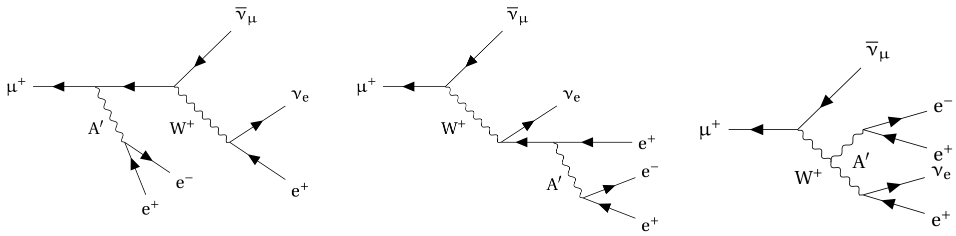


Figure 2: Feynman diagrams of dark photons A' emitted in muon decays $\mu^+ \to A'e^+\nu\nu$. The dark photons decay visibly into an electron-positron pair $A' \to e^+e^-$.

In the sensitivity study presented here, prompt $A' \to e^+e^-$ decays are investigated. Such a study has been performed previously [3] however with simplifications on the detector geometry and the expected backgrounds. In the following, signal events are generated with MadGraph5_aMC@NLO 2.4.3 [4] using the Lagrangian from [3], and the detector response is simulated with the full Geant4 [5] based Mu3e detector simulation. Signal events are simulated for dark photon masses $m_{A'}$ between 2 MeV and 80 MeV. Larger $m_{A'}$ in the reach of Mu3e are already excluded by existing experimental limits. The sources of background are the same as in the $\mu \to eee$ search. The same online and offline reconstruction is applied.

Selections on the quality of the track and vertex reconstruction as well as the distance of the reconstructed vertex to the target are applied which are especially effective against accidental background. The resulting spectra of the reconstructed invariant e^+e^- mass m_{ee} are shown in Figure 3. The distribution of signal events features a clear peak around the simulated dark photon mass $m_{A'}$ while the distribution of background events is smoothly falling towards large m_{ee}. The broader underlying distribution in the signal spectra is caused by the wrong e^+e^- combination that does not stem from the $A' \to e^+e^-$ decay. The sensitivity is enhanced by choosing the e^+e^- pair with the smaller m_{ee} for $m_{A'}$ up to 45 MeV, and the e^+e^- pair with the higher m_{ee} above.

The sensitivity is estimated by means of toy Monte Carlo studies for the full phase I of the Mu3e experiment. The expected upper limits on the branching fraction at 90 % CL range from $\mathcal{O}(10^{-9})$ at low $m_{A'}$ down to $\mathcal{O}(10^{-12})$ at high $m_{A'}$ (see Figure 4b). For $m_{A'} = 17$ MeV, the phase I Mu3e experiment is sensitive to branching fractions of a few 10^{-10}. These limits are translated to limits on the kinetic mixing parameter ϵ under the assumption that the dark photon decays exclusively to an e^+e^- pair. A comparison with current limits from dark photon searches is shown in Figure 4a.

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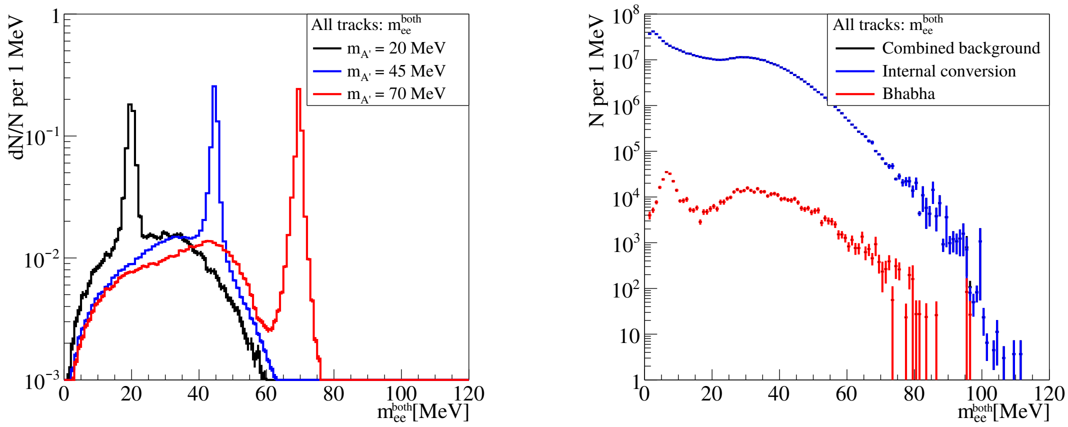
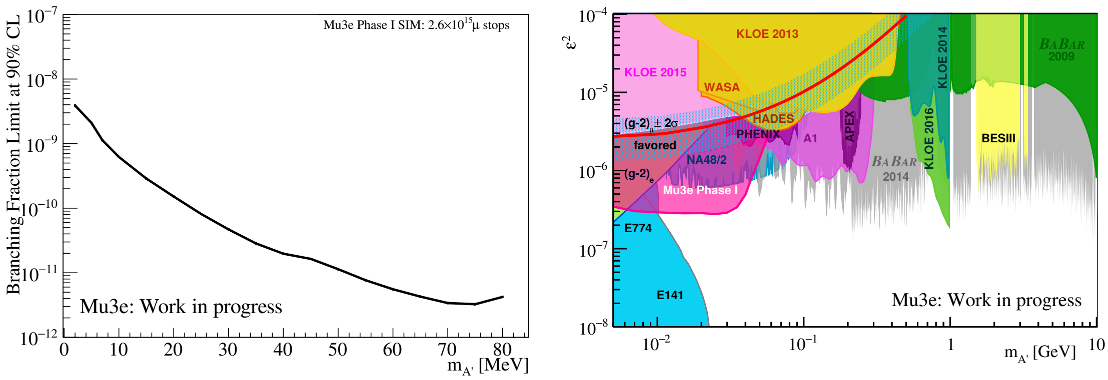


(a) Signal events from prompt dark photon decays with $m_{A'}$ of 20 MeV, 45 MeV and 70 MeV.

(b) Background events from rare muon decays and accidental combinations.

Figure 3: Spectra of the reconstructed invariant mass m_{ee} of both e^+e^- combinations for signal prompt dark photons decays and background from rare muon decays and accidental combinations. The signal spectra are drawn normalized to one. For the background spectra, 300 days of data taking at 10^8 μ/s as expected in phase I of Mu3e are assumed.



(a) Expected limits on the branching fraction of prompt dark photon decays at 90 % CL.

(b) Expected limits in the dark photon parameter space at 90 % CL assuming $\mathcal{B}(A' \to ee) = 1$. Adapted from [6].

Figure 4: Expected sensitivity on dark photons emitted in $\mu \to A' e \nu \nu$ with prompt decay $A' \to ee$ in the phase I Mu3e experiment.

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