A Novel Experiment Searching for the Lepton Flavor Violating Decay $\mu^+ \to e^+e^-e^+$

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Abstract. The proposed Mu3e experiment will search for the lepton flavor violating decay $\mu^+ \to e^+e^-e^+$, which is strongly ($< 10^{-50}$) suppressed in the standard model, but enhanced to observable levels in many models for new physics. In order to achieve the proposed branching ratio sensitivity of 10^{-16}, the detector has to have a high rate capability and a good background suppression, which in turn requires excellent momentum and vertex resolution. The Mu3e detector consists of two double layers of high voltage monolithic active pixel sensors (HV-MAPS) around a double cone target, trackers for the recurling electrons and two timing detector systems. To minimize multiple scattering of the low energetic decay electrons (< 53 MeV), an ultra-light design is proposed, using HV-MAPS thinned to 50 μm. With on-sensor pre-amplification, discrimination and zero-suppression, a separate read-out chip can be omitted, which further reduces the material budget.

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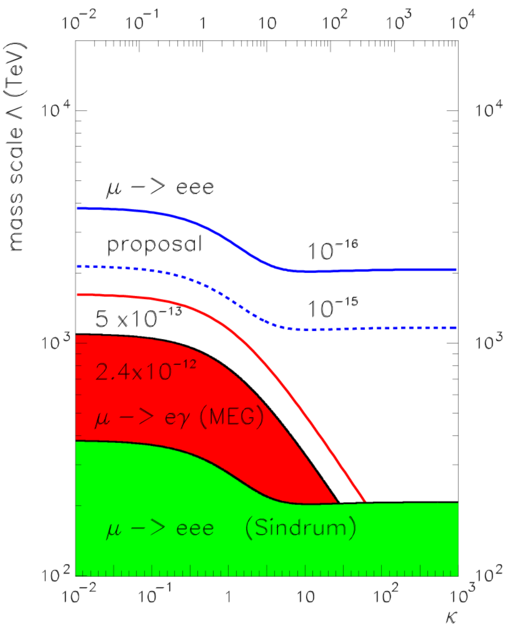

FIGURE 1. Experimental limits and projected limits on the LFV mass scale Λ as a function of parameter κ (see equation below), taken from [1], after a figure by A. de Gouvêa [2].

THEORY

In the Standard Model (SM) of elementary particle physics, the decay $\mu^+ \to e^+e^-e^+$ can occur via neutrino mixing. It is however suppressed to an unobservable low branching fraction of $< O(10^{-50})$. Any observation of $\mu^+ \to e^+e^-e^+$ would be a clear signal for new physics, and many models predict enhanced lepton flavor violation, e.g. super-symmetry, grand unified models, left-right symmetric models, models with an extended Higgs sector, large extra dimensions etc..LFV can proceed either via loops or at tree level. Introducing a common scale Λ and a relative strength κ between the dipole term and the 4-fermion contact interaction gives a simplified Lagrangian (1). The mass reach of the indirect search via the rare decay $\mu^+ \to e^+e^-e^+$ can be expressed as a function of the relative strength κ, see figure 1.

$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \overline{\mu_R} \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\overline{\mu_L}\gamma_\mu e_L)(\overline{e_L}\gamma^\mu e_L) \quad (1)$$

Background

The main sources of background are accidental coincidences of tracks from Michel decays with electron-positron pairs from Bhabha scattering, photon conversion etc. and the radiative decay with internal conversion $\mathrm{BR}(\mu^+ \to e^+e^-e^+\overline{\nu}_\mu \nu_e) = 3.4 \cdot 10^{-5}$. Suppressing the first requires excellent vertex and timing resolution, the second the best possible momentum resolution.

CHALLENGES

The Mu3e detector has to meet the following requirements:

- High rate capability (10^9 muon/s)
- Good vertex resolution (100 μm)
- Good time resolution (50 ps)
- Excellent momentum resolution (0.5 MeV/c)

The required excellent momentum resolution for the 12-53 MeV/c electrons leads to the additional requirement of extremely low material budget in the active detector volume as otherwise the electrons would be strongly scattered.

TRACKING

The concept of the Mu3e event reconstruction is to use the central part of the detector for track finding, vertexing and timing. The best resolution in presence of multiple scattering is obtained from tracks curling half turns in the B $\approx$ 1 T solenoidal field. Momentum resolutions < 0.3 MeV/c are possible over a wide phase space, making a three track mass resolution of $\approx$ 0.5 MeV/c^2 possible.

DETECTOR CONCEPT

Muon Beam

The Paul Scherrer Institute Switzerland has a very high intensity proton beam of 2.2 mA at 590 MeV/s. In phase I of the Mu3e experiment the up to few 10^8/s surface muons from target E will be used, see figure 2. In order to constrain the $\mu^+ \to e^+e^-e^+$ branching fraction to <10^{-16} or to make measurements of signal events a new muon beam line has to be established from the neutron source. Several 10^9 muons/s are possible in this scenario.

Long Tube Design

For a high acceptance of recurling particles, the detector needs to be long (1.8 m). However, only the central $\approx$ 36 cm needs to be thin, simplifying mechanics and allowing for precise timing in thick scintillator tiles, see figure 3.

FIGURE 2. The experimental hall at the Paul Scherrer Institute.

Target

A hollow double cone target made from 70 μm Aluminum with a large area for good vertex separation will be used. The proposed radius is 1 cm, with 10 cm overall length.

HV-MAPS

Using a commercial 180 nm CMOS process originating in the automotive industry, high voltage monolithic active pixel sensors (HV-MAPS) housing the pixel readout electronics inside a deep N-well can be implemented. The high voltage ($\approx$ 50 V) leads to a small depletion zone with fast charge collection. Most of the substrate is passive and the wafer can be thinned to < 50 μm. The HV-MAPS will have 1 x 2 cm^2 size for the vertex detector and 2 x 2 cm^2 for the central outer tracker and the recurl stations. The size of one pixel is 80 x 80 μm^2 and the number of pixels per sensor is either 28'800 or 57'600. The total number of pixels in the proposed Mu3e detector will be O($280 \cdot 10^6$).

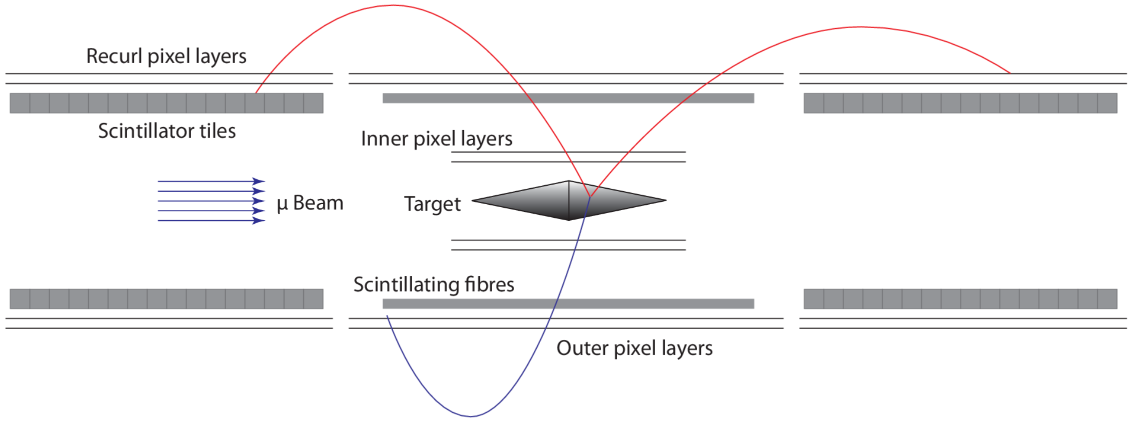

FIGURE 3. Schematic view of the Mu3e detector

Pixel Tracker

The silicon pixel detector is composed of a cylindrical double layer close to the target (vertex tracker), a central cylindrical double layer at ≈ 7.6 cm radius (central outer tracker) and cylindrical double layers both in the forward and the backward extension of the central outer tracker. The extensions precisely measure the position and thus momentum of the recurling electrons and are referred to as the recurl stations. The overall length of the silicon tracker stations is 180 cm. The sensors of the silicon tracker are High Voltage Active Pixel Sensors (HV-MAPS)[3, 4], which implies that the sensor pixels and the detector electronics are integrated into the same chip. As the sensors can be thinned to $\leq 50\,\mu$m without loss of signal amplitude and do not require an extra readout chip inside the active tracking volume, the radiation length can be kept very low ($8.2 \cdot 10^{-4} X_0$ per layer).

Timing Detectors

Two timing systems are important to separate the $>10^9$/s muon decays from each other and thus lower the chance of accidental background. The first timing detector is a fiber hodoscope around the target at $\approx$ 7 cm radius, just inside the central outer tracker. The required timing resolution is $\approx$1 ns. The central position allows to determine the time of all electrons reaching the central outer tracker (down to 12 MeV/c momentum). The fiber tracker consists of three layers of 250 μm thick fibers, read out at both ends. The second timing system is located inside the recurl stations and consists of scintillating tiles. The tile size is 1 x 1 x 0.5 cm^3 and allows for very accurate time measurement of 50 ps resolution. The vicinity of either timing system to a silicon pixel tracking layer simplifies the association of tracks and timing information.

Mechanics

FIGURE 4. Mechanical support structure for the vertex tracker

The sensors are supported by 25 μm Kapton strips with signal and power traces printed in aluminum, which is an extremely light and surprisingly sturdy mechanical unit as could be demonstrated with a full scale prototype of the vertex tracker, see figure 4.

Readout

The readout of the Mu3e experiment is continuous. A 20 MHz system clock defines readout frames, which are used to give timestamps to the data from the silicon tracking system. Zero-suppressed data from the silicon tracker sensors are sent in super-frames of 16 events to FPGAs (programmable devices) and then via optical data transmission to the counting room. The data from the timing systems are taken with a sampling chip (DRS5) and need additional signal processing before being sent to the counting room. In the counting room the data is received by a computing farm of 50 PCs equipped with graphical processing units (GPUs). With the help of the enormous computing power of the commercial GPUs the track reconstruction and momentum determination is done in real time. By this online filtering the events stored on disk will be kept at a moderate bandwidth below 100 MB/s. The events that could be signal $\mu^+ \to e^+e^-e^+$ events are kept for more precise off-line analysis.

SCHEDULE

In 2012 the Mu3e research proposal will be submitted to the Paul Scherrer Institute. The year 2013 will be used for the construction of the Mu3e detector, followed by the installation and commissioning phase at PSI in 2014. The first data taking period with up to a few 10^8 muons/s of beam will be in 2015. For the second data taking period a new beam line has to be constructed at PSI which is anticipated in the years 2016 and after. The second data taking period with up to 3 x 10^9 muon/s will then be in the years starting from 2017.

SUMMARY

The proposed Mu3e experiment will search for the lepton flavor violating decay $\mu^+ \to e^+e^-e^+$. A potential measurement of the decay $\mu^+ \to e^+e^-e^+$ would be a clear sign of new physics. To reach a branching ratio sensitivity of 10^{-16} more than 10^9 muon decays per second will be measured with a spectrometer in a B $\approx$ 1 T field. Combinatorial background will be suppressed by good time and vertex resolution, background from the radiative decay with internal conversion $\mu^+ \to e^+e^-e^+\overline{\nu}_\mu \nu_e$ will be suppressed by a very good momentum resolution of < 0.3 MeV/c per track. The Mu3e tracking detectors consists of a vertex tracker, a central tracker and recurl stations made of high voltage active pixel sensors (HV-MAPS), with a radiation length of $\approx 8.2 \cdot 10^{-4} X_0$ per layer to keep multiple scattering effects small. They are supplemented by a fiber hodoscope and a scintillating tile detector for precise timing. The Mu3e collaboration is preparing a detailed research proposal for December 2012 and plans to start taking data in 2015.

ACKNOWLEDGMENTS

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