PROCEEDINGS OF SCIENCE

Searching for Lepton Flavour Violation with the Mu3e Experiment

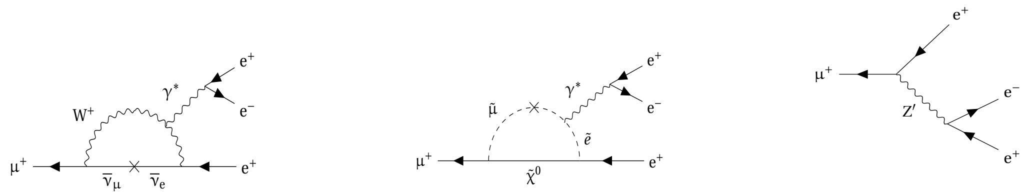
Ann-Kathrin Perrevoort* **for the Mu3e Collaboration**
Physics Institute, Heidelberg University
E-mail: perrevoort@physi.uni-heidelberg.de

The upcoming Mu3e experiment searches for the lepton flavour violating decay $\mu^+ \rightarrow e^+e^-e^+$ with the aim of a final sensitivity of one signal decay in 10^{16} observed muon decays, an improvement over the preceding SINDRUM experiment by four orders of magnitude. In the first phase, the experiment will be operated at an existing intense muon beam line at the Paul Scherrer Institute. With muon stopping rates of about $10^8 s^{-1}$, a single event sensitivity of 2×10^{-15} can be achieved. For the ultimate sensitivity, a new high intensity muon beam line is required.
In order to suppress background, the tracking detector is designed to measure low momentum electron and positron tracks with excellent precision by making use of very thin silicon pixel sensors. In addition, scintillating fibres and tiles provide precise timing information.
Currently, the collaboration is finalizing the detector design and preparing for construction and commissioning.

The 19th International Workshop on Neutrinos from Accelerators-NUFACT2017
25-30 September, 2017
Uppsala University, Uppsala, Sweden

*Speaker.

PoS(NuFact2017)105



(a) Neutrino mixing. (b) Supersymmetric particles in a loop diagram. (c) At tree level via a Z′.

Figure 1: The $\mu \to eee$ decay mediated via different processes.

1. Introduction

In the Standard Model of particle physics, lepton flavour is conserved. Yet with the observation of neutrino oscillations, it became evident that nature does not conserve lepton flavour, although an observation of lepton flavour violation for charged leptons is still missing. Extending the Standard Model to include neutrino mixing, lepton flavour violating muon decays are mediated in loop-diagrams (see figure 1a). With branching fractions of below 10^{-54}, these decays are far beyond experimental reach. Hence, any observation of charged lepton flavour violation would be a clear sign for physics beyond the Standard Model.

One channel to search for such phenomena is $\mu^+ \to e^+e^-e^+$. It can be mediated for instance in loop diagrams with super-symmetric particles (see figure 1b), or at tree-level for example via a Z′ (see figure 1c). The current limit set by the SINDRUM experiment is at $\text{BR} < 1.0 \times 10^{-12}$ at 90 % confidence level [1]. The upcoming Mu3e experiment plans for a sensitivity of about one signal event in 10^{15} muon decays in the first phase of the experiment, and ultimately one in 10^{16} muon decays in the second phase, thus improving on the existing limit by four orders of magnitude [2].

2. Signal and Background

The signature of the signal decay $\mu^+ \to e^+e^-e^+$ is defined by two positrons and one electron that emerge from a common vertex and appear coincidently in time. As muon decays at rest are observed, the energies of the three decay particles sum up to the muon rest mass and the sum of the momenta vanishes.

There are two types of background to $\mu \to eee$ searches. One is accidental background arising from the observation of positrons and electrons from multiple muon decays at a time, e. g. from the dominant Michel decay of the muon in combination with an electron-positron pair from Bhabha scattering or photon conversion. This background can be suppressed via constraints on the relative timing of the particles, the vertex and momentum.

The other type of background stems from the radiative muon decay $\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ in which the photon converts internally. It can be distinguished from the signal decay only by the missing energy resulting from the undetected pair of neutrinos. Thus, the momentum resolution of the detector ultimately limits the sensitivity of the experiment.

3. The Mu3e Experiment

The sensitivity goal defines the demands on the Mu3e experiment. On the one hand, a large number of muon decays needs to be observed. This requires not only a high muon stopping rate but also a detector and data acquisition that are capable to cope with such high rates. On the other hand, a very good vertex and time resolution and an excellent momentum resolution are required in order to operate free of background.

3.1 Muon Beam

At the Paul Scherrer Institute, secondary beams of muons are produced by an intense proton beam impinging on a carbon target. Mu3e will be located at the πE5 beamline where continuous surface muon beams of 28 MeV/c are available. The same beamline is also used by the MEGII experiment [3]. The compact muon beam line (CMBL) allows to operate both experiments alternately. The CMBL is already installed in the experimental area of Mu3e and it has been shown that the required rates of $10^8\,\mu s^{-1}$ can be provided.
The Paul Scherrer Institute is currently investigating a high intensity muon beamline with the aim to provide even higher muon beam rates. This would enable Mu3e to reach the final sensitivity goal in phase II.

3.2 Detector Concept

The geometry of the Mu3e detector is optimized for precise momentum measurements of the decay electrons and positrons. With a low momentum of maximally 53 MeV/c, the momentum resolution is dominated by multiple Coulomb scattering. Therefore, the material amount in the active detector volume needs to be kept at a minimum.
The momentum is measured via the bending radius of the particles in a magnetic field. Hence, the momentum resolution improves with the lever arm between two position measurements. The optimum momentum resolution is achieved after about a half turn because at this point uncertainties caused by multiple scattering cancel to first order. For this reason, the Mu3e experiment relies on measuring *recurling* tracks. A particle that has passed the outer detector layer will not cross further material and will eventually hit the outer layers again due to the helical trajectory. Between these two measurements lies about a half turn.
The geometry of the Mu3e detector is shown in figure 2. It has the shape of an elongated tube and is placed in a solenoidal magnetic field of 1 T. In order to increase the acceptance for recurling tracks, so-called recurl stations are installed both upstream and downstream of the central detector part. The incoming muons are stopped on a hollow double cone target made of 80 µm Mylar foil. The shape is chosen to spread the muon decays over a large surface in order to facilitate the suppression of accidental background.
The detector consists of a tracking detector made from thin silicon pixel sensors and a timing detector system built from scintillating fibres and tiles. The thinner fibres are placed in the central detector, the thicker tiles in the recurl stations as at this point the material amount is no longer crucial.
The detector has a total length of about 110 cm and a diameter of 18 cm.

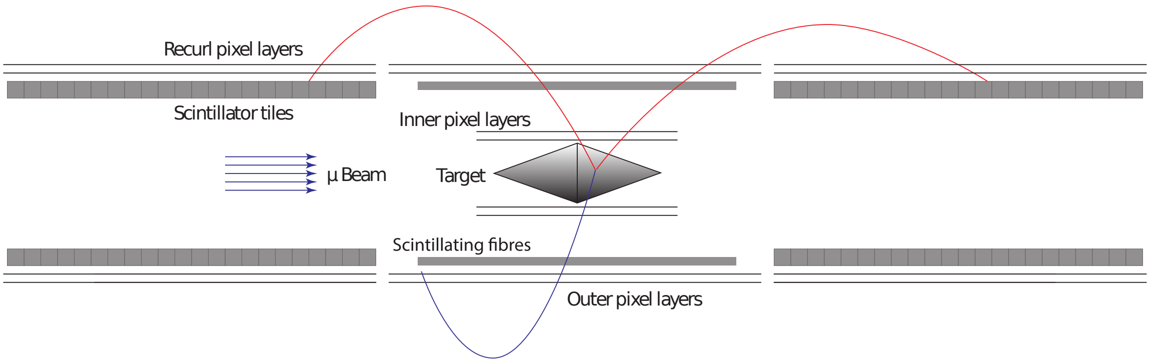


Figure 2: The Mu3e detector in the first phase of the experiment.

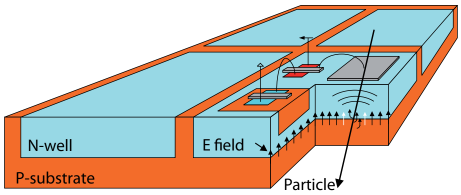


Figure 3: Schematic of an HV-MAPS [4].

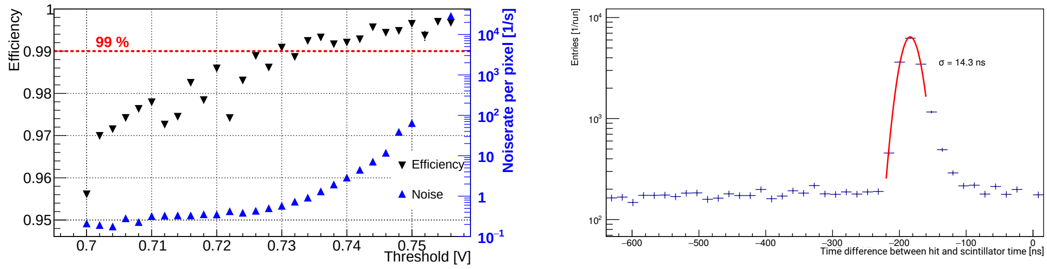
3.2.1 Pixel Tracking Detector

For the tracking detector, pixel sensors are chosen as they comprise not only an efficient and precise tracking but can also be produced very thin in the particular technology chosen for Mu3e. The target is surrounded by two layers of pixels sensors which allow for an accurate determination of the decay vertex. Two more layers of pixel sensors are placed at a larger radius enabling the momentum measurement. The recurl stations are equipped as well with a double-layer of pixel sensors with the same radii as the outer pixel layers in the central station.

Mu3e deploys High Voltage Monolithic Active Pixel Sensors (HV-MAPS) [4]. The pixels are implemented as deep n-wells in a p-doped substrate (see figure 3). By applying a reverse bias voltage of about 80 V, a depletion zone of a few 10 µm is formed. Ionising radiation that crosses the sensors creates electron-hole pairs. Due to the strong electric field in the depletion zone, the electrons are collected via drift. As particle detection is limited to a thin volume close to the surface of the sensor, HV-MAPS can be made very thin. For the final chip, a thickness of 50 µm is envisaged.

Furthermore, it is possible to implement transistors within the pixel and thus build readout electronics directly on the sensor chip. In current designs, signal amplification and shaping is performed in the pixel itself, whereas the digitisation is carried out in the periphery, a small part at the bottom edge of the sensor. The sensor has digital, zero-suppressed data output via a fast serial link of $1.25\,\mathrm{Gbit\,s^{-1}}$. For the final chip, a pixel size of $80 \times 80\,\mu\mathrm{m}^2$ is planned with an active area of $2 \times 2\,\mathrm{cm}^2$ per sensor.

The development of the sensors is currently in an advanced stage of prototyping. The MuPix7 prototype has an active area of $2.9 \times 3.2\,\mathrm{mm}^2$ with a pixel size of $103 \times 80\,\mu\mathrm{m}^2$. Despite the small size, this prototype comprises already all the functionalities required in the final chip. The sensor has been extensively tested in particle beams, yielding an efficiency well above 99 % and a timing



(a) Efficiency. (b) Timing resolution.

Figure 4: Efficiency and timing resolution obtained with the MuPix7 prototype in testbeam measurements.

resolution smaller than 20 ns [5] (see figure 4). Prototypes with a thickness of 50 µm are fully functional and perform equally well as thicker prototypes.

The latest prototype MuPix8 is the first large scale MuPix sensor with an area of $2 \times 1\,\mathrm{cm}^2$ and a pixel size of $80 \times 81\,\mu\mathrm{m}^2$. In order to improve the timing resolution, the sensor incorporates signal amplitude measurements allowing to correct for time-walk. The chip has been submitted on two different substrates: One with a resistivity of $20\,\Omega\,\mathrm{cm}$, the same as in the case of MuPix7, and one with a higher resistivity of $80\,\Omega\,\mathrm{cm}$. With the higher resistivity, the signal becomes twice as large, and thus the signal to noise ratio potentially improves. The characterisation of MuPix8 has just started. First measurements have shown that the chip is operational and indicate an overall excellent performance.

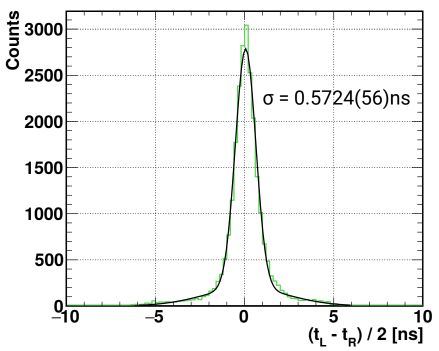
A further prototype, MuPix9, has recently been submitted. It is a small scale prototype comprising circuitries for slow control aiming at an improved system integration. In addition, a novel serial-powering scheme is investigated.

The pixel sensors produce heat with a power of about $250\,\mathrm{mW\,cm^{-2}}$ and thus need to be cooled. In order not to add too much material to the detector, this is performed with a flow of gaseous helium, both globally in the whole detector volume and locally through channels integrated in the mechanical support of the pixel sensors. Finite element simulations predict that the temperature stays below a maximum of 70 °C for power consumptions of up to $400\,\mathrm{mW\,cm^{-2}}$. The simulation results are verified in tests with a thermal mock-up of the detector. Although high flow velocities of $20\,\mathrm{m\,s^{-1}}$ are applied locally, measurements have proven that flow-induced vibrations stay below 10 µm and will thus not affect the track measurements.

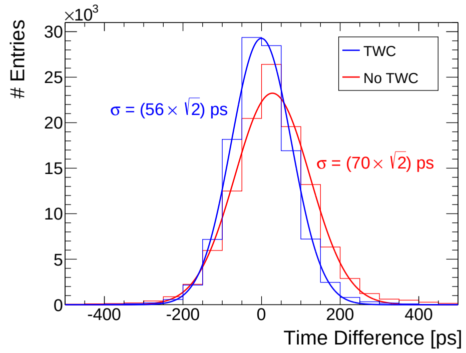
3.2.2 Scintillating Timing Detector

The accidental background can be efficiently suppressed by timing measurements. In the central detector part, a thin timing detector made of three layers of scintillating fibres is placed directly underneath the outer pixel layers. Likewise, the recurl stations are equipped with scintillating tiles. With the combination of timing information from the fibre and tile detector, suppression factors of about 100 can be achieved for backgrounds consisting of an electron-positron pair combined with a single uncorrelated positron. Backgrounds with three uncorrelated tracks are even more strongly suppressed.

The scintillation photons of the fibres are collected at both ends with a silicon photo-multiplier

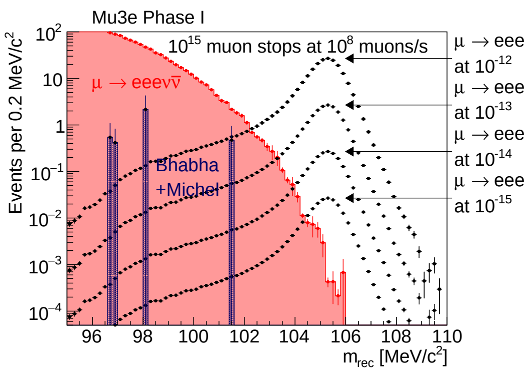


(a) Time difference between the signals at the two ends of a fibre for a prototype with three layers of square multiclad fibres.

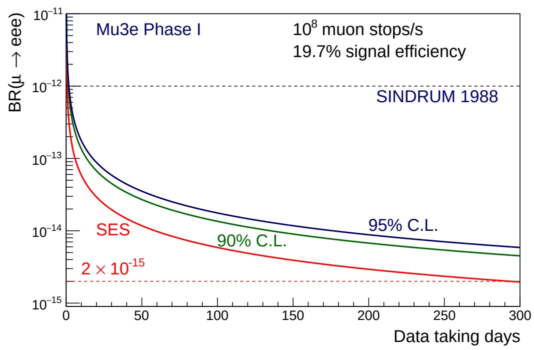


(b) Time difference between the signals of two successive tiles in the tile detector prototype. The time difference is shown with and without time-walk correction (TWC).

Figure 5: Timing resolution of prototypes for the scintillating timing detectors measured in test beam.



(a) Reconstructed muon mass for signal and background processes.



(b) Expected sensitivity to $\mu \to eee$.

Figure 6: Simulation results for the Mu3e experiment in the first phase.

(SiPM) column array as used by the LHCb experiment [6]. Currently, fibres with round and square cross sections are under investigation, and both fulfill the requirements for the use in Mu3e. For example, a fibre prototype consisting of three layers of 250 µm thick square multiclad fibres achieves timing resolutions of about 570 ps with an efficiency above 95 % (see figure 5).
Each of the scintillating tiles in the recurl stations has an individual SiPM. In both detector systems, the SiPMs are read out with an custom-designed time-to-digital converter ASIC called MuTRiG [7]. In the case of the tile detector, the MuTRiG operates in a two-threshold mode which allows for time-walk compensation. Prototypes of the tile detector yield time resolutions of 70 ps without and 56 ps with time walk correction at an efficiency of 99.7 %.

4. Sensitivity Studies

The sensitivity of Mu3e to the decay $\mu \to eee$ is estimated using a detailed Geant4 simulation

of the detector. In figure 6a, the reconstructed mass of three electrons is shown for the potential signal decay at various branching fractions as well as for background from internal conversion decays and accidental background. The accidental background is here represented by the dominant contribution of two positrons from Michel decays of which one undergoes Bhabha scattering and transfers enough momentum to the electron to be visible in the detector.
With an expected run time of 300 days of data taking in phase I at a muon stopping rate of $10^8 s^{-1}$, the expected single event sensitivity is found to be 2×10^{-15}, corresponding to a branching fraction limit of 4×10^{-15} at 90 % confidence level (see figure 6b).

5. Status

Prototypes of the various subdetectors have successfully proven the suitability of the chosen technologies for the usage in the Mu3e experiment. The outcome of the studies of MuPix8 and MuPix9 for instance will pave the way to the final pixel sensor chip.
The collaboration is currently finalizing the detector design and preparing for construction and commissioning of the experiment. Commissioning is foreseen for 2019 with potential first physics data taking in 2020.
In the first phase of Mu3e, a single event sensitivity of 2×10^{-15} is expected which poses a significant improvement on the limit to $\mu \to$ eee decays with respect to previous experiments. The final sensitivity of Mu3e will be reached in a second phase which is planned to be an upgrade of the phase I detector. The envisaged single event sensitivity of 1×10^{-16} is however only feasible when muon stopping rates of about $2 \times 10^9 s^{-1}$ become available.

Acknowledgments

The author acknowledges support by the Research Training Group ‘Particle Physics beyond the Standard Model’ (GRK 1940) of the Deutsche Forschungsgemeinschaft.

References

[1] U.Bellgardt et al., *Search for the Decay $\mu^+ \to e^+e^+e^-$*, *Nucl.Phys.* **B299** (1988) 1-6

[2] A.Blondel et al., *Research Proposal for an Experiment to Search for the Decay $\mu \to eee$*, (2013) [physics.ins-det/1301.6113]

[3] A.Baldini et al., *MEG Upgrade Proposal*, (2013) [physics.ins-det/1301.7225]

[4] I.Perić, *A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology*, in proceedings of *NSS/MIC 2007*, *Nucl.Instrum.Meth.* **A582** (2007) 876

[5] H.Augustin et al., *The MuPix System-on-Chip for the Mu3e Experiment*, in proceedings of *VCI 2016*, *Nucl. Instrum. Meth.* **A845** (2017) 194-198 [physics.ins-det/1603.08751]

[6] LHCb Collaboration, *LHCb Tracker Upgrade Technical Design Report*, *CERN-LHCC*-2014-**001** *LHCB-TDR*-**015** (2014)

[7] H.Chen et al. *MuTRiG: a mixed signal Silicon Photomultiplier readout ASIC with high timing resolution and gigabit data link*, in proceedings of *TWEPP 2016*, *JINST* **12** (2017) 01