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The Mu3e Experiment Searching for the Lepton Flavour Violating Decay $\mu^+ \rightarrow e^+e^+e^-$

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The Mu3e experiment is a novel experiment to search for the lepton flavour violating (LFV) decay $\mu^+ \rightarrow e^+e^+e^-$, with an ultimate sensitivity to a branching ratio of one in 2×10^{15} in phase I and one in 10^{16} muon decays for phase II. This is an improvement in sensitivity by four orders of magnitude compared to previous searches by the SINDRUM experiment. Since this decay is suppressed to unobservable levels in the Standard Model of particle physics, any measurement of this decay would be a clear sign of new physics. The experiment is currently under construction and will take place at the Paul Scherrer Institute in Switzerland. In order to achieve this number of muon decays, the Paul Scherrer Institute (PSI) is utilizing the worlds most intense proton beam, which is used to produce very intense $10^8\mu$/s at πE5 beamline (phase I) and a new high-intensity muon beamline HiMB is providing $10^9\mu$/s (phase II). To achieve the proposed sensitivity, the Mu3e experiment requires excellent vertex, timing and momentum resolutions. These are needed to reduce the main background processes, such as Internal conversion and accidental coincidences caused by two or more Michel decays. This paper will present an overview of the Mu3e experiment with performance of the phase I Mu3e detector, and how this sensitivity is achieved by high voltage monolithic active pixel sensors for high spatial resolution and scintillating fibres and tiles providing precise timing information at high particle rates.

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1. Motivation and Challenges

The Mu3e experiment is a new search for the decay of a muon to two positrons and one electron $\mu^+ \to e^+e^+e^-$, which if observed would be an evidence of charged lepton flavour violation. This experiment aims to improve the limits on the branching fraction set by the SINDRUM experiment of 10^{-12} to be 10^{-16} [1]. In order to achieve this, the Mu3e experiment will observe more than 10^{16} muon decays in order to investigate the existence of new physics beyond the Standard Model [2]. This experiment will utilize an intense muon beam at the Paul Scherrer Institute (PSI). The signal moun decay is defined by two positrons and one electron that emerge coincident in time from a common vertex; the invariant mass of the three decay particles equals the muon rest mass. The dominant sources of background events are where there is an internal conversion decay $\mu^+ \to e^-e^+e^+\nu_e\overline{\nu}_\mu$ or random combinations of backgrounds such as Michel decays with an electron and a positron. These backgrounds can be rejected by an excellent momentum resolution and time resolution as well as vertex resolution.

2. The Mu3e Detector Design

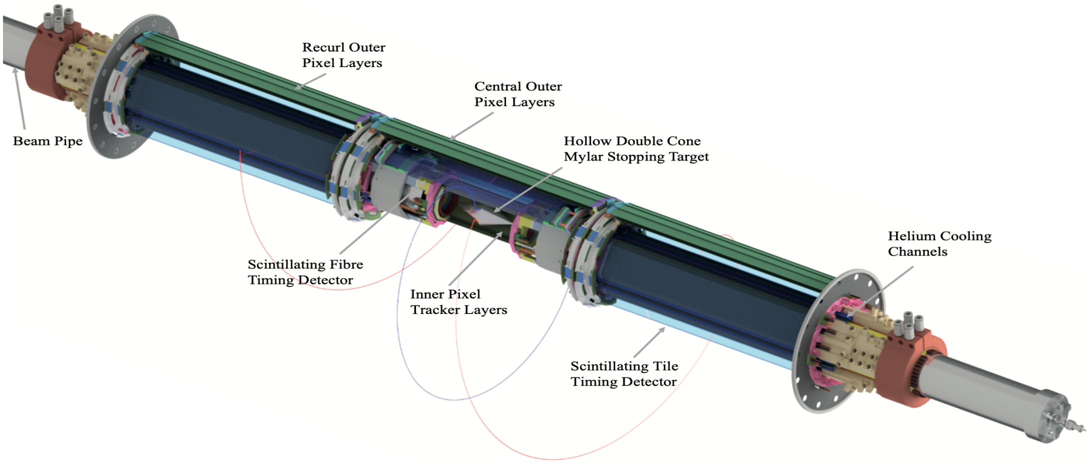

Figure 1: Illustration view of the active configuration of the Mu3e detector.

The Mu3e detector has a high geometrical acceptance of 80% and tracking efficiency of 95%, it is designed to accurately reconstruct the tracks and vertices of the muon decays with highly precise measurements of momentum and timing. Figure 1 illustrates the main components of the detector. The whole detector is placed in a solenoid magnetic field of 1 T so that the tracks of three electrons of the muon decay are bent. A continuous beam of muons of up to $10^8\mu^+$/s is stopped on a double-cone target surrounded by the pixel tracker layers, where muons decay at rest, and their products are subsequently detected by the pixels or timing detectors. It consists of two inner and outer silicon pixel layers in a central station and two upstream and downstream tracking stations. A significantly improved momentum resolution is observed for tracks with at least six pixel hits less than 0.45 MeV/c while 3 MeV/c for short tracks with four hits. Pixel sensors are built in a novel technology called High-Voltage Monolithic Active Pixel Sensor (HV-MAPS) based on a commercial 180 nm (HV-CMOS) process [3]. They should be thin to reduce the multiple Coulomb scattering, so it is crucial to minimize the material budget of layers. In addition, there are fibre and tile timing detectors to reject a combinatorial background and mis-reconstructed tracks with a resolution better than 300 and 70 ps, respectively.

3. Test-beam Data Acquisition System and Characterisation of HV-MAPS

A series of HV-MAPS prototypes (MuPix) have been designed and tested to figure out the feasibility of the HV-MAPS concepts for the Mu3e experiment. Therefore, it is very useful to test the detector components such as MuPix prototypes on a smaller scale before using in the final Mu3e experiment. PSI provides for this test-beam a mixed beam with momentum 270 MeV (pion, electrons and muons).

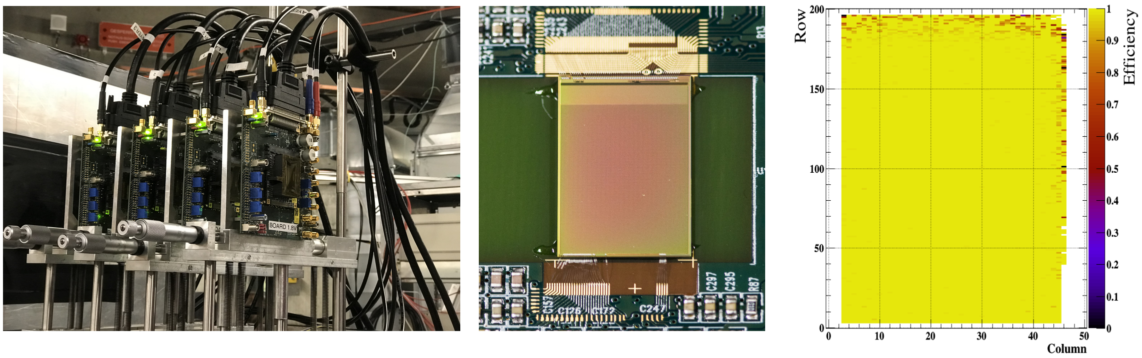

Figure 2: The MuPix Telescope (left) and MuPix8 chip (middle) used for the test-beam at PSI with the resultant measured hit efficiency of the sensor (right).

The 1×2 cm MuPix8 chip is the first large-area HV-MAPS chip, although not the final prototype in the MuPix series. This chip was used in the MuPix8 Telescope constructed of four layers of MuPix8 sensors and two classical trigger scintillators framing the pixel layers to study the timing performance. This test-beam experiment shows promising results with efficiencies $> 99.7\%$ as shown in figure 2 and noise rate per pixel is less than 20 Hz. In summary, this test-beam is an important step in establishing the HV-MAPS chip as a suitable technology for this challenging particle physics experiment.

References

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