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The Mu3e Experiment - Introduction and Current Status

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The Mu3e experiment searches for the lepton flavor violating decay $\mu^+ \to e^+e^-e^+$ aiming for a sensitivity of better than 1 in 10^{16} decays, a four order of magnitude improvement over the previous search by the SINDRUM experiment. This sensitivity is achieved by a novel experimental design based on thin monolithic active silicon pixel sensors and scintillating fibres and tiles.

Here, the Mu3e Experiment is introduced and its experimental challenges and resulting detector concept are discussed. The current state of the detector development with a focus on pixel sensor prototypes and their performance is presented.

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1. Introduction

In the original formulation of the standard model of particles physics (SM) lepton flavor is a conserved quantity. With the discovery of neutrino oscillations by Super-Kamiokande [1], SNO [2], KamLAND [3] and successive experiments it became clear that this is not the case in nature. In the current best understanding of elementary particle interactions flavor is directly broken in both the quark sector and in the neutral lepton sector. Charged lepton flavor violating (cLFV) decays, e.g. $\mu \to \mathrm{e}\gamma$ or $\mu \to \mathrm{eee}$, are induced via neutrino mixing in loop diagrams but are heavily suppressed in the SM to branching ratios below 10^{-54}. However, cLFV branching ratios can be significantly enhanced to experimentally accessible levels in many new physics models, e.g. grand unified theories [4, 5, 6] or SUSY [7]. This makes cLFV decays interesting as indirect searches for physics beyond the SM.

The Mu3e experiment [8] is a new experiment to be run at the Paul Scherrer Institut (PSI). It is designed to search for the decay $\mu^+ \to \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$ with a projected final sensitivity of 1 in 10^{16} decays. Previous searches by the SINDRUM experiment did not see any signal events and set a limit on $\mathrm{BR}(\mu^+ \to \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+)$ of 1×10^{-12} at 90 % CL [9]. The Mu3e experiment would allow an improvement of four orders of magnitude in braching ratio sensitivity compared with the previous search.

In the following sections the overall design concept of the experiment and its underlying challenges will be discussed. A special focus is given to the design and performance of silicon pixel sensor prototypes for the the tracker component of the detector.

2. Experimental Design

The basic concept of the Mu3e experiment is as follows. A high number of low-energy muons are stopped on a target surface where they decay at rest. The resulting decay electrons propagate in a homogeneous magnetic field and their trajectories are measured by a particle tracker. Signal decays are selected by looking for three reconstructed electrons that originate from a common decay vertex with the appropriate momentum and four-momenta, i.e. $(\sum P_i)^2 = m_\mu^2$ and $\sum \vec{p}_i = 0$.

To reach the projected sensitivity of 1 in 1×10^{16} decays in a reasonable time frame, a muon rate in excess of $1 \times 10^9\ \mu/\mathrm{s}$ is required. In addition, the muon beam needs to be low energetic and continuous to suppress combinatorial background from pile-up and to be able to stop the muons without a massive target. Existing beamlines at the PSI provide positive muon beams with a momentum of 28 MeV/c and rates of up to $1 \times 10^8\ \mu^+/\mathrm{s}$.

Since the electrons originate from muon decays at rest, their momentum is limited to half the muon mass of $m_\mu/2 \approx 52.8\,\mathrm{MeV/c}$. These low momentum particles will show a high amount of multiple scattering in the detector material and the momentum resolution will be limited not by the position resolution of the tracker but by the induced multiple scattering [10].

To satisfy these requirements, a very low mass detetor with a high momentum resolution and precise timing is needed. The detector geometry should be optimized for measuring low-momentum tracks in a multiple scattering dominated environment. At the same time the detector technology must be capable of handling high rates.

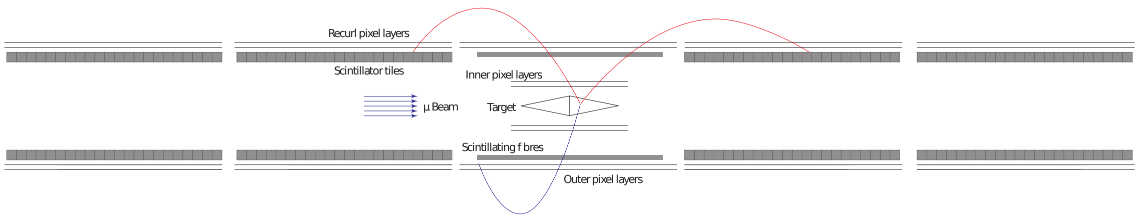

Figure 1: Schematic view of the Mu3e detector along the muon beam direction.

Figure 1 shows a schematic of the Mu3e detector. The incoming muon beam is stopped on an extended double hollow cone target. The extended target spreads out the muon decay vertices over a large area to reduce combinatoric background. Its thickness is optimized to provide a uniform distribution of the decay vertices with a high stopping power. The decay electrons propagate in a 1 T magnetic field and are measured in the central part of the detector by four layers of silicon pixel sensors arranged in a barrel-like geometry around the target. The two innermost layers are located as close as possible to the target to allow for a very precise measurement of the vertex position. After passing the central part of the detector, the electrons are allowed to propagate freely. Due to their low momentum, they will curl back and their positions are measured again by two additional layers of silicon pixels sensors located up- and downstream of the target. Two of these recurl stations are located on each side of the central station to increase the acceptance. Each of the five stations has a length of 36 cm and an outer radius of 7 cm.

Additional timing measurements are provided by thin layers of scintillating fibres in the central part of the detector and by thick scintillating tiles below the recurl stations. To separate the decays a timing resolutiong of < 1 ns for the fibre tracker and < 100 ps for the fibre detector is required.

3. Pixel Sensor Prototypes

The silicon pixel sensors for the Mu3e experiment must fulfill the following requirements: high rate capabilities, continuous readout and low material budget. All these can be fullfilled by so-called high voltage monolithic active pixel sensors (HV-MAPS) developed by Perić [11].

HV-MAPS are a novel silicon sensor technology that combines the active sensor diode and the analog and digital readout electronics on a single chip that is produced with a commercial CMOS process. This removes the need for an additional readout chip and the associated bump-bonding procedure used in hybrid sensors commonly found in current silicon trackers. The thickness of the CMOS electronics in combination with a thin depletion zone of 9–11 μm allows the sensor chip to be thinned below 50 μm. An applied high voltage of ~ 70 V enables fast charge collection via drift. This technology enable the production of fast and thin pixels sensors required for the Mu3e experiment.

3.1 MuPix4 Prototype

The MuPix4 prototype is an implementation of the HV-MAPS concept for the Mu3e experiment. It is a small scale prototype with a pixel size of 92 μm × 80 μm and a total number of 32 × 40 pixels. The chip has an active area of approx. $2.944\,\text{mm} \times 3.2\,\text{mm} = 9.42\,\text{mm}^2$ corresponding to approx. 95 % of the total area. The remaining inactive 5 % of the area are located in a small strip on one side and contain part of the readout electronics.

The prototype provides a zero-suppressed digital readout with timestamps. It uses binary hit information, i.e. only the hit position and its time without amplitude information is registered. Each pixel has a dedicated comparator with a global threshold and additional local threshold tuning DACs to correct for pixel-to-pixel variations in the signal amplitude. This prototype already integrates the full analog electronics and part of the digital electronics. Particle hits are registered by each pixel and read out asynchronously using an additional readout FPGA. The timing resolution is determined by the timestamp binsize of the stored hits and not by the readout frequency of the chip.

3.2 Testbeam Measurements

The MuPix4 prototype was tested extensively with radioactive sources and various light sources in the laboratory where it showed a good performance within the expected parameters. Additional test were performed using a 1–6 GeV/c electron beam and the Aconite EUDET beam telescope [12, 13] at the DESY testbeam facilities. In the following some results from these testbeam measurements are discussed.

The prototype was placed as a device-under-test (DUT) inside the beam telescope and was integrated into the telescope DAQ system EUDAQ [14]. The resulting data was analysed using the EUTelescope [15] analysis software.

Electron tracks are reconstructed using only the hit information from the telescope. The track position is then extrapolated to the DUT and matched to a corresponding hit regisqtered by the prototype. The mean of the resulting residual distribution is usually well below 10 μm indicating a accurate alignment of the telescope and the DUT.

The single hit efficiency is determined from the ratio of tracks with and without an associated hit on the DUT. The efficiency map over the whole pixel matrix for one configuration of threshold and high voltage is shown on the left side of figure 2. The overall efficiency is well above 99 % for most of the pixel matrix without any indications of systematic local variations. However, the measurement is limited by the low number of entries as indicated by the statistical error bars in the projections along the columns and rows and by the white pixels without any registered tracks. Minor inefficiencies are visible around column 30 where the efficiency drops to $\sim 80\,\%$. These can be attributed to a non-optimized per pixel threshold tune. This is expected to be resolved in the next measurements.

The right side of figure 2 shows the global efficiency averaged over the whole pixel matrix as a function of the global threshold. The efficiency drops as the threshold is increased due to statistical fluctuations of the hit signal, i.e. a fraction of the hit signals is below the given threshold and are not registered as hits in the sensor logic. For a given threshold the efficiency increases for a higher voltage since the signal amplitude increases with the applied voltage.

For the lowest threshold the global efficiency is $> 99.5\,\%$ but from the right side of figure 2 it is clear that the measured efficiency plateau is very small. For lower thresholds the setup seemed to run into noise problems.

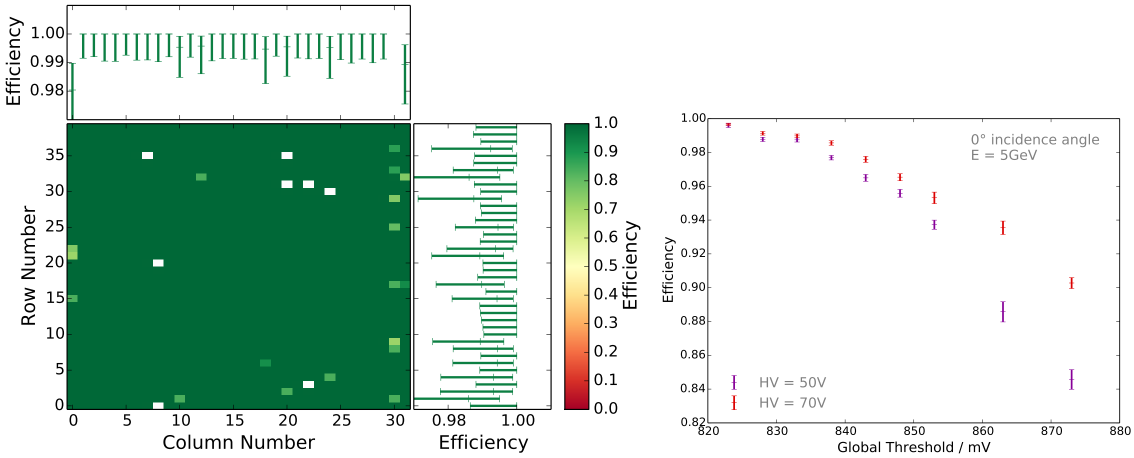

Figure 2: On the left: efficiency map for a single configurations. On the right: global efficiencies for different configurations.

The timing resolution for the hit timestamps averaged over the whole pixel matrix was measured to be $< 17\,\mathrm{ns}$.

3.3 Future Sensor Prototypes

The measurements with the MuPix4 prototypes are very promising and show that the HV-MAPS concept fulfills the requirements of the Mu3e experiment. The current prototypes are however not yet usable as the pixel sensors for the experiment. The chip needs to be scaled up to the full sensor size of $2\,\mathrm{cm} \times 2\,\mathrm{cm}$ and the readout logic, which is partially implemented on the readout FPGA, needs to be moved to the chip itself. The next two versions, MuPix6 and MuPix7, of the prototypes are already available, but both are still small-scale prototypes. MuPix6 is similar to the MuPix4 prototype but adds an additional amplifier to optimize the analog performance of the chip. MuPix7 integrates the full readout electronics on the chip.

4. Summary

Mu3e is a new experiment to search for the cLFV decay $\mu^+ \to e^+e^-e^+$ with a projected sensitivity of 1 in 10^{16} decays. The detector is based on silicon pixel tracker using thin HV-MAPS sensors with additional scintillating fibres and tiles for precise timing measurement. The detector is optimized for high-rate, low-momentum electrons. The Mu3e experiment is currently in the research and development phase. Prototypes of all detector components exists and show the required performance. Testbeam measurements with MuPix4 pixel sensor prototype showed a single-hit efficiency of 99.5 %, a high uniformity over the whole pixel matrix and a timing resolution of $< 17\,\mathrm{ns}$.

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