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A Tracker for the Mu3e Experiment based on High Voltage Monolithic Active Pixel Sensors

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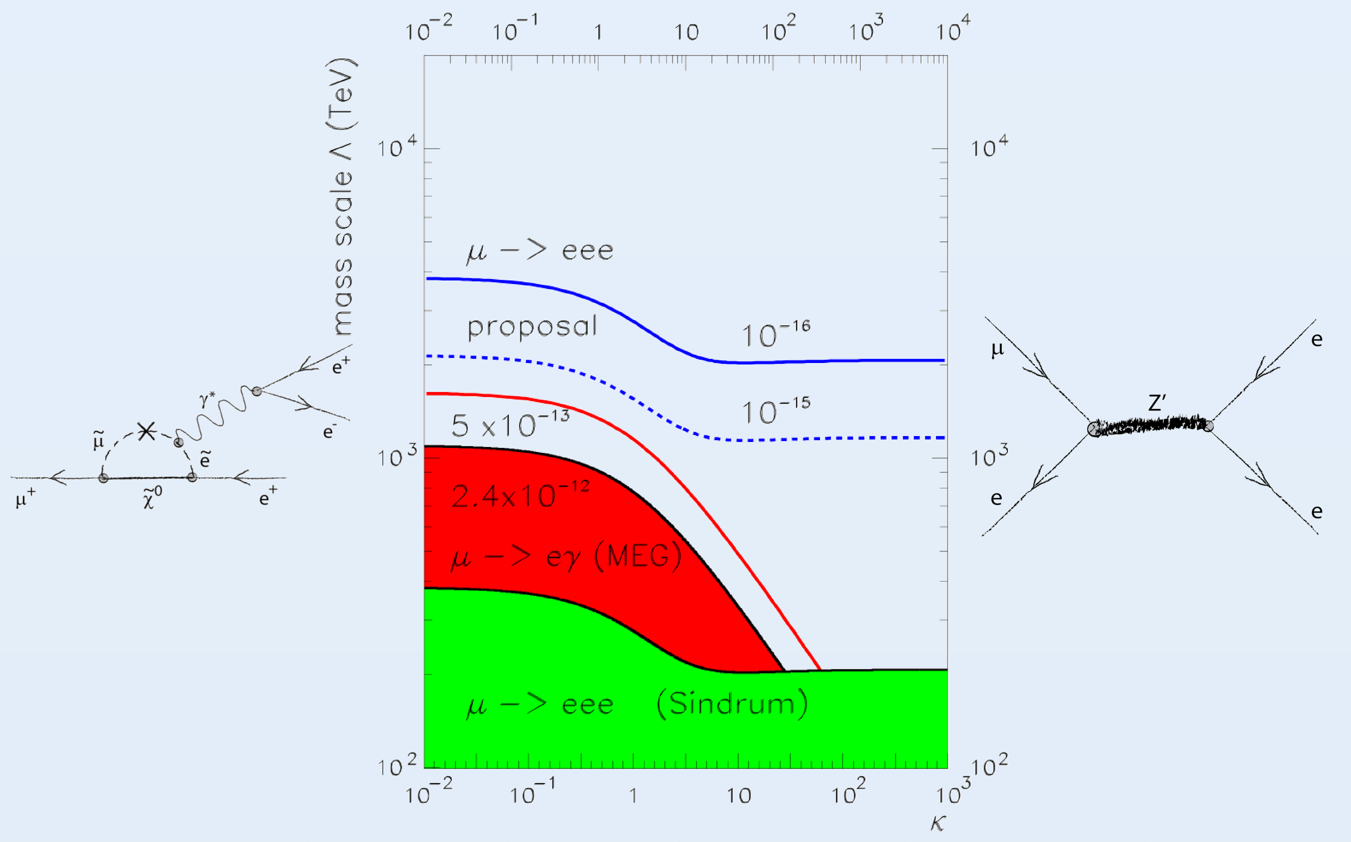
Abstract:

The proposed Mu3e experiment will study the lepton flavor violating decay μ→eee 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 target double cone. 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.

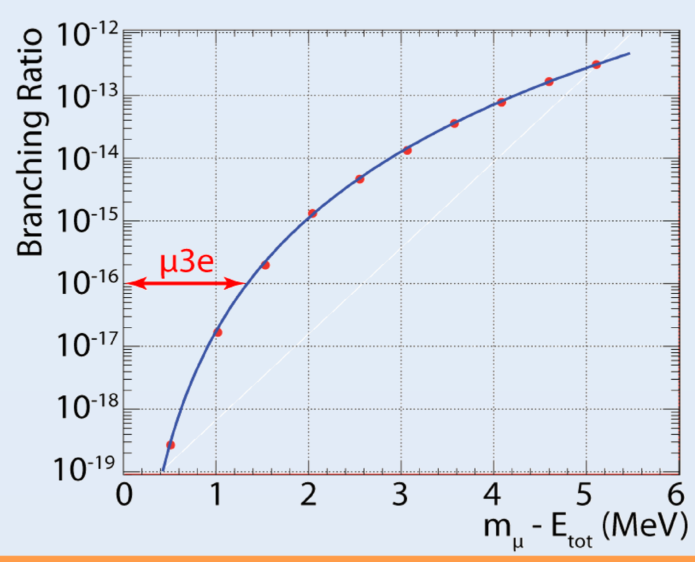
Theory:

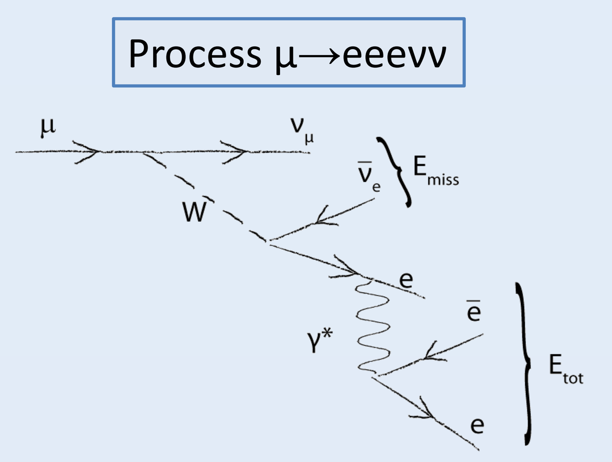
In the Standard Model (SM) of elementary particle physics, the decay μ→eee can occur via lepton mixing. It is however suppressed to an unobservable low branching fraction of O(10^{-50}). Any observation of μ→eee would be a clear signal for new physics, and many models predict enhanced lepton flavor violation, 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:

$$L_{LFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} A_R \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L)(\bar{e}_L \gamma^\mu e_L)$$



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 μ→eeevv (BR 3.4 × 10^{-5}). The first requires excellent vertex and timing resolution, the second the best possible momentum resolution.



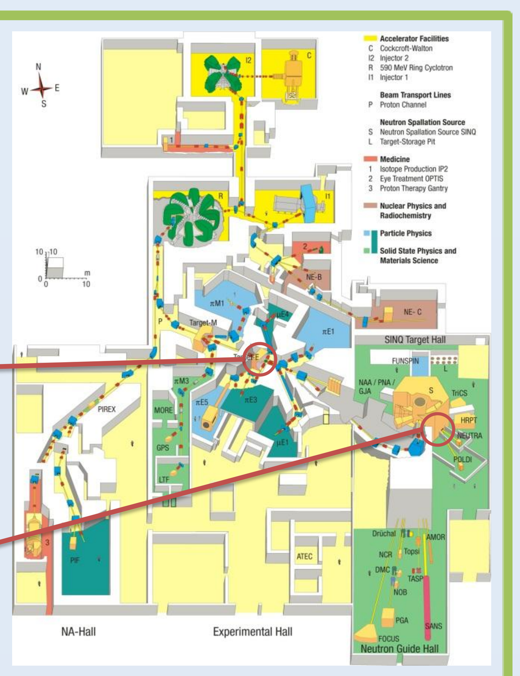


Muon beam at PSI:

Paul Scherrer Institute Switzerland:

- 2.2 mA of 590 MeV/c protons
- Future: up to 3 mA (1.8 MW)

- Phase I:
  - Surface muons from target E
  - Up to a few 10^8 µ/s
- Phase II:
  - New beam line at the neutron source
  - Several 10^9 µ/s possible



Outlook:

2012 Letter of intent to PSI, Tracker prototype, technical design

2013 Technical design report, detector construction

2014 Installation and commissioning at PSI

2015 Data taking at up to a few 10^8 µ/s

2016+ Construction of new beam-line at PSI

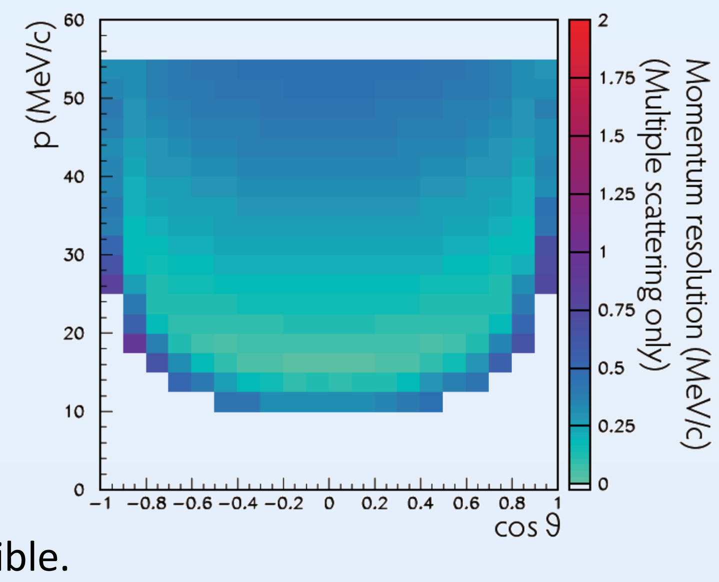
2017++ Data taking at up to 3 ·10^9 µ/s

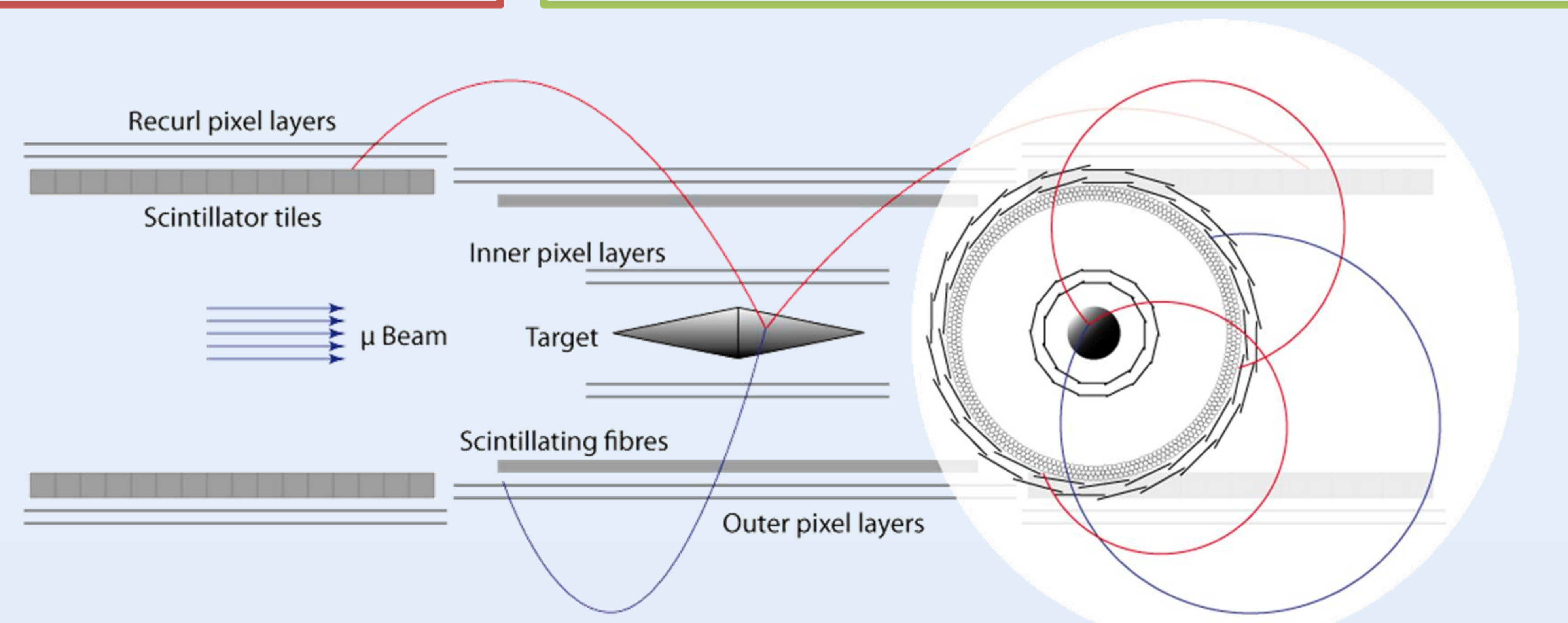
Challenges:

- **High rates**
- **Excellent momentum resolution**
- **Good vertex resolution**
- **Good timing resolution**
- **Extremely low material budget**

Tracking:

Use 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 ~ 1 T field. Momentum resolutions < 0.3 MeV/c are possible over a wide kinematic range, making a three track mass resolution of ~ 0.5 MeV/c² possible.





Detector Concept:

Long Tube Design:

For a high acceptance of recurling particles, the detector needs to be long (> 1 m). However, only the central ~ 25 cm needs to be thin, simplifying mechanics and allowing for precise timing in thick scintillator tiles.

Target:

Double cone target made from 70 µm Aluminum – large area for good vertex separation.

Mechanics:

Sensors supported on 25 µm Kapton™ strips with signal and power traces printed in Aluminum – extremely light and surprisingly sturdy.

Timing:

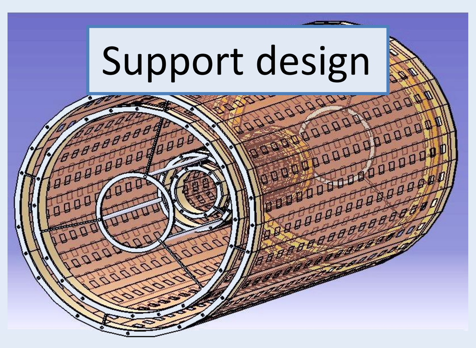
250 µm scintillating fibers in the central region for first timing measurement. Precise timing from ~ 1 cm thick scintillating tiles in the recurl tubes

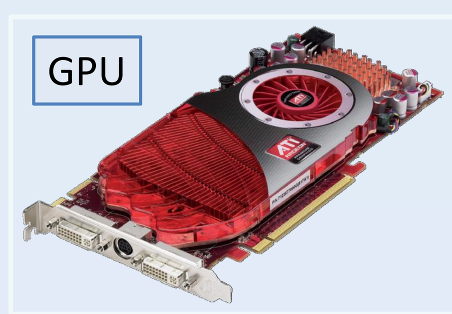
Pixel Sensor:

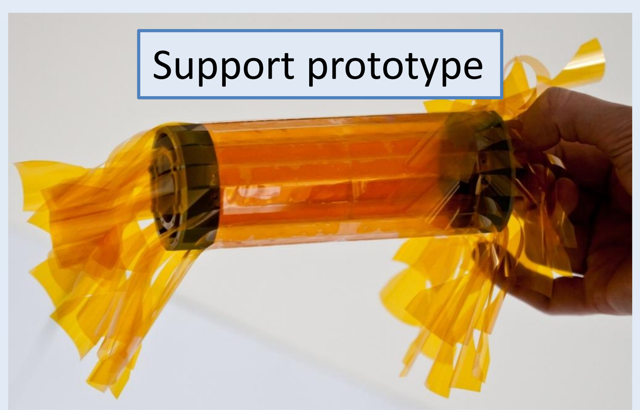
- 80 x 80 µm² pixels sensors cut to 2 × 6 or 1 × 6 cm²
- Thinned to ≤ 50 µm
  →thickness of 4 pixel layers ~ 2 ‰ X_0
- Total ~ 200 Million pixels
- Cooled by helium atmosphere
- Maximum readout frequency ~ 20 MHz
- Binary readout

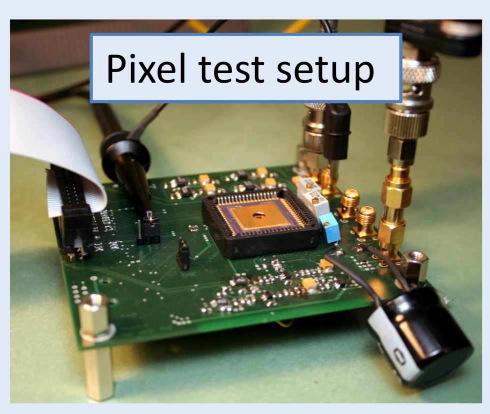
Readout:

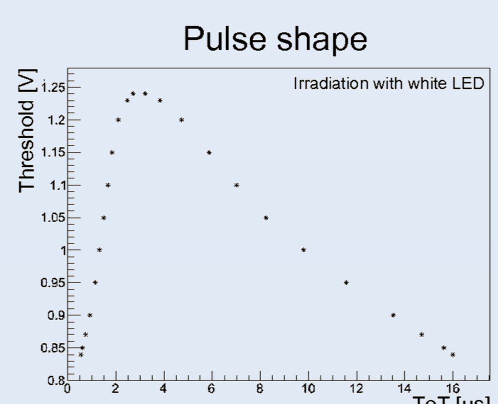
- Triggerless readout with ~ 100 Gbyte/s to an online farm.
- Fast track finding and reconstruction on GPUs (> 10^9 tracks/s).
- Reduction to ~ 100 Mbyte/s for online storage and analysis.











HV-MAPS:

Using a commercial 180 nm CMOS process originating in the automotive industry, high voltage monolithic active pixel sensors housing the pixel electronics inside a deep N-well can be implemented. The high voltage (~ 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.

Ref.: I. Peric, A novel monolithic pixelated particle detector implemented in high-voltage CMOS technology Nucl.Instrum.Meth., 2007, A582, 876