Pixel Sensors for Mu3e

The MuPix Prototypes and Readout

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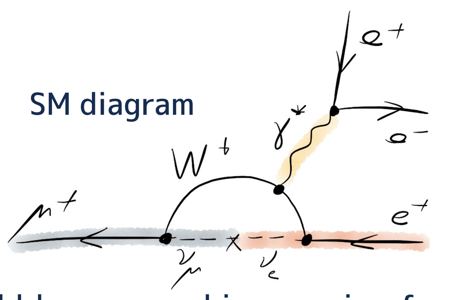
Abstract

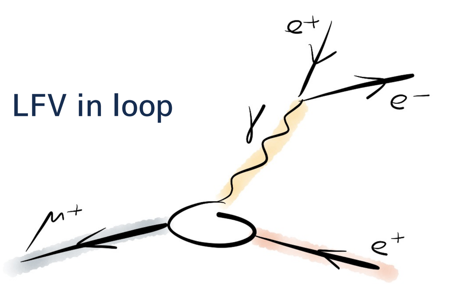
The Mu3e experiment - searching for the lepton-flavour violating decay of the muon into three electrons at an unprecedented sensitivity of better than 1 in 10^{16} decays - is based on a pixel tracking detector. The sensors are High-Voltage Monolithic Active Pixel Sensors, a technology which allows for very fast and thin detectors. This makes it an ideal fit for the high rate and low-momentum environment of Mu3e, where momentum resolution is dominated by multiple Coulomb scattering. So far, a range of prototypes of these sensors has been successfully tested. The recently submitted prototype MuPix7 for the first time features a readout control state machine on-chip. This allows it to send zero-suppressed hit data to an FPGA via an 1.25 Gbit/s LVDS link.

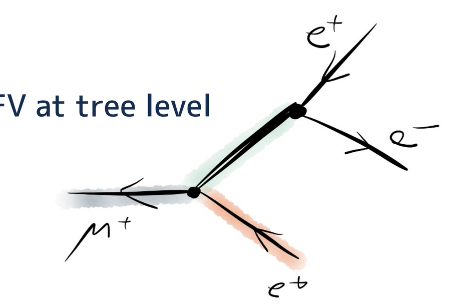
Theory

The lepton-flavour violating (LFV) decay $\mu\to eee$ can occur in the Standard Model (SM) via neutrino mixing, but is heavily suppressed to an experimentally unobservable branching ratio of BR < 10^{-54}.



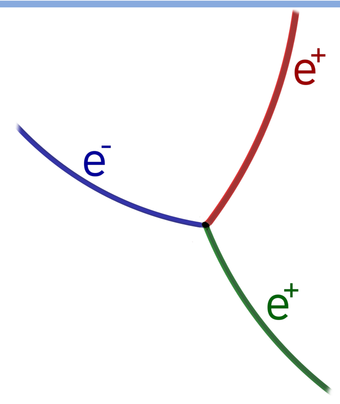
Consequently, any observation of $\mu\to eee$ would be an unambiguous sign for new physics, and indeed many models beyond the SM predict enhanced LFV mediated by virtual particles, e.g. supersymmetry, grand unified theories, left-right symmetric models. An high intensity experiment searching for $\mu\to eee$ can probe mass scales far beyond the reach of direct searches.





Signal $\mu^+\to e^+e^+e^-$

The signal in Mu3e are two positrons and one electron with rather low momenta of < 53 MeV each. The three particles stem from a single decay vertex and are coincident in time. Their energies sum up to the muon rest mass (m_μ = 105.66MeV) whereas their total momentum vanishes.



Goal: Test $\mu\to eee$ with a sensitivity of BR<10^{-16}

Requirements

Detector

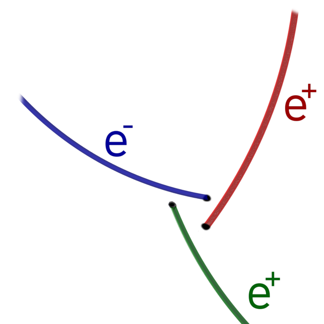
- High muon rates > $10^9\mu$/s
- Excellent momentum resolution ~ 0.5 MeV
- Great vertex resolution ~ 200μm
- Good timing resolution < 100ps
- Extremely low material budget (low multiple scattering)

Tracking detector

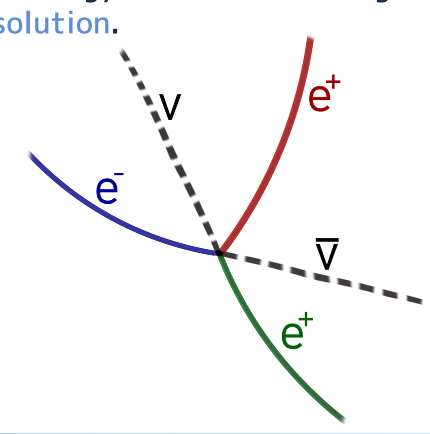
- Spatial resolution ~ 100μm
- Timing resolution ~ 20ns
- Low material budget of 1‰ per layer
- High granularity
- High efficiency > 99%
- Good signal-to-noise ratio > 20
- Readout frequency ~ 20 MHz

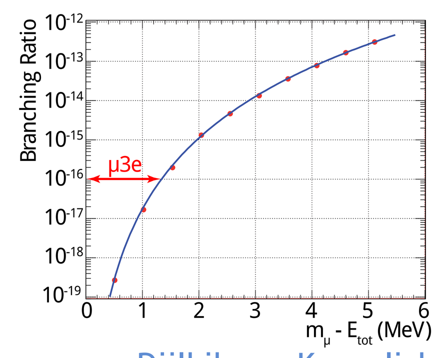
Background

Accidental coincidences of ordinary Michel decays and Bhabha scattering or photon conversion contribute to the combinatorial background. This source of background becomes more probable with higher beam intensities and can be most efficiently suppressed by a good vertex and timing resolution.



Furthermore, the SM internal conversion decay $\mu\to eee\nu\nu$ (BR = $3.4\cdot 10^{-5}$) is another source of background. The three charged leptons share a common vertex and are coincident in time. Only the neutrinos carry away part of the energy so that this background can be suppressed by a good momentum resolution.





Djilkibaev, Konoplich
Phys.Rev.D79:073004 (2009)

Detector Design

Long tube

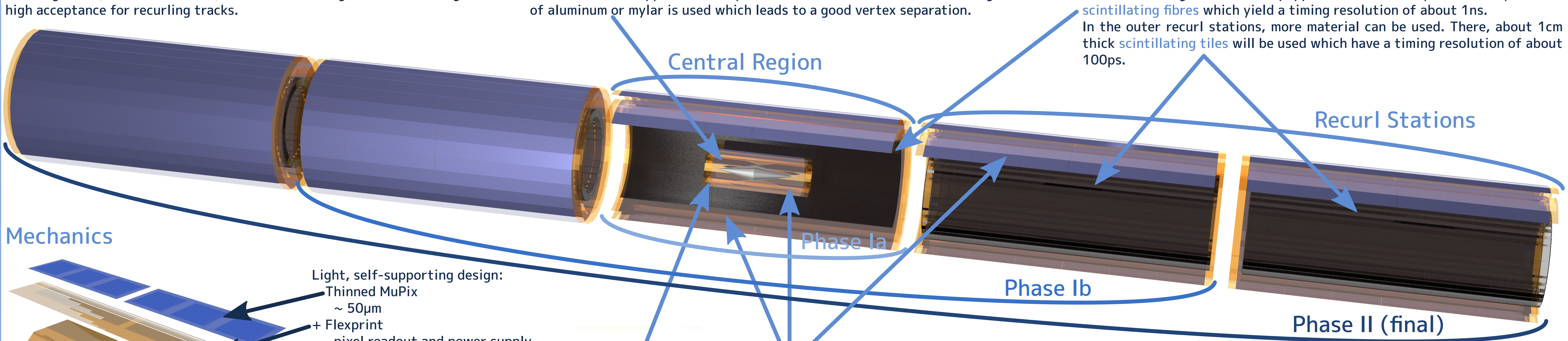
The long tube (L = 2m, ⌀ = 16cm) in a solenoidal magnetic field of 1T gives a high acceptance for recurling tracks.

Target

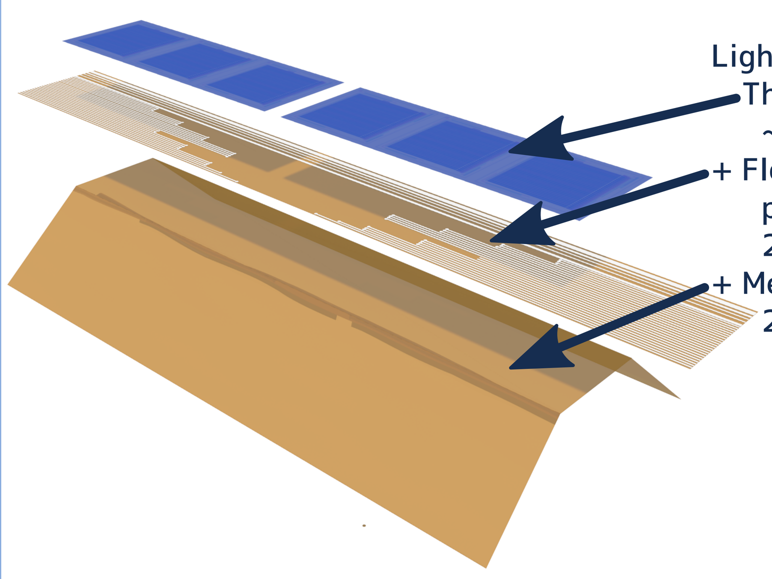
The muons are stopped and decay in an extended hollow double cone target made of aluminum or mylar is used which leads to a good vertex separation.

Timing

The central region will be equipped with three layers of 250μm thick scintillating fibres which yield a timing resolution of about 1ns.
In the outer recurl stations, more material can be used. There, about 1cm thick scintillating tiles will be used which have a timing resolution of about 100ps.



Mechanics



Light, self-supporting design:
Thinned MuPix ~ 50μm
+ Flexprint
pixel readout and power supply
25μm Kapton + 12.5μm aluminum traces
+ Mechanical support structure
25μm Kapton

Prototype of the innermost double layer

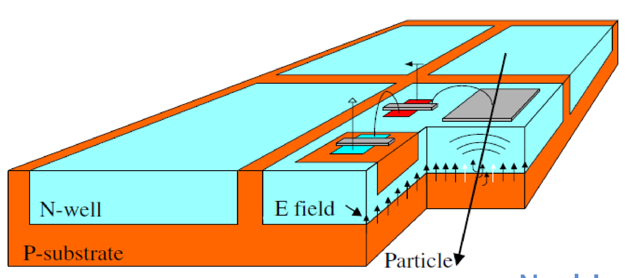
Tracking Detector

- Silicon pixel tracking detector based on HV-MAPS
- Pixel size: 80x80μm²
- Size of sensor: 2x2cm²
- Thinned sensors (~ 50μm)
- 280 million pixels in total
- Digital, zero-suppressed readout @ 20MHz
- Cooling by gaseous helium atmosphere

Muon Beam

The Paul Scherrer Institute (PSI) has a high intensity proton accelerator with 2.2mA of proton beam. This is used to produce surface muons from a target.
In phase I, an existing muon beam line (πE5) will be used that delivers rates > $10^8\mu$/s.
For phase II, rates > $10^9\mu$/s are required that can only be achieved by building a new high-intensty muon beam line (HiMB).

MuPix Sensors



HV-MAPS
The MuPix sensors are High Voltage Monolithic Active Pixel Sensors using a commercial 180nm HV-CMOS process from the automotive industry.

developed by Ivan Perić (KIT)
Nucl.Instrum.Meth. A582 (2007) 876-885

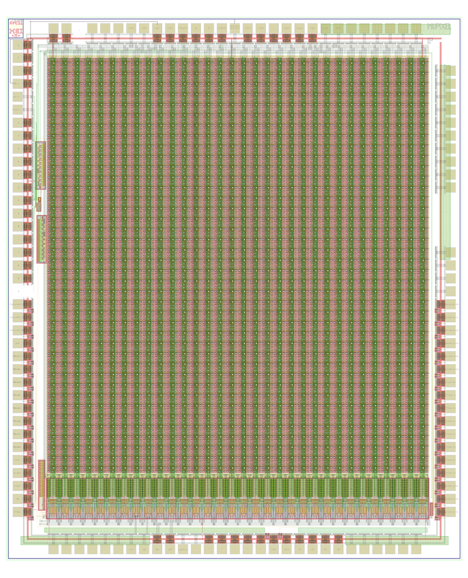
This technology perfectly meets the needs of Mu3e:

By applying a reverse bias of ~ 60V a thin depletion zone is created, so that most of the substrate remains passive. Thus, the sensors can be thinned to <50 μm. 4 layers of thinned HV-MAPS account for only 2‰ of X_0.
Furthermore, the intrisic charge collection time is < 1ns due to the strong electric field within the depletion zone.

The HV-MAPS have integrated readout electronics with analog and digital readout electronics being directly implemented on the sensor. The sensor outputs zero-suppressed hit addresses and timestamps. No additional readout-chip is needed.

MuPix7
Latest MuPix prototype (end of 2014)

- 40x32 pixels
- 103x80μm²
- 10.55mm² active area
- Second pre-amplification stage
- First fully integrated readout state machine on-chip
- High speed serial data output
- Test campaigns at DESY and PSI in 2015



Layout of the MuPix

Readout

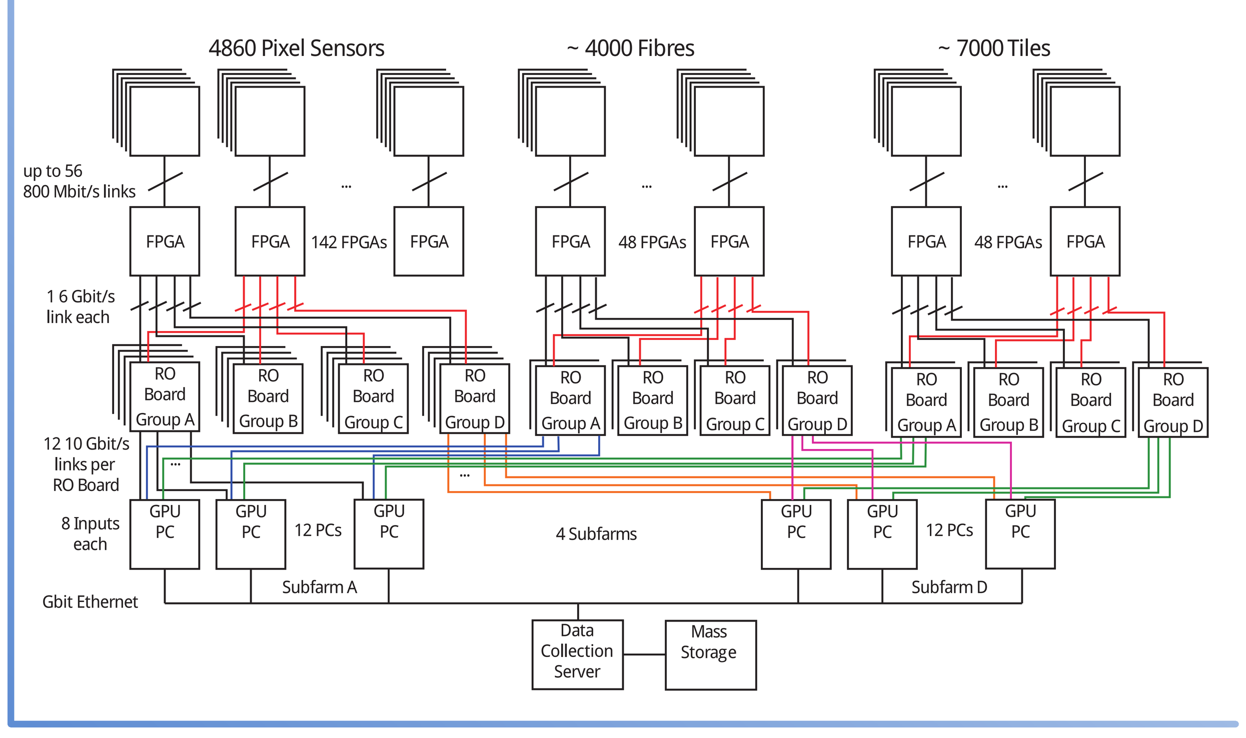
The Mu3e experiment uses a triggerless data acquisition system.

The pixel sensors send their zero-suppressed data (hit address and time stamp) via 1.25 Gbit/s LVDS links to the front-end boards. These PCBs host FPGA (Altera Stratix IV) which buffer the data and sort it by time stamp.

The sorted data is then sent via optical links (~ 6 Gbit/s) to the readout boards. On these boards, the data from the various sub-detectors is merged and transmitted to the GPU-based filterfarm via optical links.

On the GPUs of the filterfarm, fast track finding and online reconstruction of 10^9 tracks/s is performed. By event filtering, the data rate can be reduced from ~ 1Tbit/s to ~ 100 Mbyte/s for offline storage and analysis.

Readout scheme of the Mu3e detector



Outlook

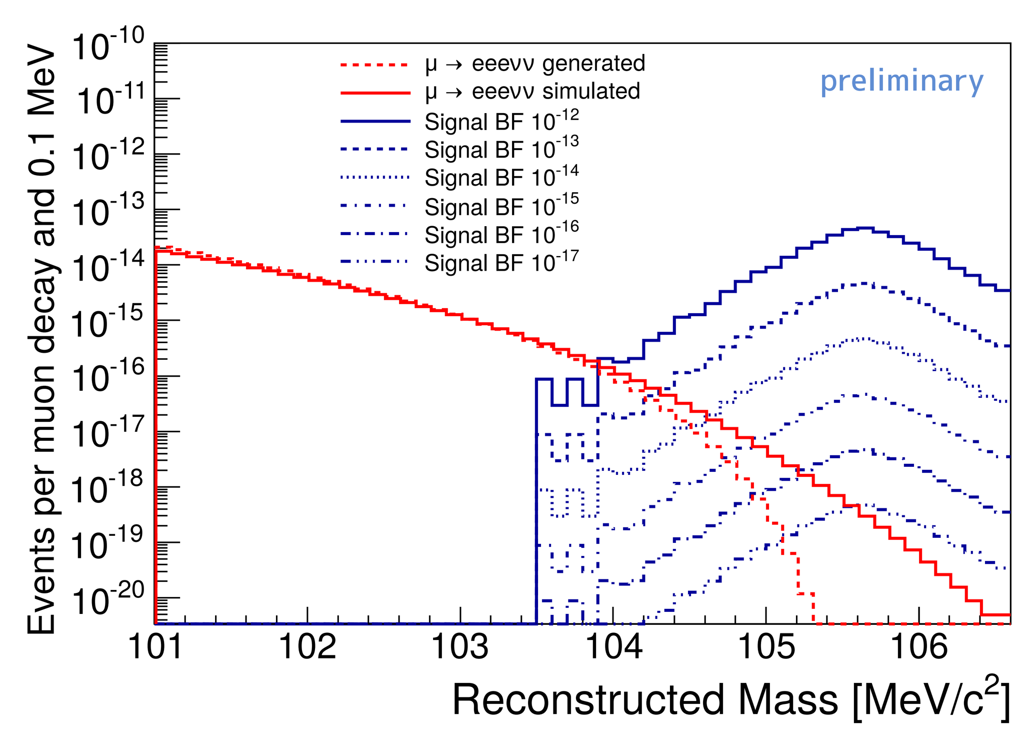
The Mu3e experiment is currently in the R&D phase.
Construction and data taking will be performed in 2 phases.

Phase I:
First data taking in 2017
$10^8\mu$/s from existing beam line
Core detector
Goal: BR ≈ 10^{-15}

Phase II:
Starting 2019+
$10^9\mu$/s from HiMB
Full detector
Final sensitivity: BR ≈ 10^{-16}

MuPix roadmap:
MuPix7
Under test (lab, DESY, PSI)
MuPix8 in summer 2015
Reduced pin count
MuPix9 by end of 2015
Large active area (1x2cm²)
To be used in phase I
Construction of tracking detector until end of 2016

Final sensitivity to $\mu\to eee$ for different branching fractions



http://www.psi.ch/mu3e