Status of the Mu3e Experiment at PSI

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on behalf of the Mu3e Collaboration

Physikalisches Institut, Heidelberg

FCCP, September 12, 2015, Anacapri

The Mu3e Experiment

Searching for the lepton flavour violating decay $\mu^+ \to e^+e^-e^+$

In this talk

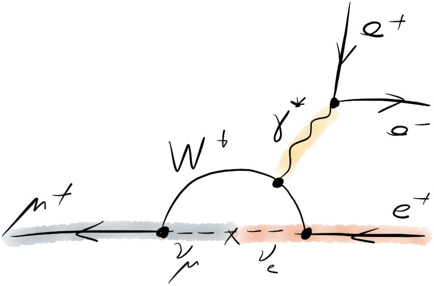
- Introduction to Mu3e
- Experimental Concept
- Current Status and Outlook

Charged Lepton Flavour Violation

Searching for New Physics in the Decay $\mu \to eee$

Lepton Flavour conserved in Standard Model

... but ν oscillations



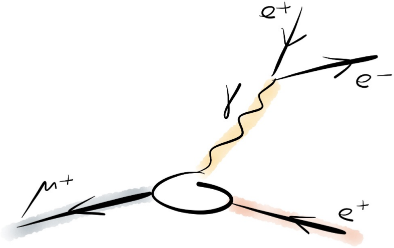
Expectation from lepton mixing: $\mathrm{BR}_{\mu \to eee} \sim \left(\frac{\Delta m_\nu}{m_W}\right)^4 < 10^{-54}$

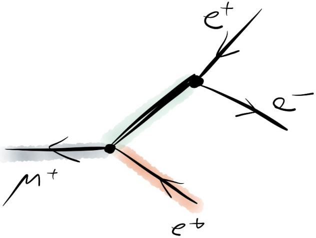
Charged Lepton Flavour Violation

Searching for New Physics in the Decay $\mu \to eee$

Observation of $\mu \to eee$ is a clear sign for New Physics

SUSY, extra heavy vector bosons (Z'), ...



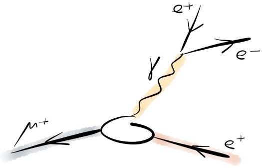


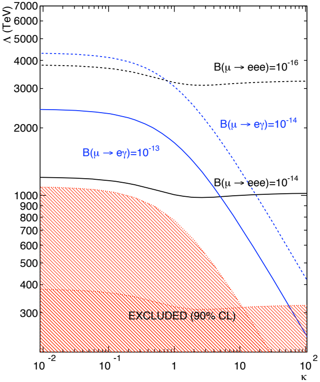
Current limit: $\text{BR}_{\mu \to eee} < 1.0 \cdot 10^{-12}$ at 90 % CL [SINDRUM, 1988]

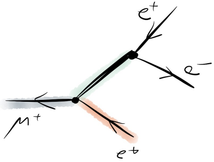
Mu3e: New experiment sensitive to BR's of 10^{-15} (10^{-16})

Charged Lepton Flavour Violation

Searching for New Physics in the Decay $\mu \to eee$





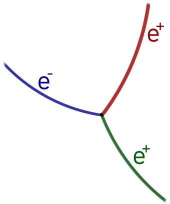


$$\mathcal{L}_{\mathrm{CLFV}} = \left[\frac{m_\mu}{(\kappa+1)\Lambda^2}\overline{\mu_R}\sigma_{\mu\nu}e_L F^{\mu\nu}\right]_{\text{dipole-like}} + \left[\frac{\kappa}{(\kappa+1)\Lambda^2}\left(\overline{\mu_L}\gamma_\mu e_L\right)\left(\overline{e_L}\gamma^\mu e_L\right)\right]_{\text{four-fermion}}$$

A. Gouvêa, P. Vogel, Prog.Part.Nucl.Phys. 71 (2013)

Signal and Background

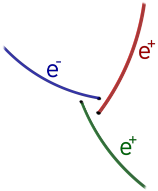
Signal



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

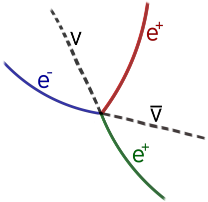
- Common vertex
- Coincident
- $\sum E_e = m_\mu$
- $\sum \vec{p}_e = 0$

Background



Accidental combinations

- No common vertex
- Not coincident
- $\sum E_e \neq m_\mu$
- $\sum \vec{p}_e \neq 0$

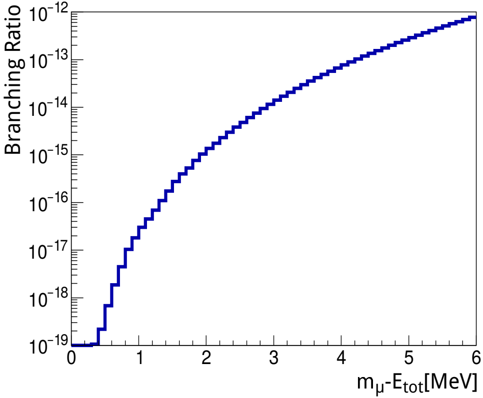


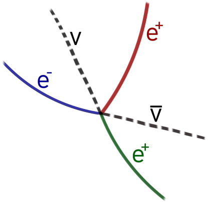
Internal conversion
$\mu^+ \rightarrow e^+e^-e^+\overline{\nu}_\mu\nu_e$

- Common vertex
- Coincident
- $\sum E_e < m_\mu$
- $\sum \vec{p}_e \neq 0$

Signal and Background

Background





Internal conversion

$\mu^+ \rightarrow e^+e^-e^+\bar{\nu}_\mu\nu_e$

Common vertex

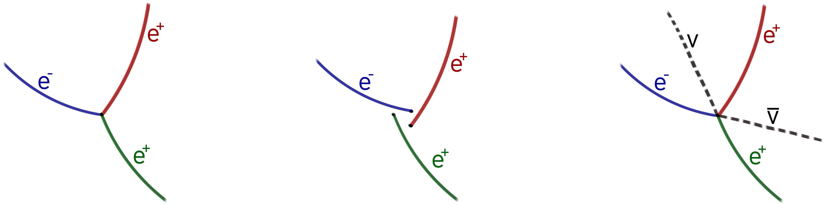
Coincident

$\sum E_e < m_\mu$

$\sum \vec{p}_e \neq 0$

Signal and Background

Signal | Background



Detector requirements:

- Very good vertex (~ 200 µm) and time resolution (~ 100 ps)
- Excellent momentum resolution (~ 0.5 MeV)
- Minimal material amount

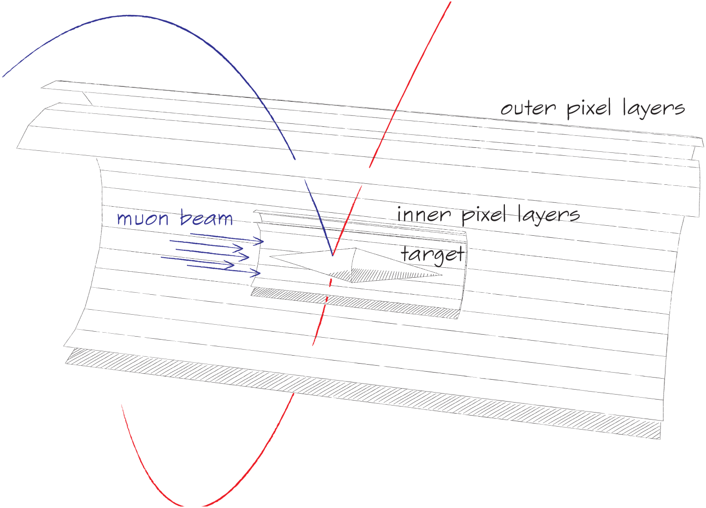
+ High muon stopping rates (10^8 to 10^9 muons/s)

Thin silicon pixel sensors
+ Scintillating fibres/tiles

Experimental Concept

Phase I: Detector Configuration A

Tracking detector with Si pixel sensors



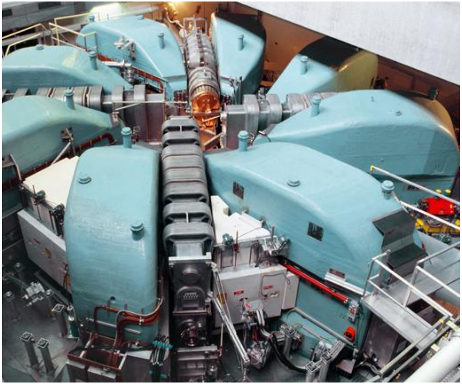
Phase IA

10^7 muons/s
BR ~ 10^{-14}
2017

Experimental Concept

Muon Beam

Paul-Scherrer Institute in Switzerland



2.2 mA proton beam with 590 MeV

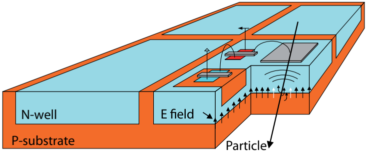
Secondary beamlines: μ^+ with 28 MeV

10^8 muons/s at existing beamline

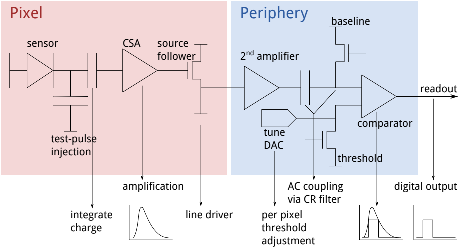
10^9 muons/s at future beamline under investigation

Experimental Concept

High-Voltage Monolithic Active Pixel Sensors



I. Perić, NIM A 582 (2007)

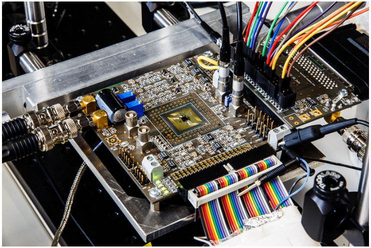


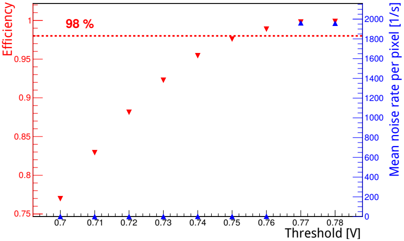
- High voltage of > 60 V
- Fast charge collection via drift
- Depletion zone of ~ 10 µm
  Thinning possible ($\lesssim$ 50 µm)
- Integrated readout electronics
- Pixel size 80 × 80µm^2
  Sensor size 2 × 2cm^2

Thin and granular

Experimental Concept

High-Voltage Monolithic Active Pixel Sensors





Latest prototype: MuPix7

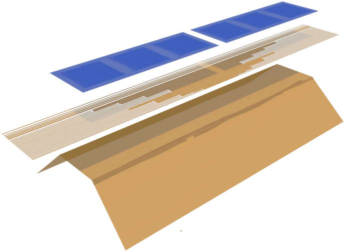
- Pixel size $103 \times 80\mu m^2$
  Sensor size $2.9 \times 3.2mm^2$
- Zero-suppressed hit addresses and timestamps via fast serial link
- Successfully tested in lab and in testbeam campaigns

Experimental Concept

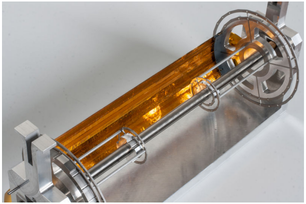
Lightweight Mechanics

- 50 µm silicon sensor
- 100 µm Kapton flexprint with aluminum traces
- 25 µm Kapton support structure

→ ~ 1 ‰ of radiation length



Cooling with gaseous helium



Experimental Concept

Data Acquisition

Triggerless data acquisition

Front-end board

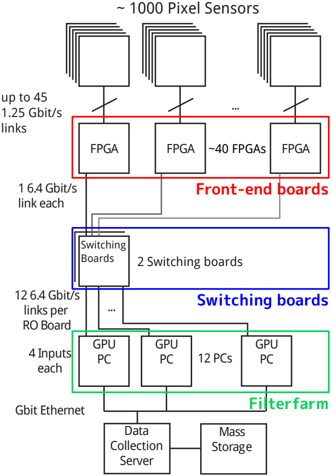
- Buffer and merge data of $\mathcal{O}(15)$ sensors
- Time-sorting
- Slow control

Switching board

- Switch between front-end and filterfarm
- Merge data of sub-detectors

GPU filterfarm

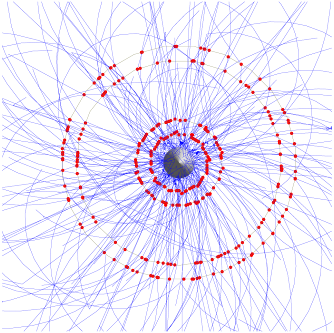
- Fast track finding and online reconstruction
- Reduce data rate from $\sim 1\,\text{Tbit/s}$ to $\sim 100\,\text{MB/s}$



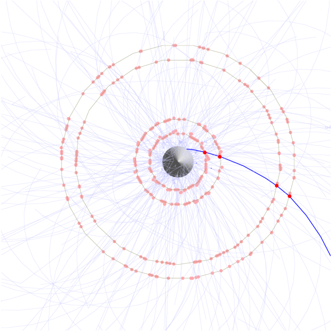
Experimental Concept

Phase I

Increase muon rate to 10^8muons/s $\longrightarrow$ precise time measurement required



Tracks expected within readout frame of 50 ns

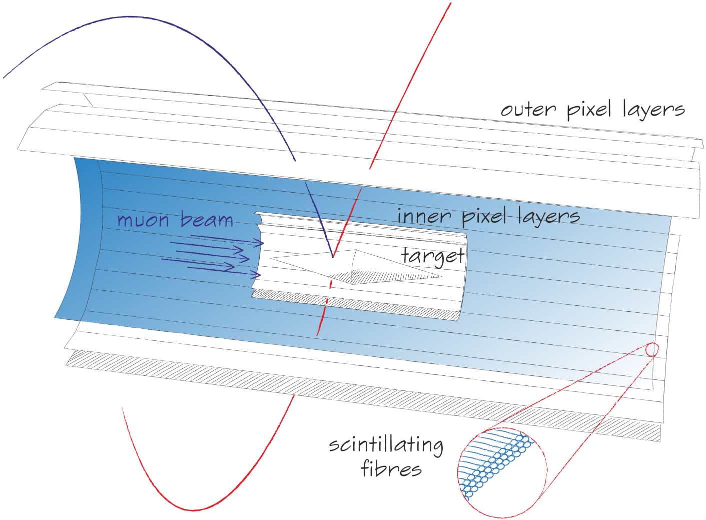


Matching with time information of scintillating fibres and tiles

Experimental Concept

Phase I: Detector Configuration B

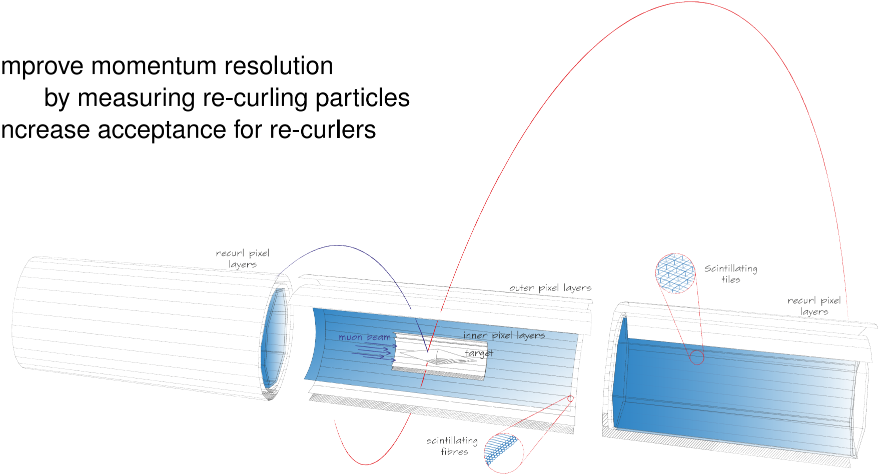
Scintillators improve time resolution



Experimental Concept

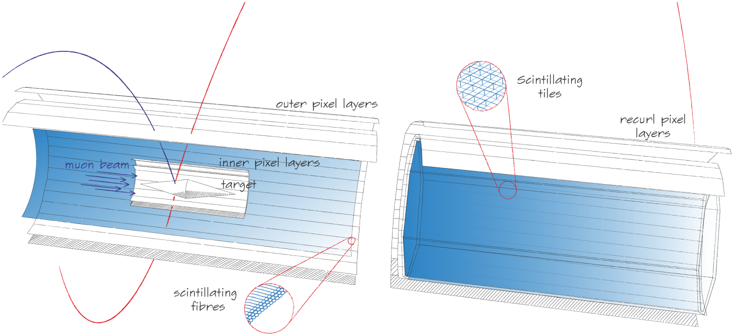
Phase I: Detector Configuration B

Improve momentum resolution
by measuring re-curling particles
Increase acceptance for re-curlers



Experimental Concept

Phase I: Detector Configuration B



Phase IB

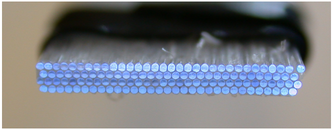
10^8muons/s

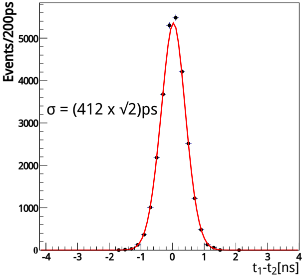
BR ~ 10^{-15}

2018

Experimental Concept

Scintillating Fibres





Time resolution of squared fibres

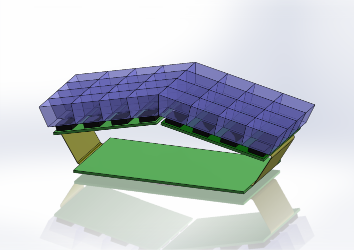
- ~ 3 layers of fibres with diameter of 250 µm
- Round and squared fibres under investigation
- Photon detection at both ends with SiPM array
- Readout with custom-designed STiC chip

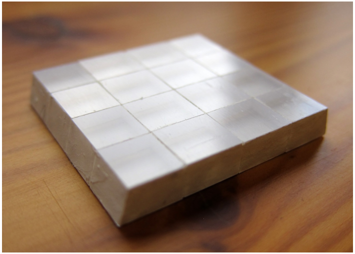
- Time resolution:

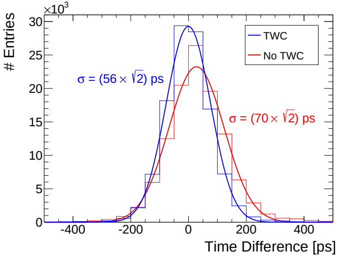
$$\frac{\sigma_{\text{round}}}{\sqrt{2}} \approx 1.5\,\text{ns}$$
$$\frac{\sigma_{\text{squared}}}{\sqrt{2}} \leq 500\,\text{ps}$$

Experimental Concept

Scintillating Tiles







- Size ~ 1 × 1 × 1cm^3
- Each tile has a SiPM
- Readout with custom-designed STiC chip
- Time resolution $\lesssim$ 100 ps

Experimental Concept

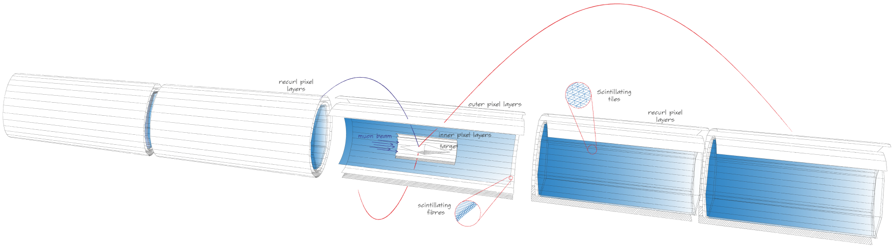
Phase II

Phase II

10^9 muons/s at future beamline

BR $\sim 10^{-16}$

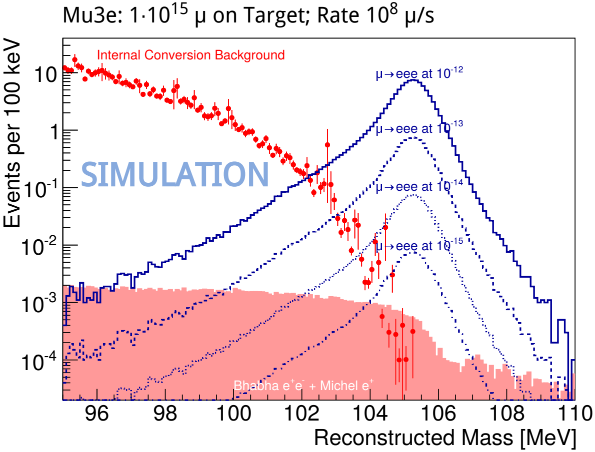
2020+



Sensitivity Studies

Reconstructed mass for signal and background events

Phase IB



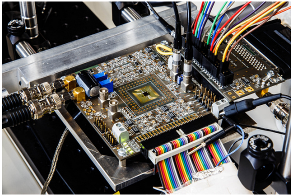
Summary

Mu3e

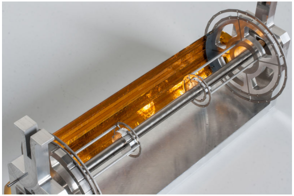
- Precision experiment searching for LFV decay $\mu \rightarrow eee$
- Aiming at a sensitivity of BR $\sim 10^{-15}(10^{-16})$

- Lightweight pixel detector made of HV-MAPS
- Precise timing by scintillating fibres/tiles
- Triggerless readout
- Operated at 10^{8}muons/s

Status and Outlook



Tests of HV-MAPS prototype



Mechanical prototype

Current status

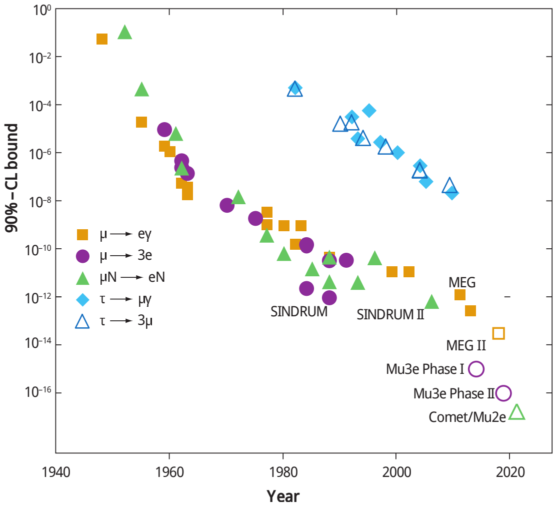
- Research proposal approved in 2013
- Technical design report in preparation (Q1 2016)
- Research and development of subsystems
- Preparation of detector construction

Outlook

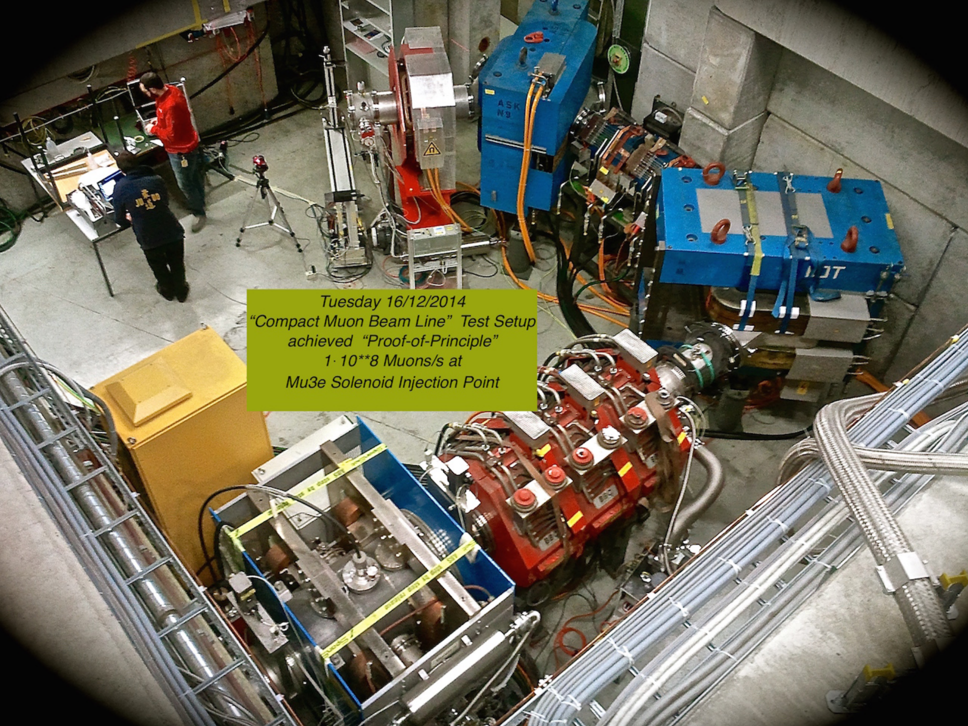
- Commissioning and first data in 2017
- Phase IA: BR ~ 10^{-14} (2017)
- Phase IB: BR ~ 10^{-15} (2018)
- Phase II : BR ~ 10^{-16} (2020+)
  requires muon rates of 10^{9}muon/s

Appendix

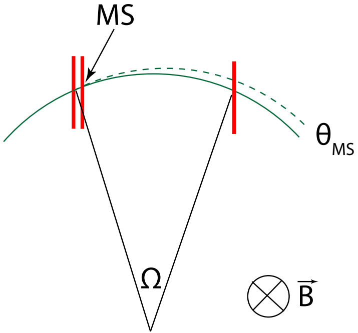
History of LFV Searches in μ and τ Decays



Adapted from Marciano et al. [Ann.Rev.Nucl.Part.Sci.58, 2008]


Tuesday 16/12/2014
“Compact Muon Beam Line” Test Setup
achieved “Proof-of-Principle”
1·10**8 Muons/s at
Mu3e Solenoid Injection Point

Multiple Coulomb Scattering



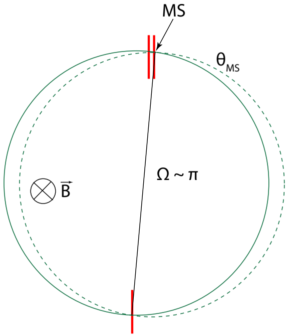
Decay electrons have low momentum $< 53\,\mathrm{MeV/c}$

Momentum resolution is dominated by multiple scattering

$$\frac{\sigma}{p} \sim \frac{\theta_{MS}}{\Omega}$$

$$\theta_{MS} \propto \frac{1}{\beta c p}\sqrt{\frac{x}{X_0}}$$

Multiple Coulomb Scattering



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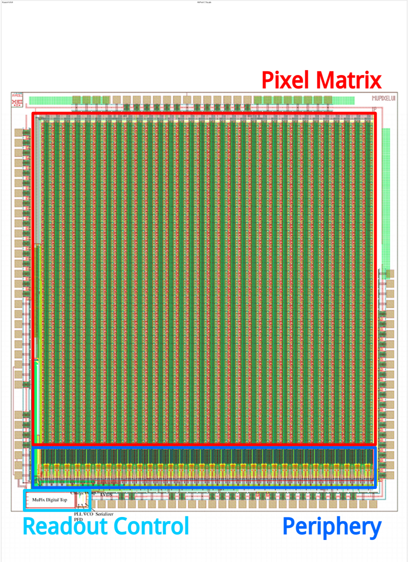
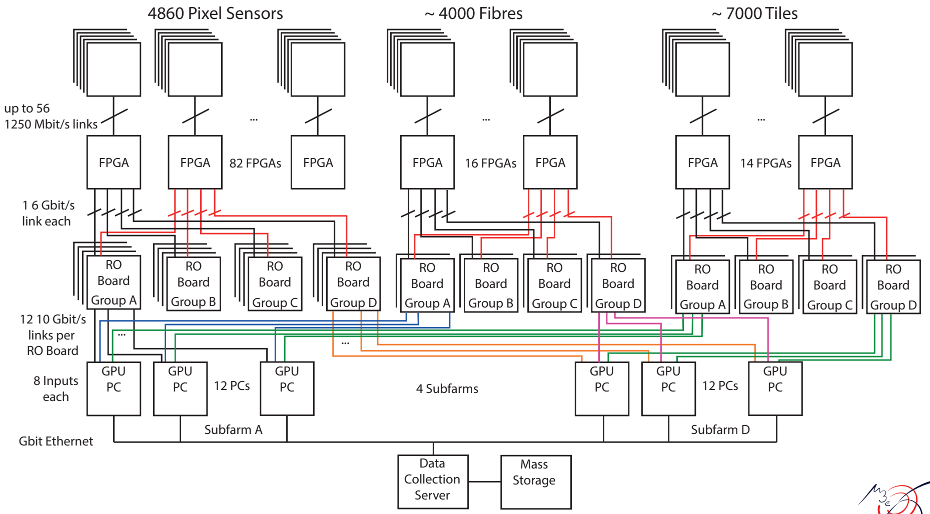
$$\theta_{MS} \propto \frac{1}{\beta c p}\sqrt{\frac{x}{X_0}}$$

Layout of MuPix7



Readout Concept



Mu3e Collaboration

DPNC, Geneva University

KIP, Heidelberg University

Physics Institute, Heidelberg University

IPE, Karlsruhe Institute of Technology

Institute for Nuclear Physics, JGU Mainz

Paul Scherrer Institute

Institute for Particle Physics, ETH Zürich

Physics Institute, Zürich University