The Mu3e Experiment: New Physics in Different Places?

Moritz Kiehn
Université de Genève
Département de physique nucléaire et corpusculaire

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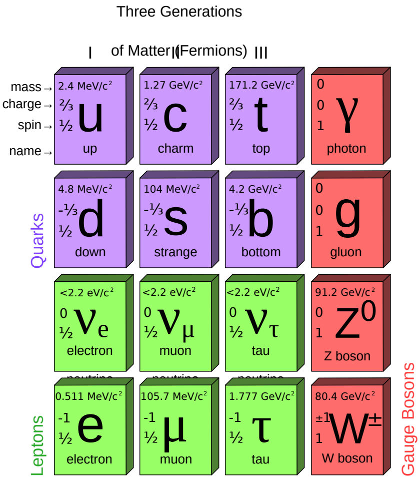
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Overview

Flavor in the Standard Model



adapted from Wikipedia

Initially:

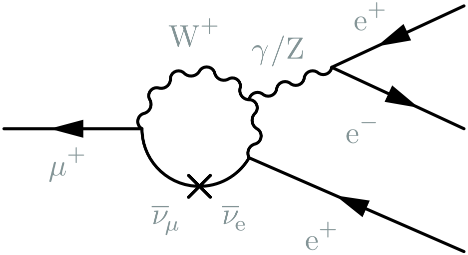
- Quark transitions via weak interaction
- Lepton flavor conserved

Neutrino Mixing

- LFV in neutral sector
- Charged sector?

Anything else?

Charged lepton flavor violation?



Example: $\mu^+ \longrightarrow e^+e^-e^+$

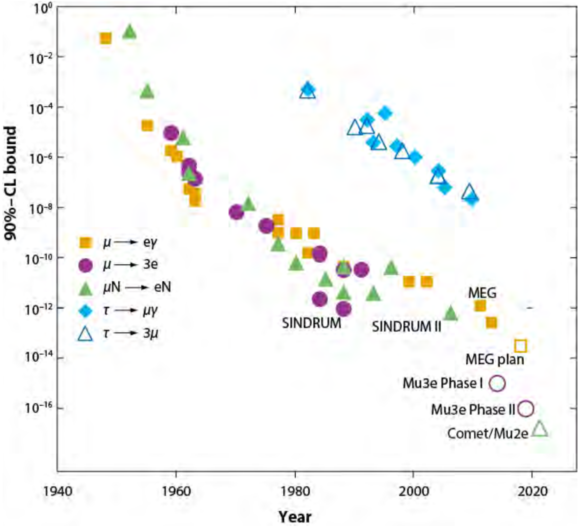
In the Standard Model

- Via neutrino mixing
- Suppressed by $\sim \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2$
- Expected BR($\mu \longrightarrow \mathrm{eee}$) $\ll 10^{-50}$

Importance

- Observable rate only from new physics
- Sensitive new physics search

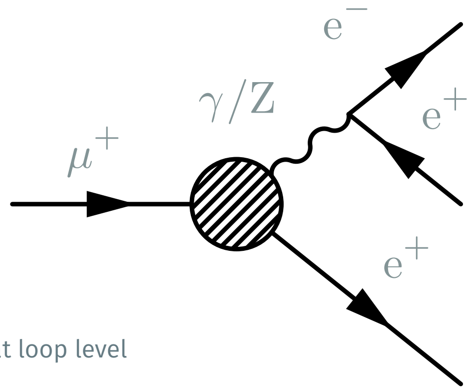
Searches for charged lepton flavor violation



W. Marciano et al. (2008), with modifications

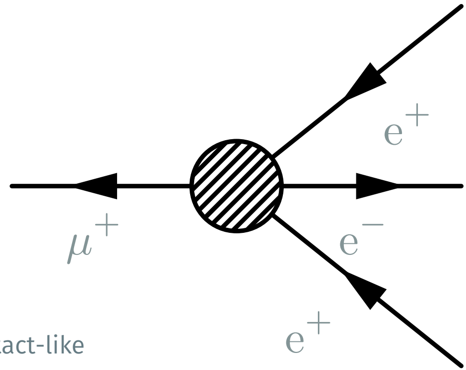
- Long history
- Multiple future experiments planned

Beyond the Standard Model



E.g at loop level

- Supersymmetry
- Seesaw
- ...

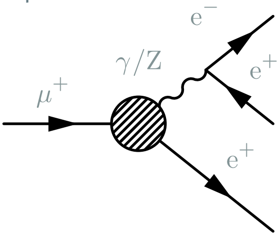


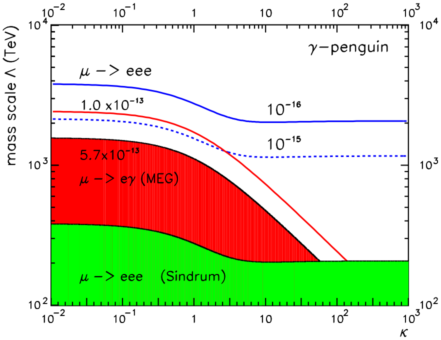
Contact-like

- Extra dimensions
- New heavy bosons
- ...

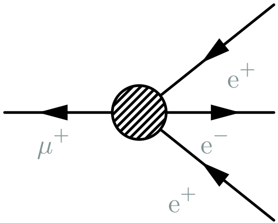
Effective theory

Dipole-like





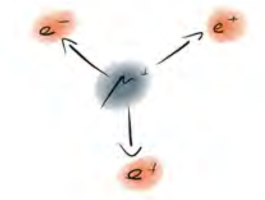
Contact-like



Sensitive up to $\mathcal{O}(1000\,\mathrm{TeV})$

Compare Kuno, Okada (2001) and de Gouvêa, Vogel (2013)

Searches with muons



$\mu^+ \to e^+\gamma$

MEG upgrade

$\mu^- + \mathrm{Au} \to e^- + \mathrm{Au}$

Comet/Mu2e

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

Mu3e: this talk

Current Limits

cLFV Process	BR @ 90 %CL	Experiment
$\mu^+ \rightarrow e^+e^-e^+$	$<1 \times 10^{-12}$	Sindrum Nucl.Phys. B299(1)
$\mu^+ \rightarrow e^+\gamma$	$<5.7 \times 10^{-13}$	MEG arXiv:1303.0754
$\mu^- + \mathrm{Au} \rightarrow e^- + \mathrm{Au}$	$<7 \times 10^{-13}$	Sindrum II Eur. Phys. J. C47 337–346

The Mu3e experiment

Search for $\mu^+ \to e^+e^-e^+$

Planned sensitivity:

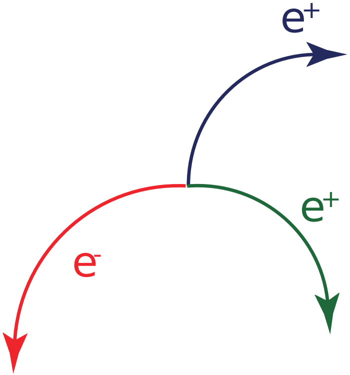
- Phase I: 2 in 10^{15} decays (existing beamline)
- Phase II: 1 in 10^{16} decays (future beamline)

4 orders of magnitude over previous experiment (SINDRUM 1988)

The Mu3e collaboration

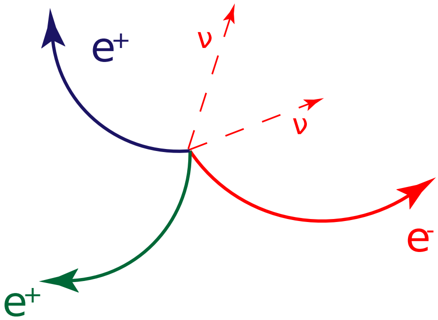
- Paul Scherrer Institute
- Université de Genève
- ETH Zürich
- University Zürich
- Heidelberg University
- Karlsruhe Institute of Technology
- Mainz University

Signal



- Common vertex
- Same time
- $(\sum P_i)^2 = m_\mu^2$
- $\sum \vec{p}_i = 0$ (muon at rest)
- $p < 53$ MeV

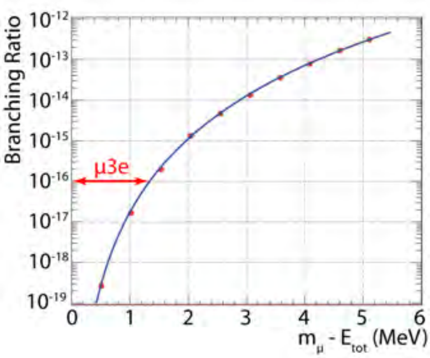
Internal conversion background



- Common vertex
- Same time
- $\left(\sum P_i\right)^2 < m_\mu^2$
- $\sum \vec{p}_i \neq 0$
- $p < 53$ MeV

→ Requires excellent momentum resolution

Internal conversion background



Djilkibaev, Konoplich, Phys.Rev.D79, 2009

- Common vertex
- Same time
- $\left(\sum P_i\right)^2 < m_\mu^2$
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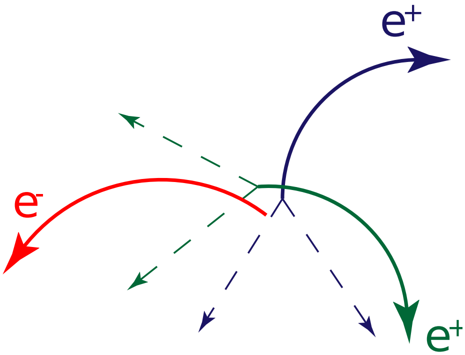
→ Requires excellent momentum resolution

Combinatorial background

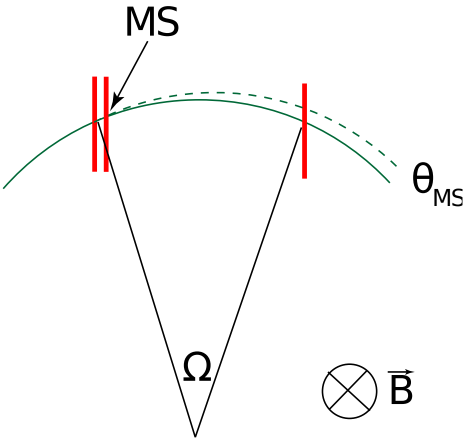


- from Michel decay, Bhabba scattering, photon conversion, ...
- No common vertex
- Not same time

→ Requires good vertex resolution

→ Requires good time resolution

Multiple scattering



$$\theta_{MS} \sim \frac{1}{p}\sqrt{x/X_0}$$

Mu3e example

- p = 35 MeV/c
- 50 µm Si
- $\Omega R = 5$ cm

→ $\Delta y \approx 320$ µm

→ Scattering dominates

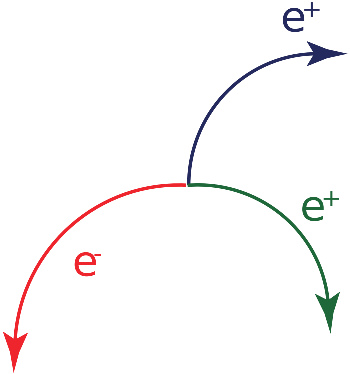
Detector requirements

Environment

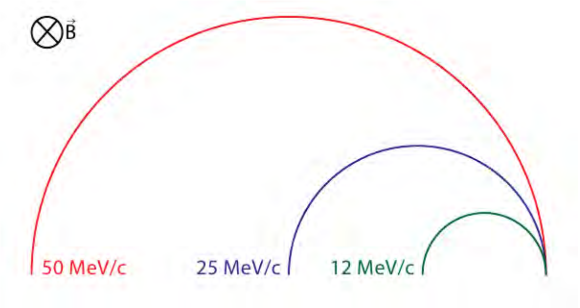
- High rate: $>10^9\ \mu^+$ Decays/s
- Low momentum: $p < 53$ MeV
- Multiple scattering dominates

Detector

- Spatial resolution: $<100\,\mu$m
- Time resolution: <1 ns
- Low mass: $x/X_0 \sim 1\,‰$
- Momentum resolution: 0.5 MeV



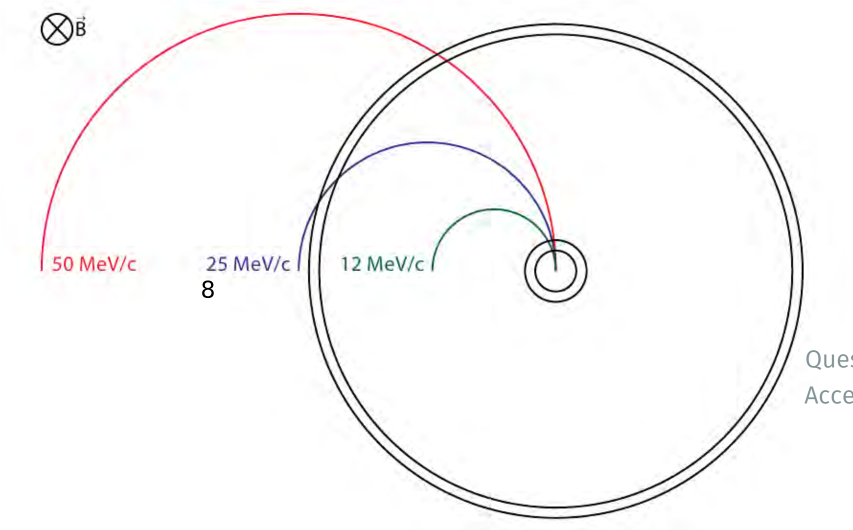
Detector Layout



Question:

Acceptance vs. resolution

Detector Layout



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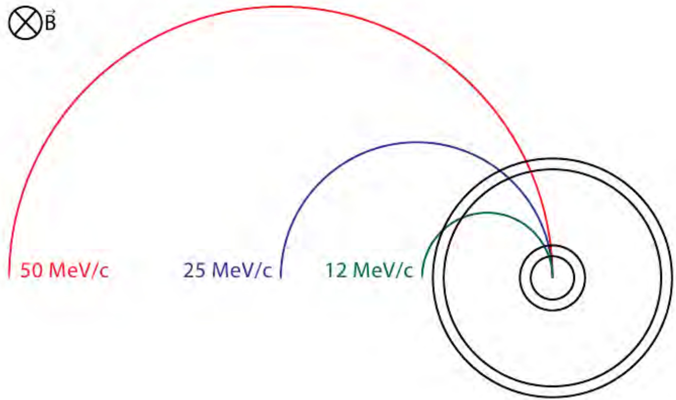

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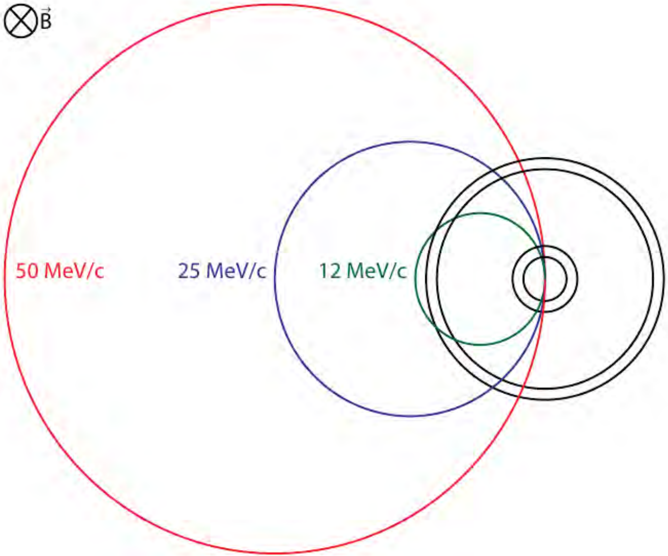
Acceptance vs. resolution

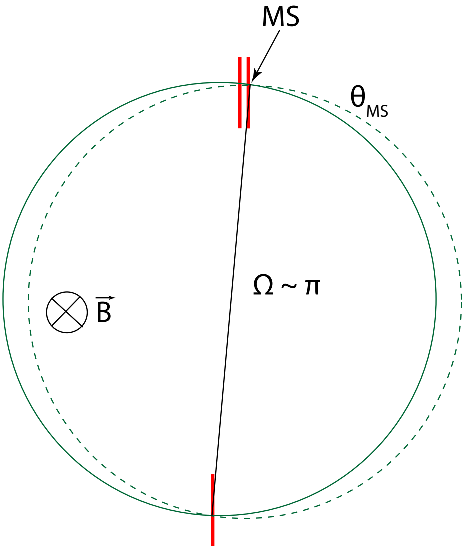


Question:

Acceptance vs. resolution

Answer: both

Recurling tracks



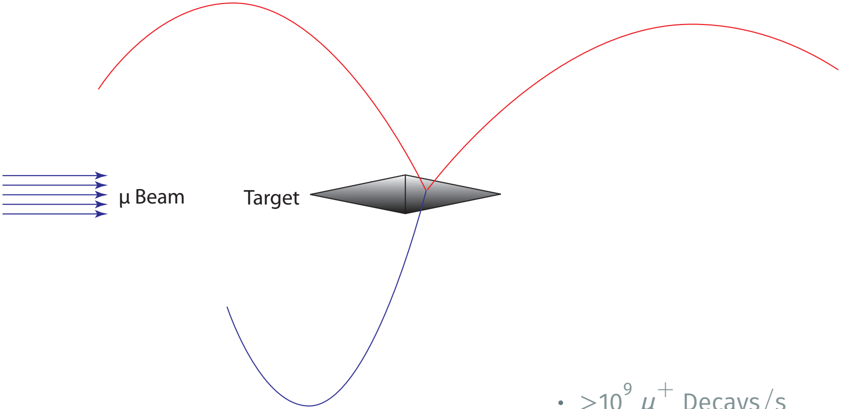
Momentum resolution dominated by multiple scattering

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

with $\theta_{MS} \sim \frac{1}{p}\sqrt{x/X_0}$

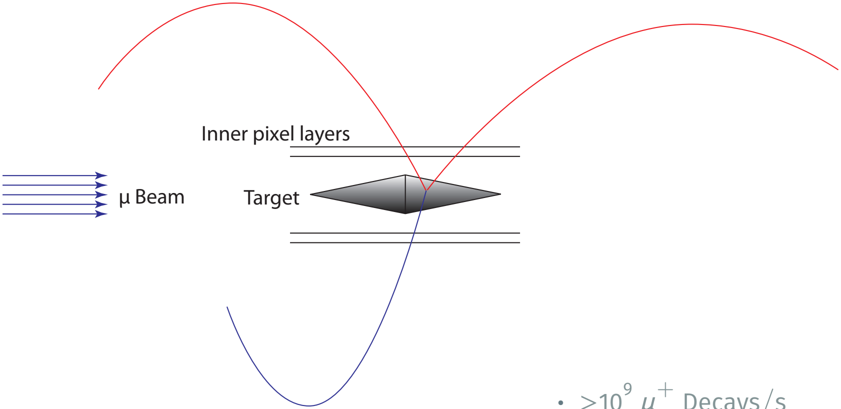
Uncertainty vanishes at $\Omega \sim \pi$ (first order)

Detector Concept



- $>10^9$ μ^+ Decays/s
- Electrons p <53 MeV
- Multiple scattering dominates

Detector Concept



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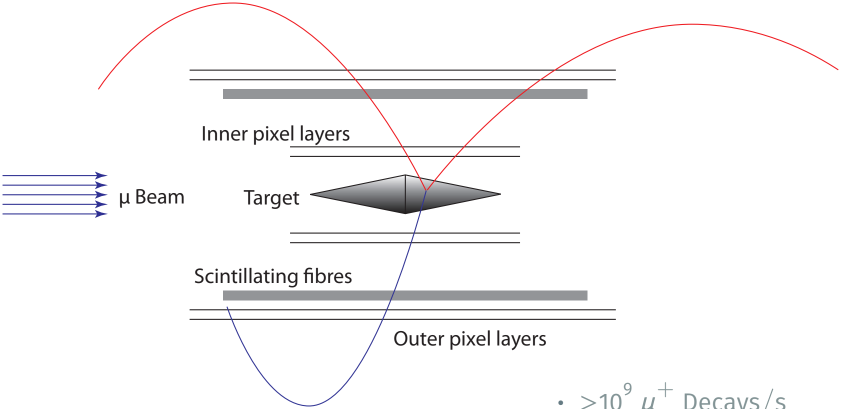

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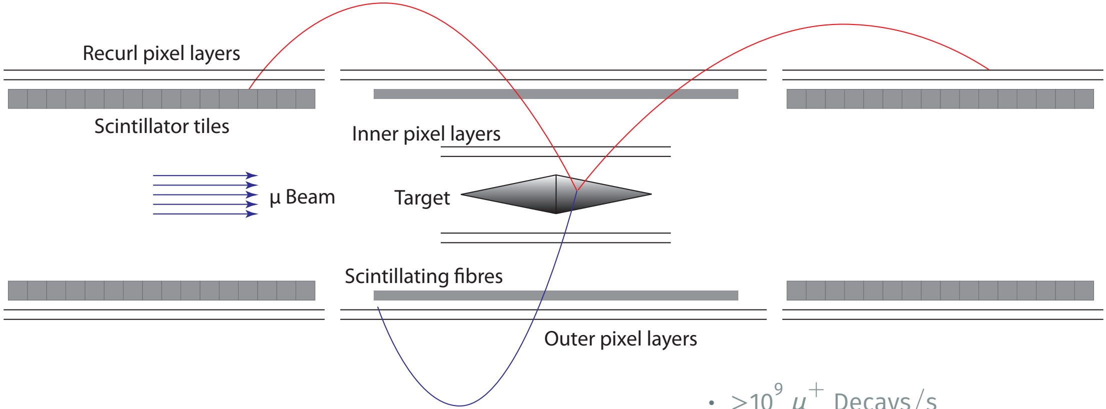
Detector Concept



- $>10^9\ \mu^+$ Decays/s
- Electrons p <53 MeV
- Multiple scattering dominates

Paul Scherrer Institut

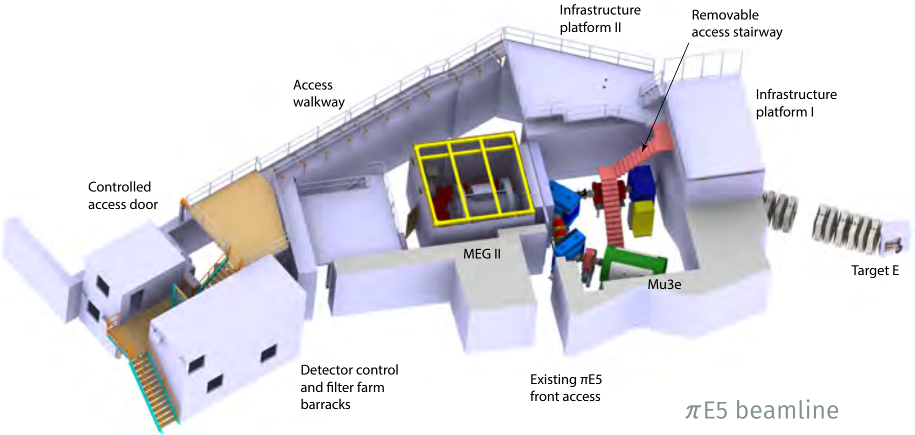
Villigen, Switzerland

Proton accelerator

Proton accelerator

2.2 mA at 590 MeV
Continuous beam
Muon beams $10^8\,\mu/\mathrm{s}$ available
Higher rates are under study

Experimental area and beamline

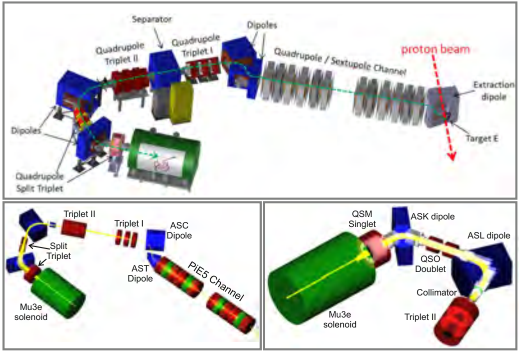


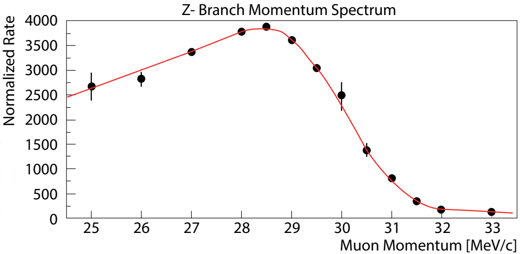
πE5 beamline

$\sim$28 MeV surface muons

Shared with MEG

Experimental area and beamline





πE5 beamline

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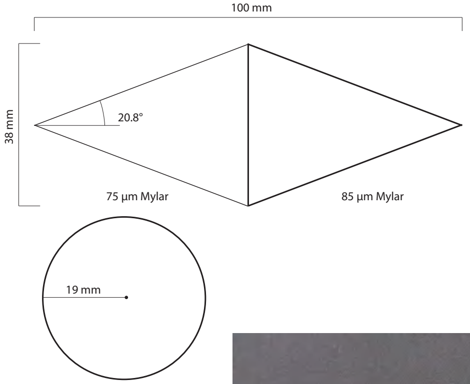
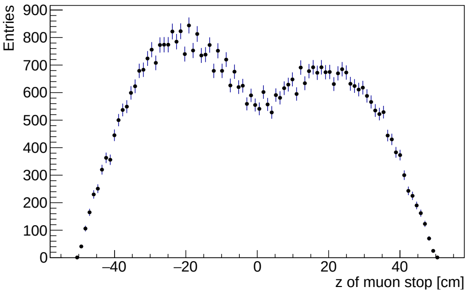
Shared with MEG

Target



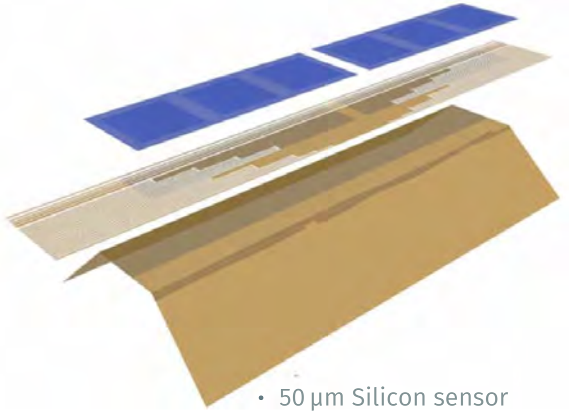
Simulated stopping distribution



Thin, hollow, double-cone geometry

Optimized stopping power

Ultra-lightweight mechanics

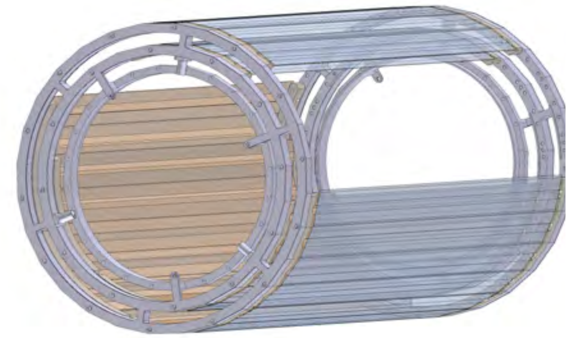


- 50 µm Silicon sensor
- 75 µm Kapton flexprint
- 25 µm Kapton support frame

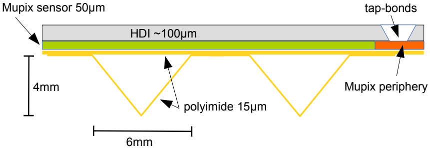
→ ~1 ‰ Radiation length

Ultra-lightweight mechanics

Outer layers



Outer layer module

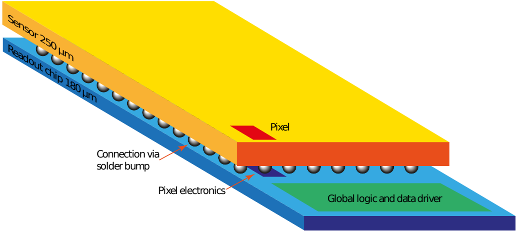


V-shaped groove for stability and cooling

Mechanical prototype

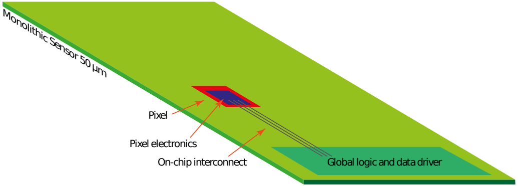
Silicon Pixel Sensors

Hybrid



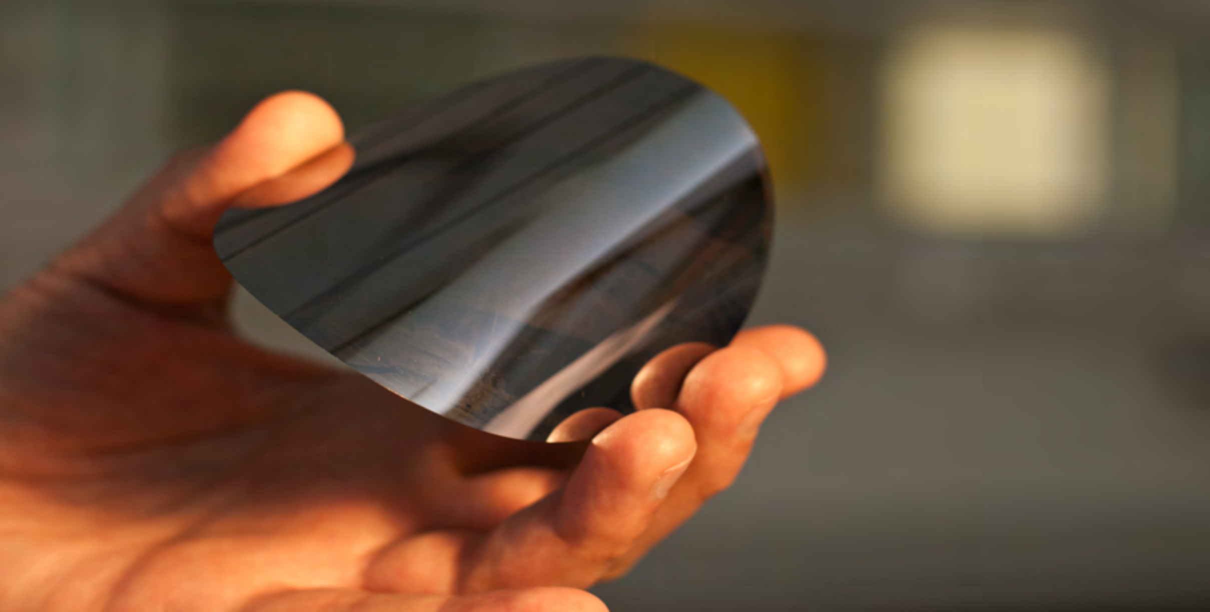
- HV ~700 V
- Sensor thickness ~250 µm
- Extra material
- Complex, (expensive)

Monolithic Active Pixel Sensor

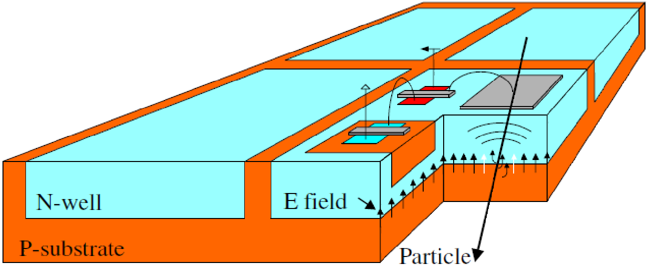


- HV ~80 V (HV-MAPS)
- Thin active zone <20 µm
- Cheap, commercial process

50 μm silicon



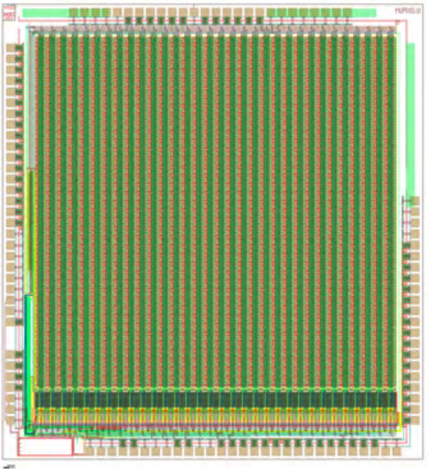
Monolithic Active Pixel Sensors



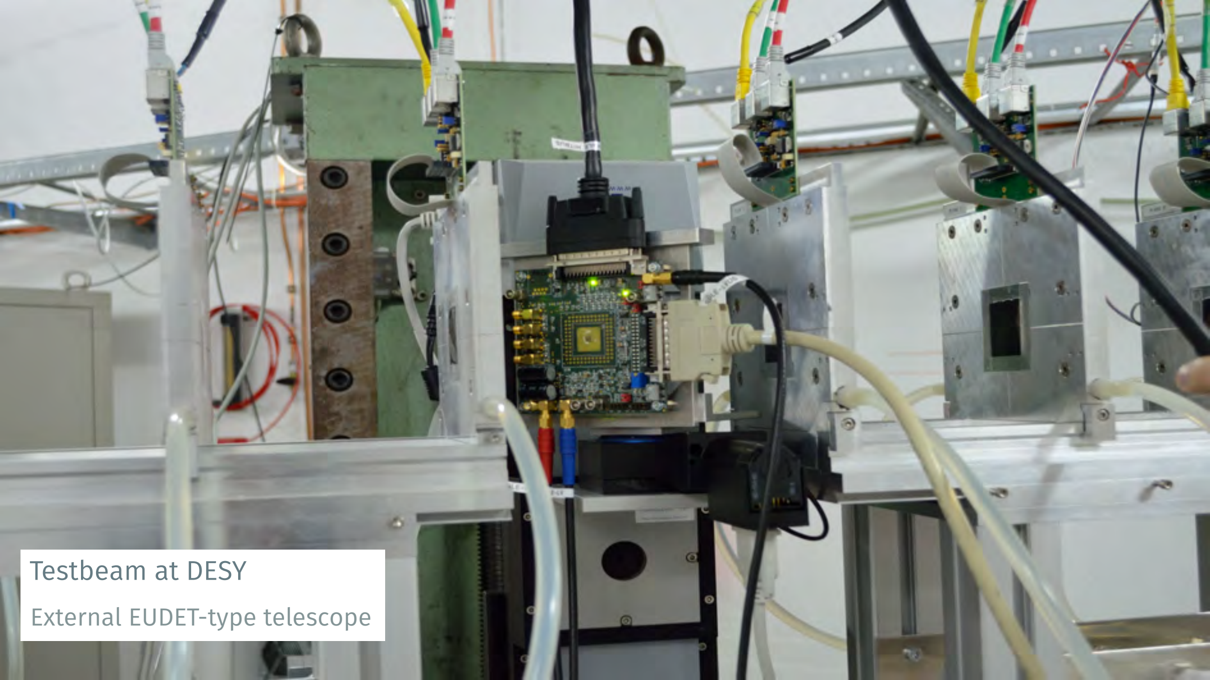
I. Peric, P. Fischer et al. NIMA 582(2007)876

- HV ~80 V (HV-MAPS)
- Fast charge collection by drift
- Thin active zone <20 µm
- Fully integrated readout electronics

MuPix7 sensor prototype

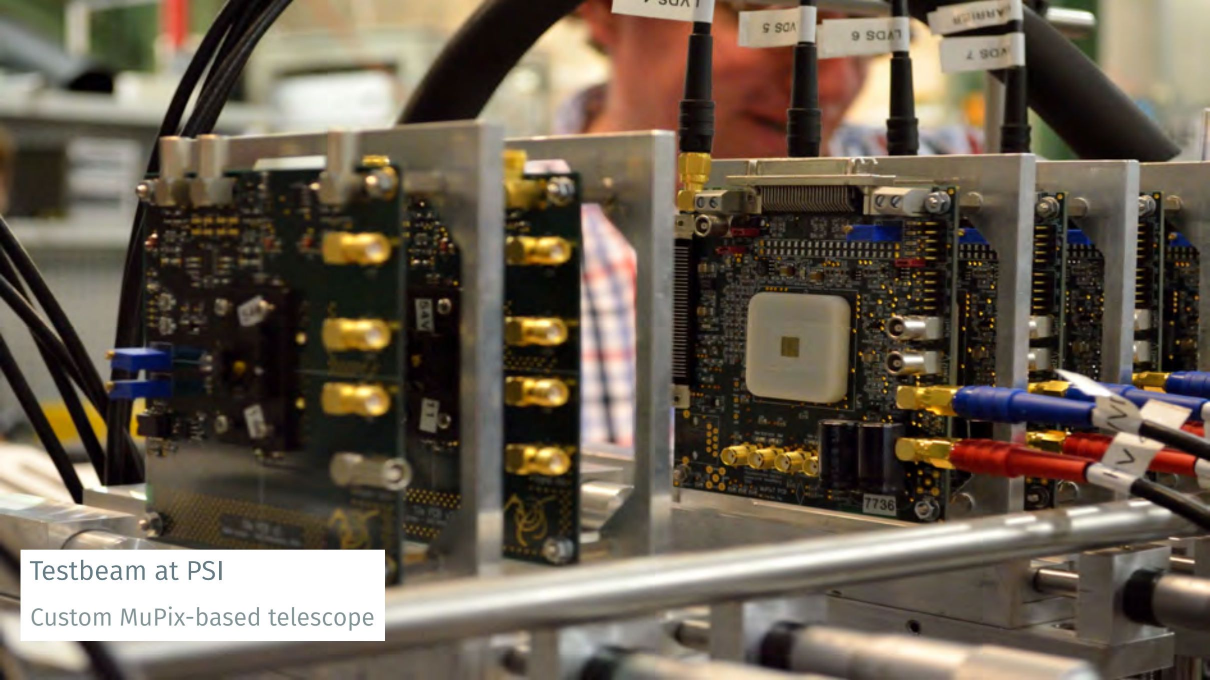


- $103 \times 80\,\mu m^2$ pixel size
- $3.8 \times 4.1\,mm^2$ sensor size
- Zero-suppressed, binary hits
- Global threshold + per-pixel tune-dac
- Fully integrated trigger-less readout
- LVDS serial link $1.6\,\mathrm{Gbit/s}$



Testbeam at DESY

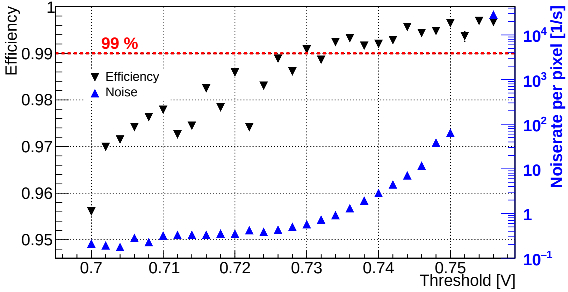
External EUDET-type telescope



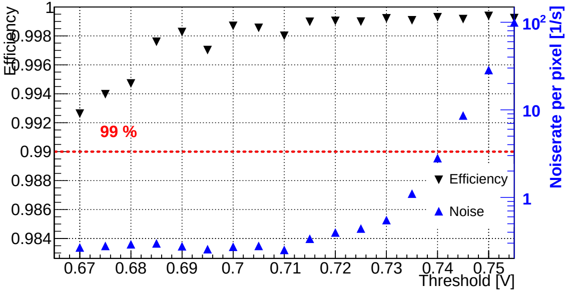
Testbeam at PSI

Custom MuPix-based telescope

0° incidence



60° incidence

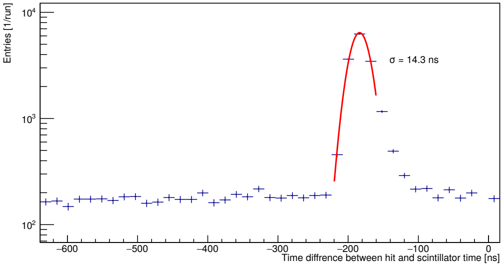


Measured at DESY

4 GeV electrons

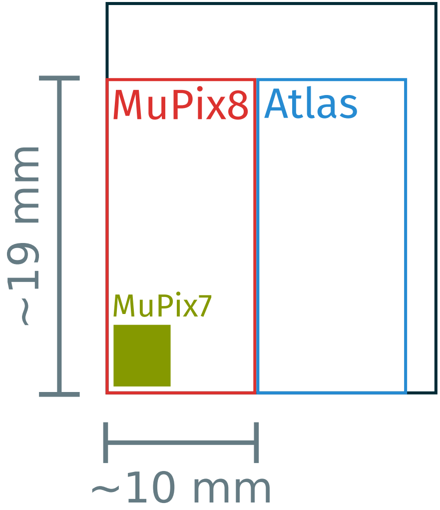
−85 V sensor bias

MuPix7 time resolution



- DESY test beam
- 4 GeV electrons
- Using external scintillator as reference

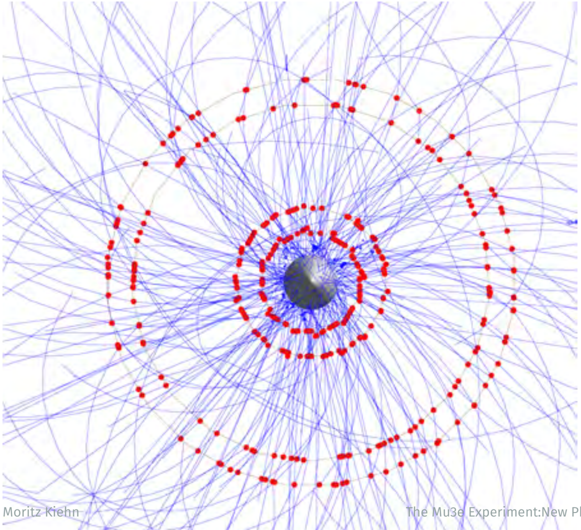
Next: MuPix8



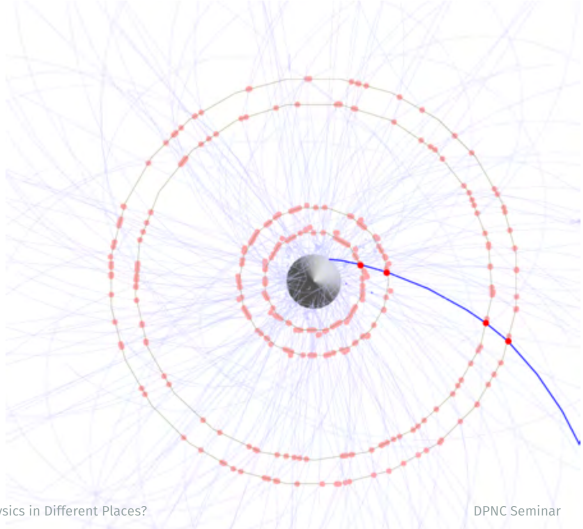
- First full-size prototype
- $80 \times 80\,\mu\text{m}^2$ pixel size
- Updated electronics
- 4x LVDS serial link $1.6\,\text{Gbit/s}$
- Joint submission with Atlas CMOS
- Submitted end of 2016, AMS 180 nm technology

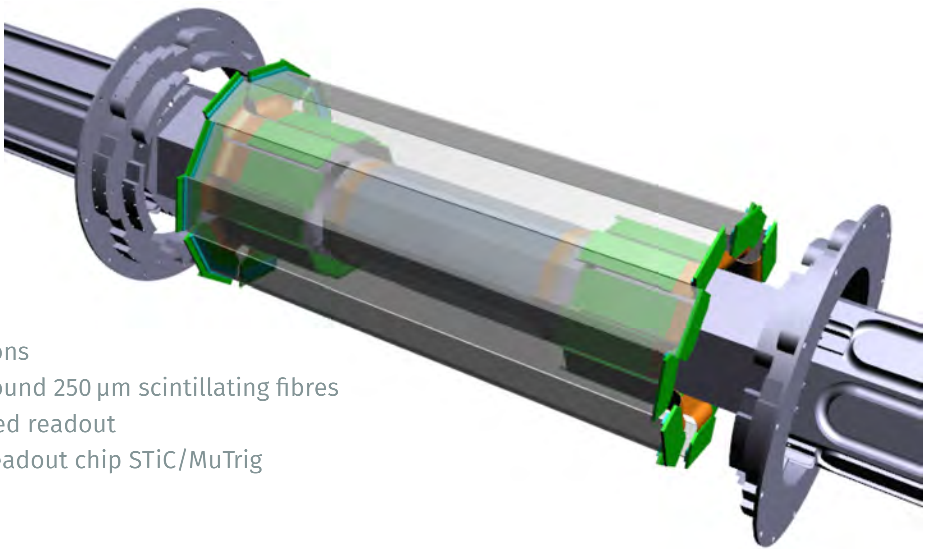
Occupancy and timing

2×10^9 decays, 50 ns integration



2×10^9 decays, 1 ns resolution

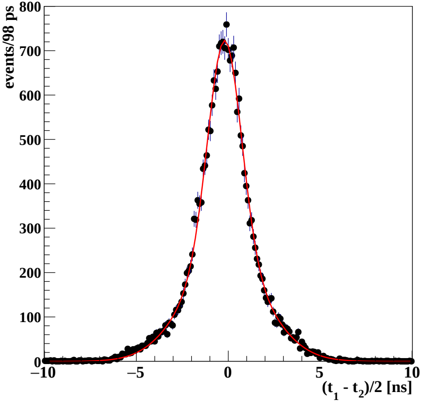




- Thin ribbons
- Square/round 250 µm scintillating fibres
- SiPM-based readout
- Custom readout chip STiC/MuTrig

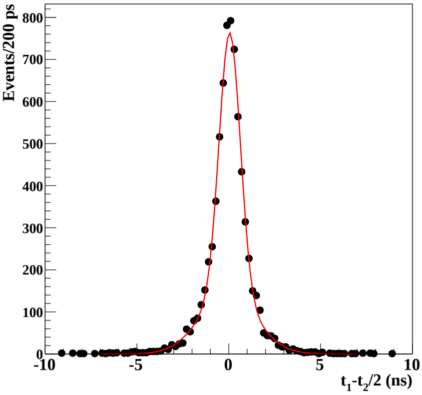
Fibre time resolution

Round fibre



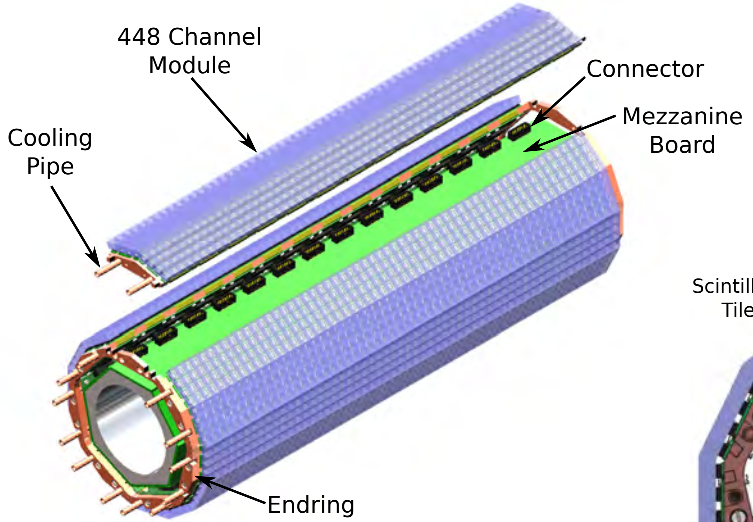
Resolution 1.1 ns

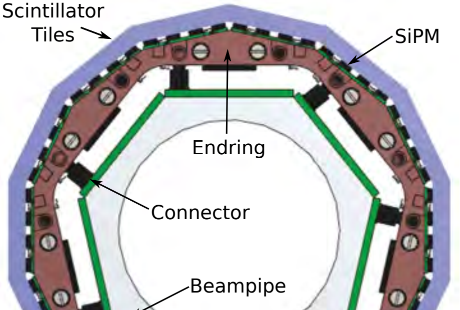
Square fibre



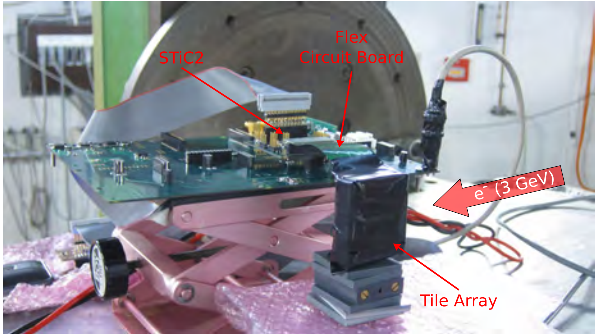
Resolution 0.75 ns

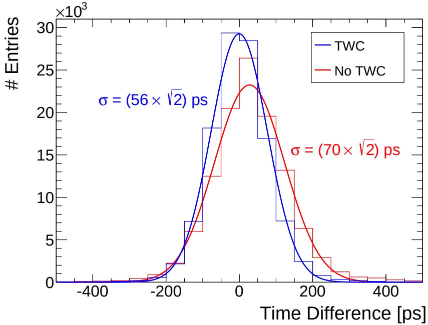
Tile detector





Tile detector prototype

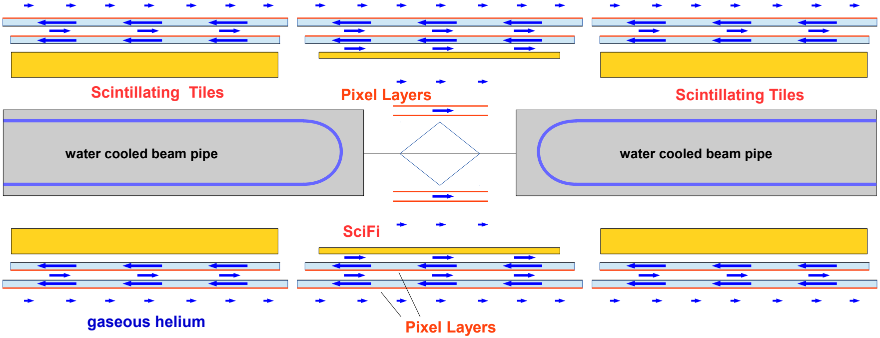




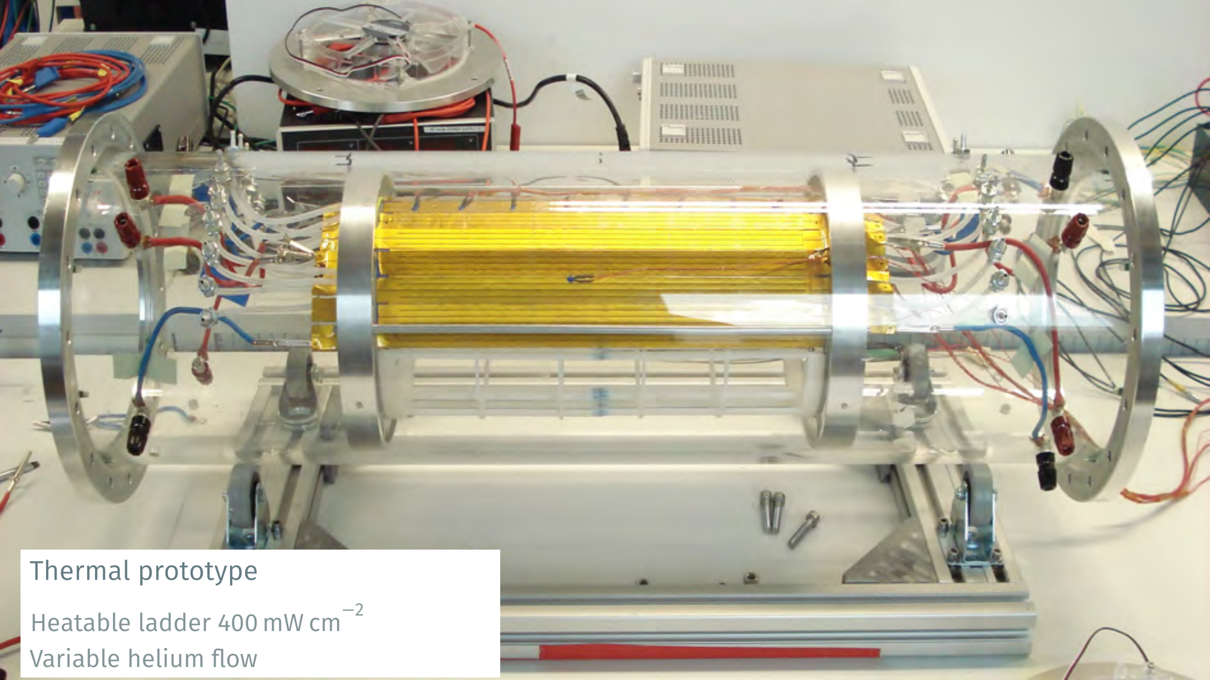
4x4 tile prototype

Test beam measurements at DESY

Cooling



- Cooling with gaseous helium
- Global and local flow



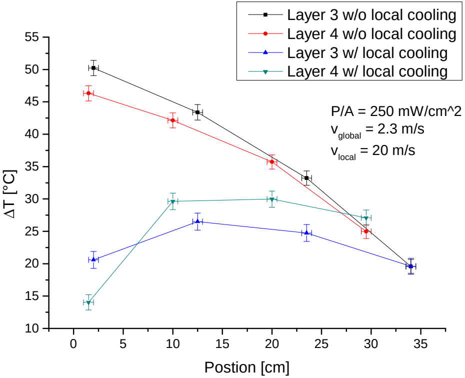
Thermal prototype

Heatable ladder $400\,\mathrm{mW\,cm^{-2}}$

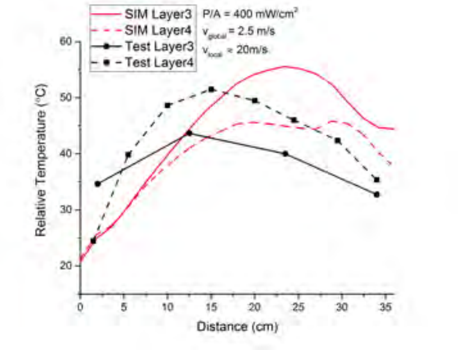
Variable helium flow

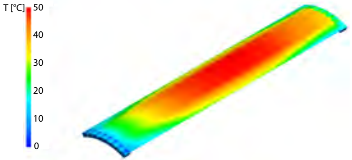
Cooling tests

Global/local cooling

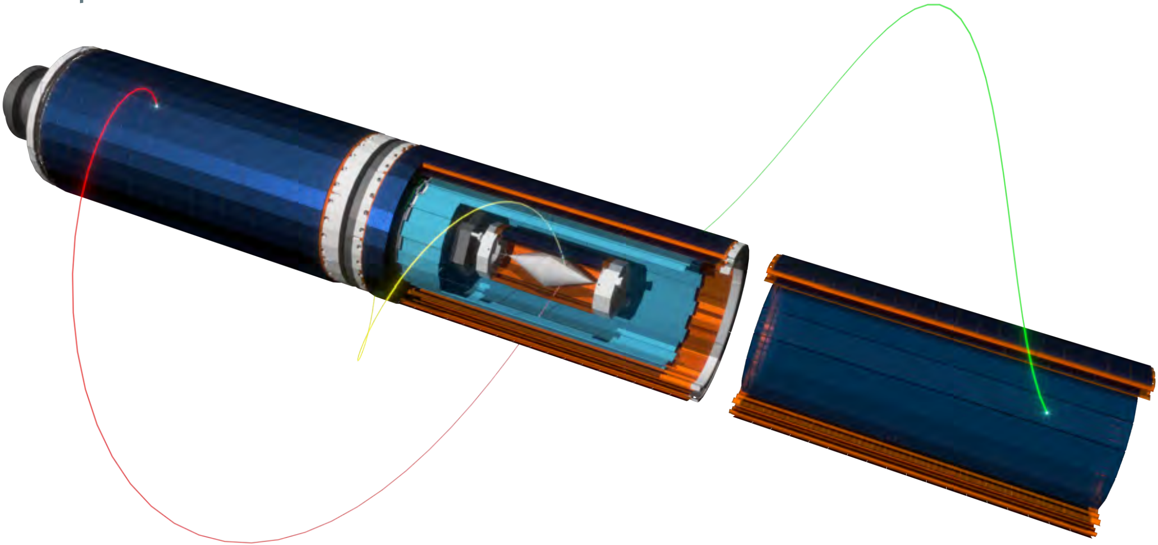


FEM simuations

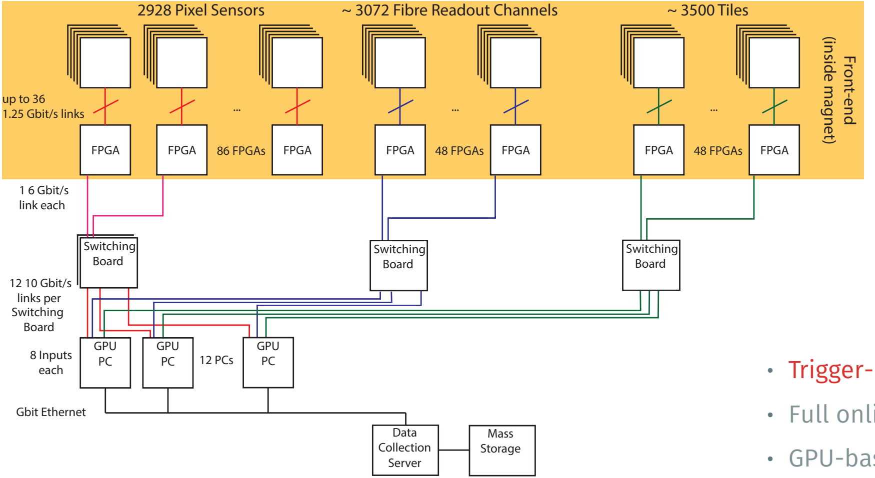




Full phase I detector



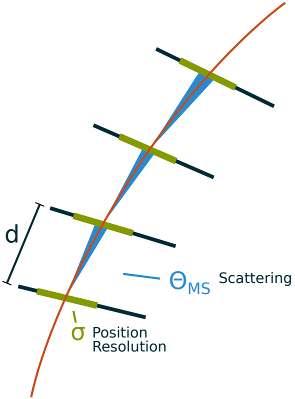
Readout architecture



- Trigger-less
- Full online reconstruction
- GPU-based filter farm

Tracking with multiple scattering

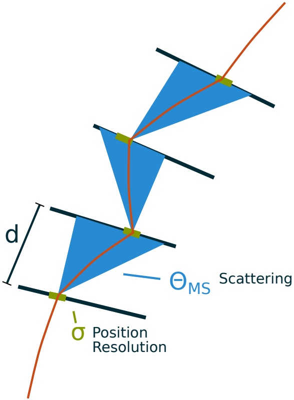
Dominating position



Reconstruction

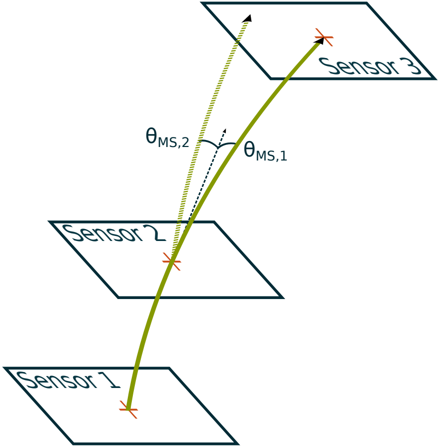
- Kalman filter
- General Broken Lines
- Anything else?

Dominating scattering



Mu3e is here

Triplet(s) track fit



Assumptions:

- No position error
- No energy loss
- Thin scatterer at middle hit

Minimize:

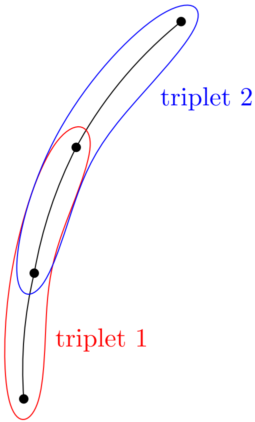
$$\chi_i^2(R_{3D}) = \frac{\varphi_{MS}(R_{3D})^2}{\sigma_\varphi^2} + \frac{\theta_{MS}(R_{3D})^2}{\sigma_\theta^2}$$

Problem: highly non-linear

Solution: linearize around circle

Berger et al., NIM A844 135–140

Triplet(s) track fit



1. Define overlapping triplets

$$\chi^2(\bar{R}_{3D}) = \sum \chi_i^2$$

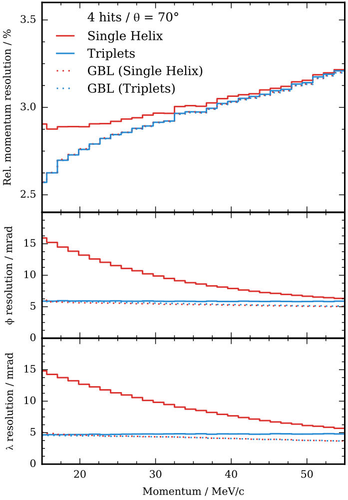
2a. Minimize χ^2 globally

2b. Equivalent: minimize each triplet

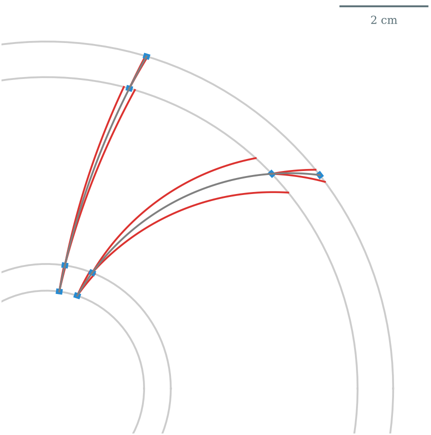
$$\bar{R}_{3D} = \frac{\sum w_i R_{3D,i}}{\sum w_i}$$

Simplified simulation

Track resolution



Layout and uncertainties

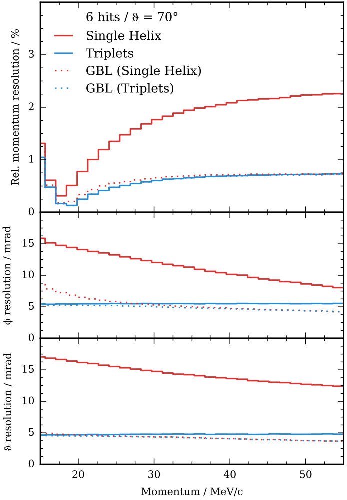


Uncertainties increased by factor 5

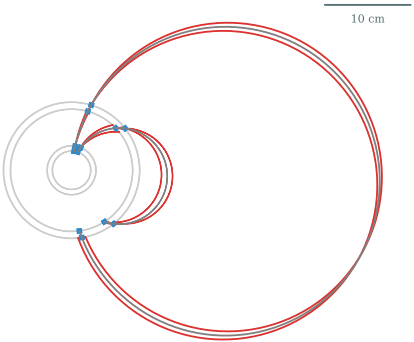
Berger et al., NIM A844 135–140

Simplified simulation

Track resolution



Layout and uncertainties

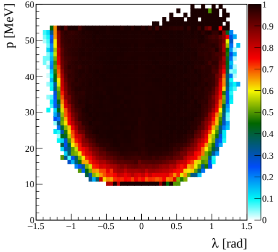


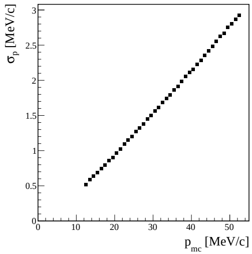
Uncertainties increased by factor 5

Berger et al., NIM A844 135–140

Phase I full simulation and reconstruction

Tracking efficiency

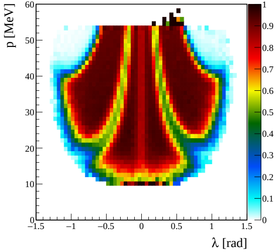


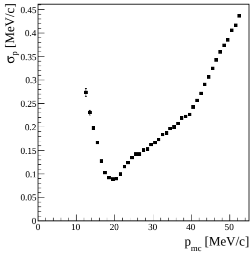


Momentum resolution

Only central tracker

4 hits

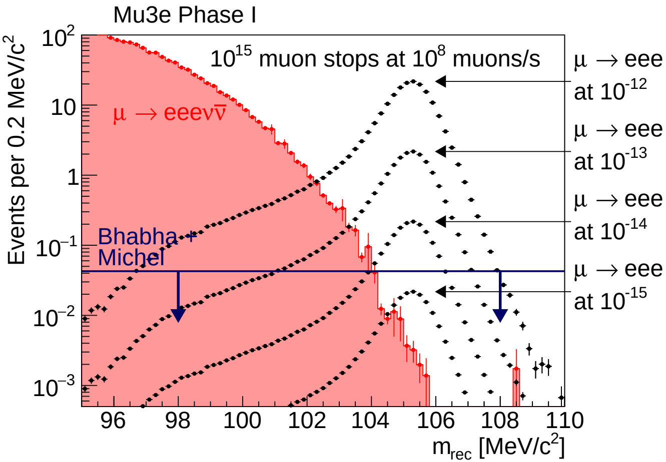




With recurl stations

6 hits

Phase I sensitivity

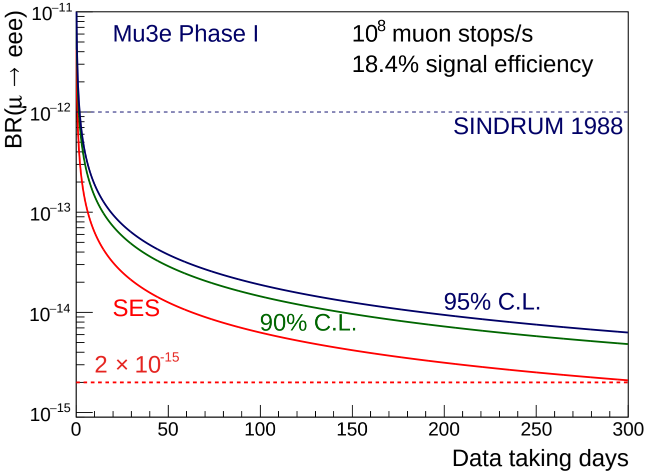


Simulated signal and background

Different signal branching ratios.

Expected background sources.

Phase I sensitivity



Simulated sensitivity

Summary

Summary

- Search for $\mu^+ \longrightarrow e^+ e^- e^+$
- Phase I sensitivity: 2 in 10^{15} decays

Status

- Technical design report submitted (January 2017)
- Detector R&D
- First prototype in 2017/2018