Searching for Lepton-Flavour Violation with the Mu3e Experiment

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BEYOND STANDARD MODEL

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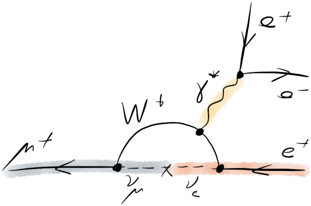
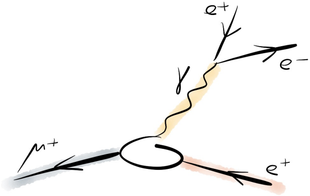
Charged Lepton Flavour Violation in $\mu \to eee$

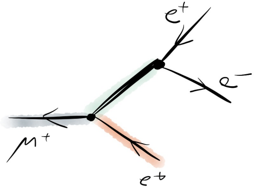
Expectation from neutrino mixing:

$$\mathrm{BR}_{\mu \to eee} \sim \left(\frac{\Delta m_\nu^2}{m_W^2} \right)^2 < 10^{-54}$$



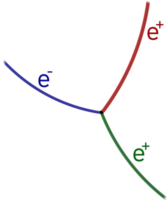
Observation of $\mu \to eee$ is a clear sign for New Physics



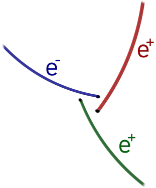


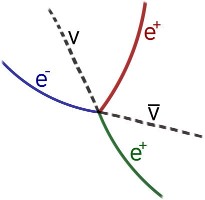
Signal and Background

Signal



Background





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

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

Combinatorial background

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

The Mu3e Experiment

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

Mu3e Sensitivity of one in 10^{15} (10^{16}) μ decays

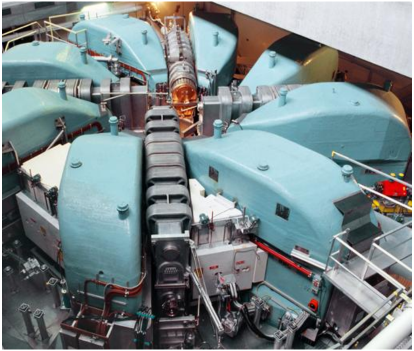
High muon stopping rates

- Phase I: $10^{8} \mu/s$
- Phase II: $> 10^{9} \mu/s$

Background suppression

- Very good vertex and time resolution
- Excellent momentum resolution

Muon Beam



Paul-Scherrer Institute

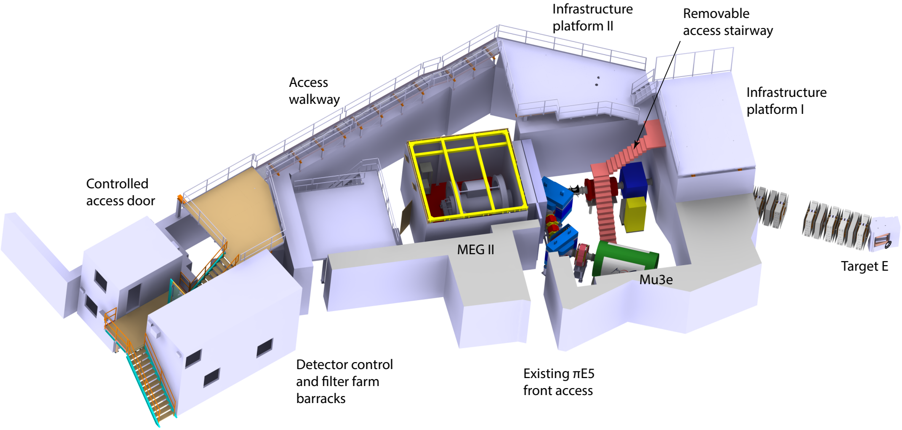
2.2 mA proton beam with 590 MeV

Secondary beamlines:
sub-surface μ^+ with 28 MeV

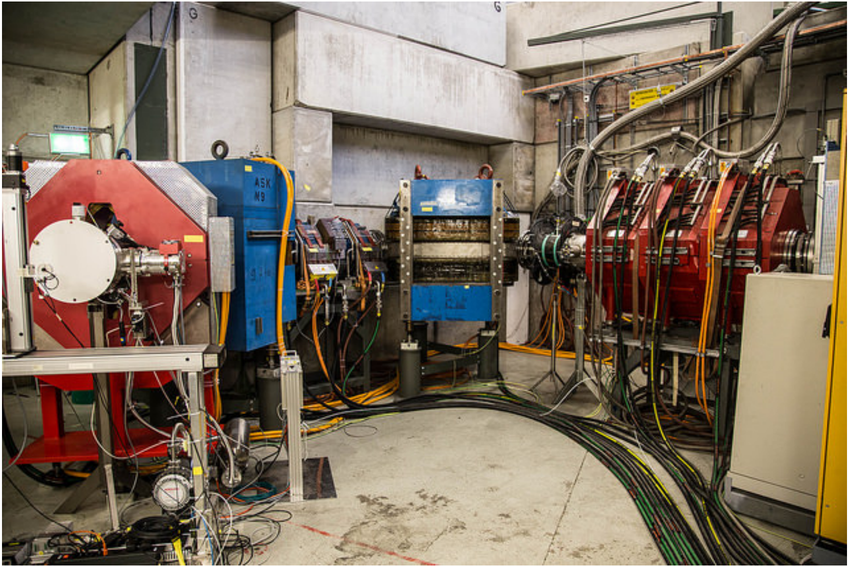
10^8 muons/s at existing beamline πE5

10^9 muons/s at future beamline HiMB
(under investigation)

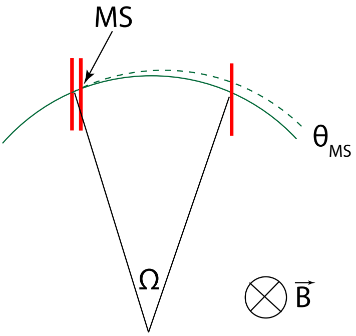
Experimental Area



Experimental Area



Multiple Coulomb Scattering



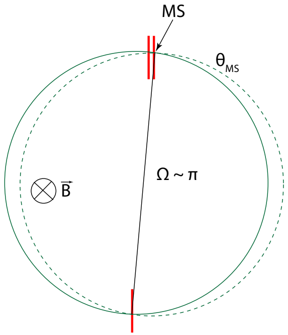
- Decay electrons have low momentum $< 53\,\mathrm{MeV/c}$
- Momentum resolution is dominated by multiple scattering

$$\frac{\sigma_p}{p} \sim \frac{\theta_{\mathrm{MS}}}{\Omega} \text{ with } \theta_{\mathrm{MS}} \propto \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

→ reduce material thickness x

→ increase opening angle Ω

Multiple Coulomb Scattering



- Decay electrons have low momentum < 53 MeV/c
- Momentum resolution is dominated by multiple scattering

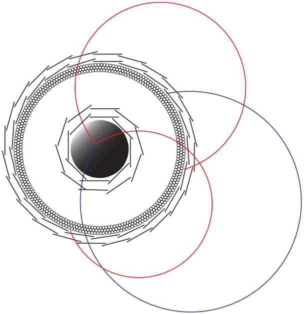
$$\frac{\sigma_p}{p} \sim \frac{\theta_{\mathrm{MS}}}{\Omega} \text{ with } \theta_{\mathrm{MS}} \propto \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

→ reduce material thickness x

→ increase opening angle Ω

at $\Omega \approx \pi \Rightarrow \frac{\sigma_p}{p} \sim \mathcal{O}(\theta^2_{\mathrm{MS}})$

Multiple Coulomb Scattering



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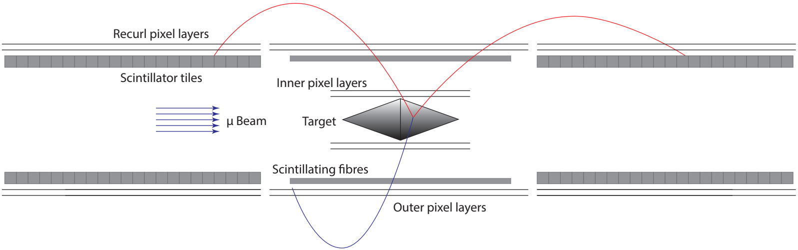
The Detector in Phase I



Tracking detector:
Thin Si pixel sensors (HV-MAPS)

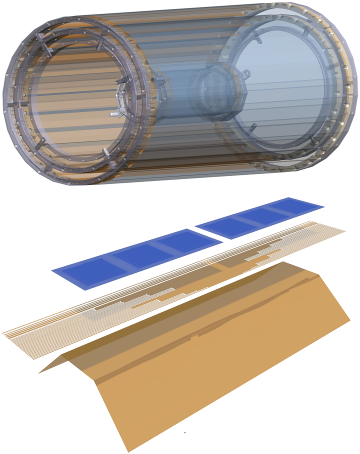
+ Timing detector:
Scintillating fibres and tiles

Stopping rate of $10^8 \mu/s$
B-field of 1 T

Length: 110 cm
Diameter: 18 cm

Pixel Tracker

Measure low momentum electron tracks with excellent precision



Minimize material to reduce multiple Coulomb scattering:

- Thin Si pixel sensors
- Flexible printed circuit boards
- Kapton support structure

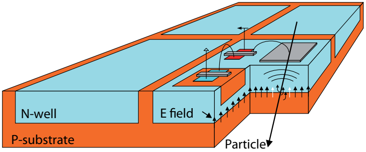
→ 1.16 ‰ radiation lengths

- Cooling with gaseous helium

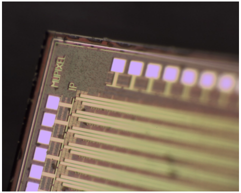
Pixel Sensors: HV-MAPS

High Voltage Monolithic Active Pixel Sensors

- AMS 180 nm HV-CMOS process
- N-well in p-substrate
- Reverse bias of ~ 80 V
  - Fast charge collection via drift
  - Depletion zone of ~ (10 – 20) µm
    Thinning possible ($\lesssim$ 50 µm)
- Integrated readout electronics
  - Signal amplification and shaping in N-well
  - Digitisation and zero-suppression in periphery
- Pixel size $80 \times 80 \mu m^2$
  Sensor size $2 \times 2 cm^2$



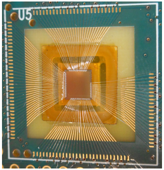
I. Perić, NIM A 582 (2007)

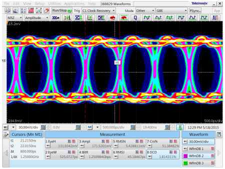


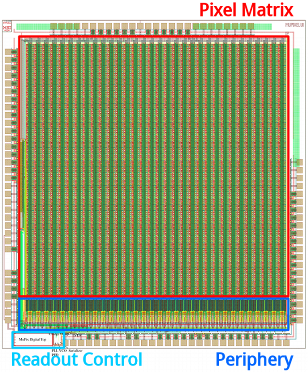
Pixel Sensors: MuPix Prototype

MuPix7: HV-MAPS prototype for Mu3e

- 32×40 pixels à $103 \times 80\mu m^2$
- $2.9 \times 3.2 mm^2$ of active area
- 50 µm thin
- ‘System-on-chip’
- Zero-suppressed hit addresses and timestamps







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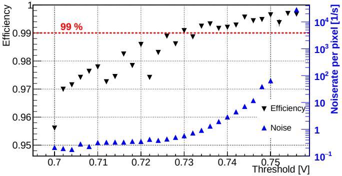
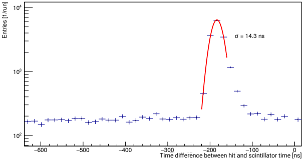
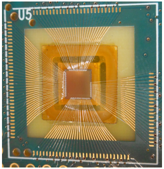
- Zero-suppressed hit addresses and timestamps

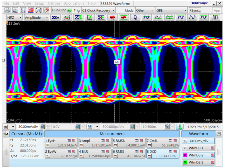
Efficiency $> 99\,\%$

Timing resolution $< 20\,\mathrm{ns}$









Pixel Sensors: MuPix Prototype

Latest prototype: MuPix8

→ Arrived in August

- First large MuPix sensor: $2 \times 1\text{cm}^2$
- 128×200 pixels à $81 \times 80\mu\text{m}^2$
- Analogue pulse information
- Different substrates:
  $20\,\Omega\,\text{cm}$ and $80\,\Omega\,\text{cm}$

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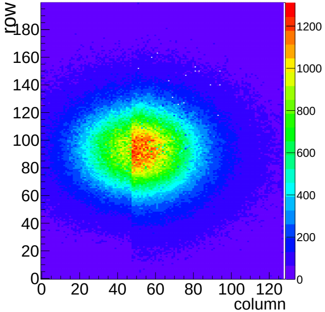

Preliminary hitmap of a Sr-90 source

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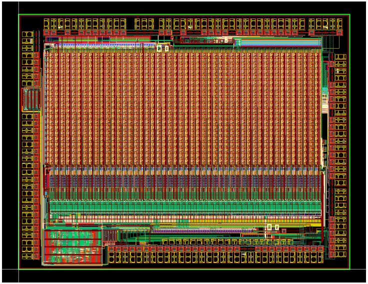

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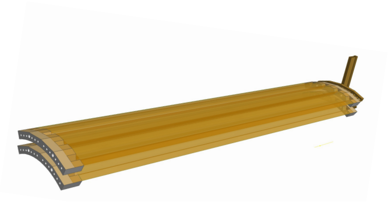
MuPix9 submitted in August

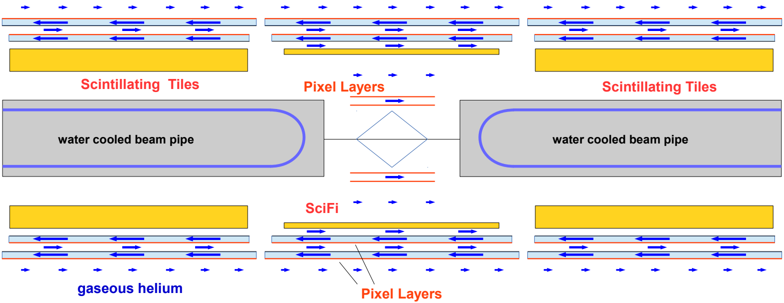
- Small-scale prototype
- Slow control, serial powering

Cooling

Cooling with gaseous helium

Power consumption of Si pixel sensors is 250 mW/cm^2





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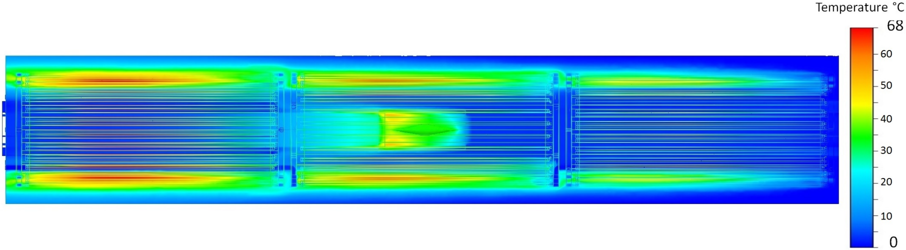
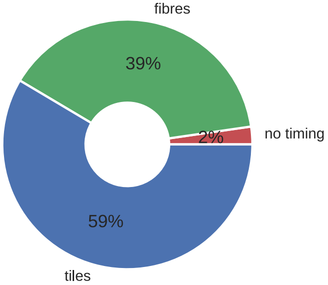
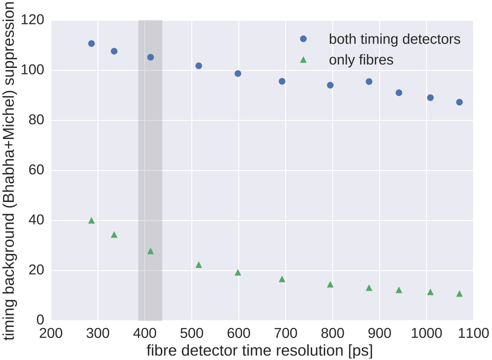


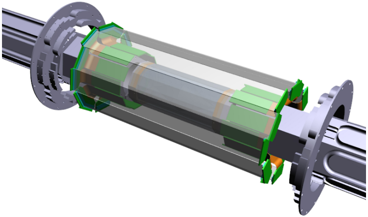
Timing Detector

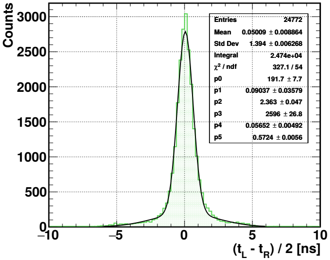
Suppression of combinatorial background by a factor of 100





Scintillating Fibres



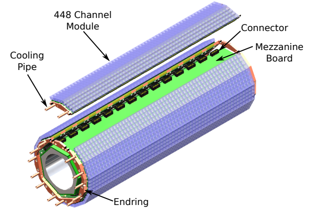


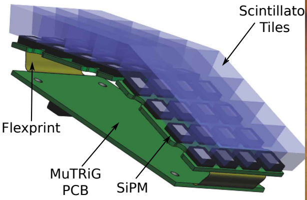
Time resolution of square fibres

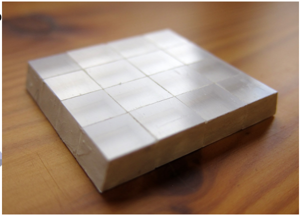
- 3 layers of fibres with $\varnothing \sim 250\,\mu\mathrm{m}$ and length of 28 to 30 cm
- Round and square fibres under investigation
- Photon detection at both ends with LHCb SiPM column array
- Readout with custom-designed MuTRiG

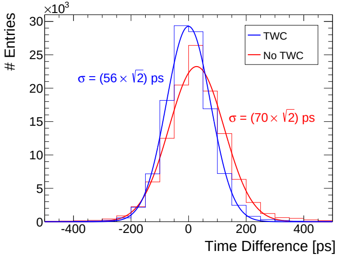
- Prototype with 3 layers of square multiclad fibres: $\sigma_t = (572 \pm 6)\mathrm{ps}$ and $\epsilon \gtrsim 95\,\%$

Scintillating Tiles



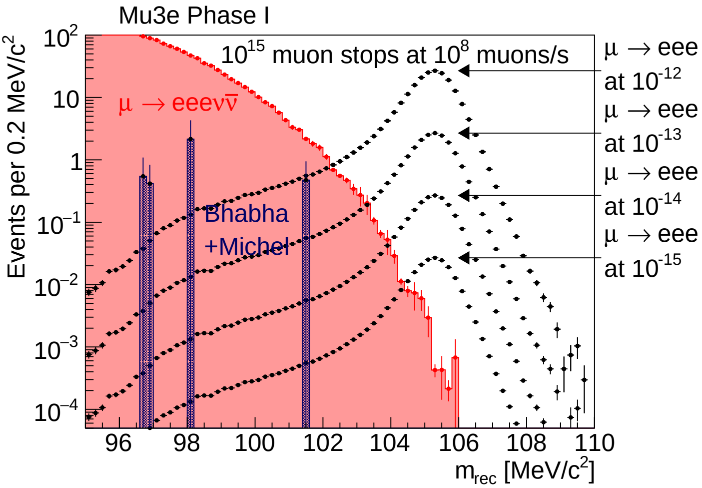






- $6.5 \times 6.5 \times 5.0\text{mm}^3$ tiles with individual SiPMs
- Custom-designed MuTRiG: TDC ASIC for SiPM readout
- Prototype yields time resolution $\sim 70\,\text{ps}$ and efficiency $\epsilon \gtrsim 99.7\,\%$

Simulation Results for Phase I



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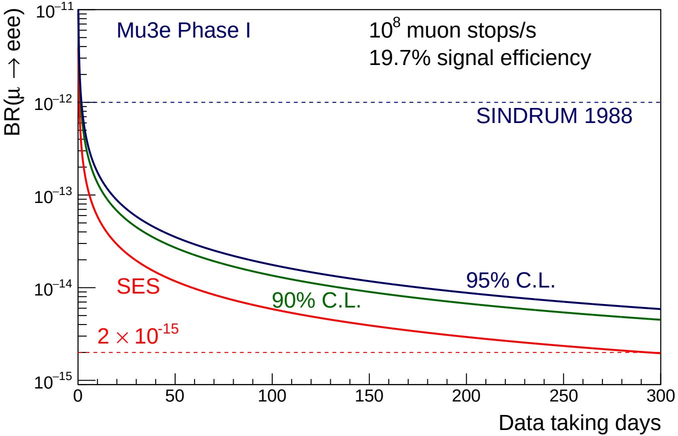


Summary

Mu3e Search for LFV decay $\mu \to eee$
with a sensitivity of BR $< 10^{-16}$

Low-material tracking detector

- High muon rates
- Thin Si pixel sensors
- Scintillating fibres and tiles

Phase I Prospected single-event sensitivity of
$2 \cdot 10^{-15}$ in 300 days of data taking

Phase II Ultimate sensitivity with detector upgrade
and high intensity muon beamline

Status

Finalizing detector design for phase I
Preparing for construction and commissioning

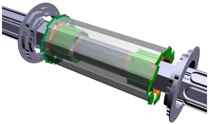
Pixel MuPix8 is first large scale prototype
In the lab and running
MuPix10 could be used for module building (2^{nd} half of 2018)

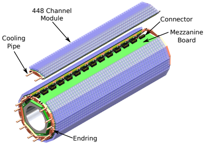
Timing Very successful prototypes
for tiles and fibres
MuTRiG is being characterized

Mechanics Challenging due to tight spacial constraints
Integration well advanced

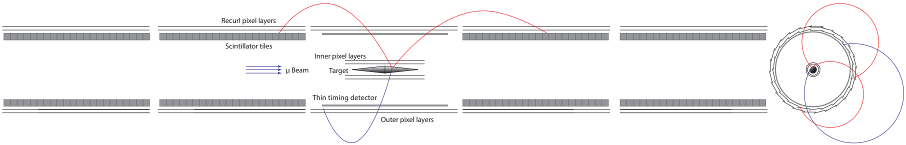
Magnet Expected 1^{st} half of 2019

Technical design report to be published soon





The Phase II Detector

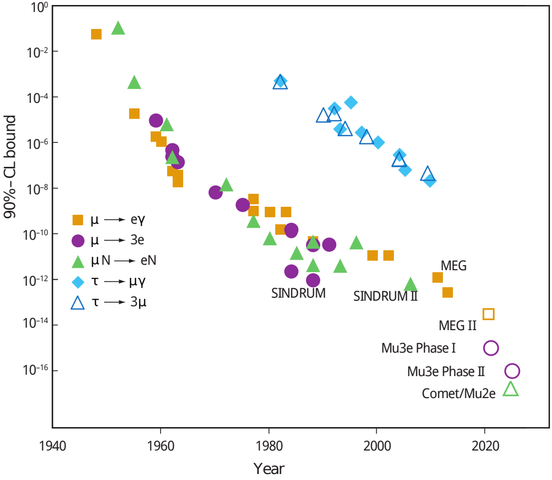


Increase muon stopping rate to $2 \cdot 10^9$ μ/s

Additional recurl stations increase acceptance for recurler

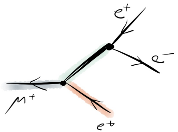
Smaller beam profile ⇒ smaller target radius

History of cLFV Searches in μ and τ Decays

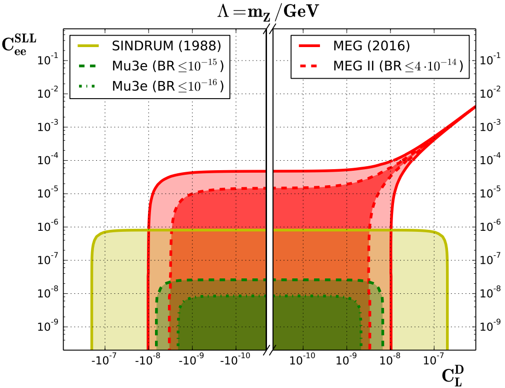


Adapted from Marciano et al. [Ann.Rev.Nucl.Part.Sci.58, 2008]

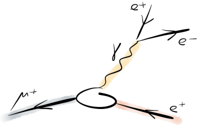
Charged Lepton Flavour Violation



$O_{ee}^{SLL} = (\bar{e}P_L\mu)(\bar{e}P_L e)$

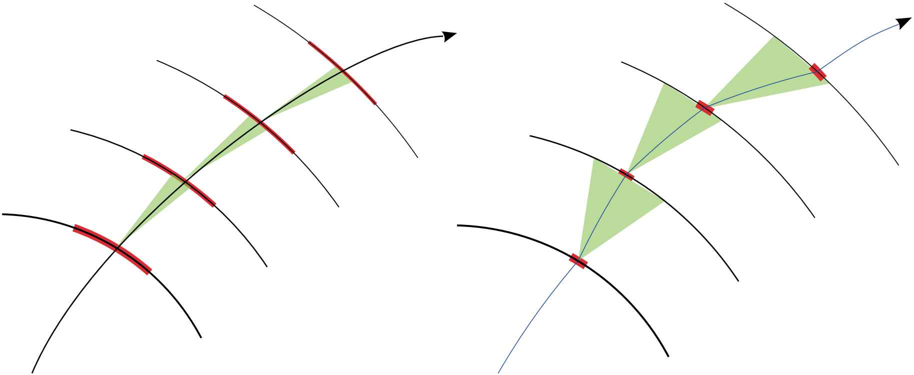


Crivellin, Davidson, Pruna, Signer [arXiv:1611.03409]

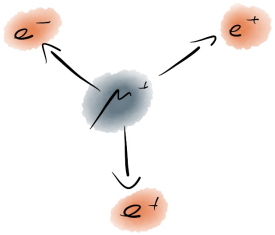


$O_L^D = e m_\mu (\bar{e}\sigma^{\mu\nu} P_L \mu) F_{\mu\nu}$

Tracking in MS-dominated Environment



Signal Decay $\mu \to eee$

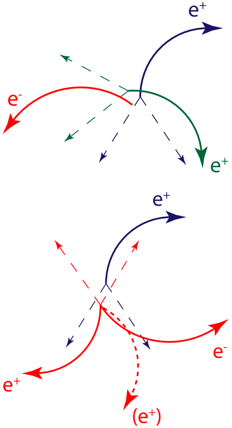


Signature for μ decay at rest

- Common vertex
- Coincident in time
- $\sum E_e = m_\mu c^2$
- $\sum \vec{p}_e = 0$

- $E_e = (0 - 53)\,\mathrm{MeV}$
- Multiple Coulomb scattering limits momentum resolution $\sigma_p \propto \sqrt{x}$

Background: Combinatorial Background



Overlays of Michel decay $\mu \to e\nu\nu$, Bhabha scattering, photon conversion, ...

- No common vertex
- Not coincident
- $\sum E_e \neq m_\mu c^2$
- $\sum \vec{p}_e \neq 0$

- Increases with beam intensity

Background: $\mu \rightarrow ee e\nu\nu$

$\mathrm{BR}_{\mu^+ \rightarrow e^+ e^- e^+ \overline{\nu}_\mu \nu_e} = (3.4 \pm 0.4) \cdot 10^{-5}$ [Nucl.Phys.B260, 1985]

Common vertex

Coincident in time

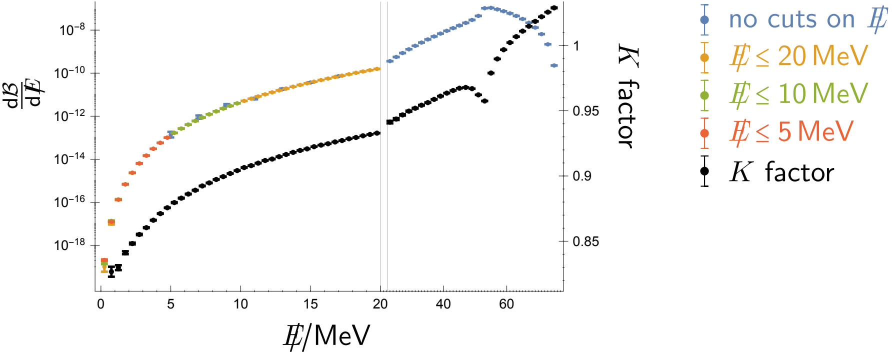
$\sum E_e < m_\mu c^2$

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

→ Missing energy due to neutrinos

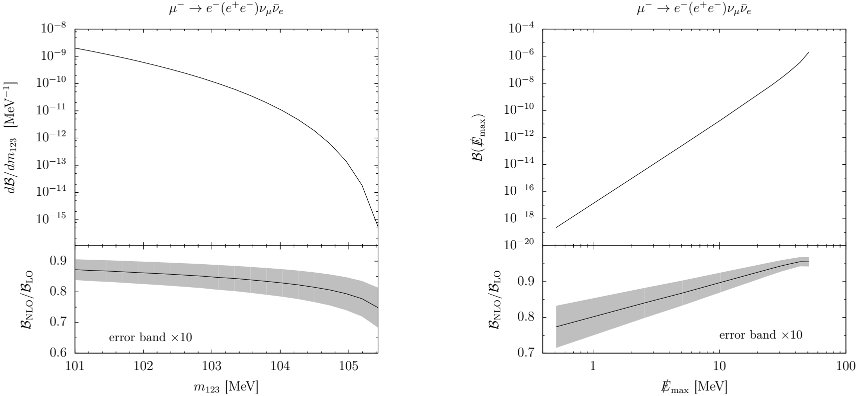
Need very good momentum resolution

Background: $\mu \to eee\nu\nu$



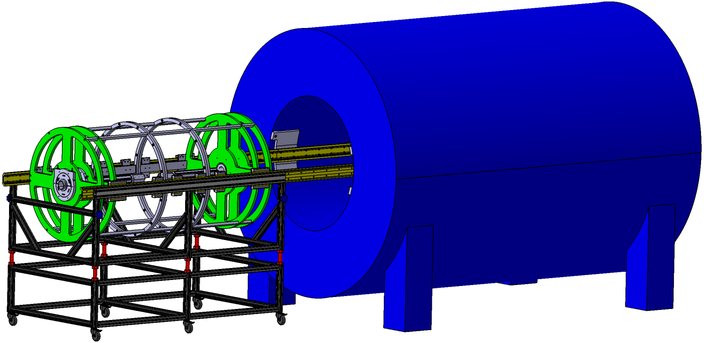
NLO calculations for $\mu \to eee\nu\nu$: Pruna, Signer, Ulrich [arXiv:1611.03617]

Background: μ → eeeνν

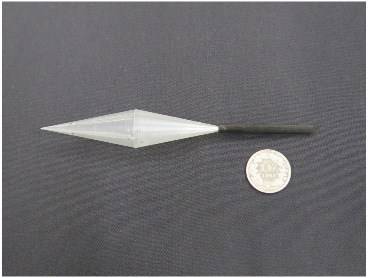


NLO calculations for μ → eeeνν: Fael, Greub arXiv:[1611.03726]

Magnet and Detector Cage



Target



Extended hollow double-cone target made of 75 μm to 85 μm mylar foil

10 cm long with a radius of 19 mm

High stopping muon stopping rate

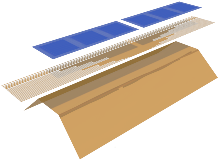
Vertex separation over a large surface

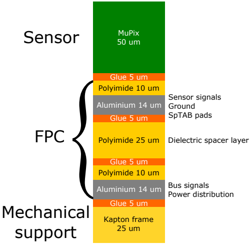
Low distortion for ‘escaping’ electrons

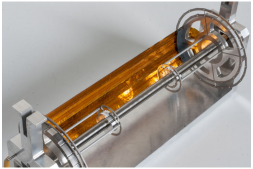
Lightweight Mechanics

- 50 µm silicon sensor
- 80 µm Flexible printed circuit board (FPC)
- 25 µm Kapton support structure

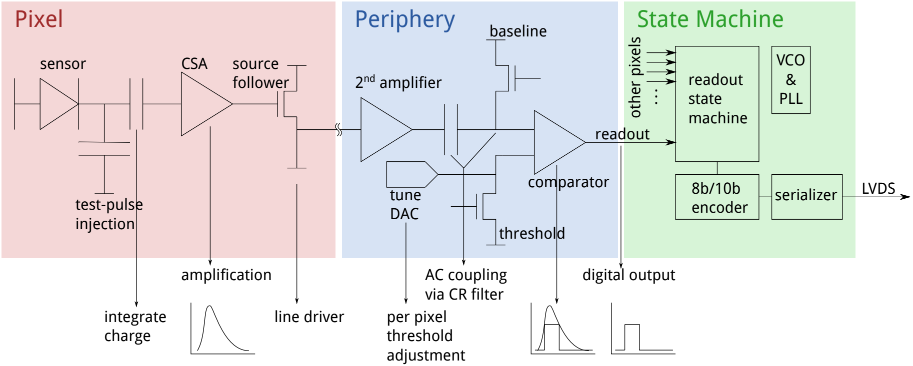
→ $\sim 0.1\,\%$ of radiation length







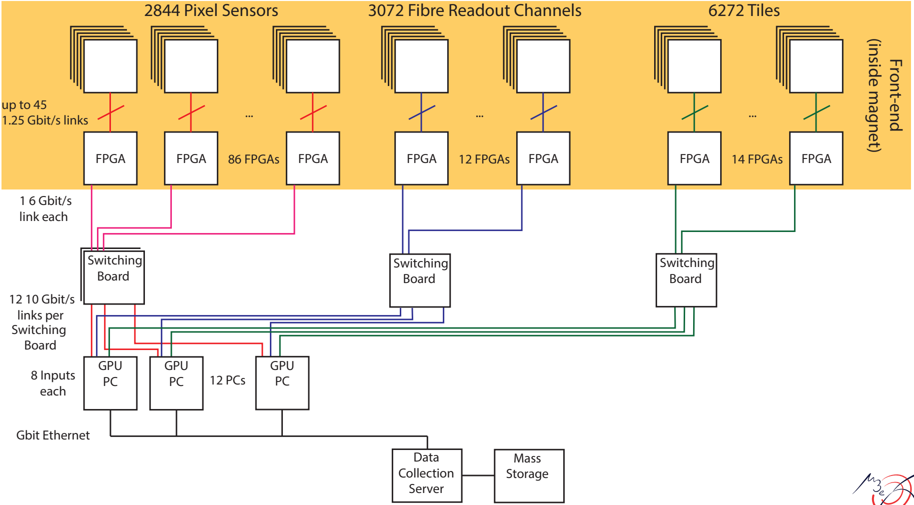
Pixel Sensors: HV-MAPS



Hit finding, digitisation, zero-suppression and readout on-chip

Continuous and fast readout at 1.25 Gbit/s

Data Acquisition



Data Acquisition

Triggerless data acquisition

Front-end board

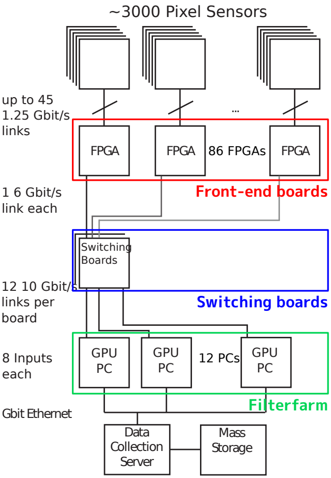
- Slow control
- Buffer and merge data
- Time-sorting

Readout board

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

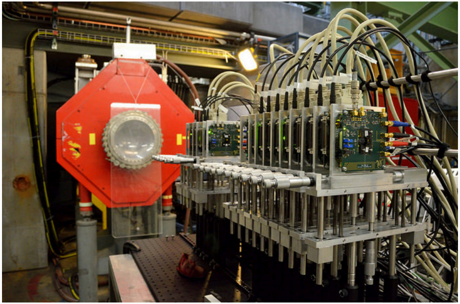
GPU filterfarm

- Fast track finding and online reconstruction
- Reduce data rate by a factor of ~ 80



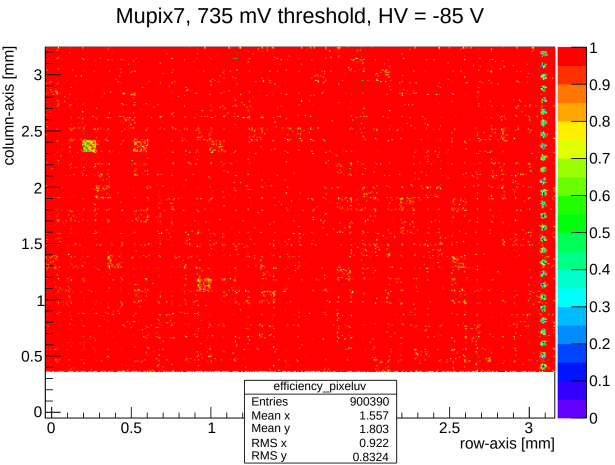
MuPix Telescope

- Tests of new prototypes and system integration
- 4 or 8 planes of MuPix7
- Scintillating tiles
- Readout via Altera Stratix IV development boards
- Test beam at PSI, DESY, SPS, MAMI



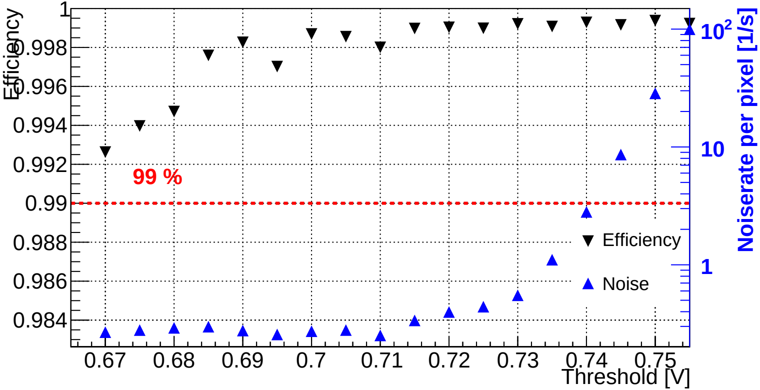
MuPix7 Results

Testbeam at DESY: 4 GeV e^+ beam; using DESY Duranta telescope

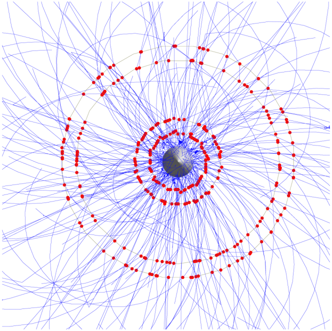


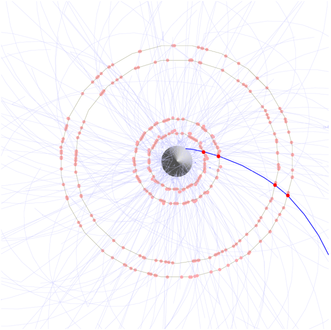
MuPix7 Results

Testbeam at DESY: 4 GeV e^+ beam; DUT rotated by 60° wrt to beam axis



Timing Information

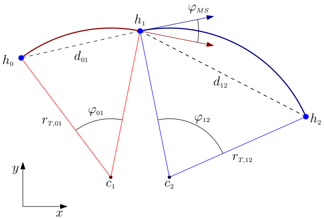


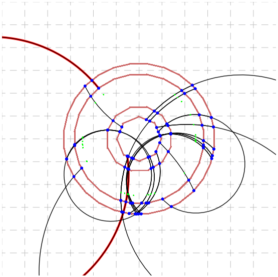


Tracks expected within readout frame of 50 ns

Matching with time information of scintillating fibres and tiles

Reconstruction



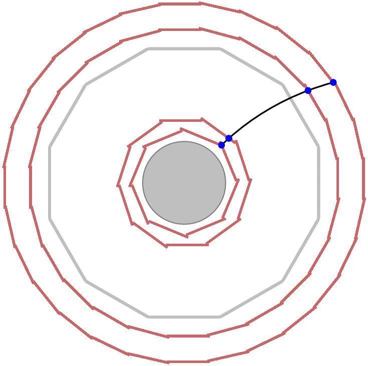


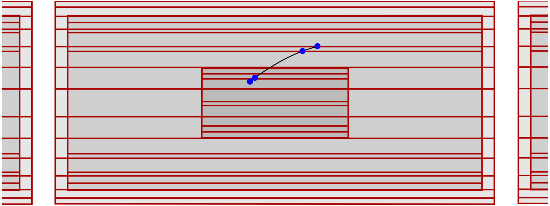
- 3D multiple scattering fit for track reconstruction
- Spatial uncertainties of hit positions are ignored as MS dominates

- Hits in 3 layers form a ‘triplet’
- Join triplets by minimizing MS angles

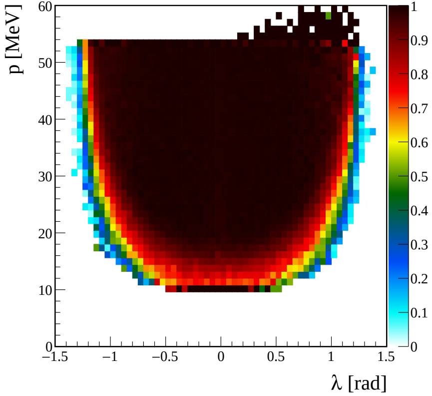
- Subsequent vertex fit with 3 trajectories of correct charge

Short Tracks: 4 Hits

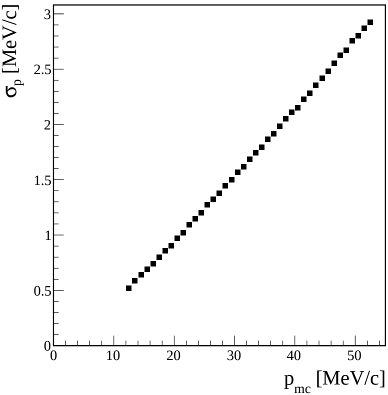




Short Tracks

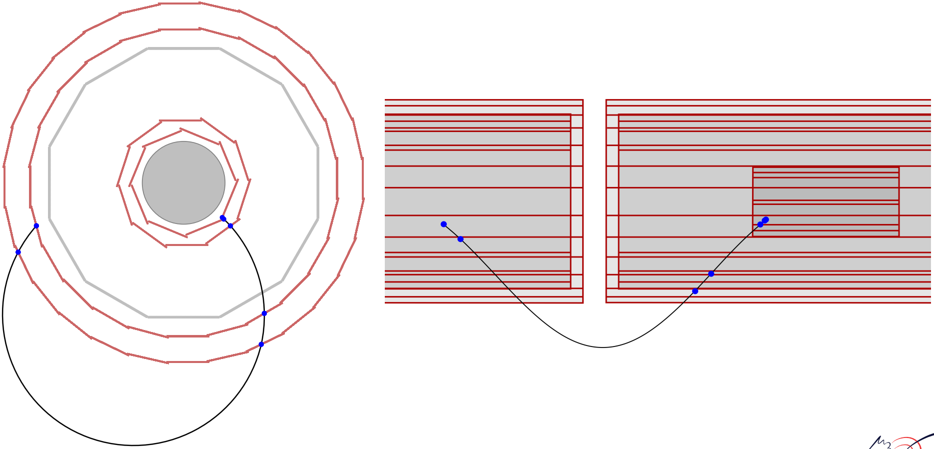


Efficiency.

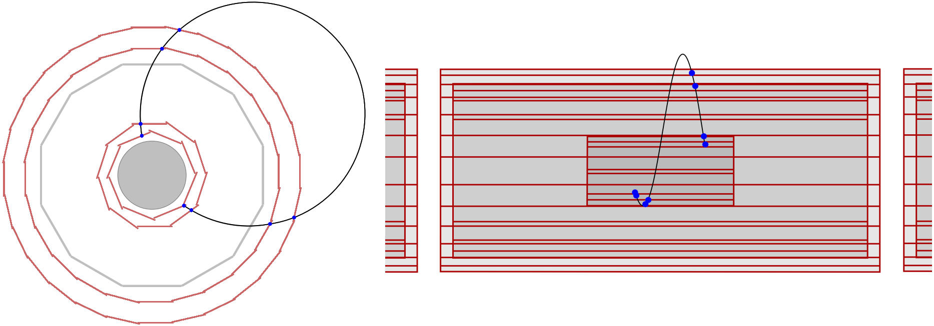


Momentum resolution.

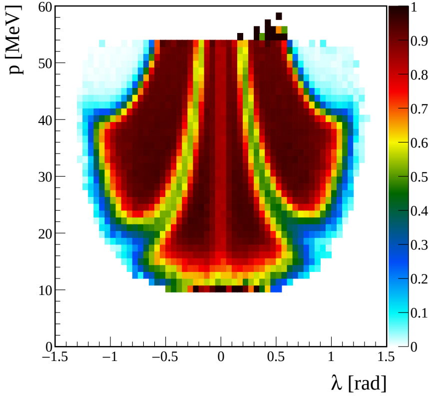
Long Tracks: 6 Hits



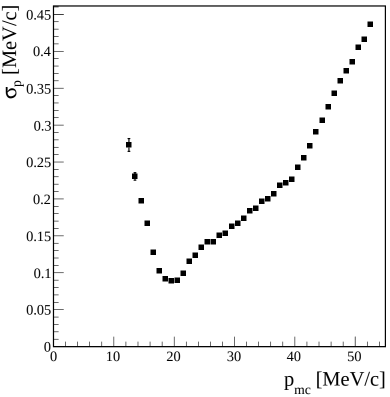
Long Tracks: 8 Hits



Long Tracks

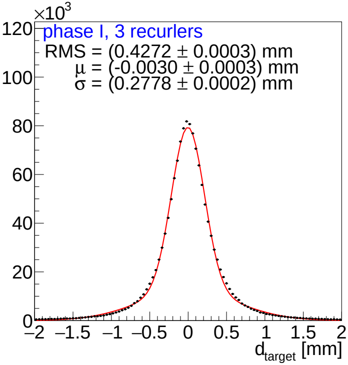


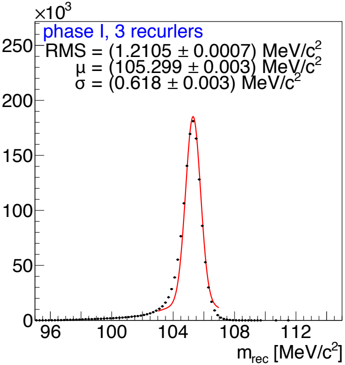
Efficiency.



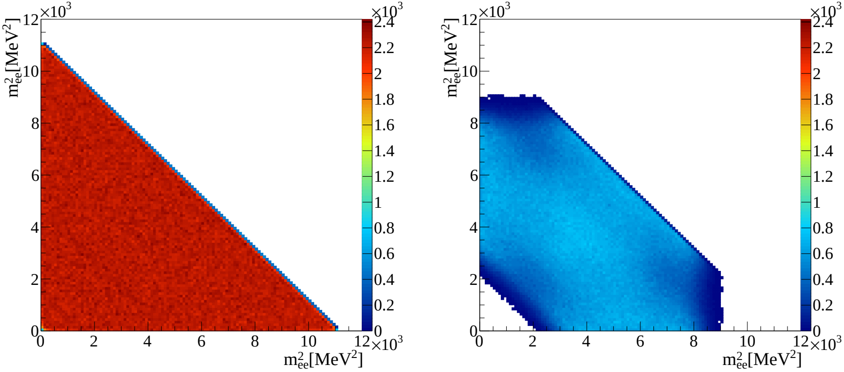
Momentum resolution.

Vertex Resolution and Mass Resolution of Signal Events





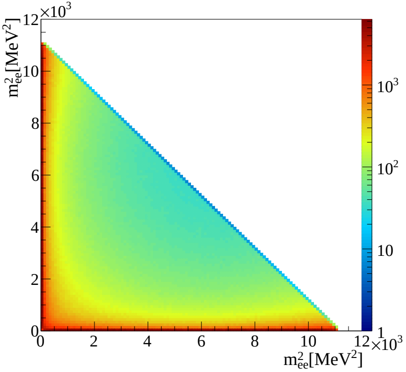
$\mu \to eee$: Phase Space



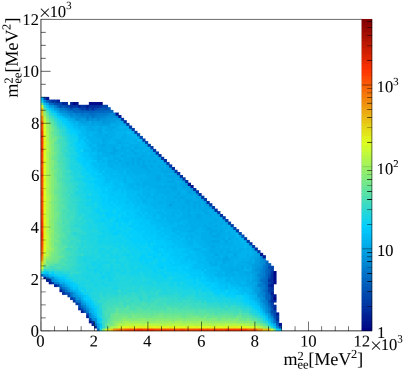
Generated

Truth information
after reconstruction and vertex fit

μ → eee: Effective Operator $em_\mu A_L \overline{\mu_L} \sigma^{\mu\nu} e_R F_{\mu\nu}$

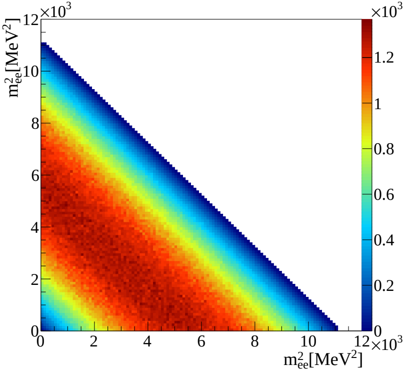


Generated



Truth information
after reconstruction and vertex fit

μ → eee: Effective Operator $(\overline{\mu_L} e_R)(\overline{e_L} e_R)$



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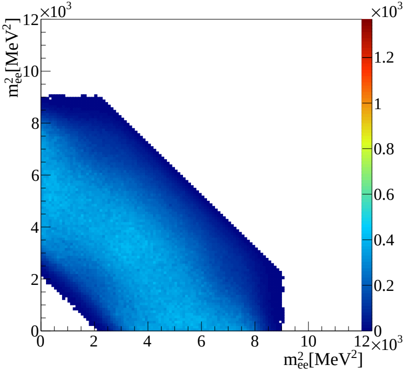
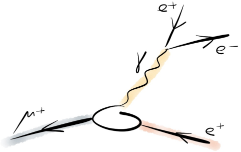


Truth information
after reconstruction and vertex fit

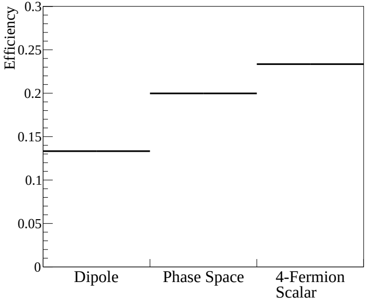
$\mu \rightarrow eee$: Effective Operators

Efficiency for reconstructing a $\mu \rightarrow eee$ decay

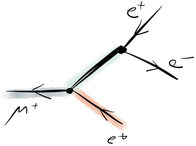
Dipole operator



$$e m_\mu A_L \overline{\mu_L} \sigma^{\mu\nu} e_R F_{\mu\nu}$$



4-fermion scalar operator

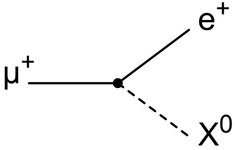


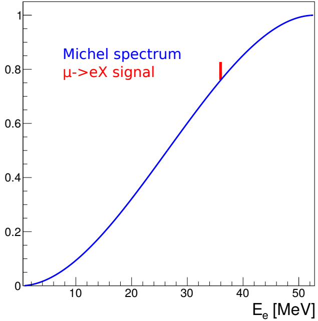
$$(\overline{\mu_L} e_R)(\overline{e_L} e_R)$$

Searching for $\mu \to eX$ with Mu3e

- Emission of unobserved neutral, light boson in $\mu^+ \to e^+ X^0$
- Familon: Goldstone boson of SSB of flavour symmetry [Wilczek, 1982]

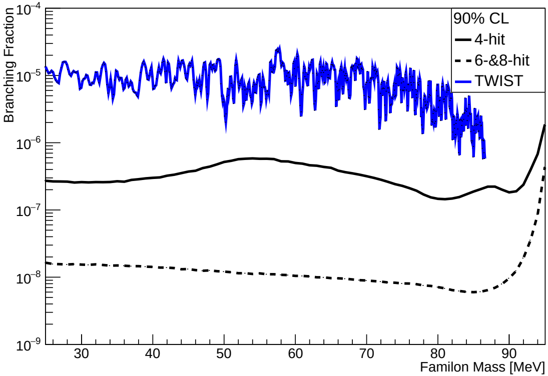
- Search for a peak on the e^+ momentum spectrum





Searching for $\mu \to eX$ with Mu3e

Sensitivity to $\mu \to eX$ for $1 \cdot 10^{15}$ muon stops using a toy MC study



TWIST results by courtesy of R. Bayes [arXiv:1409.0638]

Mu3e Collaboration

Founding members:

- University of Geneva
- Heidelberg University
- Karlsruhe Institute of Technology
- JGU Mainz
- Paul Scherrer Institute
- ETH Zürich
- University of Zürich

In the process of joining:

- University of Bristol
- University of Liverpool
- University College London
- University of Oxford