

Searches for New Physics with the Mu3e Experiment

Ann-Kathrin Perrevoort
on behalf of the Mu3e Collaboration

Physics Institute, Heidelberg University

DPG Spring Meeting Münster, March 29, 2017



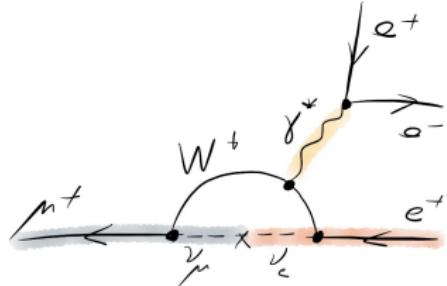
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The Mu3e Experiment

Charged lepton flavour violating decay: $\mu^+ \rightarrow e^+ e^- e^+$

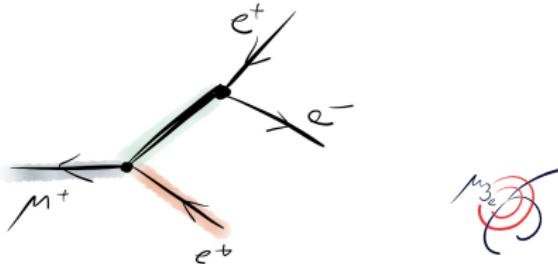
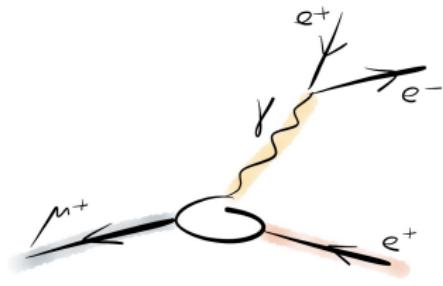
Expectation from lepton mixing:

$$\mathcal{B}_{\mu \rightarrow eee} \sim \left(\frac{\Delta m_\nu^2}{m_W^2} \right)^2 < 10^{-54}$$



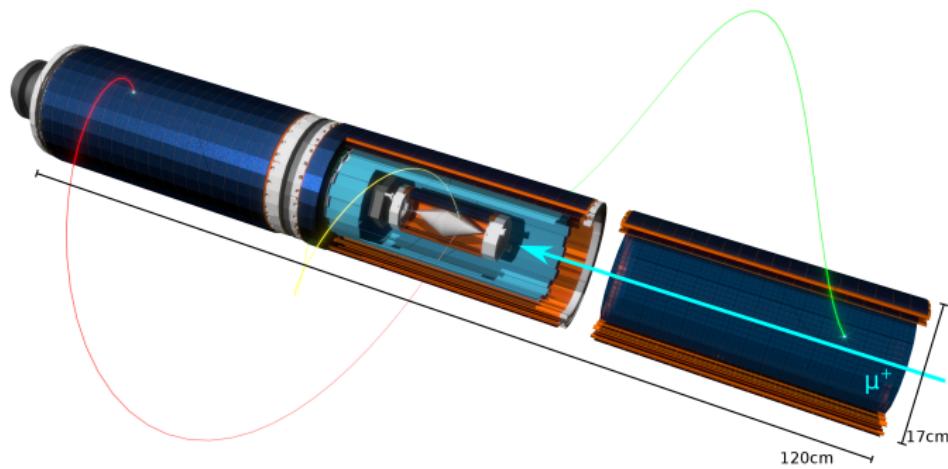
Observation of $\mu \rightarrow eee$ is a clear sign for New Physics

Mu3e: final sensitivity to $\mu \rightarrow eee$ of 1 in 10^{16} decays



The Mu3e Experiment

Measure e^+/e^- tracks precisely at muon rates of $\sim 10^8 \mu/\text{s}$ (phase I)



Tracking detector:

Thin Si pixel sensors (HV-MAPS)

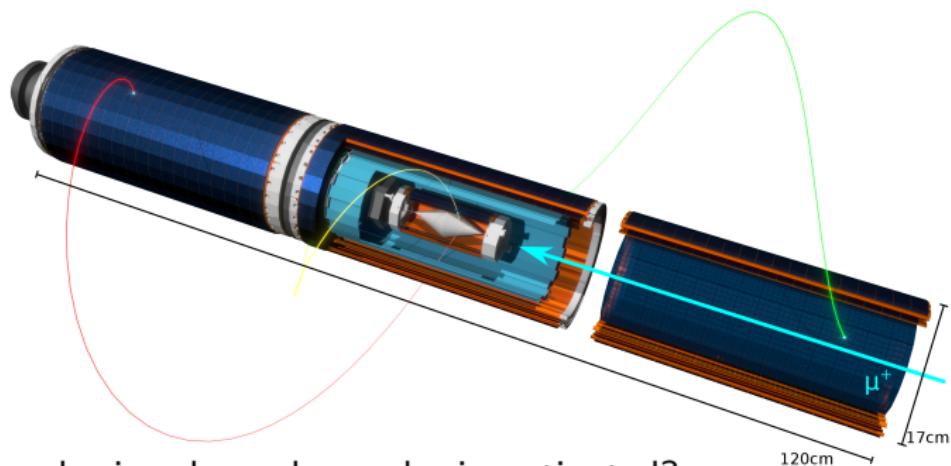
+ Timing detector:

Scintillating fibres and tiles



The Mu3e Experiment

Some 10^{15} muon decays to be observed in phase I



What other physics channels can be investigated?

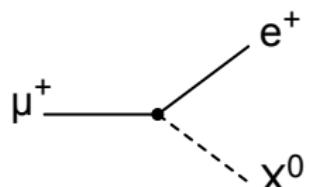


Decays with Familons: $\mu \rightarrow e X$

$$\mu^+ \rightarrow e^+ X^0$$

X is a neutral, unobserved, light boson

Familon is a Goldstone boson from the spontaneous breaking of flavour symmetry
[Wilczek, 1982]



Jodidio (1986): $\mathcal{B} < 2.6 \cdot 10^{-6}$ at 90 %CL for massless X

TWIST (2014): $\mathcal{B} < 8.1 \cdot 10^{-6}$ at 90 %CL on average for massive X



Searching for $\mu \rightarrow eX$ with Mu3e

$\mu^+ \rightarrow e^+ X^0$ is 2-body decay

Search for a peak on the
 e^+ momentum spectrum

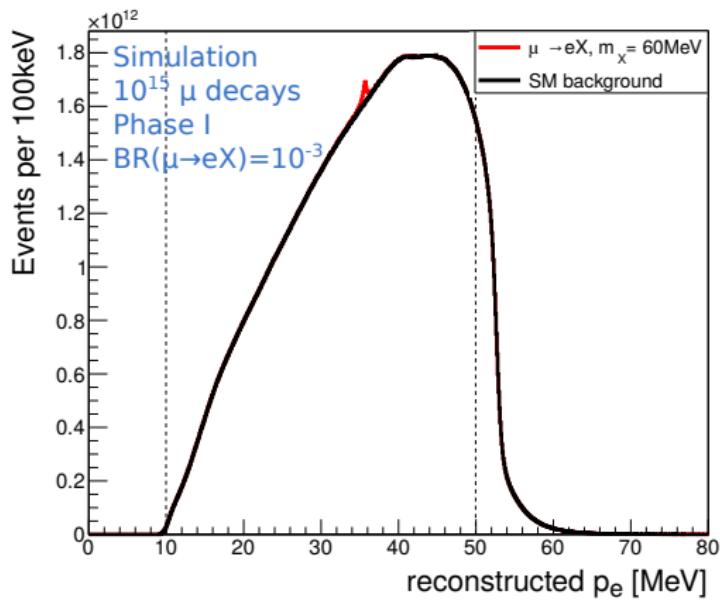
Background:

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

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

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

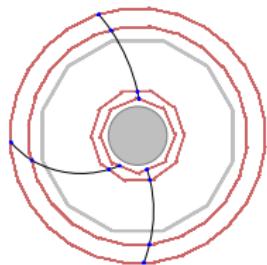
Bhabha scattering,
photon conversion, ...



Test $25\text{ MeV} \leq m_X \leq 95\text{ MeV}$

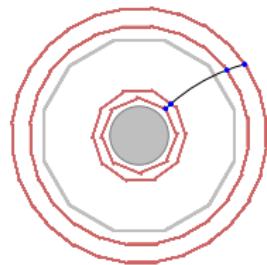


Searching for $\mu \rightarrow eX$ with Mu3e



$\mu \rightarrow \text{eee}$ search

- Tracks are reconstructed online
- Only events with $\mu \rightarrow \text{eee}$ candidates are kept



$\mu \rightarrow eX$ search

- Cannot store every track
- Keep histogram of momenta and emission angle

Online reconstruction

→ more on track reconstruction in T116.1

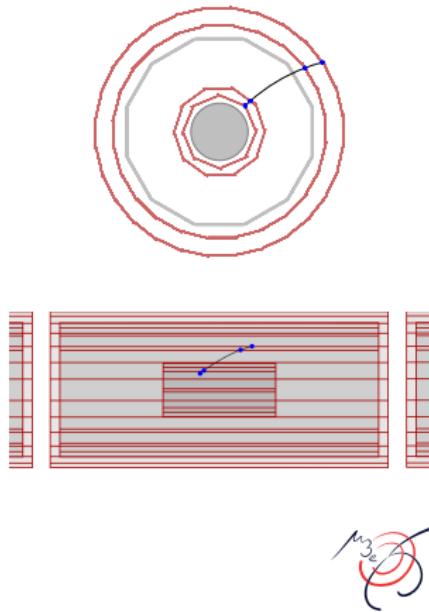
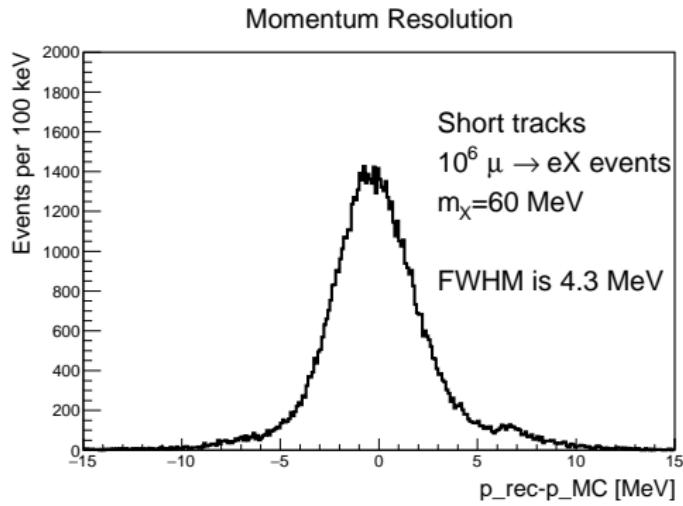
- Short tracks from hits in central detector
- Long tracks from recurling particles



Searching for $\mu \rightarrow eX$ with Mu3e

Short tracks

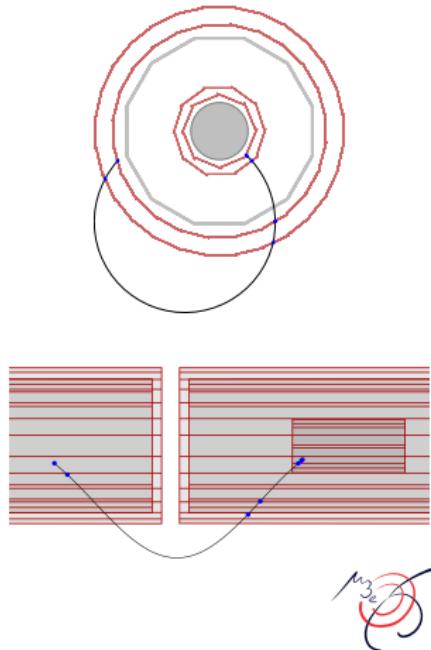
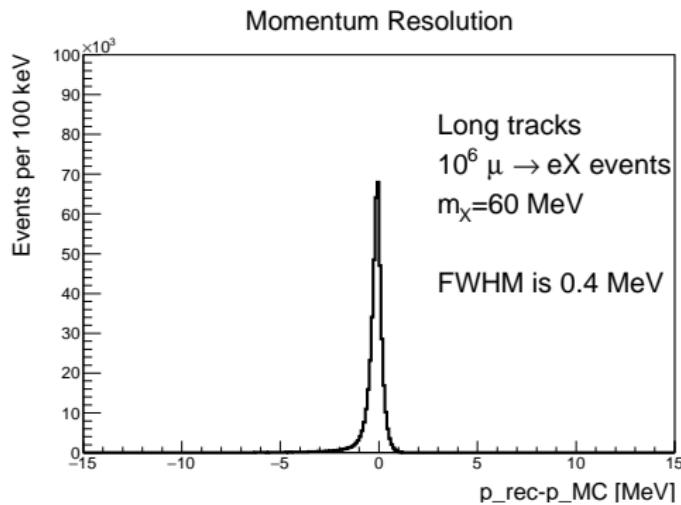
- Reconstructed from 4 hits in central detector
- Baseline design of Mu3e



Searching for $\mu \rightarrow eX$ with Mu3e

Long tracks: reconstructing recurling particles

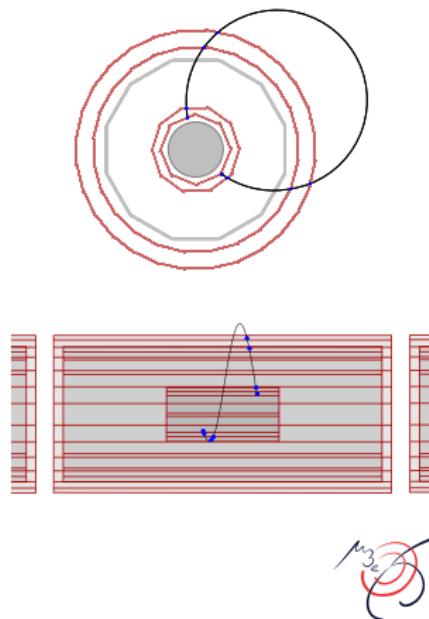
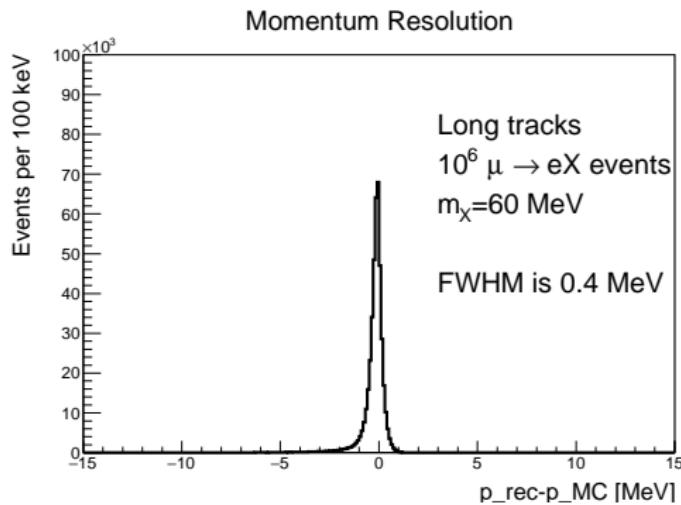
- Reconstructed from 6 or 8 hits in full detector
- Significantly improved momentum resolution
- Requires upgrade to filter farm



Searching for $\mu \rightarrow eX$ with Mu3e

Long tracks: reconstructing recurling particles

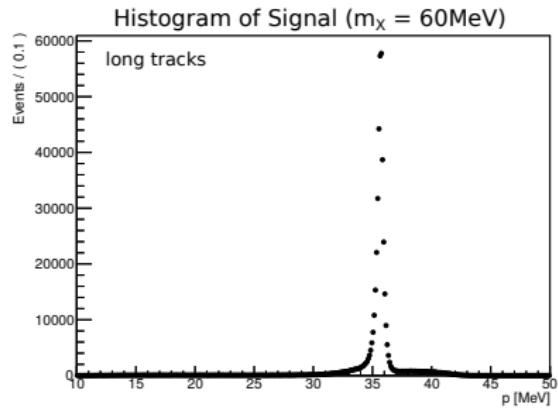
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Deriving Sensitivity Limits for $\mu \rightarrow eX$

Toy MC studies

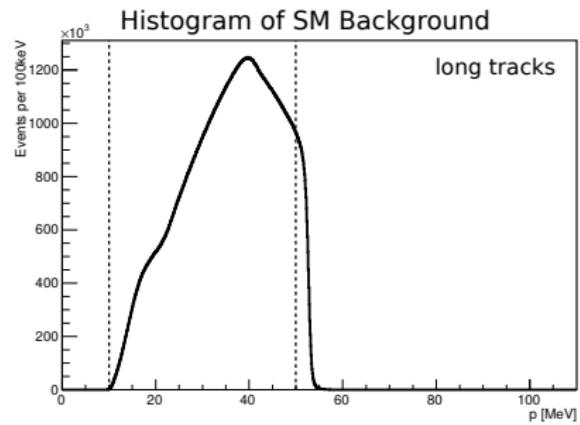
- PDF's for background b and signal s from simulation



Deriving Sensitivity Limits for $\mu \rightarrow eX$

Toy MC studies

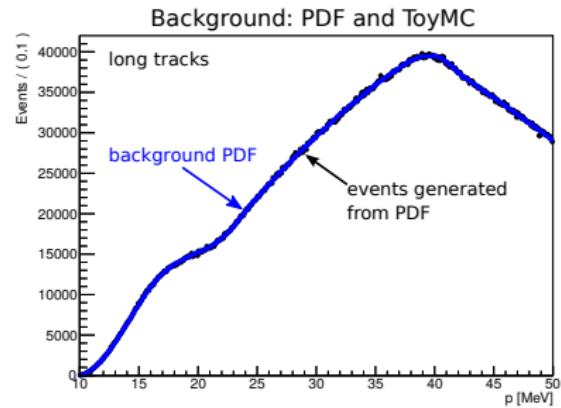
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Deriving Sensitivity Limits for $\mu \rightarrow eX$

Toy MC studies

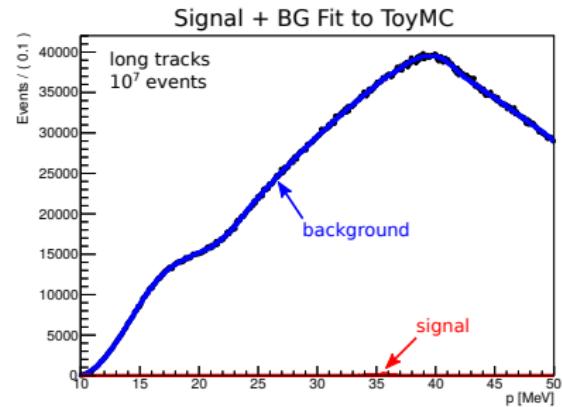
- PDF's for background b and signal s from simulation
- Generate a sample of n_{ev} events from b



Deriving Sensitivity Limits for $\mu \rightarrow eX$

Toy MC studies

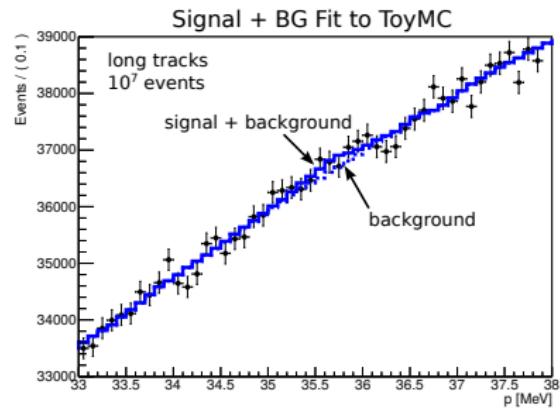
- PDF's for background b and signal s from simulation
- Generate a sample of n_{ev} events from b
- Fit $(1 - f_{\text{sig}}) \cdot b + f_{\text{sig}} \cdot s$



Deriving Sensitivity Limits for $\mu \rightarrow eX$

Toy MC studies

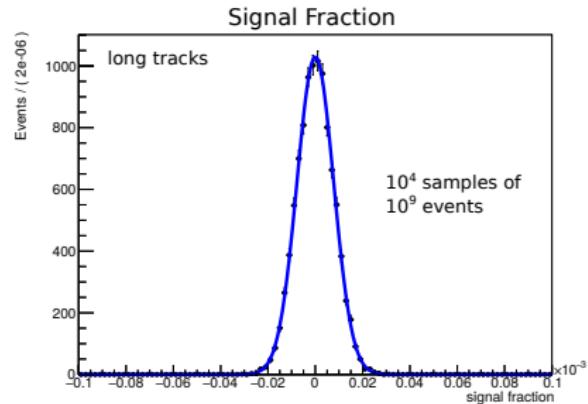
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Deriving Sensitivity Limits for $\mu \rightarrow eX$

Toy MC studies

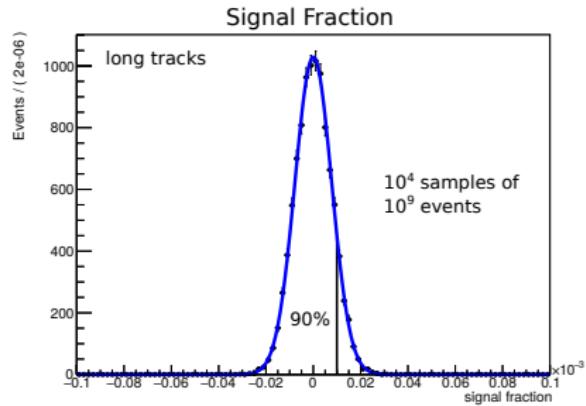
- PDF's for background b and signal s from simulation
- Generate a sample of n_{ev} events from b
- Fit $(1 - f_{\text{sig}}) \cdot b + f_{\text{sig}} \cdot s$
- Repeat n times



Deriving Sensitivity Limits for $\mu \rightarrow eX$

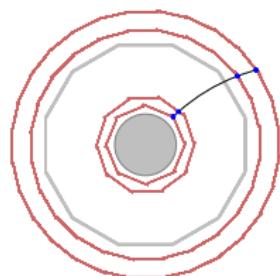
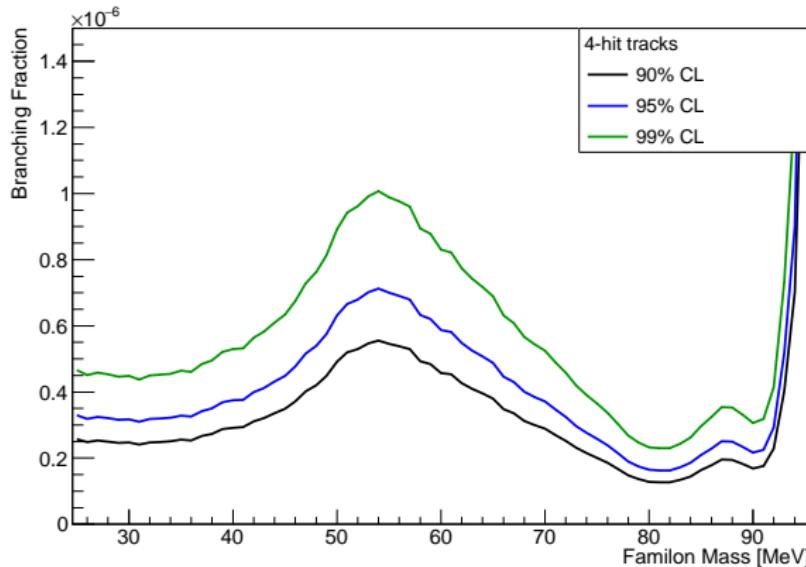
Toy MC studies

- PDF's for background b and signal s from simulation
- Generate a sample of n_{ev} events from b
- Fit $(1 - f_{\text{sig}}) \cdot b + f_{\text{sig}} \cdot s$
- Repeat n times
- Derive sensitivity limits



Searching for $\mu \rightarrow eX$ with Mu3e

Sensitivity to $\mu \rightarrow eX$ for $1 \cdot 10^{15}$ muon stops using short tracks

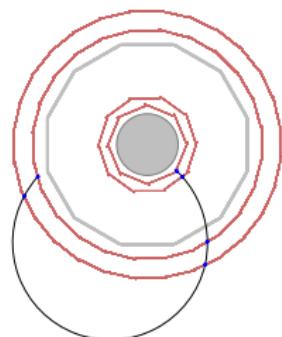
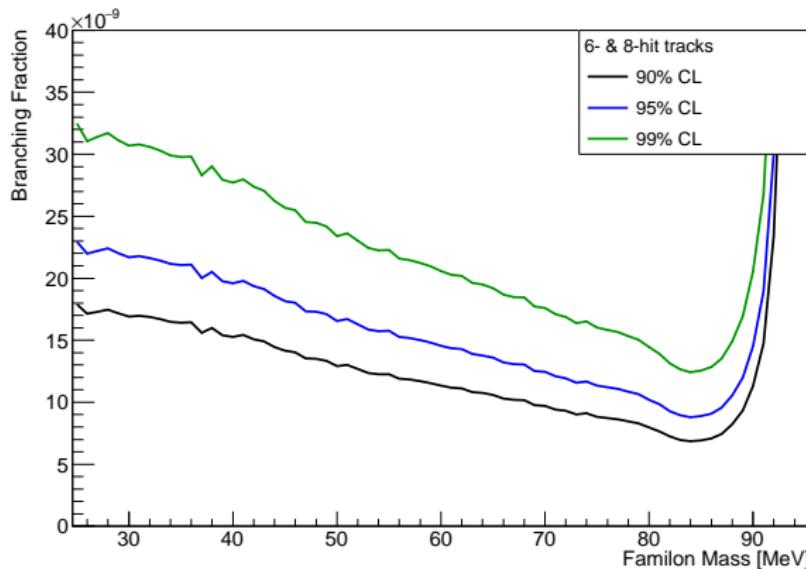


$$\mathcal{B}_{\mu \rightarrow eX} \sim 10^{-7} \text{ at } 90\% \text{ CL}$$



Searching for $\mu \rightarrow eX$ with Mu3e

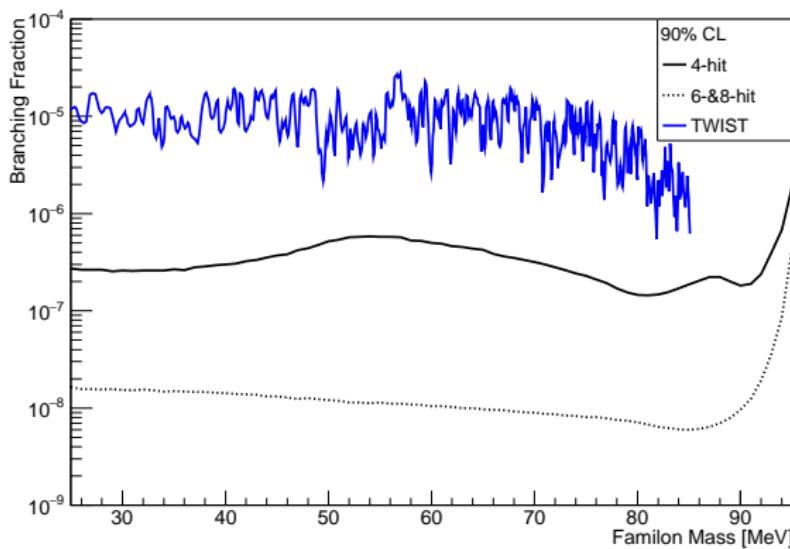
Sensitivity to $\mu \rightarrow eX$ for $1 \cdot 10^{15}$ muon stops using long tracks



$$\mathcal{B}_{\mu \rightarrow eX} \sim 10^{-8} \text{ at } 90\% \text{ CL}$$

Searching for $\mu \rightarrow eX$ with Mu3e

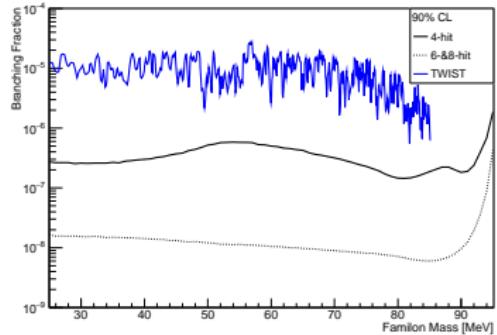
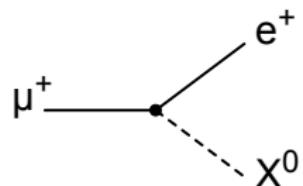
Sensitivity to $\mu \rightarrow eX$ for $1 \cdot 10^{15}$ muon stops



- Mu3e is about one order of magnitude more sensitive than TWIST
- 2 orders when using long tracks

Summary

- Mu3e is sensitive to $\mu \rightarrow e X$ decays at \mathcal{B} of $1 \cdot 10^{-7}$ to $5 \cdot 10^{-7}$ at 90 %CL for m_X in the range of 25 MeV to 95 MeV
- Reconstructing long tracks pushes reach by one order in magnitude
- Current limit by TWIST $\mathcal{B} < 8.6 \cdot 10^{-6}$ at 90 %CL on average
- Familon search can be expanded by investigating additional channels:
 $\mu \rightarrow eee$ and $\mu \rightarrow eeeee$





Mu3e Collaboration



UNIVERSITÉ
DE GENÈVE



UNIVERSITÄT
HEIDELBERG
ZEKUNFT
SEIT 1386



Karlsruhe Institute of Technology

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



PAUL SCHERRER INSTITUT



ETHzürich

DPNC, Geneva University

KIP, Heidelberg University

Physics Institute, Heidelberg University

IPE, Karlsruhe Institute of Technology

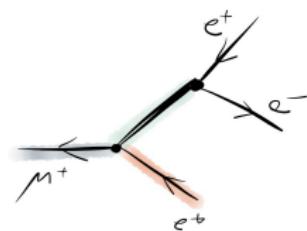
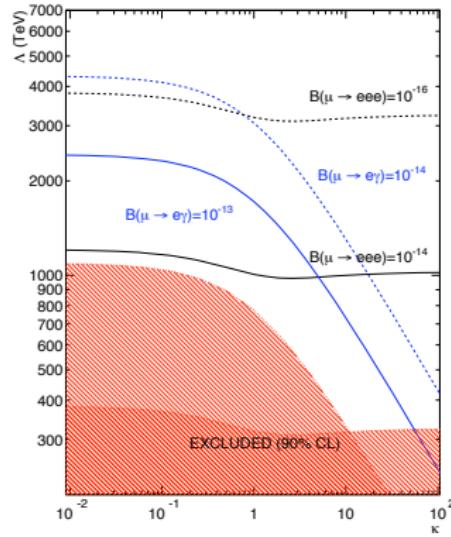
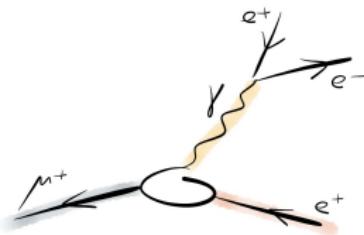
Institute for Nuclear Physics, JGU Mainz

Paul Scherrer Institute

Institute for Particle Physics, ETH Zürich



Charged Lepton Flavour Violation



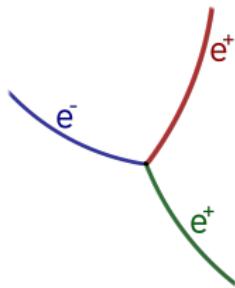
$$\mathcal{L}_{\text{CLFV}} = \left[\frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} \right]_{\text{dipole-like}} + \left[\frac{\kappa}{(\kappa+1)\Lambda^2} (\bar{\mu}_L \gamma_\mu e_L) (\bar{e}_L \gamma^\mu e_L) \right]_{\text{four-fermion}}$$

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

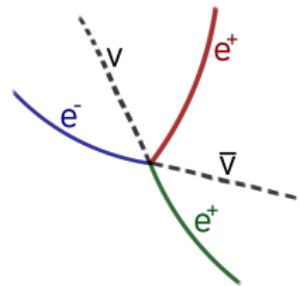
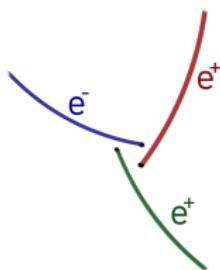


The Mu3e Experiment

Signal



Background



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

Common vertex

Coincident

$\sum E_e = m_\mu$

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

Accidental combinations

No common vertex

Not coincident

$\sum E_e \neq m_\mu$

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

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

Common vertex

Coincident

$\sum E_e < m_\mu$

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

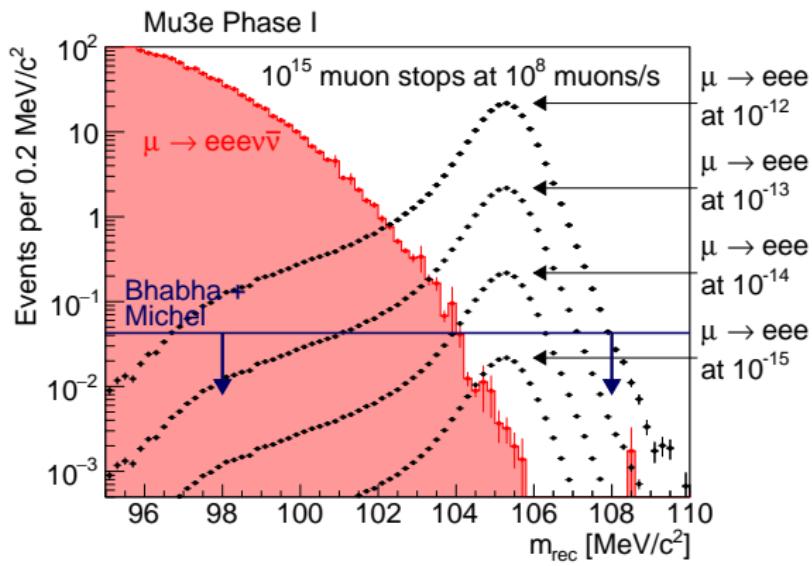


Expected Sensitivity for $\mu \rightarrow \text{eee}$ in Phase I

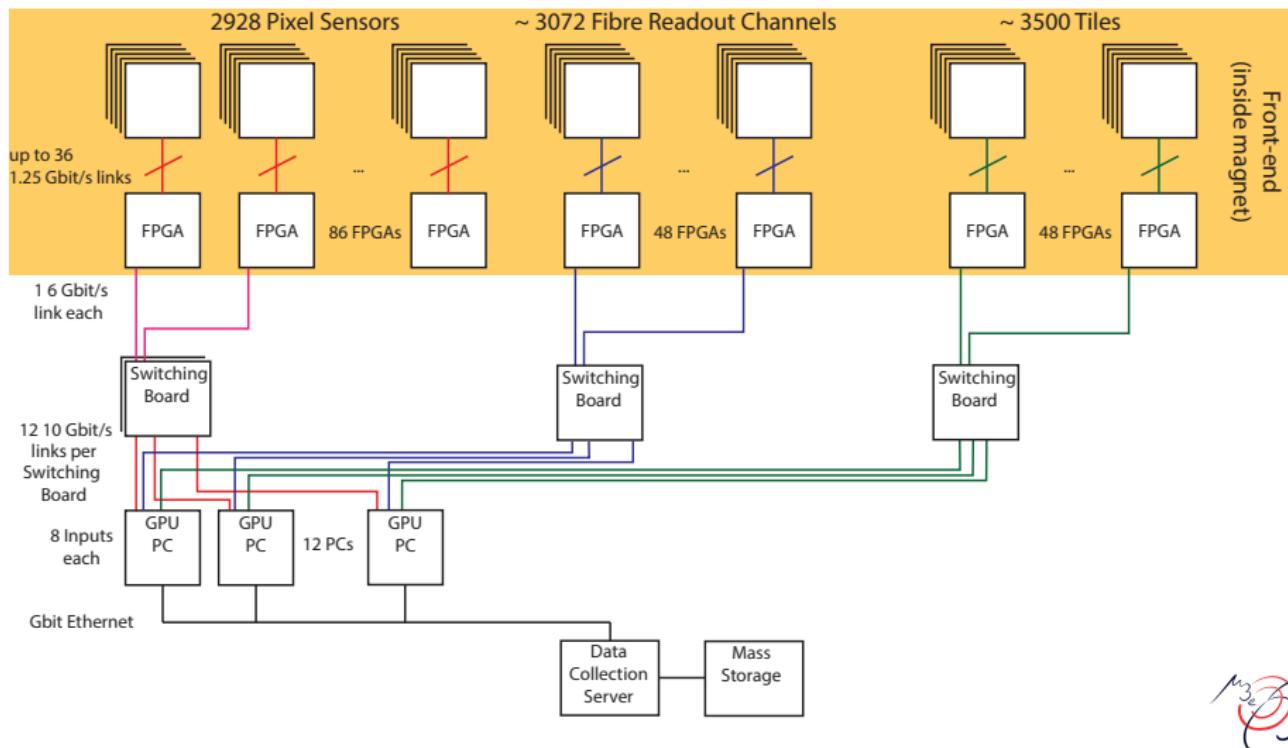
Full Geant4-based
detector simulation

Expected SM background

Prospects for $\mu \rightarrow \text{eee}$
signal at various
branching fractions



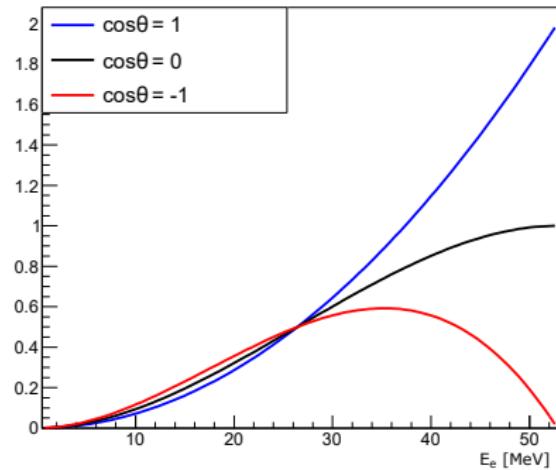
Experimental Concept of Mu3e: Data Acquisition



Previous Experiments Searching for $\mu \rightarrow eX$

Jodidio et al. (1986) at TRIUMF

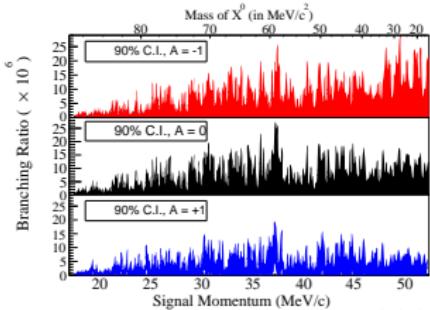
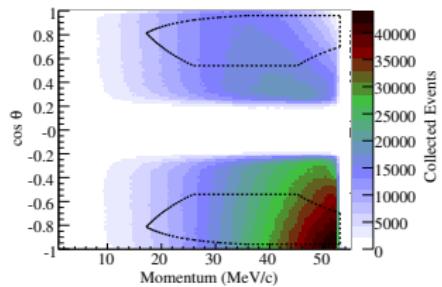
- $1.8 \cdot 10^7$ highly polarized muons
- Search for massless familon expected to be isotropic
- Look for excess in end-point of Michel spectrum
- $\mathcal{B} < 2.6 \cdot 10^{-6}$ at 90 % CL



Previous Experiments Searching for $\mu \rightarrow eX$

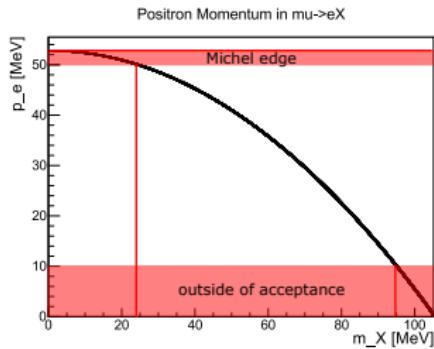
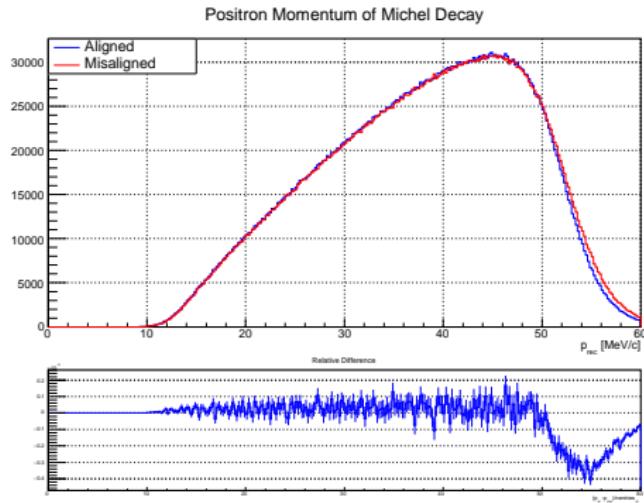
TWIST at TRIUMF (2014)

- $5.8 \cdot 10^8 \mu$ decays analyzed from highly polarized μ beam
- Search for anisotropic $\mu \rightarrow eX$ decays
$$\frac{\partial \Gamma}{\partial \cos \theta} \propto 1 - AP_\mu \cos \theta$$
- Massive X:
 \mathcal{B} around 10^{-5} excluded at 90 %CL
- Massless X:
 $\mathcal{B}_{A=0} < 2.1 \cdot 10^{-5}$ at 90 %CL
 $\mathcal{B}_{A=+1} < 1.0 \cdot 10^{-5}$ at 90 %CL
 $\mathcal{B}_{A=-1} < 5.8 \cdot 10^{-5}$ at 90 %CL



Searching for $\mu \rightarrow eX$ with Mu3e

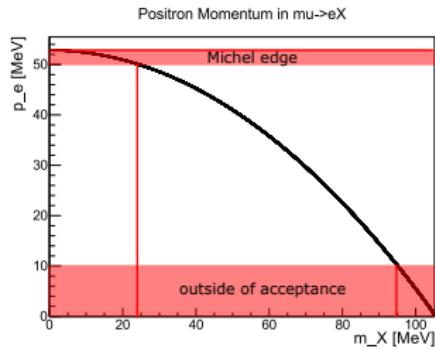
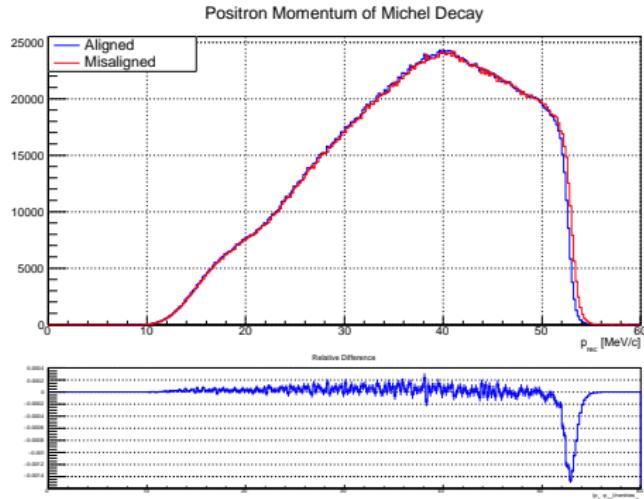
Short tracks



Plot by U. Hartenstein
increased radius by 0.8 %

Searching for $\mu \rightarrow eX$ with Mu3e

Long tracks



Plot by U. Hartenstein
increased radius by 0.8 %



Searching for $\mu \rightarrow eX$ with Mu3e

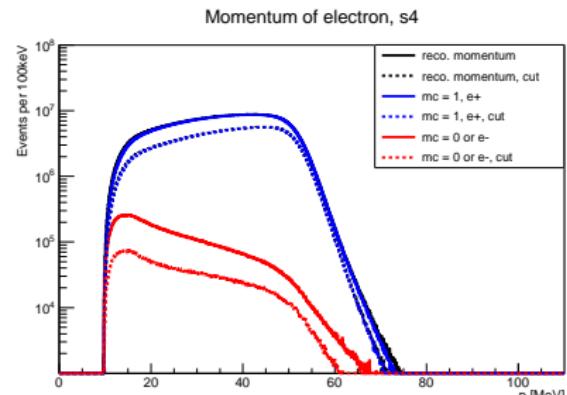
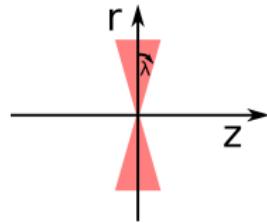
Data selection

sign of radius

χ^2 of track fit

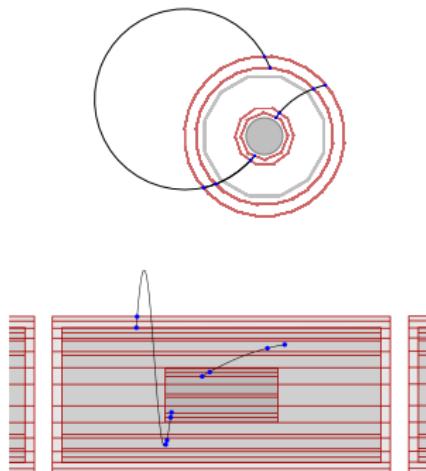
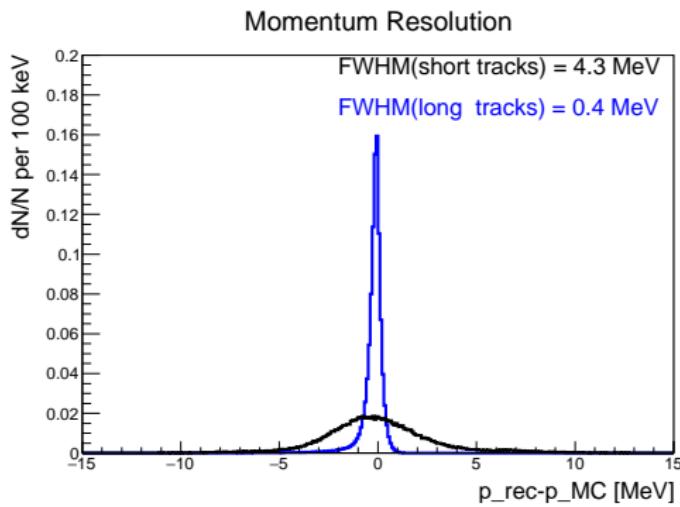
λ_{01}

z of track propagated to target region



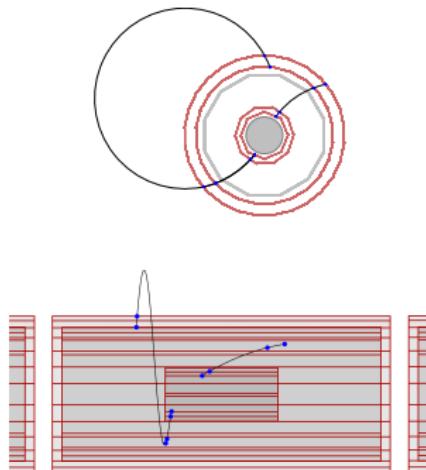
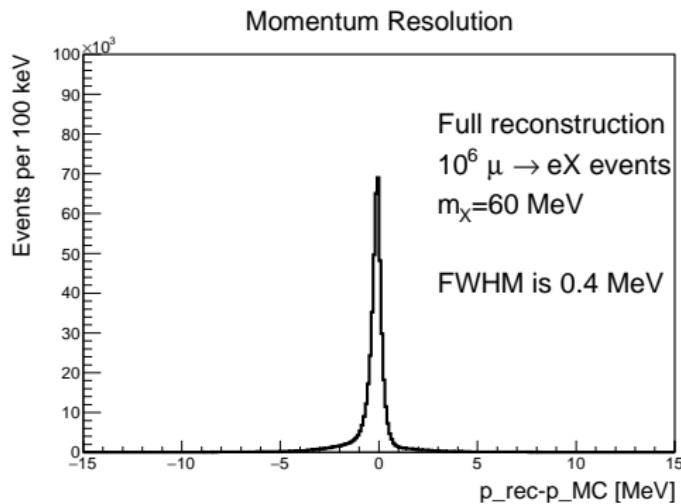
Searching for $\mu \rightarrow eX$ with Mu3e

Momentum resolution for short and long tracks



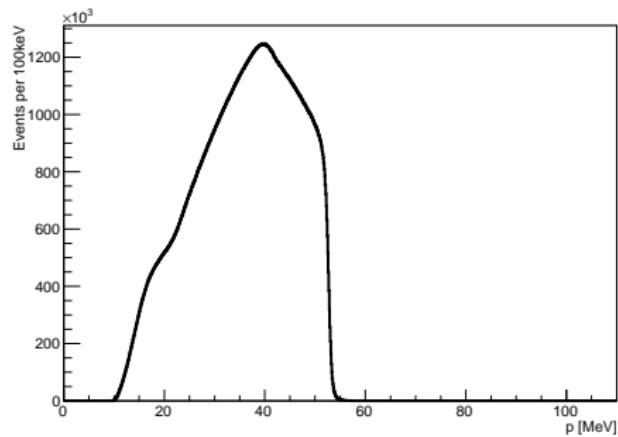
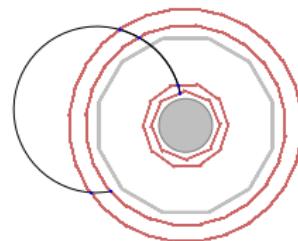
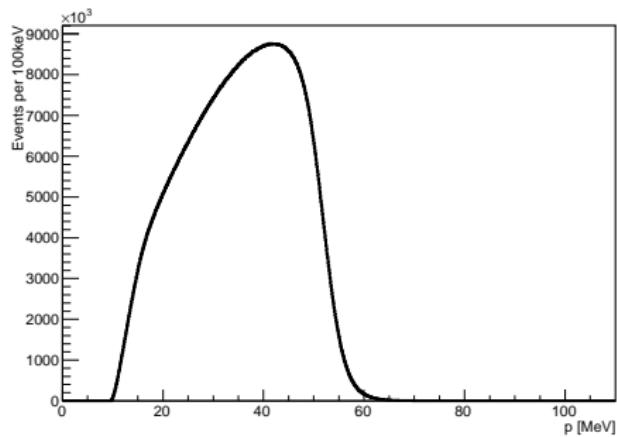
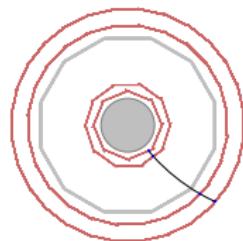
Searching for $\mu \rightarrow eX$ with Mu3e

Momentum resolution for full reconstruction



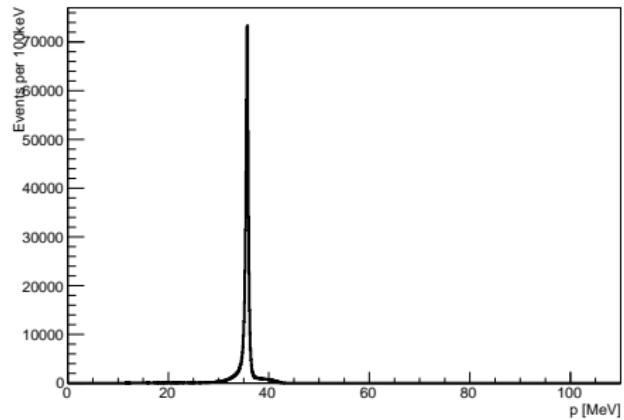
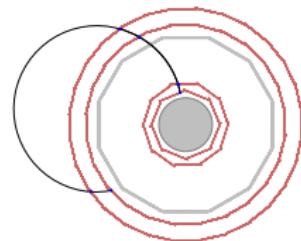
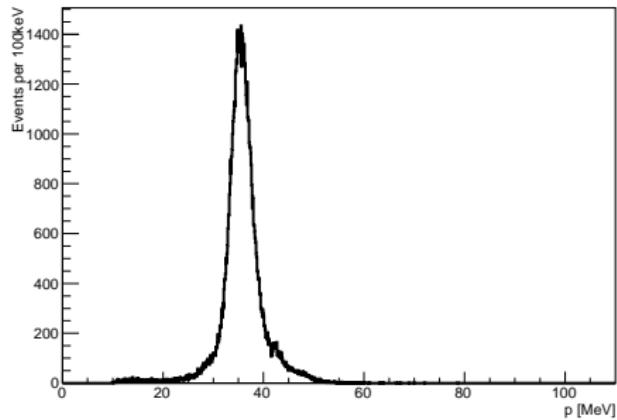
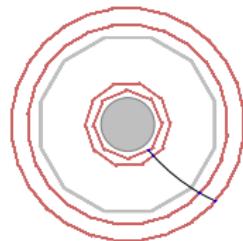
Reconstruction: Short and Long Tracks

SM processes: Michel, radiative, internal conversion decay, Bhabha, ...



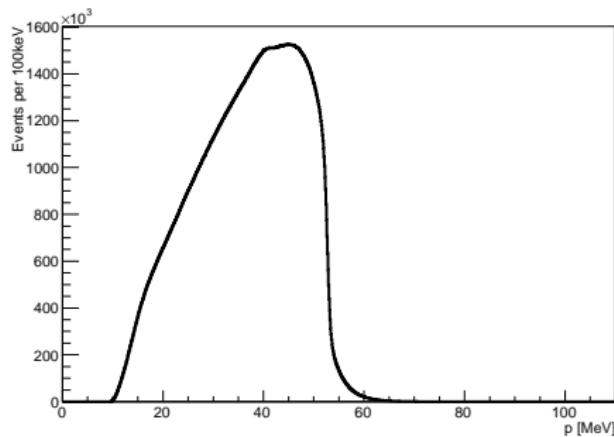
Reconstruction: Short and Long Tracks

Familon $m_X = 60$ MeV

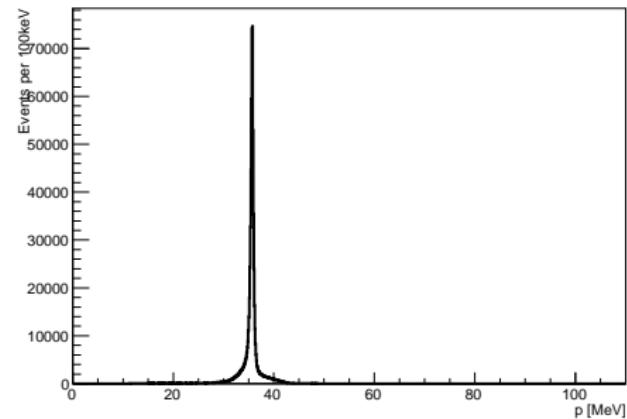


Full Reconstruction

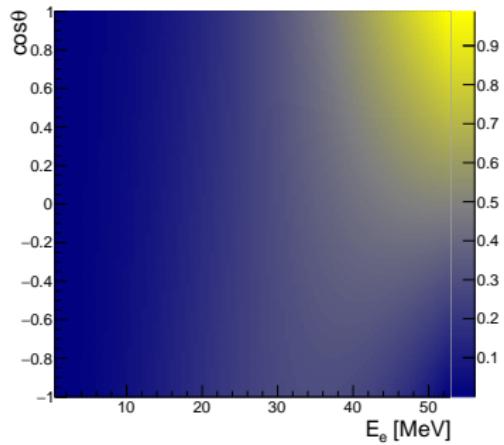
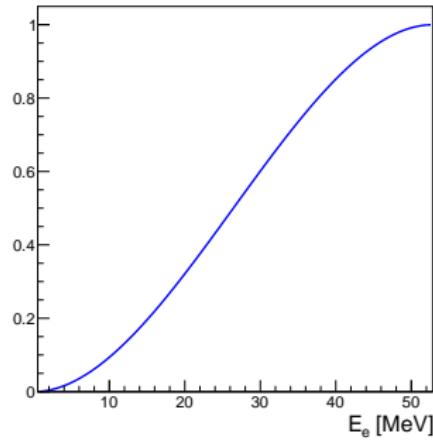
SM background



Familon $m_X = 60$ MeV



Michel decays $\mu \rightarrow e\nu\nu$



Additional decays soften Michel edge:

$\mu \rightarrow e\gamma\nu\nu$ ($\mathcal{B} \sim 10^{-2}$), $\mu \rightarrow eee\nu\nu$ ($\mathcal{B} \sim 10^{-5}$)

