Probing Physics beyond the Standard Model with the Mu3e Experiment

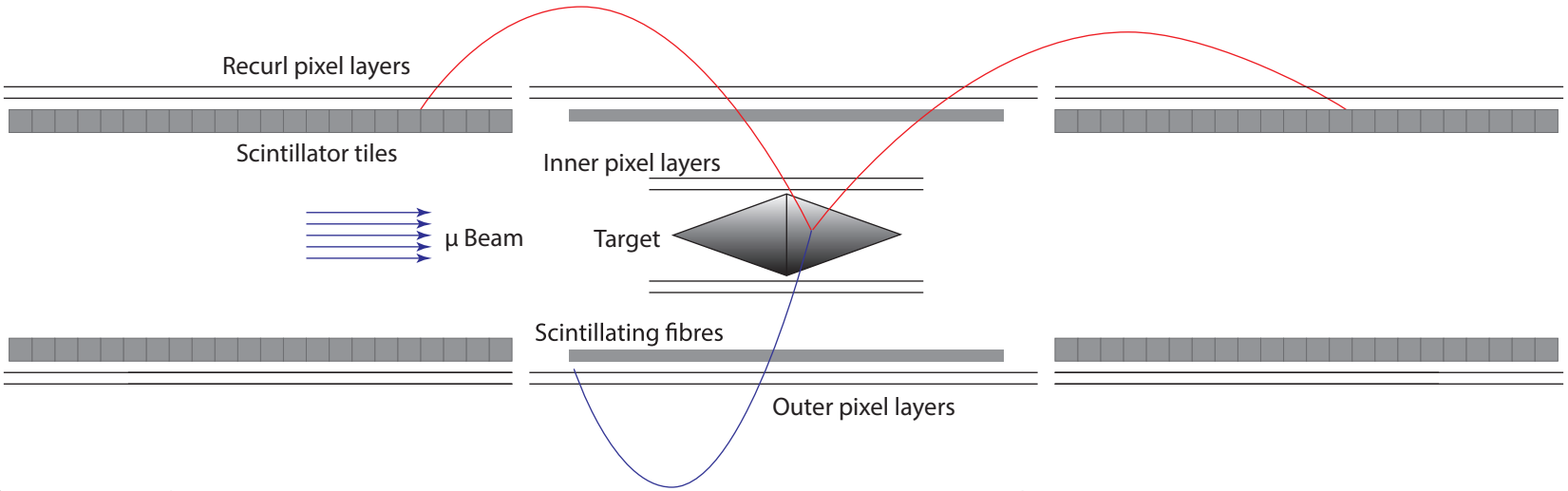
Ann-Kathrin Perrevoort
for the Mu3e Collaboration

NIKHEF, Amsterdam (formerly Physics Institute, Heidelberg)

Flavour and Dark Matter Karlsruhe

September 26, 2018


Mu3e in a Nutshell



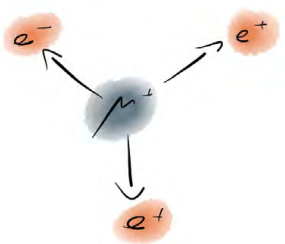
- Search for cLFV in $\mu \to eee$
- Observe $\mathcal{O}(10^{15})$ to $\mathcal{O}(10^{16})$ muons
- Precise tracking of e^+/e^-
- High geometric and momentum acceptance ($p_T > 10\,\text{MeV}$)
- Online reconstruction of all tracks
- Filtering of $\mu \to eee$ candidates

- Current limit:
  $\text{BR} < 1.0 \cdot 10^{-12}$ at 90 % CL
  (SINDRUM 1988)
  What can Mu3e achieve?

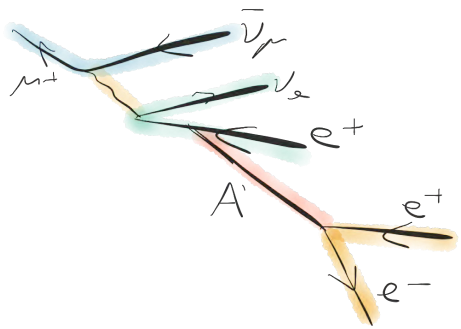
- What else can we look for with so many muon decays?

Outline

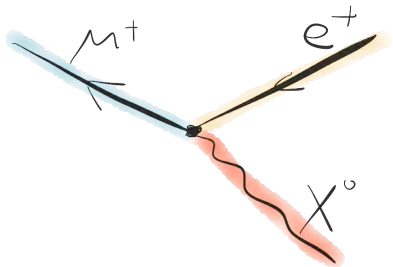
- $\mu \to eee$ in effective theories

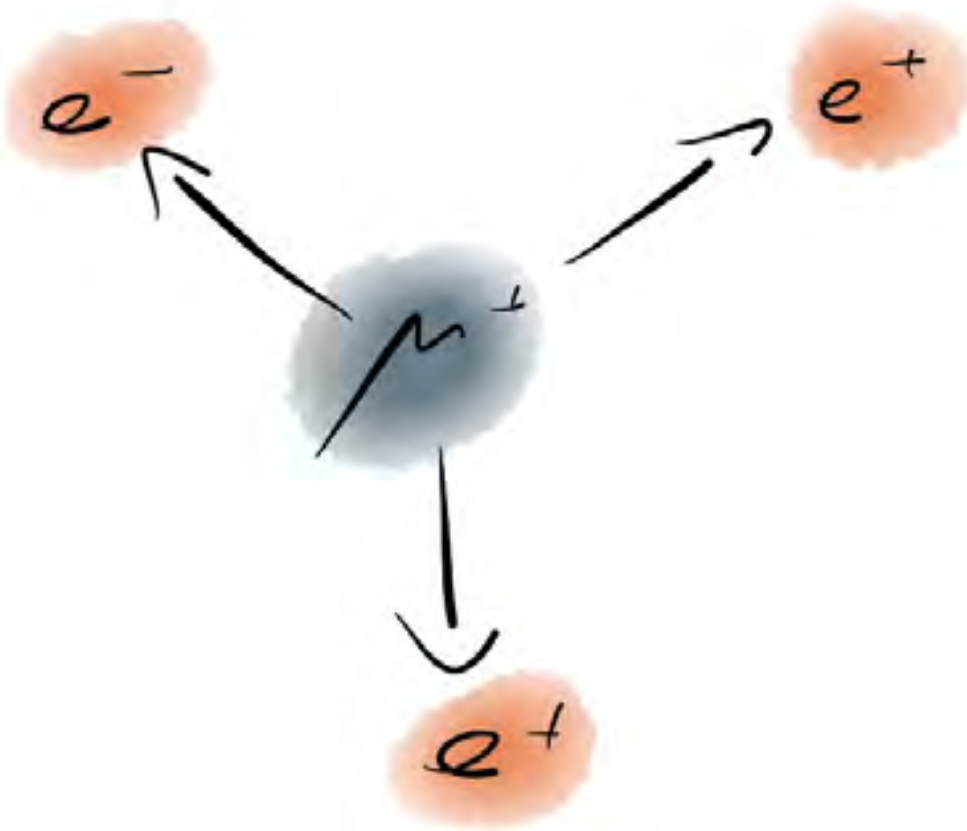


- Dark photons in μ decays



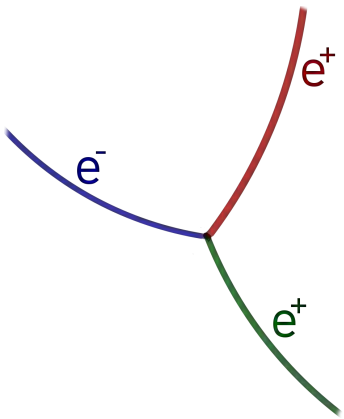
- Lepton flavour violating two body decays $\mu \to eX$



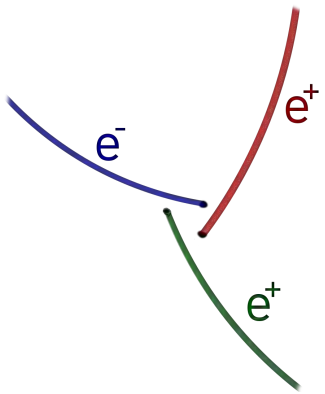

e⁻
e⁺
μ⁺
e⁺

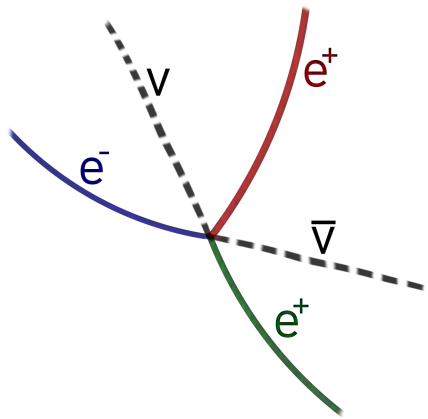
Signal and Background

Signal



Background





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

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

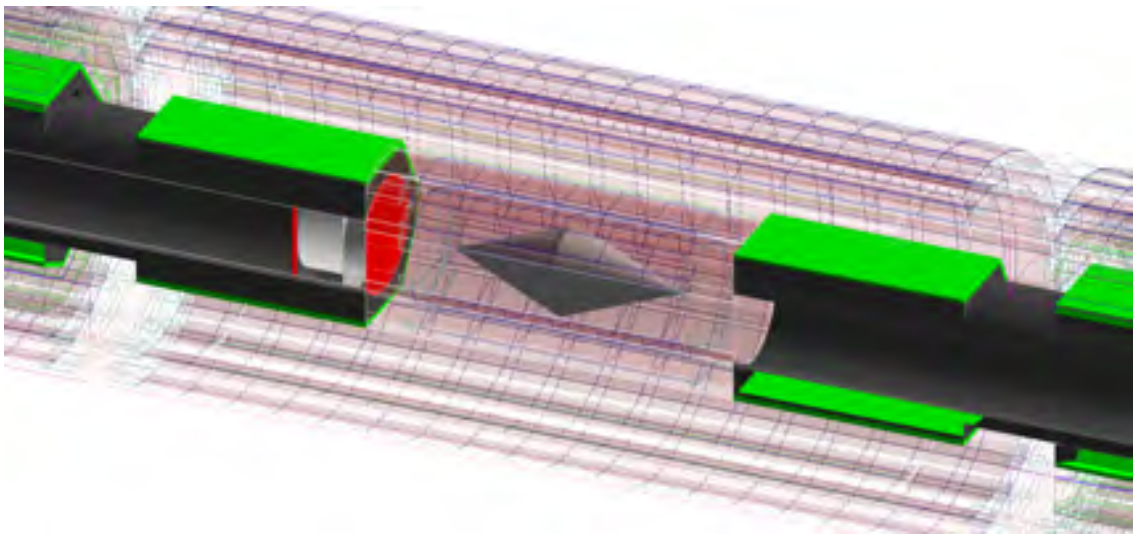
Combinatorial background

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

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

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

Sensitivity to $\mu \to eee$ in Phase I



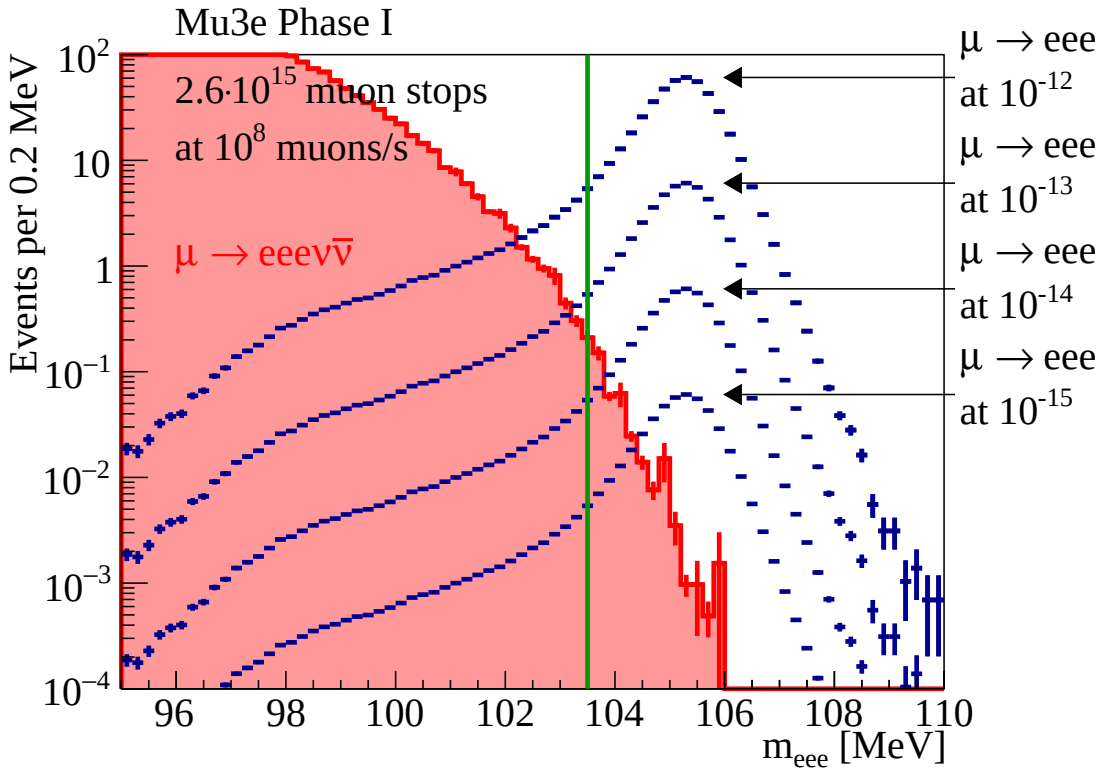
- Full Geant4-based detector simulation
- Generators of physics processes (SM and BSM)
- Track reconstruction and vertex fit

Sensitivity to $\mu \to eee$ in Phase I

Reconstructed $\mu \to eee$ events (signal and background)

- Long tracks only
- Cuts on $\Delta t_{e_i e_j}$, χ^2_{vertex}, $d_{\text{vertex-target}}$, $|\sum \vec{p}_e|$, m_{eee}
- Background-free with $2.6 \cdot 10^{15}$ stopped μ
- Signal efficiency 17 %

$\Rightarrow$ BR $\geq 5.2 \cdot 10^{-15}$ at 90 % CL

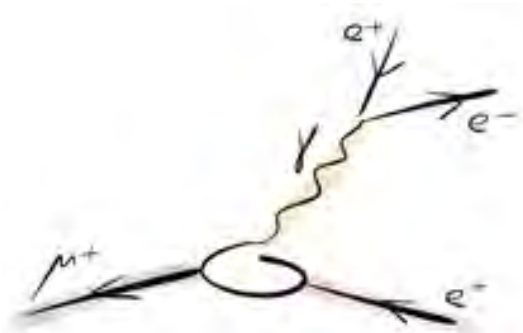


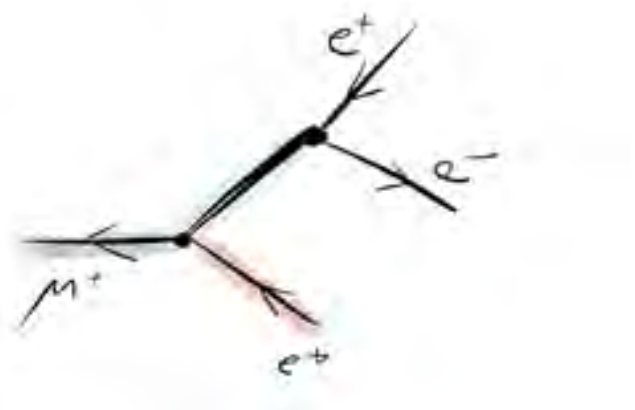
$\mu \to eee$ in Effective Theories

Use an EFT approach to model possible New Physics

$$\mathcal{L}_{\text{EFT}} = \sum_{i} \frac{c_i}{\Lambda^2} O_i$$

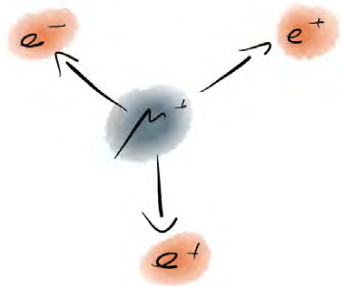
- Kinematics differ for each operator
  - → different sensitivities
  - → characteristic decay distributions
- Complementarity of $\mu \to eee$, $\mu \to e\gamma$, $\mu \to e$ conversion



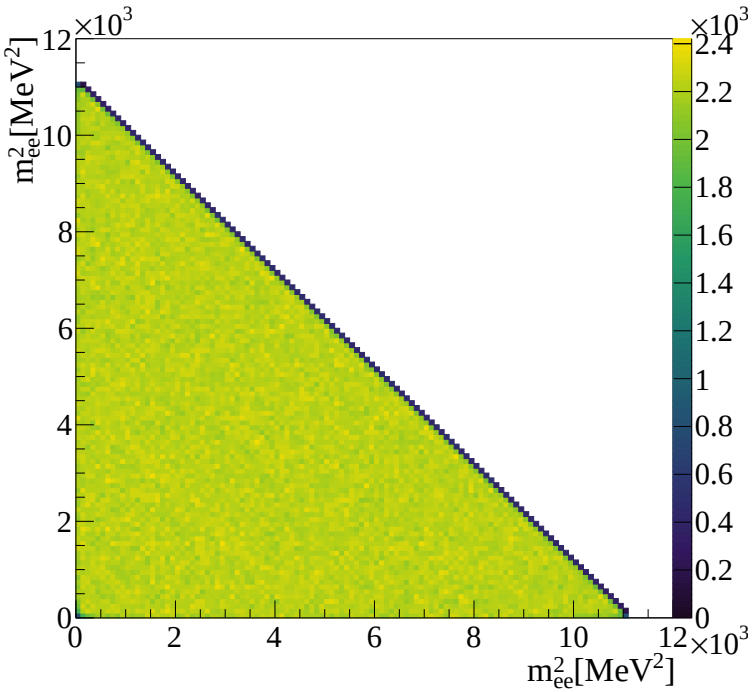


Sensitivity to $\mu \to eee$ using Effective Theories

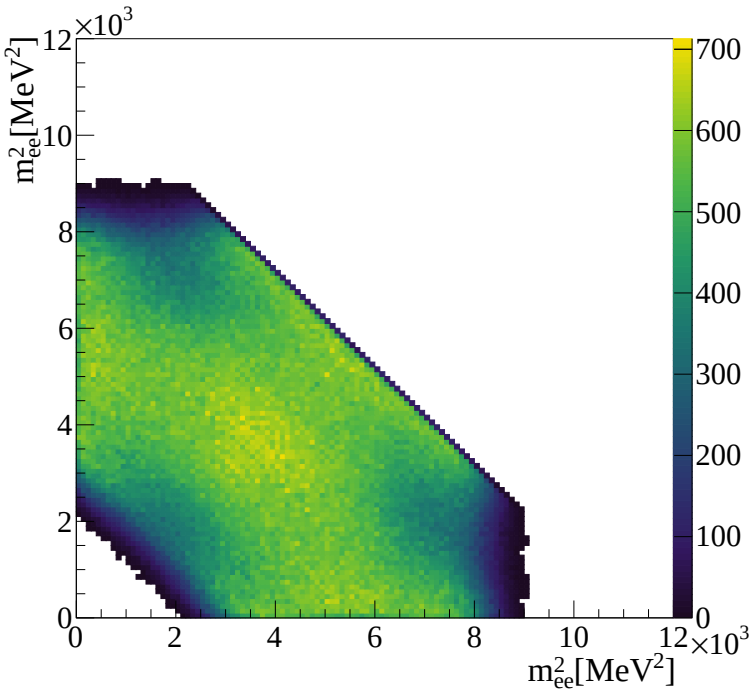
Phase space



Efficiency is 17 % $\Rightarrow$ BR $\geq 5.2 \cdot 10^{-15}$ at 90 % CL



Generated distribution

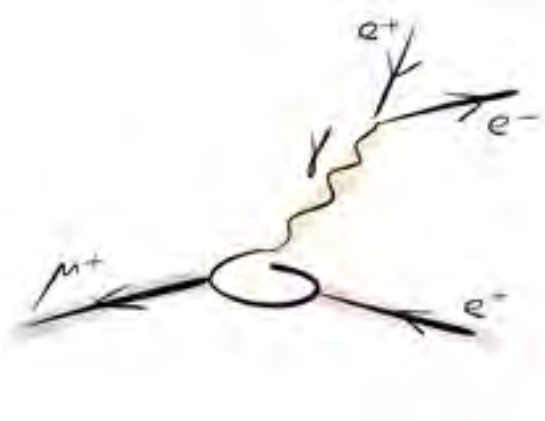


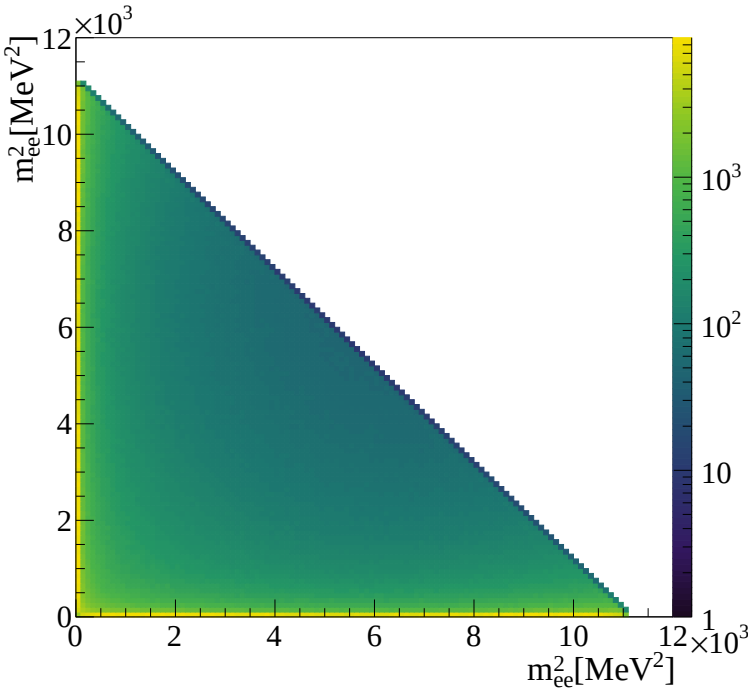
After reconstruction and vertex fit

$\mu \to eee$ in Effective Theories

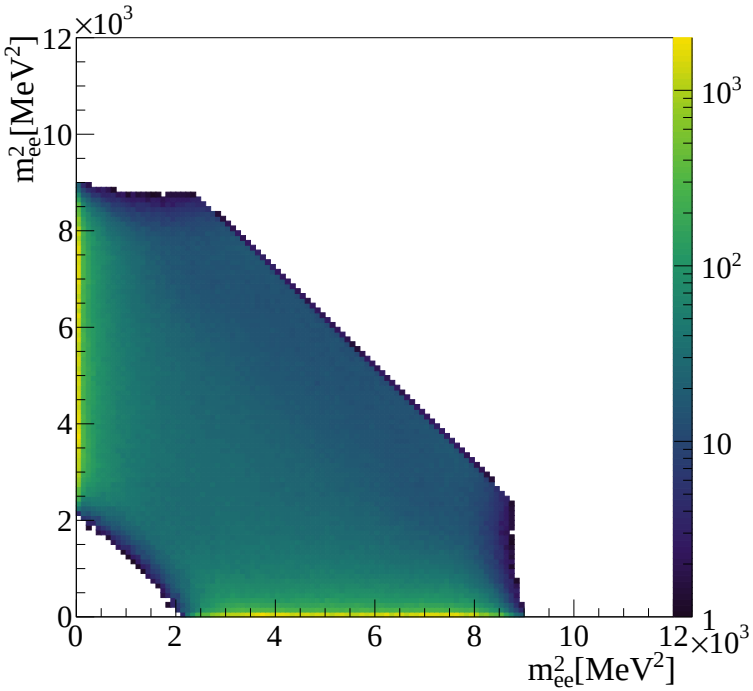
Dipole operator $em_\mu \overline{\mu_R} \sigma^{\mu\nu} e_L F_{\mu\nu}$

Efficiency is 11 % $\Rightarrow$ BR $\geq 8.5 \cdot 10^{-15}$ at 90 % CL





Generated distribution

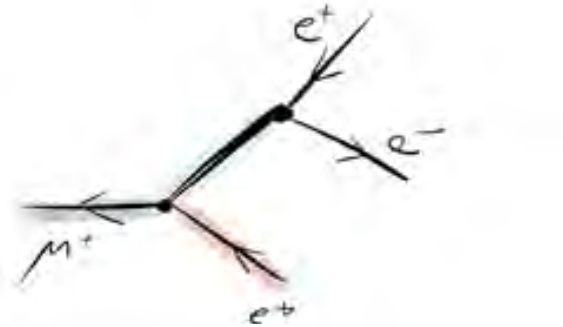


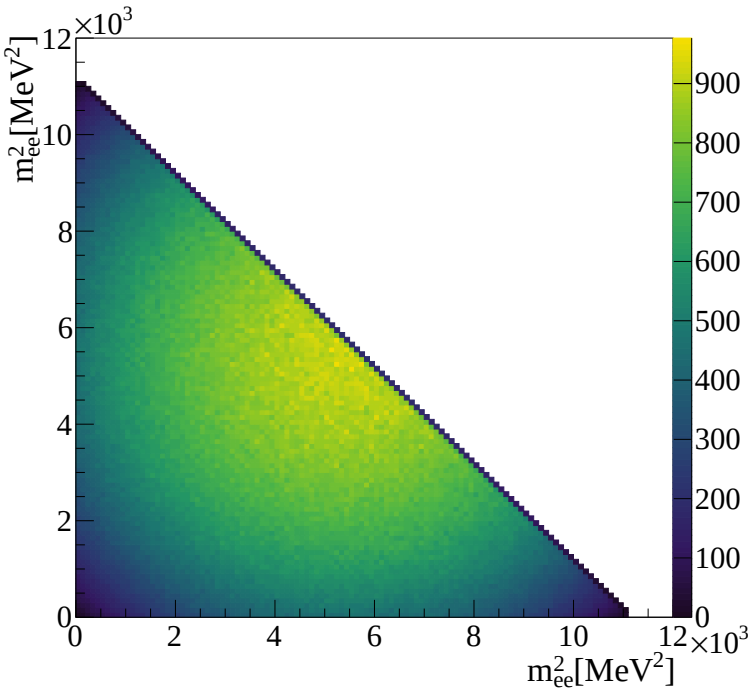
After reconstruction and vertex fit

$\mu \to eee$ in Effective Theories

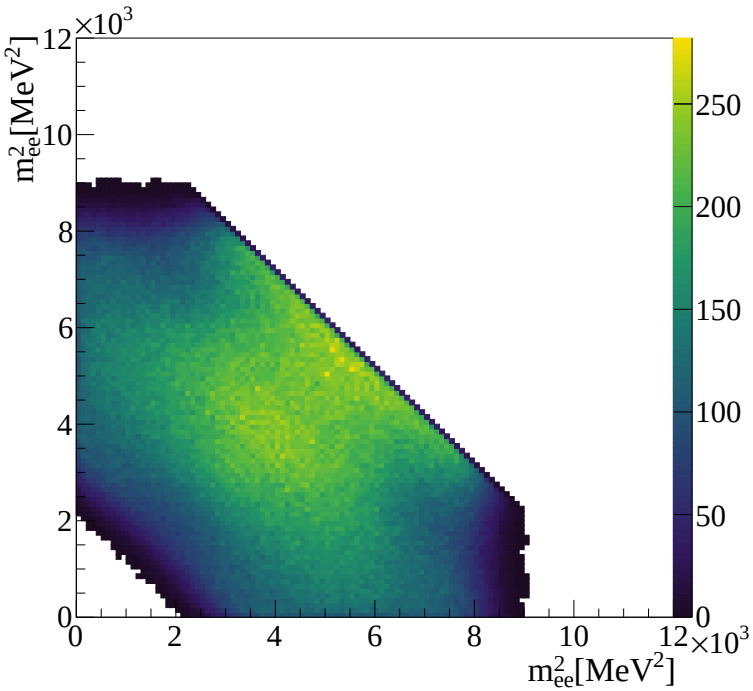
Vector 4-fermion operator $(\overline{\mu_R}\gamma^\mu e_R)(\overline{e_L}\gamma^\mu e_L)$

Efficiency is 19 % $\Rightarrow$ BR $\geq 4.6 \cdot 10^{-15}$ at 90 % CL



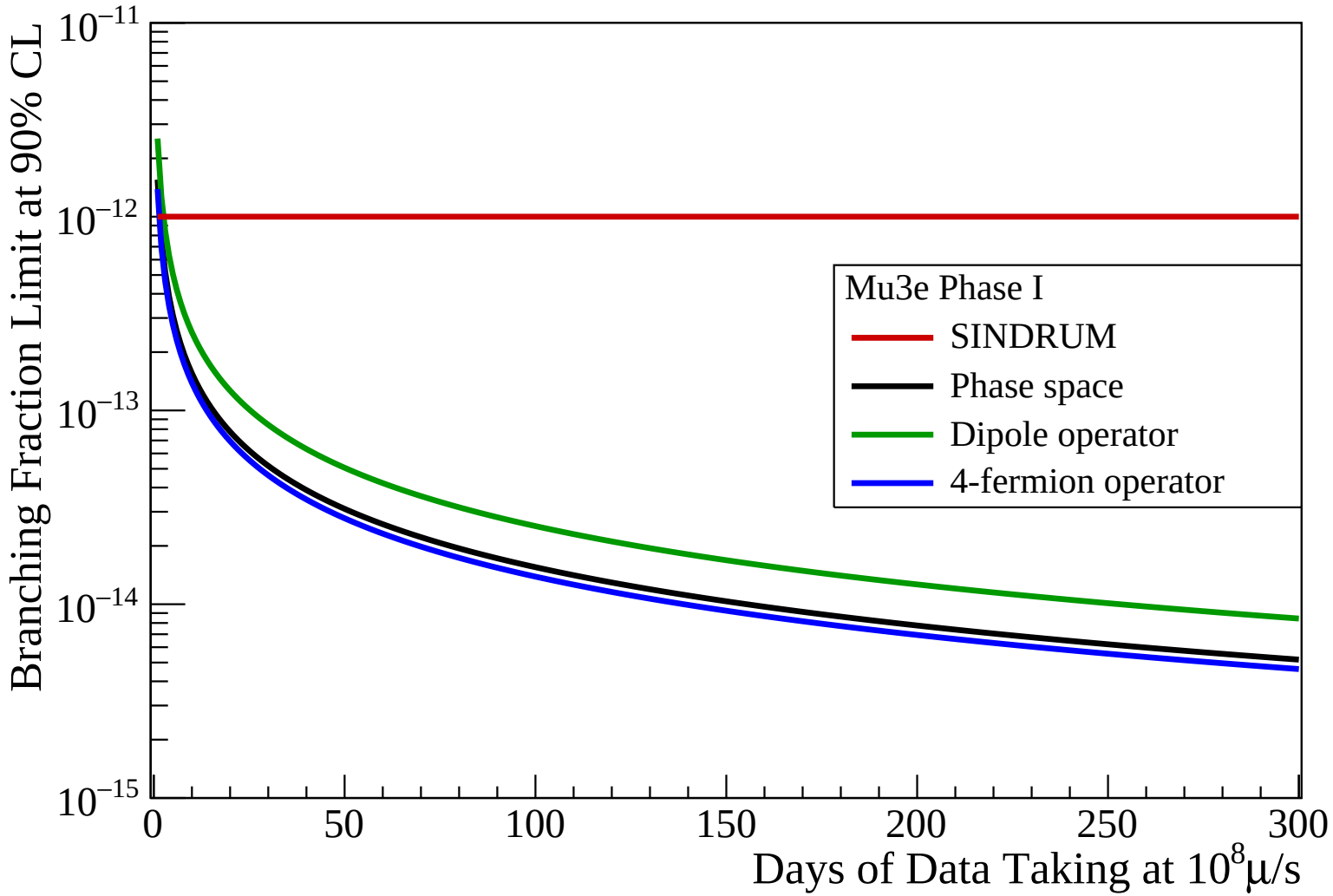


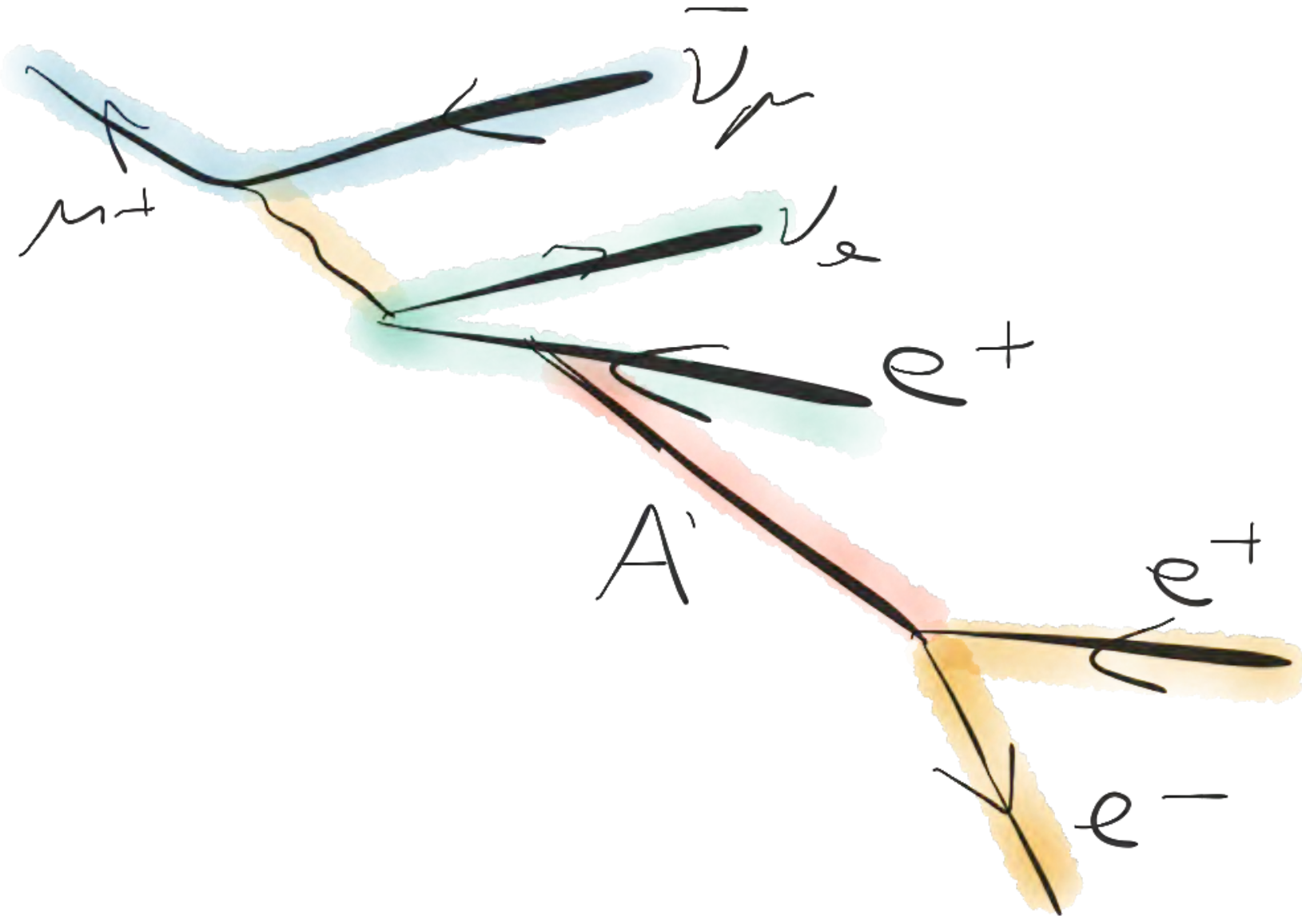
Generated distribution



After reconstruction and vertex fit

$\mu \to eee$ in Effective Theories

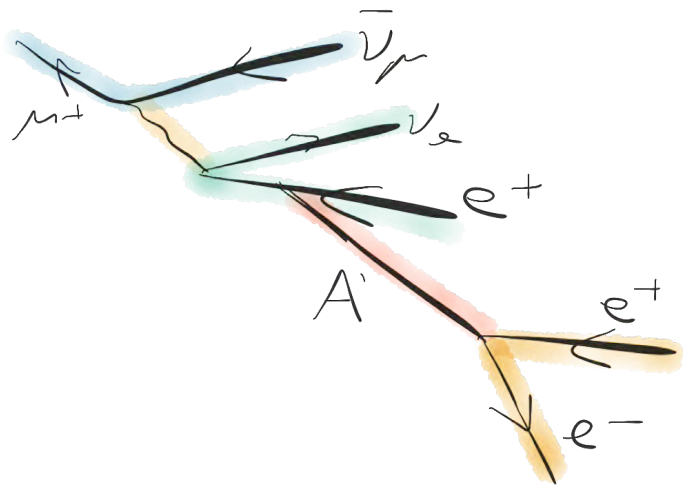



$\bar{\nu}_\mu$
μ^+
ν_e
e^+
A'
e^+
e^-

Dark Photon Searches with Mu3e

Dark Photon A′

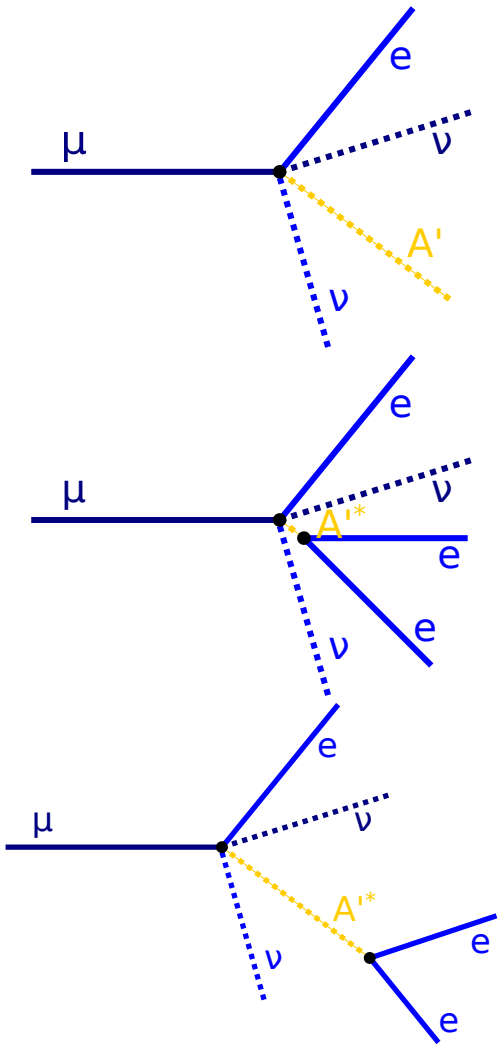
- Vector portal:
  A′ as messenger to a dark sector
- Interaction with SM particles via kinetic mixing with the photon
  $\mathcal{L}_{\mathrm{A}'} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{\mathrm{A}'} \mathrm{A}'_{\mu} \mathrm{A}'^{\mu}$
- A′ with $m_{\mathrm{A}'} < m_{\mu}$ can be emitted in muon decays



Dark Photon Searches with Mu3e

Dark photons in muon decays

- $\mu \to e\nu\nu A'$
  'stable' A' or decay to dark particles
- $\mu \to e\nu\nu(A' \to ee)$
  prompt decay of A' to e^+e^-
- $\mu \to e\nu\nu A'$ followed by $A' \to ee$
  long-lived A'

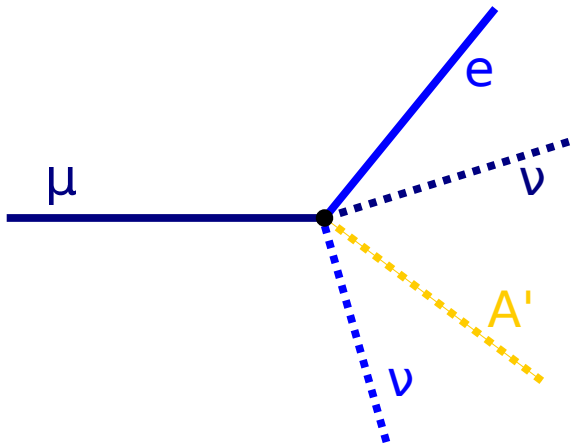


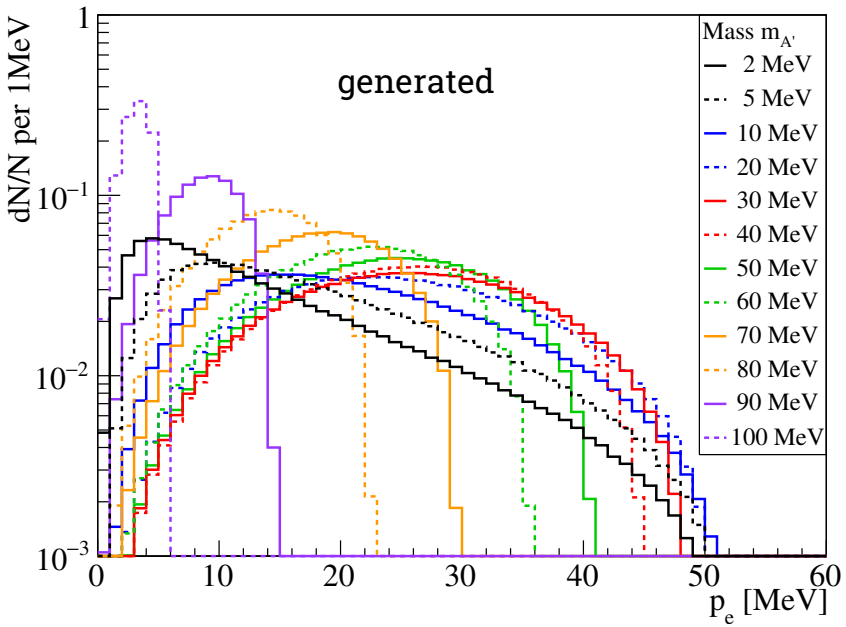
Invisible Dark Photons: $\mu \to e\nu\nu A'$

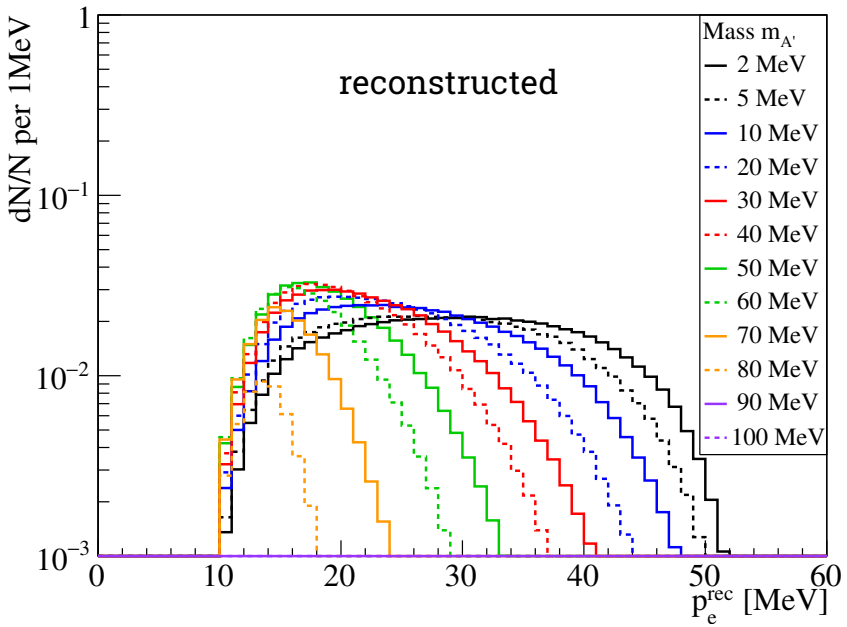
- Only e^+ can be detected

$\Rightarrow$ Deviation in the p_e spectrum of SM μ decays

- Can be easily interpreted as detector misalignment
- Single-e^+ events rejected in filter farm





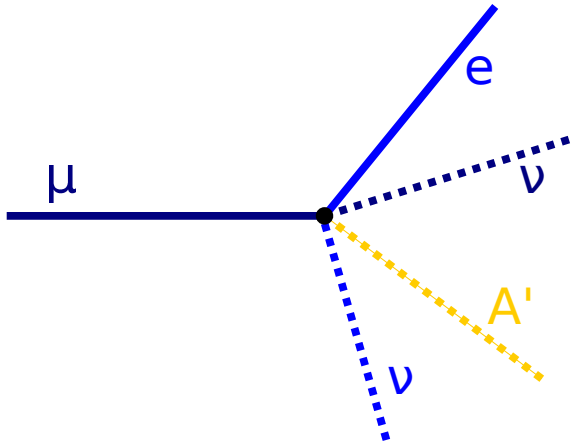


Invisible Dark Photons: $\mu \to e\nu\nu A'$

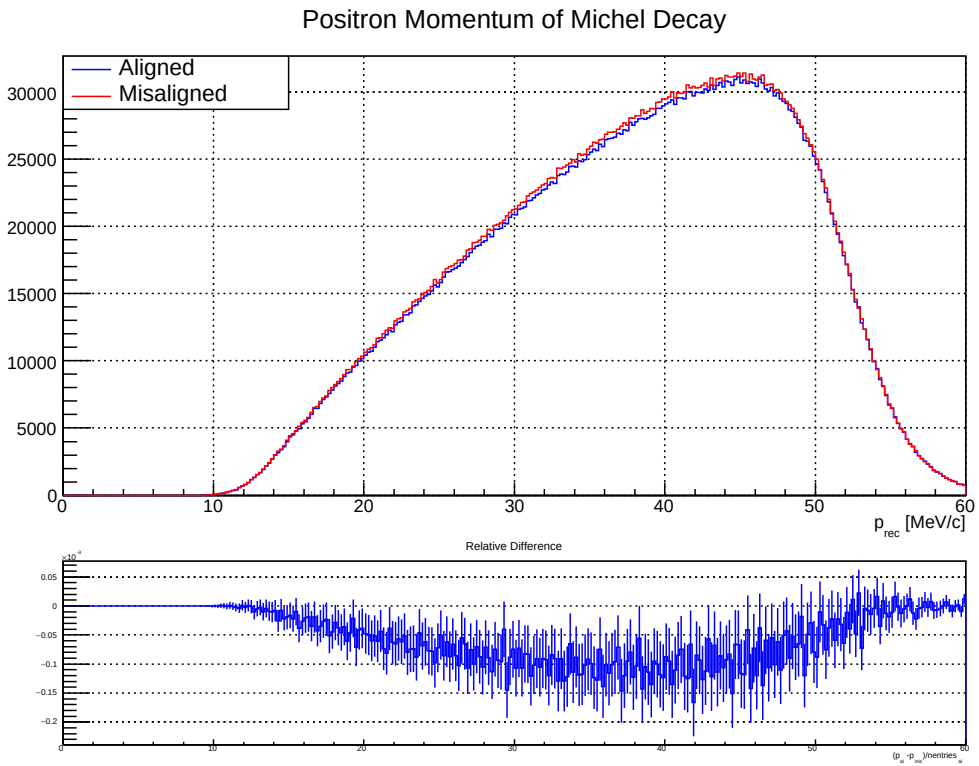
- Only e^+ can be detected

$\Rightarrow$ Deviation in the p_e spectrum of SM μ decays

- Can be easily interpreted as detector misalignment
- Single-e^+ events rejected in filter farm



Misalignment vertex layers shifted in z



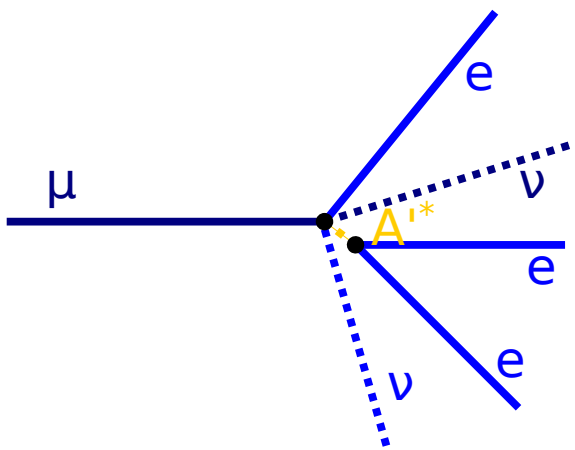
Misalignment study by U. Hartenstein

Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

- Observe three electrons from a common vertex

$\Rightarrow$ Same dataset as in $\mu \to eee$ searches

- Search for resonance in m_{ee}
- Main background from $\mu \to eee\nu\nu$ and combinations of Bhabha scattering events with Michel decays



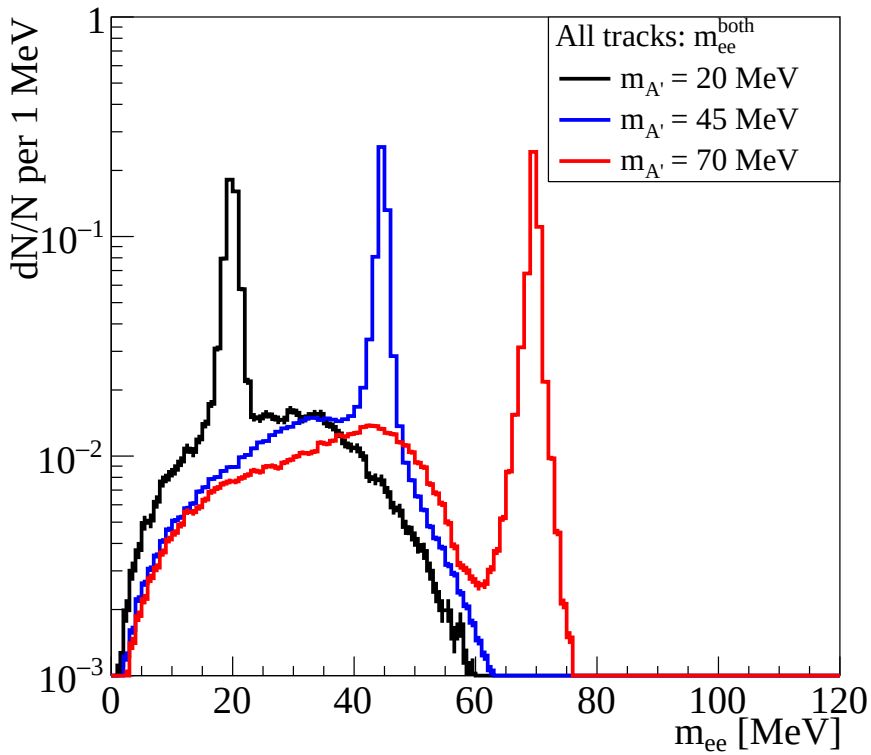
Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

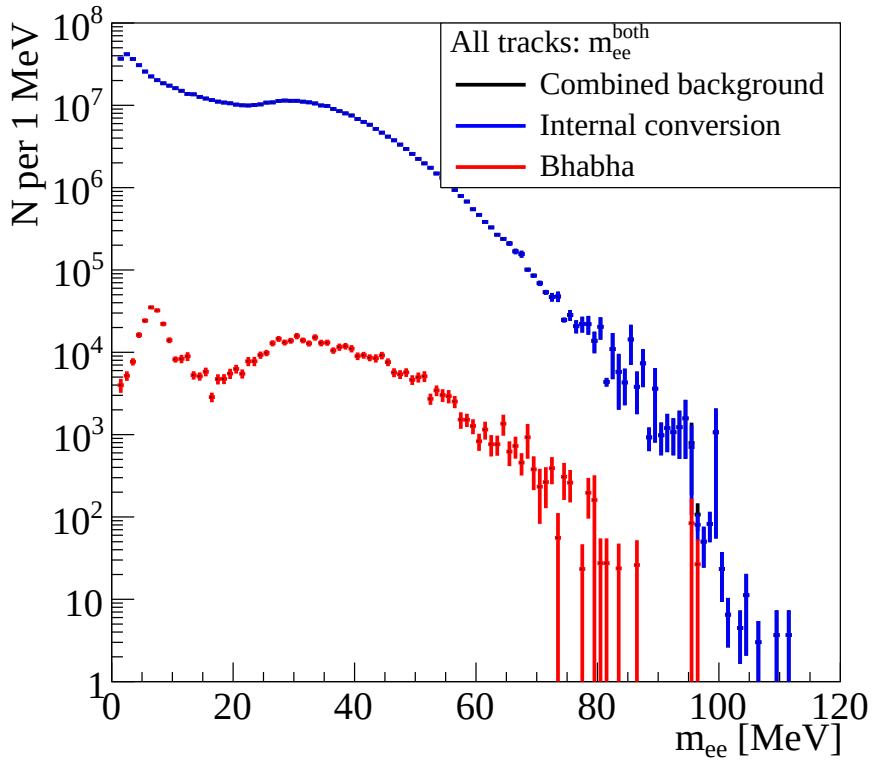
Signal

sharp peak in m_{ee}

Background

combinatorial BG contributes a factor ~800 less

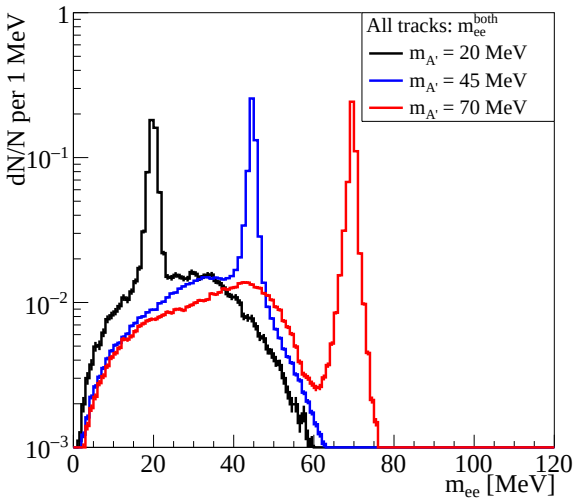




Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

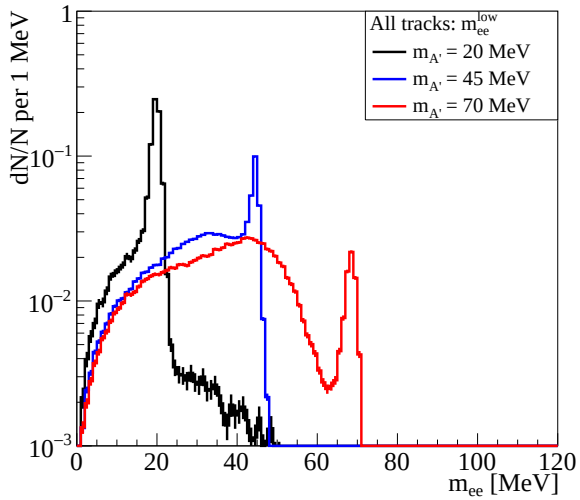
Two possible e^+e^- combinations

Both e^+e^- pairs



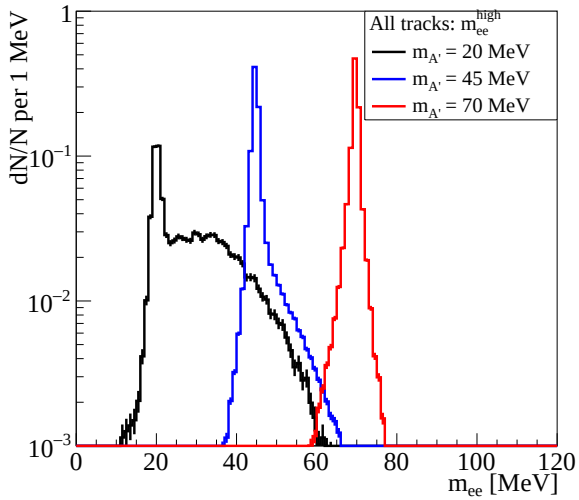
Lower m_{ee} pair

for $m_{ee} < 45\,\text{MeV}$



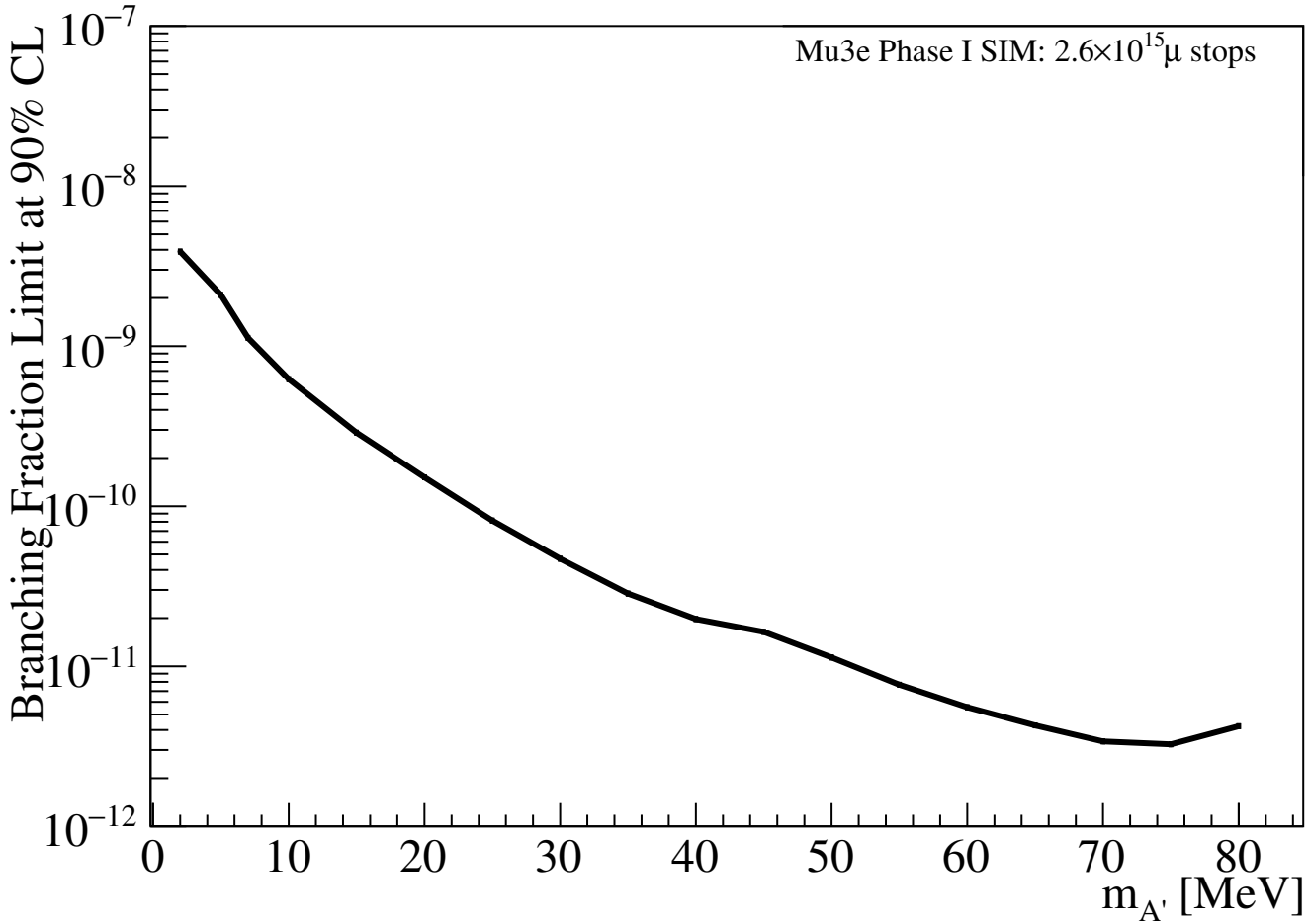
Higher m_{ee} pair

for $m_{ee} \geq 45\,\text{MeV}$



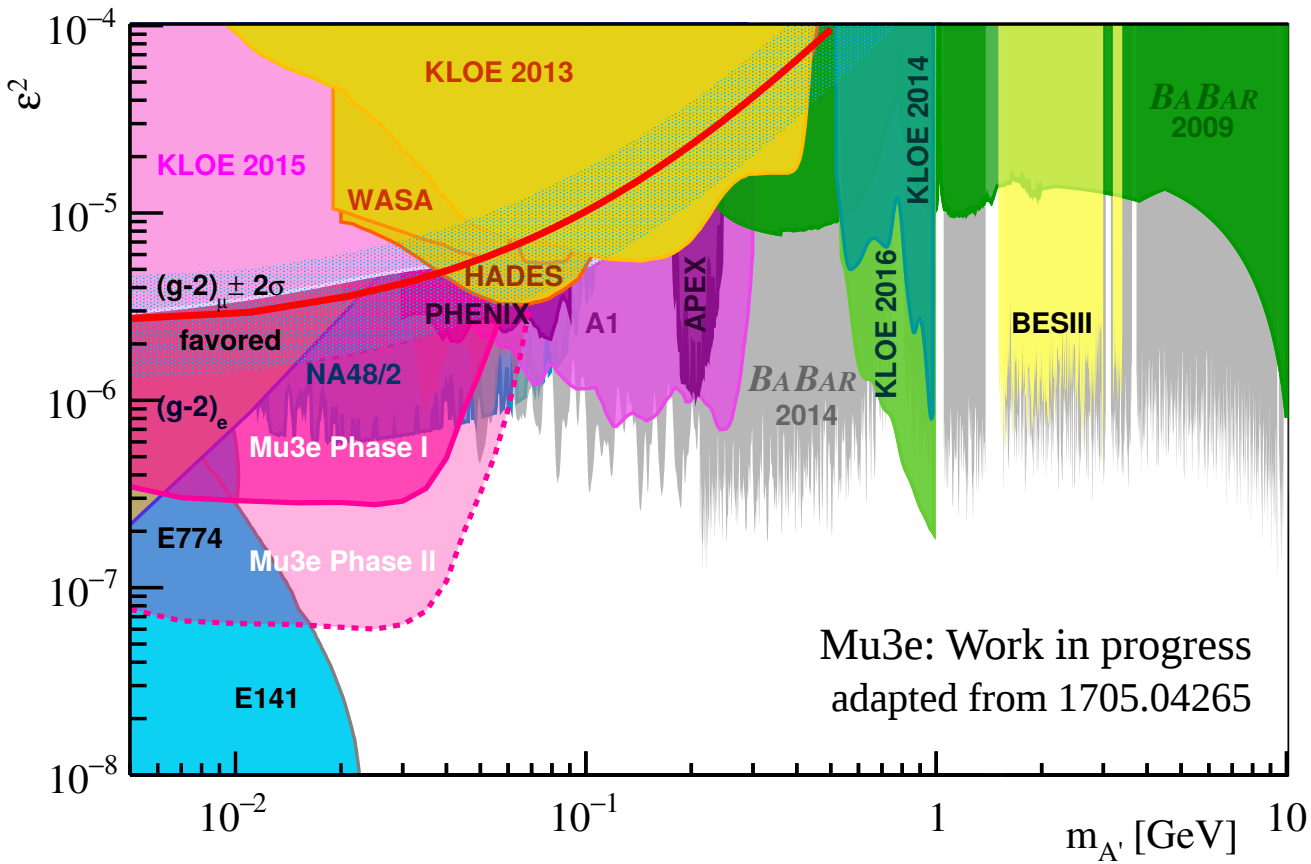
Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

Sensitivity in phase I assuming $2.6 \cdot 10^{15}$ muon decays



Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

Investigate currently uncovered parameter space $(BR(A' \to ee) = 1)$



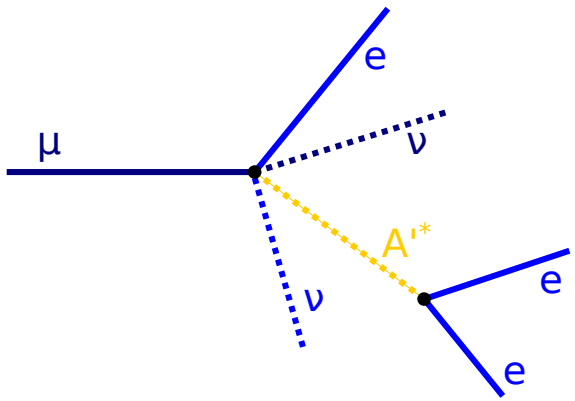
Phase II: $5.5 \cdot 10^{16}$ μ decays at $2 \cdot 10^9$ μ/s,
improvements to the detector not considered

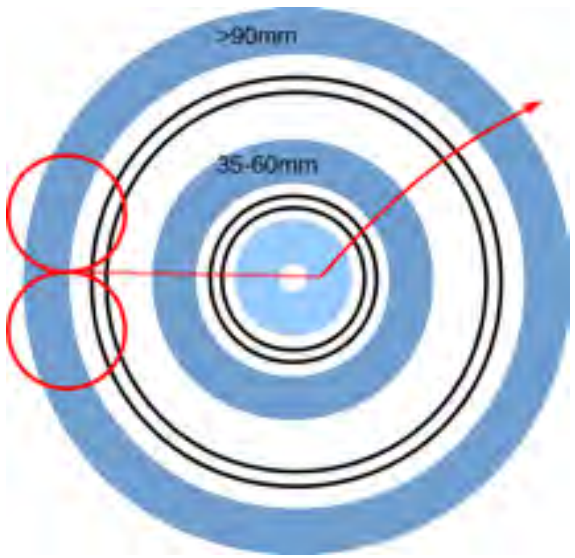
Longlived A′: $\mu \to e\nu\nu A'$ with subsequent $A' \to ee$

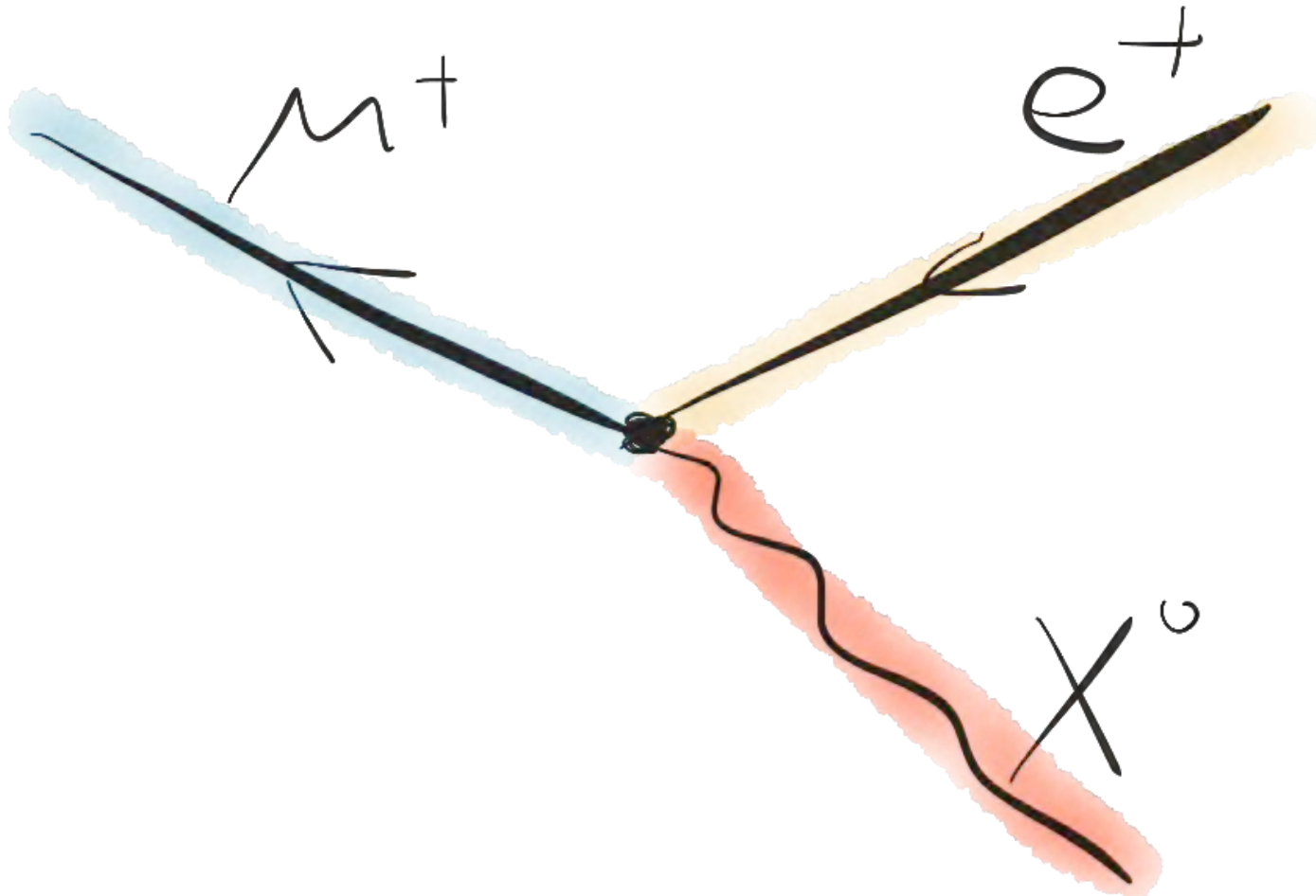
- Search for e^+e^- pairs from displaced vertices + resonance
- Background from Bhabha scattering and photon conversion
- Decay lengths of several cm can be studied
  $c\tau = 0.8\,\text{mm}\frac{10^{-8}}{\epsilon^2}\frac{10\,\text{MeV}}{m_{A'}}$
  [Echenard et al., JHEP 01 (2015), 113]

$\Rightarrow$ Extend reach to smaller ϵ^2

- Needs modifications of reconstruction and event filtering
- Currently under study





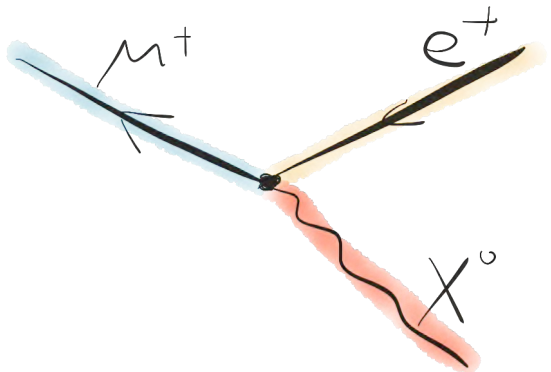

μ^+
e^+
X^0

LFV Two Body Decays: $\mu \to e X$

- Motivation: Familon
  (Wilczek, PRL 49 (1982) 1549)

  Spontaneous breaking of flavour symmetry

→ (Pseudo-)Goldstone boson
  emitted in flavour-changing decays

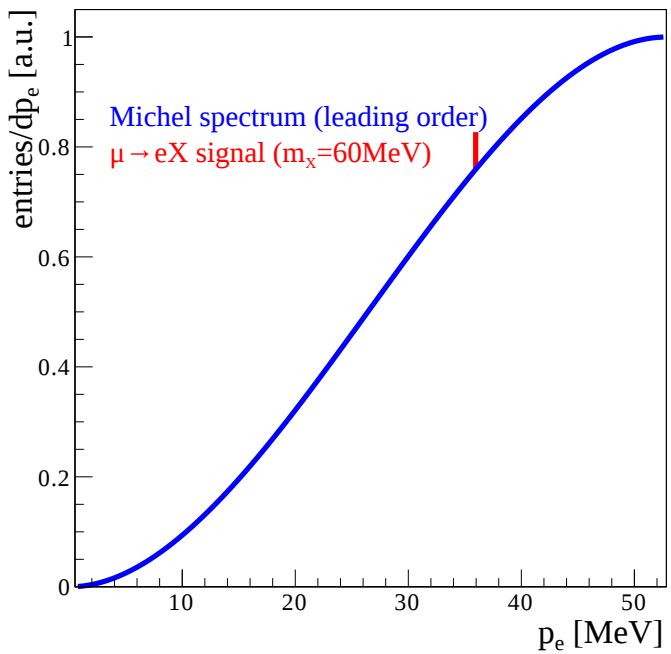


- $\mu^+ \to e^+ X^0$

  Neutral, light boson X not observed

  Monoenergetic positron

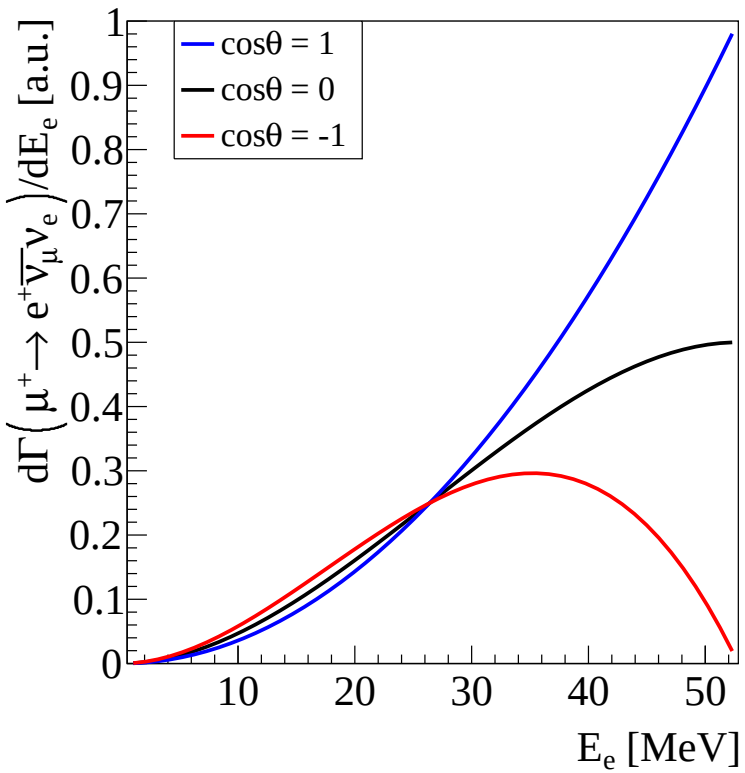
- Background:
  $\mu^+ \to e^+ \overline{\nu}_\mu \nu_e$, $\mu^+ \to e^+ \gamma \overline{\nu}_\mu \nu_e$,
  $\mu^+ \to e^+ e^- e^+ \overline{\nu}_\mu \nu_e$, Bhabha scattering,
  photon conversion, ...



Previous Experiments Searching for $\mu \to e X$

Jodidio et al. at TRIUMF
(Phys.Rev. D34, 1986)

- $1.8 \cdot 10^7$ highly polarized muons
- Search for massless familon expected to be isotropic
- Look for excess in end-point of Michel spectrum at $\cos\theta = -1$
- BR $< 2.6 \cdot 10^{-6}$ at 90 % CL



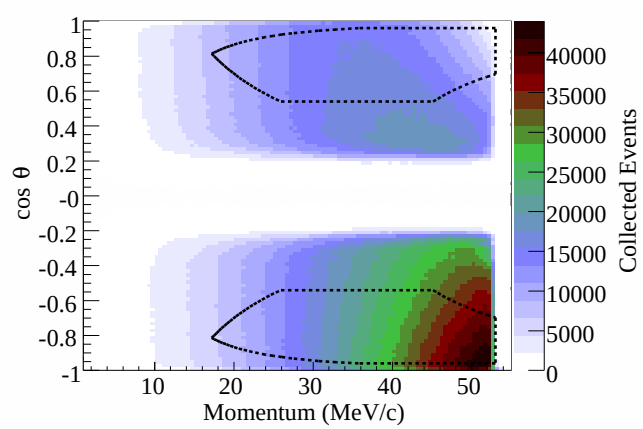
Michel spectrum, $\theta = \angle(\vec{P}_\mu, \vec{p}_e)$

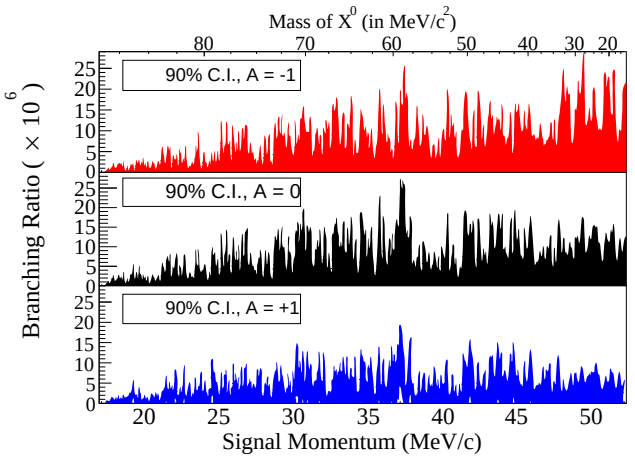
Previous Experiments Searching for $\mu \to e X$

TWIST at TRIUMF
(Bayes et al. Phys.Rev. D91, 2014)

- $5.8 \cdot 10^8$ μ decays analyzed from highly polarized μ beam
- Search for anisotropic $\mu \to e X$ decays
  $\frac{\partial \Gamma}{\partial \cos\theta} \propto 1 - A P_\mu \cos\theta$

- Massive X (on average):
  $BR_{A=0} < 9 \cdot 10^{-6}$ at 90 %CL
  $BR_{A=+1} < 10 \cdot 10^{-6}$ at 90 %CL
  $BR_{A=-1} < 6 \cdot 10^{-6}$ at 90 %CL

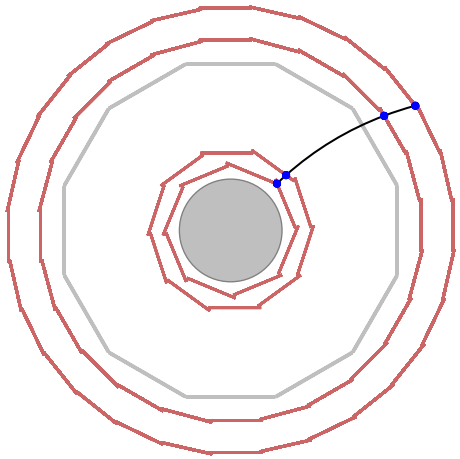




Searching for $\mu \to e X$ with Mu3e

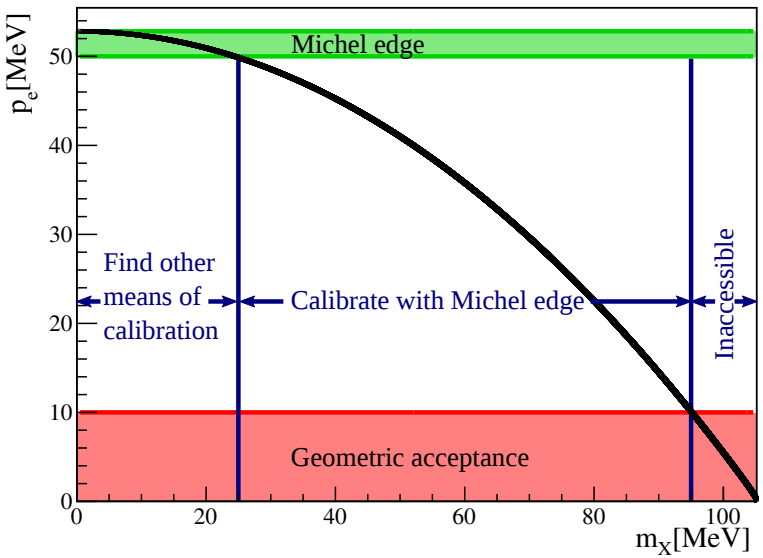
- High muon rate
  $\Rightarrow$ Cannot store all single-track events
- But: online reconstruction of all tracks as 'short' tracks
  (i.e. no reconstruction of recurler)

$\to$ Keep histogram of momenta for $\mu \to e X$ searches



- No acceptance for $p_T < 10\,\text{MeV}$
- Calibration with Michel edge, use of Mott and Bhabha scattering under investigation

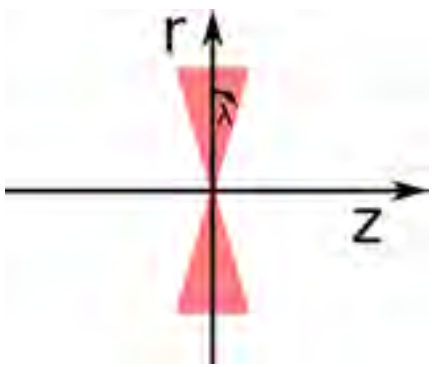
$\to$ $25\,\text{MeV} \leq m_X \leq 95\,\text{MeV}$ can be investigated

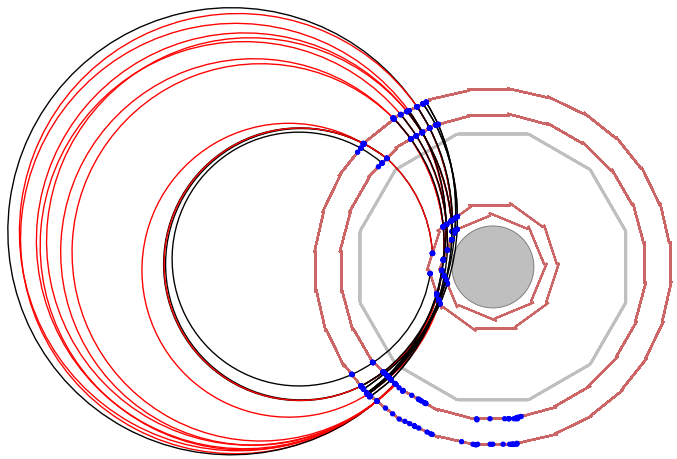


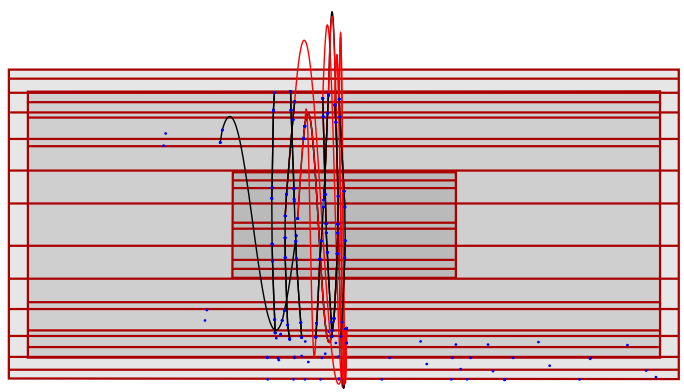
Searching for $\mu \to e X$ with Mu3e

Data selection

- χ^2 of track fit
- z of track propagated to target region
- Inclination angle λ_{01}

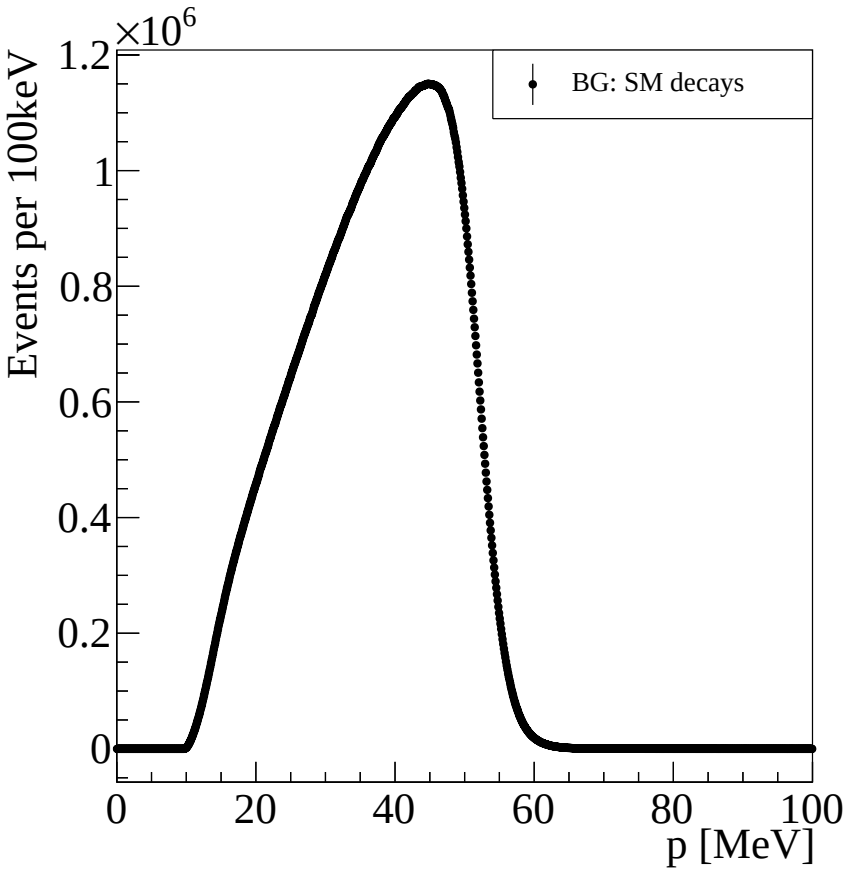




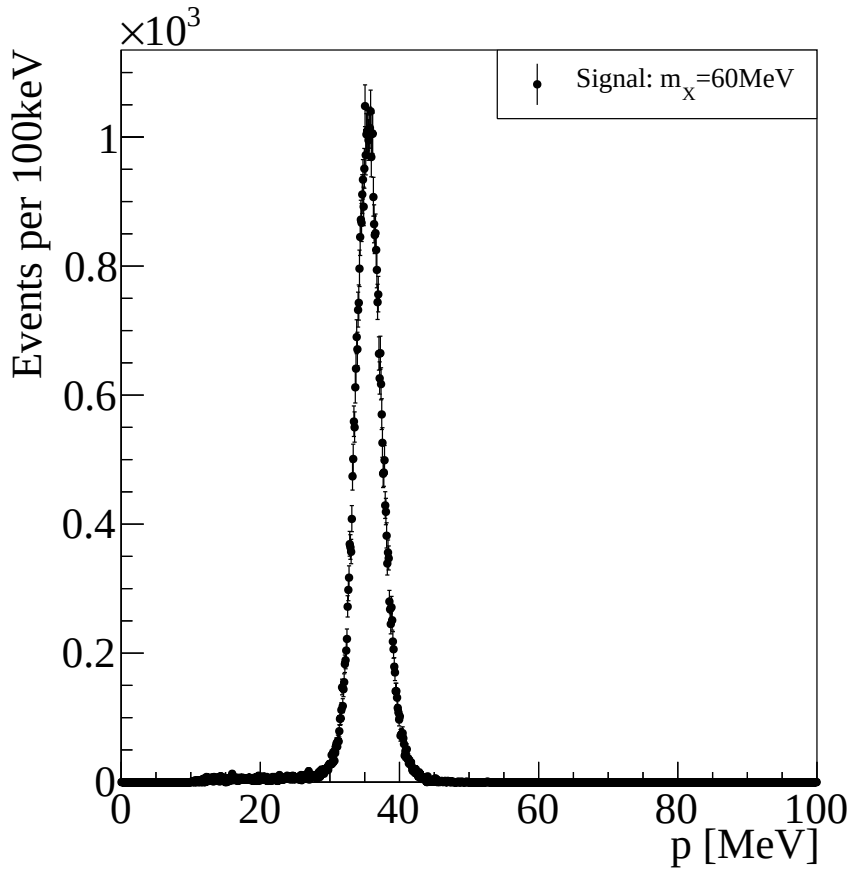


Searching for $\mu \to e X$ with Mu3e

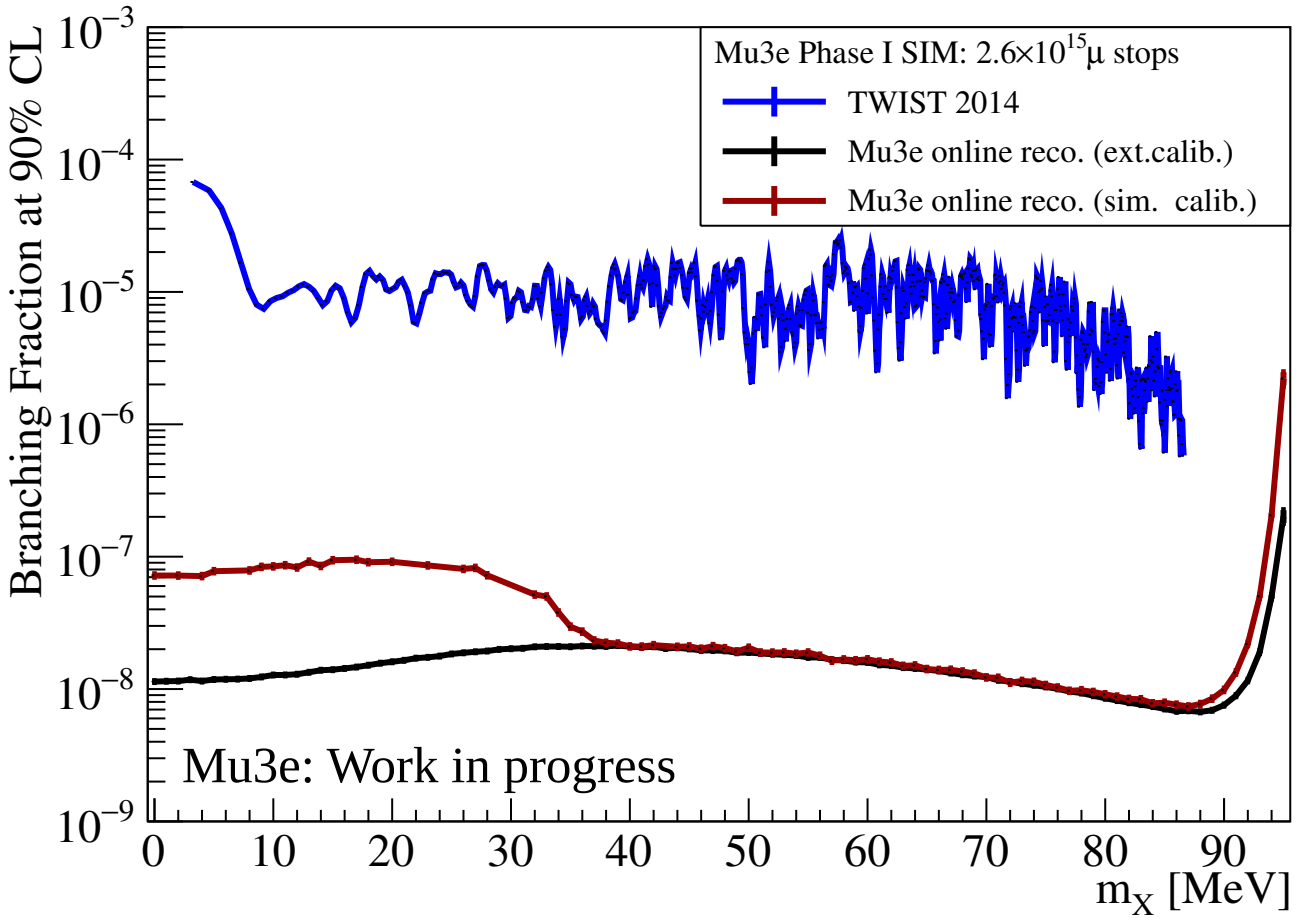
Background



Signal $m_X = 60\,\text{MeV}$



Searching for $\mu \to e X$ with Mu3e



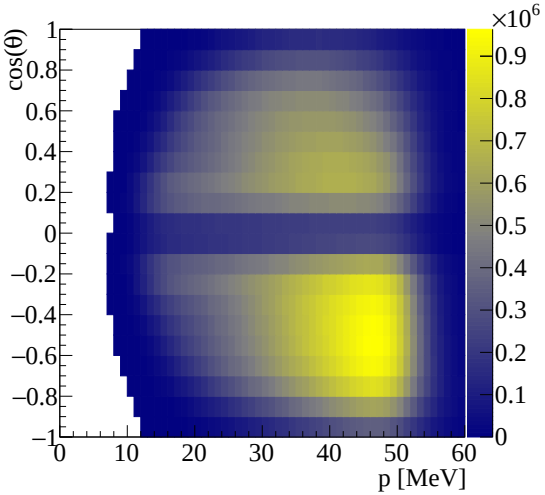
TWIST results by courtesy of R. Bayes

Searching for $\mu \to e X$ with Mu3e

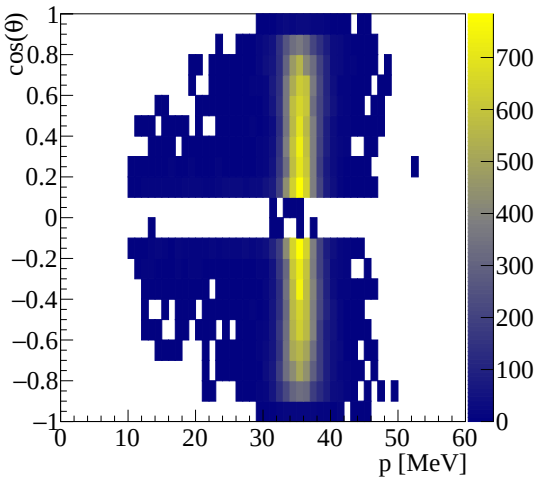
Anisotropic $\mu \to e X$ decays:

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + hP\cos\theta$$

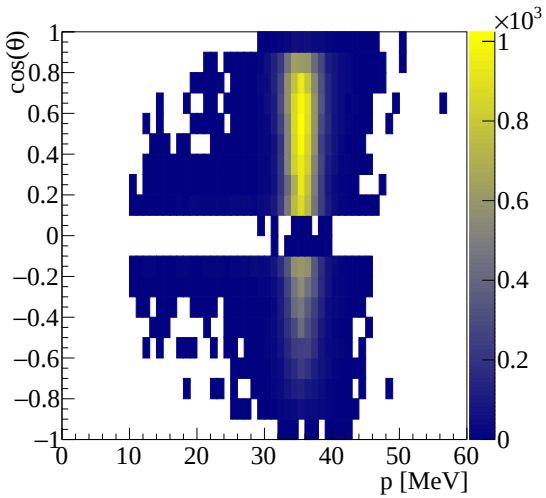
Background



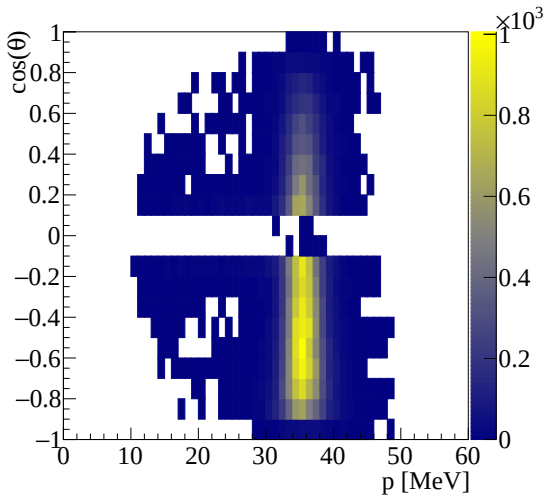
h=0, m_X = 60 MeV



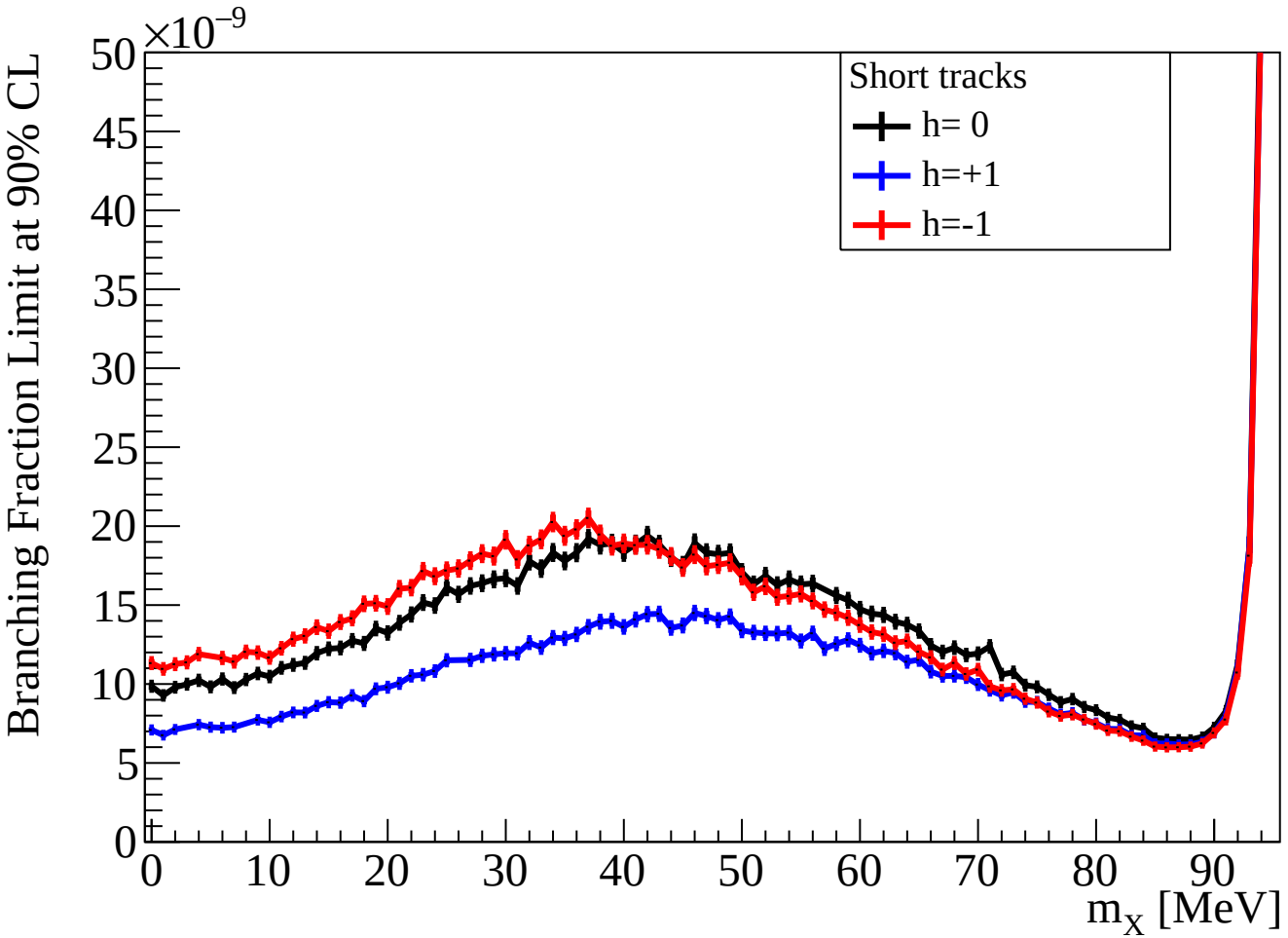
h=+1, m_X = 60 MeV



h=-1, m_X = 60 MeV



Searching for $\mu \to eX$ with Mu3e

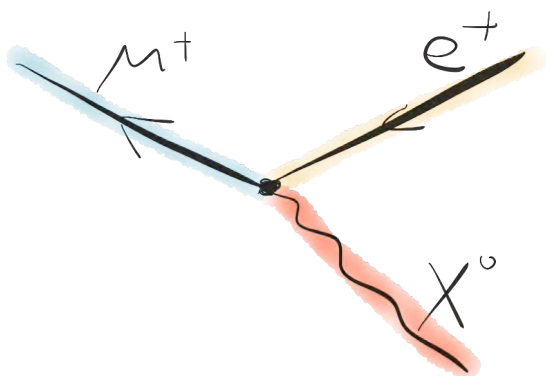


TWIST results by courtesy of R. Bayes

LFV Two Body Decays: $\mu \to e X$

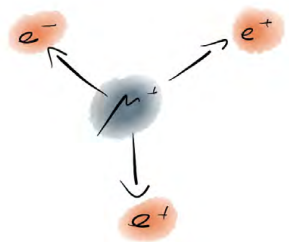
Further channels involving familons

- $\mu \to e X$, $X \to ee$:
  it's a $\mu \to eee$ search
- $\mu \to eeeee$:
  suffers from low acceptance at low p_T
  can run at lower B field

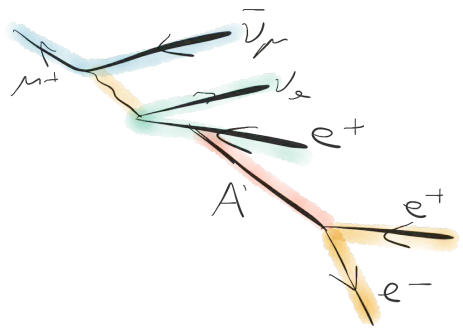


Summary

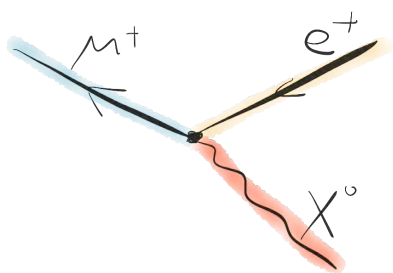
- $\mu \to$ eee in effective theories
  - Operators show characteristic decay distributions
  - Sensitivity of some 10^{-15} in phase I



- Dark photons in μ decays
  - Search for m_{ee} resonances
  - Investigate currently uncovered parameter space



- Lepton flavour violating two body decays $\mu \to$ eX
  - Bump search on e^+ momentum spectrum from online reconstruction
  - More than 2 orders of magnitude more sensitive than previous searches

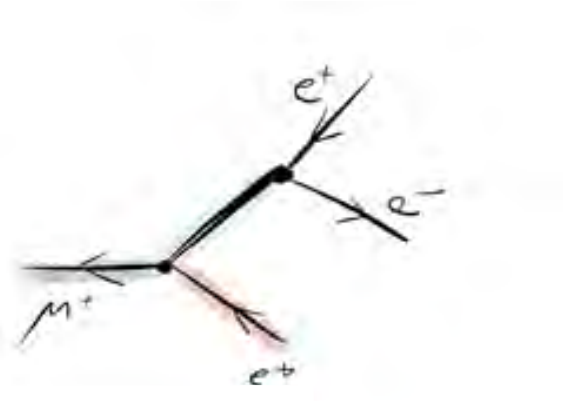


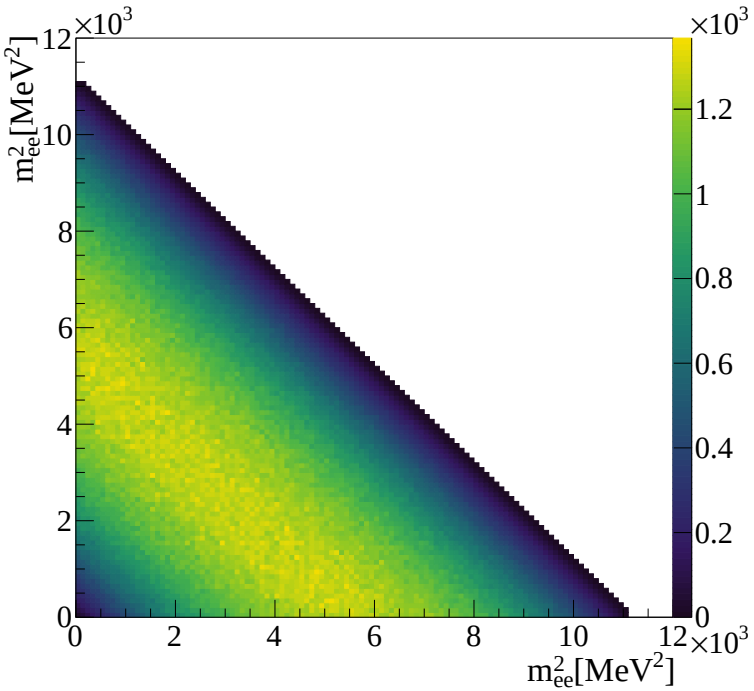

m3e

$\mu \to eee$ in Effective Theories

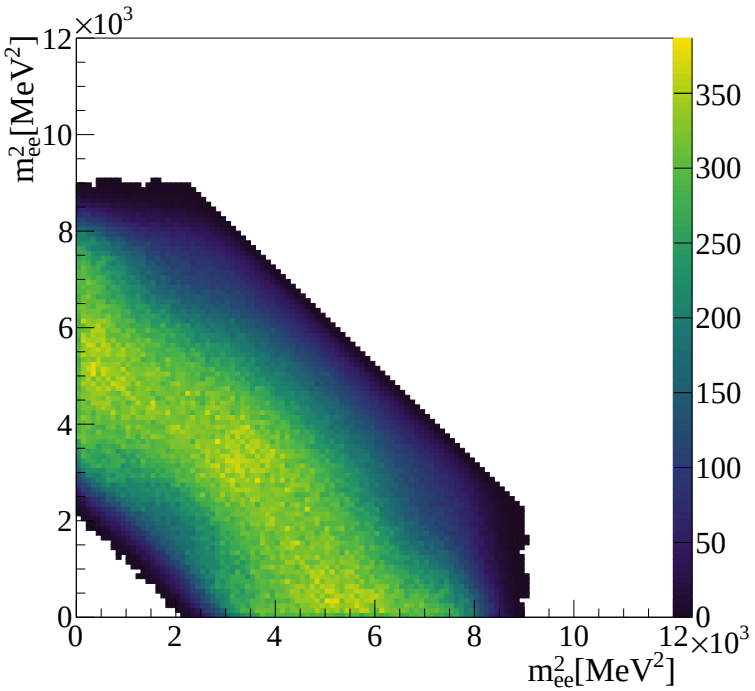
Vector 4-fermion operator $(\overline{\mu_R}\gamma^\mu e_R)(\overline{e_R}\gamma^\mu e_R)$
Scalar 4-fermion operator $(\overline{\mu_R} e_L)(\overline{e_R} e_L)$

Efficiency is 19 % $\Rightarrow$ BR $\geq 4.6 \cdot 10^{-15}$ at 90 % CL





Generated distribution

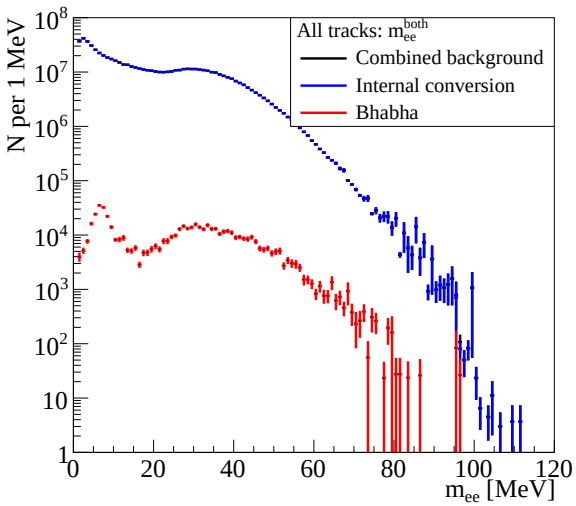


After reconstruction and vertex fit

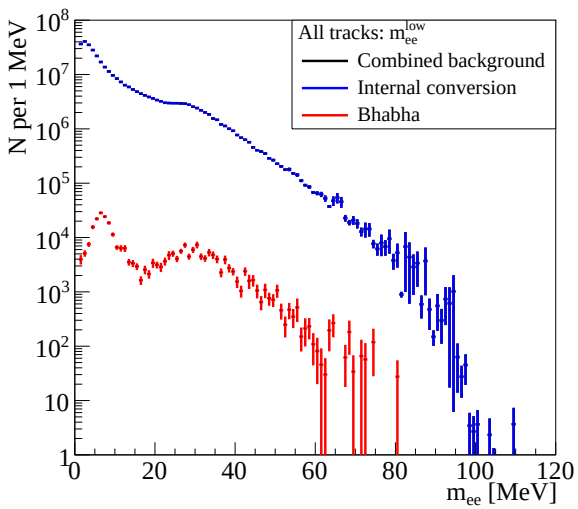
Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

Two possible e^+e^- combinations (background)

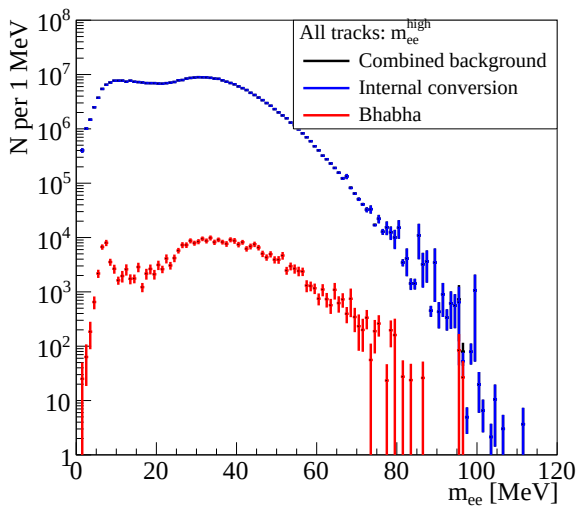
Both e^+e^- pairs



Lower m_{ee} pair for $m_{ee} < 45\,\text{MeV}$

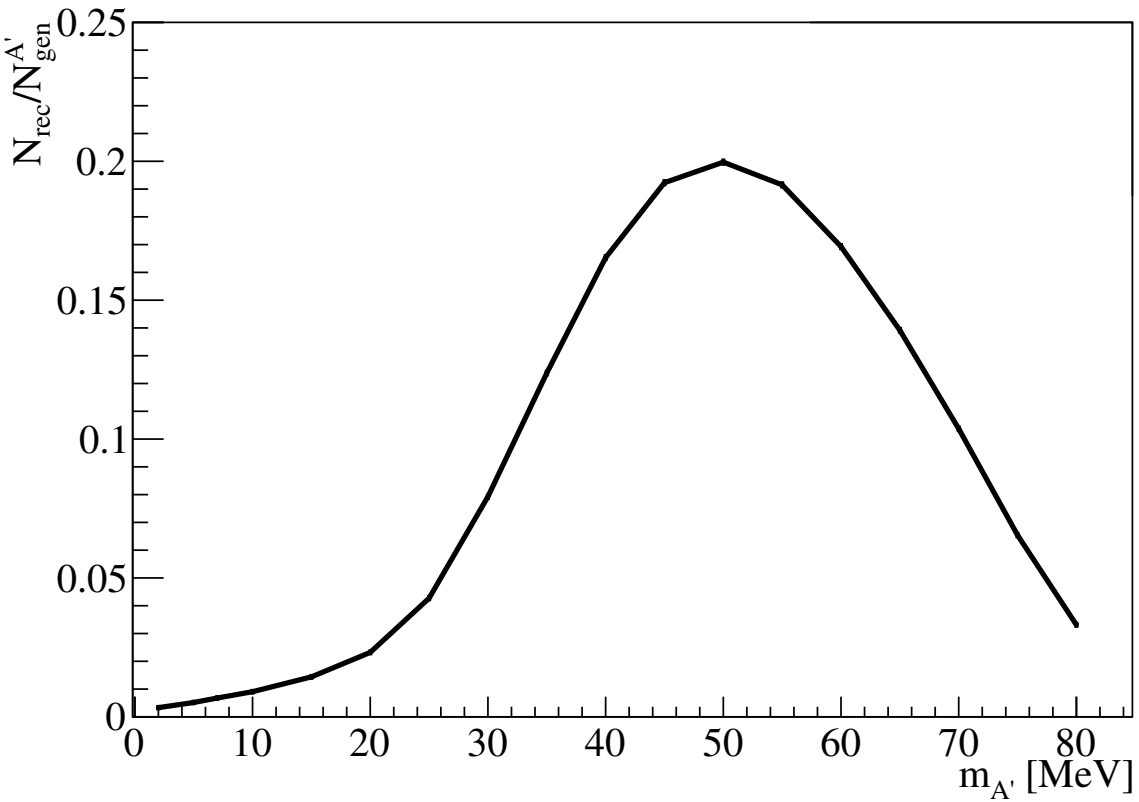


Higher m_{ee} pair for $m_{ee} \geq 45\,\text{MeV}$



Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

Acceptance low for low p_T electrons, i. e. at low and high m_{ee}

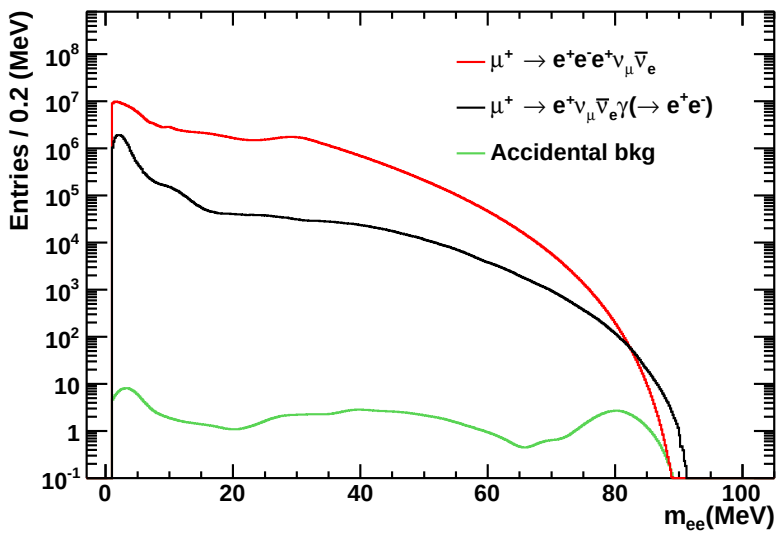


Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

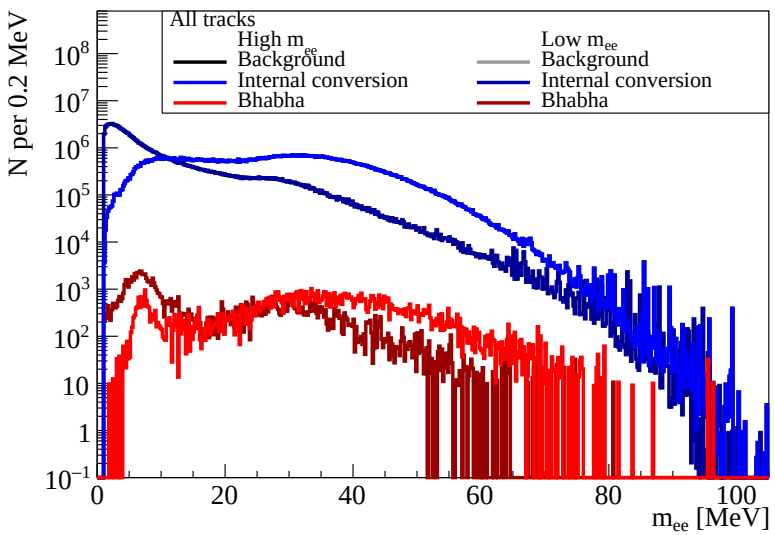
Comparison with external study

Phase I: $1 \cdot 10^{15}$ muons

Echenard et al.,
JHEP 01 (2015), 113



Mu3e simulation

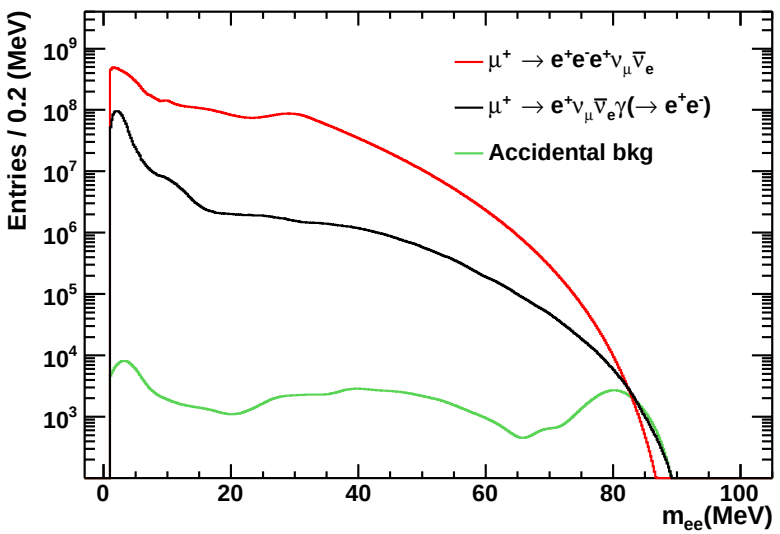


Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

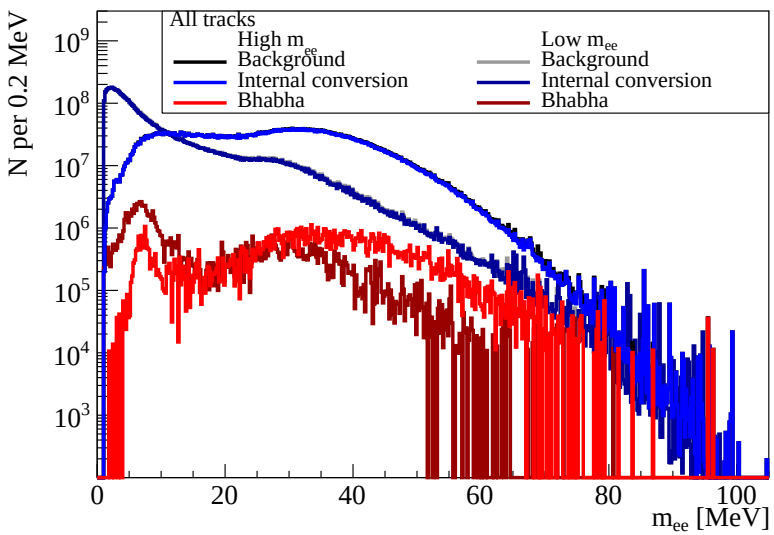
Comparison with external study

Phase II: $5.5 \cdot 10^{16}$ muons

Echenard et al.,
JHEP 01 (2015), 113



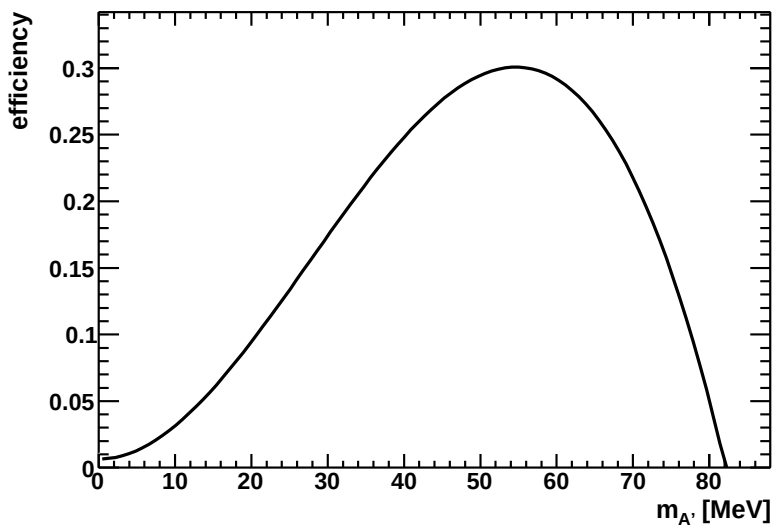
Mu3e simulation



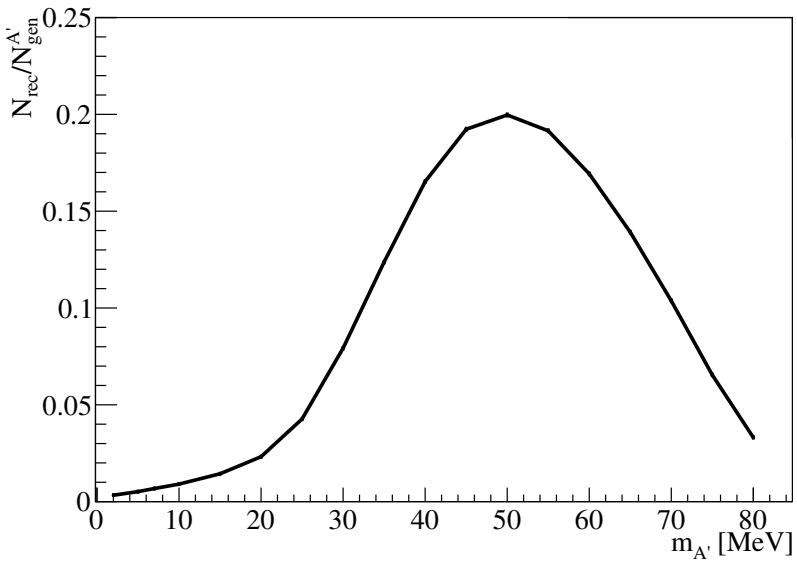
Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

Comparison with external study

Echenard et al.,
JHEP 01 (2015), 113

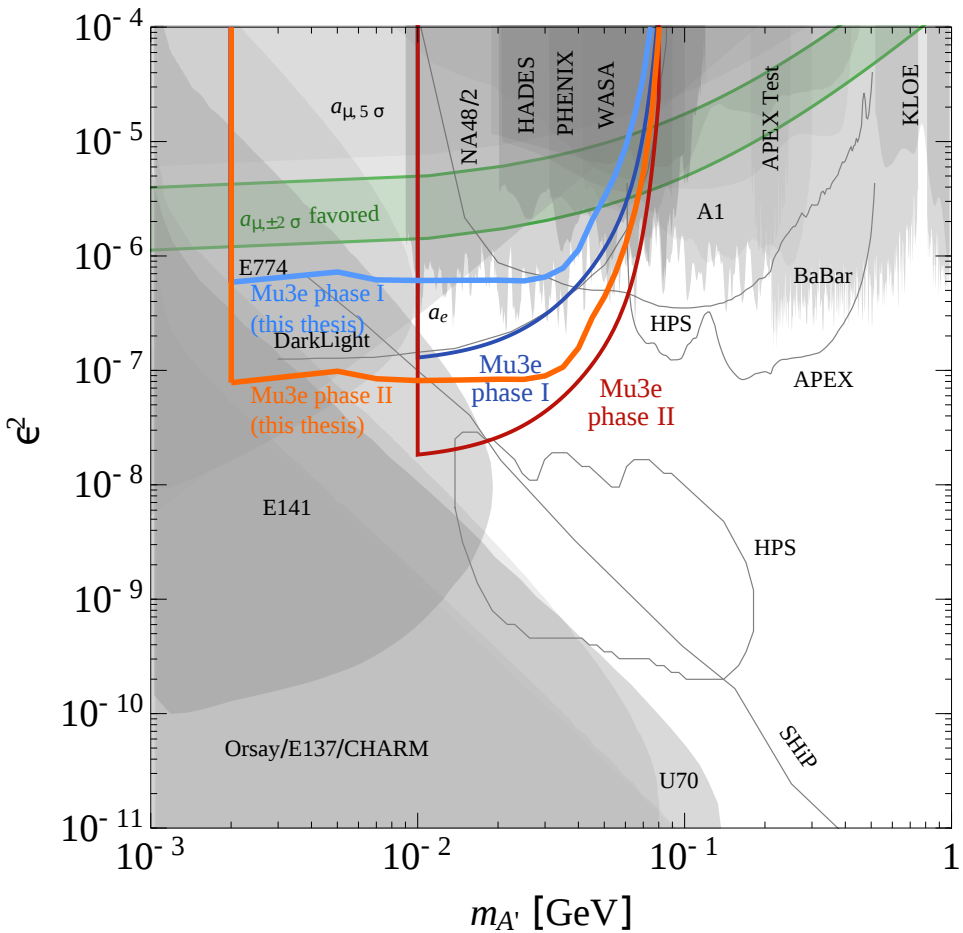


Mu3e simulation



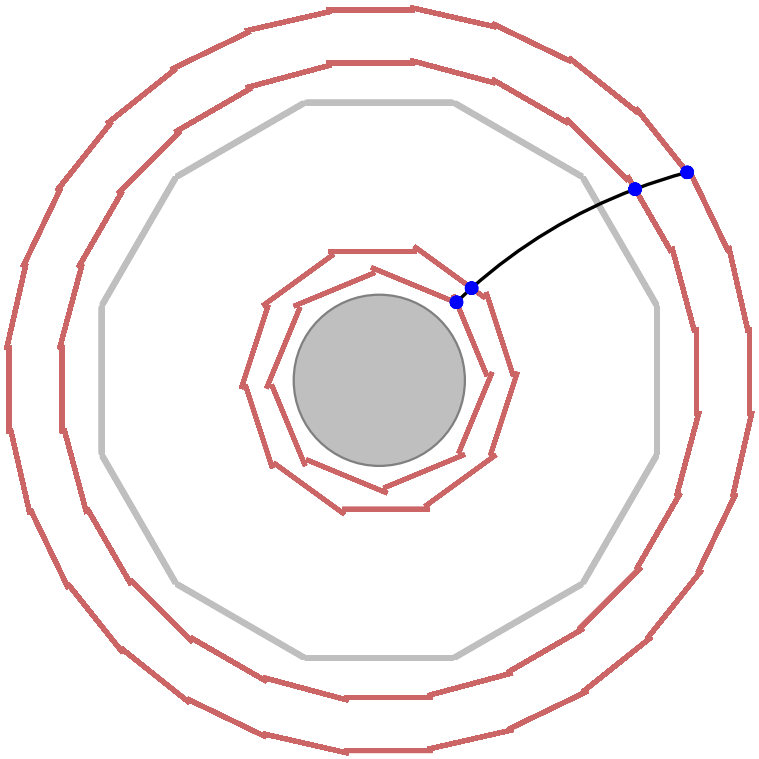
Promptly Decaying Dark Photons: $\mu \to e\nu\nu(A' \to ee)$

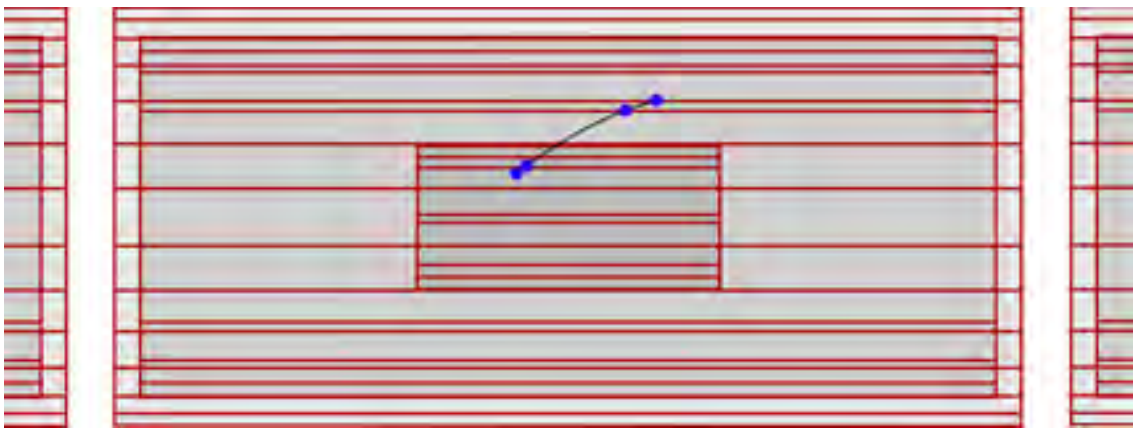
Comparison with external study



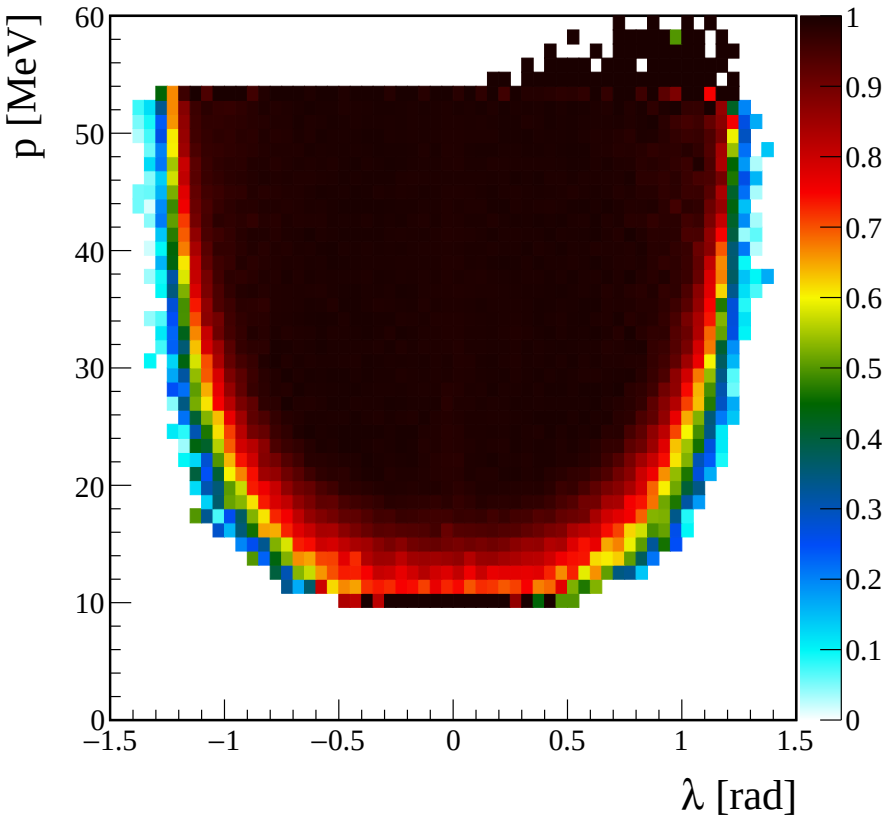
adapted from Echenard et al., JHEP 01 (2015), 113

Short Tracks: 4 Hits

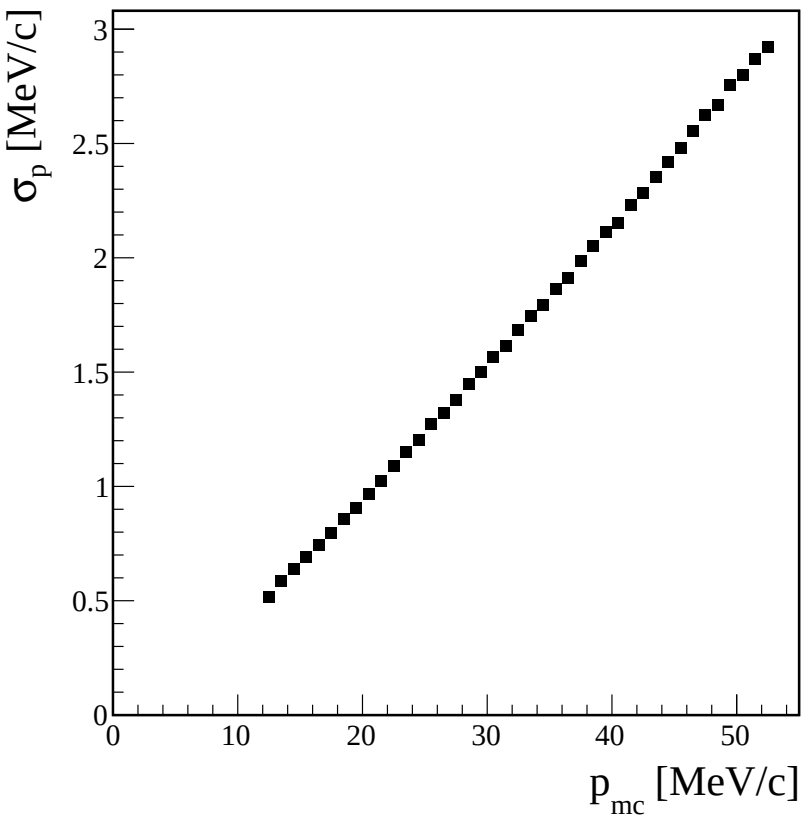




Short Tracks

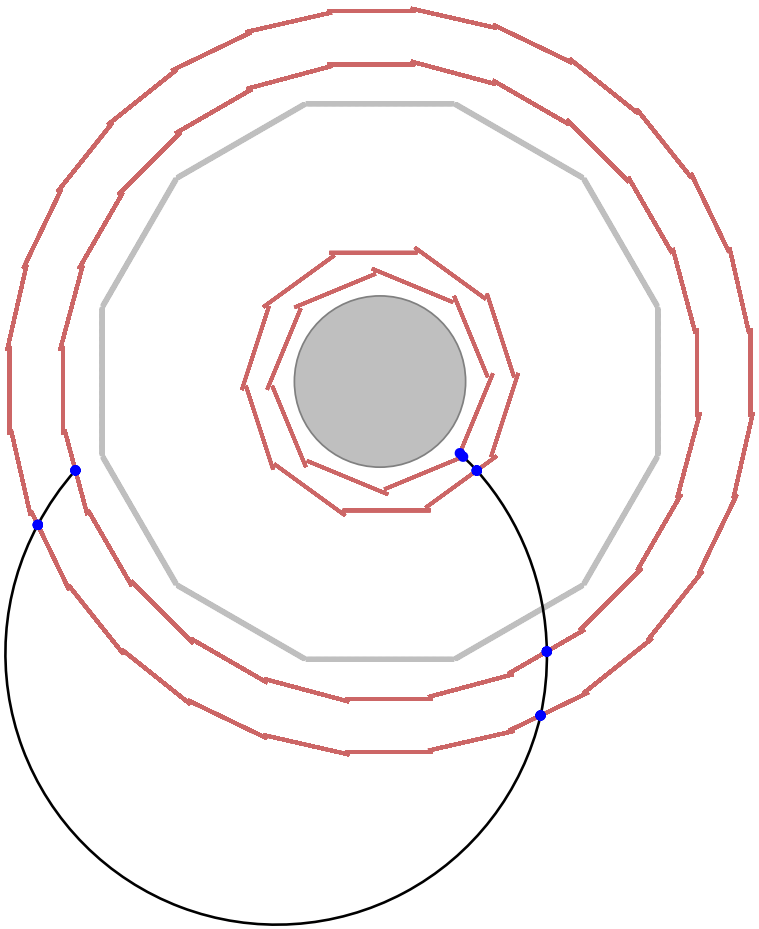


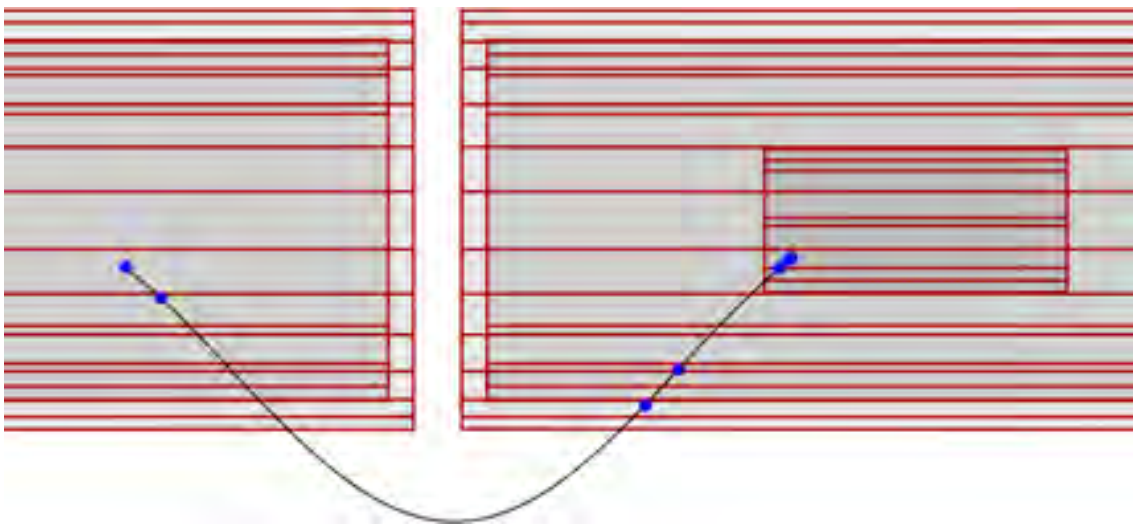
Efficiency.



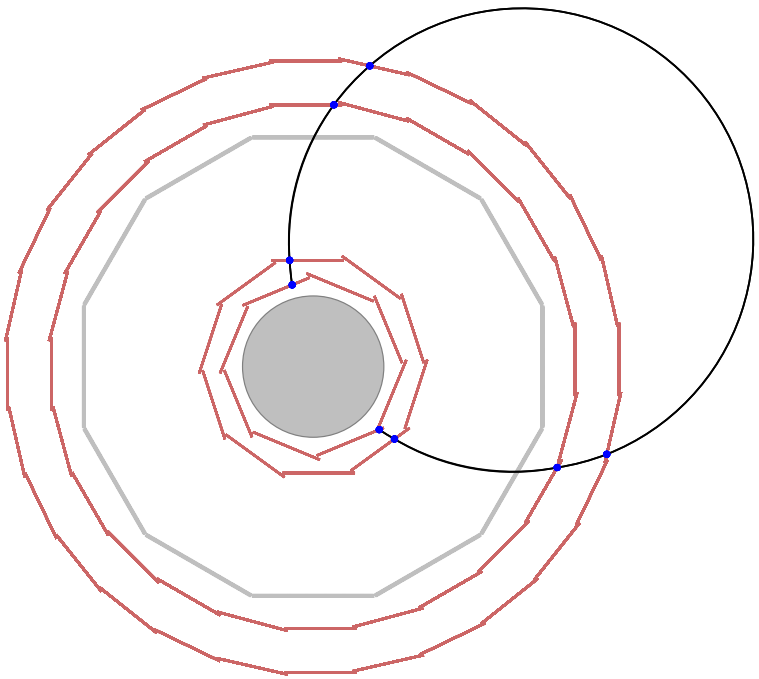
Momentum resolution.

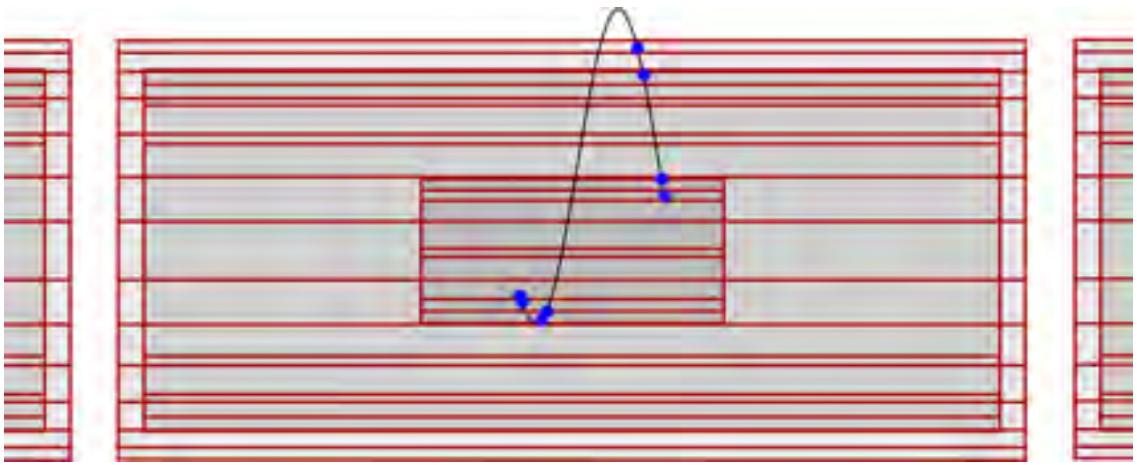
Long Tracks: 6 Hits



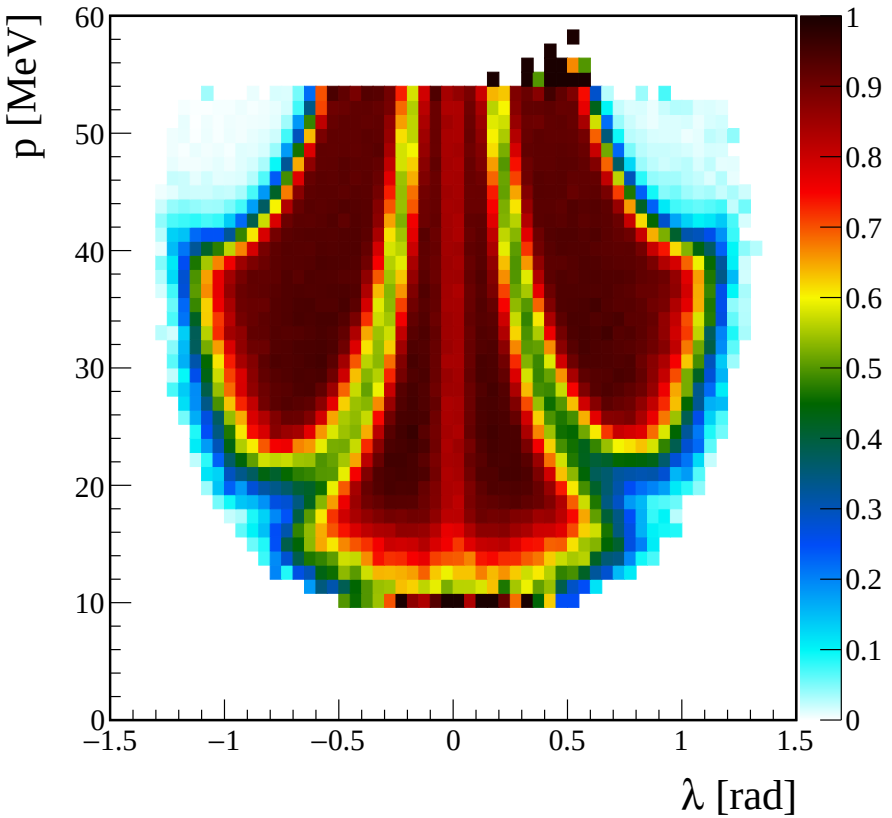


Long Tracks: 8 Hits

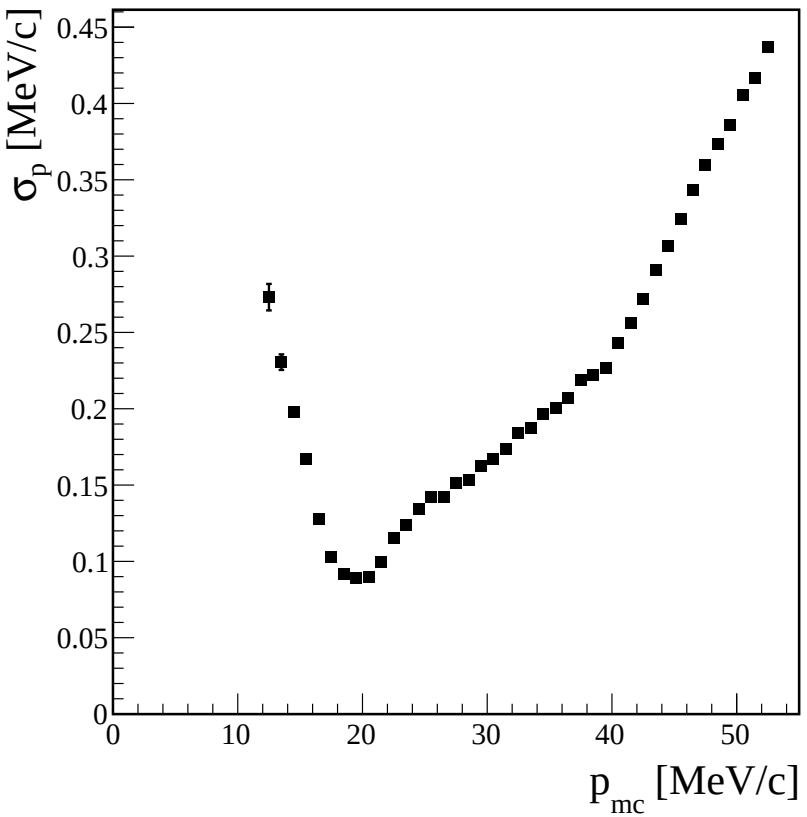




Long Tracks



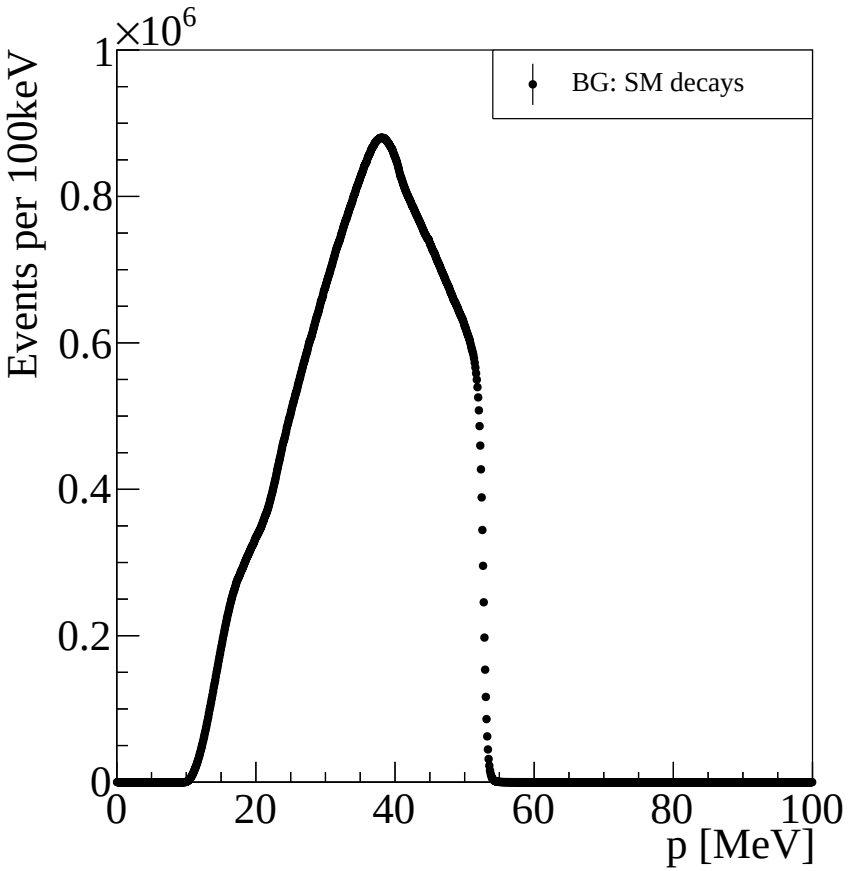
Efficiency.



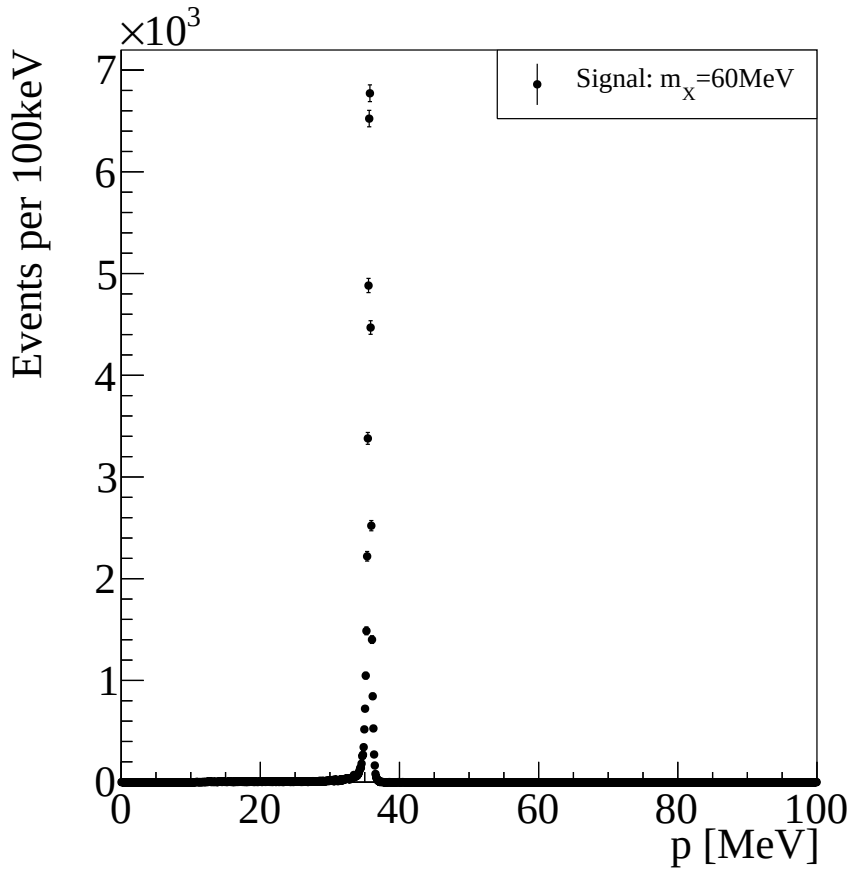
Momentum resolution.

Searching for $\mu \to e X$ with Mu3e

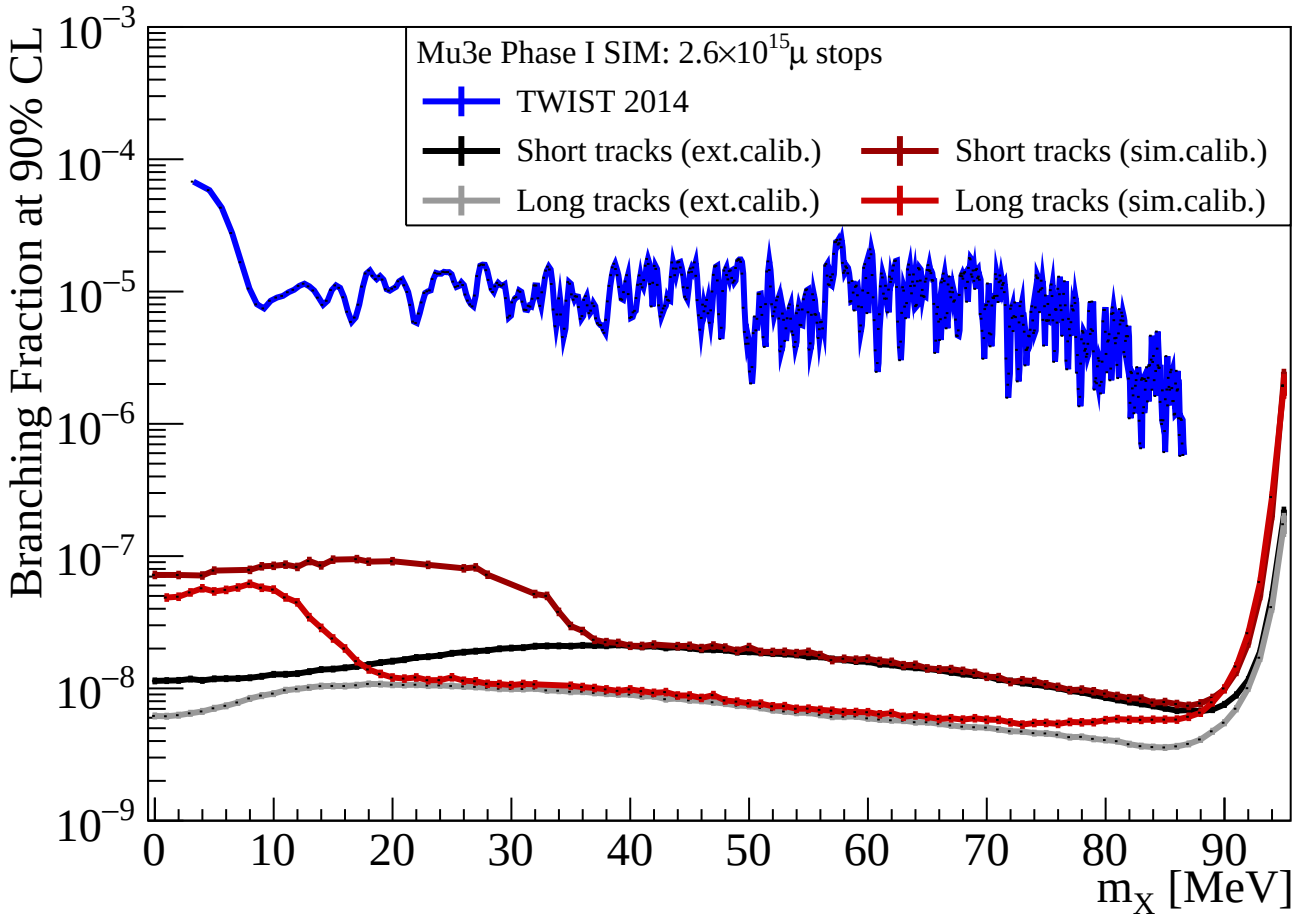
Background



Signal $m_X = 60\,\text{MeV}$



Searching for $\mu \to e X$ with Mu3e



TWIST results by courtesy of R. Bayes

Upgrades to Mu3e

Potential Mu3eGamma upgrade

- Search for $\mu \to e\gamma$
- Additional photon converter and tracking detectors
- Increase B field: from 1 T to 2 T
- Can also investigate $\mu \to e X \gamma$ and dark photons from displaced vertices