Dark Matter

@

Charged lepton flavour violation experiments

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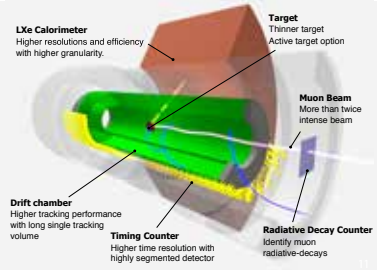
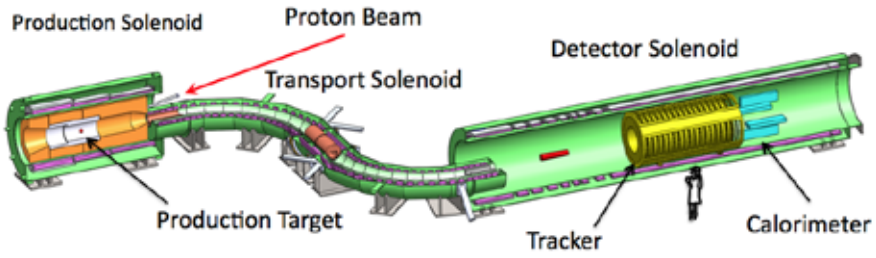
Dark Matter @ LHC
Heidelberg, April 2018

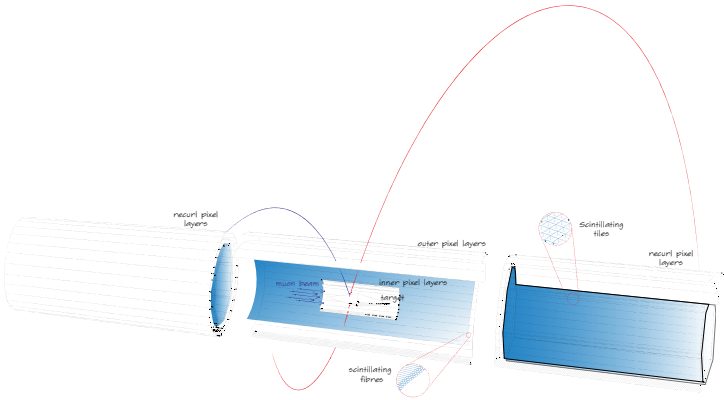
JG|U

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Overview





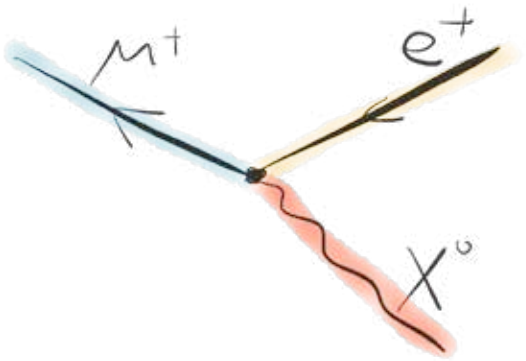


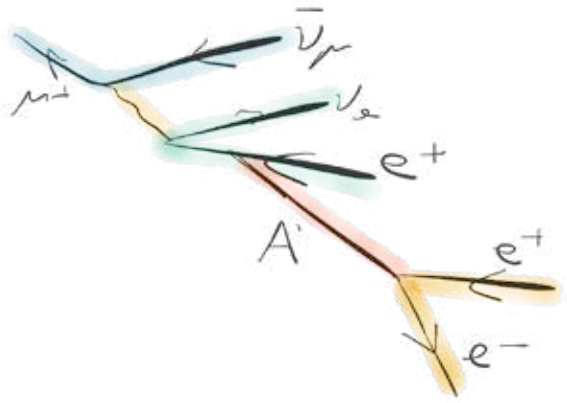
Charged lepton flavour violation experiments:

- What do we have, what do we expect?

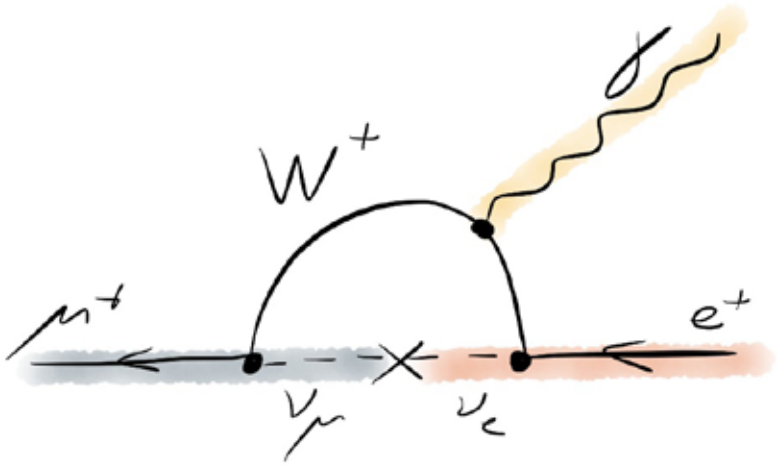
Beyond the standard channels:

- Exotics with Mu3e: μ → e X and Dark Photons





Lepton flavour violation experiments



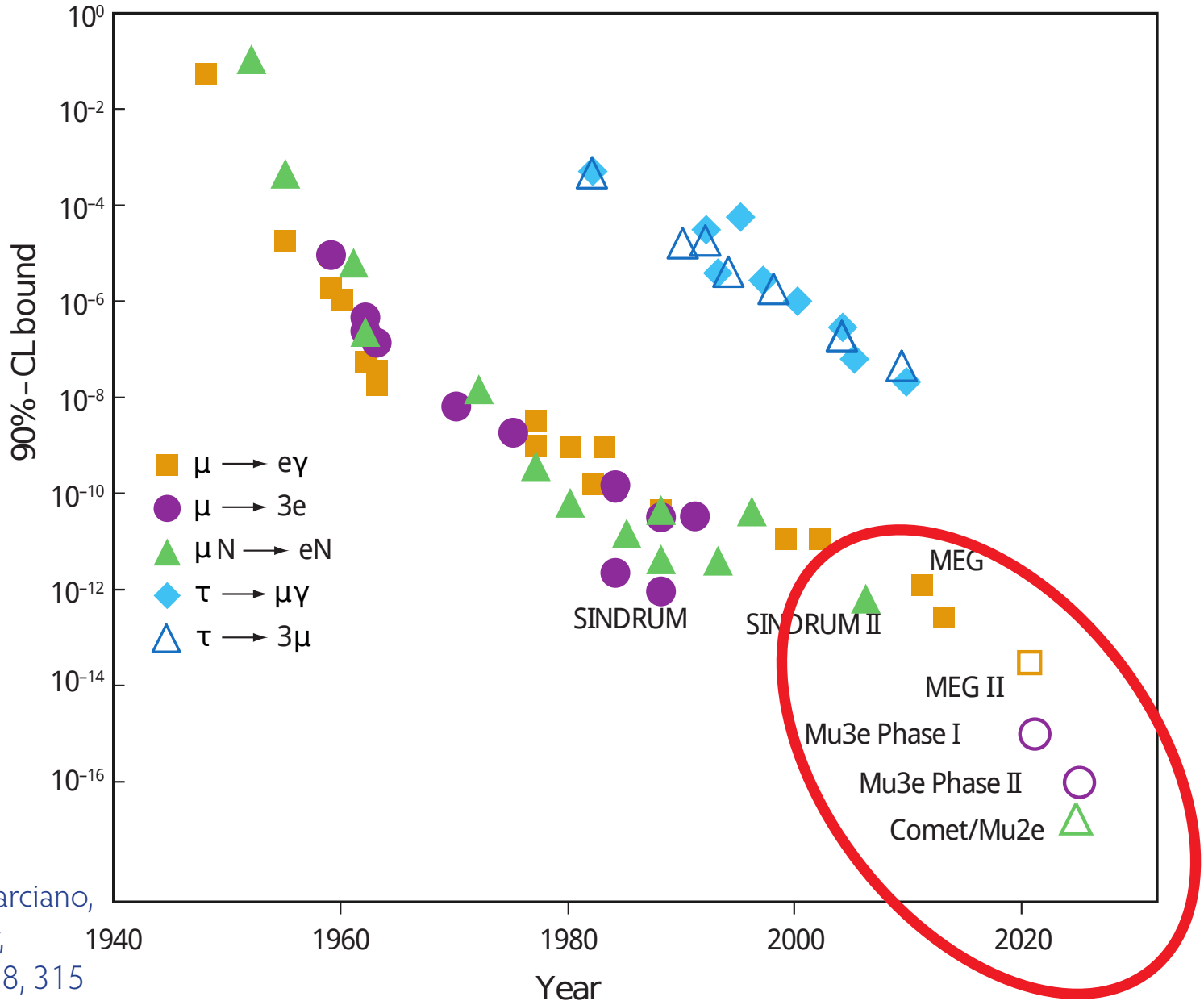
Standard Model branching fractions of

$10^{-50\text{ish}}$

Only limited by number of muons and background suppression:

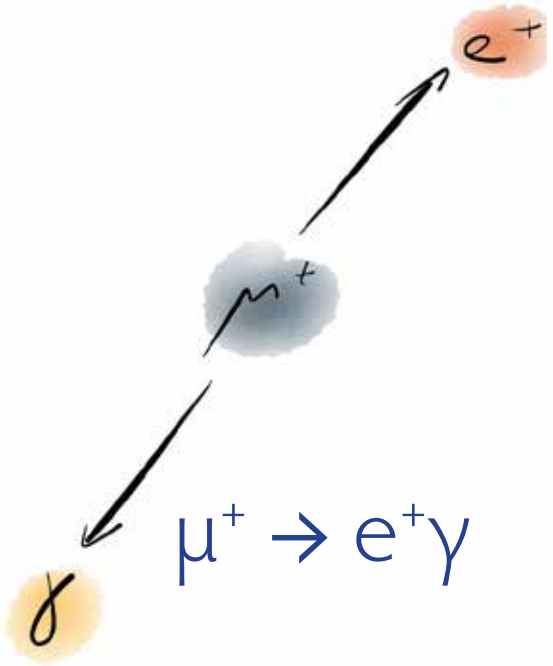
Experimental/technical challenge

History of cLFV experiments

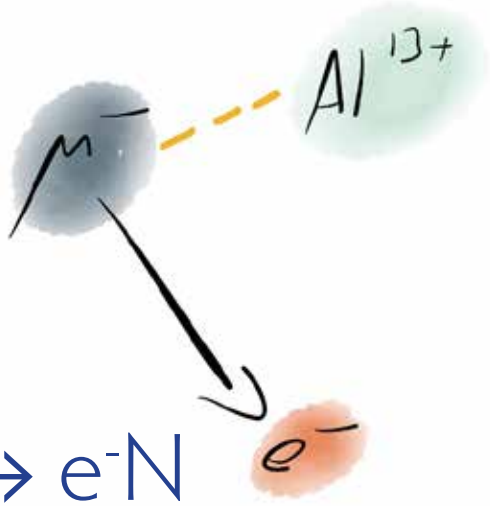


(Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008))

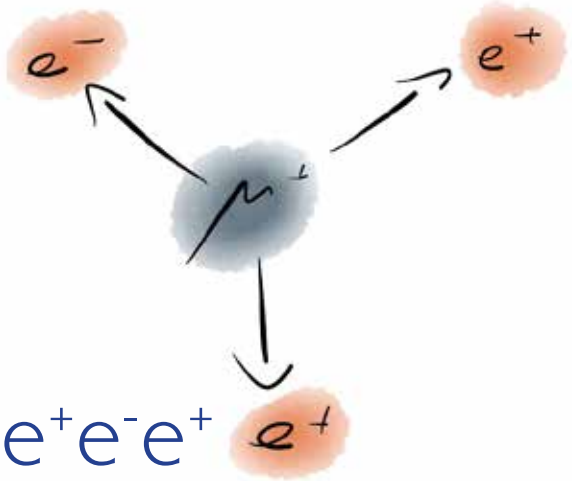
LFV Muon Decays



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

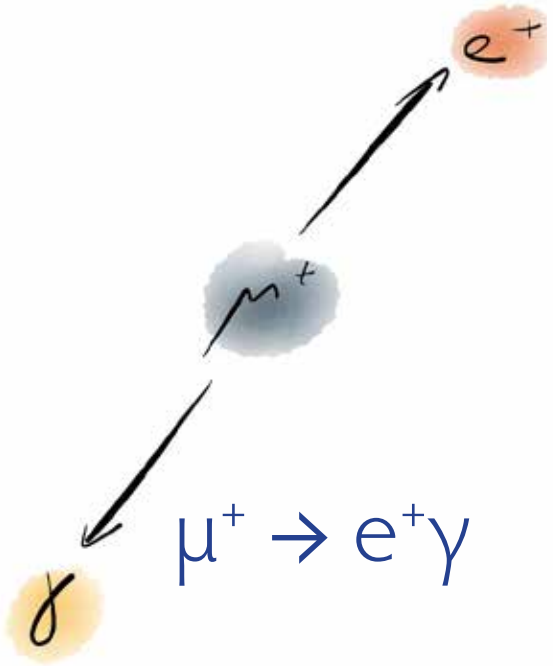


$\mu^-N \to e^-N$

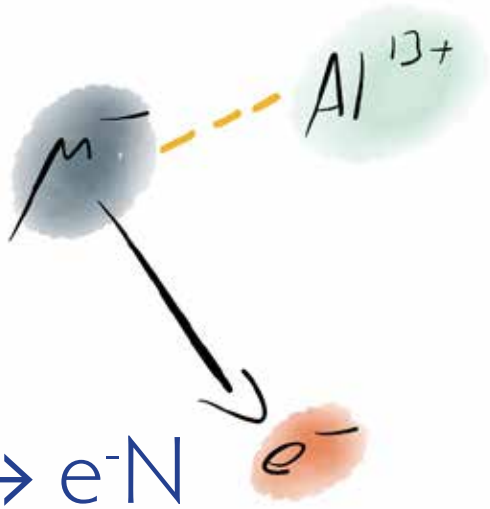


$\mu^+ \to e^+e^-e^+$

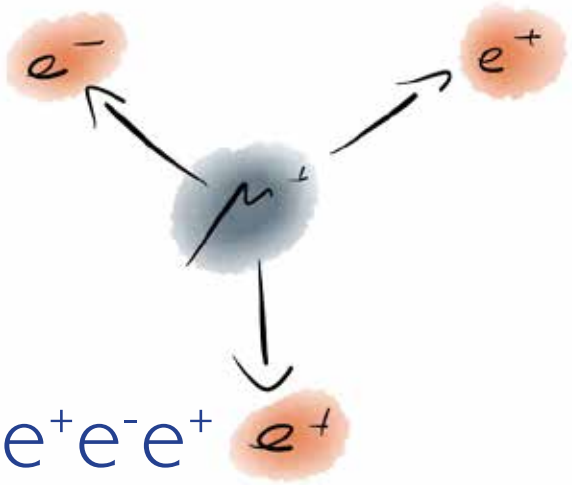
LFV Muon Decays: Experimental Situation



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



$\mu^-N \to e^-N$



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

MEG (PSI)

$B(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$

(2016)

SINDRUM II (PSI)

$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$

(2006)

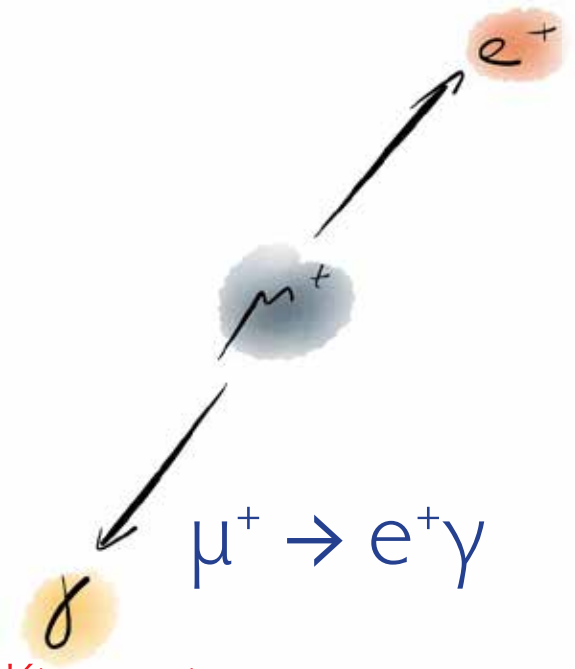
relative to nuclear capture

SINDRUM (PSI)

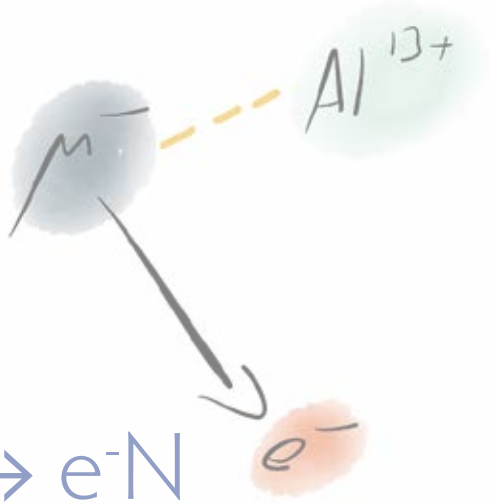
$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$

(1988)

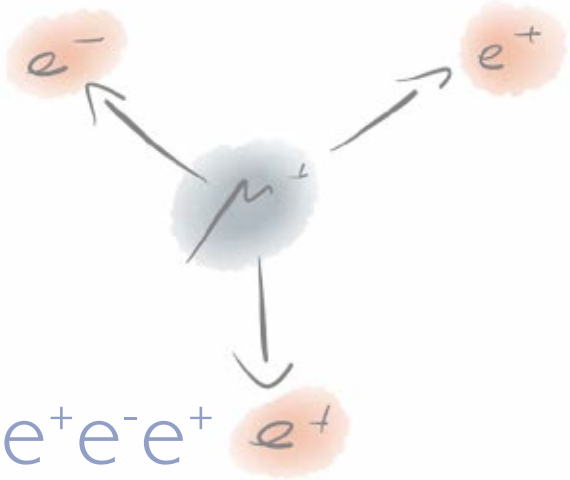
LFV Muon Decays: Experimental signatures



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



$\mu^-N \to e^-N$

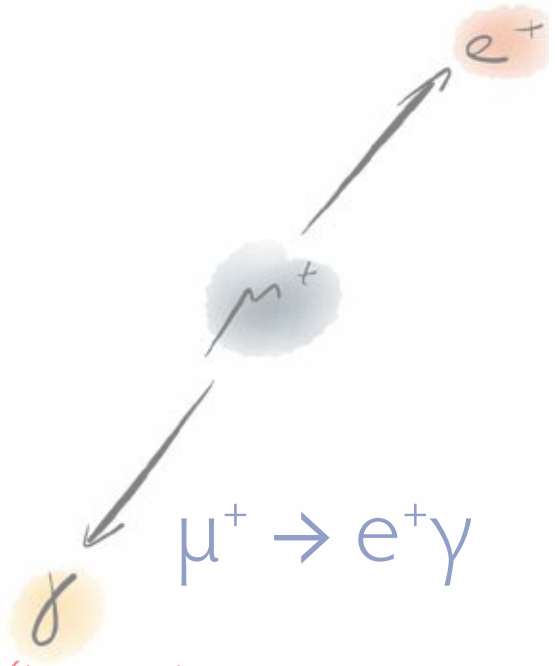


$\mu^+ \to e^+e^-e^+$

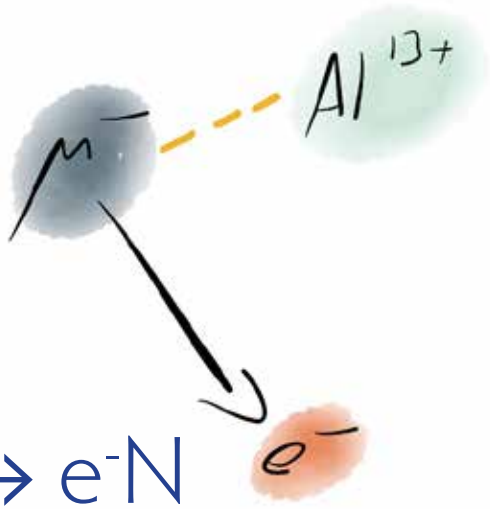
Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

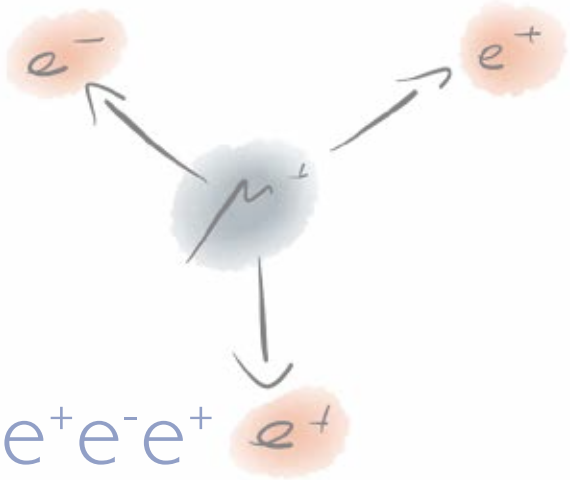
LFV Muon Decays: Experimental signatures



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



$\mu^-N \to e^-N$



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

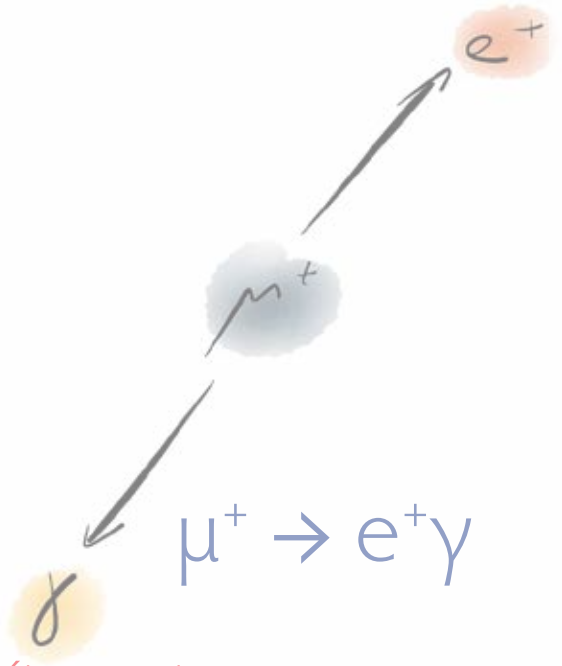
Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

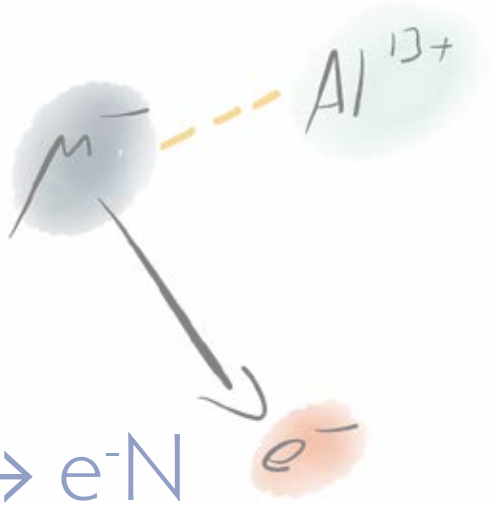
Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

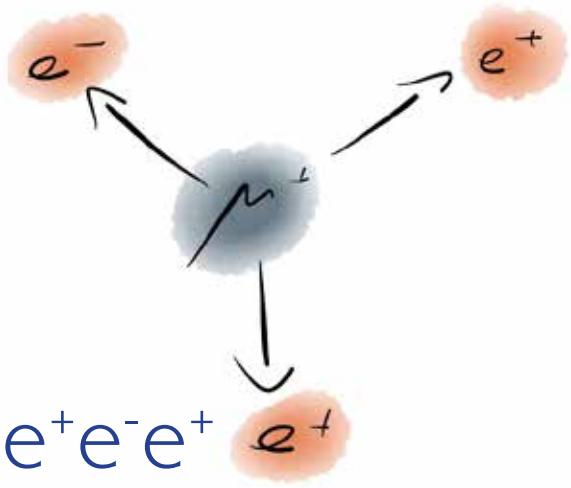
LFV Muon Decays: Experimental signatures



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



$\mu^-N \to e^-N$



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

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

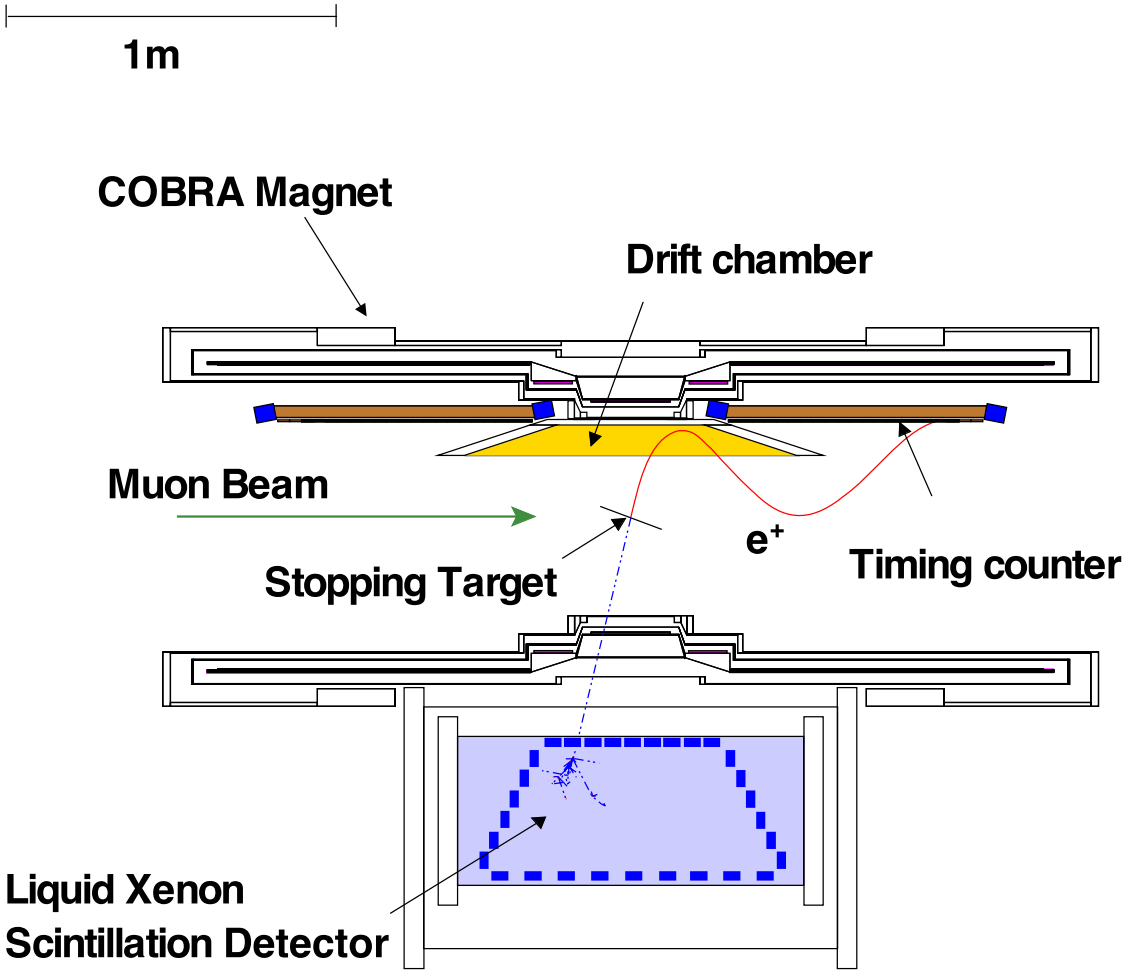
Kinematics

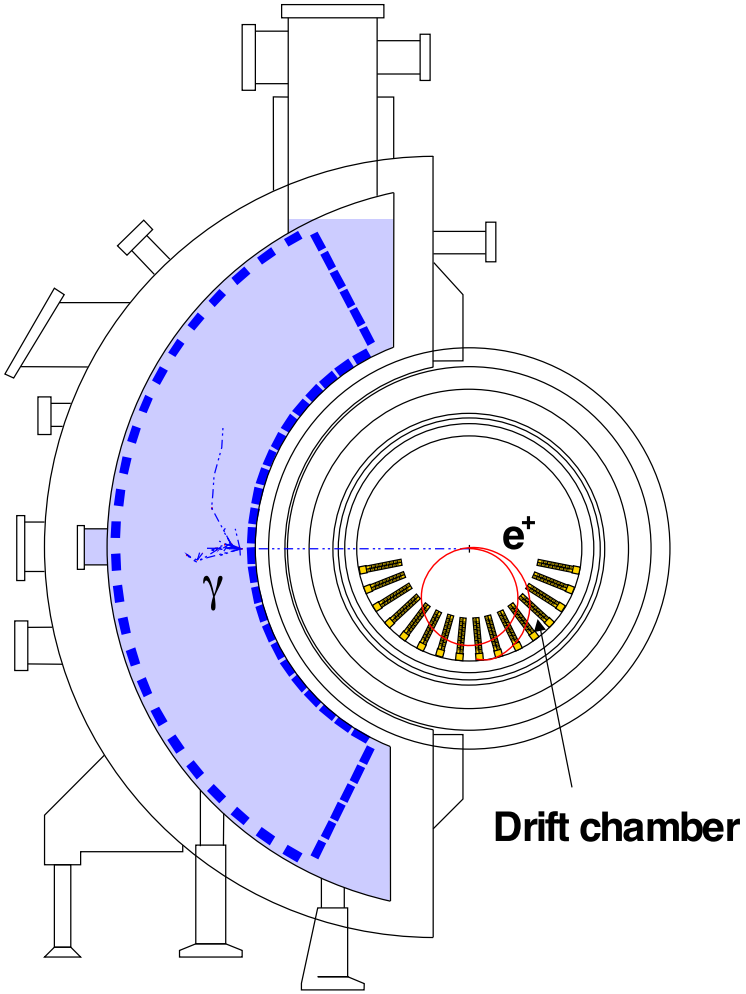
- 3-body decay
- Invariant mass constraint
- $\Sigma\, p_i = 0$

Searching for μ → eγ with

MEG

The MEG Detector





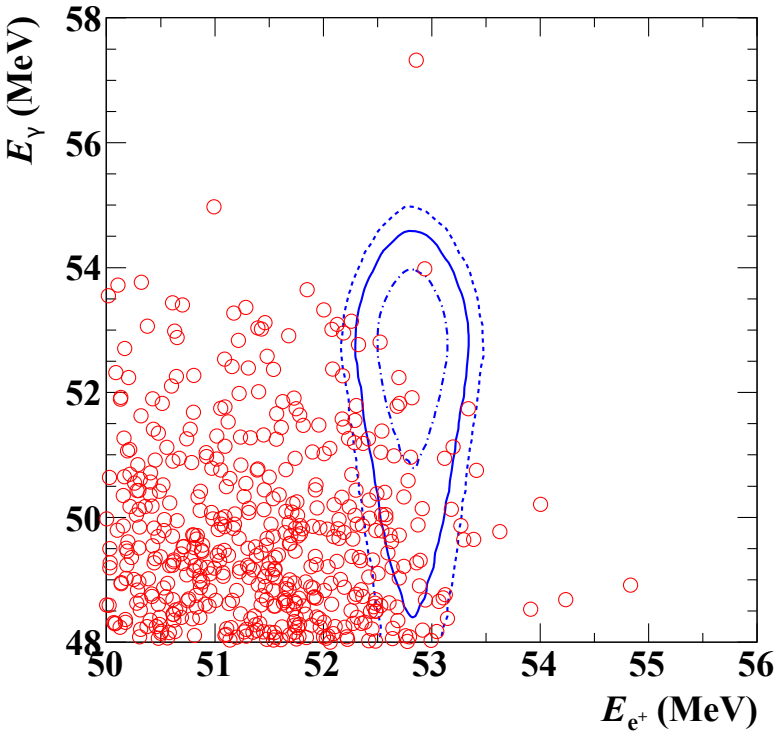
J. Adam et al. EPJ C 73, 2365 (2013)

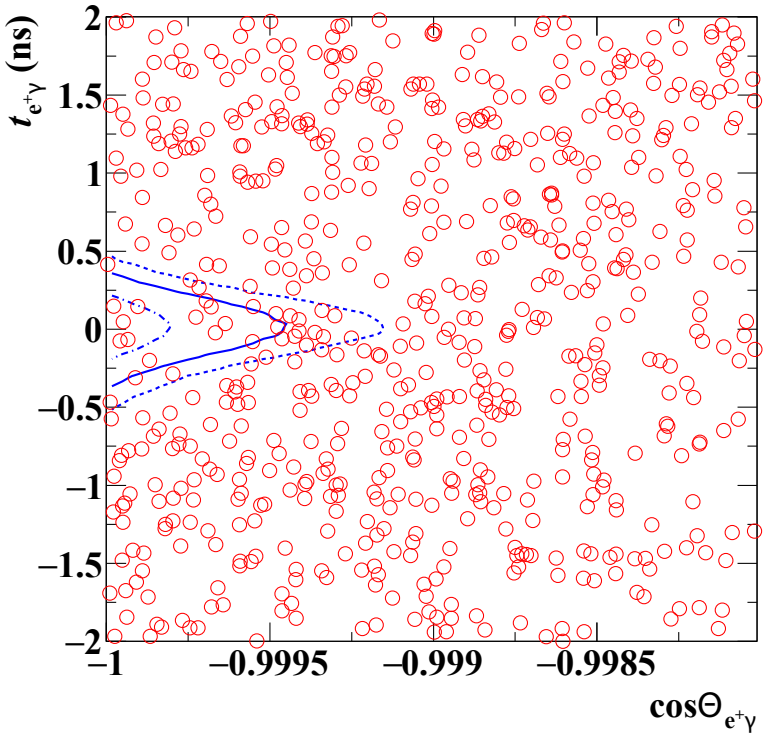
MEG Results

- 2009-2013 data
- Blue: Signal PDF, given by detector resolution
- No signal seen
- Upper limit at 90% CL:

$$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

A. M. Baldini et al. Eur.Phys.J. C76 (2016) no.8, 434



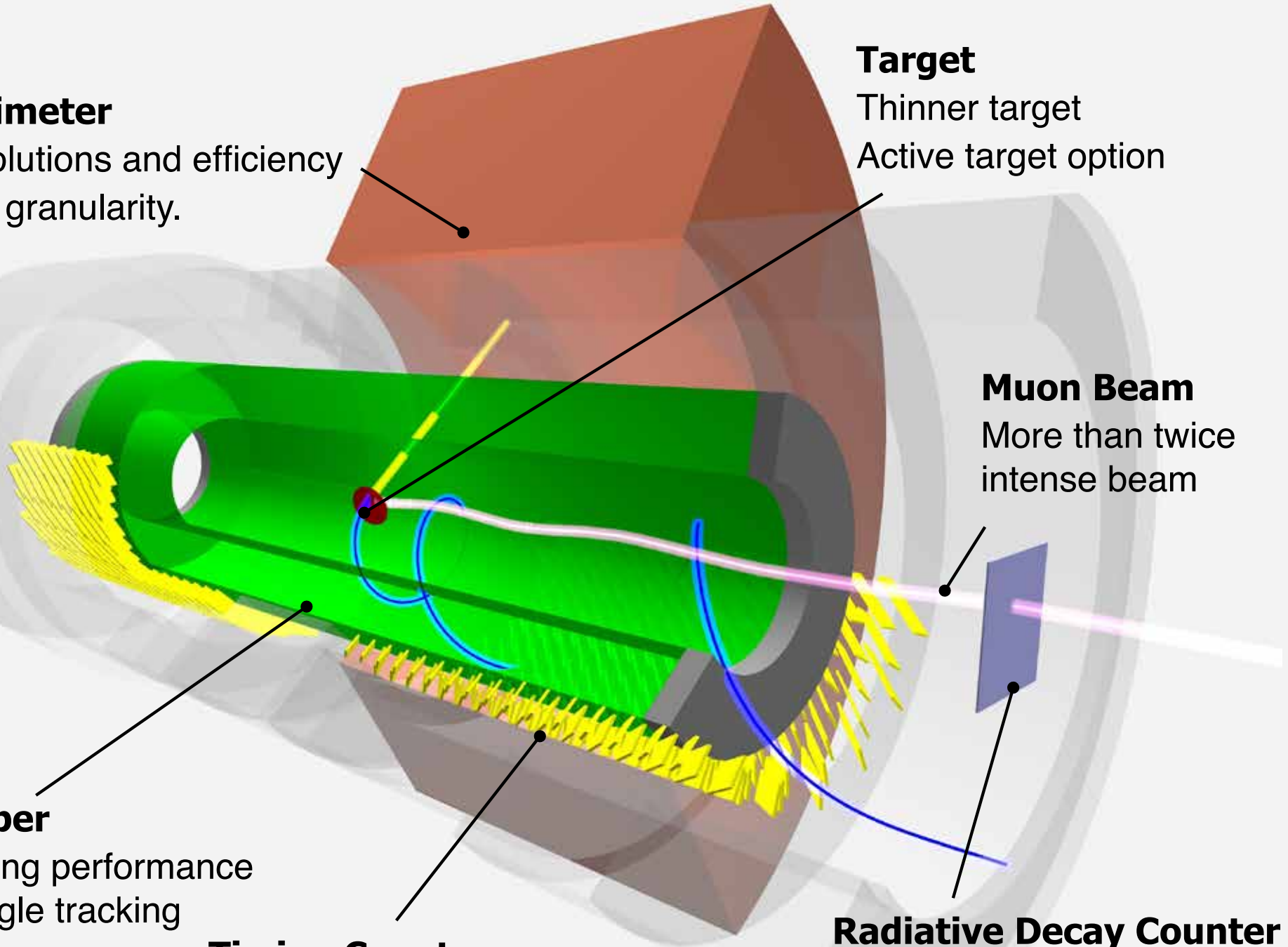


MEG II

LXe Calorimeter
Higher resolutions and efficiency with higher granularity.

Target
Thinner target
Active target option

Muon Beam
More than twice intense beam



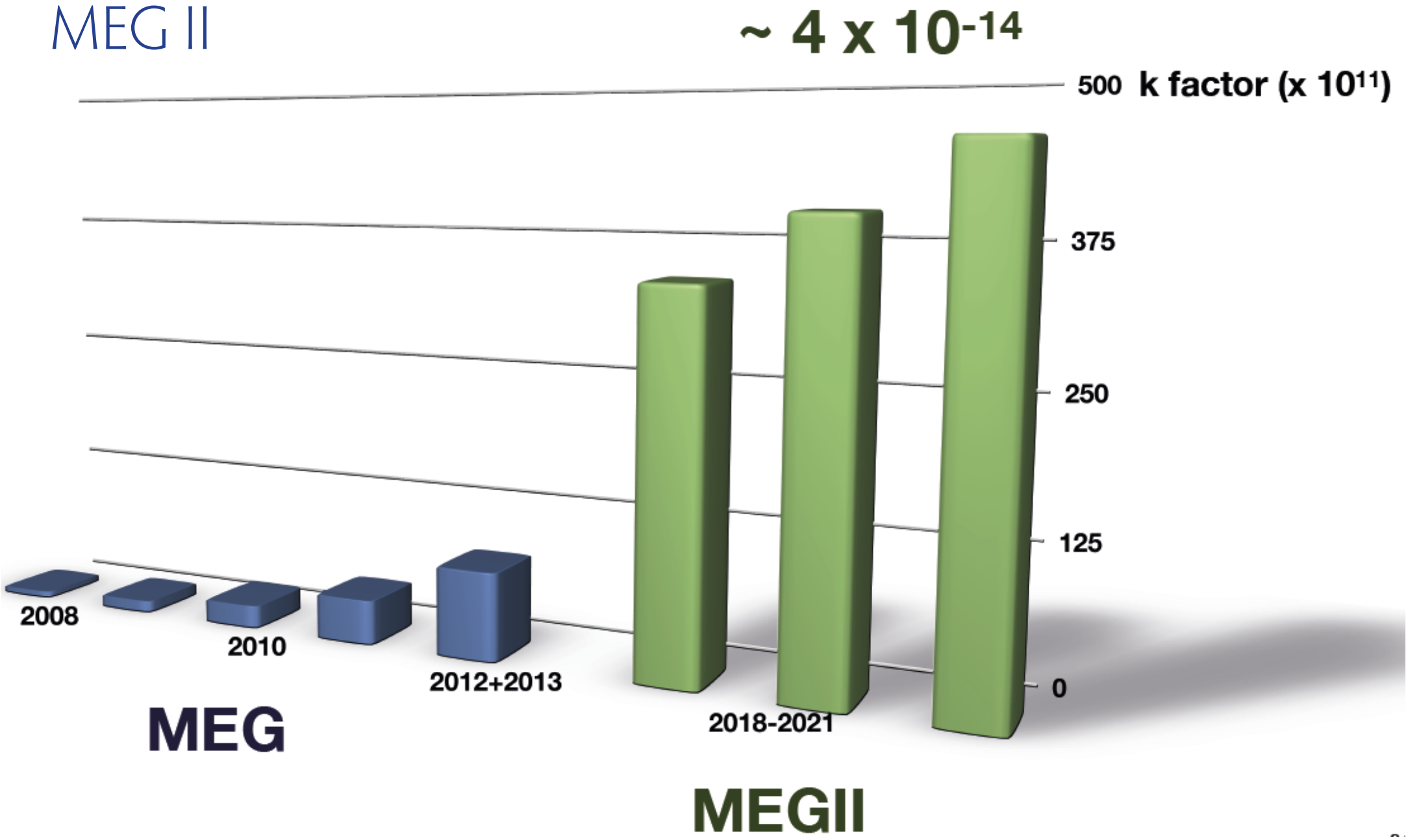
Drift chamber
Higher tracking performance with long single tracking volume

Timing Counter
Higher time resolution with highly segmented detector

Radiative Decay Counter
Identify muon radiative-decays

Where we will be

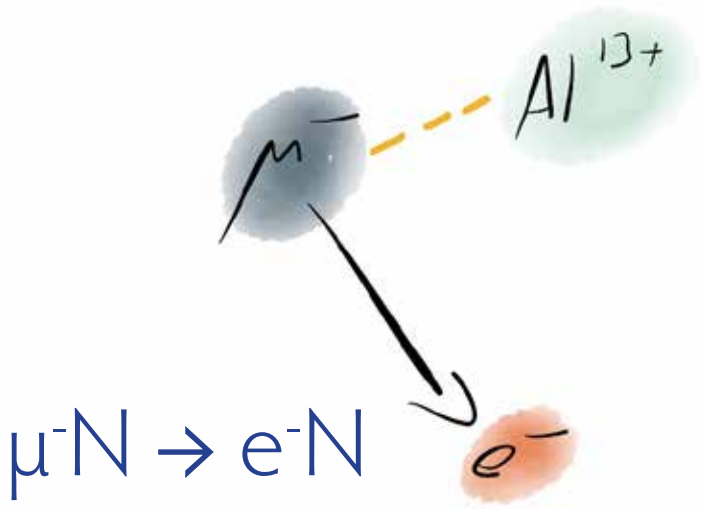
MEG II



Searching for μ → e conversion with

Mu2e, DeeMee, COMET, PRISM

Conversion Signal and Background



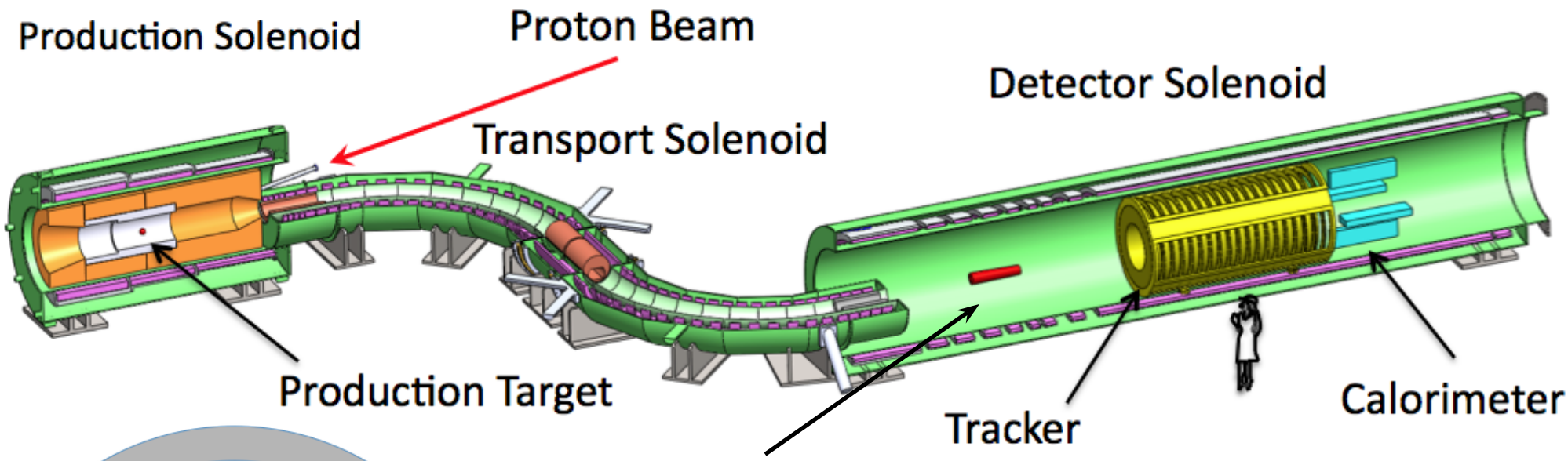
- Single 105 MeV/c electron observed

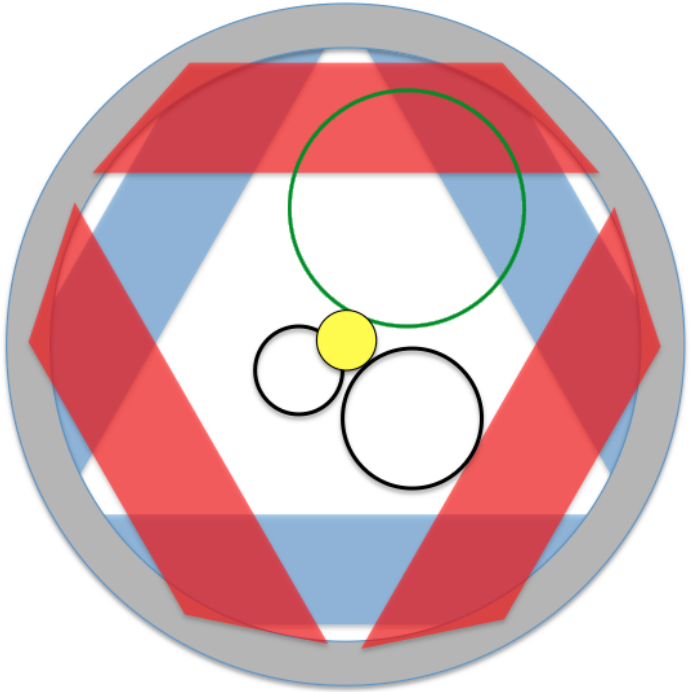
Backgrounds:

Anything that can produce a 105 MeV/c electron

- Primary proton beam
- Decay in Orbit (DIO)
- Nuclear capture (AlCap effort at PSI)
- Cosmics

Experimental layout - Mu2e





Mu2e CDR

- Separate muon production and conversion target
- Not shown: cosmic ray veto and absorbers

- Straw tubes in vacuum
- Outside of radius of Michel electrons

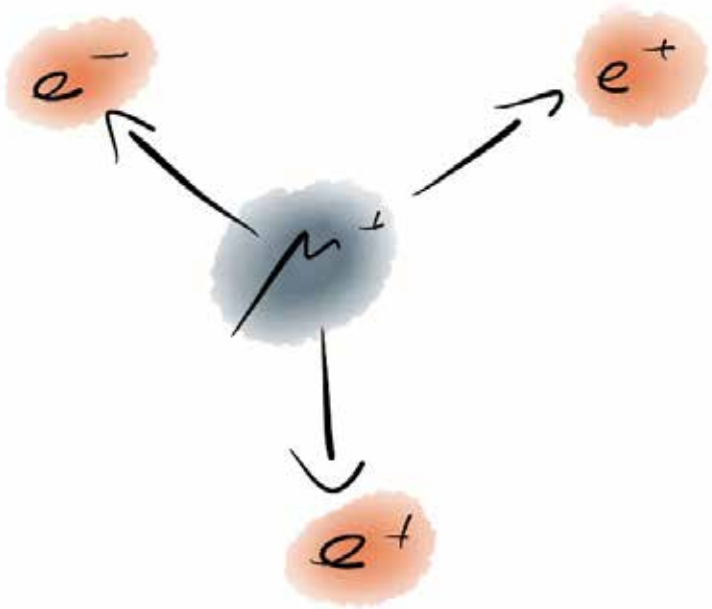
Conversion: Expected sensitivities

- J-PARC: Comet/DeeMee/Prism Fermilab: Mu2e
- Comet Phase I and DeeMee might get to ~10^{-14} as early as 2019
- Both Comet Phase II and Mu2e will start around 2020
- Should get single event sensitivities well below 10^{-16}
- Prism/Prime and Mu2e with Project X/PIP-II explore paths to 10^{-18}

Searching for $\mu^+ \to e^+e^-e^+$ with

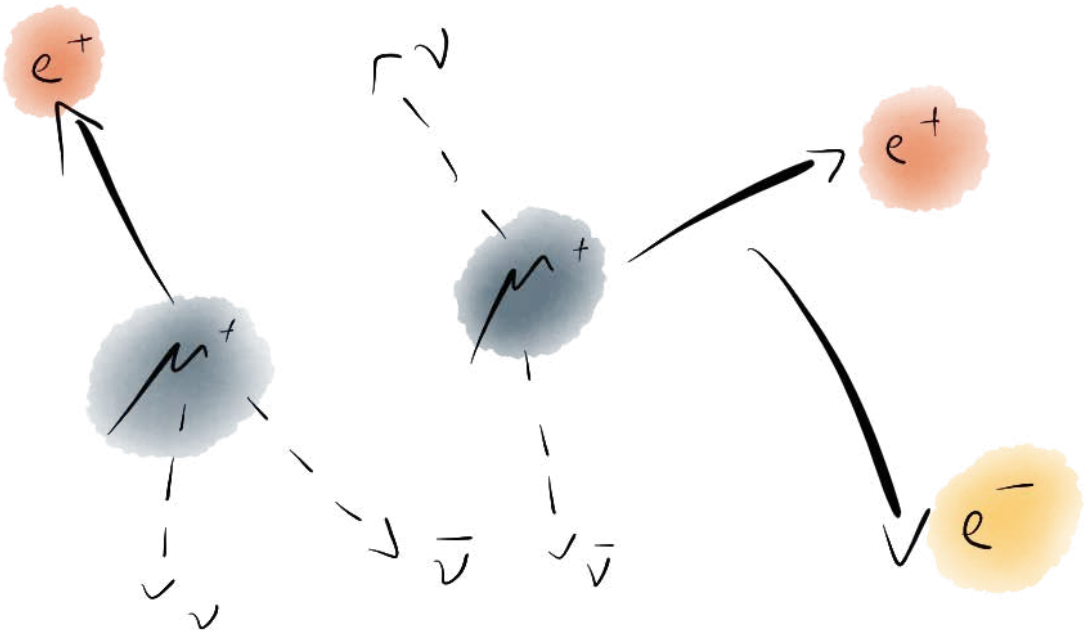
Mu3e

The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- $\Sigma p_e = m_\mu$
- Maximum momentum: $\frac{1}{2} m_\mu = 53$ MeV/c

Accidental Background



- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha (electron-positron) scattering,
  - Mis-reconstruction

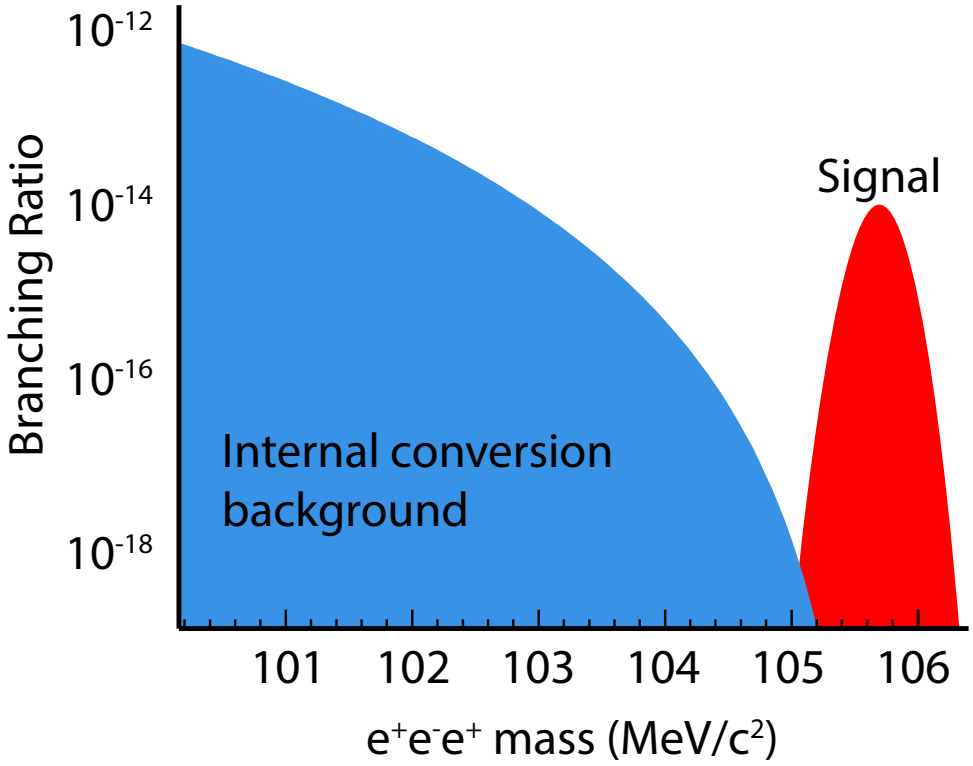
- Need very good timing, vertex and momentum resolution

Internal conversion background

- Allowed radiative decay with internal conversion:

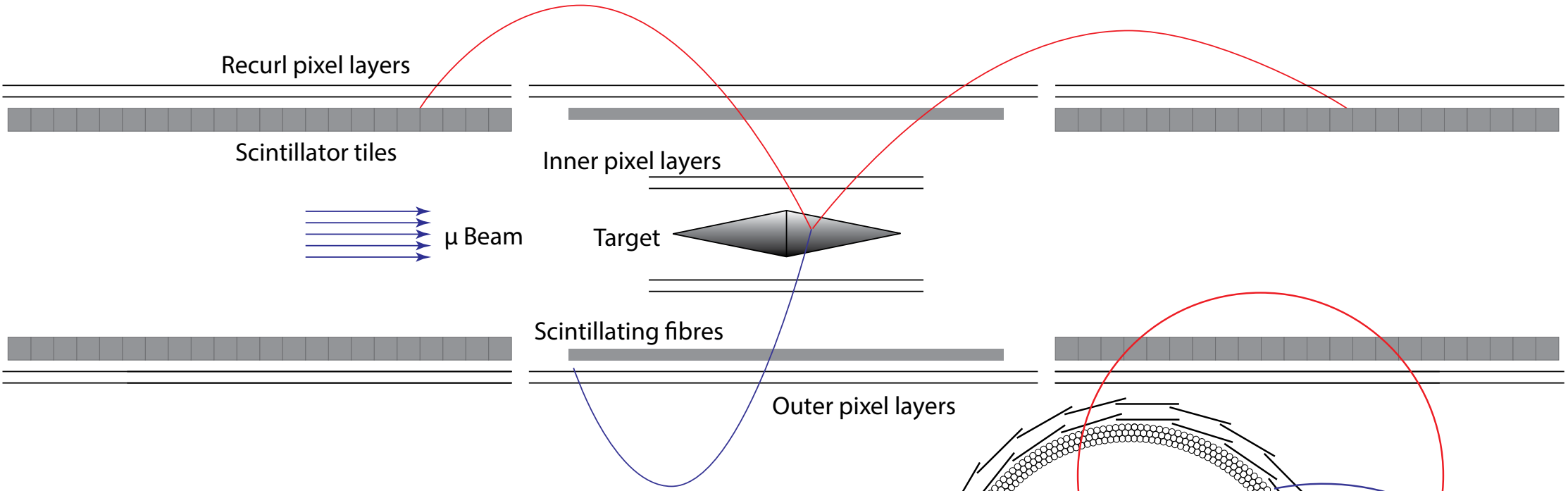
$$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$$

- Only distinguishing feature: Missing momentum carried by neutrinos

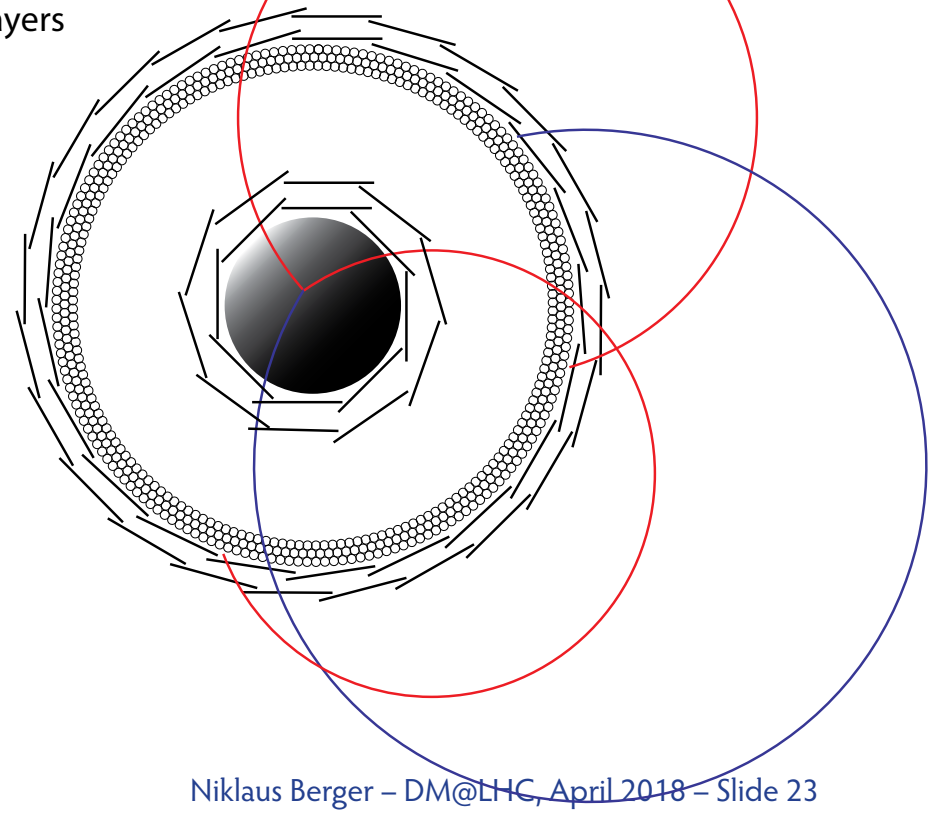


- Need excellent momentum resolution

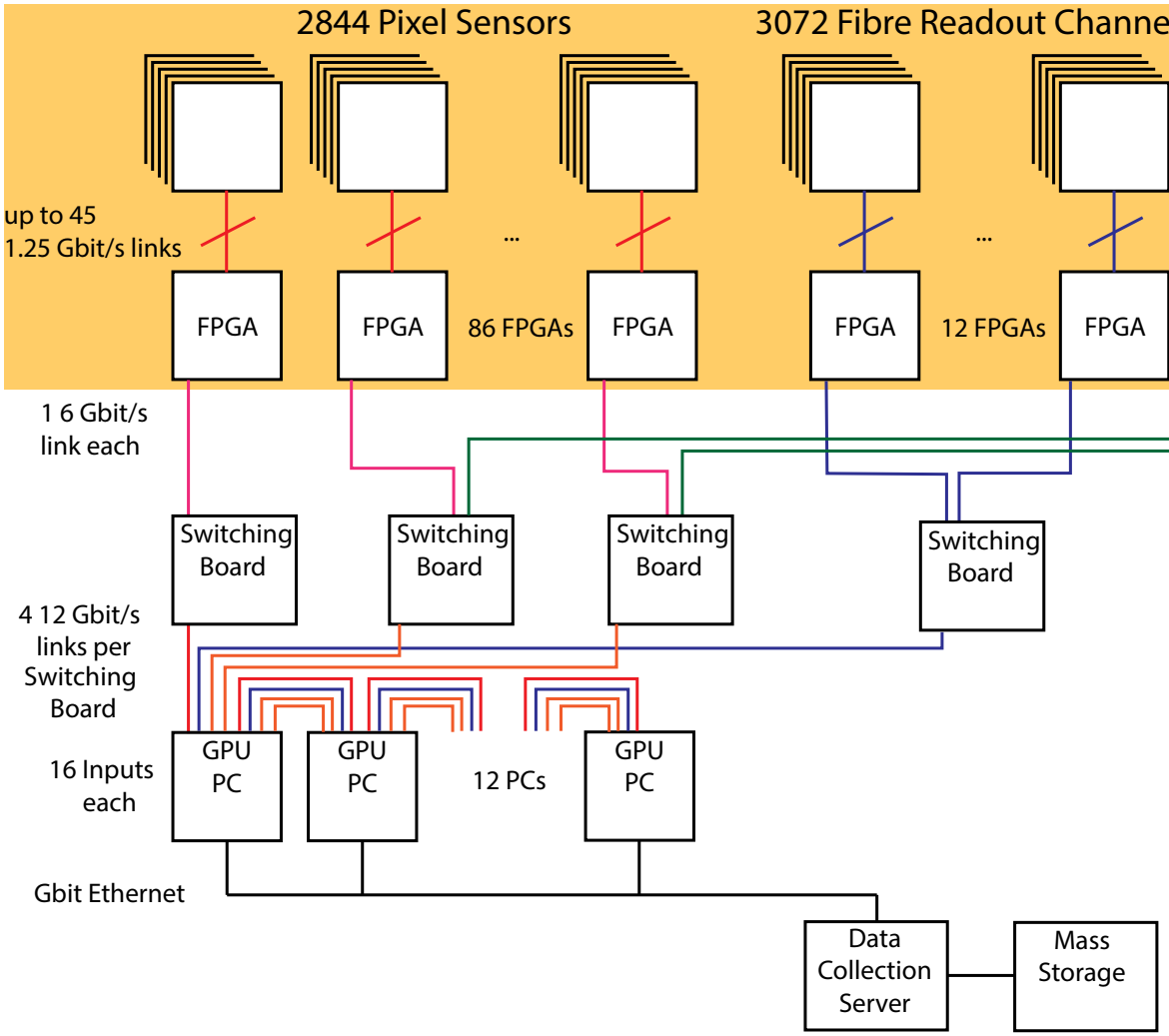
Detector Design: Phase I



- 1T magnetic field
- Up to 10^8 μ/s
- Ultra-thin, fast pixels (HV-MAPS)
- Timing from scintillating fibres and tiles
- Measure all positrons/electrons down to 10 MeV p_T

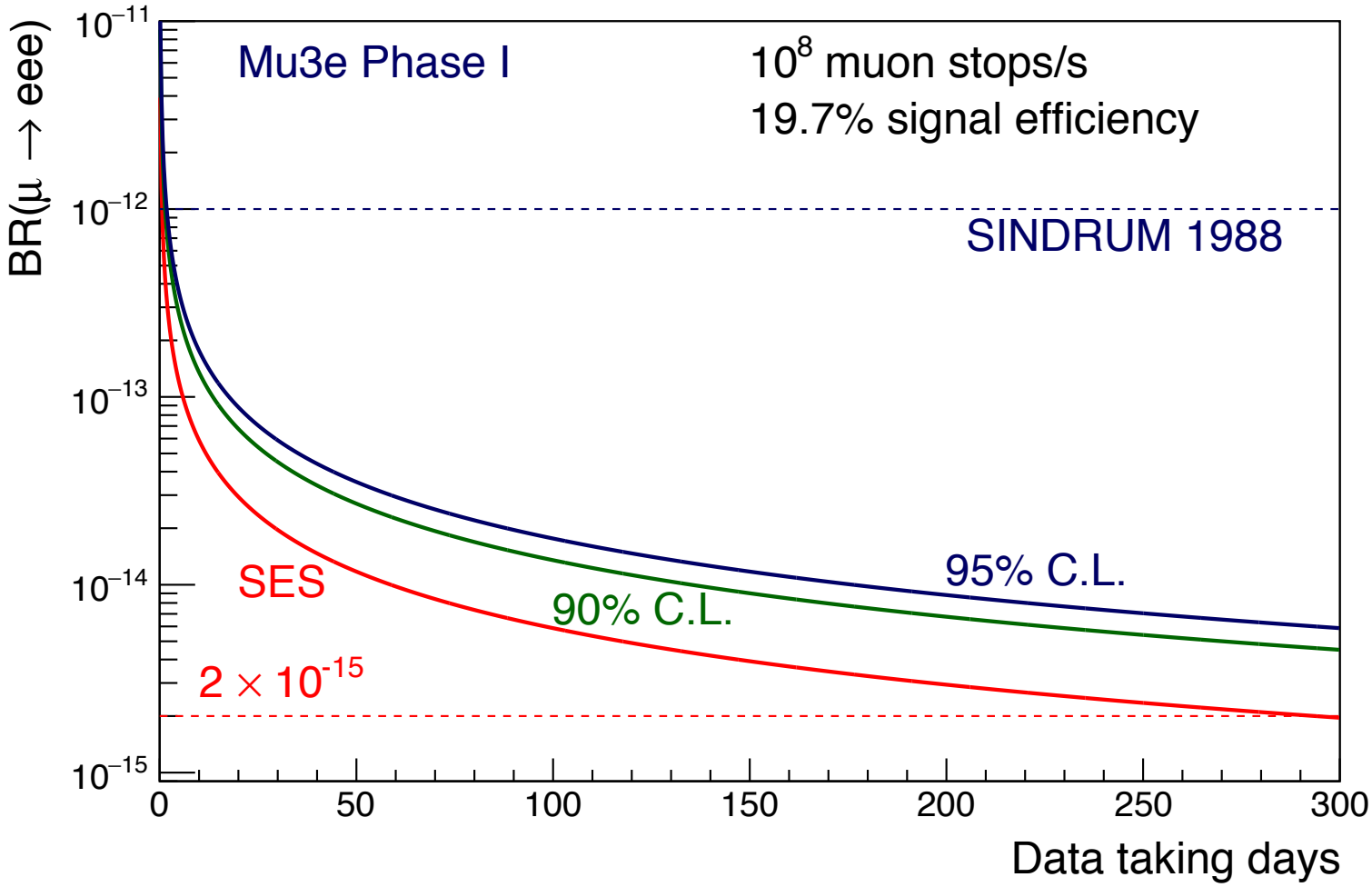


Data Acquisition



- No trigger
- ~ 1 Tbit/s
- FPGA-based switching network
- O(10) PCs with GPUs
- Only save things that look like $\mu^+ \rightarrow e^+e^-e^+$
- Or: Additional selection

Sensitivity - Mu3e Phase I



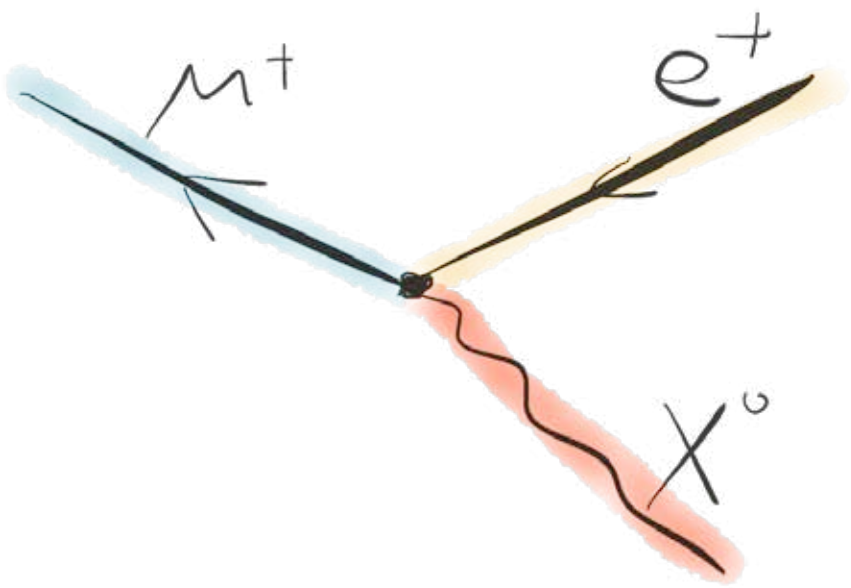
- Start 2020
- Phase II with a high intensity muon beam line at PSI under study

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

$\mu \to eX$
and
Dark Photons

Thesis Ann-Kathrin Perrevoort

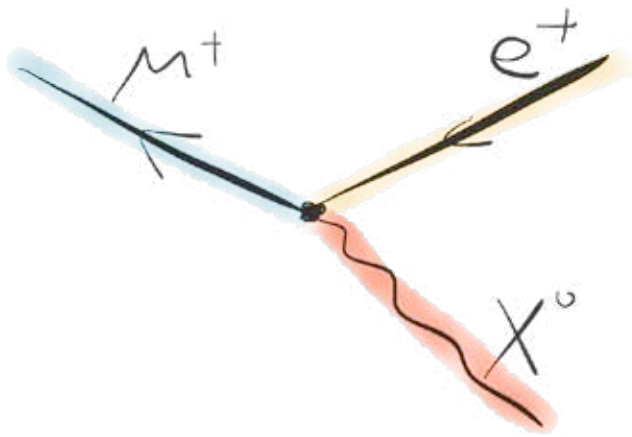
Familons in Mu3e



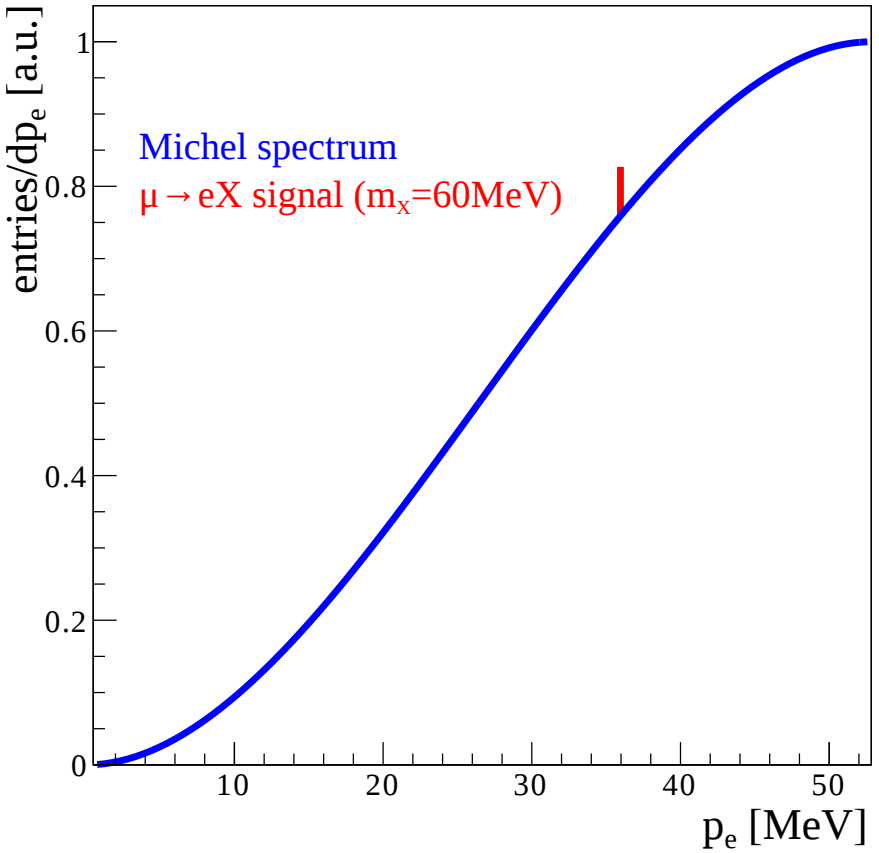
- Spontaneously broken flavour symmetry: Goldstone boson(s) called familons
- Can be a light dark matter candidate
- Lead to μ → eX, where X a familon

- μ → eX can also show up in other models, search for it with the large muon decay data set at Mu3e

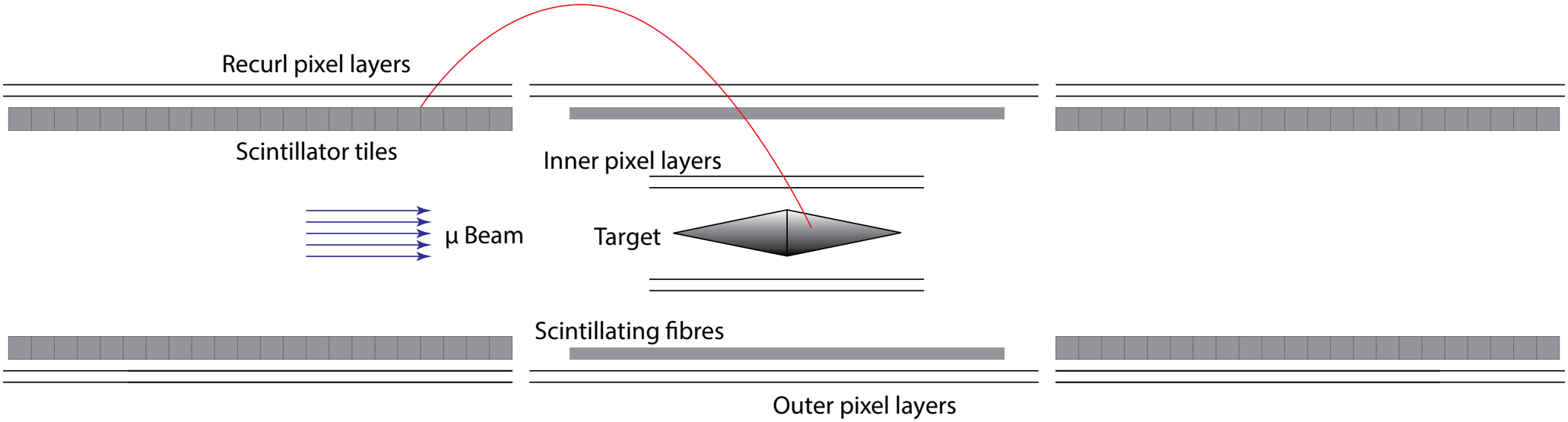
Signature and Background



- Signal: Two-body decay: Monoenergetic positron
- Background: All other positrons, dominated by Michel decay, smooth momentum distribution
- Bump hunt on the positron spectrum (all tracks...)

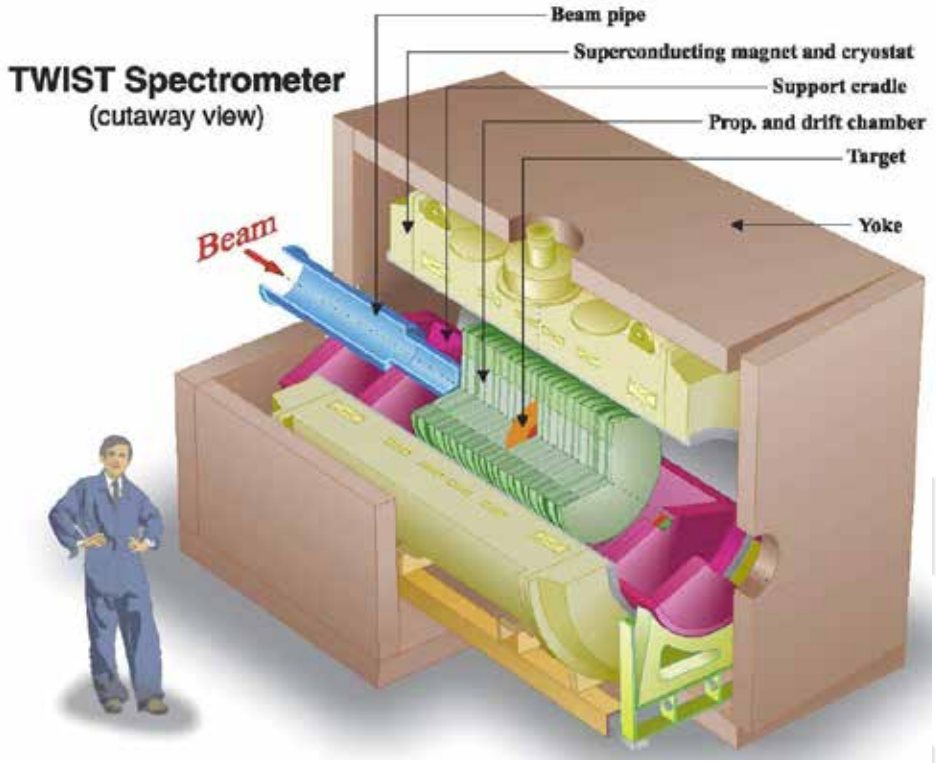


Search strategy

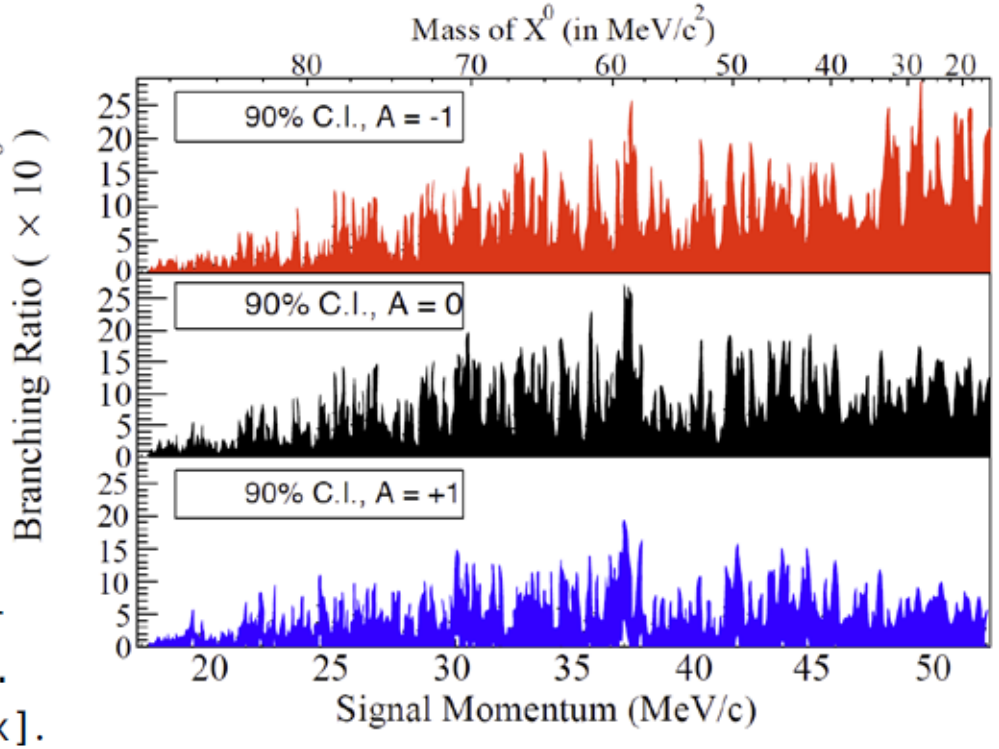


- Not possible to save all tracks: Use histograms from online reconstruction
- Baseline: Use only outgoing part of tracks (short/4 hits)
- Potential farm upgrade: Use also recurling part (long, 6/8 hit)

Previous experiment: TWIST

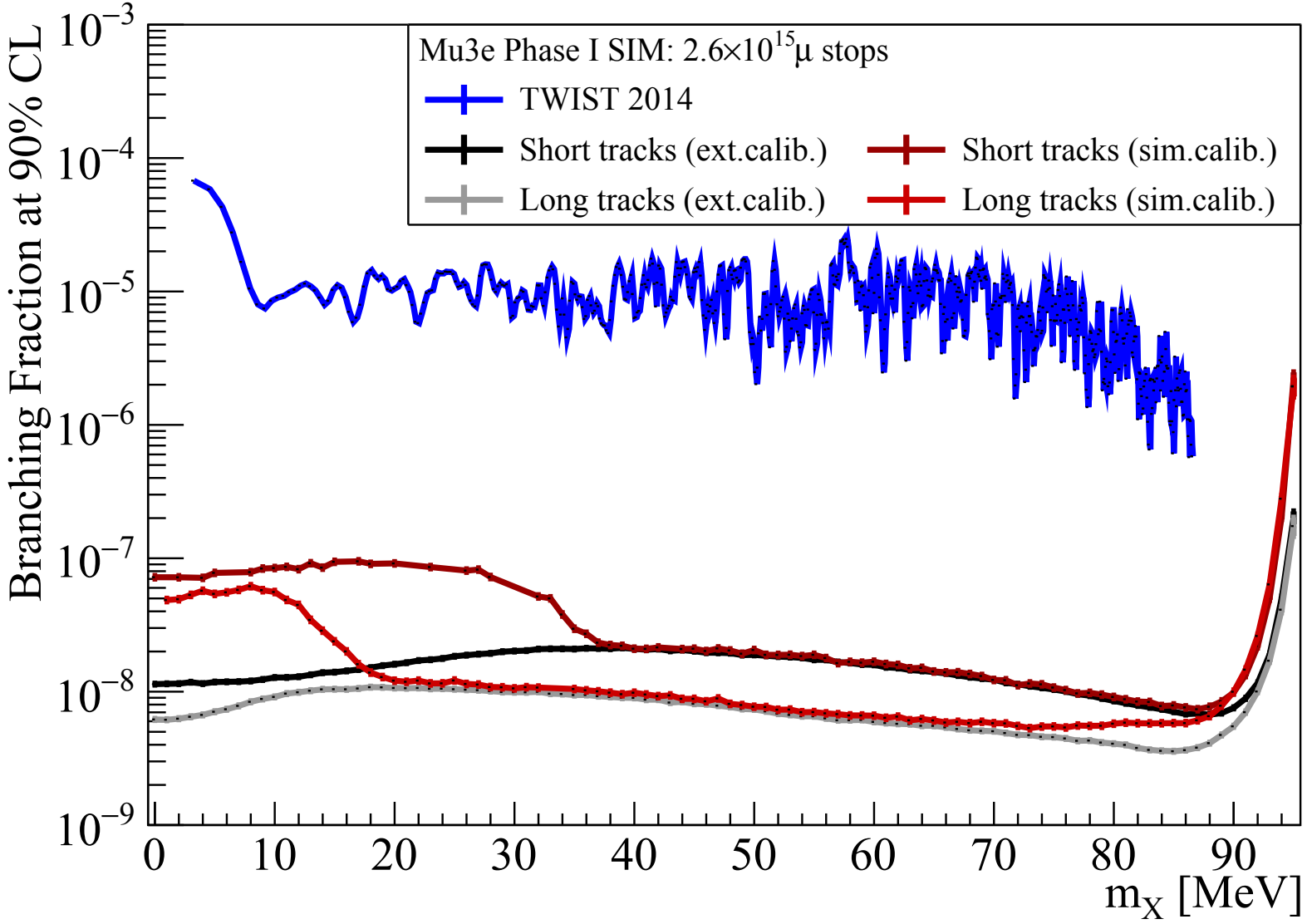


- TWIST at TRIUMF
- Limits on the μ → eX BF in the few 10^{-6} region



R. Bayes et al. "Search for two body muon decay signals". In: *Phys. Rev.* D91.5 (2015), p. 052020. DOI: 10.1103/PhysRevD.91.052020. arXiv: 1409.0638 [hep-ex].

Results

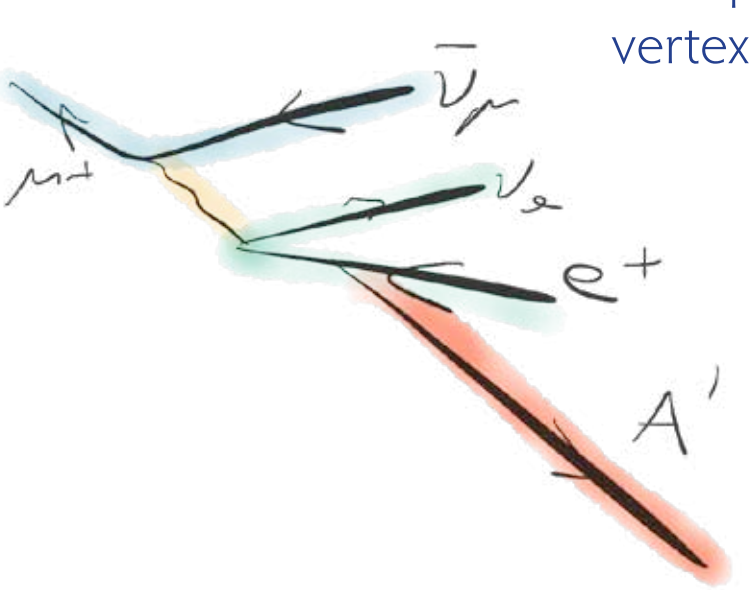

Mu3e Phase I SIM: 2.6×10^15 μ stops
TWIST 2014
Short tracks (ext.calib.)
Long tracks (ext.calib.)
Short tracks (sim.calib.)
Long tracks (sim.calib.)
Branching Fraction at 90% CL
10^−3
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
0
10
20
30
40
50
60
70
80
90
m_X [MeV]

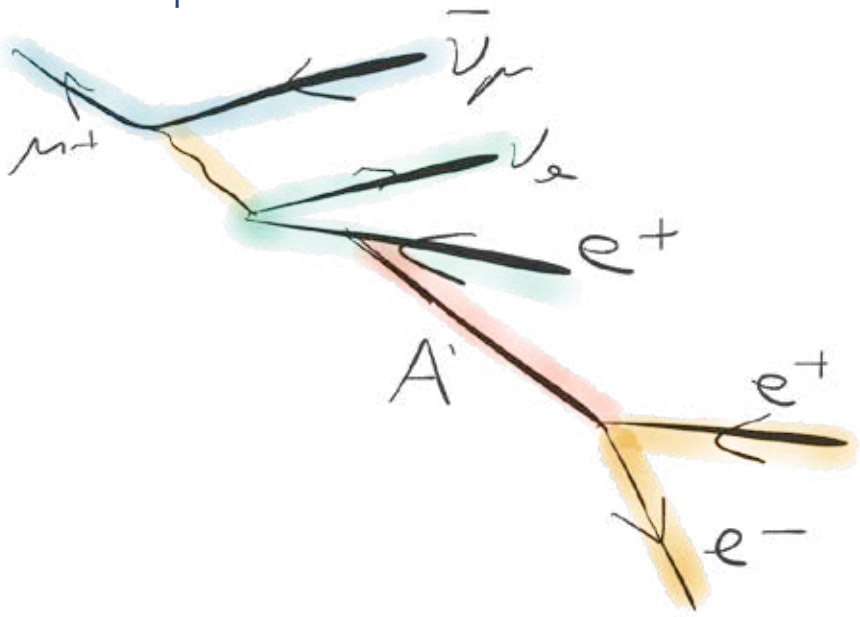
Dark Photons in Mu3e

Dark photon can be radiated, wherever a photon can be radiated

Three cases:

- Dark photon is long-lived/decays to dark particles
- Dark photon goes to e^+e^- immediately
- Dark photon goes to e^+e^- at a displaced vertex (under study)

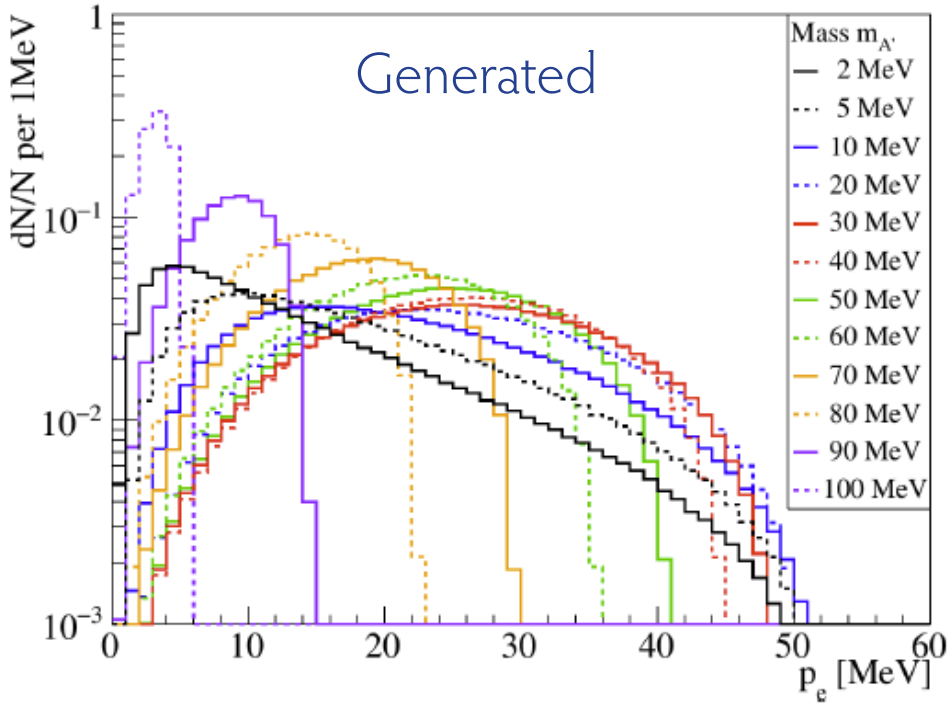




Invisible dark photons

$\mu \to e\nu\bar{\nu}A'$ is a four-body decay...

- Shift to Michel spectrum



Invisible dark photons

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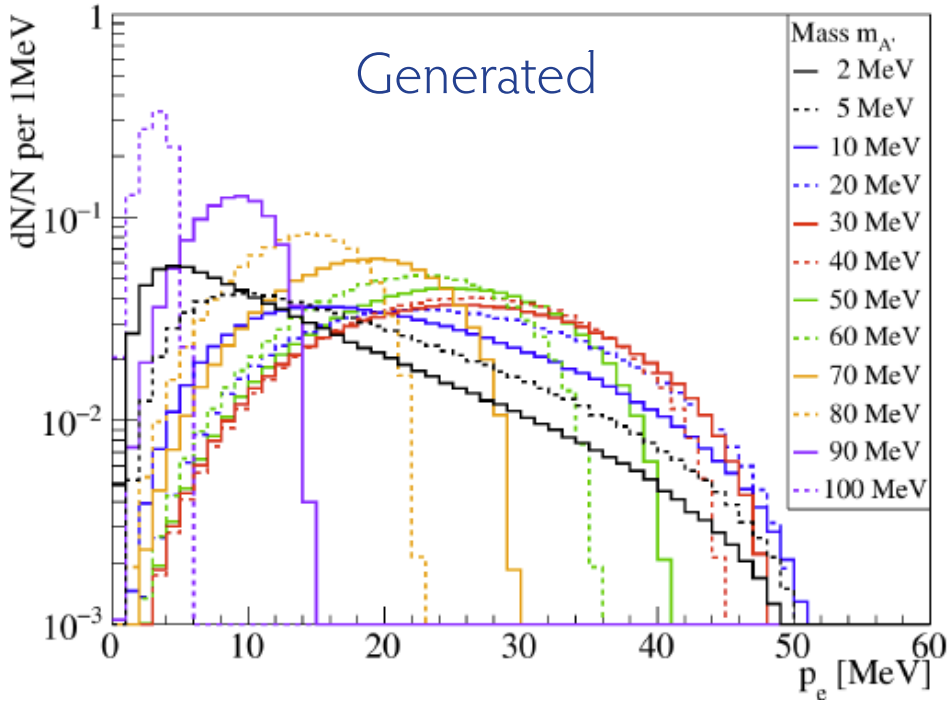
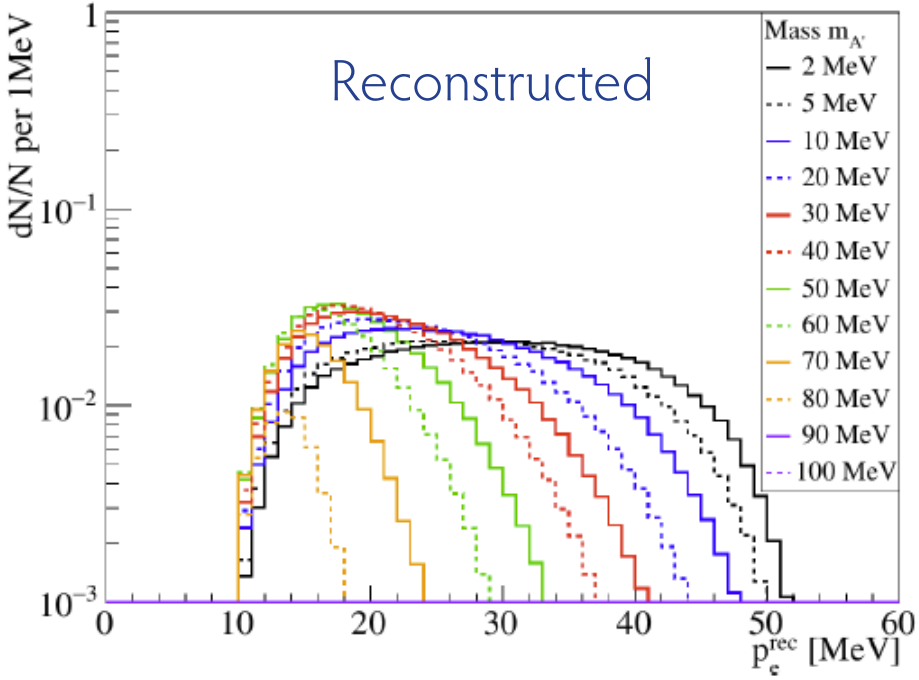
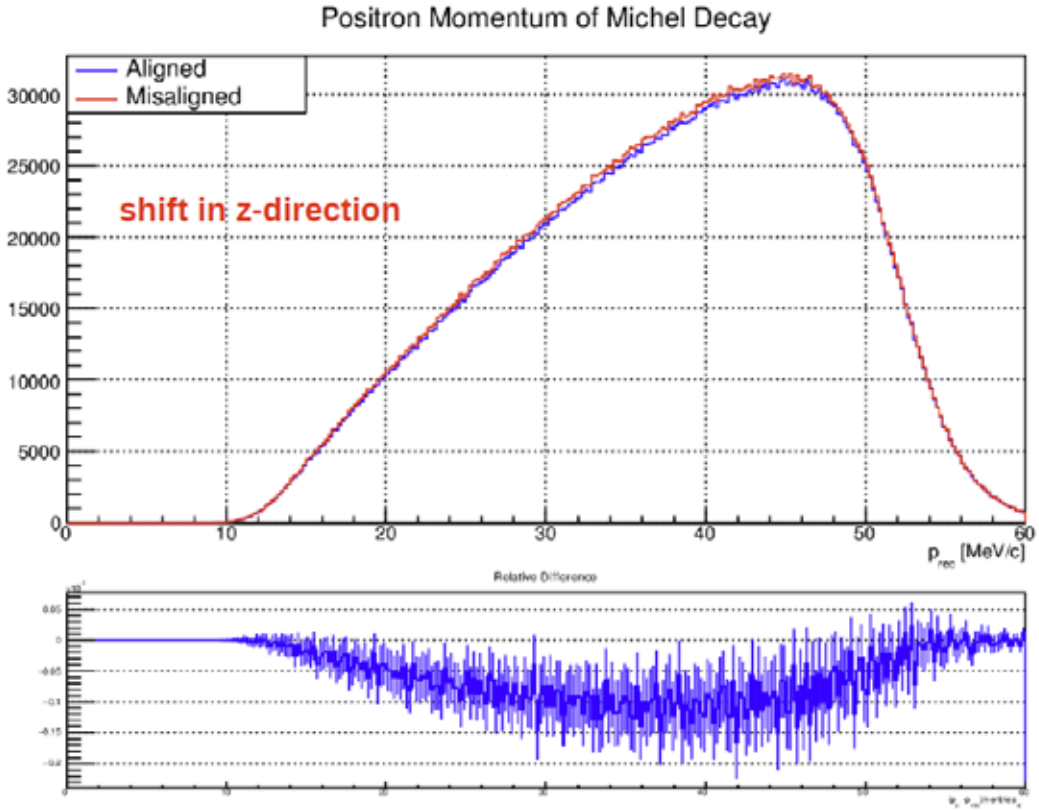


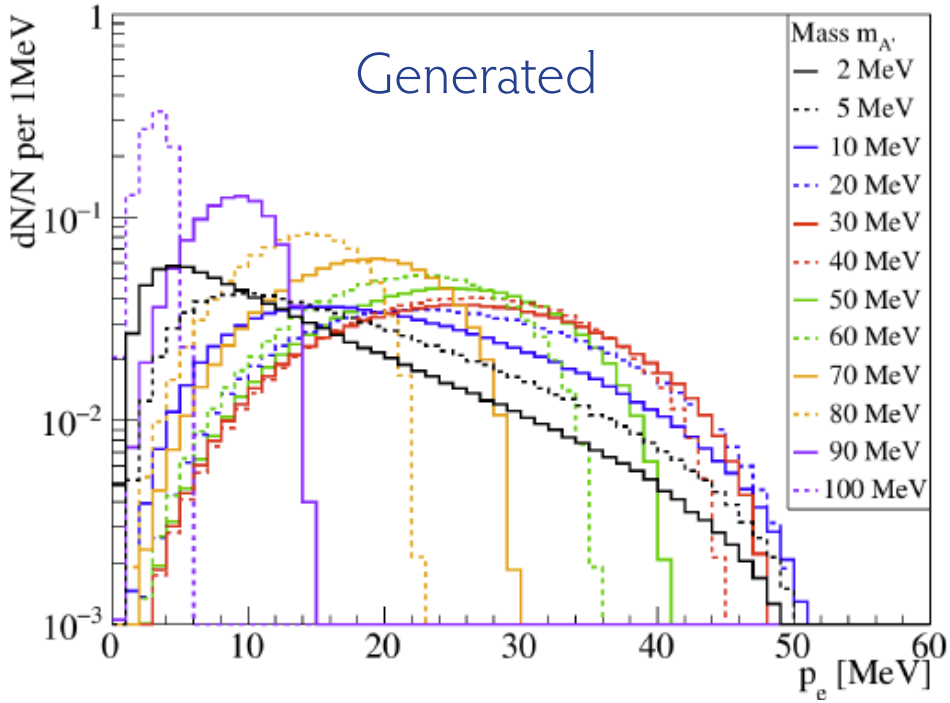


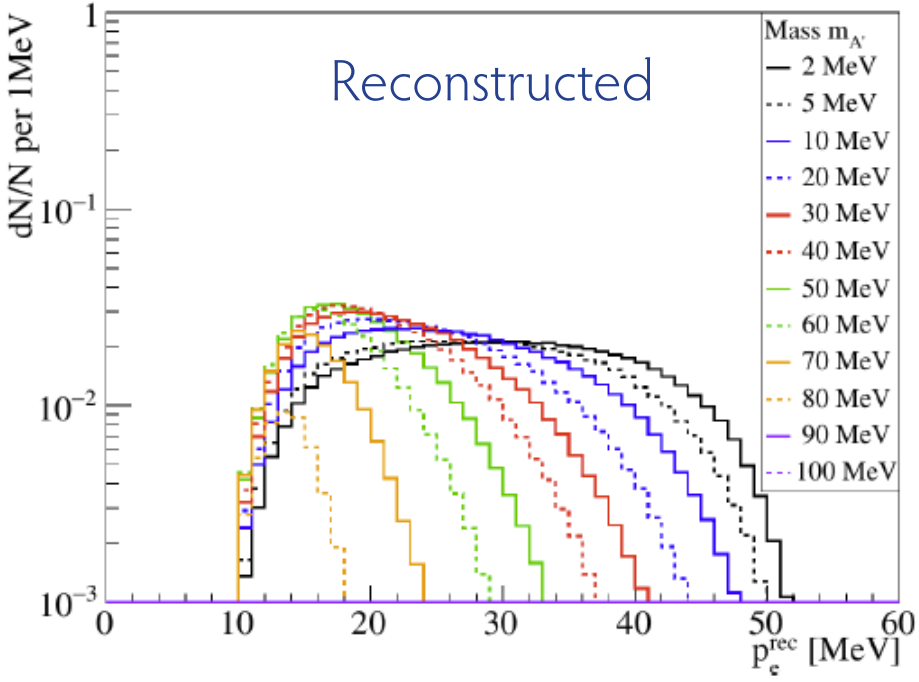
Invisible dark photons

$\mu \to e\nu\bar{\nu}A'$ is a four-body decay...

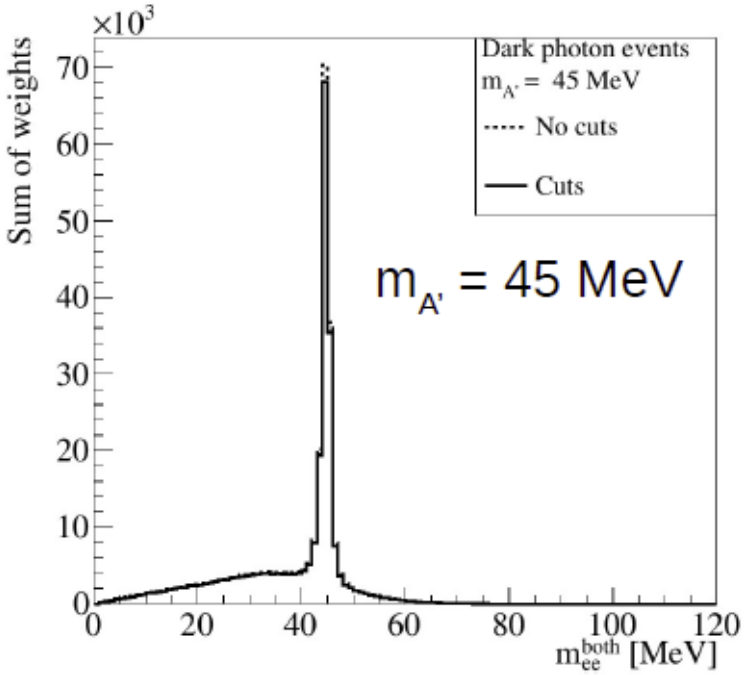
- Shift to Michel spectrum
- Can also come from detector misalignment
- Not really promising







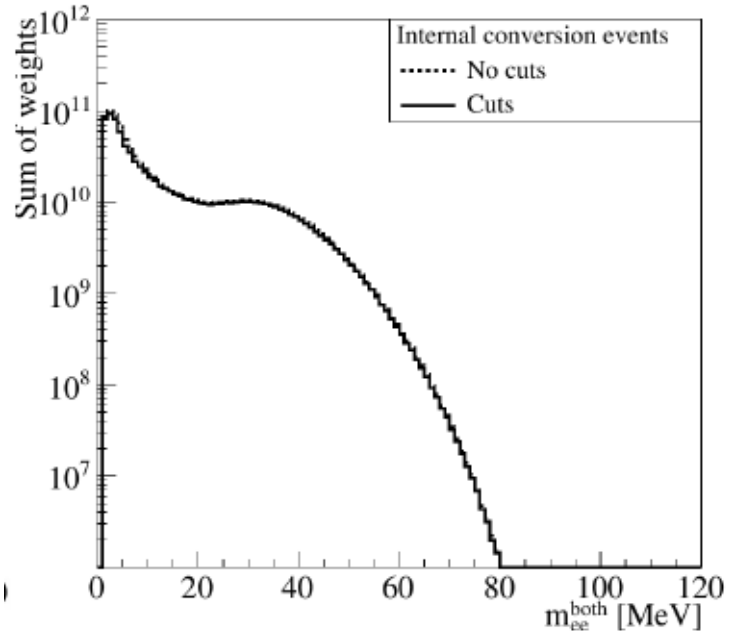
Dark Photons in e^+e^-

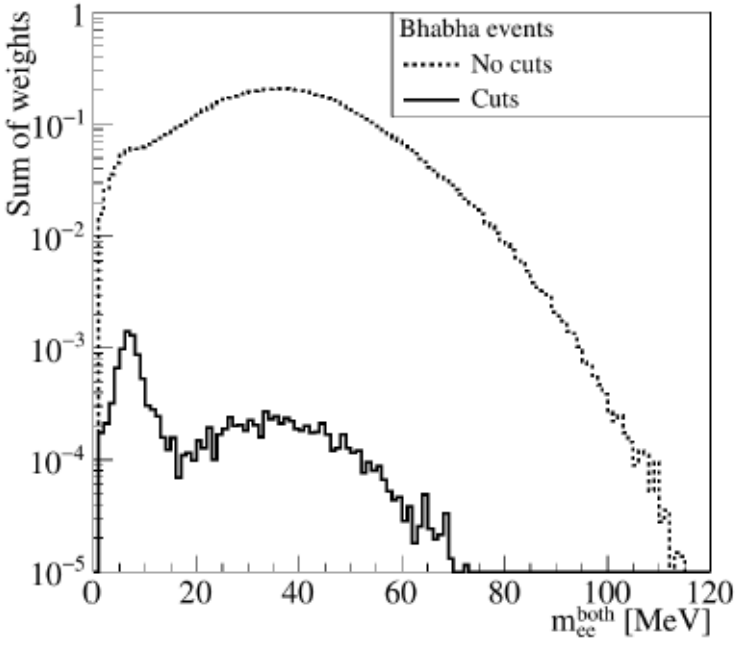


$\mu \rightarrow e\nu\bar{\nu}(A' \rightarrow ee)$ has the same visible final state as our signal: Will not be filtered away

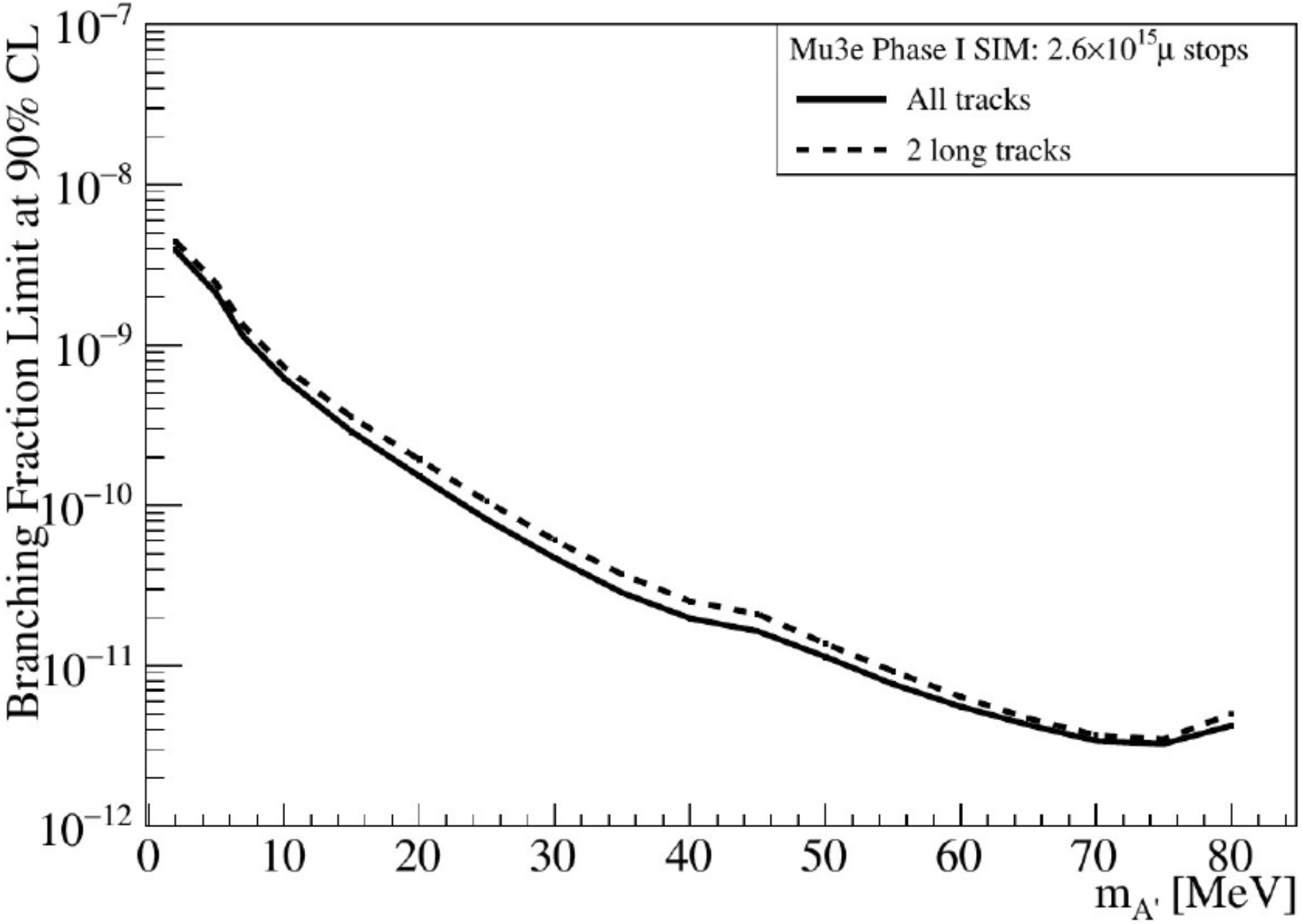
Background is internal conversion decay
$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$

Two e^+e^- combinations

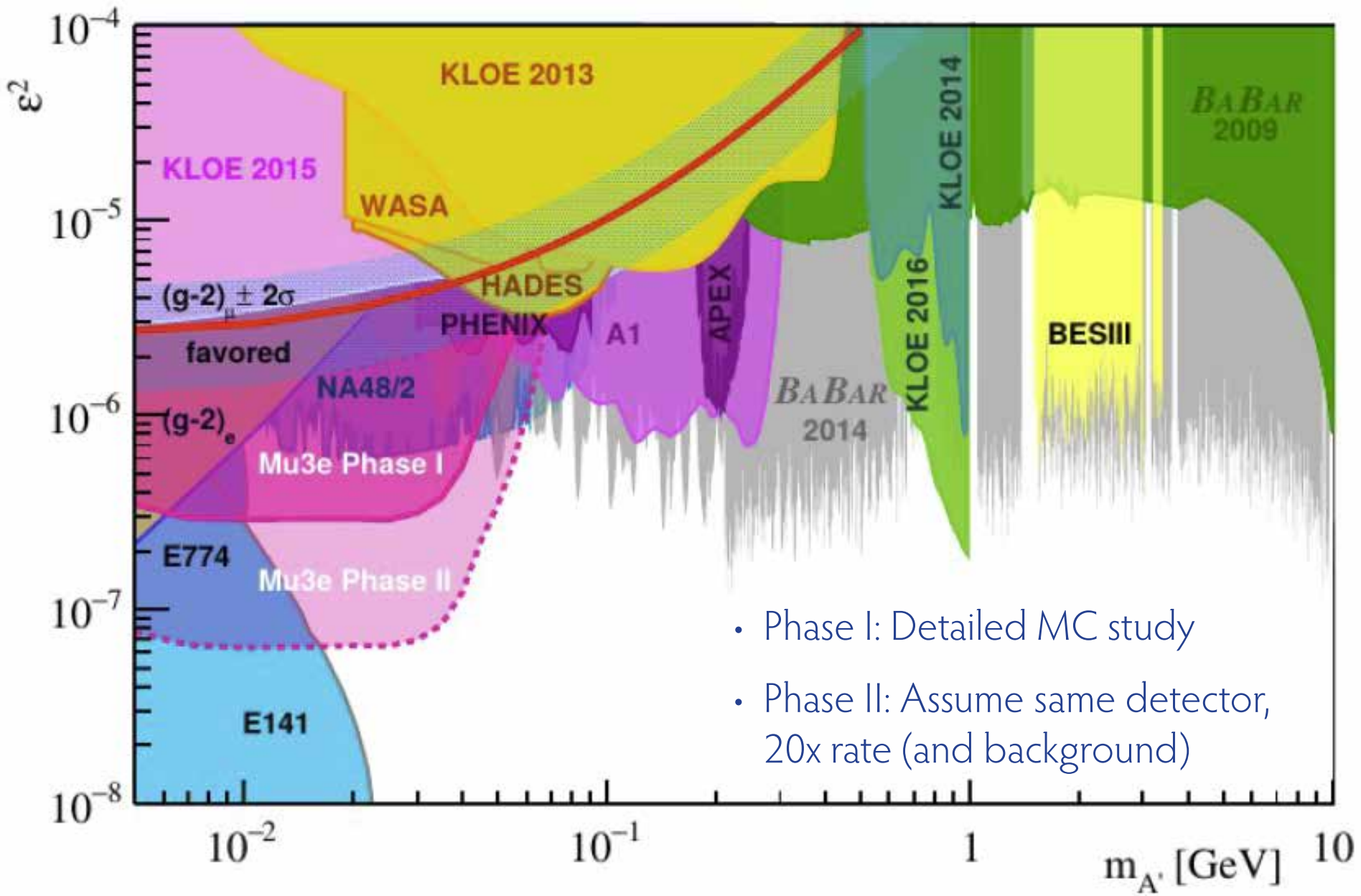




Branching Fraction Limits



And on the $m_{A'}$-ε plane



- Phase I: Detailed MC study
- Phase II: Assume same detector, 20x rate (and background)

Summary

- Exciting range of experiments going on-line:
  New lepton flavour violation limits
  upcoming
- Mu3e very competitive for
  μ → eX searches
- Improve by 2-3 orders of magnitude
  relative to TWIST in phase I
- Can access currently uncovered dark
  photon parameters
- Displaced vertices currently under study