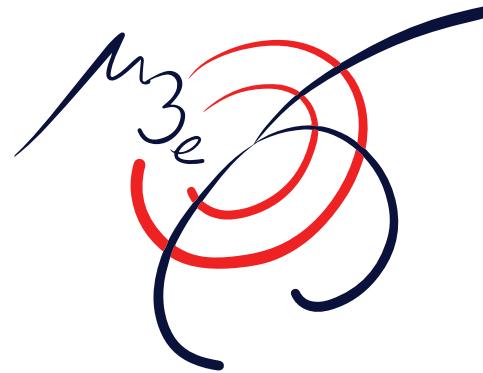


Charged lepton flavour violation with the Mu3e experiment

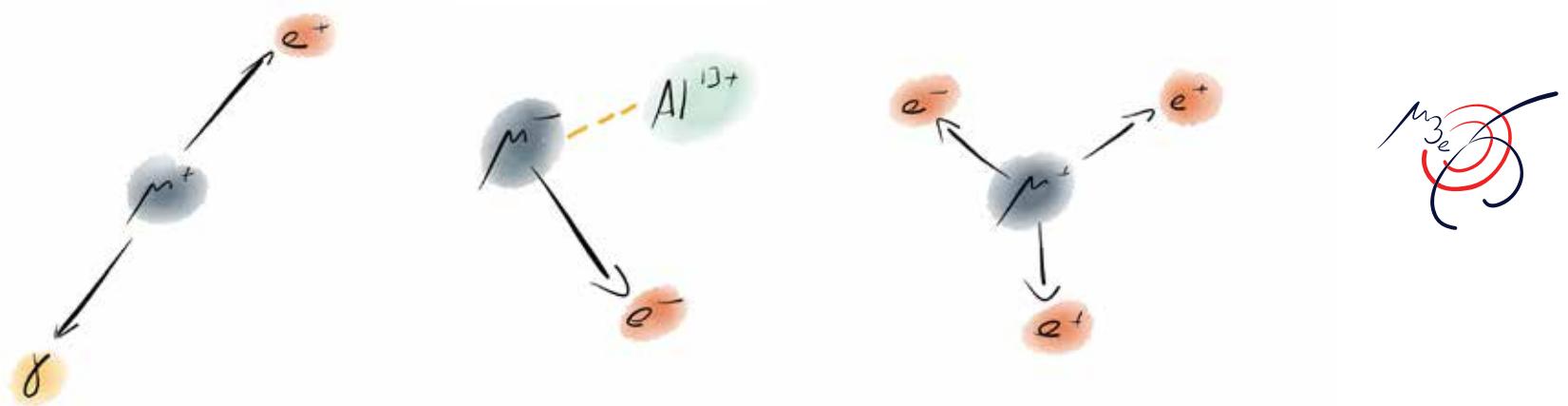


Niklaus Berger

Institut für Kernphysik, Johannes-Gutenberg Universität Mainz
for the Mu3e Collaboration

MASS2018
Odense, May 2018

Overview



Charged lepton flavour violation with muons:

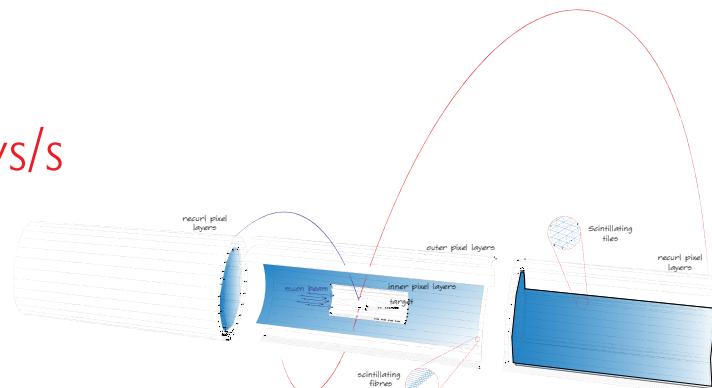
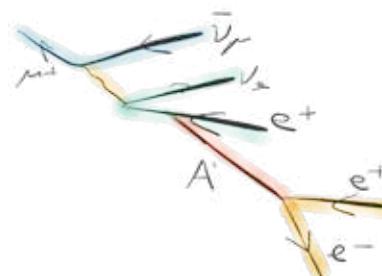
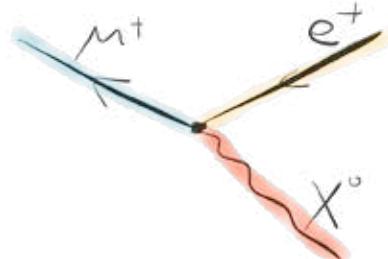
- A brief experimental overview

The Mu3e experiment:

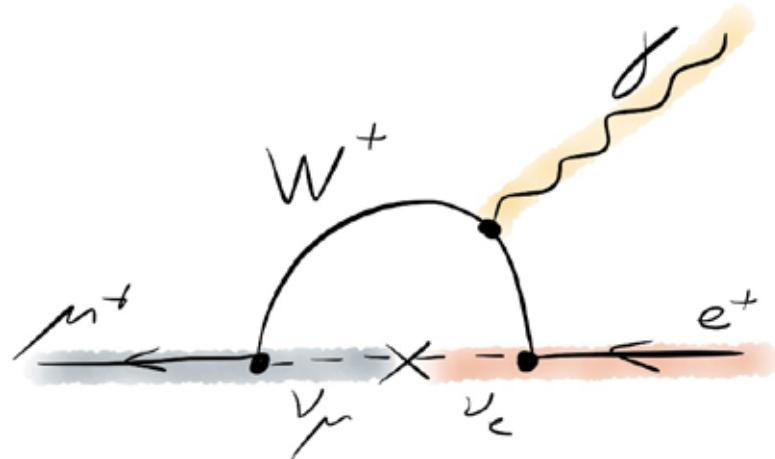
- A fast, thin, high resolution detector for $> 10^8$ muon decays/s

Beyond the standard channels:

- Exotics with Mu3e: $\mu \rightarrow e X$ and Dark Photons



Muon lepton flavour violation experiments

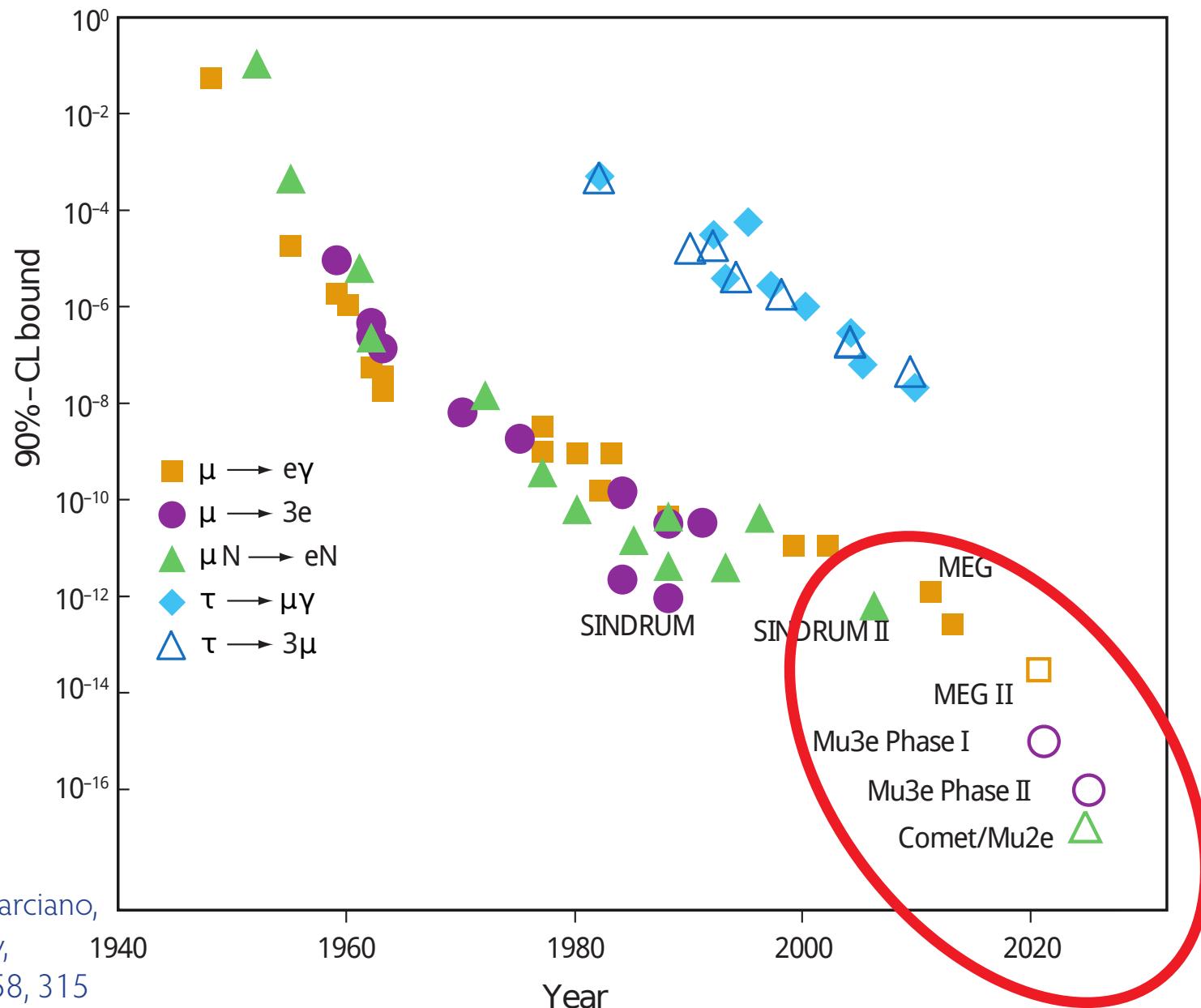


Standard Model branching
fractions of
 10^{-50} ish

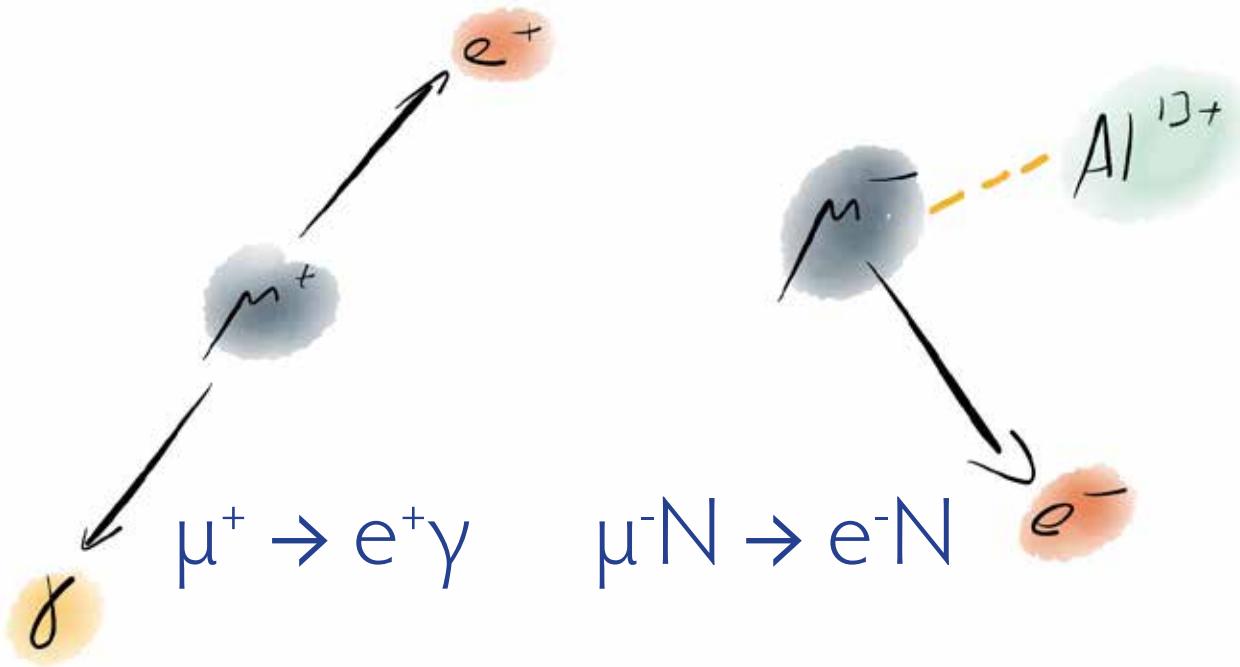
Only limited by number of muons
and background suppression:

Experimental/technical challenge

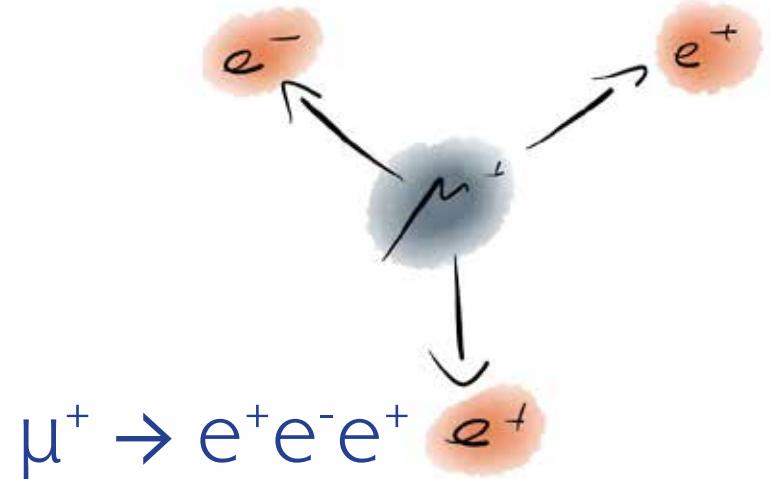
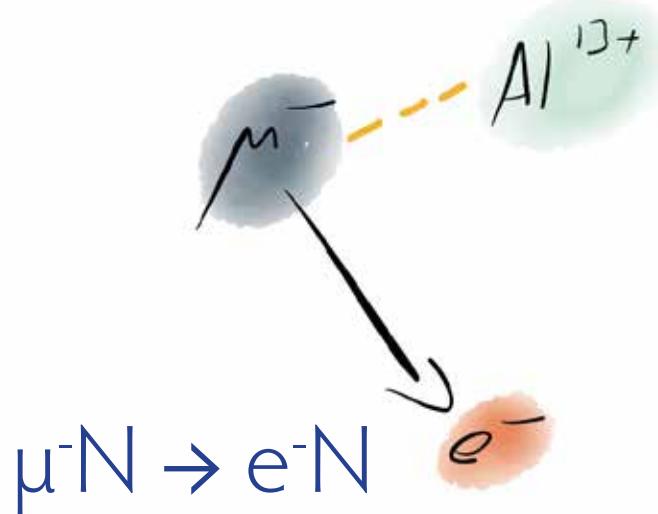
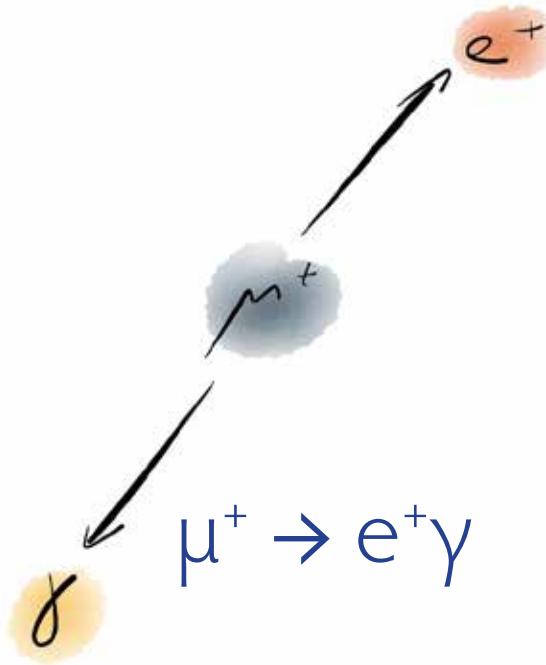
History of cLFV experiments



LFV Muon Decays



LFV Muon Decays: Experimental Situation



MEG (PSI)

$B(\mu^+ \rightarrow e^+ \gamma) < 4.2 \cdot 10^{-13}$
(2016)

SINDRUM II (PSI)

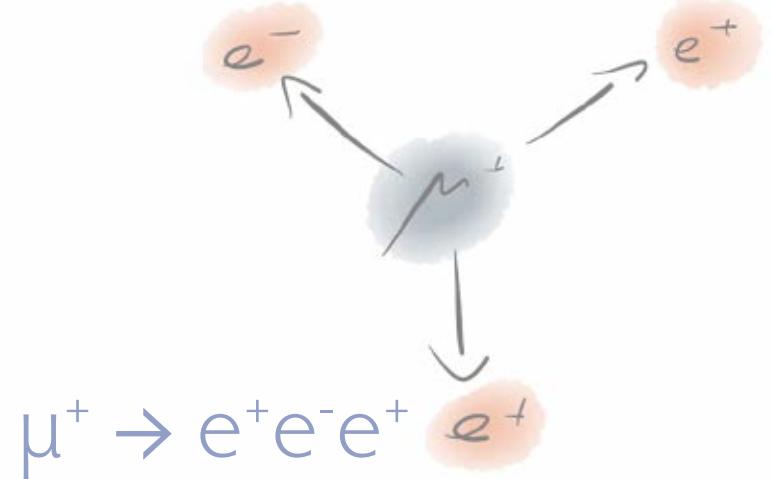
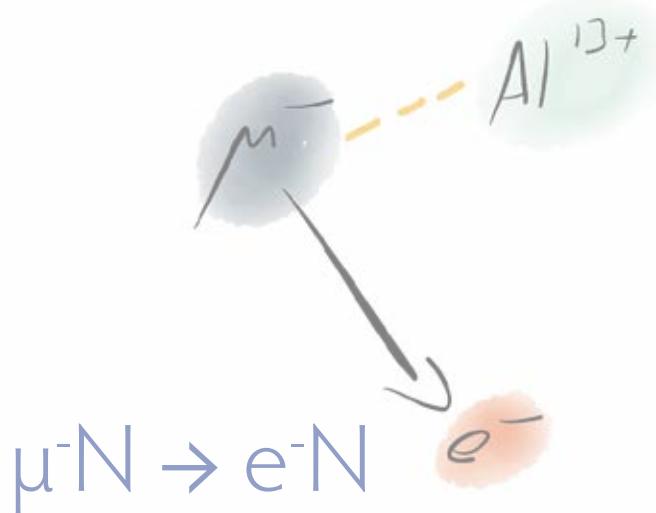
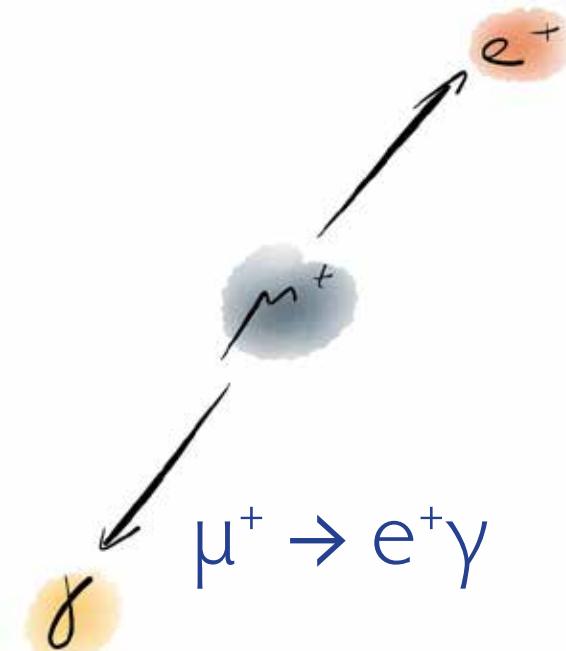
$B(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13}$
(2006)

relative to nuclear capture

SINDRUM (PSI)

$B(\mu^+ \rightarrow e^+ e^- e^+) < 1.0 \cdot 10^{-12}$
(1988)

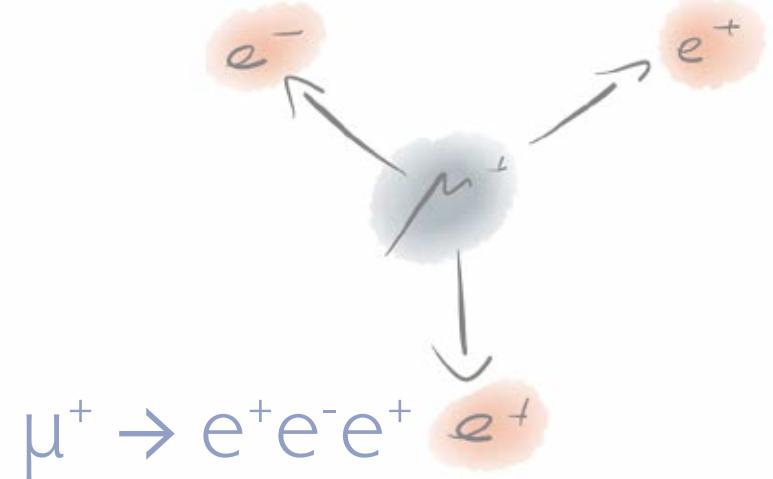
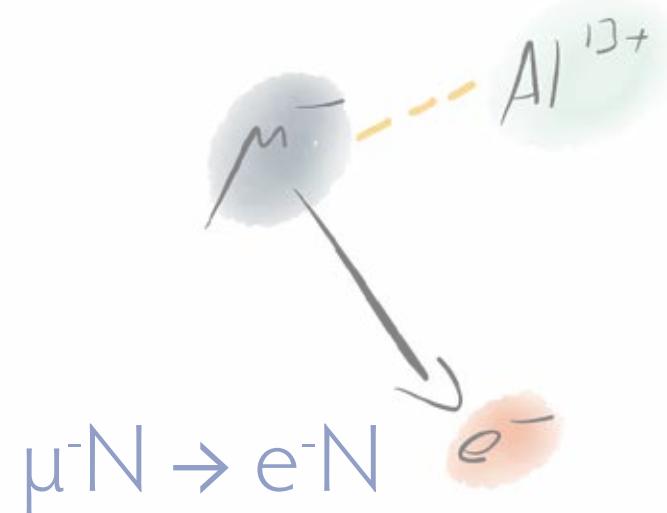
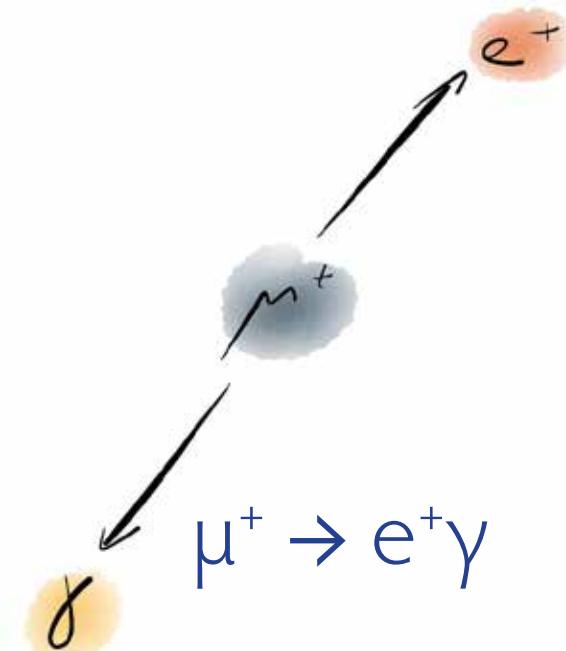
LFV Muon Decays: Experimental signatures



Kinematics

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

LFV Muon Decays: Experimental signatures



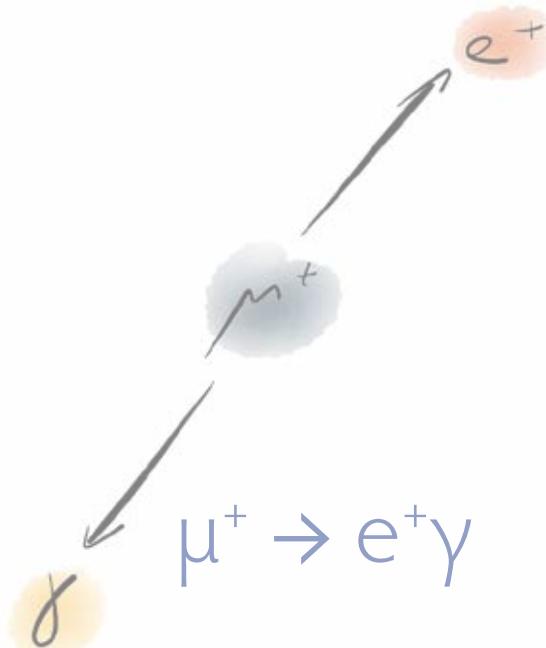
Kinematics

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

Background

- Accidental background
- Radiative decay

LFV Muon Decays: Experimental signatures

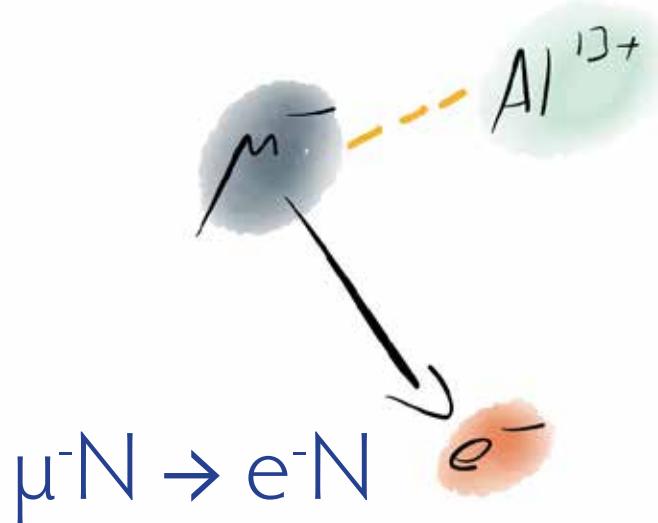


Kinematics

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

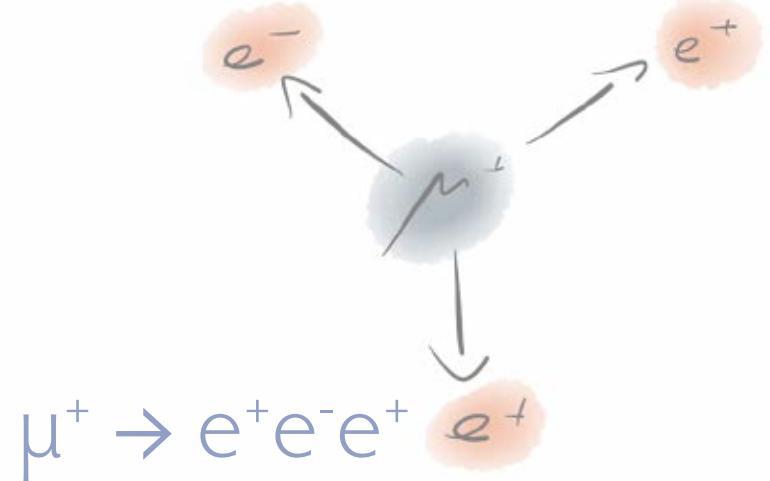
Background

- Accidental background
- Radiative decay

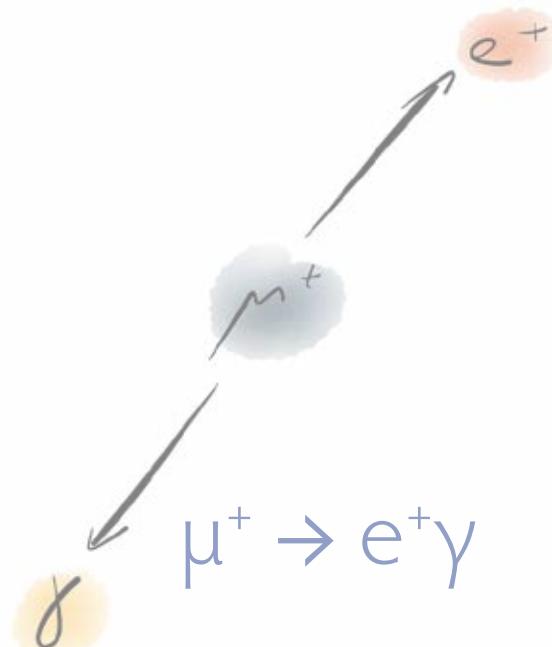


Kinematics

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



LFV Muon Decays: Experimental signatures

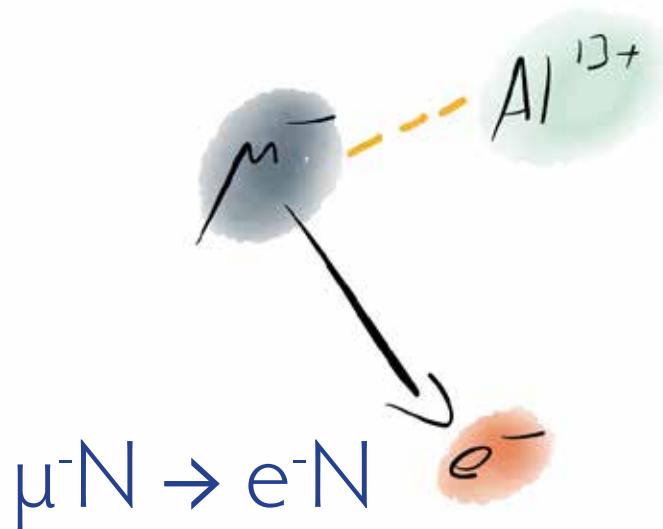


Kinematics

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

Background

- Accidental background
- Radiative decay

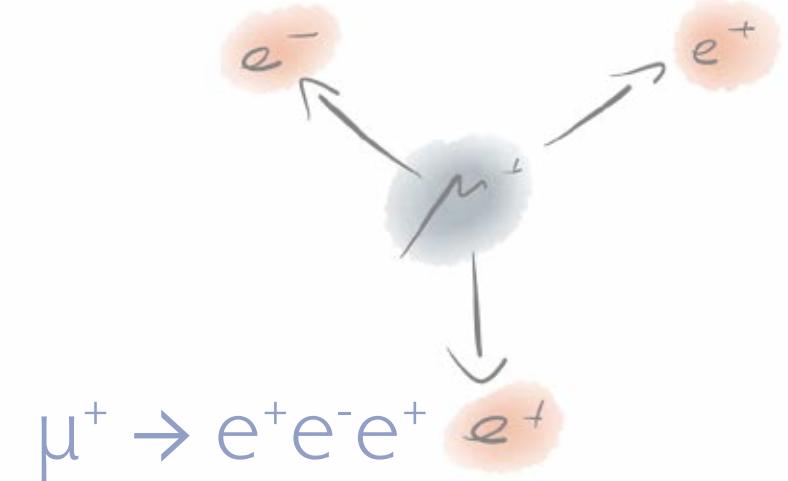


Kinematics

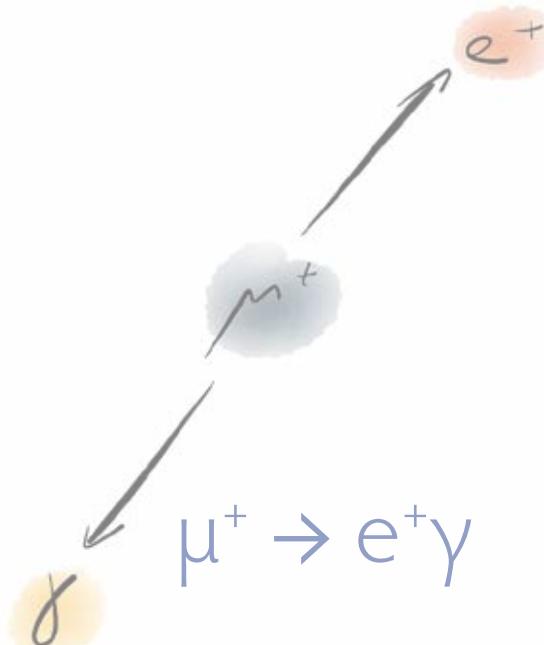
- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions, cosmics



LFV Muon Decays: Experimental signatures

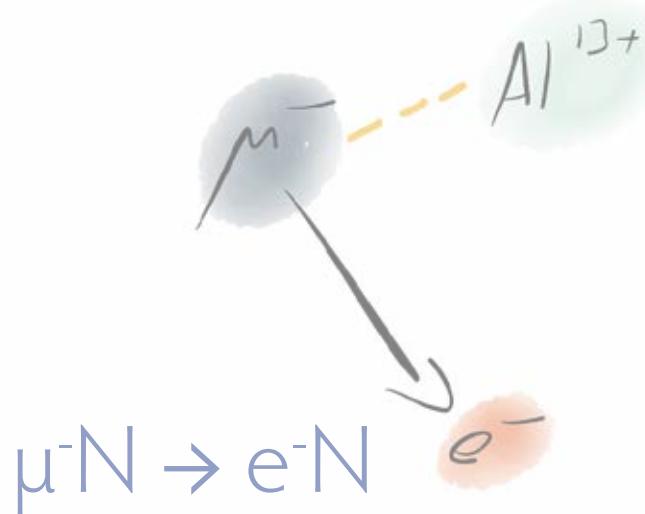


Kinematics

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

Background

- Accidental background
- Radiative decay

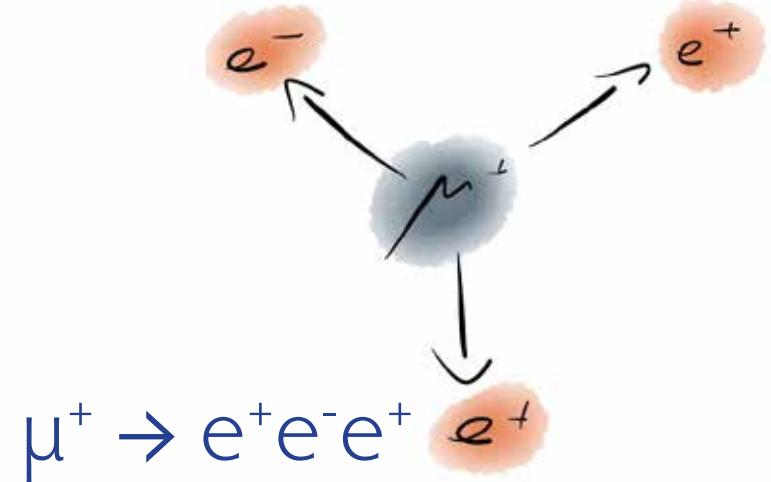


Kinematics

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

Background

- Decay in orbit
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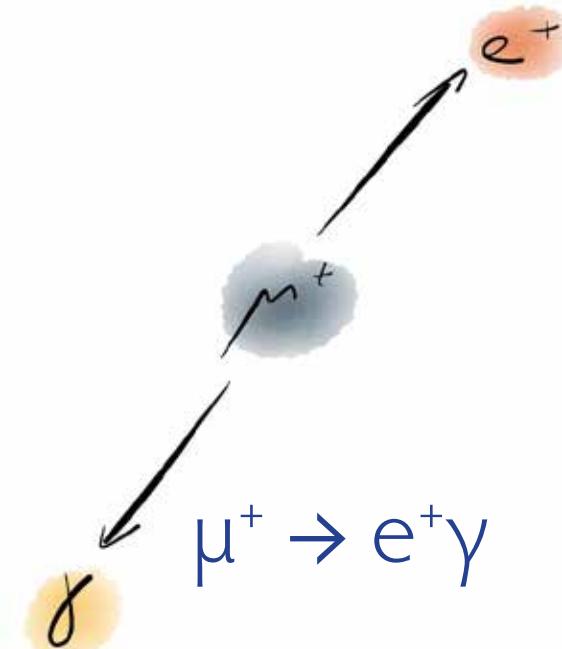
Kinematics

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

Background

- Internal conversion decay
- Accidental background

LFV Muon Decays: Experimental signatures

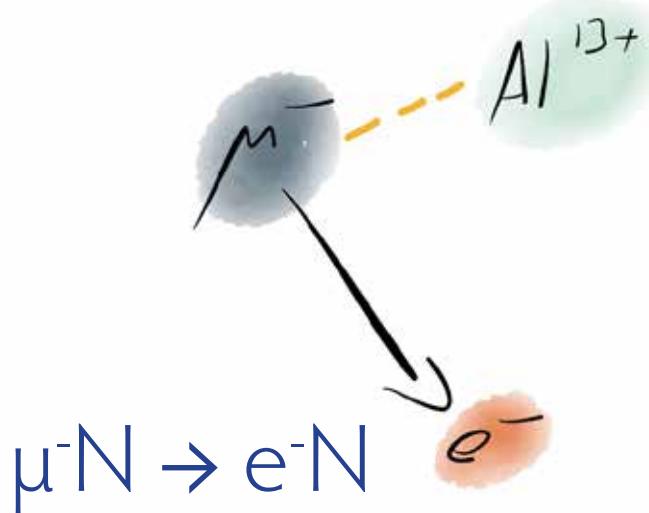


Kinematics

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

Background

- Accidental background
- Radiative decay

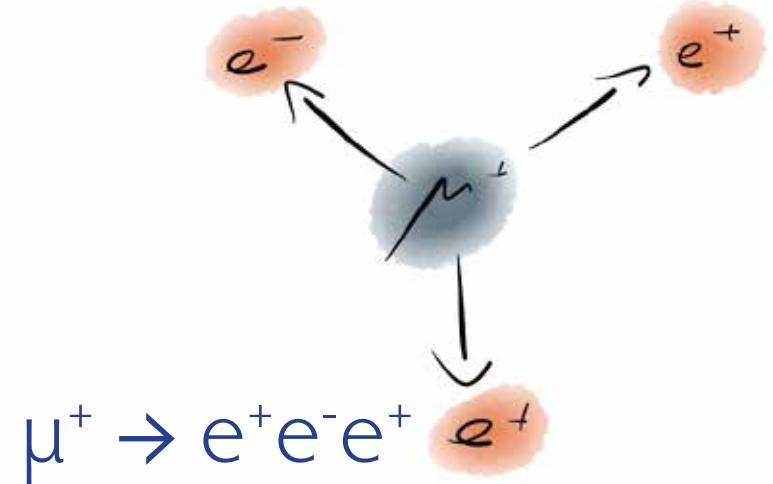


Kinematics

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

Background

- Decay in orbit
- Antiprotons, pions, cosmics



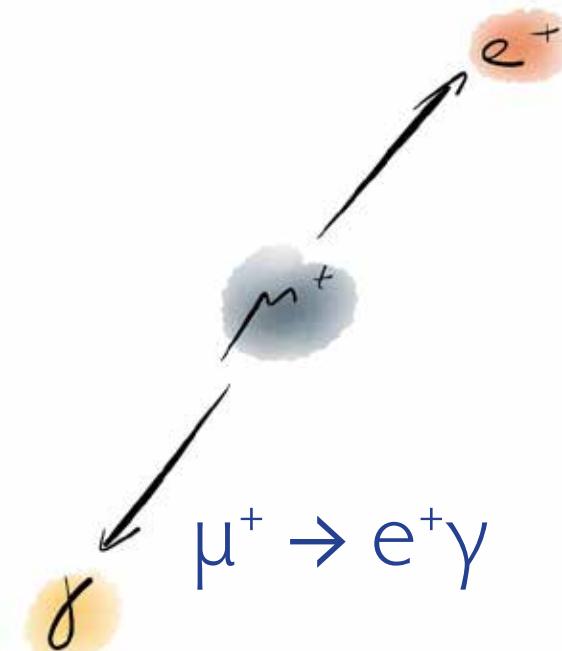
Kinematics

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

Background

- Internal conversion decay
- Accidental background

LFV Muon Decays: Experimental signatures



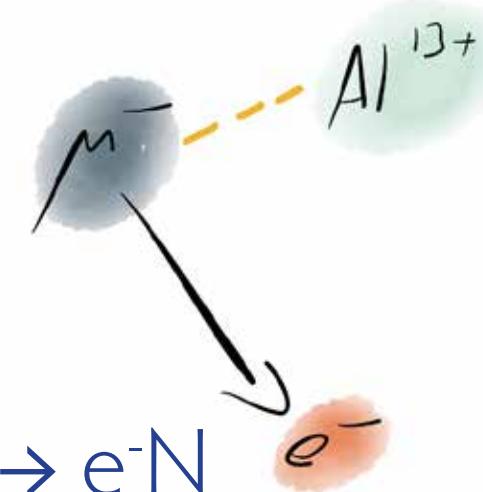
Kinematics

- 2-body decay
- Monoenergetic
- Back-to-back

Background

- A^3e signal background

Continuous Beam

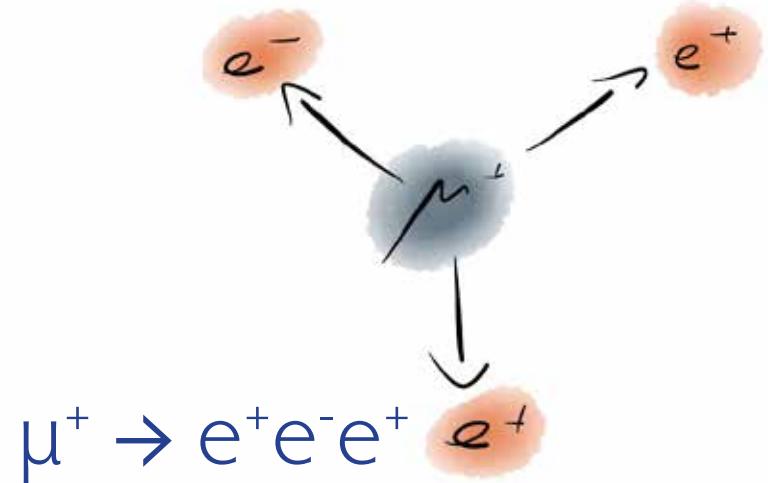


Kinematics

- Quasi 2-body decay
- Monoenergetic
- Single pions detected

Background

- A^3e orbit
- A^3e , protons, pions



Kinematics

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

Background

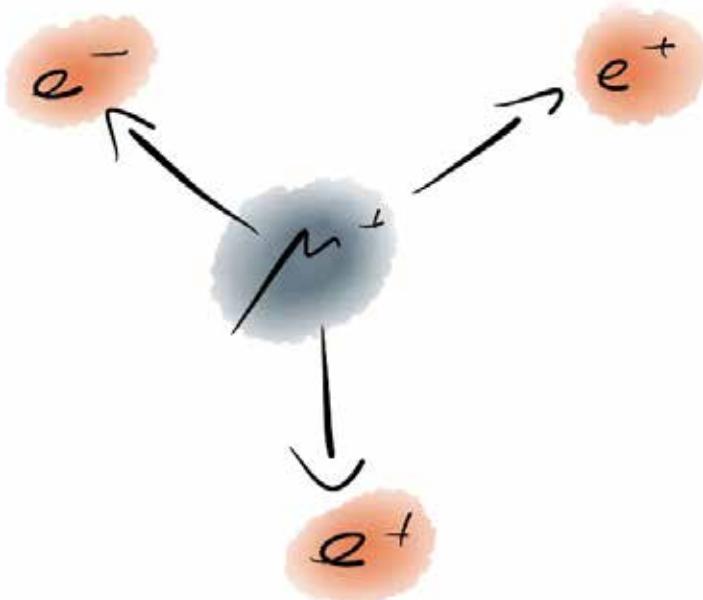
- R^3e decay
- Accidental background

Continuous Beam



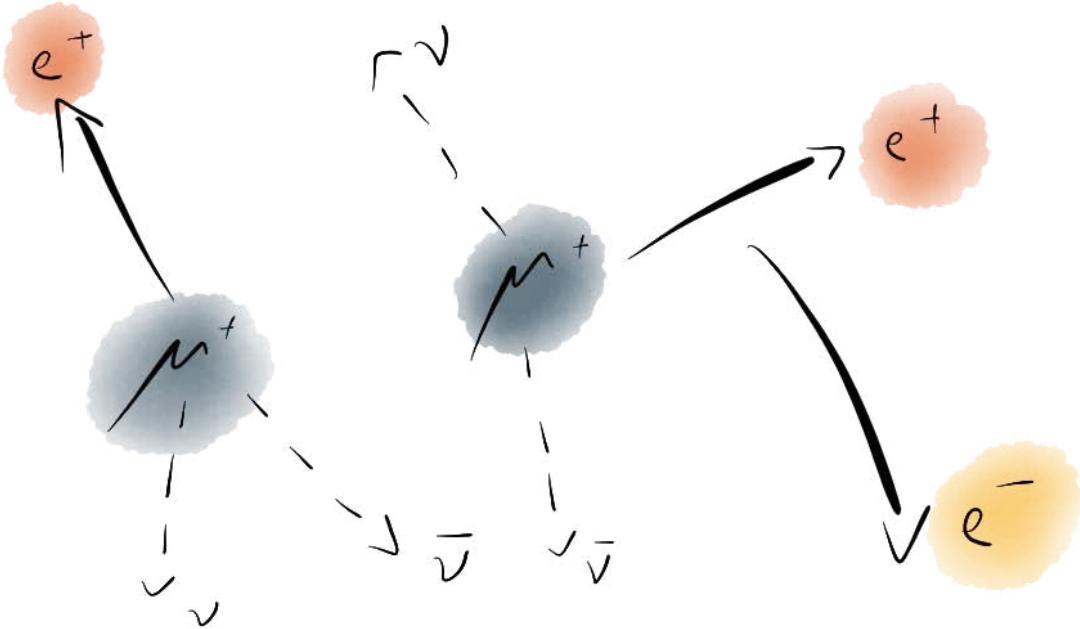
Searching for $\mu^+ \rightarrow e^+ e^- e^+$ with
Mu3e

The signal



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

Accidental Background



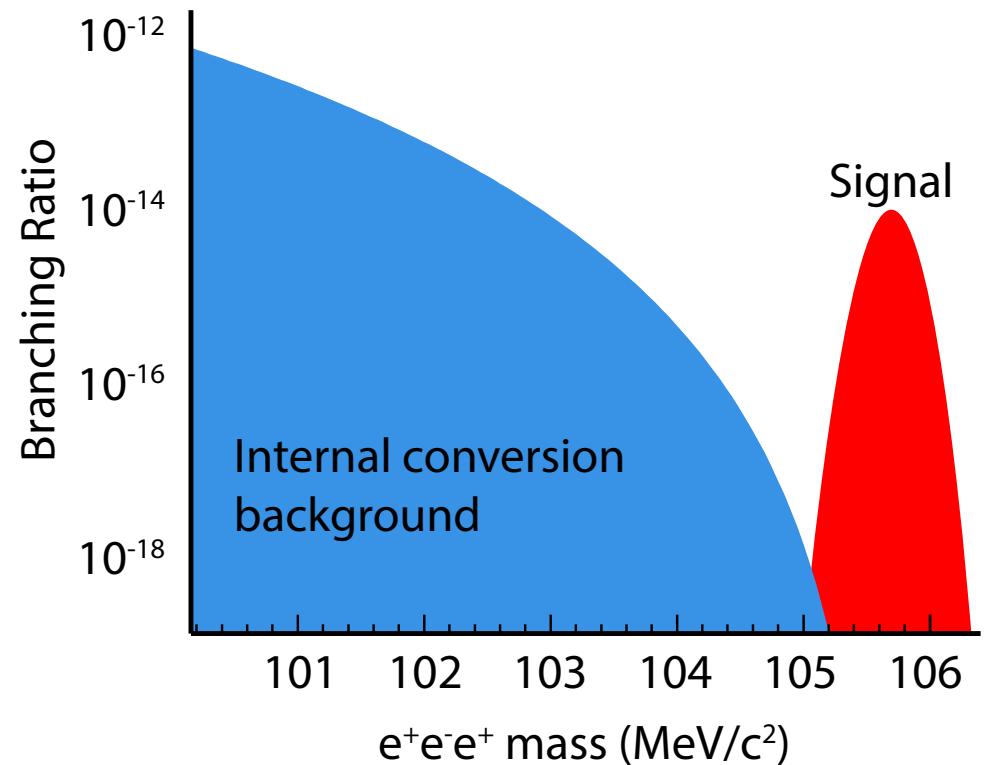
- Combination of positrons from ordinary muon decay with electrons from:
 - photon conversion,
 - Bhabha (electron-positron) scattering,
 - Mis-reconstruction
- Need very good timing, vertex and momentum resolution

Internal conversion background



- Need excellent momentum resolution

- Allowed radiative decay with internal conversion:
$$\mu^+ \rightarrow e^+ e^- e^+ \nu \bar{\nu}$$
- Only distinguishing feature:
Missing momentum carried by neutrinos



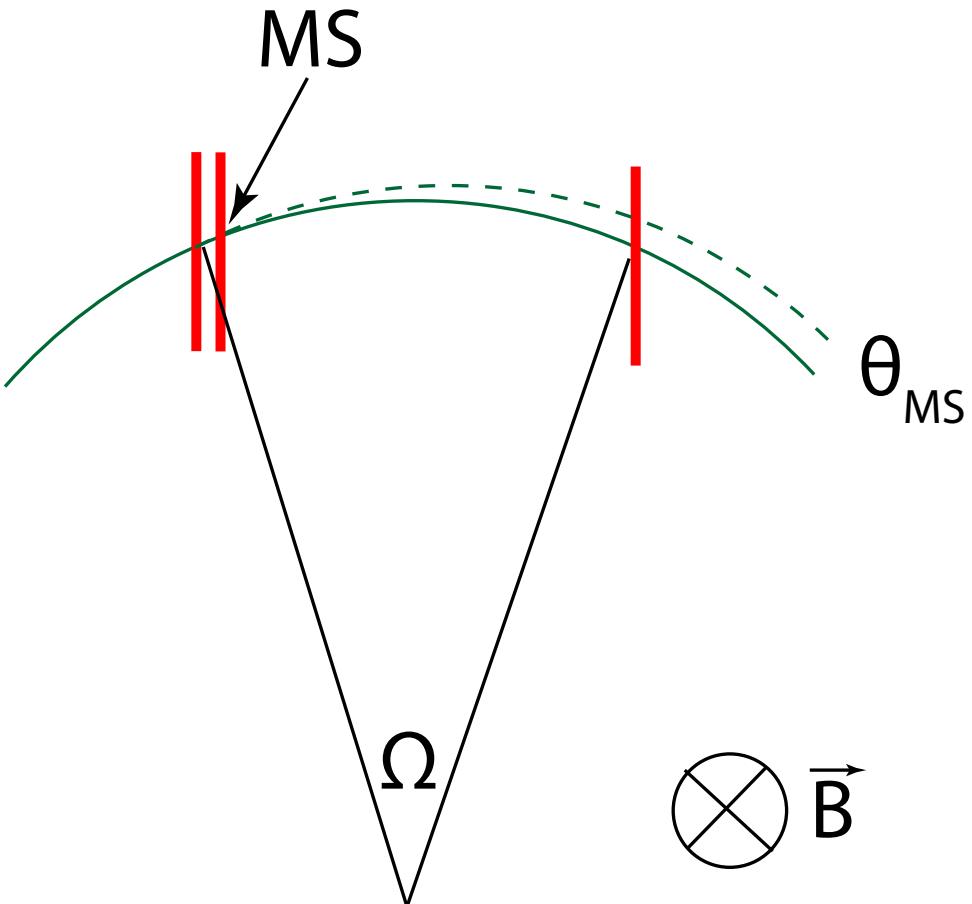


Need excellent momentum resolution
for very low momentum electrons

Momentum measurement



- 1 T magnetic field
- Resolution dominated by multiple scattering

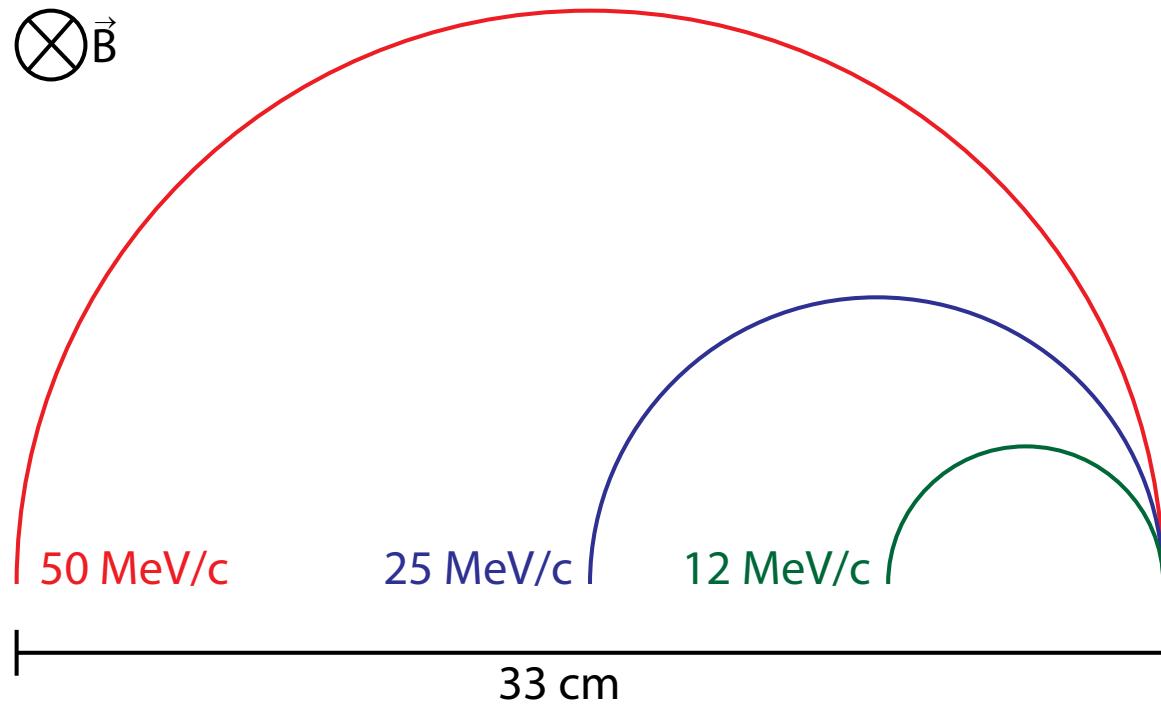


- Momentum resolution to first order:

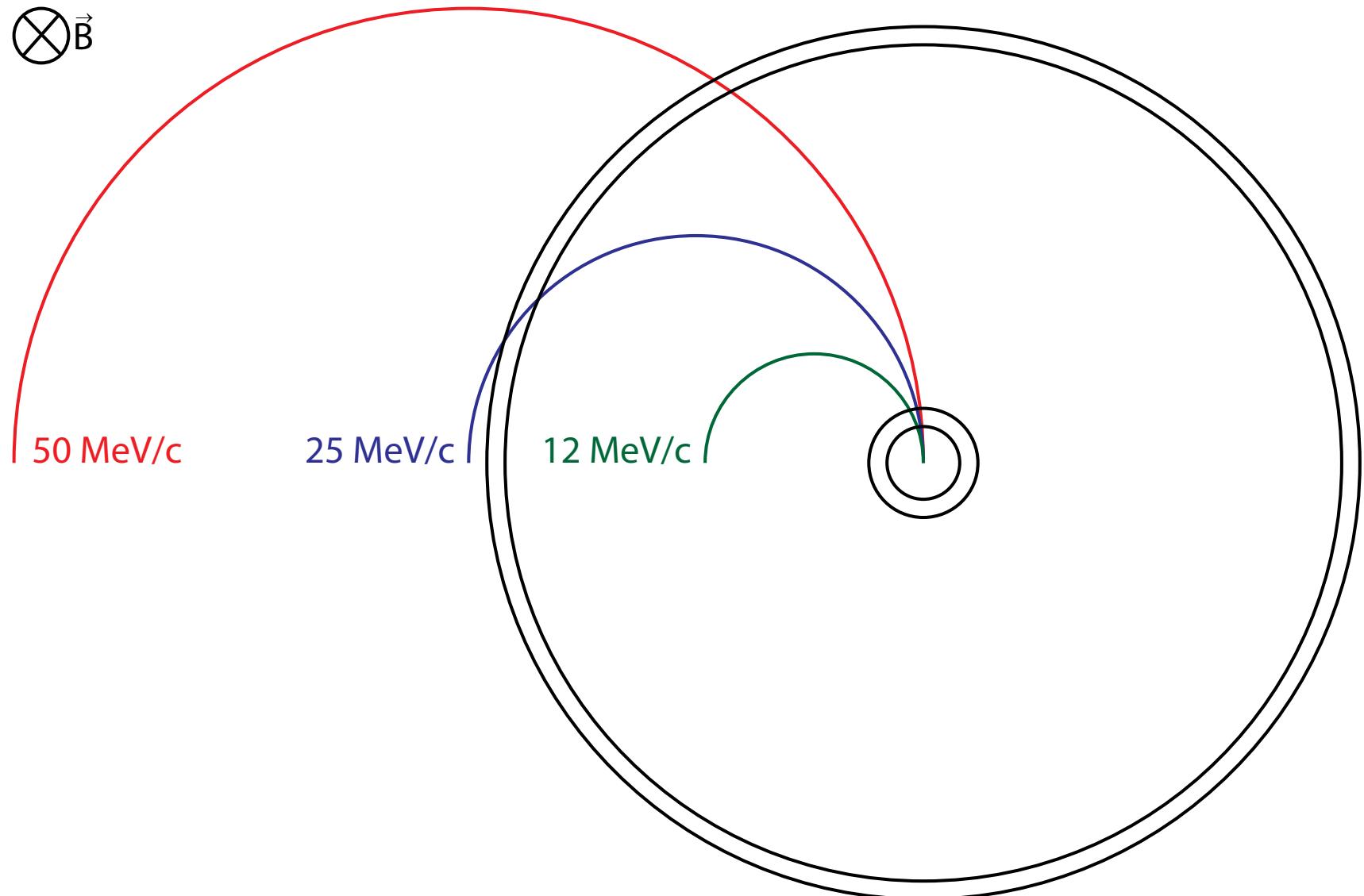
$$\sigma_p/p \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle Ω) and low multiple scattering θ_{MS}

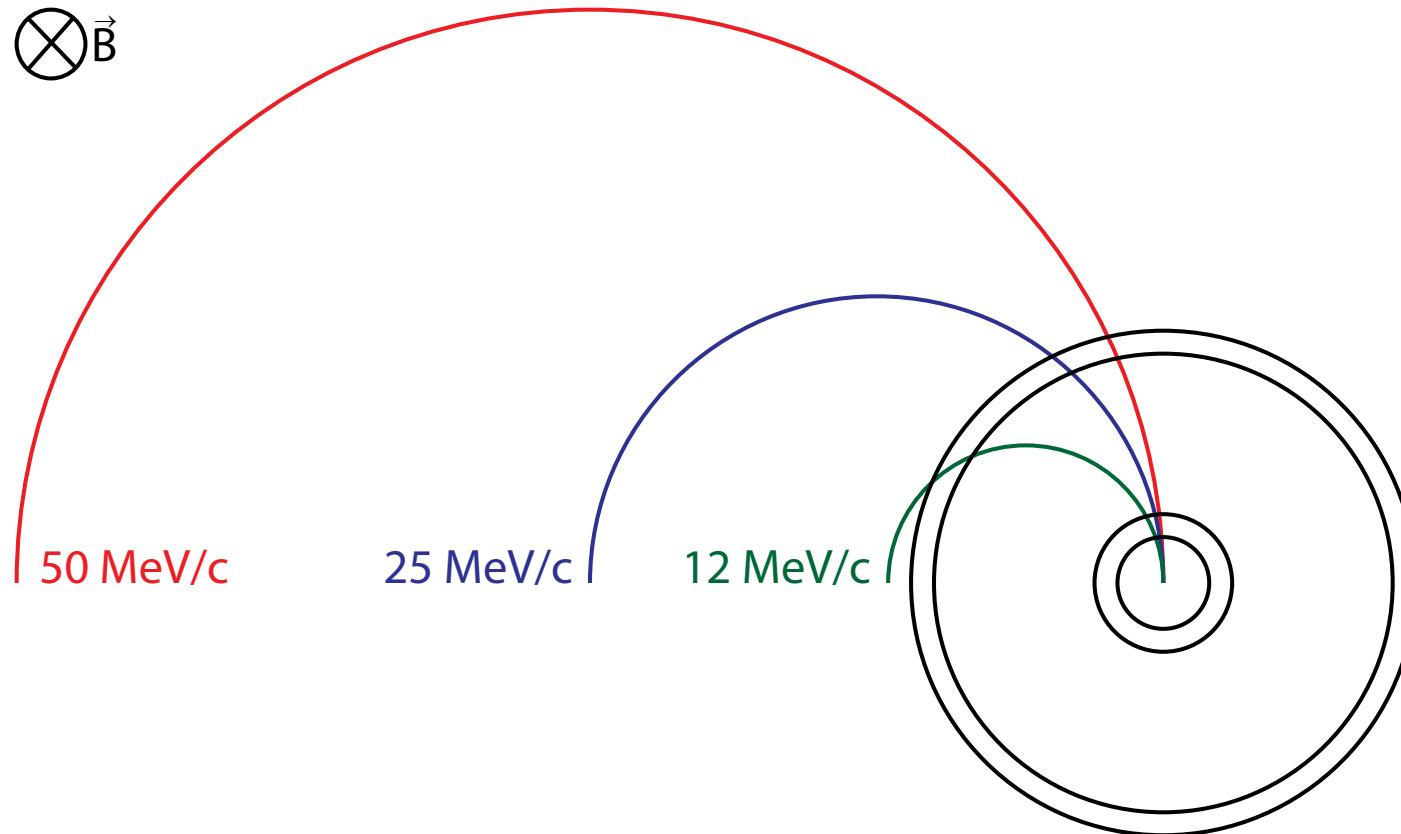
Precision vs. Acceptance



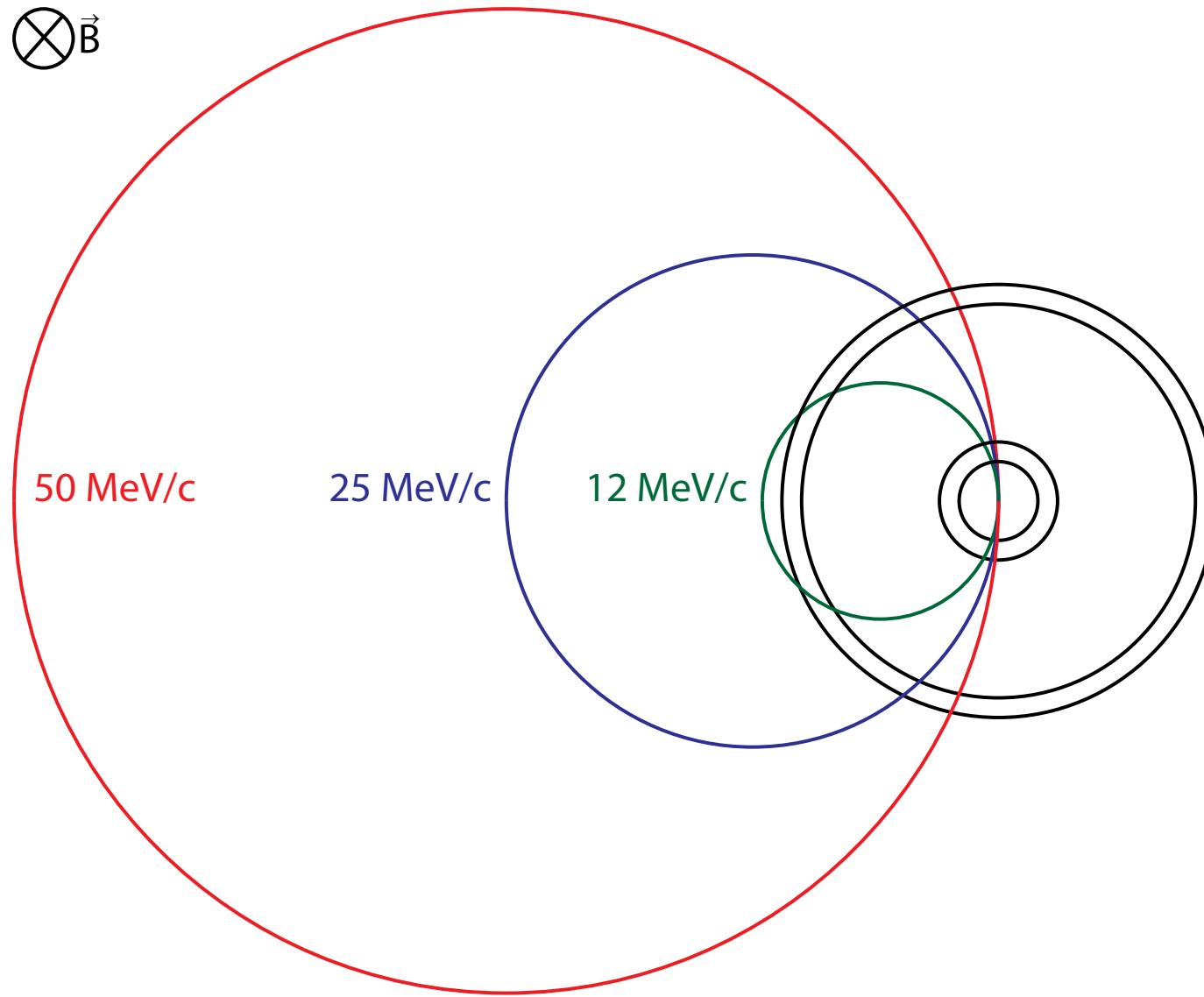
Precision vs. Acceptance



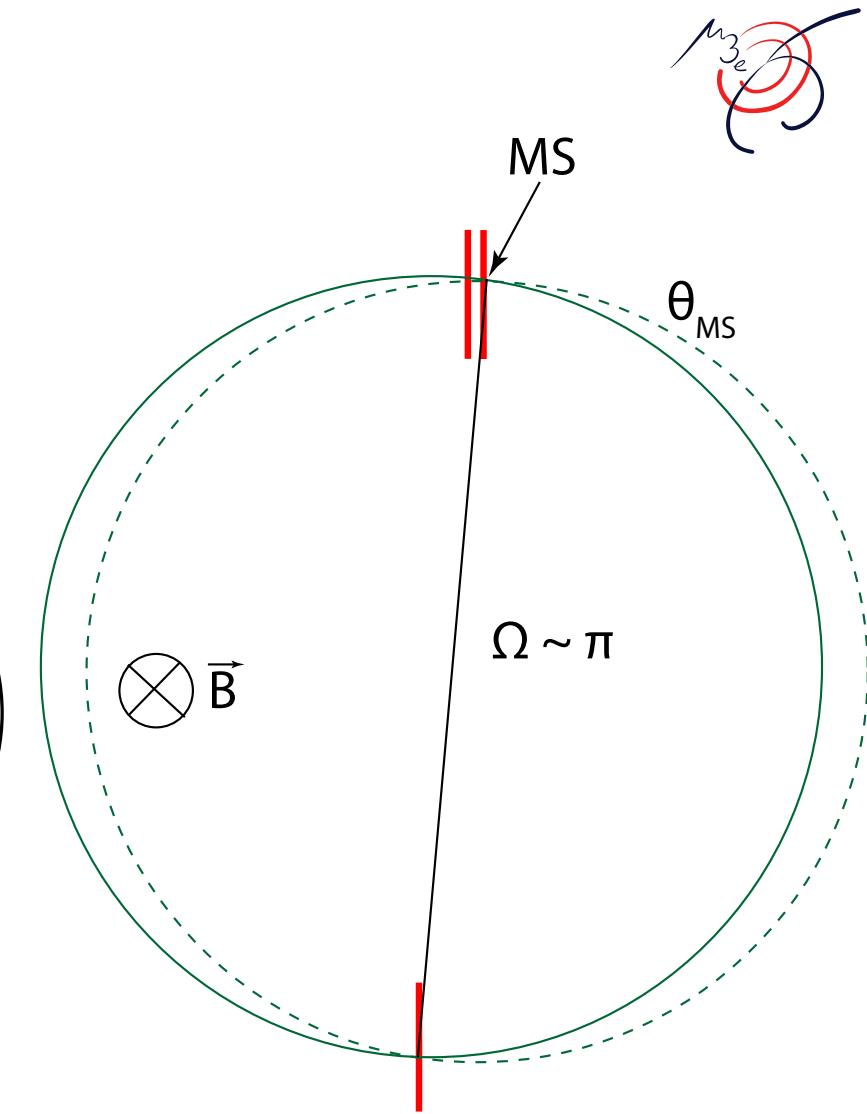
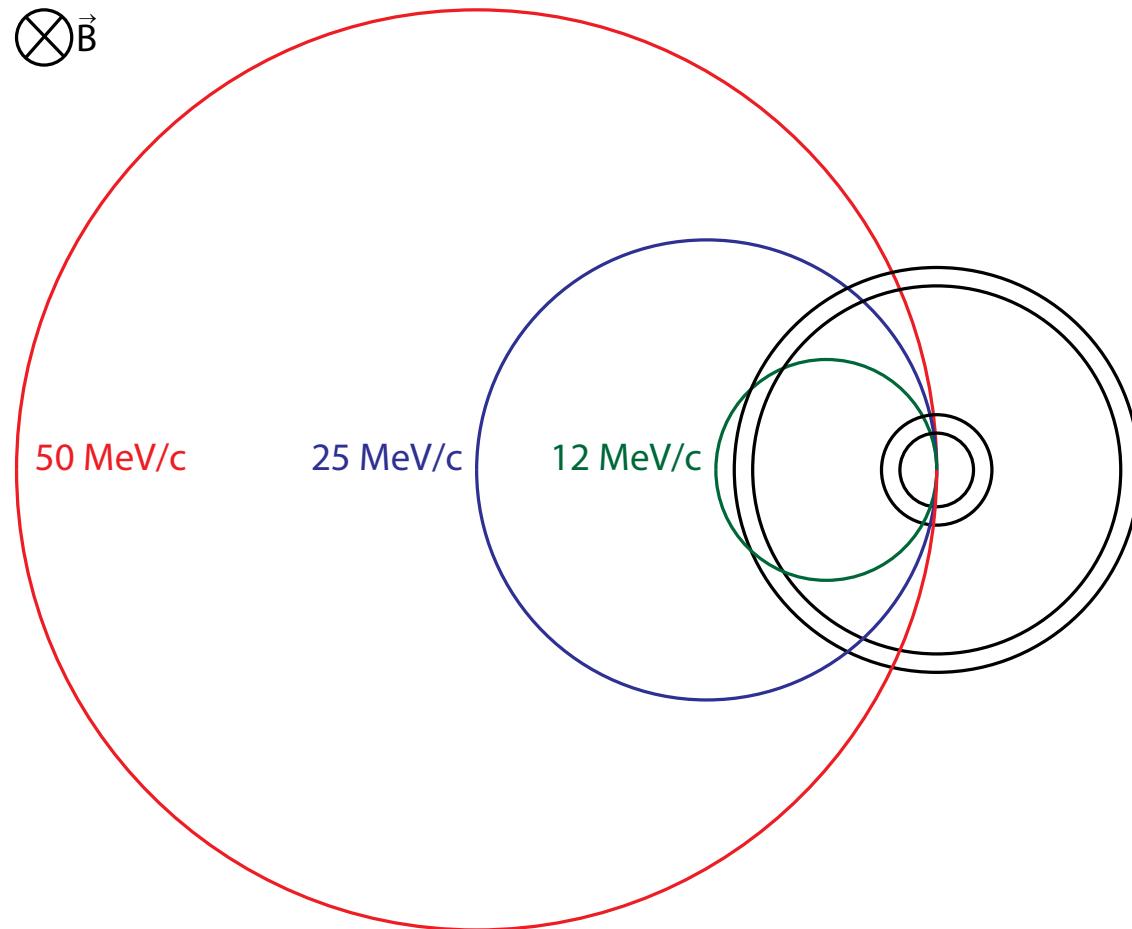
Precision vs. Acceptance



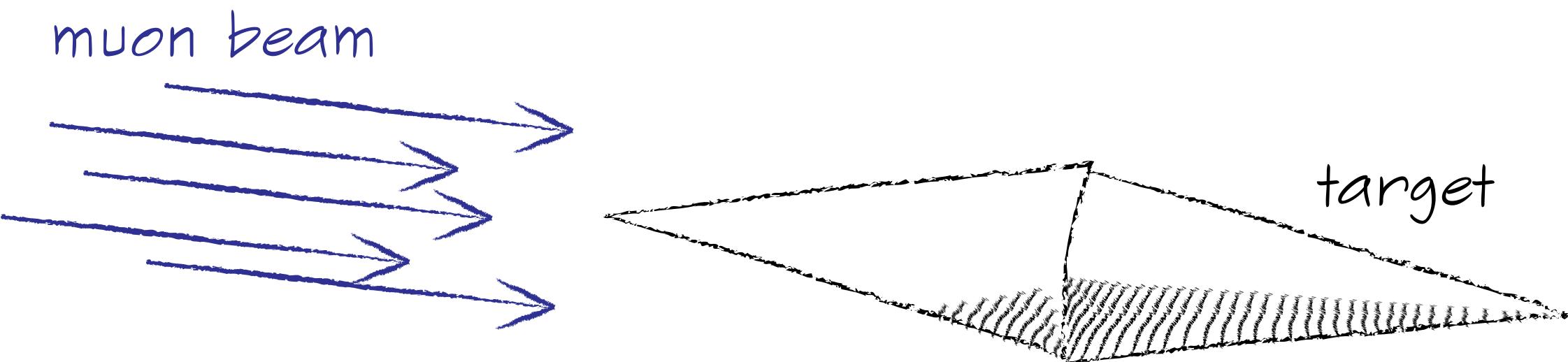
Precision vs. Acceptance



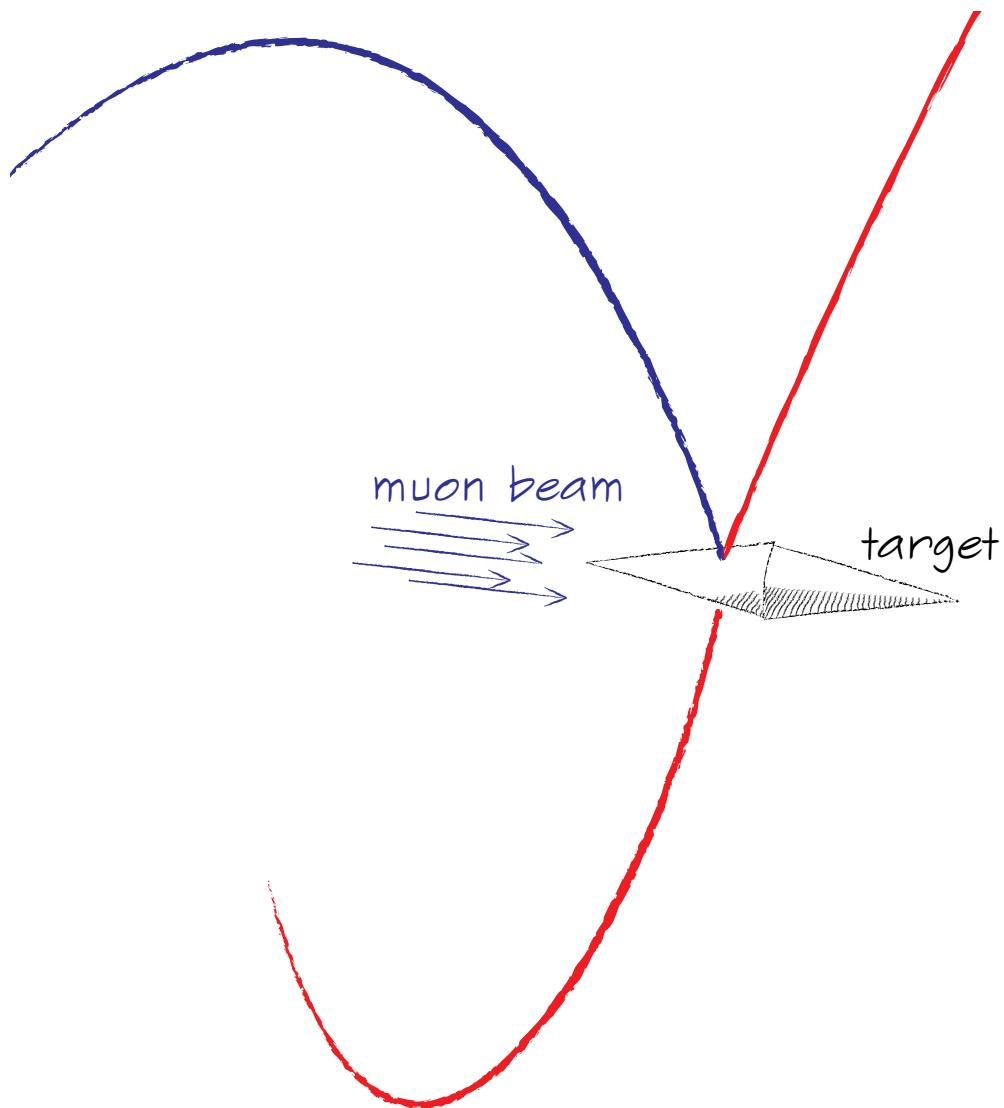
Precision vs. Acceptance



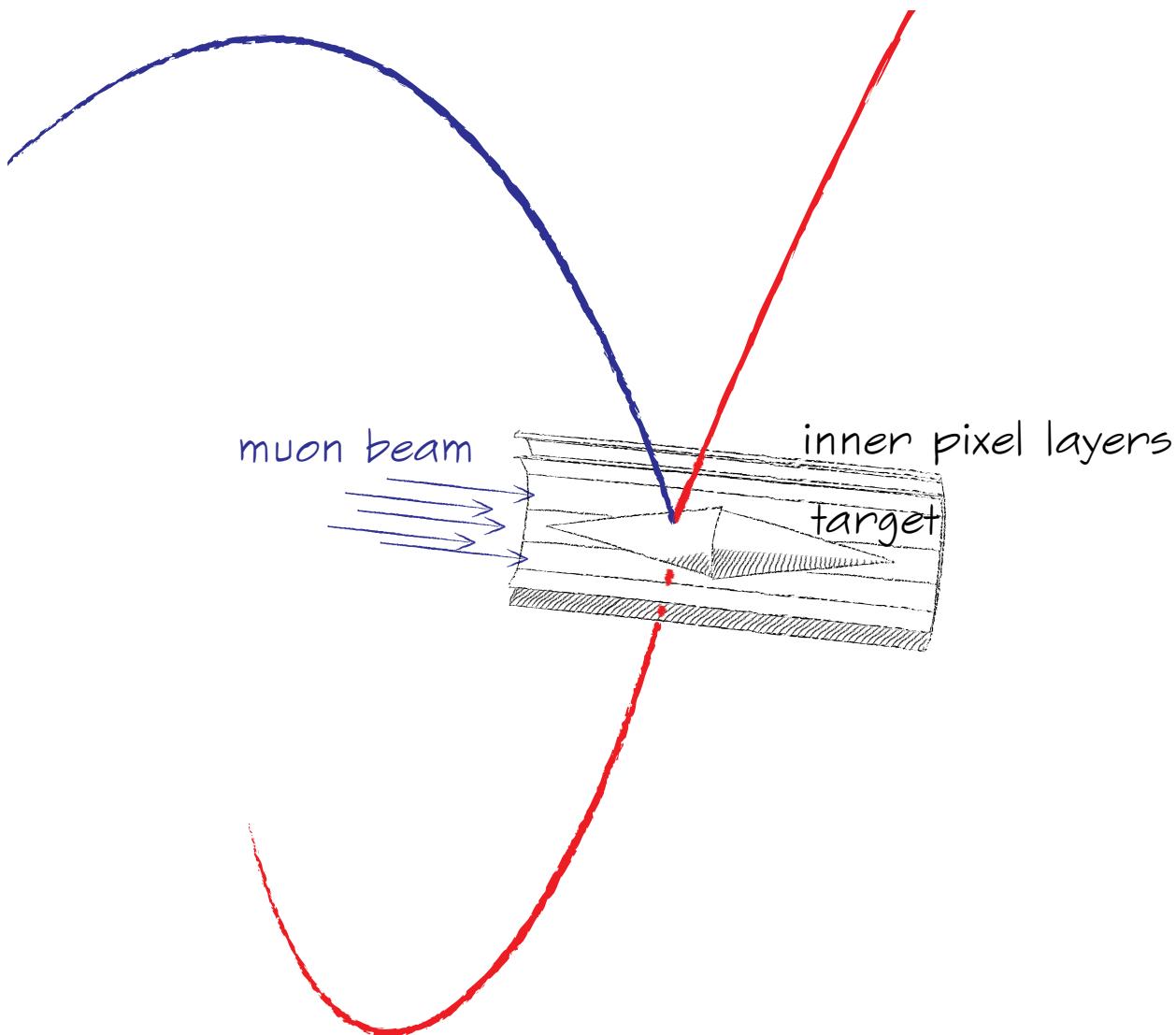
Detector Design



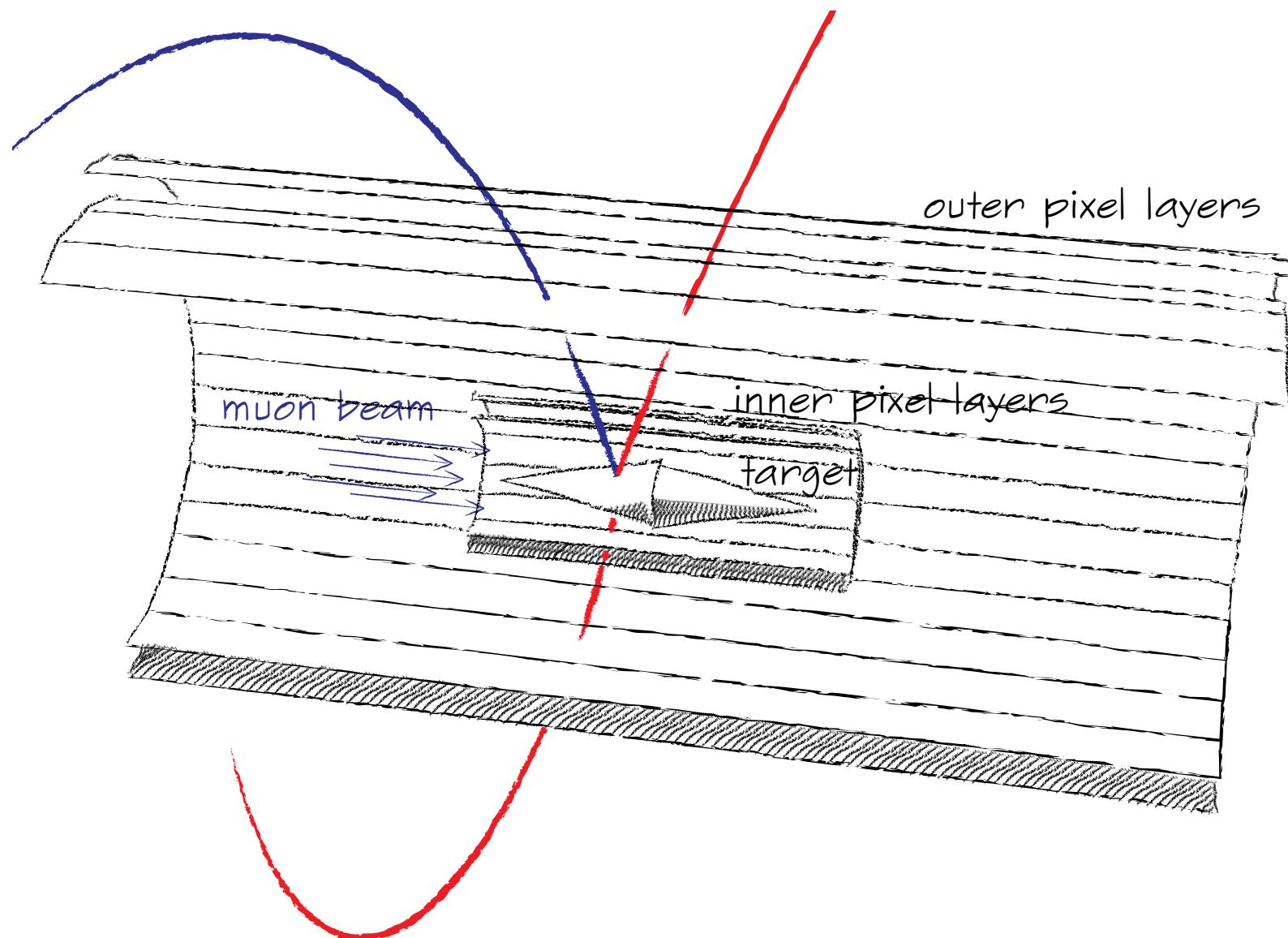
Detector Design



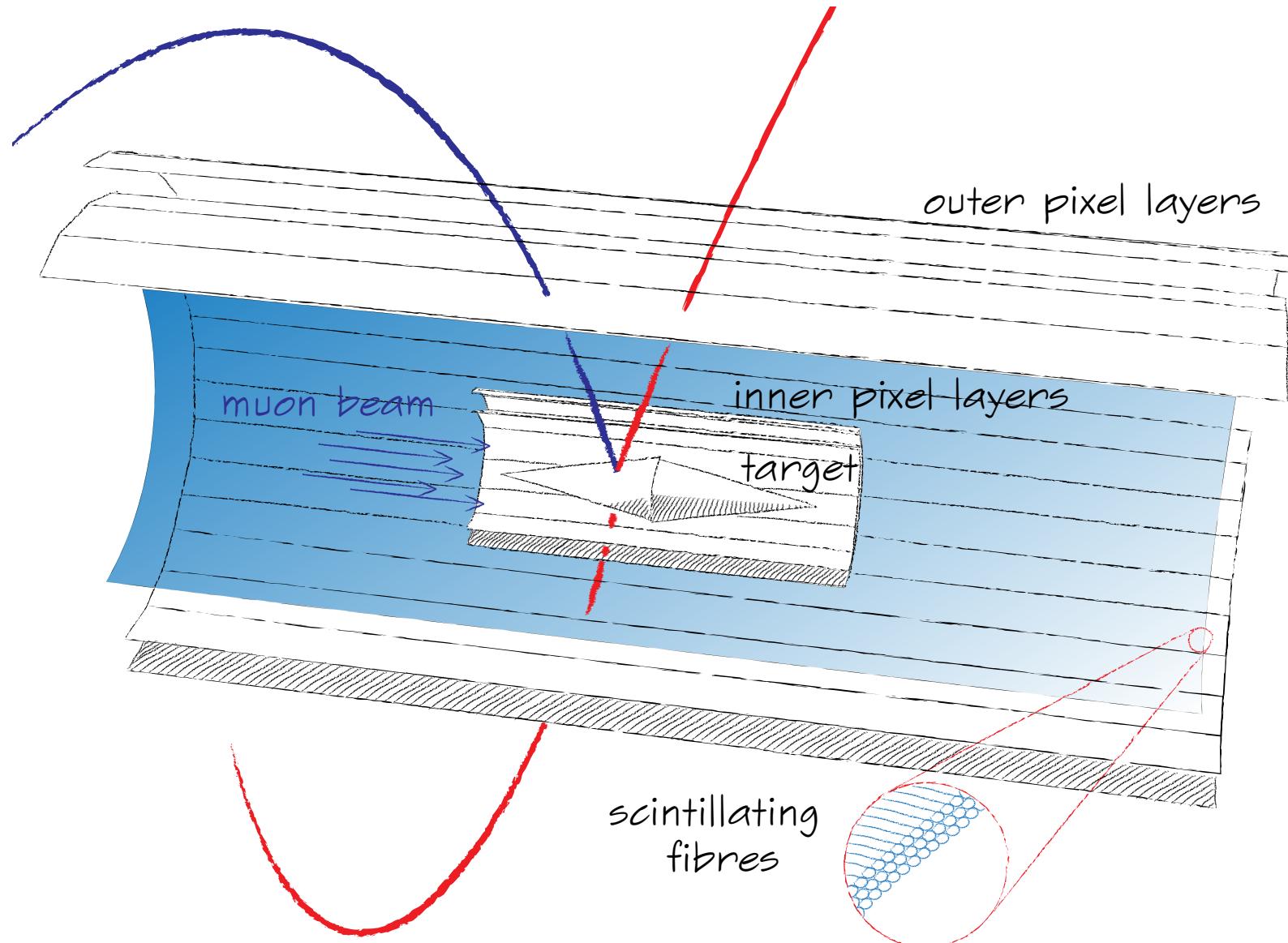
Detector Design



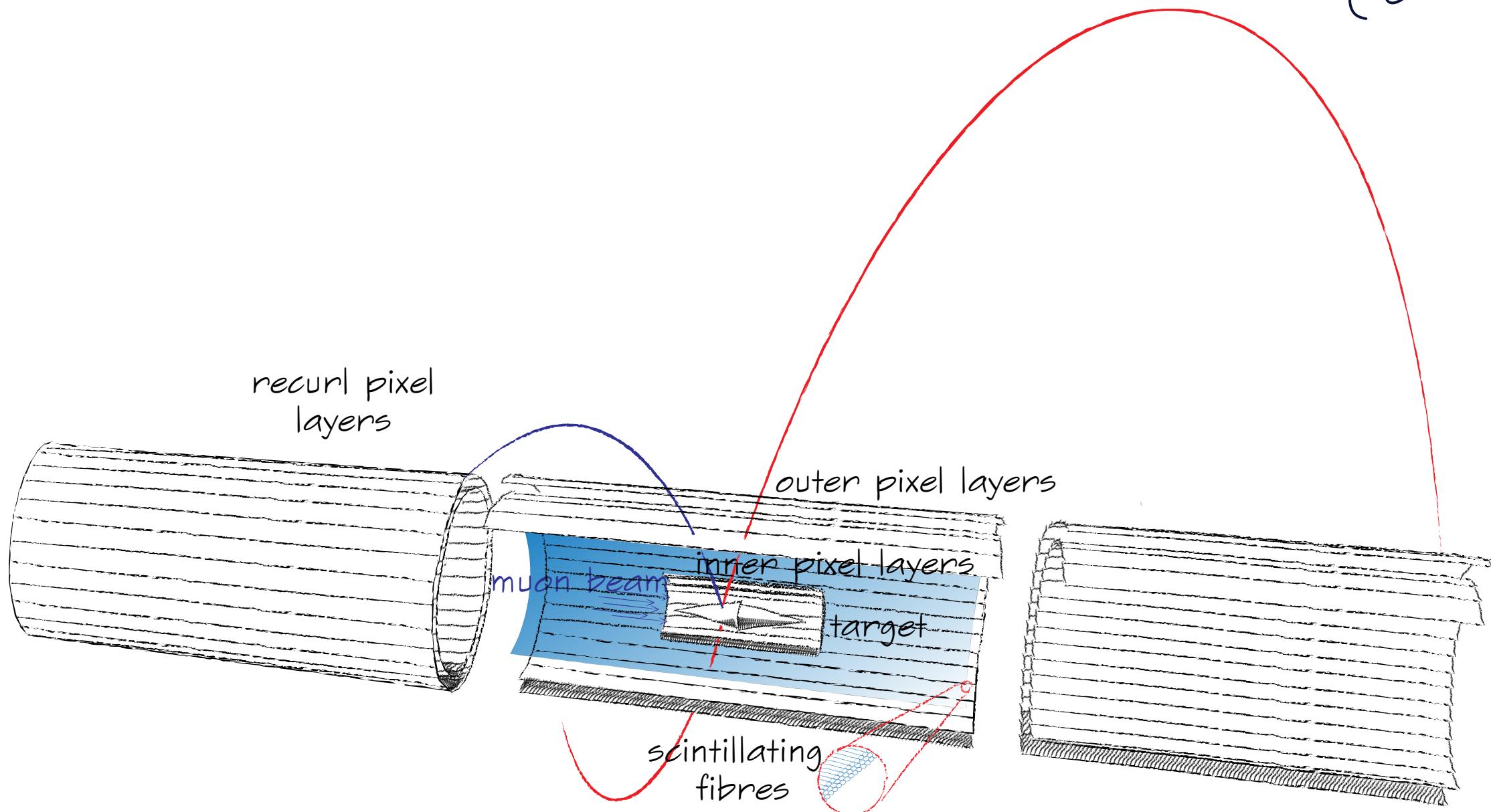
Detector Design



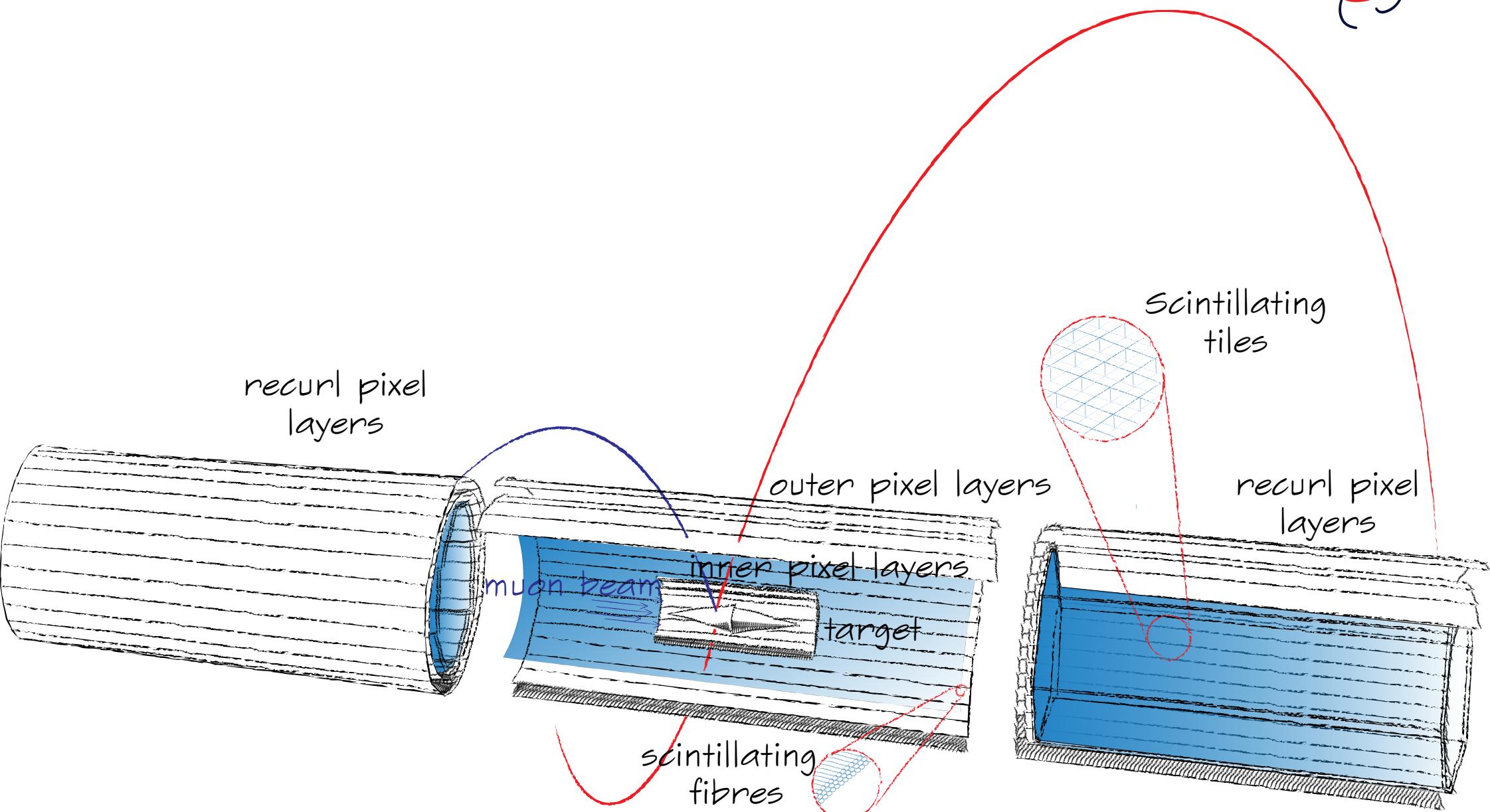
Detector Design



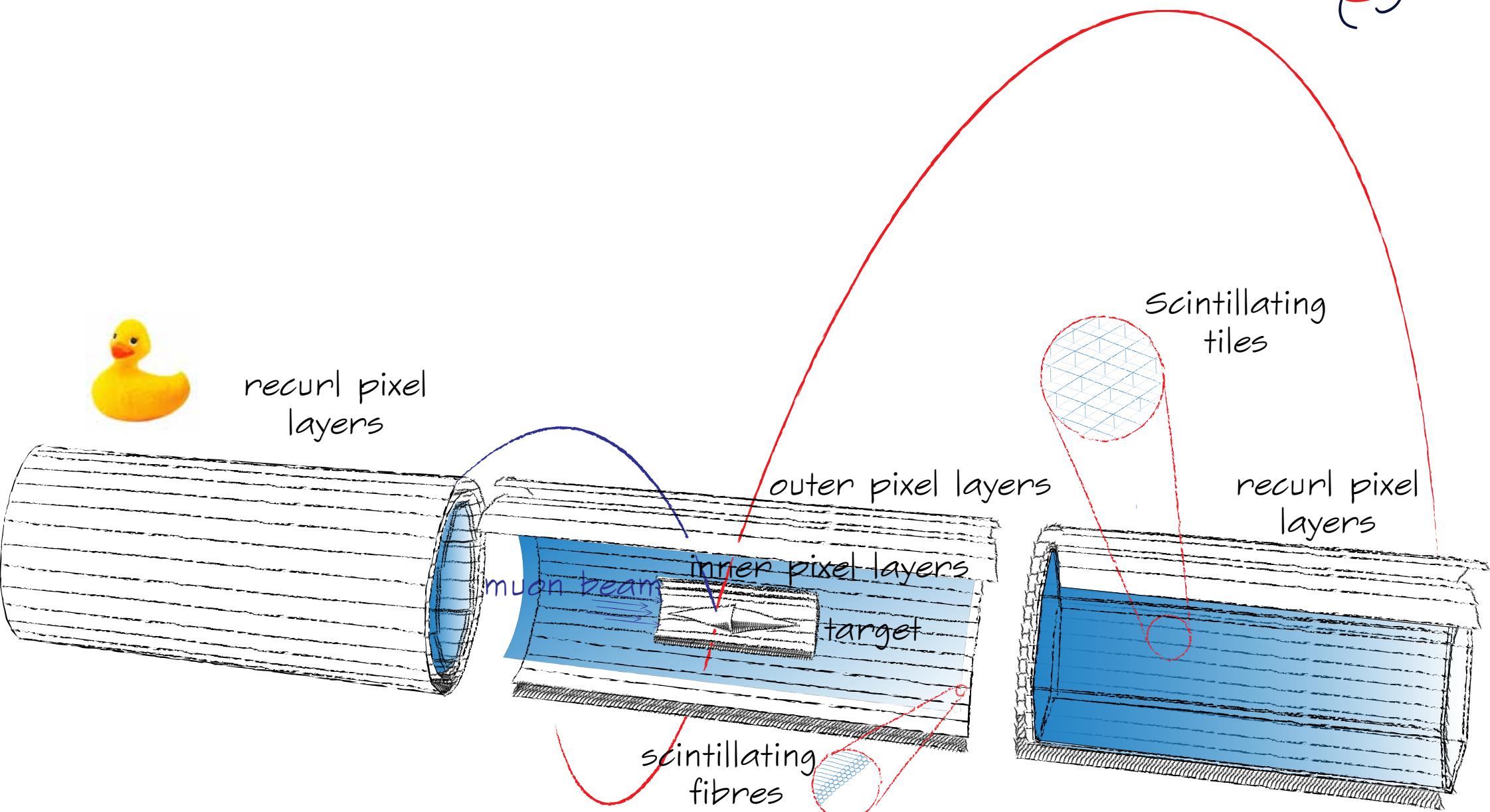
Detector Design



Detector Design



Detector Design

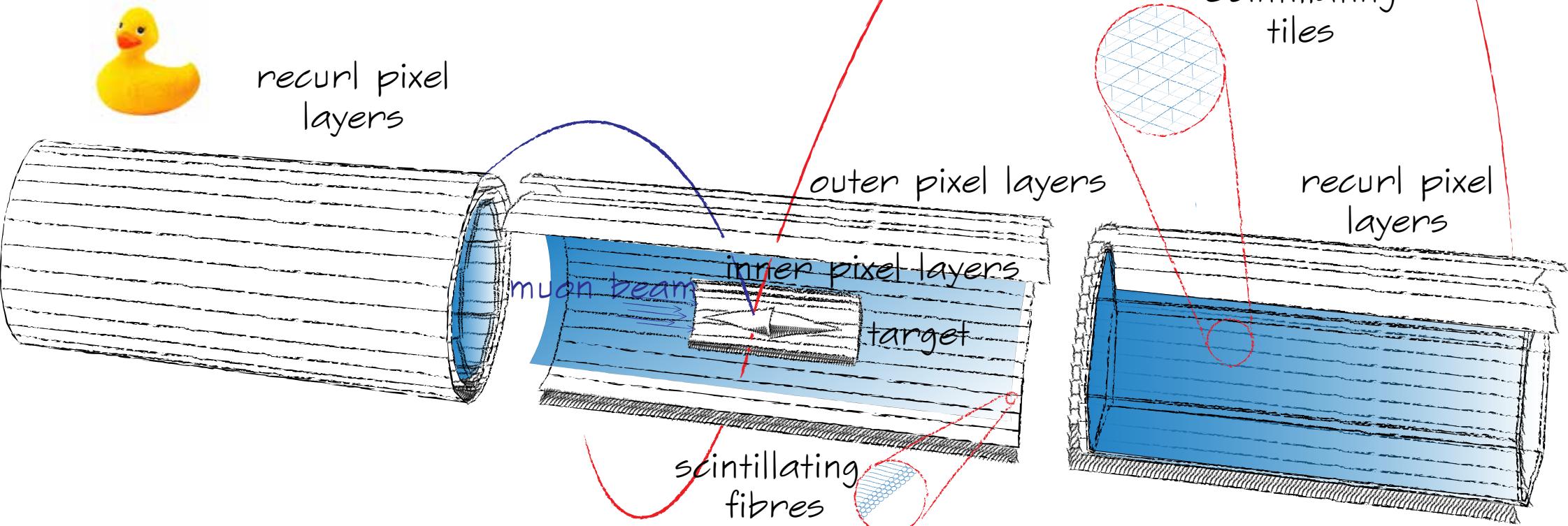


Detector Design

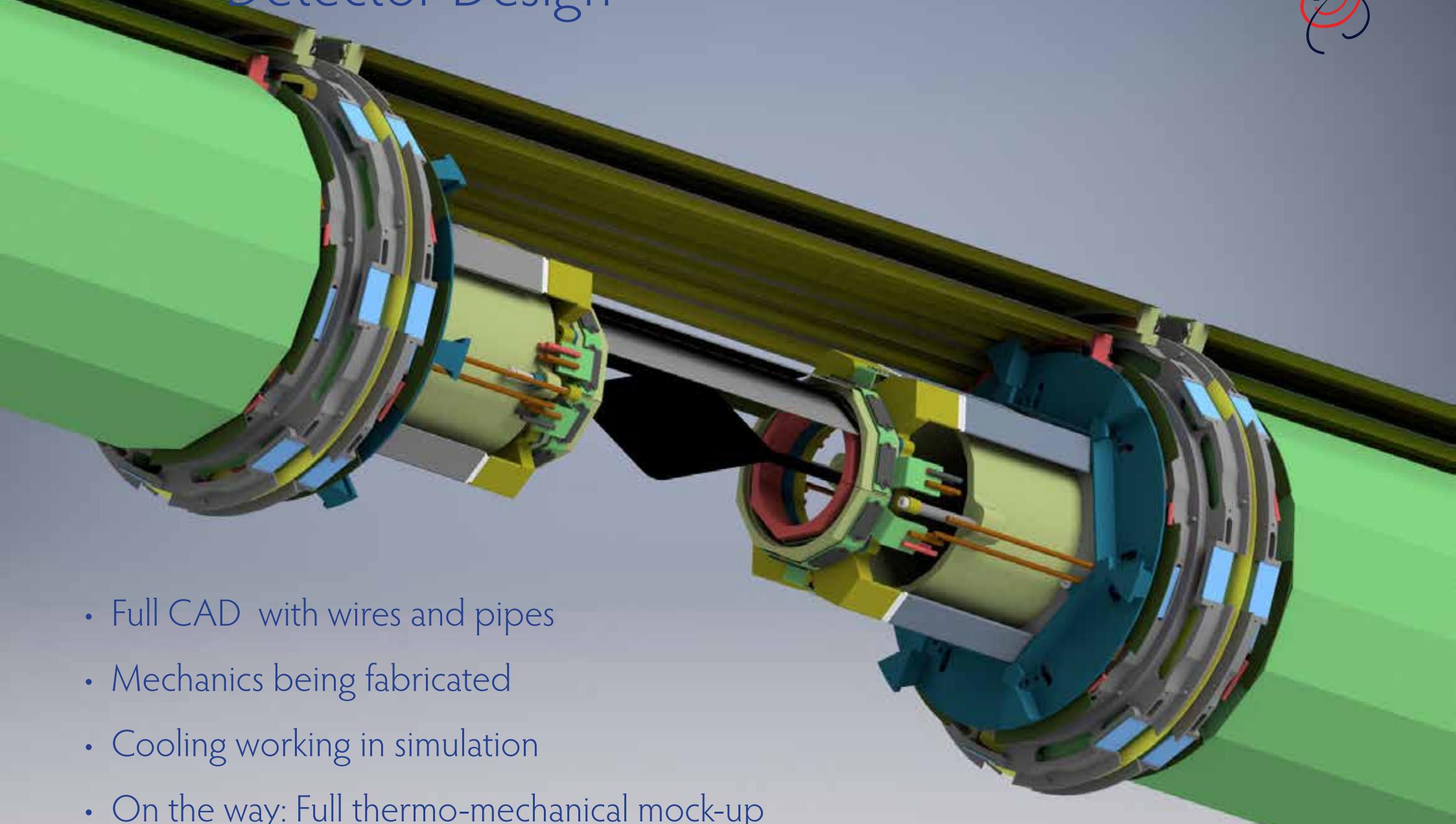


Challenges:

- Thin detectors
- Services (and beam) inside detector
- Cooling with gaseous Helium



Detector Design



- Full CAD with wires and pipes
- Mechanics being fabricated
- Cooling working in simulation
- On the way: Full thermo-mechanical mock-up



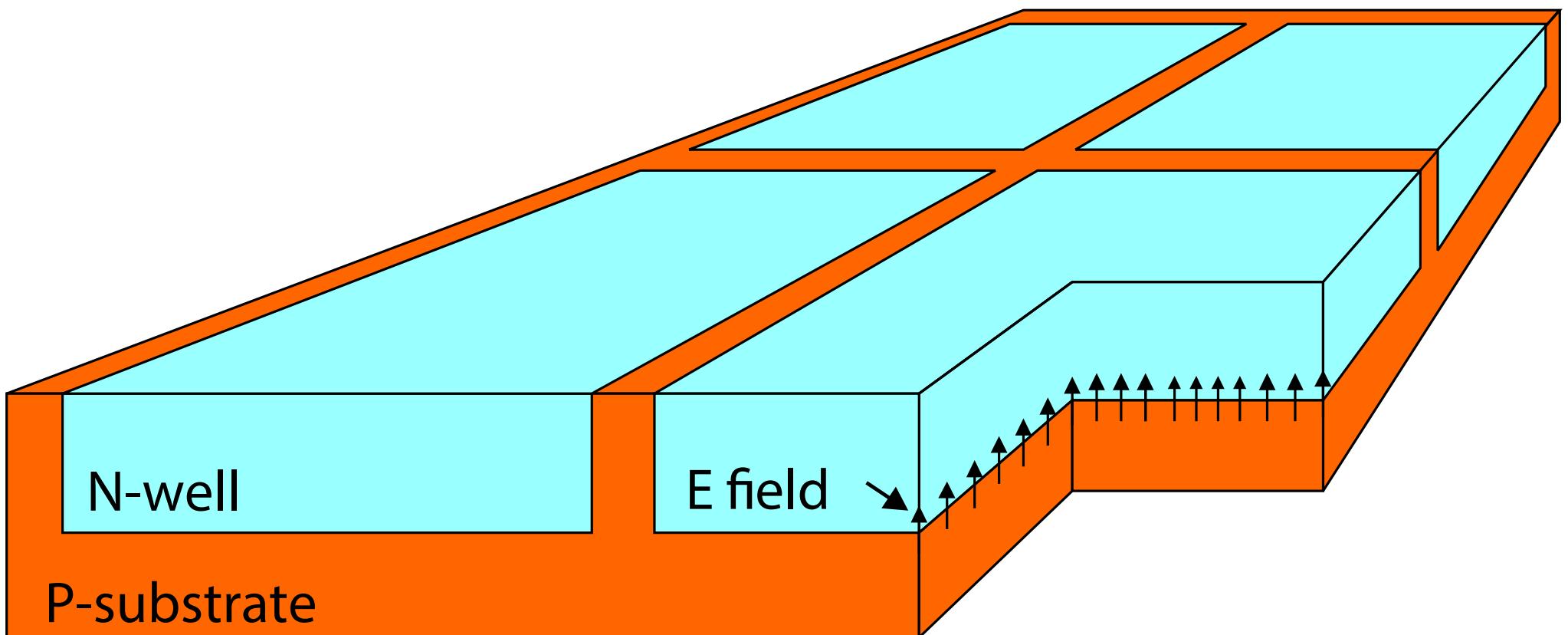
Very thin and fast silicon pixel sensors: HV-MAPS

Fast and thin sensors: HV-MAPS



High voltage monolithic active pixel
sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)

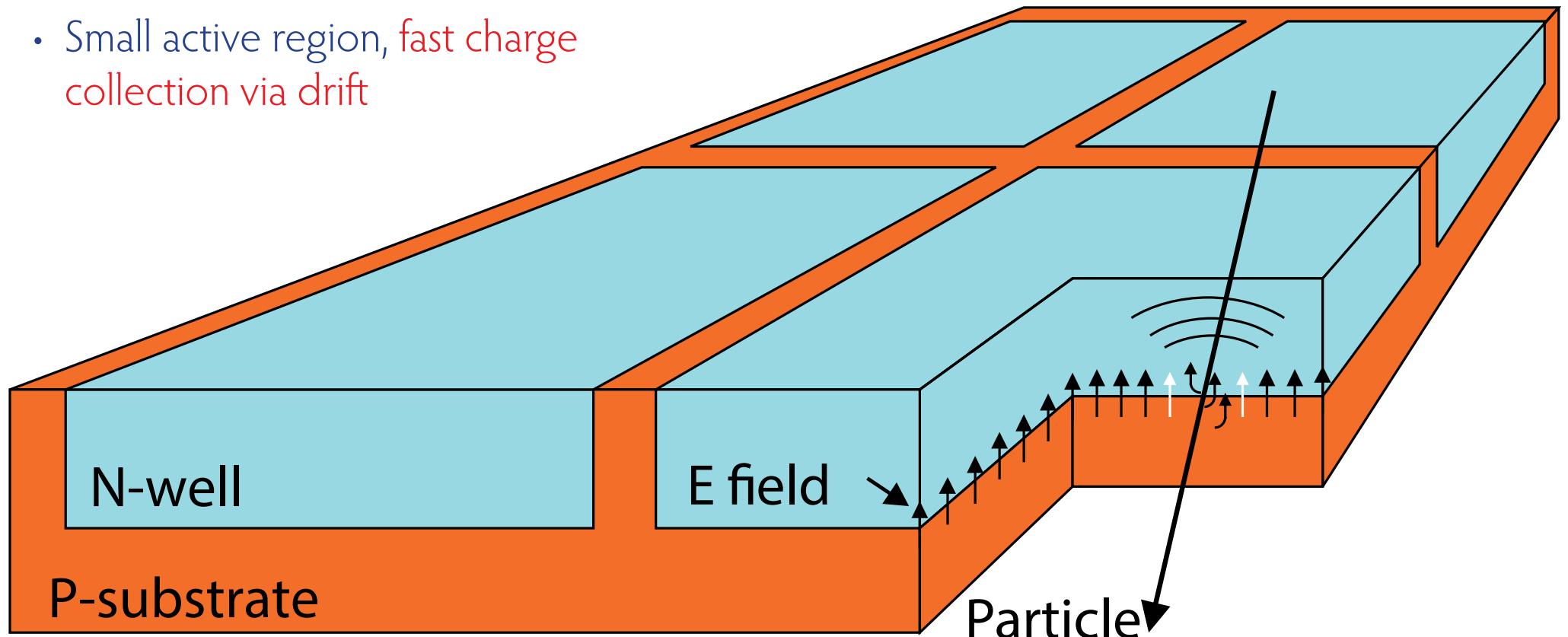


Fast and thin sensors: HV-MAPS



High voltage monolithic active pixel
sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift



Fast and thin sensors: HV-MAPS

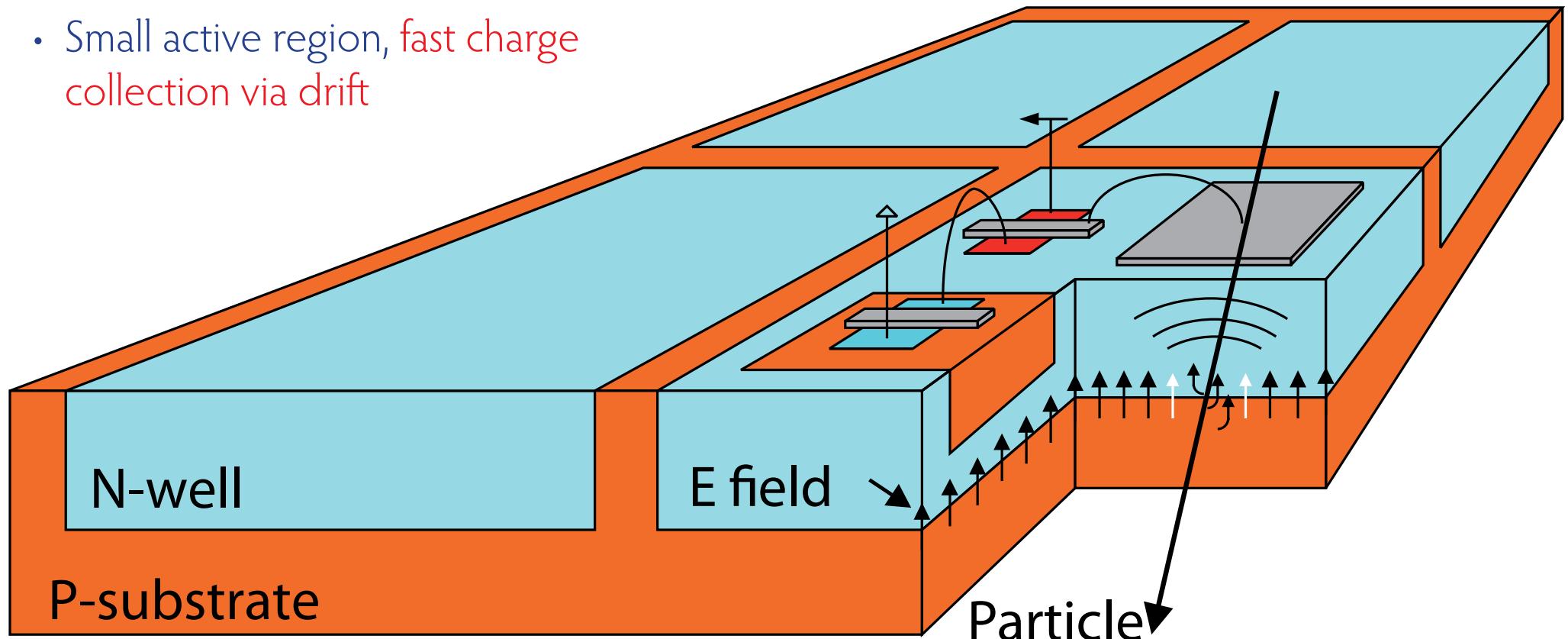


High voltage monolithic active pixel
sensors - Ivan Perić

- Use a **high voltage commercial process** (automotive industry)
- Small active region, **fast charge collection via drift**

- Implement logic directly in N-well in the pixel - **smart diode array**
- Can be thinned down to $< 50 \mu\text{m}$

(I.Perić, NIM A 582 (2007) 876)

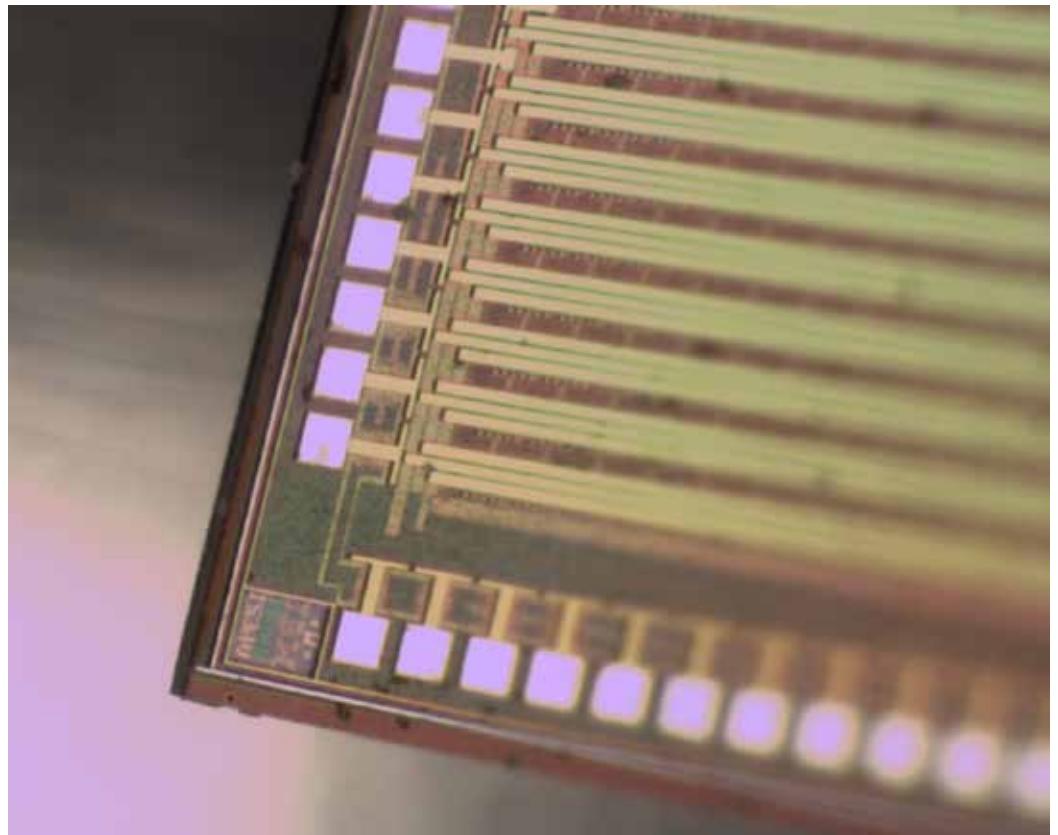


The MuPix Prototypes

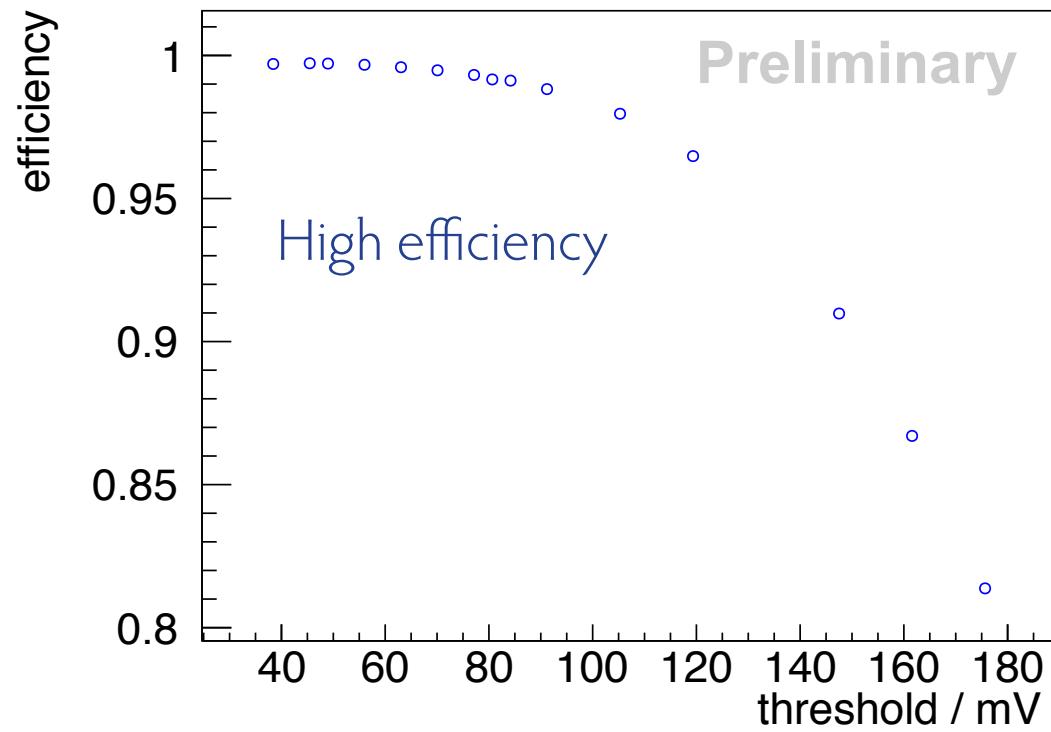


Developed a series of HV-MAPS prototypes

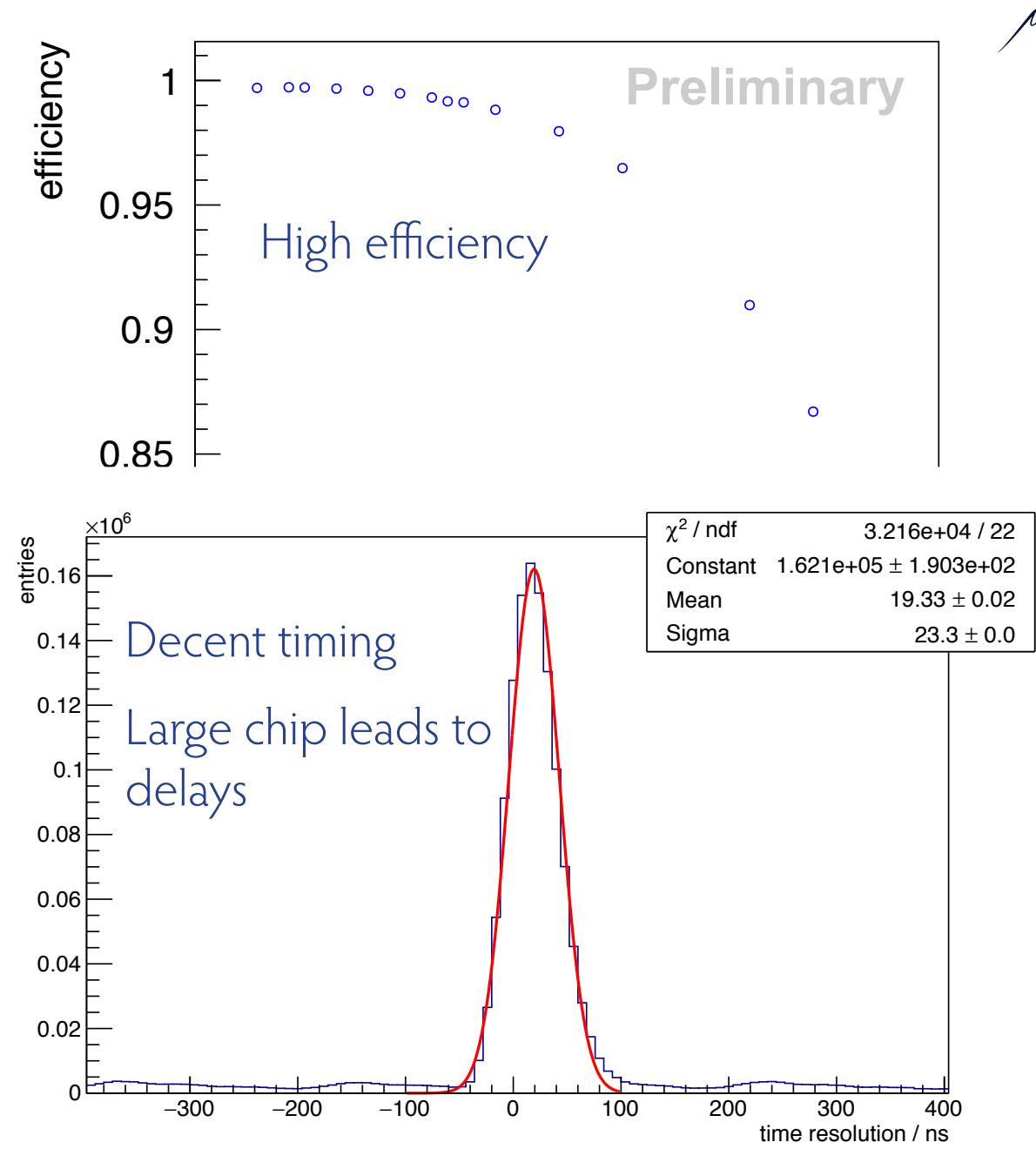
- Goal: Detection and signal processing with just $50 \mu\text{m}$ silicon
- 6th chip, MuPix7, is a **full system-on-a-chip**
- Well characterized, working very nicely
- Now: **Going "big"** $2 \times 1 \text{ cm}^2$ MuPix8 with $80 \times 80 \mu\text{m}$ pixels under test



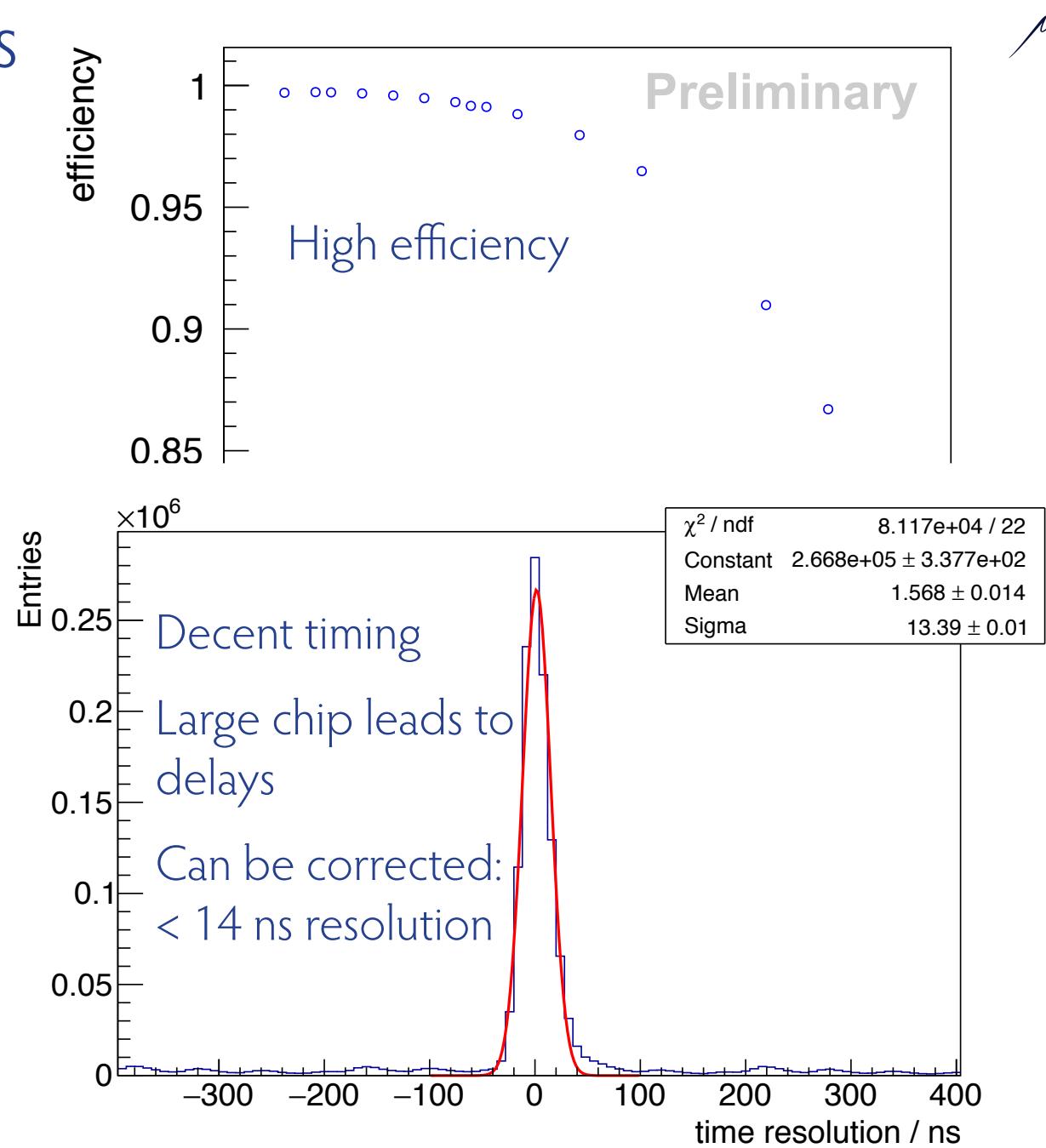
MuPix8: First results



MuPix8: First results



MuPix8: First results



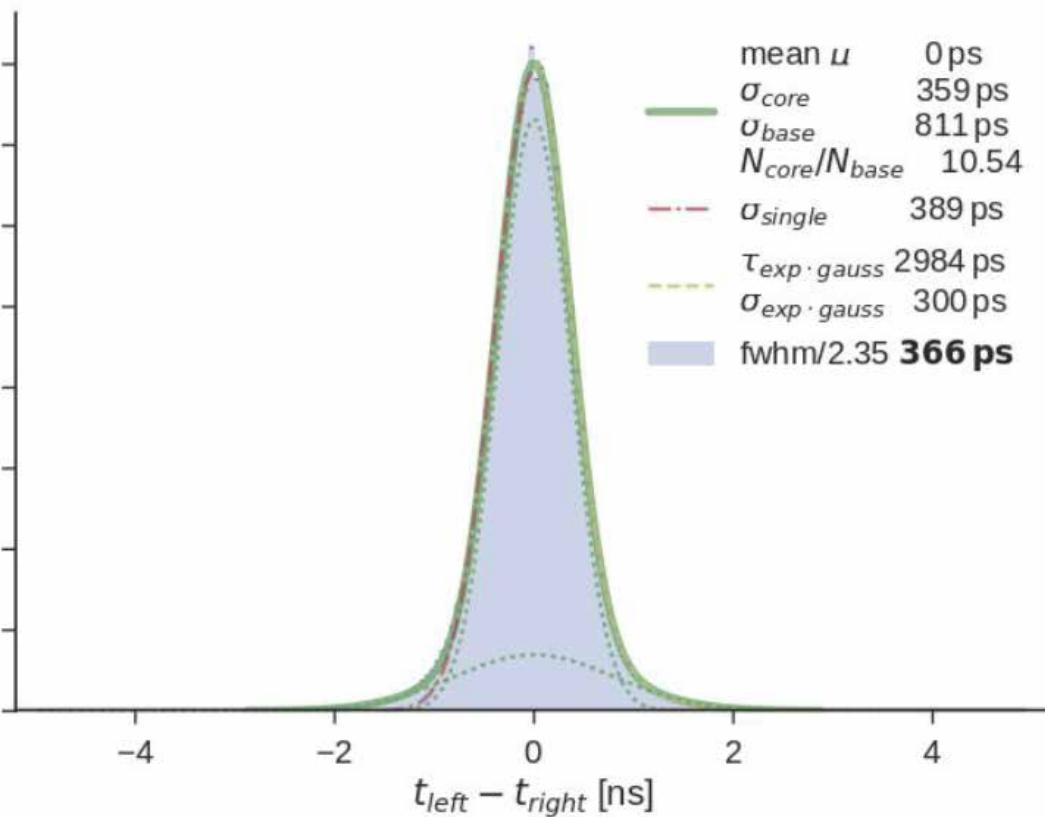
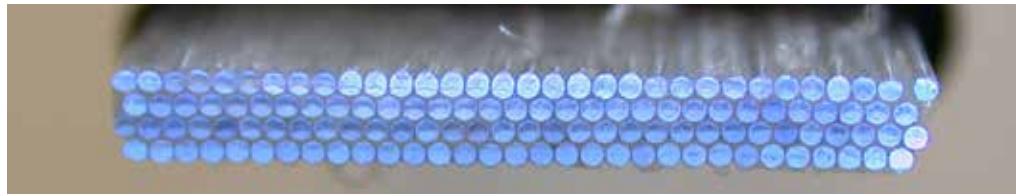


Better timing: Scintillating fibres and tiles

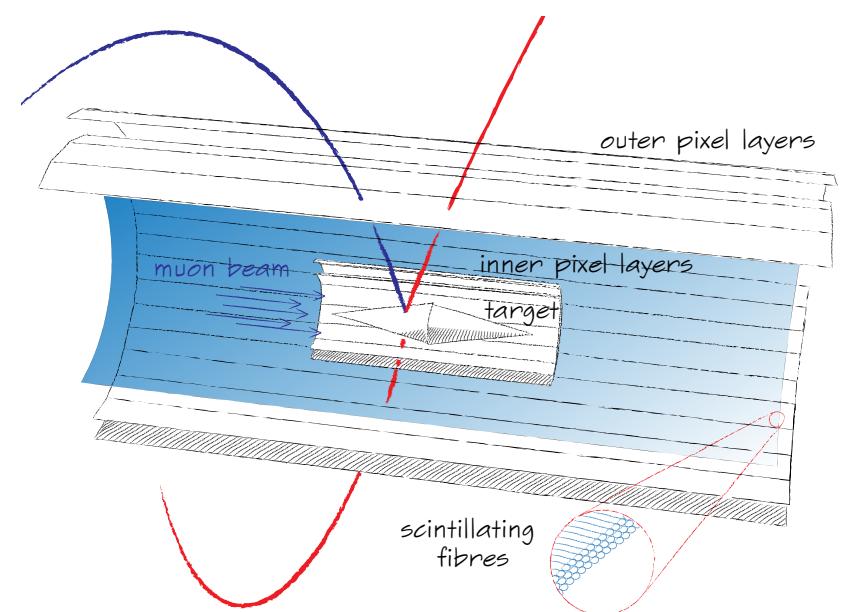
Timing Detector: Scintillating Fibres



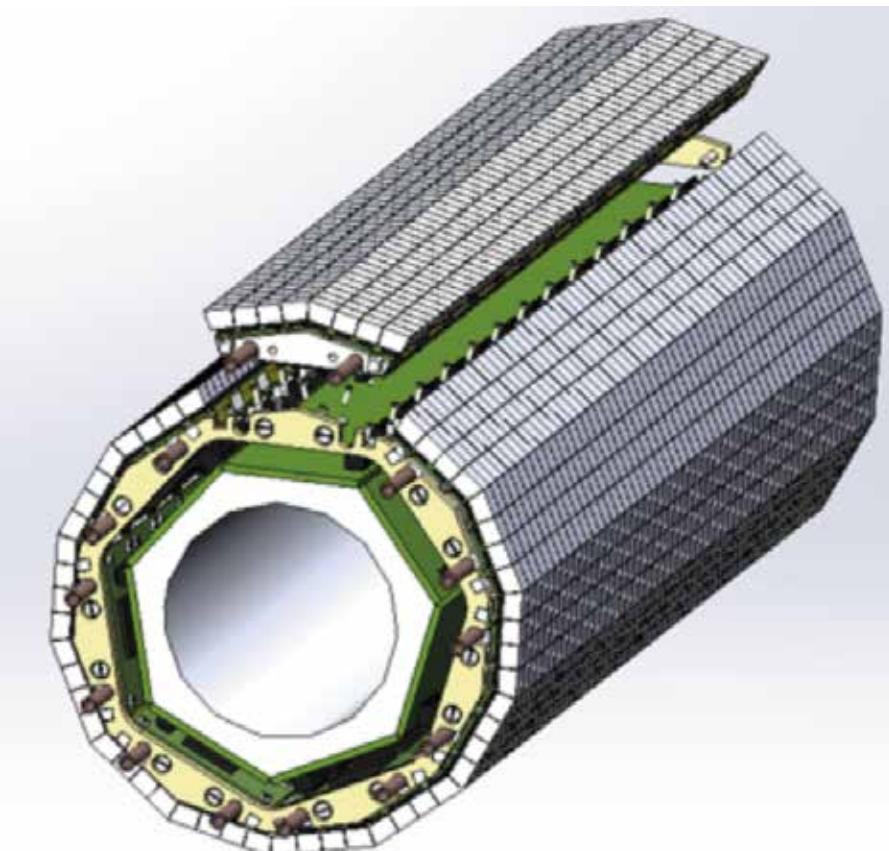
- 4 layers of $250\text{ }\mu\text{m}$ scintillating fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)



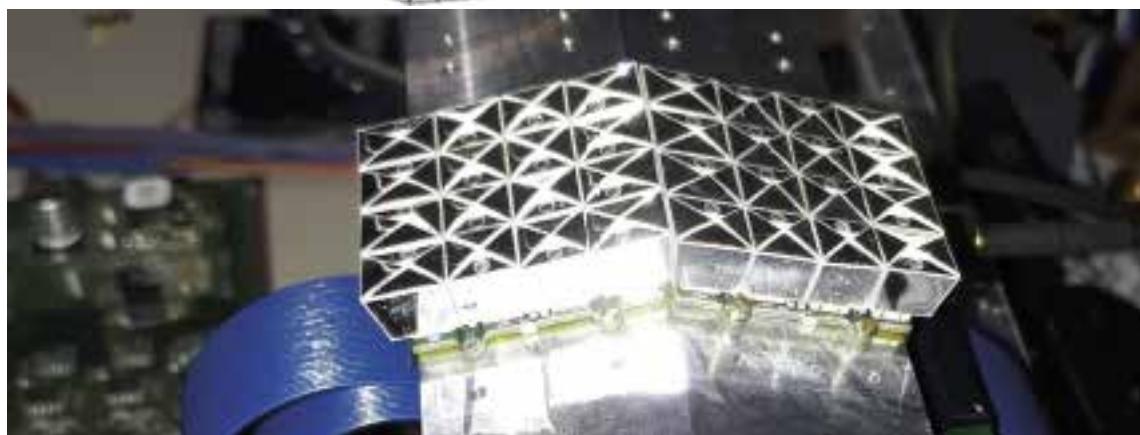
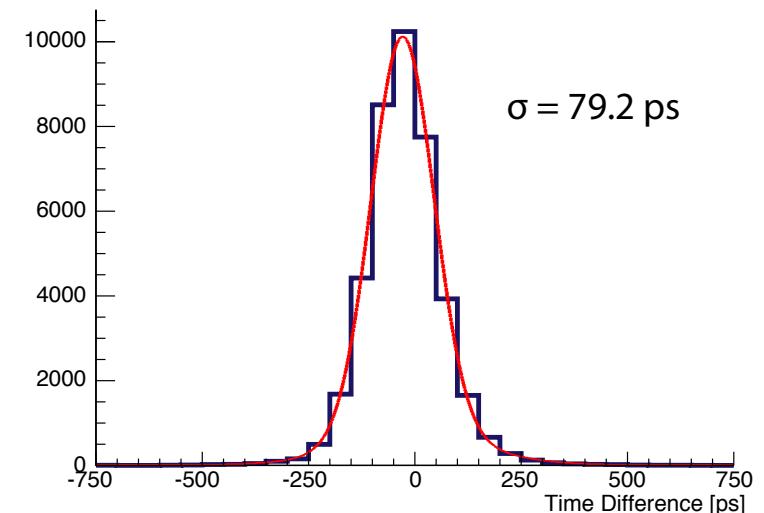
Timing resolution $< 400\text{ ps}$ including ASIC (using a Sr^{90} source)



Timing Detector: Scintillating tiles



- $\sim 0.5 \text{ cm}^3$ scintillating tiles
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)



- Test beam with tiles, SiPMs and readout ASIC
- Timing resolution better 80 ps

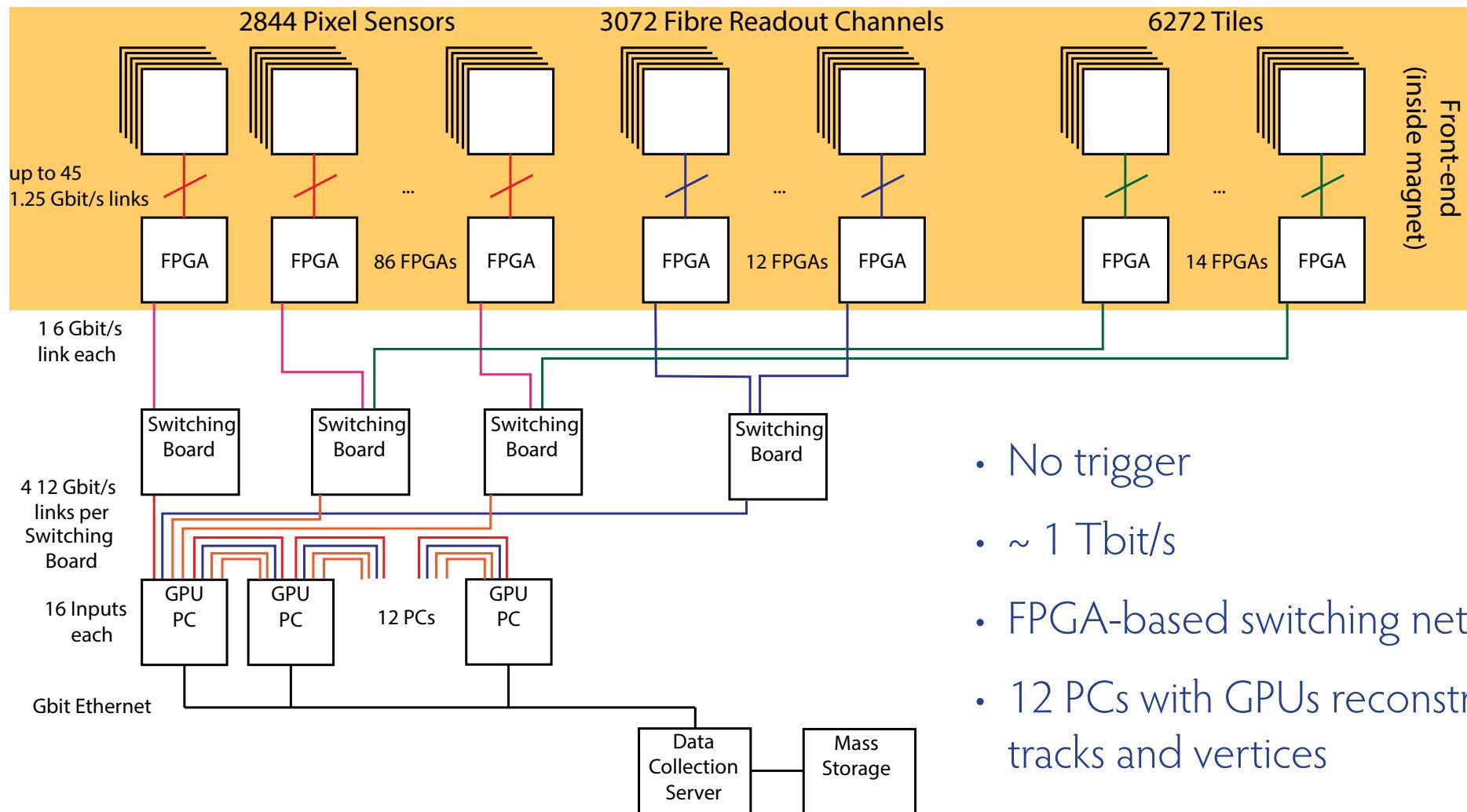


Phased experiment:

Phase I uses the existing PiE5 beam line at PSI,
shared with MEG II, 10^8 muons/s

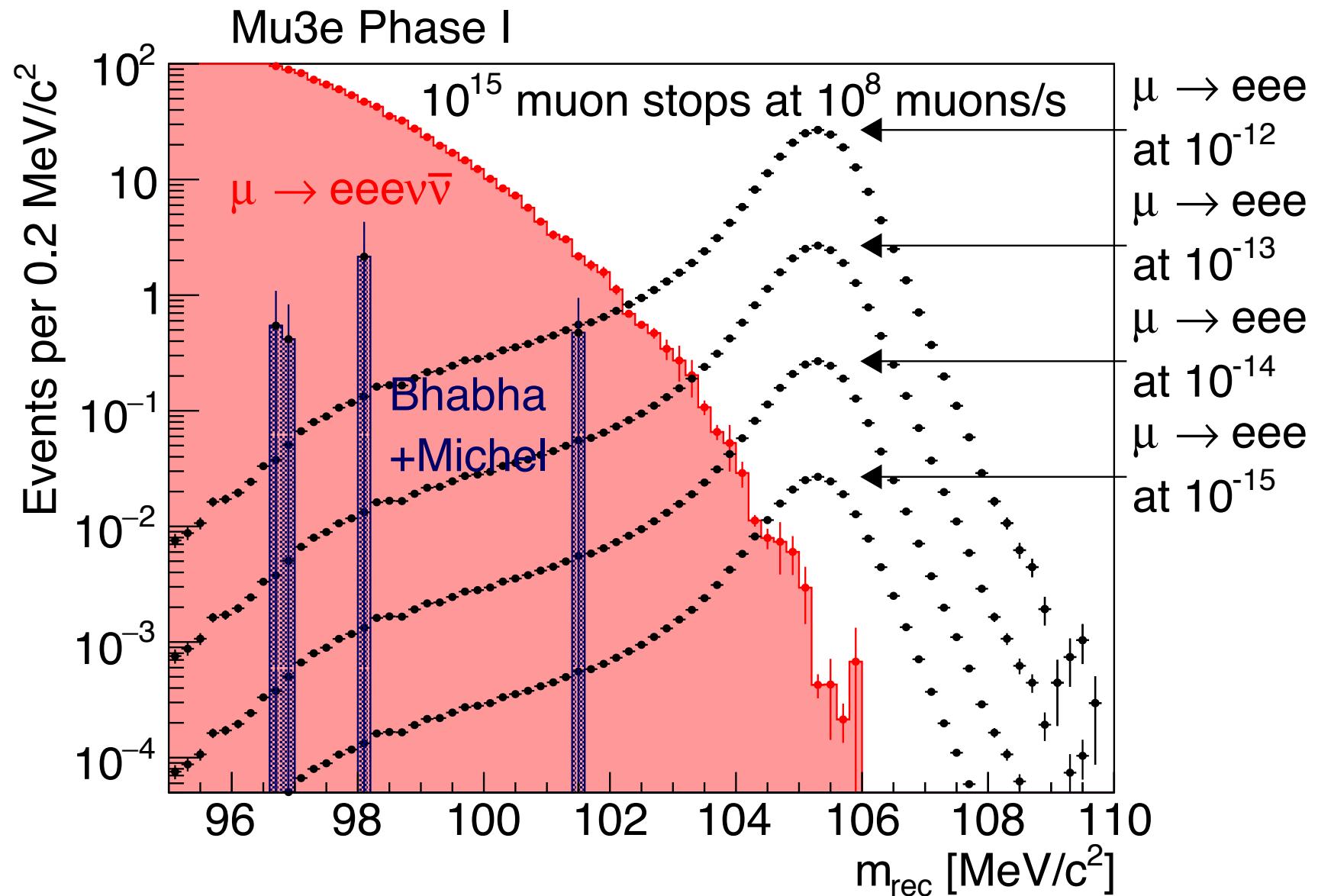
Phase II requires a High Intensity Muon Beamline
(HiMB, $> 2 \cdot 10^9$ muons/s)

Phase I Data Acquisition and Filter Farm

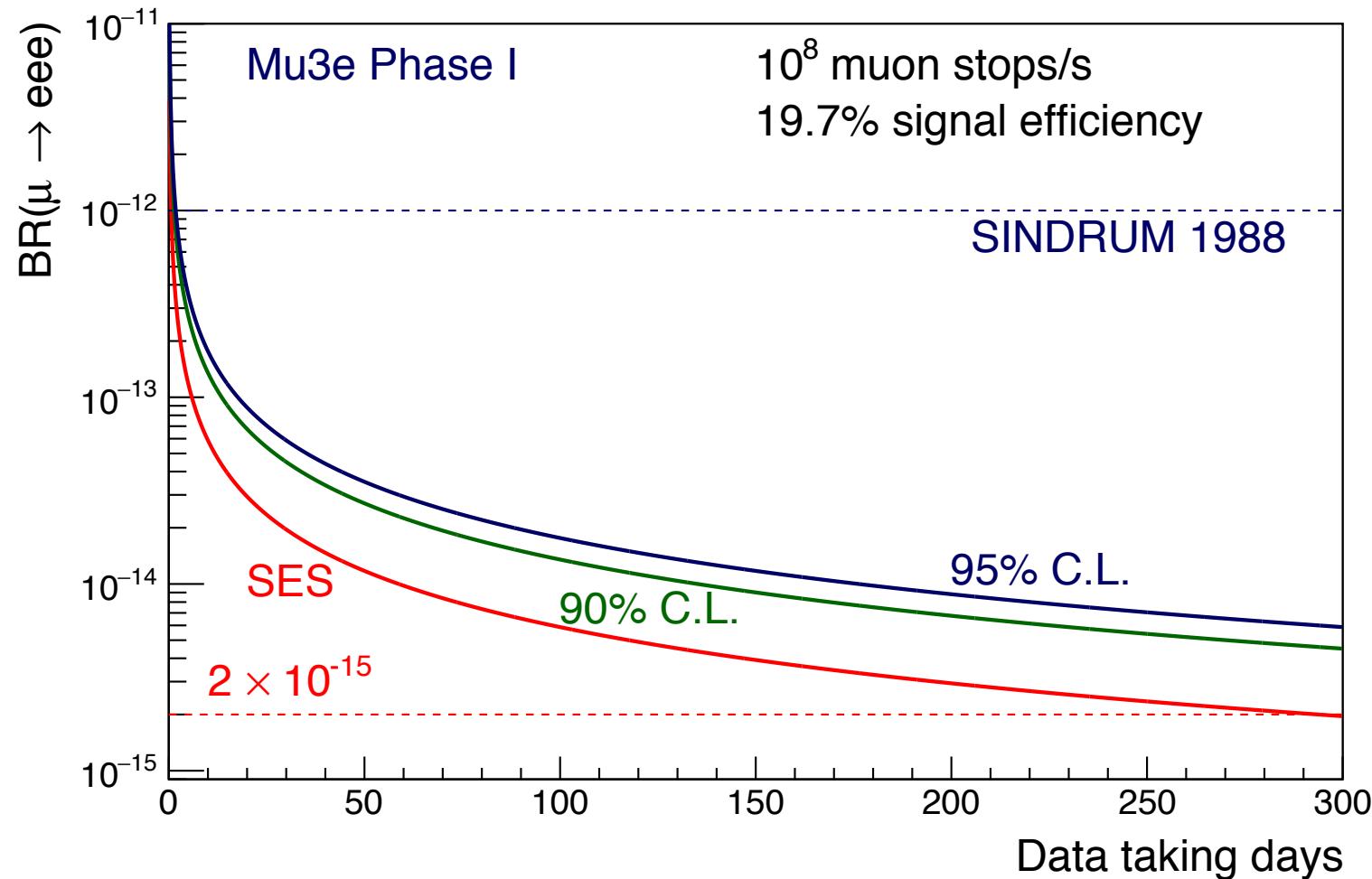


- No trigger
- $\sim 1 \text{ Tbit/s}$
- FPGA-based switching network
- 12 PCs with GPUs reconstruct tracks and vertices
- Only save things that look like $\mu^+ \rightarrow e^+e^-e^+$

Phase I Performance Simulation



Sensitivity - Mu3e Phase I



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



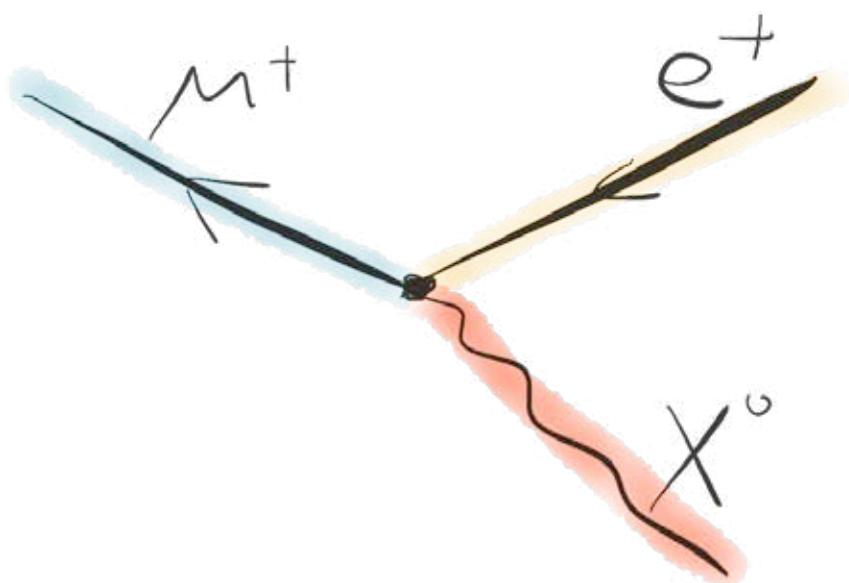
Beyond $\mu^+ \rightarrow e^+ e^- e^+$:

$\mu \rightarrow e X$

and

Dark Photons

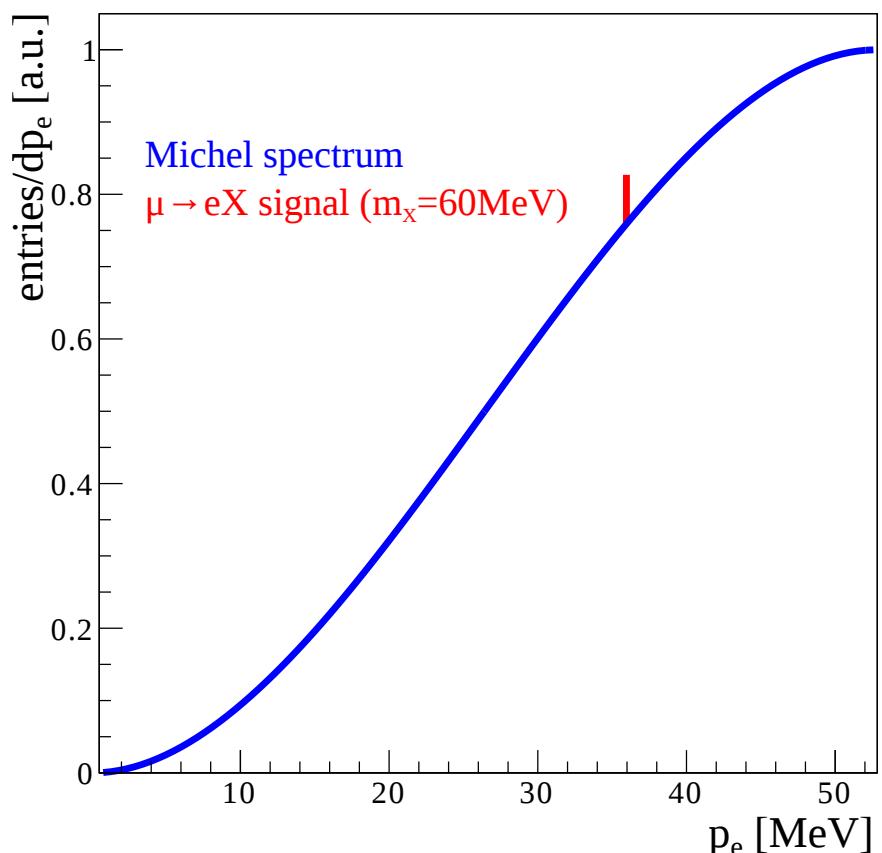
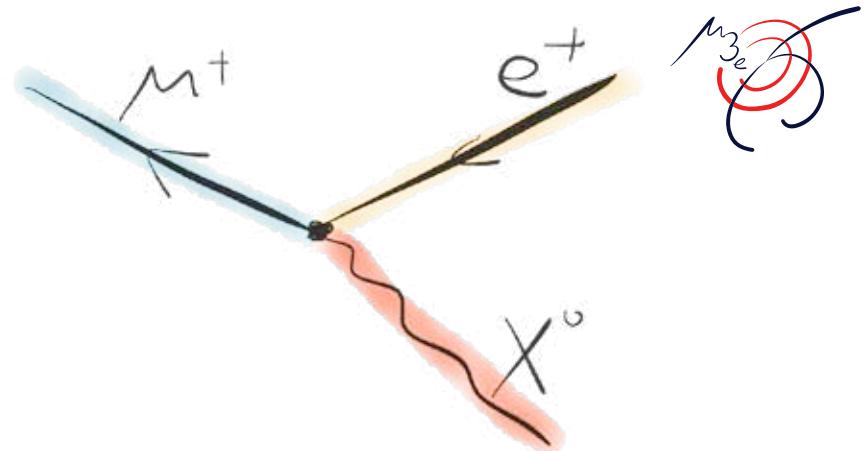
Familons in Mu3e



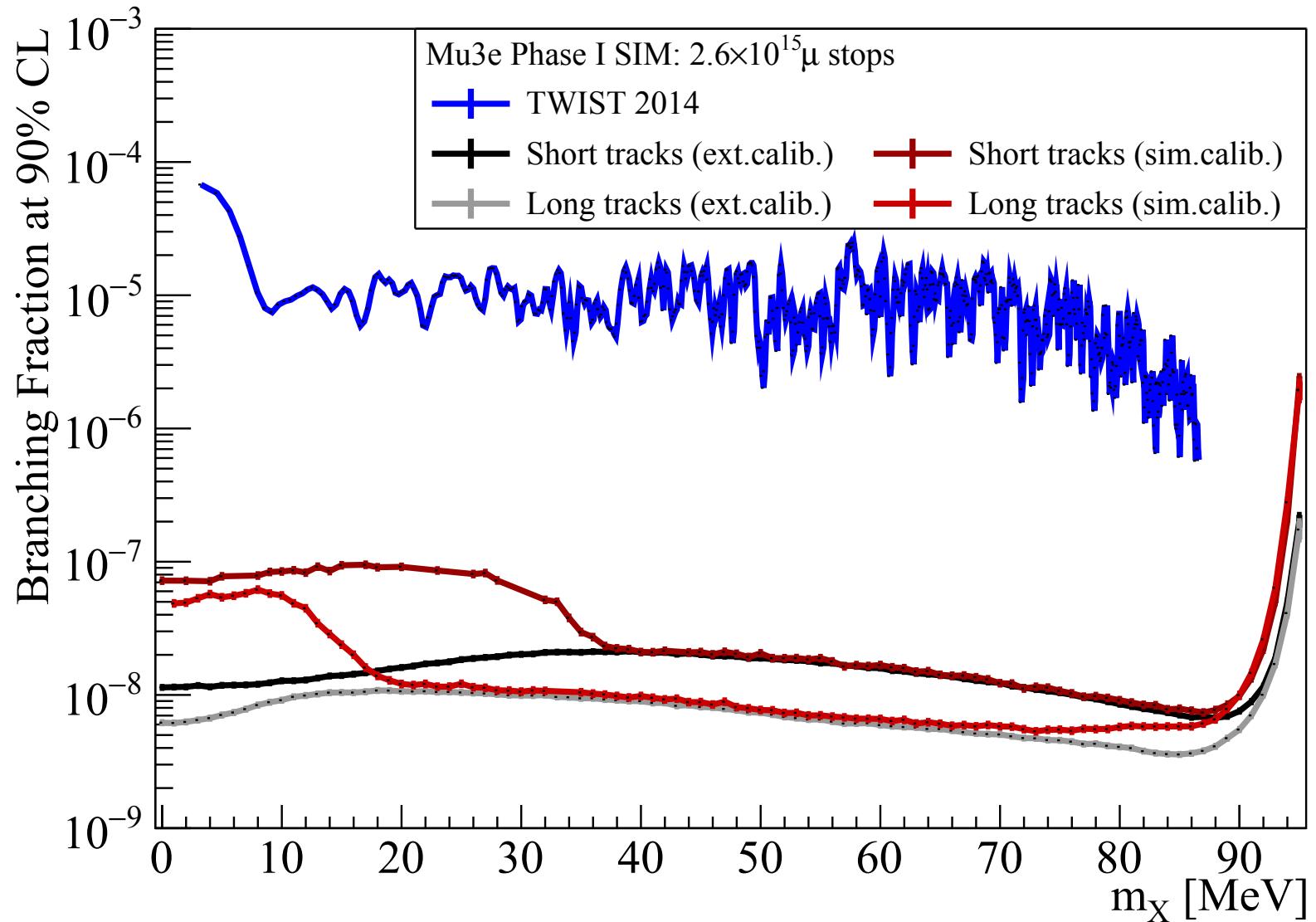
- Spontaneously broken flavour symmetry: Goldstone boson(s) called **familons**
- Can be a light dark matter candidate
- Lead to $\mu \rightarrow eX$, where X a familion
- $\mu \rightarrow eX$ can also show up in other models, search for it with the large muon decay data set at Mu3e

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 - needs to run online)



Results



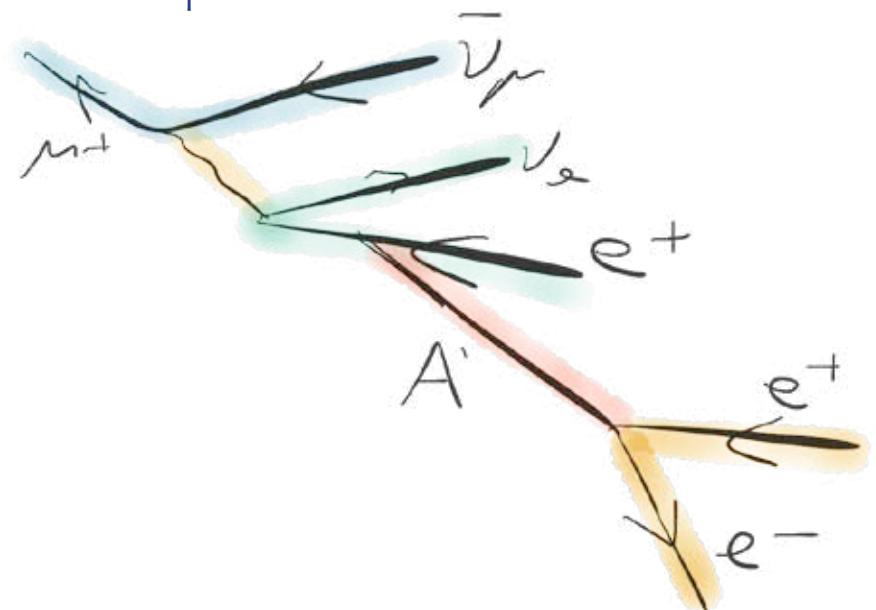
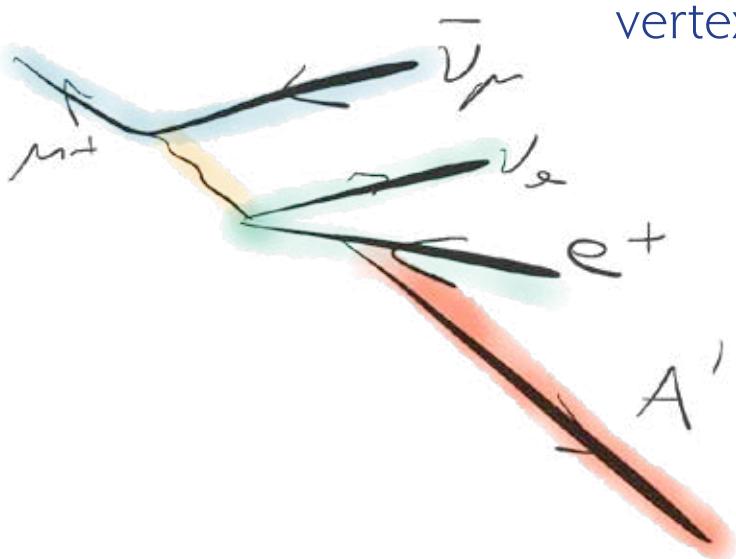
Dark Photons in Mu3e



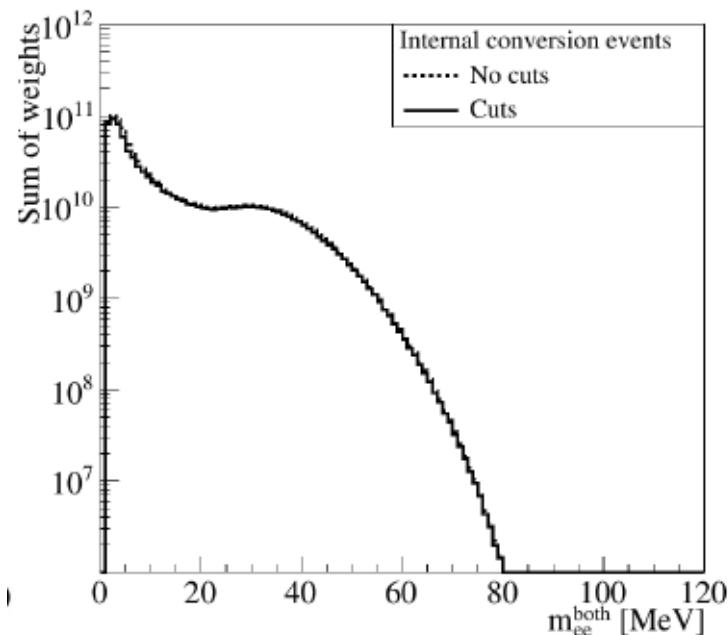
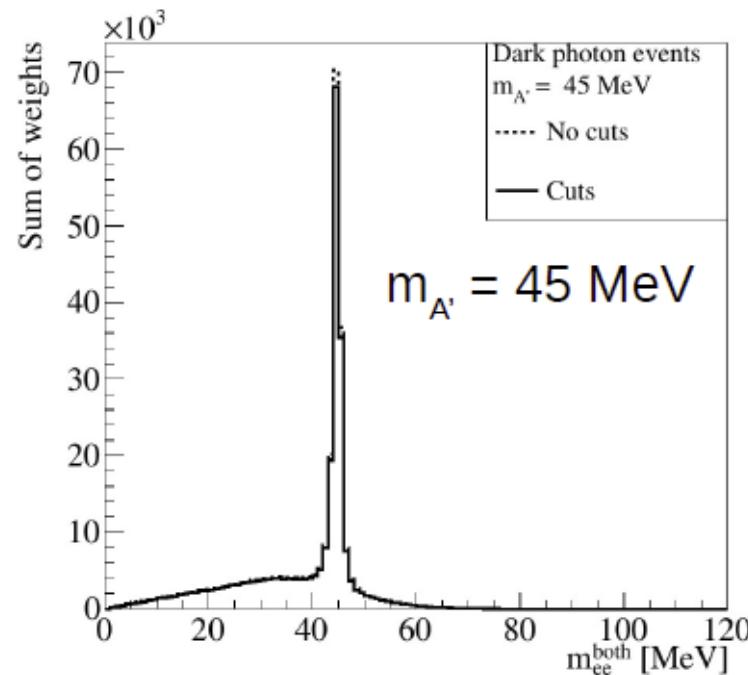
Dark photon can be radiated, wherever a photon can be radiated

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)



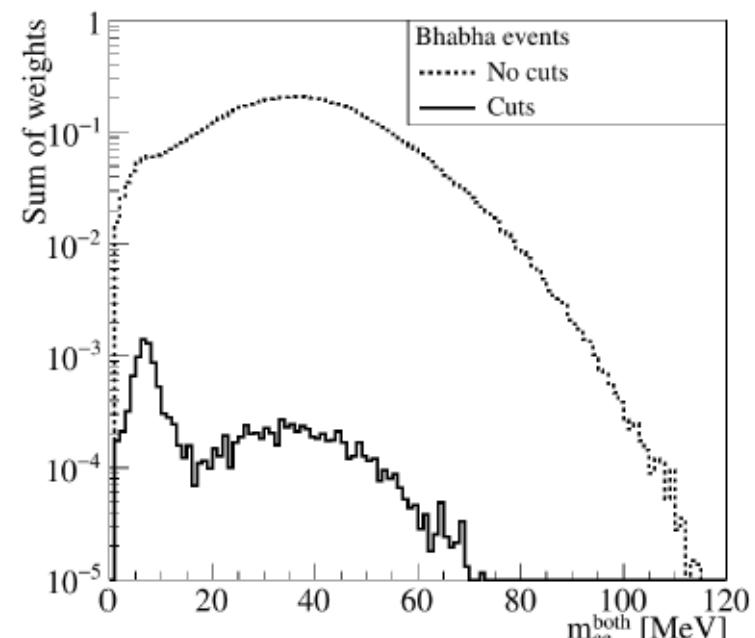
Dark Photons in e^+e^-



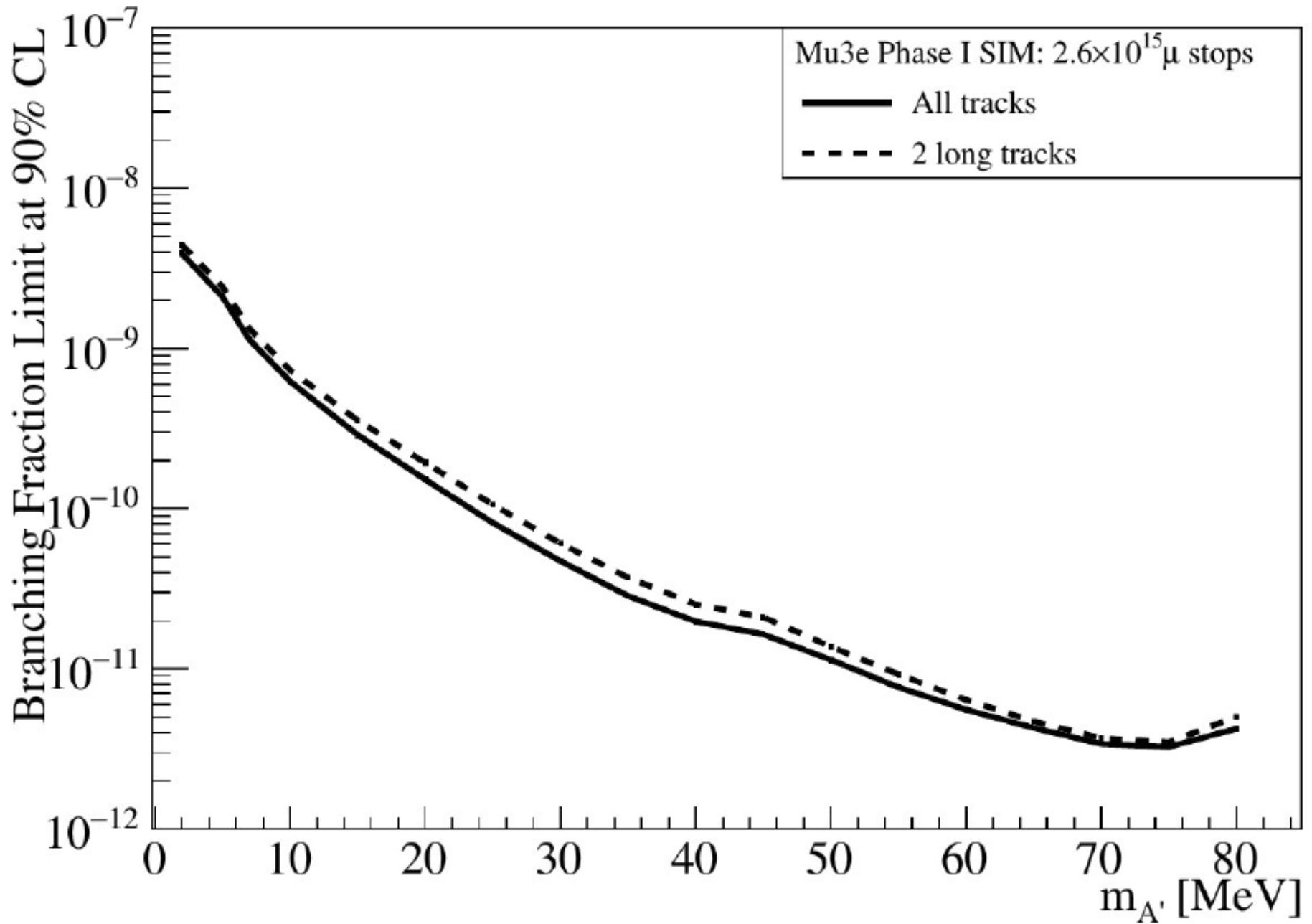
$\mu \rightarrow e\nu\bar{\nu}(A' \rightarrow ee)$ has the same visible final state as our signal: Will not be filtered away

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

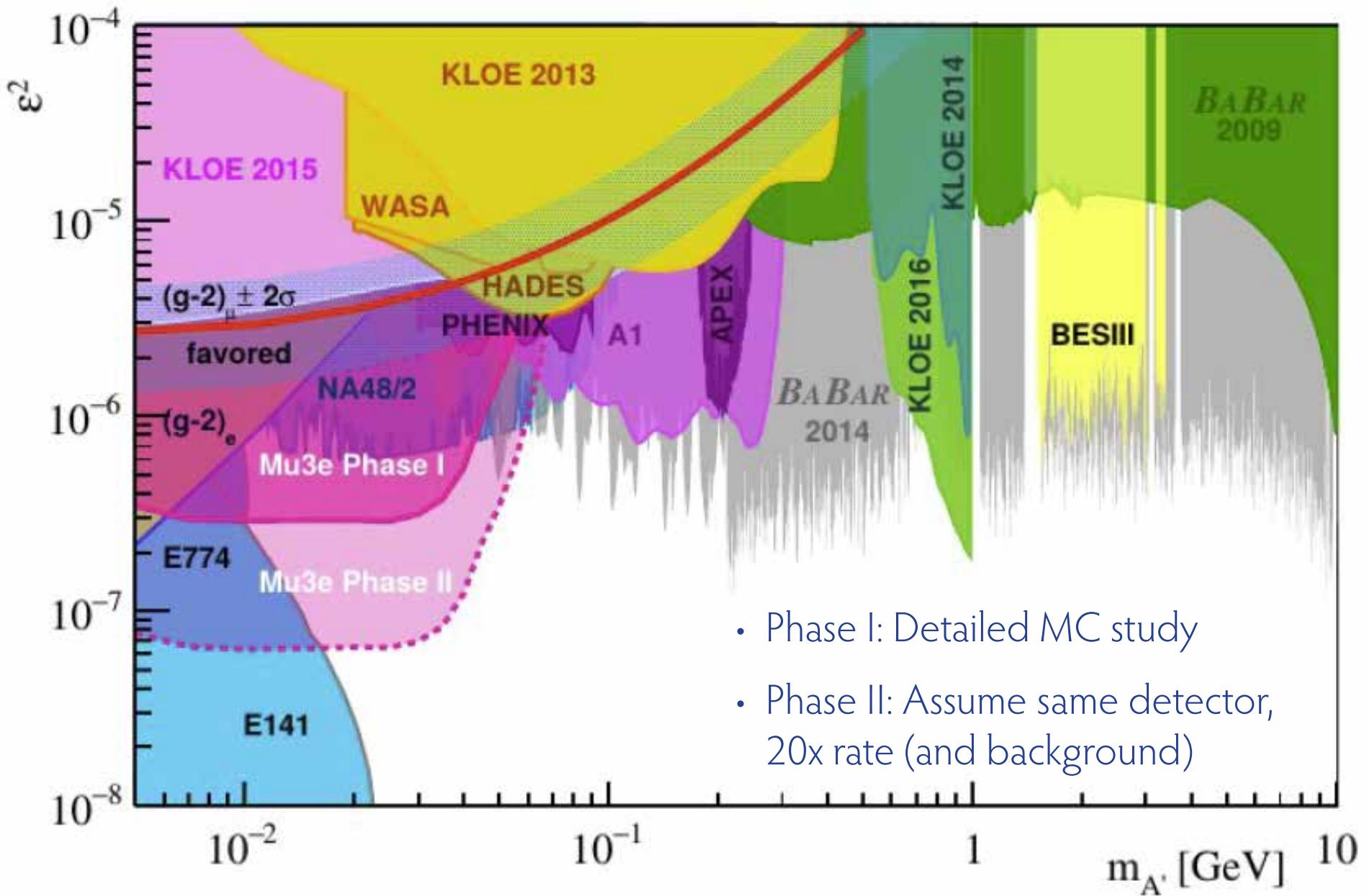
Two e^+e^- combinations



Branching Fraction Limits



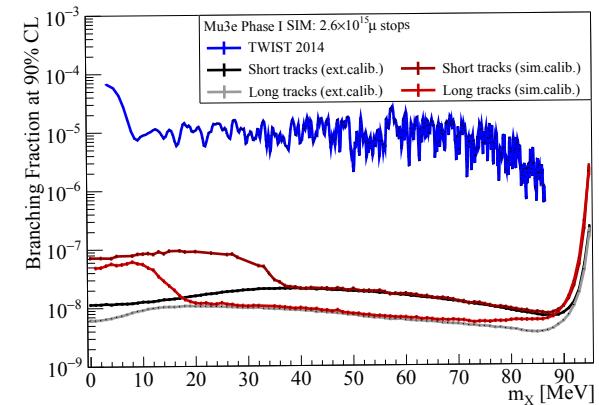
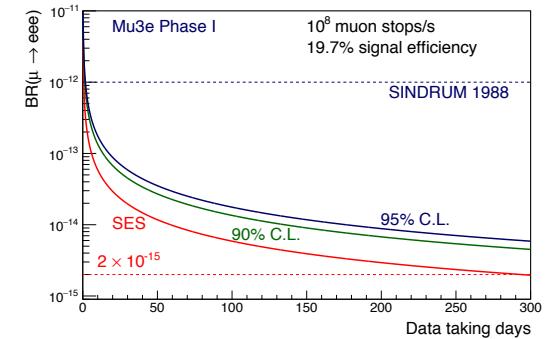
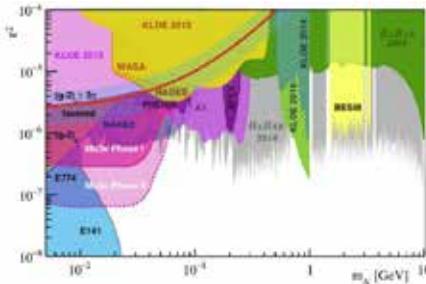
And on the $m_{A'}$ - ϵ plane



Summary



- Mu3e:
Search for $\mu \rightarrow \text{eee}$ with a sensitivity of 10^{-16} ($2 \cdot 10^{-15}$ in phase I)
- Detector:
Ultra-thin pixels, excellent timing
- Mu3e very competitive for $\mu \rightarrow \text{eX}$ searches
- Can access currently uncovered dark photon parameters





Backup Material

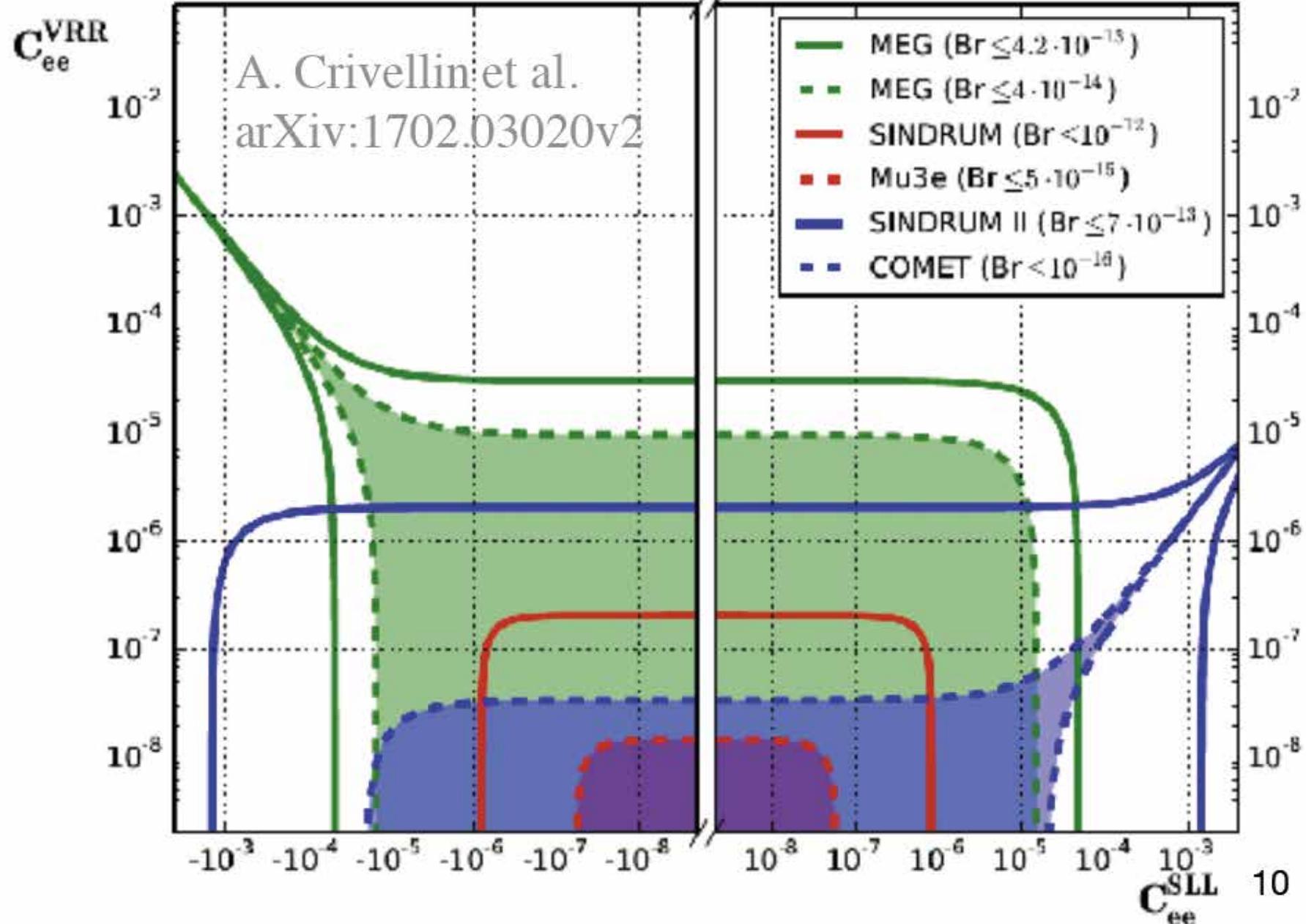




If we find something...



$\mu = m_W$

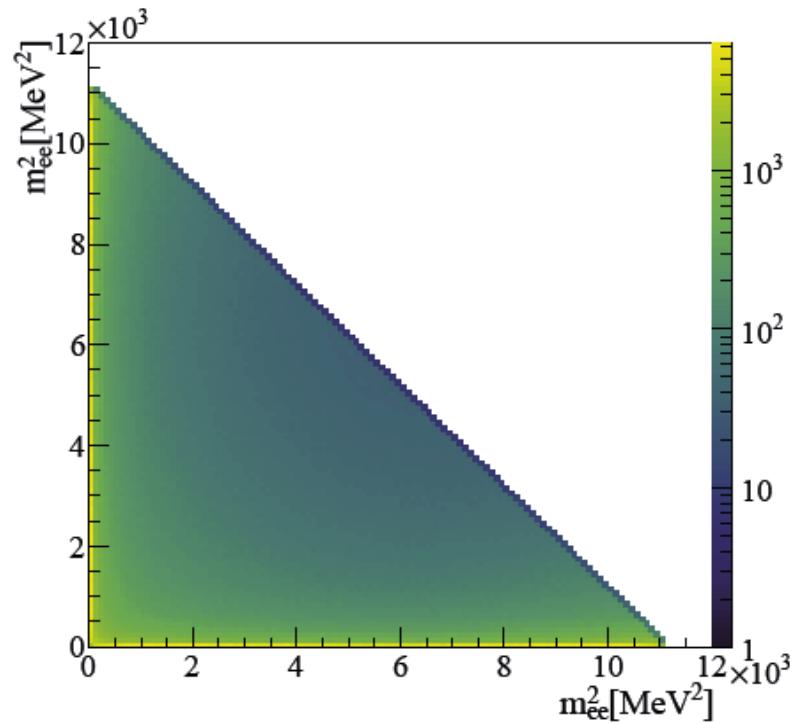
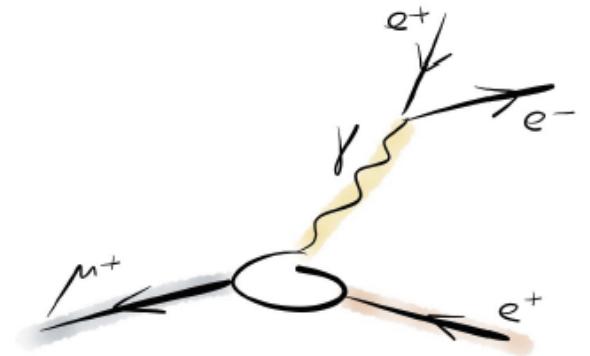


Decay distributions!

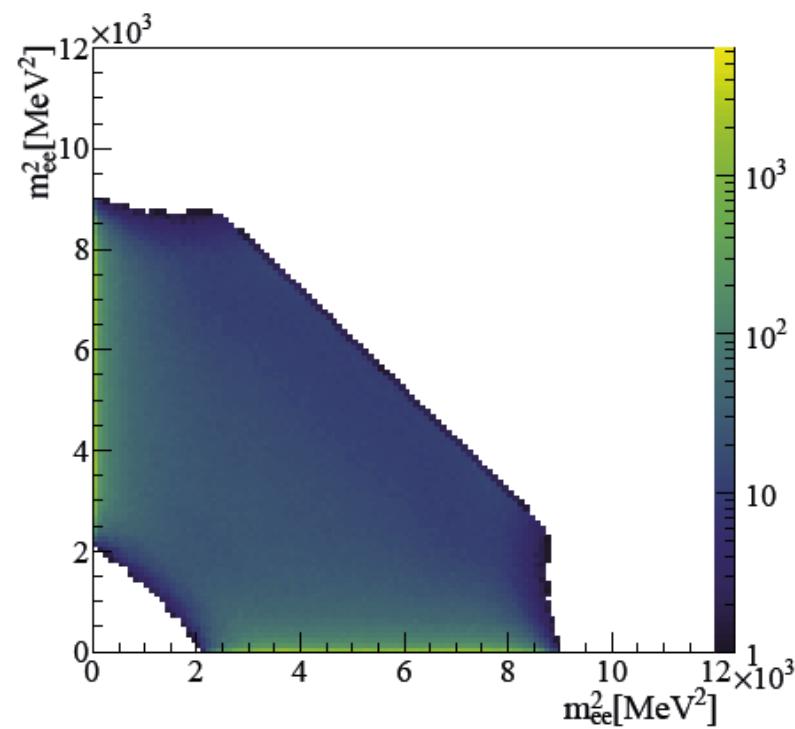


Dipole operator $em_\mu A_L \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu}$

Efficiency is 13 %



Generated distribution



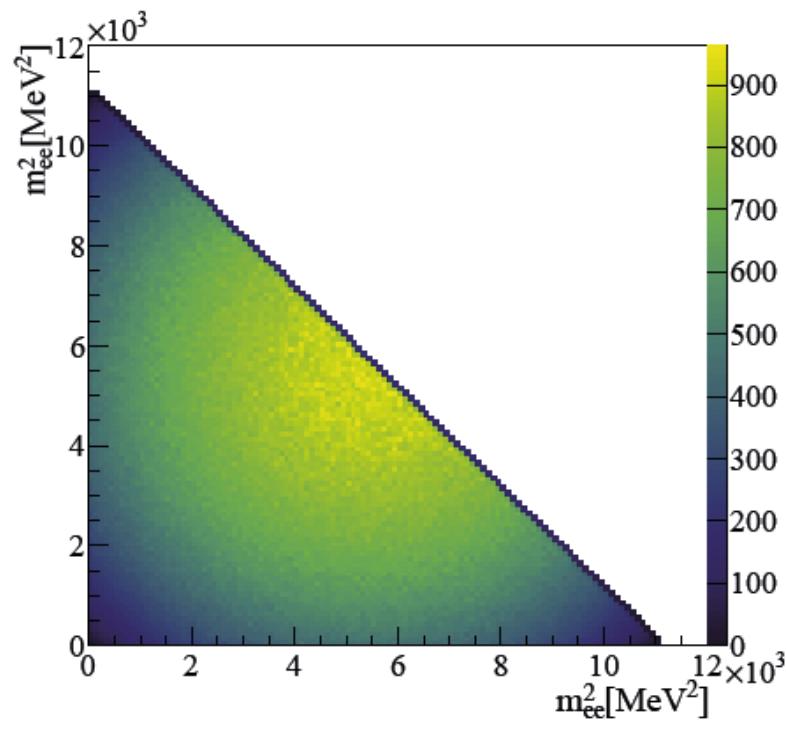
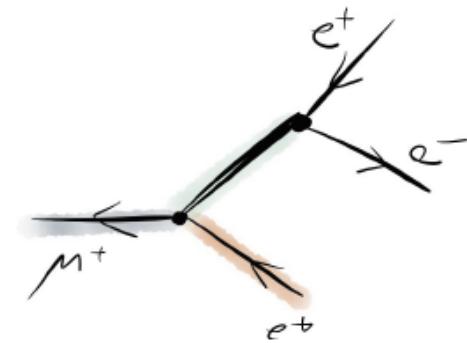
After reconstruction and vertex fit

Decay distributions!

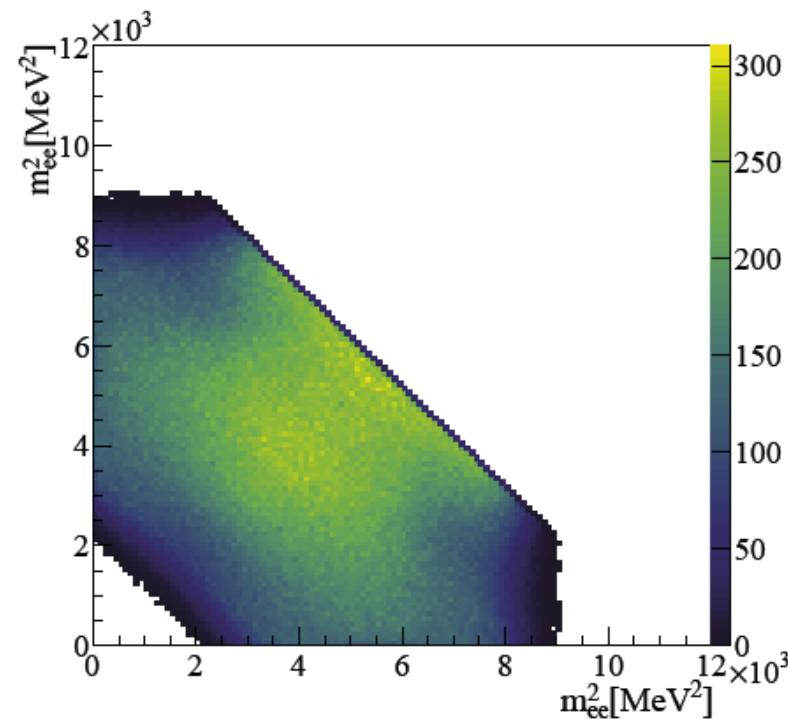


Vector 4-fermion operator $(\bar{\mu}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R)$

Efficiency is 22 %



Generated distribution

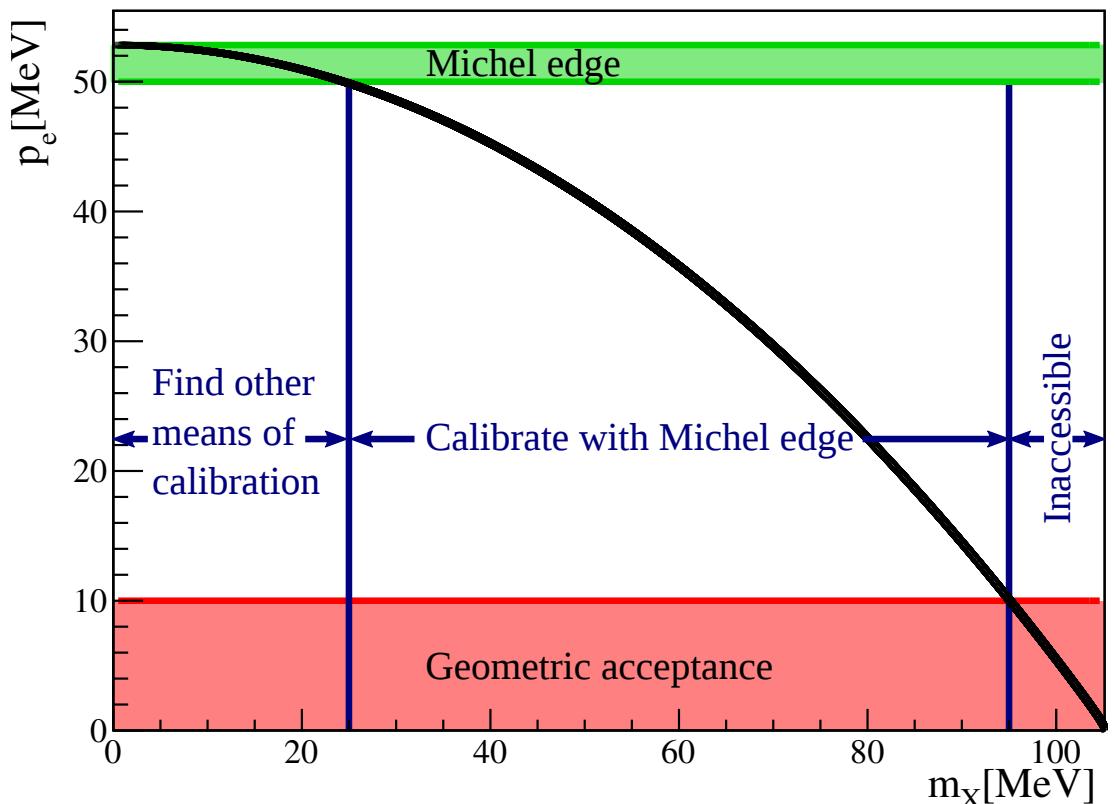


After reconstruction and vertex fit

$\mu \rightarrow eX$: Kinematic reach

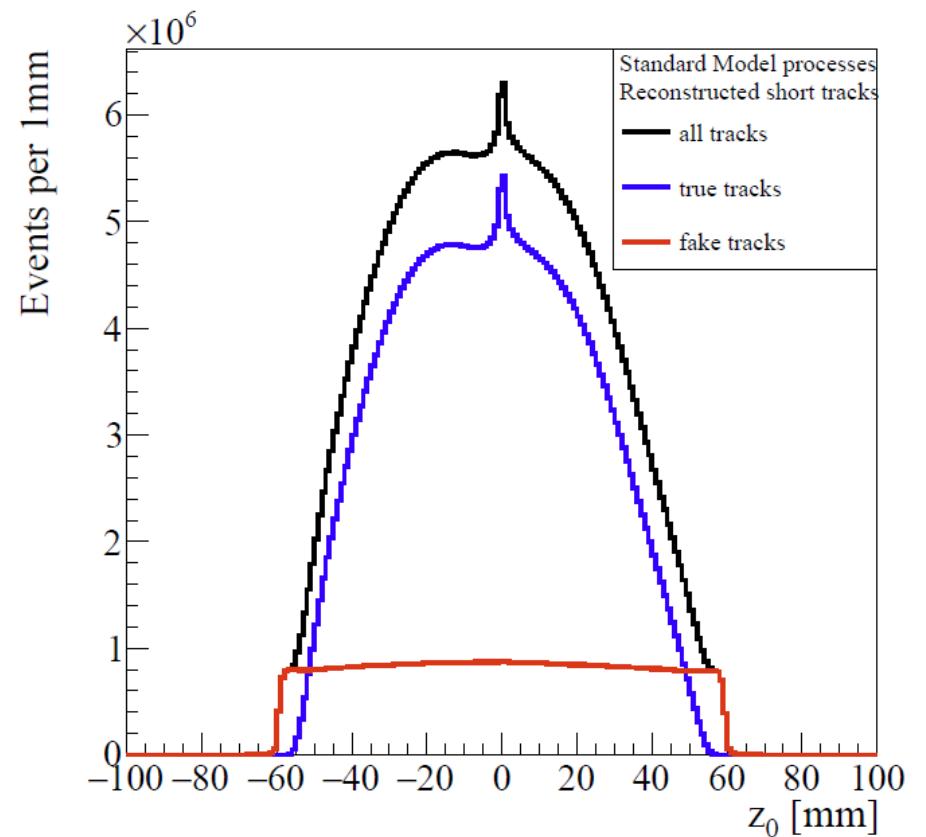
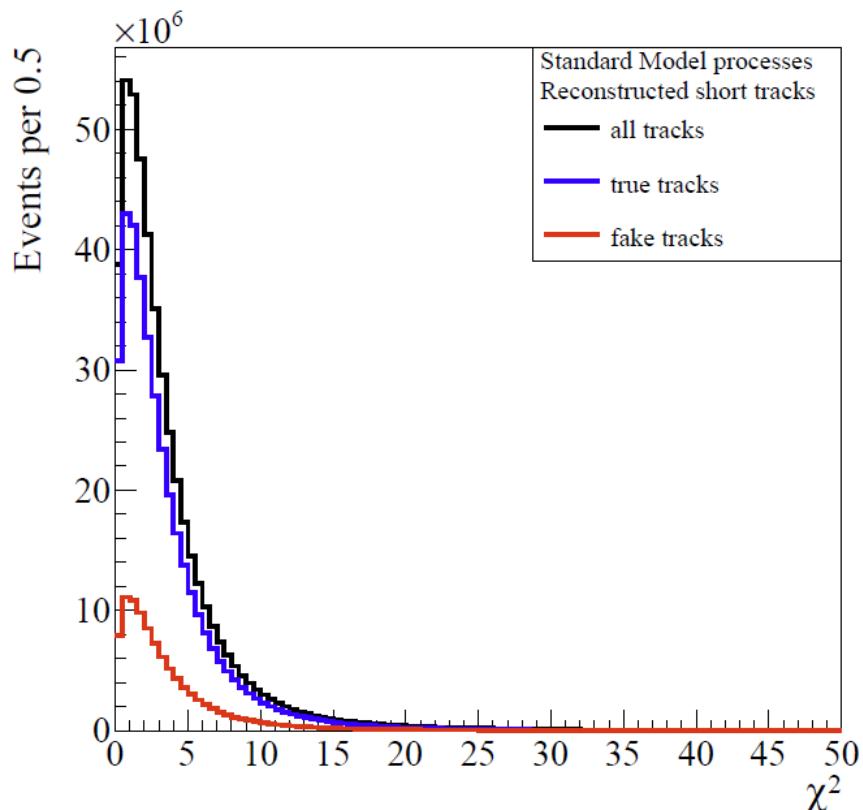


- $0 < m_X < m_\mu - m_e$
- Very large m_X : positron does not have enough momentum to be seen
- Very low m_X : "peak" sits on top of Michel edge, more a shift - have to be very careful not to calibrate it away
- m_X of 25 to 95 MeV "easy"



$\mu \rightarrow eX$: Data selection

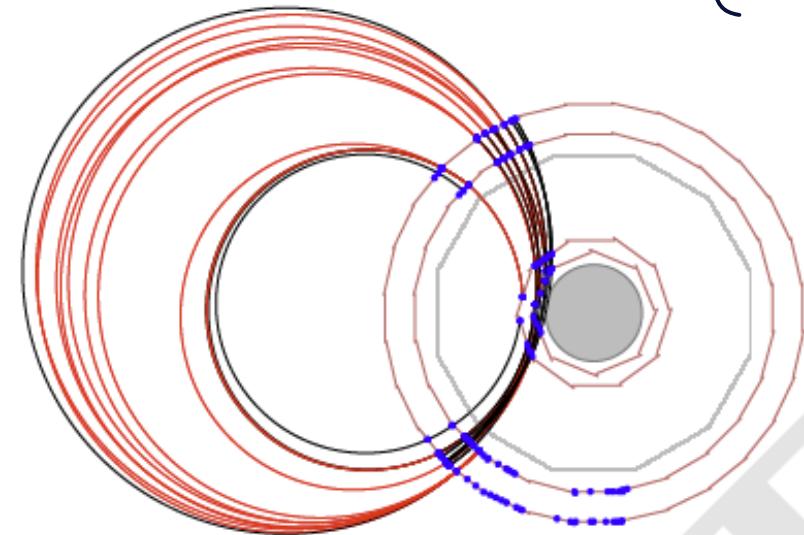
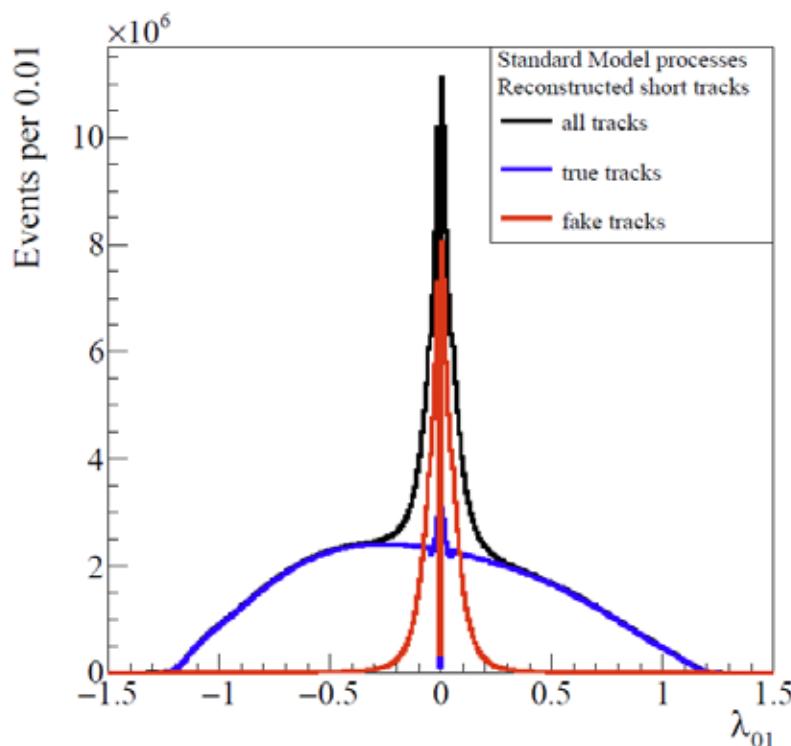
- Single tracks: Few handles for selection
- Intersection with cylinder around target z_0
- Track χ^2



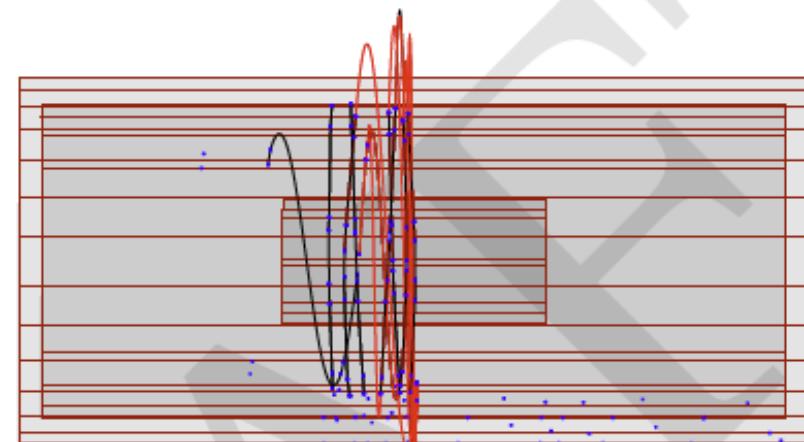
$\mu \rightarrow eX$: Data selection



- Single tracks: Few handles for selection
- Intersection with cylinder around target z_0
- Track χ^2
- And track inclination λ



(a) Transverse view.



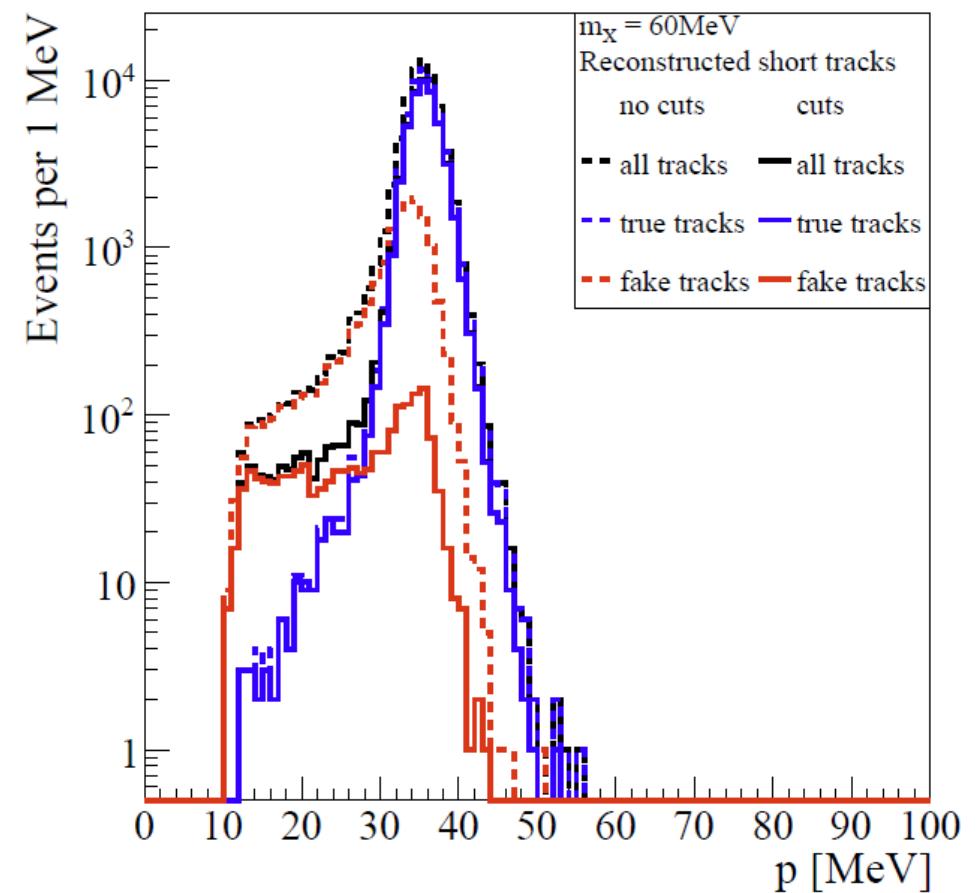
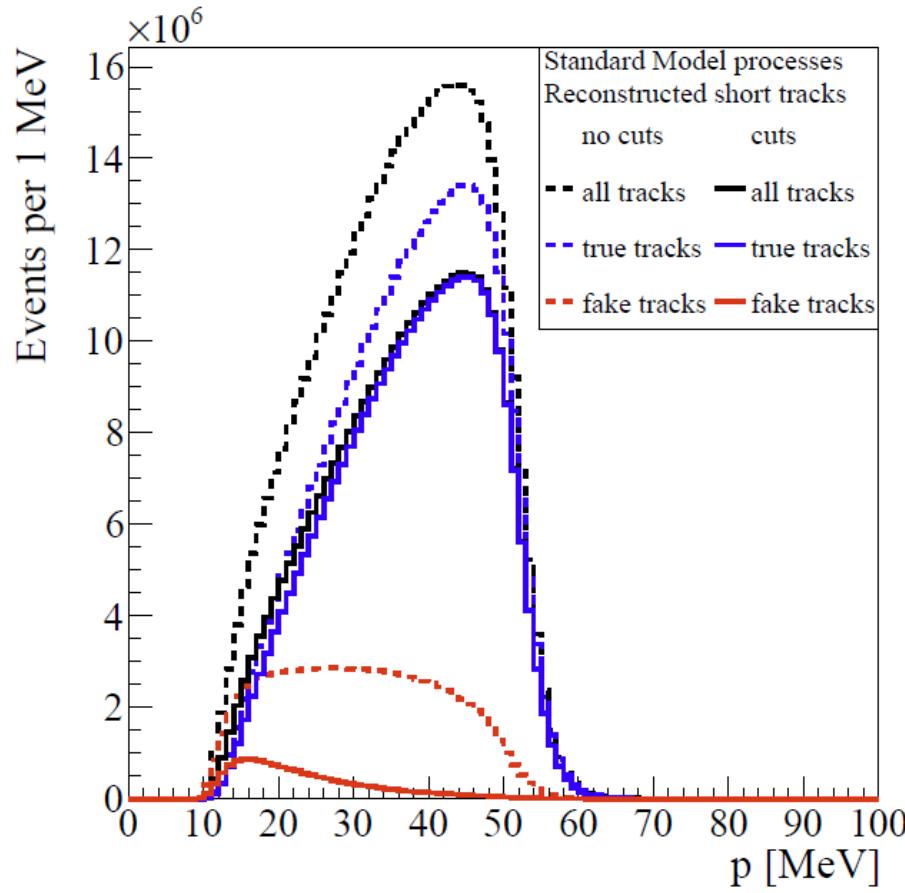
(b) Longitudinal view.

$\mu \rightarrow eX$: Track selection

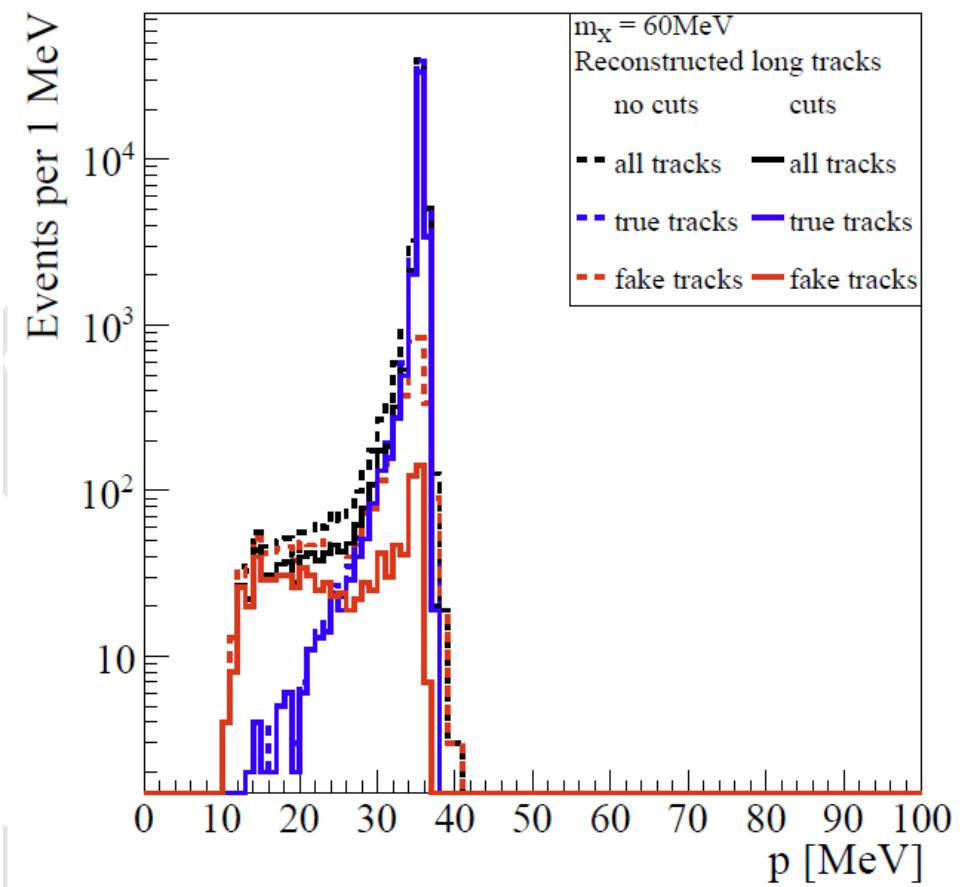
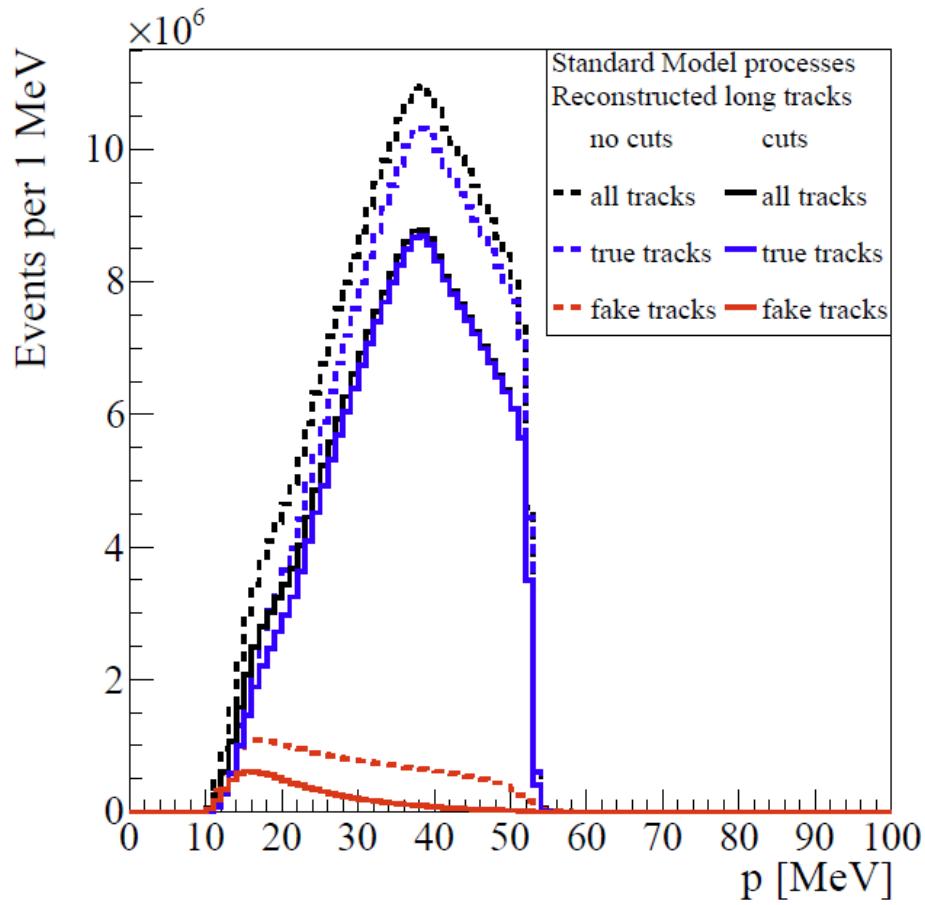


- $|z_0| < 50 \text{ mm}$
- $\chi^2 < 15$ (< 30 for long tracks)
- $|\lambda| > 0.1 \text{ rad}$
- About 85% efficient (relative to all tracks)
- Purity goes from 79% to 96%

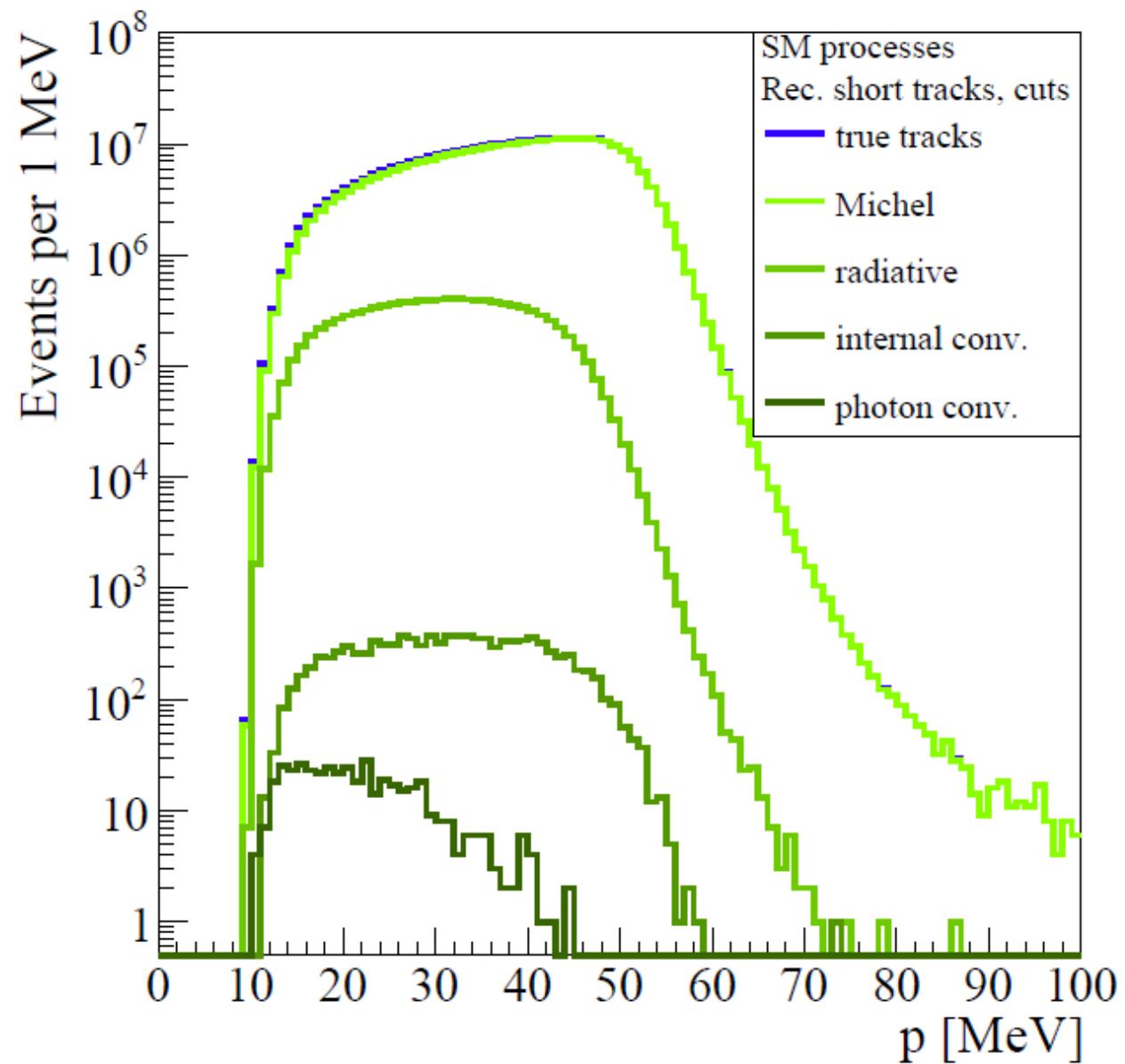
$\mu \rightarrow eX$: Spectra: Short Tracks



$\mu \rightarrow eX$: Spectra: Long Tracks



$\mu \rightarrow eX$: Background contributions



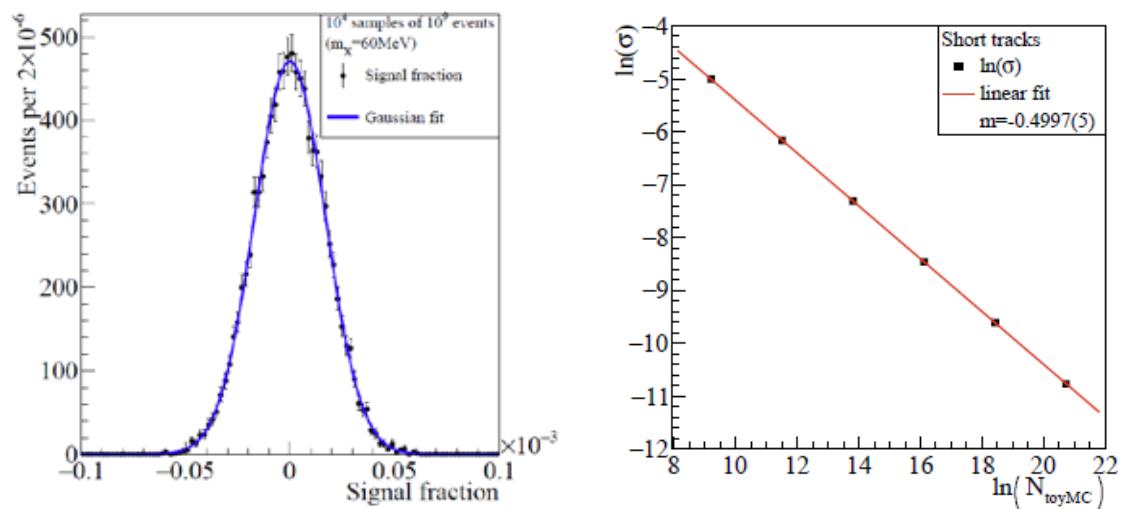
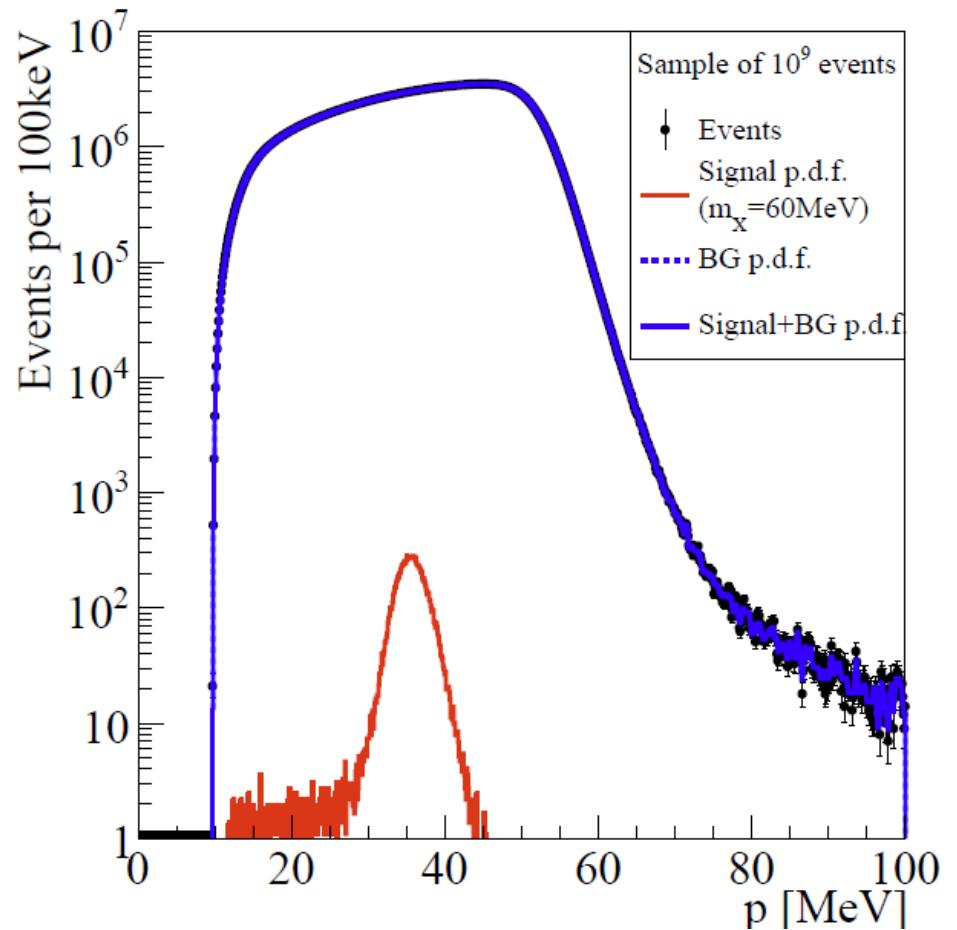
$\mu \rightarrow eX$: Absolute momentum scale



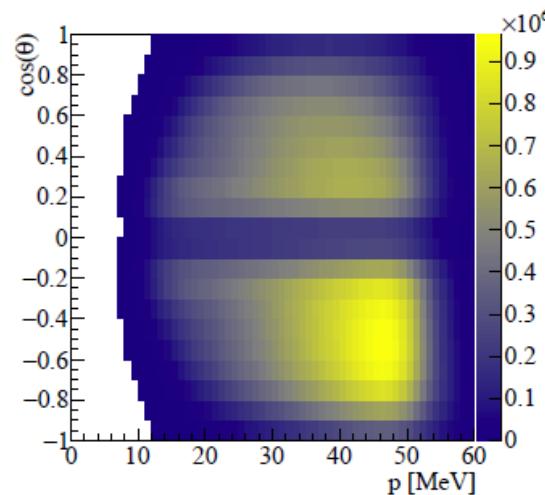
- Absolute momentum scale best known from Michel edge (muon mass)
- If Familon peak sits on edge, this is wrong
- Repeat procedure with momentum scale as a free parameter, exclude region around familon peak from scale fit
- Slightly worse sensitivity around edge

$\mu \rightarrow eX$: Toy MC studies

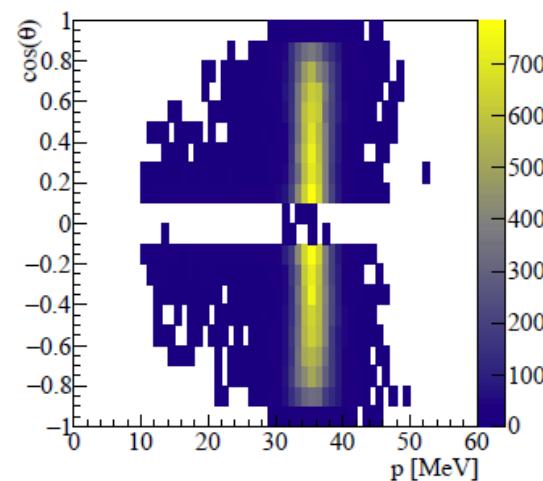
- Signal and BG PDF from simulation
- Generate a toy sample from the BG PDF only
- Fit with signal plus BG, signal fraction as a free parameter
- Repeat
- Width of signal fraction distribution gives sensitivity



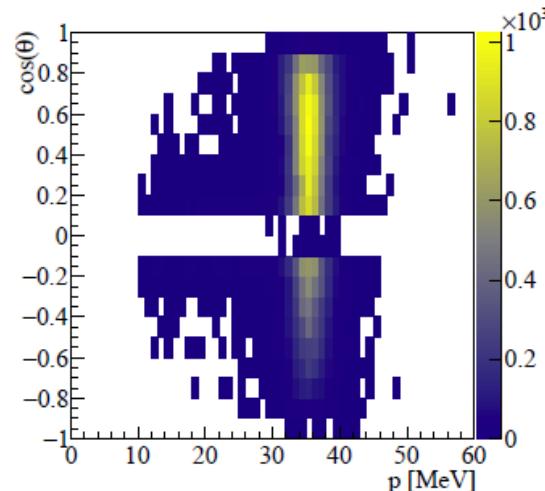
$\mu \rightarrow eX$ in 2D



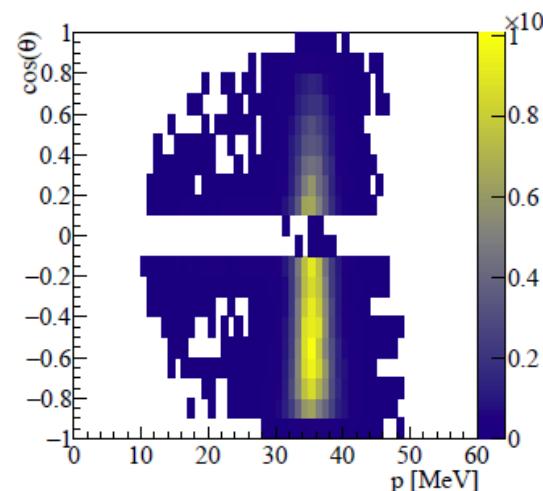
(a) SM processes.



(b) $\mu \rightarrow eX$ signal events with $m_X = 60\text{ MeV}$ and $h = 0$.



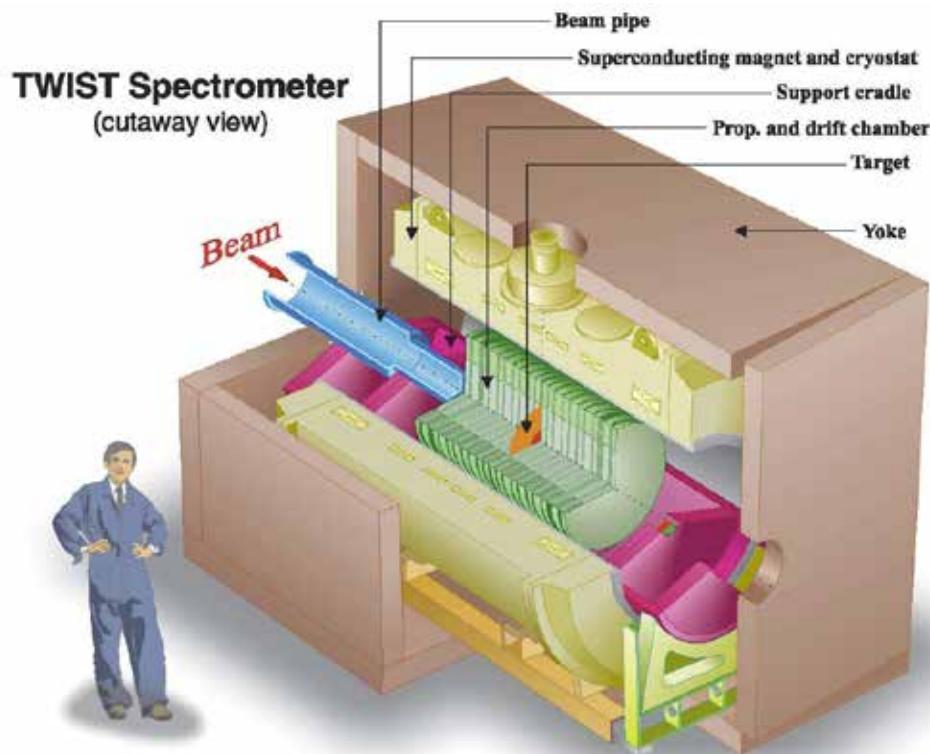
(c) $\mu \rightarrow eX$ signal events with $m_X = 60\text{ MeV}$ and $h = +1$.



(d) $\mu \rightarrow eX$ signal events with $m_X = 60\text{ MeV}$ and $h = -1$.

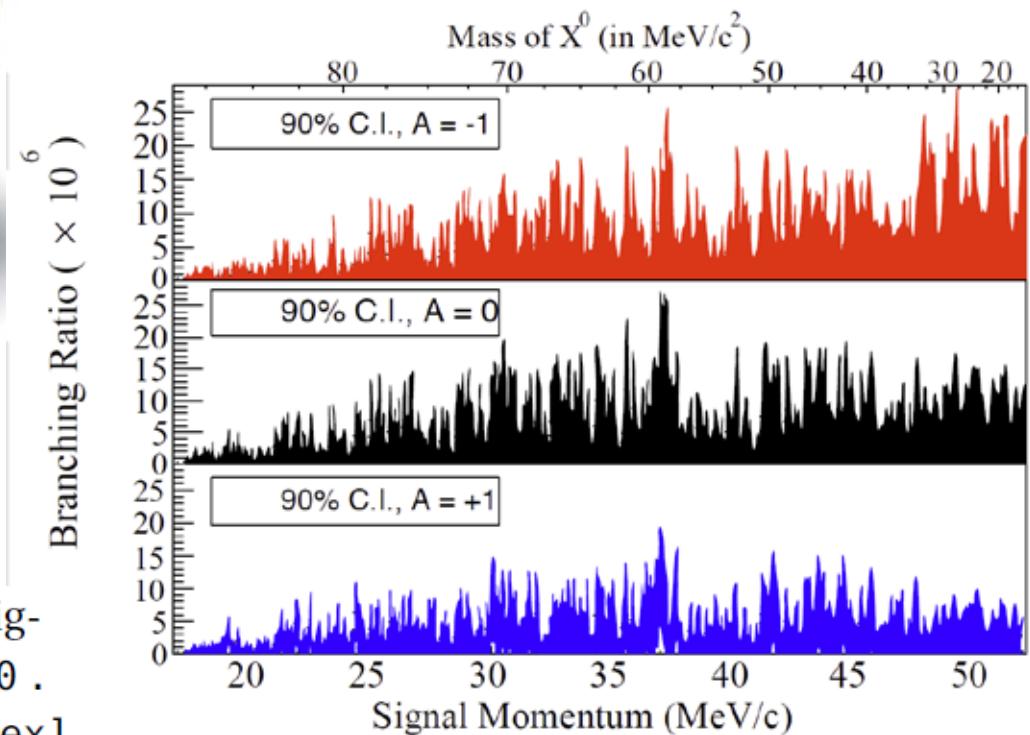
- Our muons are strongly polarized
- Familions are scalars
- (but we can also test for chiral couplings)
- Use 2D histograms in p and $\cos(\theta)$

$\mu \rightarrow eX$: Previous experiment: TWIST

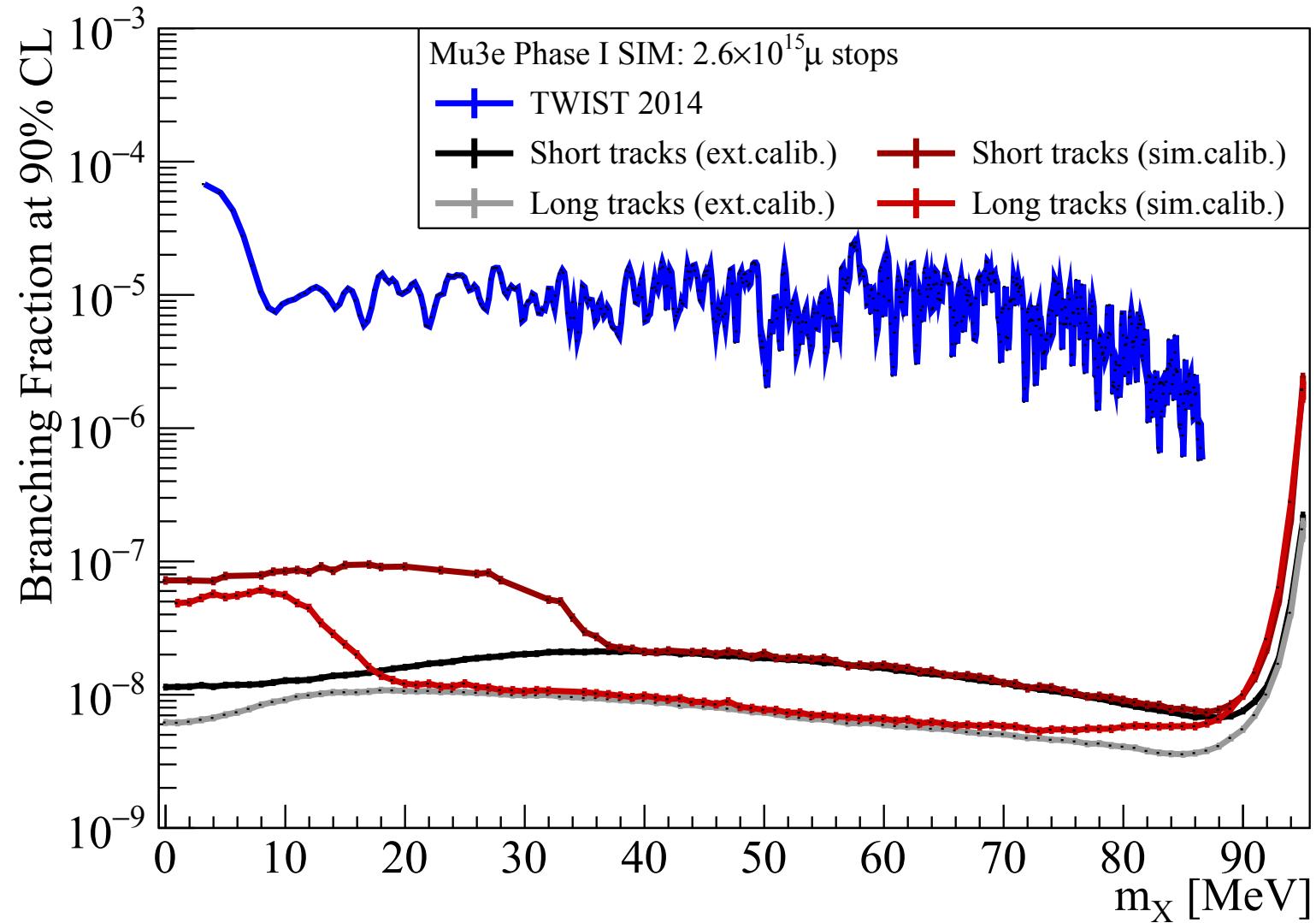


R. Bayes et al. "Search for two body muon decay signals". In: *Phys. Rev.* D91.5 (2015), p. 052020. DOI: 10.1103/PhysRevD.91.052020. arXiv: 1409.0638 [hep-ex].

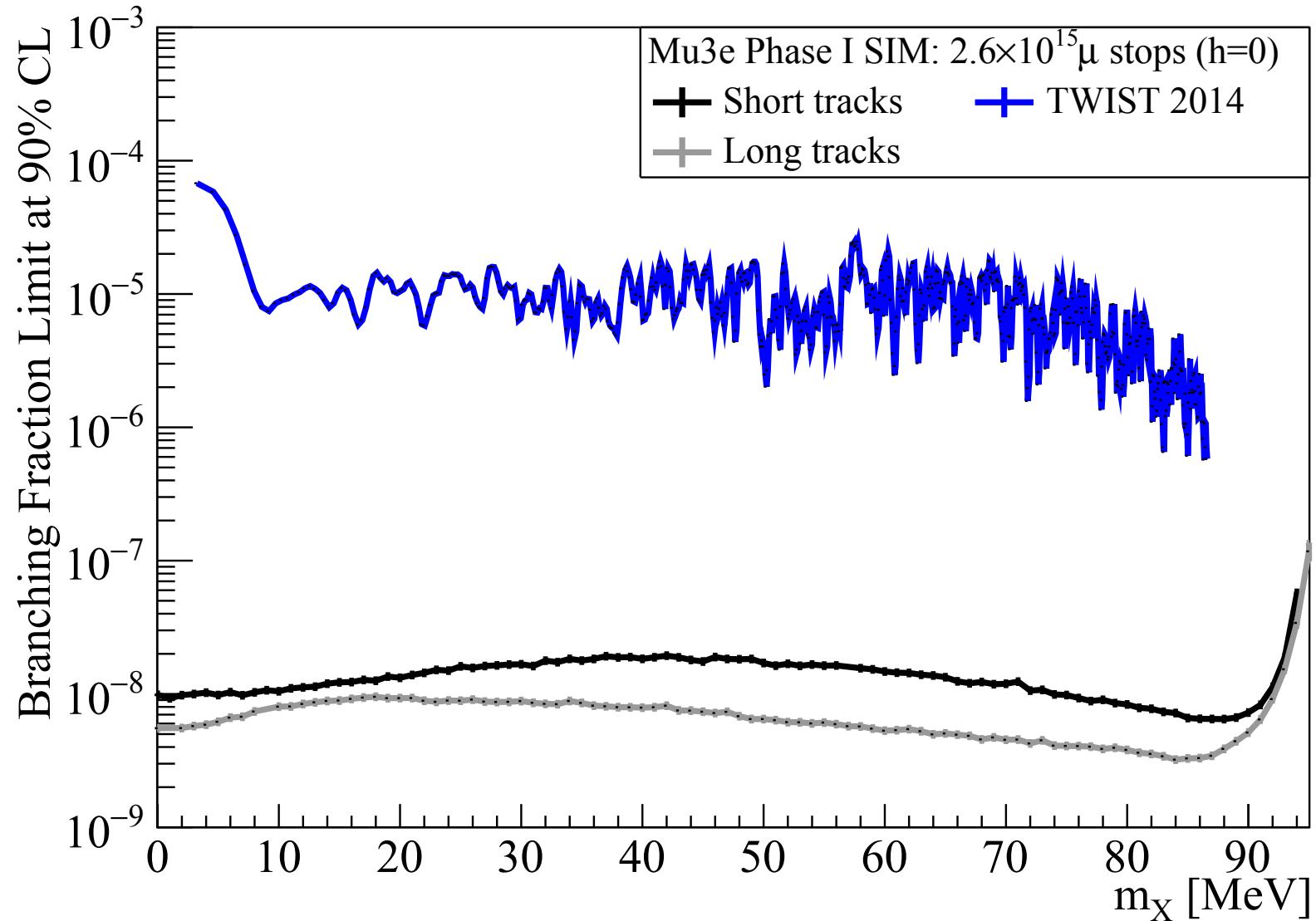
- TWIST at TRIUMF
- Limits on the $\mu \rightarrow eX$ BF in the few 10^{-6} region



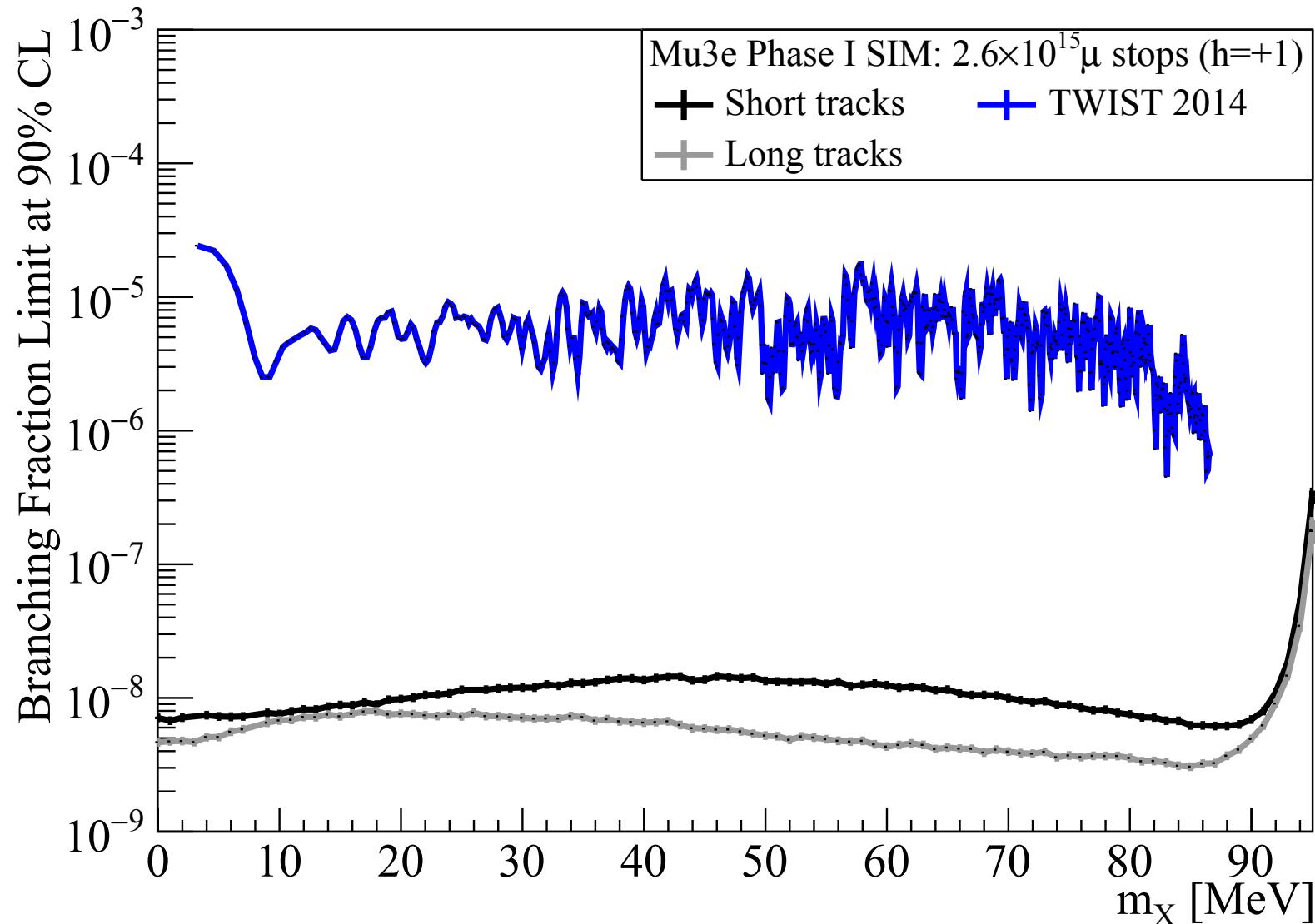
$\mu \rightarrow eX$: Mu3e Phase I expectations



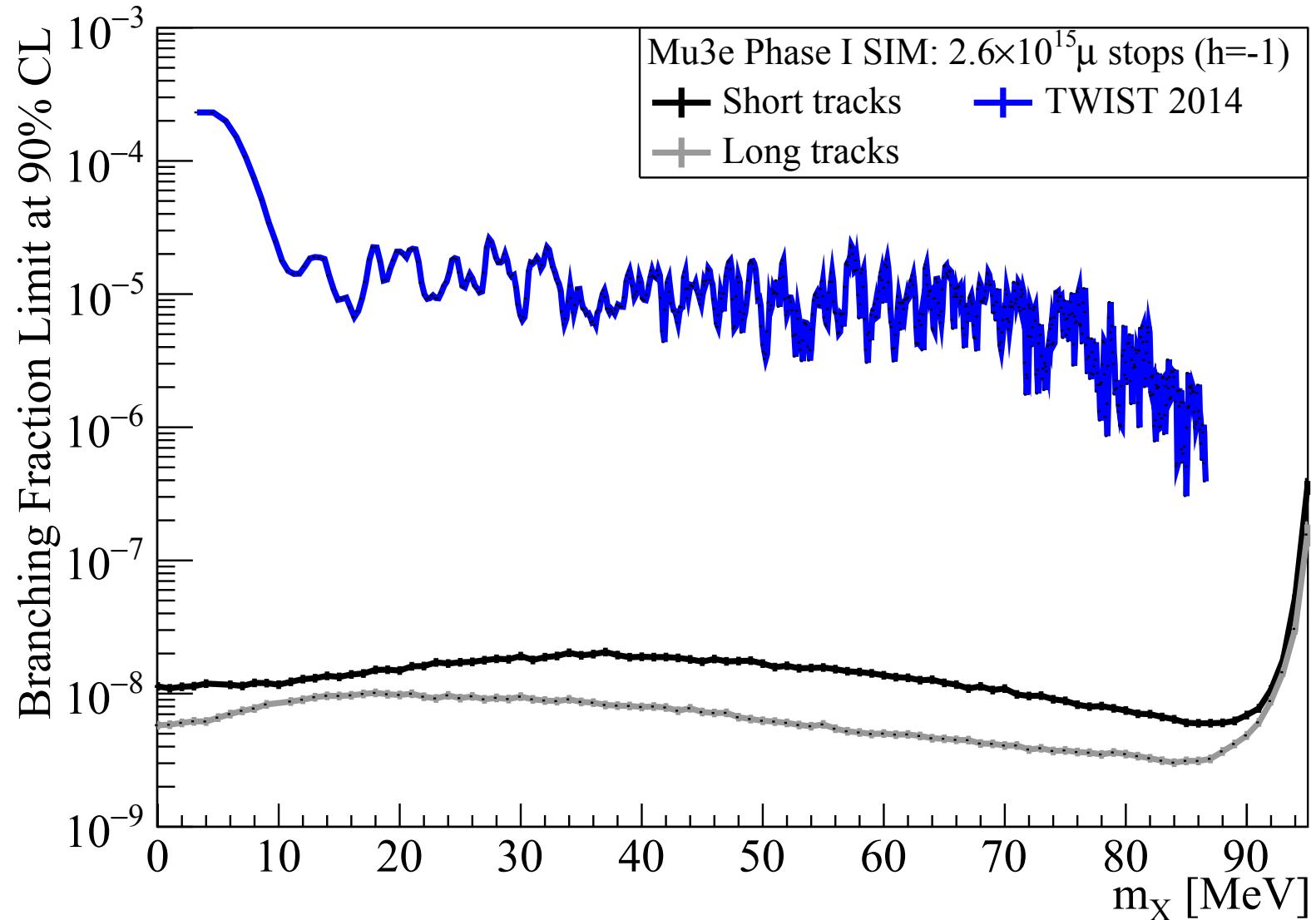
$\mu \rightarrow eX$: 2D fit, $h=0$



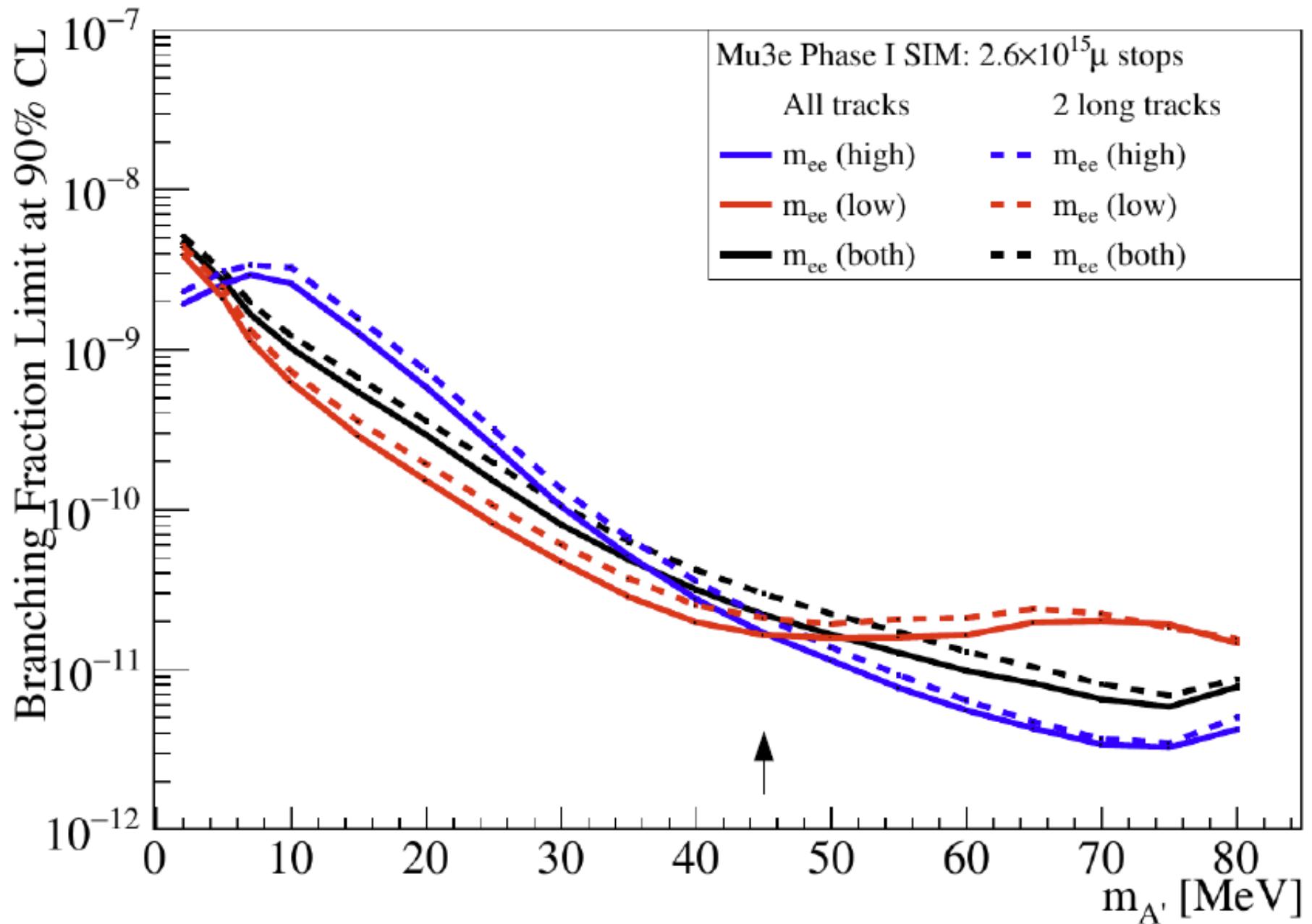
$\mu \rightarrow eX$: 2D fit, $h=1$



$\mu \rightarrow eX$: fit, $h=-1$



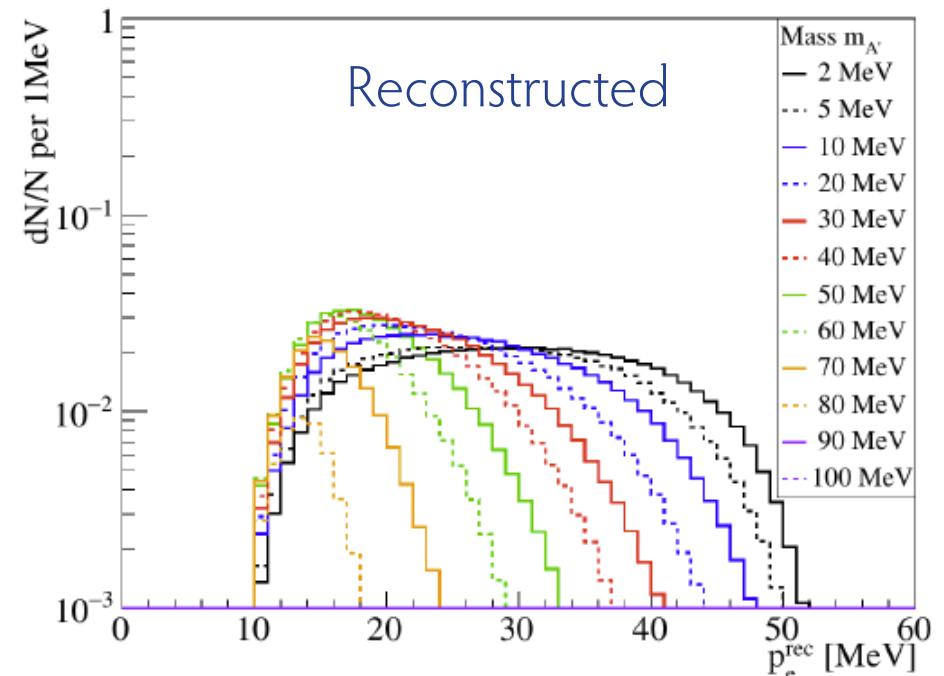
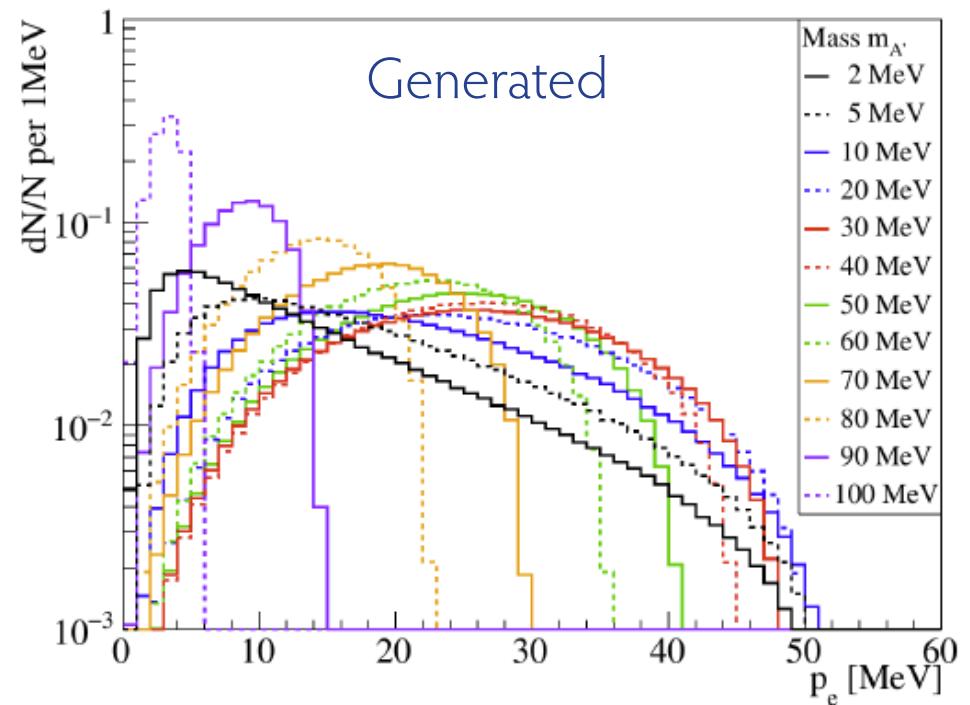
Dark Photons: Branching Fraction Limits



Invisible dark photons

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

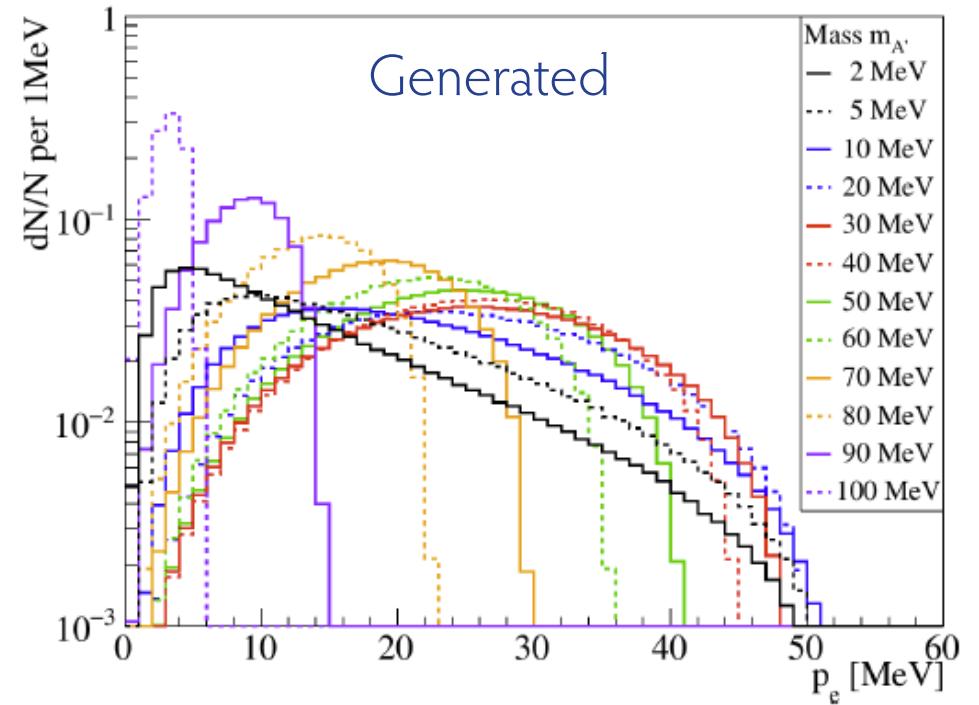
- Shift to Michel spectrum



Invisible dark photons

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

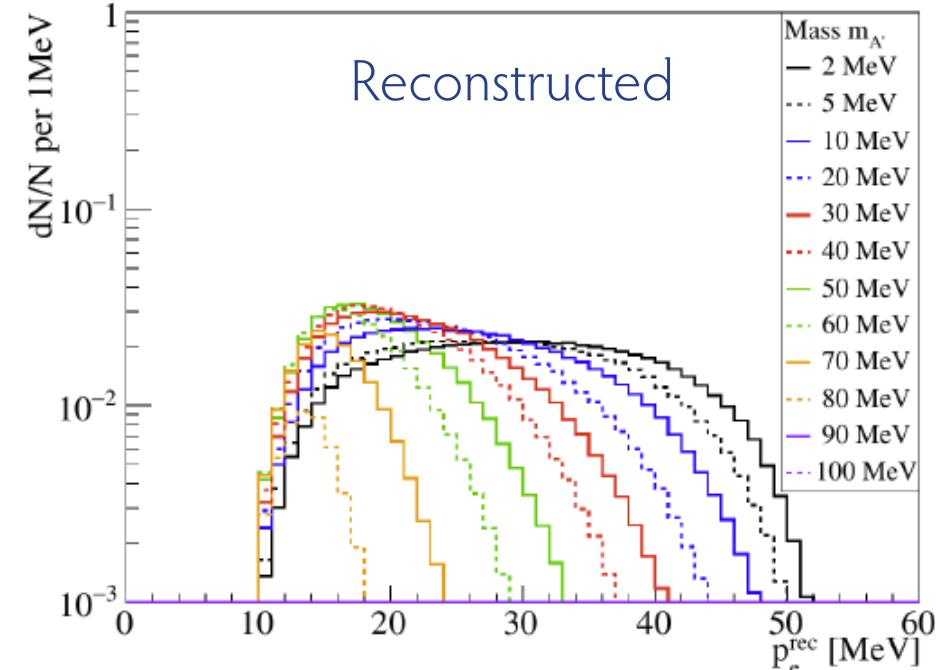
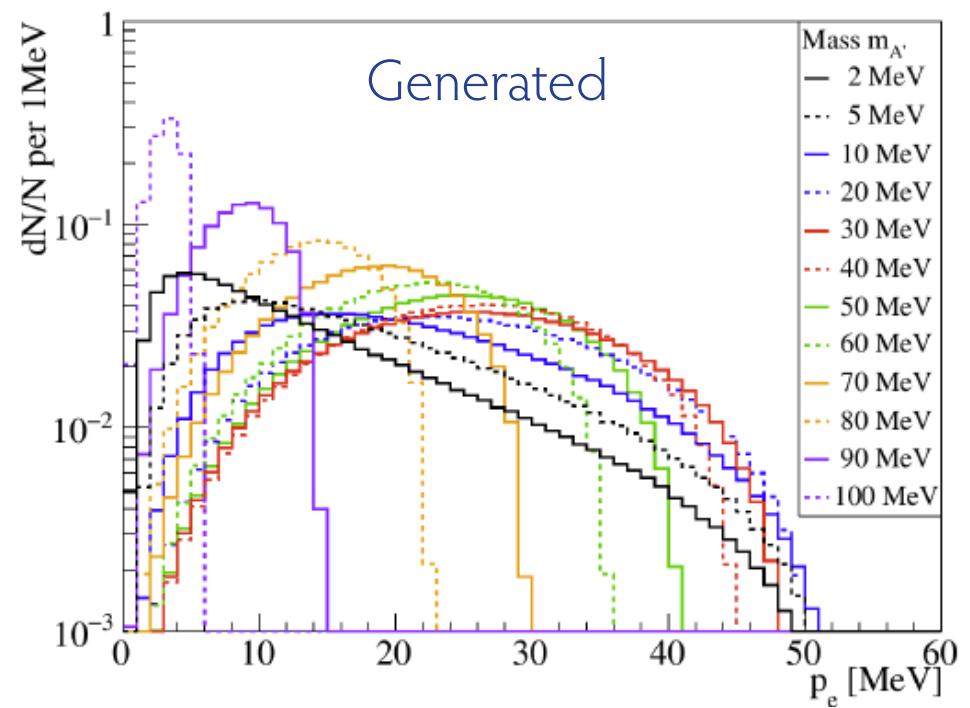
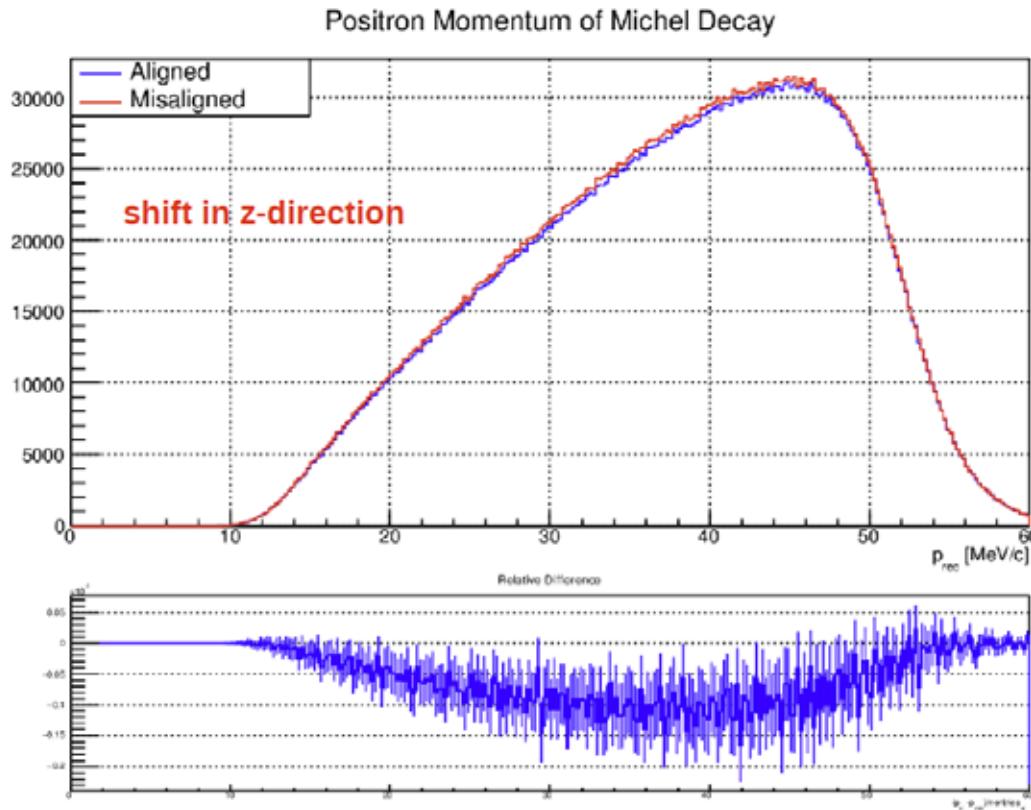
- Shift to Michel spectrum



Invisible dark photons

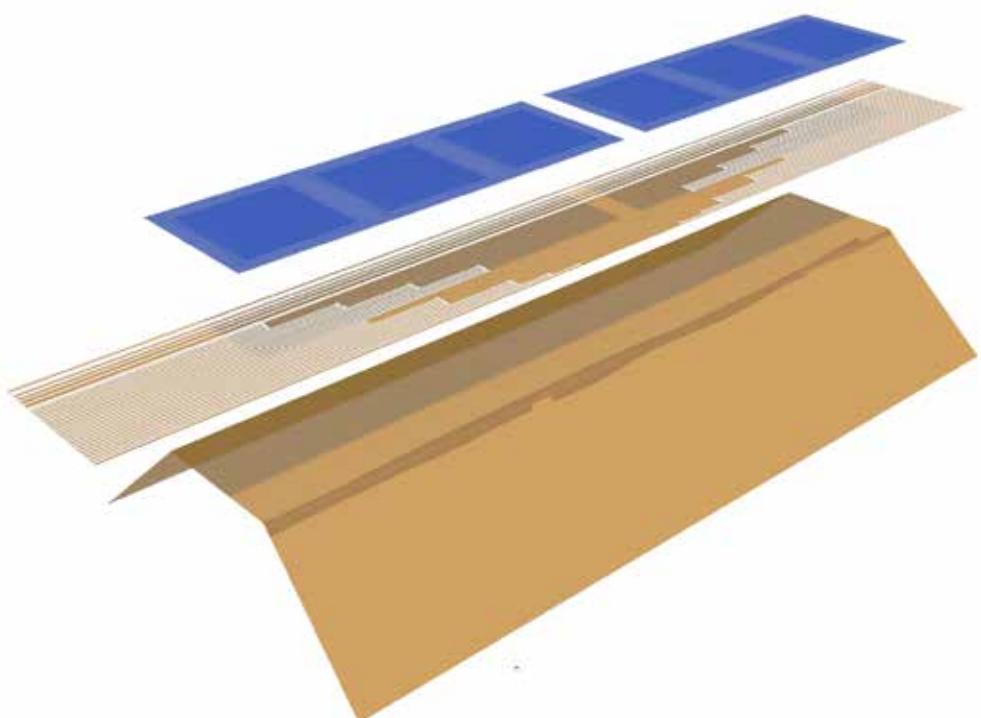
$\mu \rightarrow e\nu\bar{\nu}A'$ is a four-body decay...

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





Introduction to mechanics

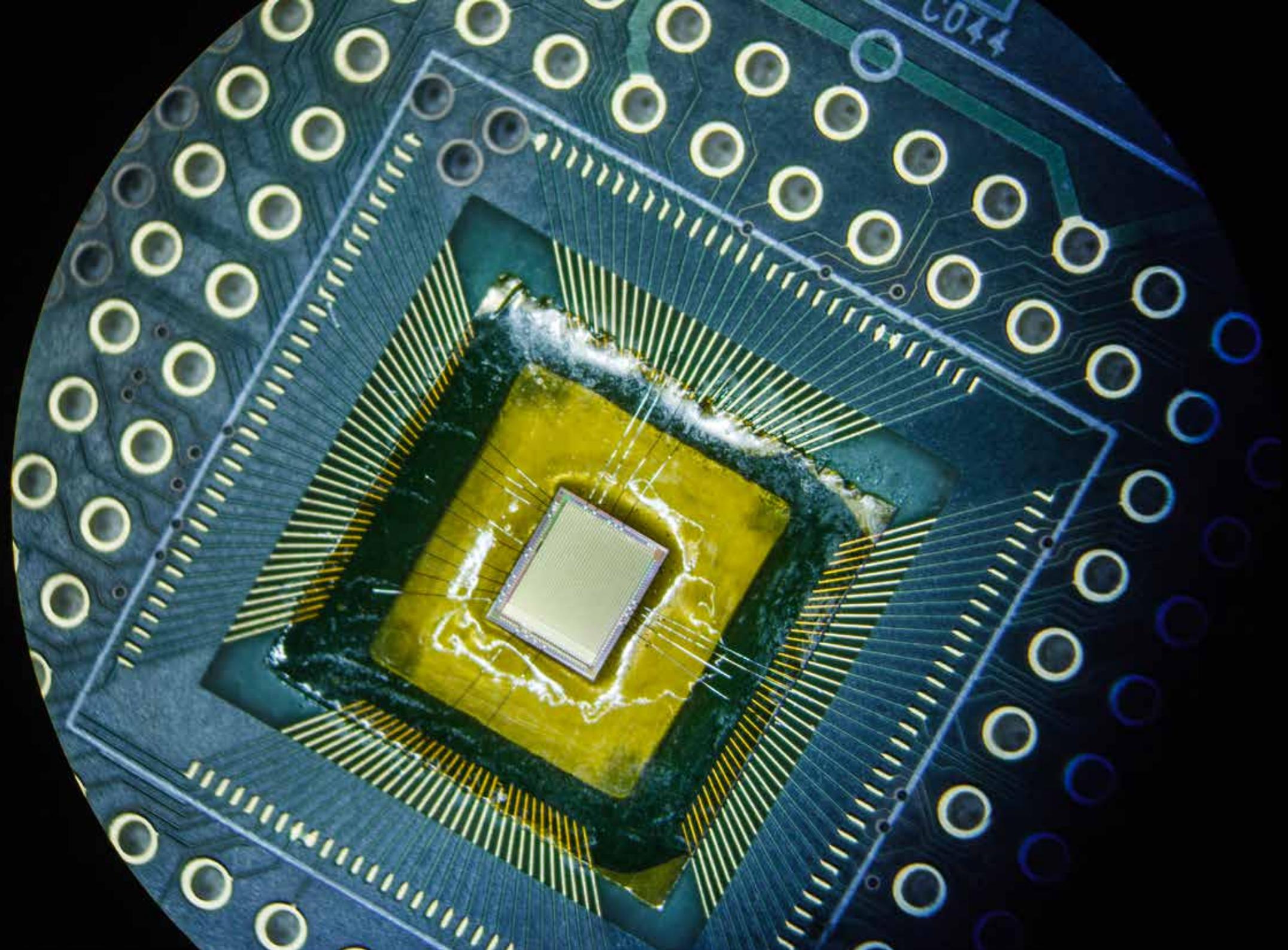


Y

- $\approx 0 \mu\text{m}$ silicon
- $25 \mu\text{m}$ Kapton™ flexprint with aluminium traces
- $25 \mu\text{m}$ Kapton™ frame as support
- About 1% of a radiation length per layer







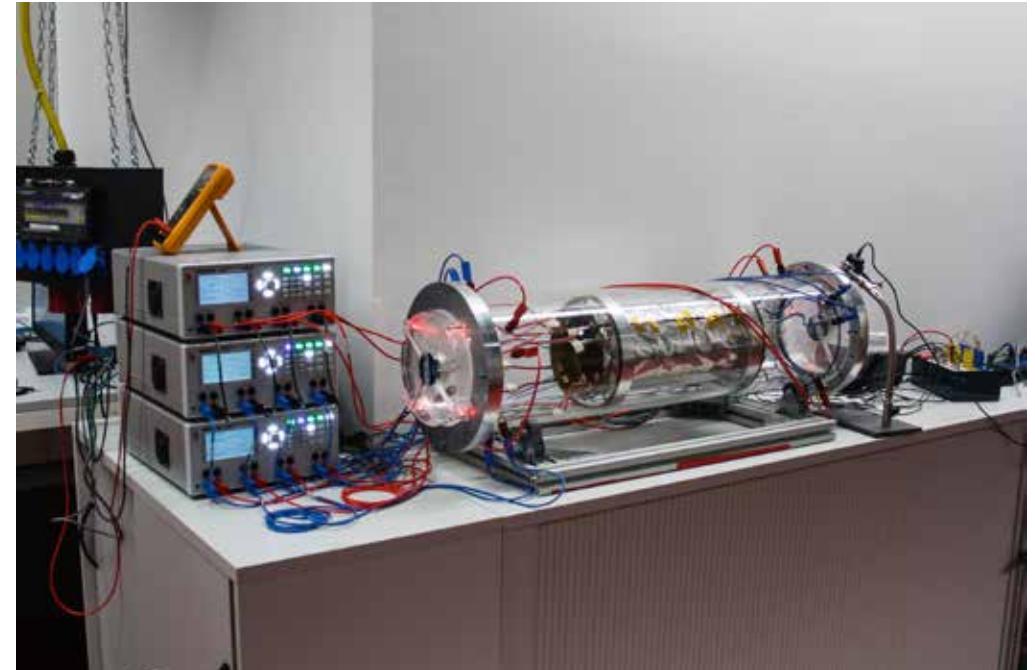
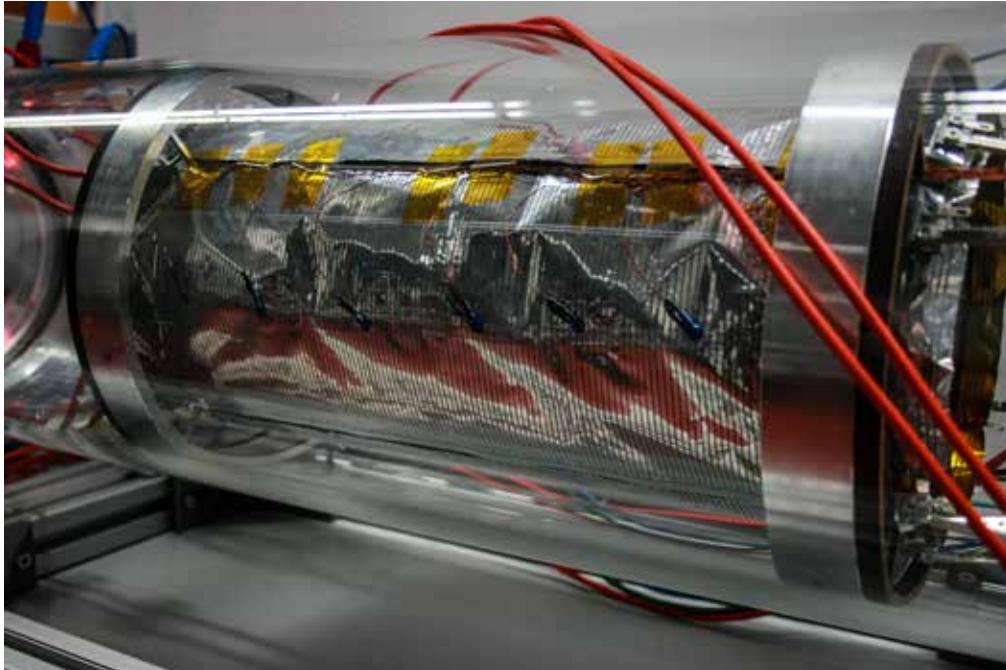
Introduction



- Add no material:
Cool with **gaseous Helium**
(low scattering, high mobility)
- $\sim 250 \text{ mW/cm}^2$ - total $\sim 3 \text{ kW}$
- Simulations: Need \sim **several m/s flow**

Y

- Full scale heatable prototype built
 - 36 cm active length
 - Vibrations studied using Michelson-Interferometer
 - Can keep temperature below 70°C





Introducing cooling tests

