university of groningen / faculty of science and engineering

Experimental Lepton Flavour Physics

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HEP Herbstschule
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Experimental Lepton Flavour Physics

Muon cLFV Experiments

Lecture 2

Lepton Flavour Violation

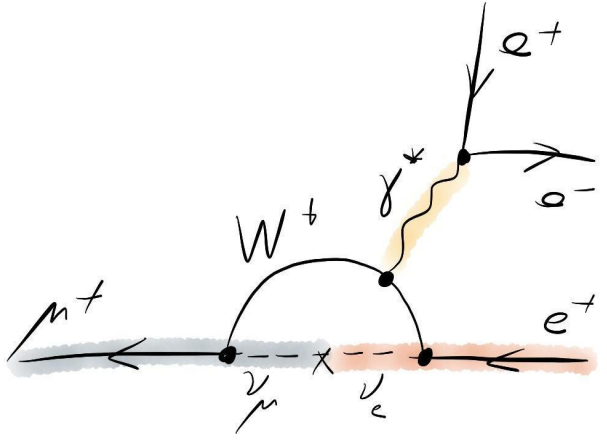
- **Lepton flavour** is conserved due to an **accidental symmetry** in the SM
- Lepton Flavour Violation (**LFV**) is a **forbidden** process
- LFV frequently predicted in **BSM**
- **Neutrino oscillations** are LFV

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

H. Murayama, Supersymmetry IV, 2005

Charged Lepton Flavour Violation

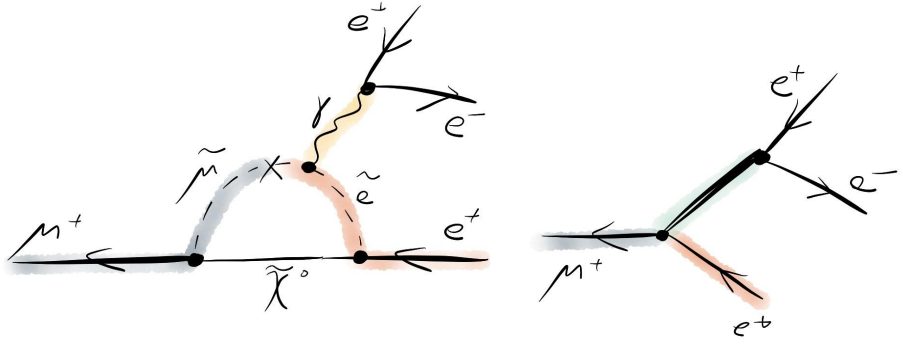
- LFV with charged leptons (**cLFV**)
  - forbidden in the SM
  - predicted in BSM models
  - not (yet?) observed



- If **neutrino mixing** is added to SM, **cLFV** still heavily **suppressed**:

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

Any **observation** of **cLFV** would be an **unambiguous sign** of **BSM** (beyond neutrino mixing)



Example: Z→ℓτ with ATLAS

Nature Physics 17, 819–825 (2021)
Phys.Rev.Lett. 127, 271801 (2021)

ATLAS search for Z→ℓτ with full Run 2 dataset (8 billion Z decays)

- $\mathcal{B}(Z\to e\tau) < 5.0\times10^{-6}$ at 95% CL
- $\mathcal{B}(Z\to \mu\tau) < 6.5\times10^{-6}$ at 95% CL

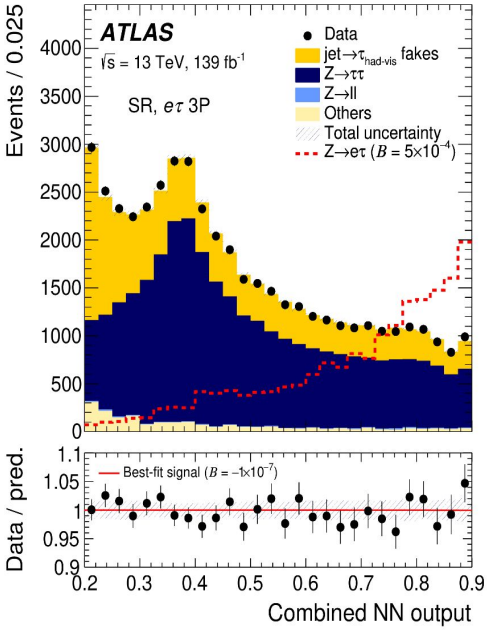
How to reach smaller $\mathcal{B}$?

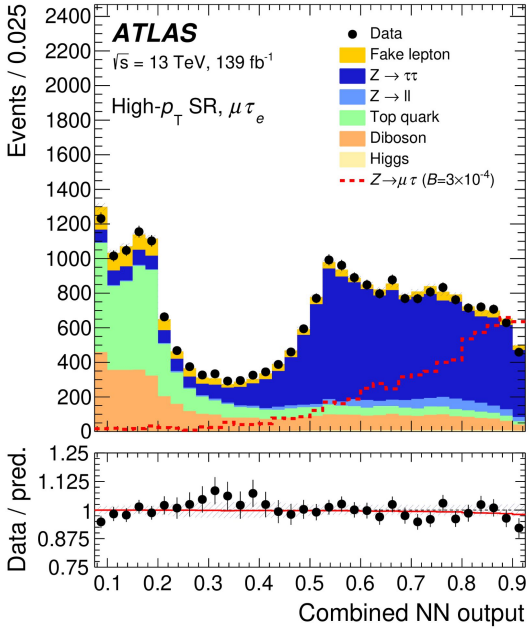
01 More stats -> Intensity

02 Lower unc. -> Precision

03 Background-free

⇒ Muons





Today

- **Searches for cLFV Muon Decays**
  - Muon production
  - 3 golden cLFV muon decays
  - Dedicated experiments
    - MEG & MEG II
    - Mu3e
    - Mu2e and COMET

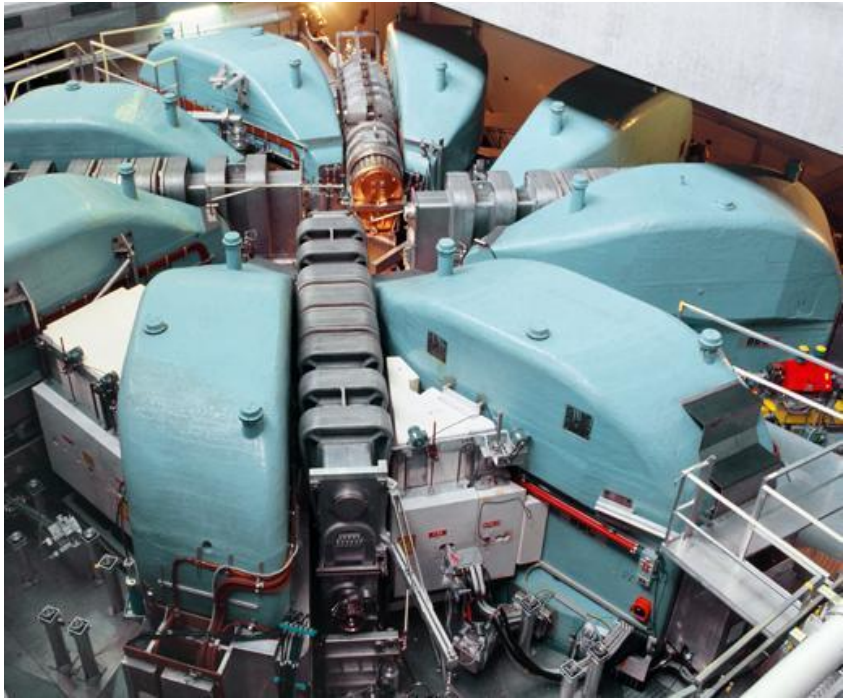
Muon Beams


electron
tau
muon-neutrino
muon
electron-neutrino
tau-neutrino

Muon Source at PSI

- Paul-Scherrer Institute (**PSI**) is home of the world's most intense continuous **muon beam**

- **Proton beam** from cyclotron
  (590 MeV, 2.2 mA)
- Production of **pions** on Carbon target
- Pion decay to **muons**



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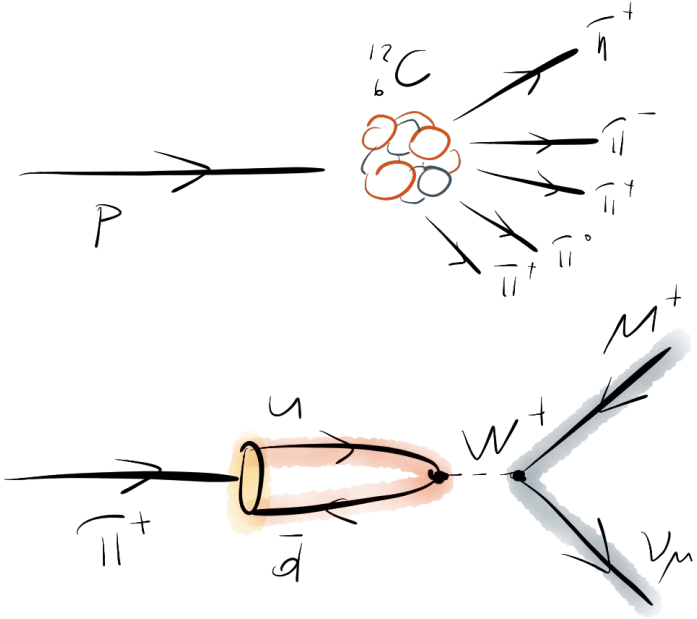
- **Proton beam** from cyclotron
  (590 MeV, 2.2 mA)
- Production of **pions** on Carbon target
- Pion decay to **muons**

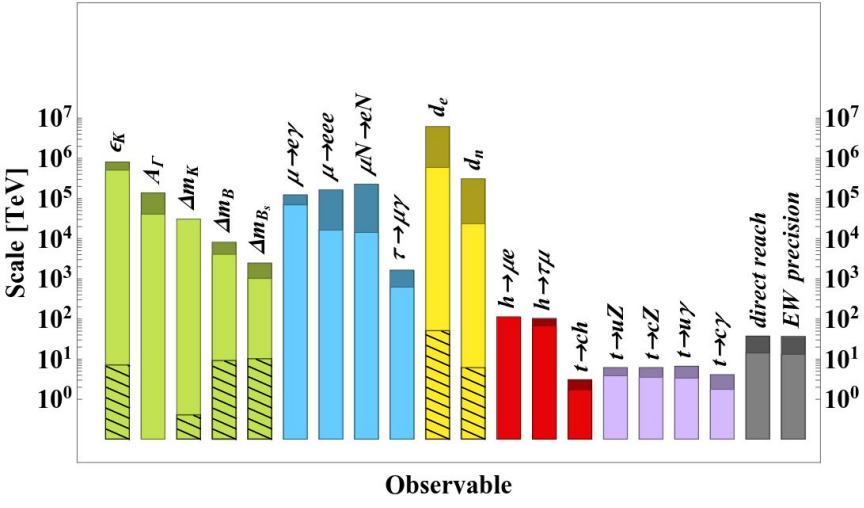
- Continuous sub-surface **μ^+ with 28 MeV**
  - **10^8 μ/s** at existing beam line
  - **10^{10} μ/s** with future High Intensity Muon Beams (HIMB) project 2029+



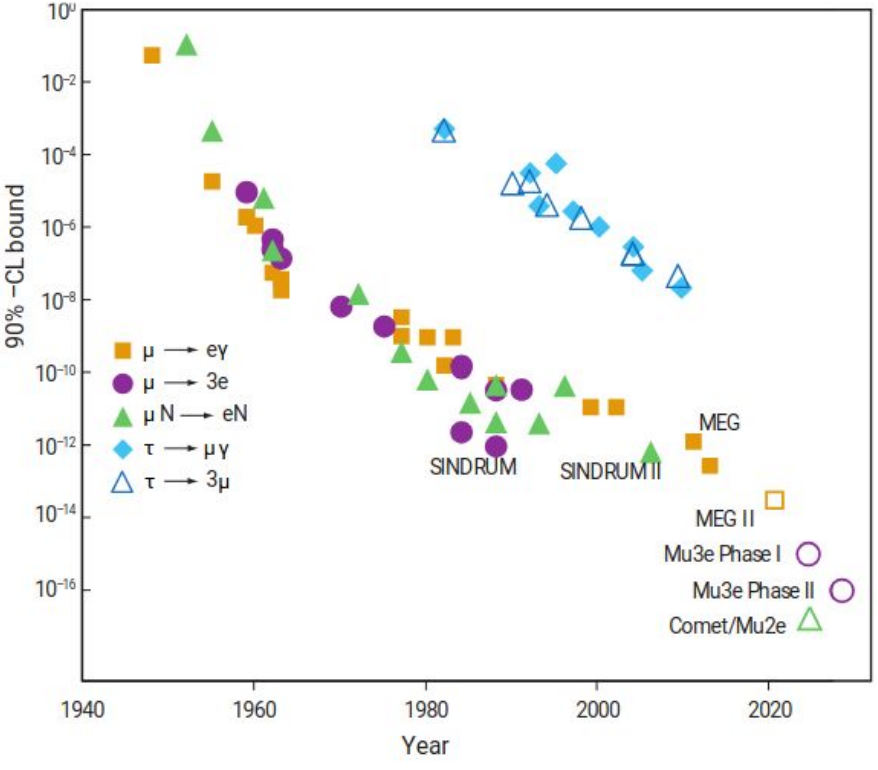
cLFV with Muons

cLFV with Muons

› **High-intensity** muon sources paired with **high-precision** experiments

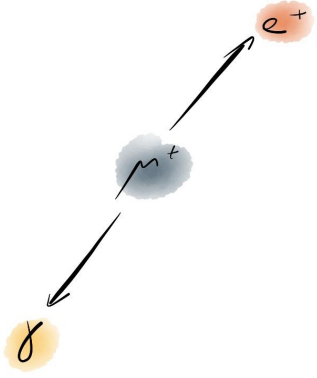


Physics Briefing Book, ESPPU2020



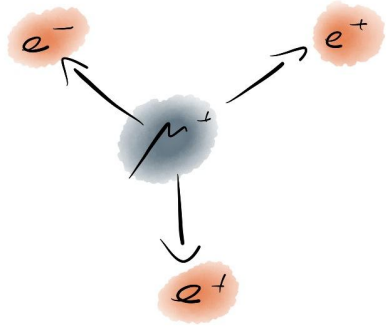
Adapted from [Ann.Rev.Nucl.Part.Sci 58 (2008) 315–341]

cLFV with Muons: Golden Channels



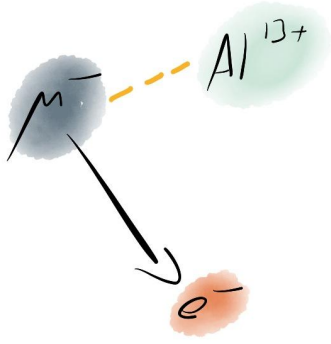
$\mu^+ \rightarrow e^+\gamma$

MEG & MEGII @ PSI



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

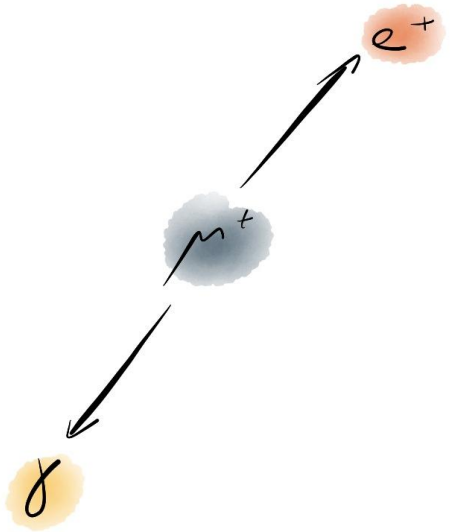
Mu3e
succeeding SINDRUM @ PSI



$\mu^-N \rightarrow e^-N$

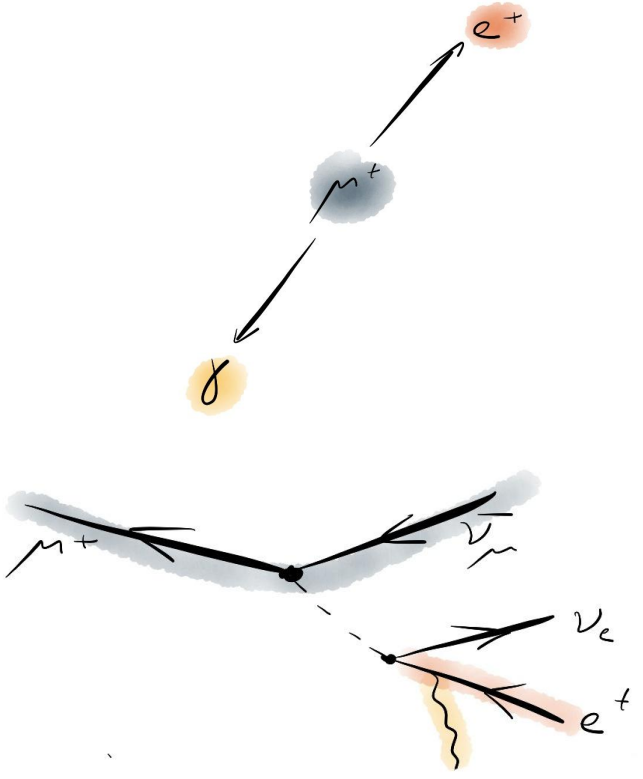
Mu2e (FNAL) & COMET (J-Parc)
succeeding SINDRUM II (PSI)

$\mu^+ \rightarrow e^+ \gamma$ with MEG (II) at PSI



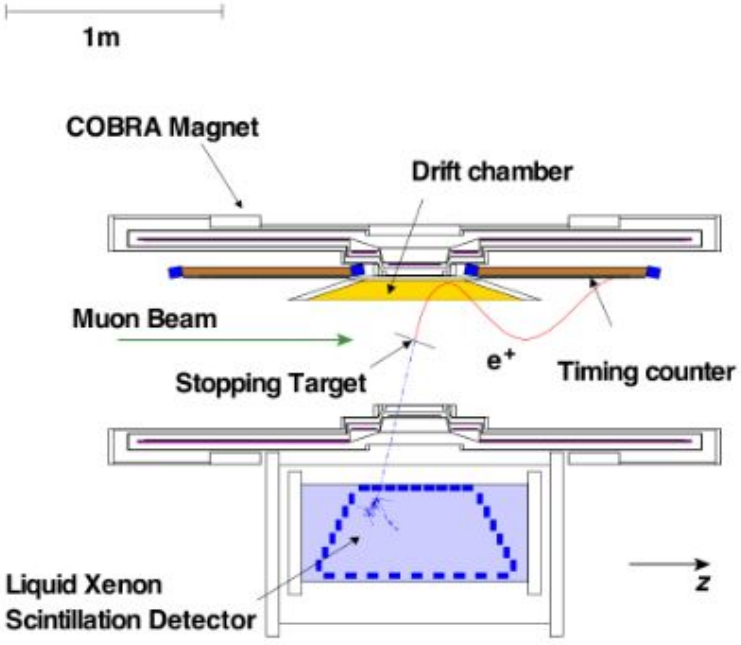
$\mu^+ \rightarrow e^+\gamma$ Decay

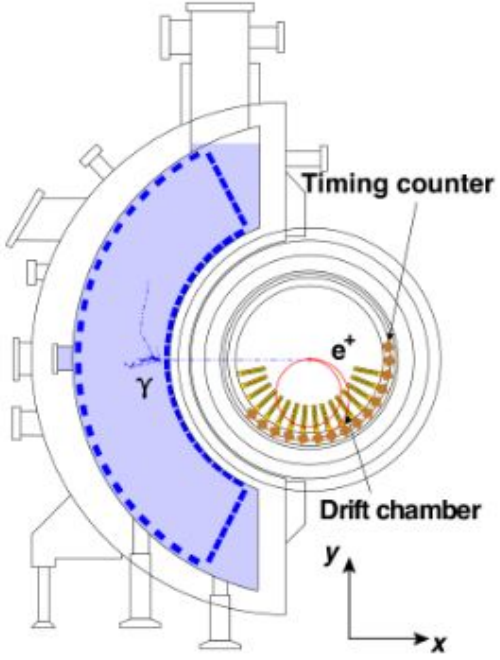
- Signal **$\mu^+ \rightarrow e^+\gamma$**
  - Muon decay at rest
  - Mono-energetic e^+ and γ, back-to-back coincident
- **Background**
  - Radiative muon decay $\mu^+ \rightarrow e^+\gamma\nu\bar{\nu}$
  - Neutrinos invisible
  - Accidental combinations
- Experiment with
  - High muon rate
  - High resolution
    - Energy/momentum
    - Timing
    - Pointing



$\mu^+ \rightarrow e^+\gamma$: MEG Experiment

- Signal $\mu^+ \rightarrow e^+\gamma$
  - Mono-energetic e^+ and γ, back-to-back, coincident





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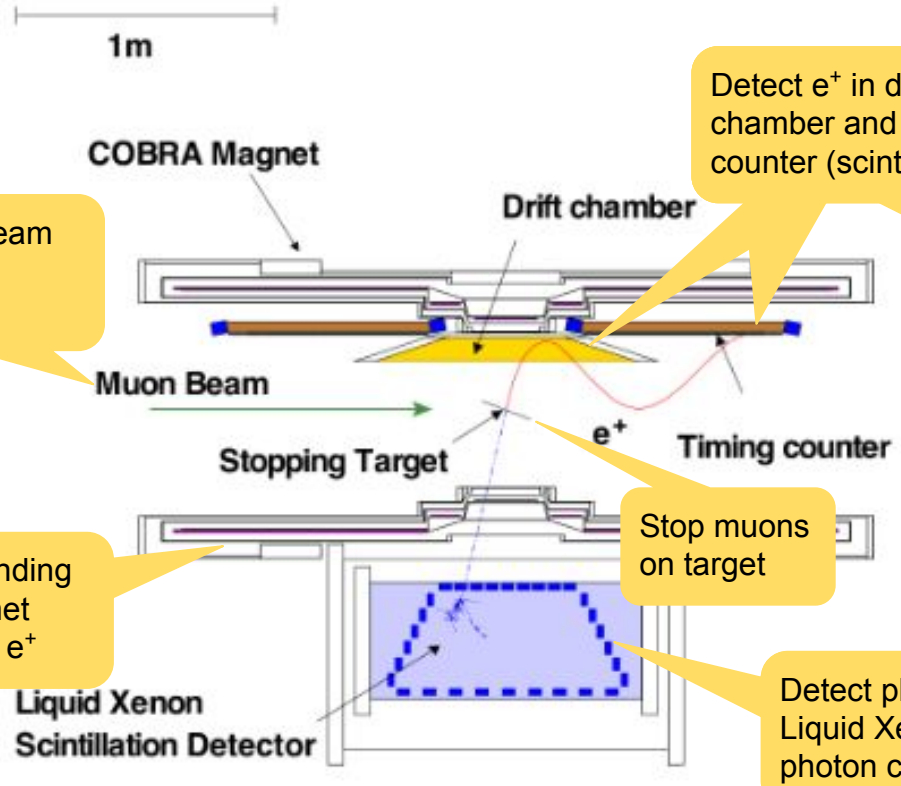


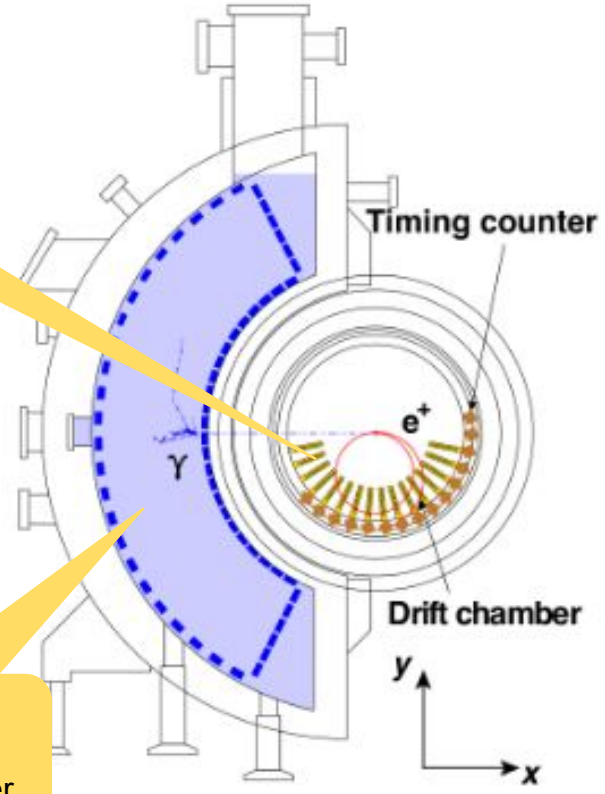
Continuous beam ⇒ reduce accidentals

Detect e^+ in drift chamber and timing counter (scint.)

COnstant Bending RAdius magnet ⇒ sweep out e^+

Stop muons on target

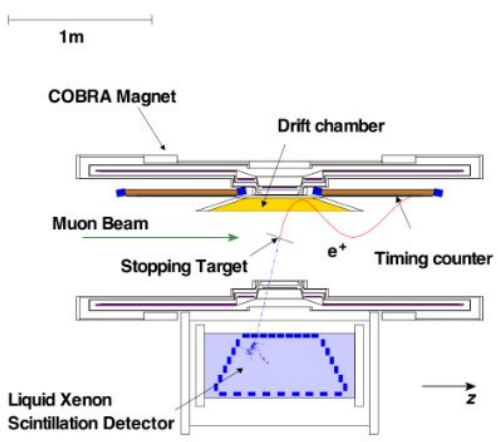
Detect photons in Liquid Xenon photon calorimeter

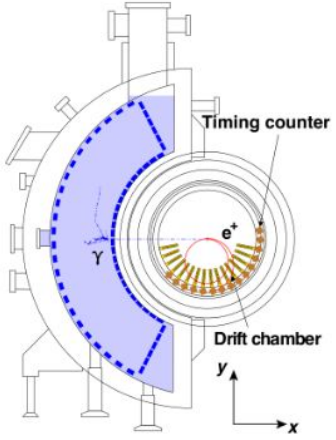


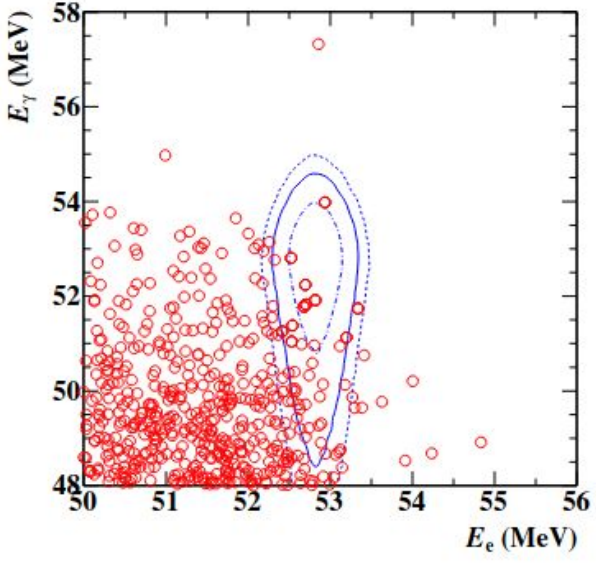
$\mu^+ \rightarrow e^+\gamma$: MEG Experiment

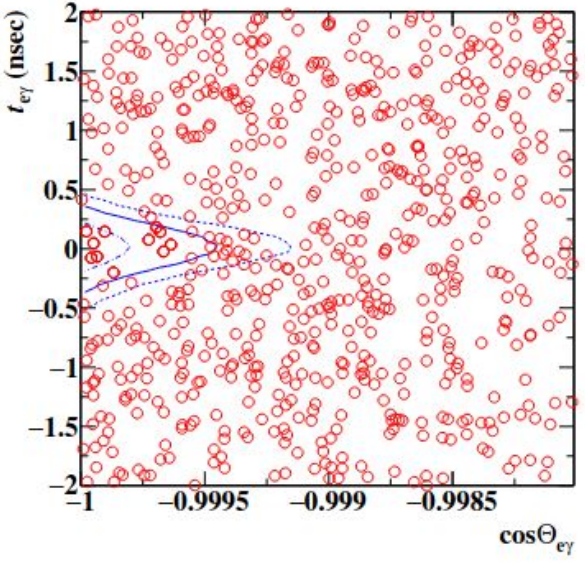
- MEG operated from 2009-2013
- No signal found

$\mathcal{B}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ at 90% CL



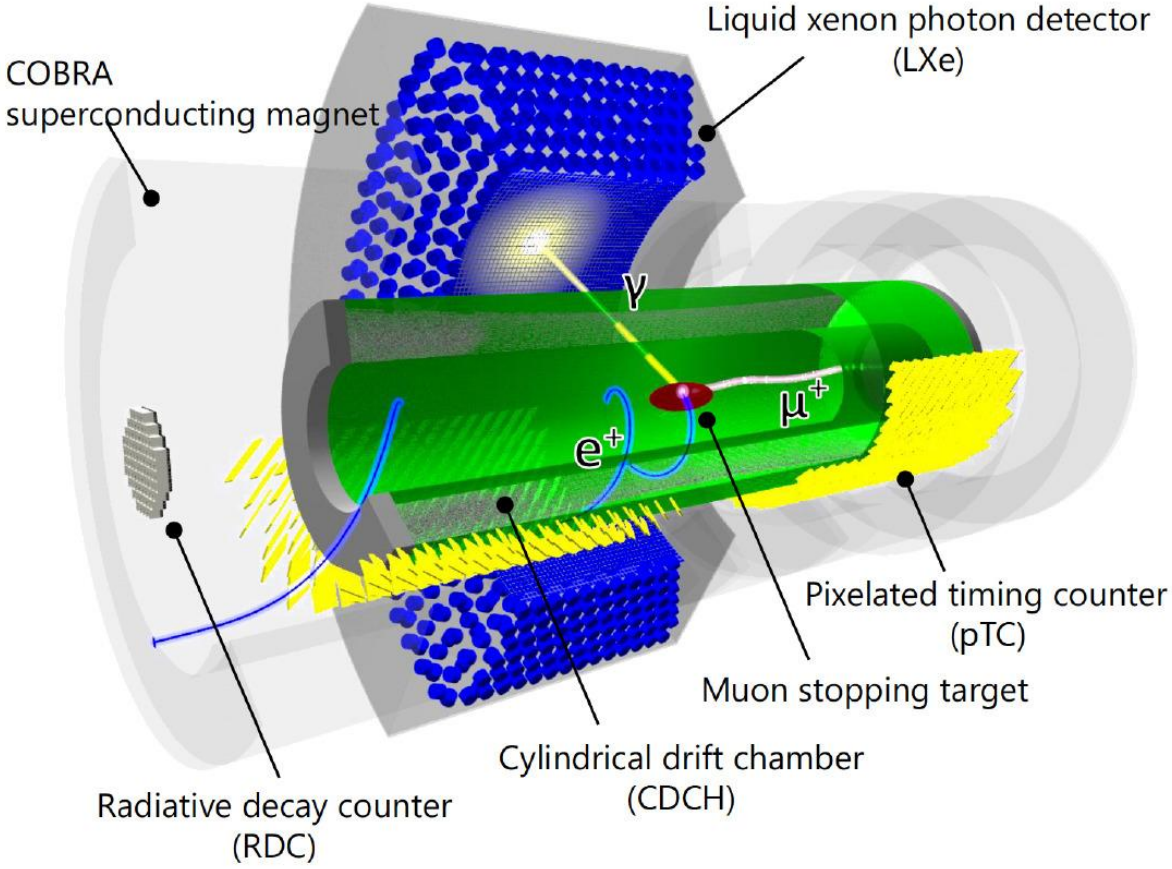






$\mu^+ \rightarrow e^+\gamma$: MEG II Experiment

- Upgrade to higher rate capabilities and higher resolution
  - Examples: Increased wire density in drift chamber, pixelated timing counter, SiPMs on entrance surface of LXe

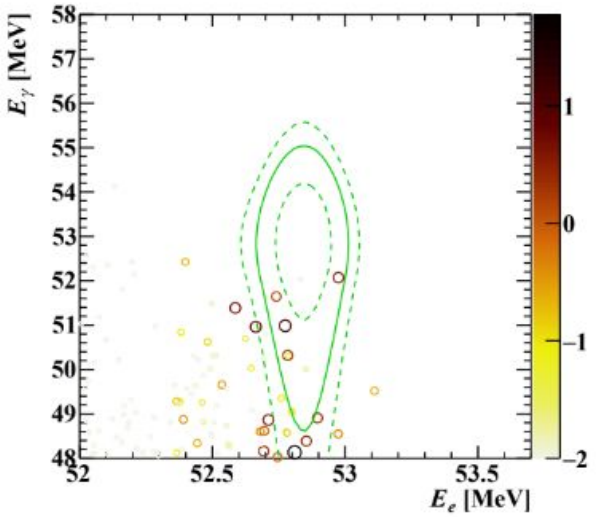


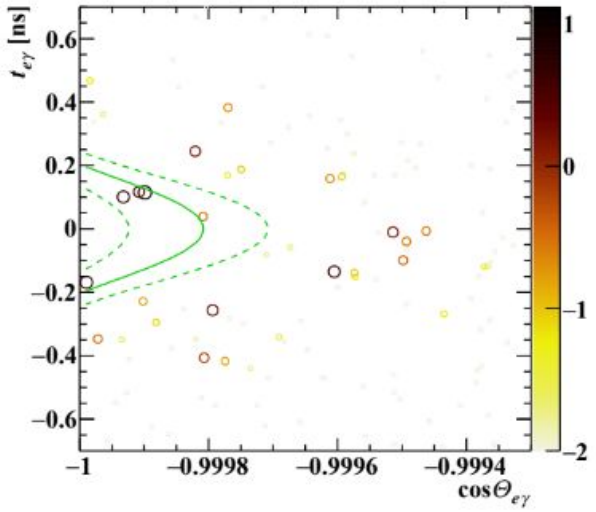
$\mu^+ \rightarrow e^+\gamma$: MEG II Experiment

- Upgrade to higher rate capabilities and higher resolution
  - Examples: Increased wire density in drift chamber, pixelated timing counter, SiPMs on entrance surface of LXe

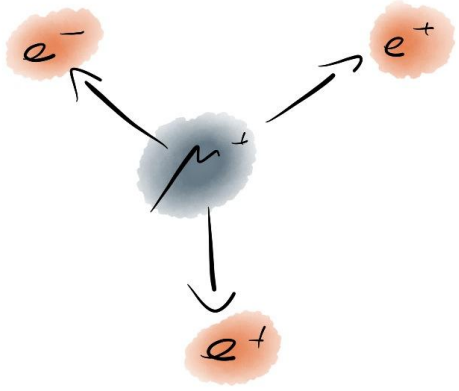
- In operation since 2021
  First results (2025)
  $\mathcal{B}(\mu \rightarrow e\gamma) < 2.2 \times 10^{-13}$ at 90% CL

- Search ongoing, expected sensitivity
  $\mathcal{B}(\mu \rightarrow e\gamma) \sim 6 \times 10^{-14}$ SES



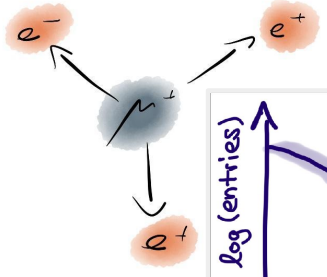


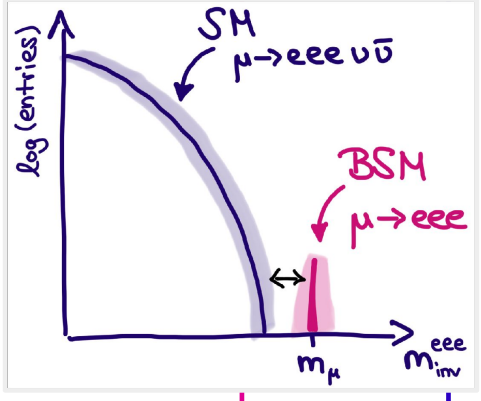
$\mu^+ \rightarrow e^+ e^- e^+$ with Mu3e at PSI



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

Signal





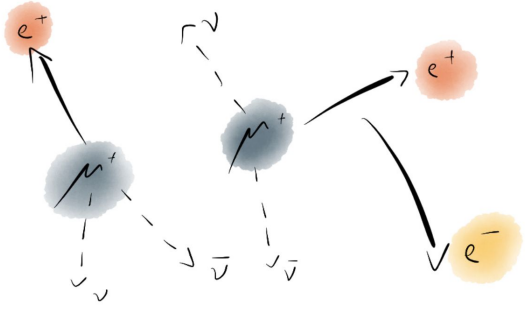
- $\mu^+ \rightarrow e^+e^-e^+$
- Same vertex
- Coincident
- Decay at rest

$\sum P_e = (m_\mu, 0, 0, 0)$

$\mathcal{O}(p_e) = 10$ MeV

Background

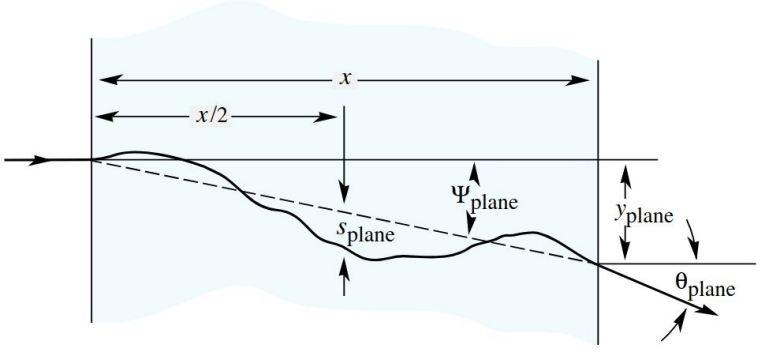
- Background from **rare decay**
  $\mathcal{B}(\mu \rightarrow eeevv) = 3.4 \times 10^{-5}$
  Missing momentum due to neutrinos
  Need excellent momentum resolution

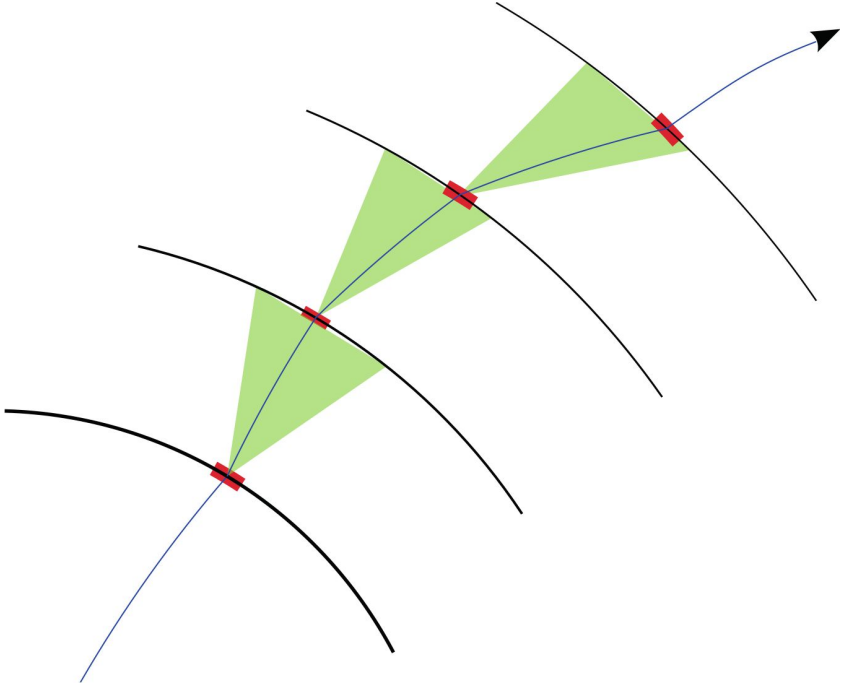


- **Accidental combinations**
  Ex. e^+ from $\mu \rightarrow ev$ with e^+e^- from Bhabha scattering
- Need good timing + vertexing, low material, continuous μ beam

Tracking in the Scattering-Dominated Regime

- Low-momentum $e^{+/-}$ affected by Multiple Coulomb Scattering (MS)
  - Energy loss and deflection
- Momentum resolution dominated MS

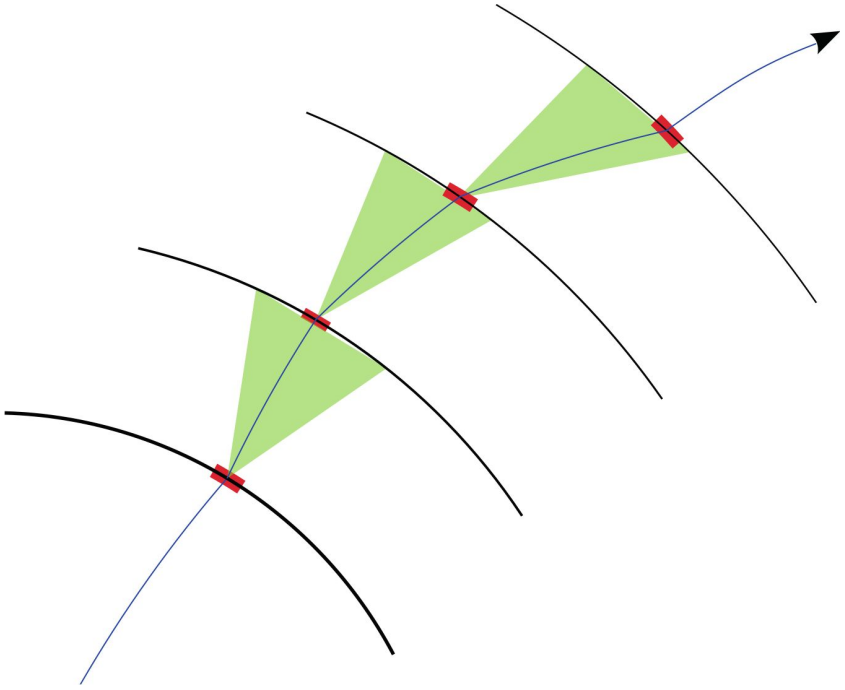




Tracking in the Scattering-Dominated Regime

- Low-momentum $e^{+/-}$ affected by Multiple Coulomb Scattering (MS)
  - Energy loss and deflection
- Momentum resolution dominated MS

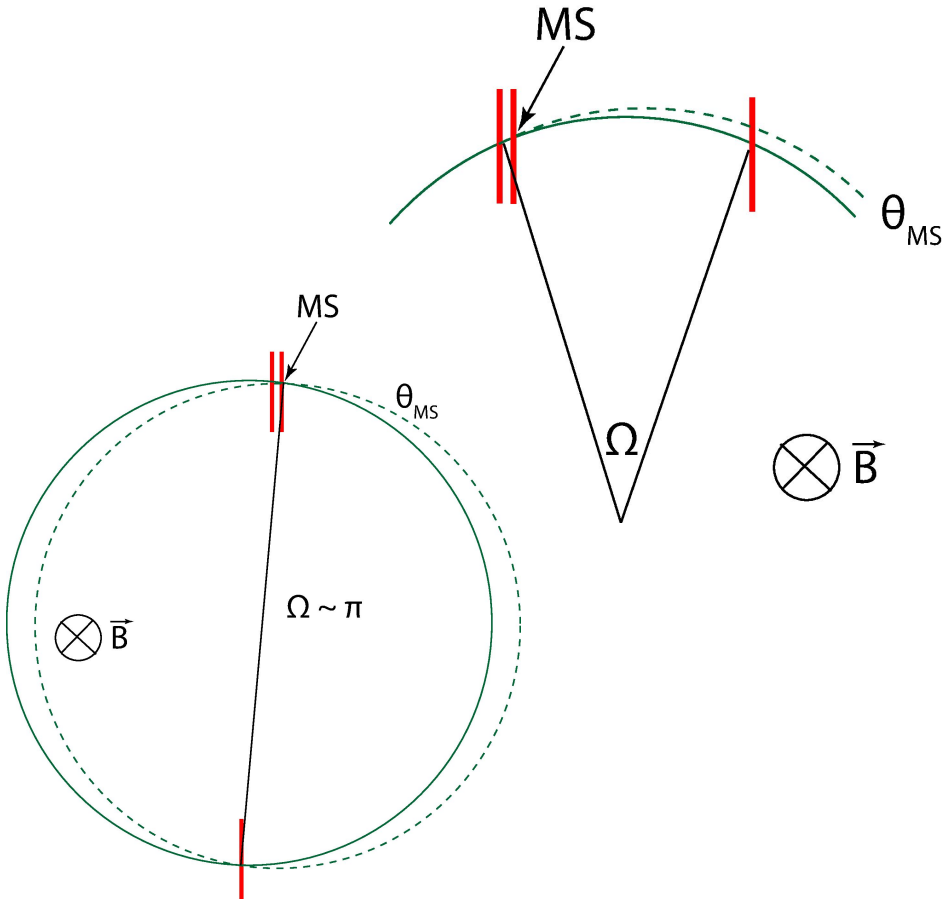
- ‘Recover’ momentum resolution
  - Consider scattering in track fit
  - Low material detector



Tracking in the Scattering-Dominated Regime

- Low-momentum $e^{+/-}$ affected by Multiple Coulomb Scattering (MS)
  - Energy loss and deflection
- Momentum resolution dominated MS

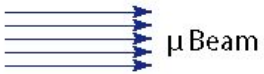
- 'Recover' momentum resolution
  - Consider scattering in track fit
  - Low material detector
  - Optimized geometry
    → large lever arm



$\mu^+ \rightarrow e^+e^-e^+$ Decay: Mu3e Experiment

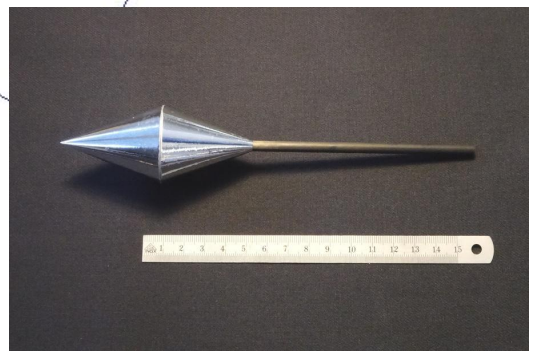
decay $e^{+/-}$ on helical trajectories in 1T solenoidal field

continuous beam of 10^8 μ/s at PSI



Target

μ stop and decay on hollow target



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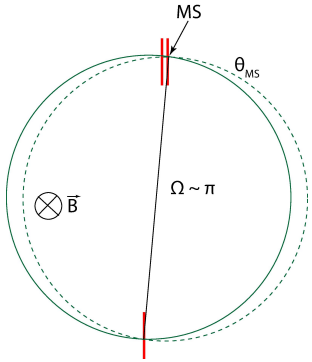
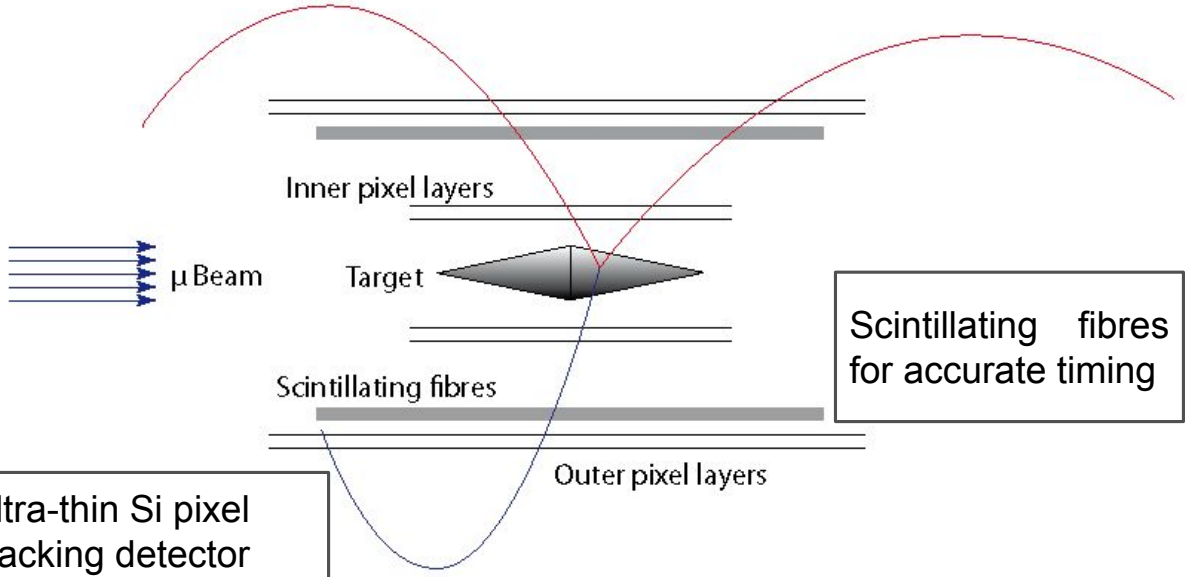
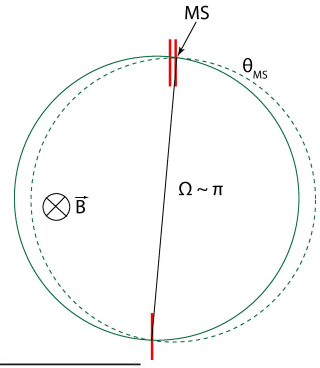


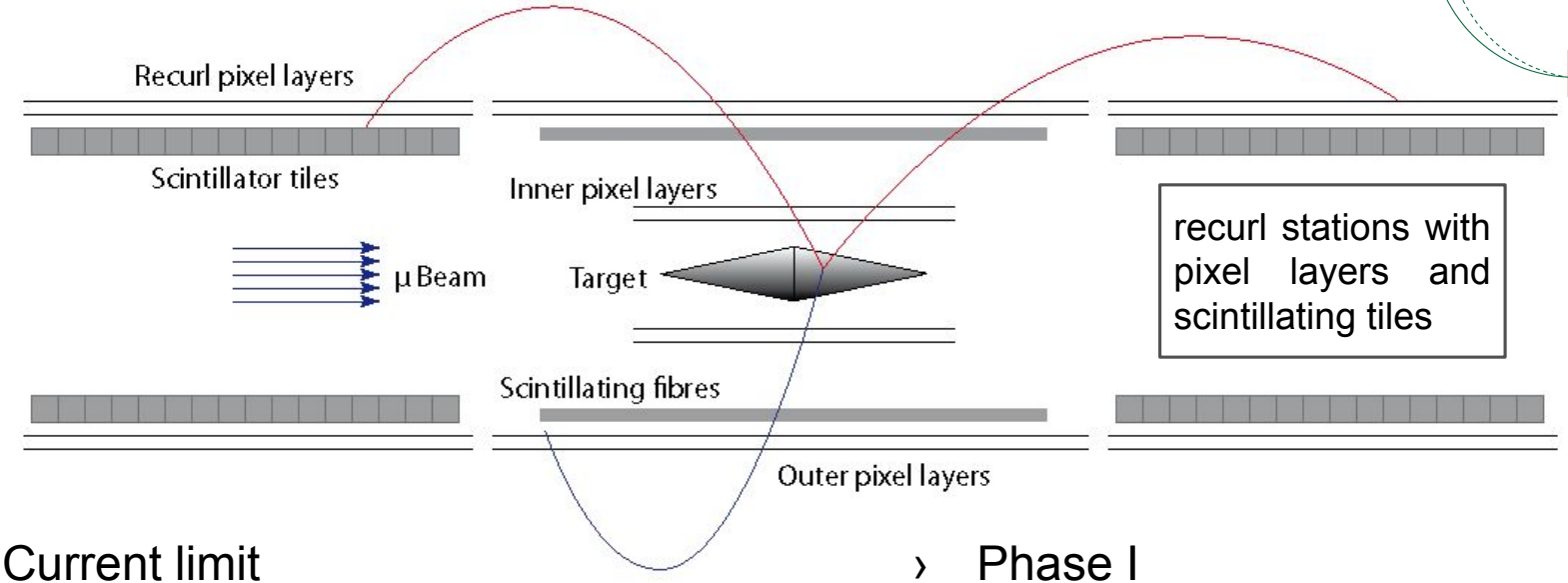


Scintillating fibres for accurate timing

ultra-thin Si pixel tracking detector (~0.1% X_0)

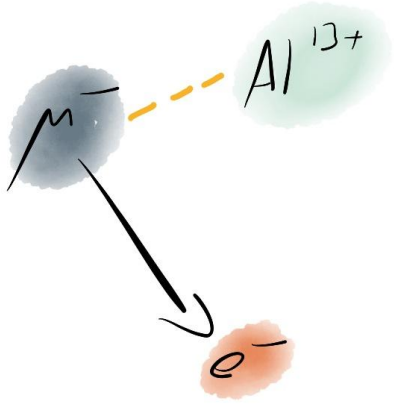
$\mu^+ \rightarrow e^+e^-e^+$ Decay: Mu3e Experiment





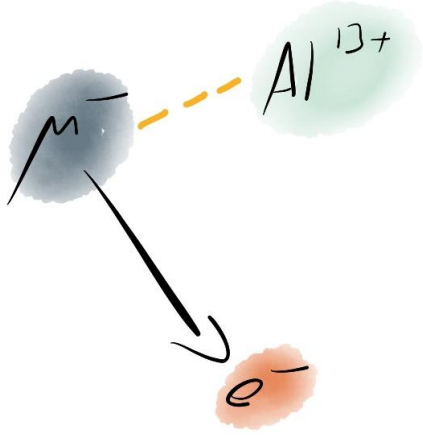
- Current limit
  - $\mathcal{B}(\mu^+ \rightarrow e^+e^-e^+) < 10^{-12}$ at 90% CL
    SINDRUM @ PSI (1988)
- Phase I
  - $\mathcal{B}(\mu^+ \rightarrow e^+e^-e^+) \sim 10^{-14}$ to a few 10^{-15}
- Phase II
  - HIMB: 10x more muons
  - $\mathcal{B}(\mu^+ \rightarrow e^+e^-e^+) \sim 10^{-16}$

$\mu^- N \rightarrow e^- N$ with Mu2e and COMET



$\mu^-N \rightarrow e^-N$ Conversion

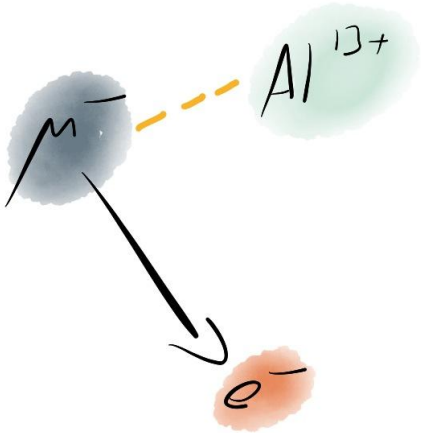
› Conversion of $\mu \rightarrow e$ within muonic atom: **$\mu^-N \rightarrow e^-N$**



$\mu^-N \rightarrow e^-N$ Conversion

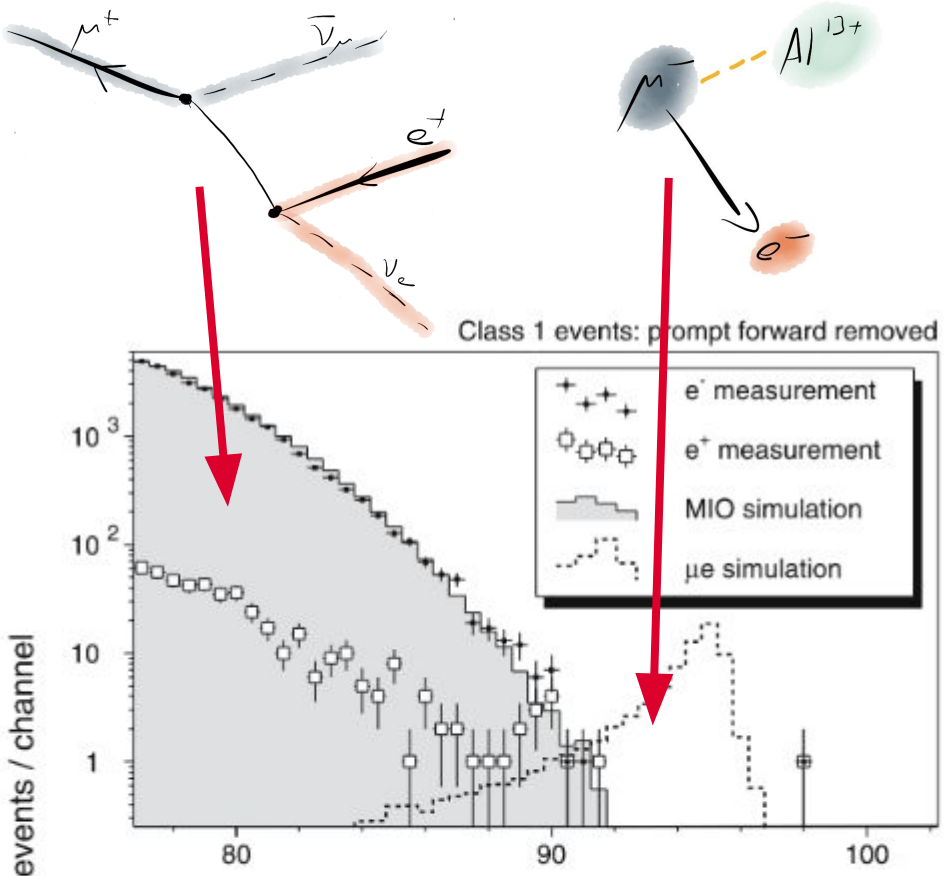
- Conversion of $\mu \rightarrow e$ within muonic atom: **$\mu^-N \rightarrow e^-N$**

- Signal
  - Mono-energetic e^-
    ~ 105 MeV for N=Al



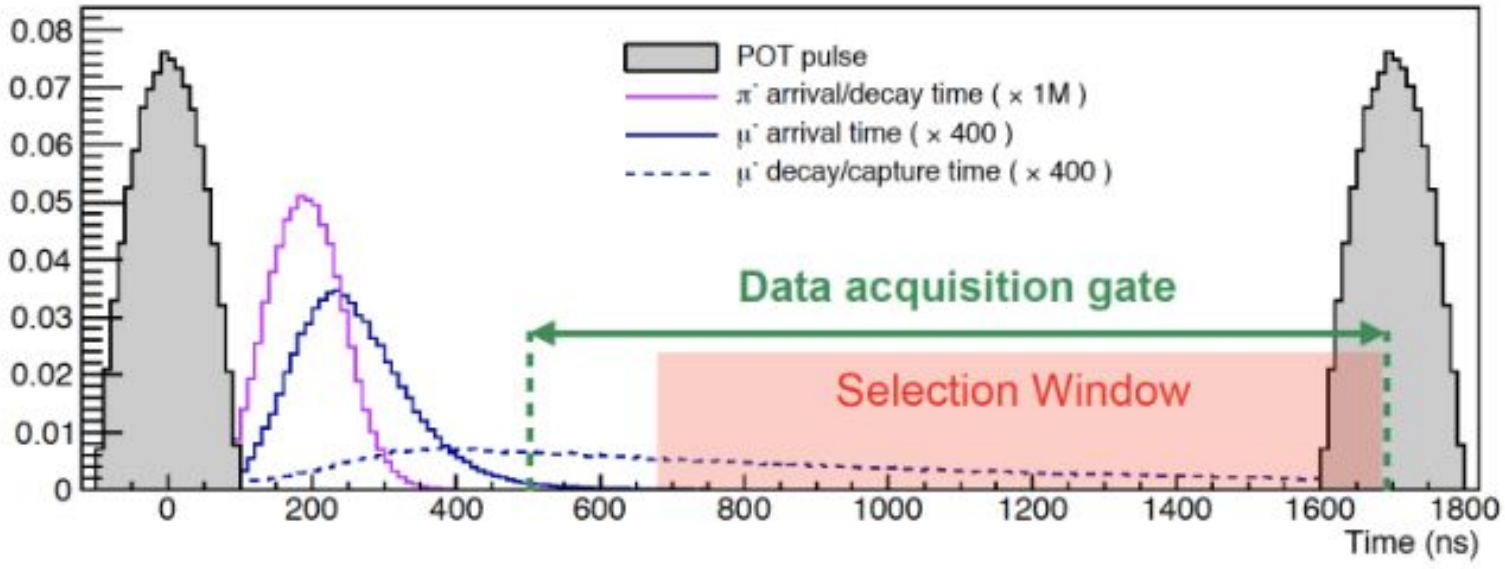
$\mu^-N \rightarrow e^-N$ Conversion

- Conversion of $\mu \rightarrow e$ within muonic atom: **$\mu^-N \rightarrow e^-N$**
- Signal
  - Mono-energetic e^-
    ~ 105 MeV for N=Al
- Background
  - Muon decay in orbit $\mu^-N \rightarrow e^-\nu\bar{\nu}N$
  - Neutrinos invisible
  - Beam-related backgrounds
    ex. muon decays in-flight, antiprotons, pions
  - Cosmics
- $\mathcal{R}(\mu Au \rightarrow eAu) < 7\times10^{-13}$ at 90% CL
  SINDRUMII @PSI (2006)



$\mu^-N \rightarrow e^-N$ Conversion: Pulsed Beam

- With **beam-related backgrounds**, need an experiment with
  - Pulsed muon beam
  - Muonic atom μ^-N with long lifetime, ex. T(μAl) = 864 ns



To be continued during Lecture 3