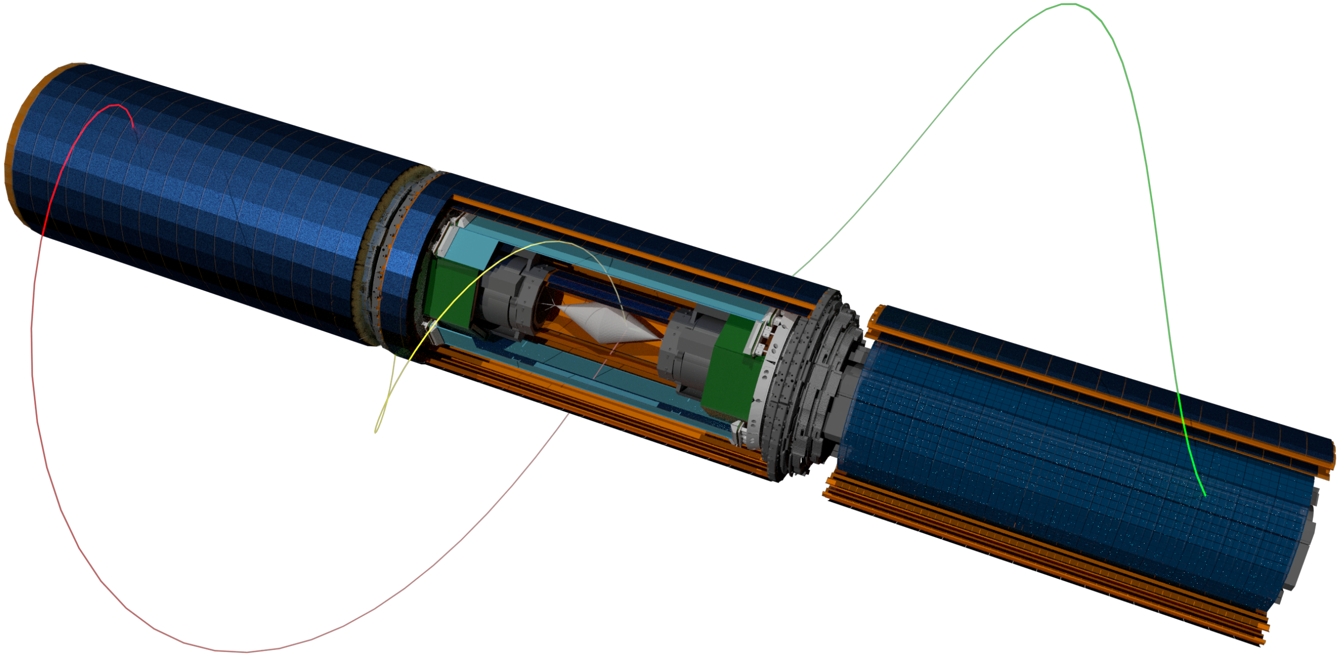
Searching for charged Lepton Flavour Violation with the Mu3e Experiment

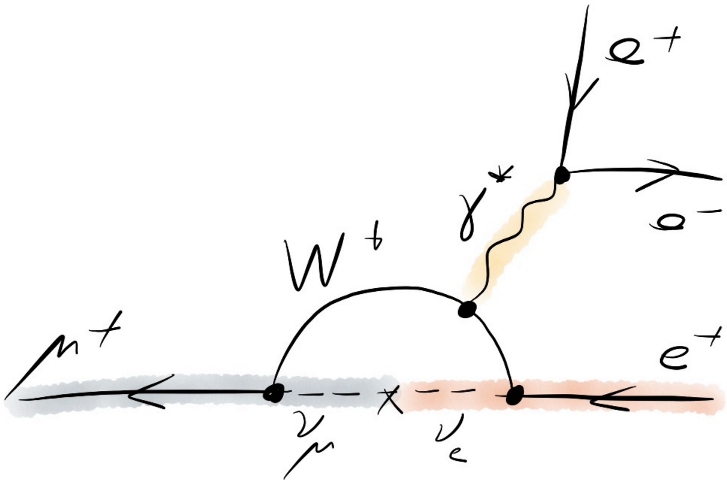
Ben Gayther - University College London (UCL)
On behalf of the Mu3e collaboration



Introduction

- Signal decay
- Backgrounds
- Principle of momentum measurement
- The detector
- Sub-detector overviews
- Integration runs

cLFV in SM

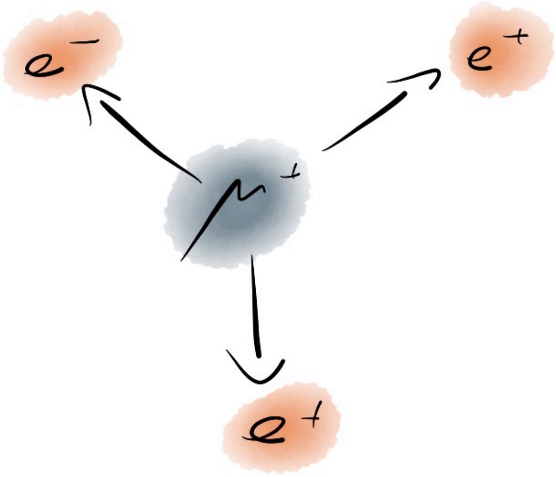


$$BR(\mu^+ \to e^+e^+e^-) \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2$$

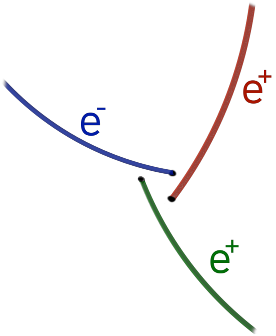
- Possible in SM via neutrino mixing
- Branching ratio ~ 10^{-54} ⟶ any observation is a sign of physics beyond the SM
- Limiting factors:
  - Number of stopped muons
  - Background suppression

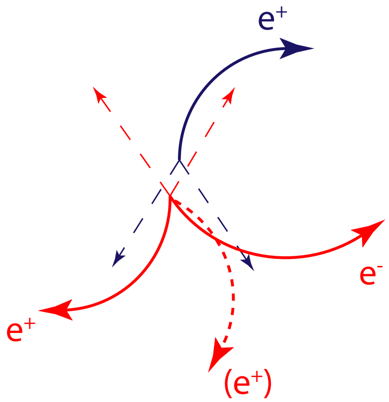
Mu3e

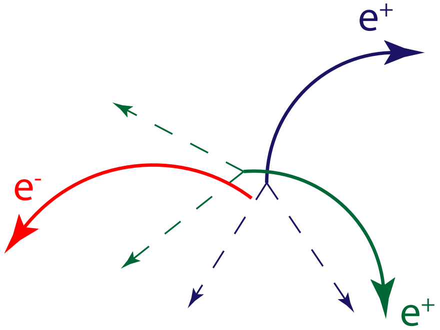
- Search for the rare cLFV decay $\mu^+ \rightarrow e^+e^+e^-$
  - Current limit: $BR < 10^{-12}$ at 90% CL (SINDRUM I, 1988)
- Kinematics:
  - Single vertex, three tracks coincident in time
  - Decay at rest $\longrightarrow \sum p_e = m_\mu$
- Mu3e Phase I at existing beam line ($\pi E5$) at Paul Scherrer Institute (PSI)
  - Single event sensitivity $\longrightarrow 2 \cdot 10^{-15}$



Combinatorial backgrounds







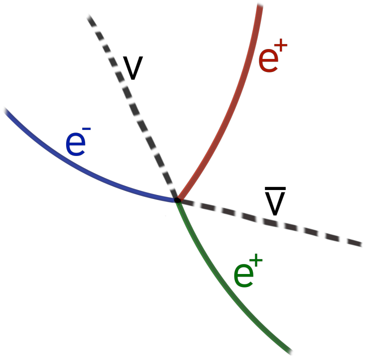
- No common vertex
- No time coincidence
- Accidental combinations

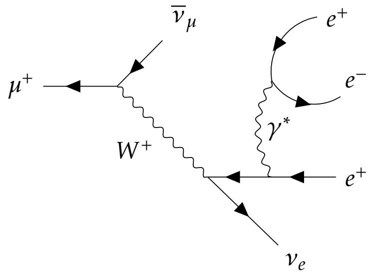
- e^+ from Michel decays
- e^- or e^+e^- from:
  - Bhabha scattering
  - Mis-reconstruction
  - Photon conversion

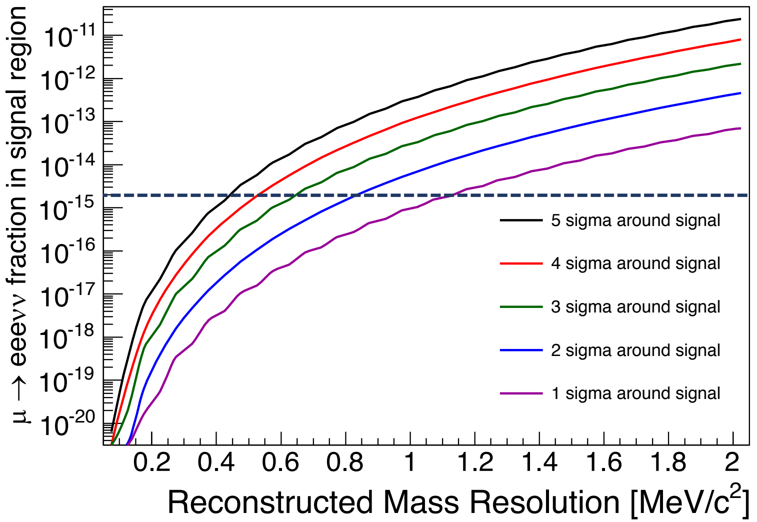
→ Need **good** vertex/time resolutions and low material amount

Internal Conversion (IC) background

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



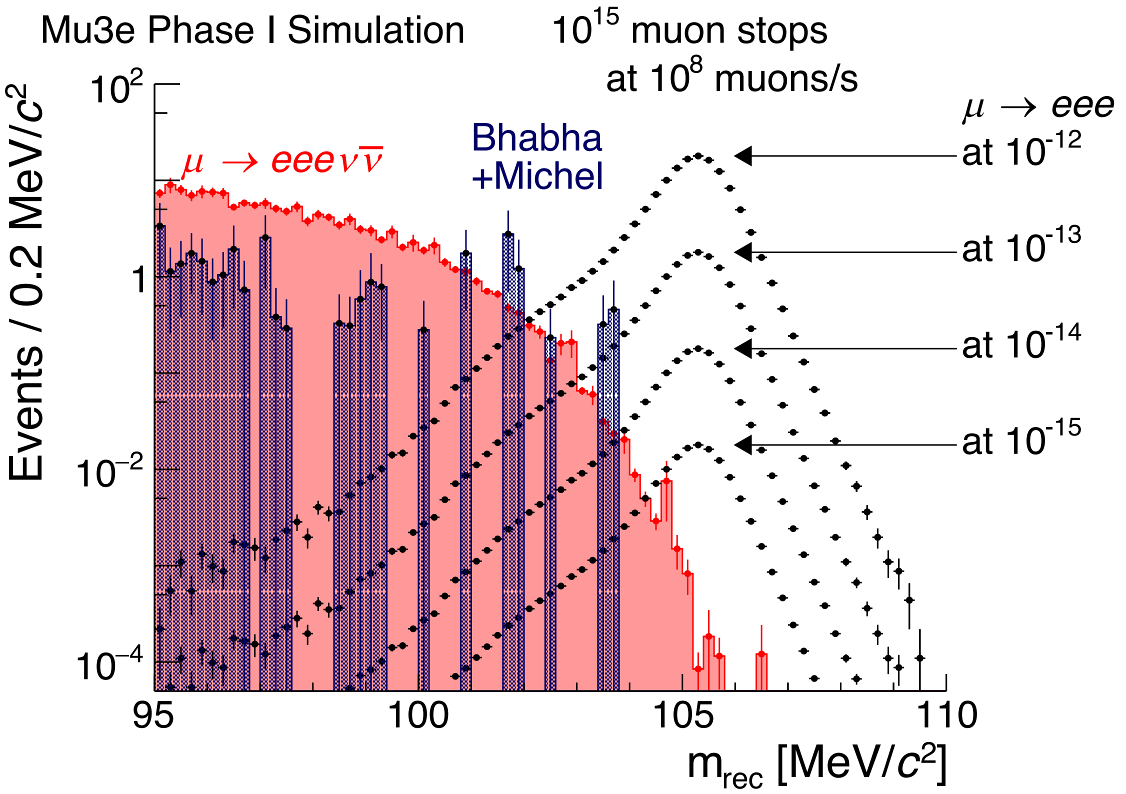




- Common vertex
- Time coincidence
- Missing momentum from neutrinos
- BR ~ 10^{-5}

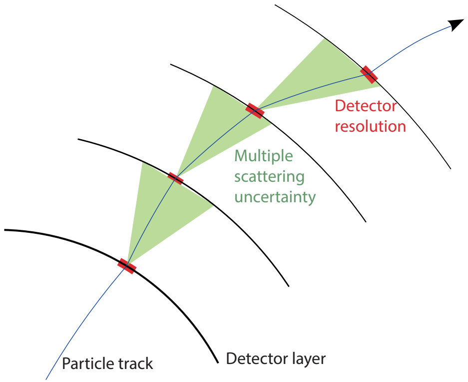
→ Need **excellent** momentum resolution ($\sigma_p < 1.0\ MeV/c$)

Simulated Phase I Mass Reconstruction

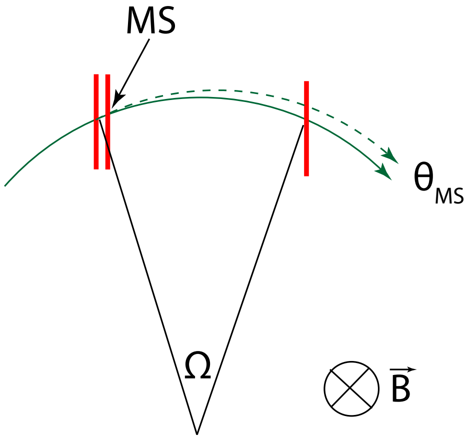


Measuring momentum

- Challenge ⟶ low momentum electrons & positrons!
- Resolution dominated by **multiple scattering** (MS)
- Track curvature (Ω) and MS angle (Θ_{MS})

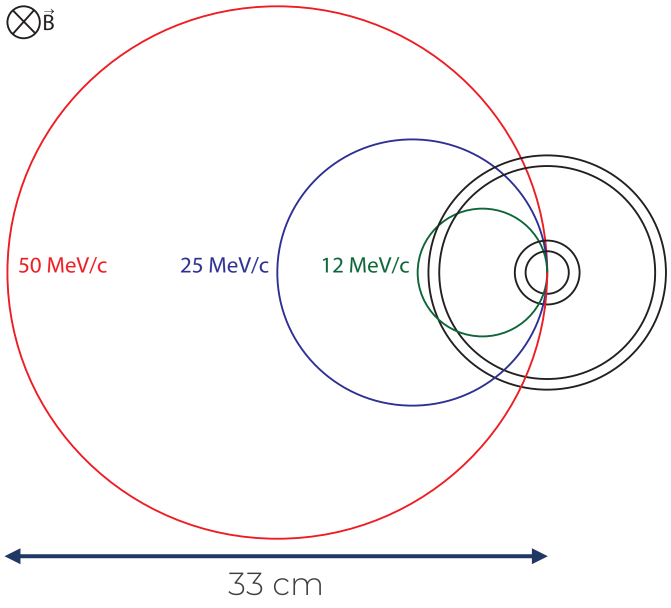


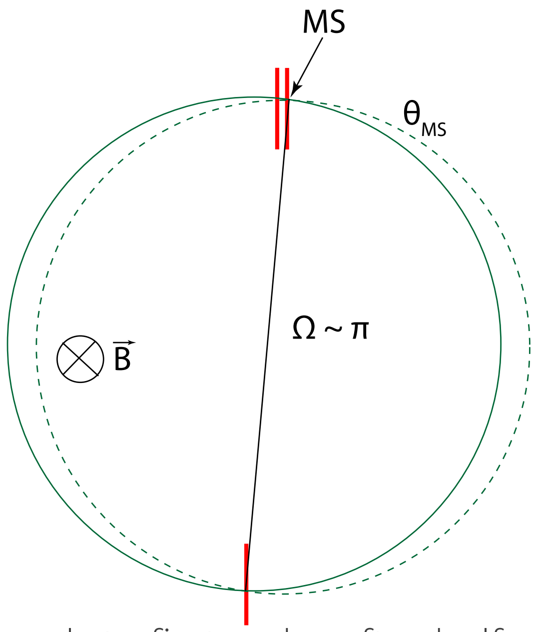
$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$



Measuring momentum

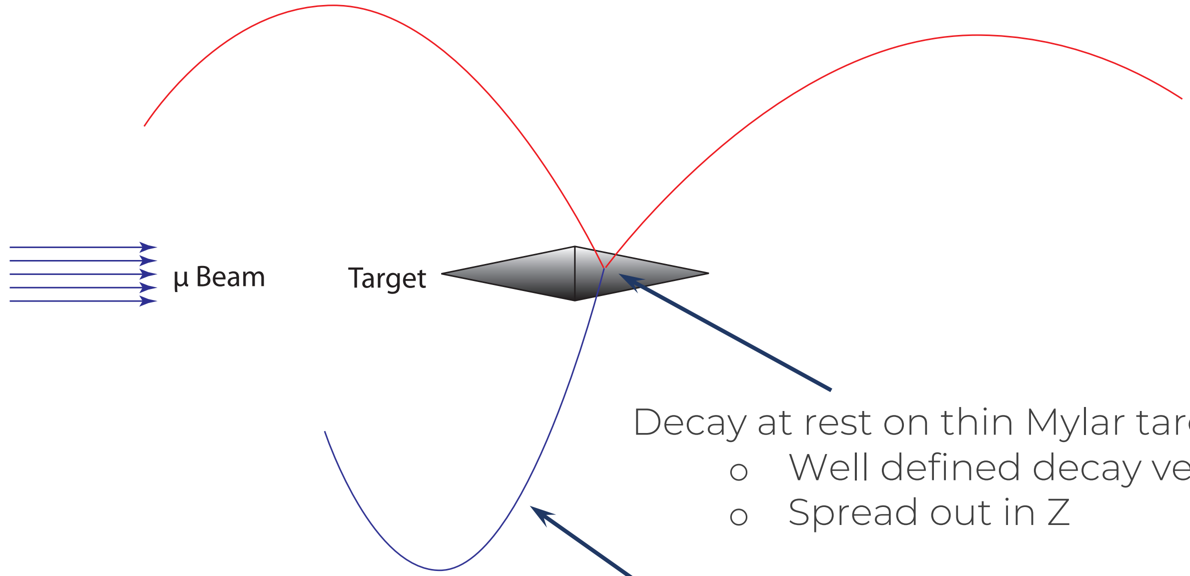
- Solution:
  - Minimise material amount, decreasing Θ_{MS}
  - Increase bending angle, Ω
  - (Include Θ_{MS} in track reconstruction)





σ_p cancels to first order after half a turn

Detector design



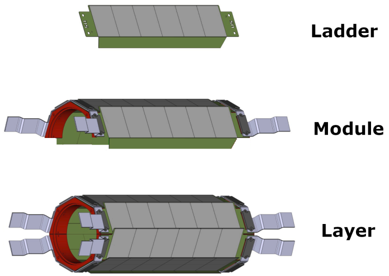
$10^8\ \mu/s$ at PSI
(~28 MeV/c)

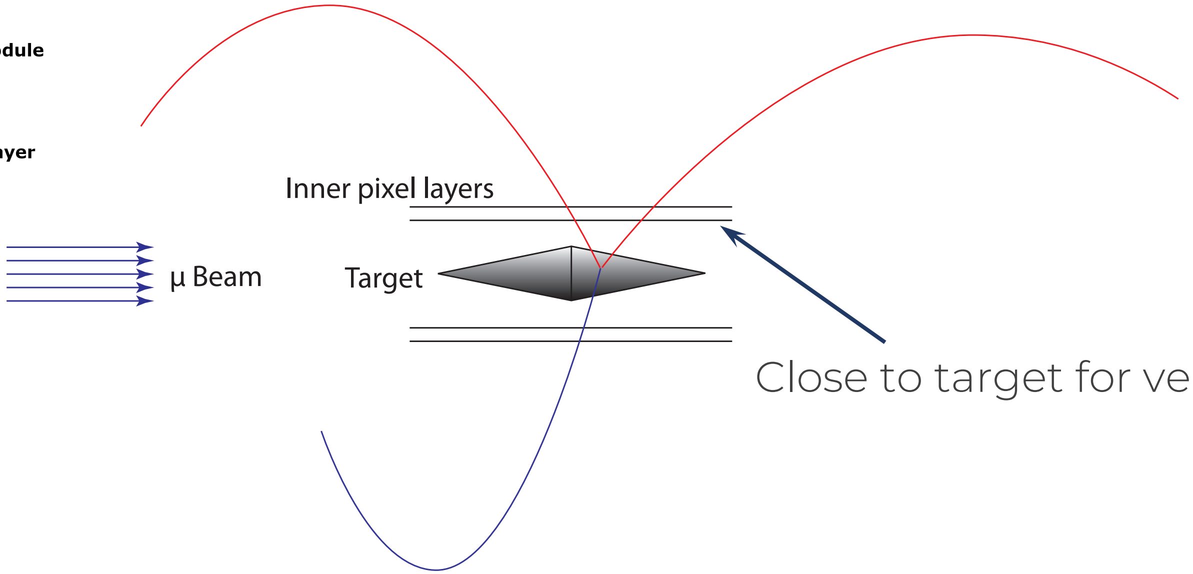
Decay at rest on thin Mylar target:
- Well defined decay vertices
- Spread out in Z

Inside 1.0 T magnetic field

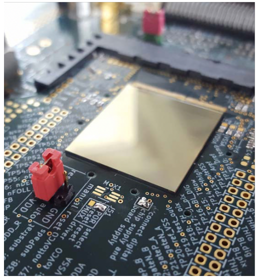
Detector design

Each pixel layer ~ 0.1 % radiation length (X_0)



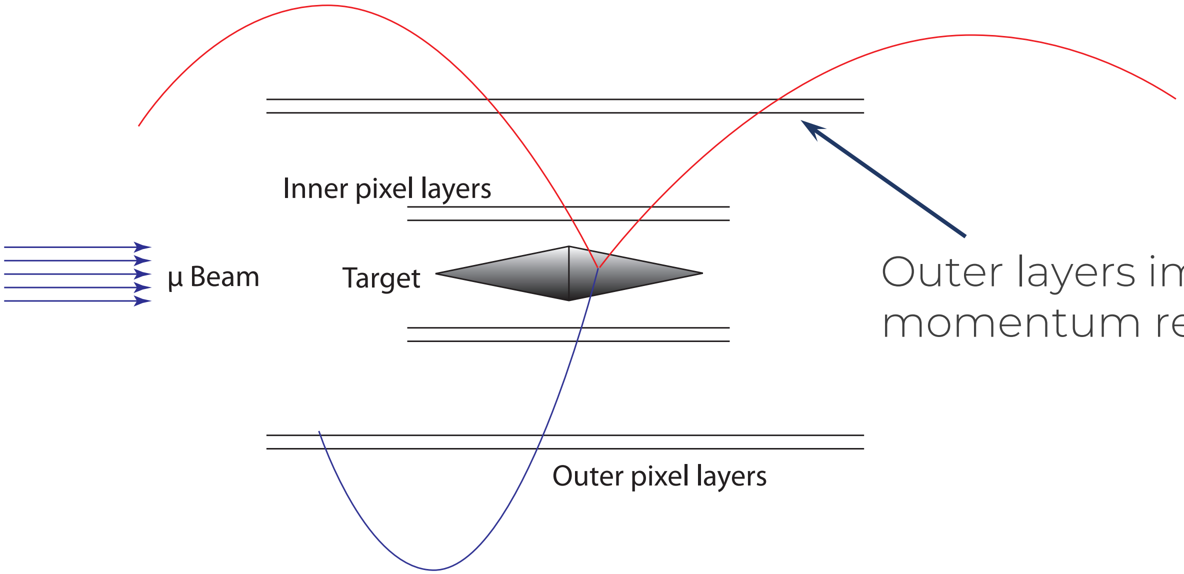


Close to target for vertexing



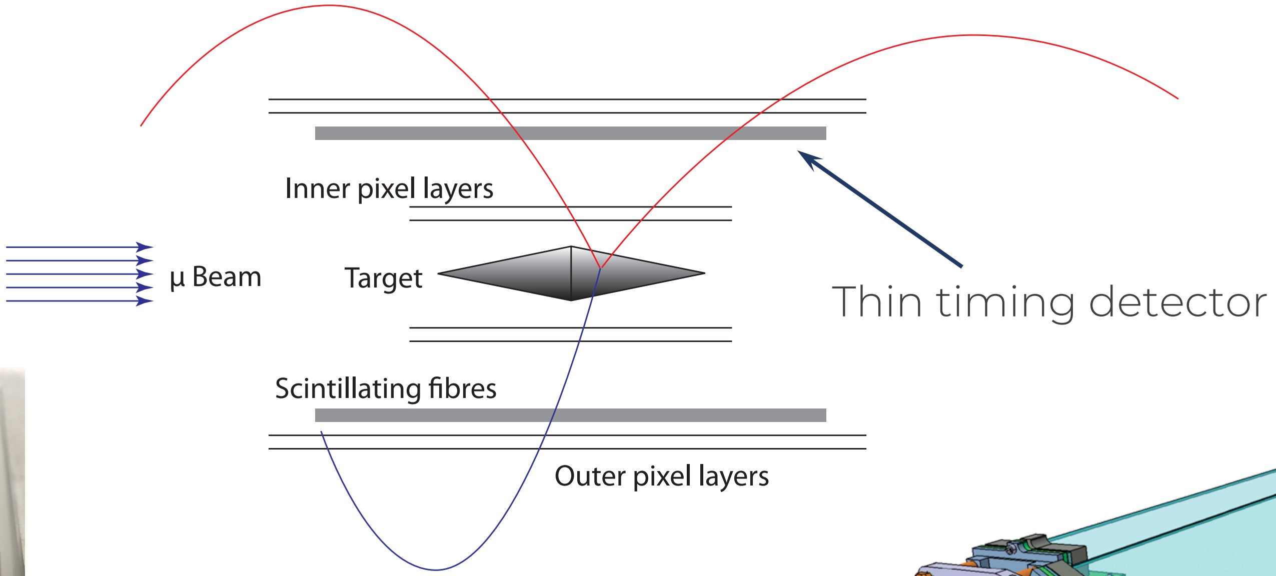
based on HV-MAPS technology ⟶ Ultra-thin

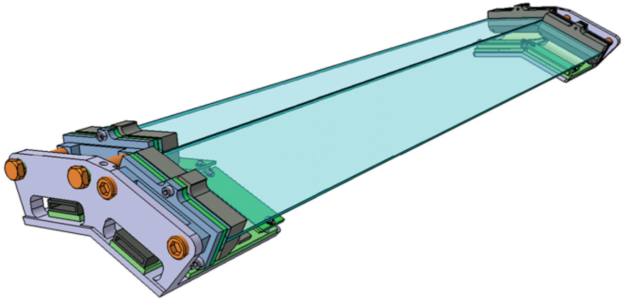
Detector design



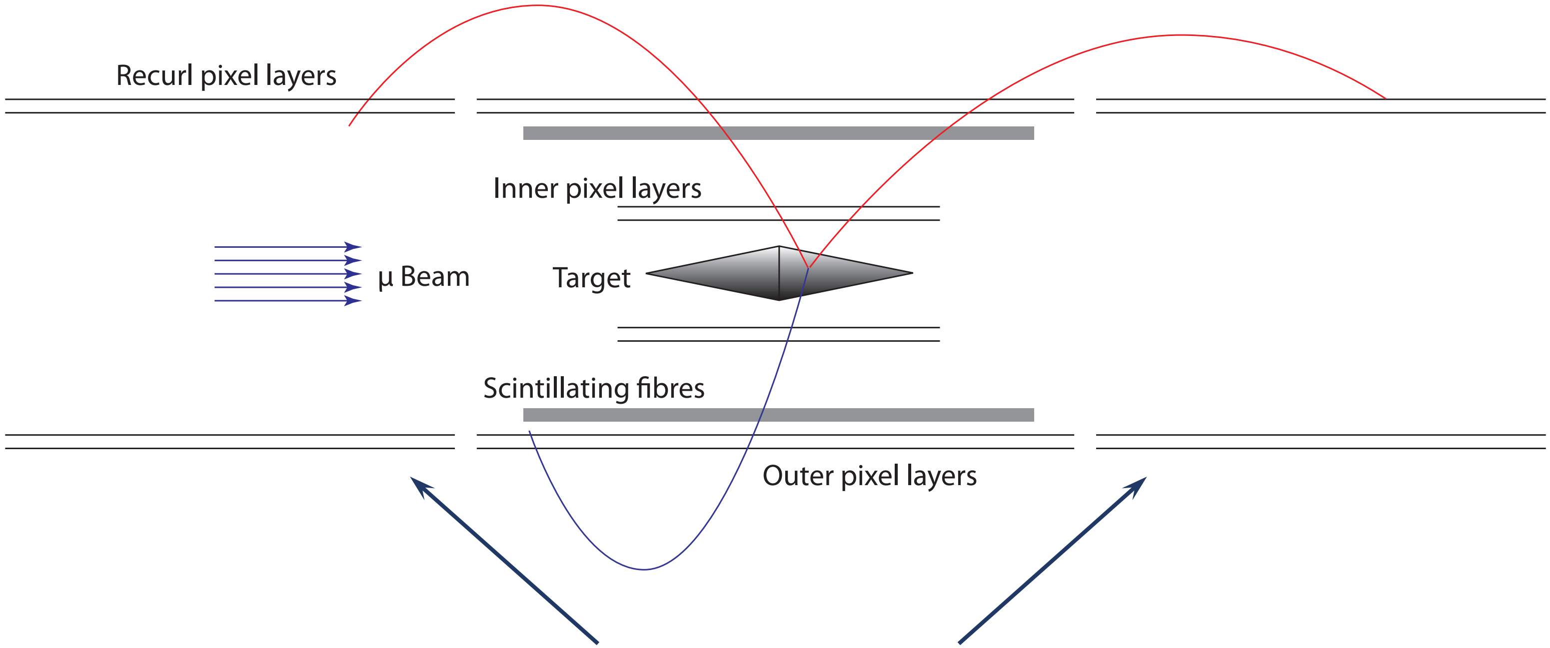
Outer layers improve momentum resolution

Detector design



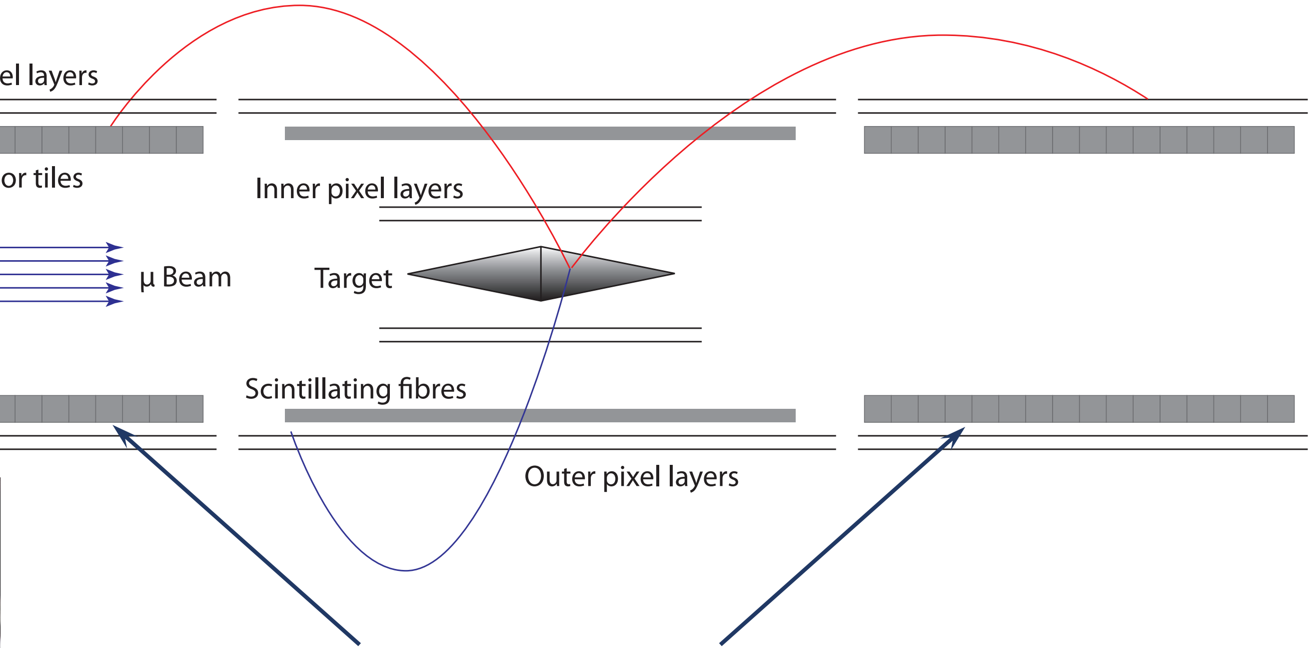


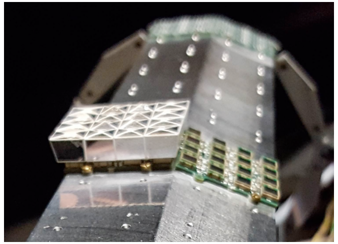
Detector design



Recurl stations increase acceptance

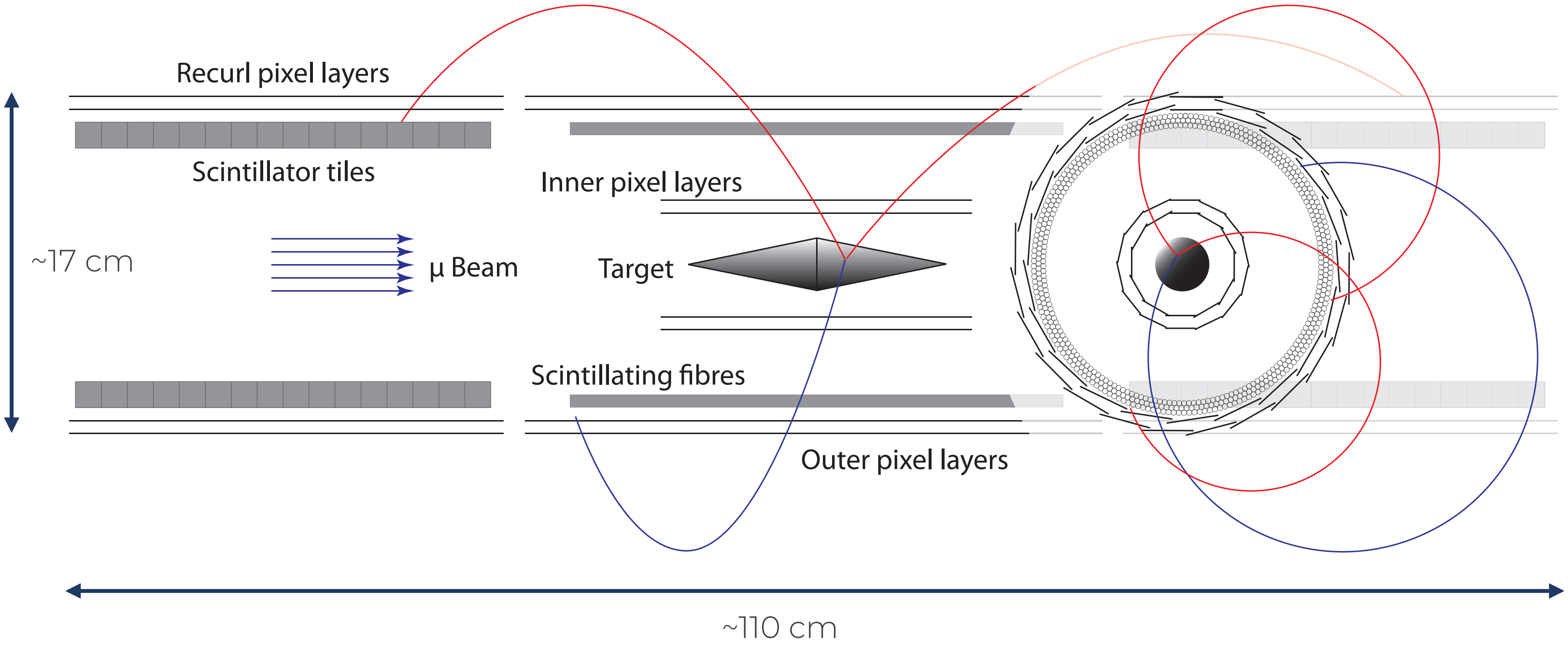
Detector design





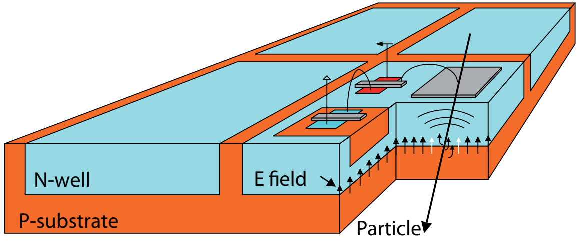
Timing detectors in recurl stations too

Detector design

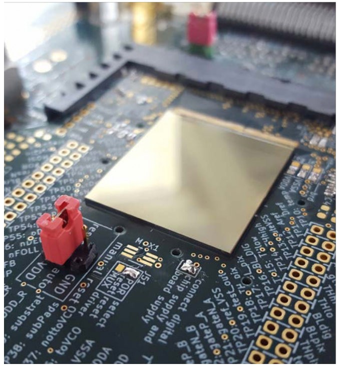


High Voltage – Monolithic Active Pixel Sensors

- Sensor and readout fully integrated
- Fast charge collection (via drift)
- Last prototype MuPix10 meets requirements:
  - Thinned down to 50 μm
  - Active sensor size 2 cm x 2 cm
  - σ_t a few ns

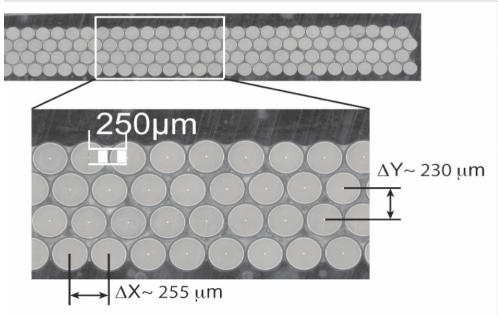


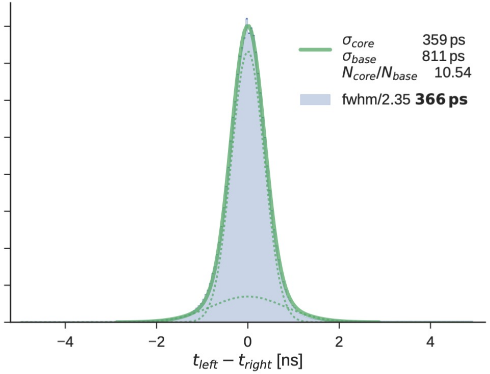
(I.Peric,NIM A 582 (2007) 876)



Scintillating Fibres (SciFi)

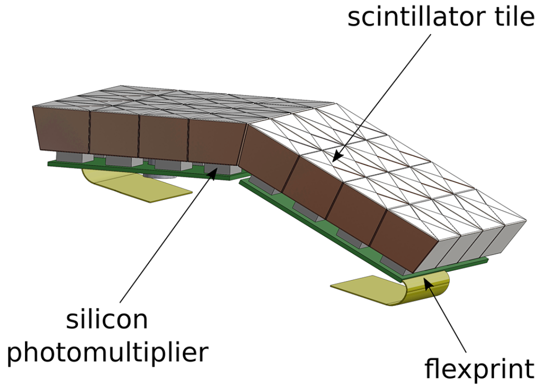
- Need timing to supress combinatorial backgrounds
- Each ribbon → three layers of staggered fibres
  - 250 μm fibre diameter
  - < 0.2 % X_0
- Silicon photomultiplier (SiPM) arrays detect light at both ends of ribbon
- σ_t a few hundred ps

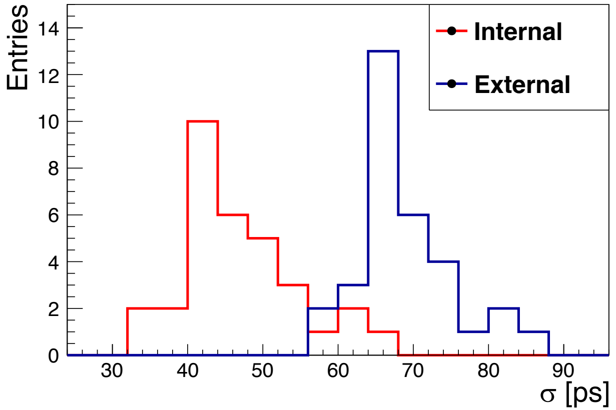


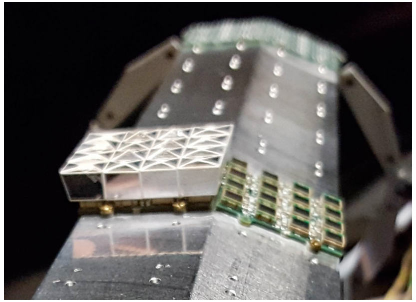


Scintillating Tiles

- Placed at end of recurler trajectory → can be thicker
- Tile is finely segmented plastic scintillator
- Each tile read out by it's own SiPM
- $\sigma_t \sim$ tens of ps

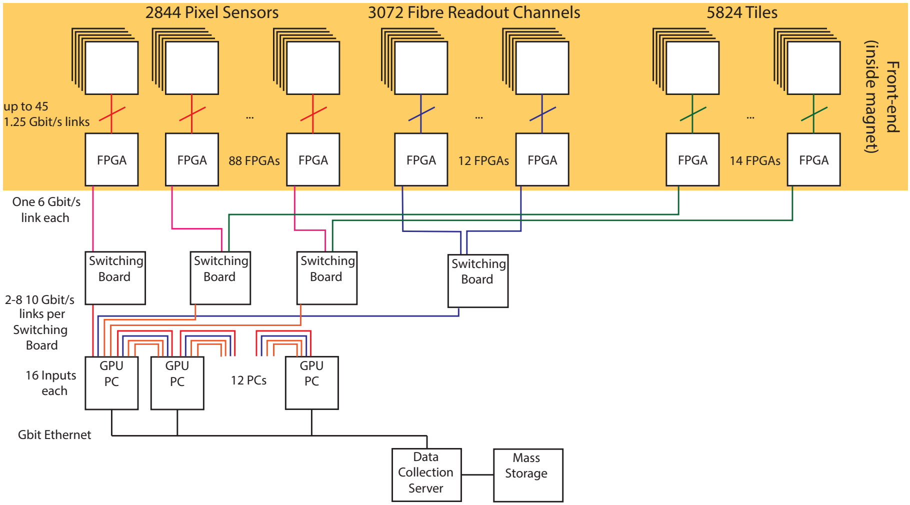






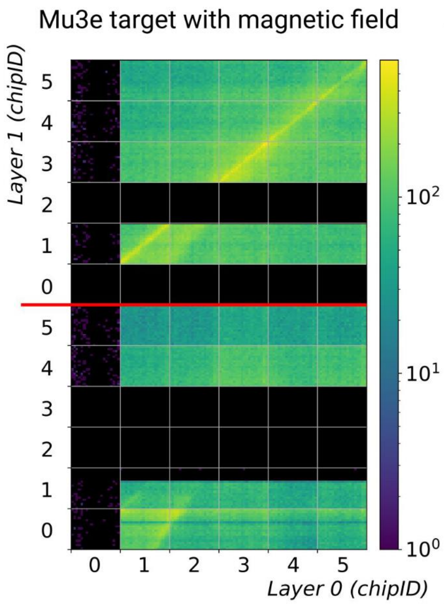
Data Acquisition (DAQ)

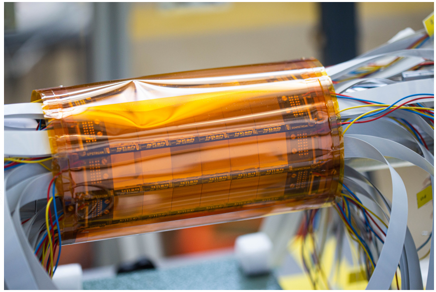
- No trigger
- Synchronise data from all sub-detectors
- Online event selection
  - Tracking & vertexing on GPUs
- Only signal candidates saved
- Tested during two integrations runs



Integration run 2021

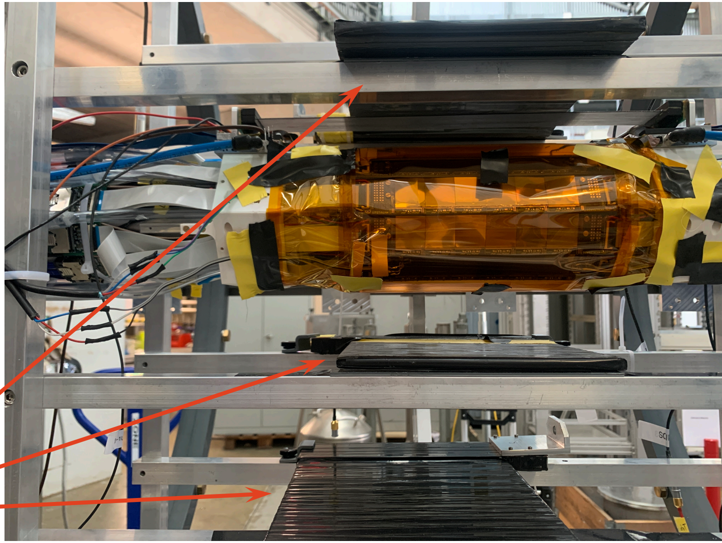
- Detector setup:
  - Vertex detector prototype with MuPix10
  - Two SciFi ribbons
  - Phase I magnet
- Services:
  - He cooling
  - Cage
  - Beam ($\pi E5$)
- Correlations between ladders observed





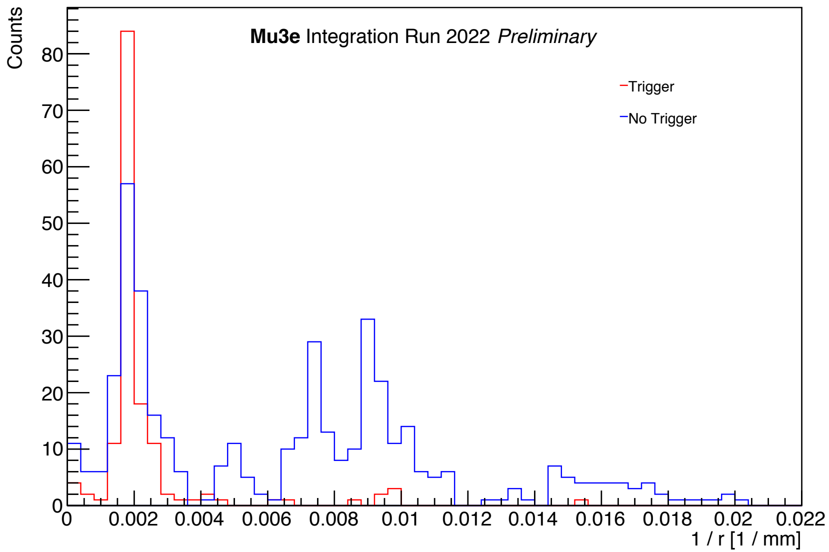
Integration run 2022

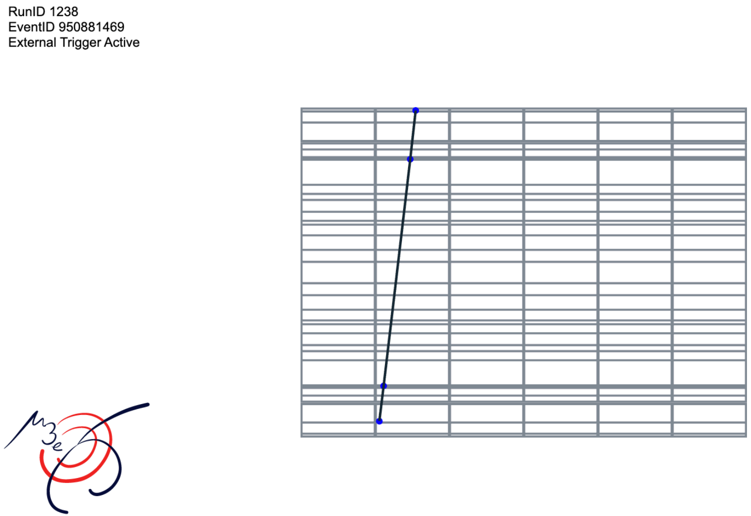
- Recently finished
- Same setup but **without magnet** and only one SciFi ribbon
- Looking for **cosmics** ⟶ requires well tuned detector
- External trigger from scintillator blades



Integration run 2022 results

- (Cosmic) reconstruction integrated into online analyzer
- Observed potential cosmic rays in event display





Summary

- The Mu3e experiment will search for the rare cLFV decay $\mu^+ \rightarrow e^+ e^+ e^-$
- Find or exclude at a branching ratio above 10^{-15} (Phase I) or 10^{-16} (Phase II)
- Detector prototypes built and tested together (in Magnet & Helium)
- Commissioning to start in late 2023
- Physics data taking to start in 2024

Thanks for listening!

- Questions?

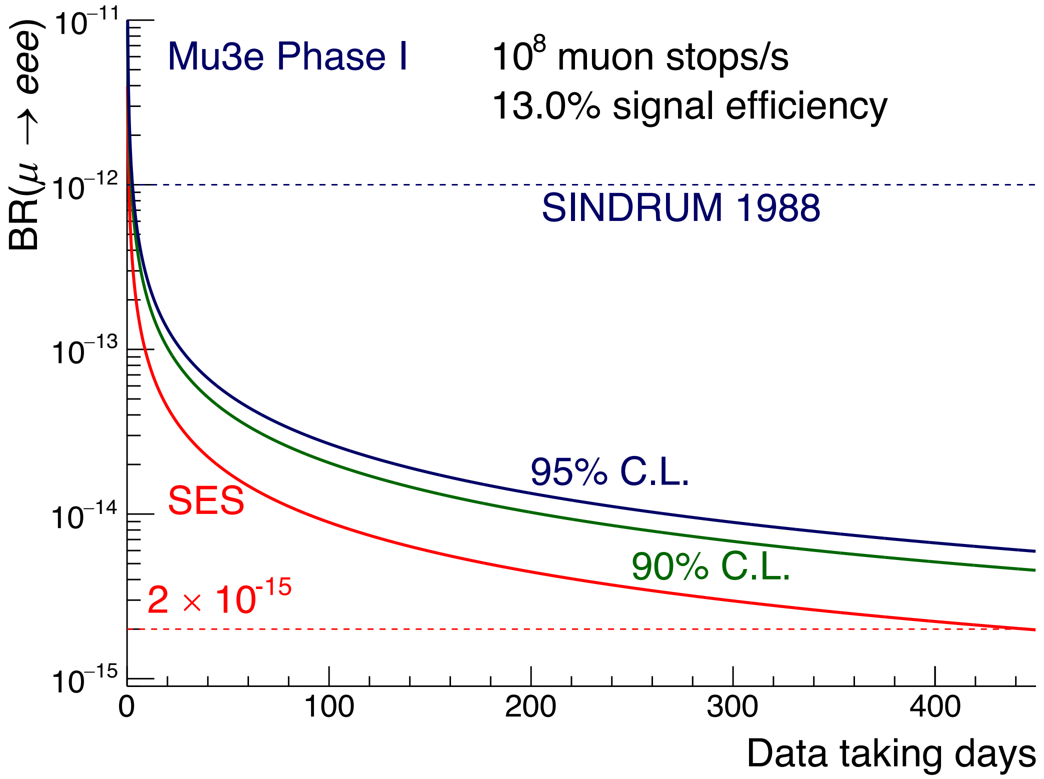
Bibliography

- Mu3e:
  - K. Arndt *et al.*, "Technical design of the phase I Mu3e experiment," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* vol. 1014, p. 165679, 2021/10/21/ 2021, doi: https://doi.org/10.1016/j.nima.2021.165679.
  - Niklaus Berger, Moritz Kiehn, Alexandr Kozlinskiy, and Andre Schöning. 2017. A New Three-Dimensional Track Fit with Multiple Scattering. Nucl. Instrum. Meth. A 844, (2017), 135. DOI:https://doi.org/10.1016/j.nima.2016.11.012
- SINDRUM I:
  - U. Bellgardt et al., “Search for the Decay mu+ -> e+ e+ e-,” Nucl. Phys. B, vol. 299, pp. 1–6, 1988, doi: https://doi.org/10.1016/0550-3213(88)90462-2
- Muon beamline:
  - Felix Anton Berg. 2017. CMBL - A High-Intensity Muon Beam Line & Scintillation Target with Monitoring System for Next-Generation Charged Lepton Flavour Violation Experiments. PhD Thesis. ETH Zurich, Zurich. DOI:https://doi.org/10.3929/ethz-b-000213470
- BR for CLFV:
  - Calibbi L, Signorelli G (2018) Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction. Riv Nuovo Cim 41:71–174. https://doi.org/10.1393/ncr/i2018-10144-0

Backup

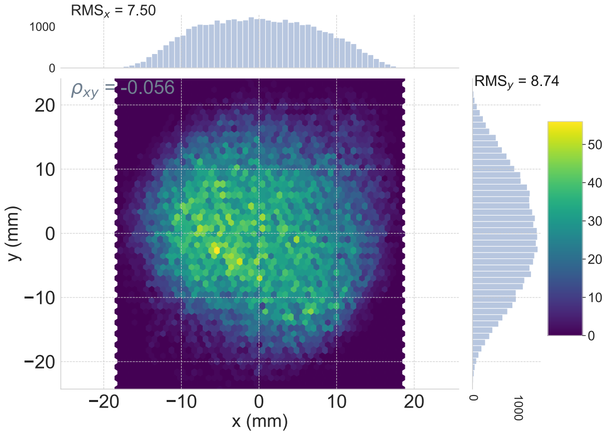
Summary of Phase I

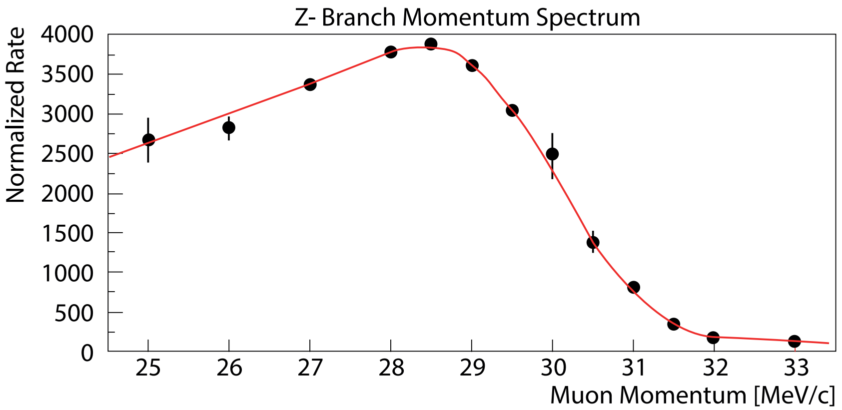
- Muon beam rate of 10^8 Hz
- 1 Year of data taking
- Find or exclude $\mu^+ \rightarrow e^+e^+e^-$ at branching ratio above 10^{-15}
  - Phase II above 10^{-16}
- $SES = \frac{1}{\varepsilon \cdot N_\mu}$



Muon beam

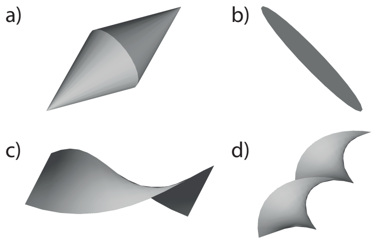
- $\pi E5$ at Paul Scherrer Institute
- Demonstrated rates of O(10^8) Hz

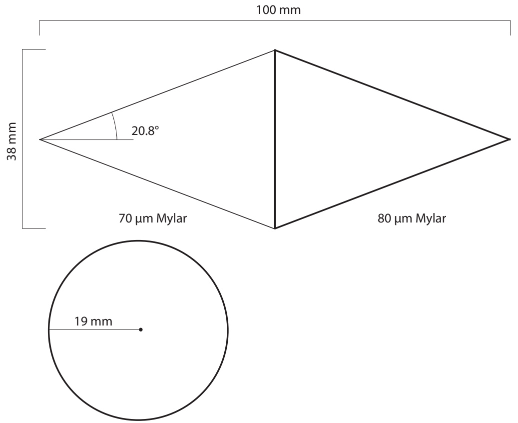


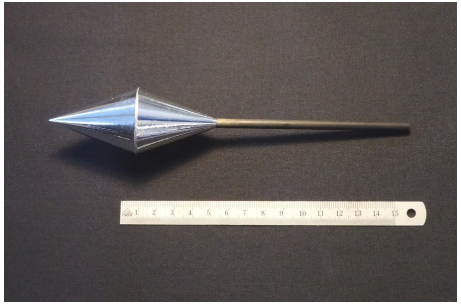


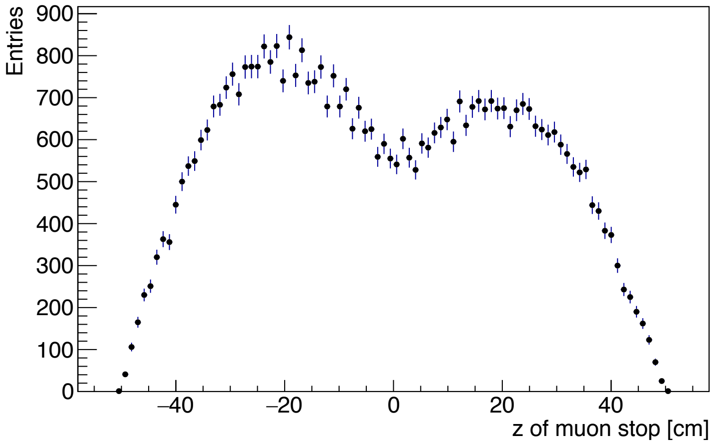
Target

- Maximise stopping power & minimise material amount
- Low Z material, Mylar
- Decay vertices well spread out
  ⟶ reduce combinatorial background & even occupancy in vertex layers
- Corresponds to 0.15 % X_0
- Stopping fraction ~ 95.5 %







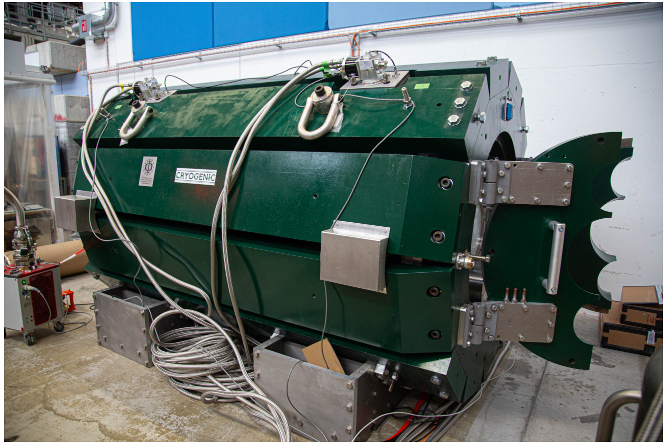


Magnet

- Delivered in 2020 by Cryogenics Ltd.

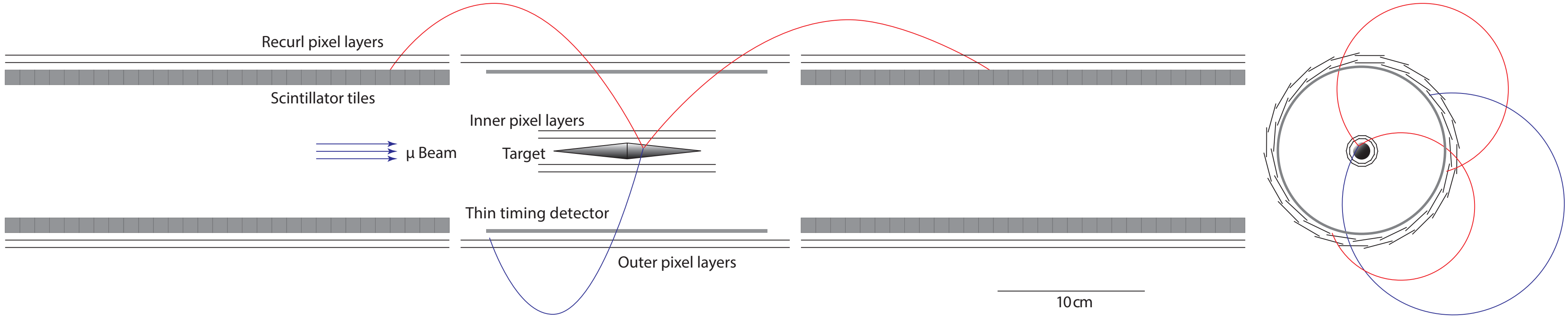
MAGNET PARAMETER	VALUE
nominal field	1.0 T
warm bore diameter	1.0 m
warm bore length	2.7 m
field inhomogeneity $\Delta B/B$	$\leq 10^{-3}$
field stability $\Delta B/B$ (100 days)	$\leq 10^{-4}$
field measurement accuracy $\Delta B/B$	$\leq 2.0 \cdot 10^{-4}$
outer dimensions: length	≤ 3.2 m
width	≤ 2.0 m
height	≤ 3.5 m

Requirements



Phase II detector

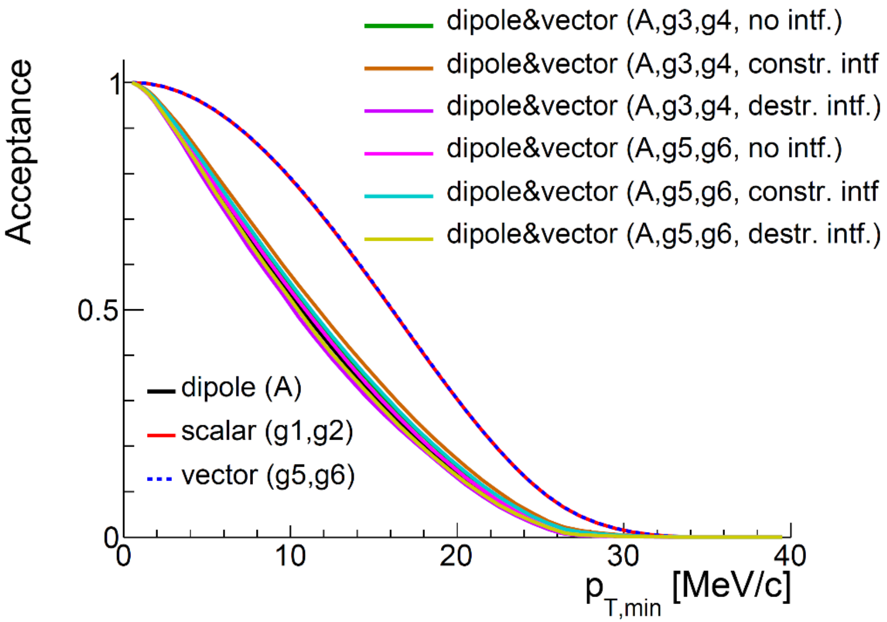
- High intensity muon beamline (HIMB) under study at PSI
  - Would deliver > 10^9 Hz
- Possible setup:
  - Longer recurl stations
  - Smaller target



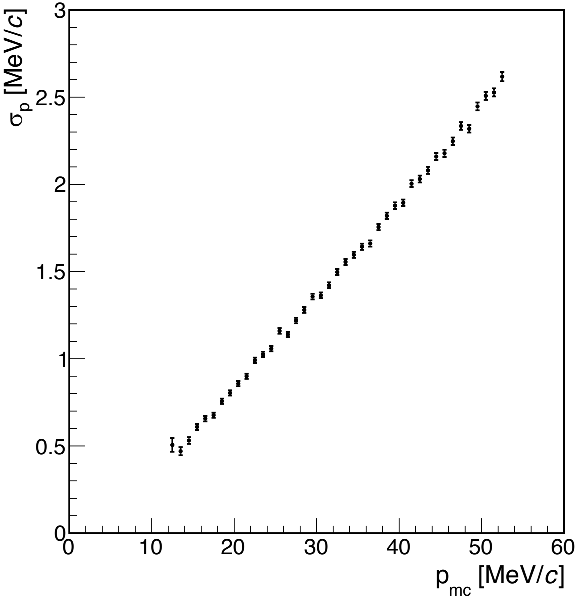
Simulated efficiencies

Step	Step efficiency	Total efficiency
Muon stops	100%	100%
Geometrical acceptance, short tracks	38.1%	38.1%
Geometrical acceptance, long tracks	68.0%	25.9%
Short track reconstruction	89.5%	34.1%
Long track reconstruction[1]	67.2%	17.4%
Recurler rejection/Vertex fit convergence	99.4%	17.3%
Vertex fit $\chi^2 < 15$	91.3%	15.8%
CMS momentum $< 4\,\mathrm{MeV/c}$	95.6%	15.1%
$m_{ee,low} < 5\,\mathrm{MeV/c^2}$ or $> 10\,\mathrm{MeV/c^2}$	98.0%	14.9%
$103\,\mathrm{MeV/c^2} < m_{rec} < 110\,\mathrm{MeV/c^2}$	97.0%	14.4%
Timing	90.0%	13.0%

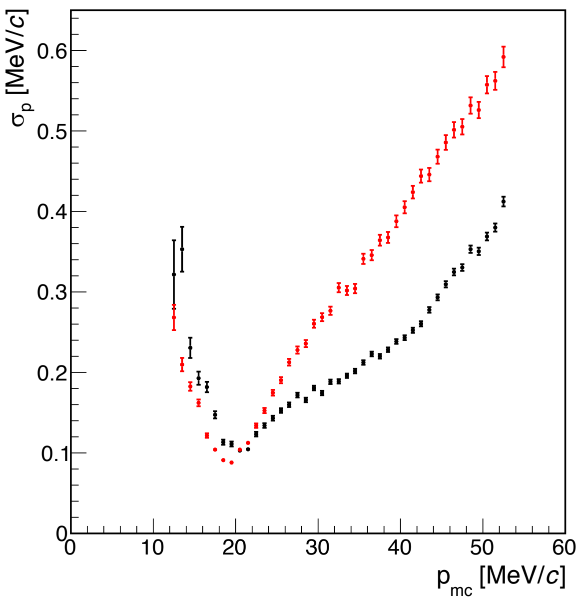
Acceptance to different interaction types



Track momentum resolutions

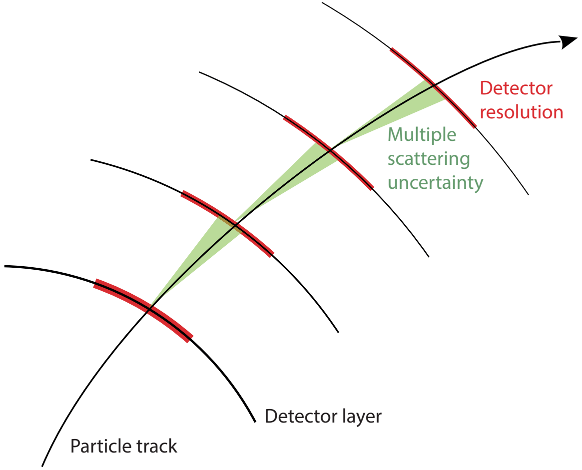


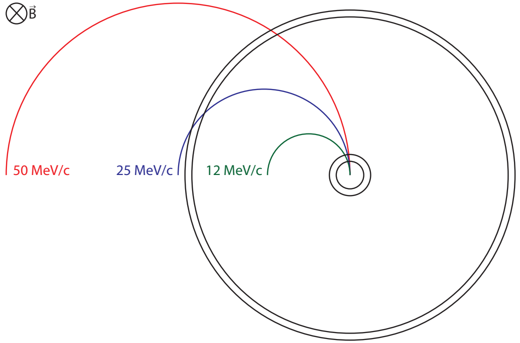
4-hit tracks



6-hit and 8-hit tracks

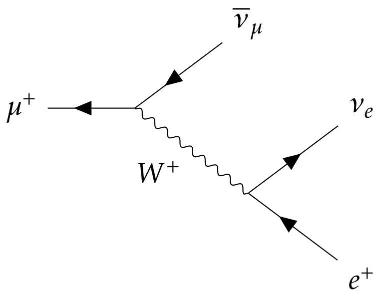
Multiple Scattering / Momentum measurements



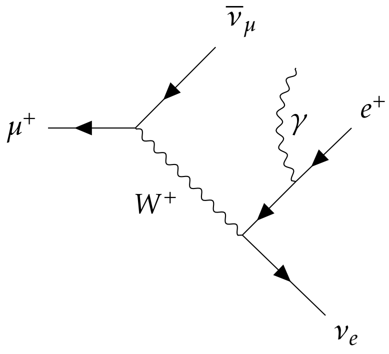


$$\sigma_{MS} = \frac{13.6\ MeV}{p\beta c} q \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right) \propto \frac{1}{p} \sqrt{\frac{x}{X_0}}$$

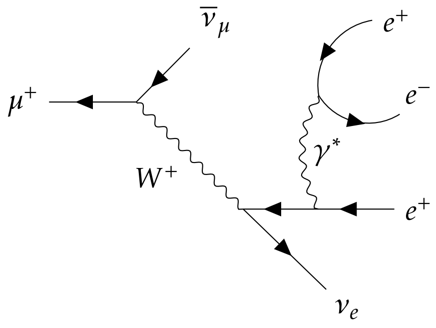
Feynman Diagrams



Michel decay, $\mu \to e\overline{\nu}\nu$.



Radiative muon decay, $\mu \to e\gamma\overline{\nu}\nu$.



Radiative muon decay with internal conversion, $\mu \to eee\overline{\nu}\nu$.

Integration run 2022 timing results

- Observed time correlations between pixels, SciFi and external trigger