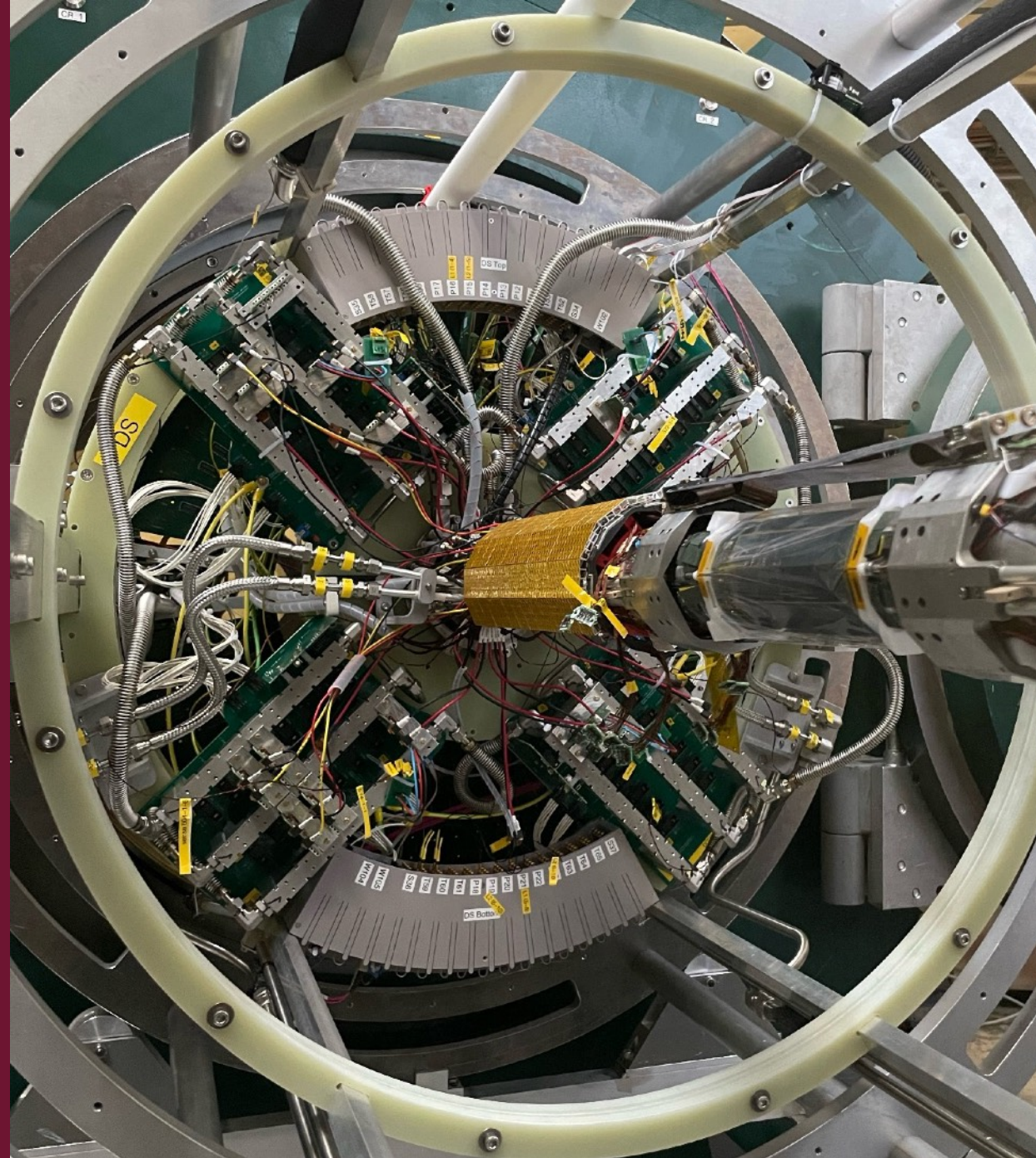


# Status of the Mu3e experiment at PSI



Mikio Sakurai

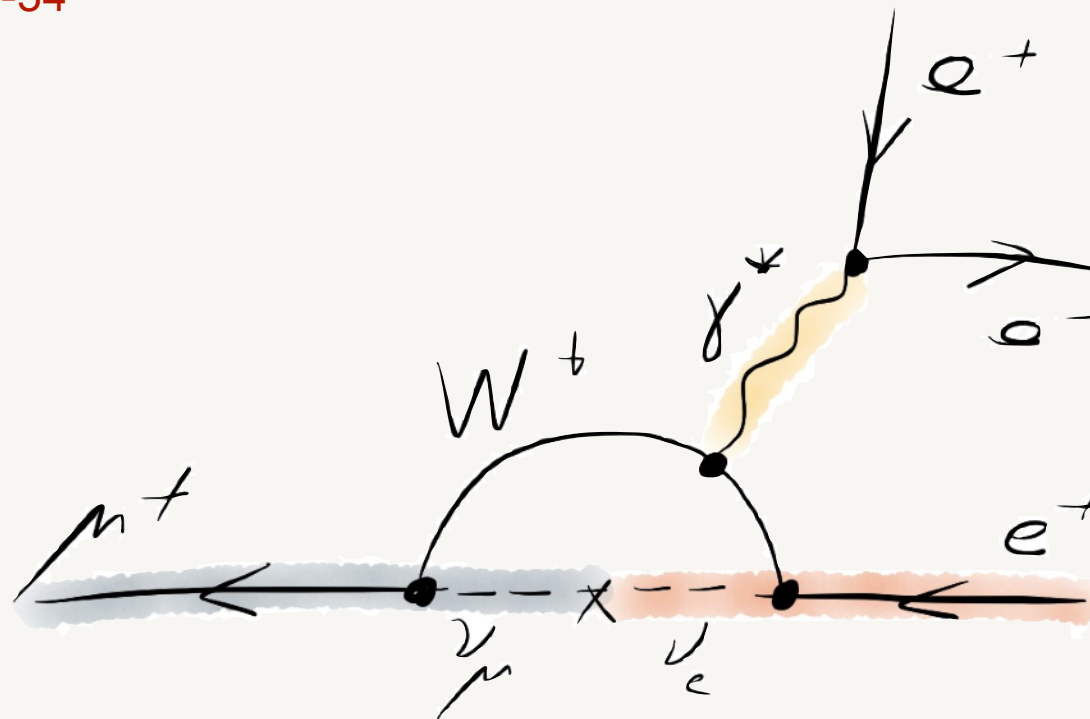
[m.sakurai@ucl.ac.uk](mailto:m.sakurai@ucl.ac.uk)

on behalf of the Mu3e collaboration



# Charged Lepton Flavour Violation (cLFV)

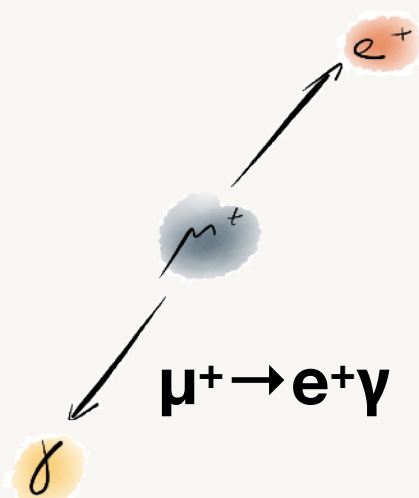
- Lepton flavour is conserved in the Standard Model
  - **Neutral** lepton flavour violation was observed via  **$\nu$  oscillations**
- **Charged** lepton flavour violation can be naturally possible but has not been observed
  - Heavily suppressed in the SM by  $(\Delta m_\nu^2/m_W^2)^2$   
 $BR(\mu^+ \rightarrow e^+ e^- e^+) < 10^{-54}$



- Any observation of cLFV is a clear sign of **new physics**
  - Many BSM models (SUSY, GUT,...) predict large cLFV effects

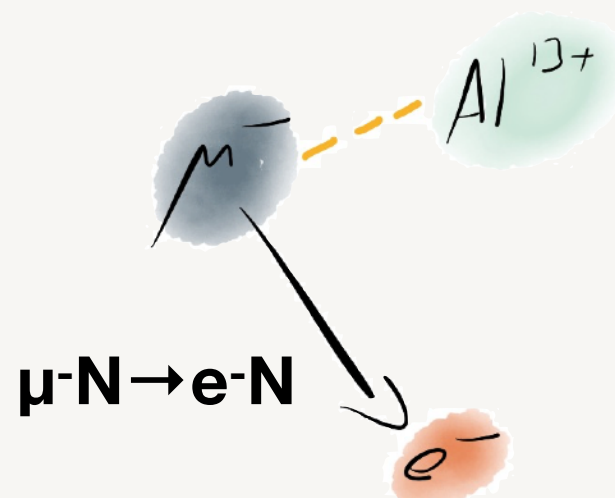
# The golden muon channels

- Muon is an excellent probe of cLFV process
  - Sensitive: New physics sensitivity scales with  $m_l^2$
  - Clean: Relatively long lifetime & simple decay channels
  - Available: High-intensity muon beams at PSI, J-PARC, Fermilab
- The three golden muon channels
  - Complementary cLFV searches with model-dependent sensitivity



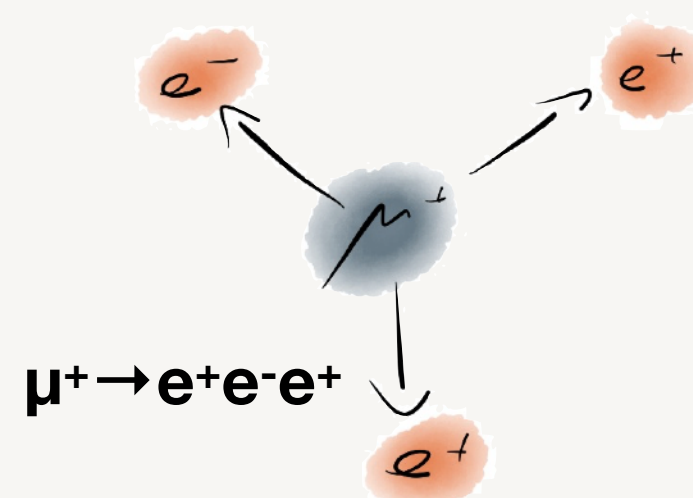
MEG/MEG II (PSI)  
BR  $< 1.5 \times 10^{-13}$  (2025)<sup>1</sup>

MEG II (PSI)



SINDRUM II (PSI)  
BR(Au)  $< 7 \times 10^{-13}$  (2006)<sup>2</sup>

COMET (J-PARC)  
Mu2e (Fermilab)



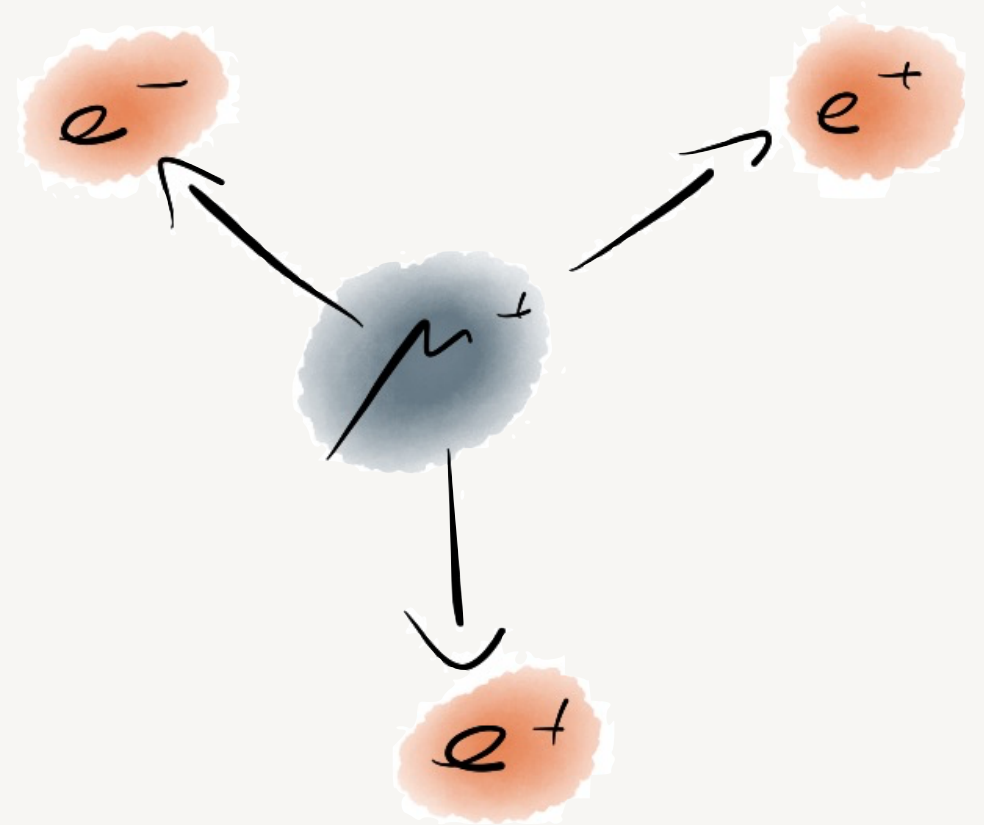
SINDRUM (PSI)  
BR  $< 1.0 \times 10^{-12}$  (1988)<sup>3</sup>

Mu3e (PSI)

(1) K. Afanaciev et al., arXiv:2504.15711 (2025), (2) W. Bertl et al., Eur.Phys.J.C 47 (2006) 337  
(3) U. Bellgardt et al., Nucl.Phys.B 299 (1988) 1



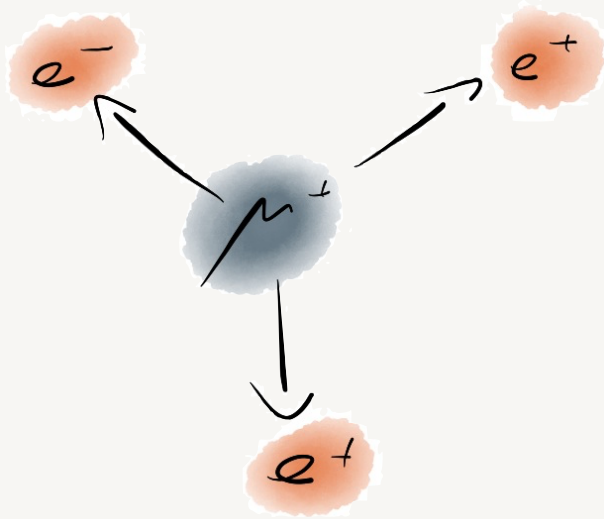
- The Mu3e experiment searches for the cLFV decay  $\mu^+ \rightarrow e^+ e^- e^+$
- Two-phase approach:
  - Phase I:  $\text{BR} < 2 \times 10^{-15}$
  - Phase II:  $\text{BR} < \mathcal{O}(10^{-16})$   
→ **4 orders of magnitude improvement** over the current limit
- Preparation for Physics Run in 2026 at PSI
  - Successful Commissioning Run in 2025





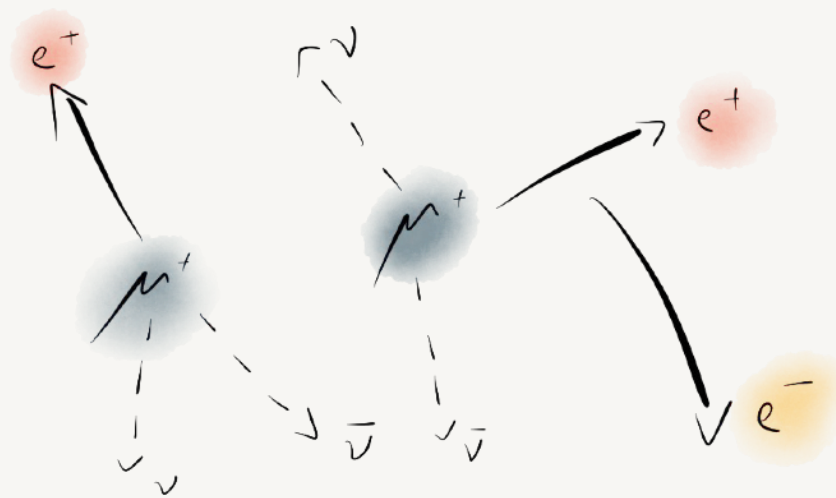
# The Mu3e signal and backgrounds

## Signal



- Common vertex
- Time coincidence
- $\Sigma \vec{p} = 0$
- $\Sigma E = m_\mu$

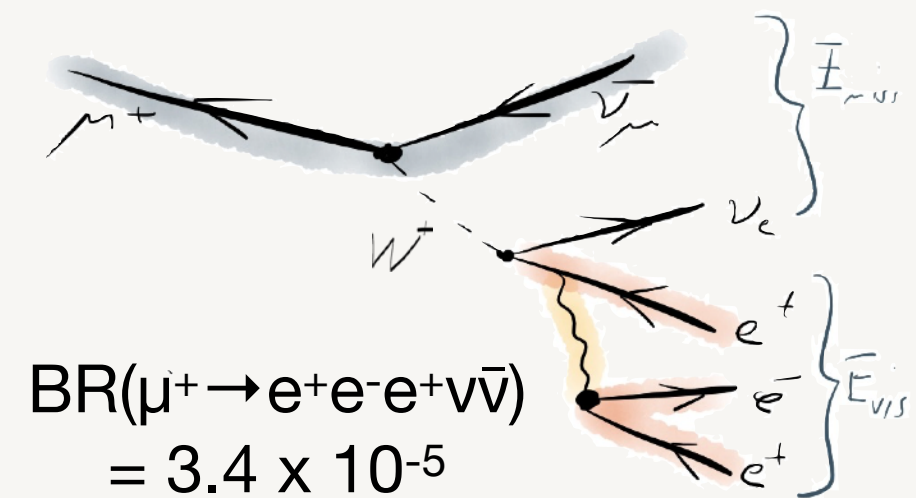
## Accidental



- **No common vertex**
- **No time coincidence**
- $\Sigma \vec{p} \neq 0$
- $\Sigma E \neq m_\mu$

Need excellent **vertex**,  
**timing** and **momentum**  
resolution

## Internal conversion

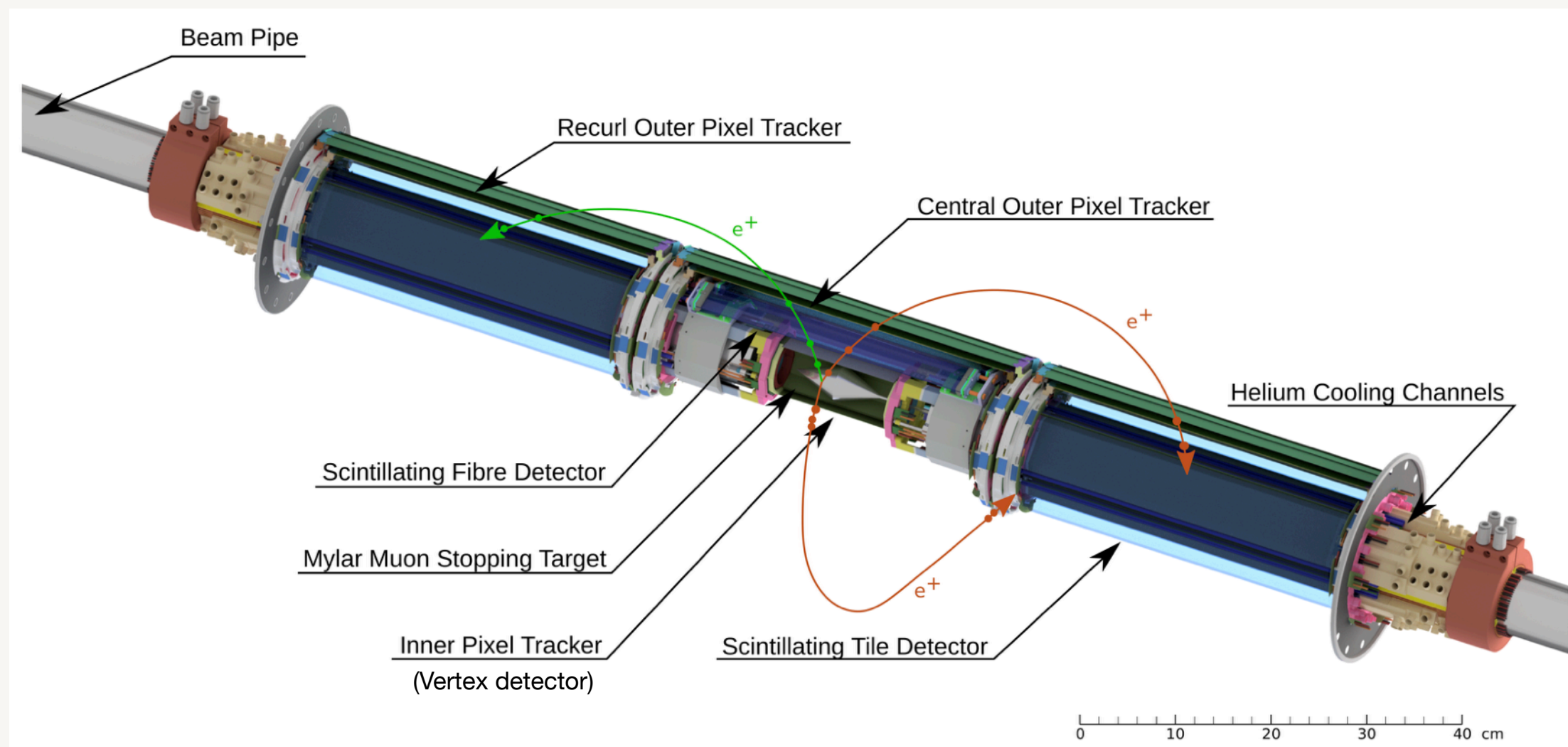


- Common vertex
- Time coincidence
- $\Sigma \vec{p} \neq 0$
- $\Sigma E \neq m_\mu$

Need **momentum** resolution

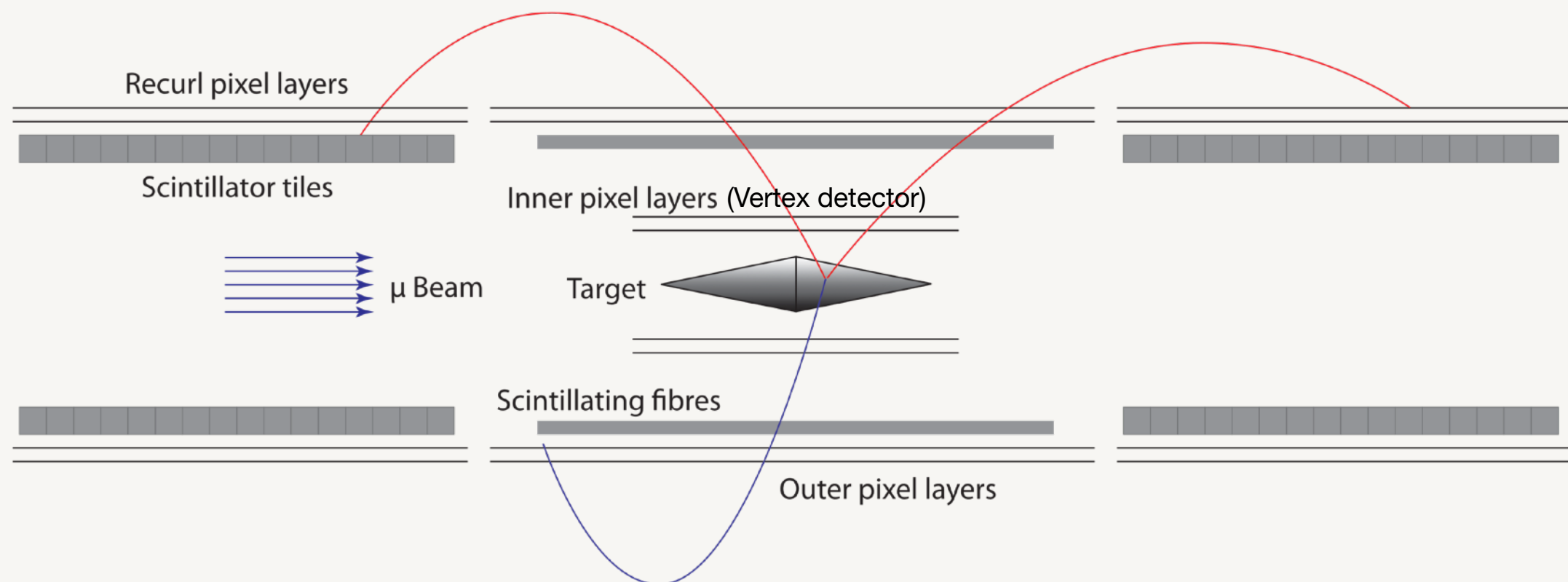
# Mu3e - Experimental requirements

- High-intensity beam → **High granularity** and **fast** processing ( $10^8$  Hz)
- MeV/c range  $e^+/e^-$  → **Low material budget**
- Accidental background → Good **vertex** ( $\sim 200$   $\mu\text{m}$ ) and **timing** ( $\sim 100$  ps) resolution
- Internal conversion → Excellent **momentum** resolution ( $< 1$  MeV/c) and **recurl stations**
- Compact design → High integration (detectors, DAQ, cooling, ...)



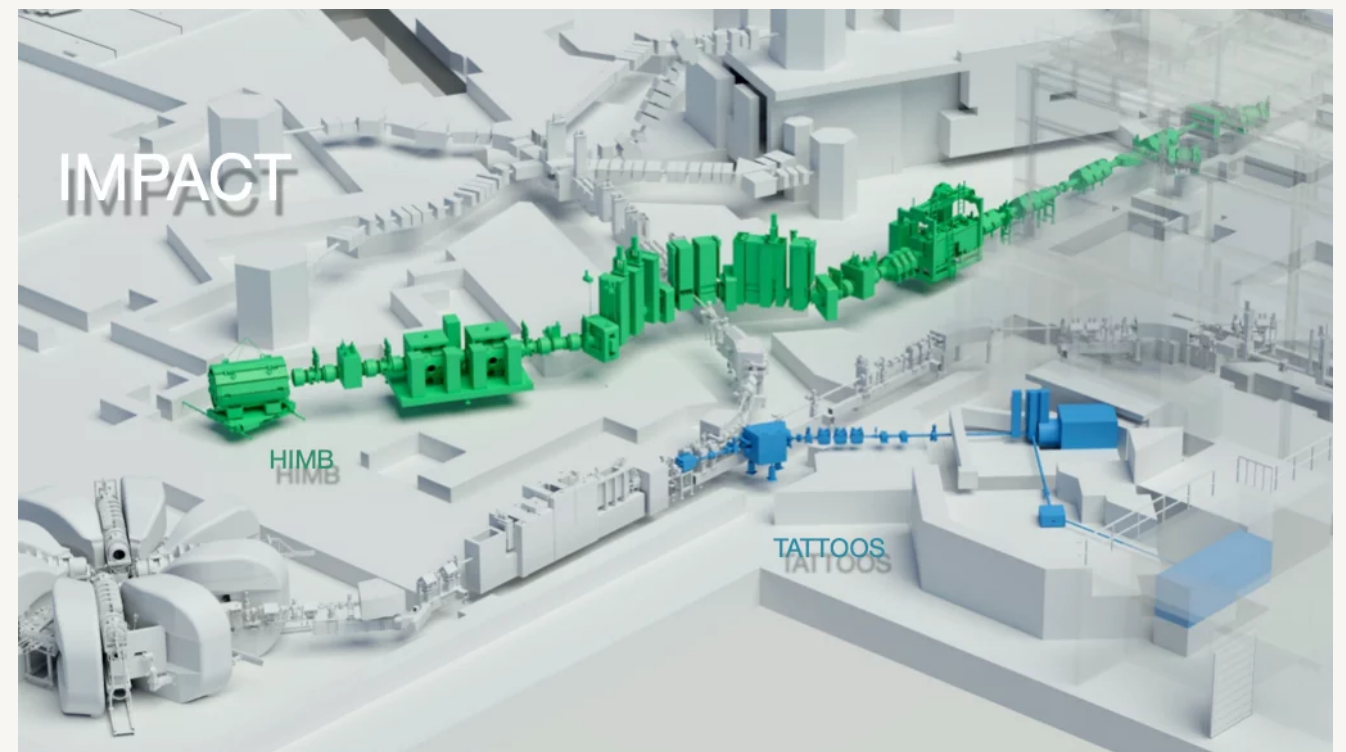
# Mu3e - Experimental principle

- $10^8 \mu^+/\text{s}$  at 28 MeV/c stopped on a double hollow-cone target
- Helical decay  $e^+/e^-$  tracks in a uniform 1 T magnetic field
- 2 ultra-thin inner pixel layers: precise vertexing
- 2 outer pixel layers: 4+ hit track reconstruction
- Scintillating fibres: timing and  $e^+/e^-$  identification
- Recurl pixel layers: optimal momentum resolution and acceptance
- Scintillating tiles: precise timing

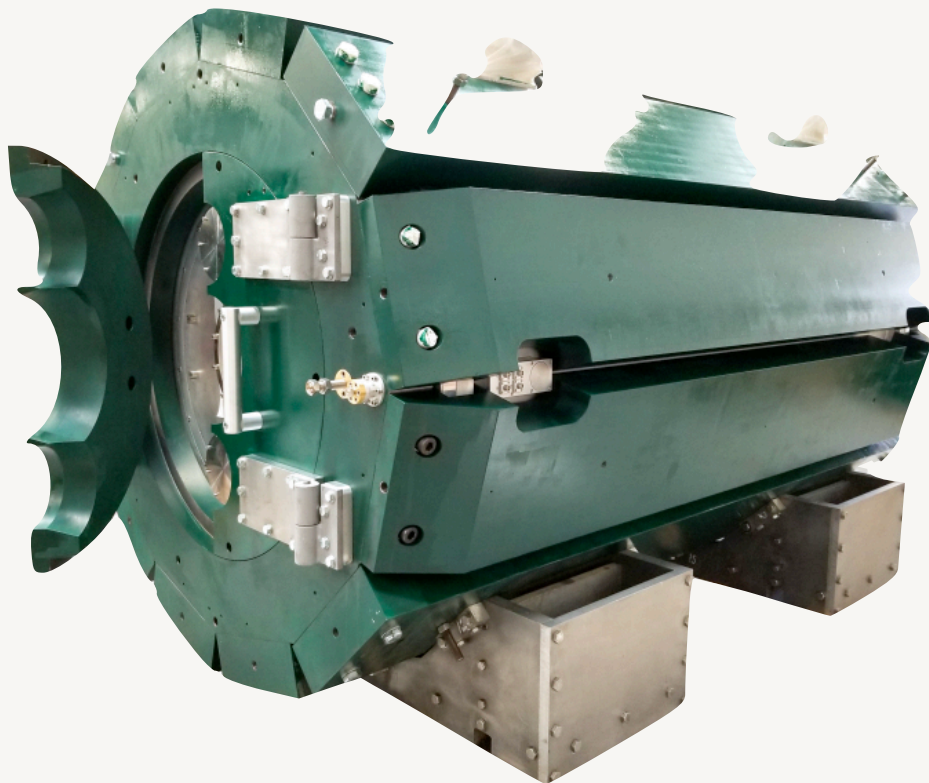
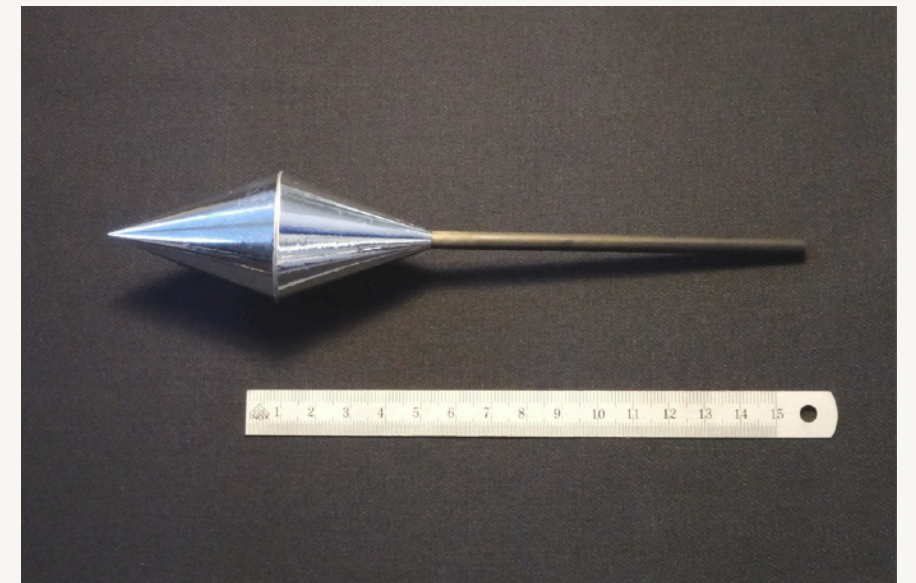




- **HIPA** at Paul Scherrer Institute in Switzerland
  - 590 MeV proton beam with up to 2.4 mA
  - Graphite target → pion production → decay to surface muons
- World's most intense DC muon beam
  - Up to  $10^8 \mu^+/\text{s}$  available at existing  **$\pi\text{E5}$**  beamline → **Mu3e Phase I**
  - High-Intensity Muon Beamline (**HIMB**) with up to  $10^{10} \mu^+/\text{s}$  → **Mu3e Phase II**



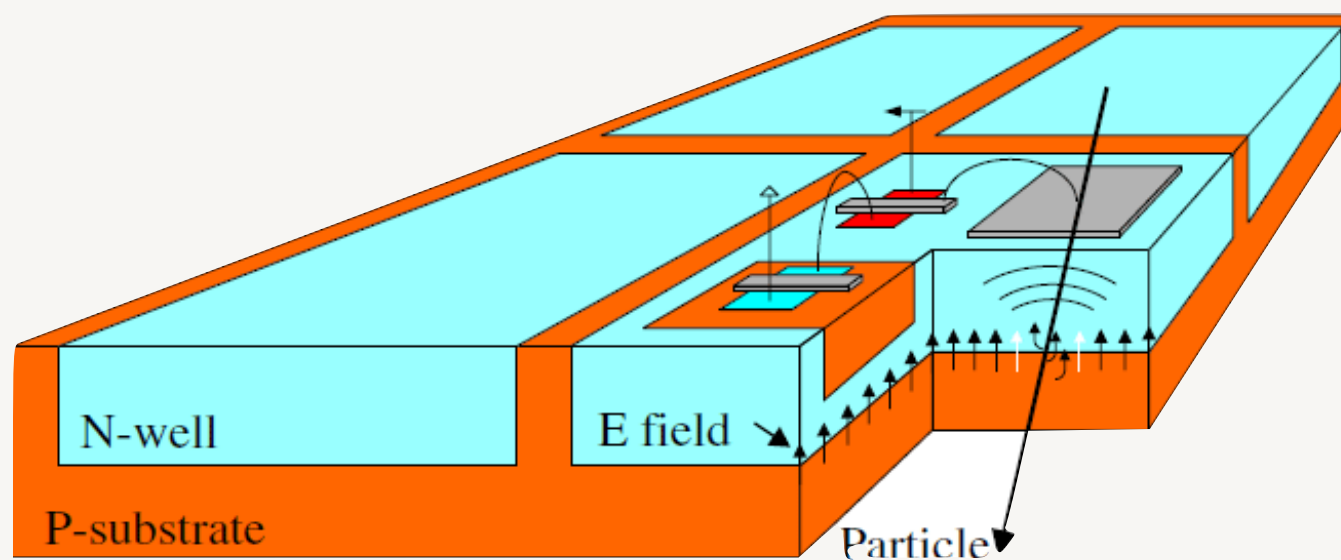
- Stopping target (70  $\mu\text{m}$  thick, 100 mm long, 19 mm radius)
  - **Aluminised mylar:**  
High stopping rate ( $\sim 95.5\%$ )
  - **Thin and hollow:**  
Minimal material budget ( $\sim 0.15\% X_0$ )
  - **Double cone:**  
Well spread decay vertices along the beam direction



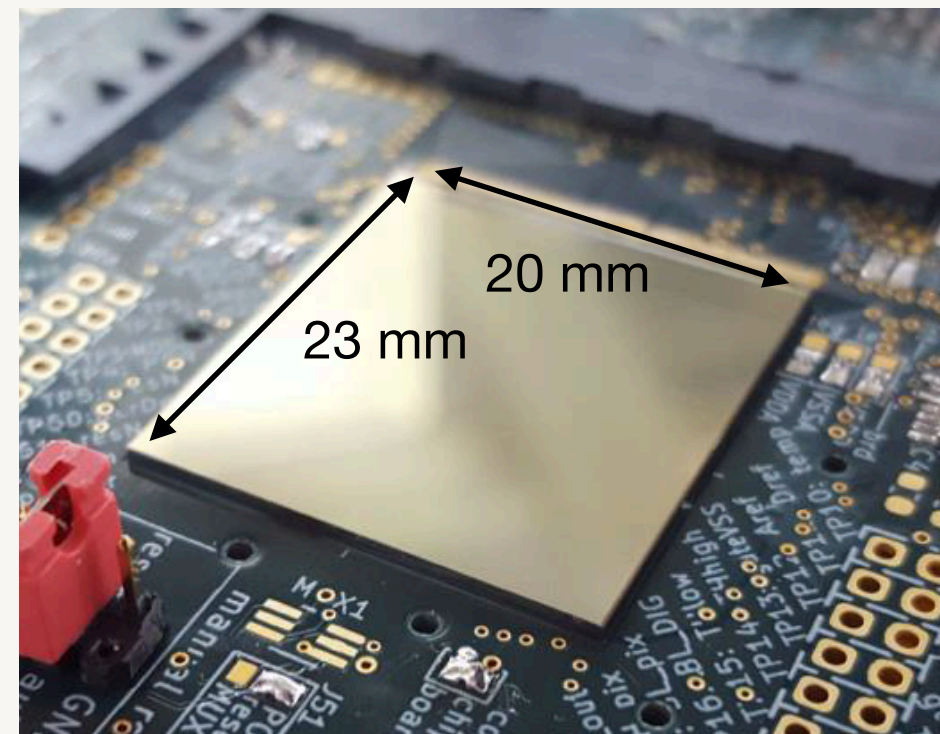
- Mu3e magnet
  - Superconducting **solenoid**
  - Provide a **uniform 1 T** field
  - Enable precise momentum reconstruction
  - Guide  $\mu^+$  beam to the target



- High Voltage Monolithic Active Pixel Sensors (**HV-MAPS**)
  - Produced in commercial 180 nm high voltage CMOS process
  - Fully integrated detection and digital readout with logic implemented in N-well
  - **Fast** charge collection in small active region
  - Can be thinned down to **50  $\mu\text{m}$**
- **Mupix11** - Production chip
  - Thin: 50  $\mu\text{m}$  • 70  $\mu\text{m}$
  - Efficiency: > 99.9%
  - Time resolution: < 20 ns

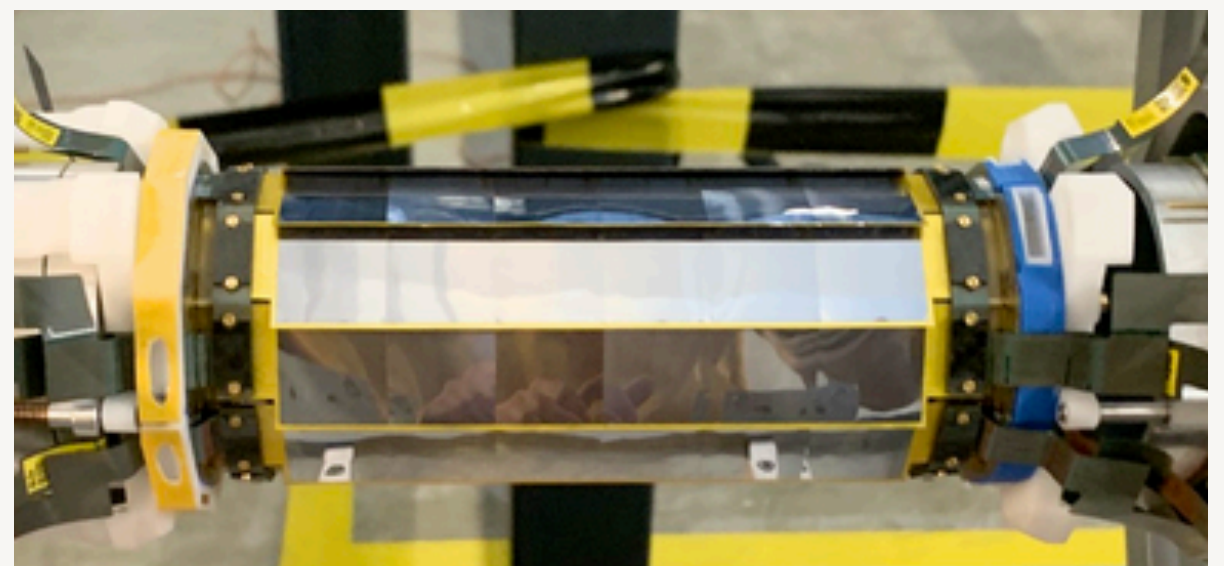
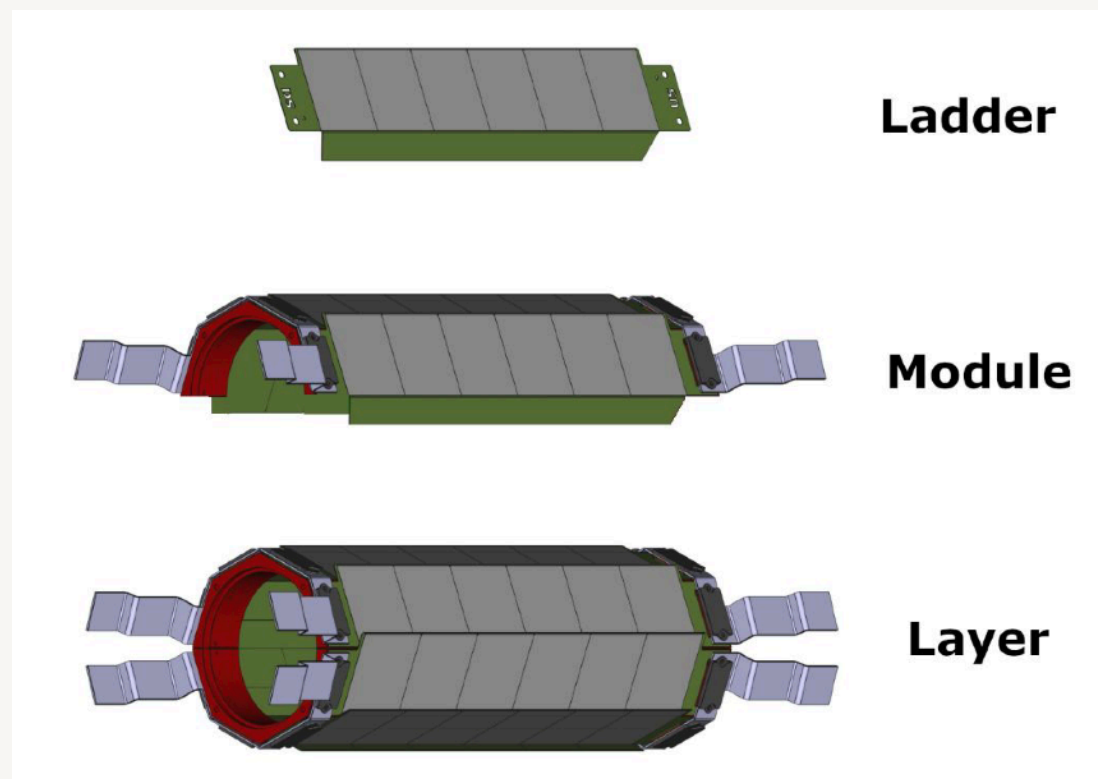


I.Perić, NIM A 582 (2007) 876



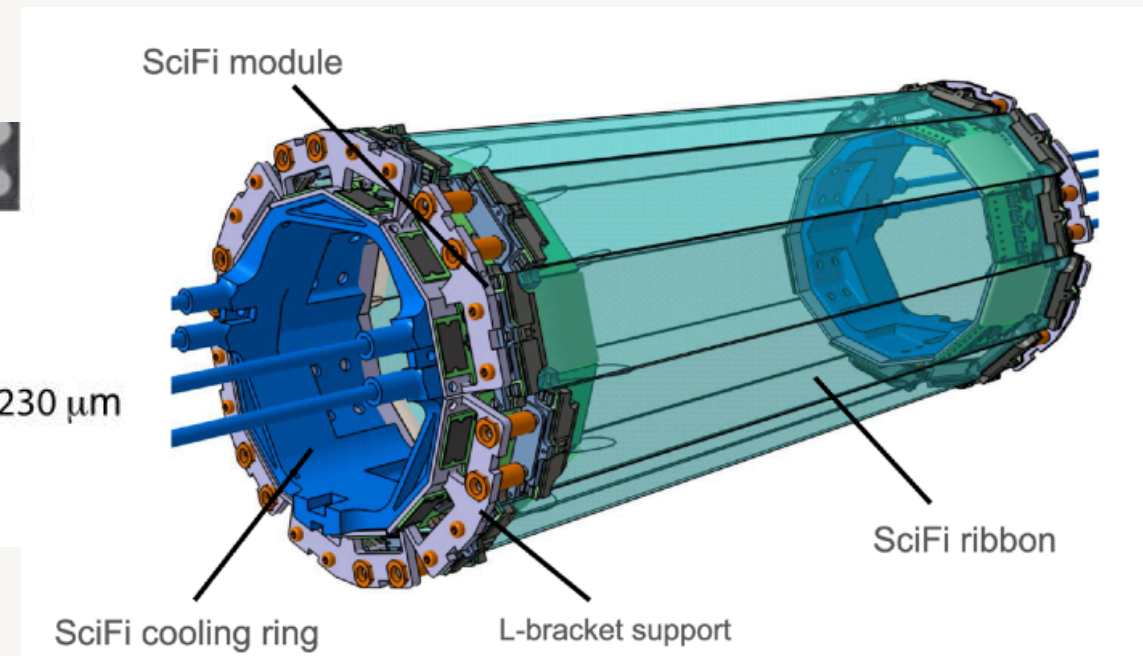
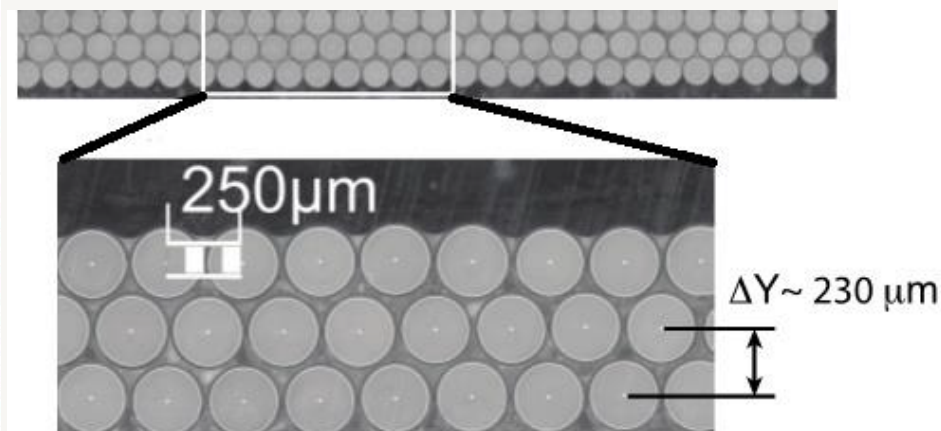


- **Ultra-thin** pixel tracker for precise **vertexing** and **momentum** reconstruction
- **Modular** design: Built from ladders made of Mupix11 chips on HDI
- **Minimal** material budget:  $\sim 0.1\%$   $X_0$  per layer
- Arranged in 3 stations
  - Central: 2 inner ‘vertex’ layers + 2 outer layers
  - Up/Downstream: 2 outer ‘recurl’ layers
- Cooled by a **gaseous helium** flow through layers



# Timing detectors - Scintillating fibres

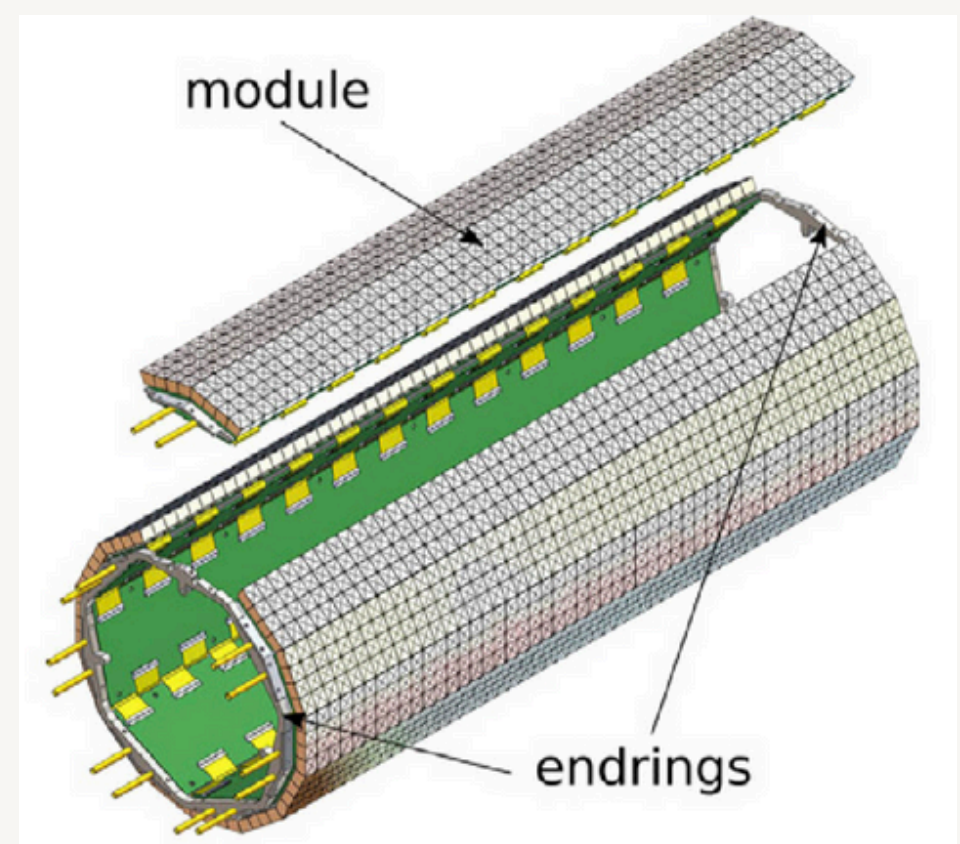
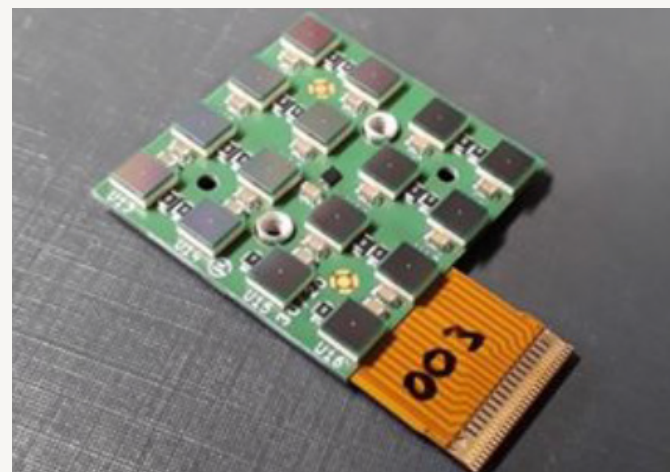
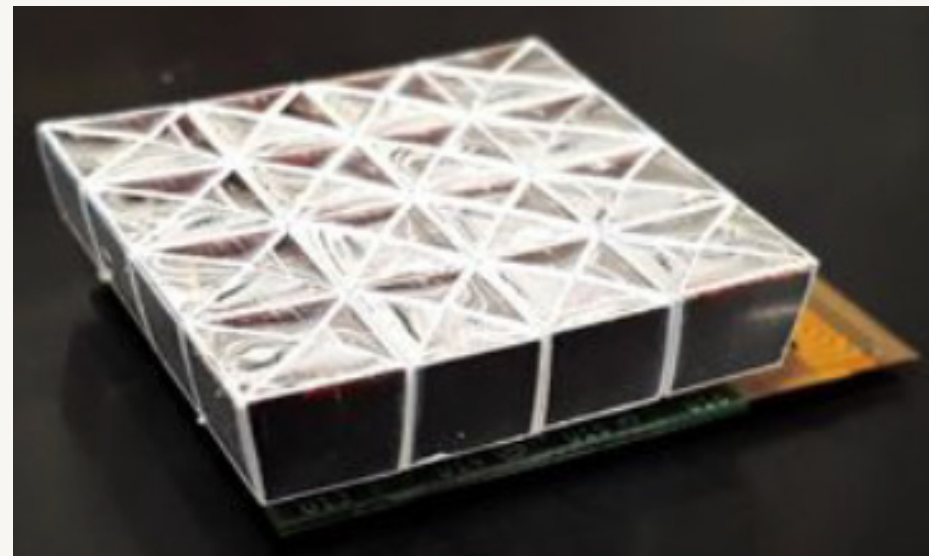
- Suppress **accidental background** and enable  $e^+/e^-$  identification
- Scintillating fibres (SciFi)
  - 12 ribbons (30 cm long) with 3 layers of 250  $\mu\text{m}$  staggered fibres ( $< 0.02\% X_0$ )
  - Placed after the vertex layers to minimise multiple scattering
  - Readout by SiPM arrays at both ends and custom ASIC (MuTRiG)
  - Time resolution:  **$\sim 250$  ps**
  - Cooled by Si oil to reduce SiPM dark count rate





# Timing detectors - Scintillating tiles

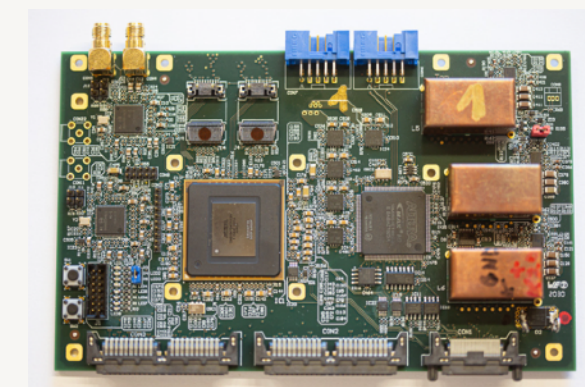
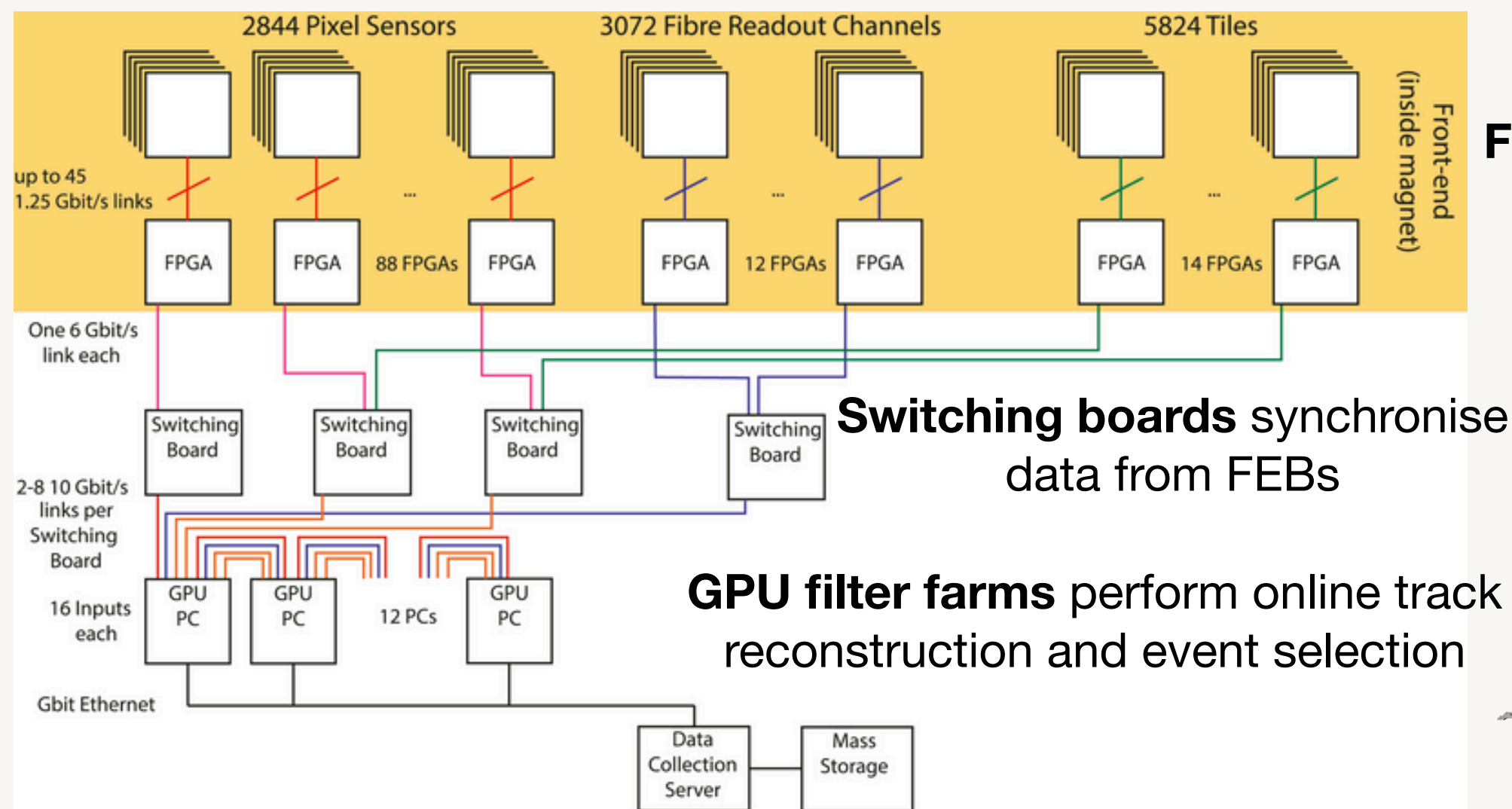
- Scintillating tiles (SciTile)
  - Highly granular tiles ( $6 \times 6 \times 5 \text{ mm}^3$ )
  - Wrapped in reflector foil for light yield and optical isolation
  - Each tile readout by a SiPM with custom ASIC (MuTRiG)
  - Placed at the end of the recurling particle trajectory - before outer 'recurl' layers
  - Provide the most precise timing:  **$\sim 80 \text{ ps}$**
  - Cooled by Si oil to reduce SiPM dark count rate



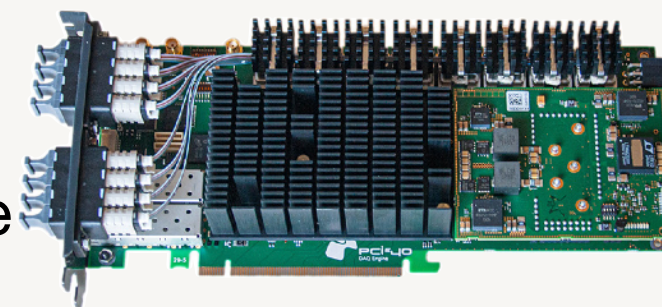


# Data acquisition system

- Fully **streaming, triggerless** continuous readout of all sub-detectors
- Network of FPGAs and optical links



**Front-end boards (FEBs)** collect and sort data



**Switching boards** synchronise data from FEBs

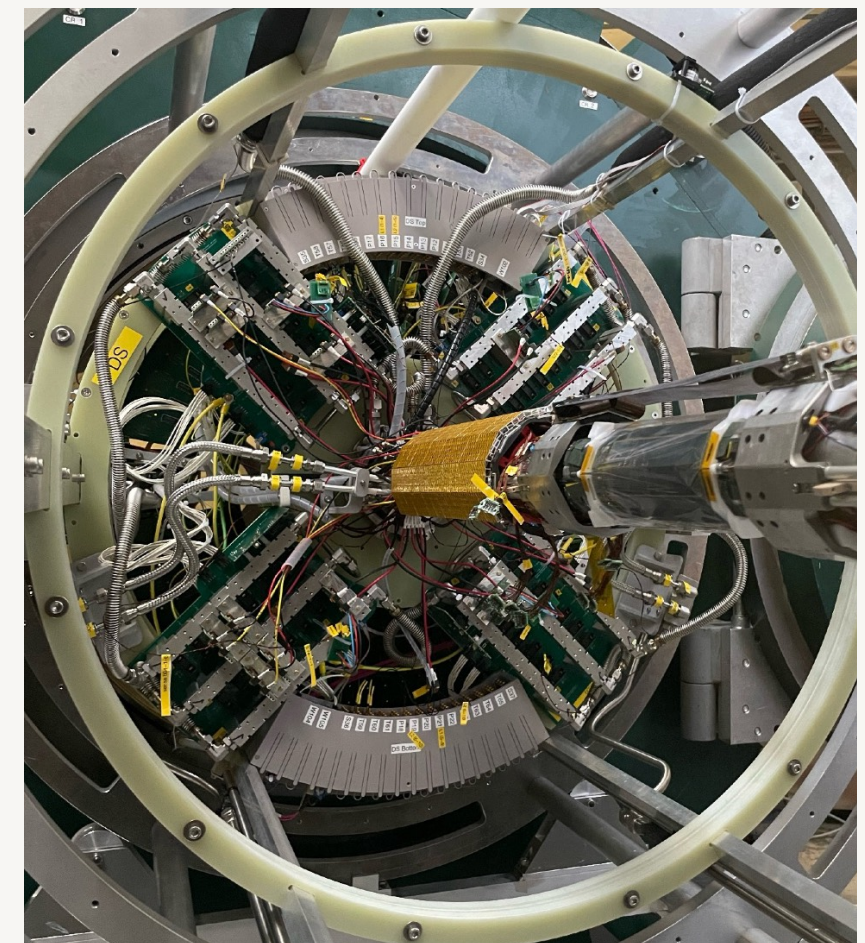
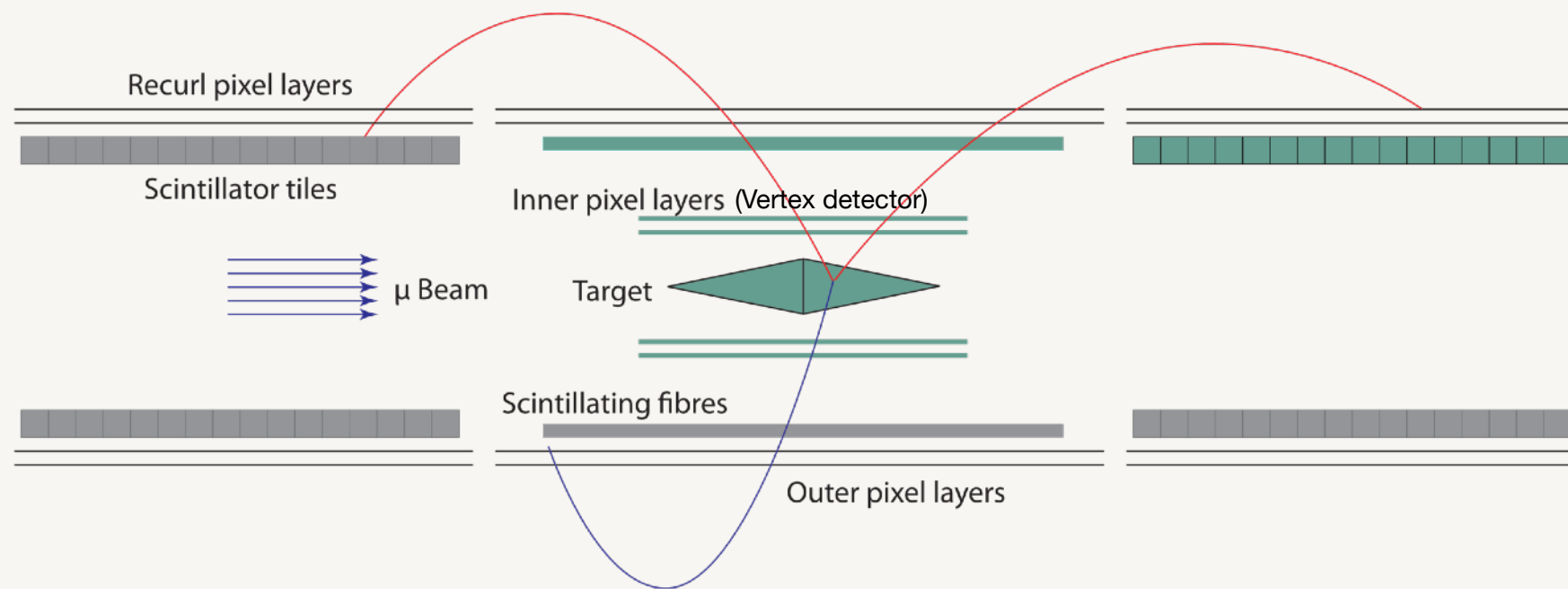


**GPU filter farms** perform online track reconstruction and event selection

Only write interesting events to disk

# Successful Commissioning Run 2025

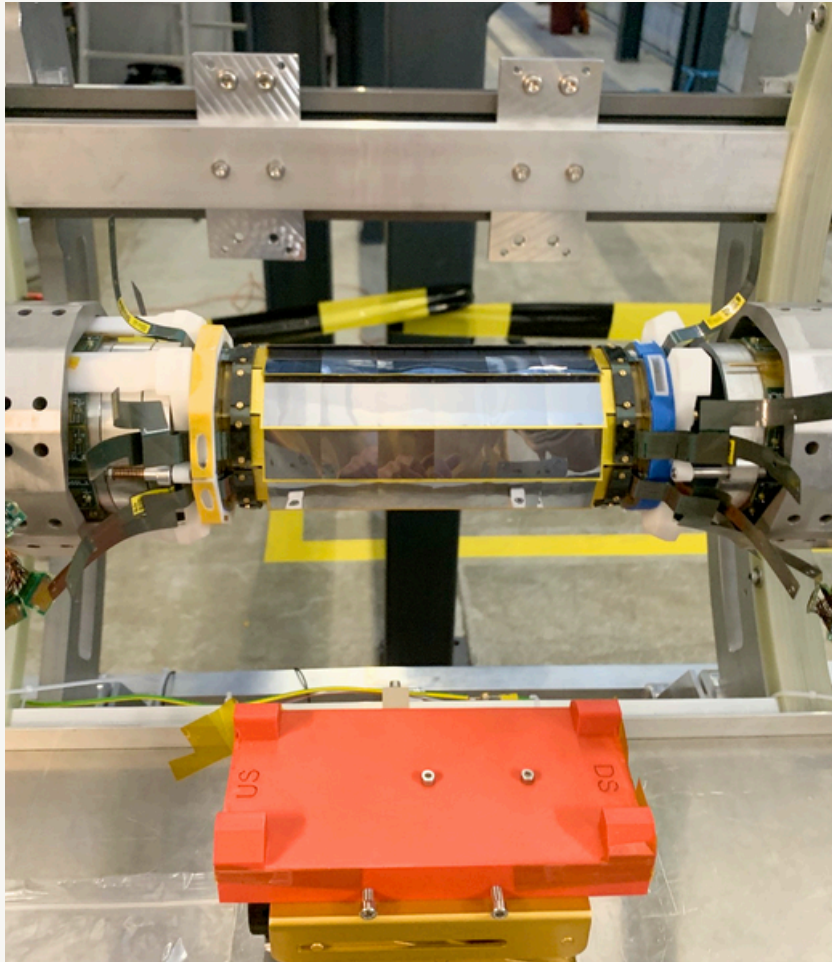
- **3 weeks of Commissioning Run** campaign in June 2025 at PSI  $\pi$ E5 beamline
  - First full integration test of **detector+infrastructure+DAQ chain**
  - Operation in **gaseous helium cooling, 1 T magnetic field** and **beam** environment
  - A week of **stable data-taking** with  $10^4 - 6.5 \times 10^7 \mu^+/\text{s}$
  - Minimal detector setup commissioned with **production modules** towards Physics Run





# Commissioning Run 2025 - Detector

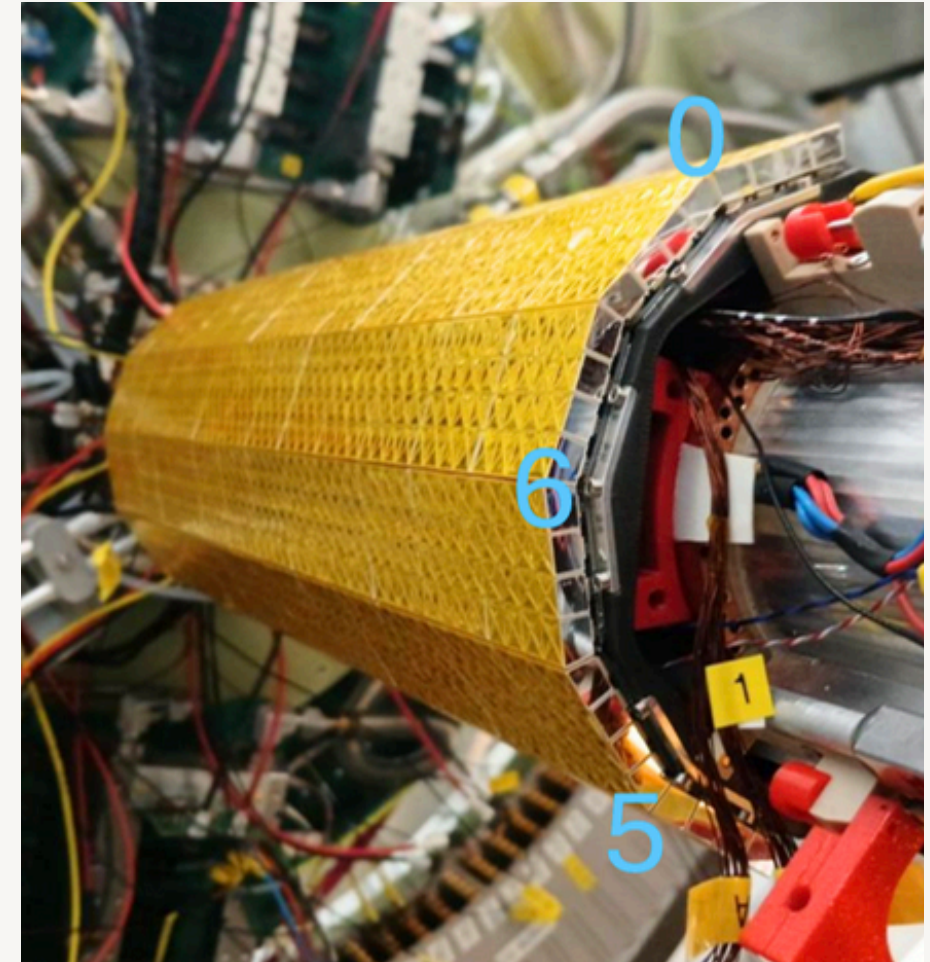
**Vertex**



**SciFi**



**SciTile**

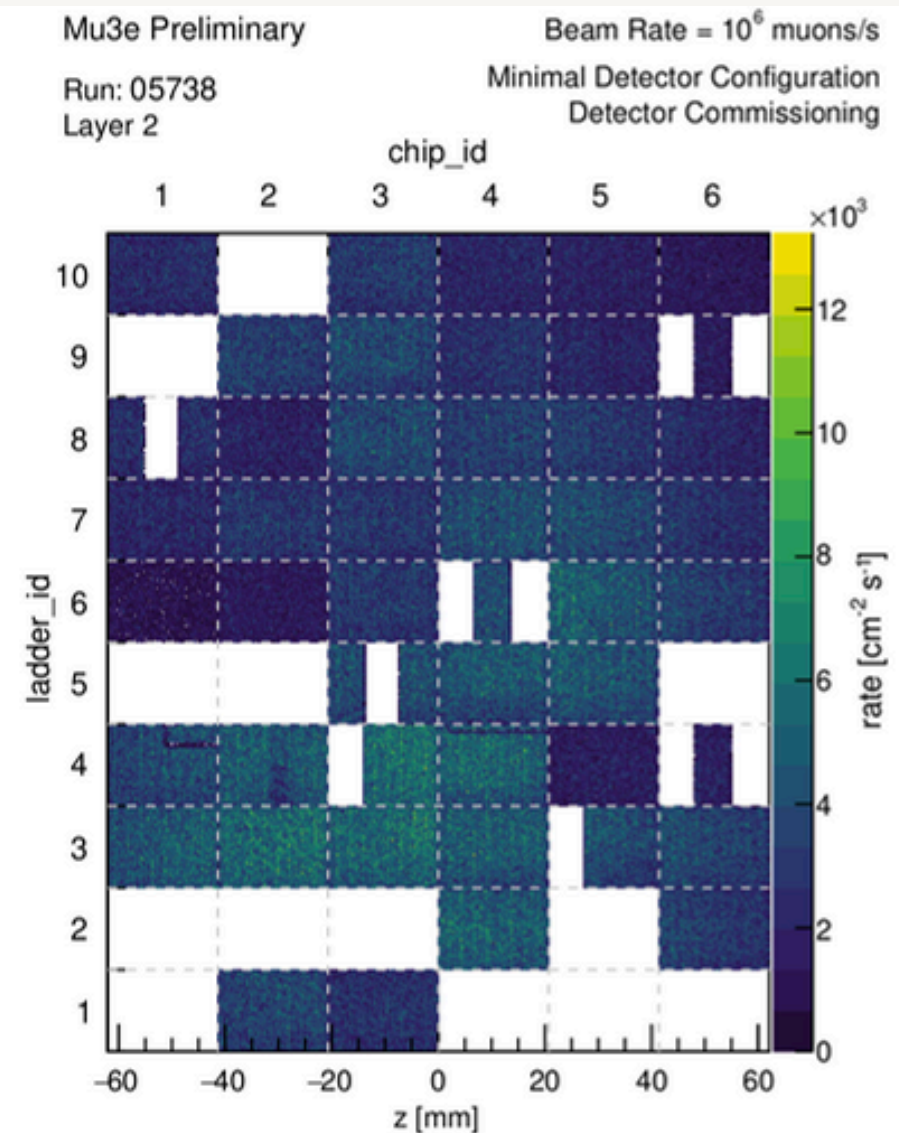
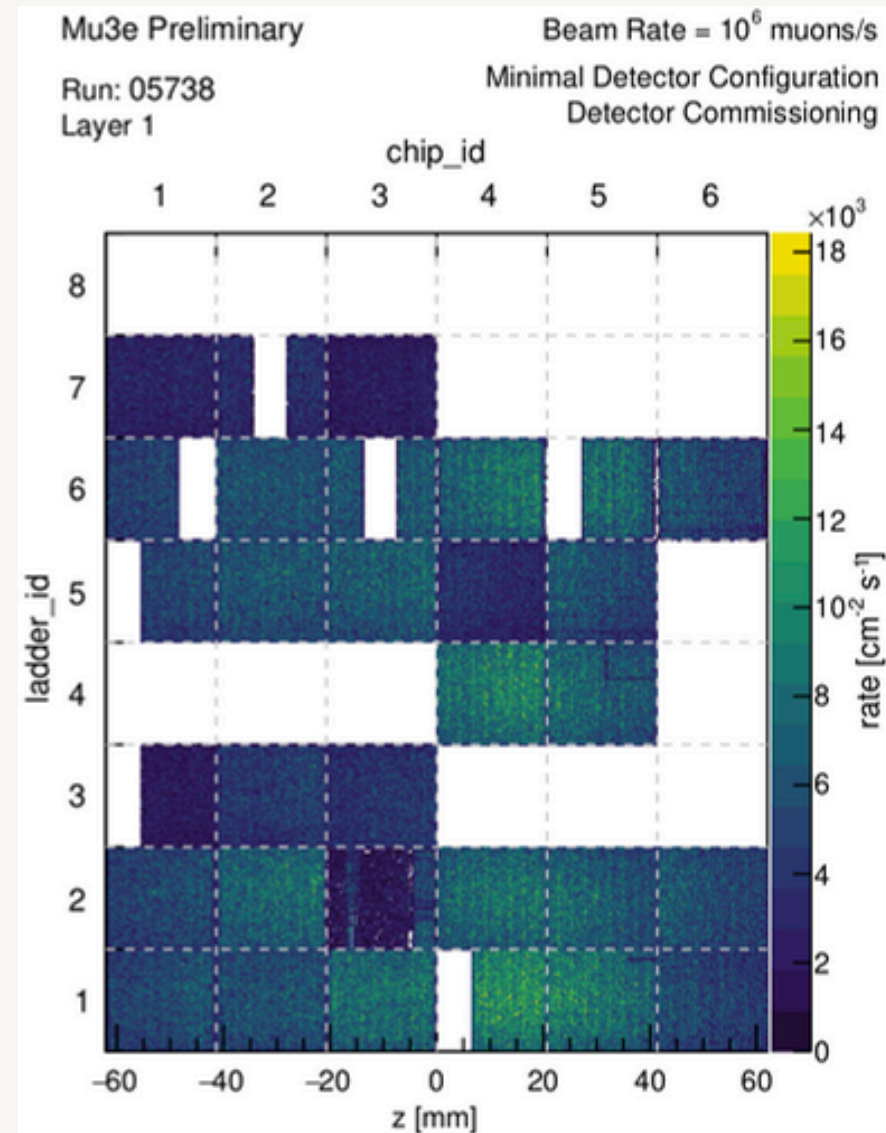
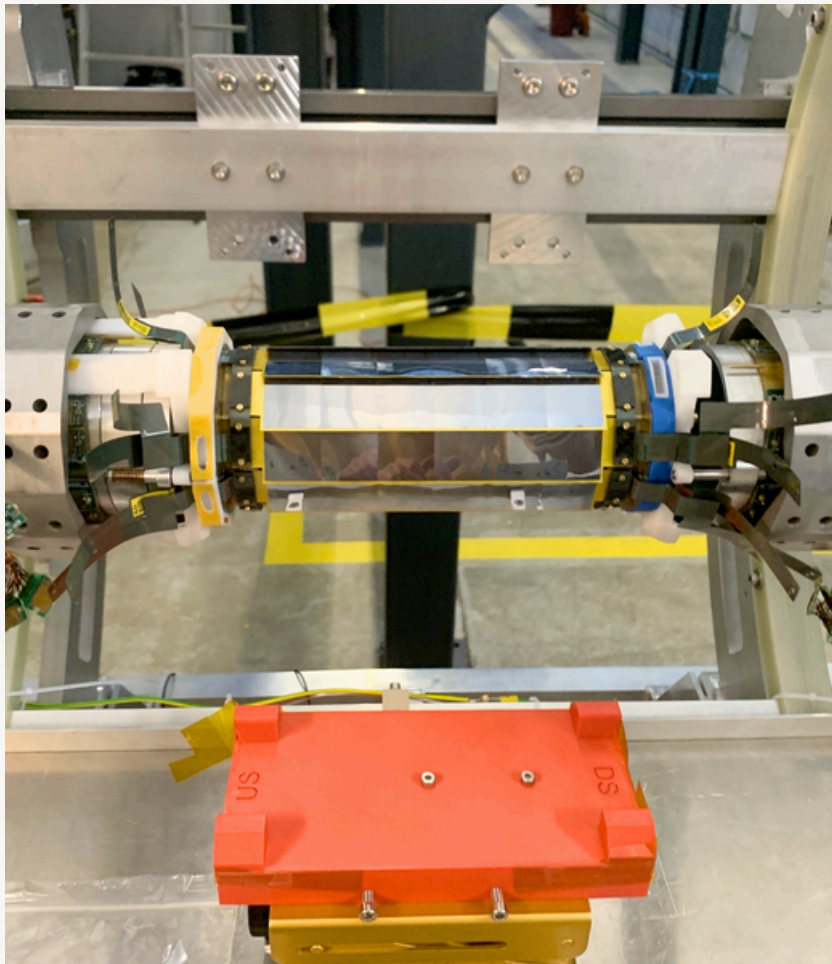


- Production modules installed and commissioned
  - Full vertex detector - Full 18 ladders = 108 Mupix11 sensors
  - SciFi - 2/12 ribbons
  - SciTile - 3/14 modules on downstream



# Commissioning Run 2025 - Vertex

## Vertex

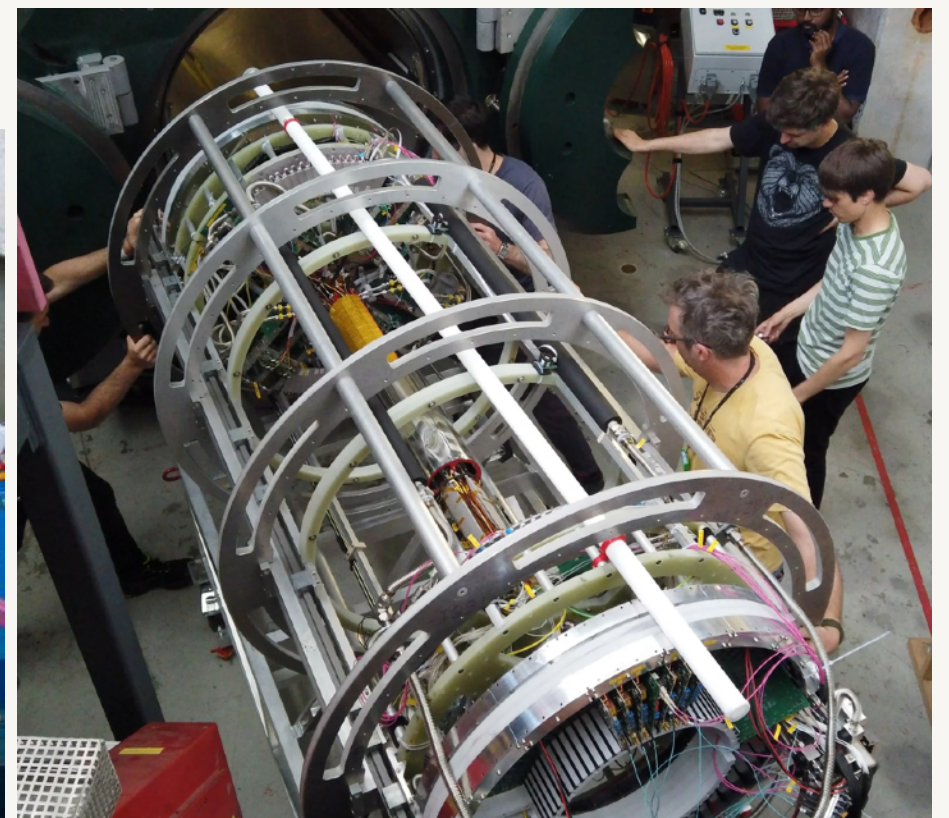
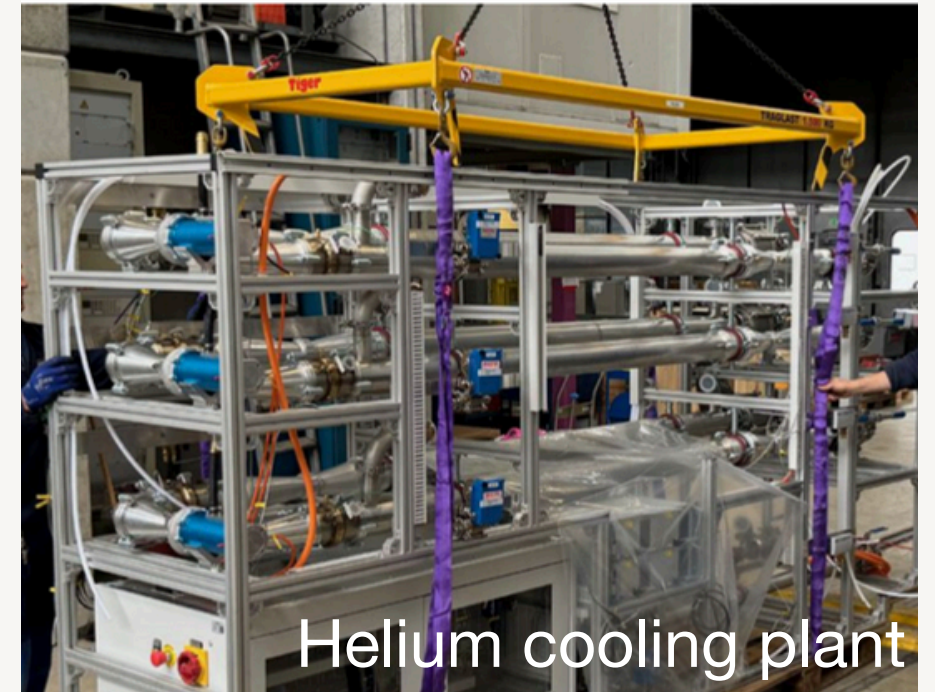


- Hit maps from Layer 1 and Layer 2 of vertex detector
  - Successful **3-week** operation under **high rate**, **helium cooling** and **1 T** environment
  - 26/108 Mupix11 sensor either mechanically damaged, unstable or lost
  - A few additional unstable or inefficient links



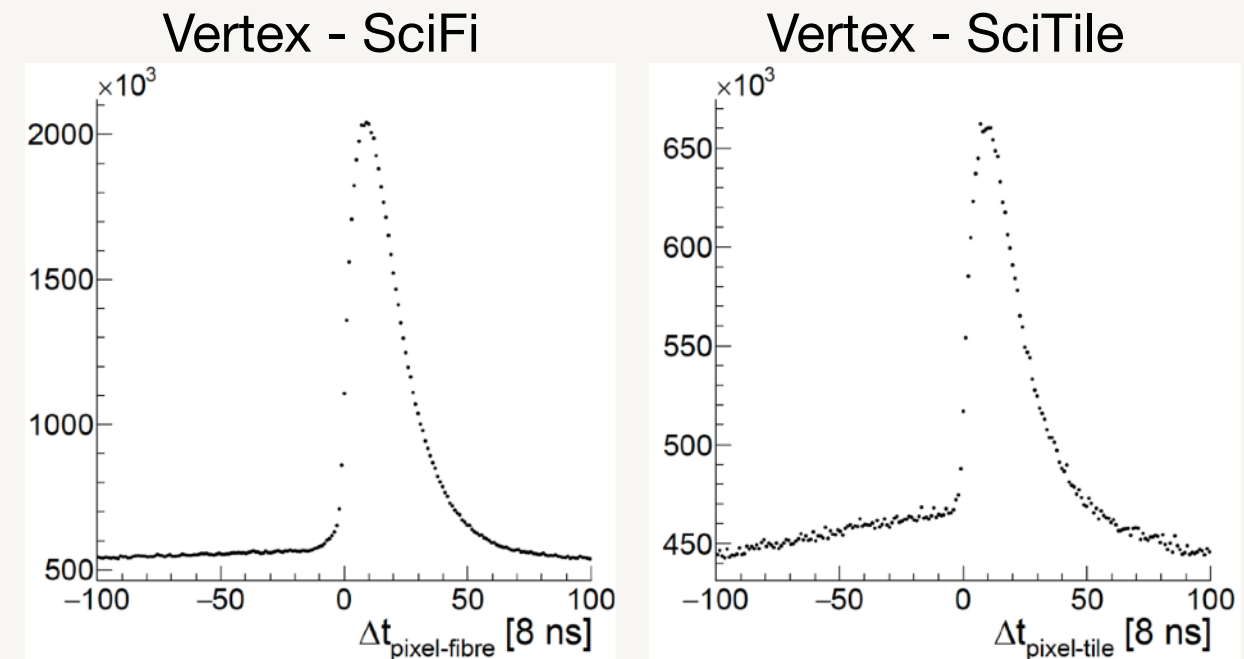
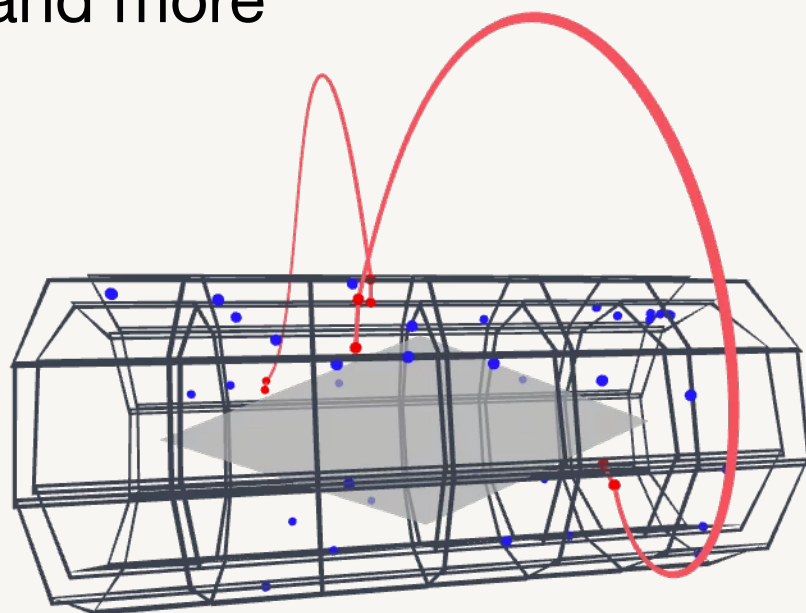
# Commissioning Run 2025 - Infrastructure

- **Final services** installed and commissioned
  - **Gaseous helium cooling** for vertex detector
  - **Liquid cooling** for SciFi and SciTile
  - **Powering system** for all detectors
- Compact Muon Beam Line (**CMBL**) setup at  $\pi E5$ 
  - **Mu3e solenoid** fully operational at **1 T**
  - Deliver  $10^4 - 6.5 \times 10^7 \mu^+/\text{s}$  to the target

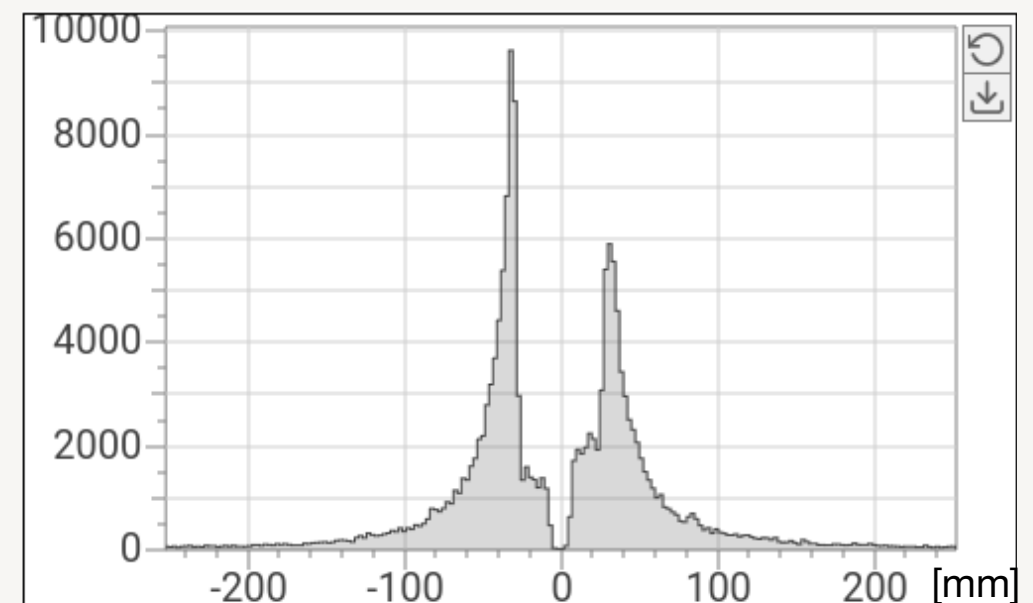




- Demonstrated **streaming readout**
  - **High-rate** capability with sub-detector **synchronisation**
  - Online track reconstruction with **GPU** filter farm
  - Online monitoring tools developed
- Ongoing analysis efforts
  - Michel spectrum using reconstructed tracks with full sub-system
  - Detector alignment with cosmic data
  - ... and more



Online reconstructed track transverse radius



## Tentative Mu3e Schedule

**Minimal Configuration** (commissioning)

Production Outer Pixel Central

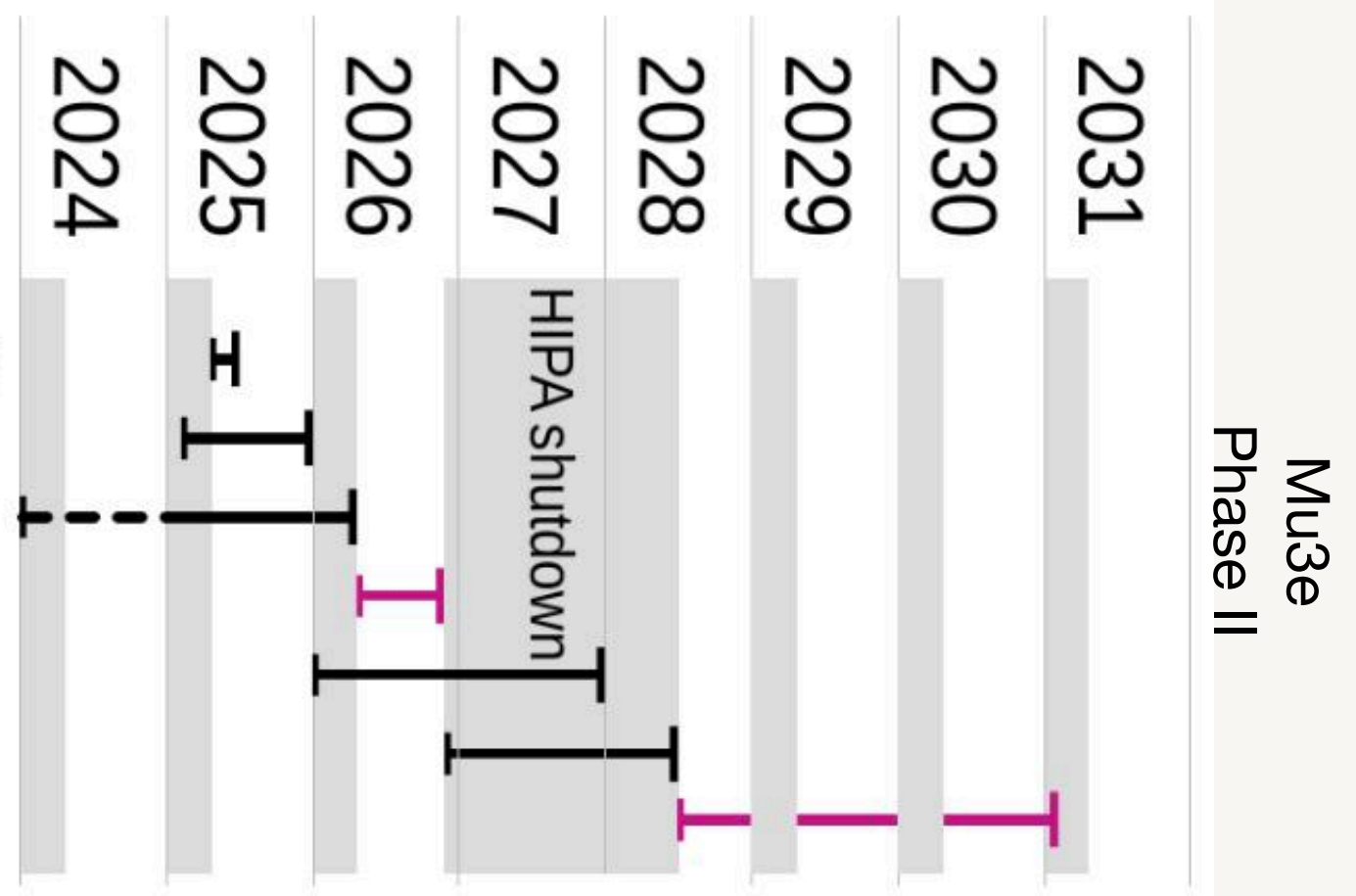
Production SciTiles

**Phase 0 data taking**

Production Outer Pixel Recurl

Consolidation (HW & SW)

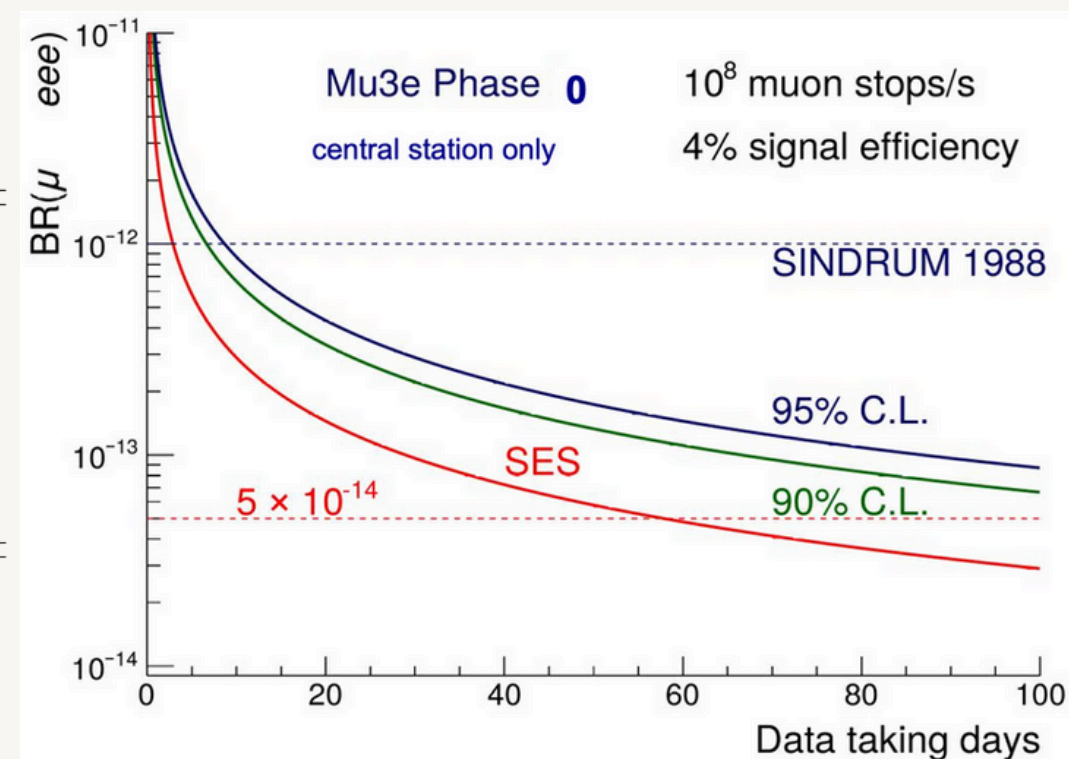
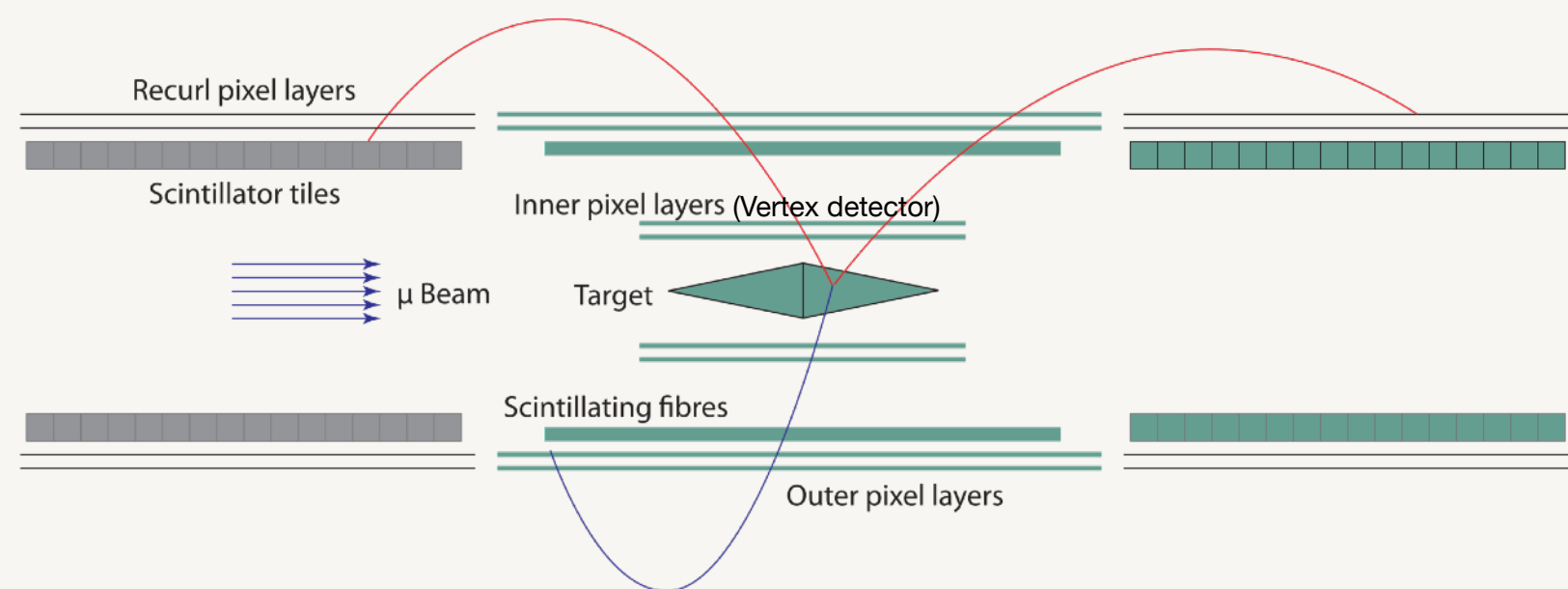
**Phase I data taking @HIMB**



- Aim for a long-term Physics Run in 2026 (Phase 0)
  - Full central station with additional 2 outer pixel layers and full downstream SciTile
- Data-taking with full recurl stations to start after HIMB upgrade



# Towards Physics Run in 2026



- **Phase 0** configuration can already surpass the current **SINDRUM** limit
- Central station outer pixel ladders under production and QC  
→ C. Kinsman's poster: "Search for  $\mu^+ \rightarrow e^+ e^+ e^-$  at the Mu3e experiment and the Commissioning of the Pixel Tracker"
- Vertex detector v2 with 70  $\mu\text{m}$  Mupix11 sensors being produced based on operational experience in 2025 campaign
- SciTile production for downstream recurl station

- The **Mu3e** experiment searches for the cLFV decay  $\mu^+ \rightarrow e^+ e^- e^+$  at the  **$10^{-16}$**  level
- **Successful Commissioning Run** in June 2025
  - First full integration of **detector, infrastructure** and **DAQ**
  - Operation in **gaseous helium cooling, 1 T magnetic field** and **beam** environment
  - A week of **stable data-taking** at up to  **$6.5 \times 10^7 \mu^+/\text{s}$**
  - **Streaming readout** with **GPU**-based online track reconstruction
  - Analysis efforts ongoing: Michel spectrum, alignment,...
- Preparation towards Physics Run in 2026
  - Already able to improve sensitivity at the  **$10^{-12}$**  level
  - Active production of outer pixel layers, Vertex v2 and SciTile



# Thank you!



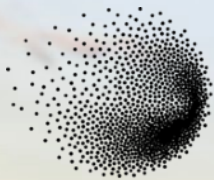
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02/09/2025 |

NuFact 2025, Liverpool

| Mikio Sakurai

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