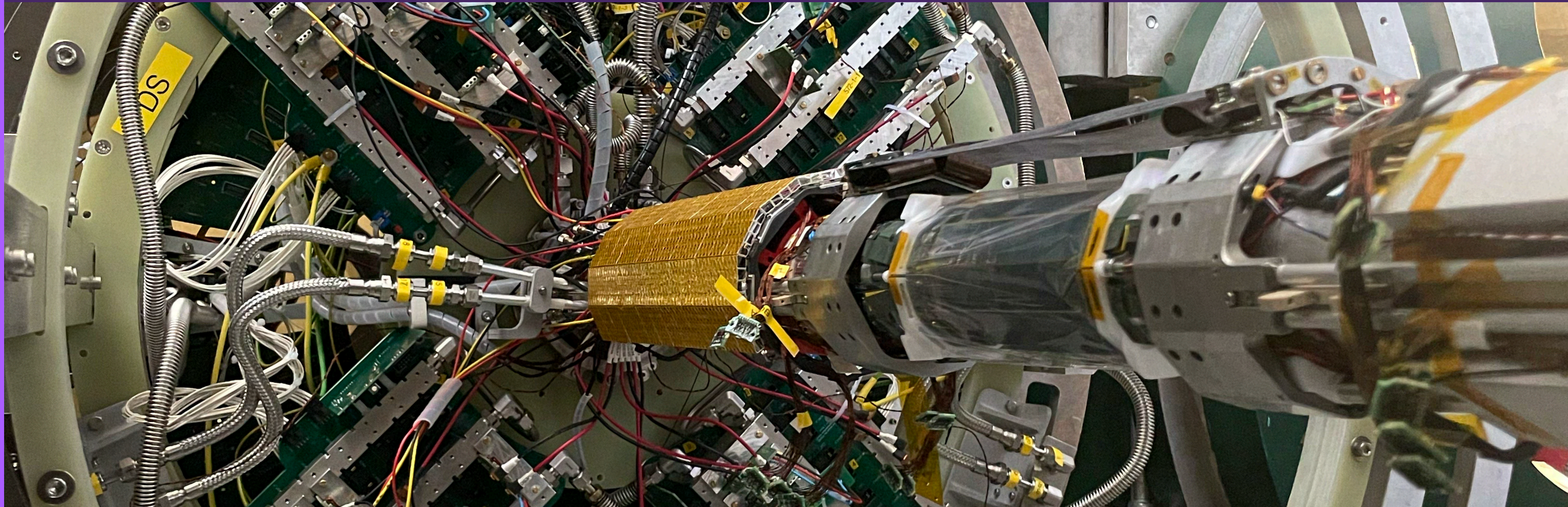


# The Mu3e Experiment at PSI

## Recent Commissioning Results and Outlook



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

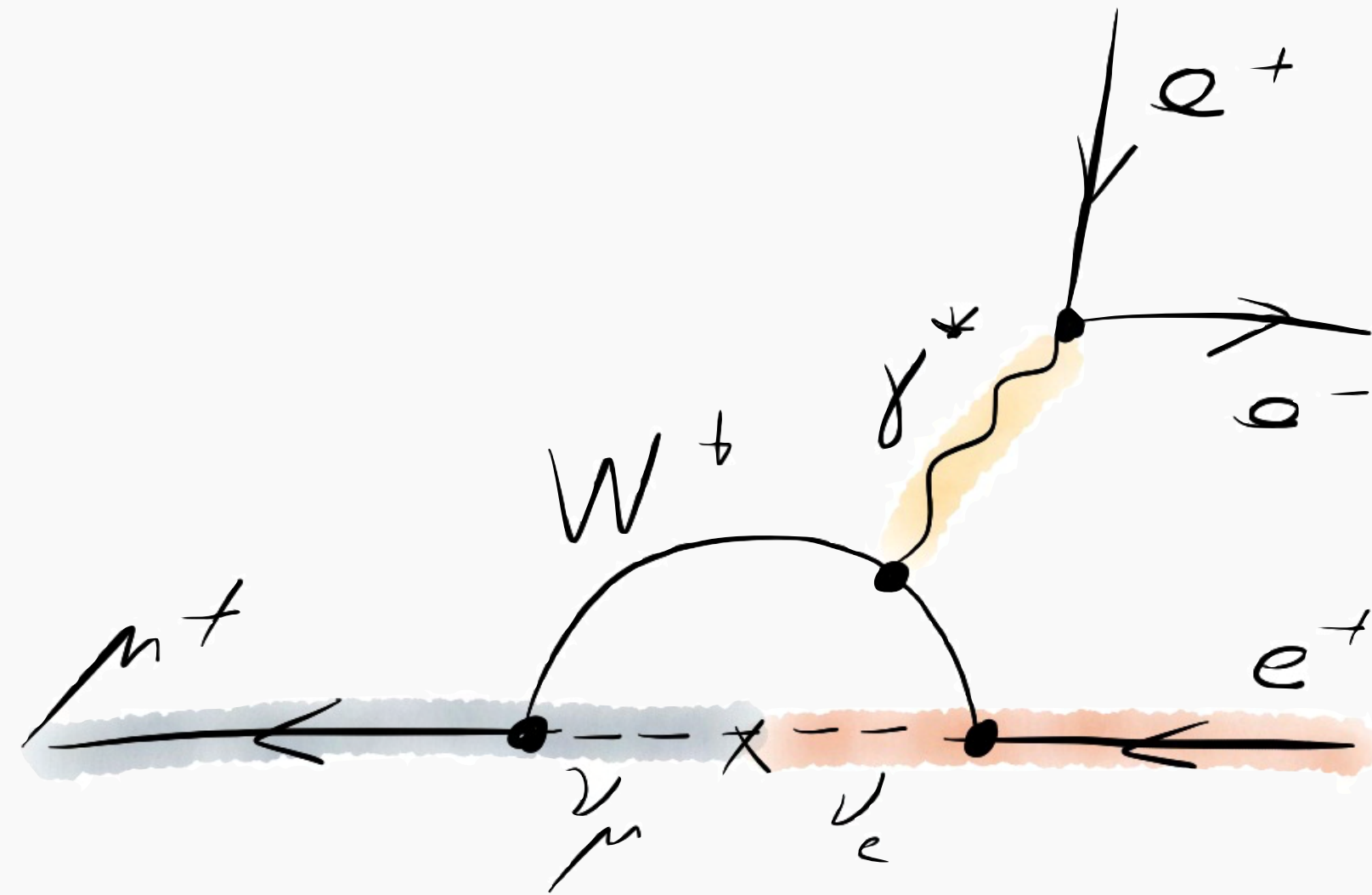
on behalf of the Mu3e collaboration  
PhiPsi26, Pisa, 09/06/2026



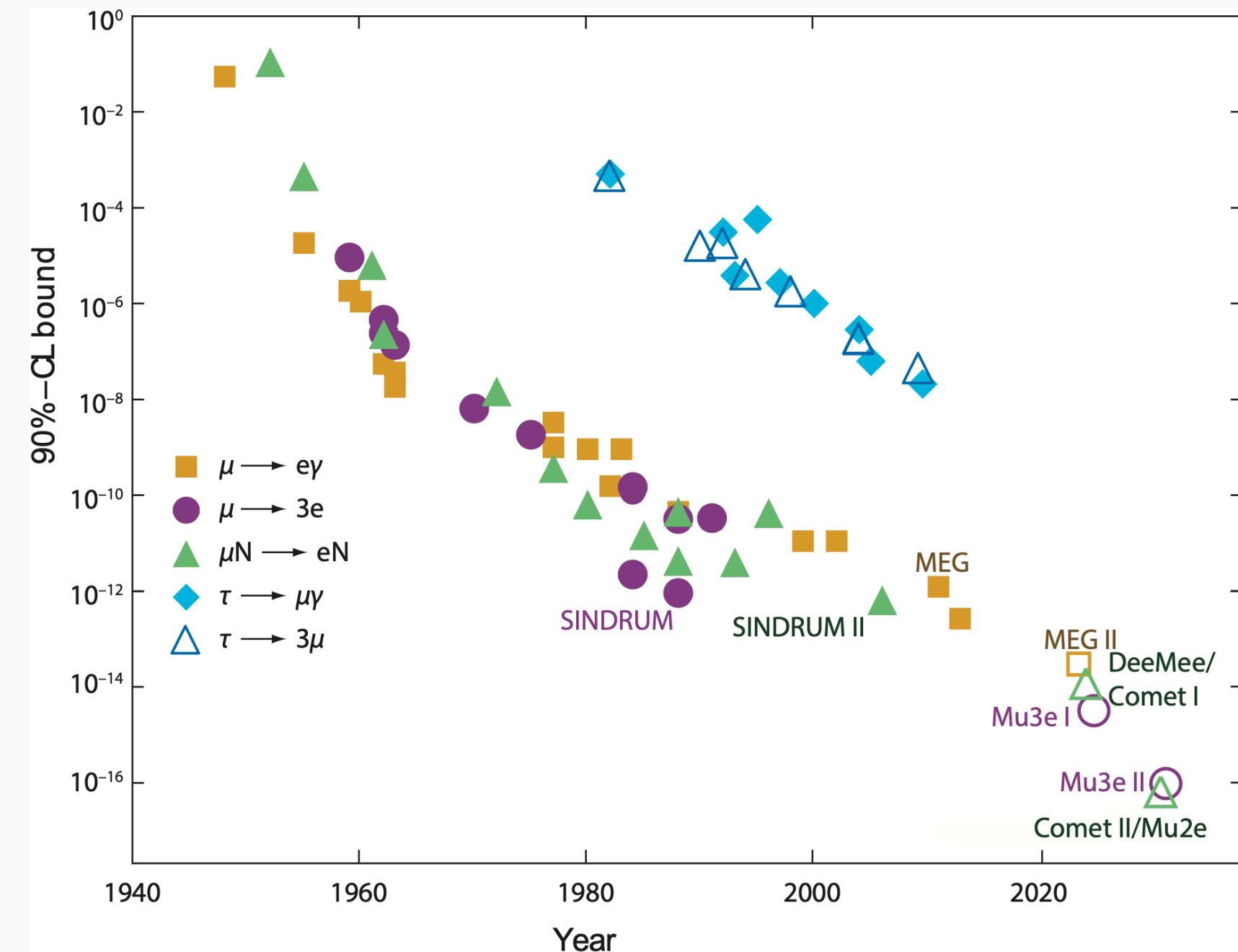
# Charged Lepton Flavour Violation (cLFV)



BR <math>10^{-54}</math> in the SM with  $\nu$  oscillation



Muon is an excellent probe of cLFV

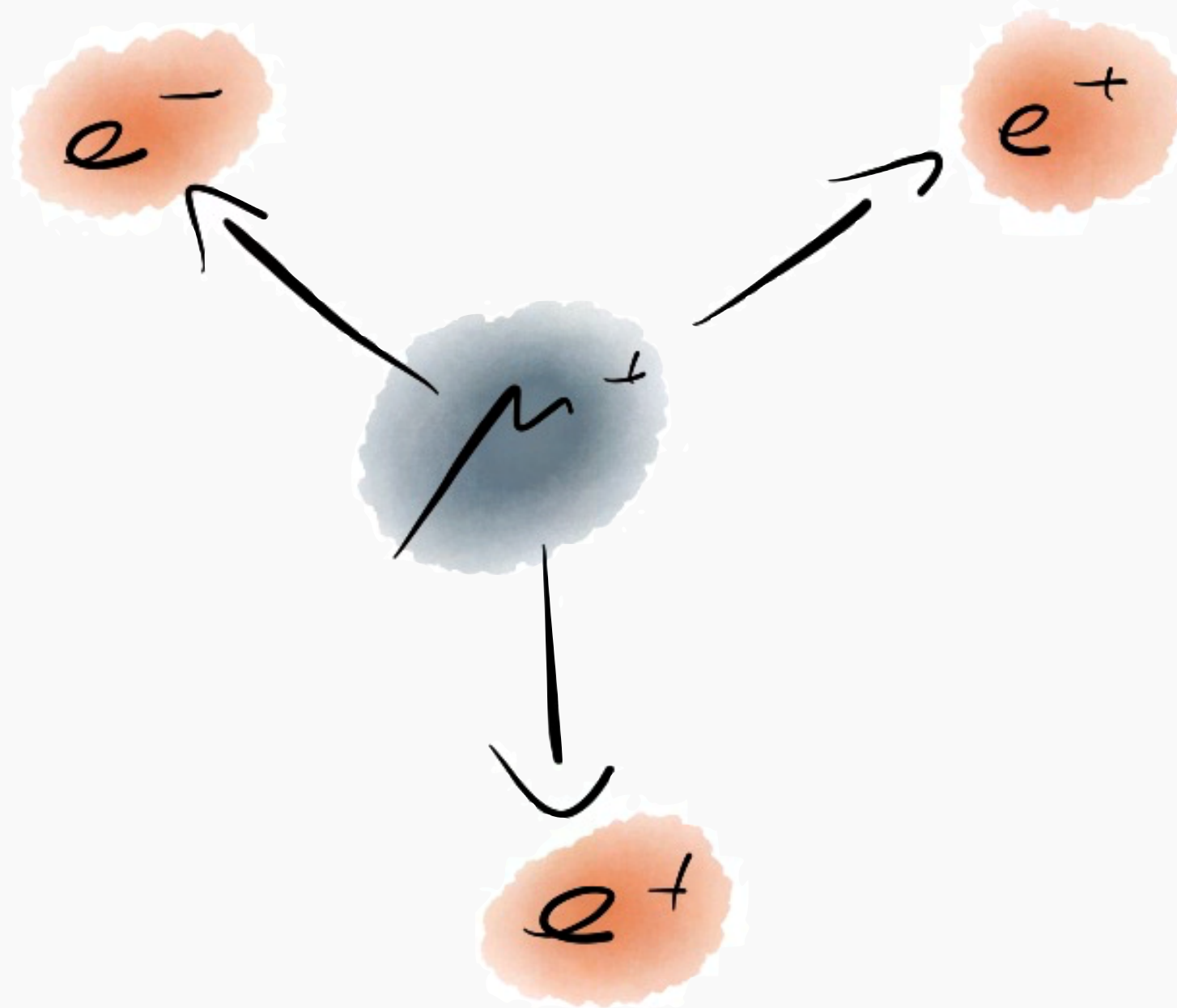


- cLFV can be naturally possible
- Heavily suppressed in the SM by  $(\Delta m_\nu^2/m_W^2)^2$
- Any observation is a clear new physics sign

- **Sensitive:** New physics sensitivity scales with  $m_1^2$
- **Clean:** Relatively long lifetime & simple decay channels
- **Available:** High-intensity muon beams around the world

Adapted from W. J. Marciano et al., Annu. Rev. Nucl. Part. Sci. 58 (2008) 315

# The Mu3e experiment at PSI

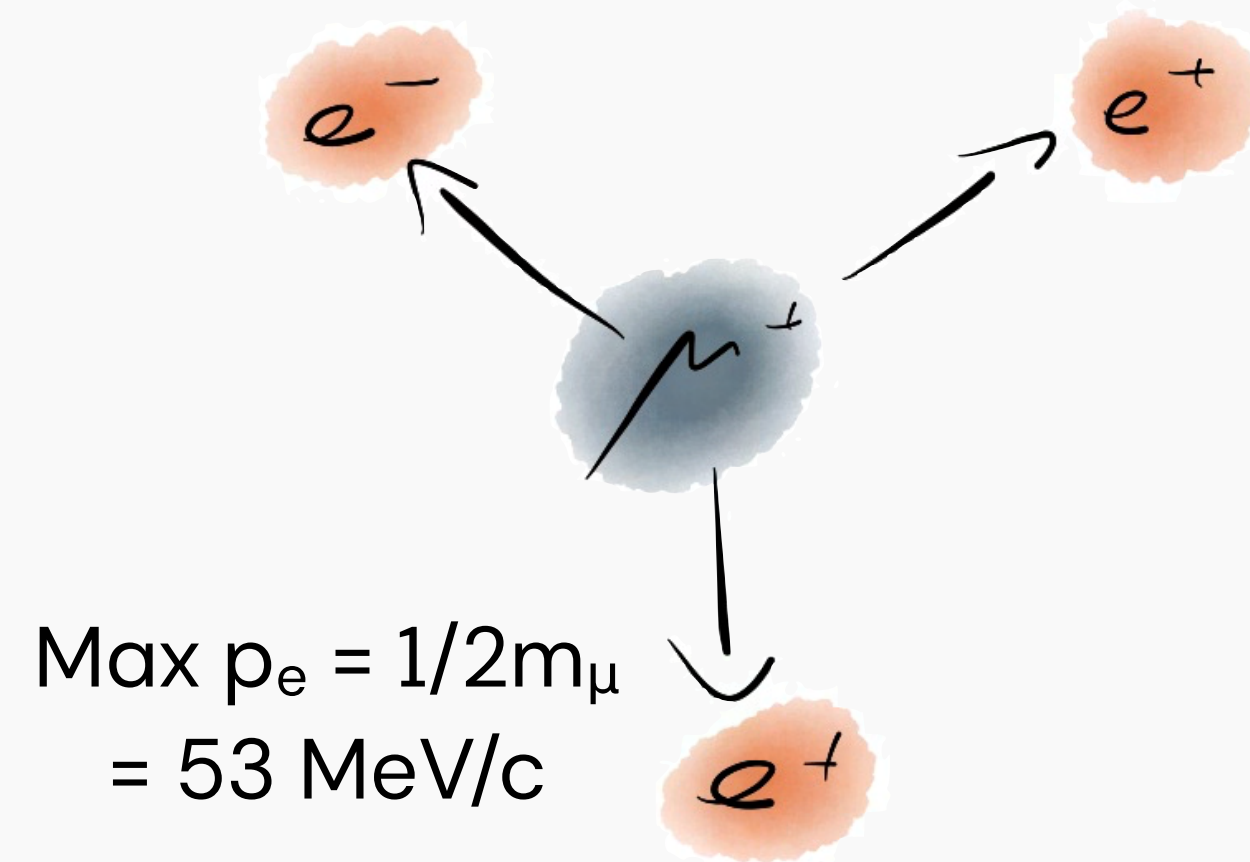


- The Mu3e experiment searches for the cLFV decay  $\mu^+ \rightarrow e^+e^-e^+$
- Current best limit:  $BR < 10^{-12}$  (90% CL) by SINDRUM experiment (1988)  
U. Bellgardt et al., Nucl. Phys. B 299 (1988) 1
- Two-phase approach targeting SES
  - Phase I:  $BR < 2 \times 10^{-15}$  K. Arndt et al., NIM A 1014 (2021) 165679
  - Phase II:  $BR < 10^{-16}$   
→ **4 orders of magnitude improvement** over the current limit
- First Physics Run scheduled for 2027
  - 2025: Successful commissioning run completed
  - 2026: Actively preparing for an 8-week Beam Campaign

# The Mu3e signal and backgrounds

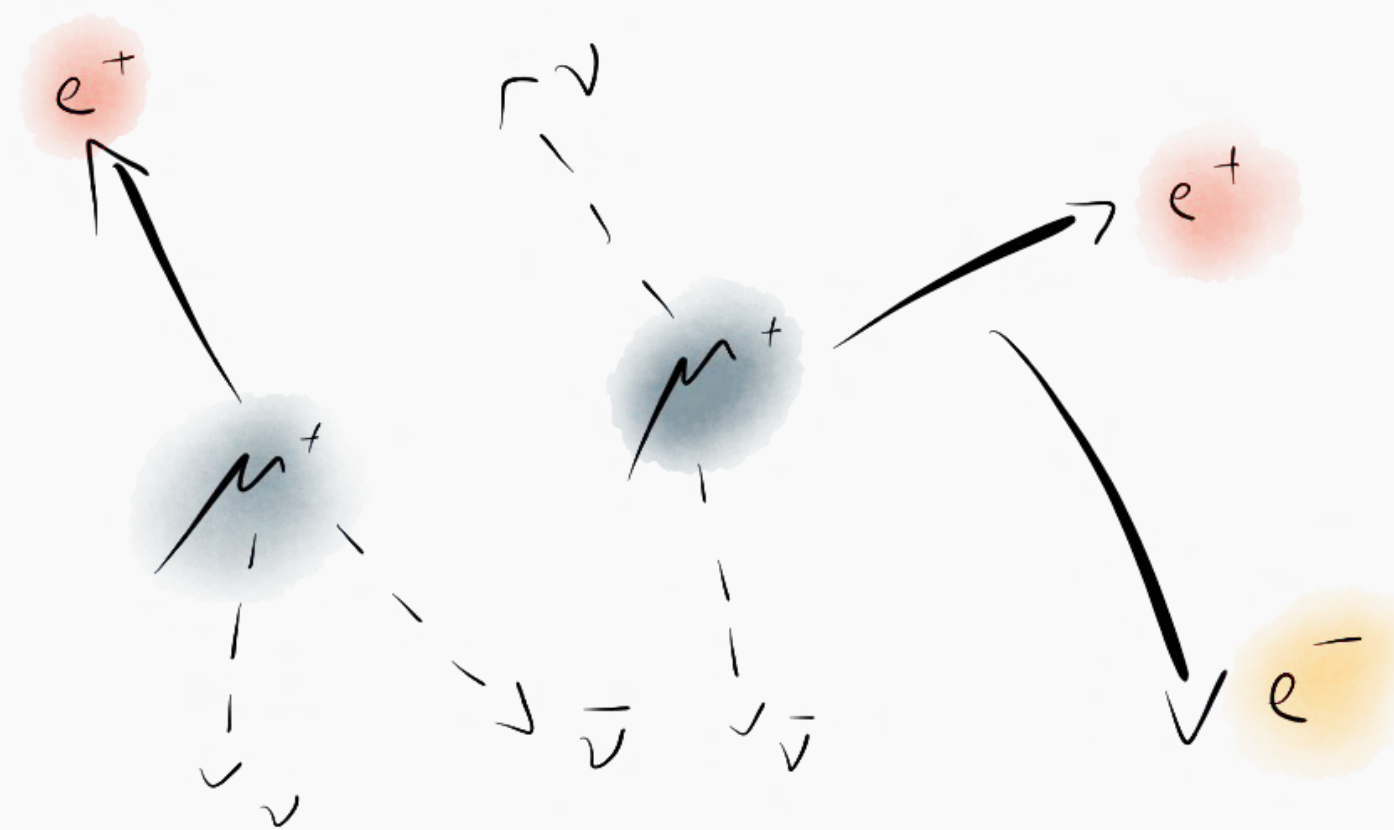


## Signal



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

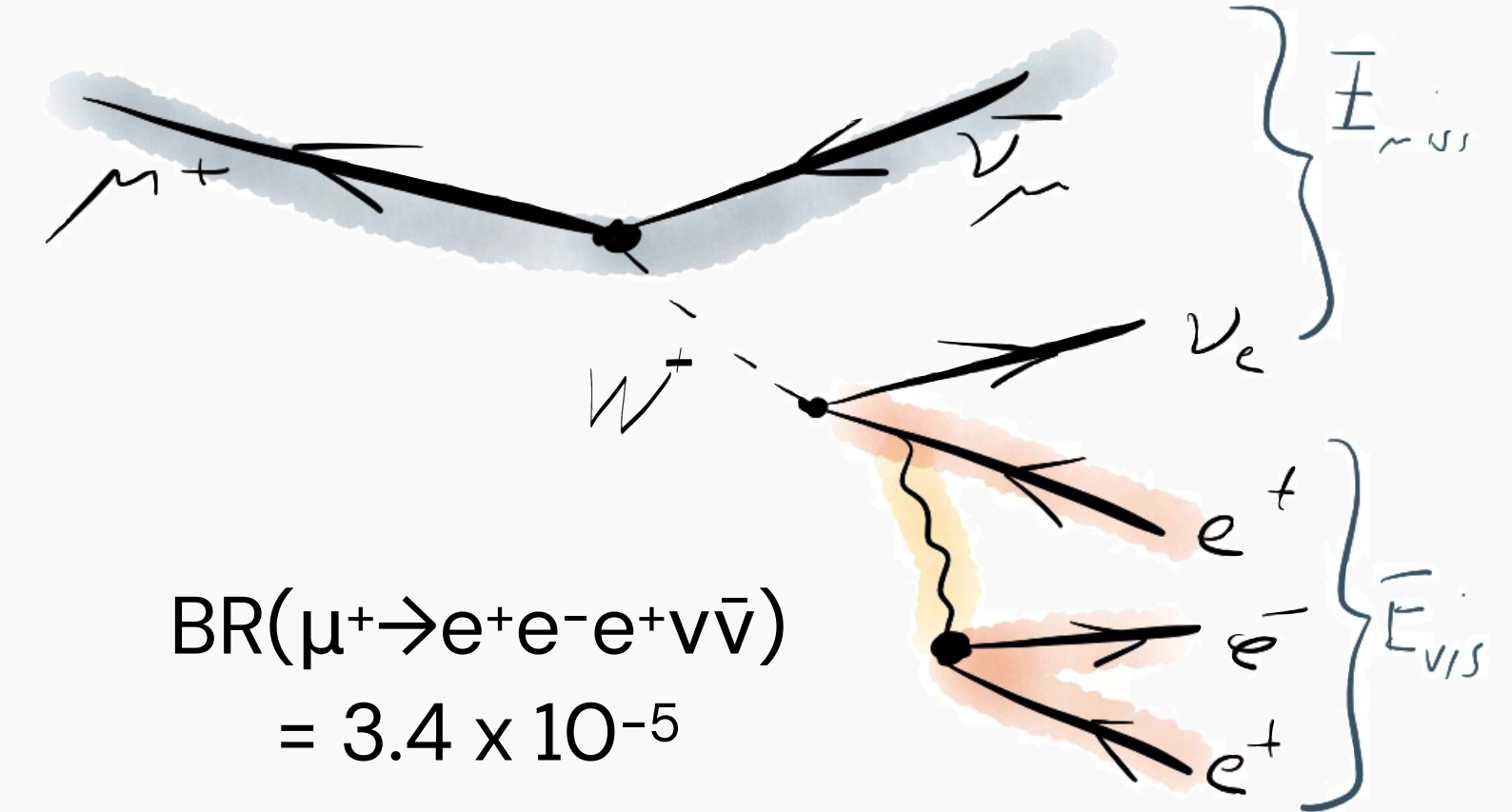
## Accidental background



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

Require very good  
**vertex, timing and momentum** resolution

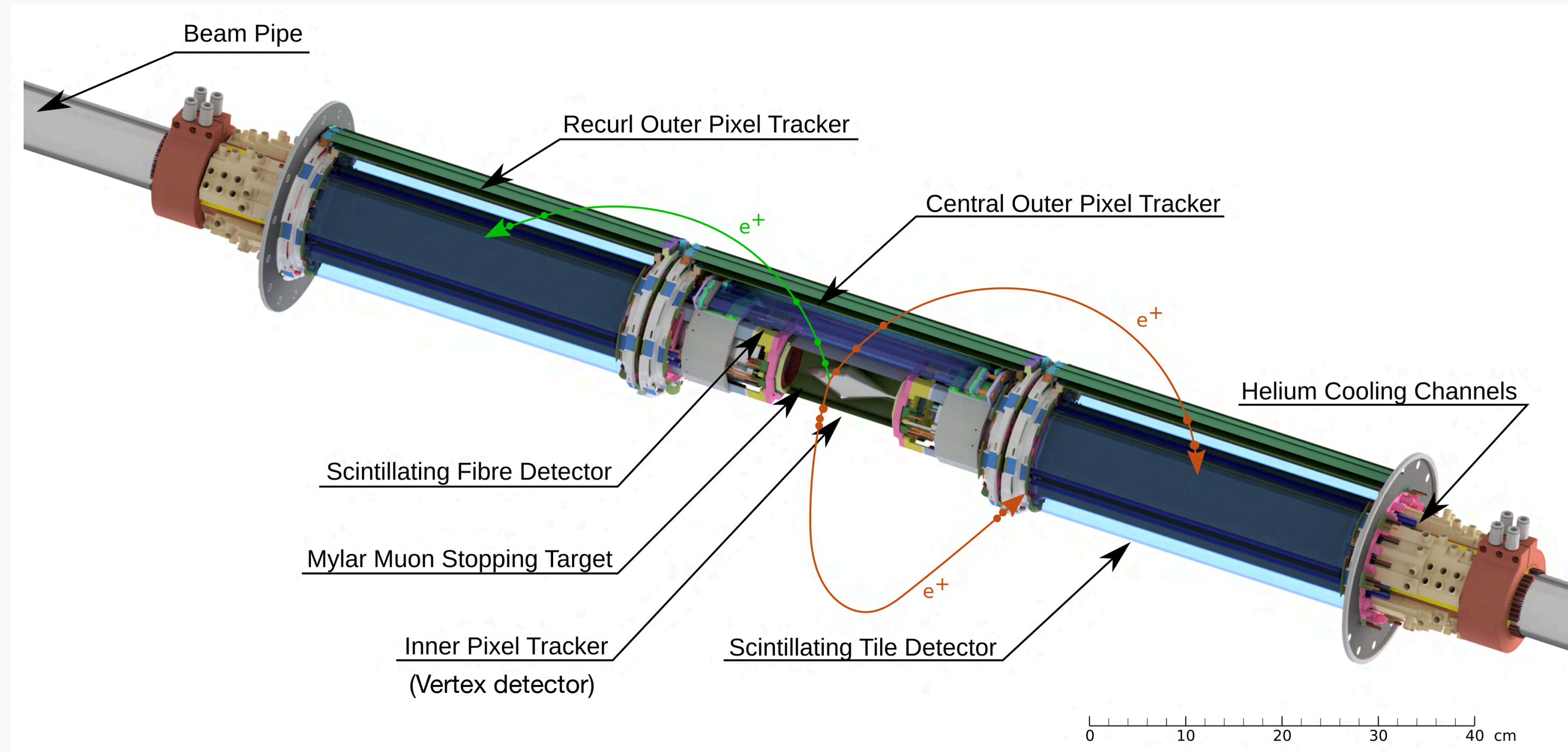
## Internal conversion background



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

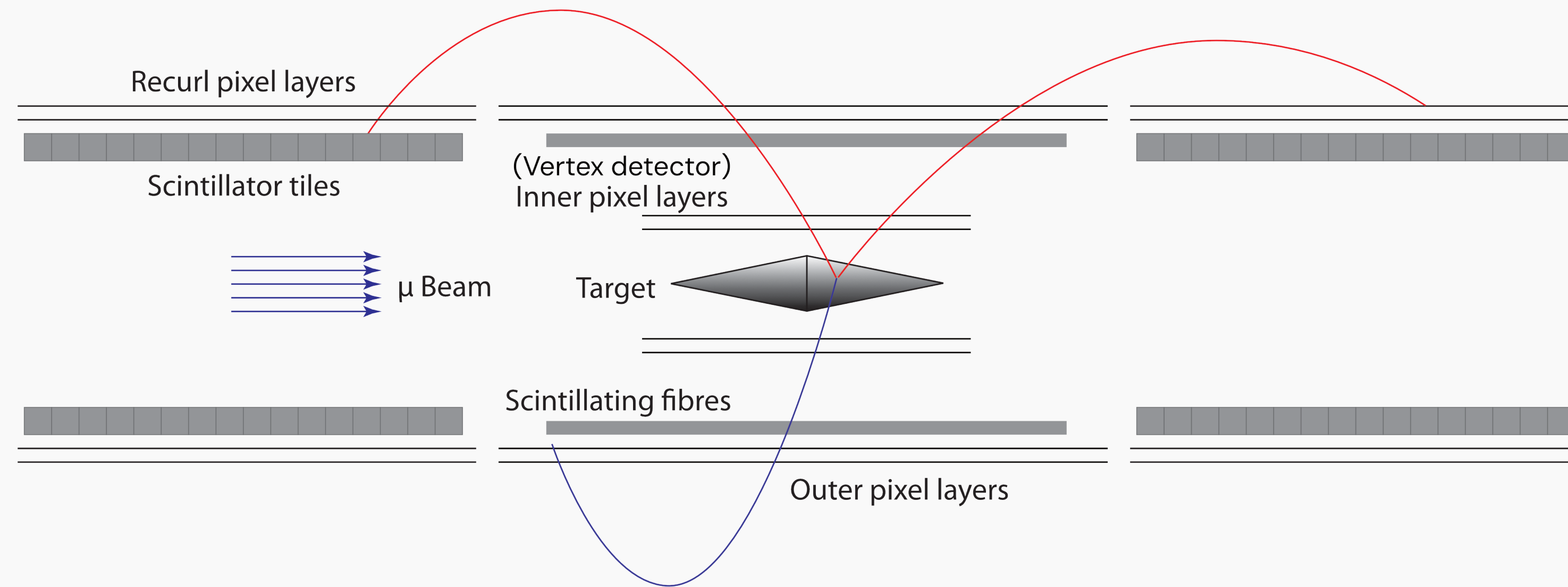
Require excellent  
**momentum** resolution

# Mu3e - Experimental requirements



- High-intensity beam → **High granularity** and **fast** processing ( $10^8$  Hz)
- MeV/c range  $e^+/e^-$  → **Low material budget** to handle multiple Coulomb scattering
- Accidental background → Good **vertex** ( $\sim 200$   $\mu\text{m}$ ) and **timing** ( $< 500$  ps) resolution
- Internal conversion → Excellent **momentum** resolution ( $< 1$  MeV/c) and **recurl stations**
- Compact design → High **integration** (detectors, DAQ, cooling, ...)

# Mu3e - Experimental principle



- **Beam & Target:**  $10^8 \mu^+/\text{s}$  at 28 MeV/c stopped on a double hollow-cone target in a 1 T field
- **Vertex detector:** precise vertexing for helical decay  $e^+/e^-$  tracks
- **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

# Muon beam

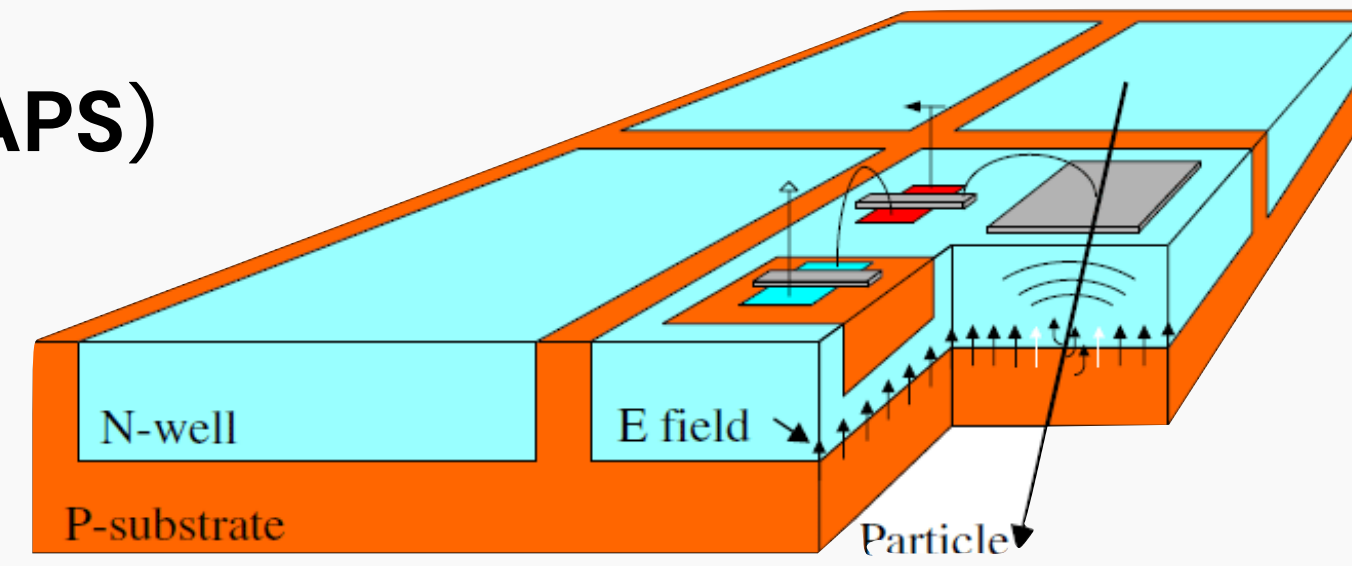


- **HIPA** at Paul Scherrer Institute in Switzerland
  - 590 MeV proton beam with up to 2.4 mA
  - Proton  $\rightarrow$  Graphite target  $\rightarrow$  Pion production  $\rightarrow$  Decay to surface muons
- World's most intense DC muon beam
  - Up to  $10^8 \mu^+/\text{s}$  available at existing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

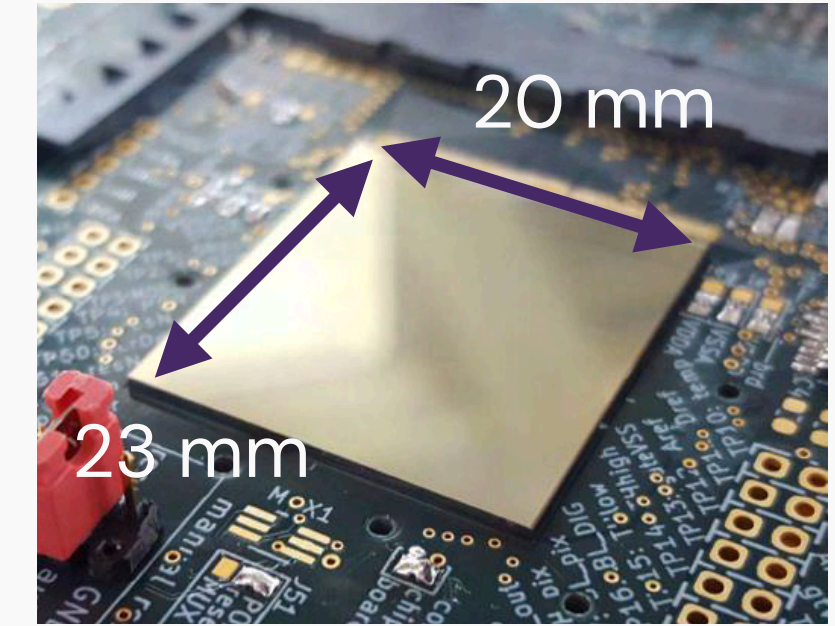


# Pixel detectors

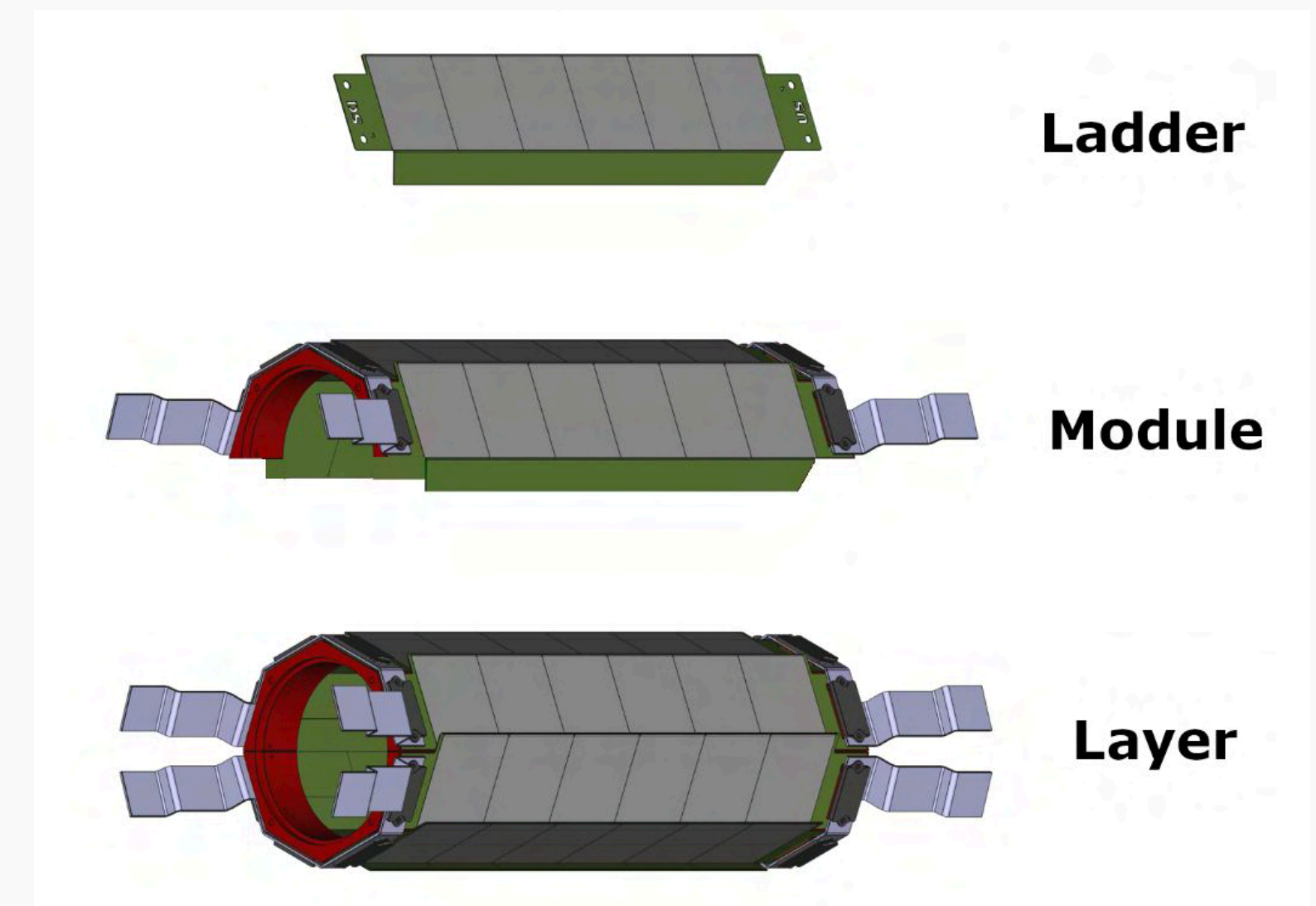
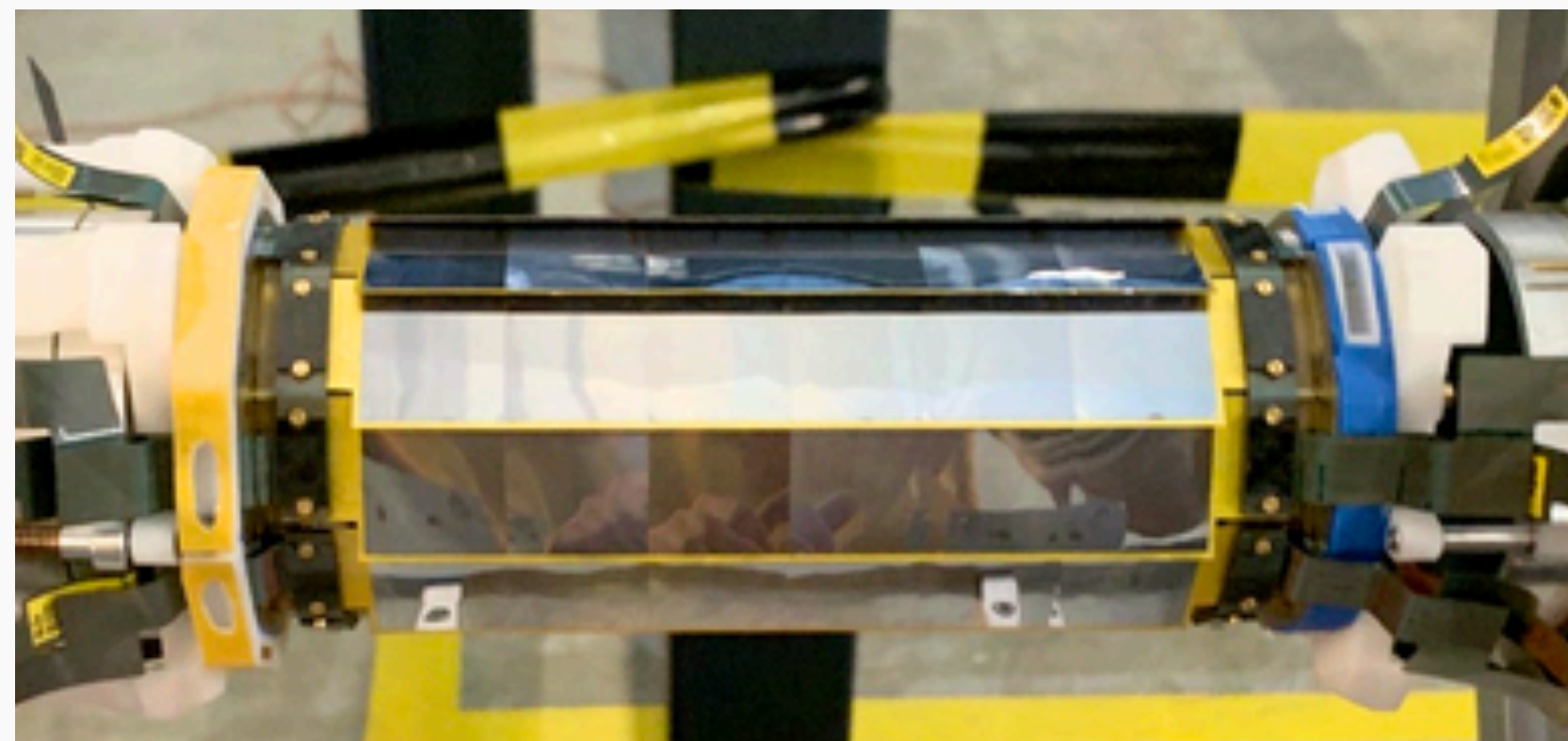
- **MuPix11** – Production chip
  - High Voltage Monolithic Active Pixel Sensors (**HV-MAPS**)
  - **Fast** charge collection via drift
  - Thickness: **50/70  $\mu\text{m}$**
  - Time resolution:  **$\sim 20$  ns**



I. Perić, NIM A 582 (2007) 876



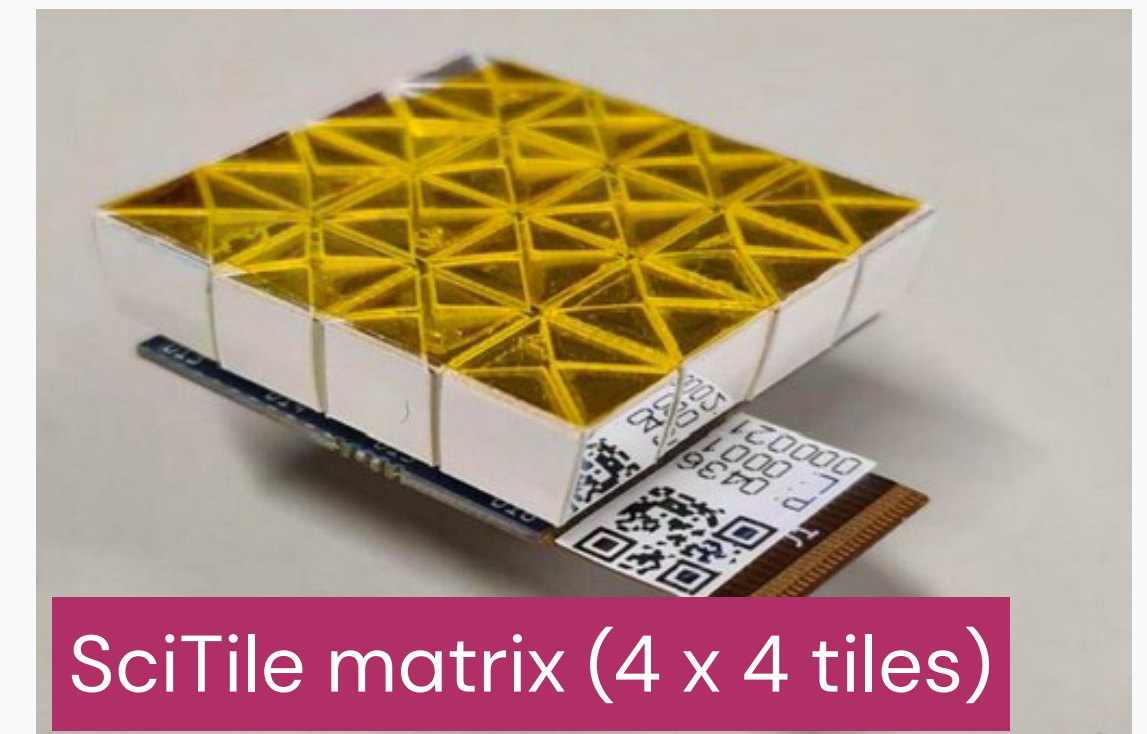
- **Ultra-thin** pixel tracker for precise **vertexing** and **momentum** reconstruction
  - **Modular** design: Built from ladders of MuPix11 chips on HDI
  - **Minimal** material budget:  **$\sim 0.1\%$   $X_0$**  per layer
  - **Gaseous helium cooling** to minimise material budget



# Timing detectors

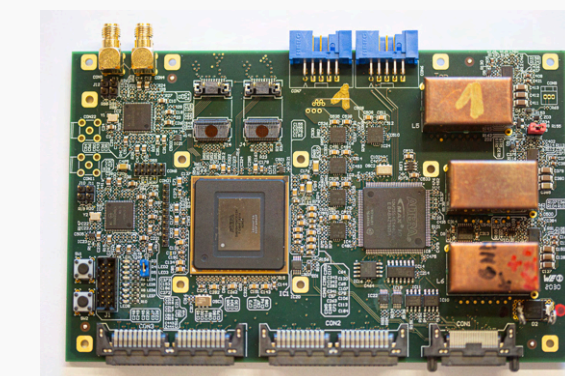
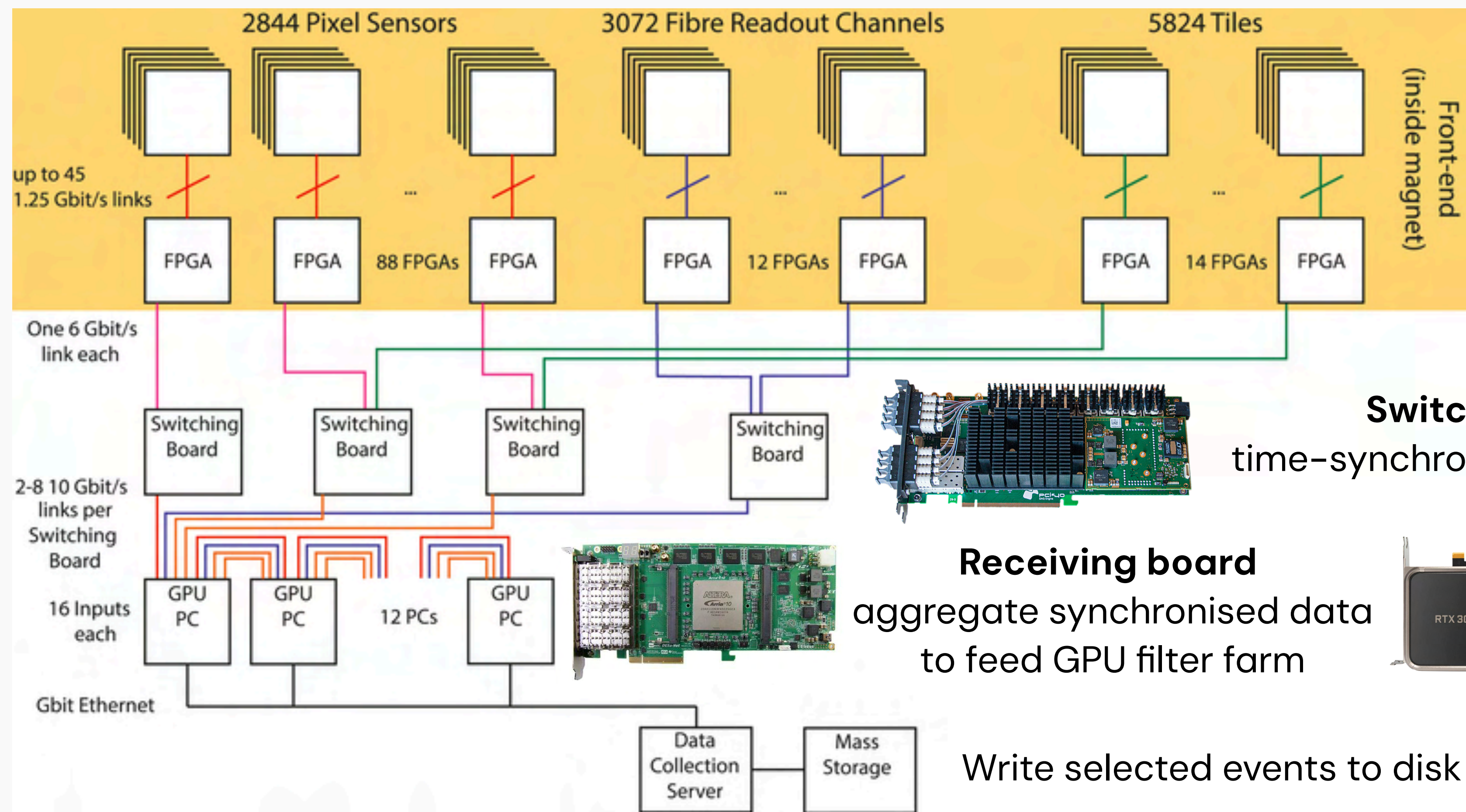


- Suppress **accidental background**
- **Scintillating Fibres (SciFi)** – time resolution  $< 250$  ps
  - Enables  **$e^+/e^-$  identification**
  - 12 ribbons total, each formed by 3 layers of staggered  $250\ \mu\text{m}$  fibres ( $< 0.2\% X_0$ )
  - Placed after Vertex detector to minimise multiple scattering
  - Readout by SiPM arrays at both ends
- **Scintillating Tiles (SciTile)** – most precise timing  $< 70$  ps
  - Highly granular tiles ( $6 \times 6 \times 5\ \text{mm}^3$ )
  - Placed at the end of the recurling particle trajectory
  - Each tile readout by a SiPM

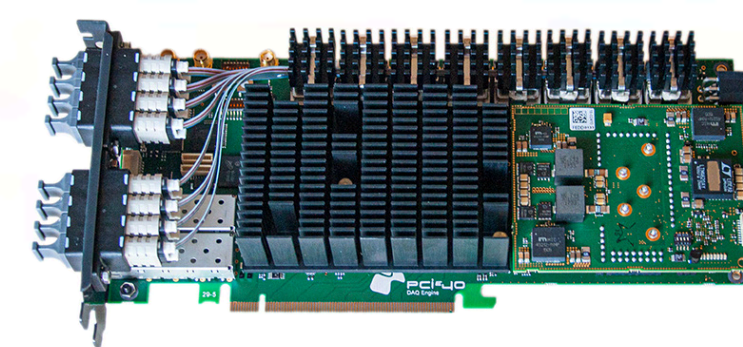


# Data acquisition system

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



**Front-end board (FEB)**  
collect and time-sort data



**Switching board**  
time-synchronise data from FEBs



**Receiving board**  
aggregate synchronised data to feed GPU filter farm



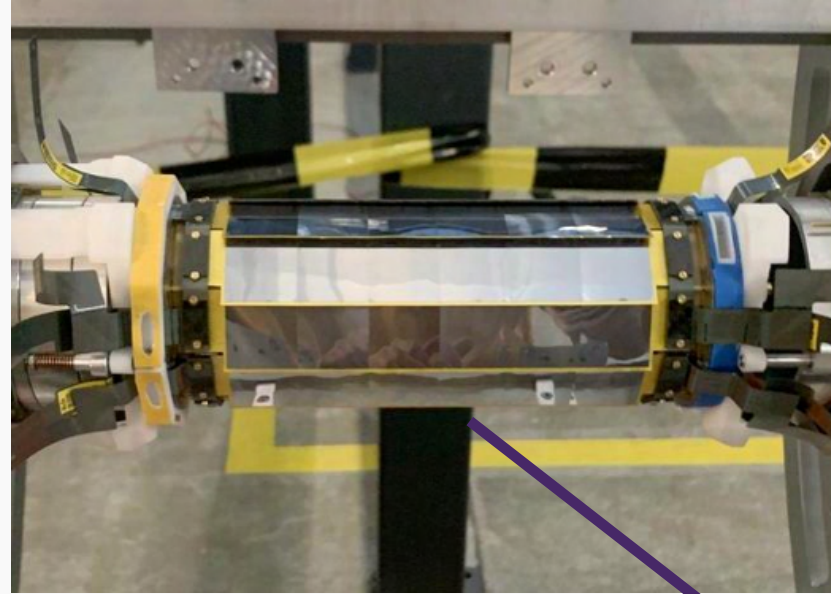
**GPU filter farm**  
online event selection

Write selected events to disk (~100 MB/s)

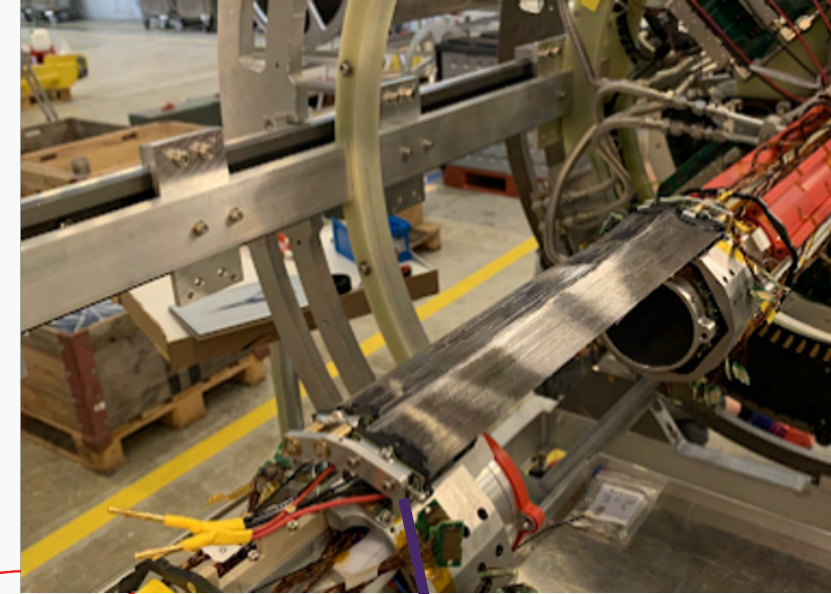
# Commissioning Run 2025



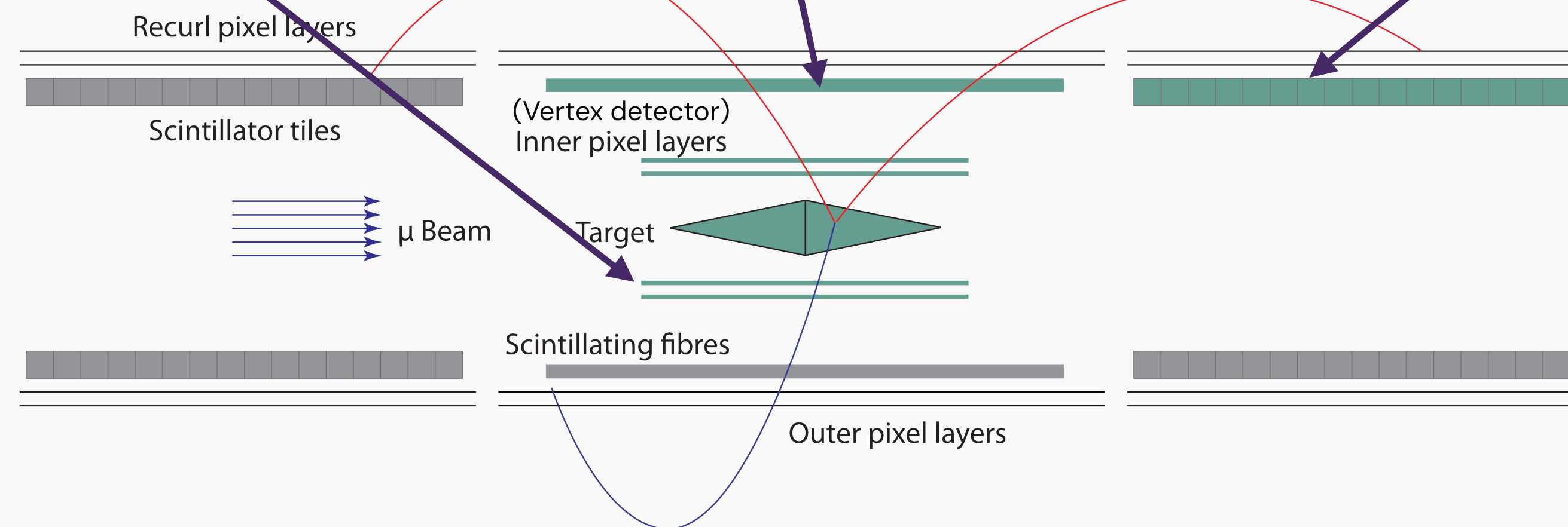
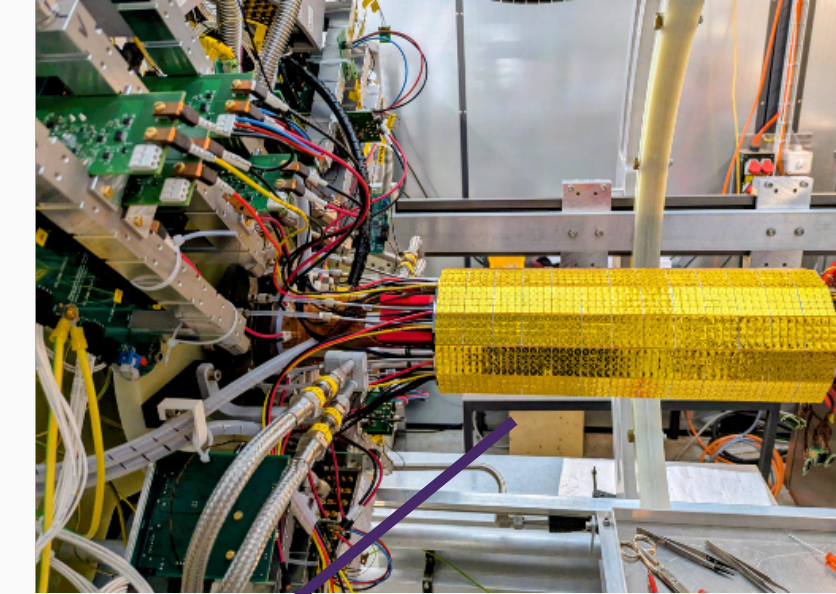
## Vertex detector



## SciFi modules

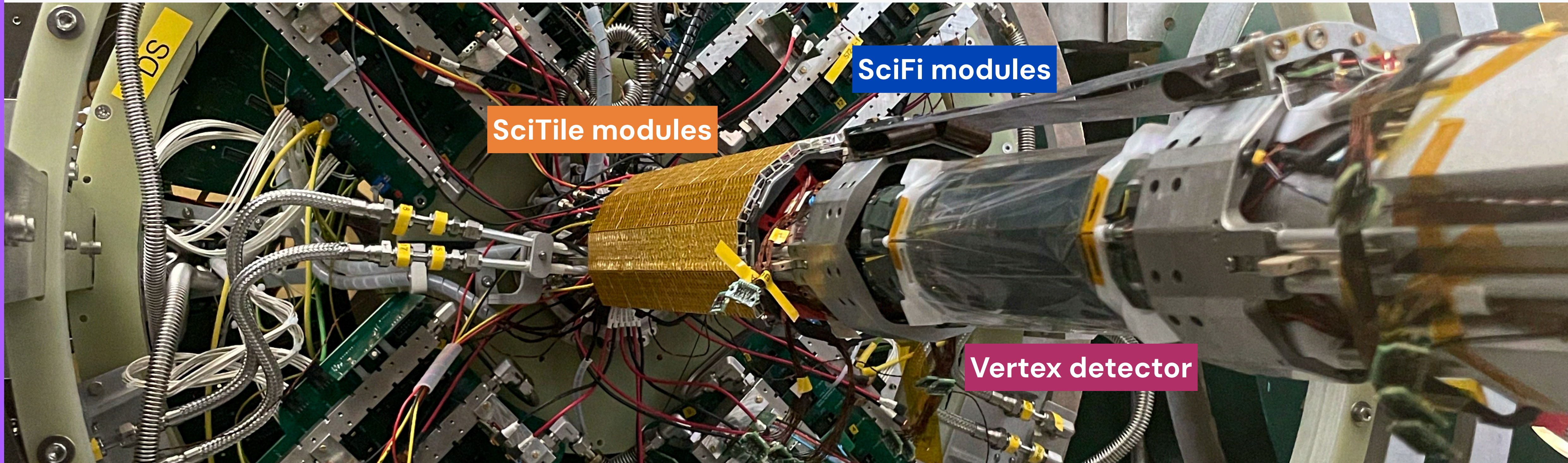


## SciTile modules



- **3-week** Commissioning Run in June 2025 at PSI  $\pi$ E5 beamline
  - First **full integration of detector+services+DAQ**
  - Operation under **beam conditions** with **He gas cooling** and **1 T magnetic field**
  - **Data-taking** at  $10^7 \mu^+/\text{s}$  using **production modules**

# Commissioning Run 2025 – Detector setup

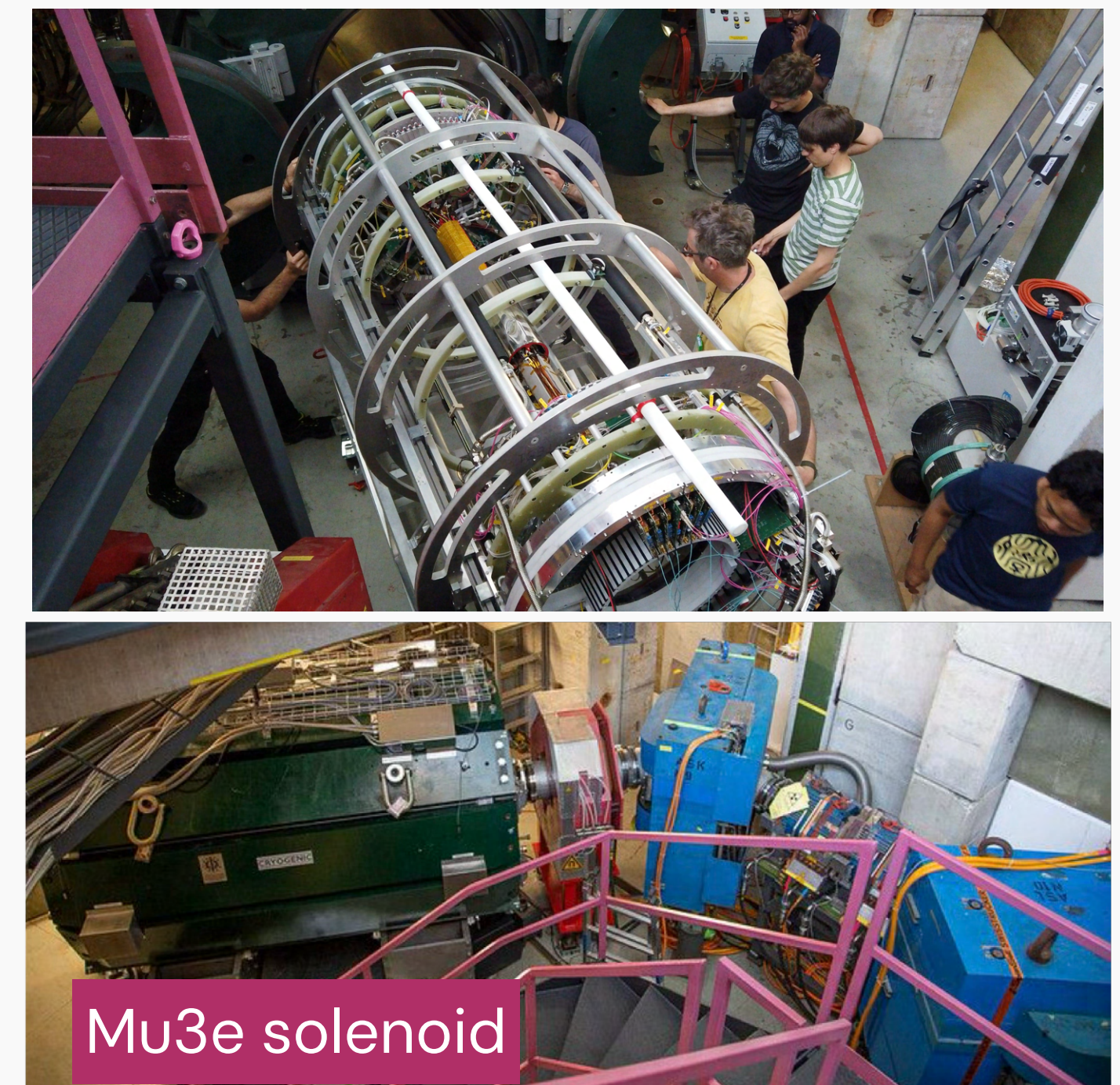


- **Production modules** installed and commissioned
  - Full MuPix11 based Vertex detector
  - 1/6 SciFi modules
  - 3/(2 x 7) SciTile modules on downstream

# Commissioning Run 2025 – Services

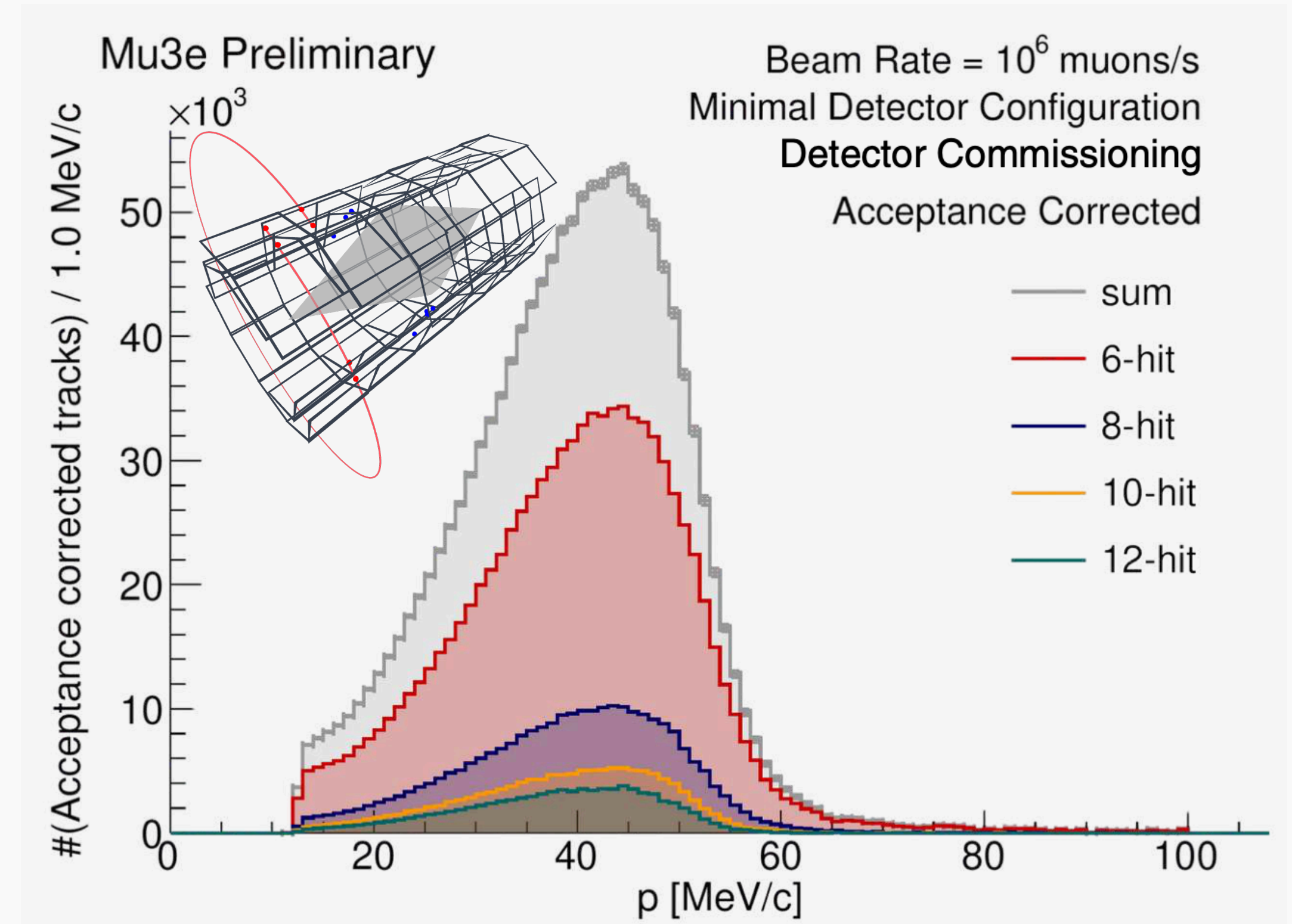
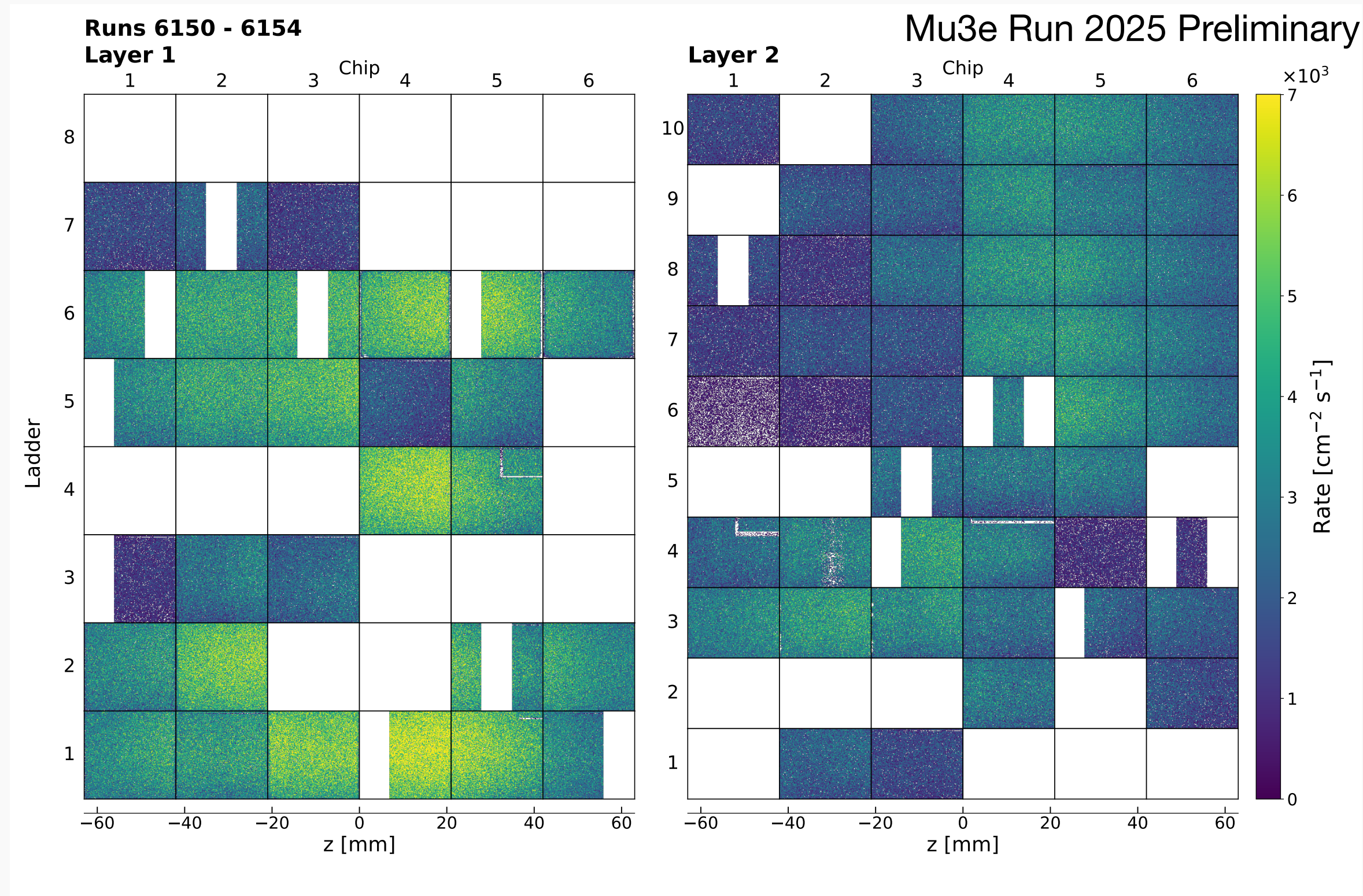


## The flight of Mu3e



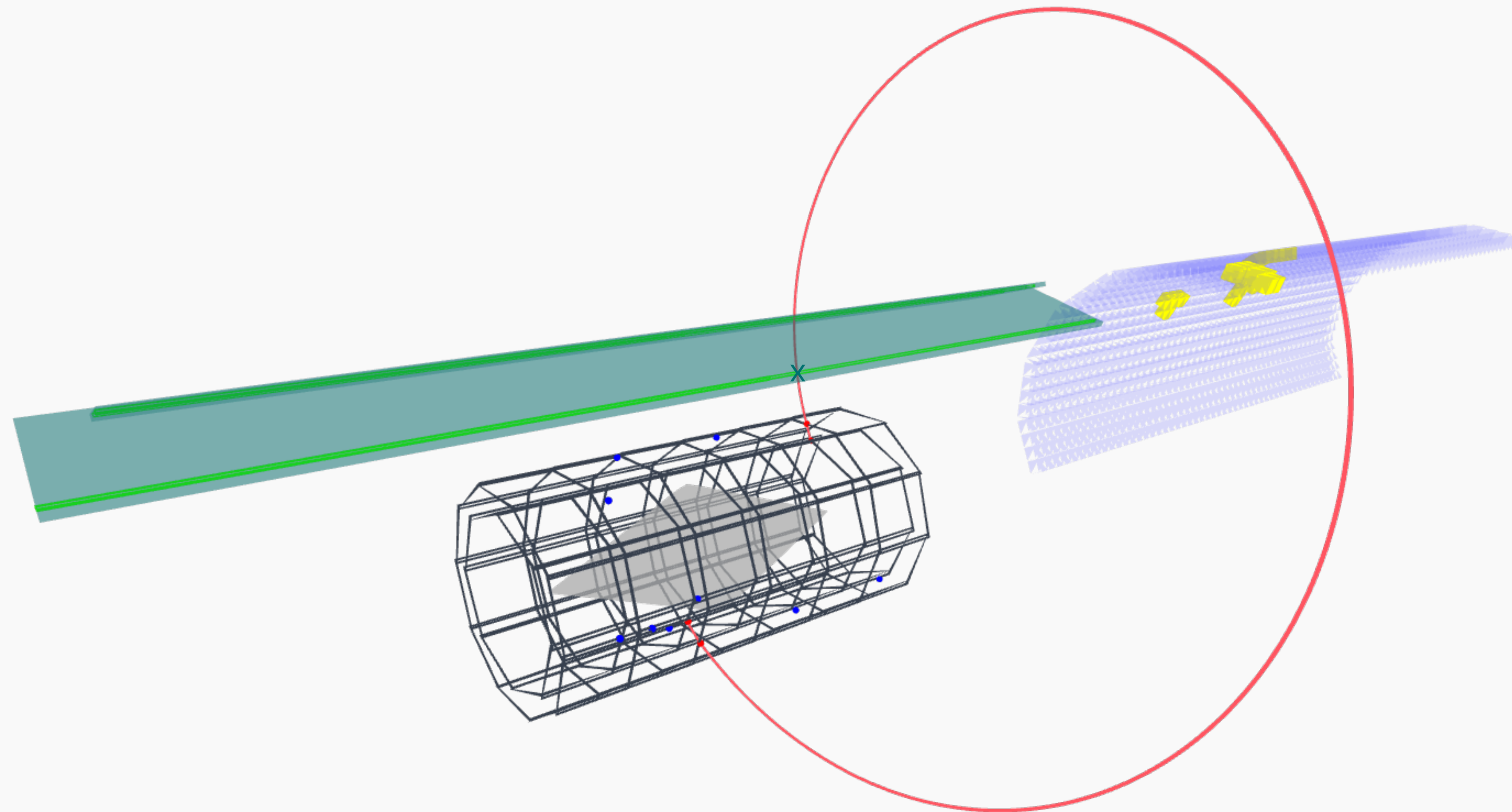
- **Final services** (cooling, power) installed and commissioned
- **Compact Muon Beam Line** setup at  $\pi E5$  area with fully operational **1 T Mu3e solenoid**

# Vertex detector performance

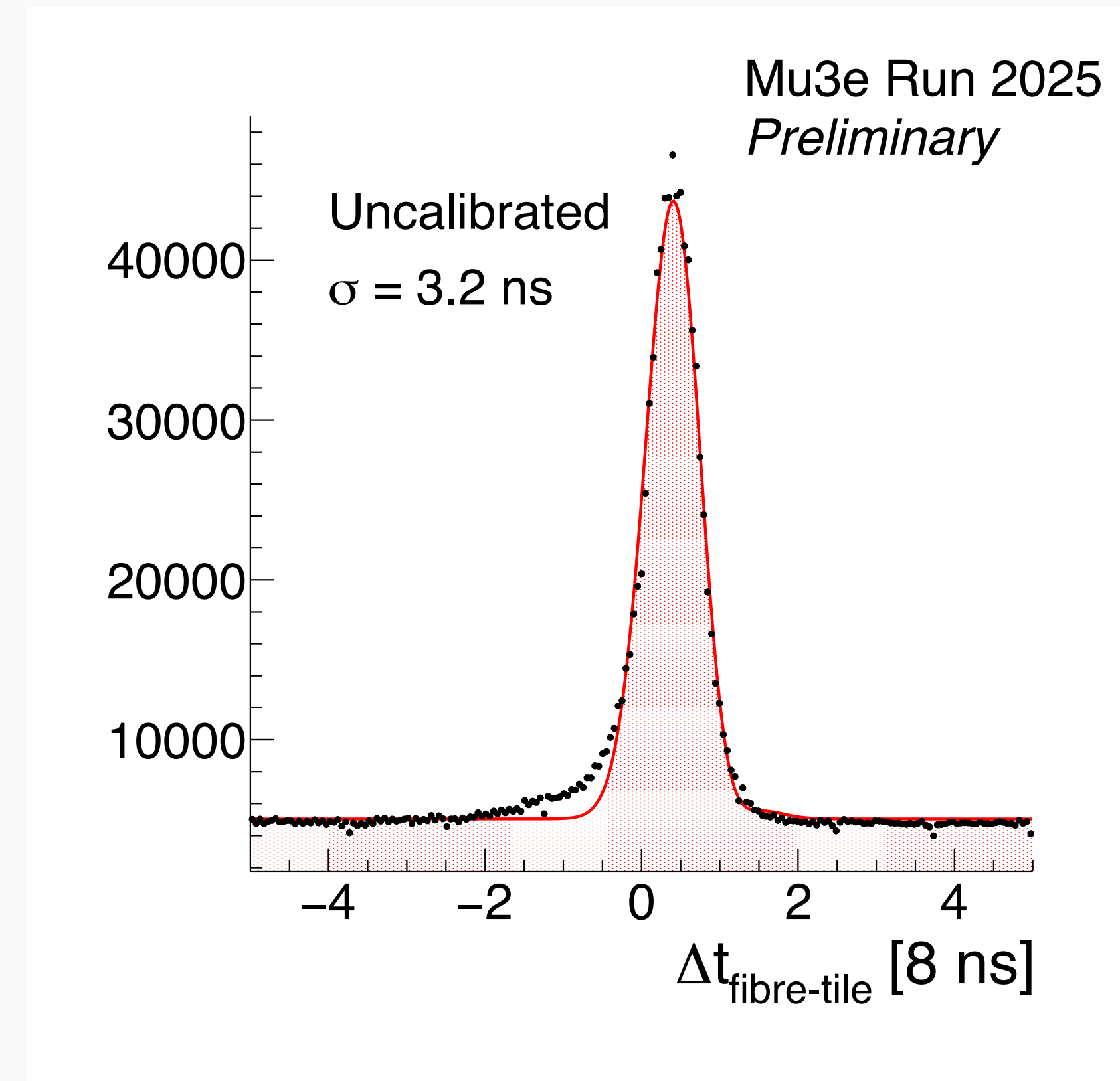
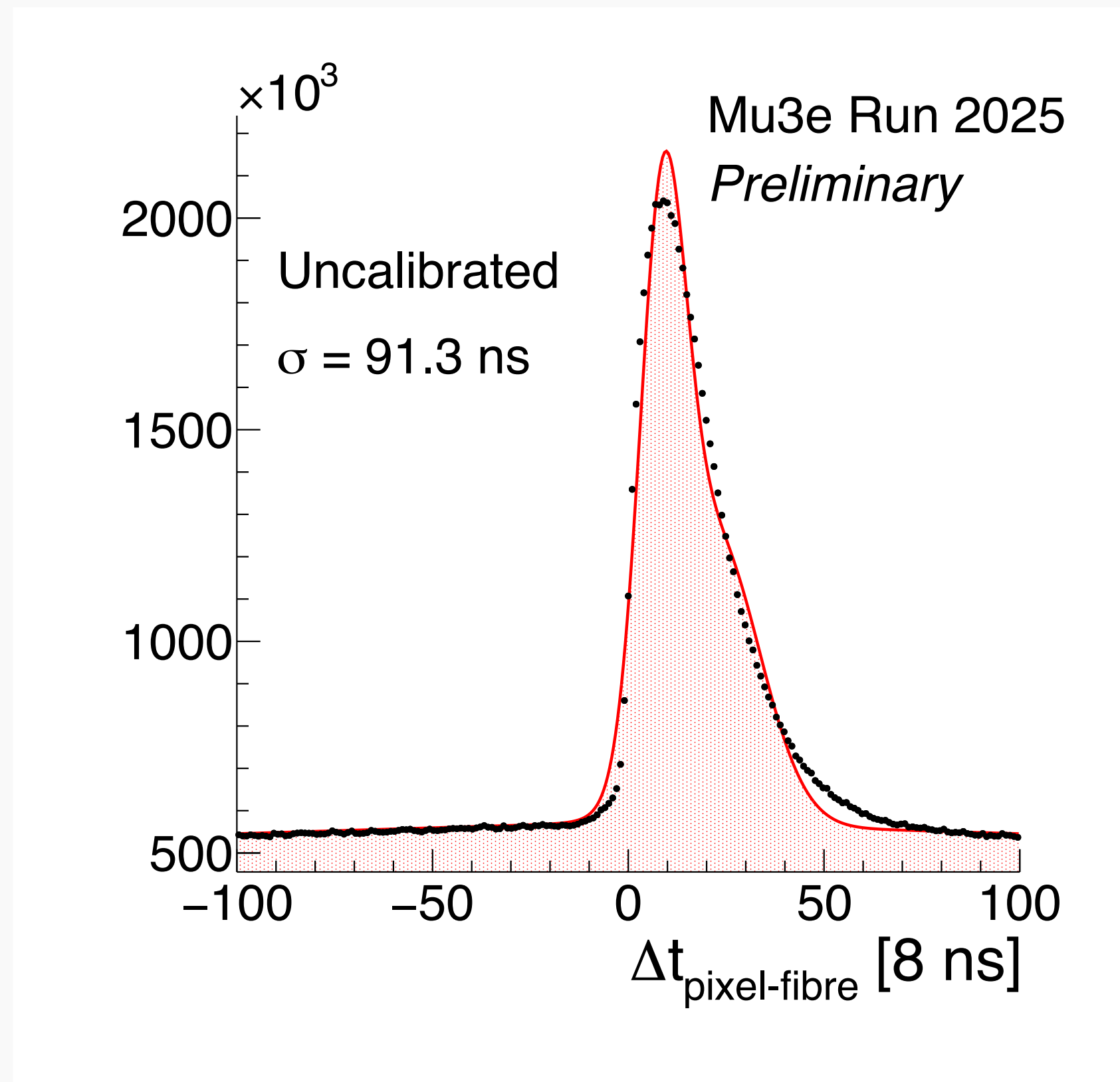
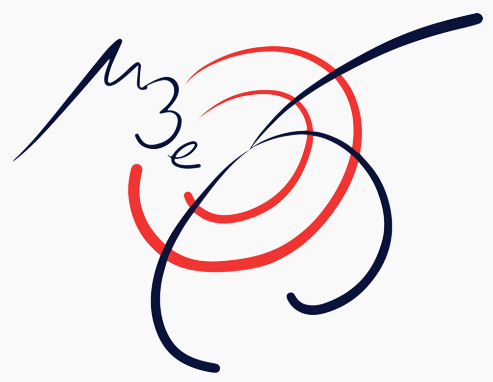


- Operated with 70% active data links due to sensor, link and power/HV line damage before/during installation
- Tracking with Vertex detector enables Michel  $e^+$  momentum measurements
- Detector alignment (cosmic & beam) routine developed and realistic MC under active improvement

# Track matching with SciFi

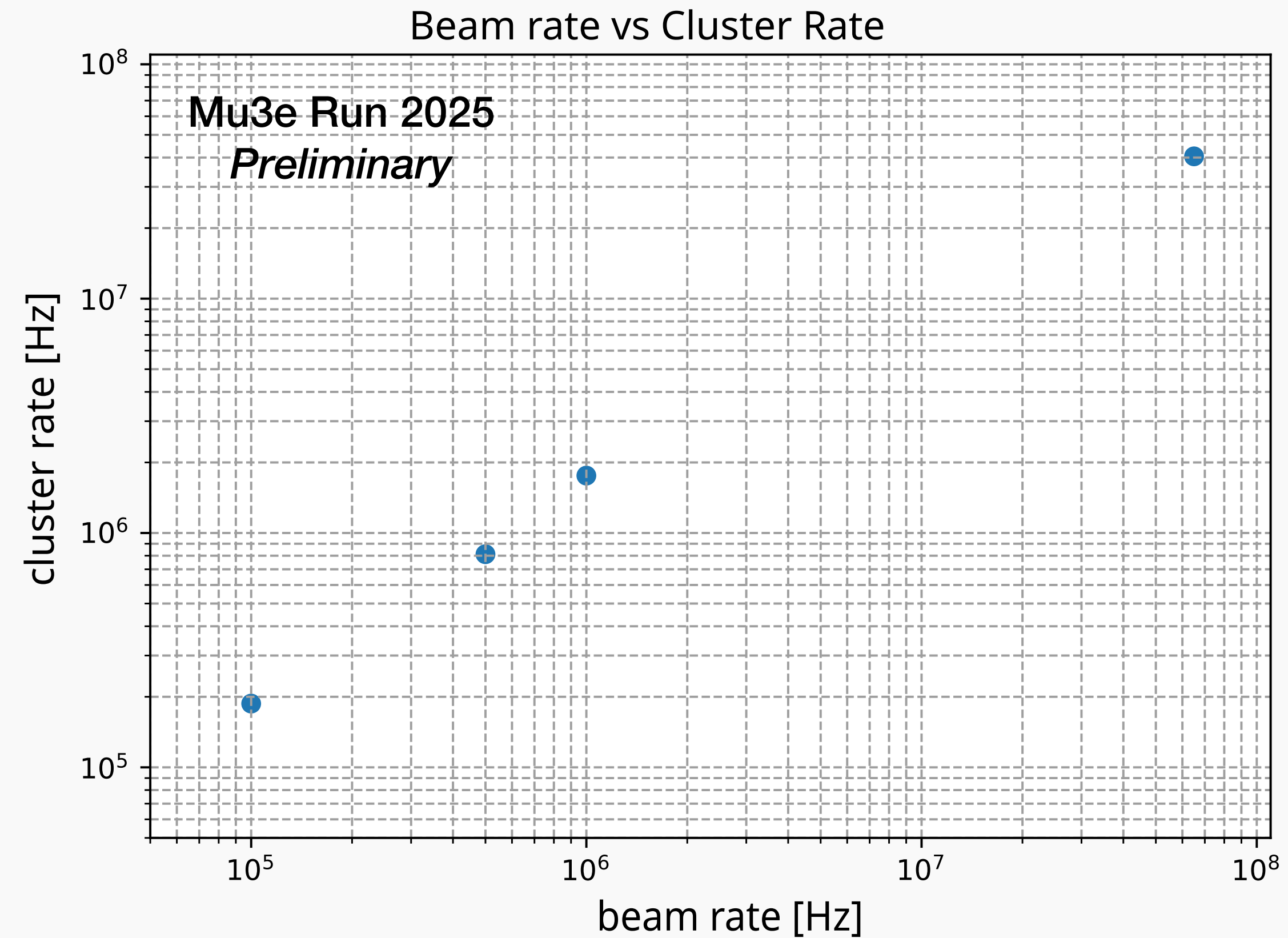


# Timing detectors – Subsystem synchronisation



- Subsystem synchronisation demonstrated during beam time without any calibration

# Timing detectors – Beam monitoring with SciFi

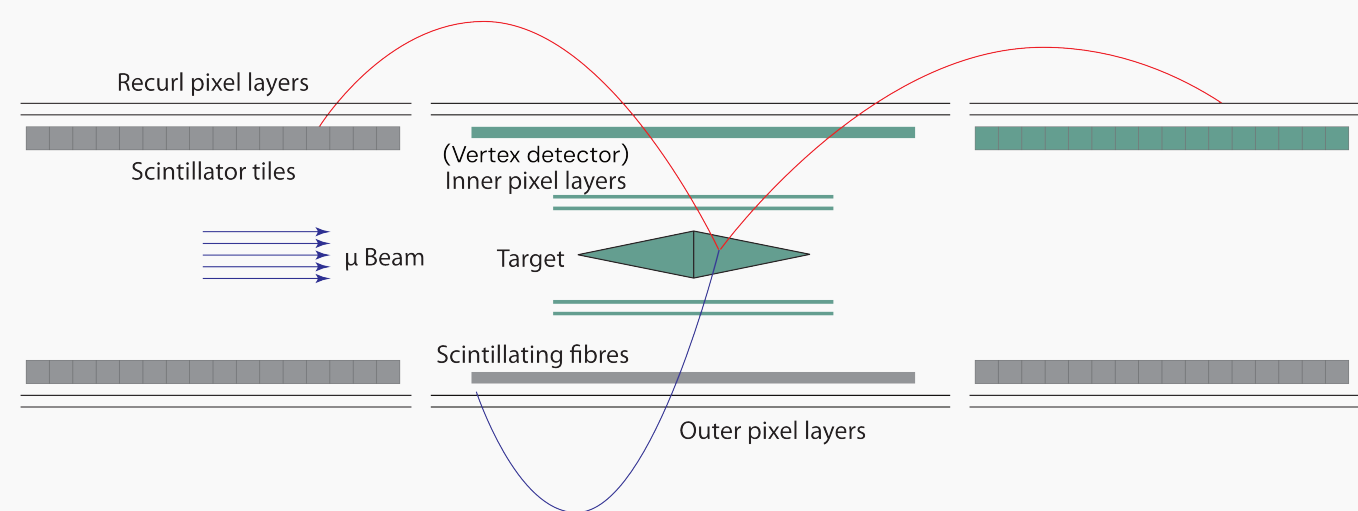


- Online beam monitoring capability demonstrated using a single SciFi module

# Mu3e timeline

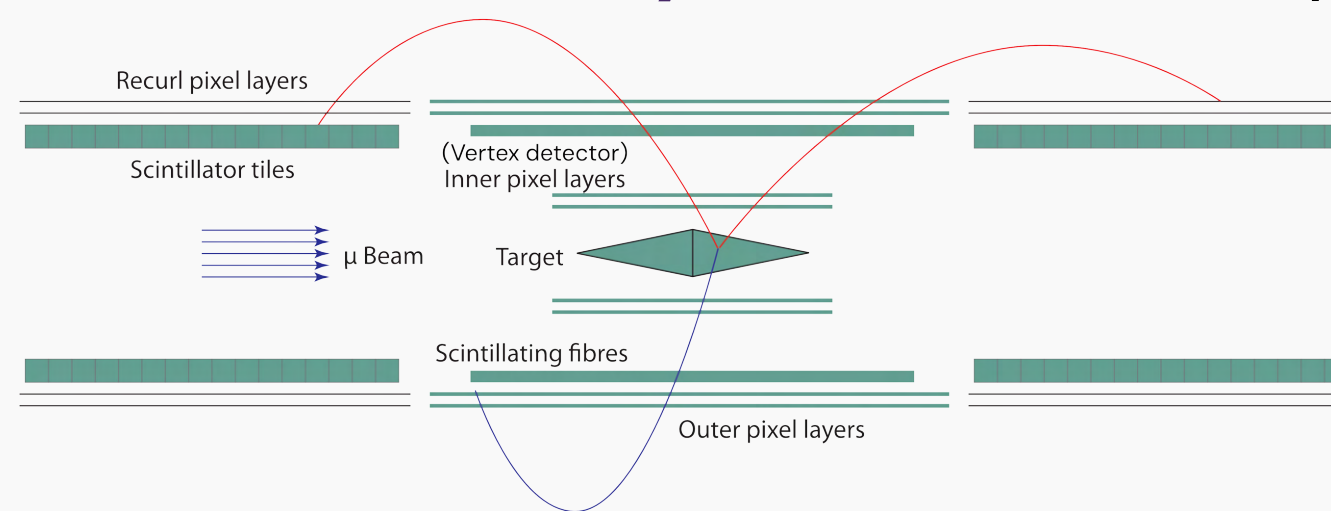


**2025**  
3-week Commissioning Run



**2027**  
First Physics Run

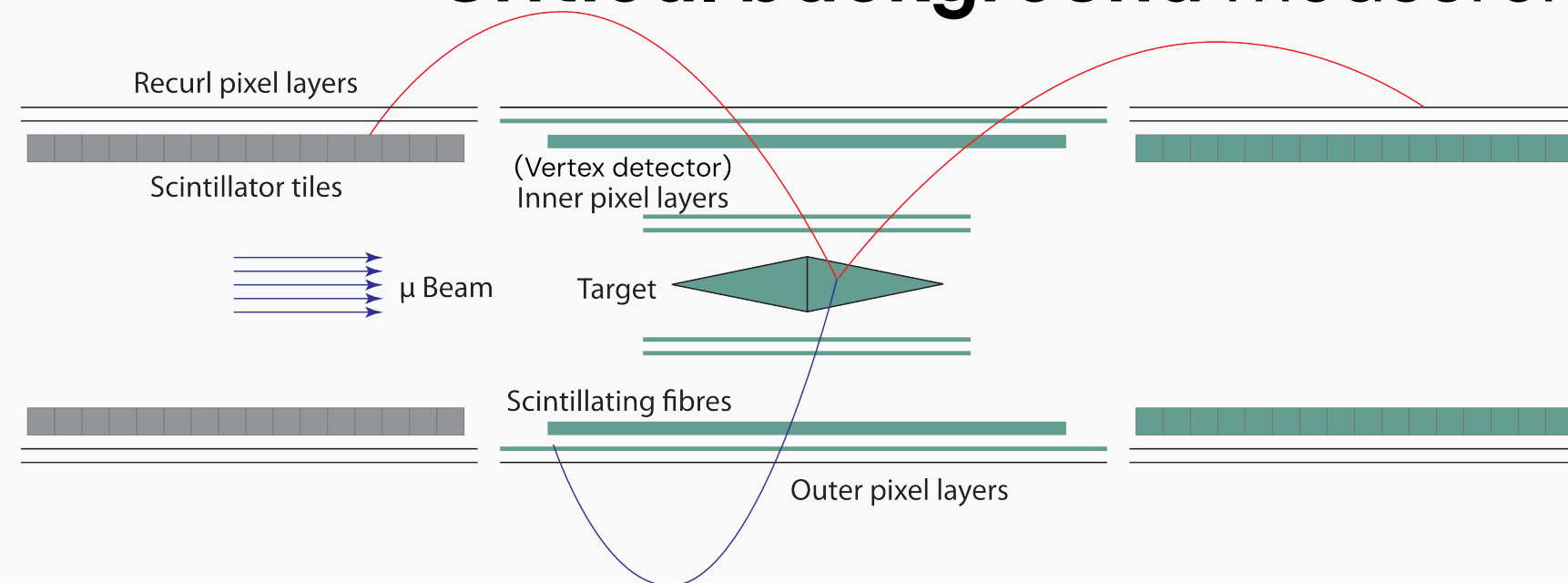
- Full central station + Full SciTile
- Improve SINDRUM limit



**2026 late September**  
8-week Beam Campaign

**2028 January**  
PSI HIMB upgrade start

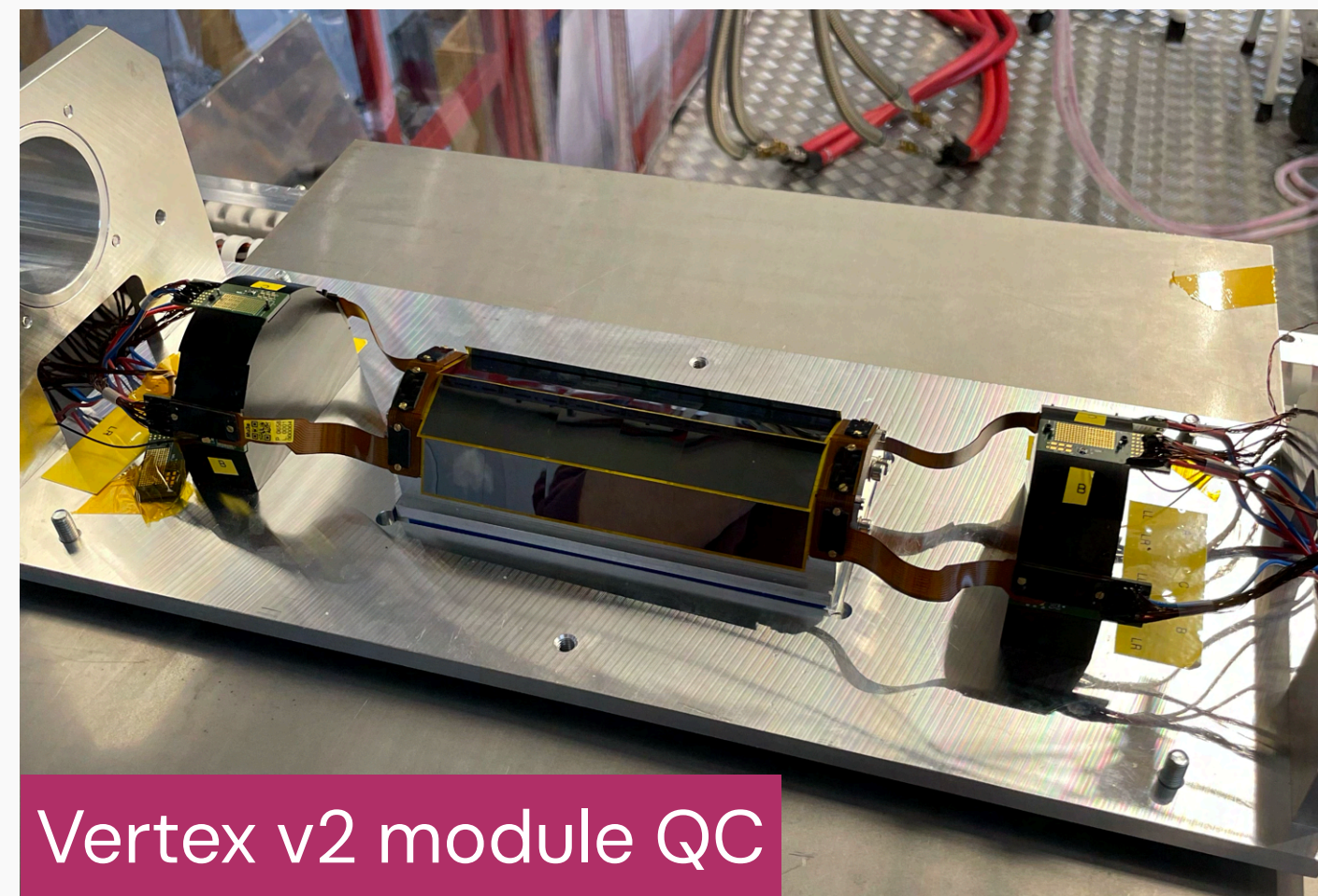
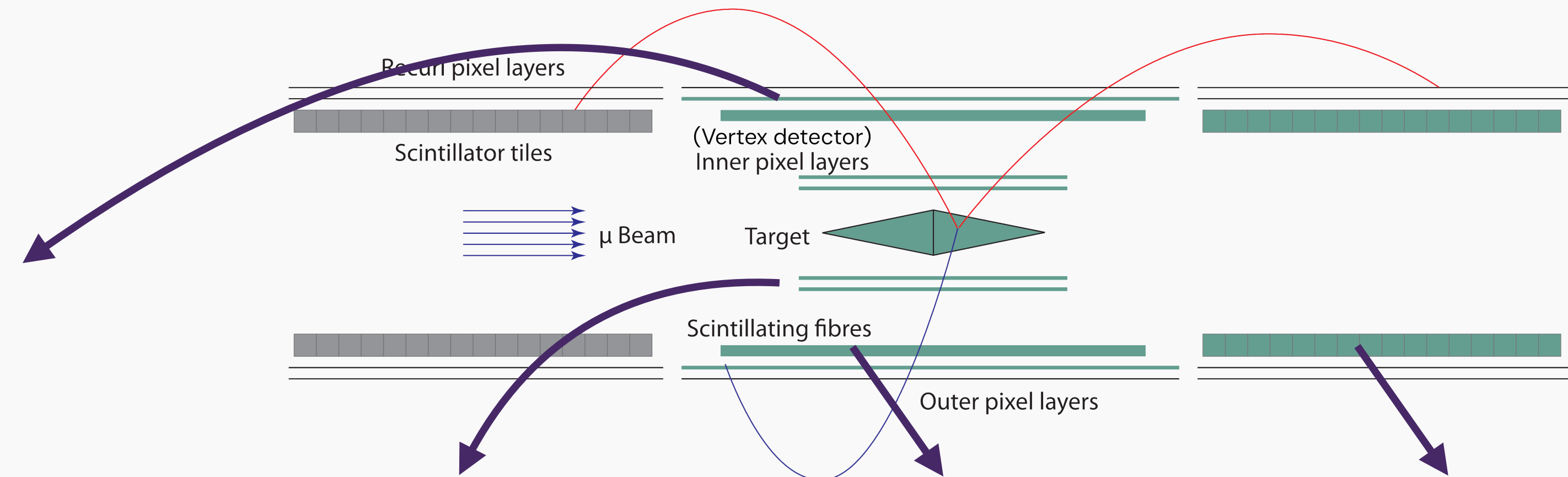
- Commissioning of new detectors
  - Vertex v2
  - **Outer pixel layer3**
  - Full SciFi
  - Full DS SciTile
- Commissioning of **GPU filter farm**
- **Critical background** measurements



# Towards 2026 Beam Campaign



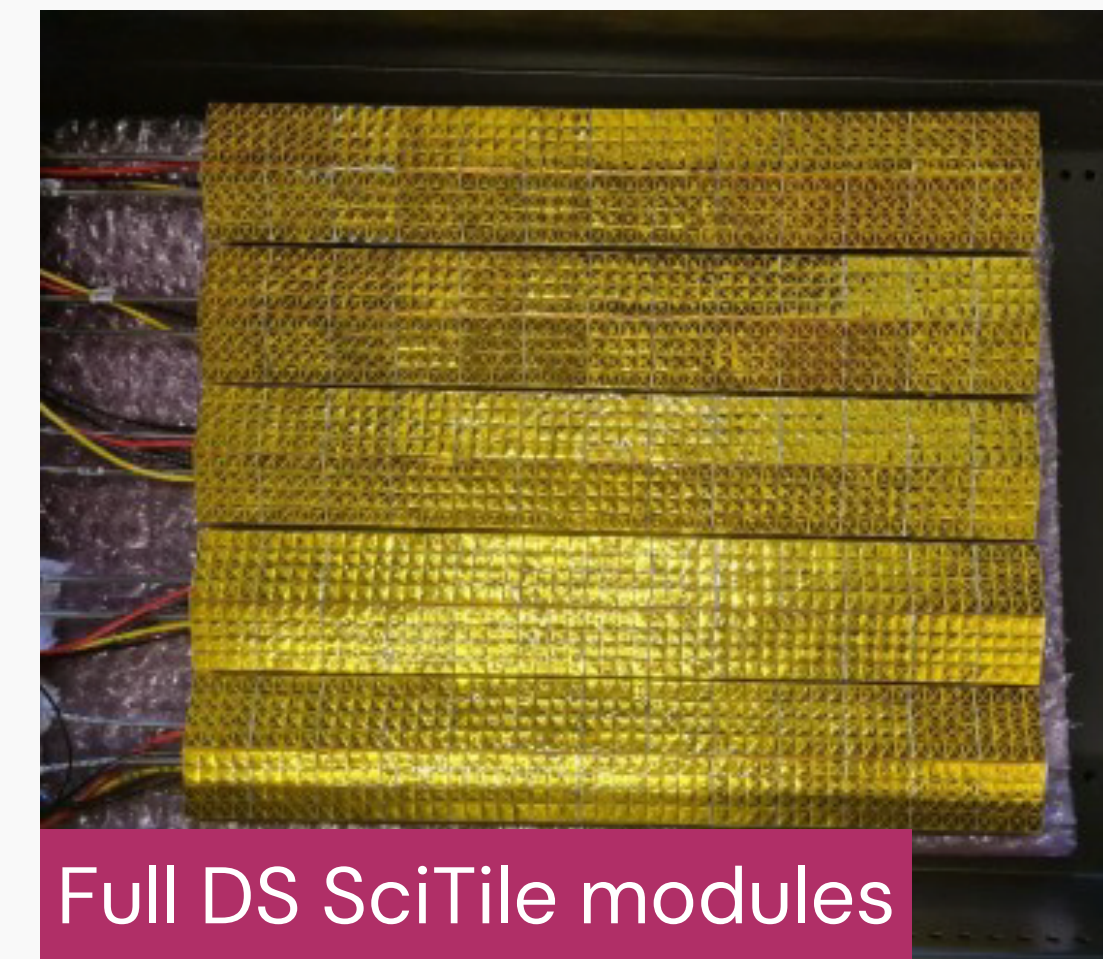
Outer pixel layer3 module assembly



Vertex v2 module QC



Full SciFi modules



Full DS SciTile modules

- Finalising QC efforts ahead of the upcoming sequence of detector installations

# Summary



- The **Mu3e** experiment searches for the cLFV decay  $\mu^+ \rightarrow e^+e^-e^+$  at the  **$10^{-16}$**  level
- **Successful Commissioning Run** in 2025
  - First full integration of **detector, services** and **DAQ**
  - Operation under **beam** conditions with **gaseous helium cooling** and **1 T magnetic field**
  - **Stable data-taking** at  **$10^7 \mu^+/s$**
  - Developed baseline **analysis tools** for the upcoming beam campaign
- **8-week Beam Campaign** in 2026
  - Commissioning of **GPU filter farm** and new detectors including **Outer pixel layer3**
  - **Critical background** measurements
  - Final stage of QC efforts is ongoing; detector installation to begin shortly
- **First Physics Run** planned for 2027 to improve the SINDRUM limit

# Thank you!



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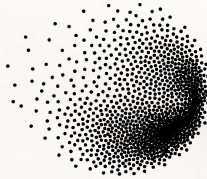
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PSI *ETH* zürich



Universität  
Zürich <sup>UZH</sup>



University of  
BRISTOL



UNIVERSITY OF  
LIVERPOOL



UNIVERSITY OF  
OXFORD

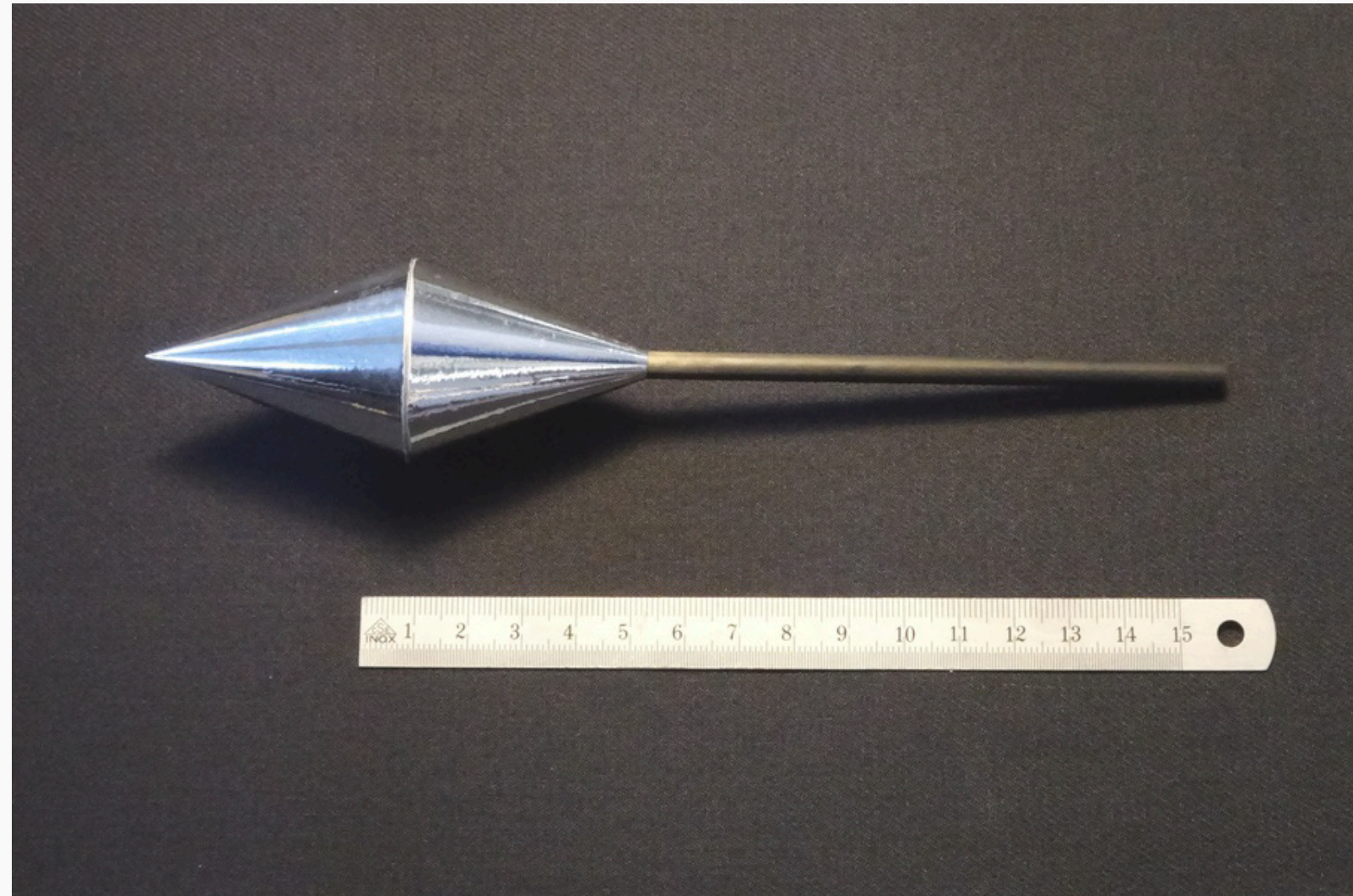
UCL





**Backup**

# Target and Magnet



- 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