The search for Charge Lepton Flavour Violation with

The Mu3e Experiment

Tamasi Kar

On behalf of the Mu3e Collaboration

17th – 23rd of August 2025

Rencontres du Vietnam

4th Flavour Physics Conference 2025

DFG Deutsche Forschungsgemeinschaft

German Research Foundation

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Outline

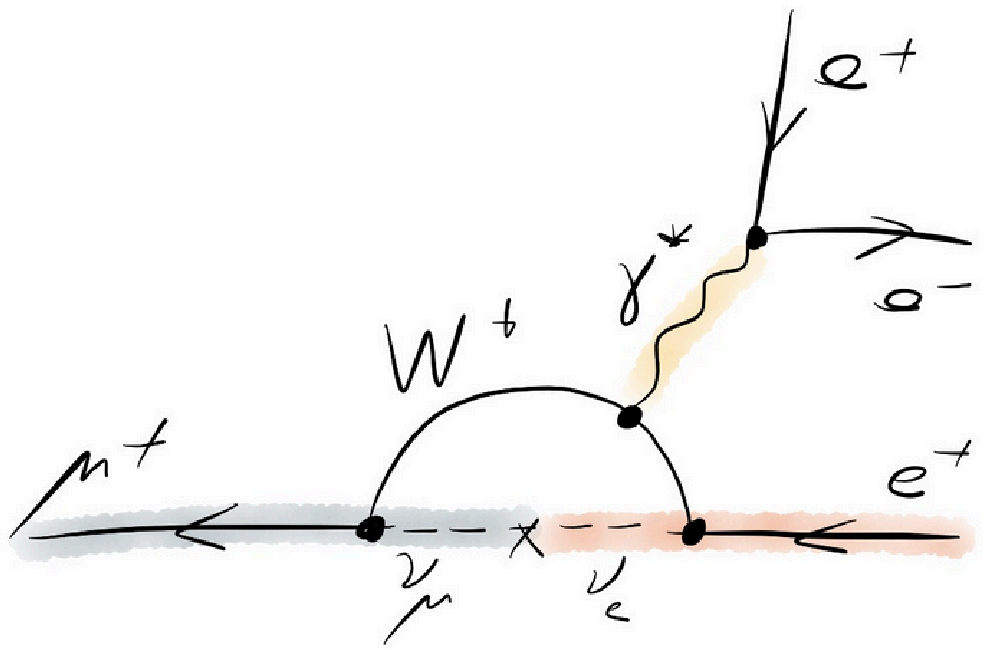
- Charge Lepton Flavour Violation
- Mu3e Kinematics and Backgrounds
- The Mu3e Detector
- Current Status
  June 2025 Commissioning Run Highlights
- Tentative Schedule

Charge Lepton Flavour Violation

A sign for Physics Beyond the Standard Model …

- Lepton Flavour Violation (**LFV**) is established: Neutrino Oscillations
- Charge Lepton Flavour Violation (**cLFV**) in the e-μ transition is heavily suppressed in the SM+neutrino mixing: $\Gamma \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \sim \mathcal{O}(10^{-54})$

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



SM process via neutrino mixing

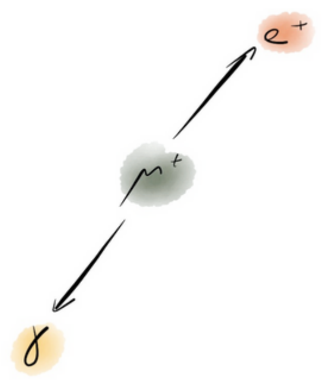
Charge Lepton Flavour Violation

A sign for Physics Beyond the Standard Model …

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

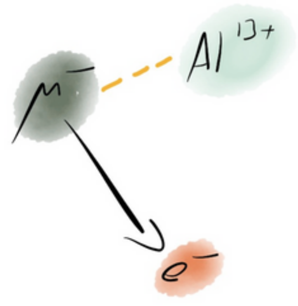
- Lepton Flavour Violation (**LFV**) is established: Neutrino Oscillations
- Charge Lepton Flavour Violation (**cLFV**) in the e-μ transition is heavily suppressed in the SM+neutrino mixing: $\Gamma \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \sim \mathcal{O}(10^{-54})$
- **cLFV** in the muonic sector is particularly interesting: three golden channels with complementary sensitivities to new physics

Observation would be an unambiguous sign for new physics!



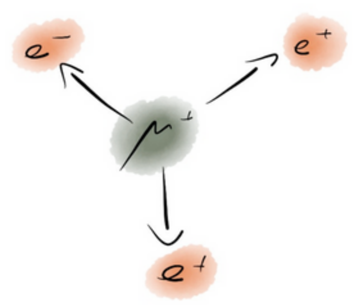
$\mu^+ \to e^+\gamma$

MEG/MEG II (PSI)
$B(\mu^+ \to e^+\gamma) < \mathbf{1.5 \cdot 10^{-13}}$
(2025)



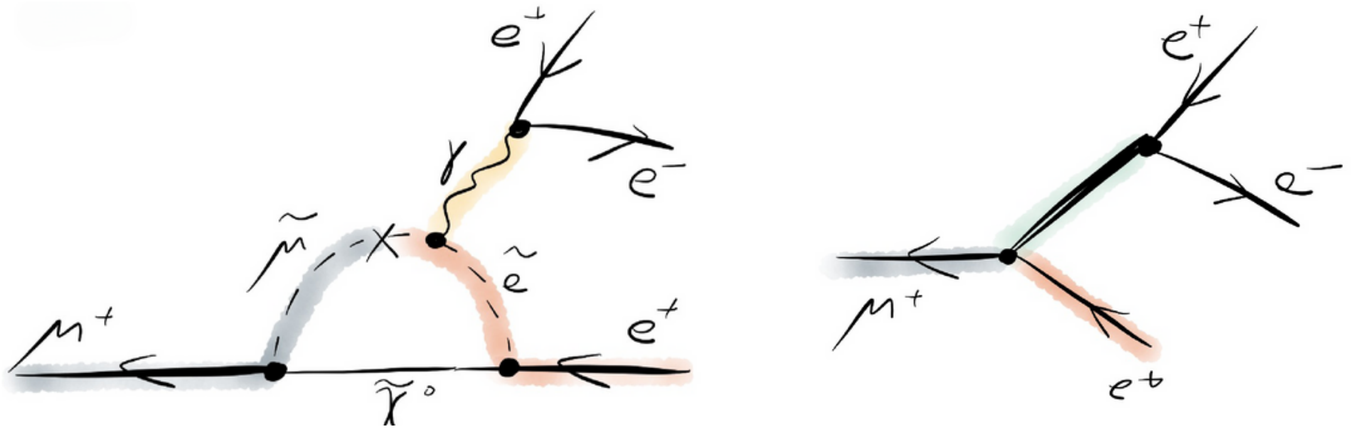
$\mu^- N \to e^- N$

SINDRUM II (PSI)
$B(\mu^- Au \to e^- Au) < \mathbf{7 \cdot 10^{-13}}$
(2006)



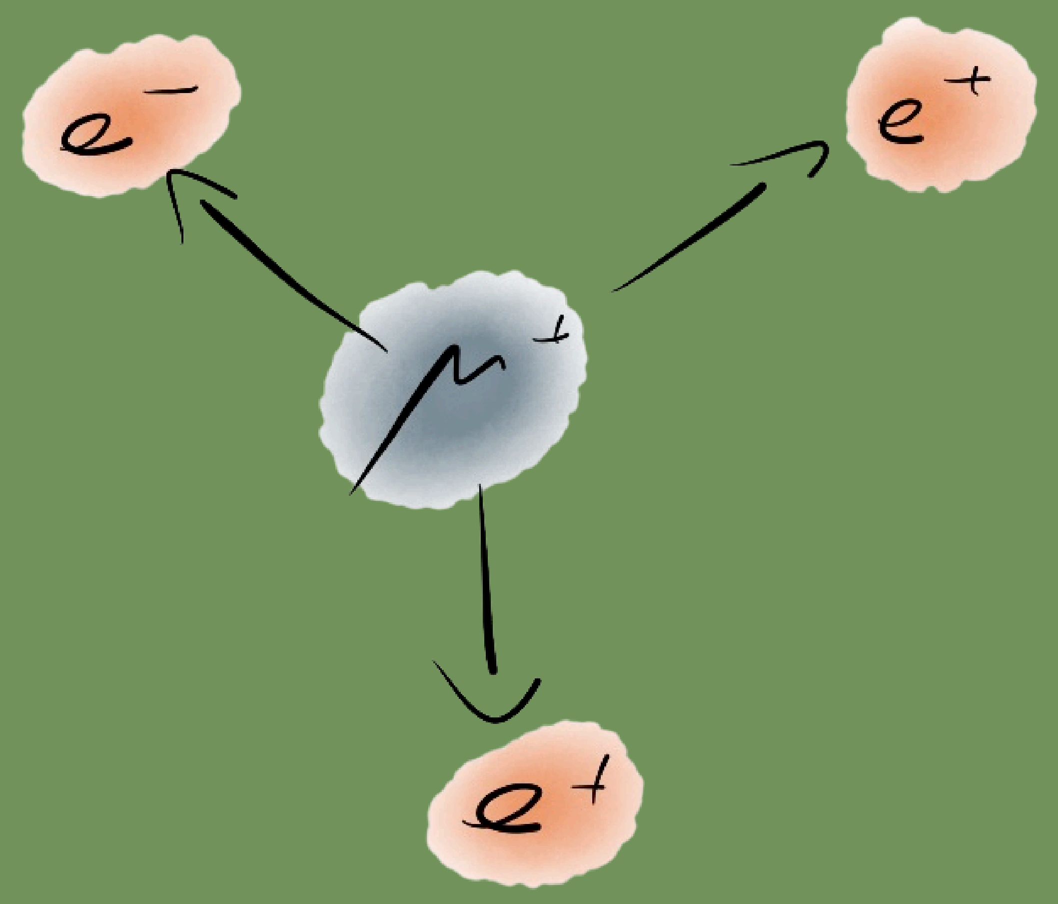
$\mu^+ \to e^+e^-e^+$

SINDRUM (PSI)
$B(\mu^+ \to e^+ e^- e^+) < \mathbf{1.0 \cdot 10^{-12}}$
(1988)



BSM processes involving supersymmetric particles in loop and at tree level

Mu3e



Branching ratio sensitivity goal ($\mu^+ \rightarrow e^+e^-e^+$) ~ $\mathbf{10^{-16}}$ → In two phases

⇒ *Improvement by up to 4 orders of magnitude compared to the current limit*

How do we achieve this sensitivity goal?

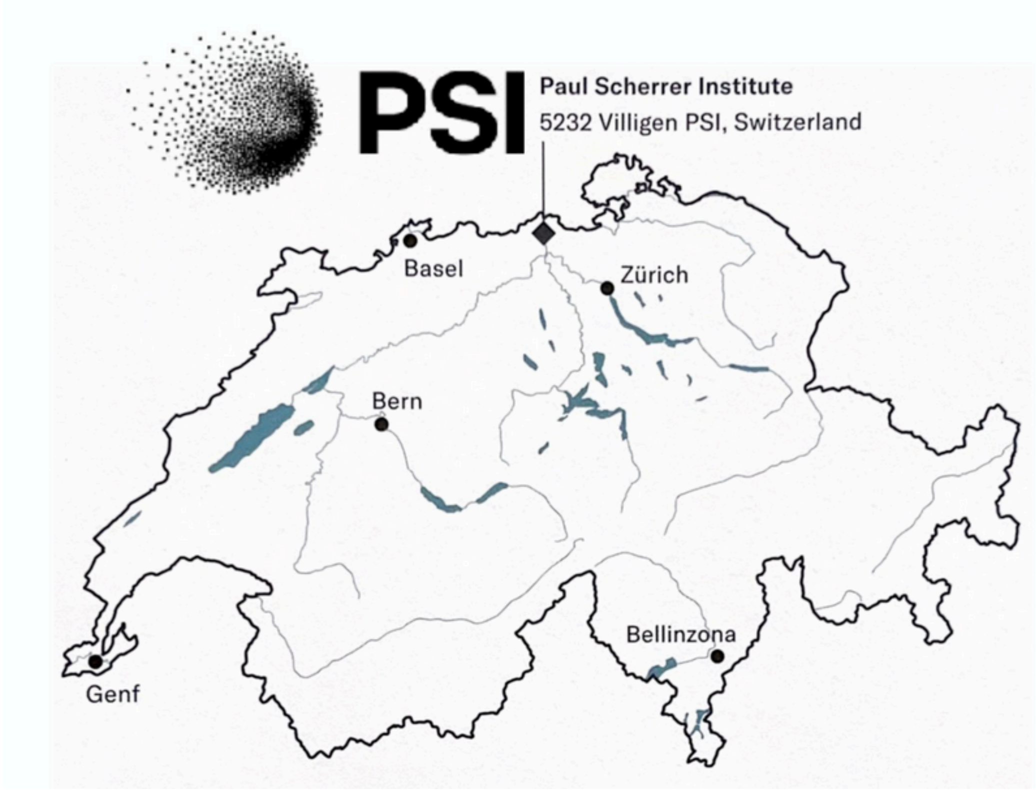
↳ Need muons (a lot of muons!)

- Paul Scherrer Institute in Switzerland:
  → Highest intensity continuous muon beamline
  → Currently available ~ 10^8 μ/s

- **Phase I goal:** BR($\mu^+ \rightarrow e^+e^-e^+$) ~ $\mathcal{O}(10^{-15})$
  → Need at least 10^8 μ/s

- **Phase II goal:** BR($\mu^+ \rightarrow e^+e^-e^+$) ~ $\mathcal{O}(10^{-16})$
  → Need at least 2 x 10^9 μ/s
  → **High Intensity Muon Beamline (HIMB) ~ 10^{10} μ/s**

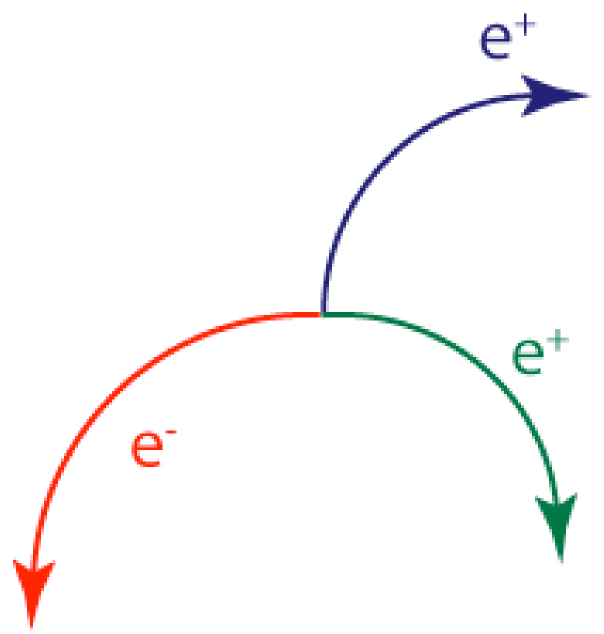
1. ***Need an experiment with a detector technology that can handle such high rates!***



Mu3e

$\mu^+ \rightarrow e^+ e^- e^+$ Signal Kinematics ...

- Signal topology: **two positrons** and **one electron** from a muon decay at rest
- 4-momenta sum $(\Sigma P_e) \approx (m_\mu, 0, 0, 0)$
- Maximum momentum of $e^{+/-}$: $\frac{1}{2} m_\mu$ (~53 MeV/c)
- Should originate from a common vertex and at the same time



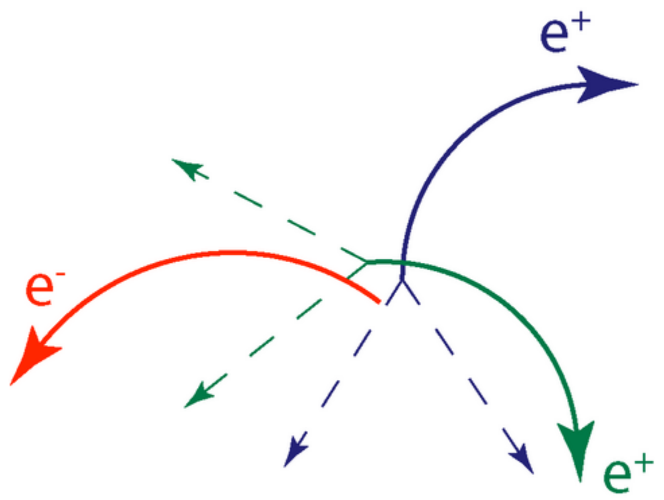
Challenge: Low momentum electrons and positrons
⇒ Multiple Coulomb scattering effects dominate

Mu3e

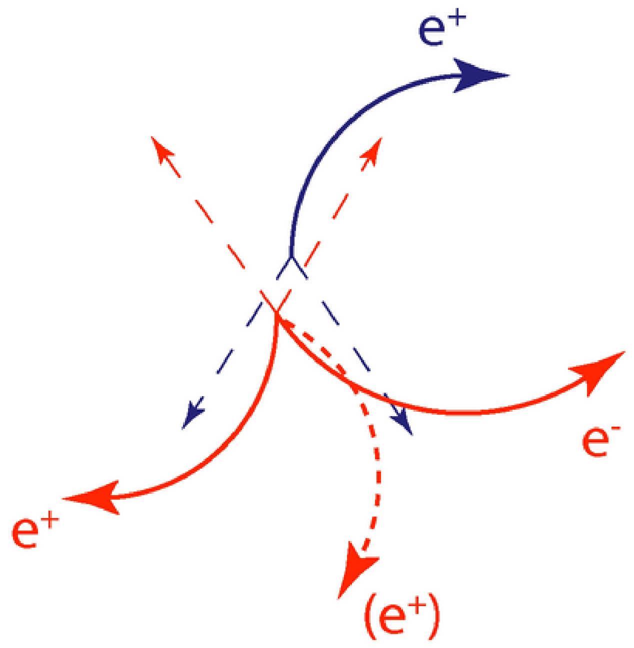
Background processes mimicking the $e^+e^-e^+$ final state

↳ **Accidental combinatorial background**

- Muon decays (~100%) via $\mu^+ \rightarrow e^+ \nu \bar{\nu}$
- Accidental combinations of **e^+ from $\mu^+ \rightarrow e^+ \nu \bar{\nu}$** decay(s) with an **$e^-$ or e^+e^-** originating from:
  - Bhabha scattering
  - photon conversion
  - mis-reconstruction



Two Michel decays + e-



Michel decay + Internal Conversion

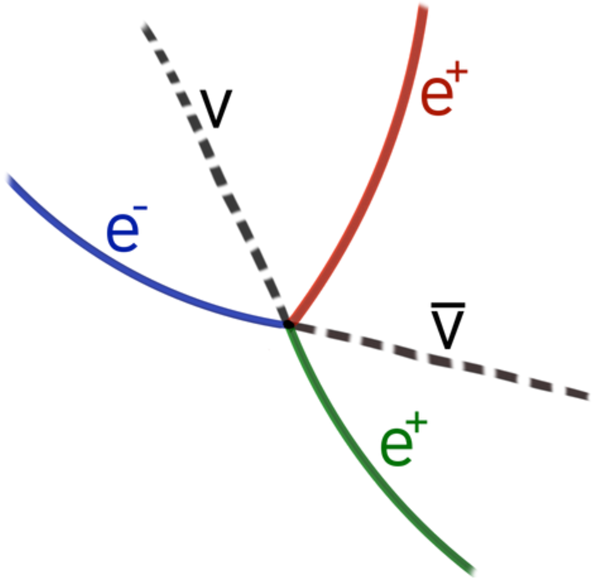
2. *Need very good timing and vertexing!*
⇒ Low material, continuous muon beam

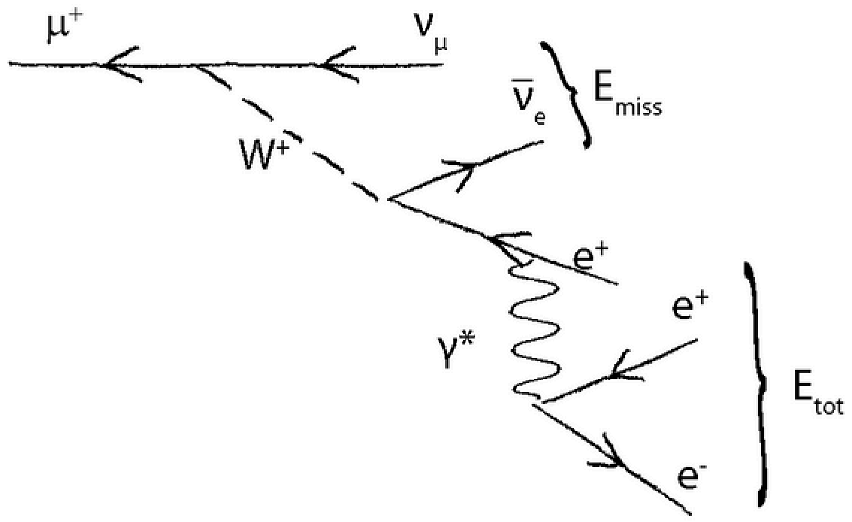
Mu3e

Background processes mimicking the $e^+e^-e^+$ final state

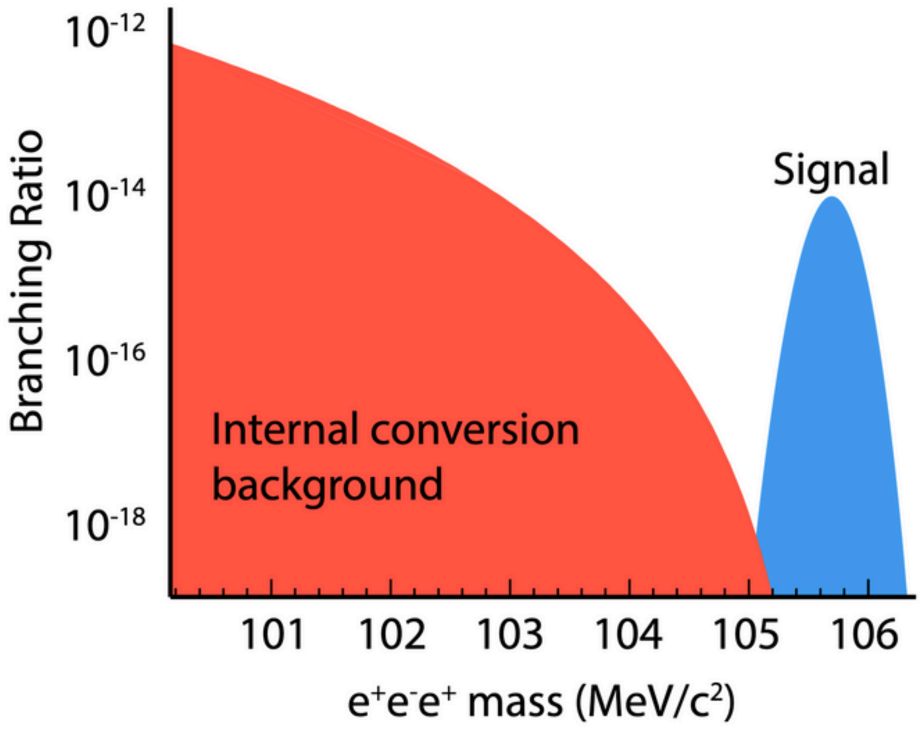
↳ Internal conversion background

- Rare muon decay $B(\mu^+ \rightarrow e^+e^-e^+ \nu \bar{\nu}) = 3.4 \times 10^{-5}$
- Have a common vertex and are coincident
- Distinguishable only by the missing momentum carried by neutrinos





Radiative decay with internal conversion

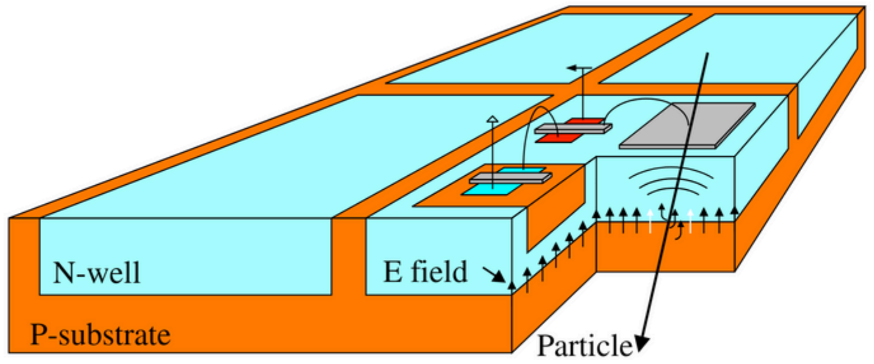


3. *Need excellent momentum resolution!* $(\sigma_p < 1.0\ MeV/c)$

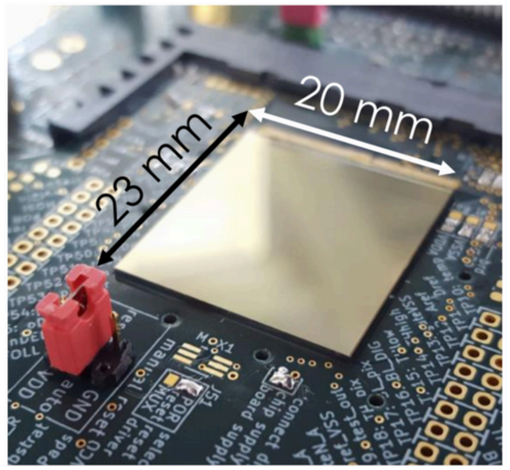
How do we measure $\mu^+ \to e^+ e^- e^+$?

Technology choice

- Need an ultra light detector technology that can handle high rates



I. Peric et al., NIMA 582 (2007) 876



High Voltage - Monolithic Active Pixel Sensors

- Detection and readout in the same unit
- Uses a high voltage **commercial process**
- Fast charge collection via **drift**
- Can be thinned to ~ **50 µm**

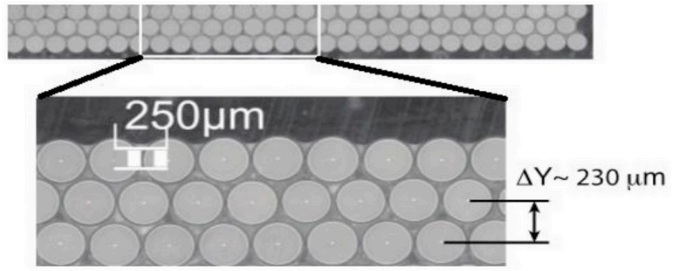
Mupix11

- Size: 20 x 23 mm^2, thickness: 50 µm, 70 µm
- ~ **0.05% X_0**
- Pixel size: 80 x 80 µm^2
- Time resolution: ~20 ns
- hit efficiency > 99%

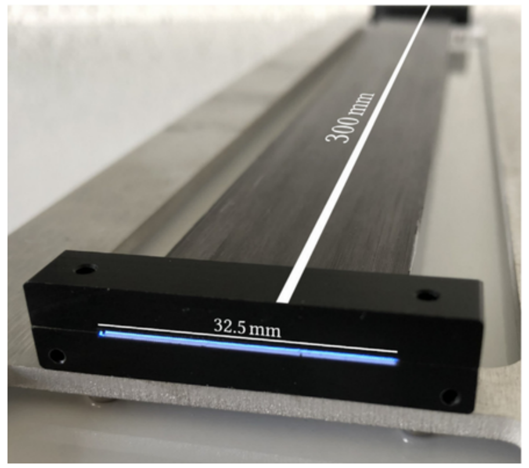
How do we measure $\mu^+ \to e^+e^-e^+$?

Technology choice

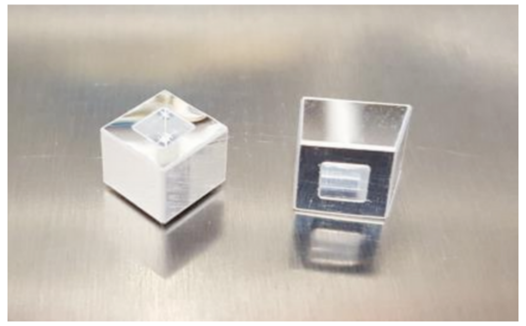
- Need an ultra light detector technology that can handle high rates
- **Very good timing resolution ~ $\mathcal{O}$(100)ps**



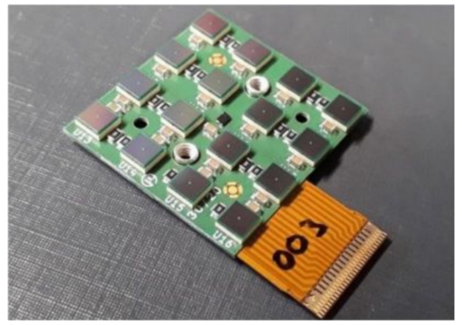
SciFi ribbon cross-section



SciFi ribbon prototypes



Wrapped Sci Tiles



SiPM array

Scintillating Tiles

- ~0.5 cm^3 scintillating tiles
- Each tile read out by its own Silicon Photomultiplier (**SiPM**) with custom ASIC (**MuTRiG**)
- Time resolution: ~ **80 ps**

MuTRiG: Muon Timing Resolver including Gigabit-link

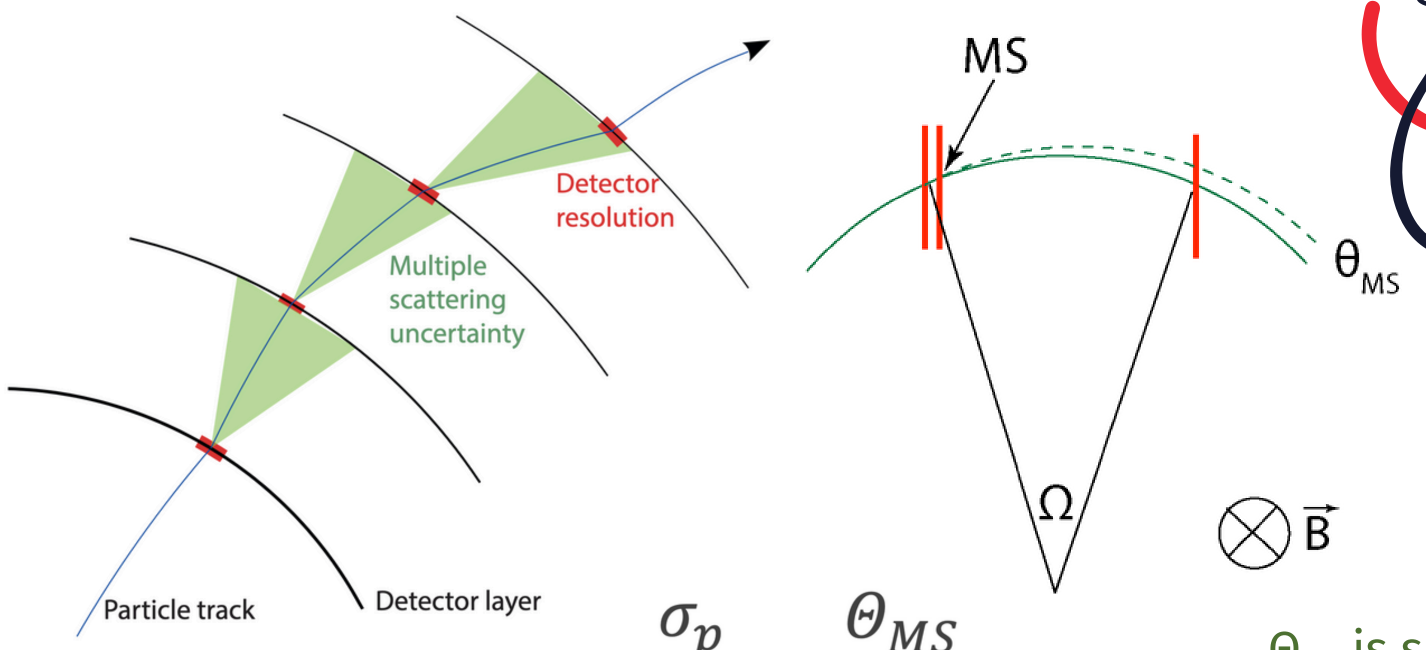
Scintillating Fibres

- Each **ribbon**: three layers of staggered fibres → **250 µm** fibres diameter, < **0.02% X_0**
- **SiPM** based readout on both ends with custom ASIC (**MuTRiG**)
- Time resolution: ~ **250 ps**

Need very good momentum resolution

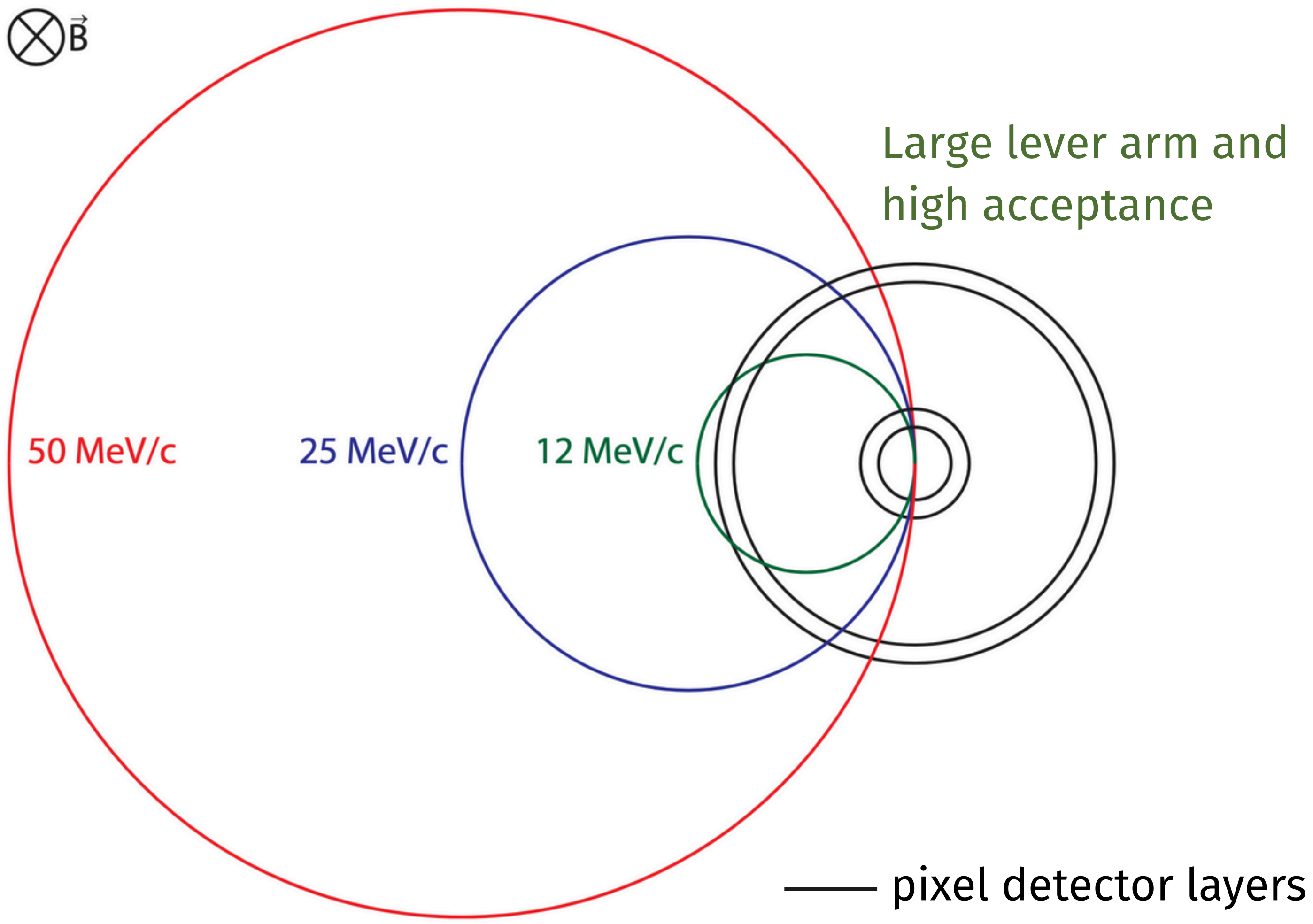
Mu3e Tracking Concept

- Tracking in a **homogeneous B-field of 1 T**
- High granularity pixel tracker (**80 x 80 μm²**): 3D space point
- **Tracking in multiple scattering dominated environment**
  - Ultra thin pixel tracker with only four layers
  - Gaseous helium environment
- Optimise for precision and acceptance (momentum)



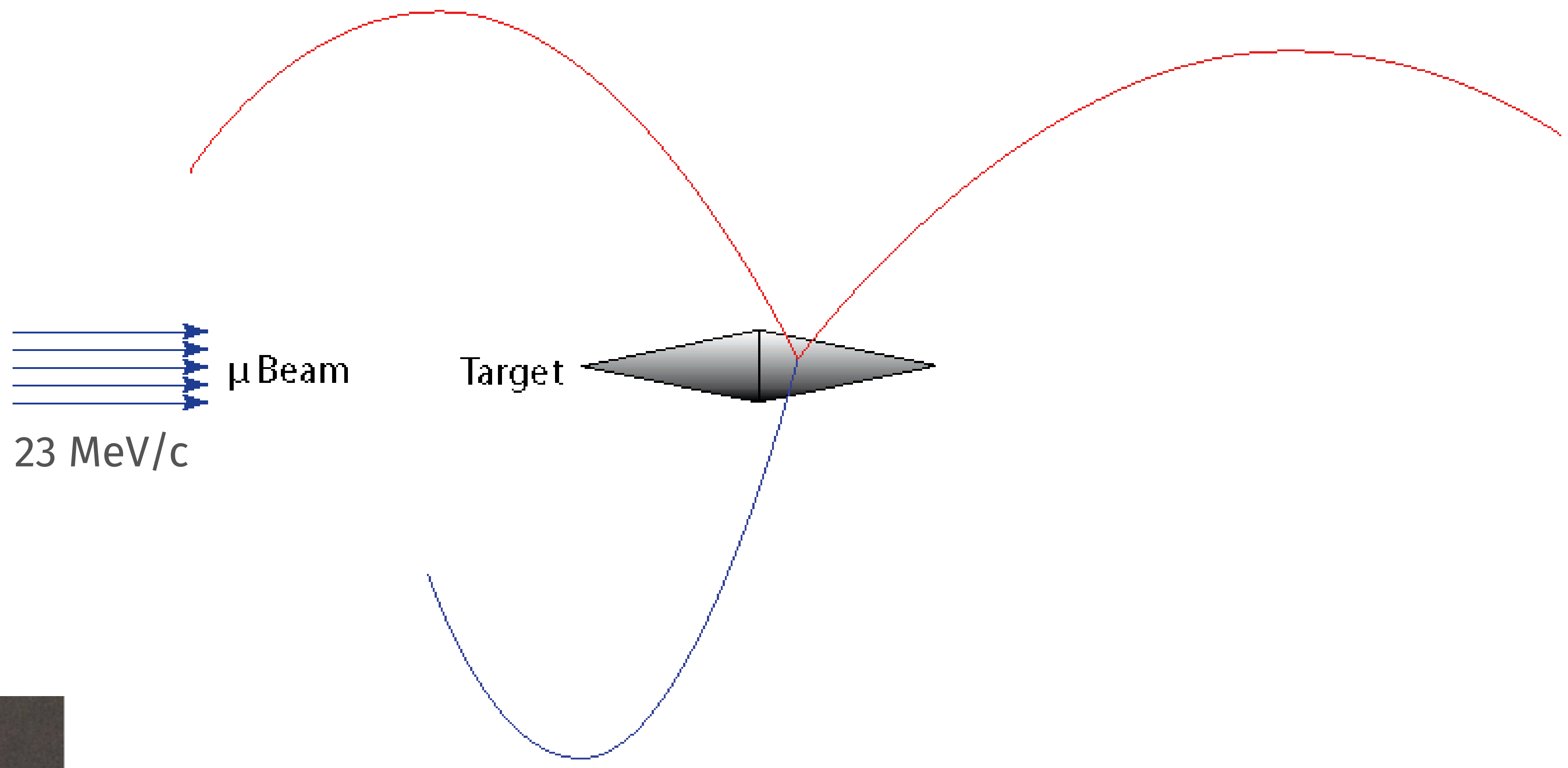
$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$

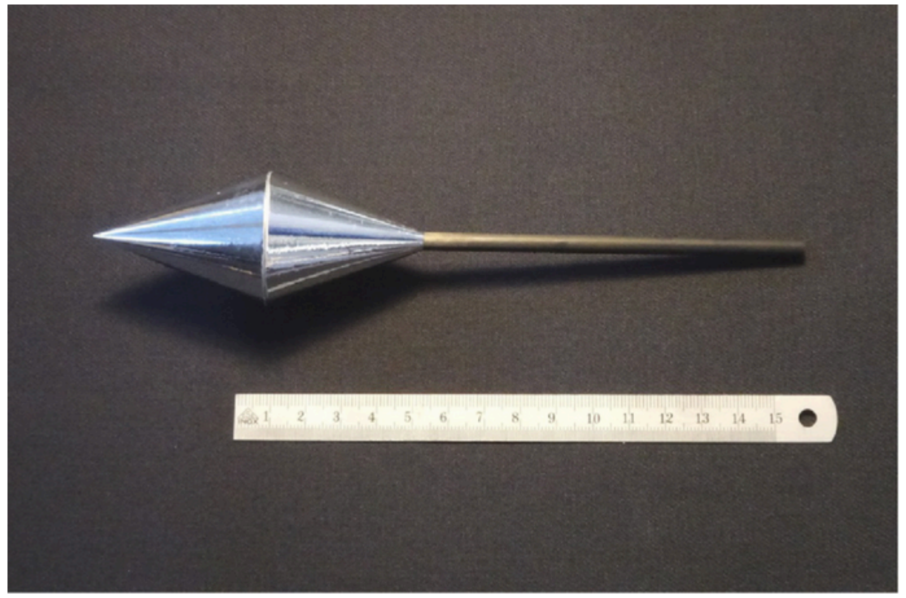
Θ_{MS} is small for measurements at Ω ~ π



Mu3e Phase I Detector Design

The Muon Stopping Target



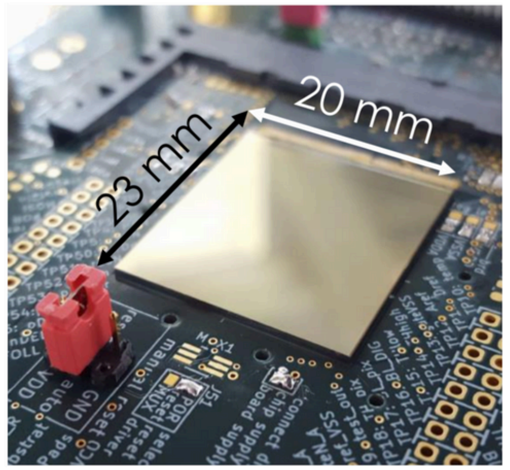


Muon stopping target

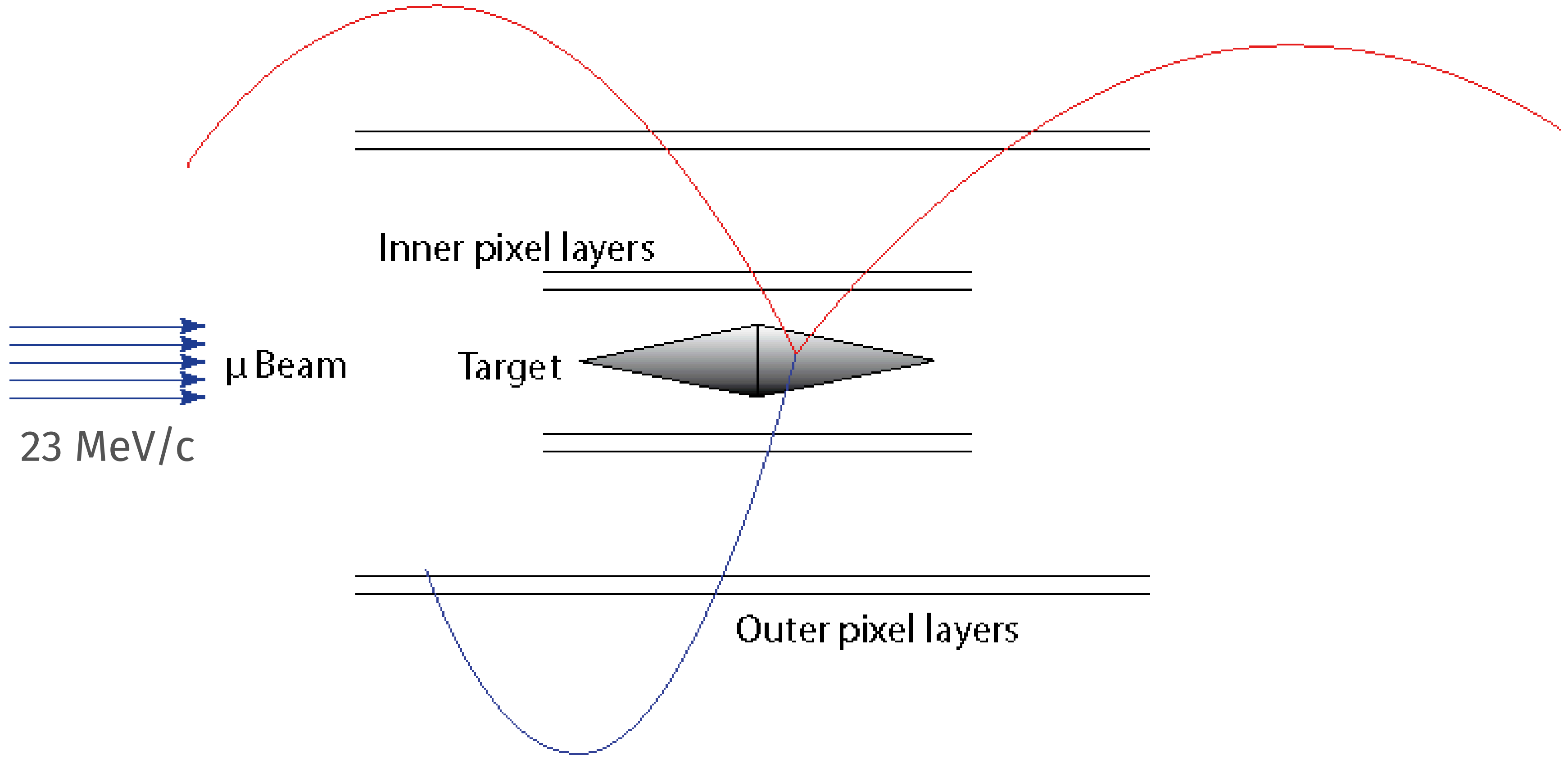
- Double hollow cone **aluminised mylar** muon stopping target (length: ~10cm, diameter: 3.8cm)
  → **maximum muon stopping** (stopping fraction ~ 95.5%)
  → **minimum material in flight direction of electrons** (~0.15% X_0)
- Decay vertices are well **spread out**
  → reduce combinatorial background & even occupancy in vertex layers

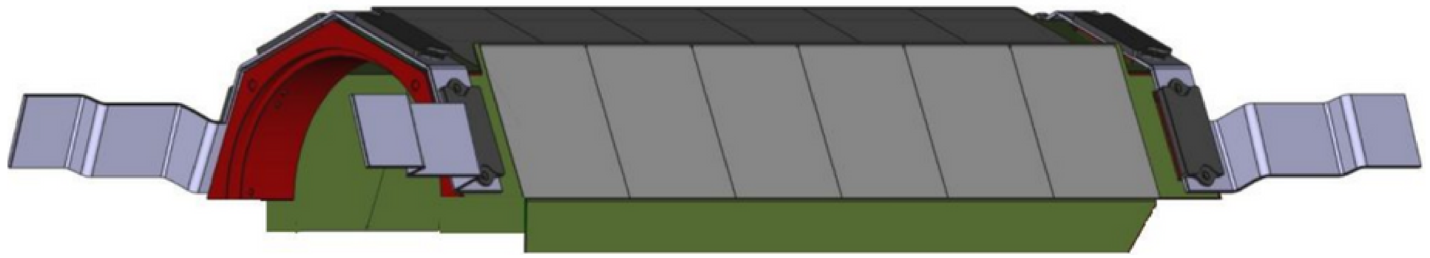
Mu3e Phase I Detector Design

Central Pixel Tracker



Mupix11



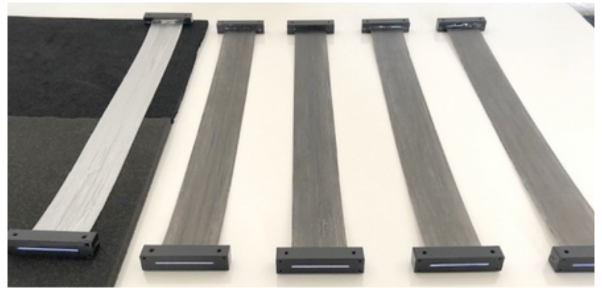


Vertex module

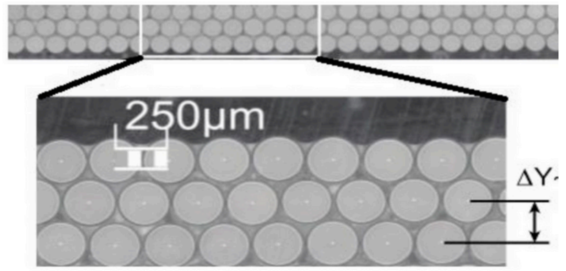
- MuPix chips (vertex: 6, outer: 17/18) are glued on the HDI and bonded to form a **ladder**
  → ~ **0.1% X_0 per layer**
- Four or five ladders form a **module**
- Two inner pixel layers close to the target for **precise vertexing (~ 200μm)**
- Two outer pixel layers optimised for **good momentum resolution and high p acceptance**
- Cooled to ~0°C by low-density **gaseous helium.**

Mu3e Phase I Detector Design

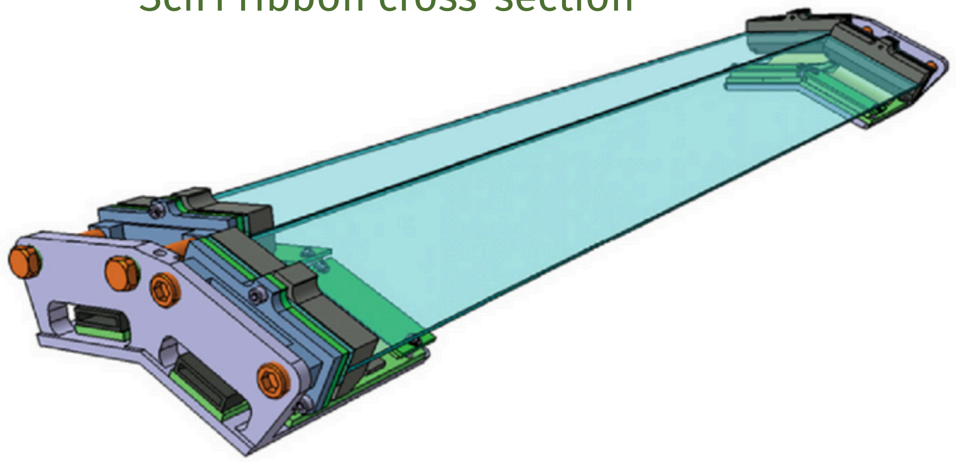
The Scintillating Fibre Detector



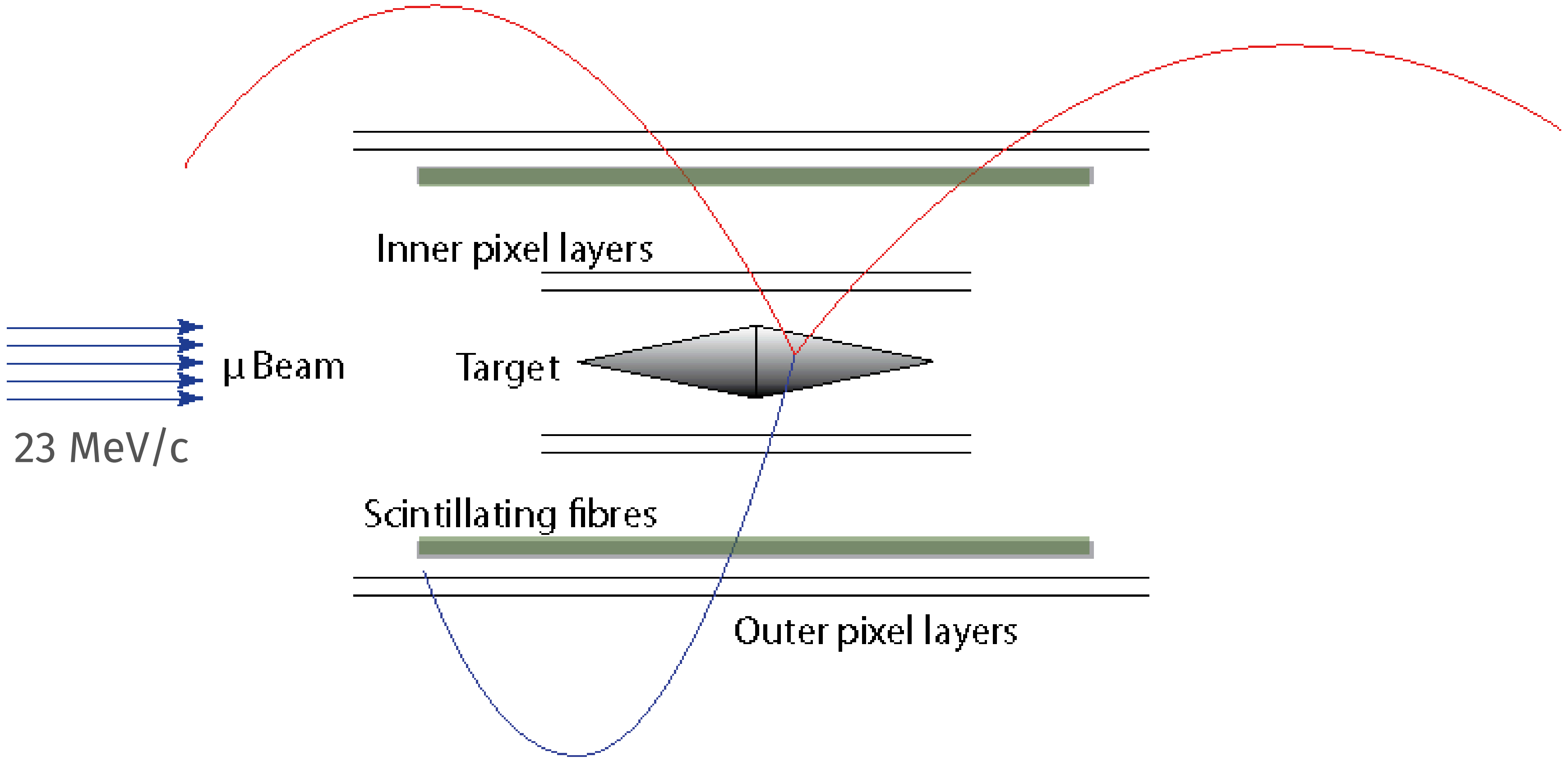
SciFi ribbon prototype



SciFi ribbon cross-section



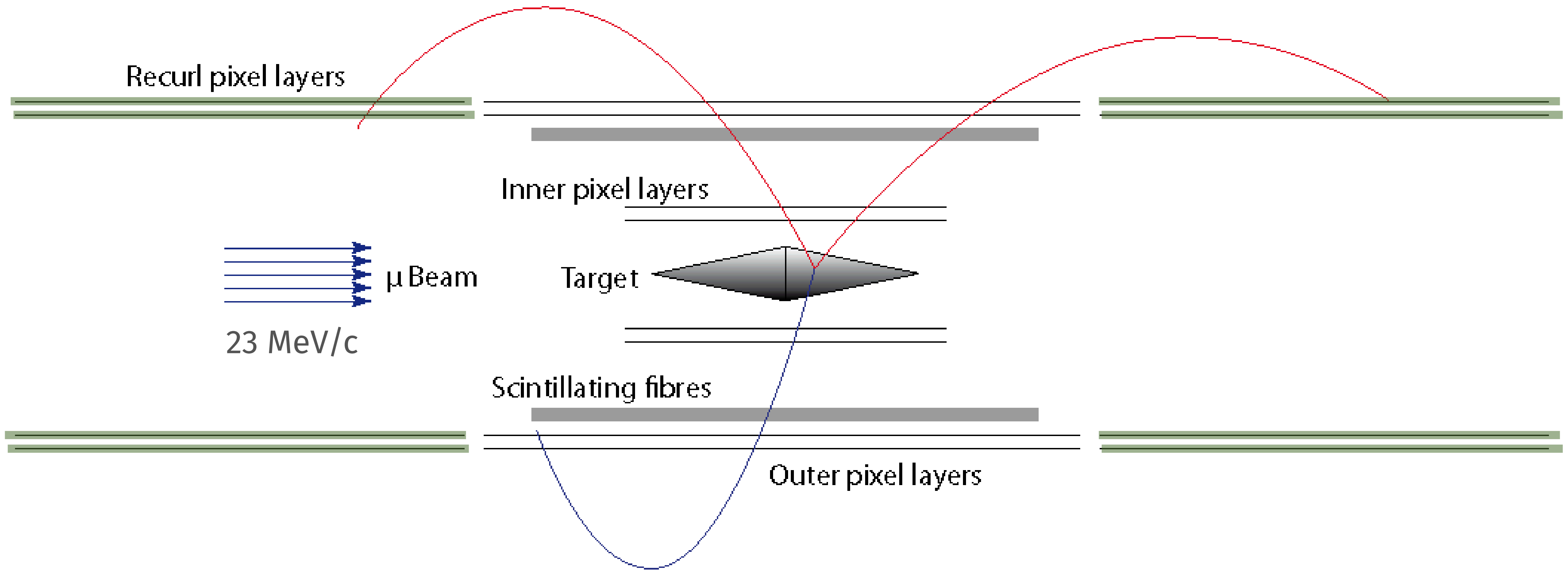
SciFi module consisting of two ribbons
(CAD rendering)



- Placed so as to **minimise the MS effects**.
- **Timing** + **resolves** the rotational direction (i.e., the **charge**) of the **recurling tracks** in the central region of the Mu3e detector by time of flight measurements.
- 128 fibres per ribbon, each measuring 30 cm in length
  → 256 channels per SciFi ribbon
  → **cooled with Silicon oil < 0°C** to reduce dark-count rate

Mu3e Phase I Detector Design

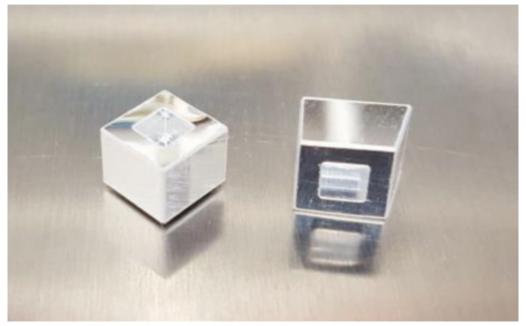
The Recurl Pixel Layers



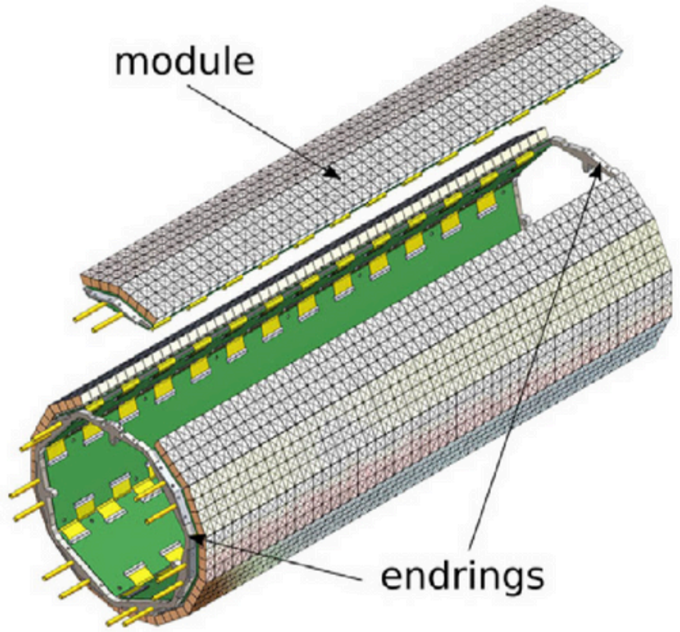
- Increases the **acceptance** in the polar direction
- Further improves the **momentum resolution < 1MeV/c**
  → reconstruction of **recurling tracks**

Mu3e Phase I Detector Design

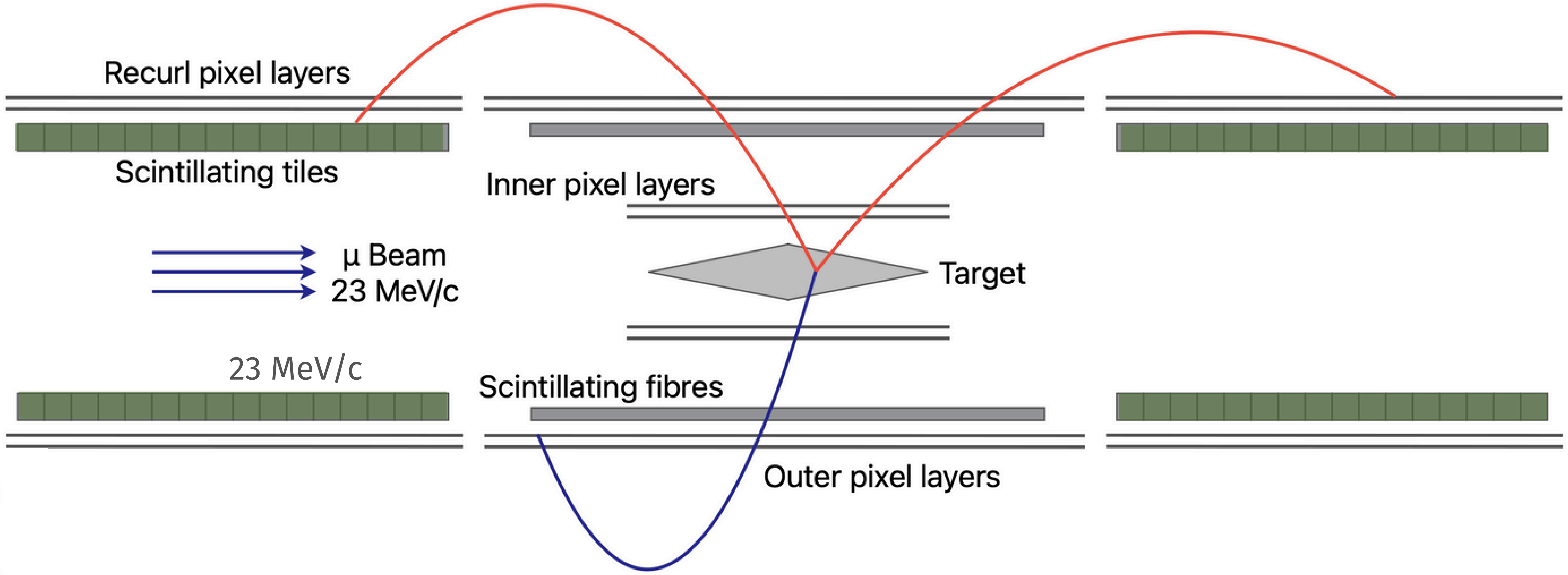
The Scintillating Tile Detector



Wrapped Sci Tiles



Full tile detector exploded view
CAD rendering



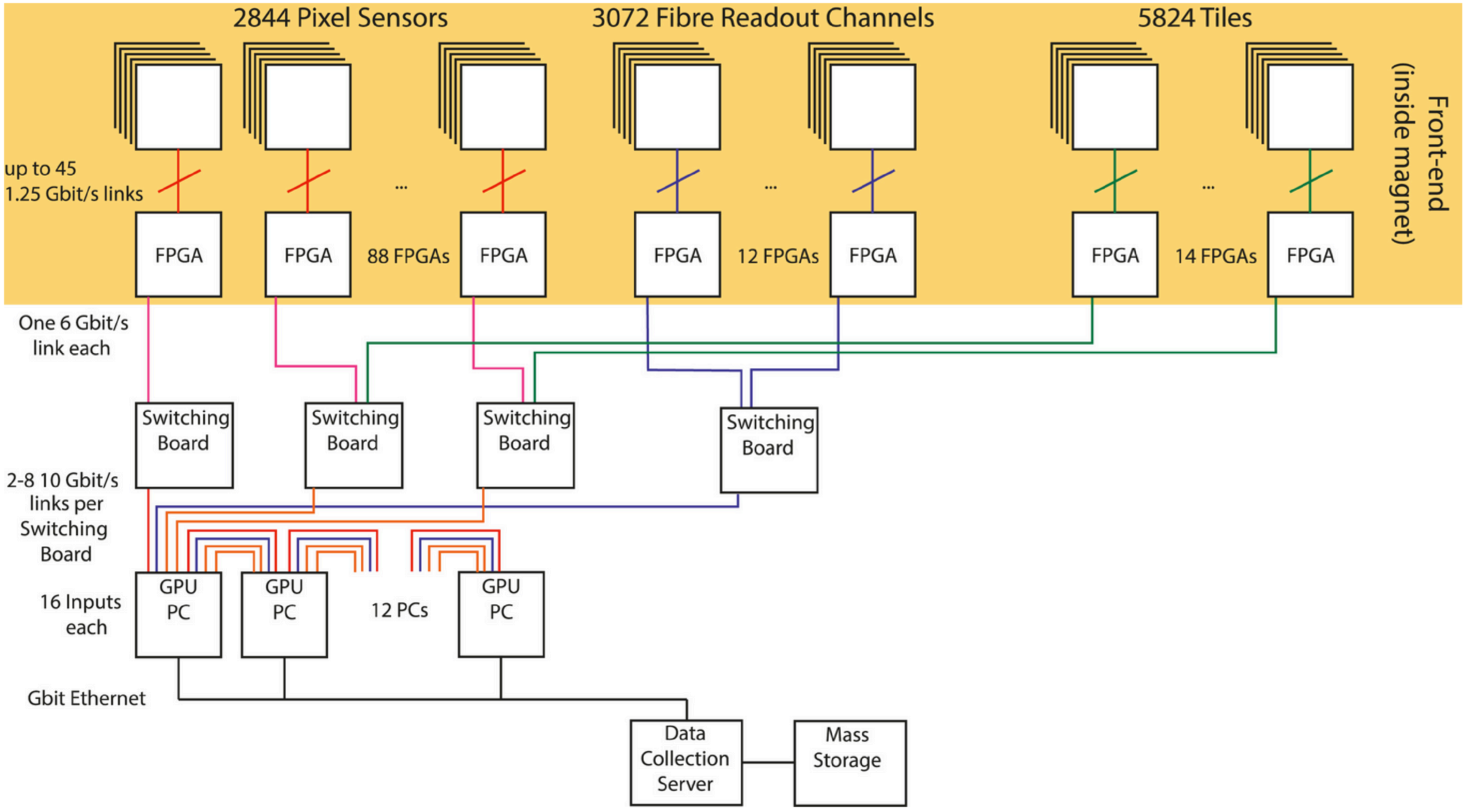
- Placed at the end of the recurling particle trajectory
  → **not critical w.r.t the amount of material**, hence can be thick
  → provides the **most precise timing information**
- 416 SciTiles form a **SciTile module**.
  → **cooled with Silicon oil < 0°C** to reduce dark-count rate

Mu3e Data Acquisition (DAQ)

Heart of the experiment...

Mu3e DAQ Design

- **Synchronises** data from **all sub-detectors**
- **Fully streaming DAQ → triggerless readout**
- Network of **FPGAs** and **optical links**
- Collect all data of a time slice on one PC
- **GPU Filter Farm for online event selection**
  - track reconstruction & vertexing
- Write interesting events to disk



Mu3e DAQ design

Current Status as of June 2025

Sub-systems	Produced (Required)
Vertex Detector	**18 ladders (18)**
Outer Pixel Detector Central station	0 ladders (24 + 28 = 52)
Outer Pixel Detector Recurl Station	0 ladders (2 x (24 + 28) = 104)
SciFi Detector	**6 modules (6)**
SciTile Detector	**4 modules (2 x 7 = 14)**

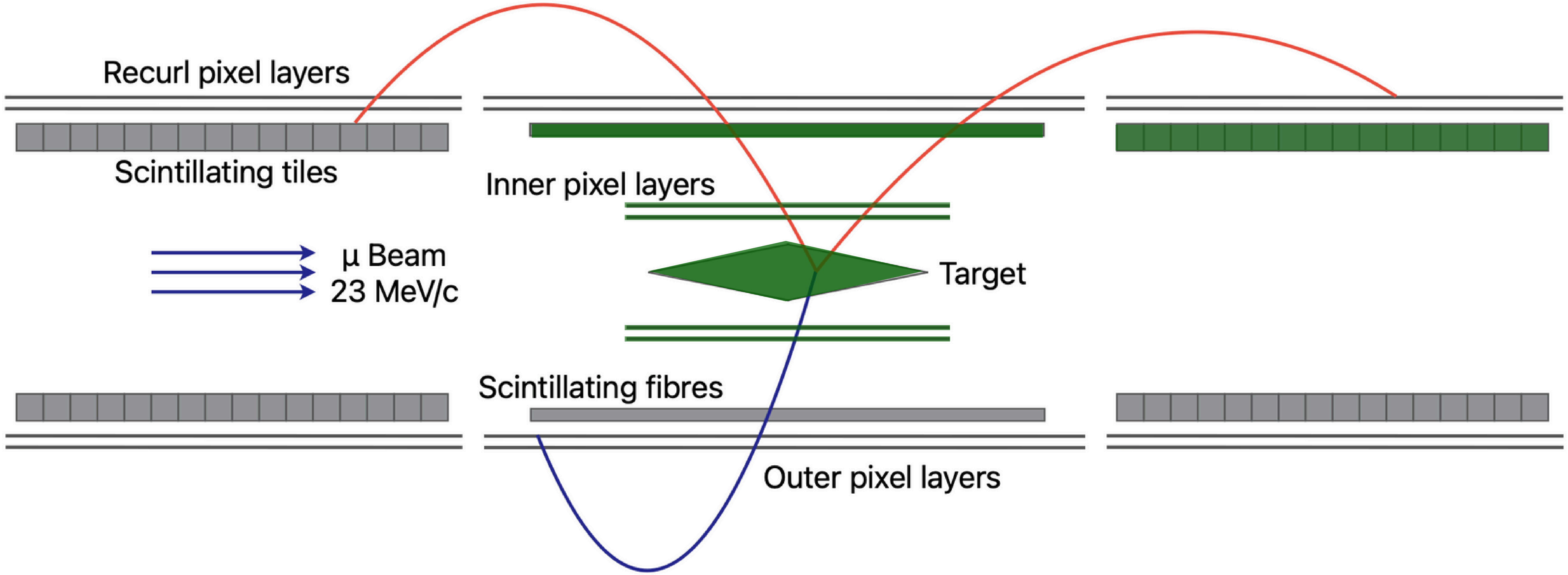
Pre-production of Outer layers have already started!

↳ Most services independent of the sub-systems, **e.g. the Magnet and the Helium cooling infrastructure** are ready and have been tested in the commissioning run in June!

Minimal Detector Configuration

Installed in the June 2025 Commissioning Run:

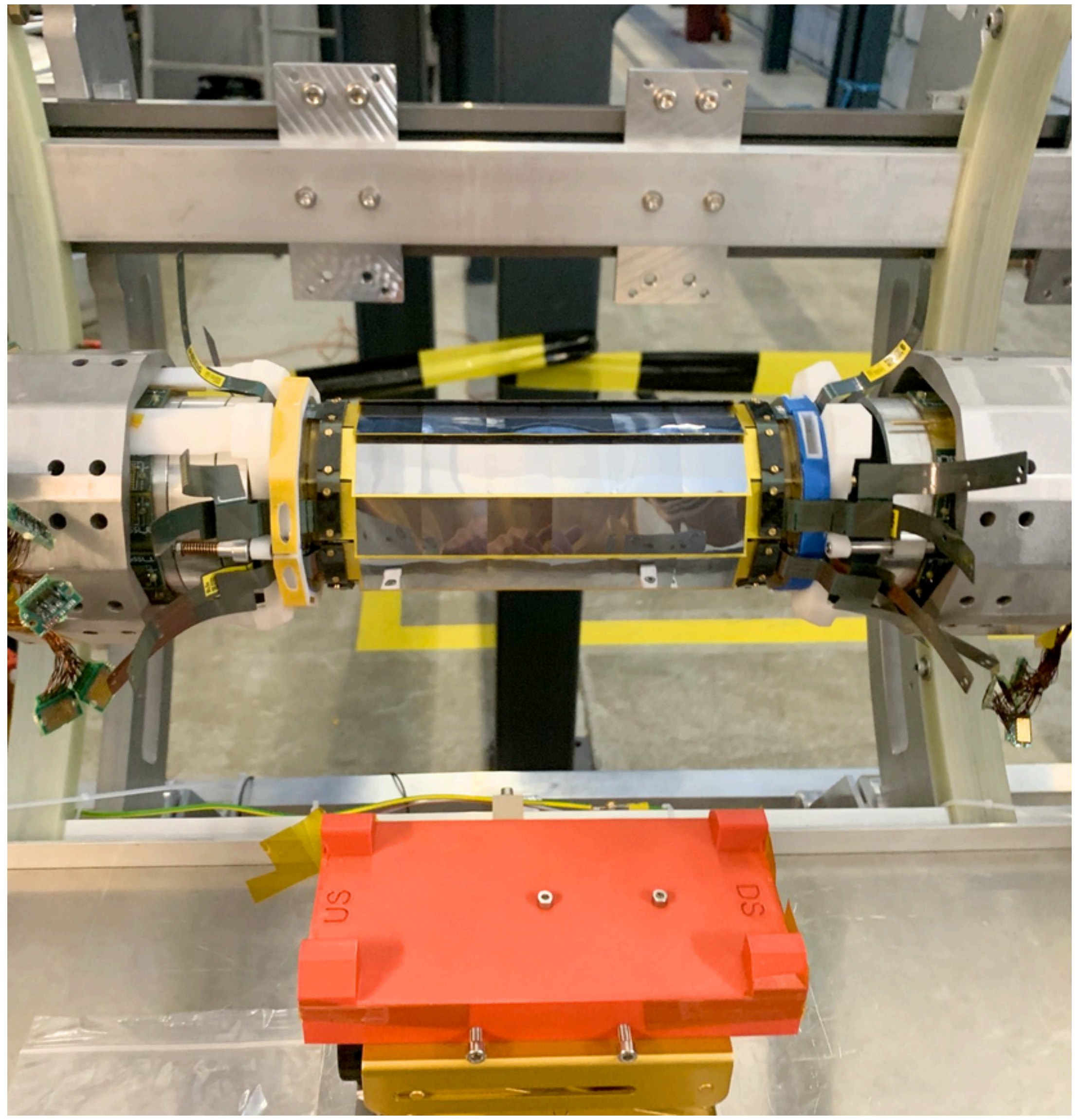
- Target
- **Full vertex detector**: 108 (50 µm thick) Mupix 11 sensors
- **One** out of six **SciFi modules**
- **Three** out of fourteen **SciTile modules**



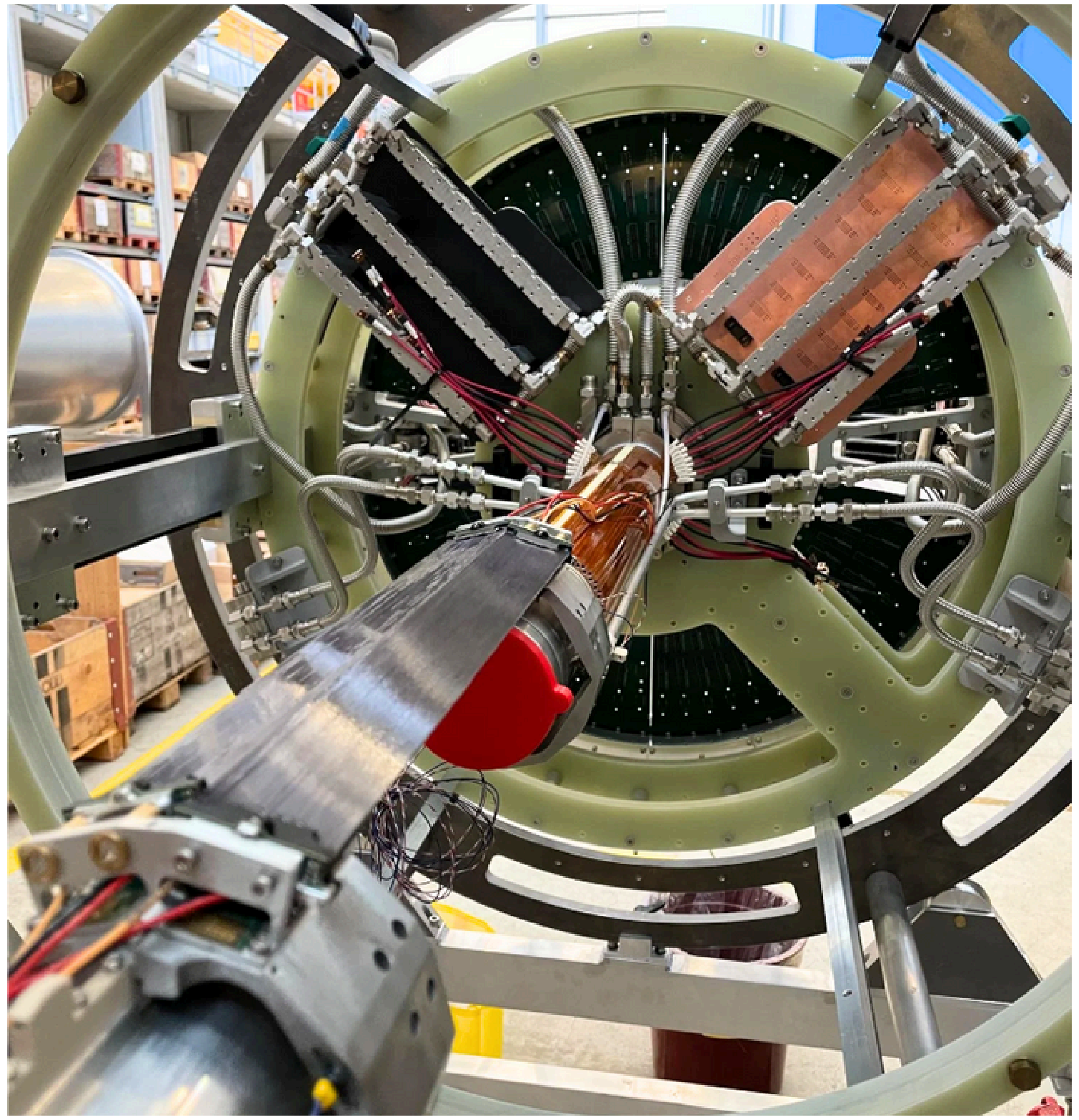
June 2025 Commissioning Run Highlights!

Current Status of the Mu3e Experiment

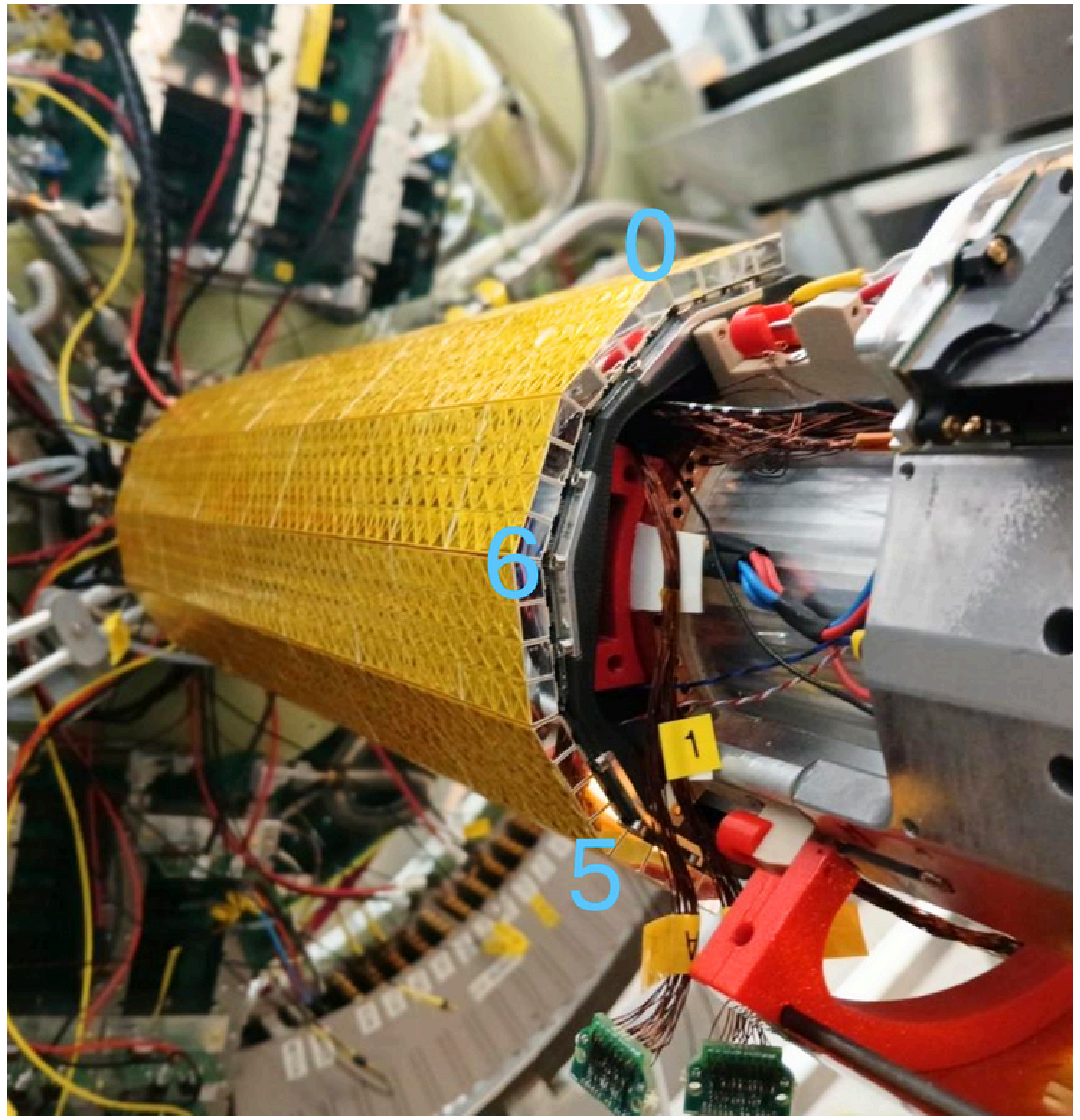
The full vertex detector commissioned



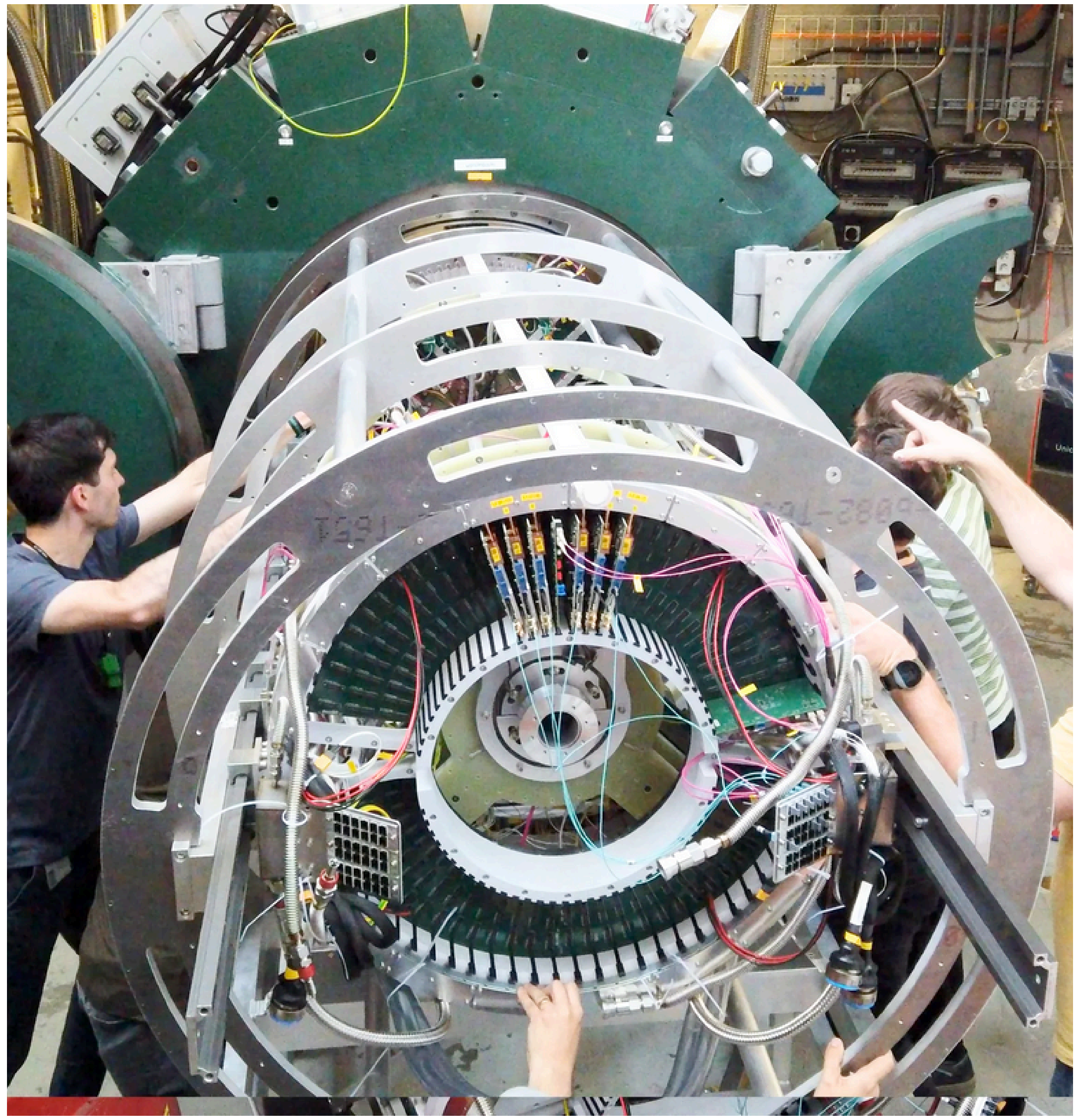
2/12 Scifi ribbons commissioned

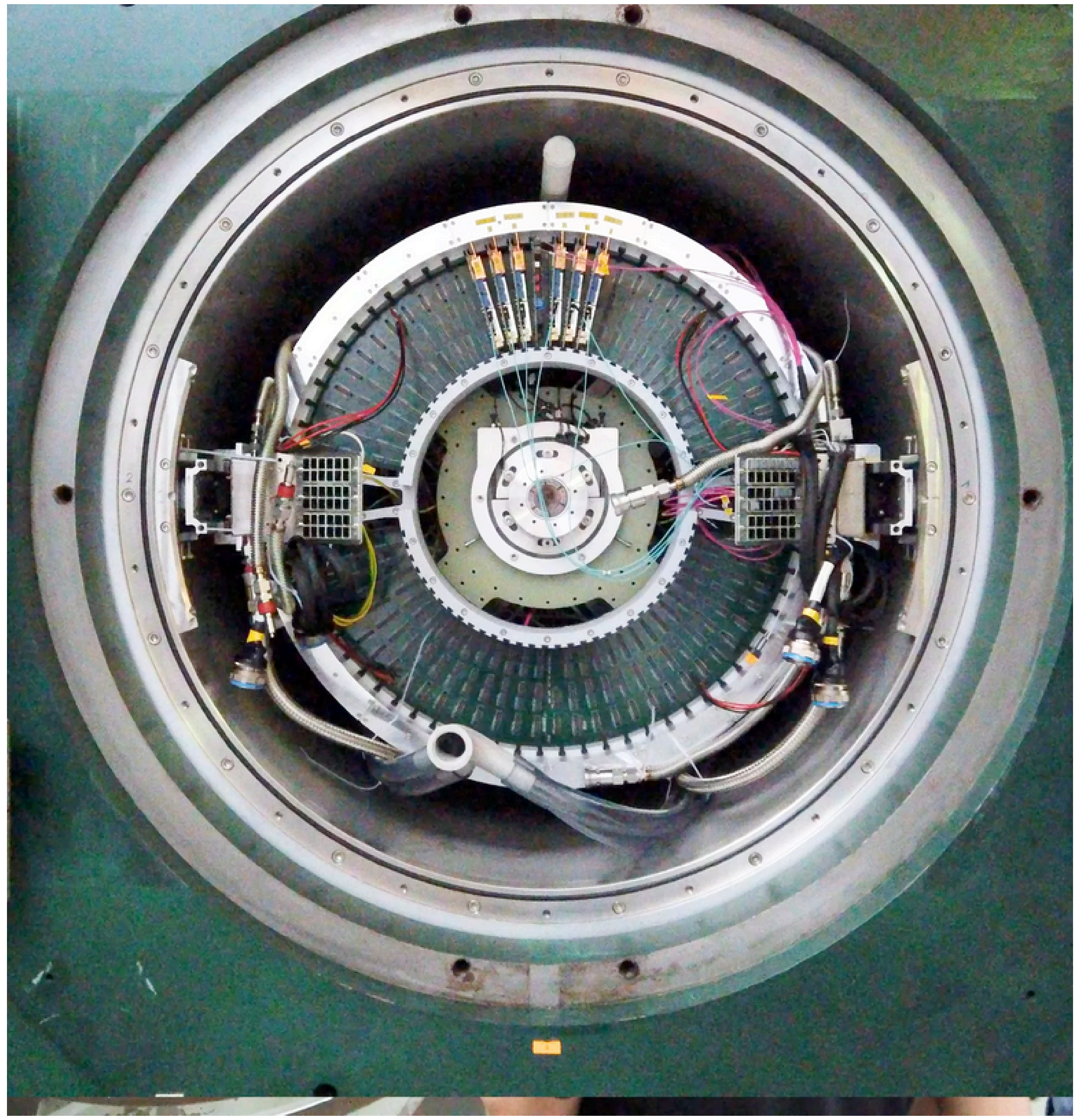


3/14 Scitile modules commissioned DS



Mu3e craned into the magnet for the June 2025 commissioning run





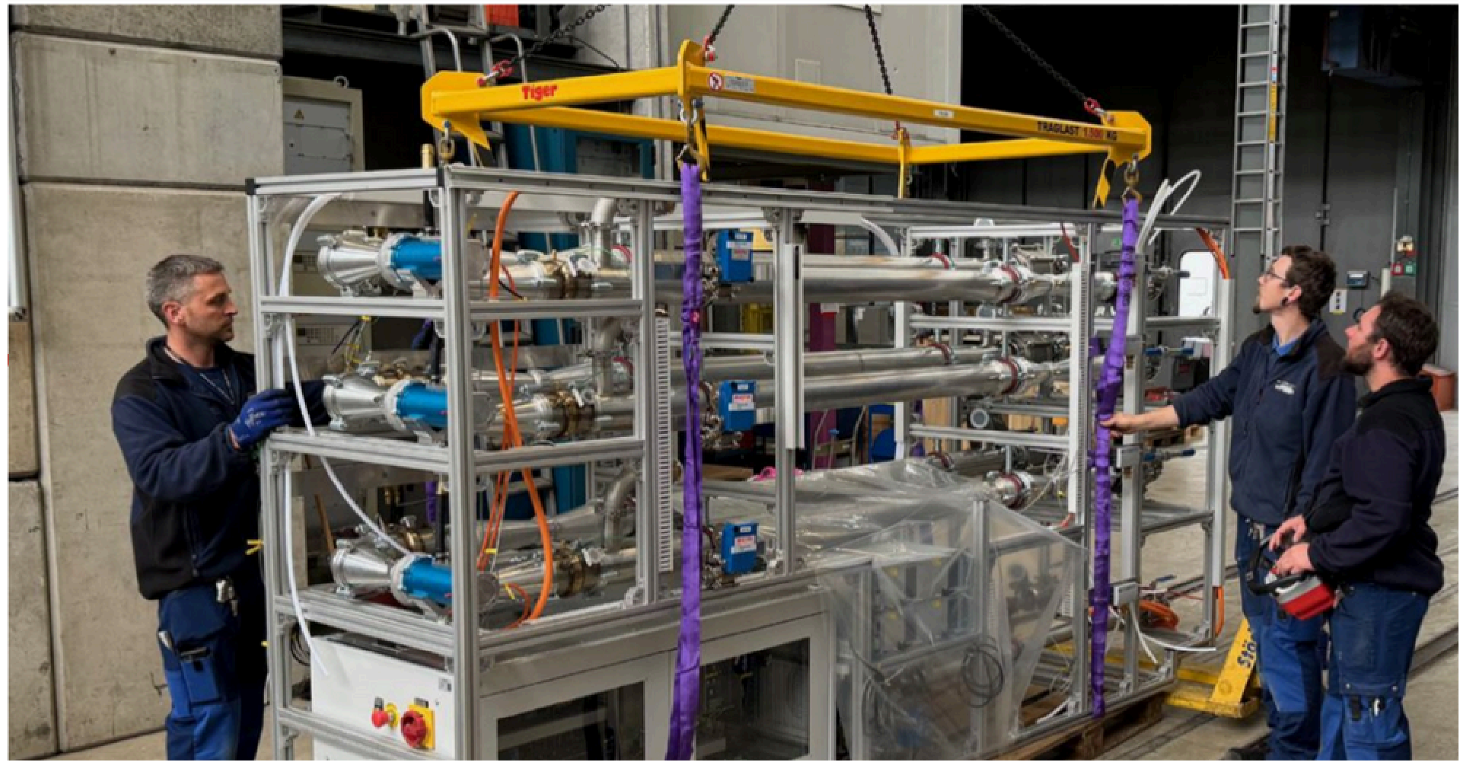
June 2025 Commissioning Run Highlights!

Successful Commissioning

↳ The minimal detector configuration saw three weeks of μ^+ beam in June

↳ Many first-time operational experiences were made

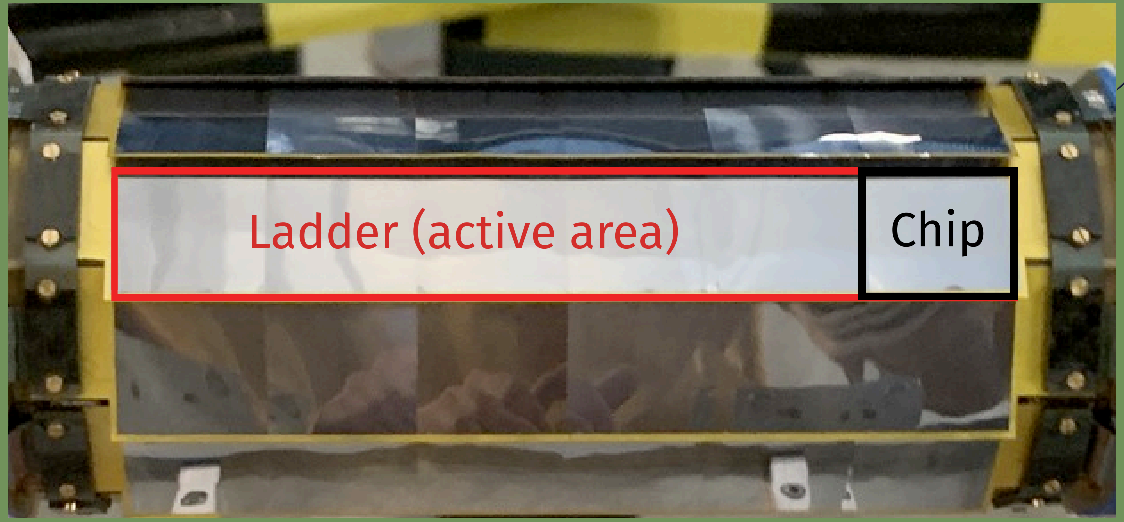
- Sub-system operations in **B-field (1 T), gaseous helium cooling, & beam**.
- Sub-system **synchronisation** and **DAQ** consolidation.
- Online track reconstruction with the **GPU Filter Farm**!
- Tuning, debugging & online monitoring tool development.
- **A few days of stable data taking and beam rate scans: 10^4 – 10^7 μ^+/s.**



Helium compressor rack

June 2025 Commissioning Run Highlights!

Successful Commissioning



↳ Hit Maps of Layer 1 and Layer 2 of the vertex detector

- All 108 Mupix11 chips installed
- 4 chips had mechanical damage before installation
- 12 chips were unstable
- 10 chips were lost before/during the operation
- A few others showed link instabilities or were inefficient

Layer 1

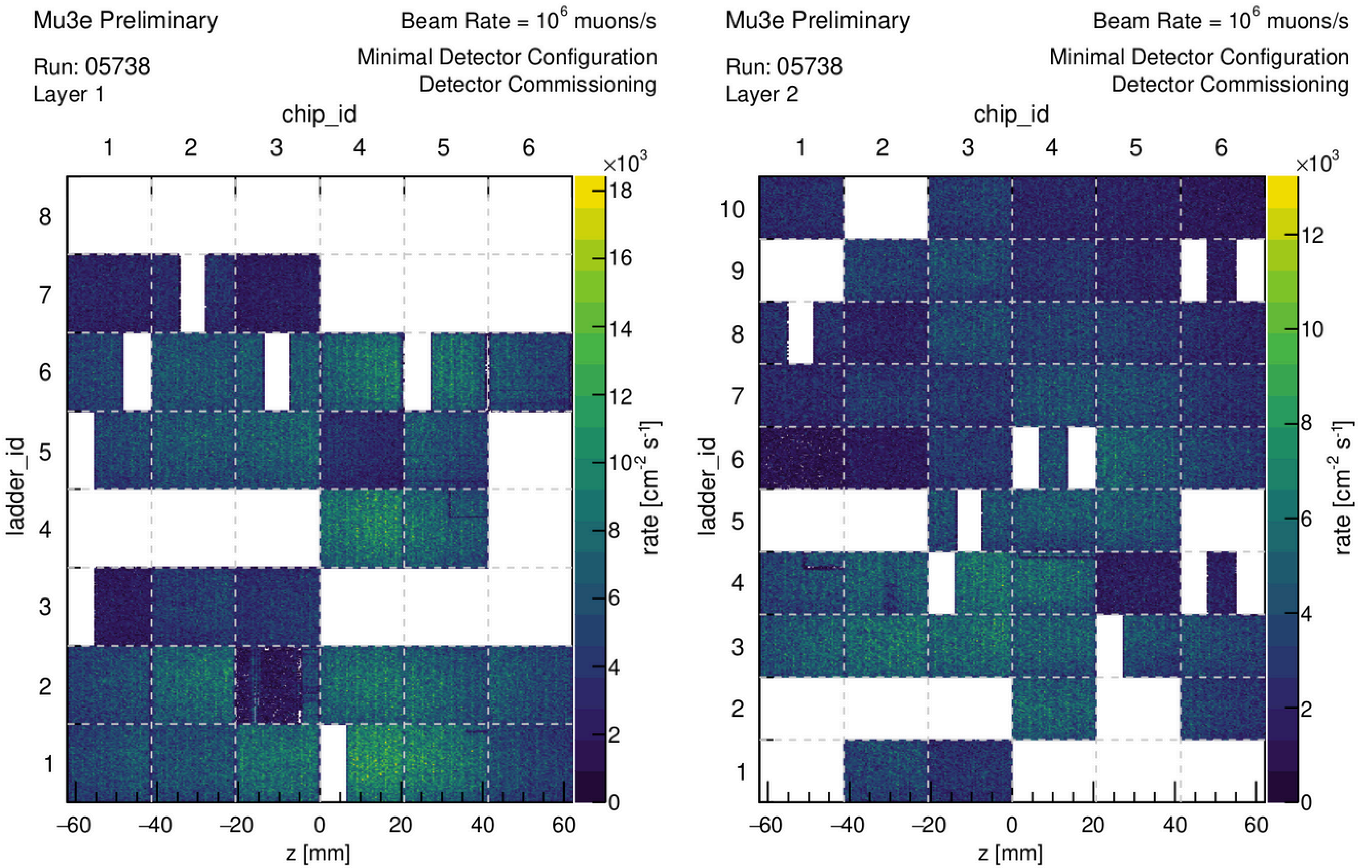
	C1	C2	C3	C4	C5	C6
Ladder 1	✓✓✓	✓✓✓	✓✓✓	✓✓X	✓✓✓	✓✓✓
Ladder 2	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ladder 3	✓✓X	✓✓✓	✓✓✓	XXX	XXX	XXX
Ladder 4	XXX	XXX	XXX	✓✓✓	✓✓✓	✓✓✓
Ladder 5	✓✓X	✓✓✓	✓✓✓	✓✓✓	✓✓✓	
Ladder 6	X✓✓	✓✓✓	✓X✓	✓✓✓	✓✓X	✓✓✓
Ladder 7	✓✓✓	✓X✓	✓✓✓	XXX	XXX	XXX
Ladder 8	XXX	XXX	XXX	XXX	XXX	XXX

Green: Working chip; Red: Mechanical damage;
Gray: Disconnected HV; Link instabilities on-cage;

Layer 2

	C1	C2	C3	C4	C5	C6
Ladder 1		✓✓✓	✓✓✓	XXX	XXX	XXX
Ladder 2	XXX	✓✓✓	XXX	✓✓✓	XXX	✓✓✓
Ladder 3	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓X	✓✓✓
Ladder 4	✓✓✓	✓✓✓	✓✓X	✓✓✓	✓✓✓	X✓X
Ladder 5	XXX	X✓X	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ladder 6	✓✓✓	✓✓✓	✓✓✓	X✓X	✓✓✓	✓✓✓
Ladder 7	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ladder 8	✓X✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ladder 9	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ladder 10	✓✓✓	XXX	✓✓✓	✓✓✓	✓✓✓	✓✓✓

Black: Not usable (missing SIN/CLK coonection);
Orange: Lost before/during operation;
✓: Link working; X: Link not working.

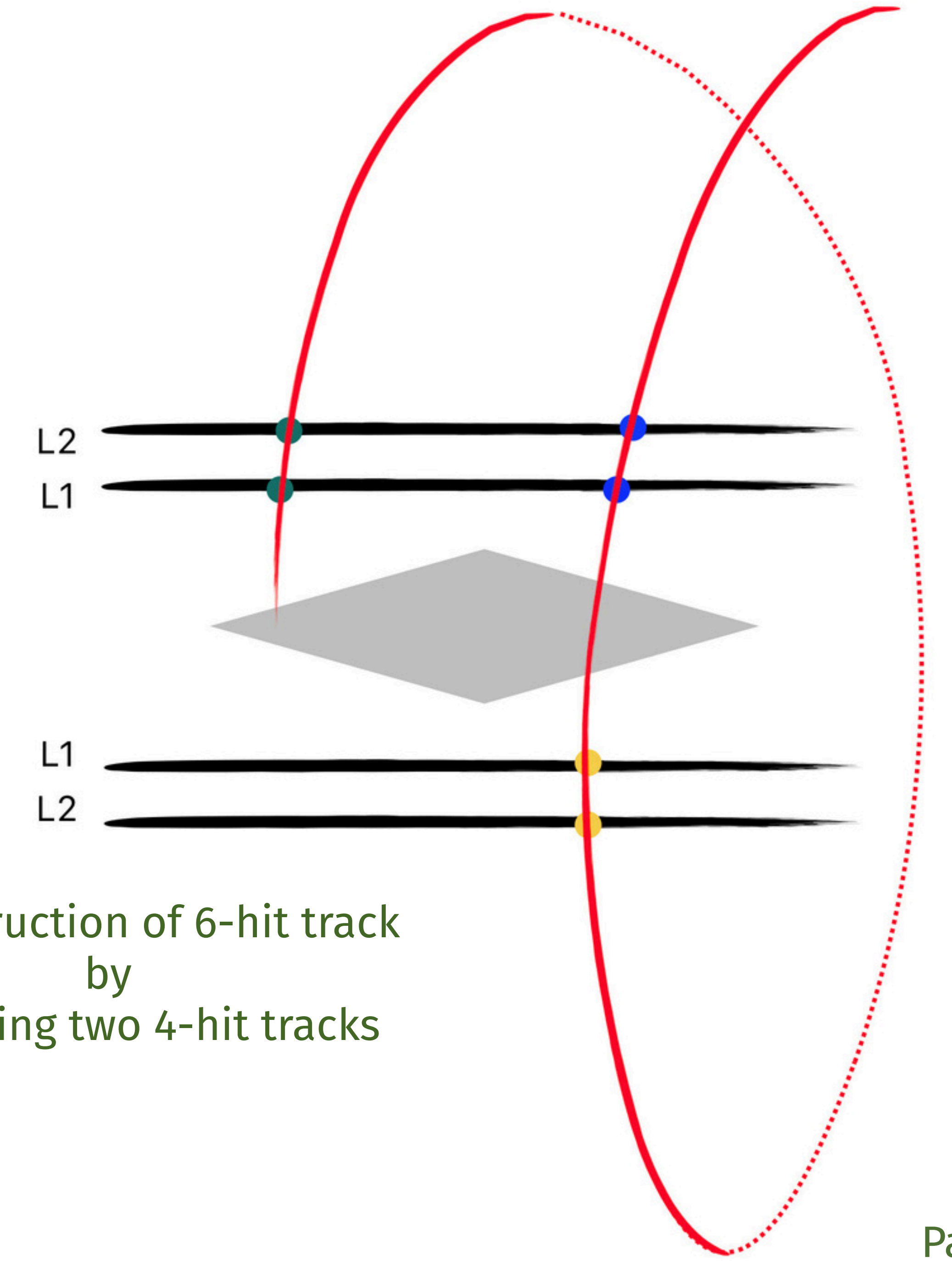


Vertex Detector Hit Maps for Layer 1 and Layer 2

June 2025 Commissioning Run Highlights!

Tracking with the Mu3e vertex detector alone

- **Short tracks** are reconstructed by fitting **4-hit** combinations
- 4-hit tracks **1221** (outside-in) and **2112** (inside-out) are combined to form **6-hit tracks**
- (**n+2**)-hit tracks: combine **n**-hit tracks with matching 4-hit track combinations



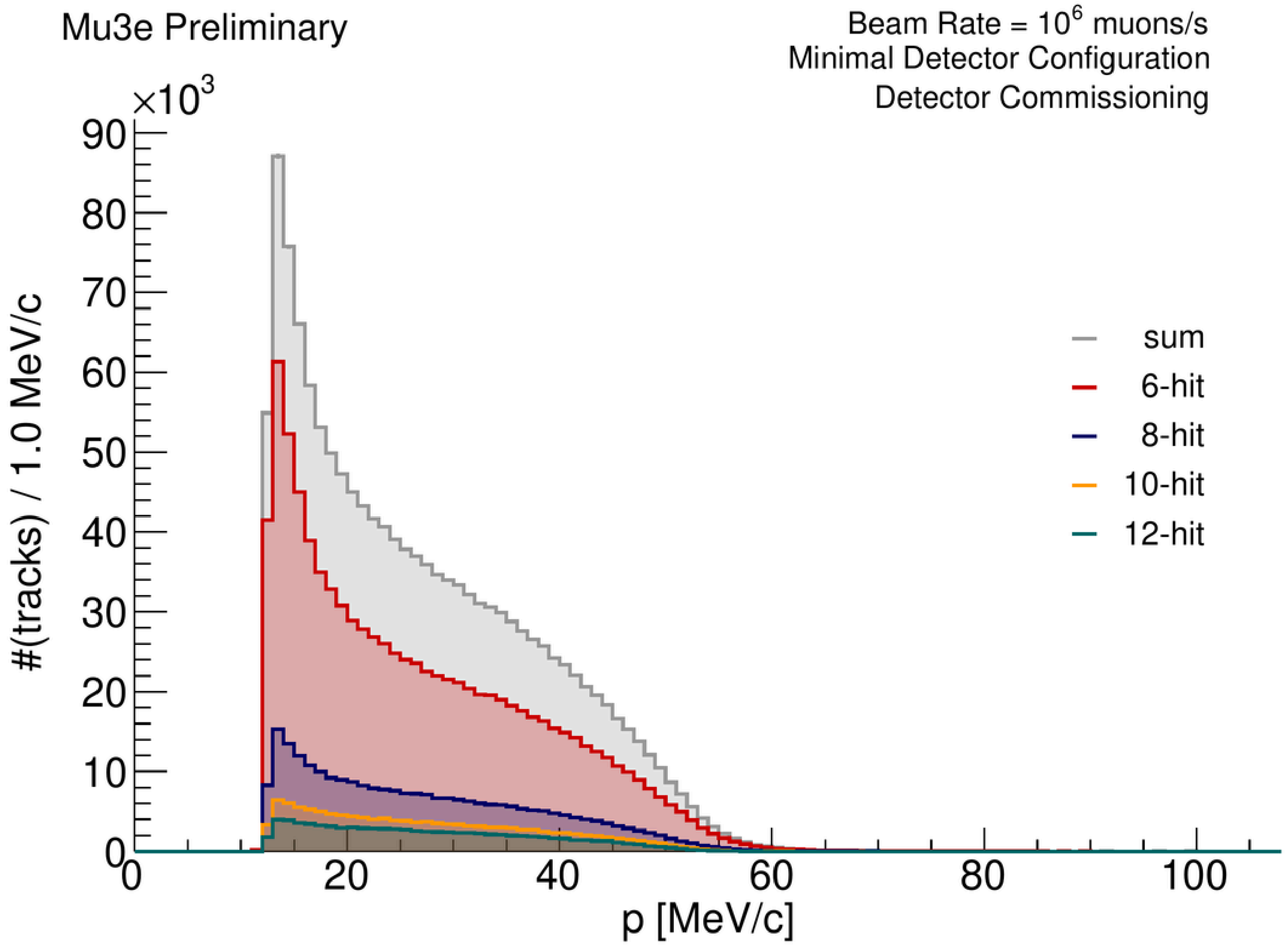
Reconstruction of 6-hit track
by
combining two 4-hit tracks

June 2025 Commissioning Run Highlights!

Momentum distribution measured with the vertex detector

First preliminary analysis result from the commissioning run…

- Measured momentum distribution for 6-, 8-, 10- and 12-hit long tracks
- Many factors affect the shape of the distribution, e.g. :
  - sensor efficiency and noise
  - track direction (θ and φ)
  - misalignment
  - …
- Planned improvements: use Monte Carlo simulations to model and correct for these effects



Momentum distribution for n-hit tracks

June 2025 Commissioning Run Highlights!

Re-weighted momentum distribution measured with the vertex detector

First preliminary analysis result from the commissioning run…

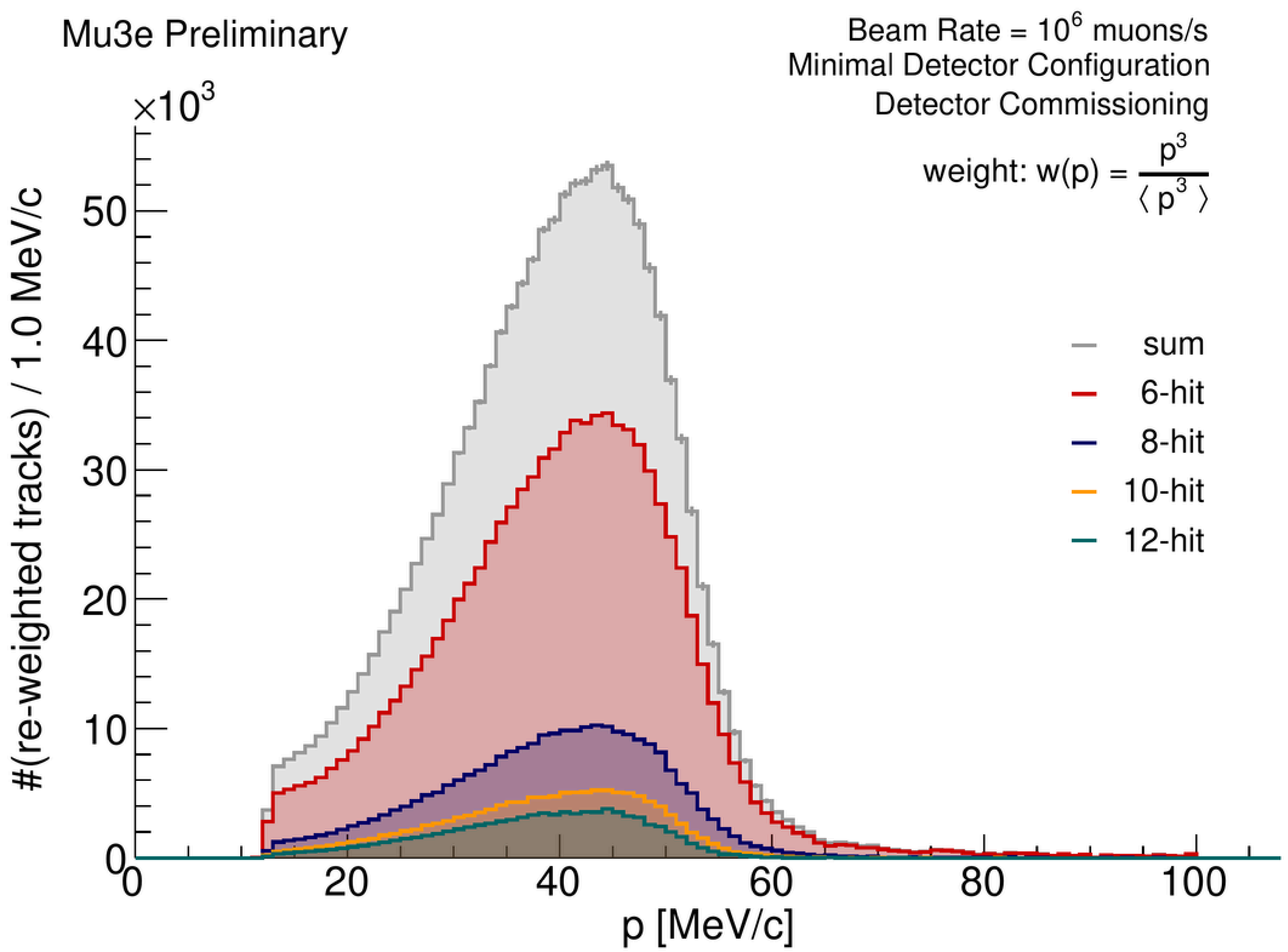
↳ The momentum distribution is **re-weighted** using a **very simple ansatz** to correct for the

- limited polar angle of the vertex detector

$$\propto \frac{1}{R_{3D}} = c_{3D}$$

- momentum dependence of a misaligned detector

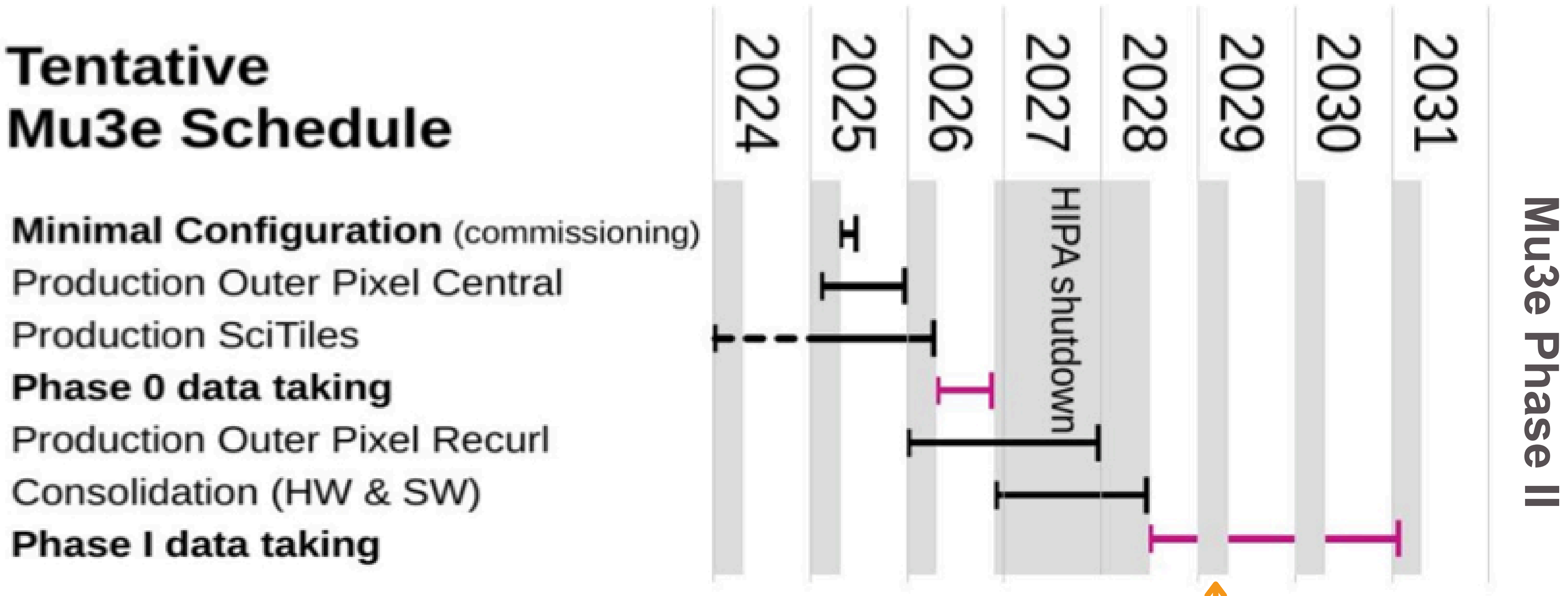
$$\propto \frac{1}{R_{3D}^2} = c_{3D}^2$$



Note: R_{3D} and c_{3D} are reconstructed 3D radius and curvature of a track

Re-weighted momentum distribution for n-hit tracks

The exact run period for 2026 is to be decided



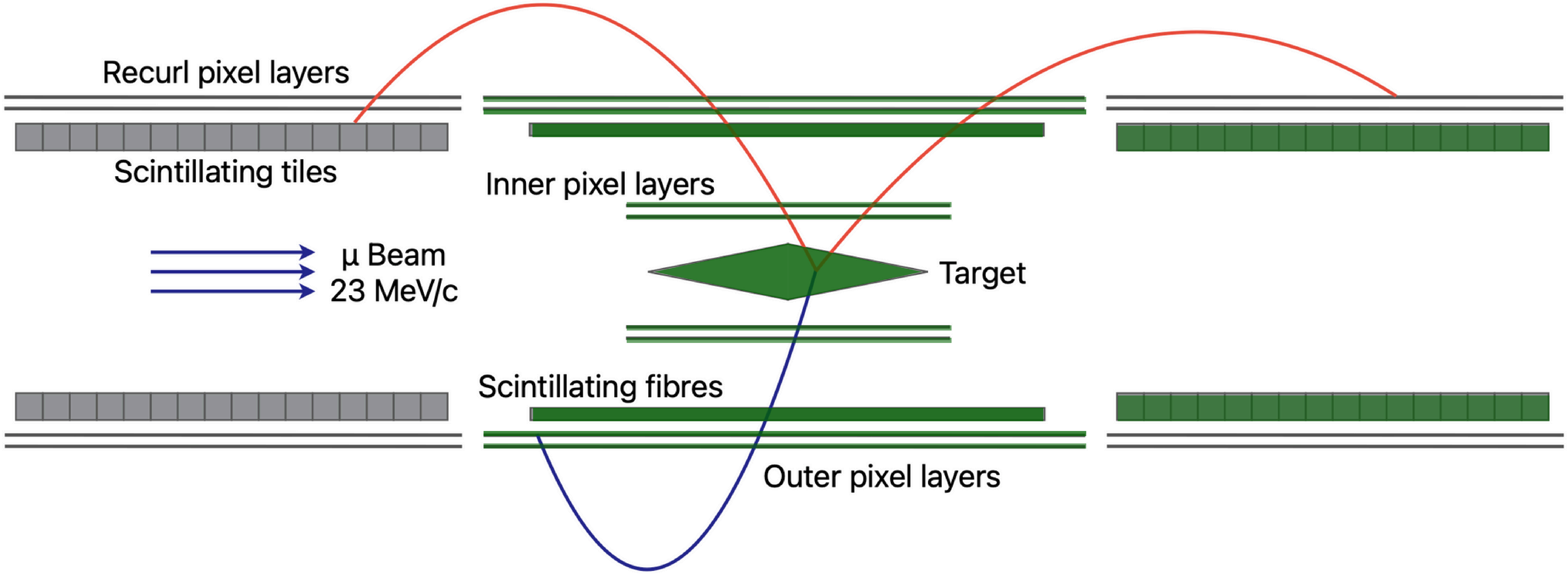
Note: “Phase” refers to detector configuration/setup

move experiment to HIMB

What’s Next?

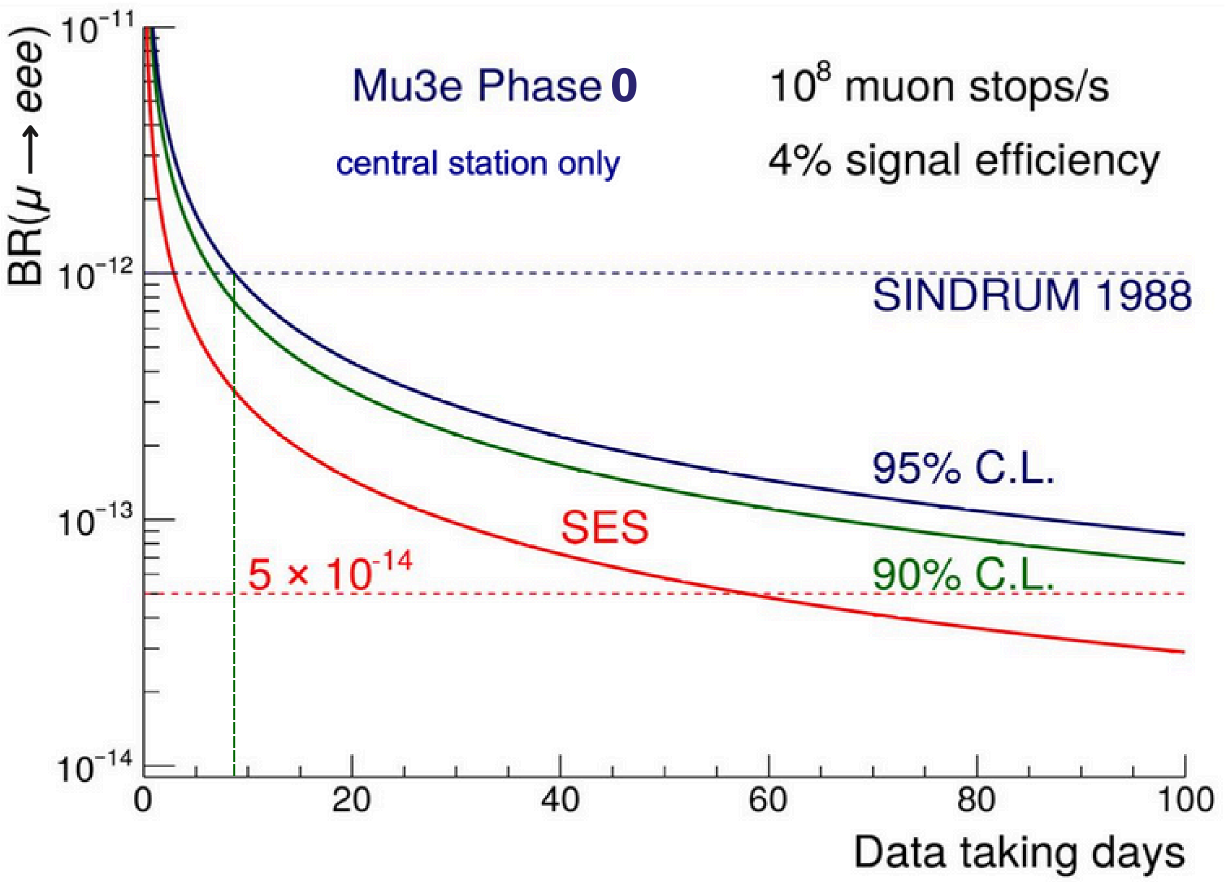
Phase 0 Detector Setup

For Data Taking in 2026



Single Event Sensitivity Projections

Phase 0

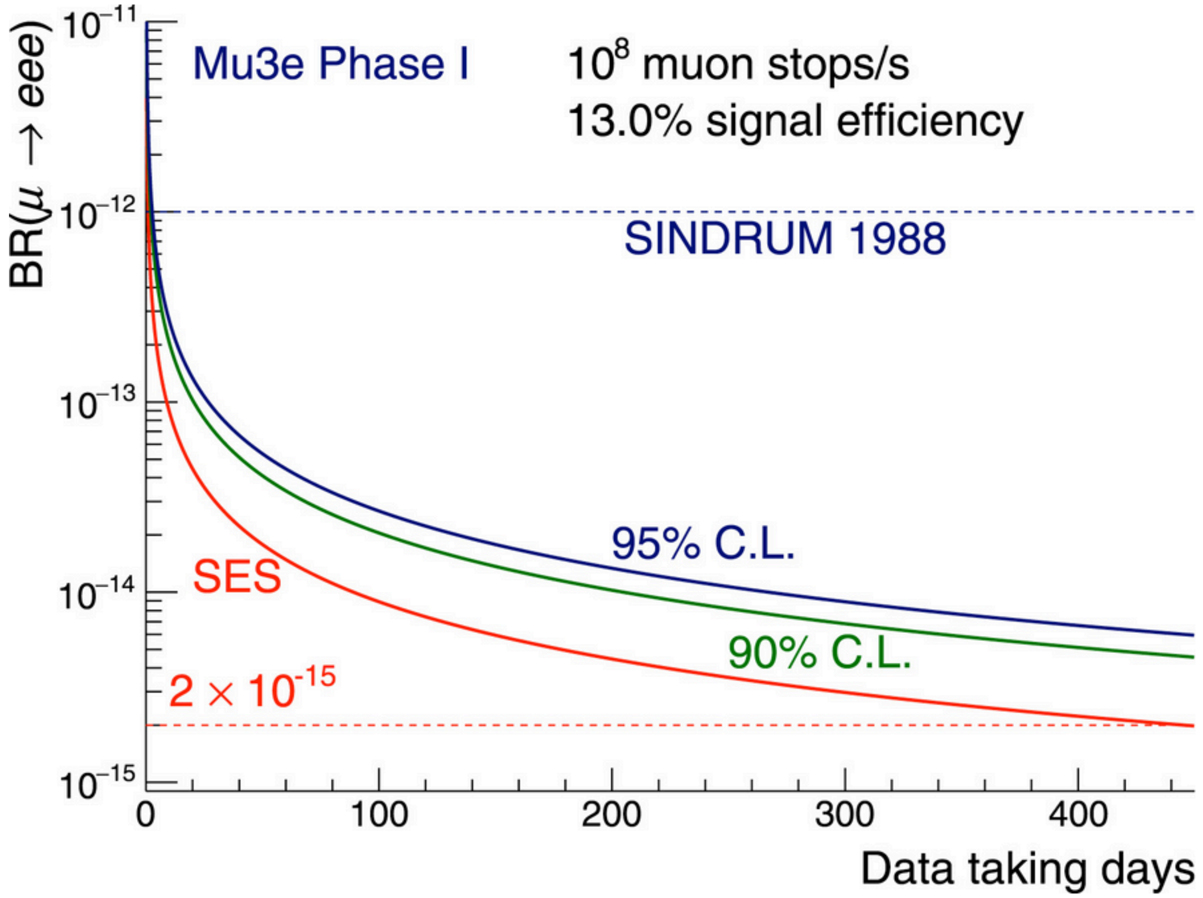


Phase 0 projection of SES vs Data taking days

Surpass the SINDRUM limit in less than two weeks

$$\text{SES} = \frac{1}{(\varepsilon \cdot N_\mu)}$$

Phase I



Phase I projection of SES vs Data taking days

~ 1 year of data taking to find or exclude $\mu^+ \to e^+e^-e^+$ at branching ratio above 10^{-15}

Ongoing Activities

In preparation for the Phase 0 detector setup

↳ Cosmic run

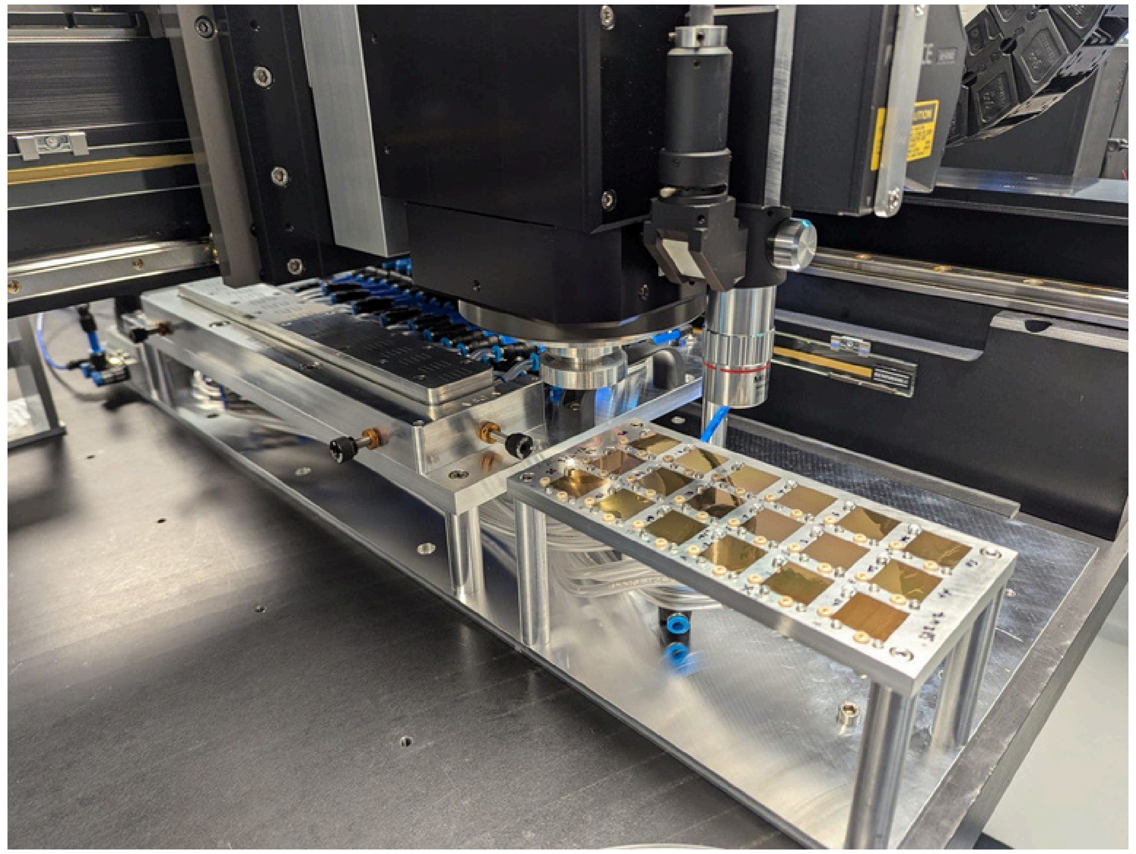
↳ Hardware activities

- Vertex version 2 production with 70 μm Mupix11 sensors
- Outer pixel central station ladder production
- Tile module production for the downstream

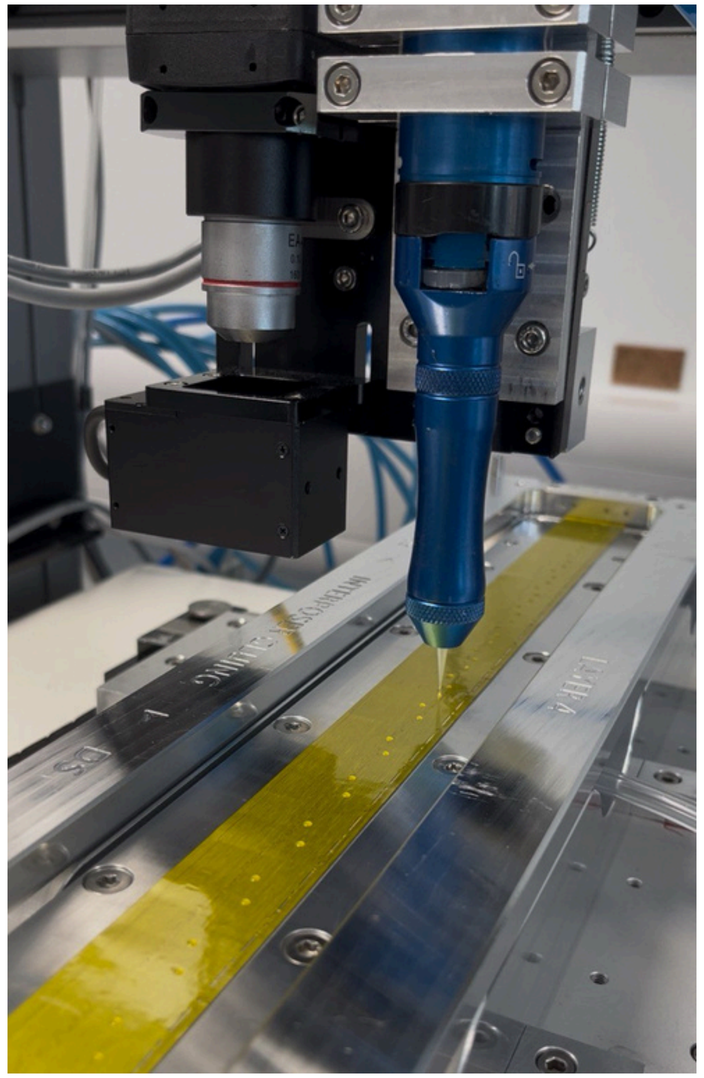
↳ Software activities

- Analysing June 2025 dataset
- Ensure software readiness for 2026 data taking

Stay tuned!



Automated sensor positioning on outer pixel ladders using a gantry

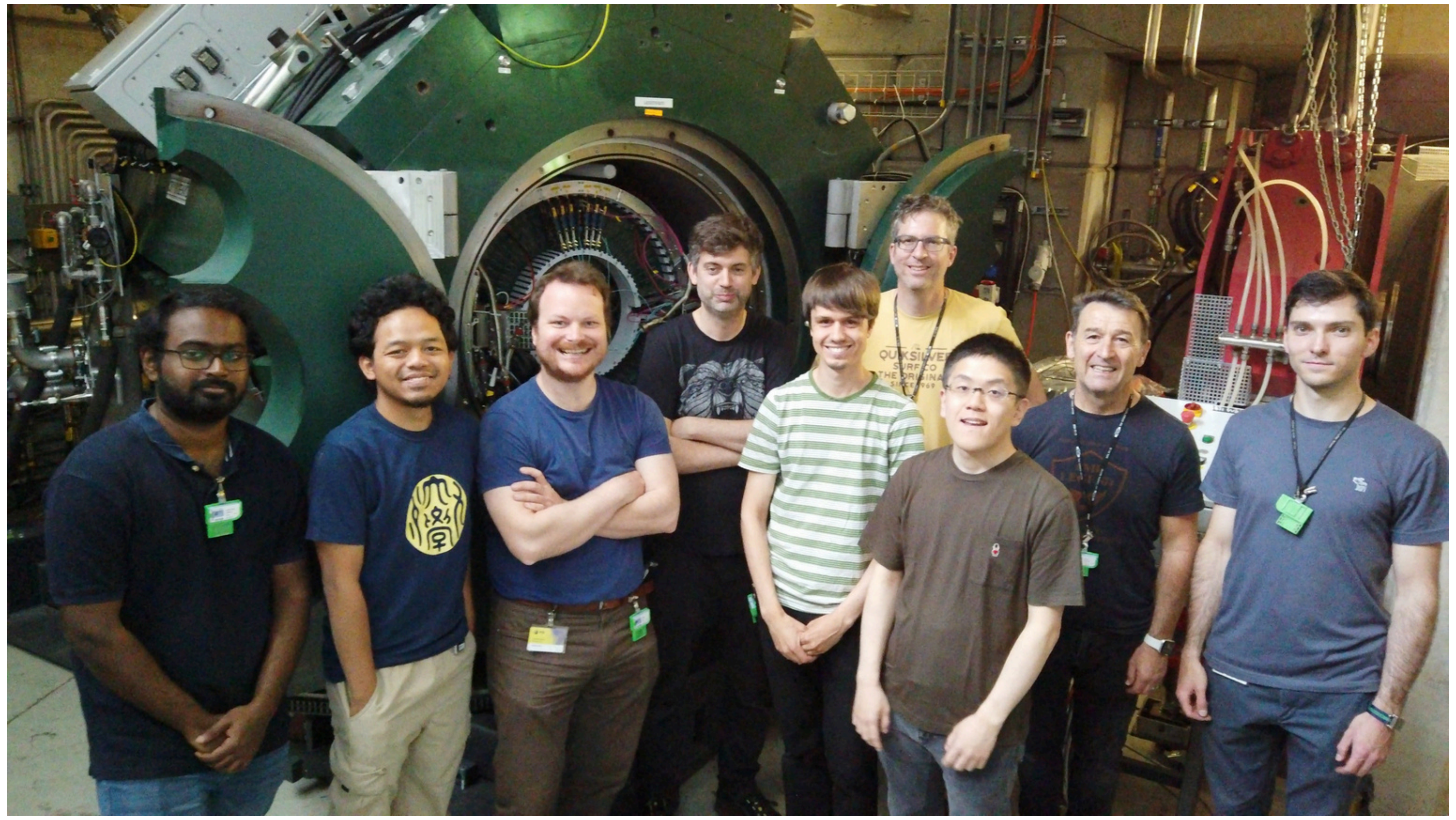


Automated gluing procedure

Summary

↳ A **successful commissioning run** in June with a minimal detector configuration

- All sub-systems partially installed and operated in a magnetic field and helium environment!
- DAQ consolidation
- GPU Filter Farm tested for rates up to 10^7 μ^+/s
- Successfully reconstructed tracks with the **thinnest (0.001 X_0 / layer)** vertex detector currently operational



A few from the core hardware team that played a significant role in the success of June beamtime!

Thank you!

Bibliography

Mu3e:

- K. Arndt et al., "*Technical design of the phase I Mu3e experiment*," Nucl. Instrum. Meth. 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
- A. Schöning, "*A general track fit based on triplets*" Nucl.Instrum.Meth.A 1075 (2025) 170391 DOI: https://doi.org/10.1016/j.nima.2025.170391

SINDRUM I:

- U. Bellgardt et al., "*Search for the Decay μ^+ -> e^+ e^+ e^-*", Nucl. Phys. B, vol. 299, pp. 1–6, 1988, DOI: https://doi.org/10.1016/0550-3213(88)90462-2

BR for CLFV

Calibbi L, Signorelli G (2018) "*Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction.*" Riv Nuovo Cim 41:71–174. DOI: https://doi.org/10.1393/ncr/i2018-10144-0

Backup…

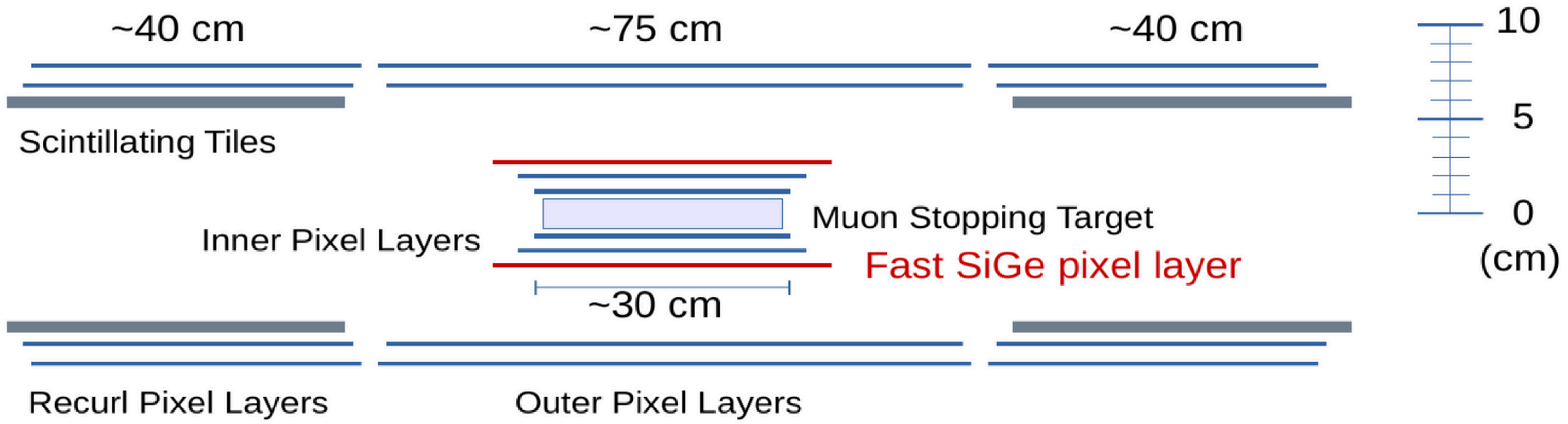
Phase 2 Challenge

- Ultimate sensitivity for the BR ($\mu \rightarrow e^+e^-e^+$) ~ 10^{-16} requires 20 times higher beam rate
  → **2×10^9 μ/s**
  - **Accidental background** (Bhabha scattering + Michel decay) will increase by **20 x 20 = 400** (without any detector improvements)

- Possible suppression of the accidental background by:
  - increase length of muon stopping target: **x 1/3**
  - reduce transverse thickness of muon stopping target: **x 1/4**
  - [reduce material in first tracking layer]: [**x 2/3**]
    - improve vertex resolution: x 1/2
    - improve momentum resolution: x 1/2
    - improve time resolution: x 1/3

  → **combined suppression: x 1/300** (optimistically) → needs to be studied in detail!

Tentative Phase 2 Detector Design



Magnet

Magnet parameter		Value
nominal field		$1.0\,\mathrm{T}$
warm bore diameter		$1.0\,\mathrm{m}$
warm bore length		$2.7\,\mathrm{m}$
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	$\leq 3.2\,\mathrm{m}$
	width	$\leq 2.0\,\mathrm{m}$
	height	$\leq 3.5\,\mathrm{m}$

Requirements

31-ton mu3e magnet