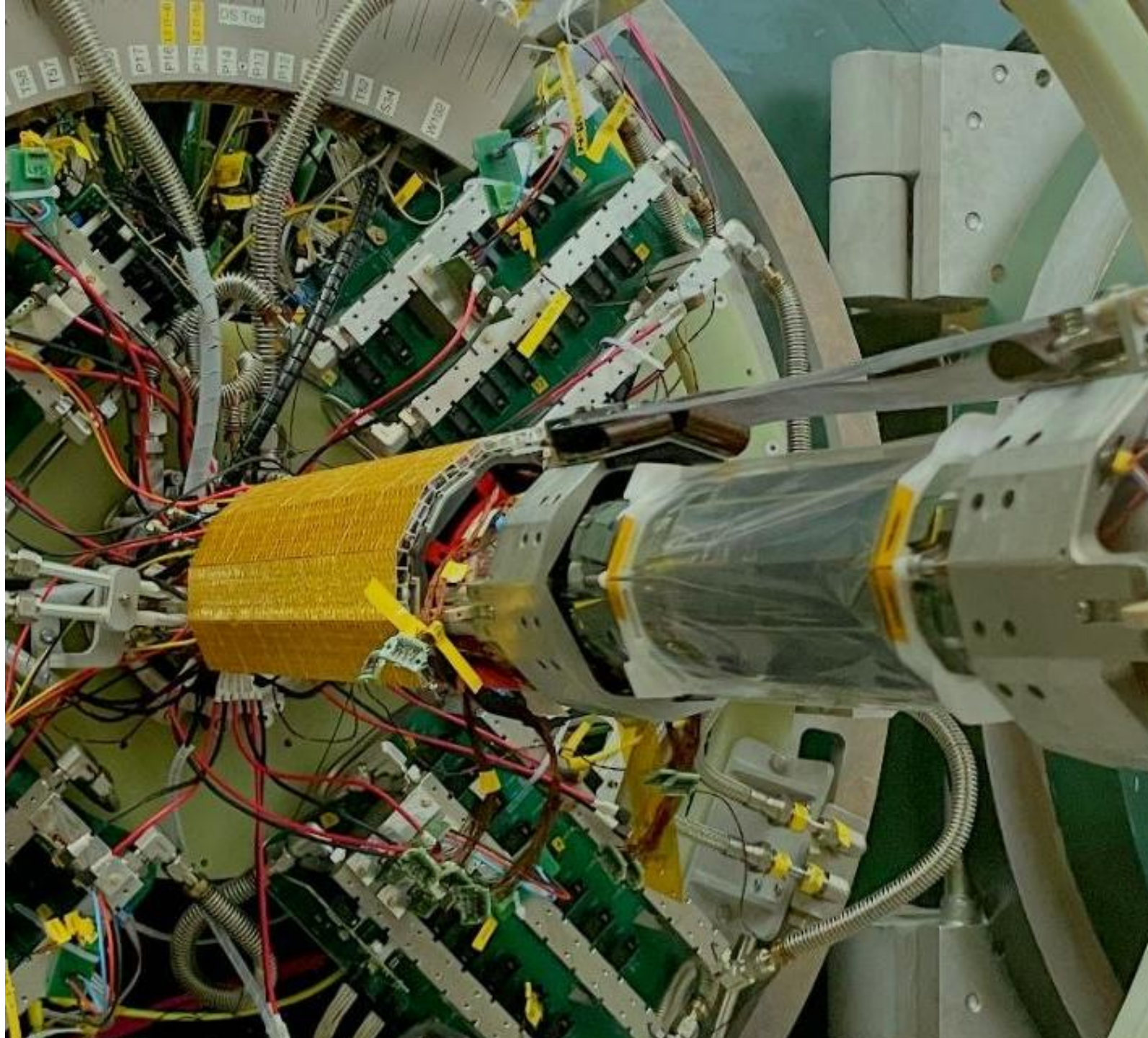
Universität Zürich[UZH]

The Mu3e Vertex Detector

Thomas Christian Senger on behalf of the Mu3e collaboration

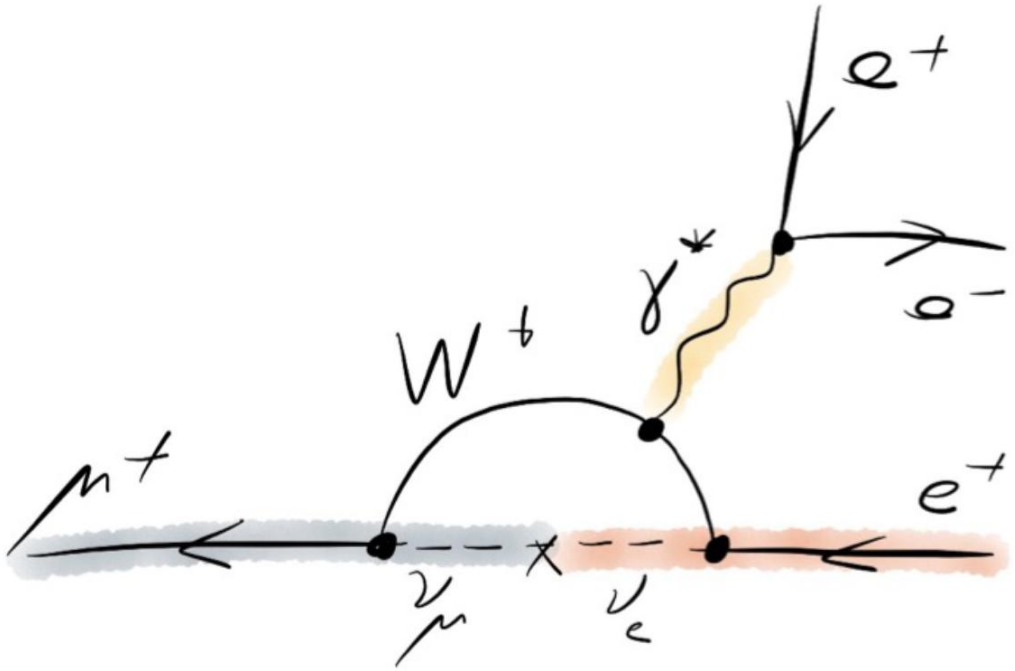


Charge Lepton Flavor Violation

- Lepton flavor violation is experimentally **observed** in the neutral lepton regime (neutrino oscillations)

- Many new Physics Models predict cLFV (e.g SUSY)
  - Any observation of cLFV is a clear sign of **new physics**

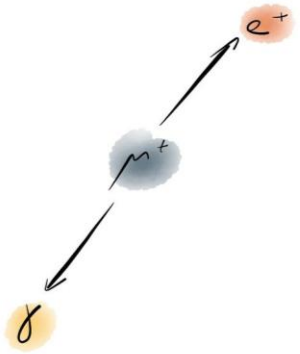
- Heavily **suppressed** in the SM + neutrino mixing
  - $\Gamma \propto \left(\frac{\Delta\ m_\nu^2}{m_W^2}\right)^2 \approx \mathcal{O}(10^{-54})$



The golden muon channels

Muons are an excellent probe of cLFV

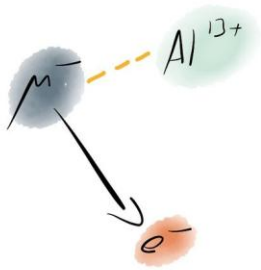
- **Sensitive**: New physics effects scale with the squared lepton mass m_l^2
- **Clean**: Relatively long lifetime and simple, well-understood decay channels, allowing for precise and background-free measurements



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

MEG /MEG II (PSI 2025)

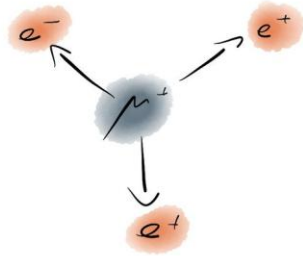
BR $(\mu^+ \rightarrow e^+ \gamma) < 1.5 \cdot 10^{-13}$



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

SINDRUM II (PSI 2006)

BR $(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13}$



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

SINDRUM II (PSI 1988)

BR $(\mu^+ \rightarrow e^+ e^- e^+) < 1.0 \cdot 10^{-12}$

The Mu3e experiment at PSI

The Mu3e Experiment is located at Paul Scherrer Institute in Switzerland

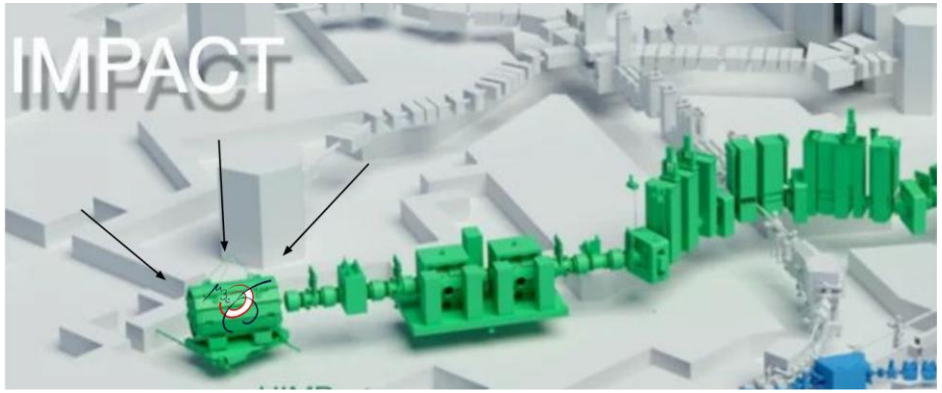
- **Most intense** muon beam with low momentum muons 28MeV
- Up to $\mathbf{10^8}$ Muons/s

Muon production at HIPA

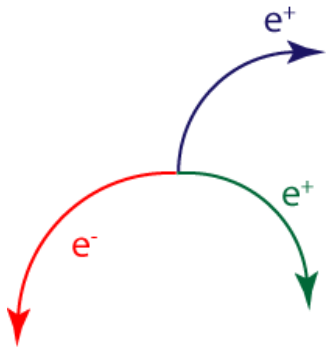
- 590 MeV proton accelerator
- Carbon target, produce pions, decay to surface muons

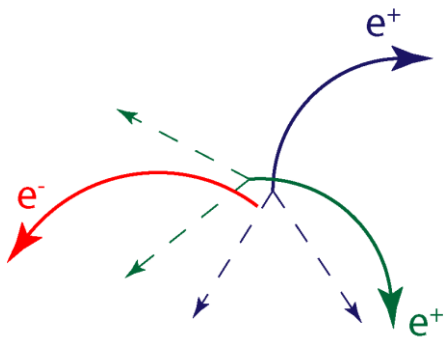
Goal: Improvement of the current limit by **4 orders** of magnitude in two phases

- **Phase 1** aims for a sensitivity of $< 2.0 \cdot 10^{-15}$ (Start in 2027)
  - First commissioning run in 2025
  - Currently under construction at PSI
- **Phase 2** aims for a sensitivity of $< 1 \cdot 10^{-16}$ (from 2030)
  - High intensity muon beamline **HIMB** (up to 10^{10} Muons/s)
  - R&D started

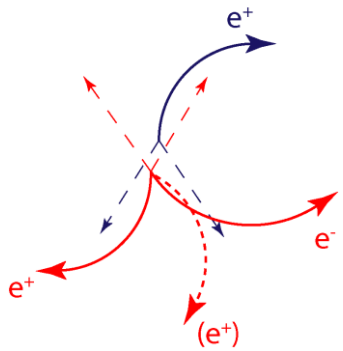


Mu3e signal and backgrounds

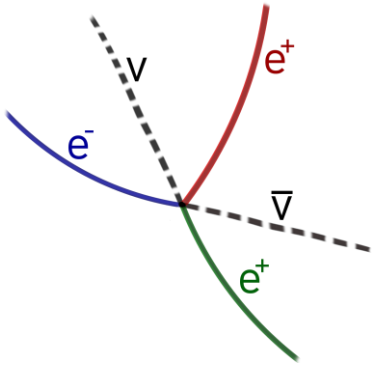




Two Michel decays + e^-



Michel decay + Internal Conversion



Signal

- Common Vertex
- Time coincidence
- $\Sigma\, P_e = (m_\mu\,, 0, 0, 0)$

→ Multiple Coulomb scattering effects dominates due to low momentum $e^{+/-}$

Accidental combinatorial background

- Accidental combinations of e^+ from $\mu^+ \to e^+\bar{\nu}\nu$ decays with an e^- or e^+e^- originating from
  - Bhabha scattering
  - photon conversion,
  - mis-reconstruction

→ Need very good timing and vertexing

Internal conversion

- Rare muon decay $BR(\mu^+ \to e^+e^-e^+\bar{\nu}\nu) = 3.4 \cdot 10^{-5}$
- The three electrons have a common vertex and are coincident
- Distinguishable only by the missing momentum carried by neutrinos

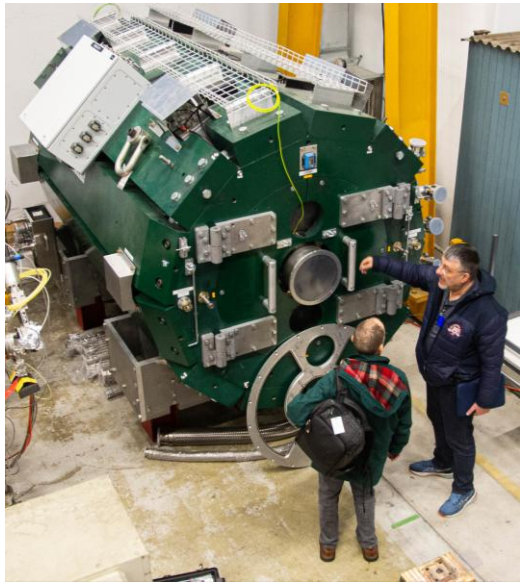
Need excellent momentum resolution

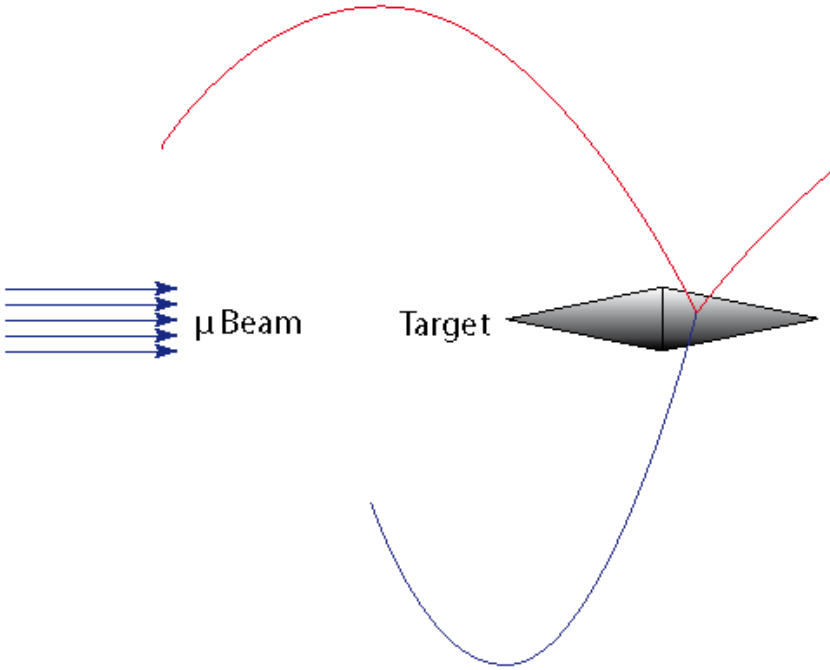
→ $\sigma_p < 1$ MeV/c

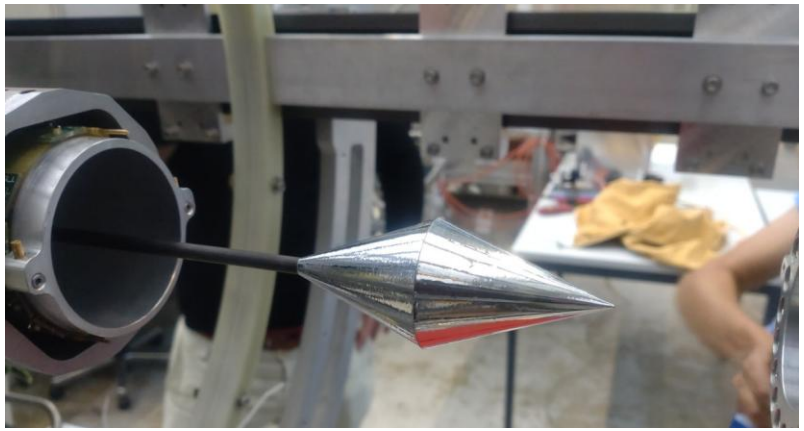
Mu3e Detector

Mu3e magnet

- Superconducting solenoid
- Provides a **uniform 1 T** field
- Enable precise momentum reconstruction







Target

- Muons are stopped on **aluminised mylar** double hollow cone
- Maximum stopping fraction 95%

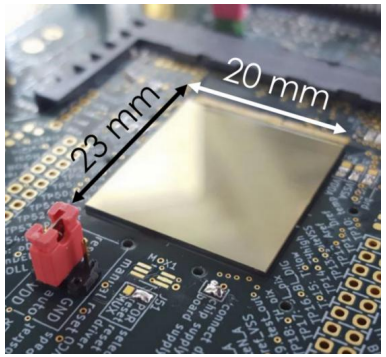
Pixel Detector

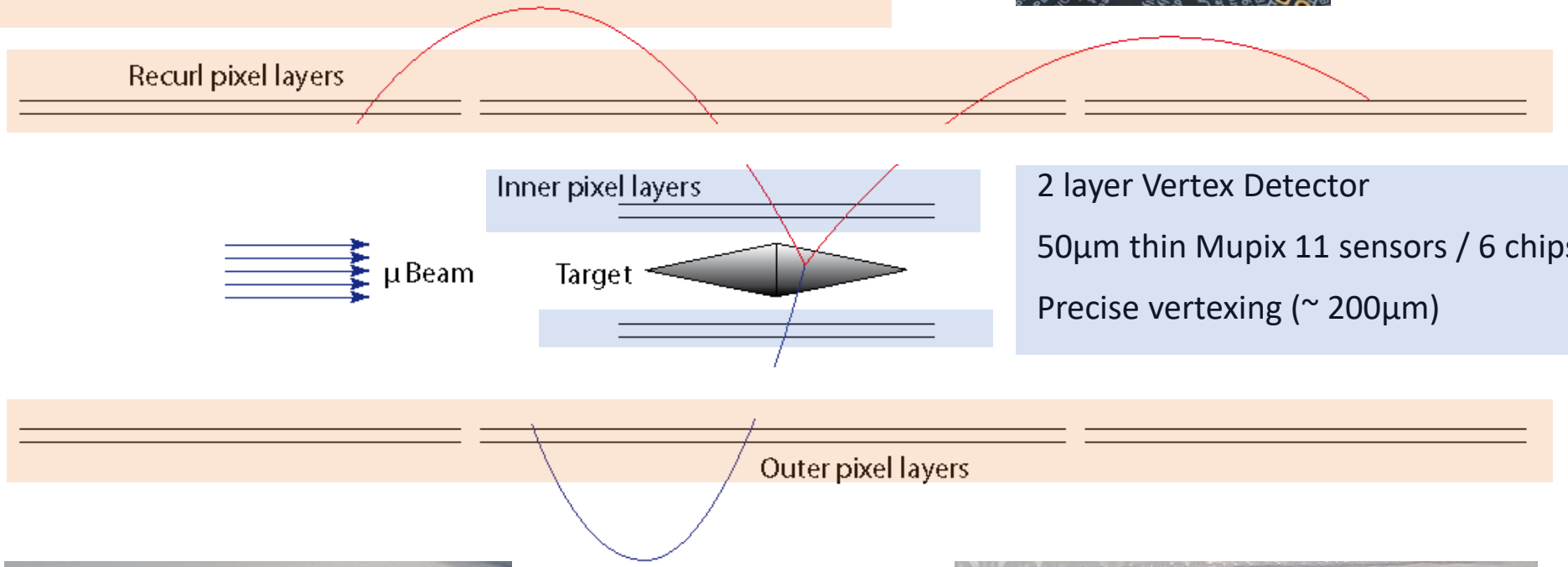
2 Outer Pixel Layers

70µm thin Mupix 11 sensors / Up to 18 sensors per ladder

For good momentum resolution and high p acceptance

→ reconstruction of recurling tracks

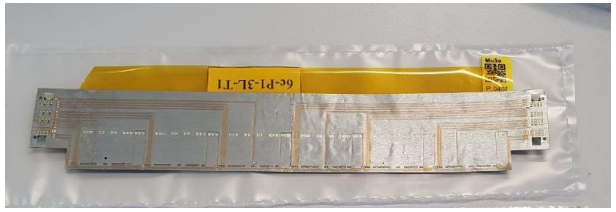


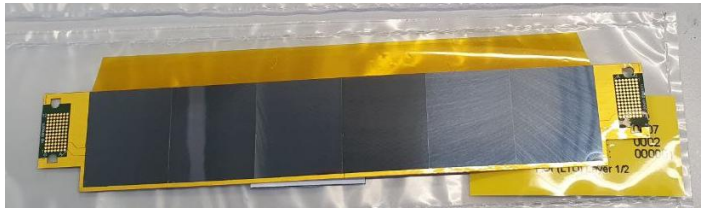


2 layer Vertex Detector

50µm thin Mupix 11 sensors / 6 chips per ladder

Precise vertexing (~ 200µm)





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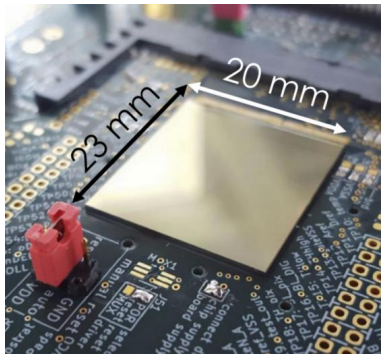

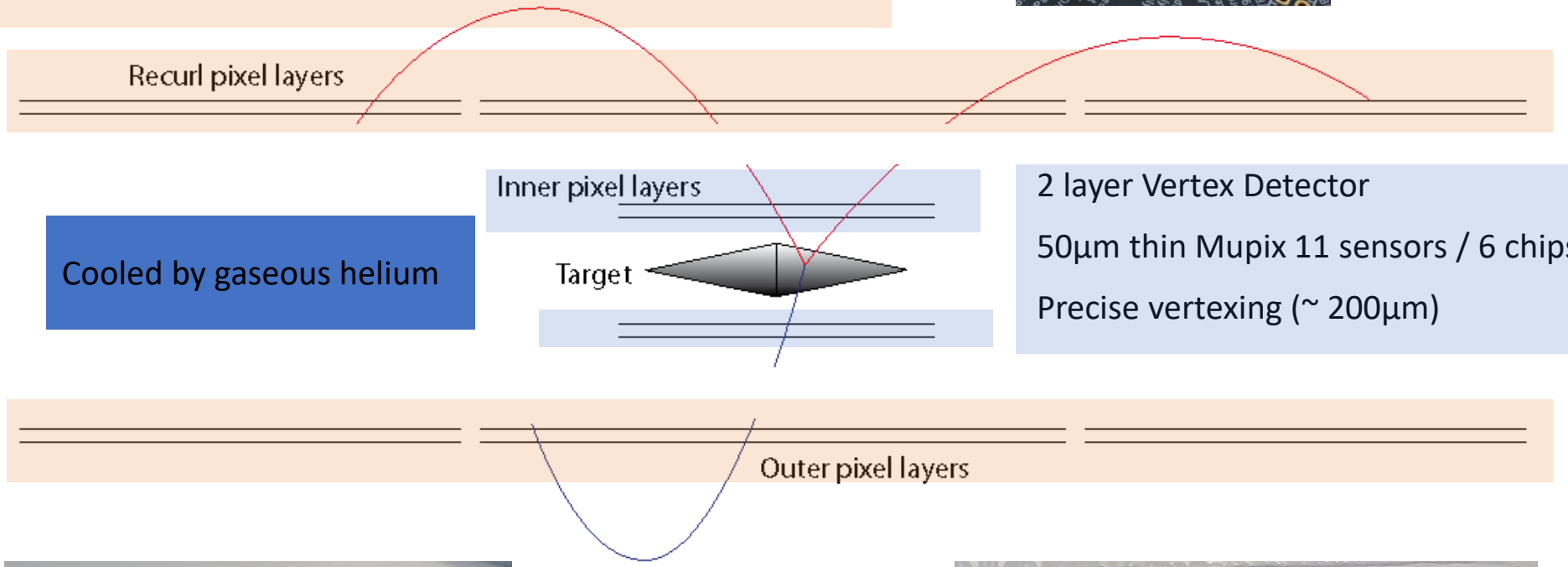

Cooled by gaseous helium

2 layer Vertex Detector

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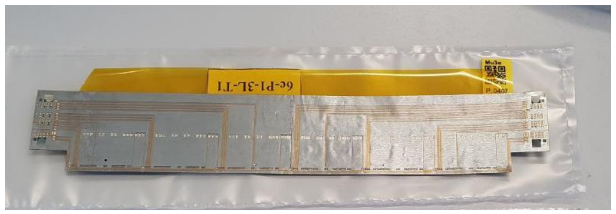
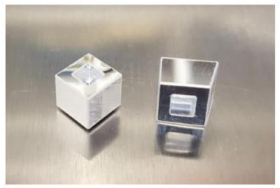
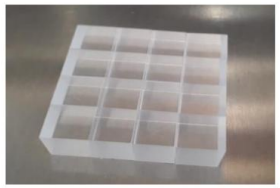
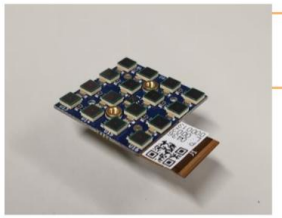
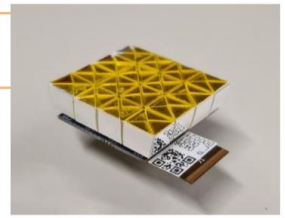
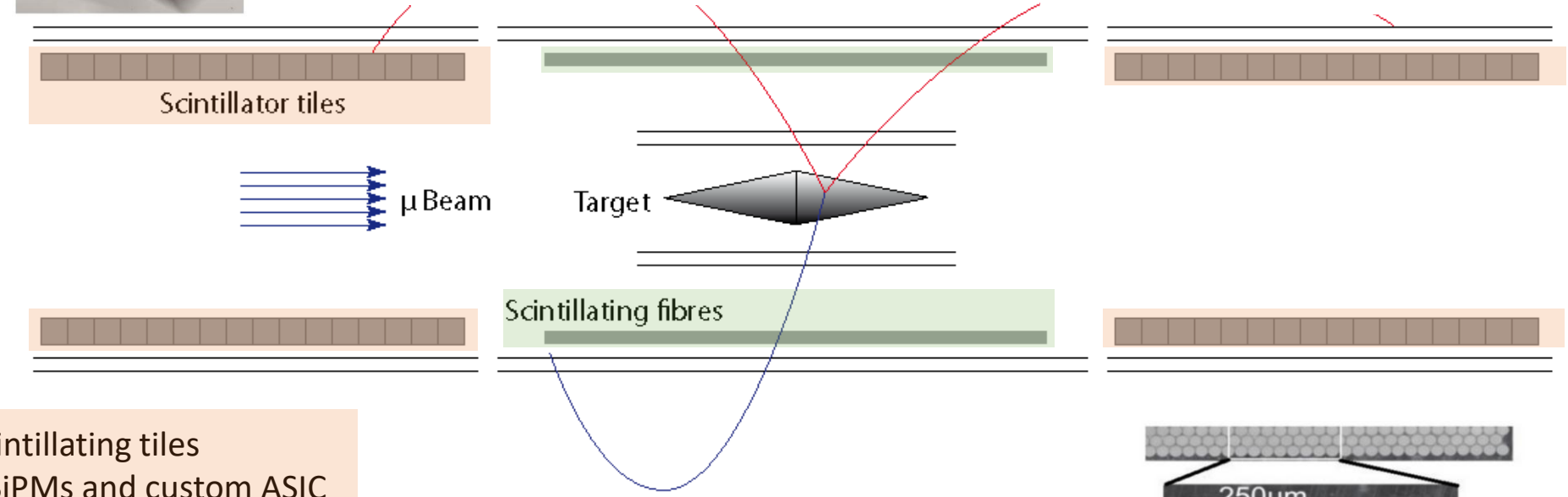


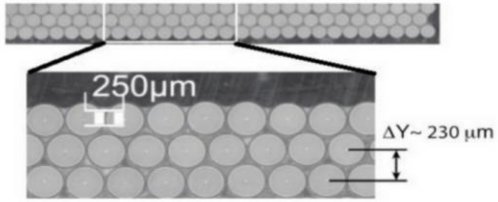
SciFi & SciTile Detector

3 layers of 250µm scintillating fibres
Read-out by (SiPMs) and custom ASIC
Timing resolution < 0.5 ns

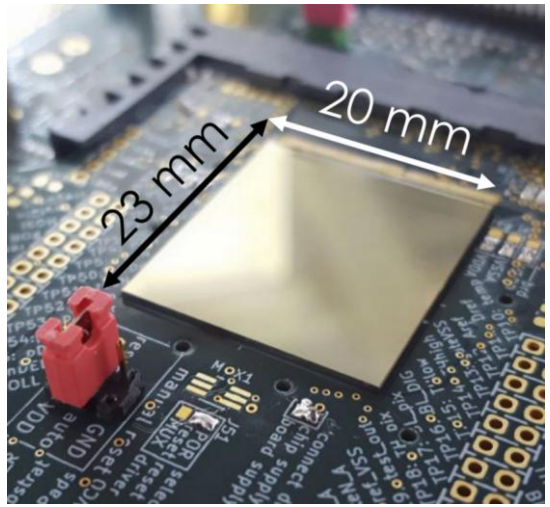


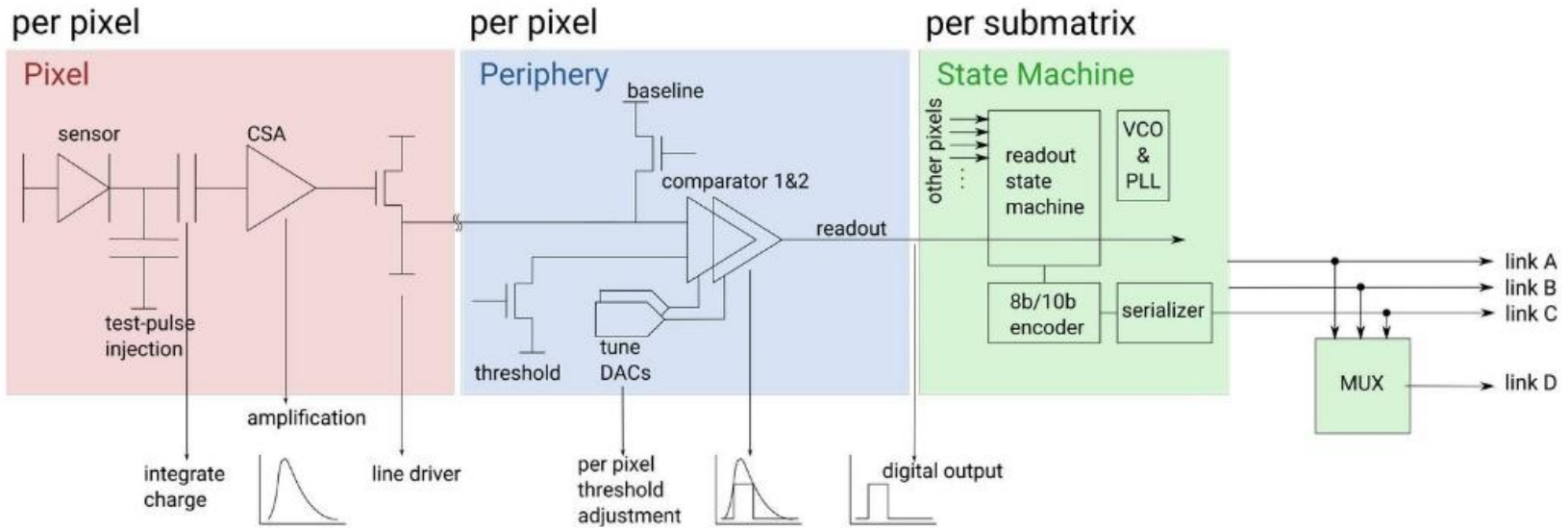
$\approx 0.5\text{cm}^3$ scintillating tiles
Readout by SiPMs and custom ASIC
Timing resolution 80ps



Mupix 11

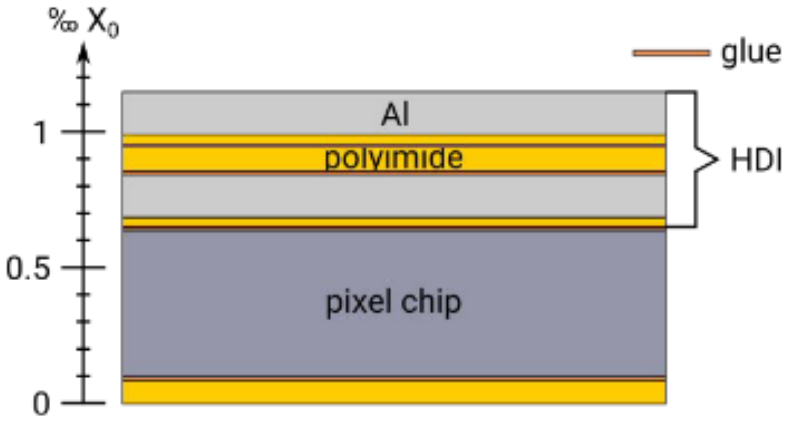
- High-Voltage Monolithic Active Pixel Sensor (HV-MAPS)
- Detection and Readout combined in one chip
- Fully digital 1.25Gbit/s LVDS output
- 250x256 pixel with a size of 80 x 80 μm^2
- 99% efficiency with less than 20ns time resolution
- 2 comparator design
- Tuning/trimming and masking available
- Chip sub-divided into 3 matrices → 1 data link each + 1 multiplexed link

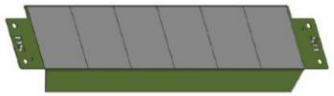




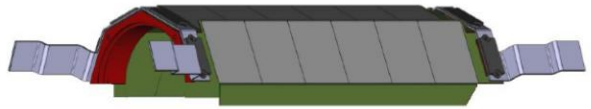
Mu3e Vertex Detector

- 8 or 10 ladders per layers
- Each Ladder carries 6 sensors
- 108 sensors in total
- Mechanical support with minimized material budget
  - Aluminized Kapton interfaces by LTU (X/X_0 ≈ 0.15 % per layer)
  - Sensors glued on foils + spTAB for electrical connection
- DAQ to sensor connection via micro-twisted pair cables and other flexes produced through standard processes

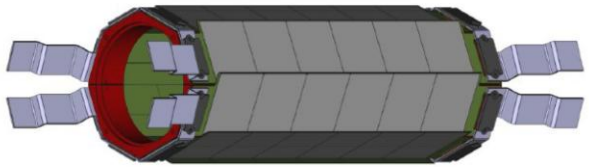




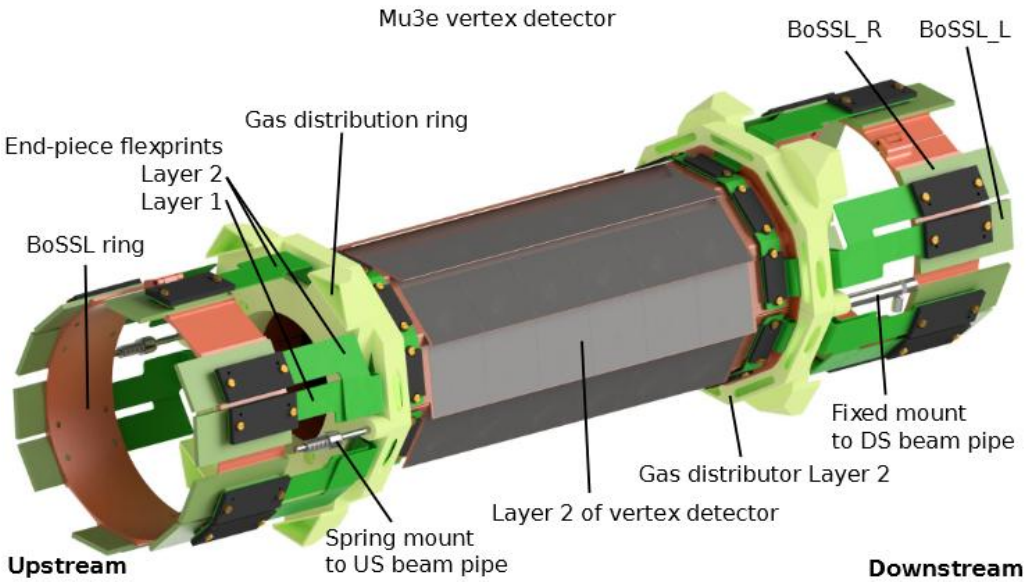
Ladder



Module

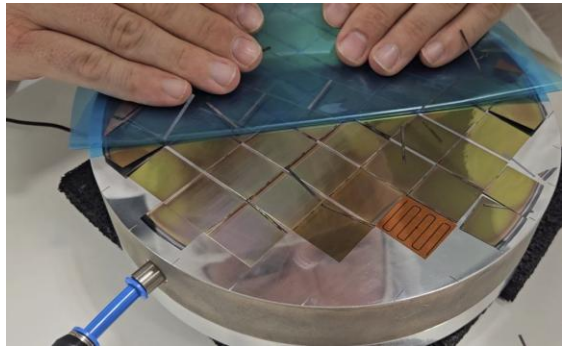


Layer

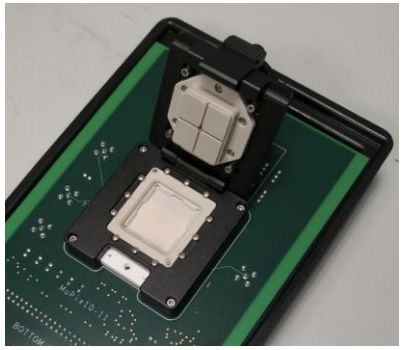


Challenges in the Construction and the Operation of the Mu3e Vertex Detector

Construction and Handling



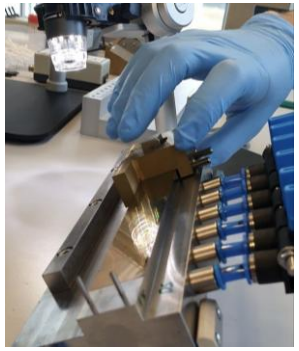
Wafer Peeling + Picking



Chip QC

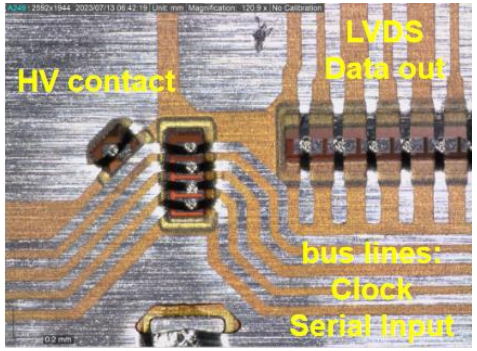
Probe card with manual actuator

Yield of up to 80%

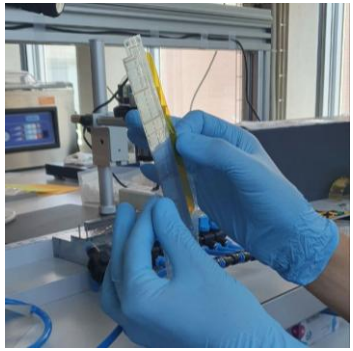


Manual Chip Placement

Glue Distribution



spTa-Bonding

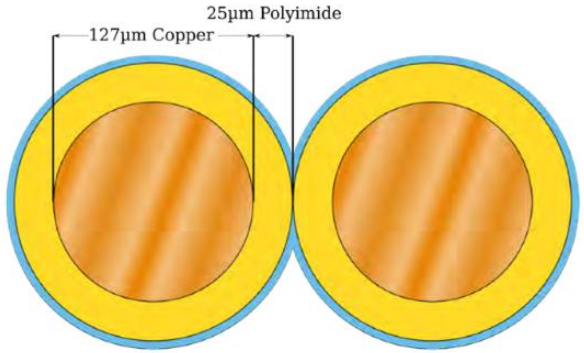


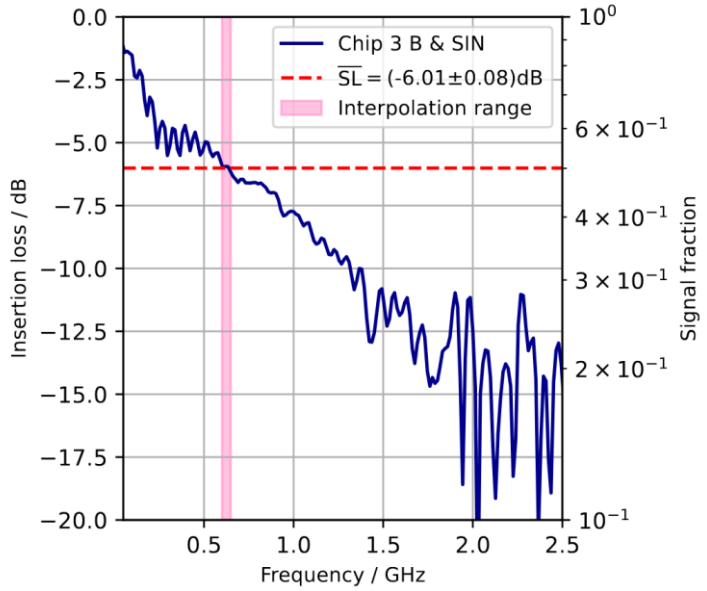
Handling + QC

Signal transmission challenge

- Need to transmit all differential LVDS data over µTP cables
  - Space limitations
  - Used in the CMS experiment at much lower data readout rate
- Huge challenge to transmit data error free
  - Loss of up to **70%** of signal amplitude at maximum data rate (1.25 Gbit/s)

- Can be partially recovered through the chip internal **pre-emphasis** (VNLVDSDel) and **signal amplification** (VNLVDS)
  - With increase of the preemphasis the eye opening factor increases and signal amplitude decreases
  - Signal amplitude saturates at certain DAC setting point
  - Higher DAC settings increase power consumption of the sensor
- Use full readout chain to characterize each ladder for error free data transmission





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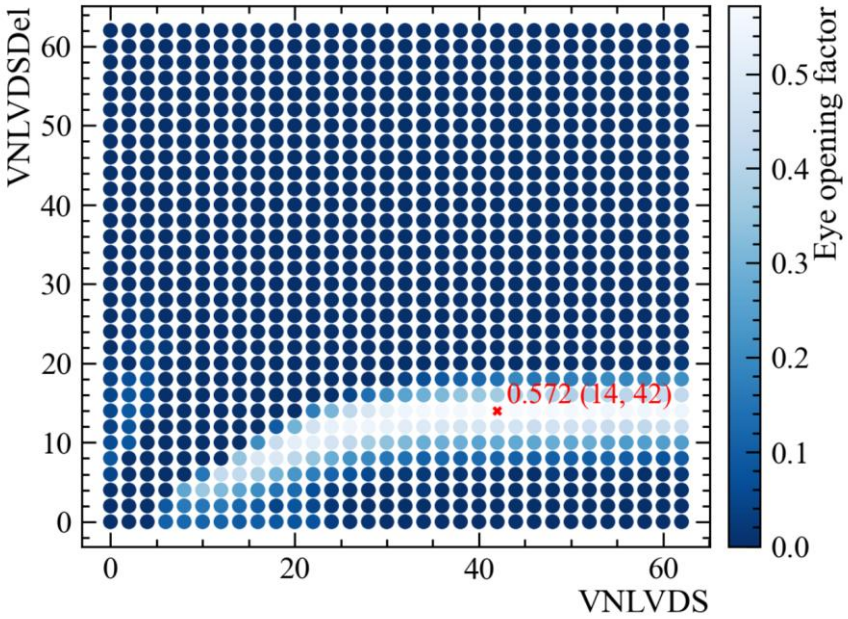

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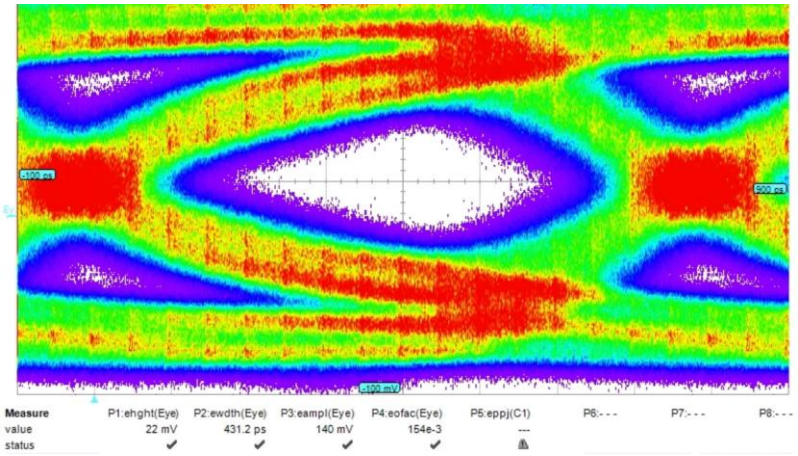
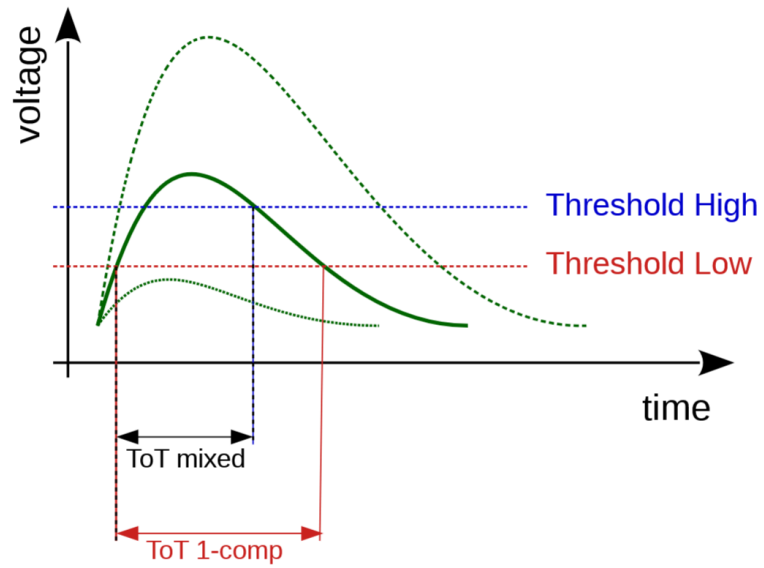
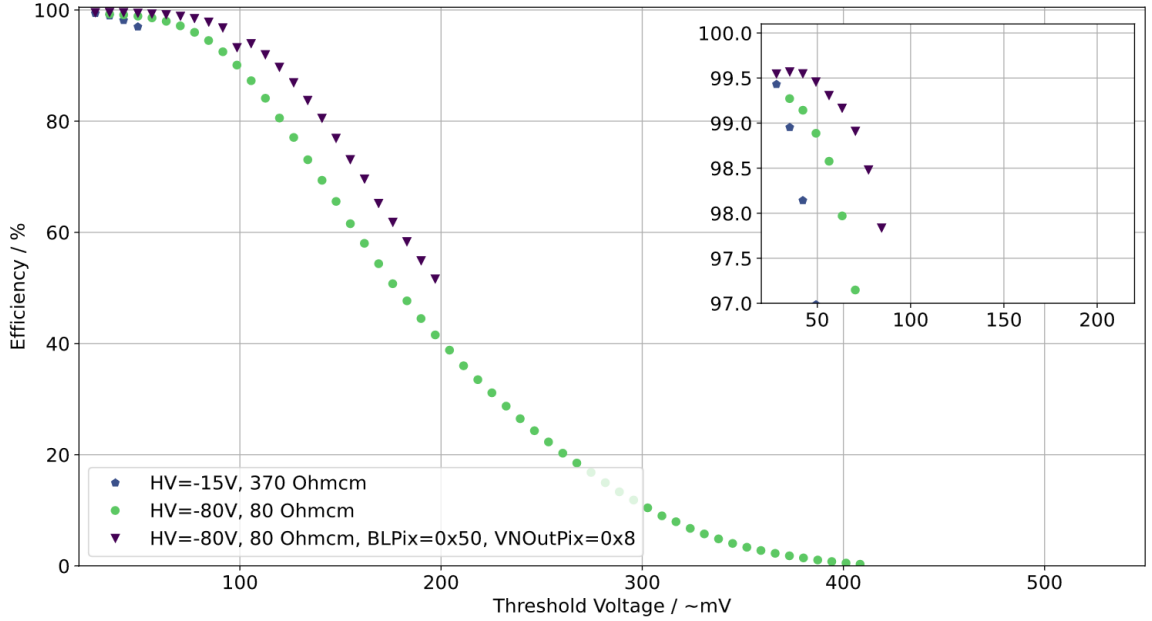


Efficient pixel operation

- Can set a global threshold per chip
  - Set **as low as possible** to detect small pulses
- Only narrow plateau region with >99% efficiency
- 50 µm thin chips show **noisy pixels** at **high thresholds** due to
  - Thinning process
  - Mechanical stress
  - Guard ring induced noise
- High noise occupancy can cause buffer saturation and data corruption and prevent other pixels from being read out
- Masking of noisy pixels is required but each masked pixel **lowers the total efficiency**

- In-pixel tuning is **essential**
  - Can set threshold adjusting bits **per pixel**
  - Very time extensive to find the best settings per sensor

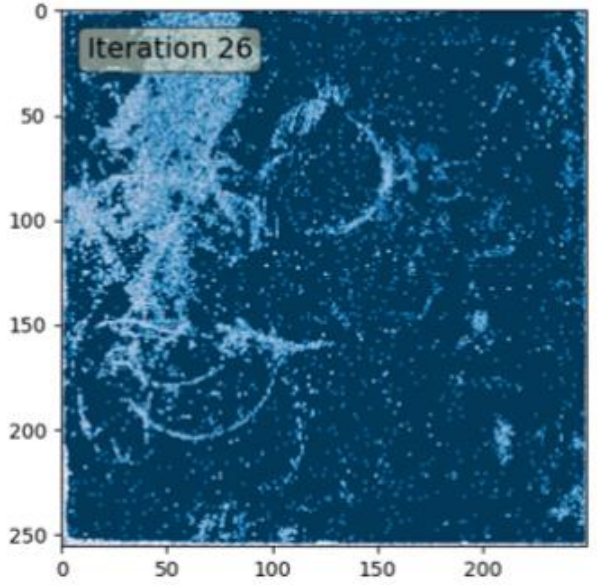


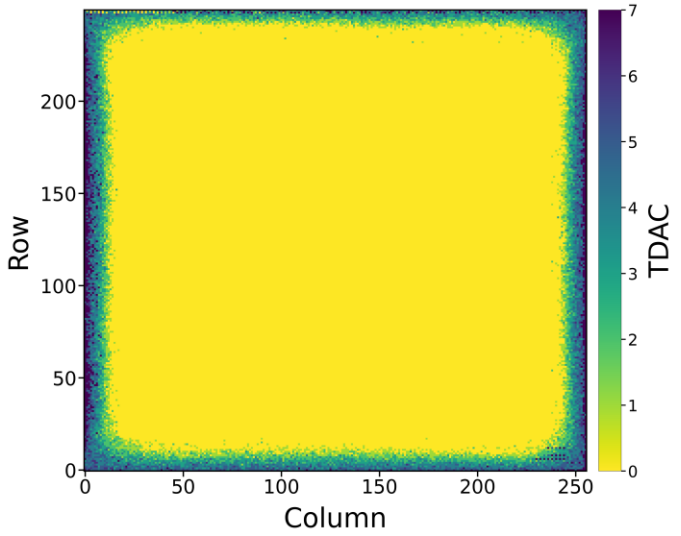


Efficient pixel operation

- Can set a global threshold per chip
  - Set **as low as possible** to detect small pulses
- Only narrow plateau region with >99% efficiency
- 50 µm thin chips show **noisy pixels** at **high thresholds** due to
  - Thinning process
  - Mechanical stress
  - Guard ring induced noise
- High noise occupancy can cause buffer saturation and data corruption and prevent other pixels from being read out
- Masking of noisy pixels is required but each masked pixel **lowers the total efficiency**

- In-pixel tuning is **essential**
  - Can set threshold adjusting bits **per pixel**
  - Very time extensive to find the best settings per sensor

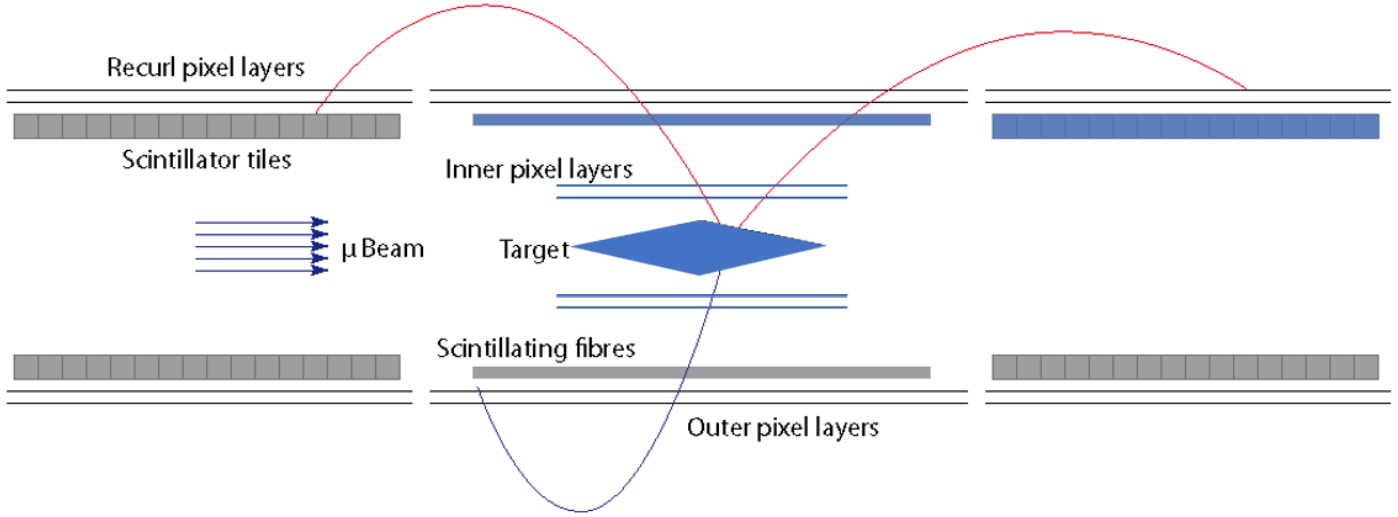


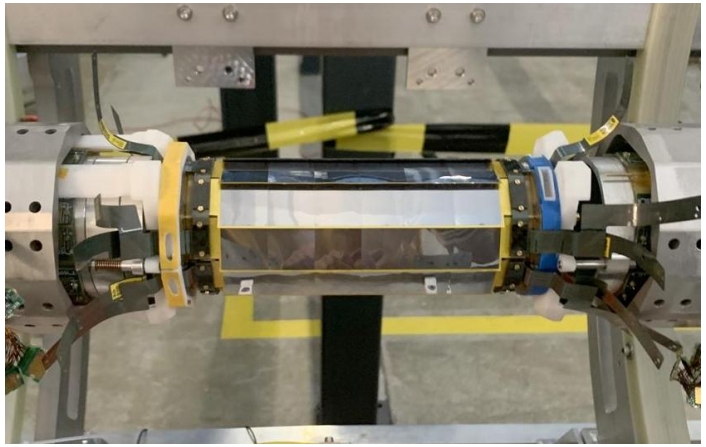


Commissioning Run 2025

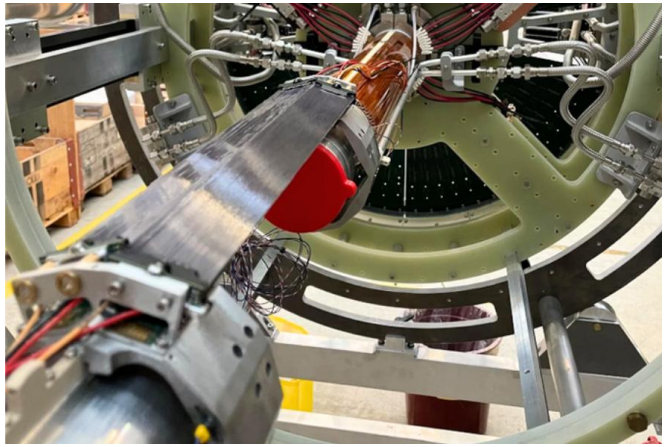
Three weeks of commissioning run campaign in 2025 at PSI in PiE5

- Minimal detector configuration
- Operation with **gaseous helium cooling**
- 1 T magnetic field
- Most services independent of the sub-system have been installed and tested

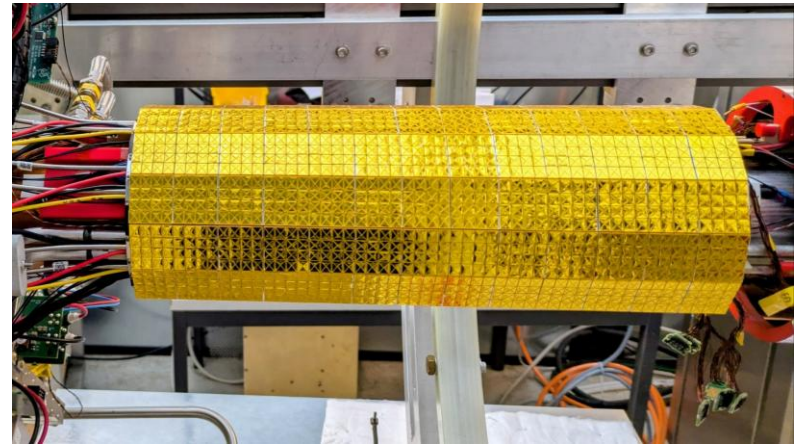




Full Vertex Detector
(108 sensors)



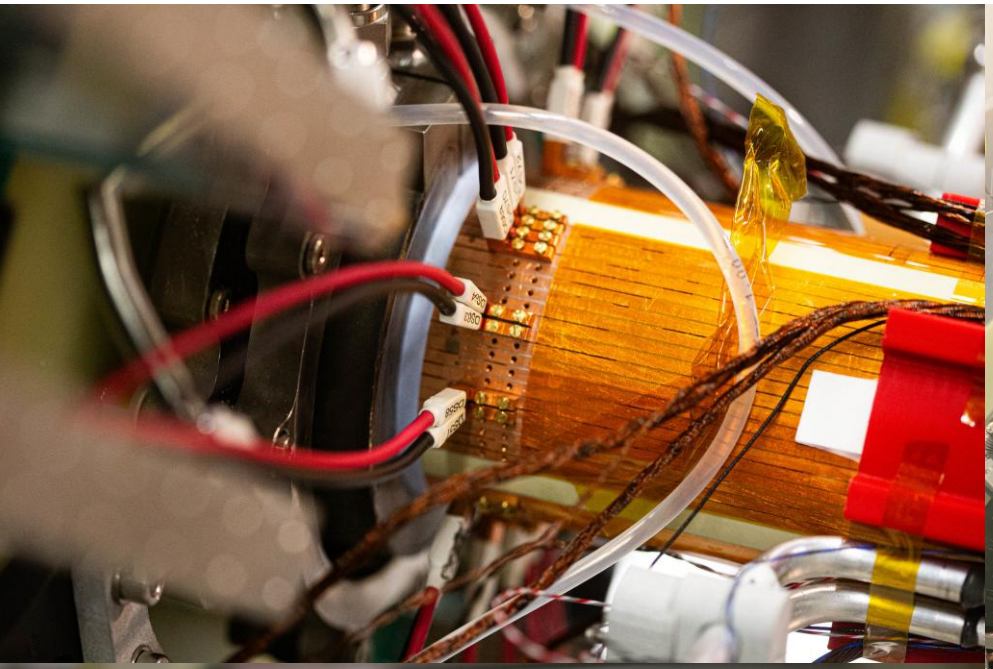
2/12 SciFi ribbons

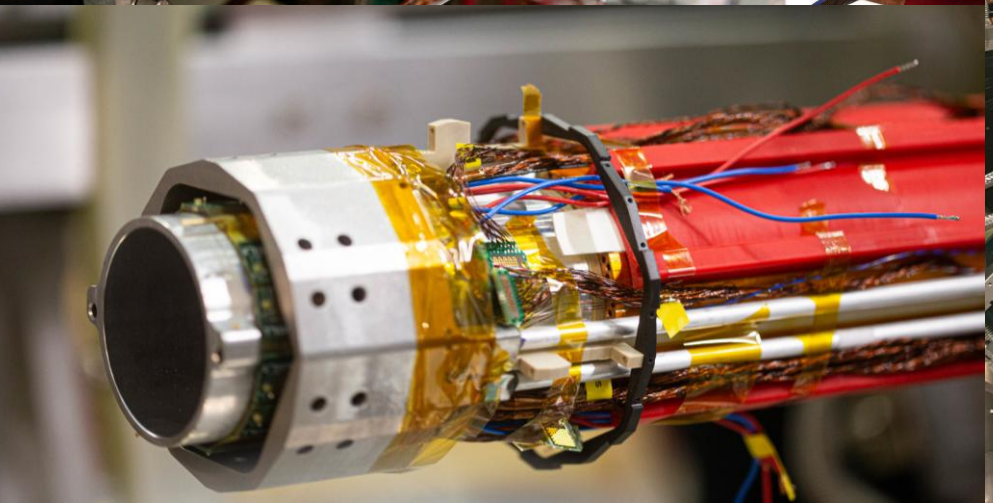


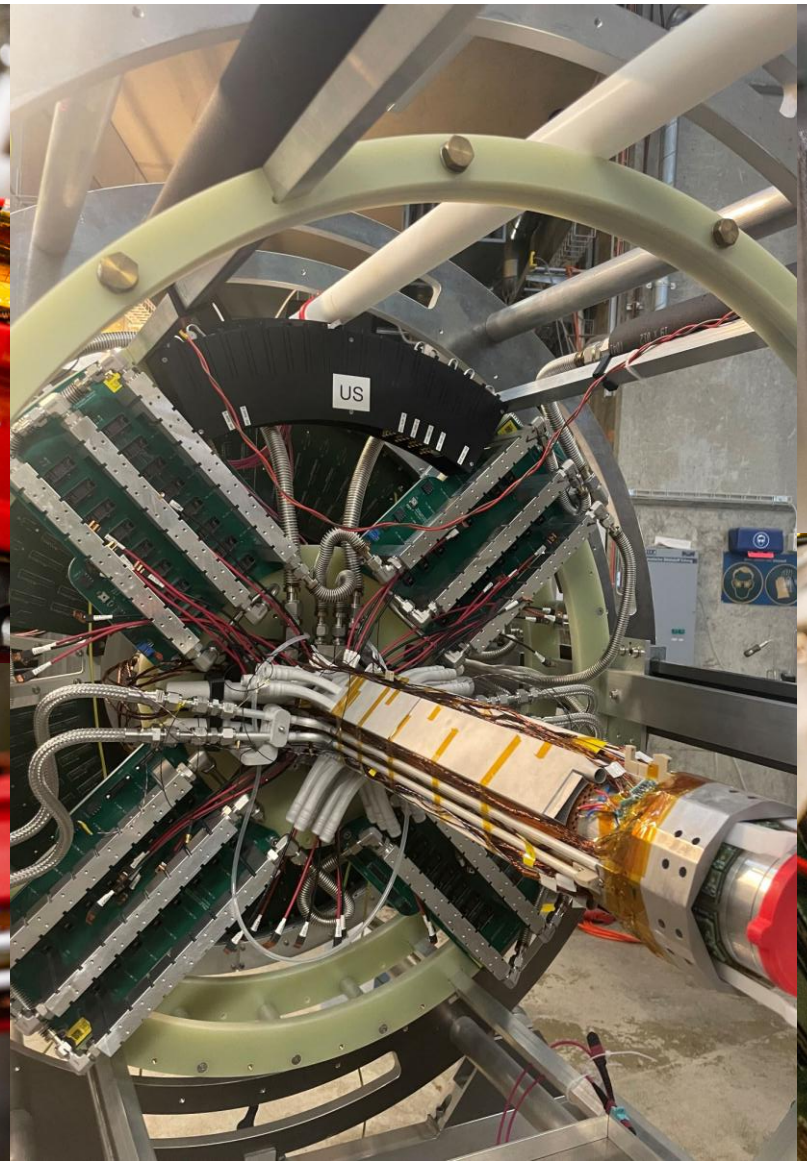
3/14 SciTile modules (DS)

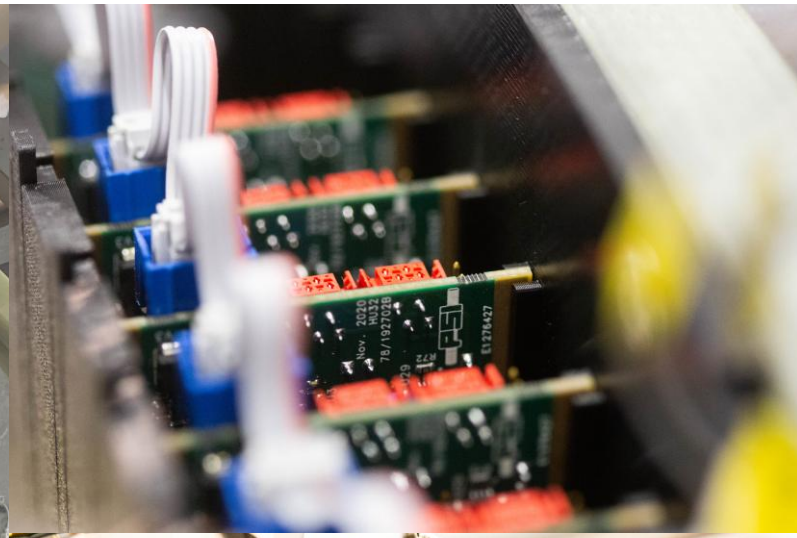
University of Zurich[UZH]

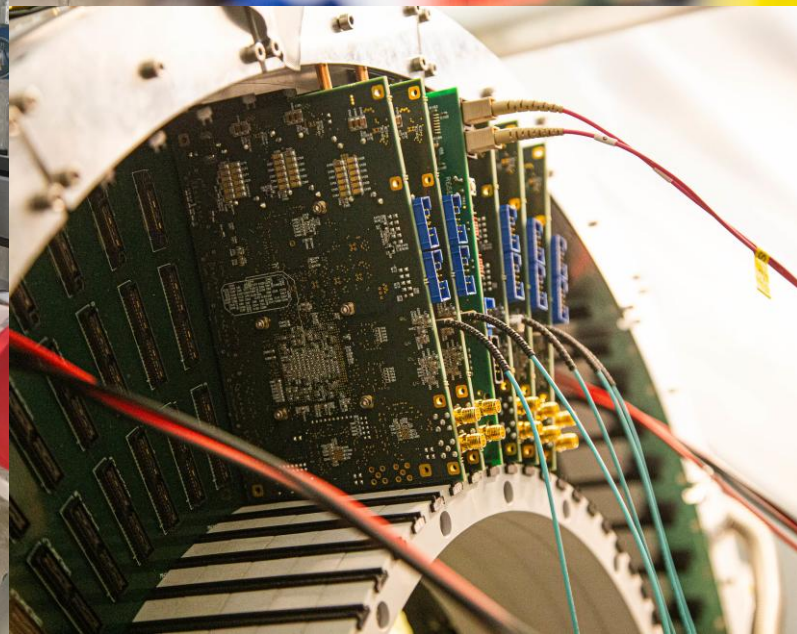
Service Installation



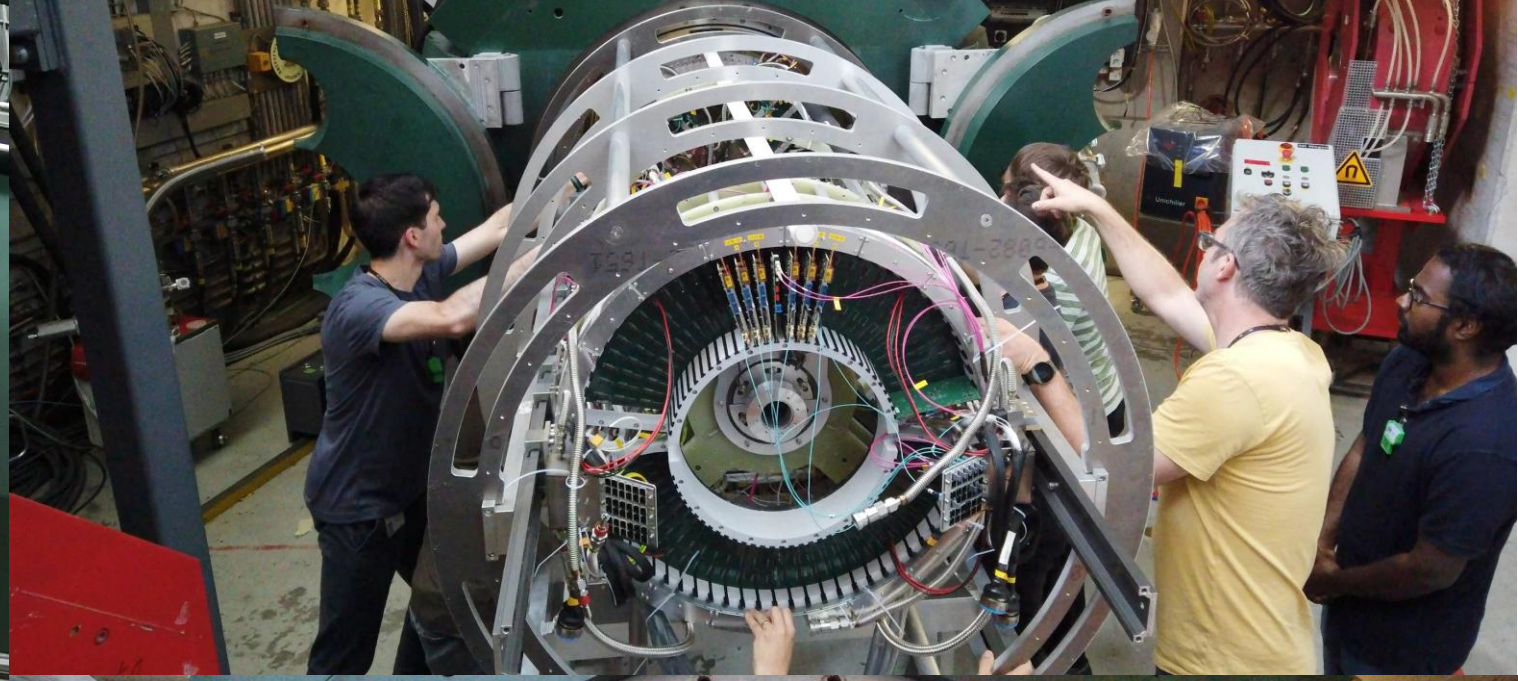


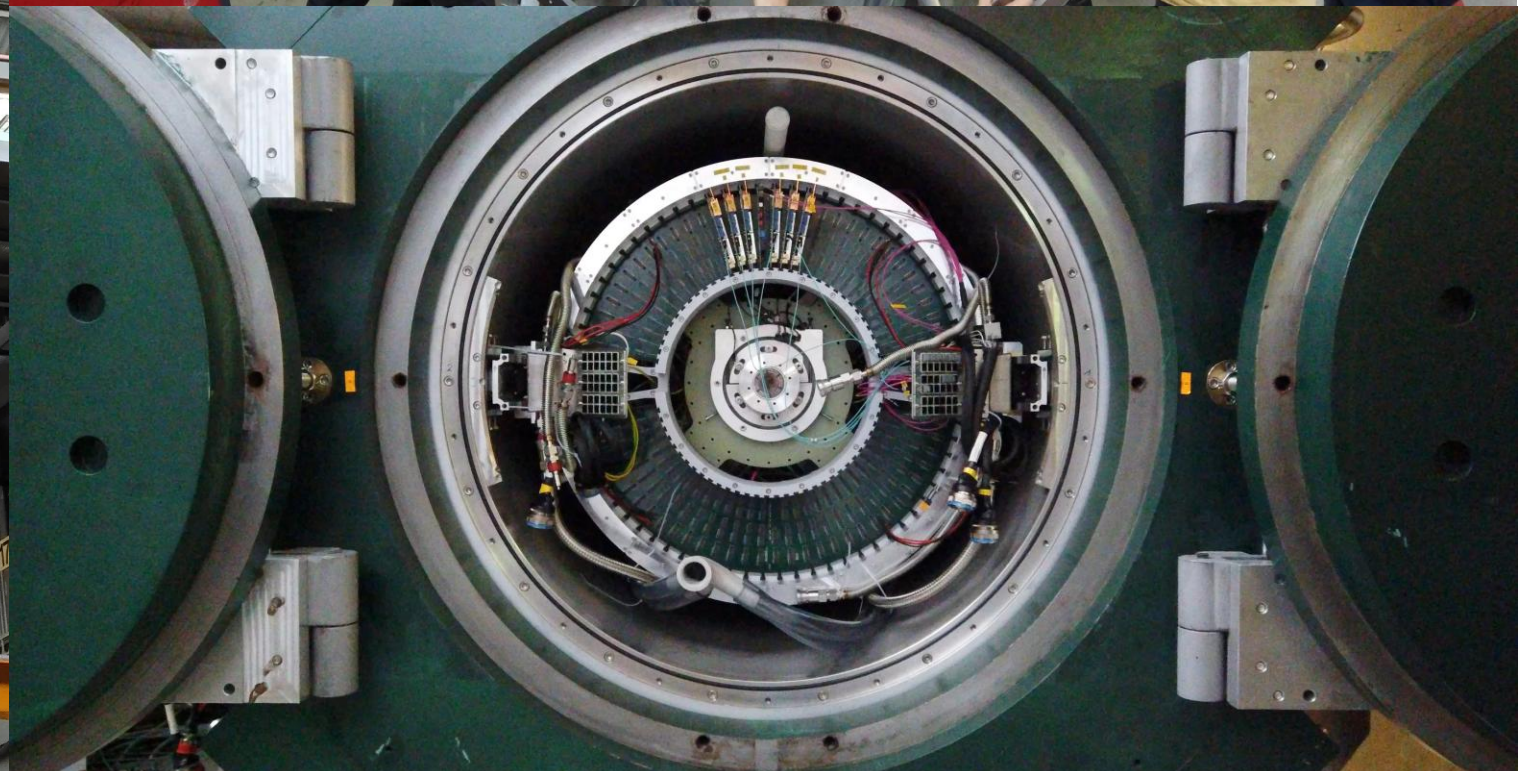






The flight of Mu3e





Successful Commissioning of the Mu3e Vertex Detector

- **Thinnest** (0.12% X_0/ layer) **vertex detector currently operational**
- Demonstrated **efficient** data collection after successful **tuning**
- All 108 sensors installed
  - 75 % of the submatrices were operational

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

	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	✓M✓	✓✓✓	✓✓✓	✓✓✓
Ladder 6	✓✓✓	✓✓✓	✓✓✓	X✓✓	✓✓✓	✓✓✓
Ladder 7	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ladder 8	✓X✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ladder 9	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Ladder 10	✓✓✓	XXX	✓✓✓	✓✓✓	✓✓✓	✓✓✓

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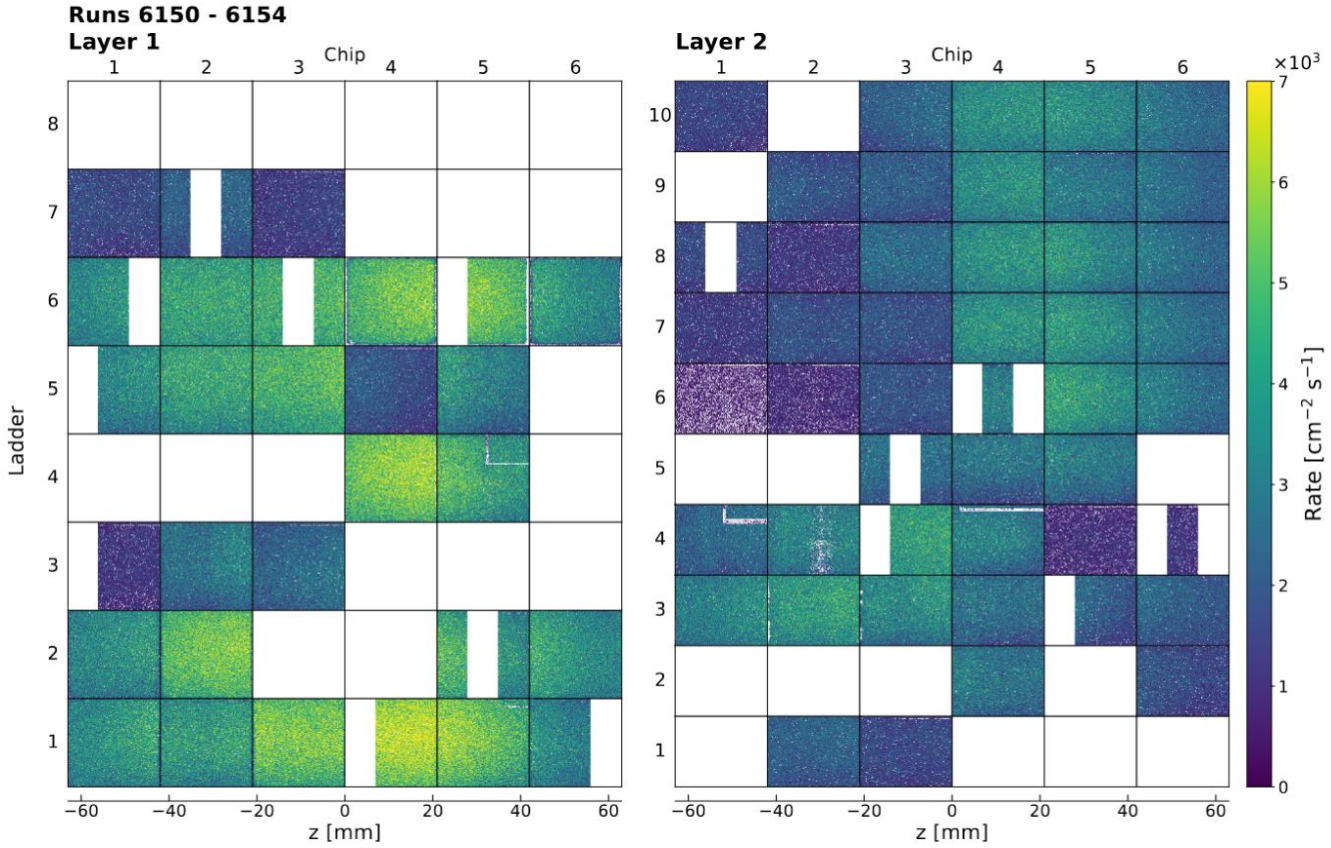

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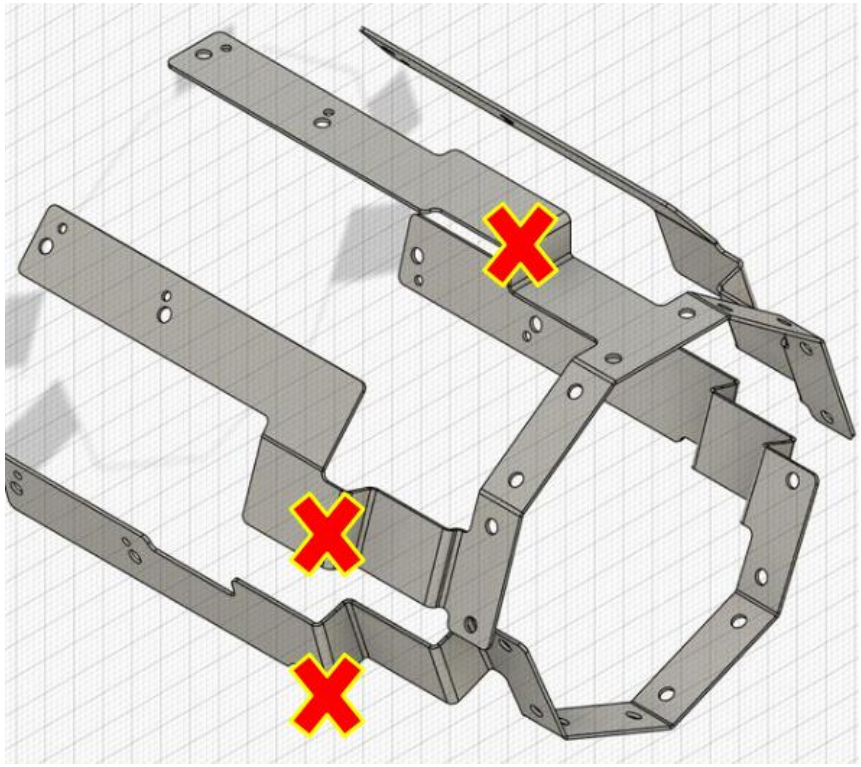

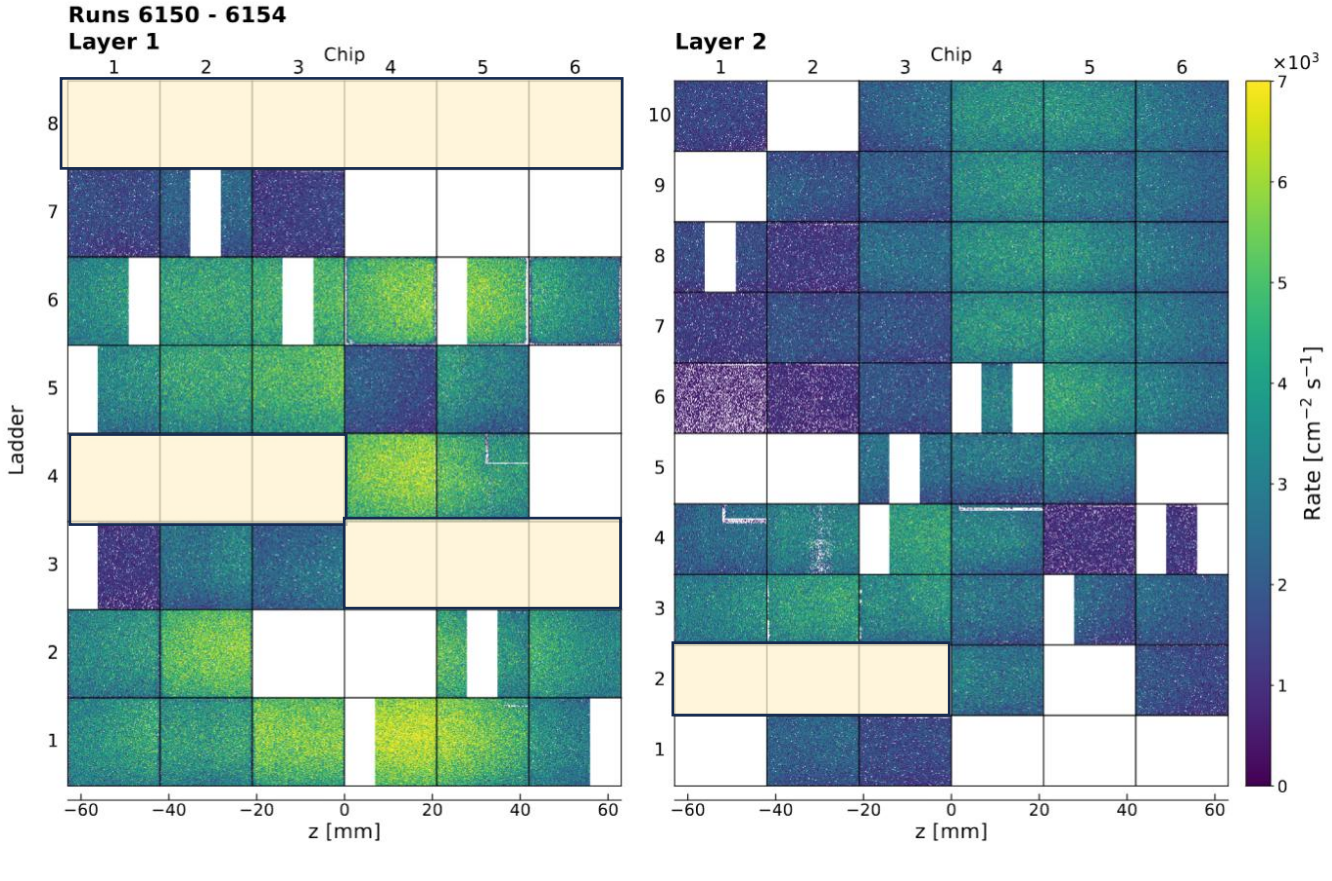

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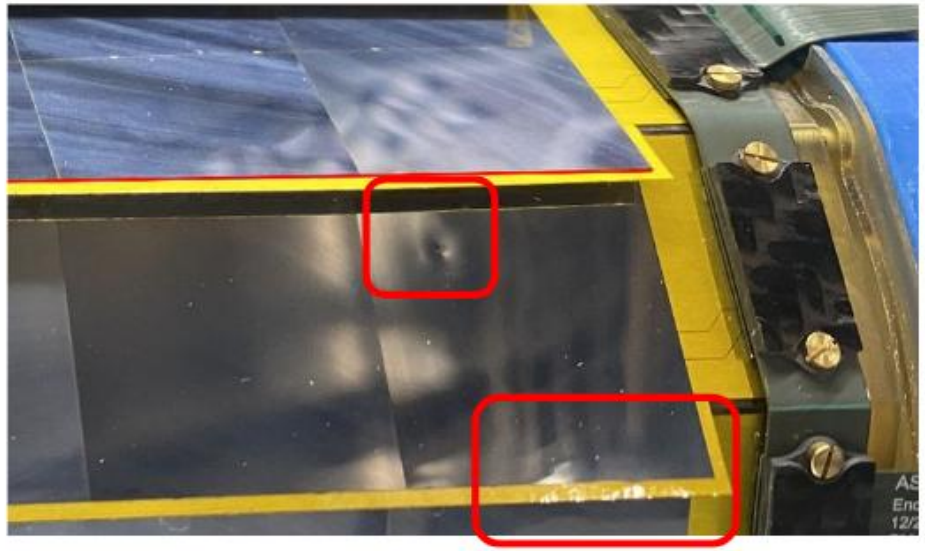

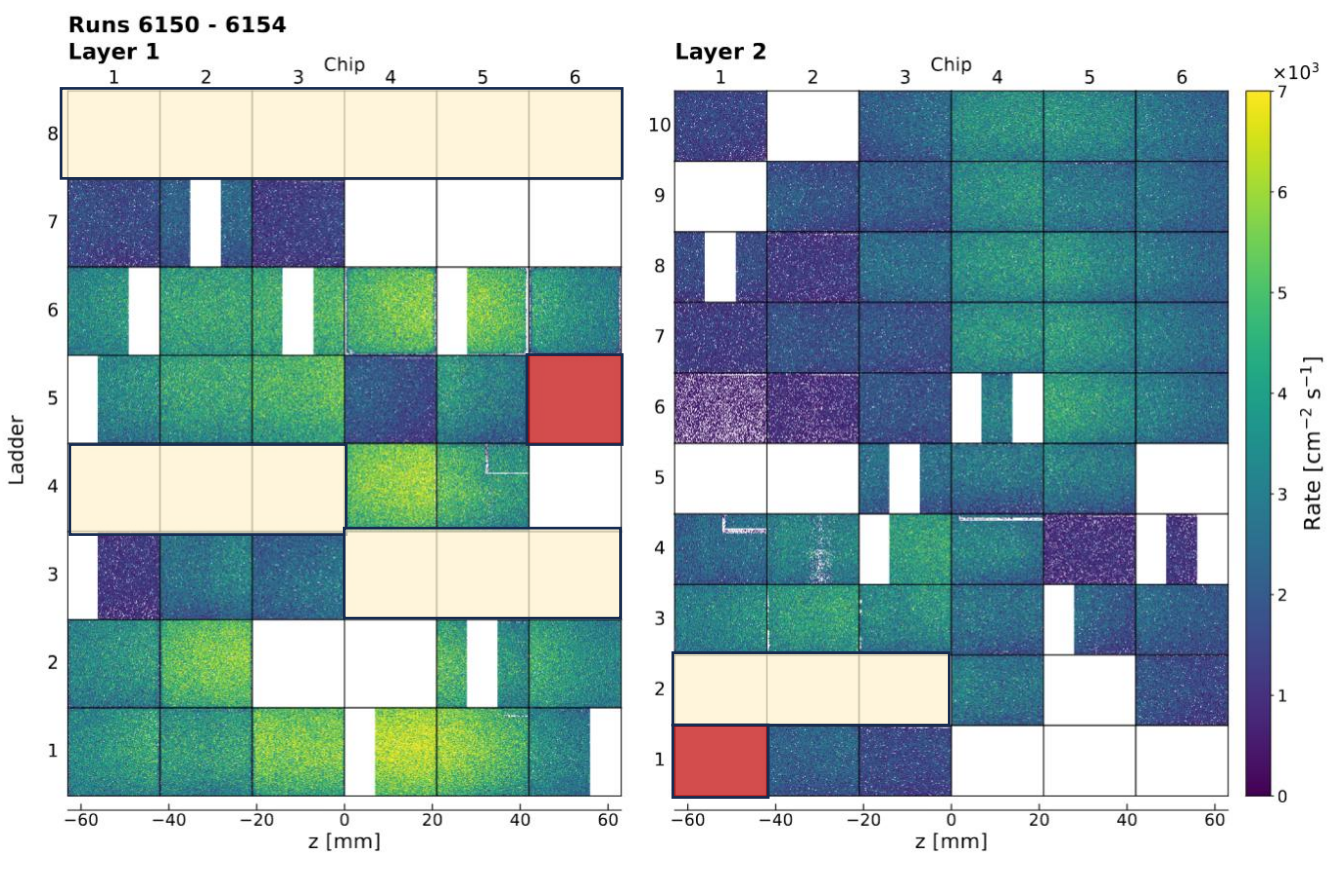

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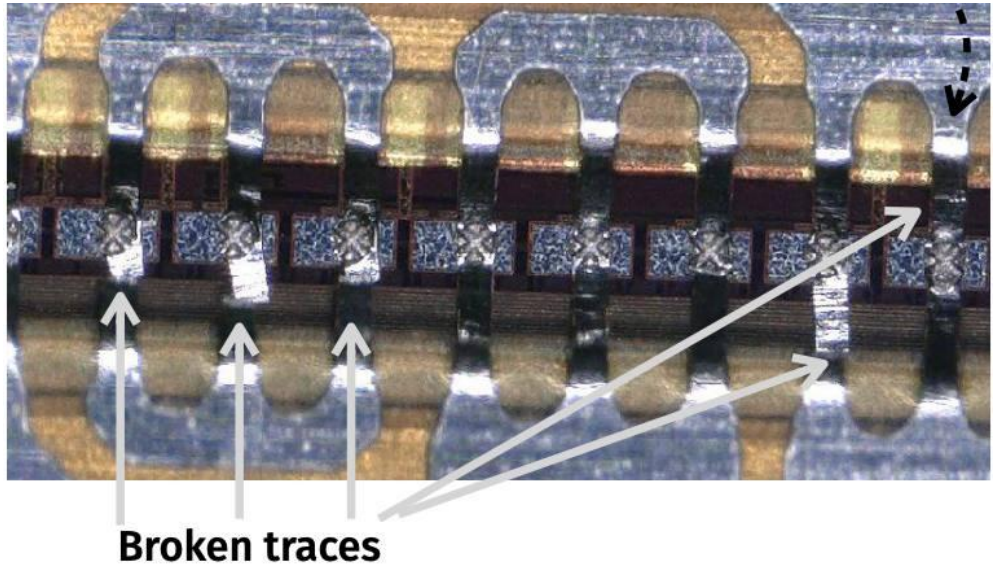
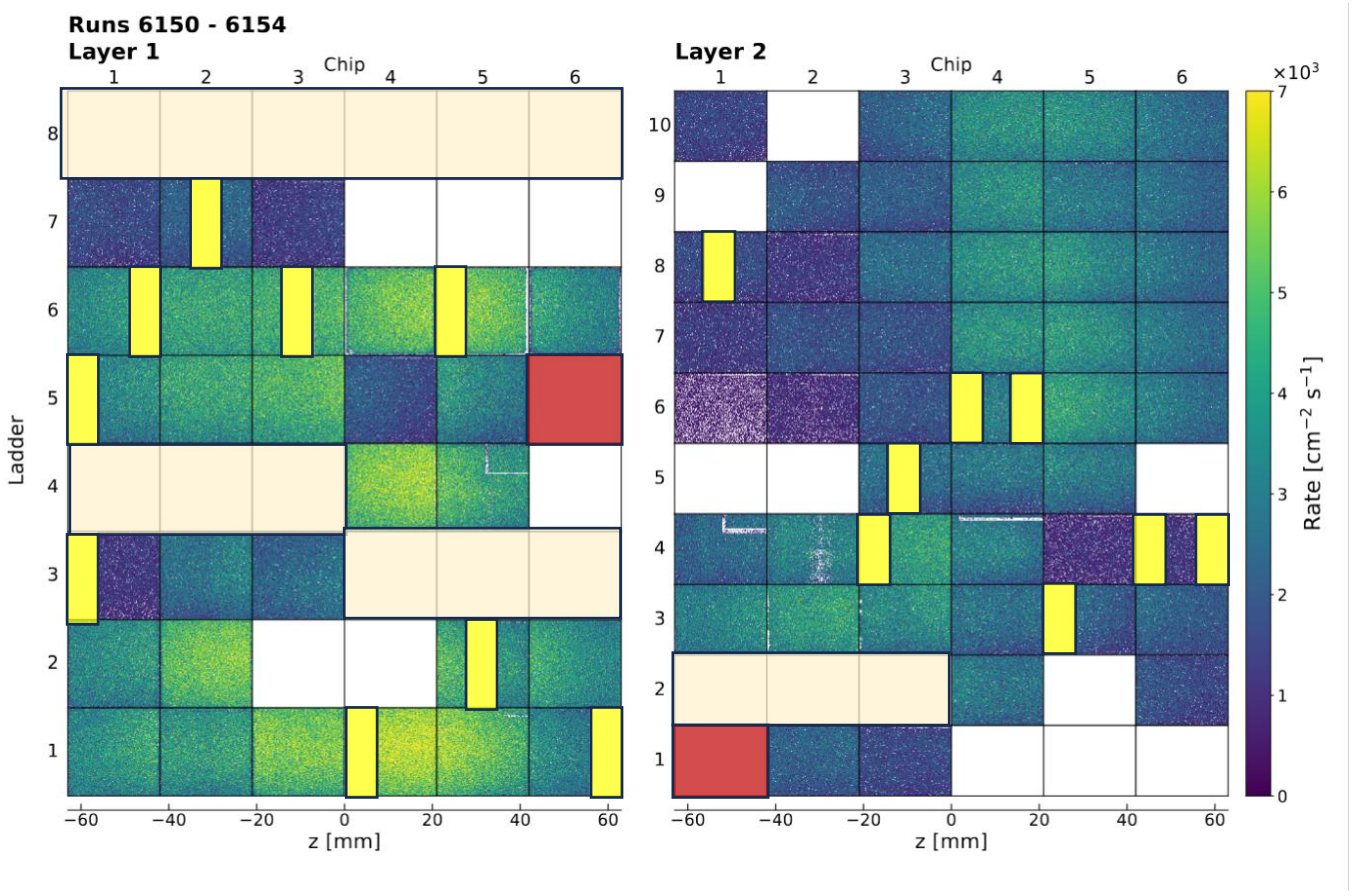
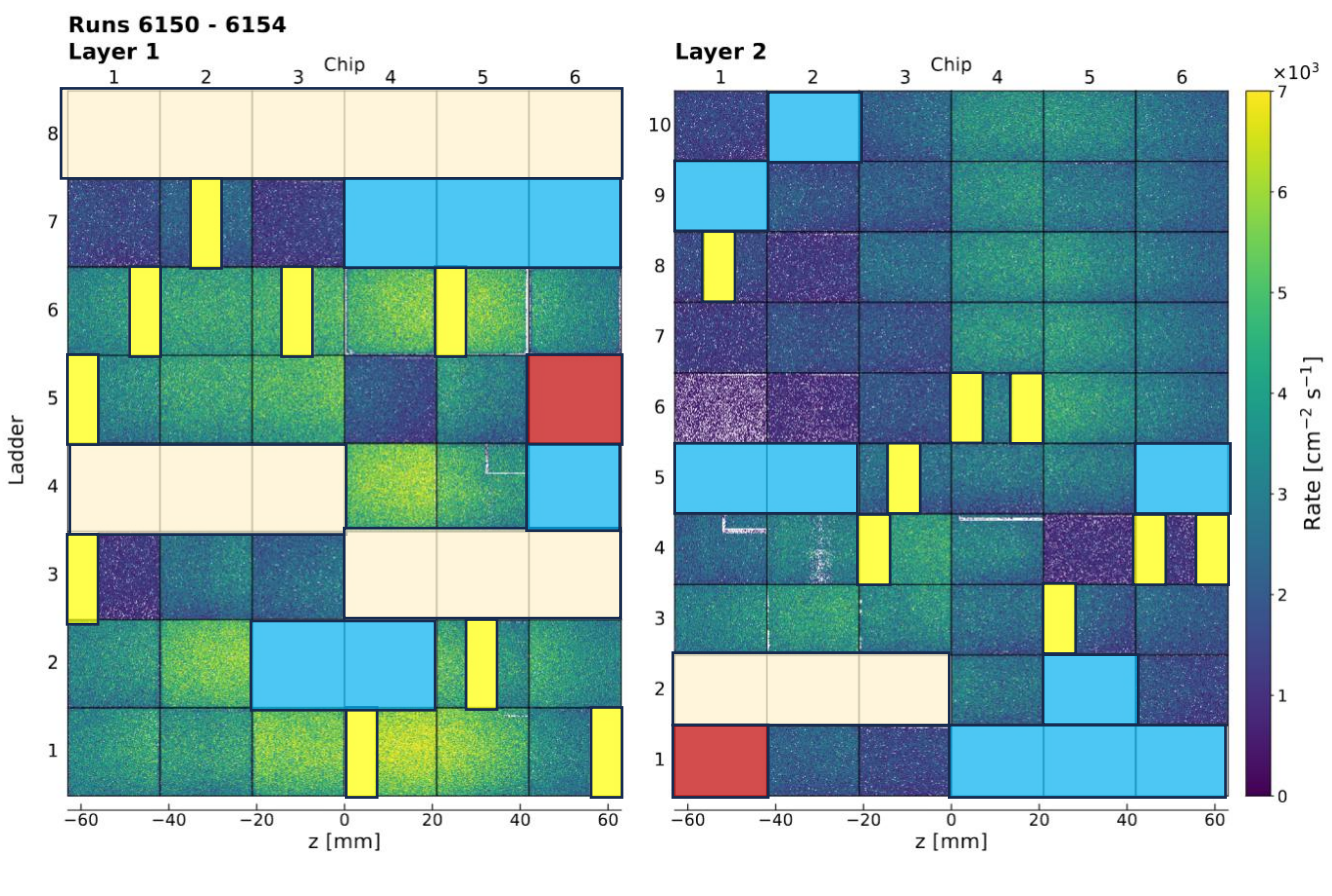




Successful Commissioning of the Mu3e Vertex Detector

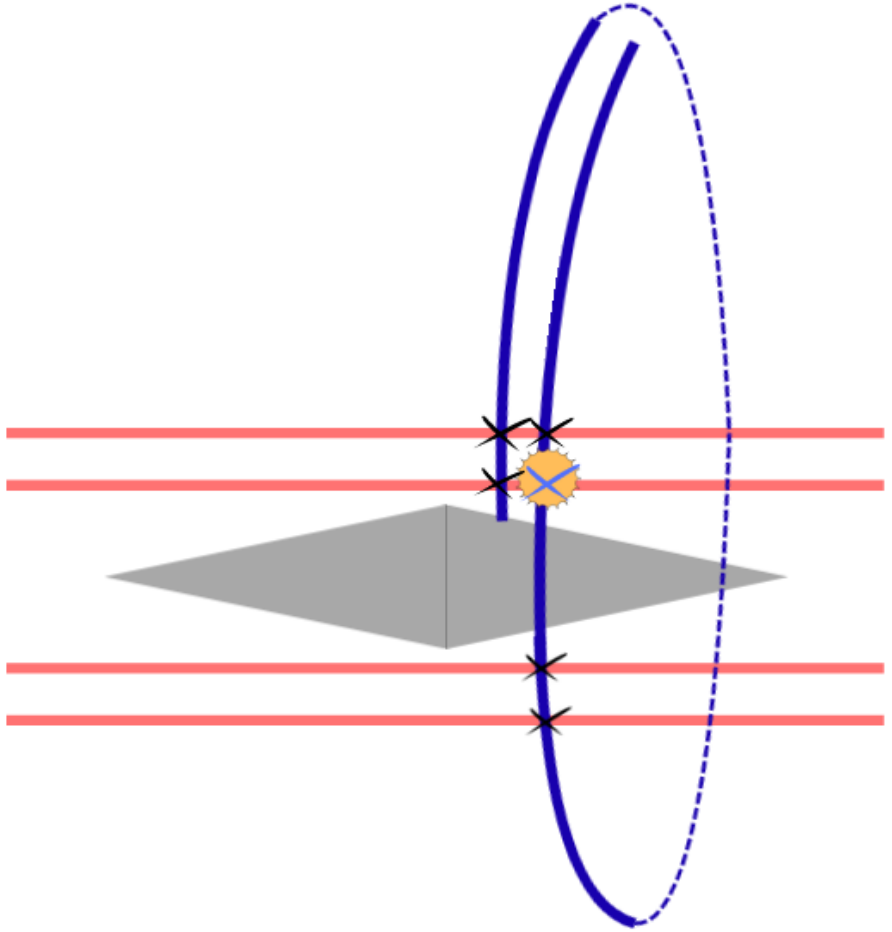
- Blue regions:
  - Damaged while running or unstable
  - Overpower (HV or LV)
  - Bad LV connections
  - During mounting
  - Hot pixel
- Still **ongoing** investigations



- Many **first** times and unknowns
  - Were the first to build such a detector
  - We **learned** a lot
- Improved ladder **tooling** and **flex designs** for the second version of the Mu3e Vertex Detector

Determination of the Pixel Efficiency

- Using “(n – 1)-hit method”
- Separate reconstruction of :
  - full tracks
  - pseudo tracks (track with a missing hit)
- Efficiency determination:
  - xxxxXx => efficient (full track reconstructed and found)
  - xxxx0x => not efficient (full track missing)
- Method validated using "realistic“ MC
- Very preliminary result:
  - Some sensors show >95% efficiency
  - No HV supplied to certain modules
    →Lower hit efficiency
- 8 hit tracks as compromise between purity and statistic



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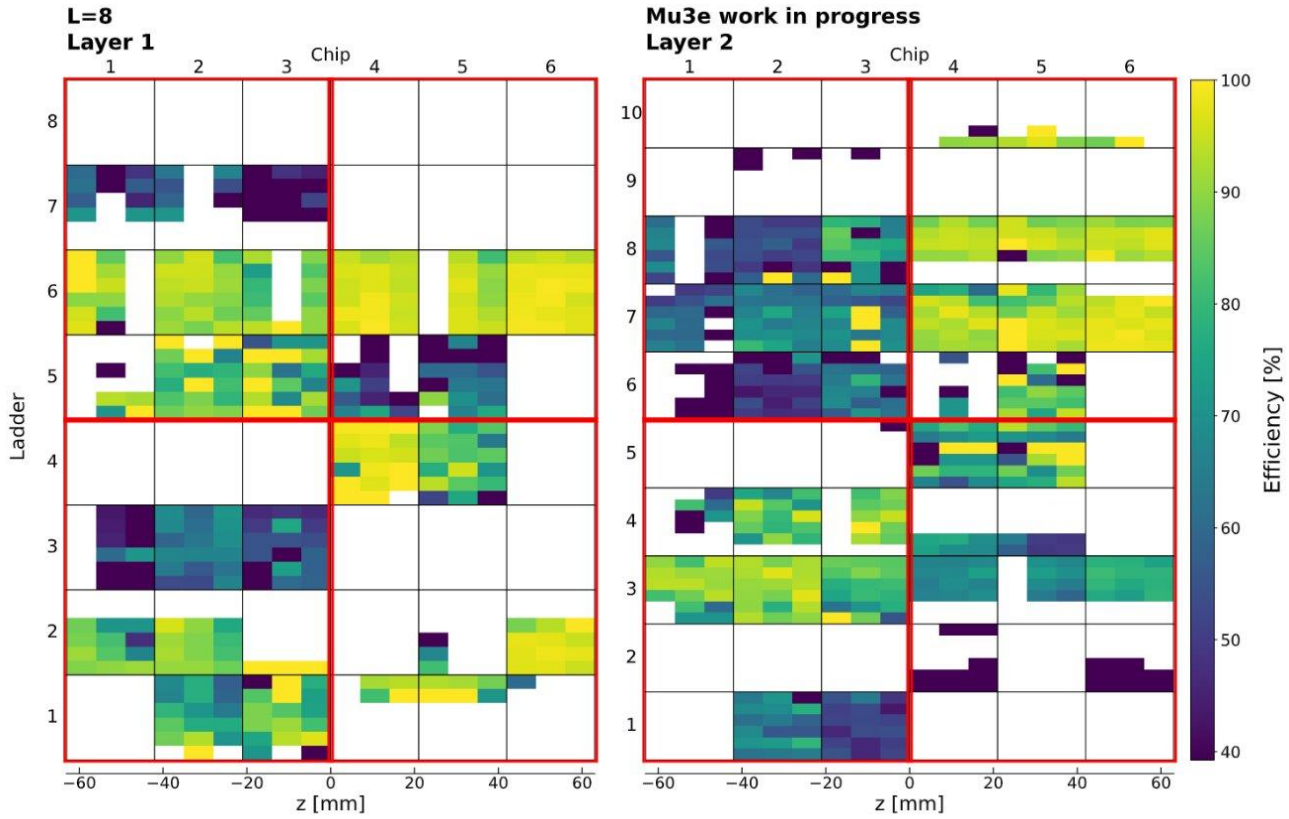
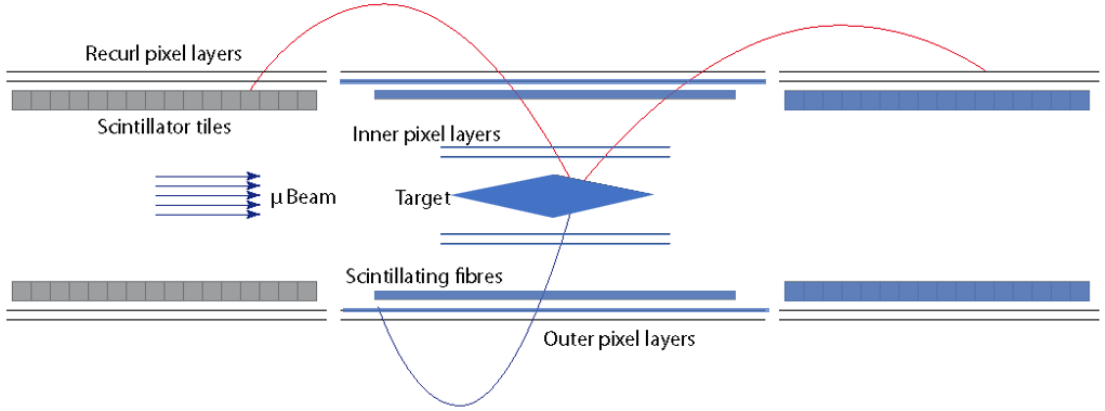


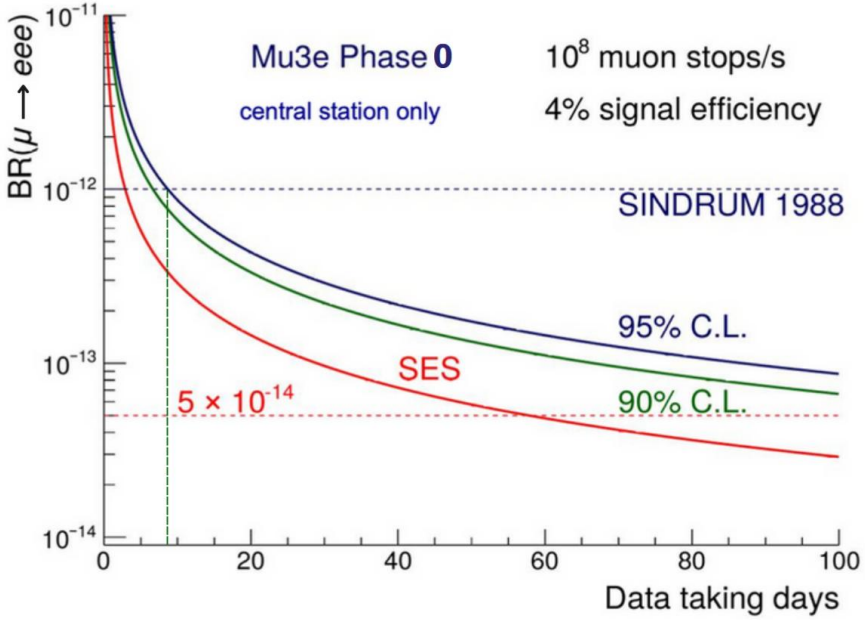
Towards physics

- Plan for 2026 (**8 weeks granted at PIE5**)
  - Construct Vertex V2 (70µm thin sensors)
  - Outer pixel production (Layer 3)
  - SciFi & Tile production
  - Outer pixel commissioning + filter farm commissioning
  - Study physics backgrounds

- **Physics data taking** in 2027
  - Full central station + Recurl station?
  - Surpass the SINDRUM limit
  - < O(1e-13)
- HIPA Shutdown in 2028
- Full phase I data taking from 2029 onwards



Detector Setup for 2026 Physics data taking campaign



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ZUKUNFT SEIT 1386

KIT
Karlsruher Institut für Technologie

University of BRISTOL

UNIVERSITY OF LIVERPOOL

UCL

Thank you

Literature / Links with further information

- MuPix: An HV–MAPS for the Mu3e Experiment
- TelePix2
- An ultra-light helium cooled pixel detector for the Mu3e experiment
- TelePix
- High-Voltage CMOS Active Pixel Sensor
- The Mu3e experiment: Toward the construction of an HV-MAPS vertex detector
- MuPix10: First Results from the Final Design
- The MuPix sensor for the Mu3e experiment