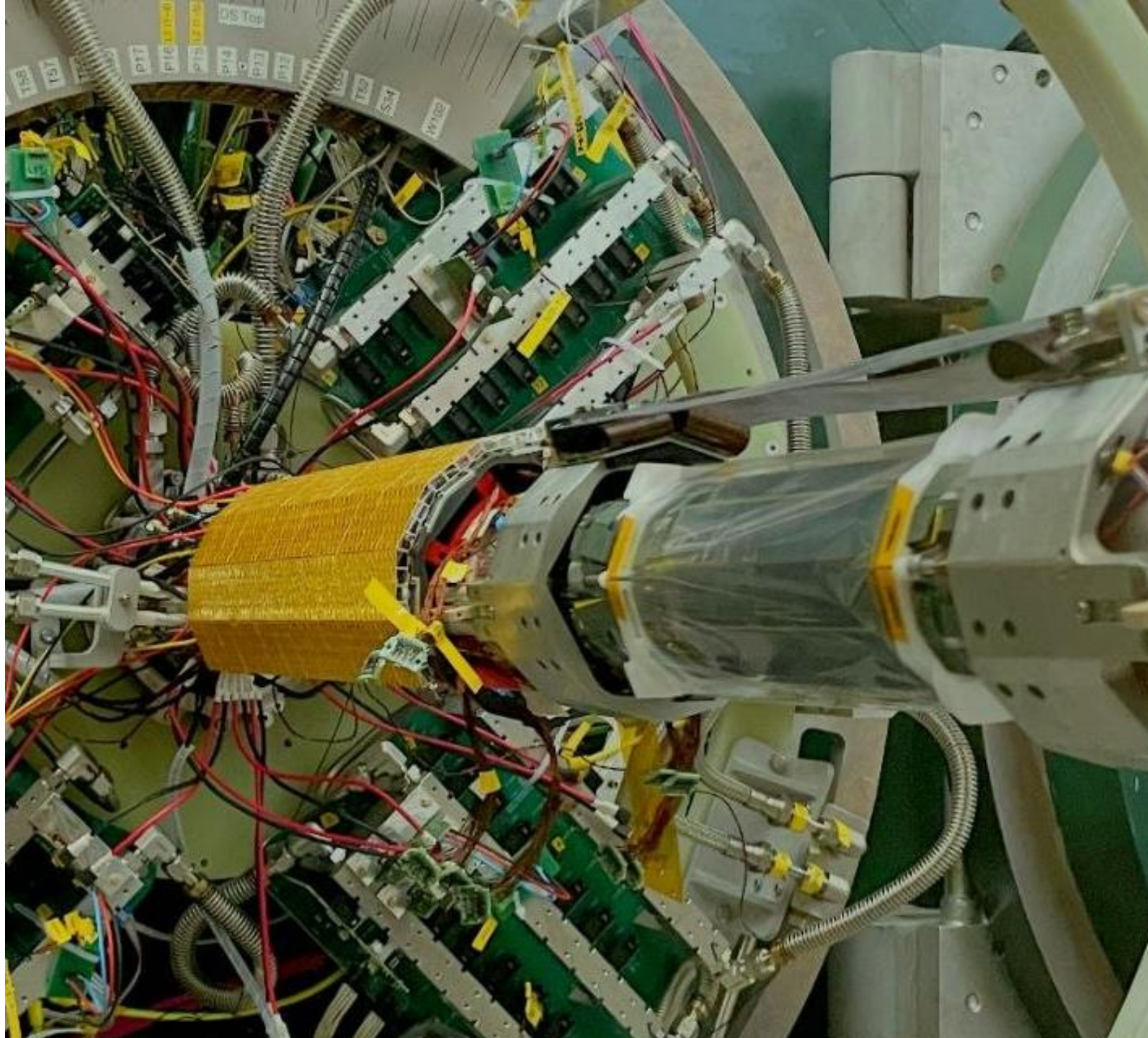
Universität Zürich[UZH]

# Construction and Commissioning of the Mu3e Vertex Detector

Thomas Christian Senger on behalf of the Mu3e collaboration

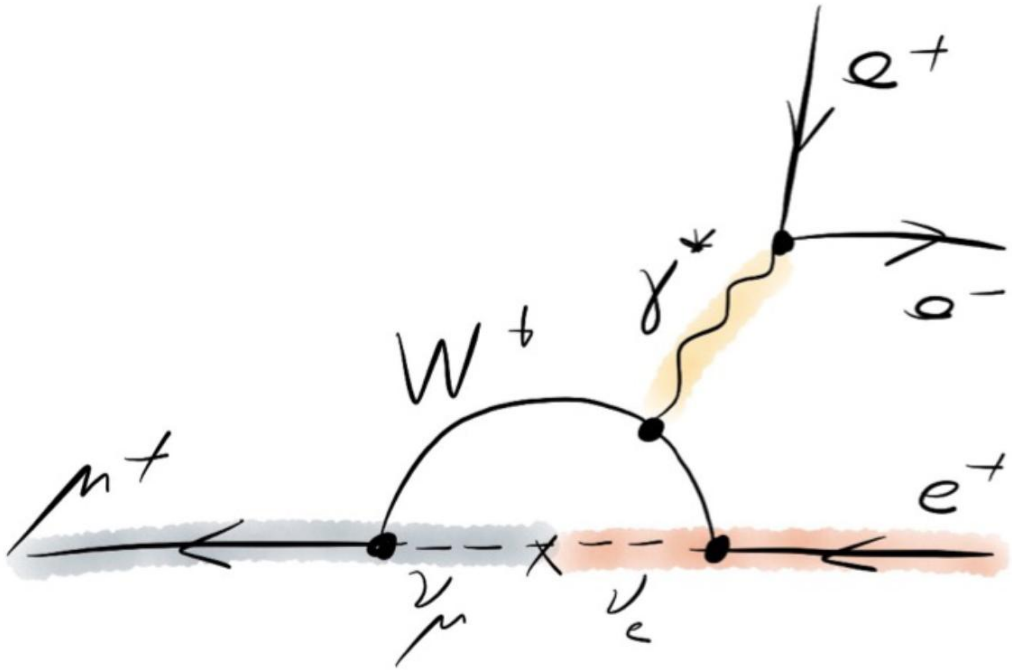


# Charge Lepton Flavor Violation

- 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

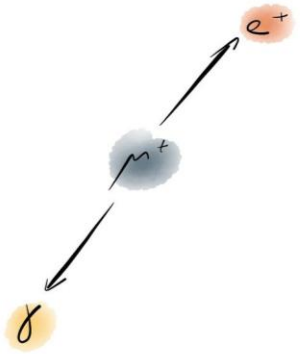
- Heavily suppressed in the SM + neutrino mixing
  - $\Gamma \propto \left(\frac{\Delta\ m_\nu^2}{m_W^2}\right)^2 \approx \mathcal{O}(10^{-54})$



# The golden muon channels

Muons are an excellent probe of cLFV

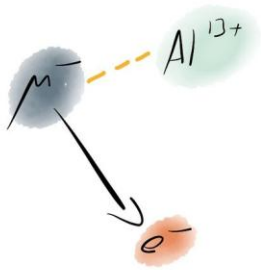
- **Sensitive**: New physics effects scale with the squared lepton mass $m_l^2$
- **Clean**: Relatively long lifetime and simple, well-understood decay channels, allowing for precise and background-free measurements




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

MEG /MEG II (PSI 2025)

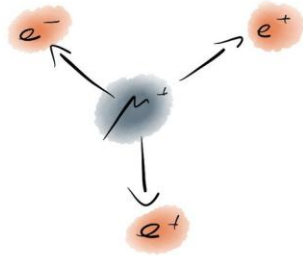
BR $(\mu^+ \rightarrow e^+ \gamma) < 1.5 \cdot 10^{-13}$




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

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

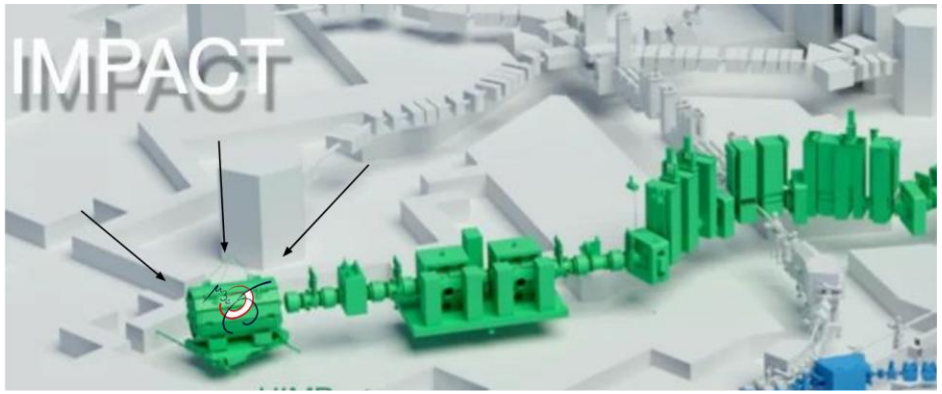
- **Most intense** muon beam with low momentum muons 28MeV
- Up to $\mathbf{10^8}$ Muons/s

Muon production at HIPA

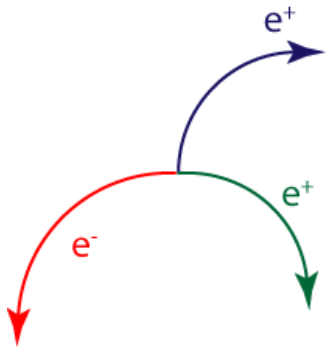
- 590 MeV proton accelerator
- Carbon target, produce pions, decay to surface muons

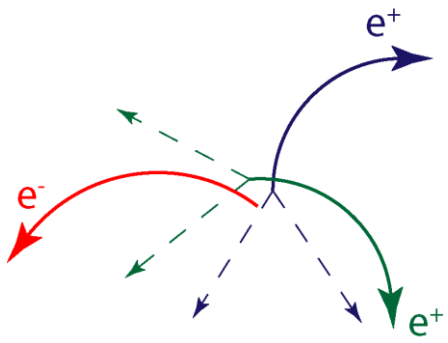
Goal: Improvement of the current limit by **4 orders** of magnitude in two phases

- **Phase 1** aims for a sensitivity of $< 2.0 \cdot 10^{-15}$ (Start in 2026)
  - 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

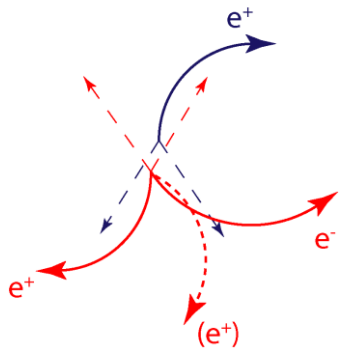


# Mu3e signal and backgrounds

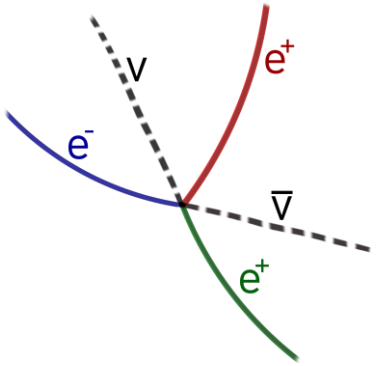



Two Michel decays + $e^-$




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

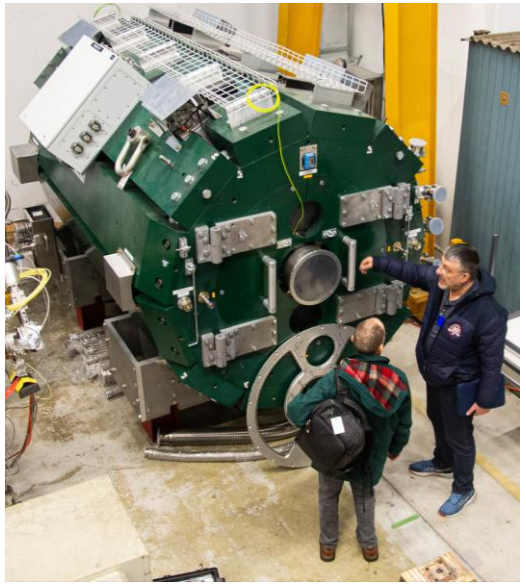
Need excellent momentum resolution

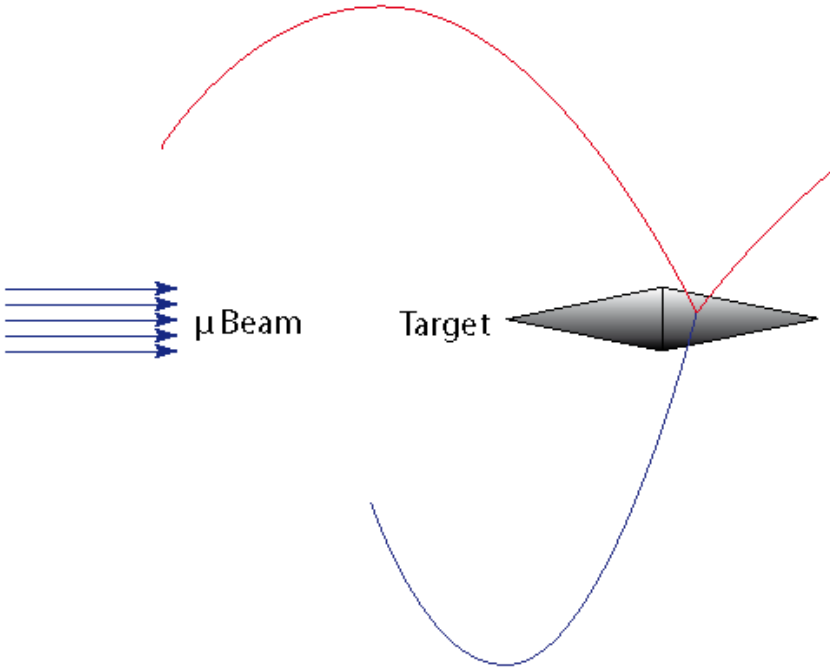
→ $\sigma_p < 1$ MeV/c

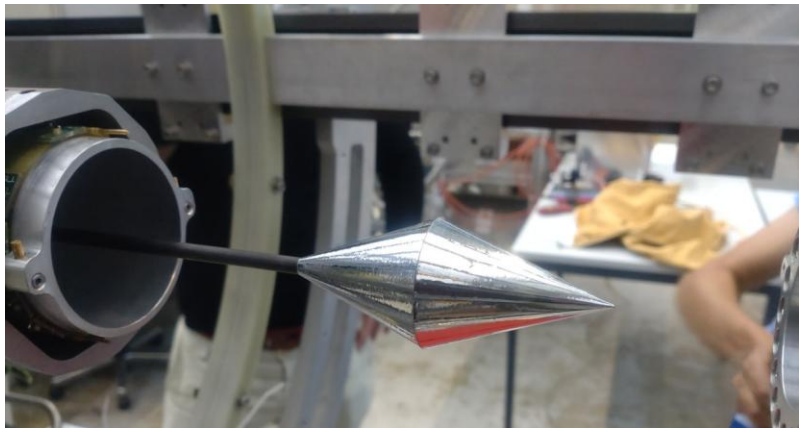
# The Mu3e experiment

## Mu3e magnet

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





**Target**

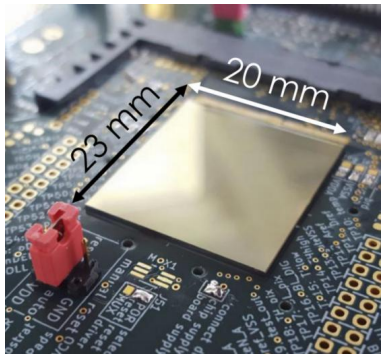
- Muons are stopped on **aluminised mylar** double hollow cone
- Maximum stopping fraction 95.5%
- Minimal material budget (~0.15%)

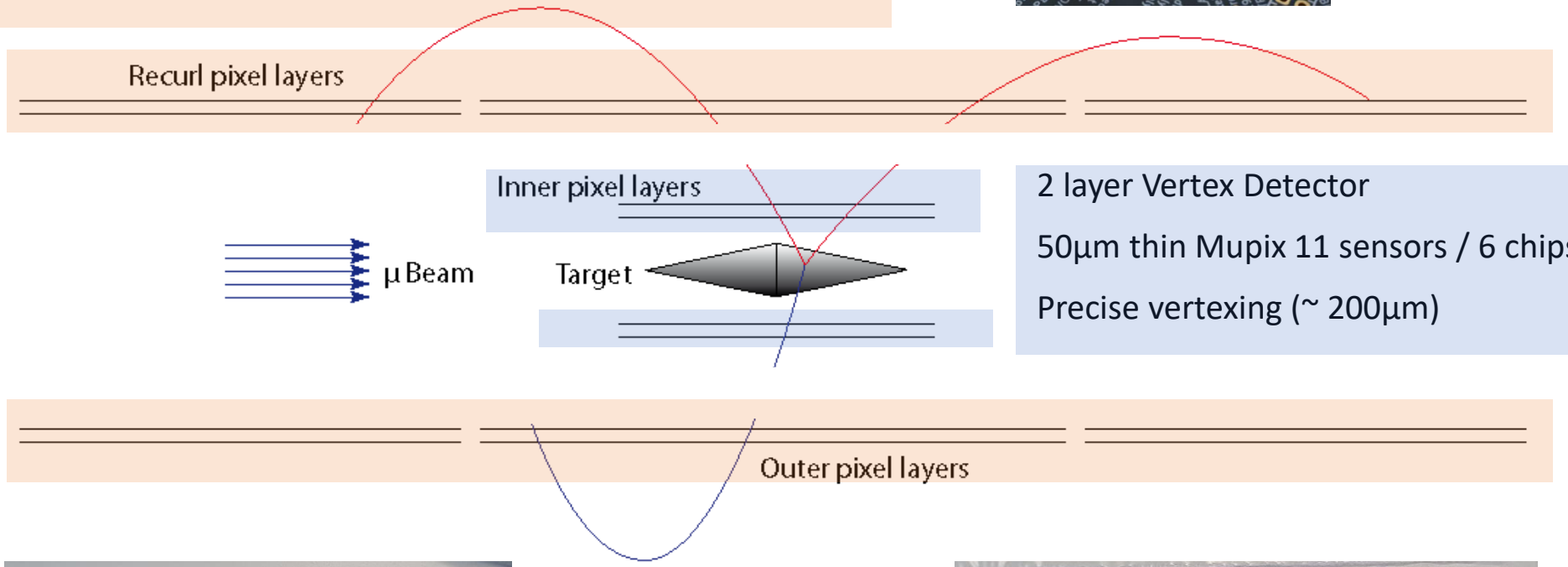
2 Outer Pixel Layers

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

For good momentum resolution and high p acceptance

→ reconstruction of recurling tracks

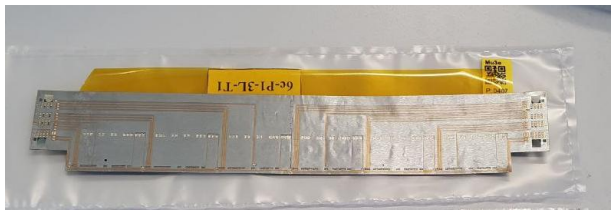



2 layer Vertex Detector

50µm thin Mupix 11 sensors / 6 chips per ladder

Precise vertexing (~ 200µm)



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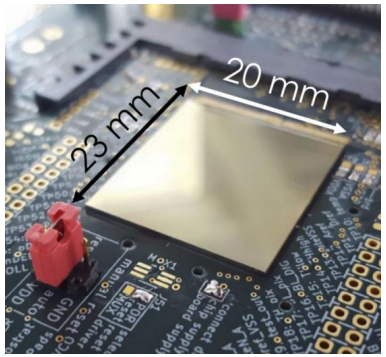
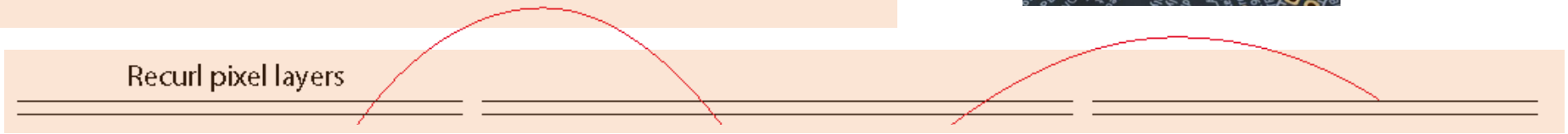
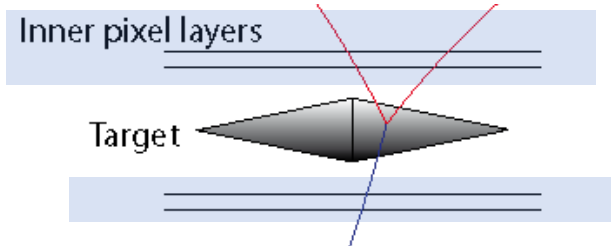



Cooled by low-density gaseous helium

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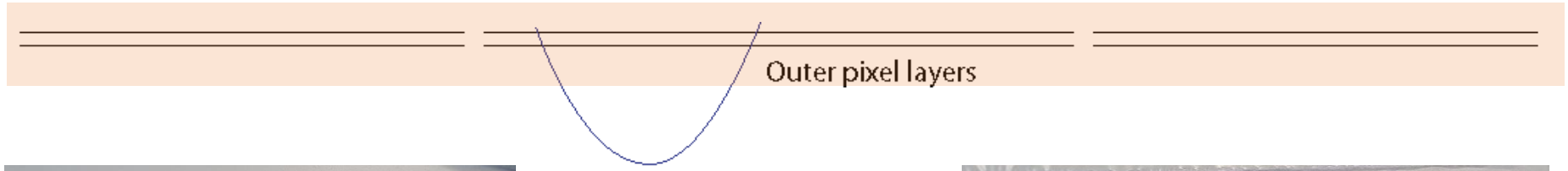
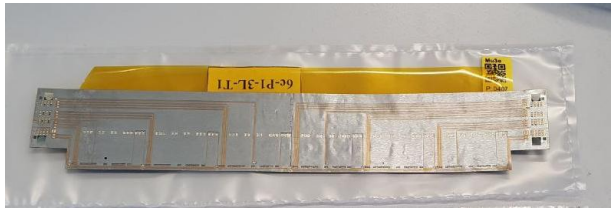
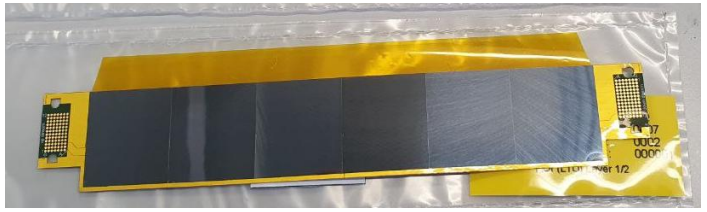
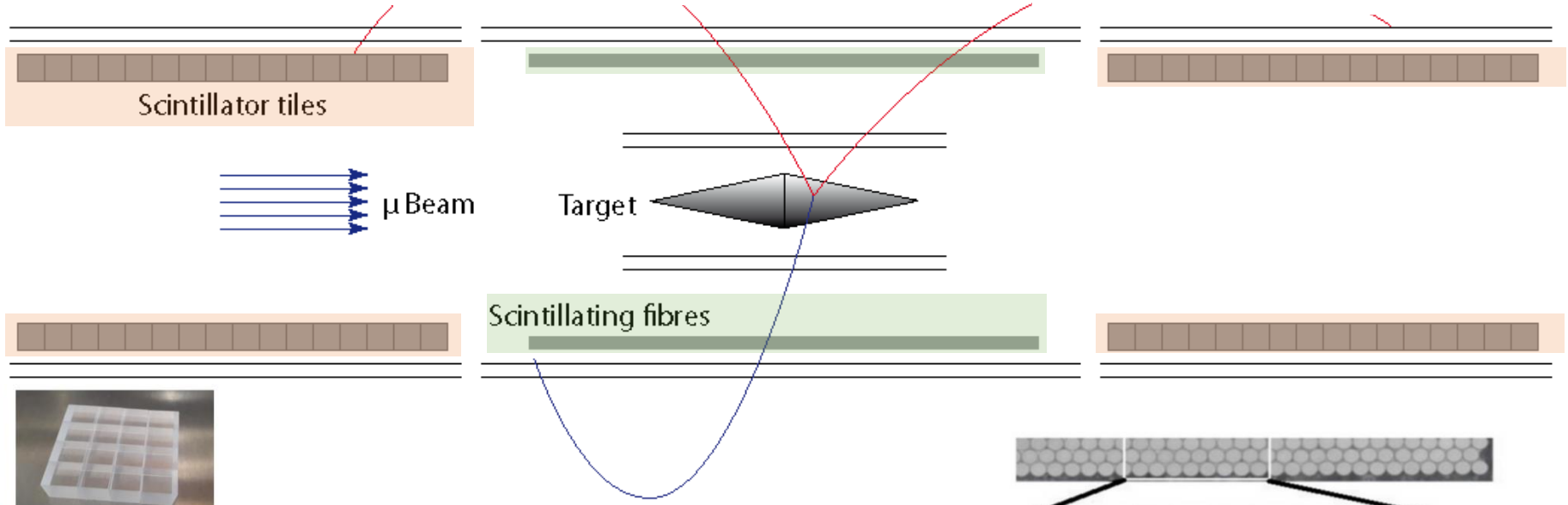


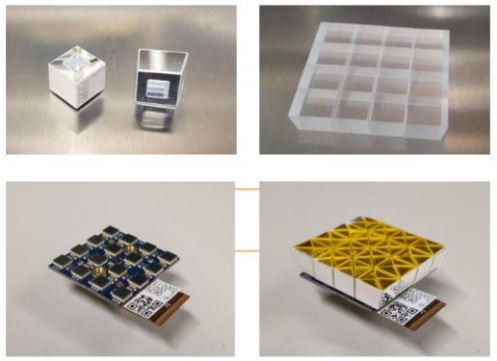



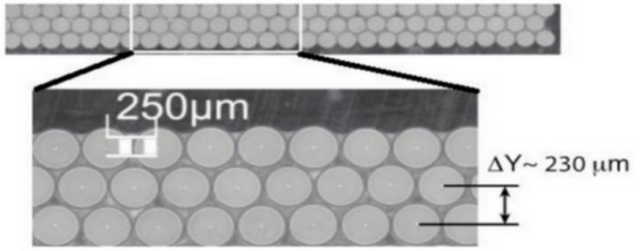


# SciFi & SciTile Detector

See Yifengs Talk

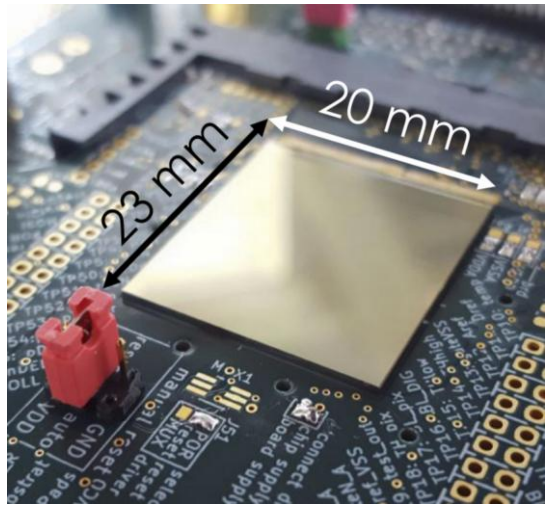


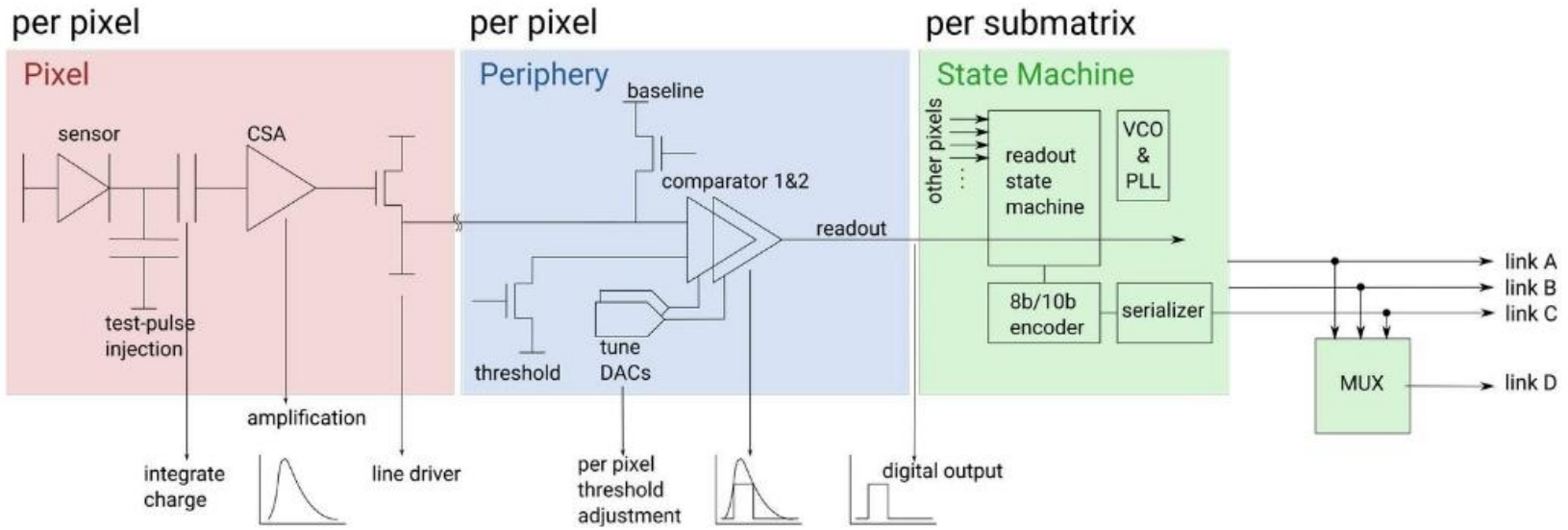





# Mupix 11

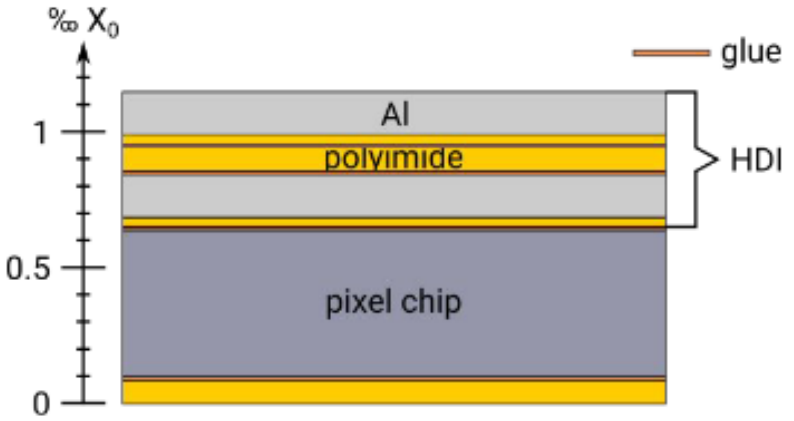
- High-Voltage Monolithic Active Pixel Sensor (HV-MAPS)
- Detection and Readout combined in one chip
- Fully digital 1.25Gbit/s LVDS output
- Pixel size 80 x 80 $\mu m^2$
- 99% efficiency with less than 20ns time resolution
- 2 comparator design
- Tuning/trimming and masking available
- Chip sub-divided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

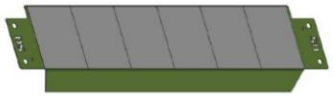


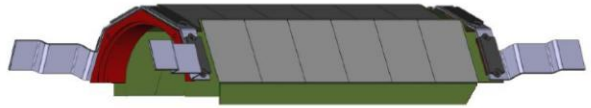
# Mu3e Vertex Detector

- 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

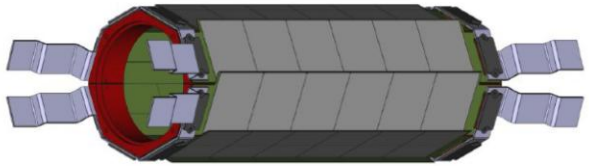


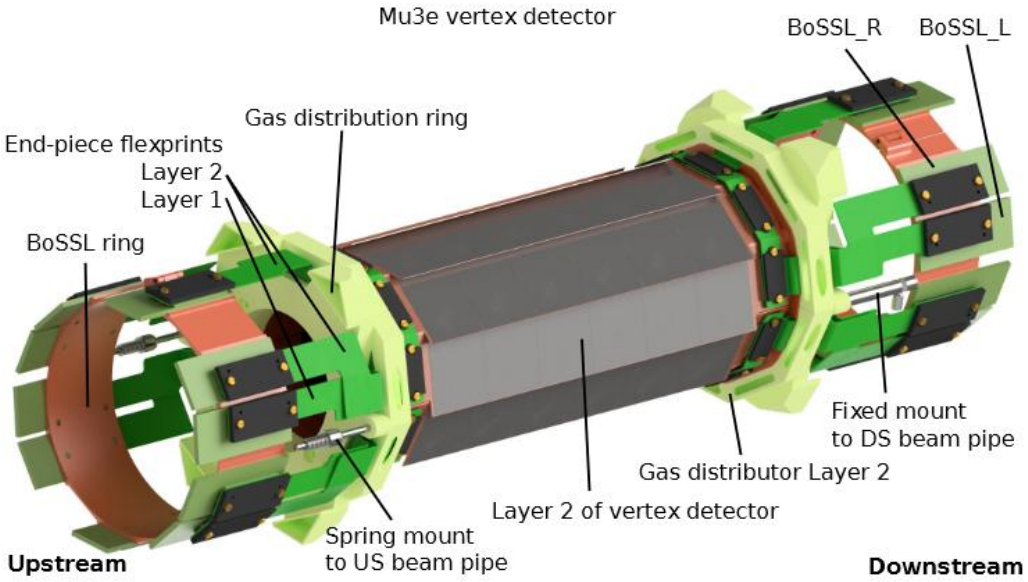
**Ladder**



**Module**

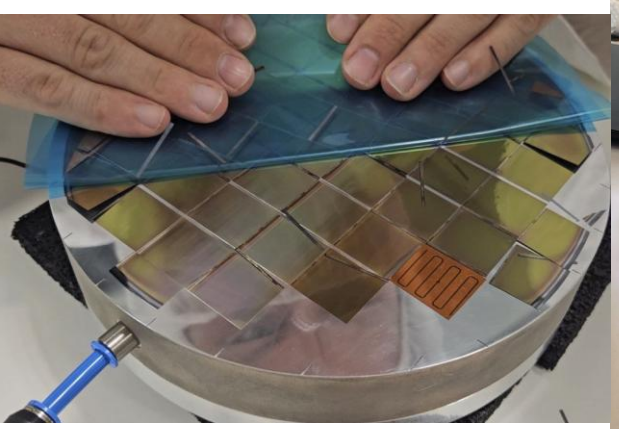


**Layer**

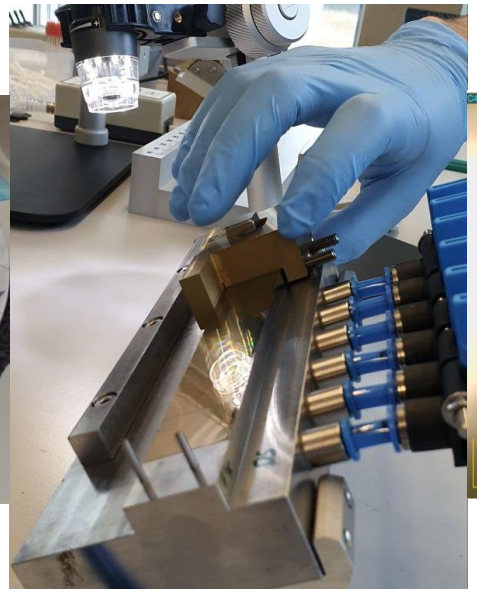


# Challenges in the Construction and the Operation of the Mu3e Vertex Detector

# Construction and Handling

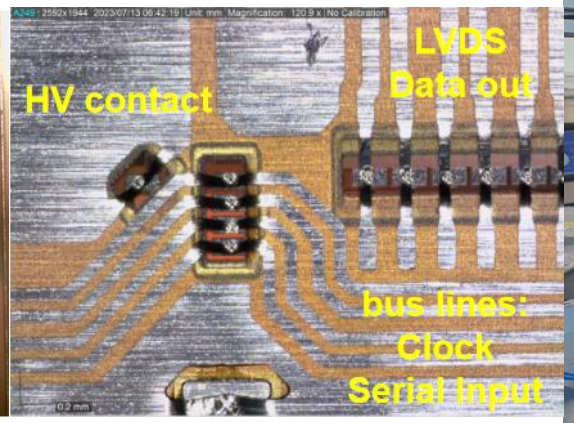


Wafer Peeling

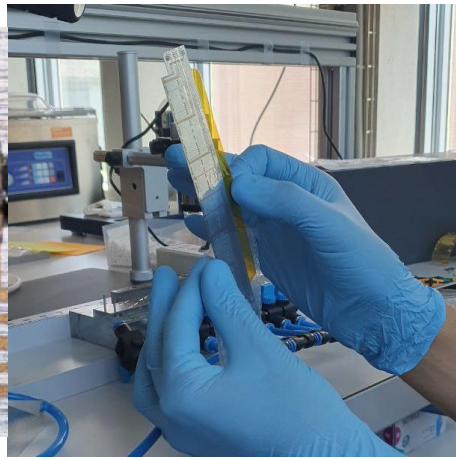


Manual Chip Placement

Glue Distribution



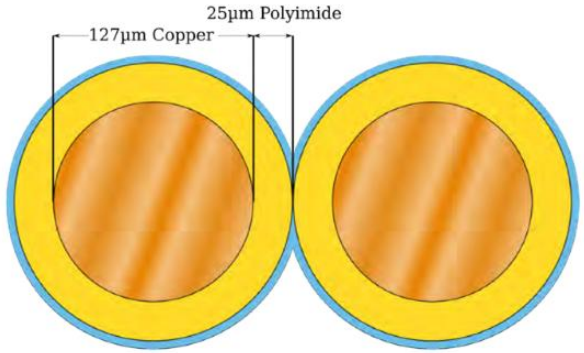

spTa-Bonding

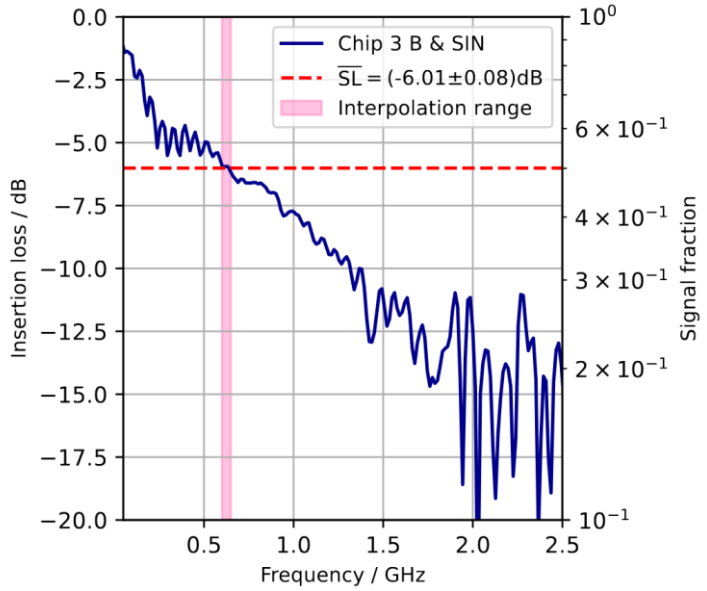


Handling

# 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 (factor 10 lower)
- 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 **preemphasis** (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
- Have ladder qualification criteria to check each ladder for error free data transmission



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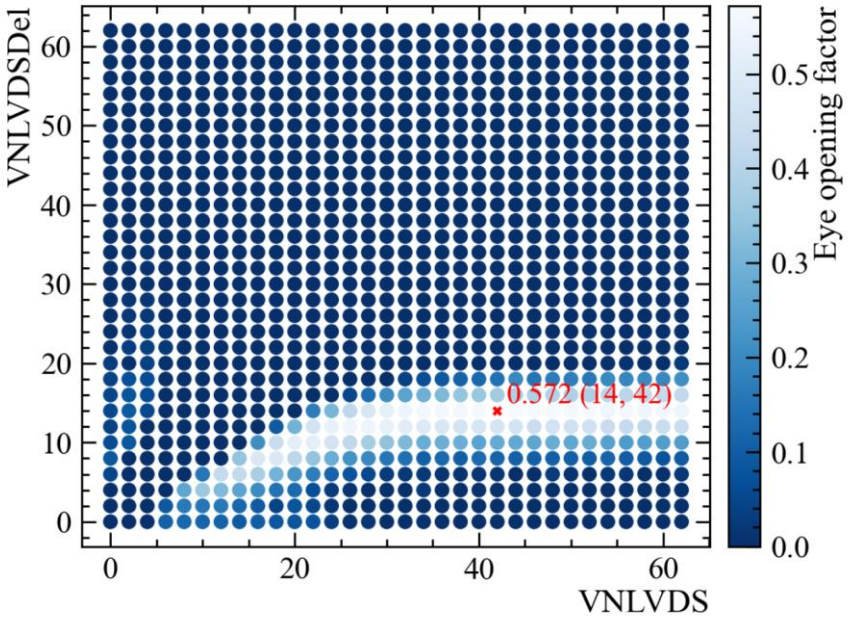


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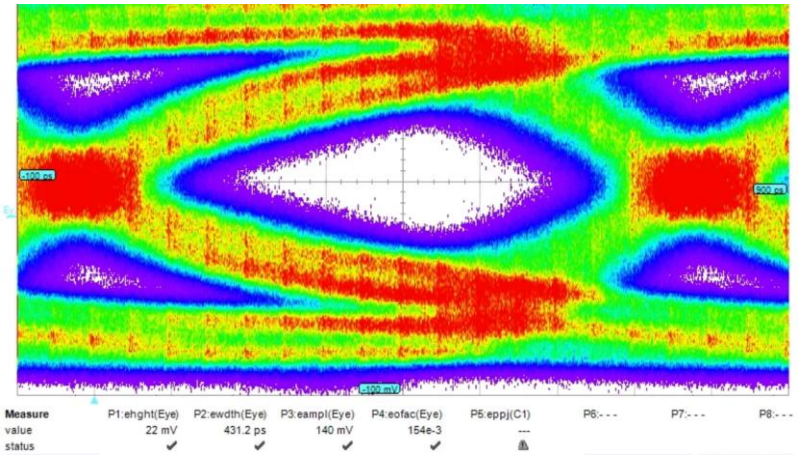
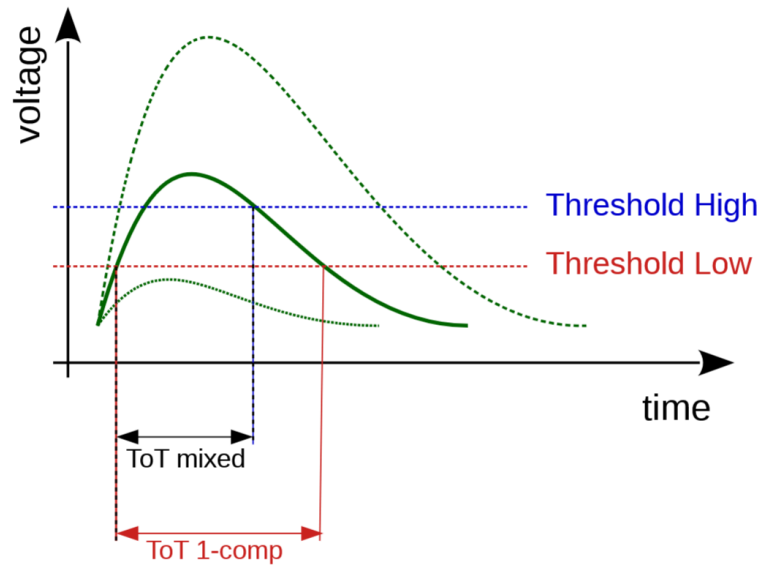
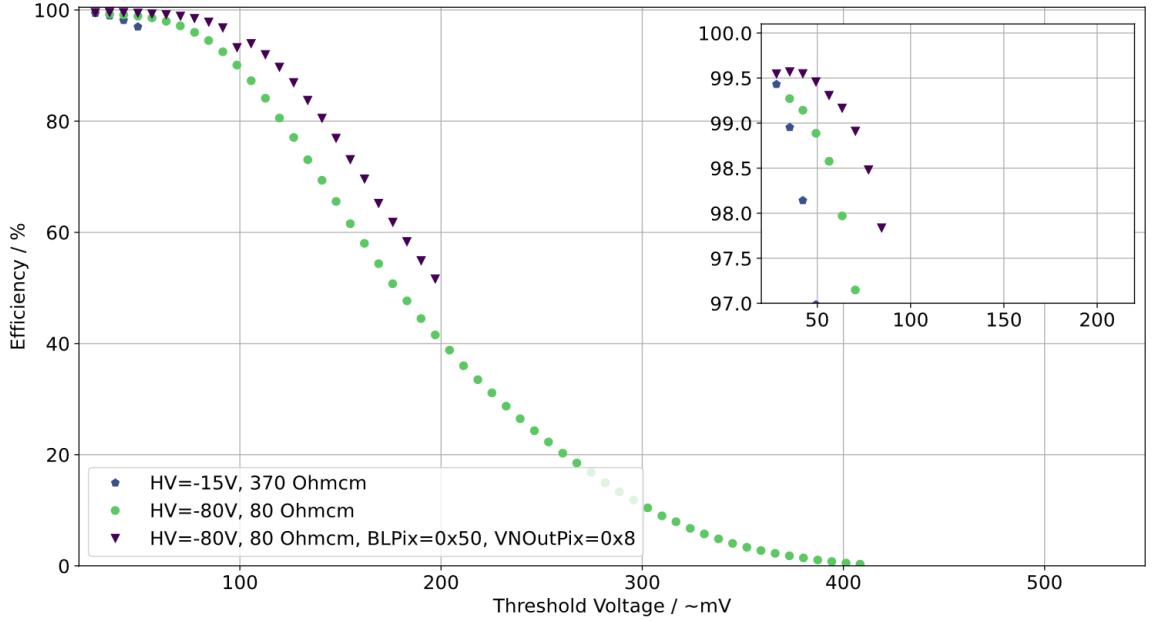


# Efficient pixel operation

- 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



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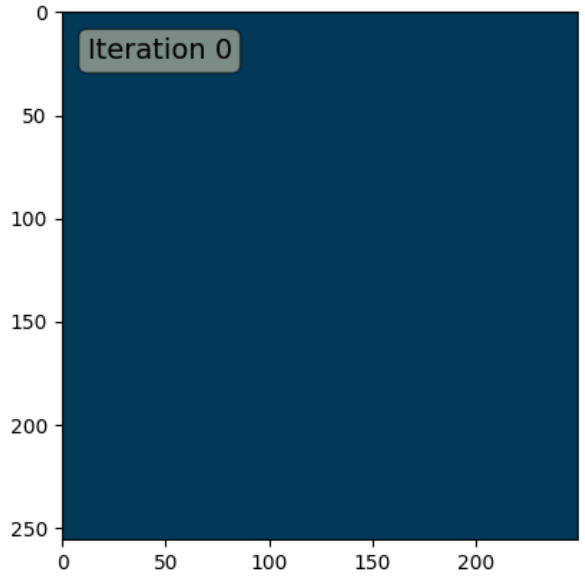
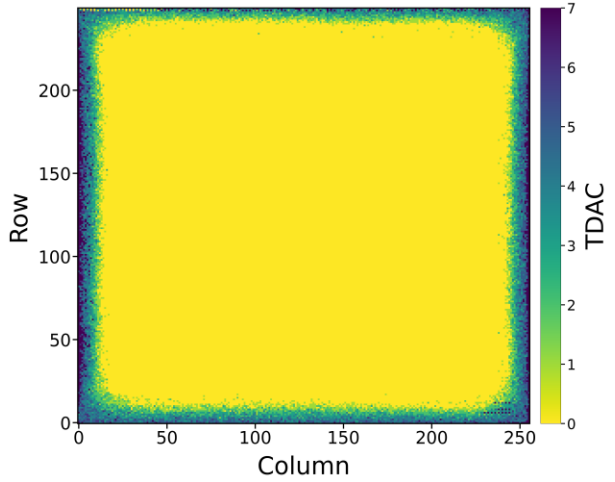
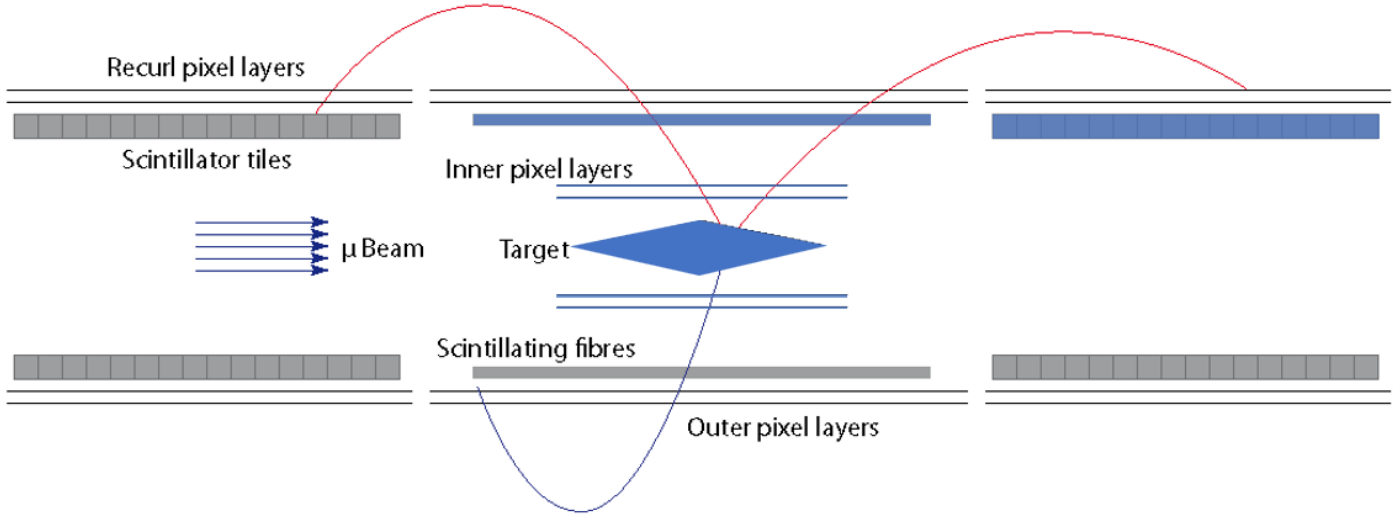


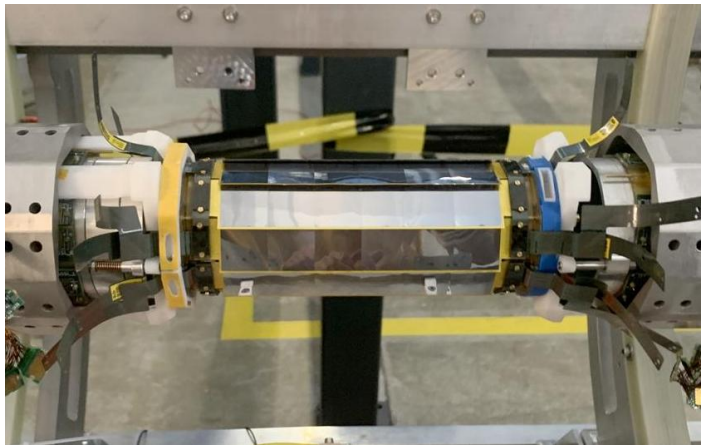



# Commissioning Run 2025

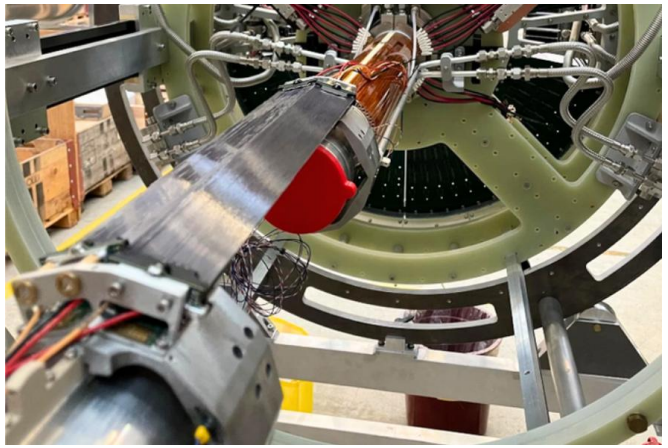
Three weeks of commissioning run campaign in 2025 at PSI in PiE5

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

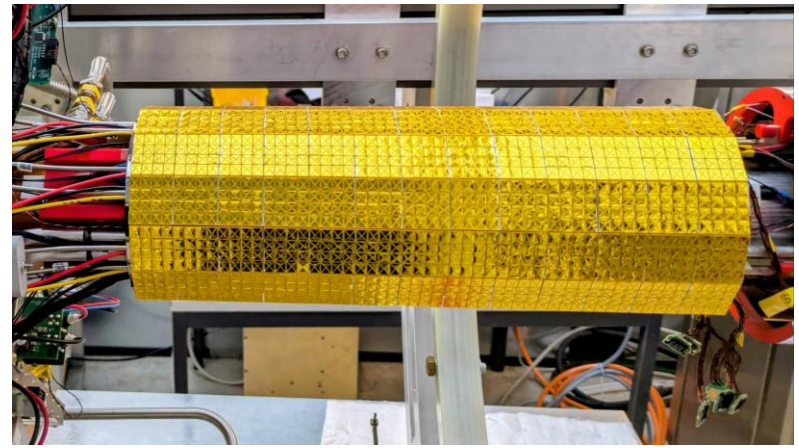


Full Vertex Detector
(108 sensors)



2/12 SciFi ribbons



3/14 SciTile modules (DS)

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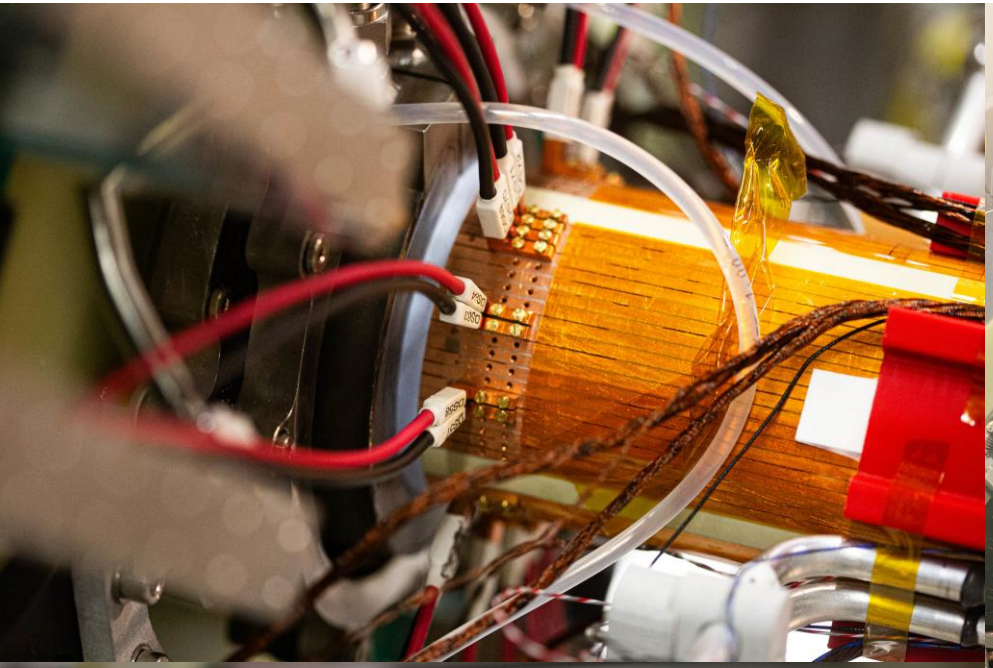
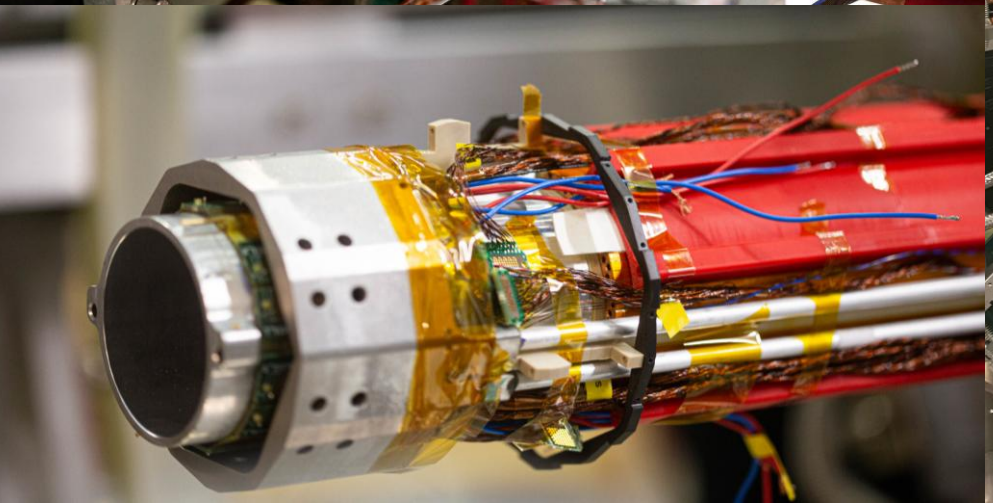
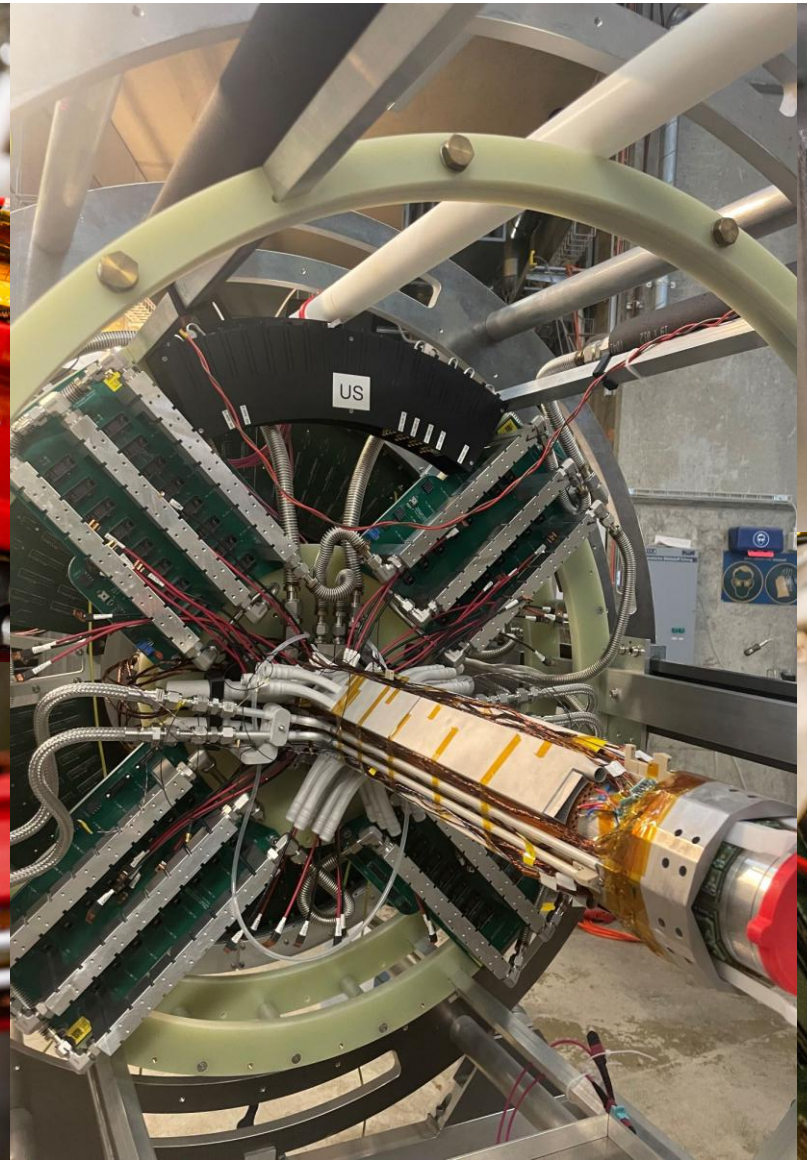
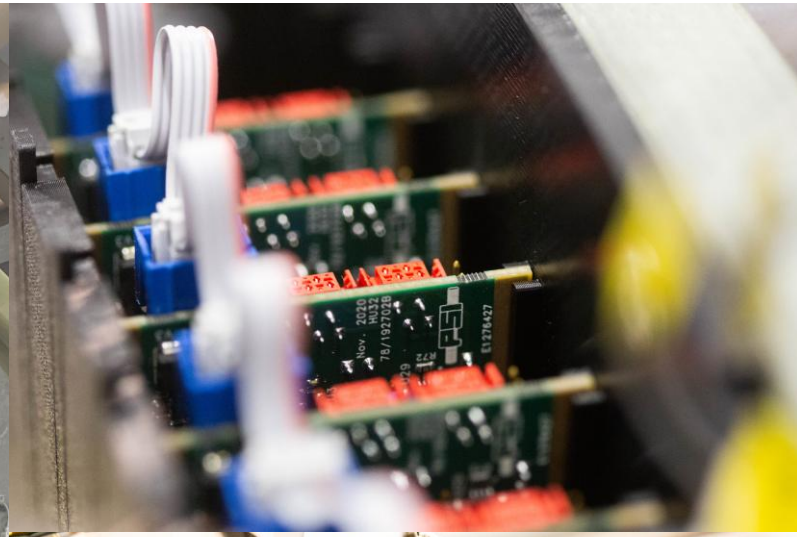
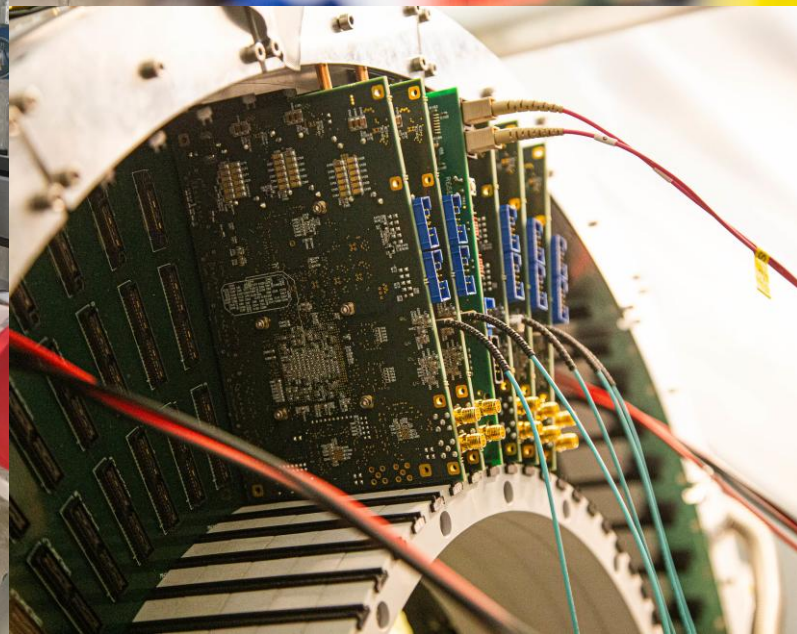
# Service Installation



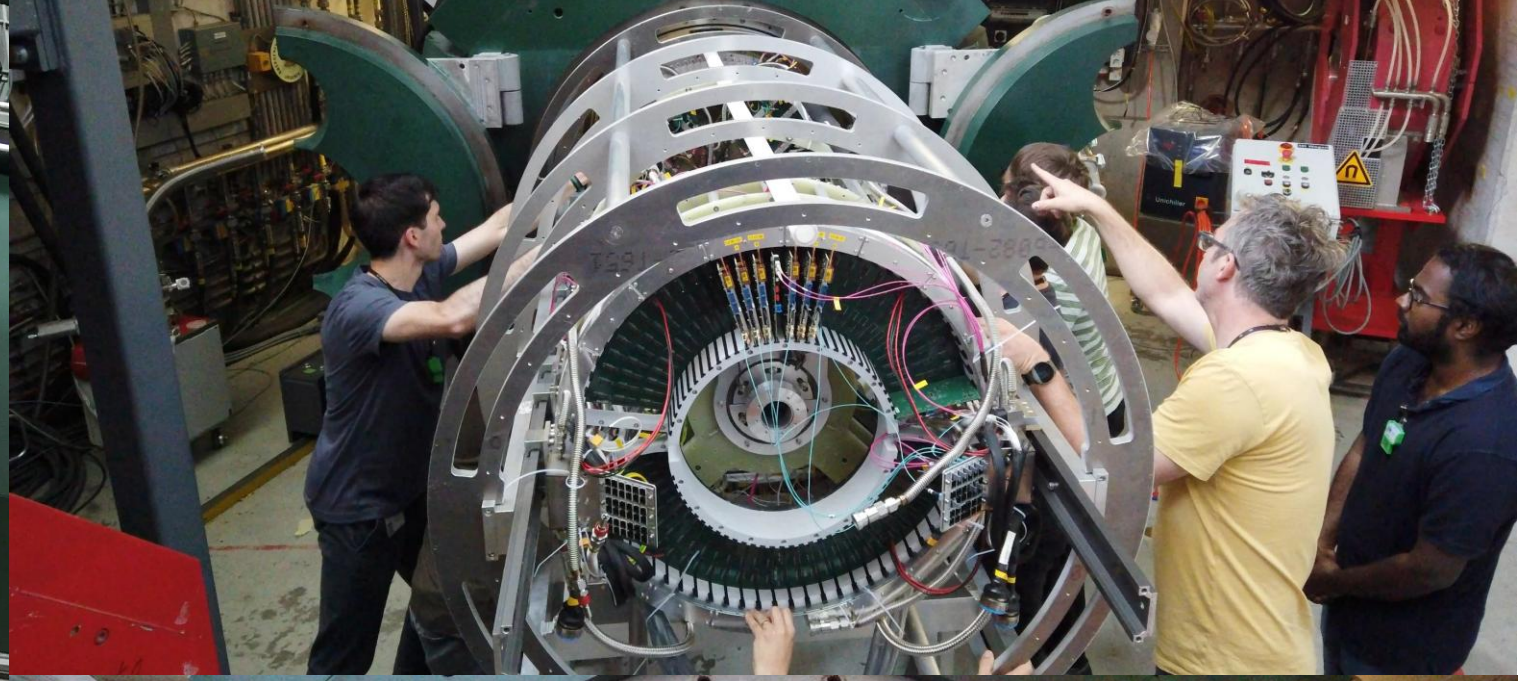


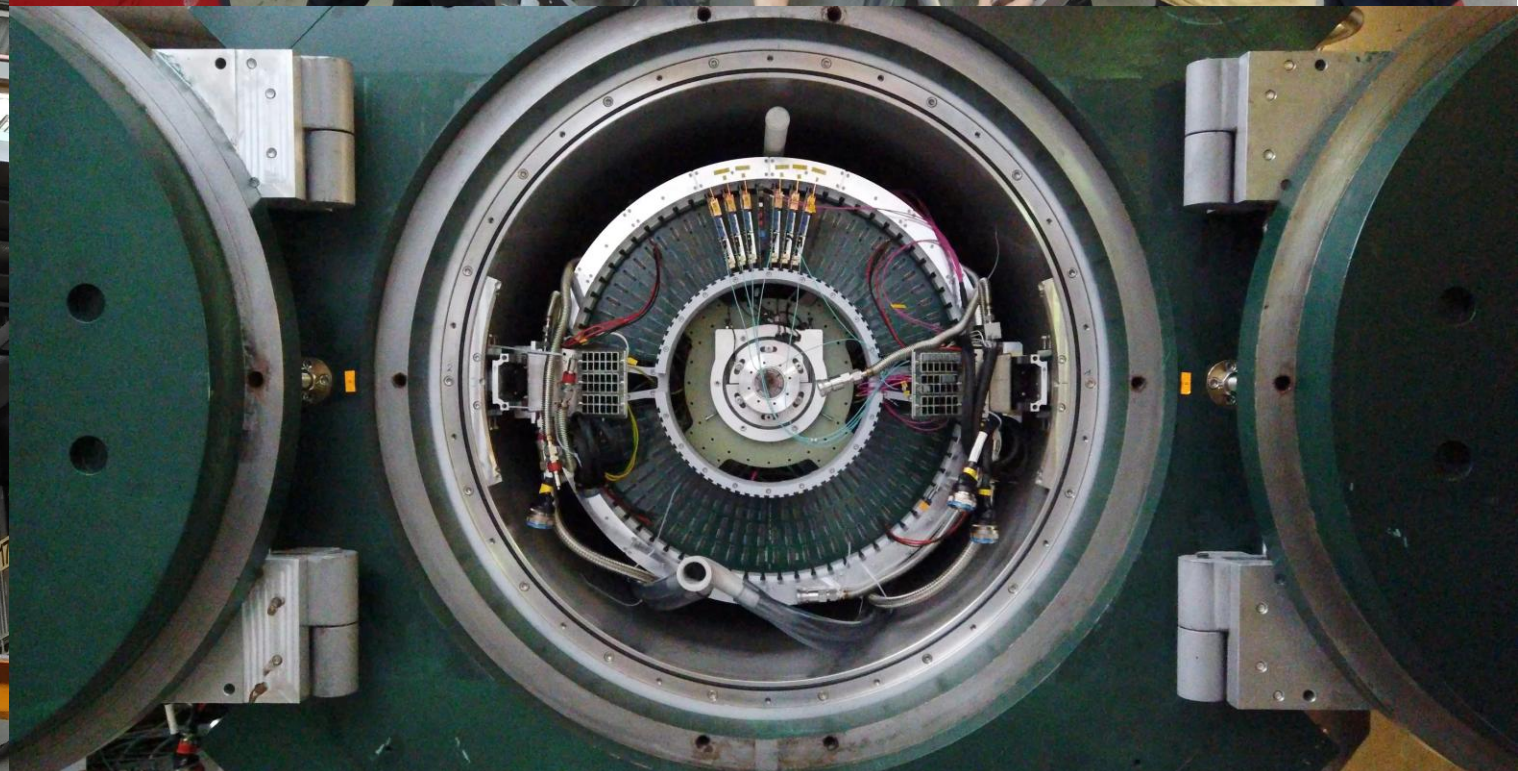




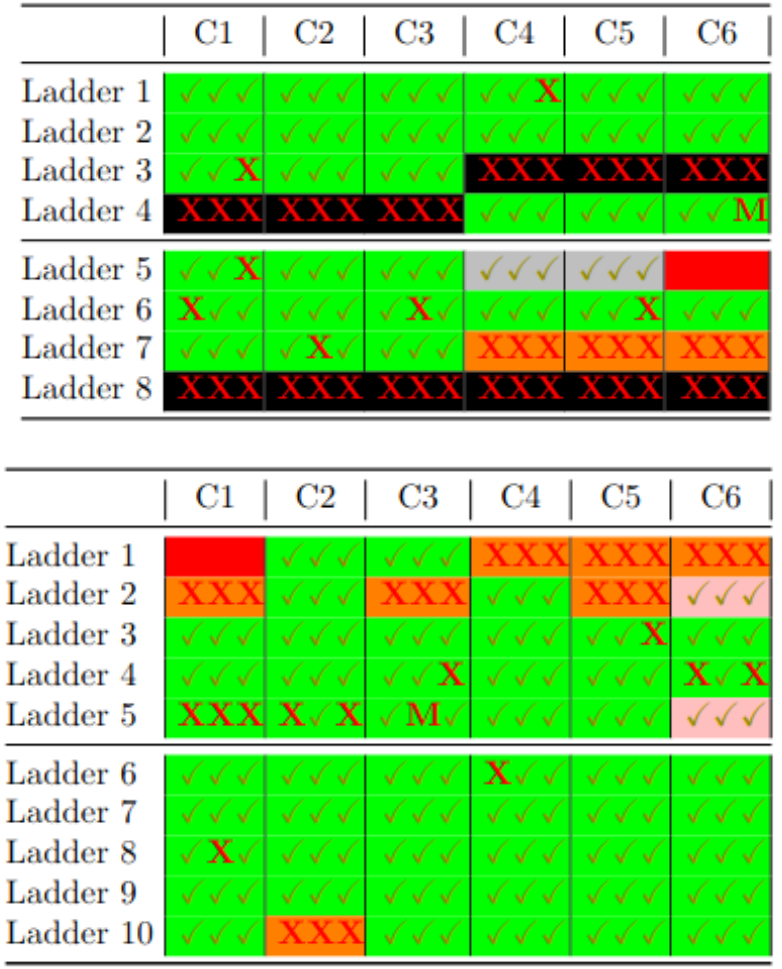
# The flight of Mu3e





# 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
  - 4 had a mechanical damages before installation
  - Lost ladders during installation
  - A few sensors were lost during operation
- 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



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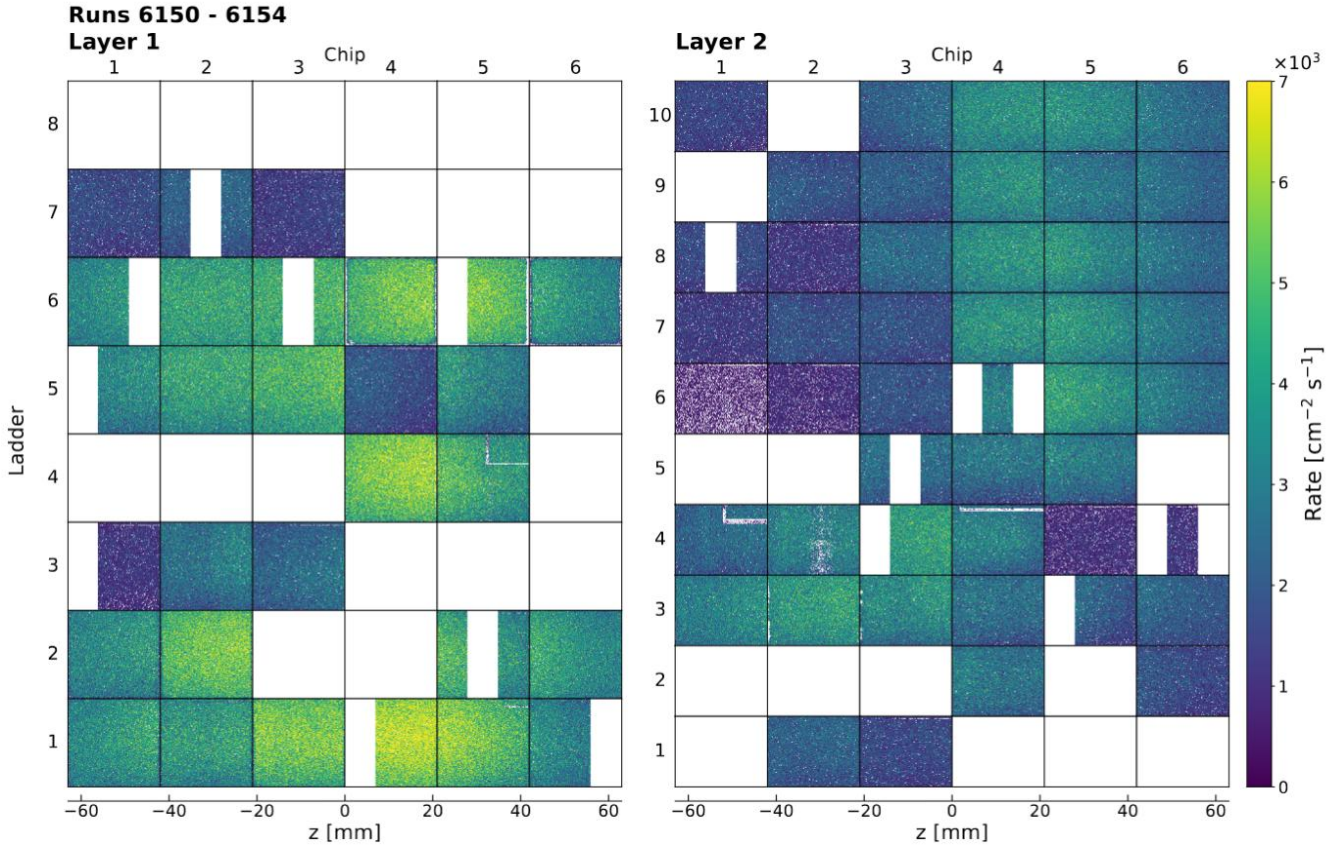
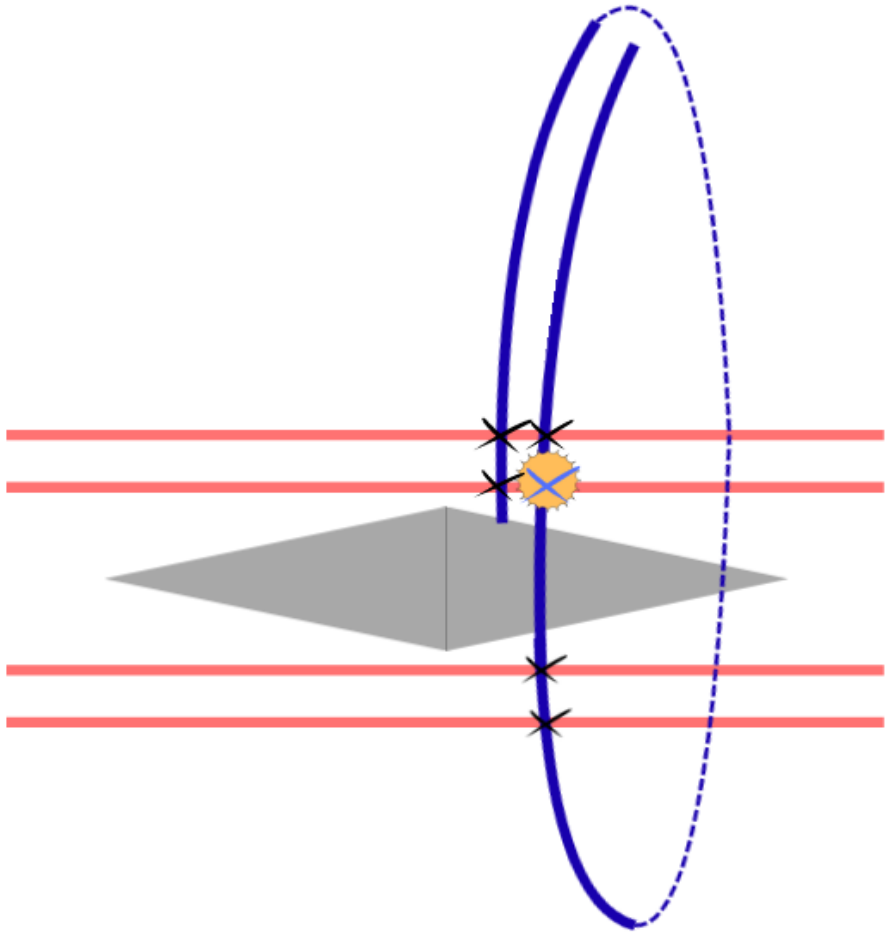


# Determination of the Pixel Efficiency

- Using “(n – 1)-hit method”
- Separate construction of :
  - full tracks
  - pseudo tracks (track with a missing hit)
- Start with a pseudo track and search for a compatible full track
  - (two tracks are considered compatible if they contain the same set of hit IDs, apart from the missing hit)
- Efficiency determination:
  - xxxxXx => efficient (compatible full track found)
  - xxxx0x => not efficient (full track missing)

- Pseudo tracks has to be highly pure, i.e. low fake rate
  - Cuts on Chi2, momentum etc
- Validation using "realistic" monte carlo simulation

- 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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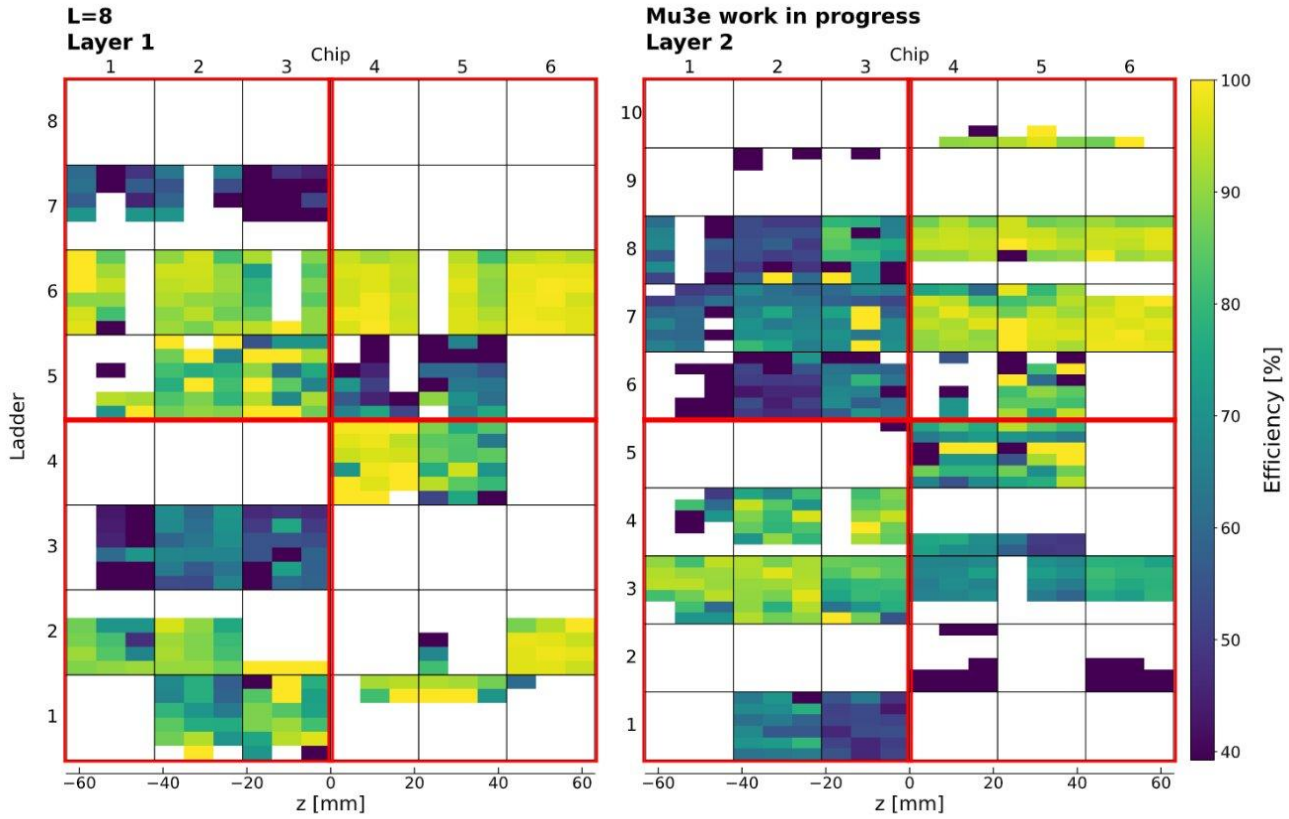
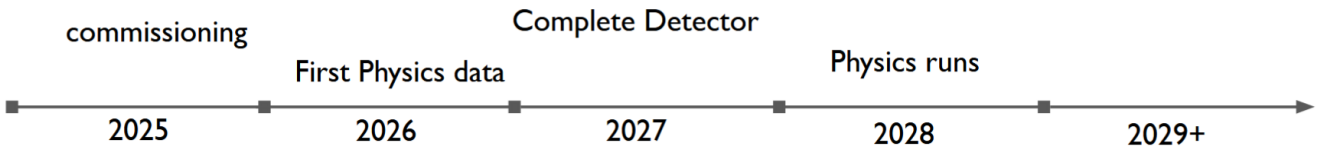
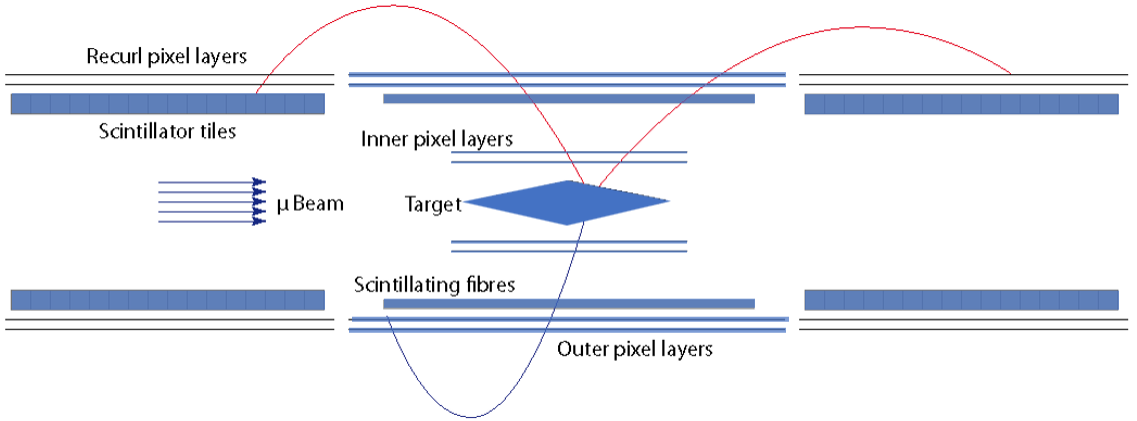


# Towards physics

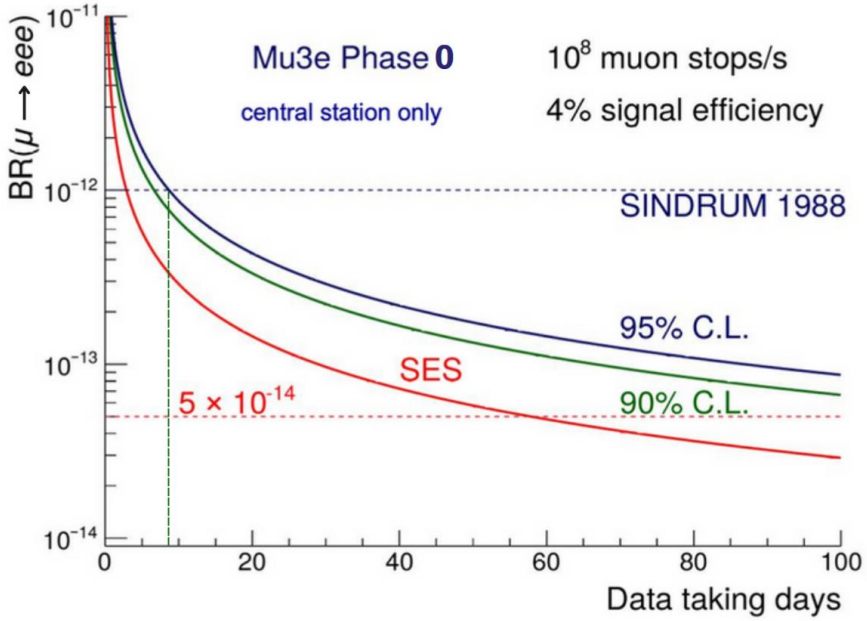
- Plan for 2026 (**8 weeks granted at PIE5**)
  - Construct Vertex V2 (70µm thin sensors)
  - Outer pixel production (Layer 3)
  - SciFi & Tile production
  - Comissioning of the filter farm
  - Study physics backgrounds

- Physics data taking in 2027
  - Full central station + Recurl station?
  - Surpass the SINDRUM limit
  - < O(1e-13)




Detector Setup for 2026 Physics data taking campaign



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Universität Zürich[UZH]

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UNIVERSITÄT HEIDELBERG
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KIT
Karlsruher Institut für Technologie

University of BRISTOL

UNIVERSITY OF LIVERPOOL

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# Thank you