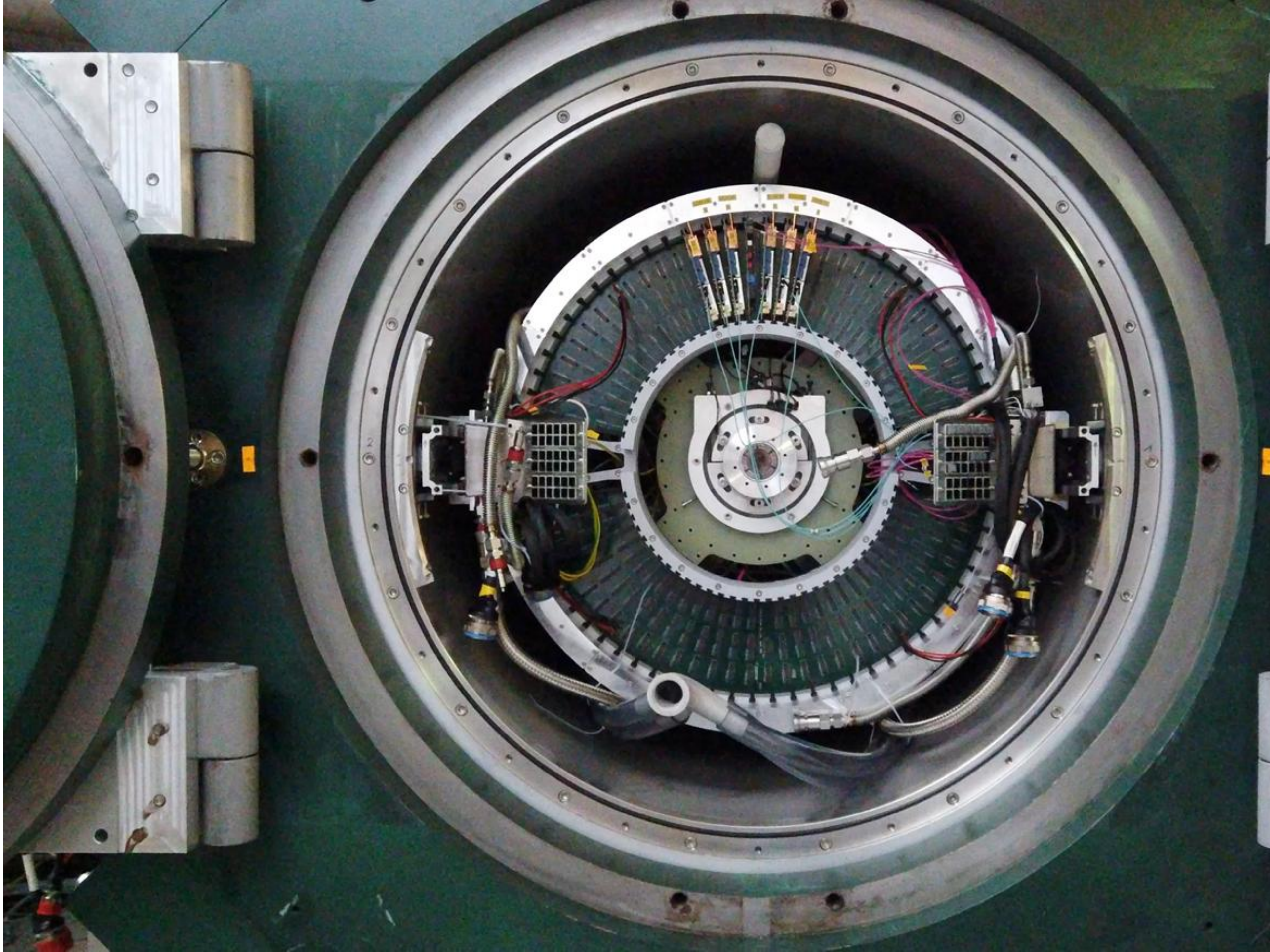
Mu3e

Thomas Christian Senger on behalf of the Mu3e collaboration

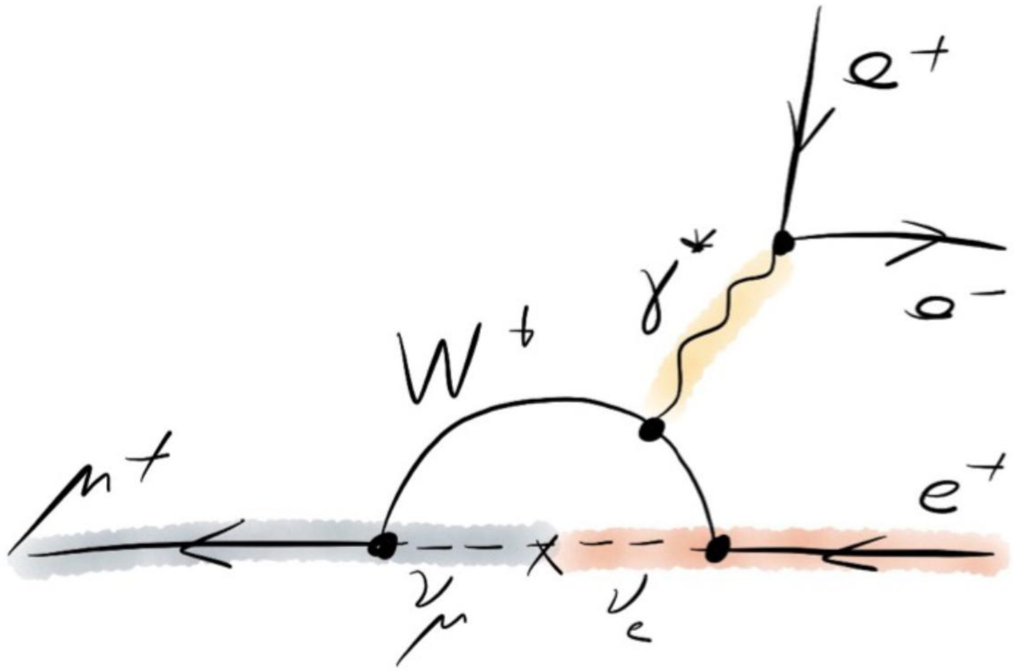


Charge Lepton Flavor Violation

- 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

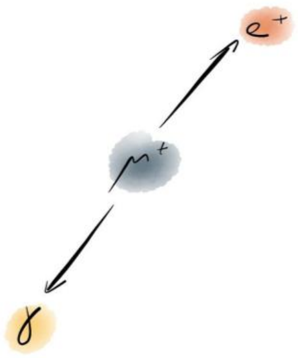
- Heavily suppressed in the SM + neutrino mixing
  - $\Gamma \propto \left(\frac{\Delta\ m_\nu^2}{m_W^2}\right)^2 \approx \mathcal{O}(10^{-54})$



The golden muon channels

Muons are an excellent probe of cLFV

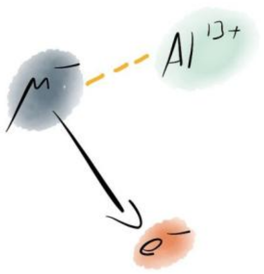
- **Sensitive**: New physics effects scale with the squared lepton mass m_l^2
- **Clean**: Relatively long lifetime and simple, well-understood decay channels, allowing for precise and background-free measurements



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

MEG /MEG II (PSI 2025)

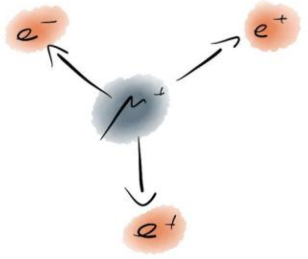
BR $(\mu^+ \rightarrow e^+ \gamma) < 1.5 \cdot 10^{-13}$



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

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

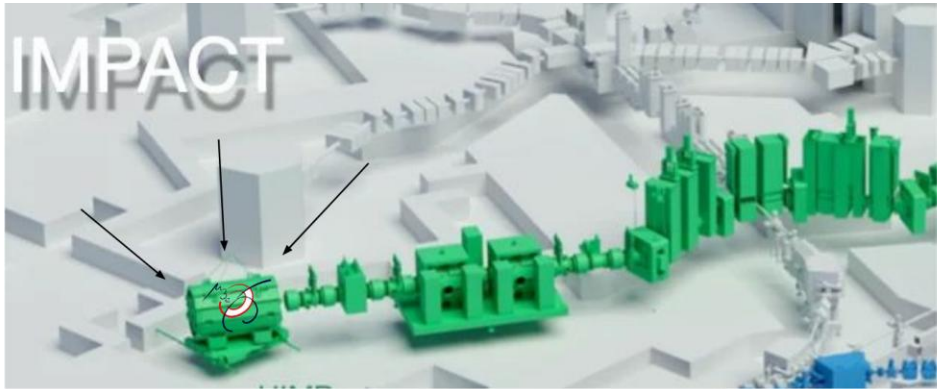
- **Most intense** muon beam with low momentum muons 28MeV
- Up to $\mathbf{10^8}$ Muons/s

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



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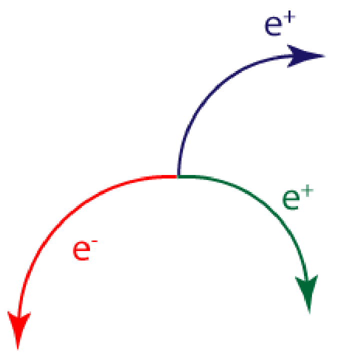
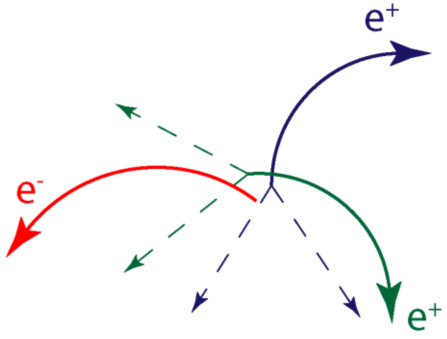
Mu3e signal and backgrounds



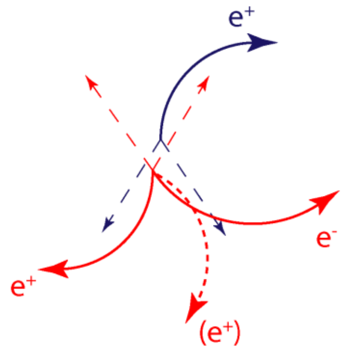
Signal

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

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



Two Michel decays + e^-

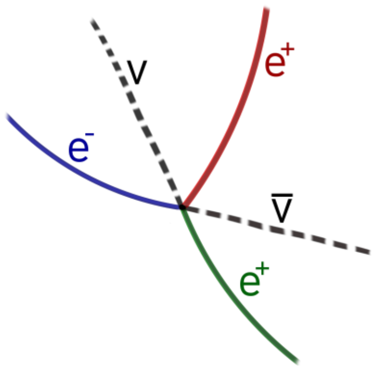


Michel decay + Internal Conversion

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 $\mathrm{BR}(\mu^+ \to e^+e^-e^+\bar{\nu}\nu) = 3.4 \cdot 10^{-5}$
- 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

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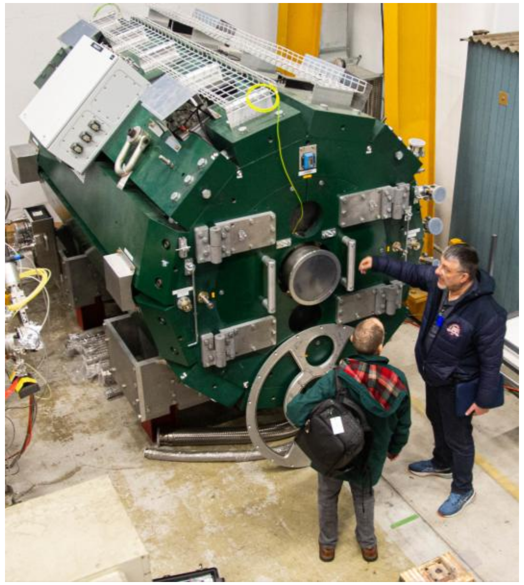
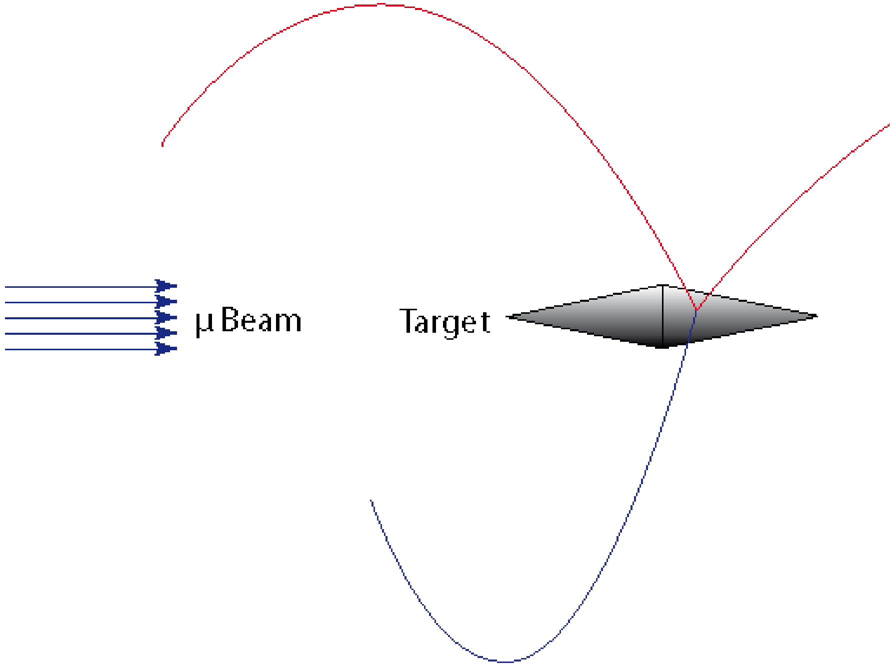
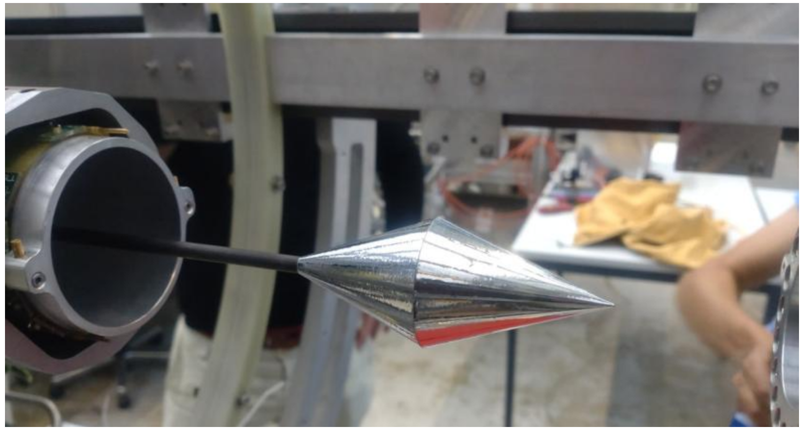
The Mu3e experiment

Mu3e magnet

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







Target

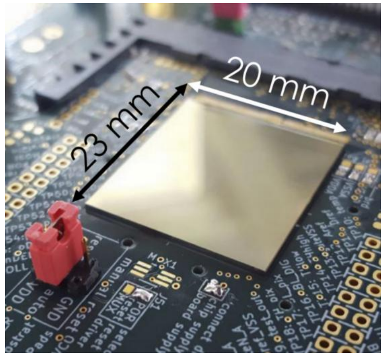
- Muons are stopped on **aluminised mylar** double hollow cone
- Maximum stopping fraction 95.5%
- Minimal material budget (~0.15%)

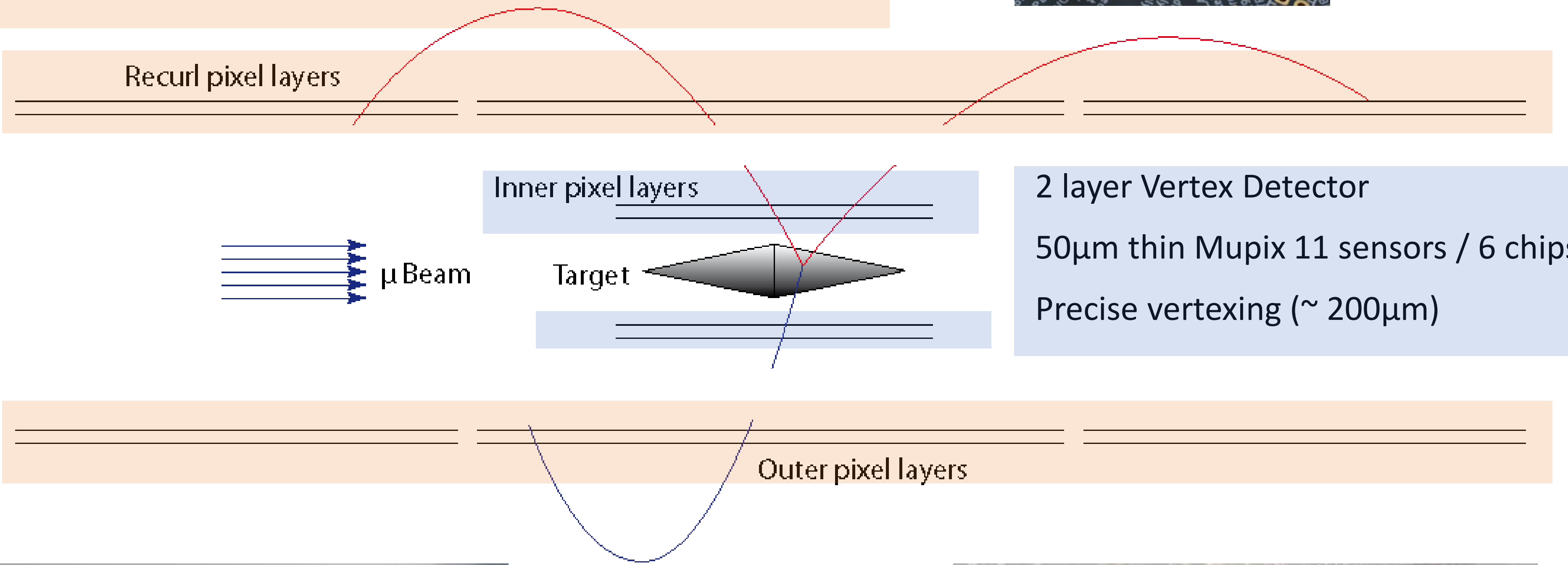
2 Outer Pixel Layers

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

For good momentum resolution and high p acceptance

→ reconstruction of recurling tracks

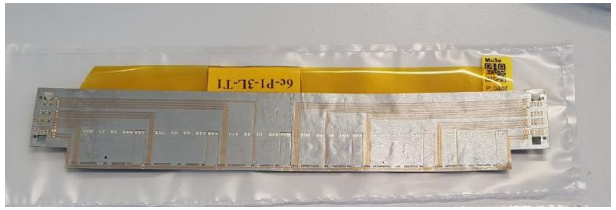


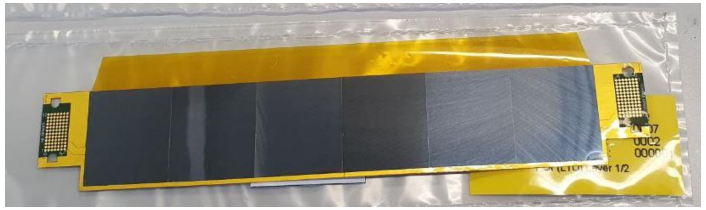


2 layer Vertex Detector

50µm thin Mupix 11 sensors / 6 chips per ladder

Precise vertexing (~ 200µm)





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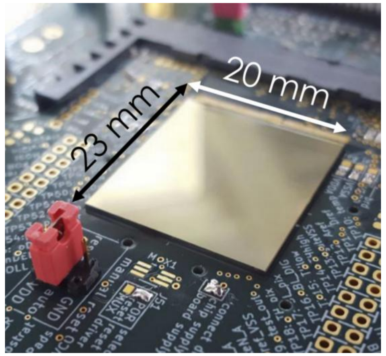

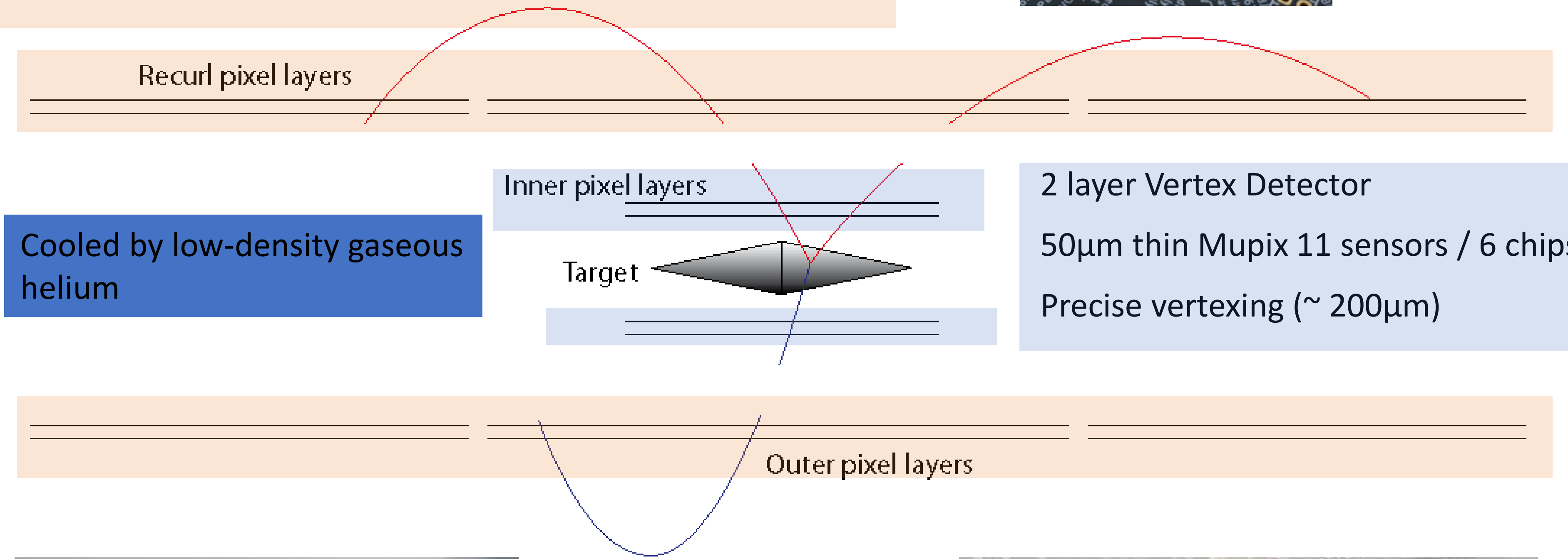

Cooled by low-density gaseous helium

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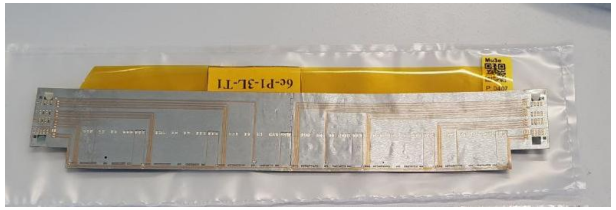
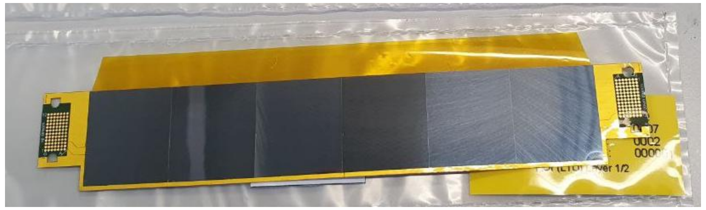
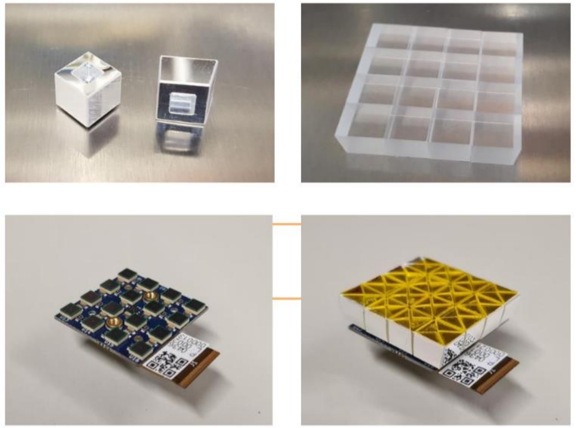
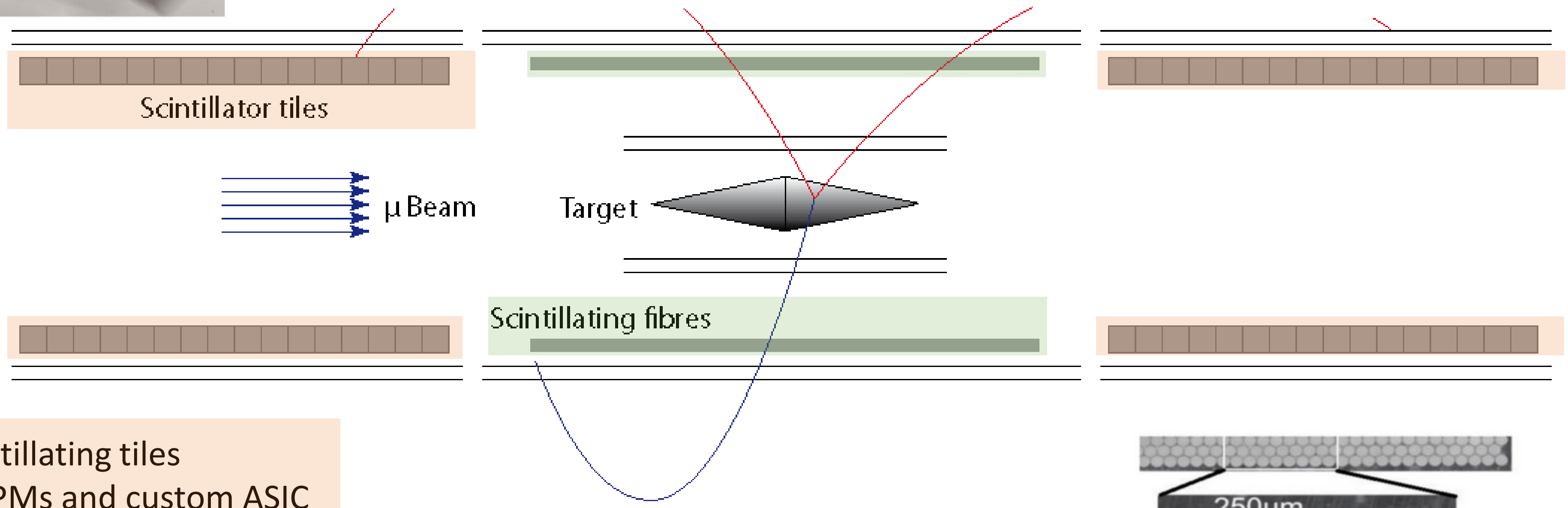


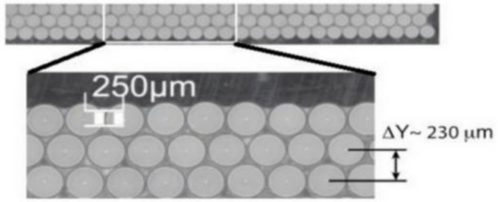




3 layers of 250µm scintillating fibres
Read-out by (SiPMs) and custom ASIC
Timing resolution < 0.5 ns



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



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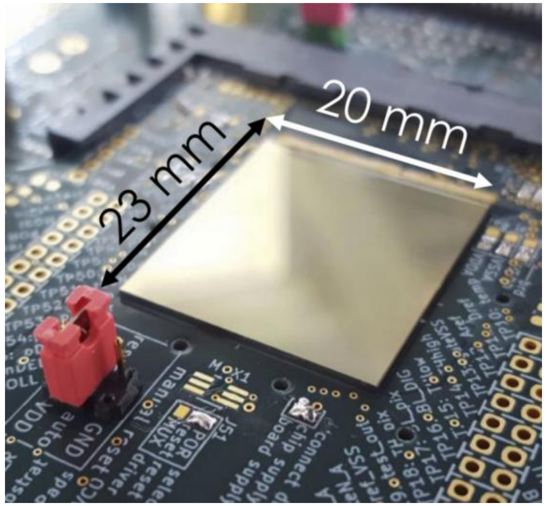
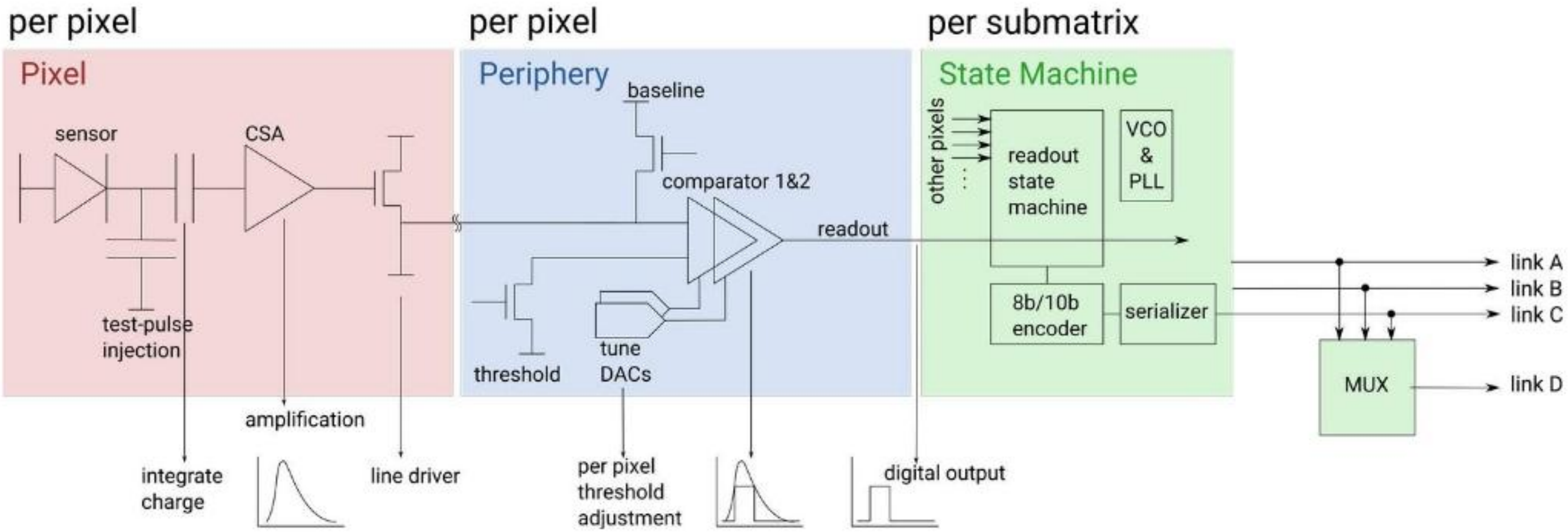
Mupix 11

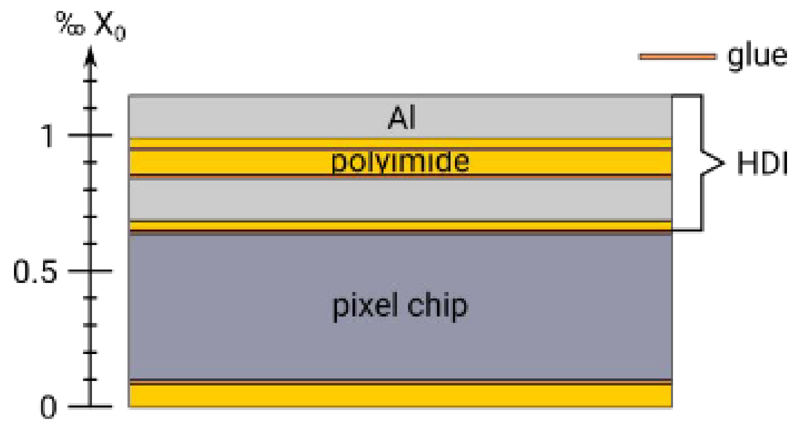
- High-Voltage Monolithic Active Pixel Sensor (HV-MAPS)
- Detection and Readout combined in one chip
- Fully digital 1.25Gbit/s LVDS output
- Pixel size 80 x 80 μm^2
- 99% efficiency with less than 20ns time resolution
- 2 comparator design
- Tuning/trimming and masking available
- Chip sub-divided into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

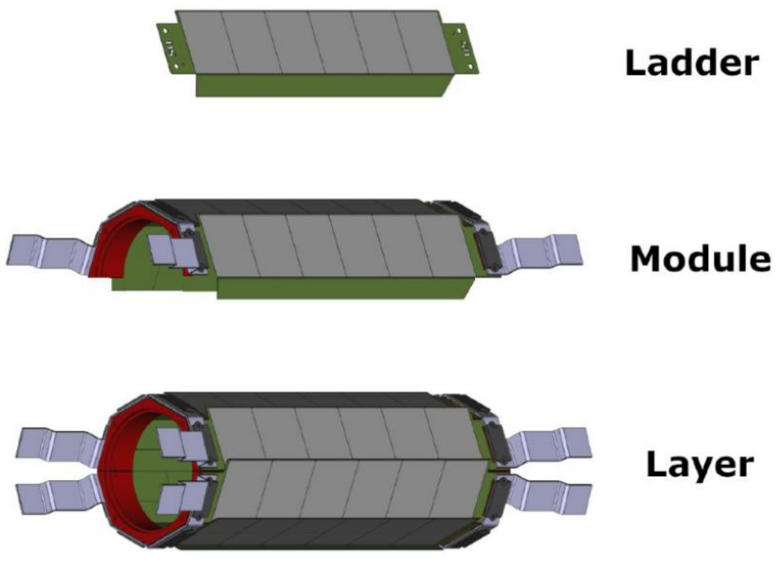


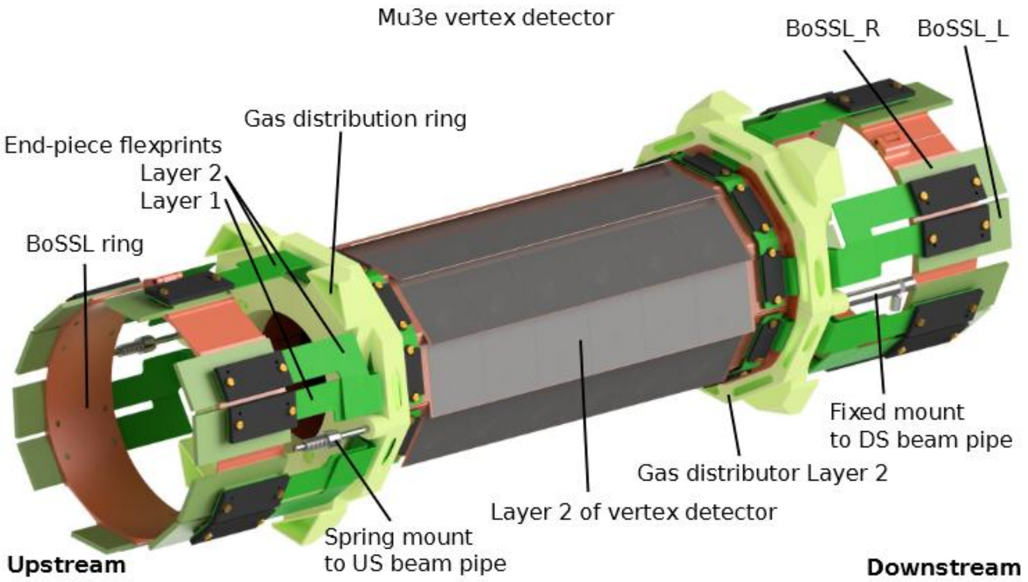


Mu3e Vertex Detector

- 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 ($X/X_0 \approx 0.15$ % 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







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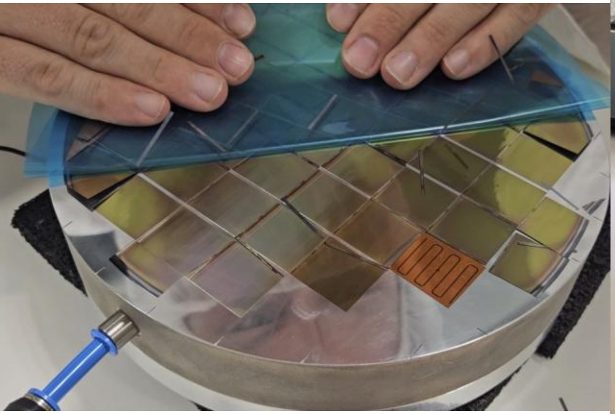
Physik-Institut

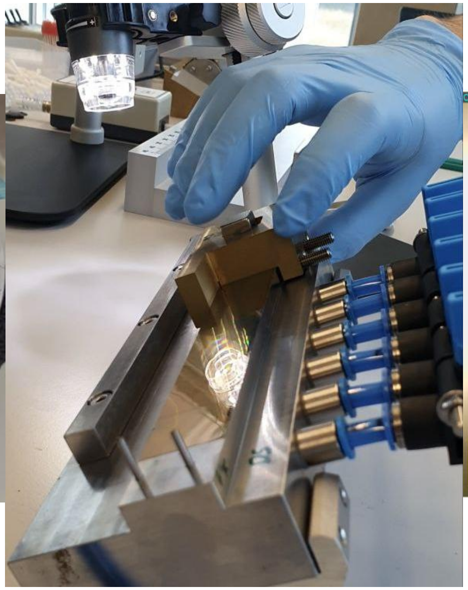
Challenges in the Construction and the Operation of the Mu3e Vertex Detector

University of Zurich[UZH]

Construction and Handling

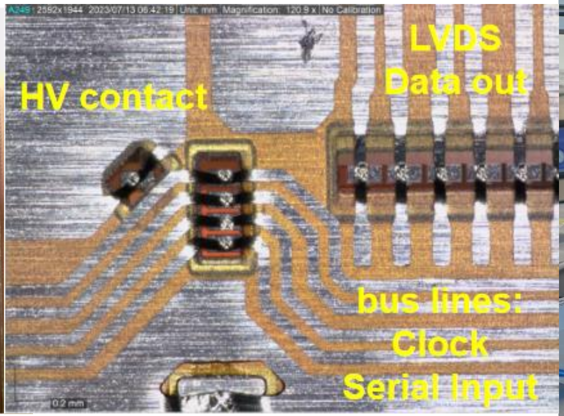


Wafer Peeling

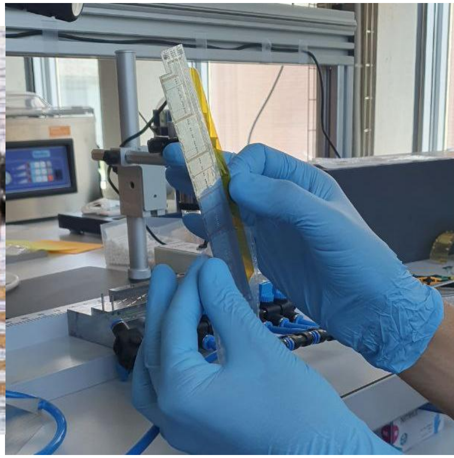


Manual Chip Placement

Glue Distribution



spTa-Bonding



Handling

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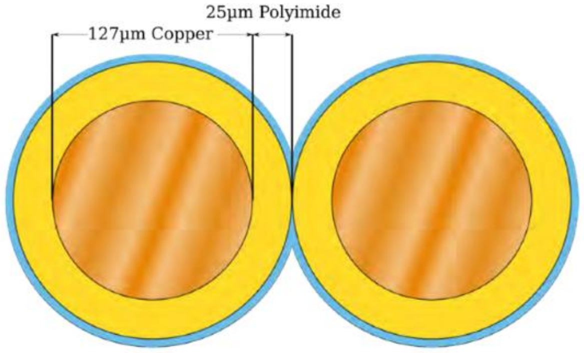
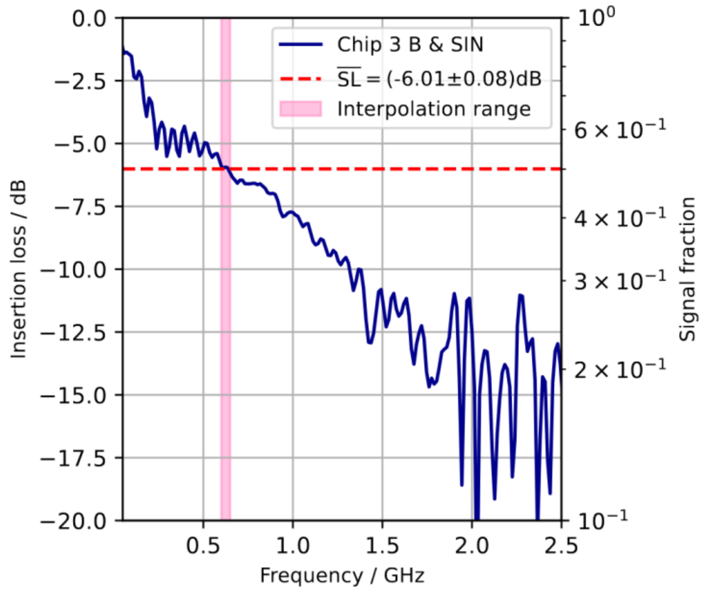
Signal transmission challenge

- 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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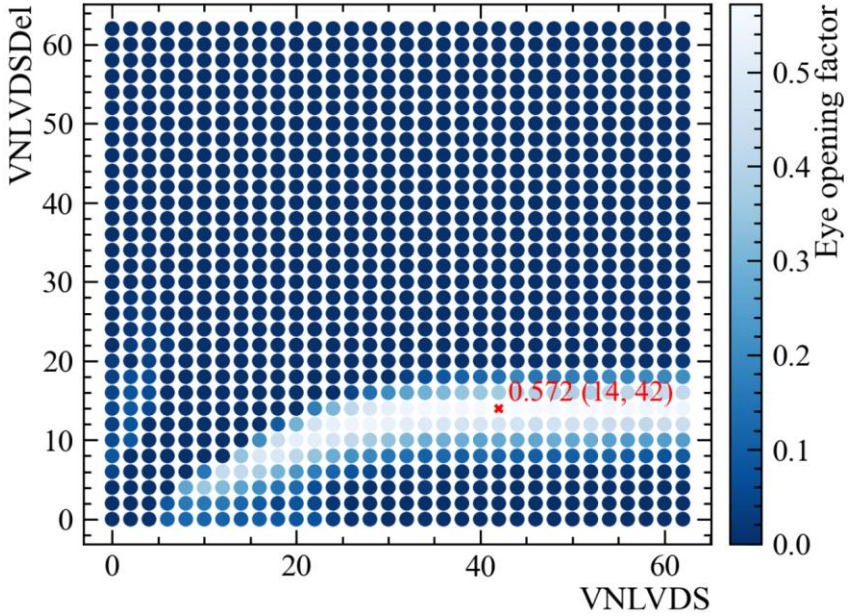

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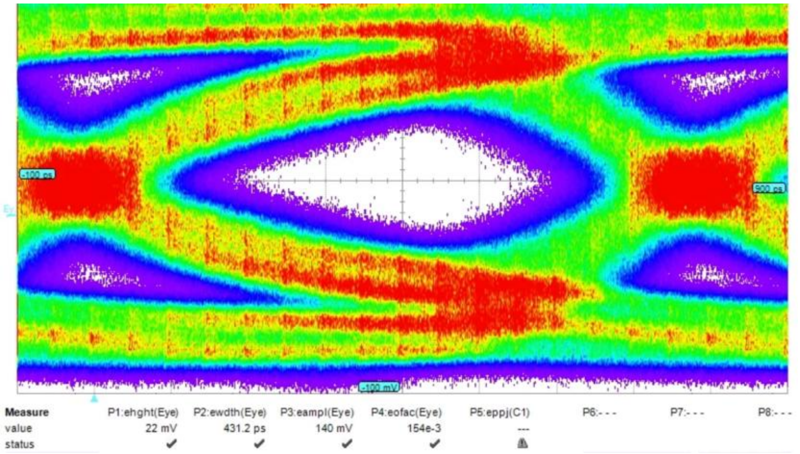
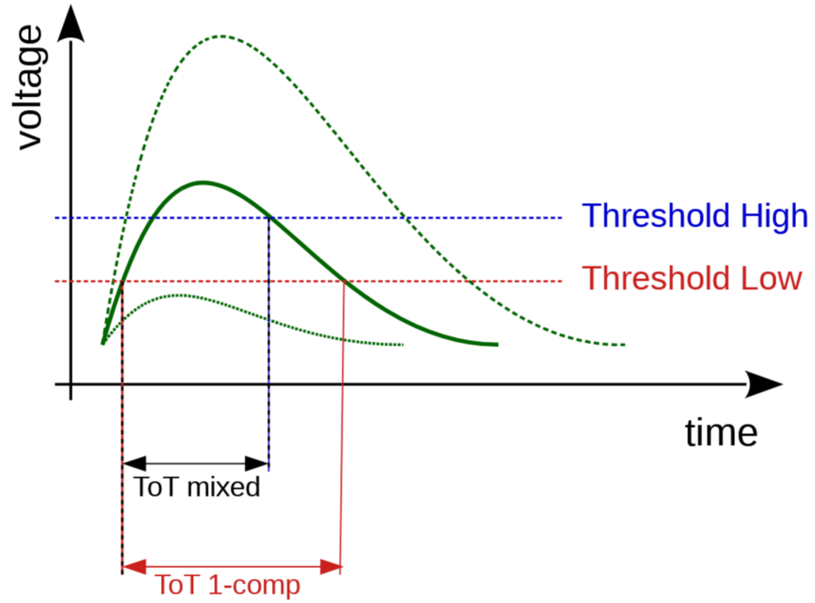
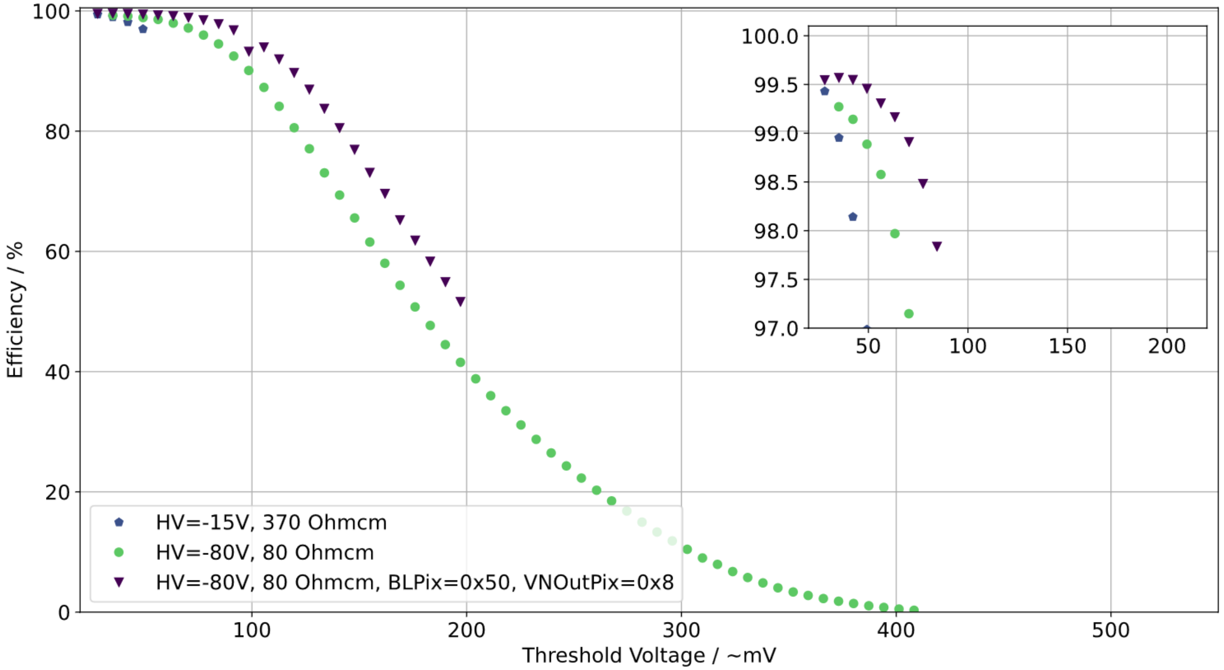


Efficient pixel operation

- 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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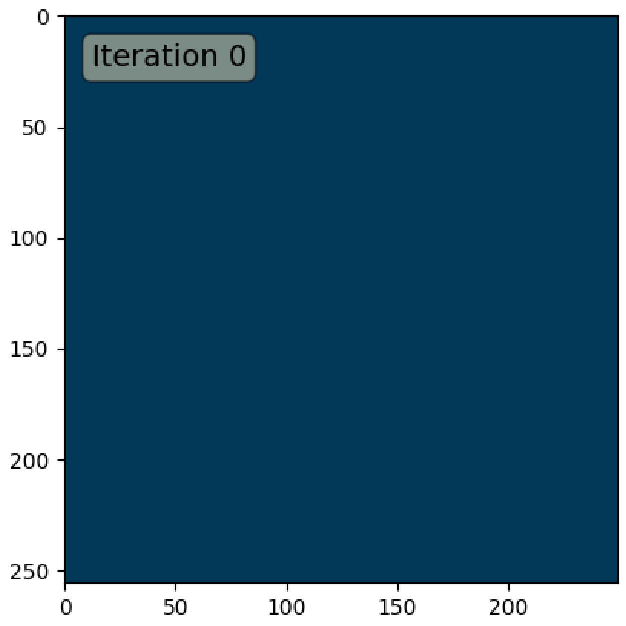
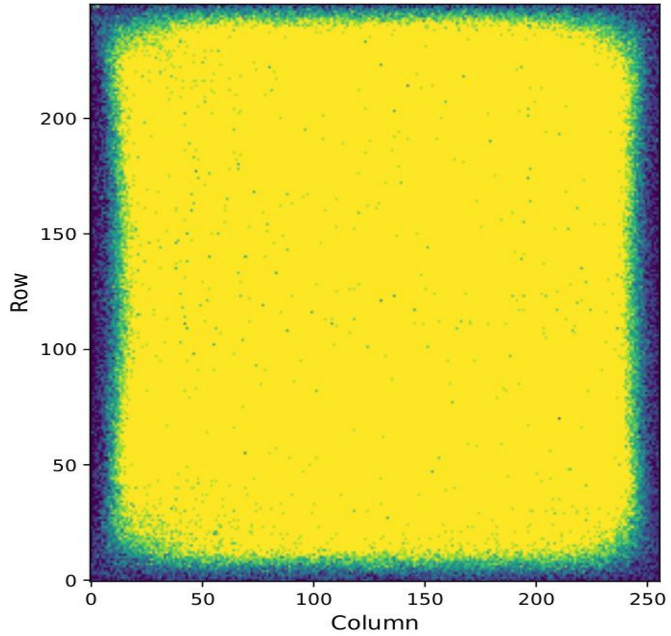
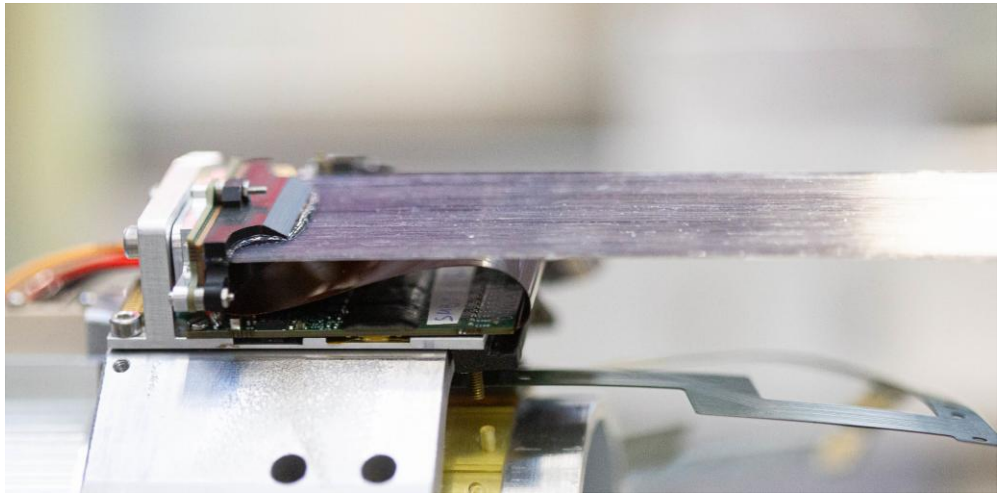
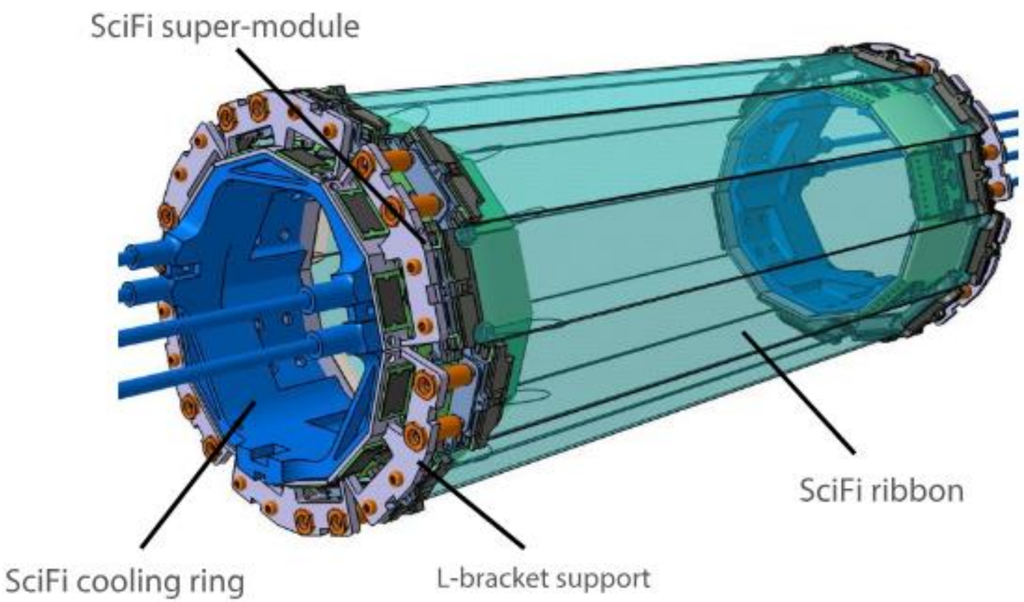


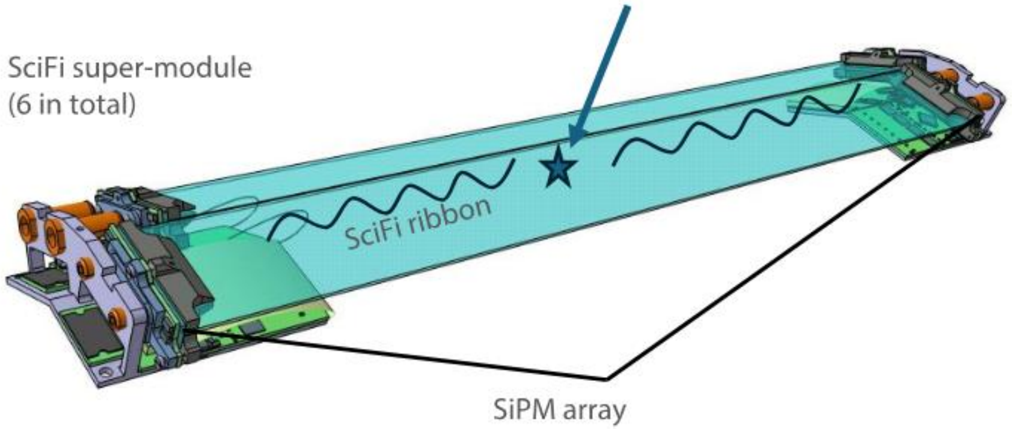


Scintillating Fibres

- 3 layers of 250 µm staggered fibres
- 12 long fibre ribbons covering 4 π
- 1 ribbon = 720 µm thick, 0.2 % radiation length
- 300 ps time resolution
- Readout by SiPM arrays at both ends and custom ASIC (MuTRiG)
  - 256 channels per ribbon
- Liquid cooling (SilOil, -20°) through the Cooling Ring

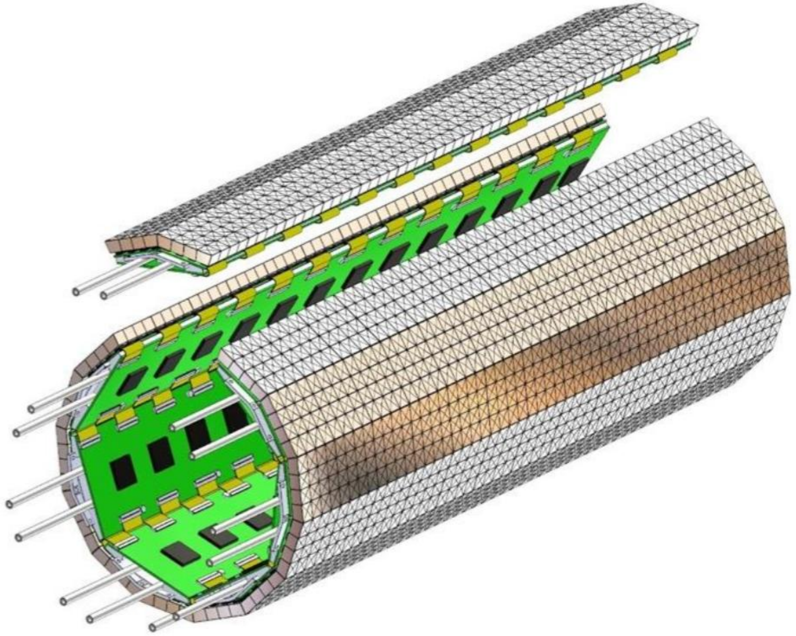




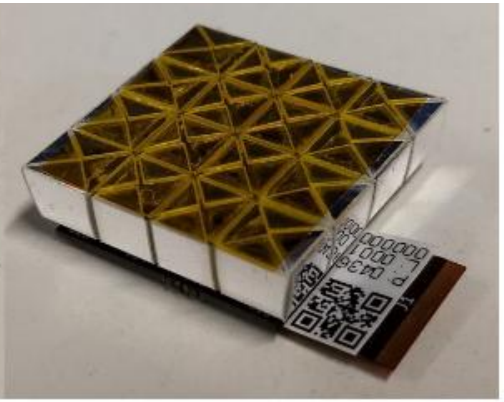


Scintillating Tiles

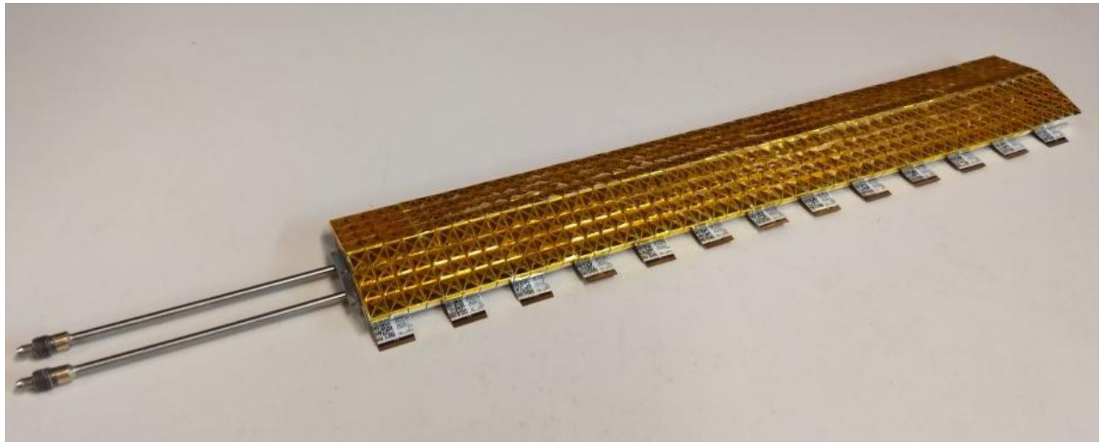
- Highly segmented in ~6k tiles
- Very compact design
- Tiles from fast Ej-228 plastic scintillator (6 x 6 x 5 mm3)
- Individually wrapped in ESR foil - Minimize crosstalk
- Coupled to Hamamatsu SiPMs read out by Mutrig ASIC
- (S13360-3050VE @ -10°C, Silicon oil cooling)
- Efficiency > 99%, single-channel time resolution ~ 40 ps
- Performance validated in Demonstrator Modules



SIPM matrix

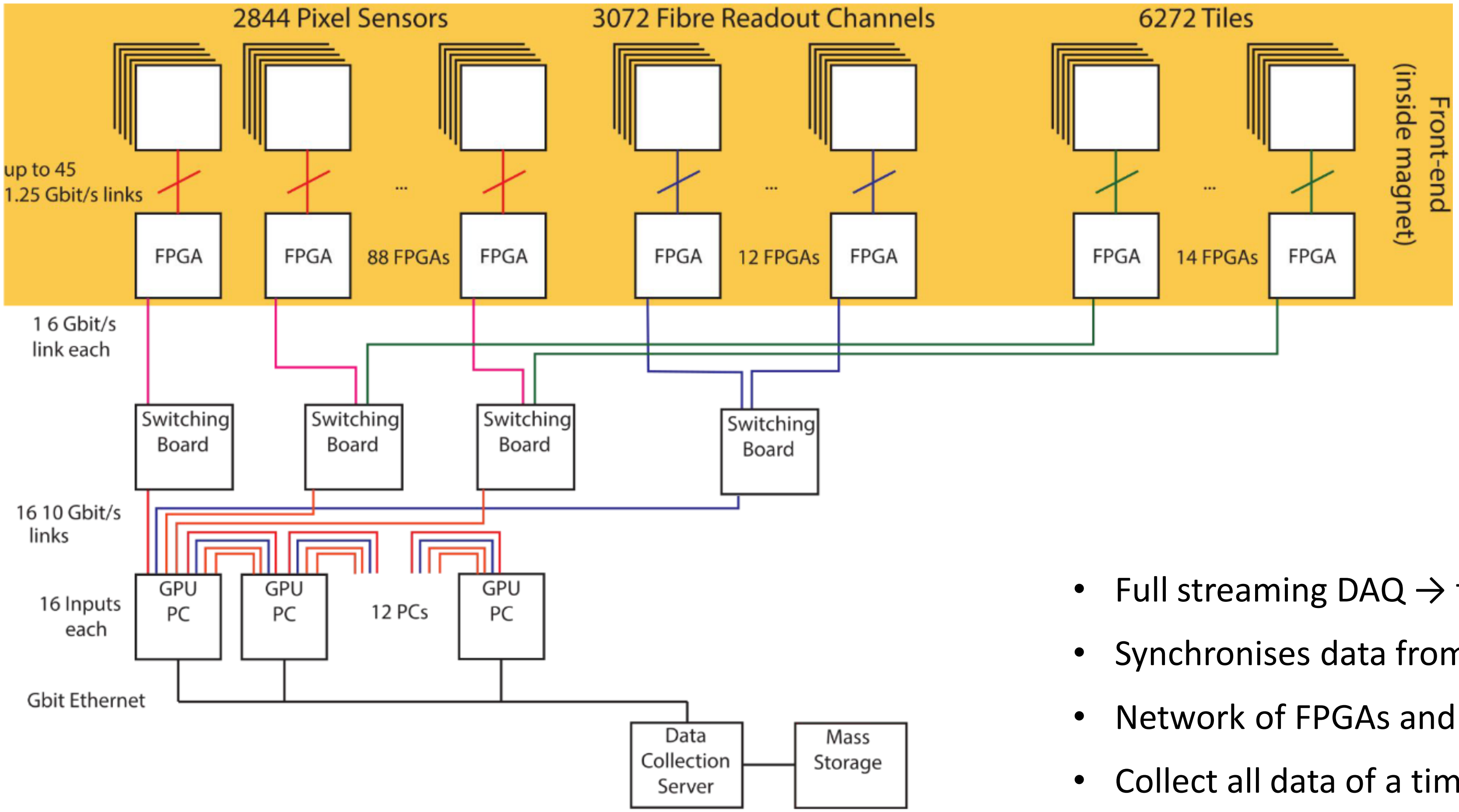


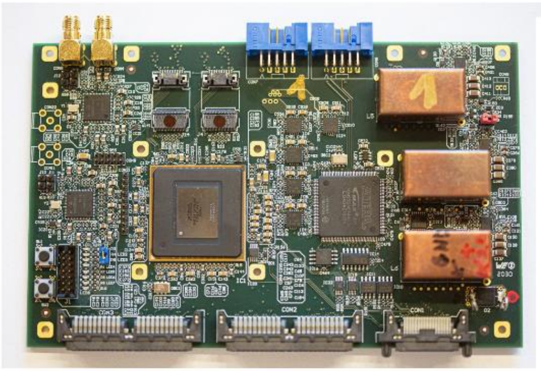
Tile matrix



Tile module

Mu3e Data Acquisition





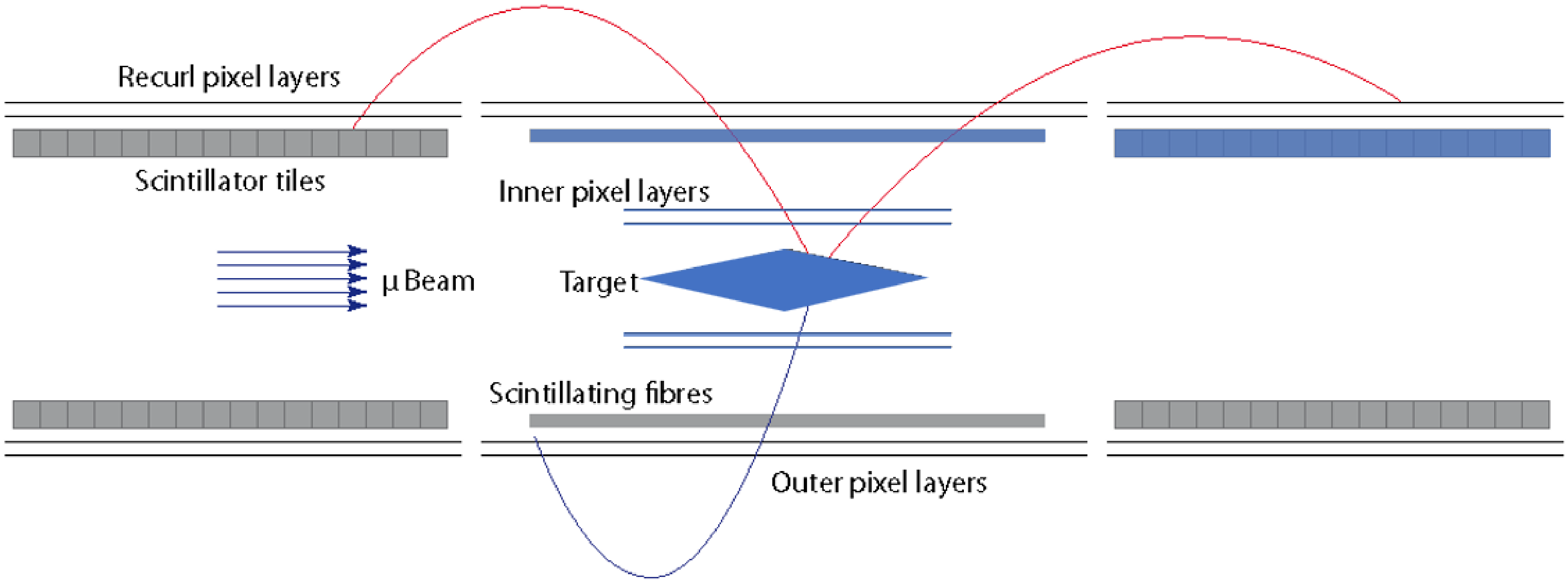
Custom readout board electronics inside the magnet.
Front-end board

- Full streaming DAQ → triggerless readout
- Synchronises data from all sub-detectors
- Network of FPGAs and optical links
- Collect all data of a time slice on one PC
- Reconstruct tracks, then vertices on a GPU
- Write interesting events to disk

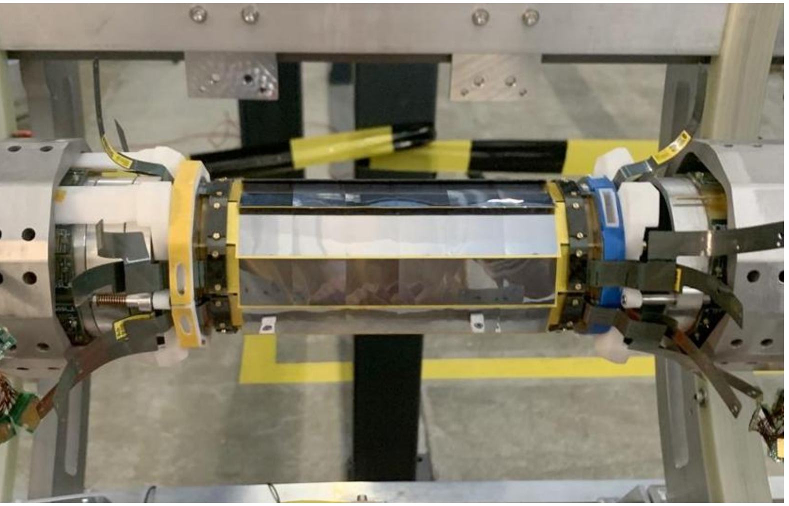
Minimal detector configuration

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

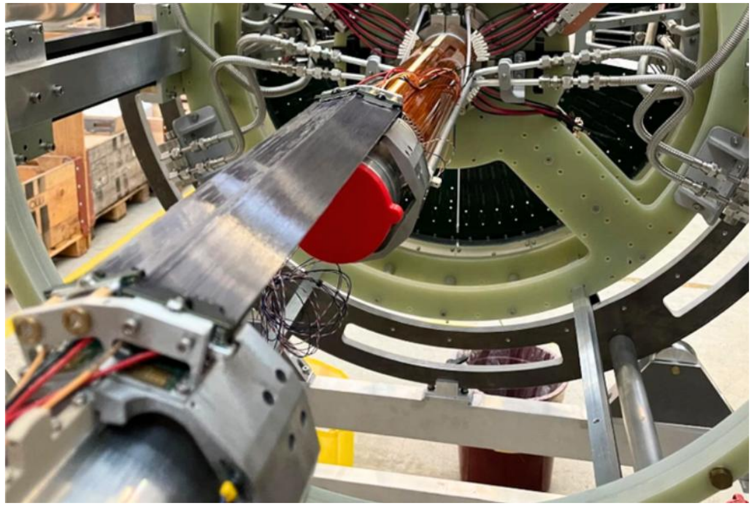
- **Full vertex detector** installed with 108 sensors
- **One** of six SciFi modules
- **Three** of fourteen SciTile modules
- Operation with **gaseous helium cooling** and 1 T magnetic field
- Most services independent of the sub-system have been installed and tested



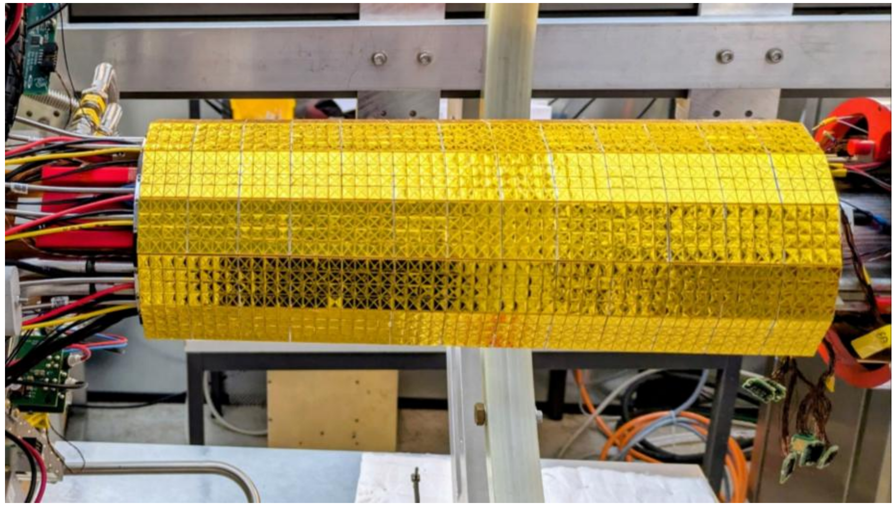
Commissioning Run 2025



Full Vertex Detector

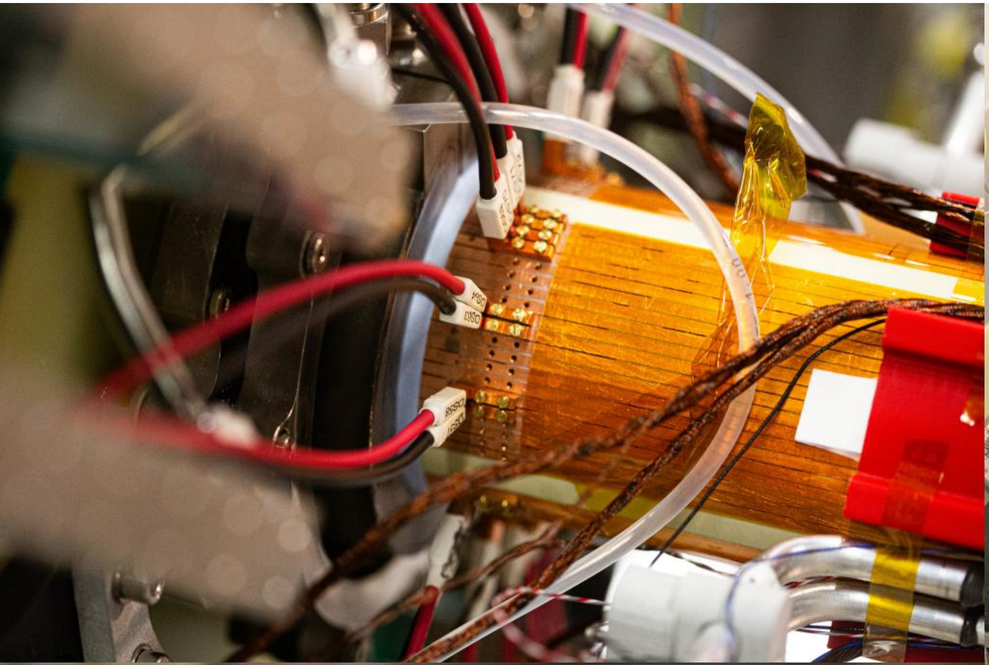


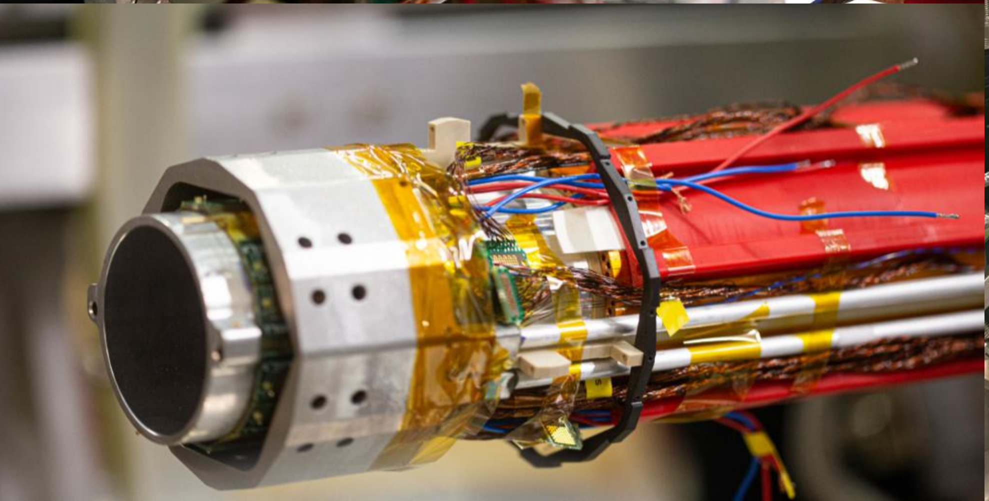
2 SciFi ribbons

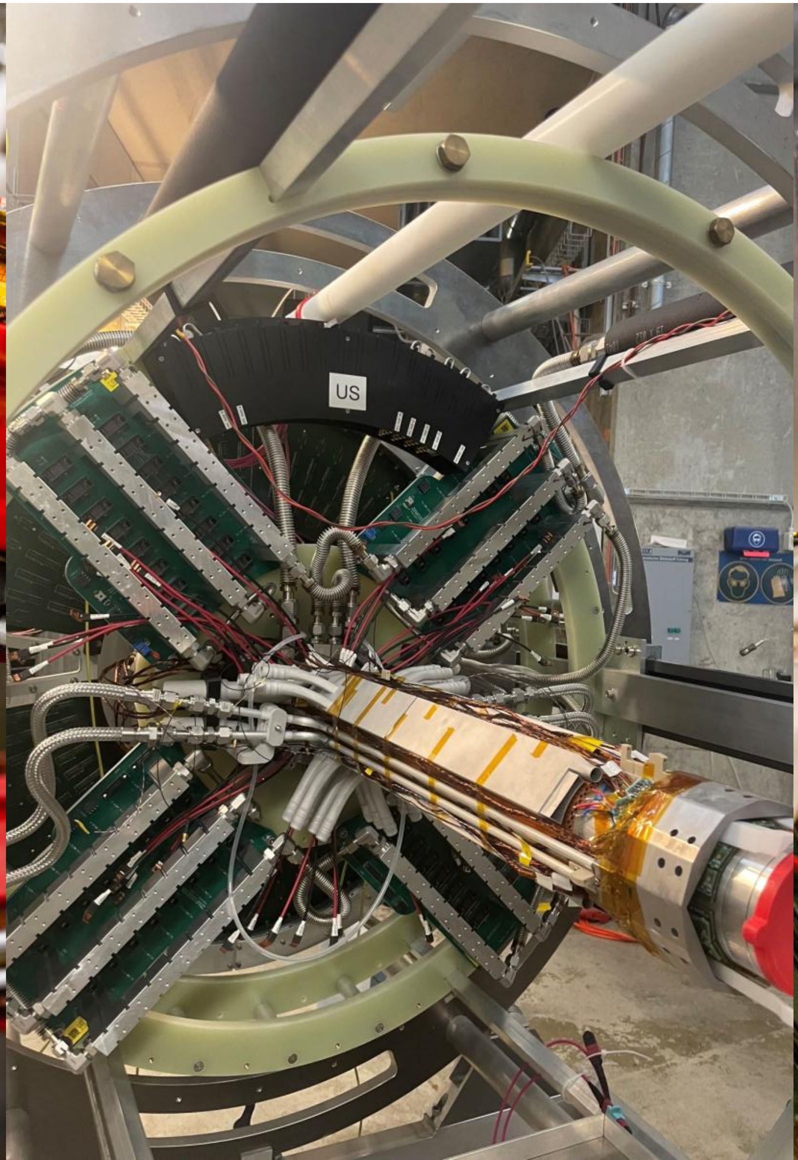


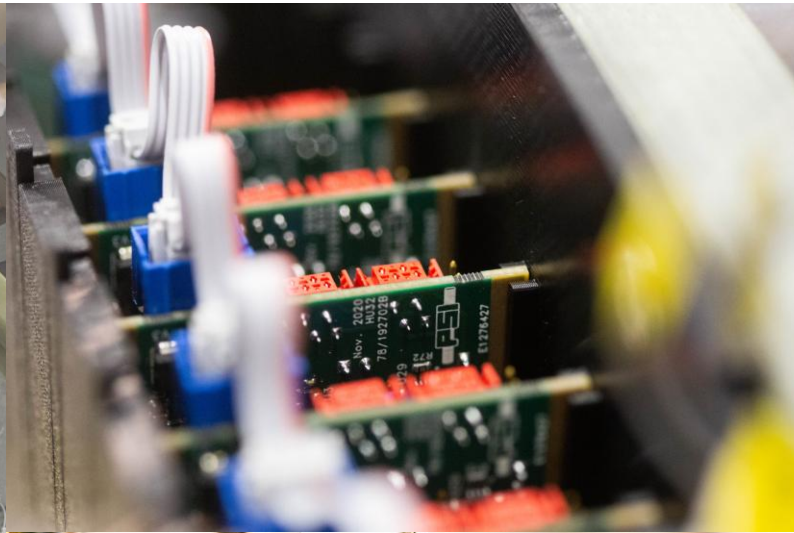
3 SciTile modules (DS)

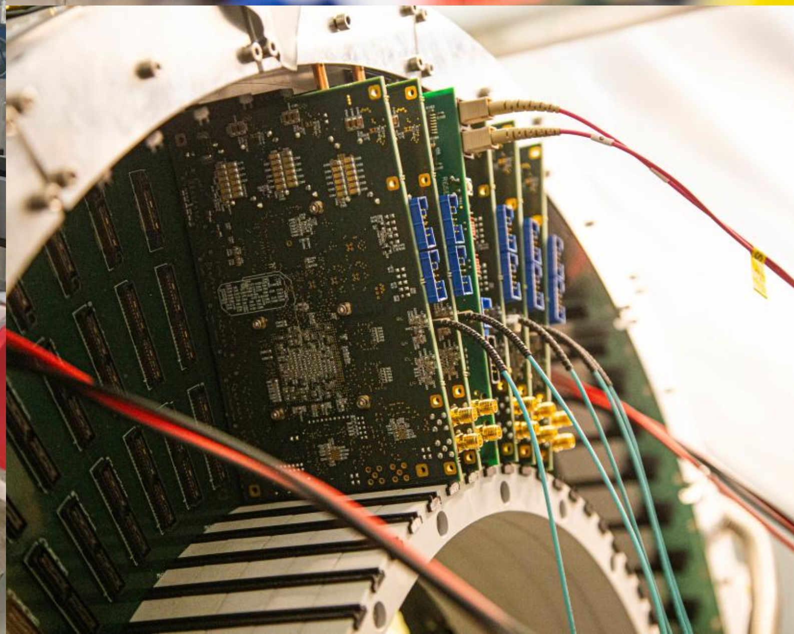
Service Installation



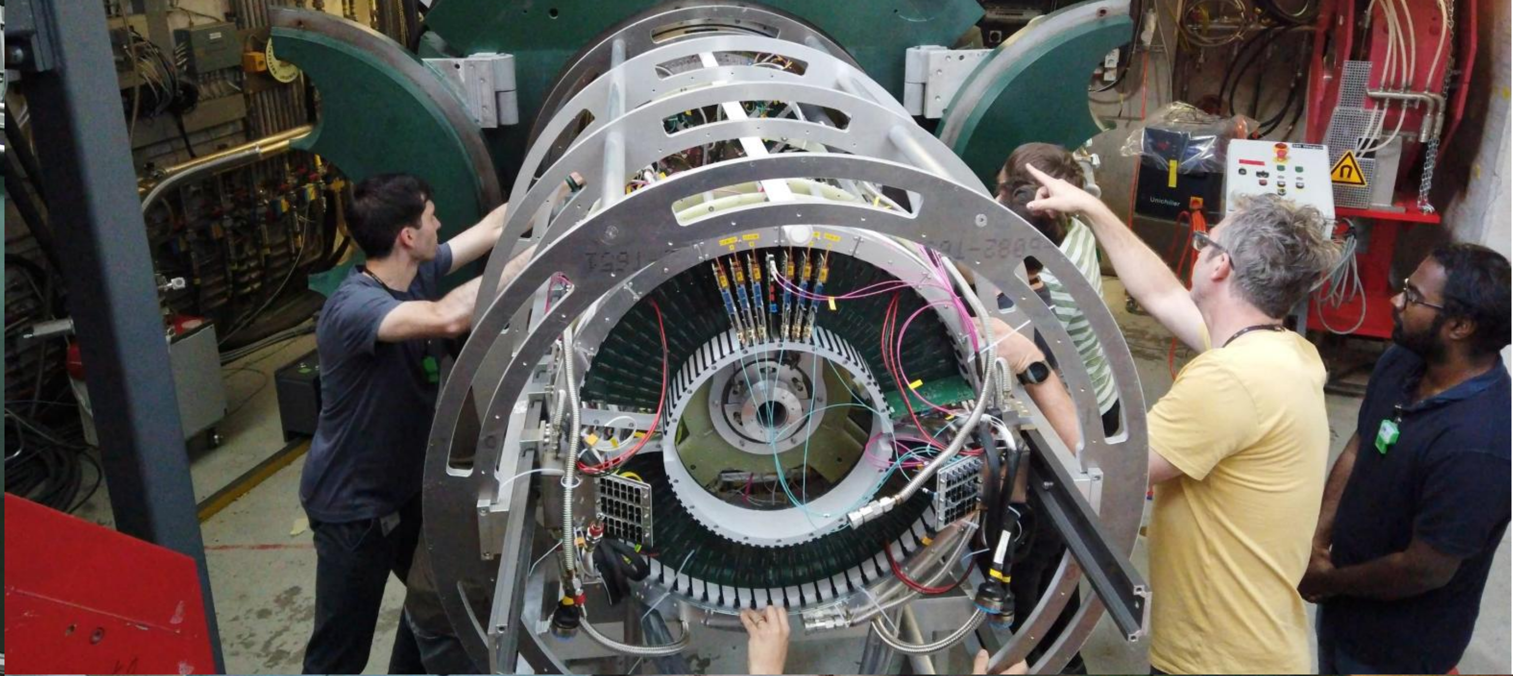


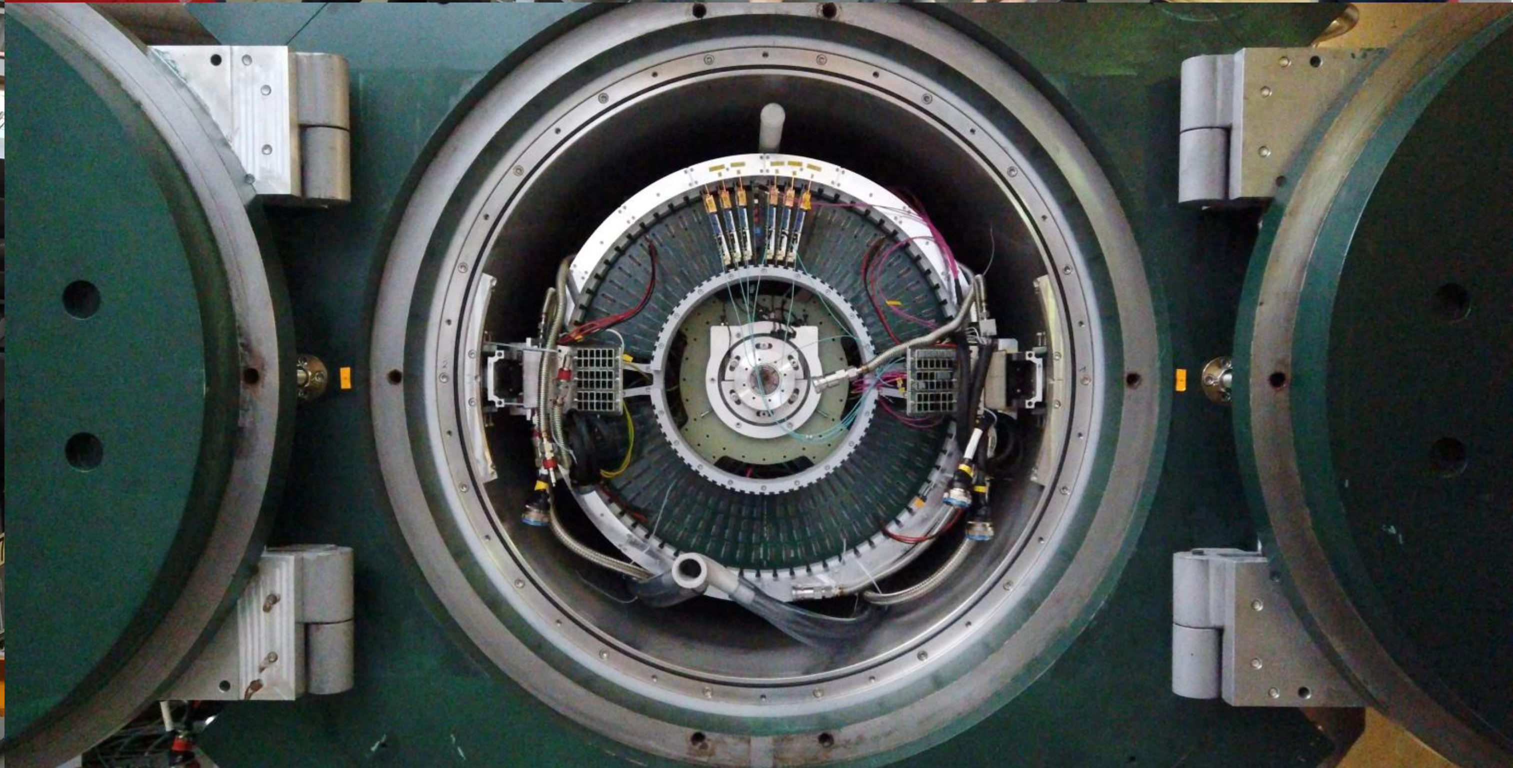






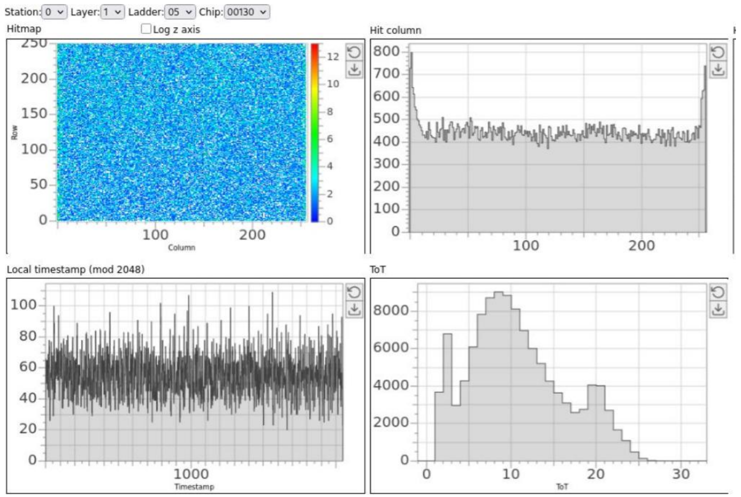
The flight of Mu3e





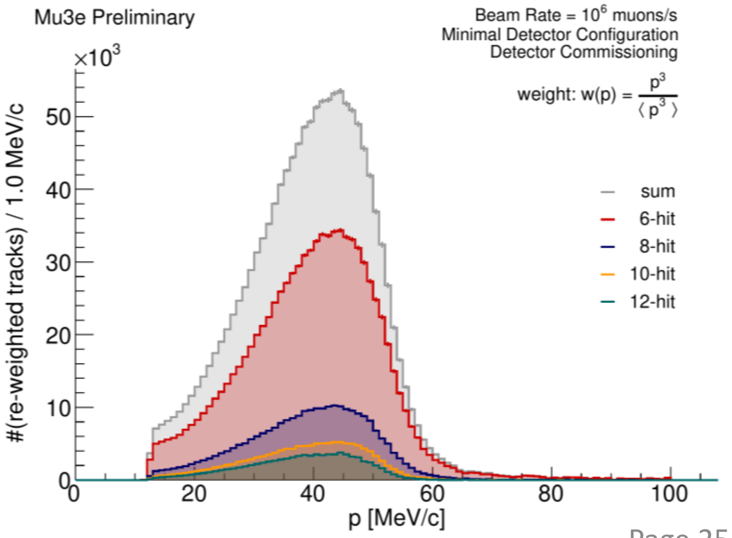
Successful Commissioning of the Mu3e Detector

- Operate vertex, scintillating fibres and tile detector with beam
- Showed high-rate capability with sub-detector synchronisation
- Stress test at 10^7 muons / s
- Demonstrated online track reconstruction with GPU filter farm
- PIE5 services commissioned



First preliminary **result**

- Measured momentum distribution for 6-,8,-10- and 12-hit long tracks
- Re-weighted momentum distribution to correct for:
  - limited polar angle of the vertex detector
  - momentum dependence of a misaligned detector
- Michel edge visible



Successful Commissioning of the Mu3e Detector

- **Thinnest** (0.12% X_0/ layer) **vertex detector currently operational**
- Demonstrated **efficient** data collection after successful **tuning**
- All 108 chips installed
  - 75 % of the submatrices were operational
  - 4 had a mechanical damages before installation
  - Lost ladders during installation
  - A few chips 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

	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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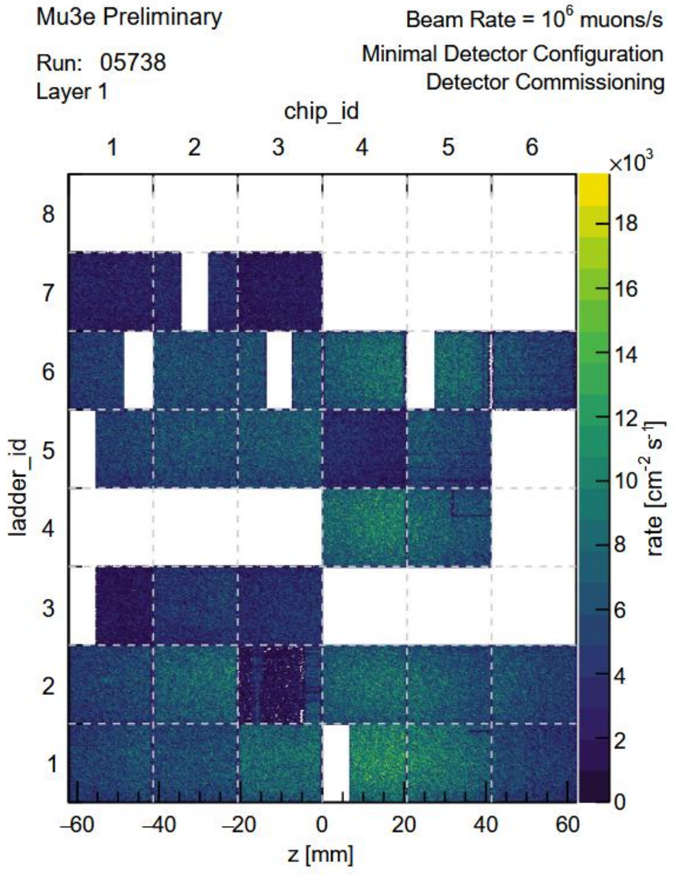
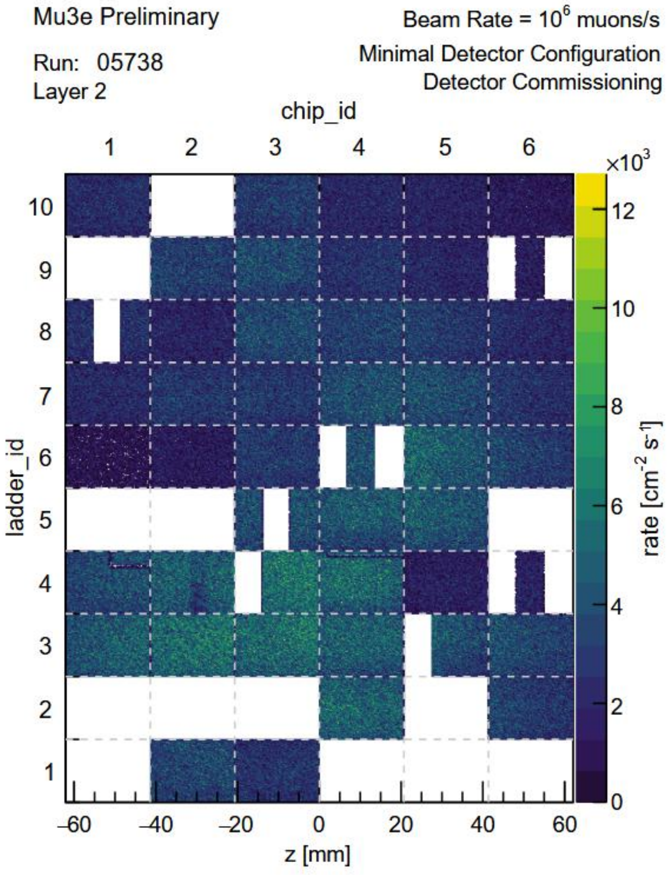
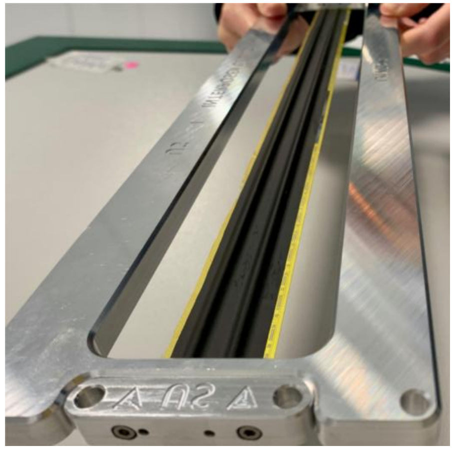


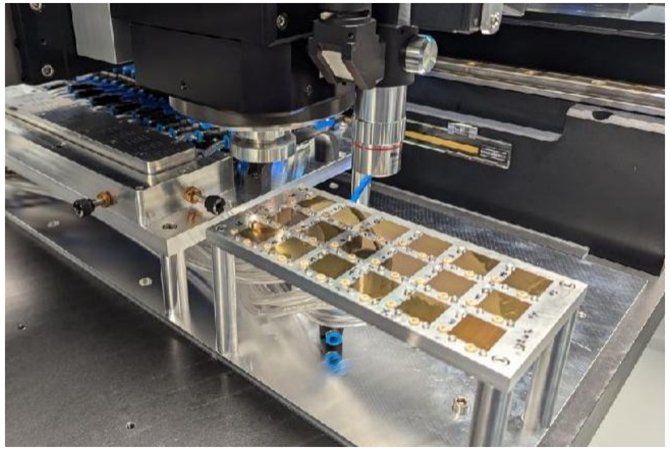


Towards physics in 2026

- Aim for a **physics run** in 2026
  - Construct Vertex V2 (70µm thin sensors)
  - Outer pixel production (central detector)
    - Use 25 µm uni-directional carbon-fibre stiffner
    - Robotic gantry used for placement of chip
  - SciFi & Tile production
- Could **surpass** the SINDRUM limit in less than two weeks

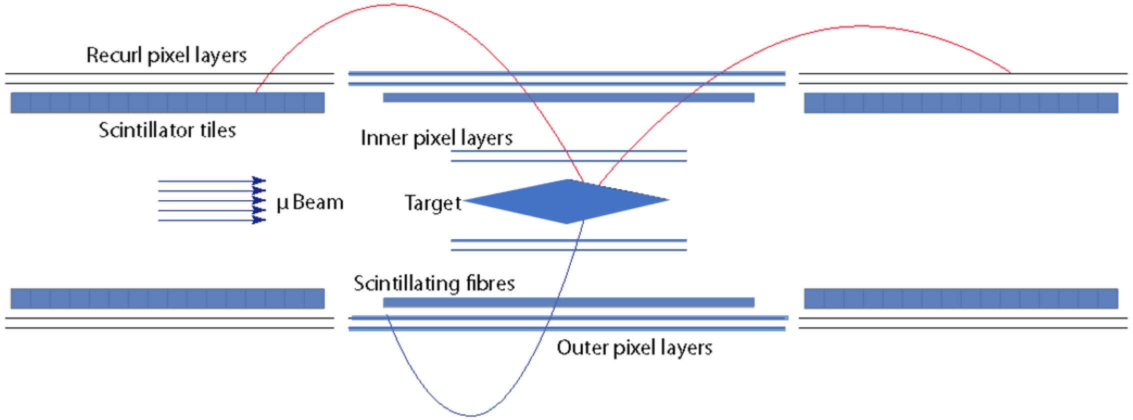


Carbon stiffner attached to a ladder

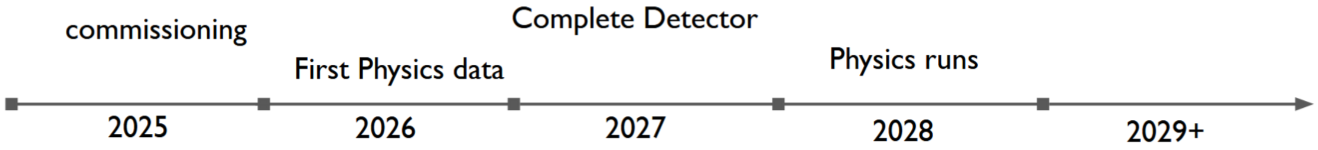


Robotic gantry for chip placement

- Install the **full detector** in 2027
  - Production of recurl stations (2026)
- Phase I data taking in HIMB
  - Need 1 year of data taking to reach the branching ratio of 10^{-15}



Detector Setup for 2026 Physics data taking campaign



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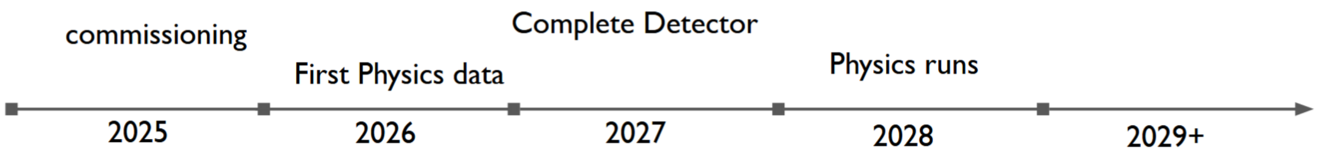

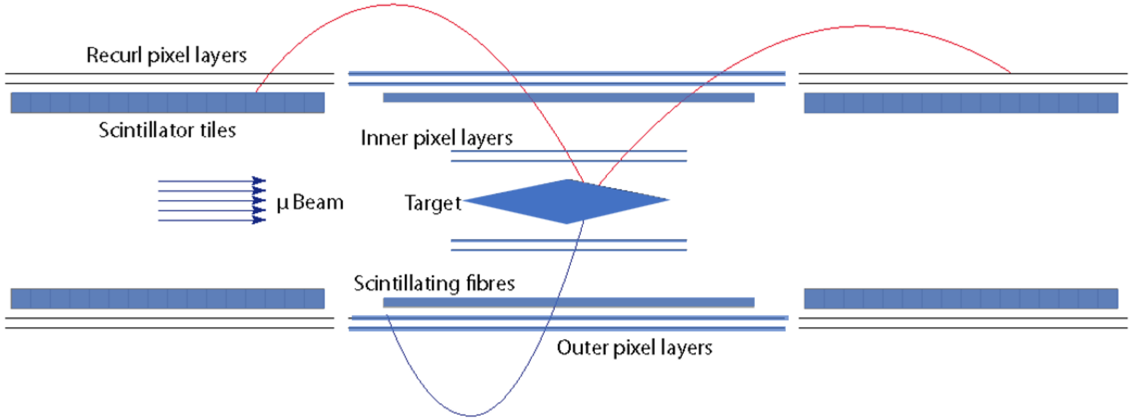

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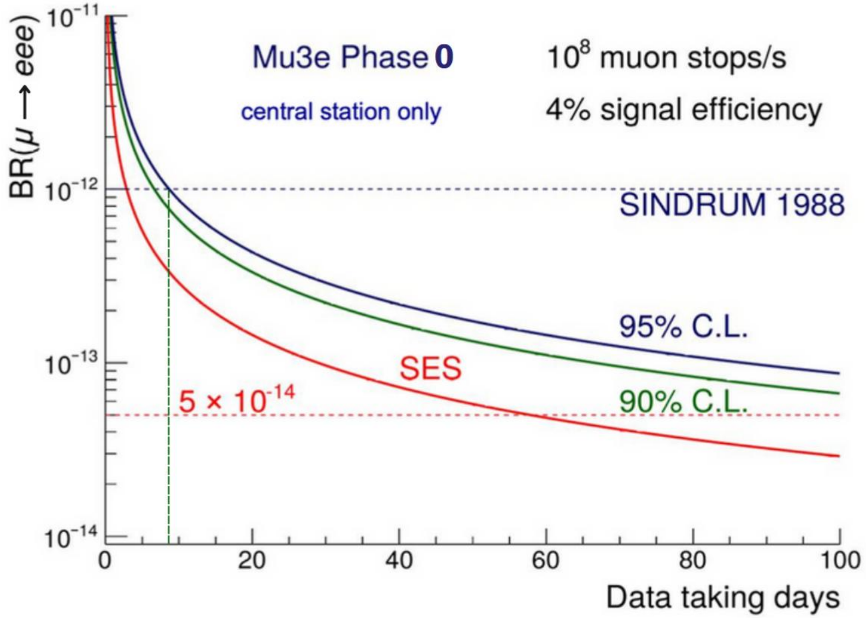


Phase II from 2030 onwards

New challenges

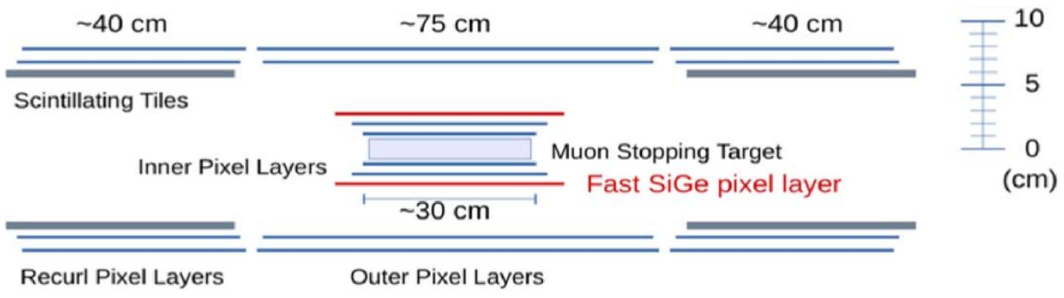
- At least a factor 20 times higher hit rates

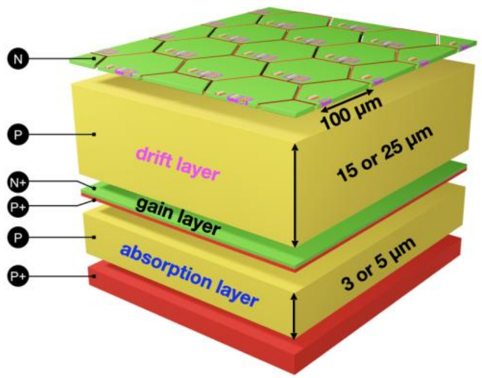
  → higher readout bandwidth (faster links)
- Accidental BG (Bhabha & Michel) will increase by a factor of 400
- Power consumption will be critical
- More hit combinatorics

  → complexity of reconstruction will increase

Detector R&D

- Ultra long ladders, thinner Vertex detector (30µm)
- Serial powering (reduction of material)
- Faster MuPix20 pixel tracker (σ ≤ 1ns)
- PicoAD sensor (σ ≤ 100ps)
- Radiation tolerance of SciTiles
- New readout system with optical
- Transceivers closer to the detector frontend





PicoAD

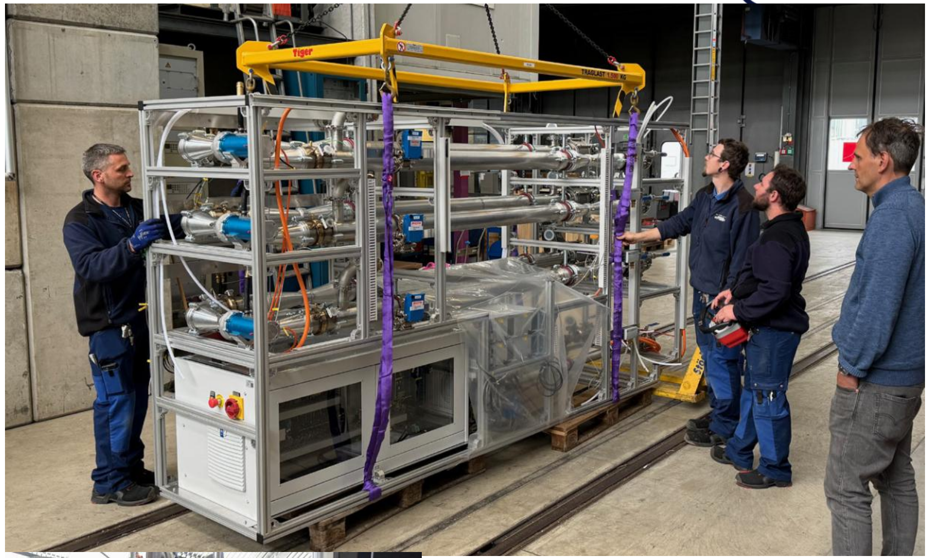
Thank you

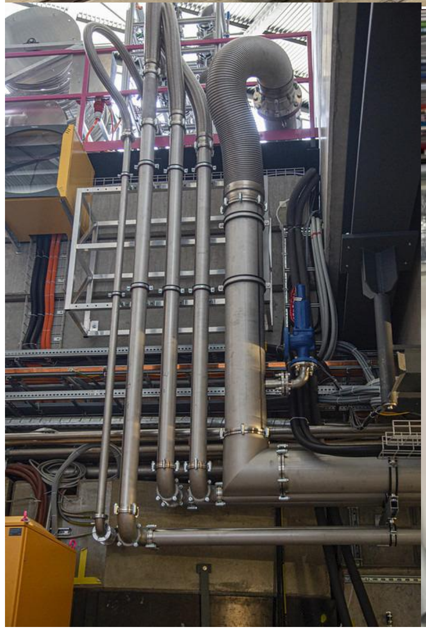
Backup

University of Zurich[UZH]

Helium cooling

- Mass flow of several g/s provided to pixel detectors
- Based on novel industry technology transferred to science: Miniature turbo compressors
- 2 g/s circuit for Vertex Detector
- 16 g/s circuit for Outer Central Station





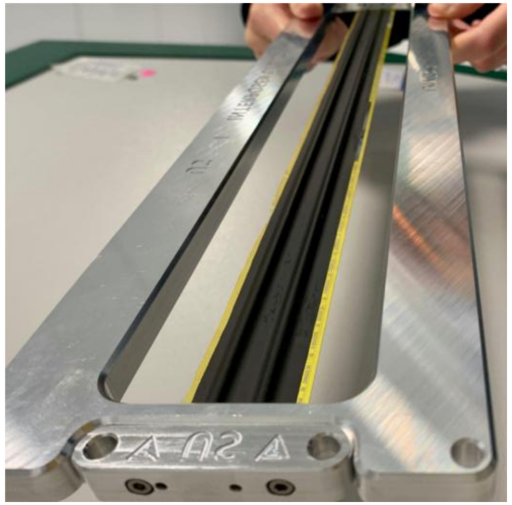
Outer Pixel Central station

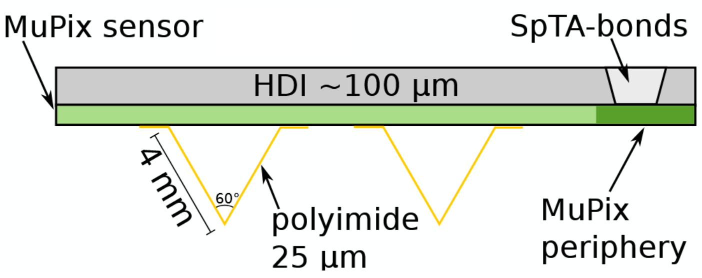
- 17 (18) x MuPix11 sensors in layer 3 (4)
  - 70µm thick sensors for Phase I
- 4 ladders per module
- 6 (7) modules in layer 3 (4)

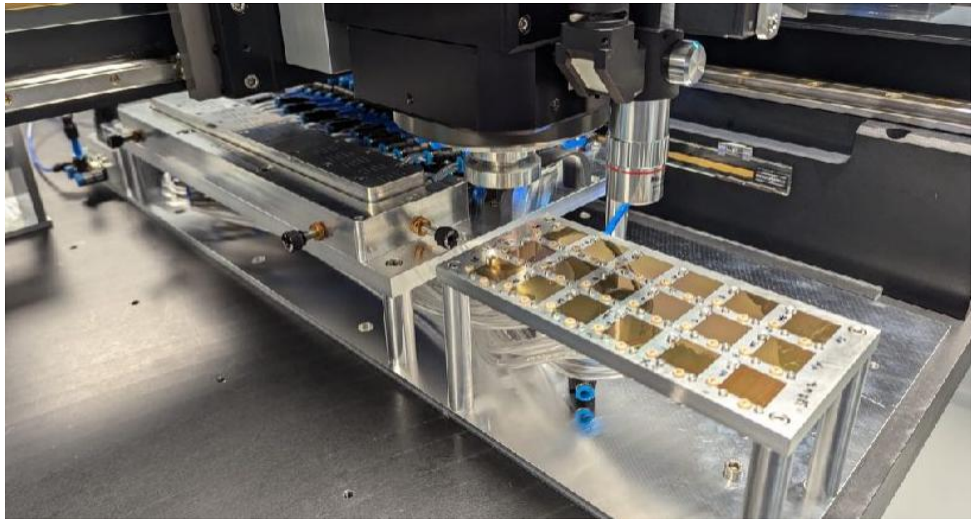
→ 52 ladders (912 sensors)

- 25 µm uni-directional carbon-fibre stiffner
  - very stiff along length (impact on yield and Transportation)

- Automate ladder building procedure as much as possible
  - Robotic gantry used for placement of chips
- Sensors are tested manually, but semiautomatic probestation is available







Towards physics in 2026