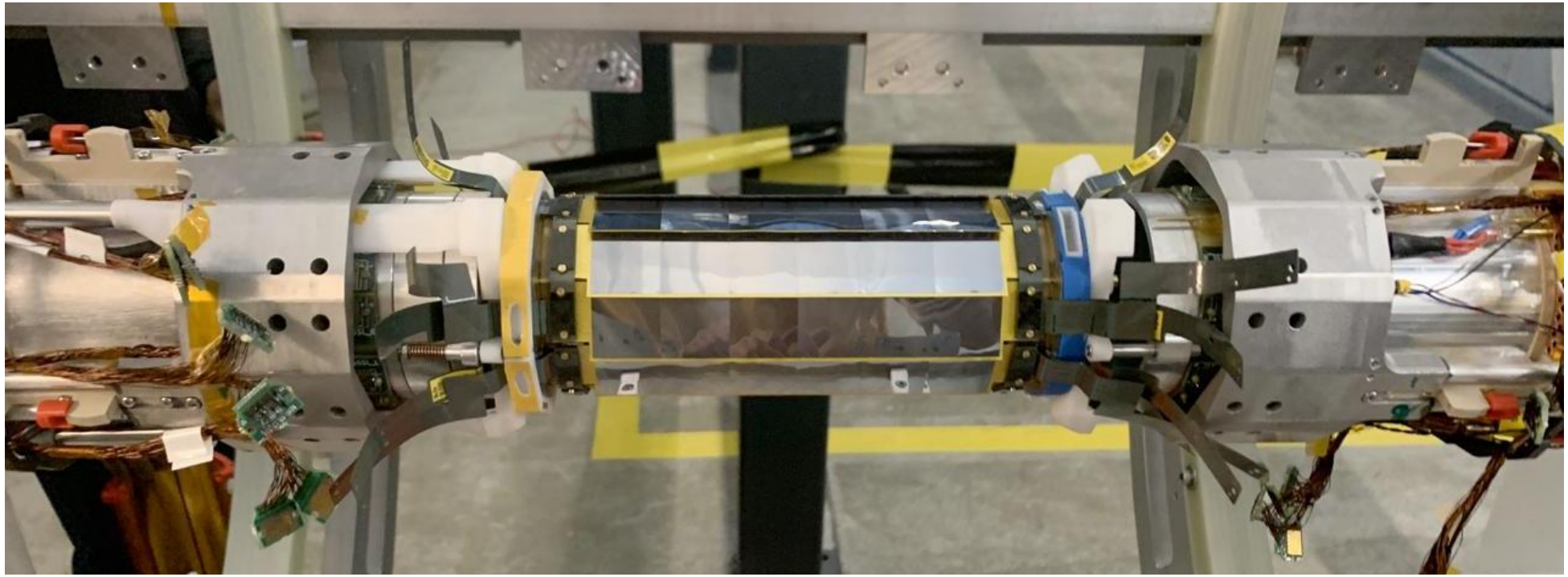
University of Zurich[UZH]

Physik-Institut

Construction and Calibration of the Mu3e Vertex Detector

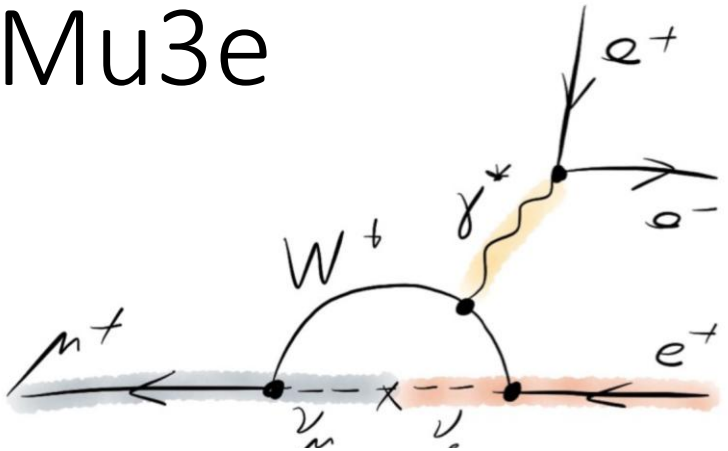


ÖPG-SPS Meeting

Vienna 2025

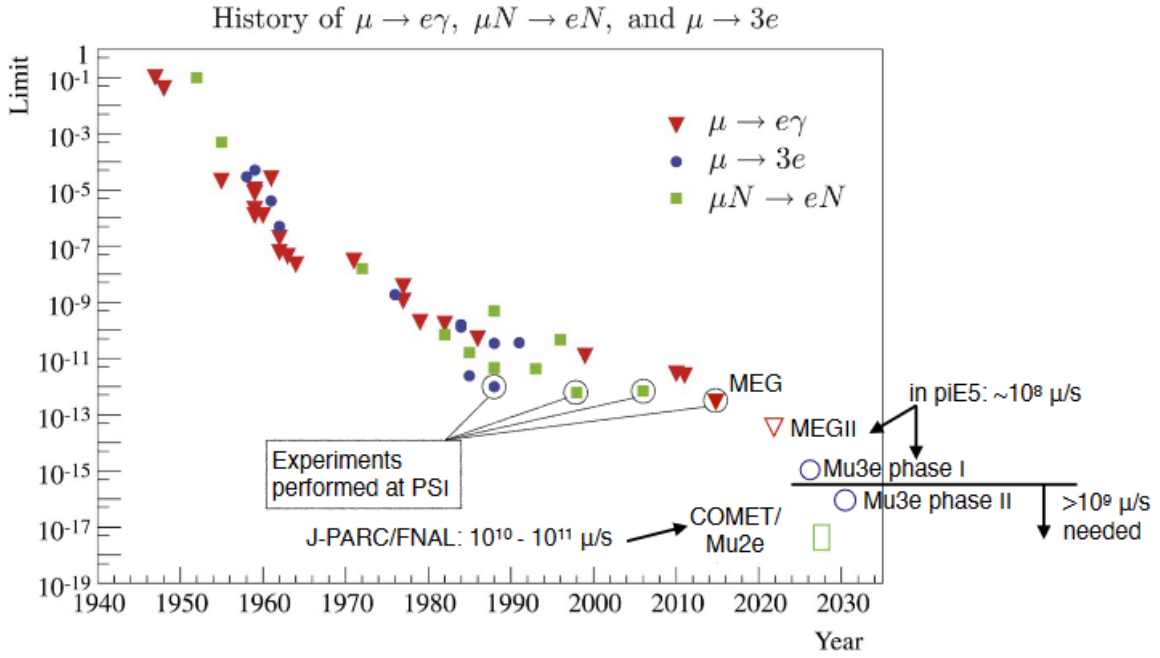
Thomas Christian Senger

Probing the standard model with Mu3e



- Search for the Charged LFV decay $\mu \rightarrow eee$
  - Highly suppressed in the SM + neutrino mixing
    - $\Gamma \propto \left(\frac{\Delta\, m_\nu^2}{m_W^2}\right)^2 \approx \mathcal{O}(10^{-54})$
  - Best current upper limit $\mu \rightarrow eee \approx 10^{-12}$ @90%C.L. from SINDRUM in 1988

- **Goal of Mu3e**
  - Improve limit by 3 to 4 orders of magnitude
  - $\mu \rightarrow eee \approx 2 \times 10^{-15}$ in phase I (Start 2026 -2029)
  - $\mu \rightarrow eee \approx 10^{-16}$in phase II (2029+)

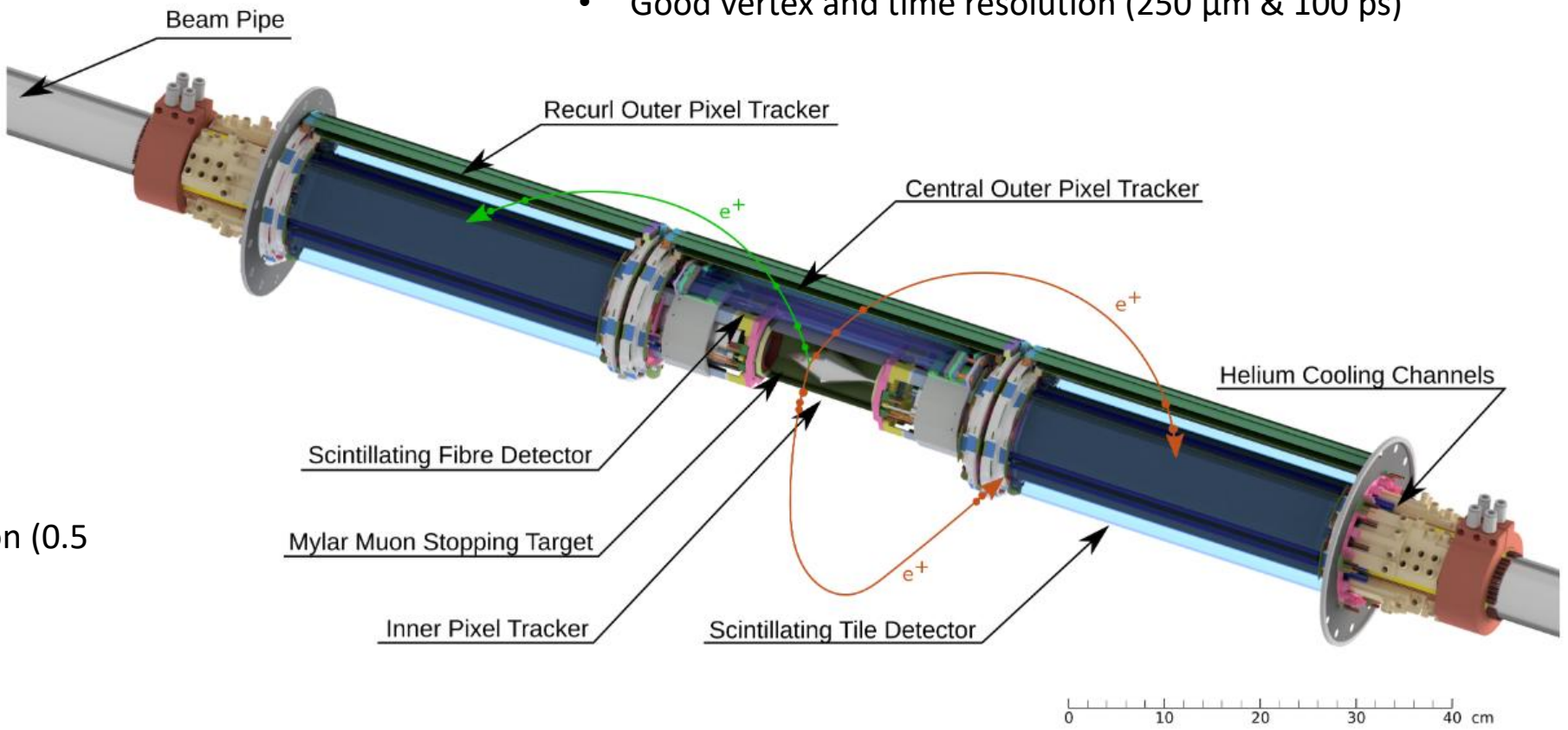


The Mu3e detector

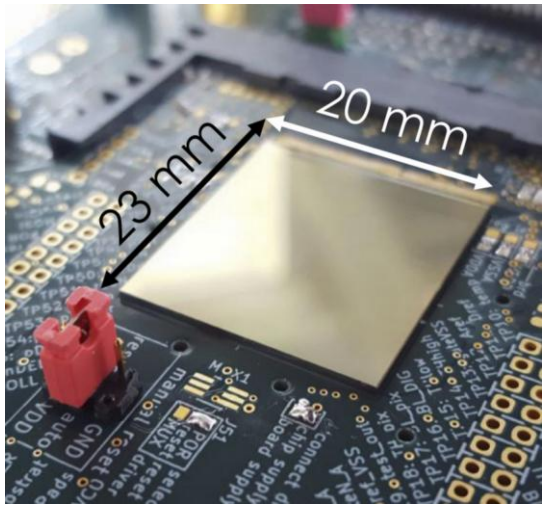
- Hollow double cone stopping target
- Homogeneous solenoidal magnetic field (1T)
- 10^8 muon decays per second with continuous beam

- 4 layers of pixel sensors
- Helium Gas Cooling
- Excellent momentum resolution (0.5 MeV/c)

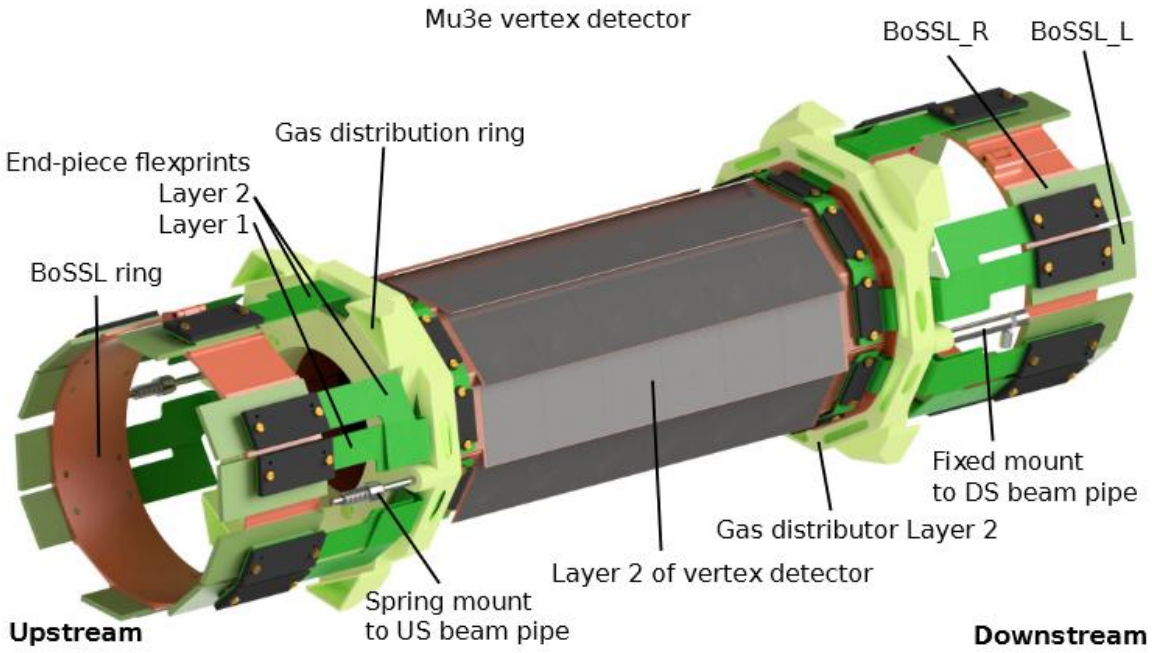
- Scintillating fibres and tiles
- Good vertex and time resolution (250 µm & 100 ps)



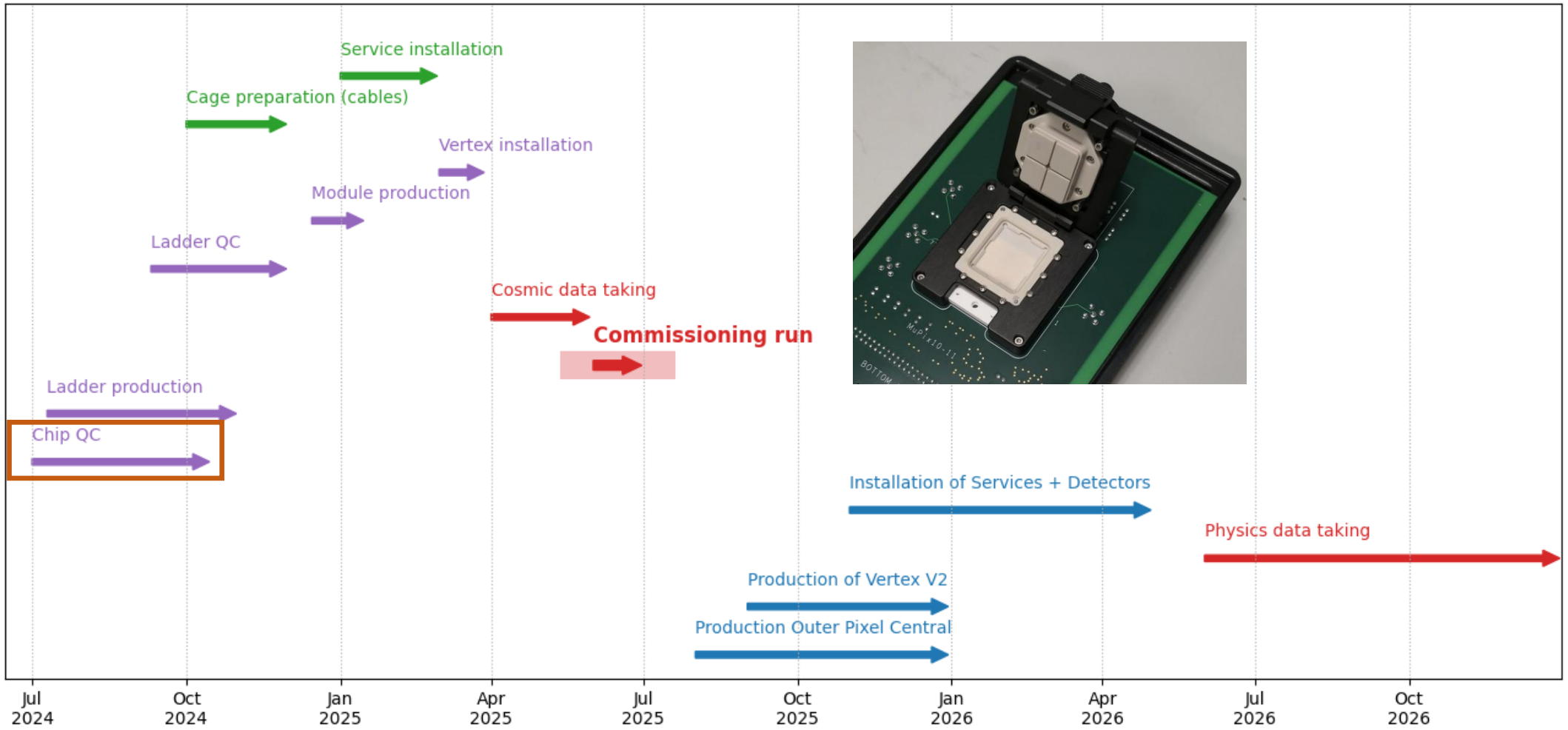
Mu3e Vertex Detector



- Two layers of **50µm** thin Mupix 11 pixel sensors
  - High-Voltage Monolithic Active Pixel Sensor (HV-MAPS)
  - Detection and Readout combined in one chip
  - Fully digital 1.25Gbit/s LVDS output
  - 99% efficiency with less than 20ns time resolution
- Mechanical support with least material budget as possible
  - $X/X_0 \approx 0.12$ % per layer
  - Aluminized Kapton interfaces
  - Sensors glued on foils + spTAB for electrical connection
- DAQ to sensor connection via micro-twisted pair cables and other flexes produced through standard processes



Timeline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Cage preparation (cables)
Vertex installation
Module production
Ladder QC
Cosmic data taking
Commissioning run
Ladder production
Chip QC
Installation of Services + Detectors
Physics data taking
Production of Vertex V2
Production Outer Pixel Central
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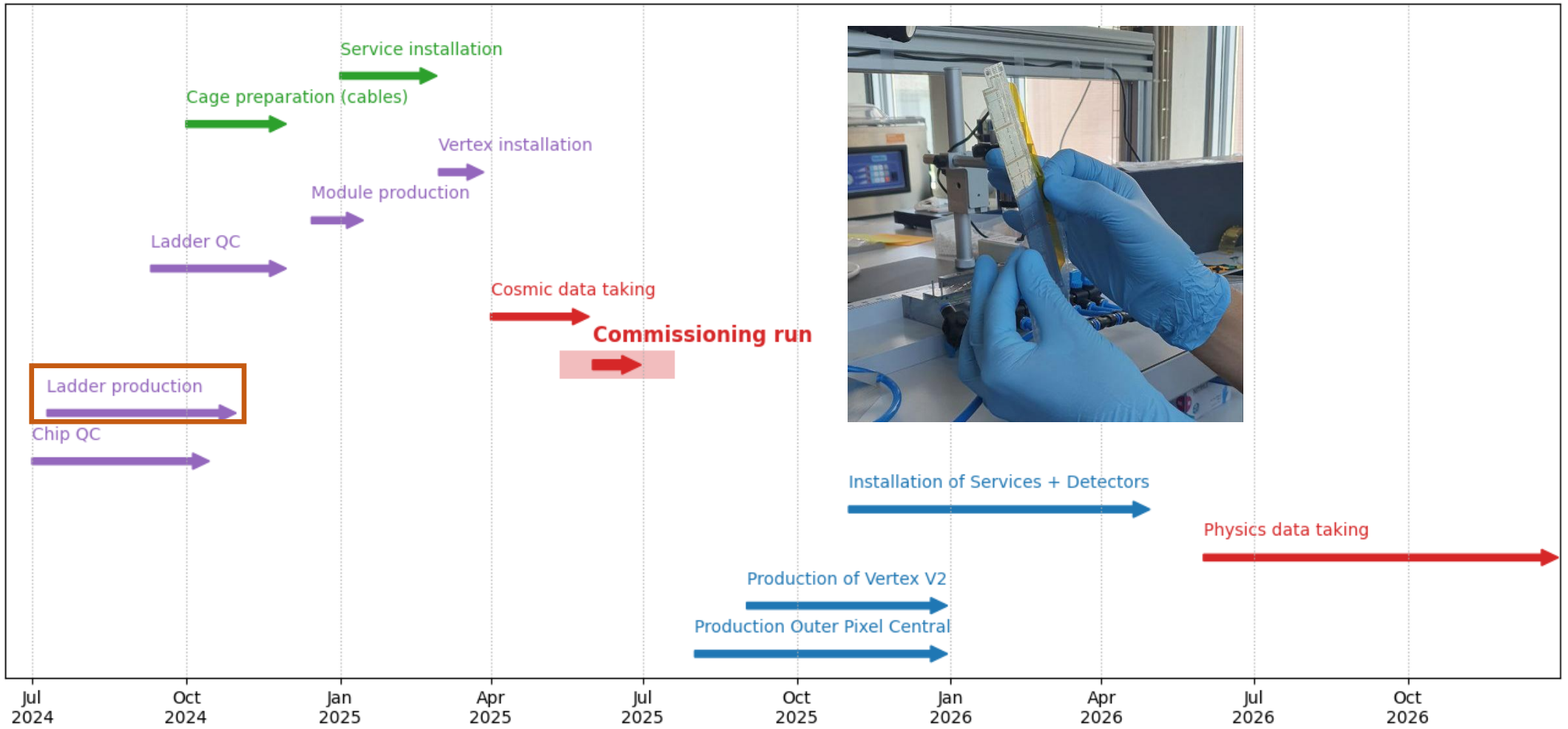
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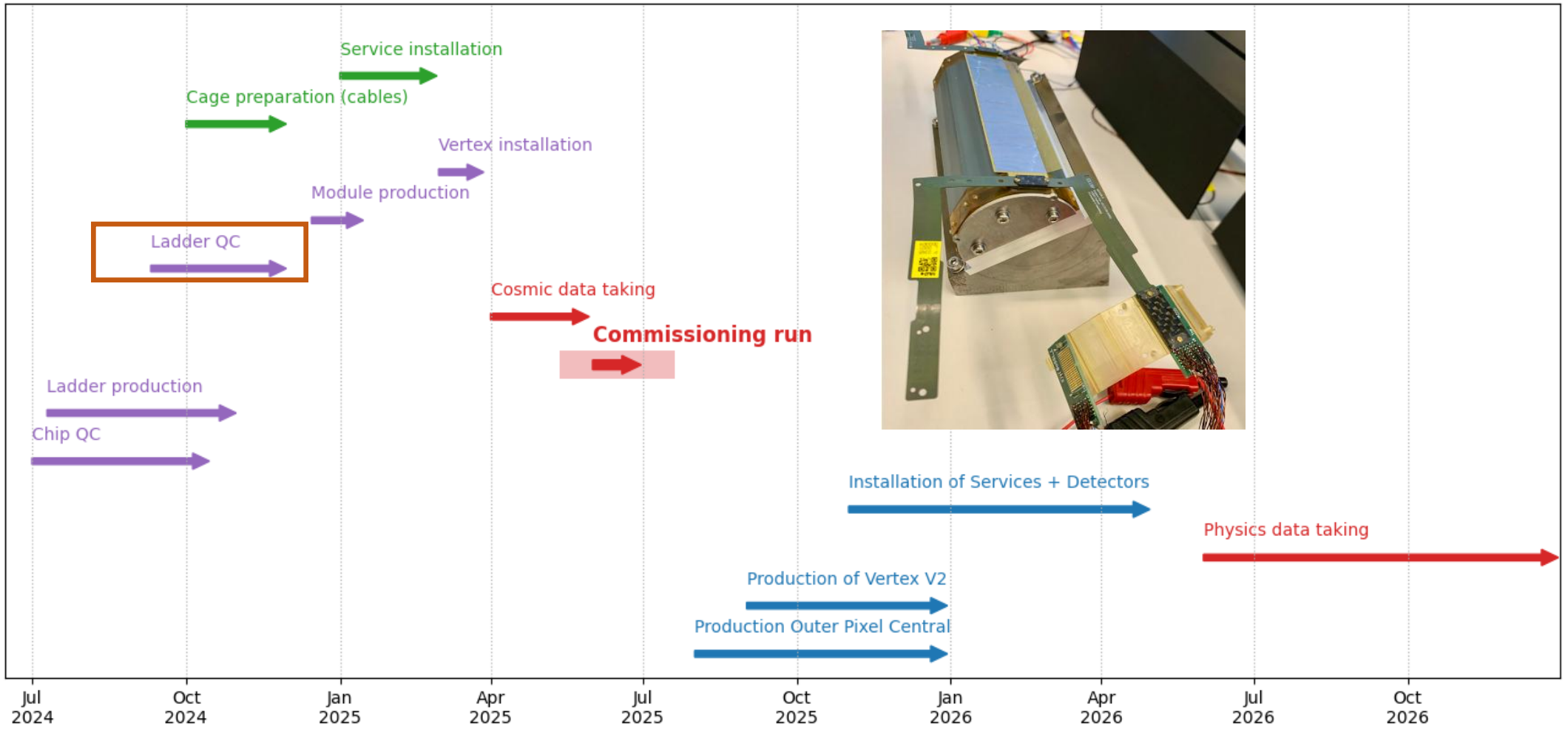
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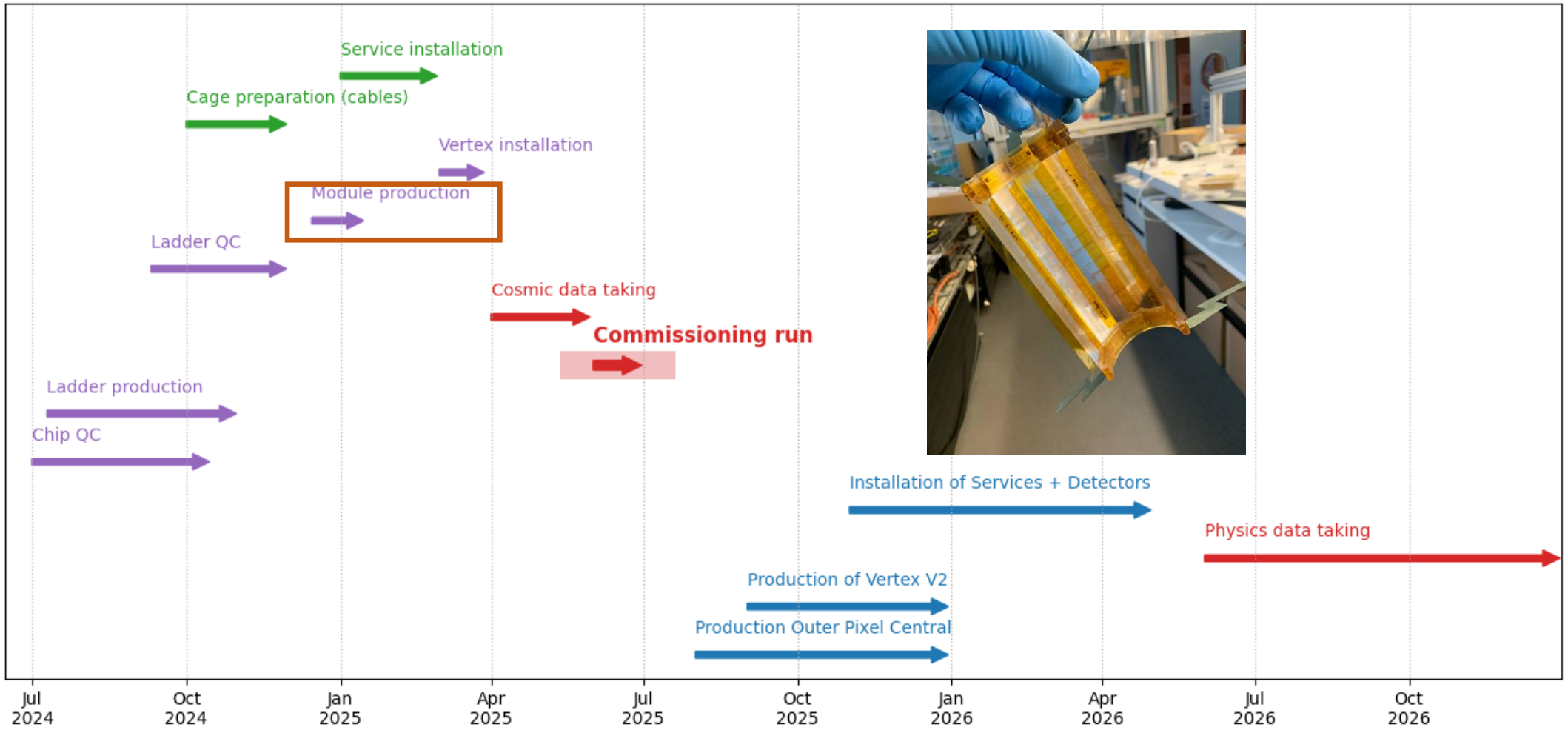
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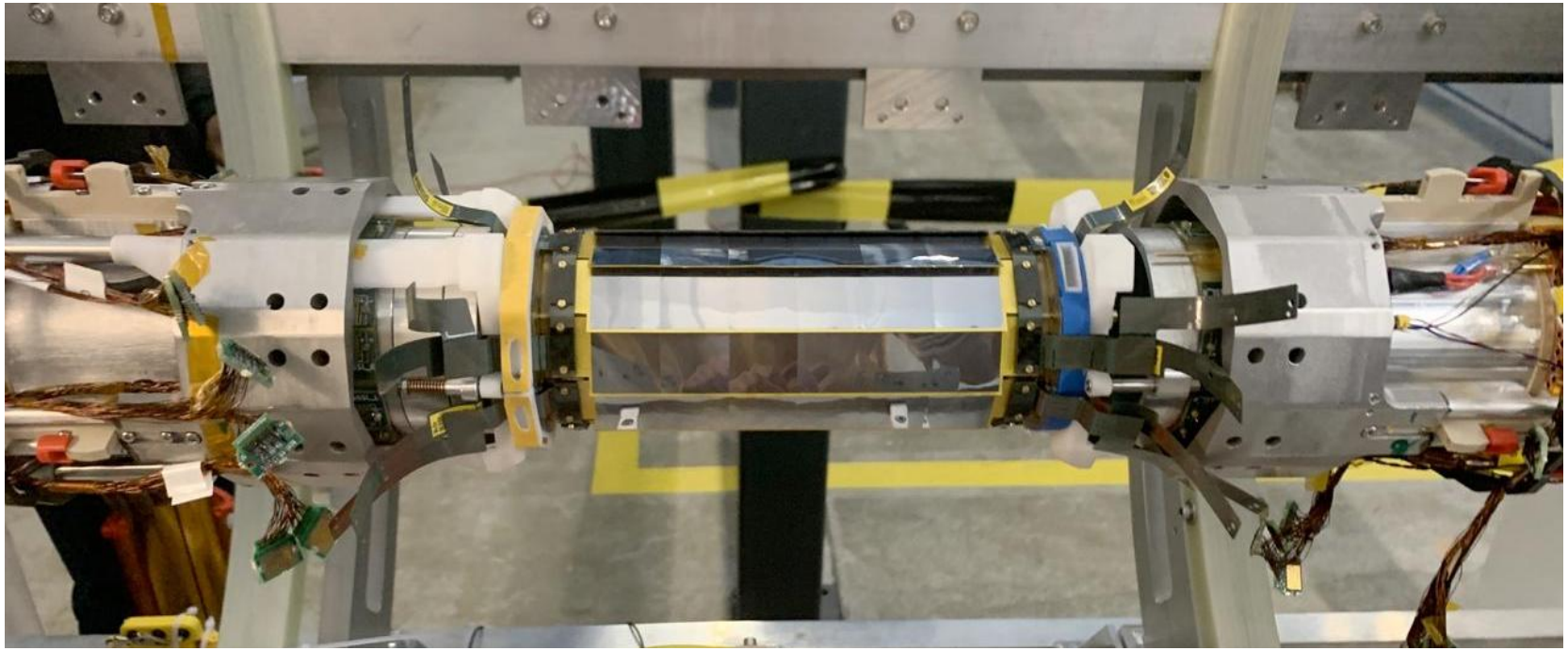
The Mu3e Vertex Detector



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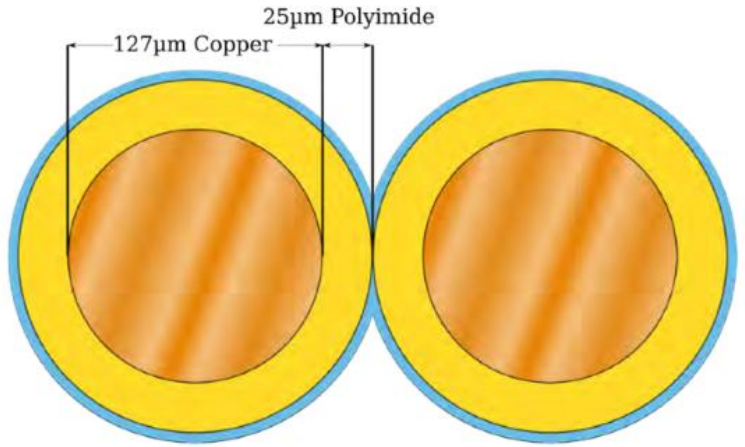
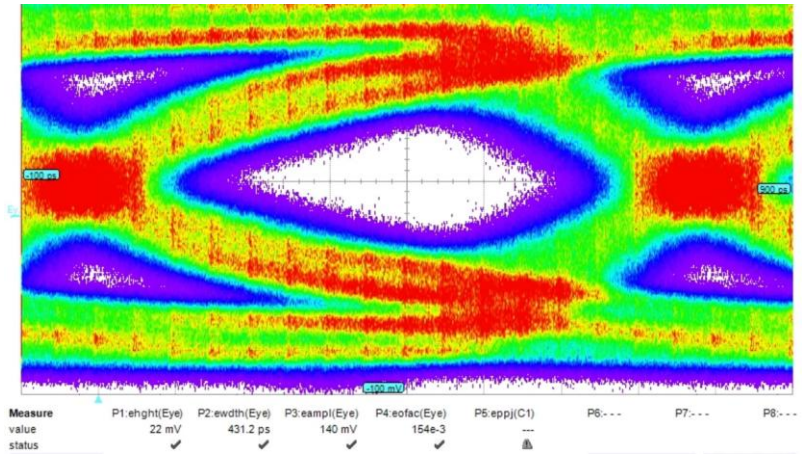
Calibration

Signal transmission challenge

- Need to transmit all differential LVDS data over µTP cables
  - Space limitations
  - Comparable to the thickness of a hair
  - Used in the CMS experiment at much lower data readout rate (Factor 10 lower)
- Huge challenge to transmit data errorfree
  - Loss of up to 70% of signal amplitude at maximum data rate (1.25 Gbit/s)
- Can be partially recovered through chip internal preemphasis (VNLVDSDel) + signal amplification (VNLVDS)
  - With increase of preemphasis eye opening factor increases, but Signal amplitude decreases
  - Signal amplitude saturates at certain DAC setting point
  - Higher settings increase power consumption on chip
- Designed Qualification test for each ladder to check for error free data transmission





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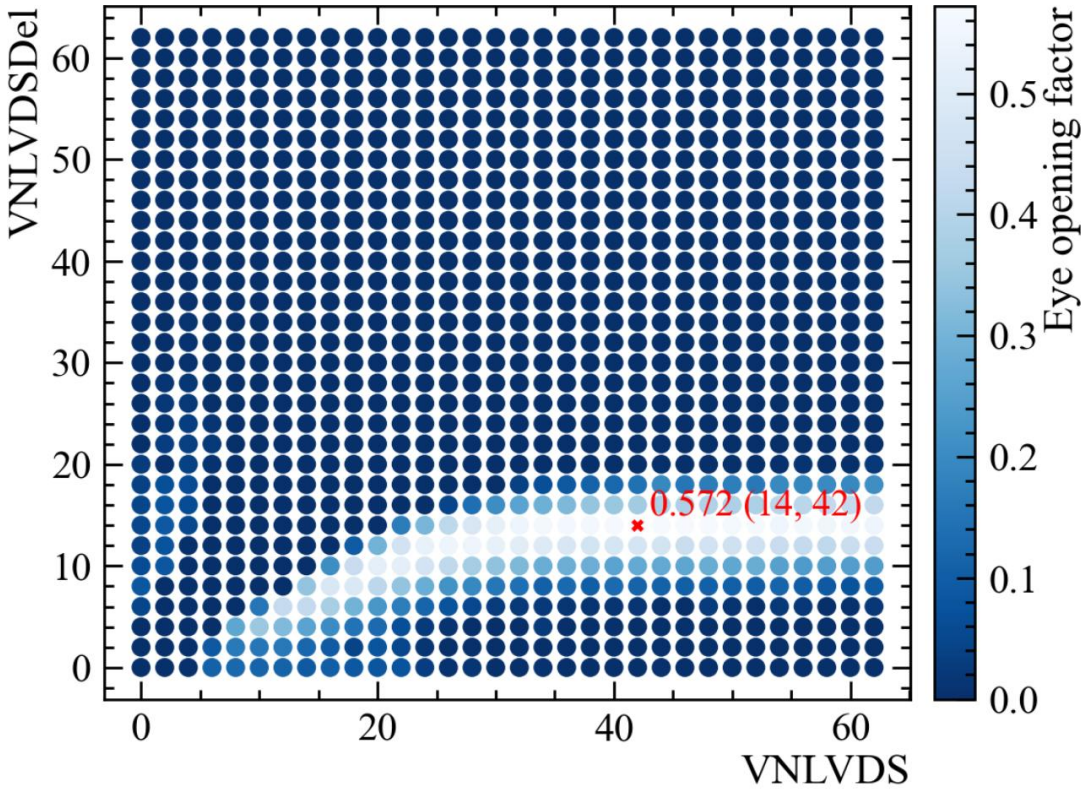
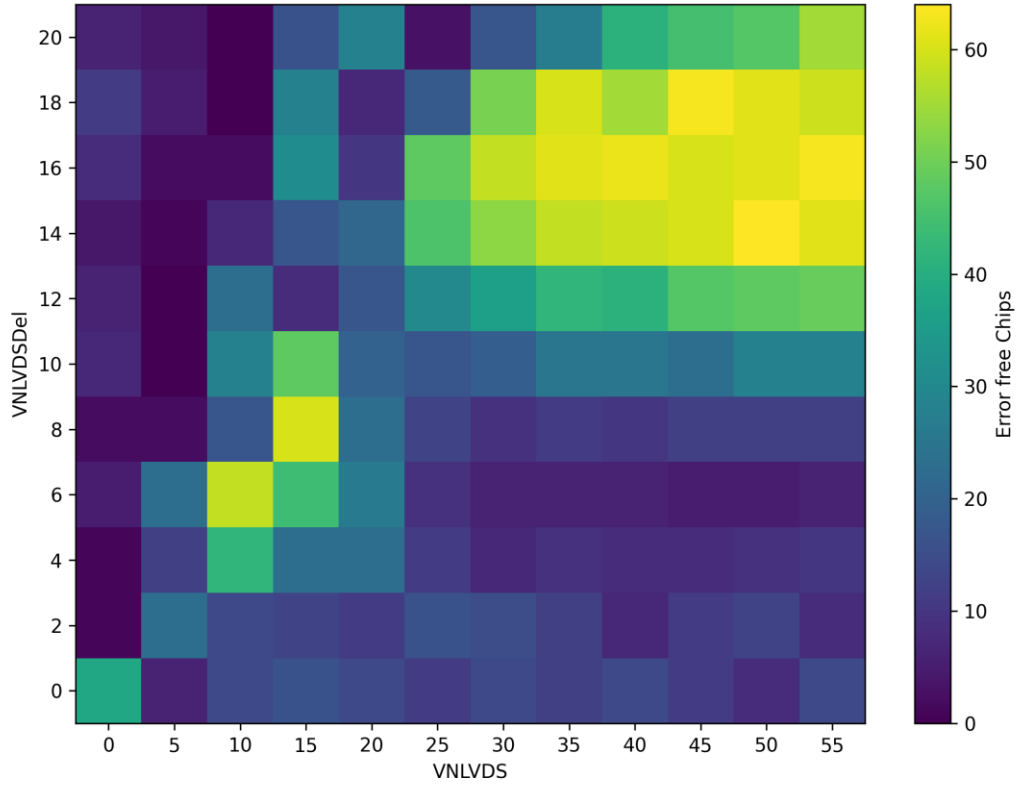
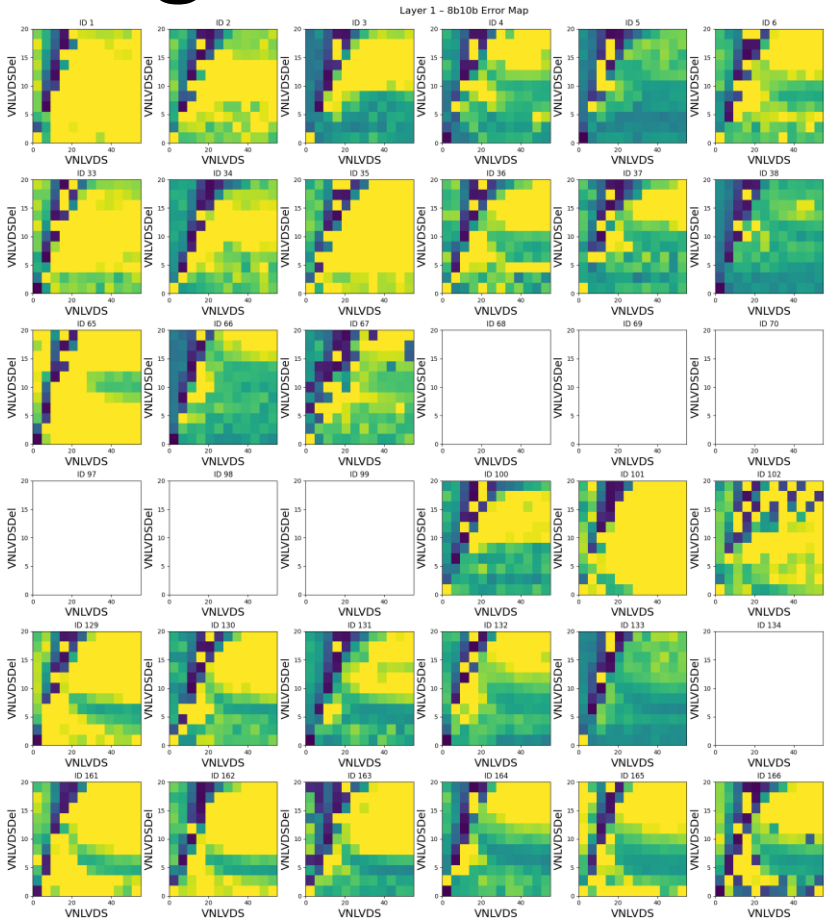


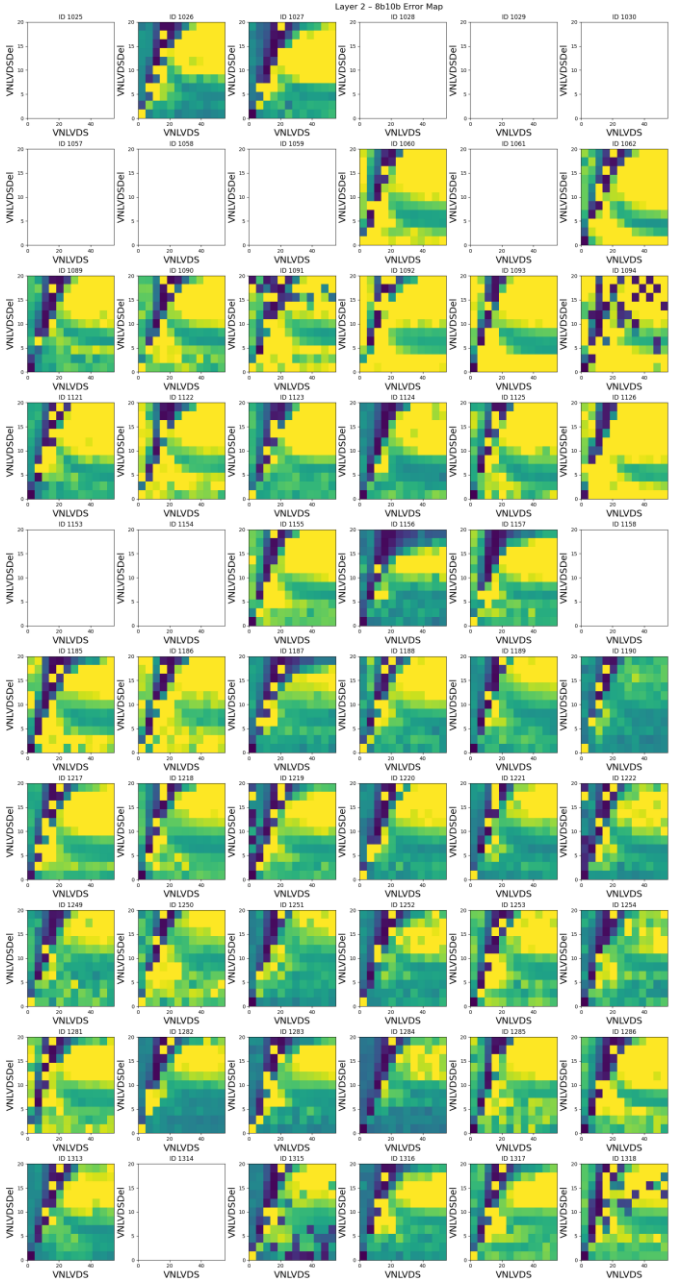
Eye diagramm measurement on a single ladder



Data transmission Scan results of the Vertex Detector

Signal transmission challenge





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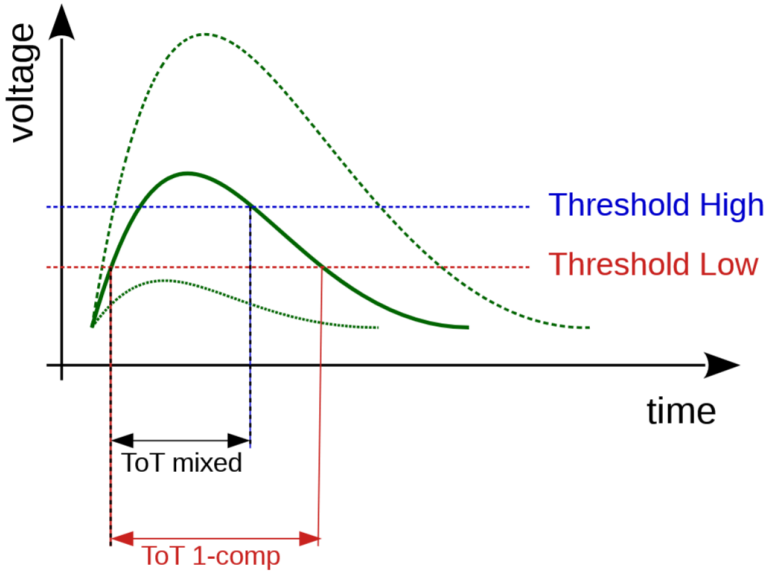
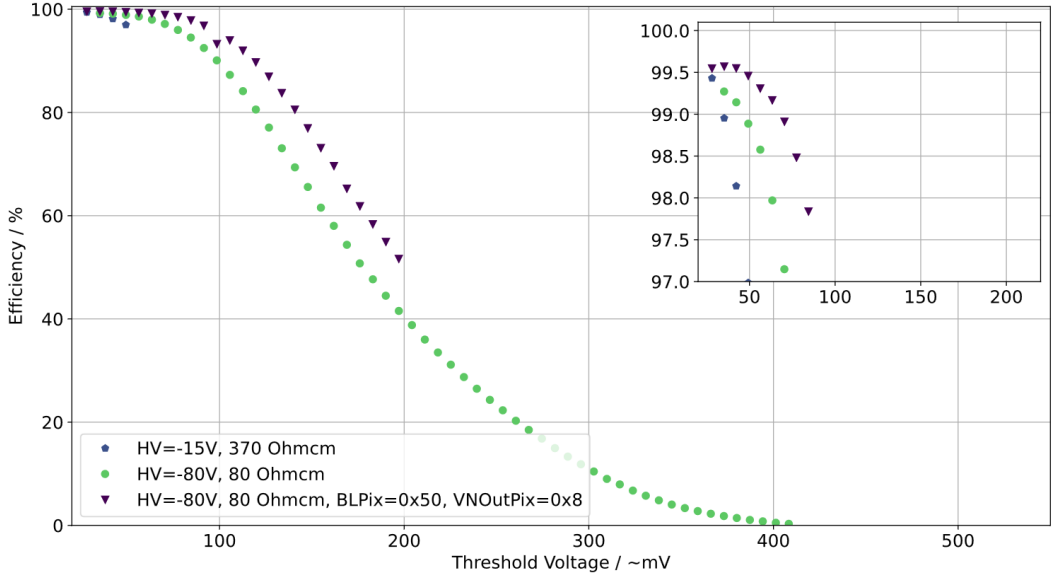
Pixel Masking and Tuning

Pixel Masking and Tuning

- Can set a global threshold per chip
  - Set **as low as possible** to detect small pulses
- Only small plateau region, where chip is operating efficient >99%
- 50 µm thin chips show noisy pixel at even higher thresholds
  - Thinning process
  - Mechanical stress through handling
  - Edge noise (under investigation)
- To reach low thresholds, pixels need to be masked
  - Every masked pixel lowers the total efficiency
- Chips become **unstable** at low thresholds
- In-pixel tuning is essential for operation with 50 µm thin sensors





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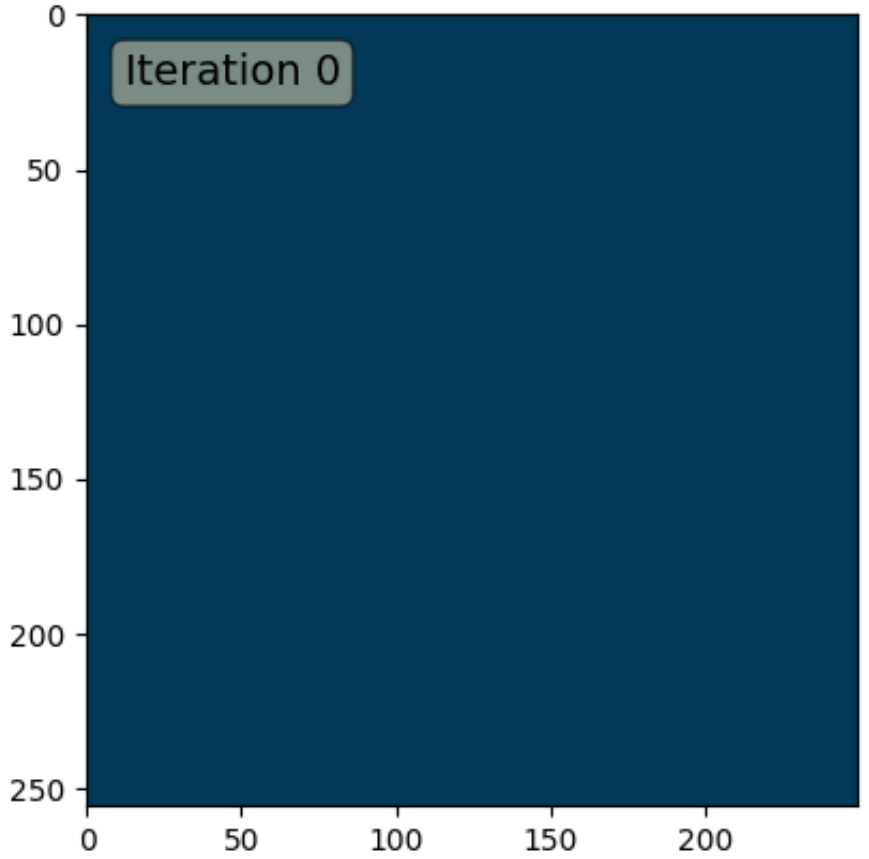
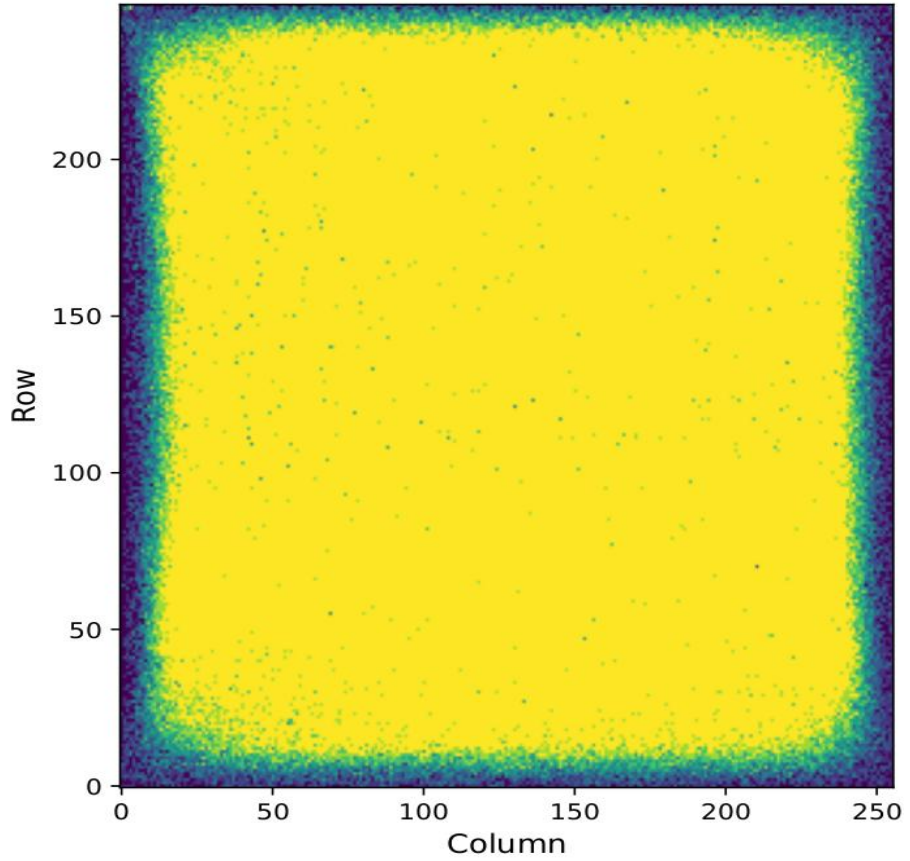


Pixel Masking and Tuning

- Would like to tune **all** pixels, but edge pixels dominate
- Strategy
  - Mask pixels above a certain threshold
  - Tune pixels below until target working point is reached
  - **Trade-off**: could tune more pixels, but tuning range becomes too coarse (3bit range, 8 values)
- Need to determine highest efficiency point per chip
- Full vertex tuning takes ~10 h
- At low thresholds: data errors (8b/10b,disparity, phase)

  → noise patterns visible
- Ongoing MuPix11 noise studies



Successful Commissioning of the Mu3e Vertex Detector

- All 108 chips installed
  - 75 % of the submatrices were operational
- **Thinnest** (0.12% X_0/ layer) **vertex detector currently operational**
- Many first times
  - We had to learn a lot
  - Were the first to build such a detector
- Planned from the beginning to use the first version for a commissioning run
- Will construct second Vertex Detector for physics data taking

	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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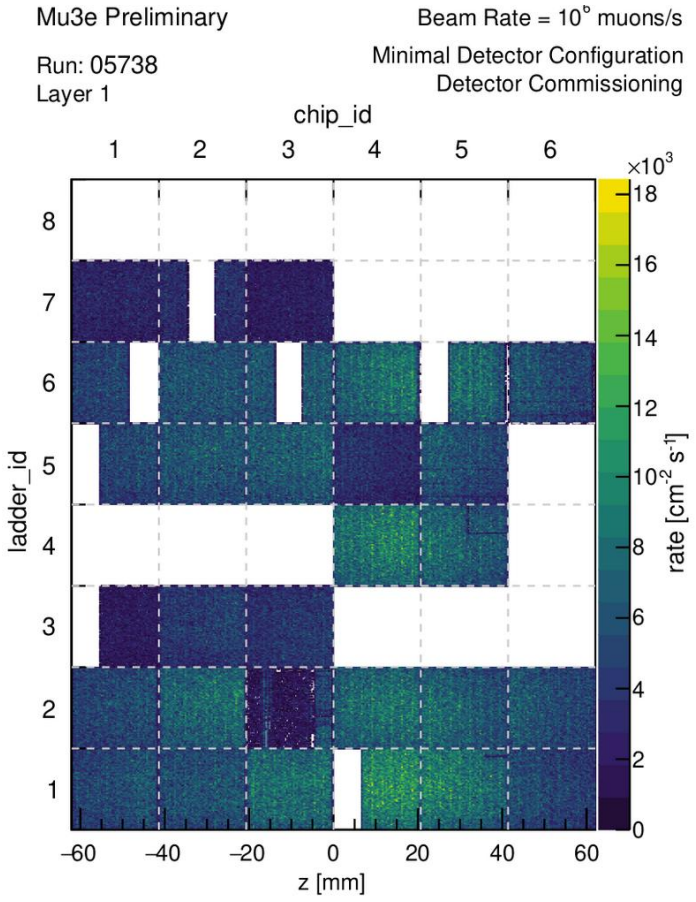
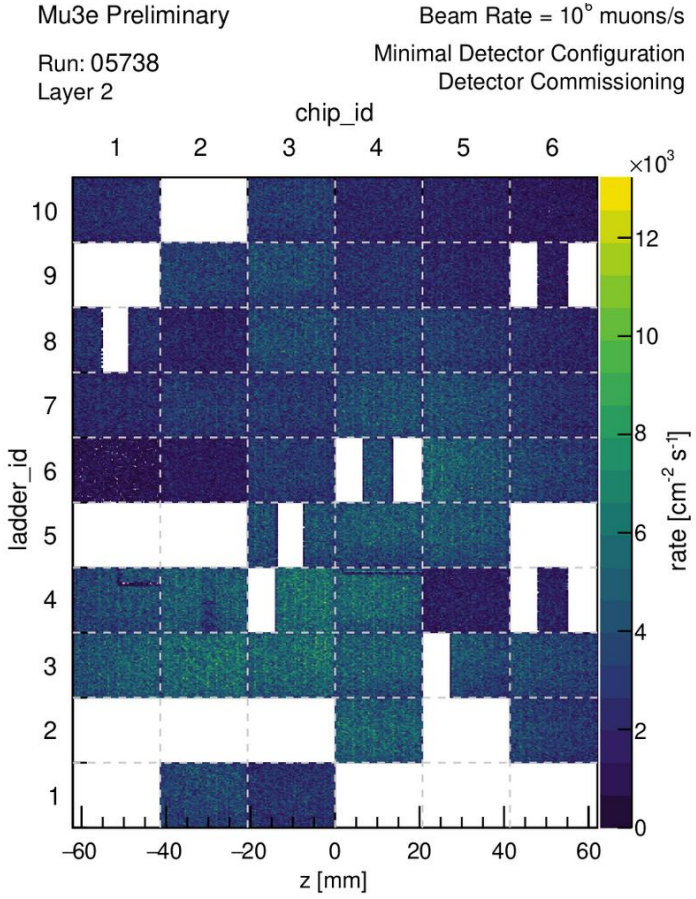
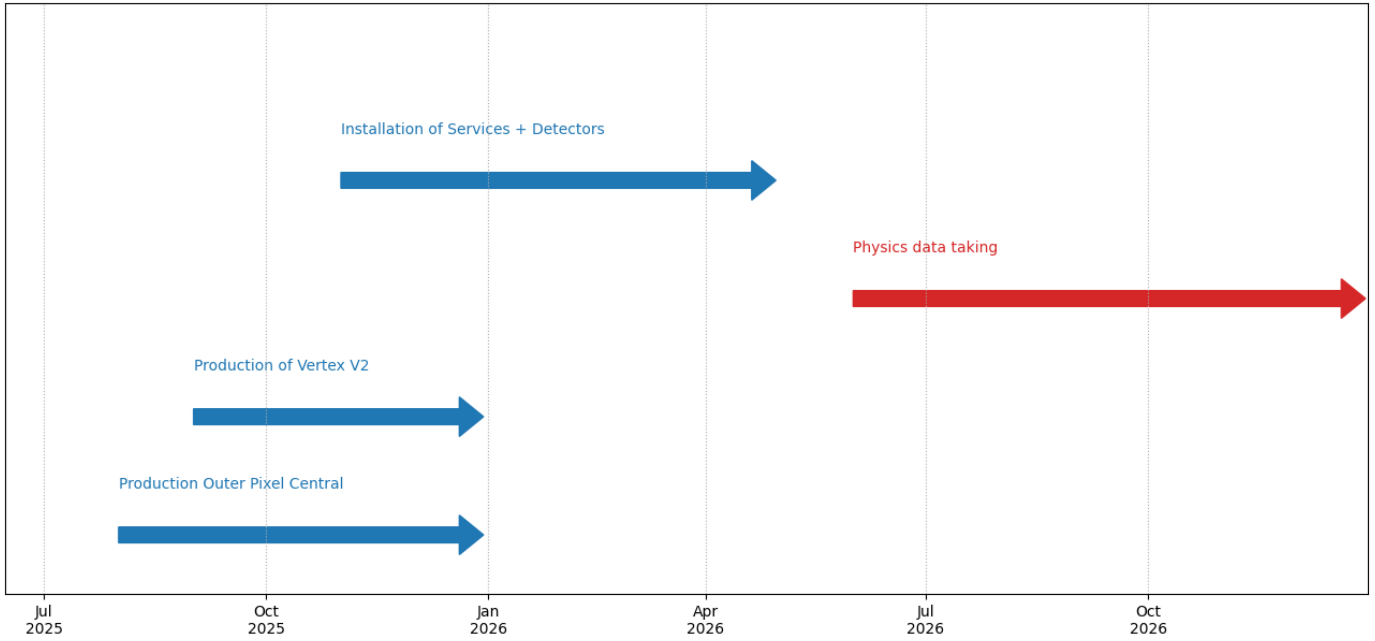




T.Kar

Summary and Outlook

- Successful 3 weeks of commissioning run in June with a minimal detector configuration
  - SciFi + SciTiles detector partially installed and commissioned
- Successfully reconstructed tracks after detector calibration + tuning
  - First analysis is ongoing
  - Results + publication will follow
- Second Vertex version and outer pixel layers are currently under construction
- Will aim to take physics data before the beam facility maintenance in 2027



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Thank you