Thomas Rudzki - PSI 1.10.2024
Exploring BSM physics with muons

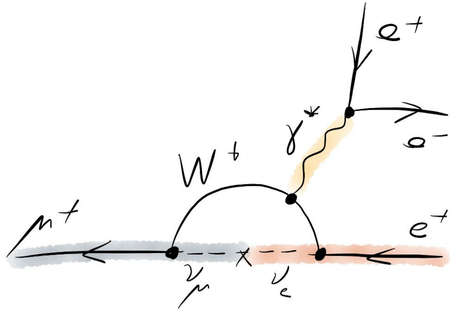
Mu3e

Probing the SM with a monolithic pixel tracker

Physics motivation

Charged lepton flavor violation (CLFV)

- LFV observed in neutrino mixing
- **Charged** LFV not yet observed
- μ decays are clean searches
  (only decay products ν, e, γ)



Standard Model $\mu \rightarrow eee$ decay, BR < 10^{-54}

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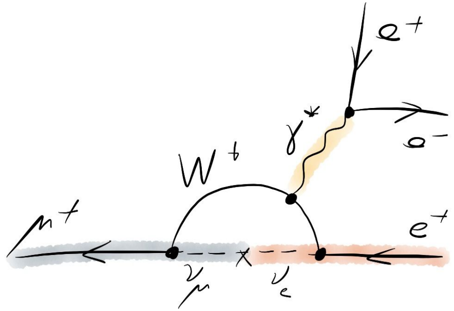

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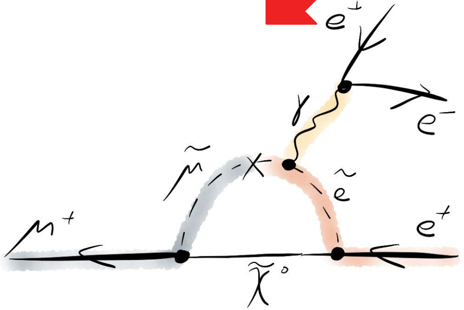
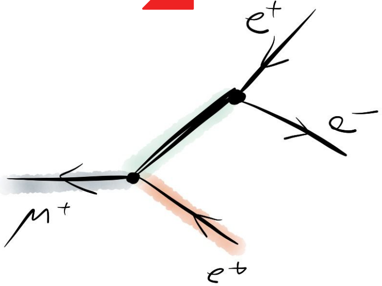
Physics beyond SM





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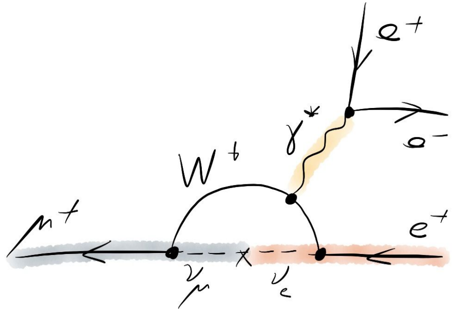
- **Charged** LFV not yet observed
- μ decays are clean searches
  (only decay products ν, e, γ)
- Sensitive to **beyond SM** loop & contact interactions
- Current Limit of $\boldsymbol{\mu^+ \rightarrow e^+ e^- e^+}$:
  SINDRUM: BR < 1×10^{-12}

Goal of Mu3e: Improve by 3 to 4 orders
to a SES of $2 \cdot 10^{-15}$
(~ 10^{-16} in Phase II)



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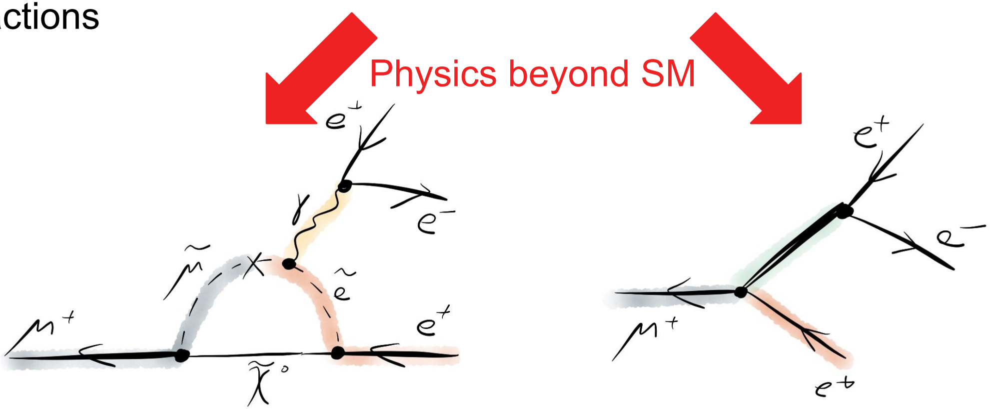
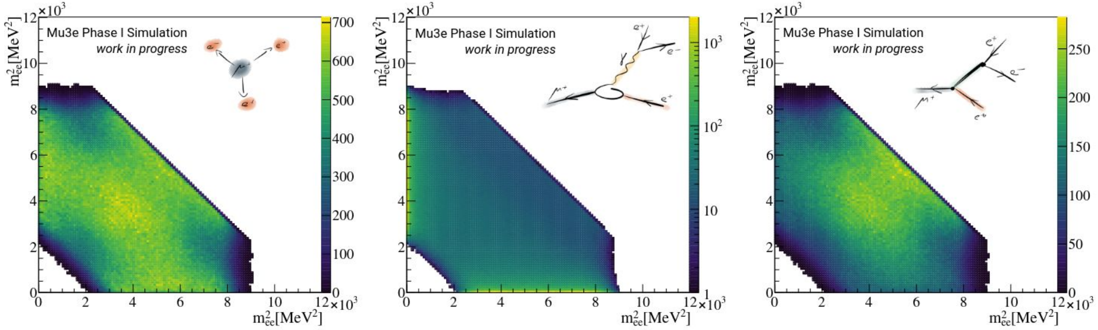


Complementary muonic CLFV searches

- **μ → e γ**
  - **MEG-II:** aimed sensitivity < 6 x 10^{-14}
- **μ → e**
  - **COMET/Mu2e:** aimed sensitivities < 10^{-16}
- **μ → eee**
  - **Mu3e:** aimed sensitivity ~ 10^{-16}

μ→eee offers 3-body decay kinematics:

- Phase space decay
- Potentially distinguish dipole and four-fermion interactions



A.-K. Perrevoort, https://doi.org/10.3390/psf2023008030

The Mu3e experiment

- **High muon rate** needed → 10^8 μ decays/s
- DC surface muon beam at PSI (πE5 beam line)
  - Low momentum, 28 MeV/c
  - Muons stopped on target
  - **Decay at rest**

For phase II:
➡ ≥ 10^9 μ decays/s at MUH2 beamline of HIMB upgrade at PSI
https://doi.org/10.1051/epjconf/202328201012

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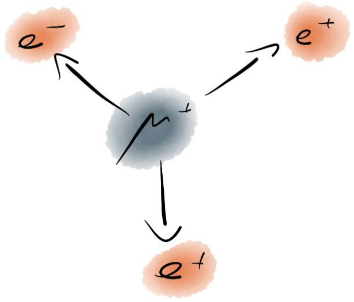
- **Signal decay: μ→eee**
    - Three prompt $e^{+/-}$
    - Common vertex
    - $\Sigma E = m_\mu$
    - $\Sigma \mathbf{p} = 0$



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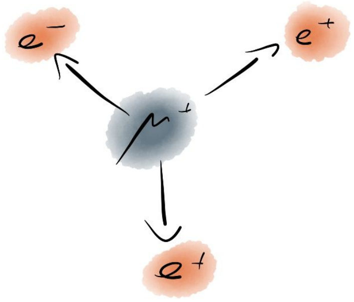
  - Internal conversion

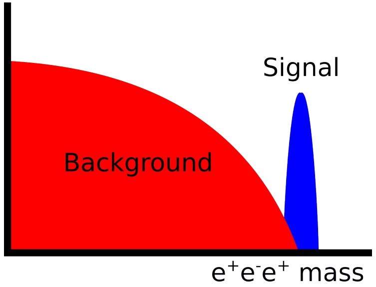


Signal decay

vs.

Internal conversion

Excellent momentum resolution needed
Max. momentum: 53 MeV/c
➡ resolution is **multiple Coulomb scattering limited**



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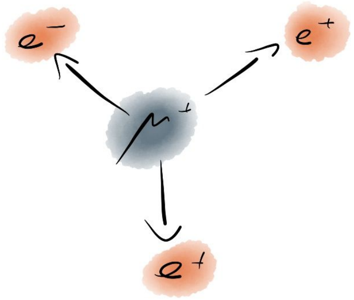

Signal decay

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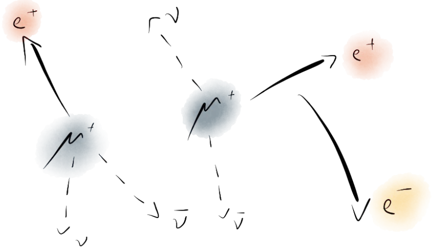

Michel e^+ & e^- from Bhabha or γ conversion

Time and vertex resolution
- Fast detectors
- High granularity

High rate capability

The Mu3e experiment

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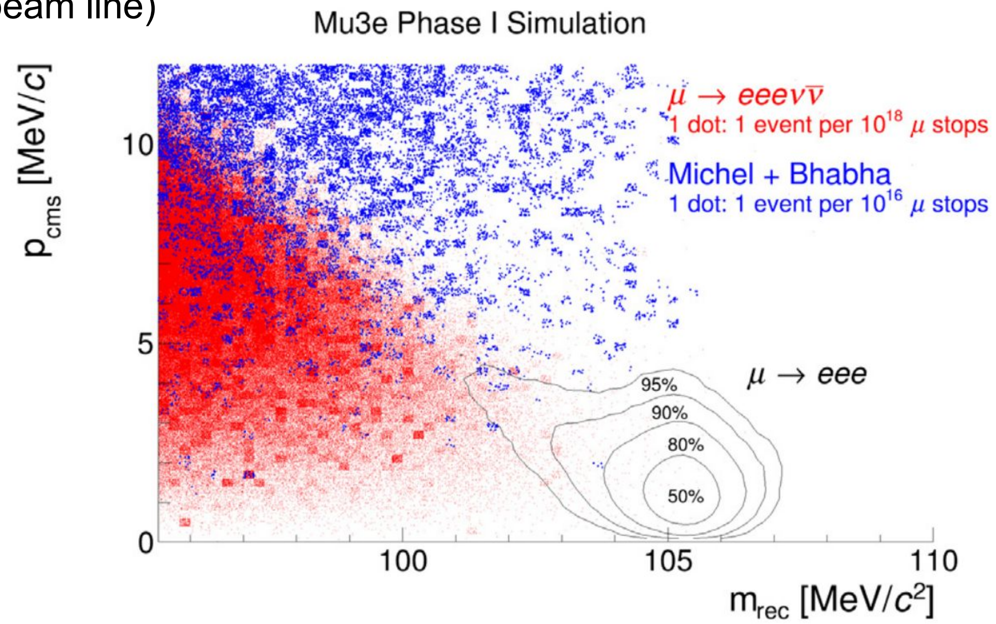
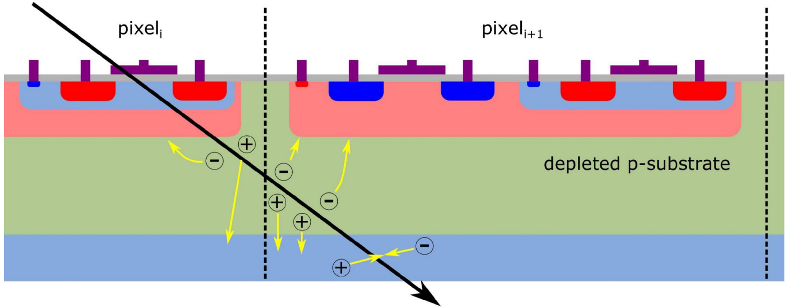


Mu3e TDR, https://doi.org/10.1016/j.nima.2021.165679

MuPix sensor

High-Voltage monolithic active pixel sensors (HV-MAPS)

- Monolithic: Detection and readout on the same chip
- In-pixel electronics
- Deep n-well diode
- Charge collection via drift (high voltage)
- Can be thinned to ≤ 50 µm



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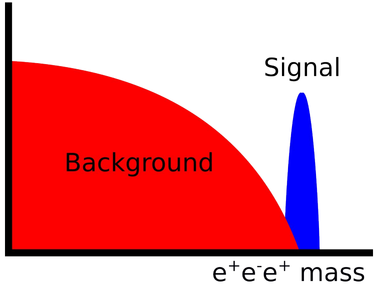

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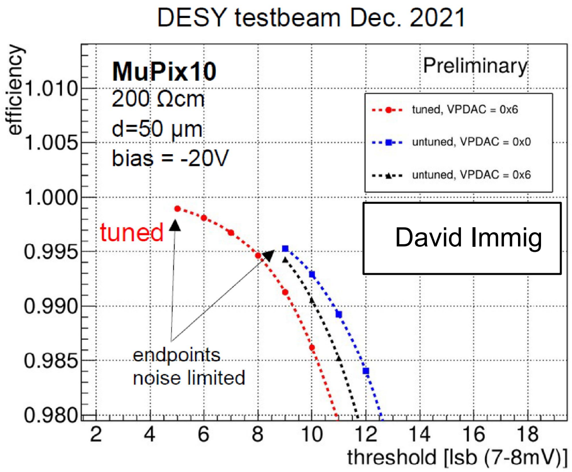
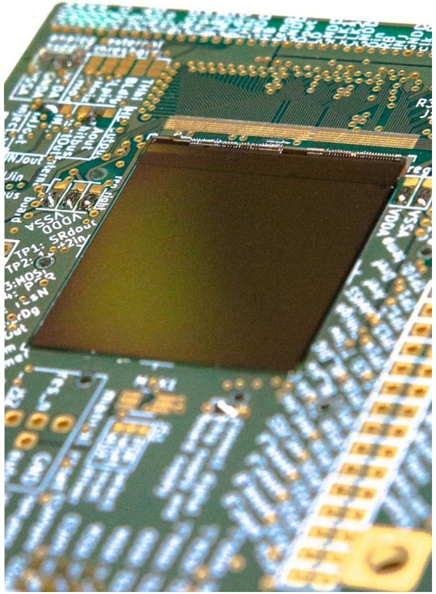
MuPix11

- Chip size: ~ 20 x 23 mm²
- Pixel size: 80 x 80 µm²
- time resolution < 20 ns
- Hit efficiency > 99 %

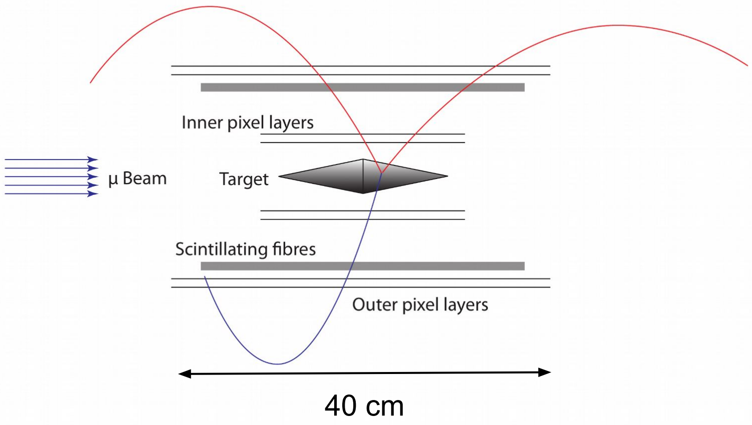




Detector design

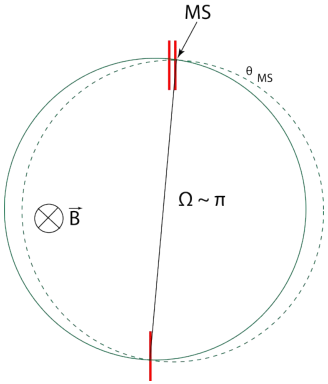
- 4x **pixel** tracking layers only ➡ minimize material
- 1T magnetic field

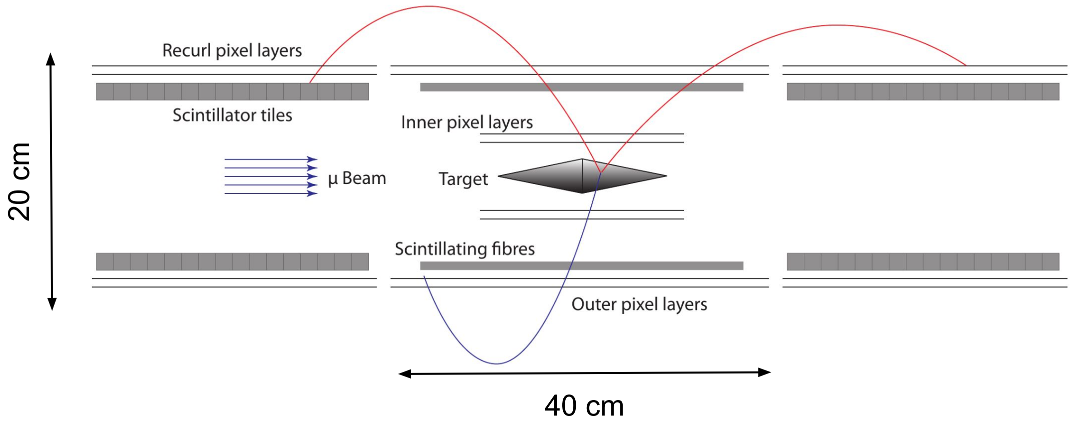
Mu3e solenoid



Detector design

- 4x **pixel** tracking layers only ➡ minimize material
- 1T magnetic field
- Recurl pixel station to get **optimal momentum resolution**
- **Fast scintillating fiber and tile detectors** for optimal timing resolution





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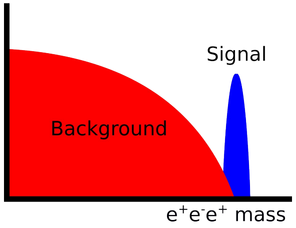


Time and vertex resolution
- Fast detectors
- High granularity

High rate capability

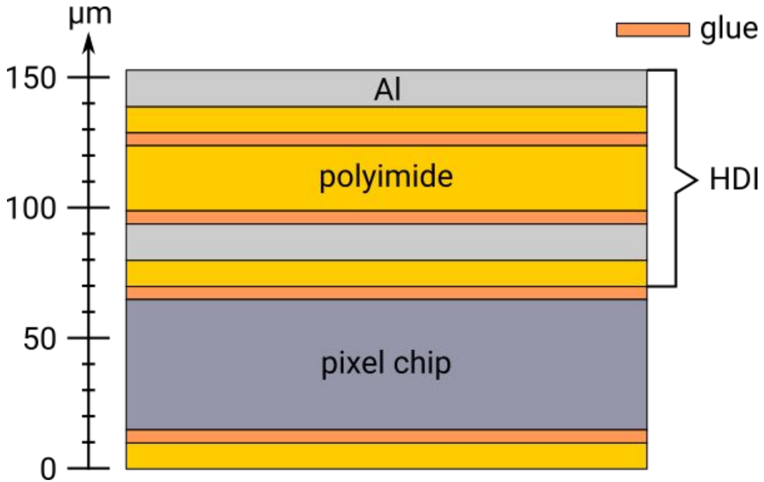
Low mass pixel detector

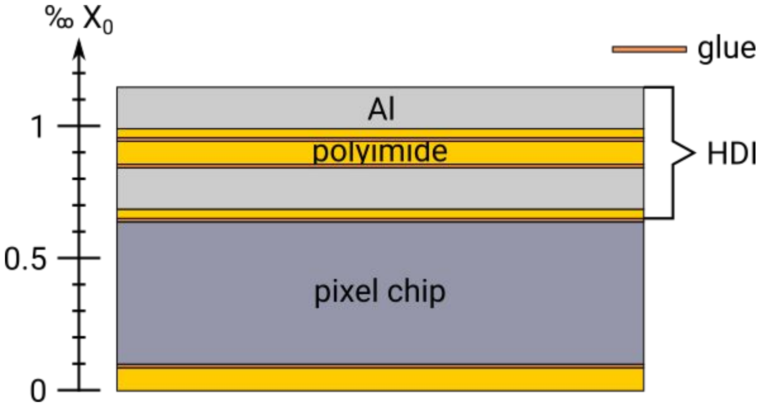
Detector composition:

- High-density interconnect (HDI) + HV-MAPS (50 µm thin)
- HDI = Aluminium-based flexprints
- $X/X_0 \approx 1.15$ ‰ per tracking layer

Aluminium vs. Copper

Radiation lengths
$X_0(Cu) = 12.86\ g/cm^2 \rightarrow 1.436\ cm$
$X_0(Al) = 24.01\ g/cm^2 \rightarrow 8.897\ cm$

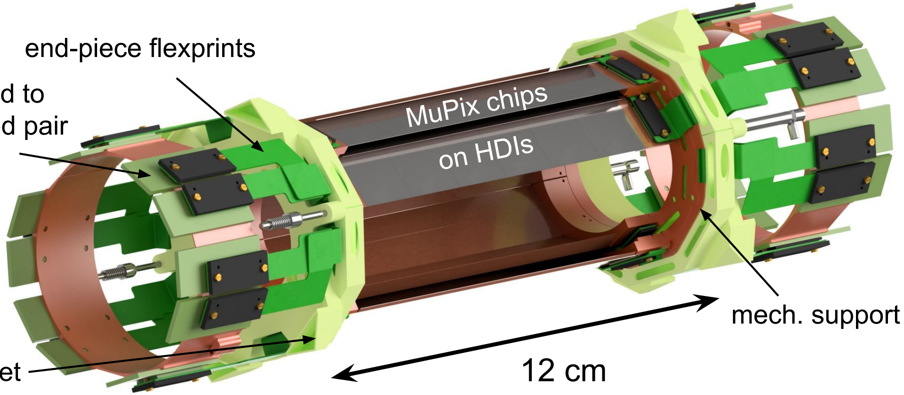




Low mass pixel detector

Vertex detector:

- Two innermost tracking layers
- 50 µm thin chips
- 8 / 10 ladders carrying 6x MuPix11
- 108 chips



Status:

- Production ongoing
- Ladders produced by HD in Oxford
- Ladder QC at PSI by HD/Uni Zürich
- Modules with both 380 Ω cm & 80 Ω cm MuPix11

  expected to be ready for cosmic run in November/December 2024

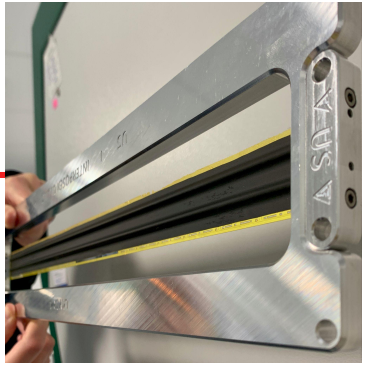
Low mass pixel detector

Outer layers:

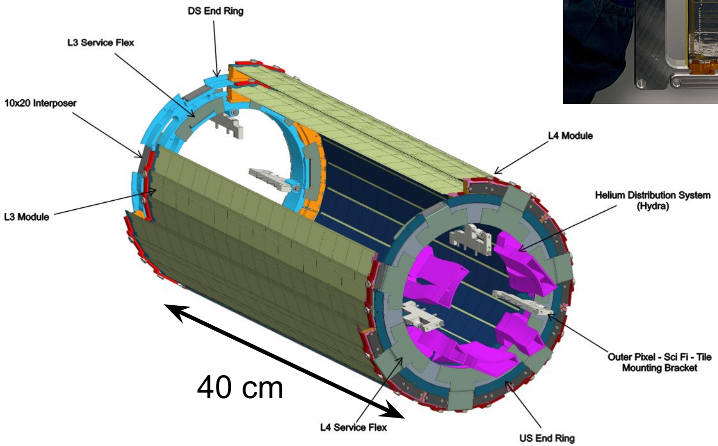
- Two outer tracking layers (central + recurl stations)
- 70 µm thin chips
- Ladders stabilized by 25 µm thin CFRP stiffeners
- 24 / 28 ladders carrying 17x / 18x MuPix11
- 2,736 chips

Status:

- Entered pre-production phase
- Production and QC in Oxford with support from Bristol
- Module construction in Liverpool
- **Expect central station within 2025**

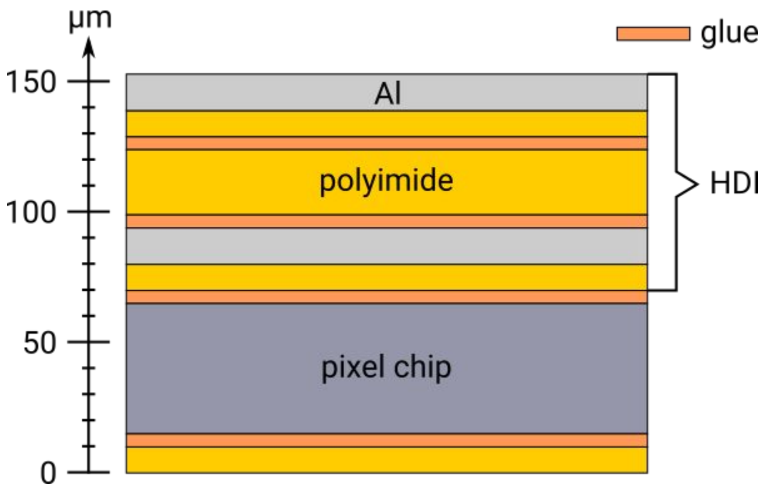


Mechanical prototype of a Layer 4 ladder supported by a CFRP stiffener



Low mass coolant

- MuPix dissipates ~ 215 mW/cm²
- Active cooling is required



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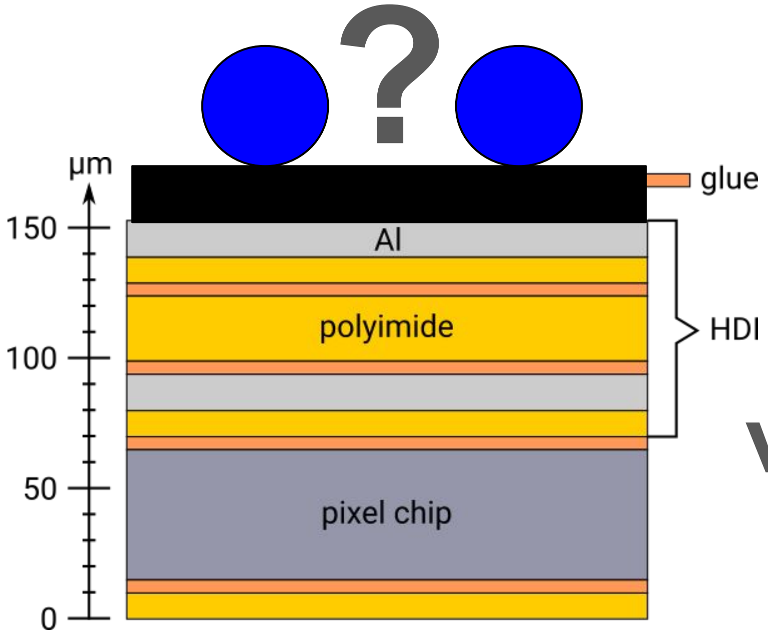
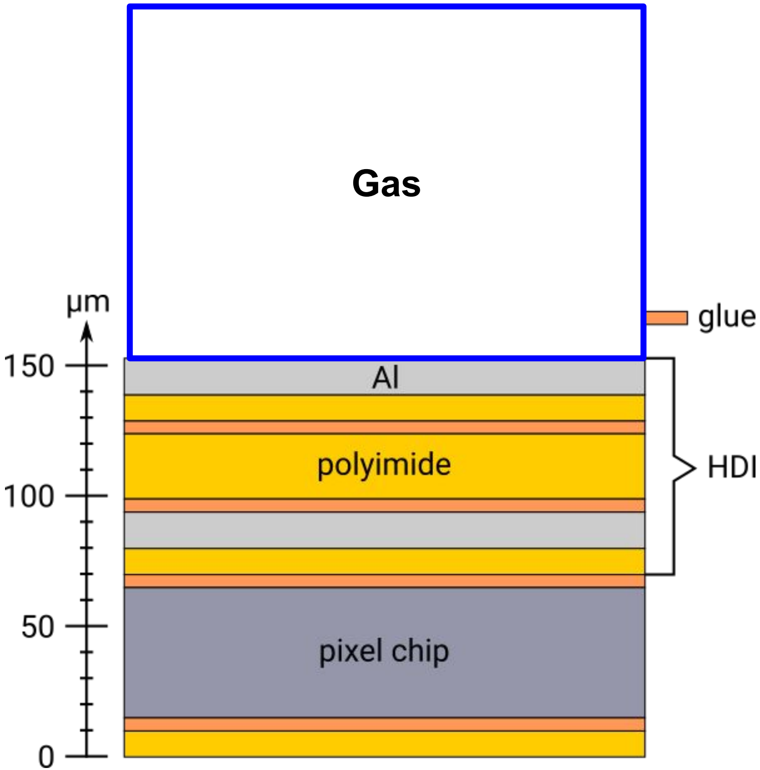
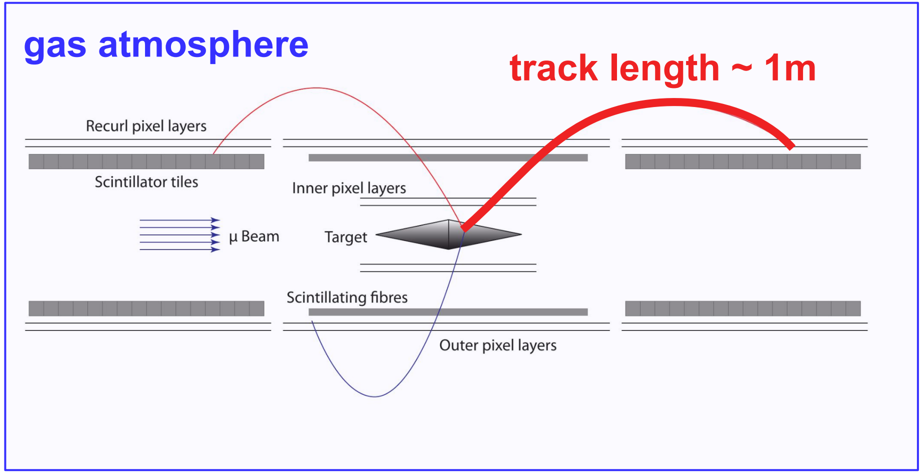


vs.



Low mass coolant → Gaseous helium

- Naive idea: Air cooling like at STAR PXL
- But: **Air is too much material!**
- 1 m of air corresponds to ~ 0.33 % X_0 ➡ equivalent to 3(!) more tracking layers
- **Solution:** Helium ➡ 0.018 % X_0 per meter



Helium cooling

- Providing a flow of a **few grams per second** of gaseous helium at **ambient pressure** is non-trivial
- Novel industry application in recent years: **Miniature turbo compressors**

Turbo compressor providing 16 g/s helium (from FISCHER spindle)

Helium cooling

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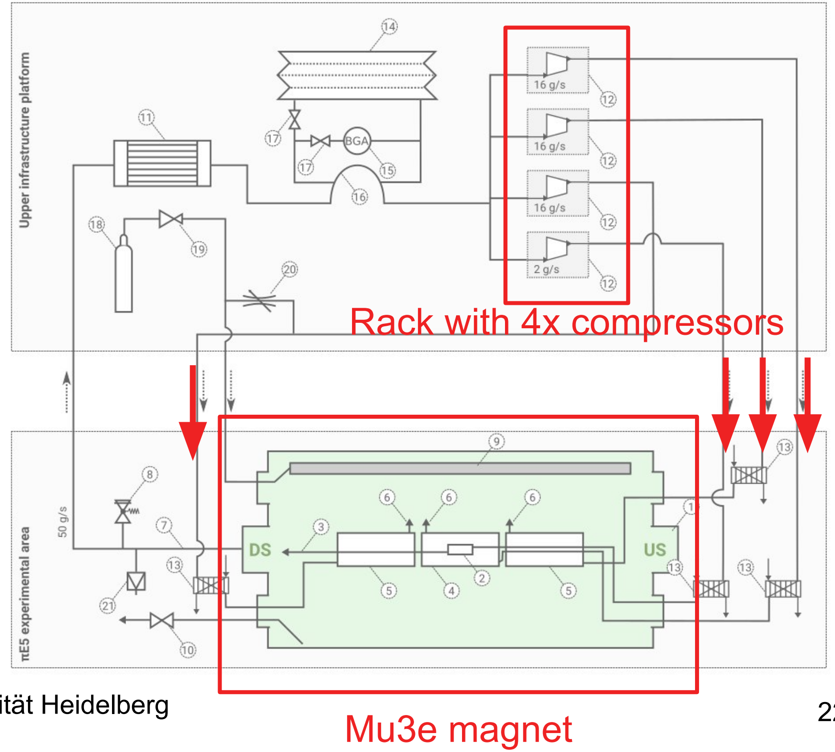
- Novel industry application in recent years: **Miniature turbo compressors**
- 4x pixel stations are cooled by separate circuits
  - 1x 2 g/s for the vertex detector
  - 3x 16 g/s for the outer layer stations
- All compressors **commissioned in 2023**



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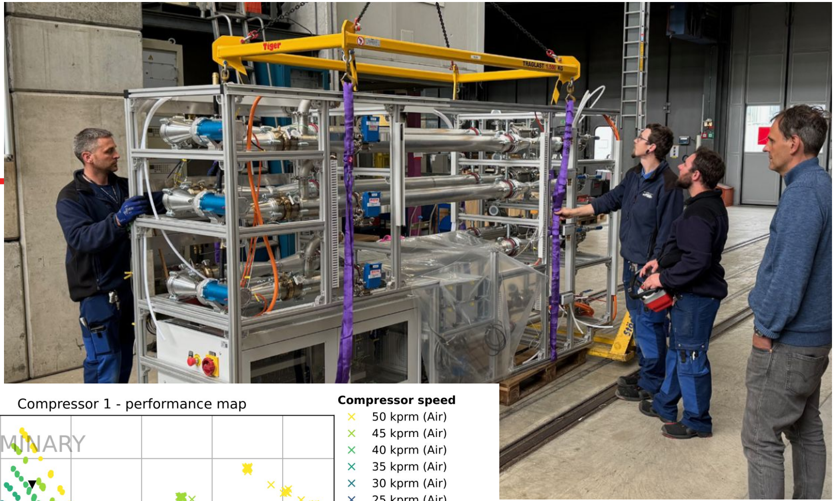
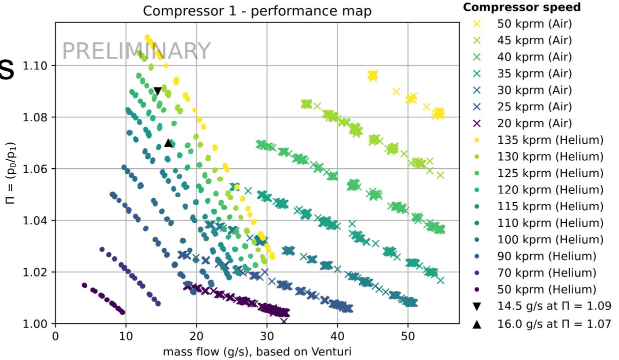
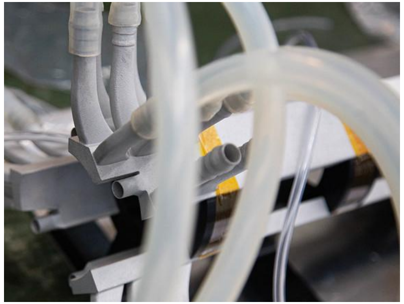


Helium compressor rack



Helium compressor performance map

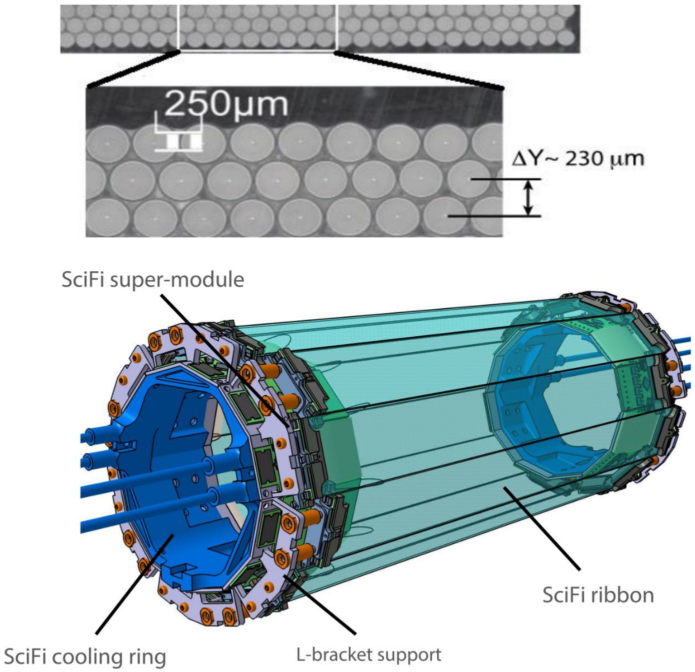


3D printed alumnium ducts to provide helium to the detectors

Timing detectors

Scintillating fibers

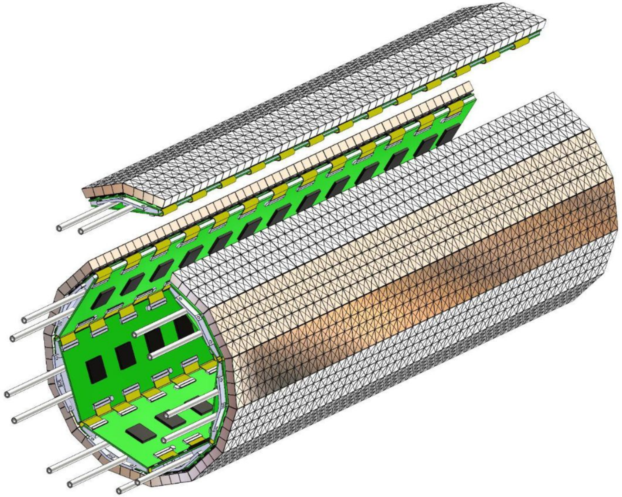
- 3 layers of 250 µm scintillating fibers
  - resulting material budget: $X/X_0 \approx 0.2$ %
- SiPM based readout with custom ASIC (MuTRiG)
  - 256 channels per SciFi ribbon
  - 3,072 channels in total
- Time resolution: < 500 ps
- SiPMs cooled below < 0°C to reduce dark-count rate
  - Silicon oil through cooling ring



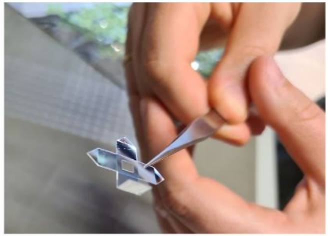
Timing detectors

Scintillating tiles

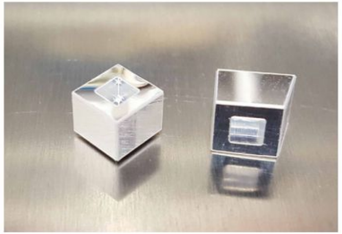
- ~ 0.5 cm³ scintillating tiles
  - no dedicated restriction on material budget
  - ~ 6000 tiles
- SiPM based readout with custom ASIC (MuTRiG)
- Time resolution < 80 ps
- SiPMs cooled below < 0°C to reduce dark-count rate
  - Silicon oil through cooling ring



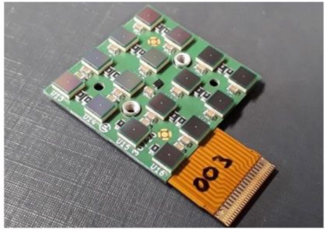
K. Briggl [Terascale Detector Workshop 2024]



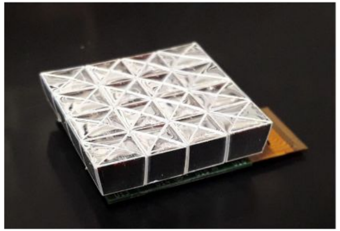
cutting of reflective foil



wrapped tiles



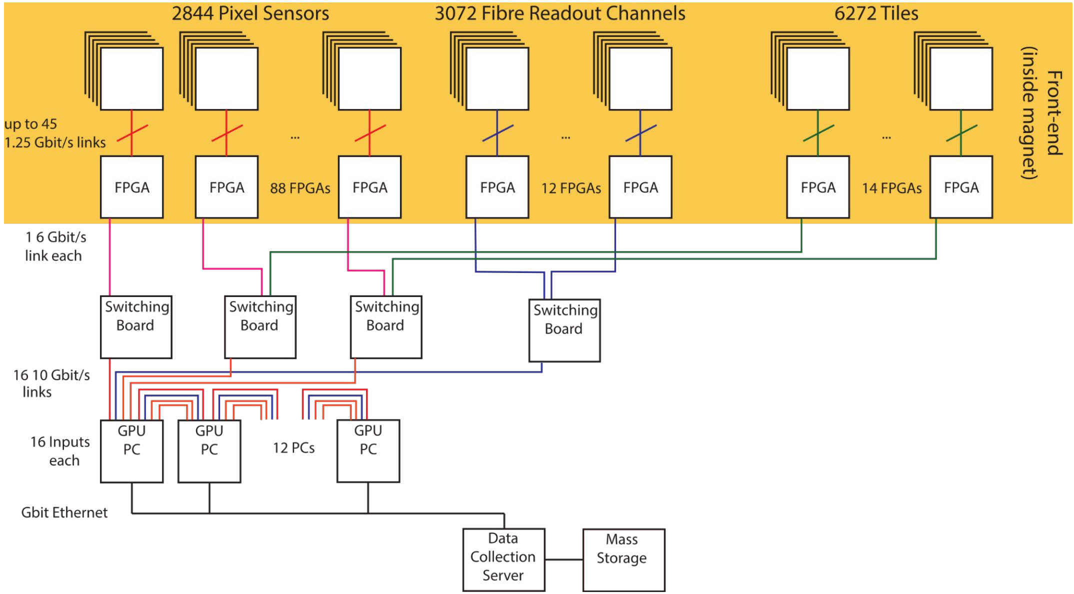
SiPM aray



Equipped tile module

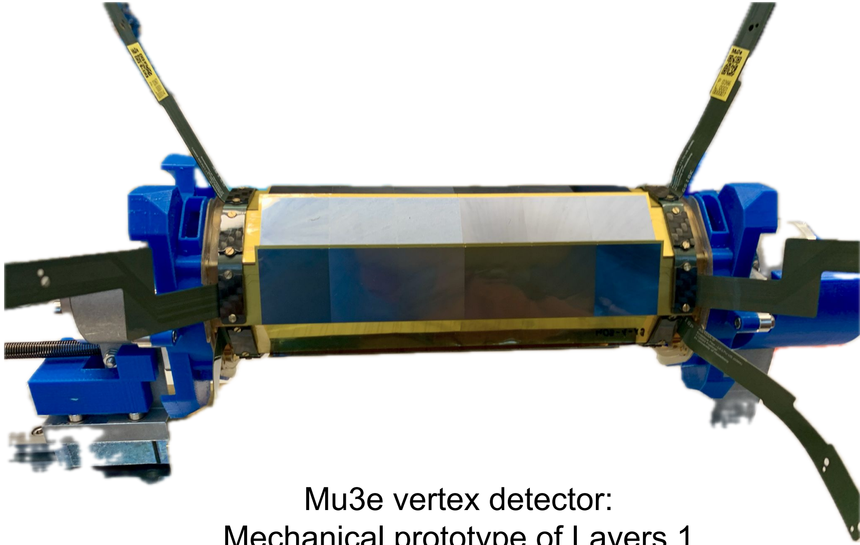
DAQ

- Full streaming DAQ → no trigger
- Network of FPGAs and optical links
- Full time slice of the full detector on one PC
- Reconstruction on GPUs
- Is being setup to prepare for the cosmic run in November/December 2024



Summary

- Mu3e is based on a **low mass tracker** with an unprecedented low material budget of **~ 0.1 % X_0 per tracking layer**
- **Gaseous helium cooling** is employed to further minimize the overall material budget
- **Vertex detector** & **SciFi detector** under construction now!
    - Cosmic run in November/December this year
    - First beam data in 2025
- **SciTile detector** & **outer pixel stations** commissioning in 2025/2026
- **DAQ** under preparation for the cosmic run



Mu3e vertex detector: Mechanical prototype of Layers 1 (bottom) and 2 (top)

The Mu3e collaboration

KIRCHHOFF-INSTITUT FÜR PHYSIK

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Karlsruher Institut für Technologie

ETH zürich

UNIVERSITÉ DE GENÈVE

University of Zurich[UZH]

University of BRISTOL

UNIVERSITY OF OXFORD

UNIVERSITY OF LIVERPOOL

UCL

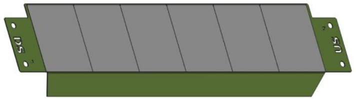
PSI

Backup

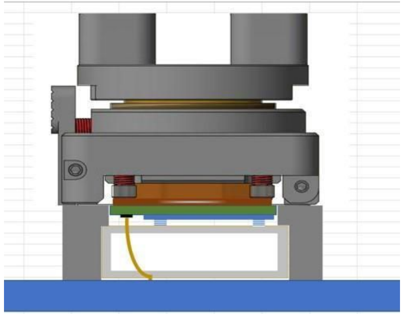
Low mass pixel detector

From HDIs and sensor chips to a detector

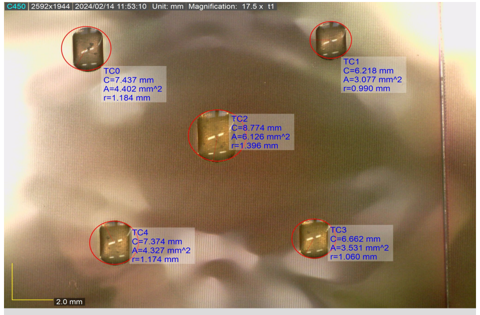
1. MuPix chips are **qualified** in probe card
2. MuPix chips are **aligned** on assembly tool
3. MuPix chips are **glued** on the HDI and **bonded** to a **ladder**



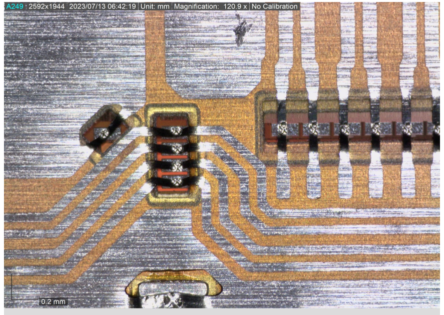
Ladder



Manual MuPix probe card



Glue dots on a MuPix chip



spTAB connections from HDI to the MuPix chips

Low mass pixel detector

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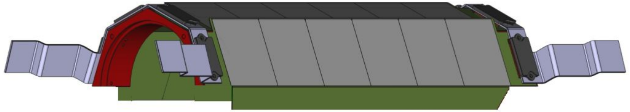
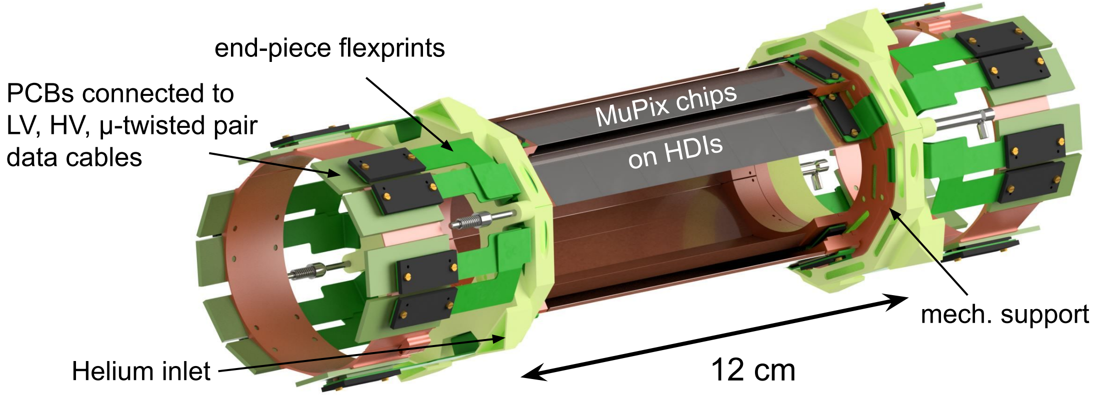
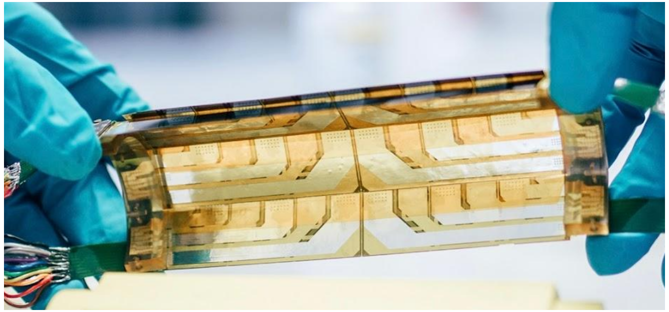
3. MuPix chips are **glued** on the HDI and **bonded** to a **ladder**
4. Ladders are glued to each other forming half-shell **modules**
5. 4 modules mounted as two barrel layers forming the **vertex detector**



Module



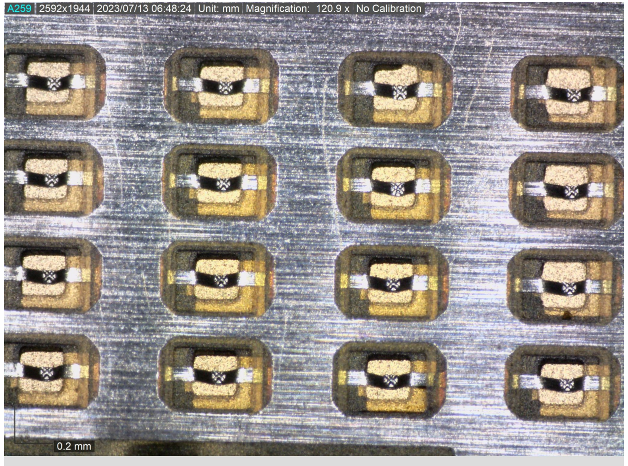


Silicon heater mock-up module

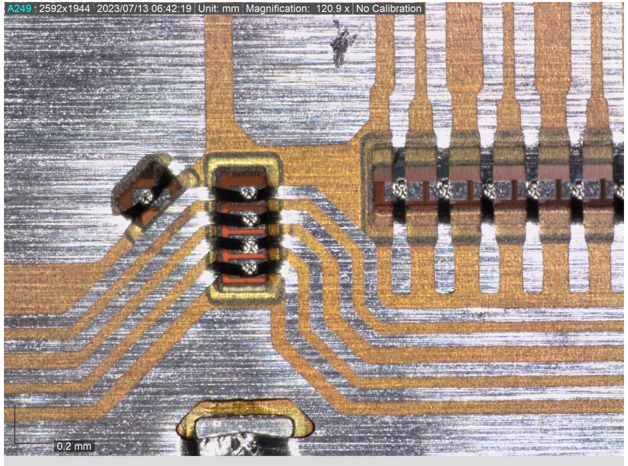
“Building a low mass tracker is easy”

Contact density

- Electrical connections via **spTAB** (single point tape-automated bonding)
- Limited contact density due to minimum structure size



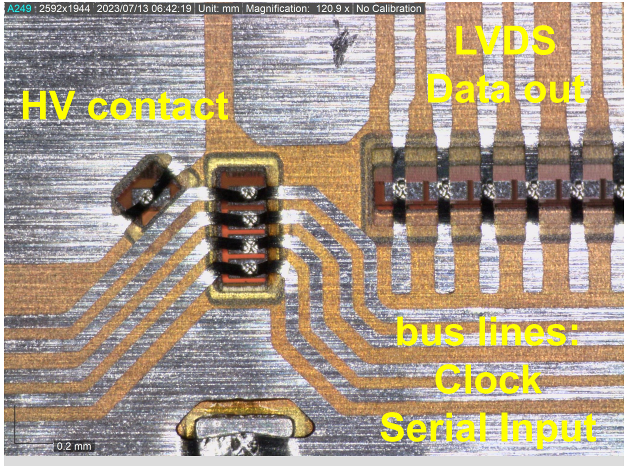
spTAB connections from HDI to conventional flexprints (away from detector)



spTAB connections from HDI to the MuPix chips

Contact density

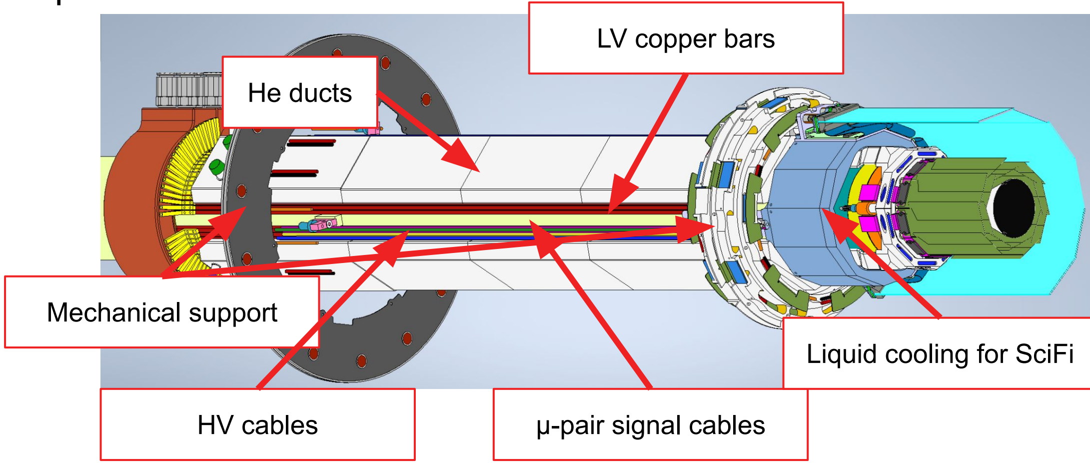
- Electrical connections via **spTAB** (single point tape-automated bonding)
- Limited contact density due to minimum structure size
- Narrowest line width: 63 µm
- Electrical contacts:
  - Differential Clock (bus line)
  - Differential Serial Input (bus line, communication to chip)
  - 3x Differential Data Out lines per chip
  - LV (VDD & GND)
  - HV
- Sensor is operated with a single supply voltage



spTAB connections from HDI
to the MuPix chips

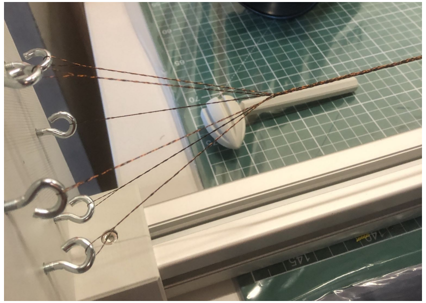
Integration of services

- Extremely dense detector integration
- Central station services need to **fit below recurl stations**
- **Shared volume for services** of Vertex detector, SciFi detector, Tile detector and Outer pixel layers
  - A little hint: “Avoid shared volumes if possible!”
- Everything integrated on the beam pipe

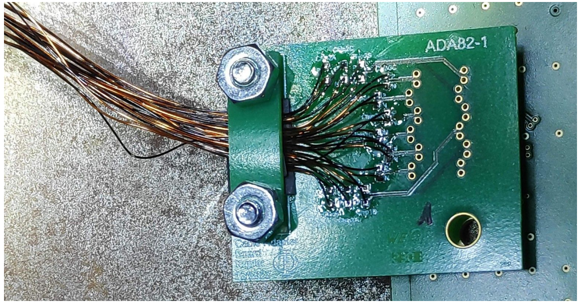


Integration of services

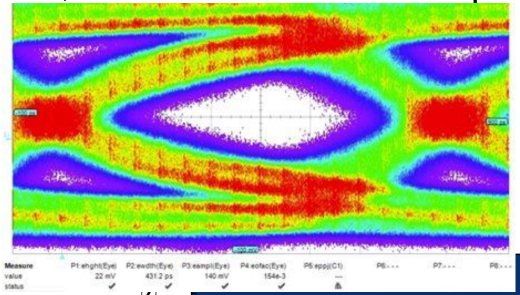
- Extremely dense detector integration
- Central station services need to **fit below recurl stations**
- **Shared volume for services** of Vertex detector, SciFi detector, Tile detector and Outer pixel layers
    - A little hint: “Avoid shared volumes if possible!”
- Everything integrated on the beam pipe
- Data transmission via **µ-twisted pair cables**

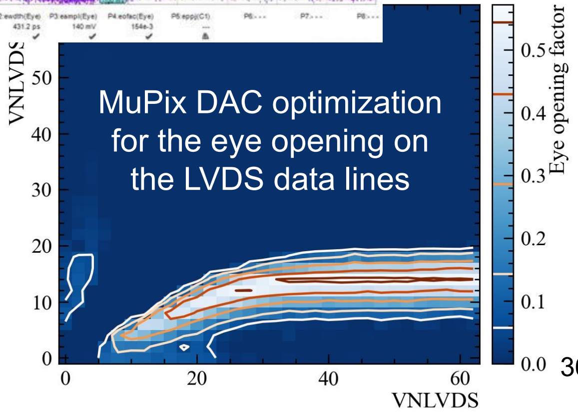


self-made 44-pair bundles



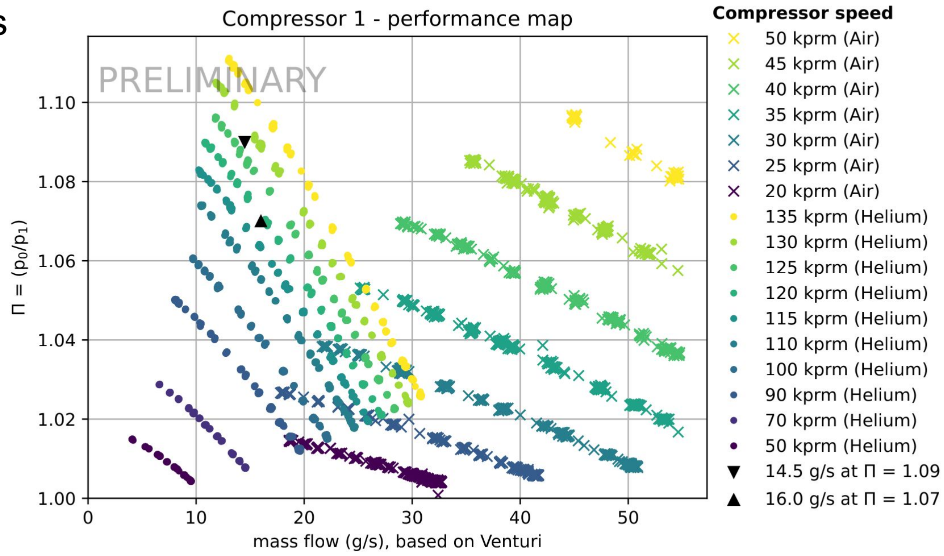
µ-twisted pair cables soldered to readout adapter board





Helium cooling

- Providing a flow of a **few grams per second** of gaseous helium at **ambient pressure** is non-trivial
- Novel industry application in recent years:
  Miniature turbo compressors
- 4x pixel stations are cooled by separate circuits
  - 1x 2 g/s for the vertex detector
  - 3x 16 g/s for the outer layer stations
- Measure mass flow with custom **Venturi tubes**
- 16 g/s compressors commissioned 2023



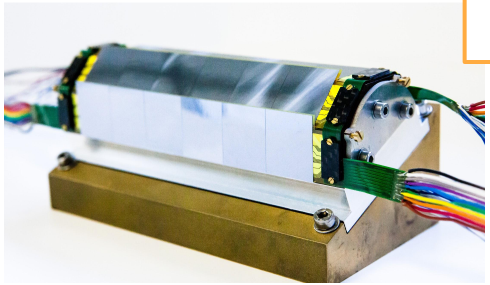
Helium cooling

Cooling studies for the vertex detector

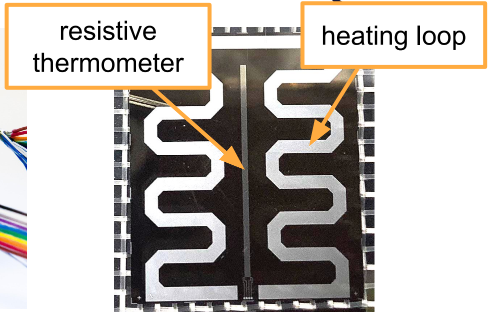
- Silicon heater modules as thermal mechanical mock-up
- Studied heat dissipations of up to 350 mW/cm² (expected ~215 mW/cm²)
- ΔT = chip temperature - gas inlet temperature

	350 mW/cm²	215 mW/cm²
Max. ΔT	< 54 K	< 35 K
Avg. ΔT	~ 31 K	~ 17 K

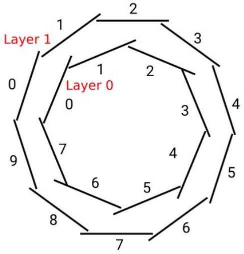
- Requirement of Max. ΔT < 60 K ✅

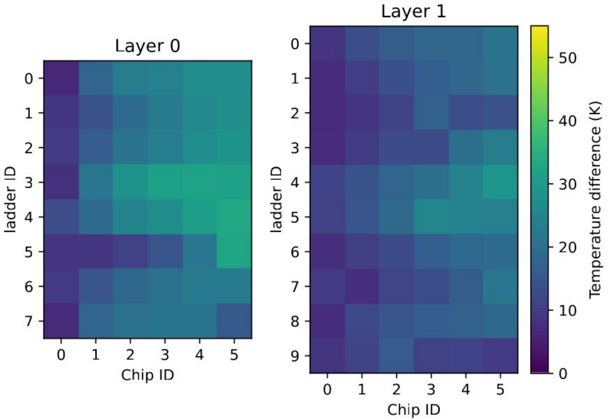


Silicon heater module



Silicon heater chip





temperature difference maps 215 mW/cm² **(expected scenario)**