Thomas Rudzki - 16th Terascale Detector Workshop - Mainz 2024

21.2.2024

Mu3e

How to build a low mass pixel detector?

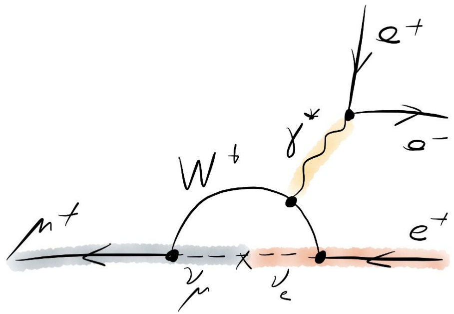
HighRR

DFG

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 μ→eee decay, BR < 10^{-54}

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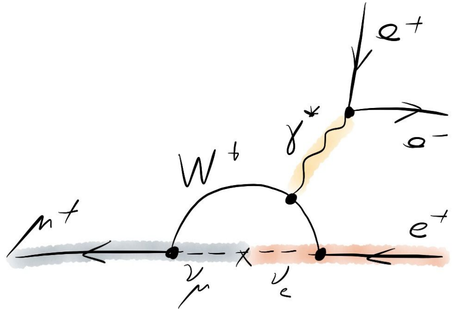
- Sensitive to **beyond SM** loop & contact interactions

More information on CLFV searches: Talk by Konrad Briggl - 22.2.2024 (tomorrow)



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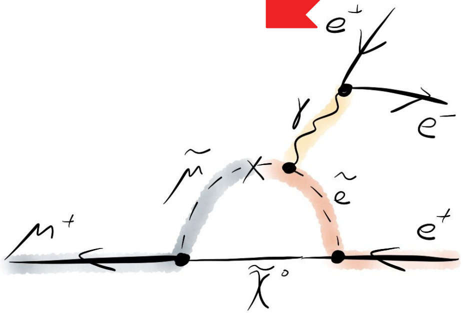

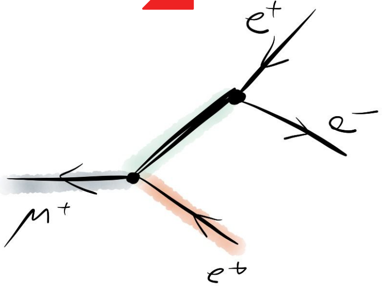

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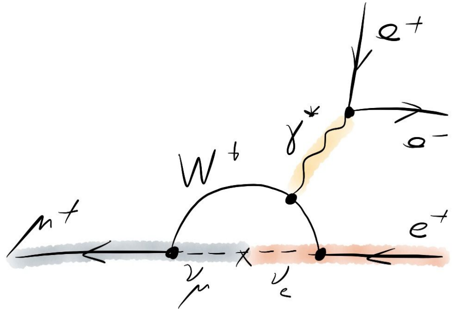
- **Charged** LFV not yet observed
- μ decays are clean searches (only decay products ν, e, γ)
- Sensitive to **beyond SM** loop & contact interactions
- Current Limit of $\mathbf{\mu^+ \rightarrow e^+ e^- e^+}$:
  SINDRUM: BR < 1×10^{-12}

Goal of Mu3e: Improve limit by 3 to 4 orders to < 10^{-15} (< 10^{-16} in Phase II)



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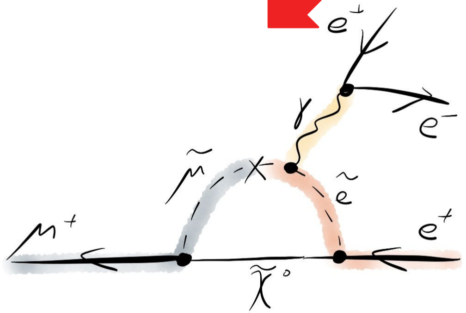

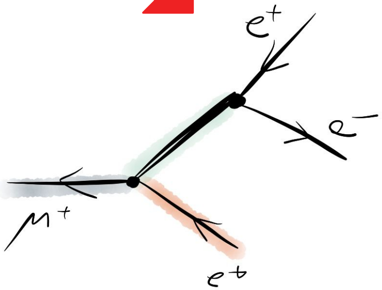

The Mu3e experiment

- **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**

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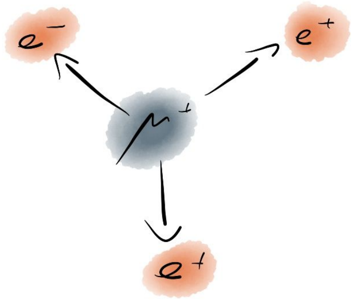
- **Signal decay: μ→eee**
  - Three prompt $e^{+/-}$
  - Common vertex
  - $\Sigma E = m_\mu$
  - $\Sigma \mathbf{p} = 0$



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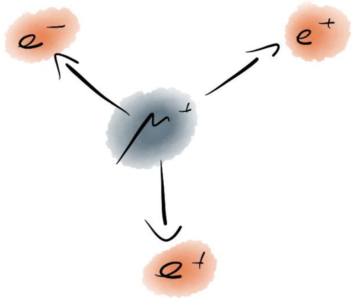
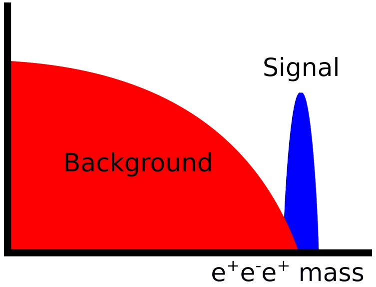


Signal decay

vs.

Internal conversion

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



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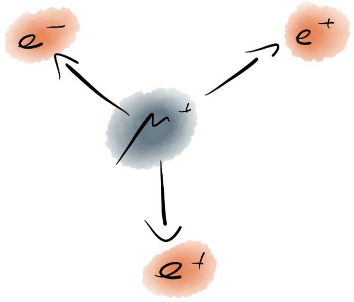
  - Accidental background



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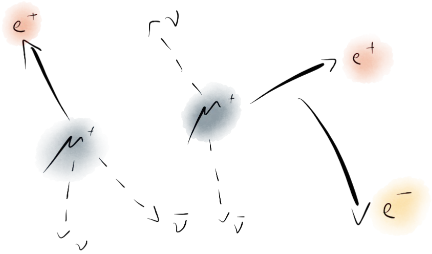


Michel e^+ & e^- from Bhabha or γ conversion

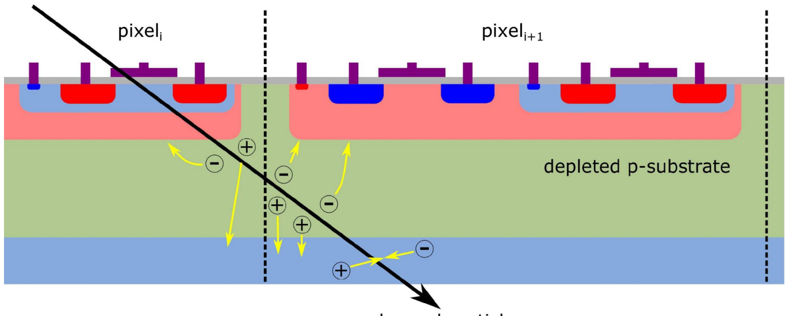
Time and vertex resolution
- Fast detectors
- High granularity

High rate capability

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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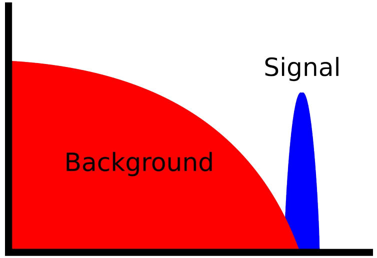

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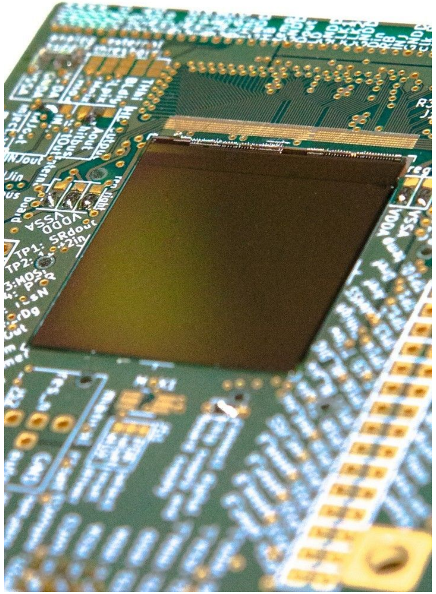
MuPix11

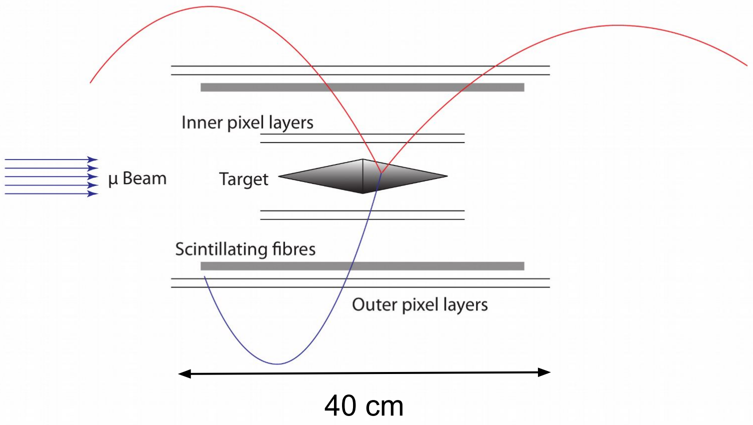
- Chip size: ~ 20 x 23 mm²
- Pixel size: 80 x 80 μm²
- time resolution < 20 ns
- Hit efficiency > 99 %

More details on MuPix:
Talk by H. Augustin - Terascale Workshop 2023



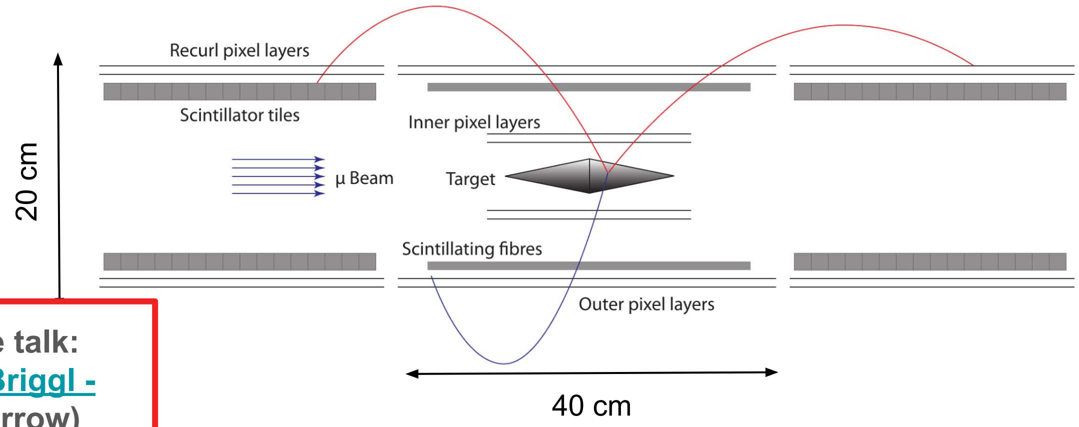
Detector design

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



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



Dedicated Mu3e talk:
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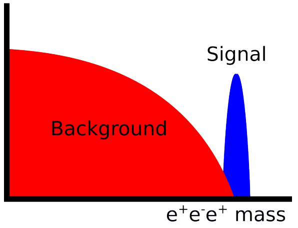


Time and vertex resolution
- Fast detectors
- High granularity

High rate capability

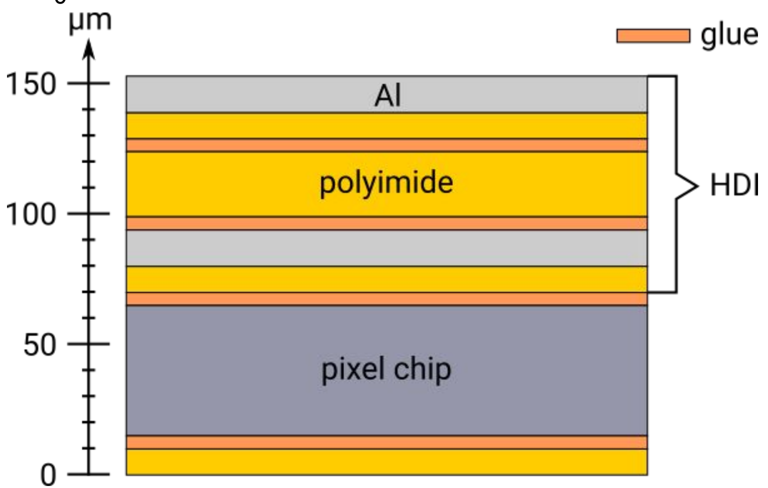
Low mass pixel detector

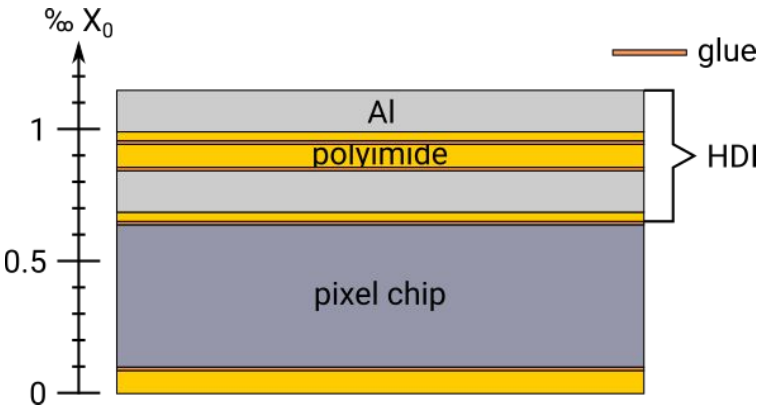
Detector composition:

- 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/cm² → 1.436 cm
$X_0(Al)$ = 24.01 g/cm² → 8.897 cm

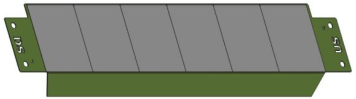




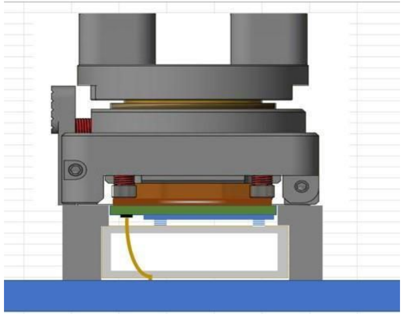
Low mass pixel detector

From HDIs and sensor chips to a detector

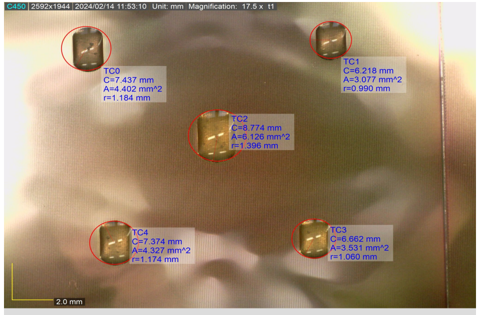
1. MuPix chips are **qualified** in probe card
2. MuPix chips are **aligned** on assembly tool
3. MuPix chips are **glued** on the HDI and **bonded** to a **ladder**



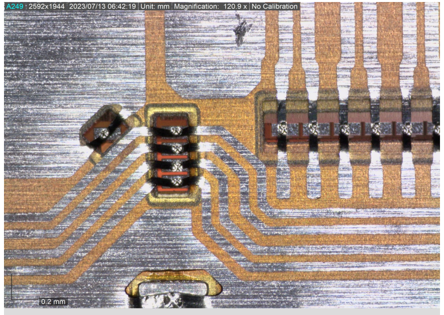
Ladder



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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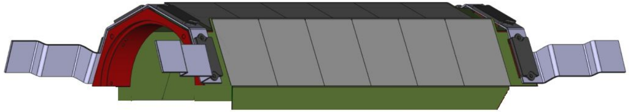
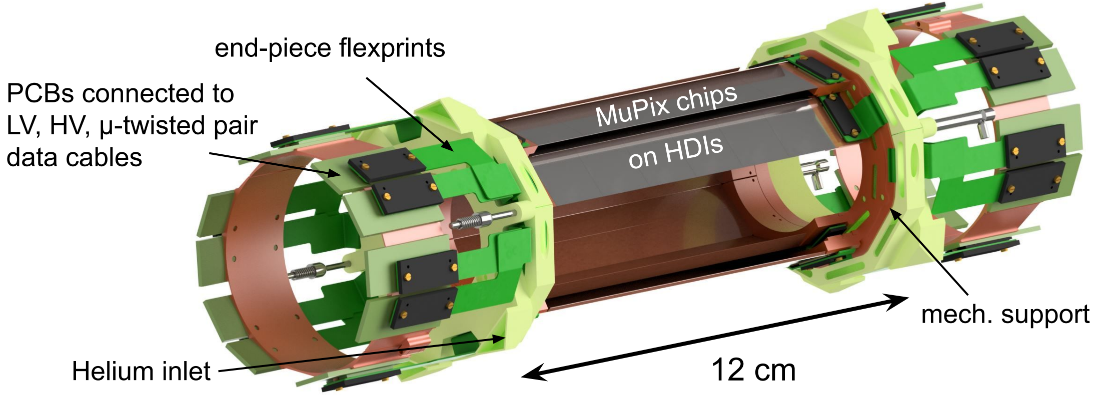
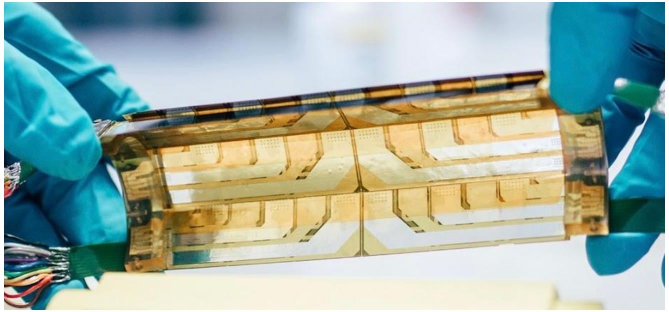
4. Ladders are glued to each other forming half-shell **modules**
5. 4 modules mounted as two barrel layers forming the **vertex detector**



Module

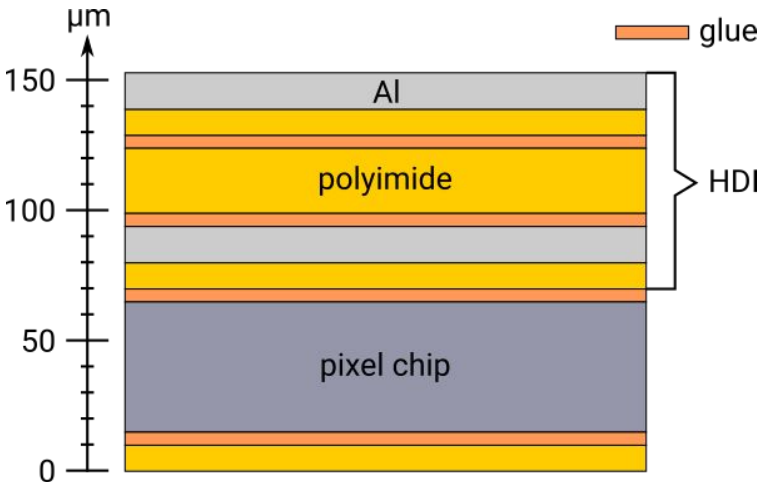




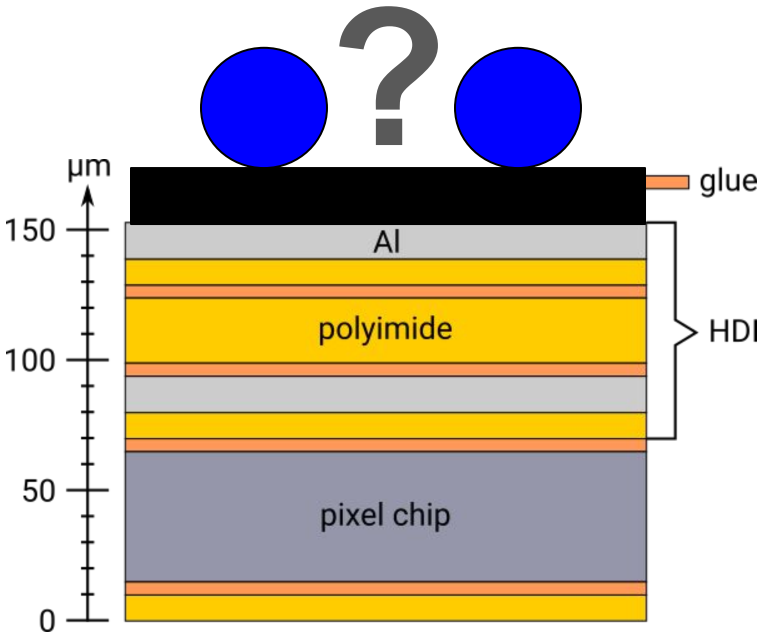
Silicon heater mock-up module

Low mass coolant

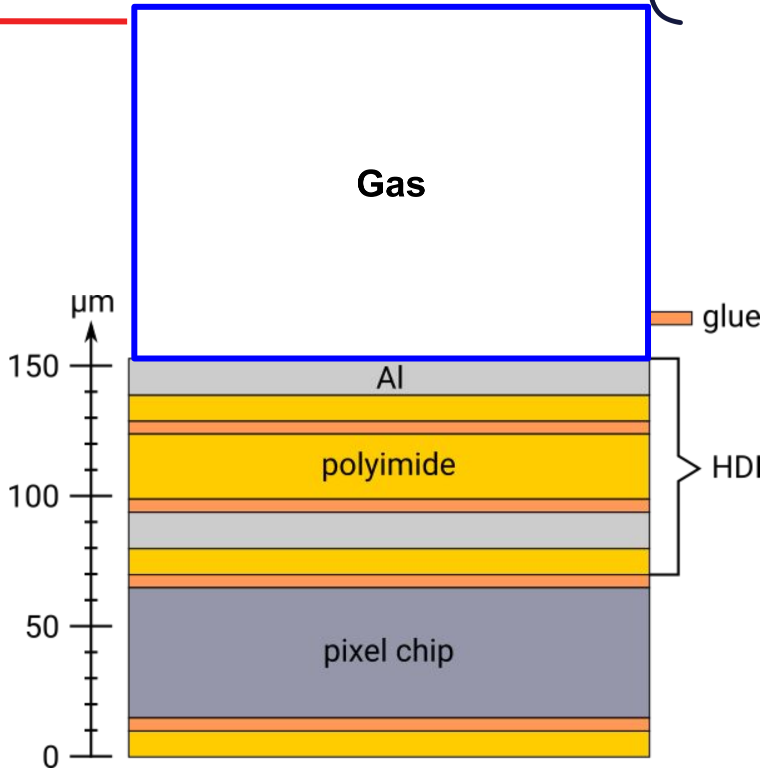
- MuPix dissipates ~ 215 mW/cm²
- Active cooling is required



Low mass coolant

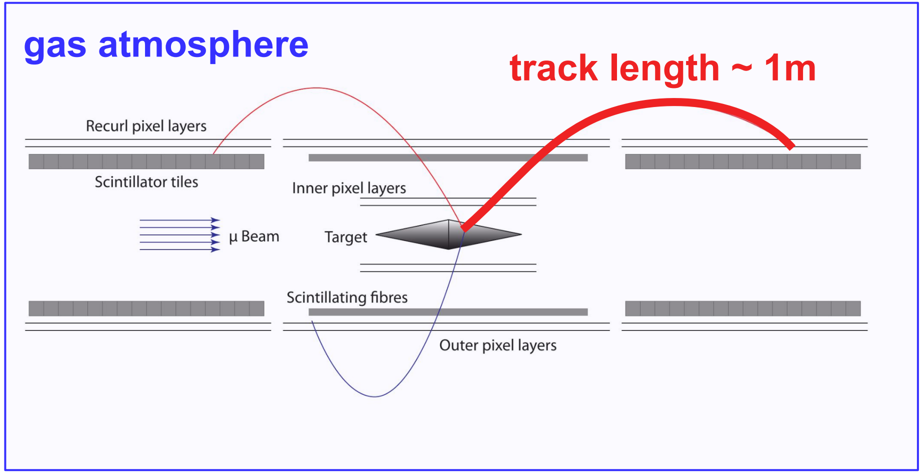


vs.



Low mass coolant → Gaseous helium

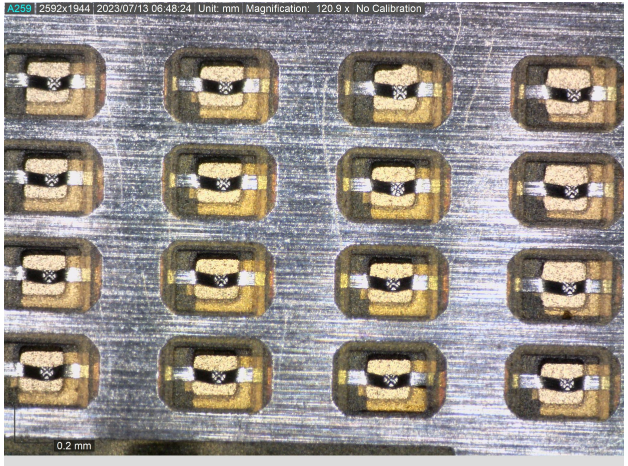
- Naive idea: Air cooling like at STAR PXL
- But: **Air is too much material!**
- 1 m of air corresponds to ~ 0.33 % X_0 ➡ equivalent to 3(!) more tracking layers
- **Solution:** Helium ➡ 0.018 % X_0 per meter



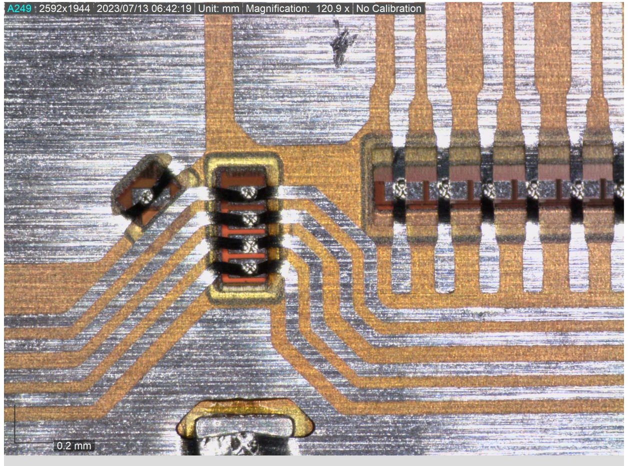
“Building a low mass tracker is easy”

Contact density

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



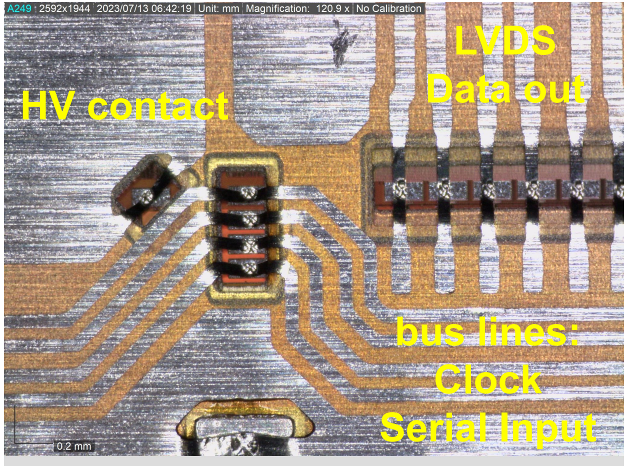
spTAB connections from HDI to conventional flexprints (away from detector)



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
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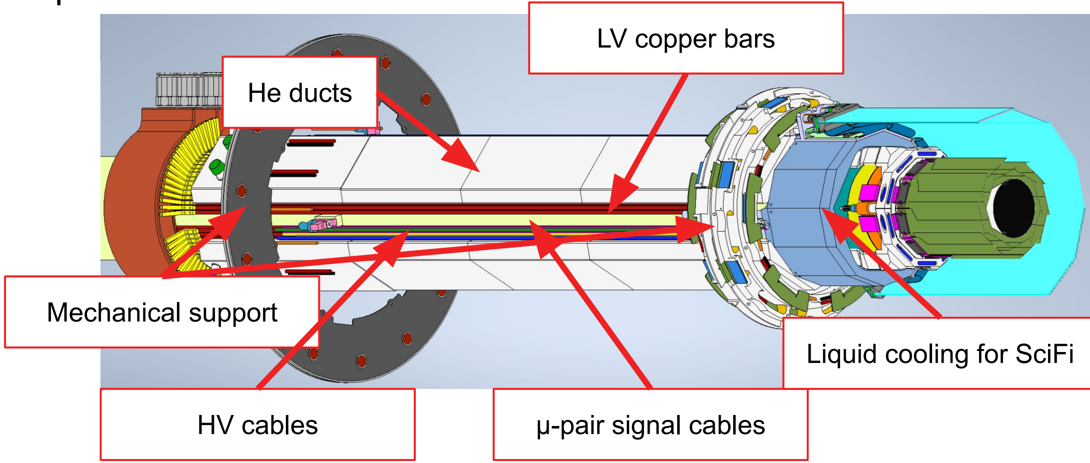
Integration of services

- 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



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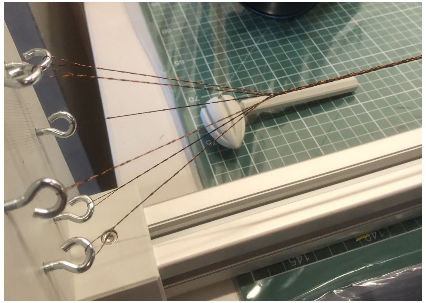
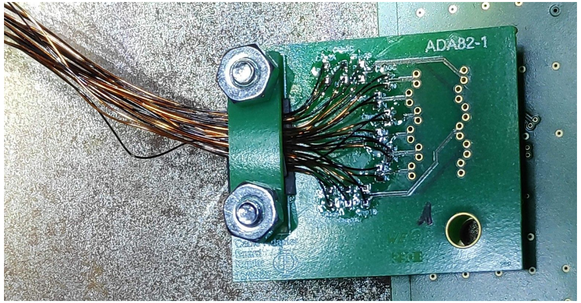
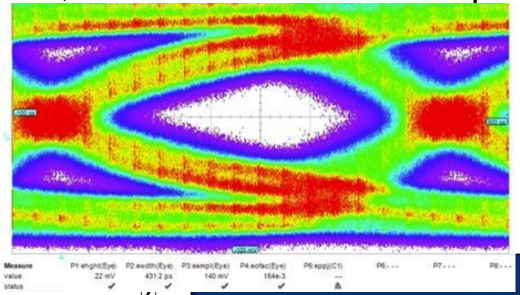
- Everything integrated on the beam pipe
- Data transmission via **µ-twisted pair cables**

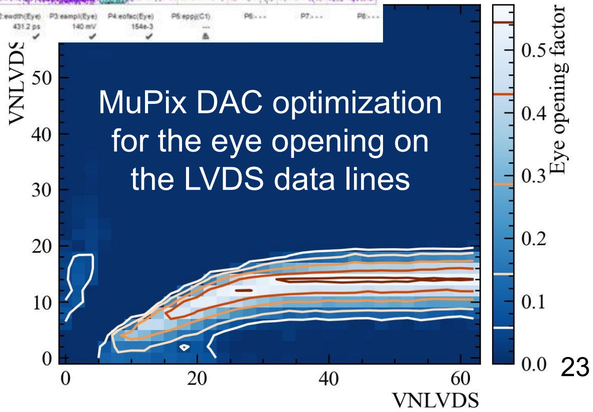


self-made 44-pair bundles



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

Turbo compressor providing 16 g/s helium (from Fischer)

Helium cooling

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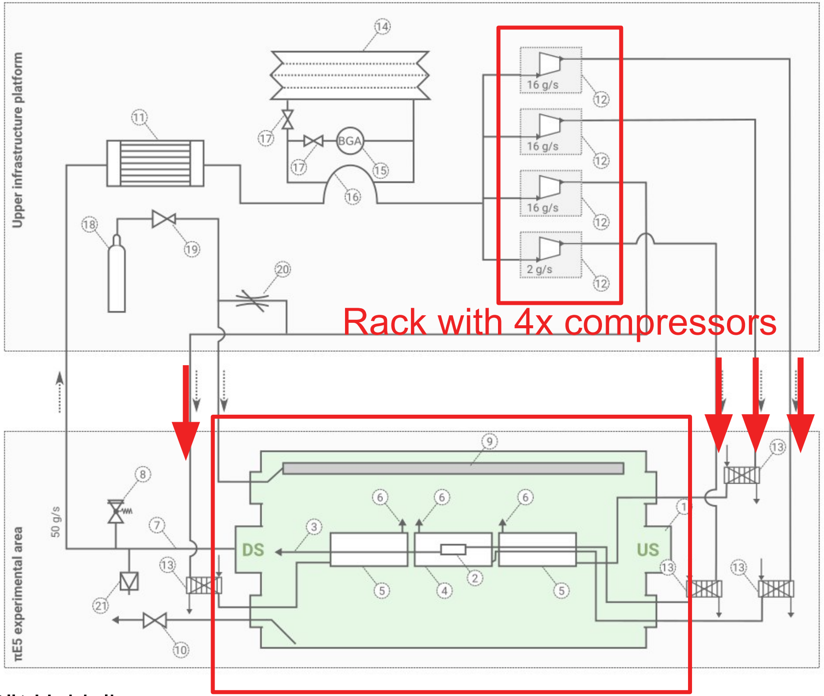
- 4x pixel stations are cooled by separate circuits
  - 1x 2 g/s for the vertex detector
  - 3x 16 g/s for the outer layer stations



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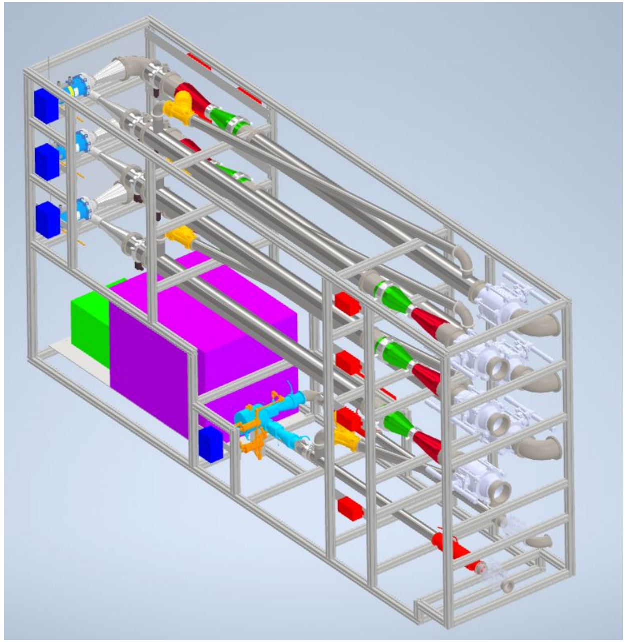

Helium compressor rack

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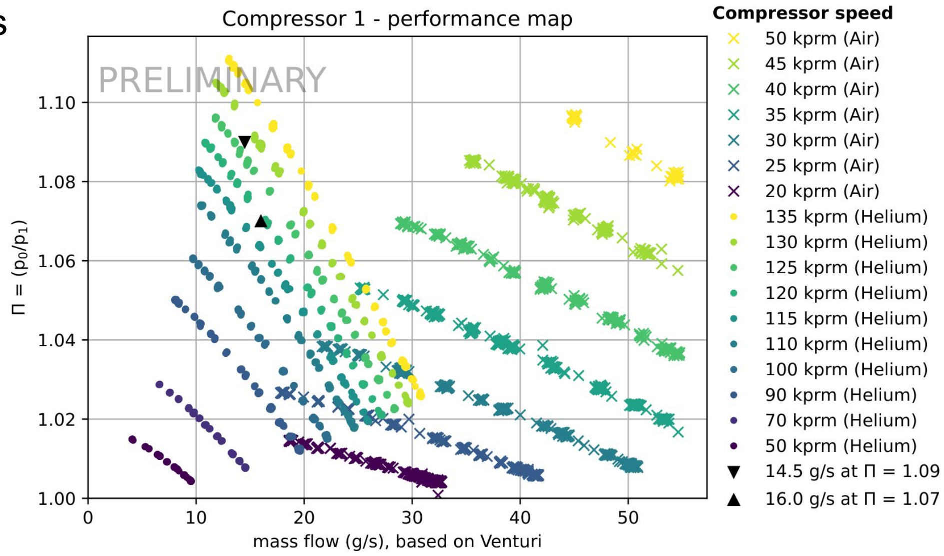
- Measure mass flow with custom **Venturi tubes**
- 16 g/s compressors commissioned 2023



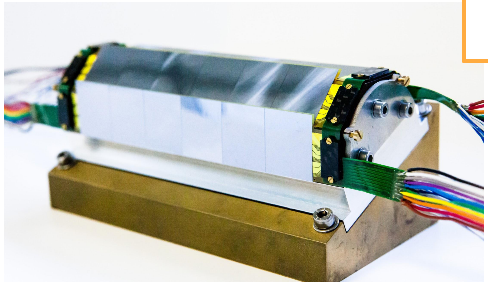
Helium cooling

Cooling studies for the vertex detector

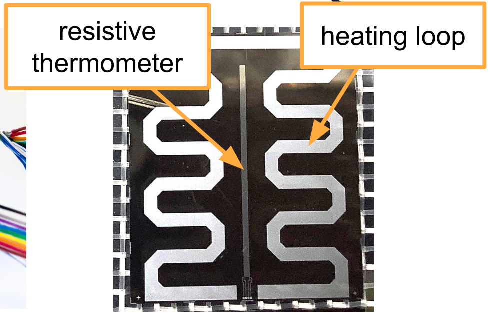
- Silicon heater modules as thermal mechanical mock-up
- Studied heat dissipations of up to 350 mW/cm² (expected ~215 mW/cm²)
- ΔT = chip temperature - gas inlet temperature

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

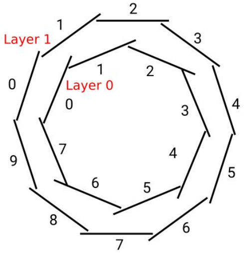
- Requirement of Max. ΔT < 60 K ✅

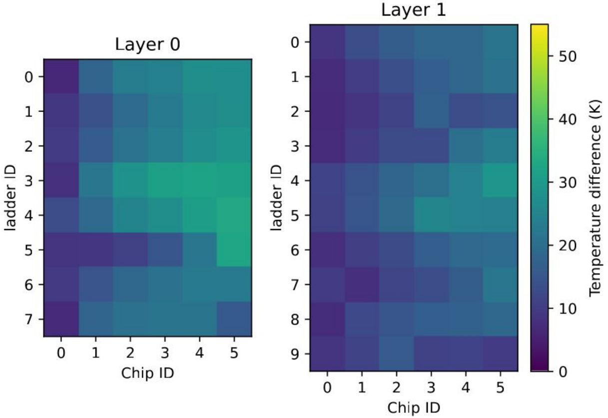


Silicon heater module



Silicon heater chip

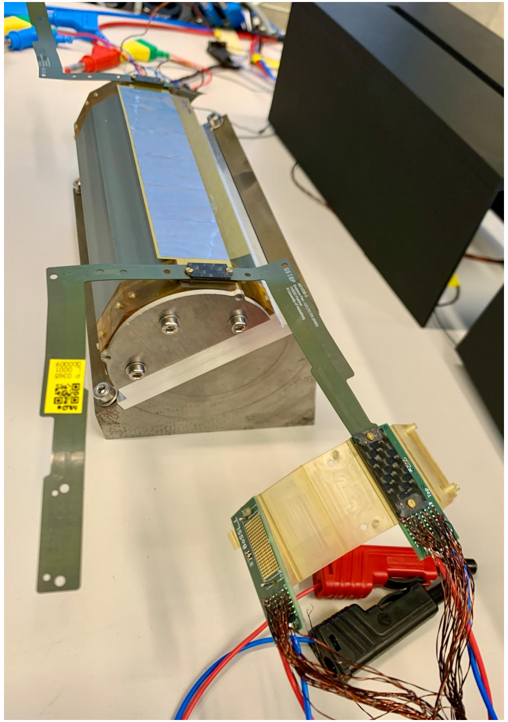




temperature difference maps 215 mW/cm²
(expected scenario)

Summary

- Mu3e bases on a **low mass tracker** with an unprecedented low material budget of **~ 0.1 % X_0 per tracking layer**
- Solely silicon-only trackers will do even better (see next talk I guess 😉)
- **Gaseous helium cooling** is employed to further minimize the overall material budget
- **Material reduction** extends to the **passive volume** to accommodate integrated services within limited space (incl. µ-twisted pair cables, LV copper bars, no conventional connectors, etc…)
- Mu3e vertex detector under construction now!
  - Cosmic run in summer/autumn this year (2024)
  - First beam data by the end of this year (2024)



QC stand of 1st final vertex detector ladder