The Mu3e pixel detector: Ultra-light, helium cooled, HV-MAPS based

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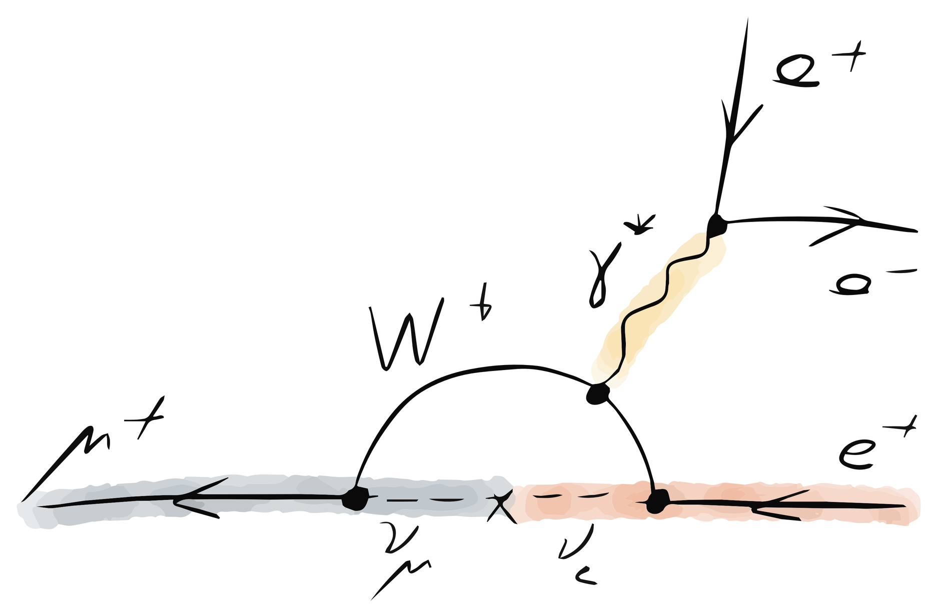
Physics motivation of Mu3e

- Search for **charged lepton flavor violation** in the decay:

$$\mu^+ \rightarrow e^+ e^- e^+$$

- In the Standard Model including neutrino mixing, this process is **highly suppressed** with a branching fraction of $\mathcal{B} < 10^{-54}$ (Figure below).

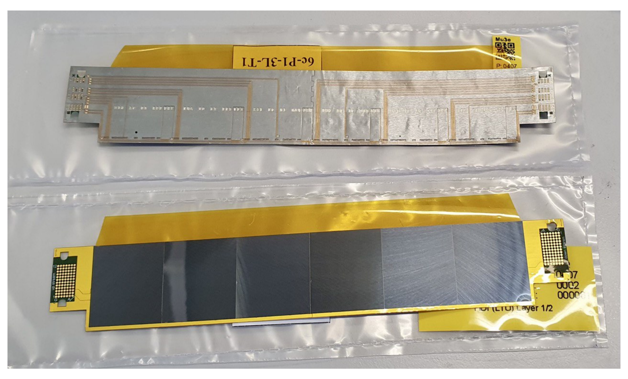


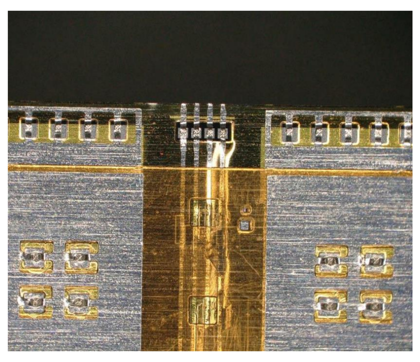
- Thus, an observed signal would indicate the presence of new physics.

Detector building blocks

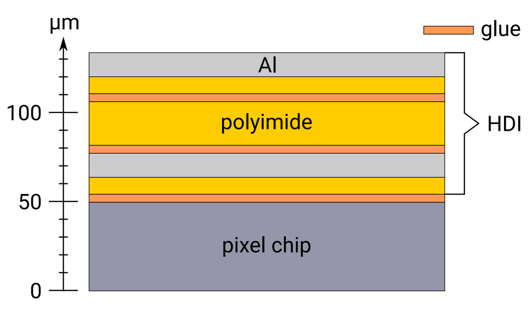
- **MuPix11**, 50/70 µm thin, High-voltage monolithic pixel sensor **(HV-MAPS)**

- **High-density interconnects** Al-polyimide laminates, electrical serives + mechanical support





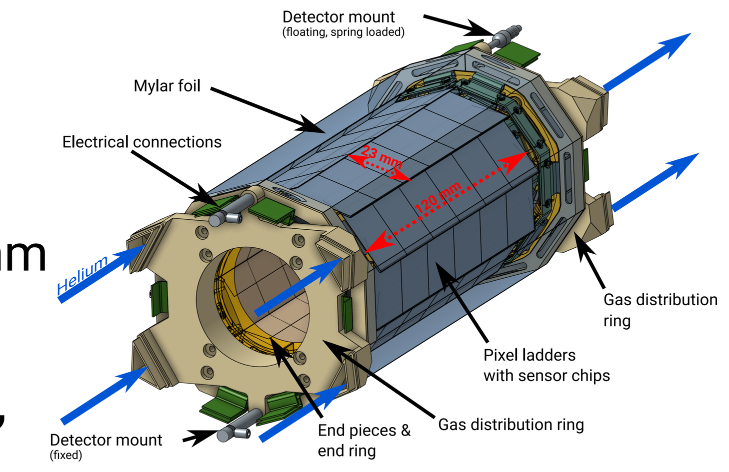
el. connections via **spTAB**



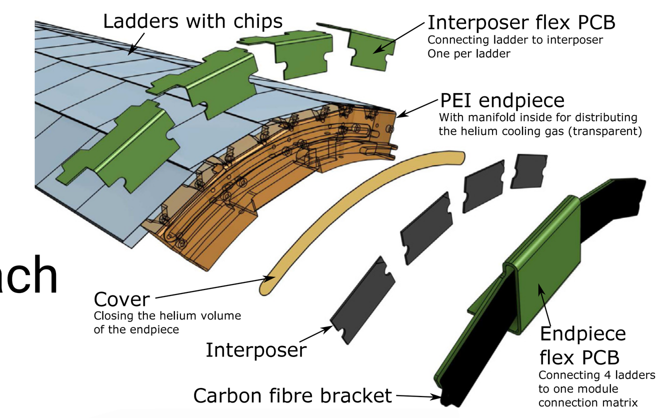
material stack of a detector ladder

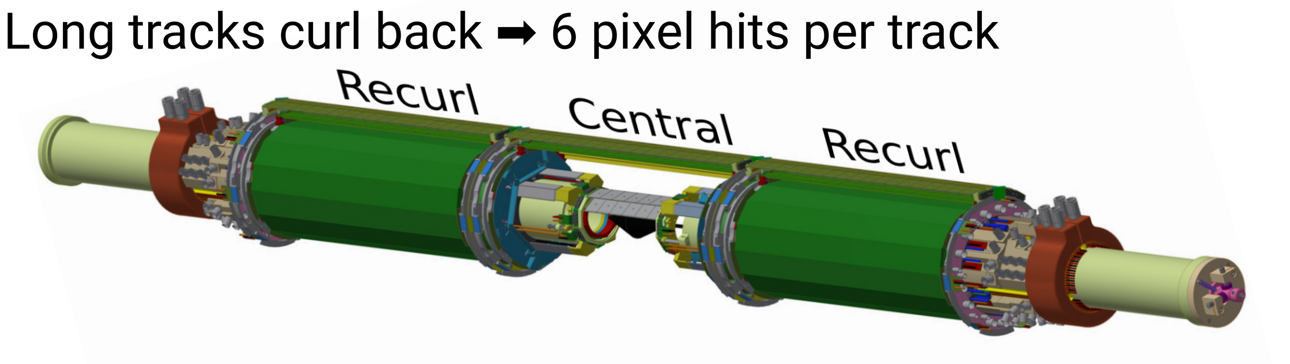
Vertex detector & Outer pixel layers

- **Pixel detector**
  - ◇ 2,844 pixel chips ➡ 182,016,000 channels
  - ◇ cooled by **gaseous helium**
- **Vertex detector**
  2x inner tracking layers
  - ◇ Radii: 1) 23.3 mm, 2) 29.8 mm
  - ◇ Sensor thickness: 50 µm
  - ◇ 8 + 10 ladders, 6 chips each,



- **Outer layers**
  2x outer tracking layers
  - ◇ Radii: 3) 73.9 mm, 4) 86.3 mm
  - ◇ Sensor thickness: 70 µm
  - ◇ 24 +28 ladders, 17/18 chips each
  - ◇ 3 stations:
    1x central: around target
    2x recurl: upstream & downstream
    Long tracks curl back ➡ 6 pixel hits per track





Helium as coolant for the pixel detectors

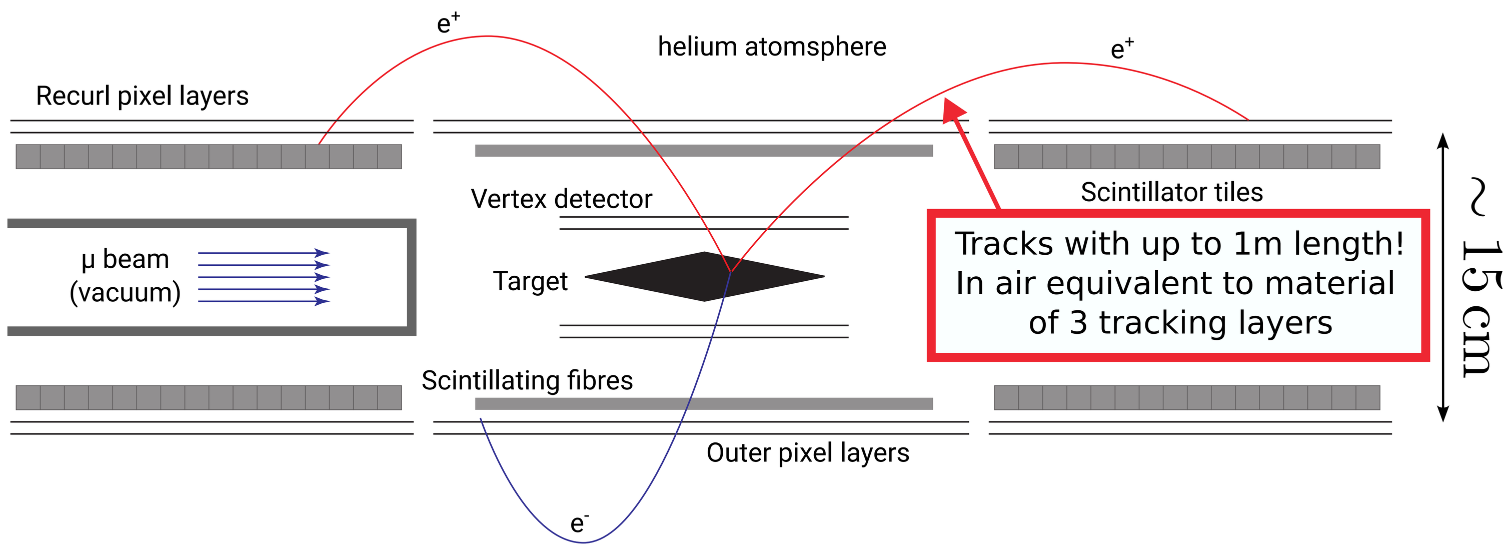
- Signal decay has to be distinguished from: $\mu^+ \rightarrow e^+ e^- e^+ \nu\bar{\nu}$
- Only possible for sufficient **momentum resolution.**
- Resolution is **multiple-Coulomb scattering** dominated

little material budget: $\sim 0.1\,\%X_0$ per tracking layer

negligible scattering in passive part of detector

gaseous cooling adds least material

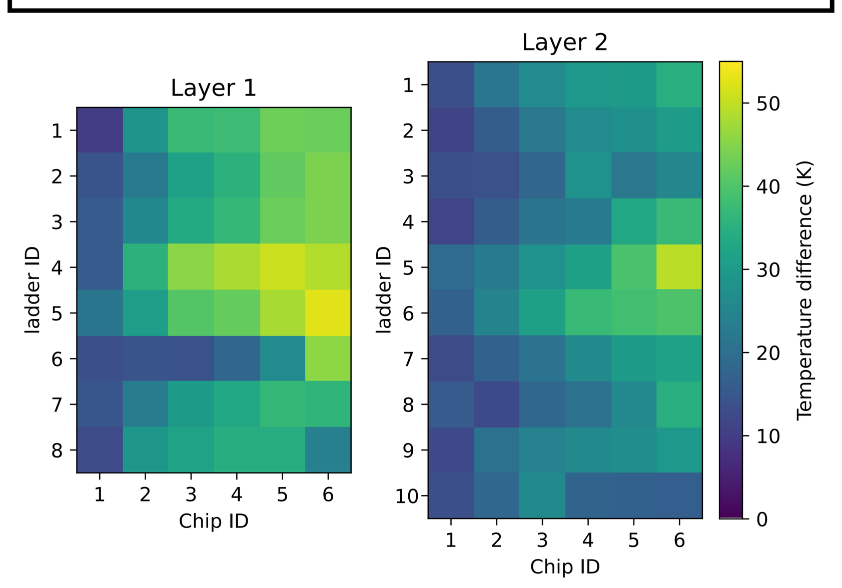
	Helium	Air
density:	$0.18\,\mathrm{kg/m^3}$	$1.29\,\mathrm{kg/m^3}$
therm. conductivity:	$1.43\,\mathrm{mW/(cm\cdot K)}$	$0.241\,\mathrm{mW/(cm\cdot K)}$
spec. heat capacity:	$5.23\,\mathrm{kJ/(kg\cdot K)}$	$1.01\,\mathrm{kJ/(kg\cdot K)}$
radiation length:	$0.018\,\%\ X_0/m$	$0.33\,\%\ X_0/m$

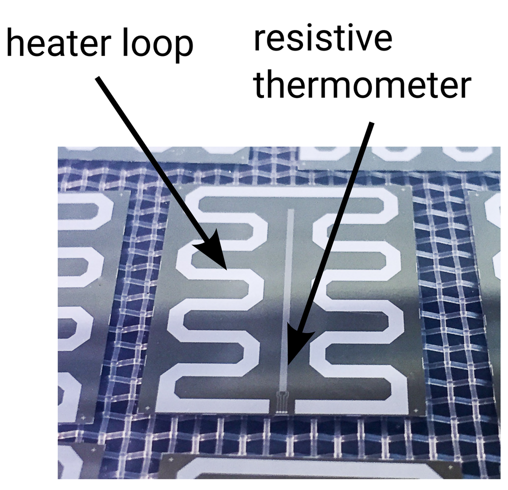


Thermal studies of the Mu3e vertex detector

- Thermal-mechanical mock-up using **silicon heater chips** instead of MuPix11
- Vertex detector: **2 g/s helium** are provided in two flow channels for cooling
- Outer pixel layers: **16 g/s helium** in two flow channels per each station
- **Measured** temperature difference to gas inlet temperature on each heater chip of the vertex detector
  - ◇ **All temperature below 70°C** for 350 mW/cm² (mechanical limit)
  - ◇ **Linearity** of temperature to power as well as temperature to mass flow

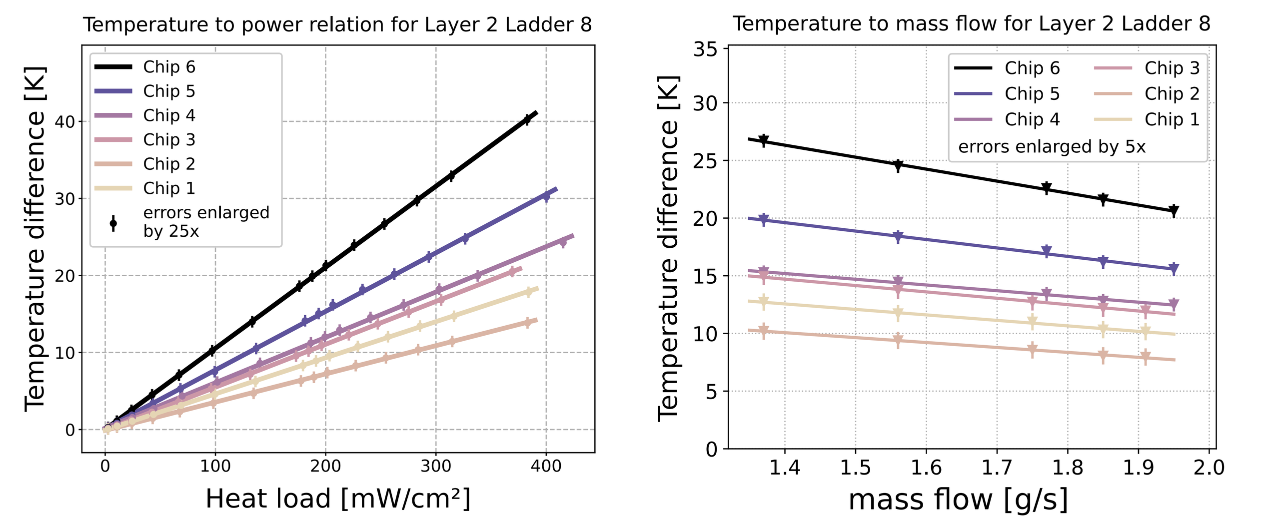
Temperature maps for a uniformly heated vertex detector with 350 mW/cm²





silicon heater chip

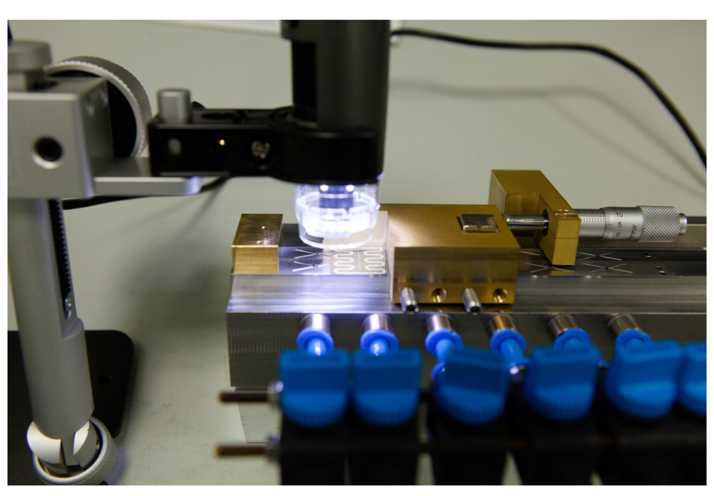
Temperature to mass flow and temperature to power relation for all chips of a heater ladder in Layer 2

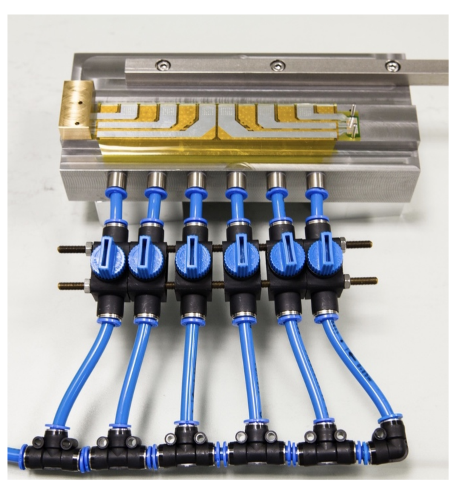


Plots are taken from: https://doi.org/10.1016/j.nima.2023.168405

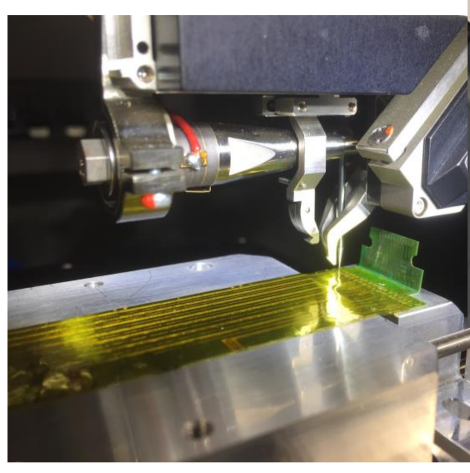
Detector production and QC

- Module/detector production verified with silicon heater chips
- Vertex detector produced manually by Heidelberg at Paul Scherrer Institut (PSI)
- Outer layers produced highly automatized in Oxford & Liverpool



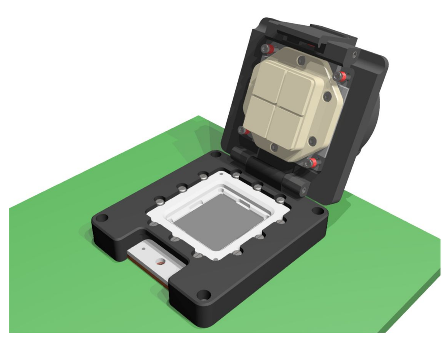


Chip alignment and ladder production tool for the vertex detector

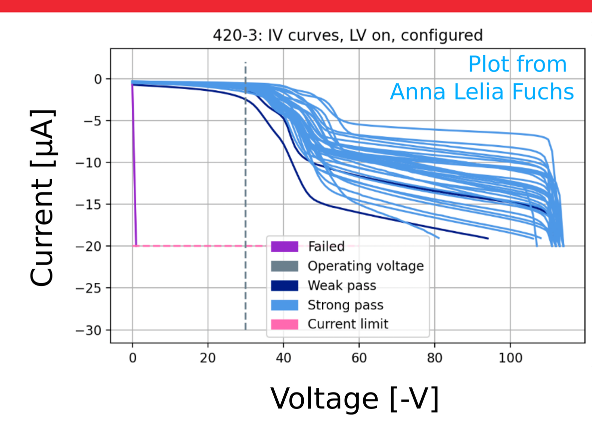


spTAB bonding of an outer pixel ladder in Oxford;

ring frame holding a manufactured ladder with 18 chips



Single chip probe card



- Working on single chip QC in Heidelberg
- Ladder QC algorithms under development, same building blocks as chip QC
- Testing vertical slice with Ladder QC, all final electrical components in hand
- Finish vertex detector construction in 2023

4th Conference on Charged Lepton Flavor Violation - 2023 - Heidelberg