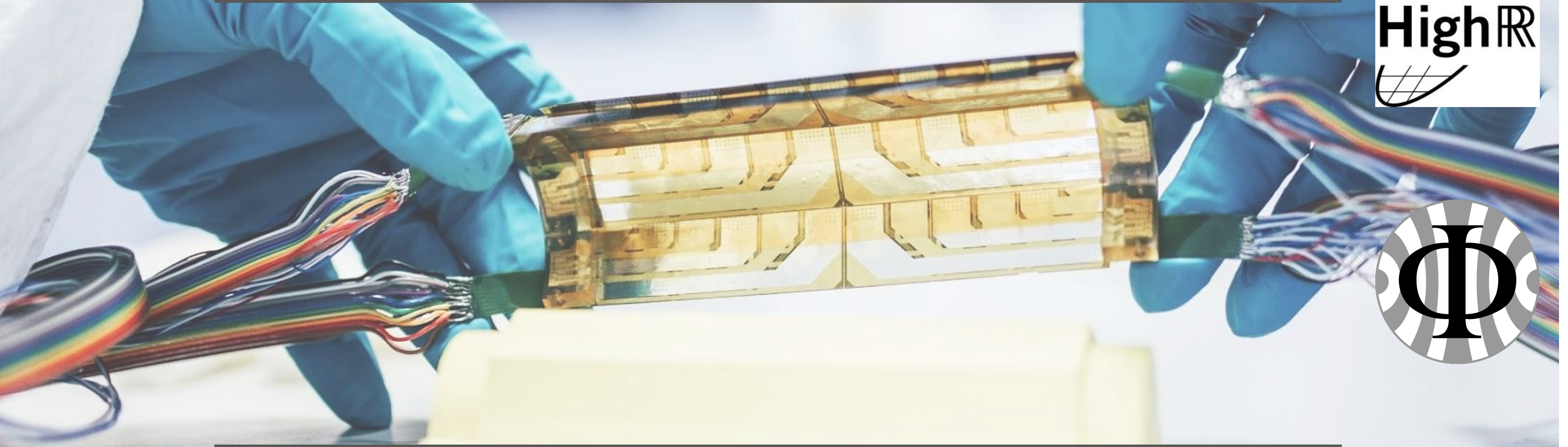
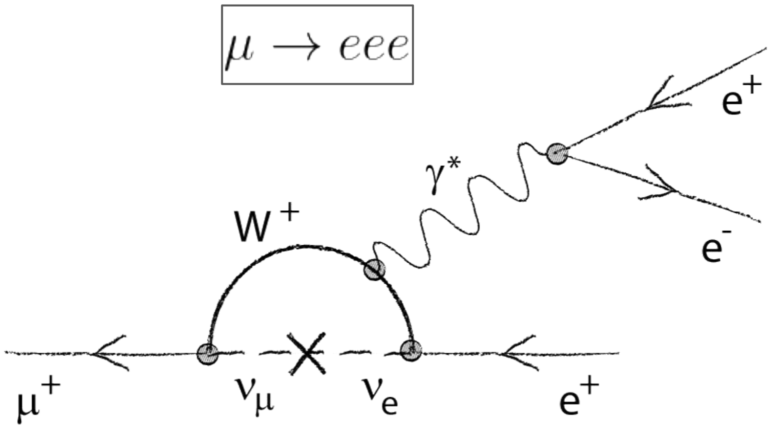
An ultra-light helium cooled pixel detector for the Mu3e experiment



Thomas Rudzki - Physikalisches Institut Heidelberg
NeFroLeF 2023 - 16.05.2023

Probing the Standard Model with Mu3e

- **Mu3e** is a high-precision experiment at Paul Scherrer Institut (PSI), Switzerland
- **μ→eee** in SM (including neutrino mixing):
  - BR (μ→eee) < 10^{-54}
  - beyond observable levels
- Enhancement of BR by several orders possible by new physics
- Current limit:
  - SINDRUM (1988): **BR < 10^{-12}**
- Aimed single-event sensitivity:
  - Phase I: **BR < $2 \cdot 10^{-15}$**
  - Phase II: **BR < 10^{-16}**



Standard Model decay via neutrino mixing

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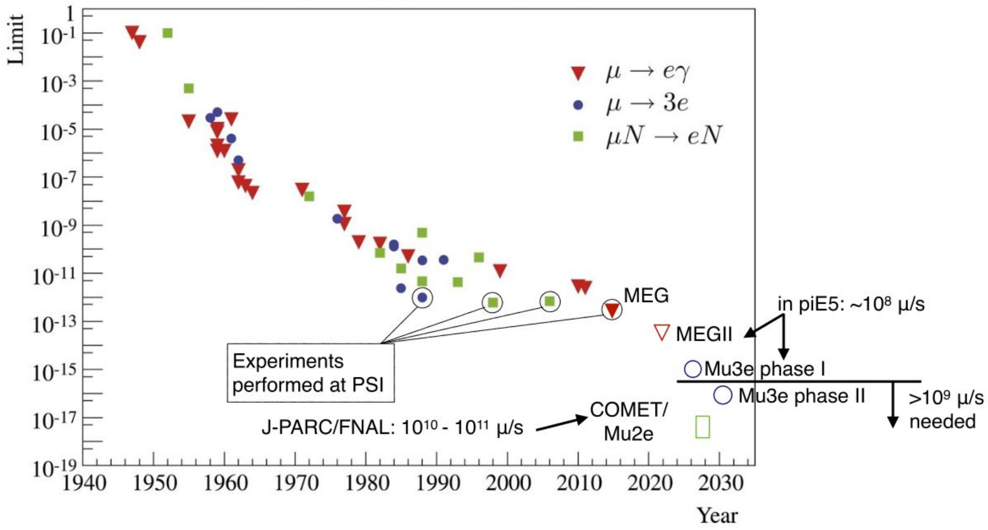
History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



arXiv:2111.05788v1

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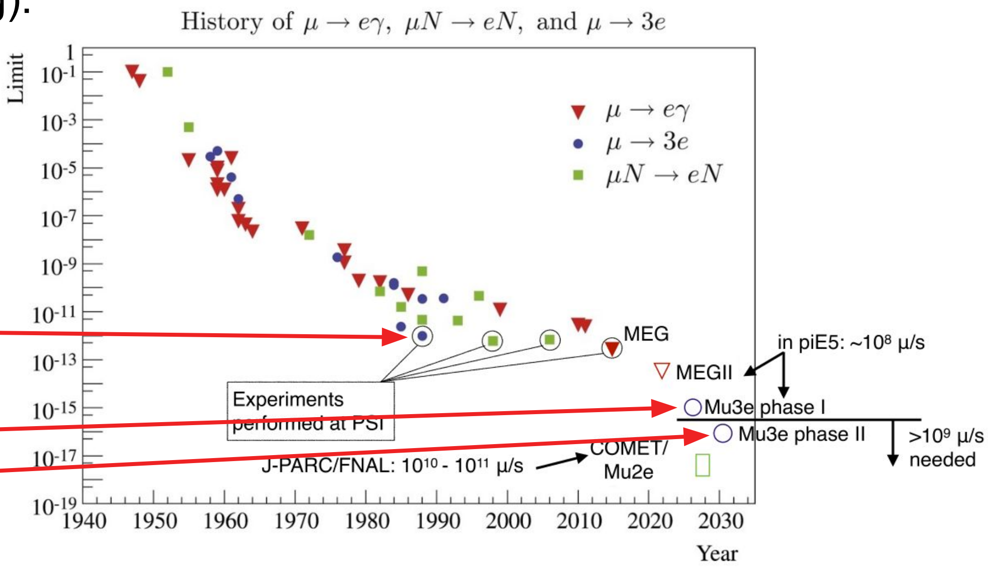

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Experimental challenges

- **High rates** (≥ 10^8 μ^+ decays per second)
- **Low-momentum** particles
  - Muons decay at rest
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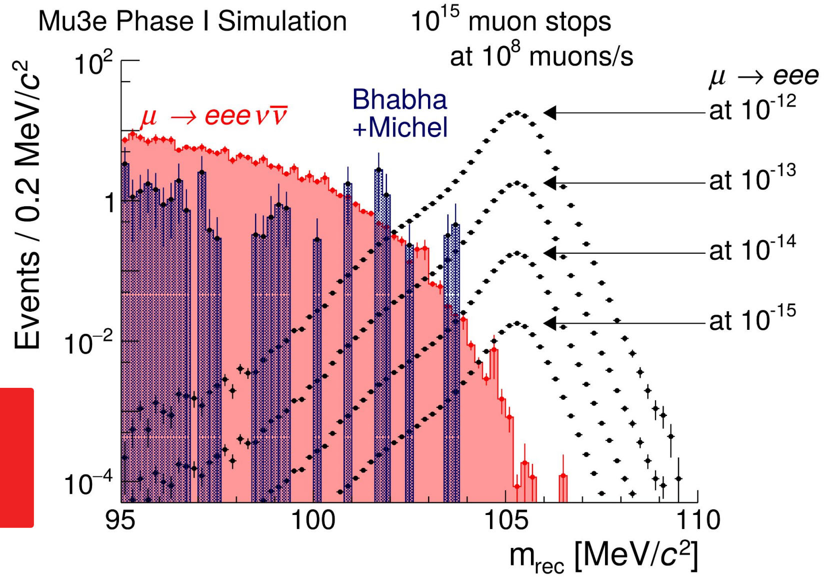
- Signal-to-**background** discrimination
  - μ→eeevv (main background channel)
  - **Limited by multiple-Coulomb scattering**
  - Accidental background

➡ **low material budget**

gaseous helium as coolant
50 µm thin pixel detector

➡ **fast detectors**

➡ **high granularity**

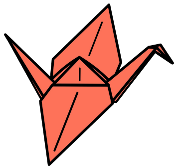


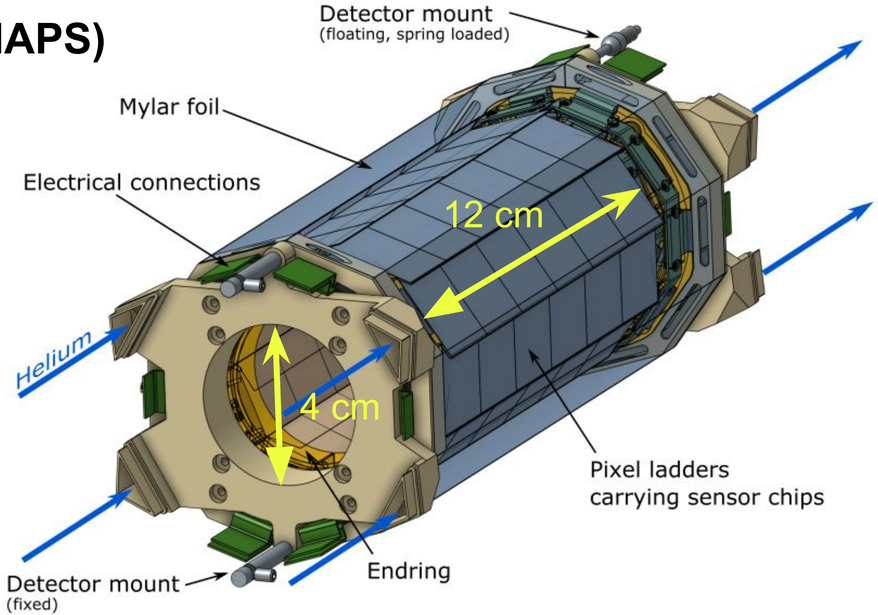
Invariant mass of signal decay, radiative decay and accidental background (Bhaba+Michel) [Mu3e TDR]

Mu3e vertex detector

more general overview on Mu3e:
past talk by
Cristina Martin Perez - 16.05.2023 - 11:30

- Innermost two pixel layers
- High-voltage monolithic pixel sensors **(HV-MAPS)**
  - 50 µm thin
  - Expected heat dissipation of ~ 215 mW/cm²
- Mechanical support:
  - Aluminized Kapton foils **(HDI)**
  - Some Origami skills
  - Chips glued on foils + **spTAB** for electrical connections
- Cooled by **gaseous helium**
  - 2 flow channels (between layers, and around outer layer)
  - Mass flow of 2 g/s





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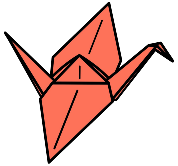
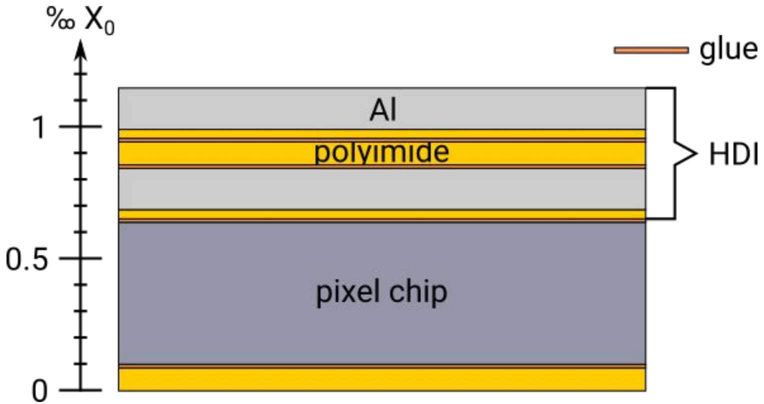
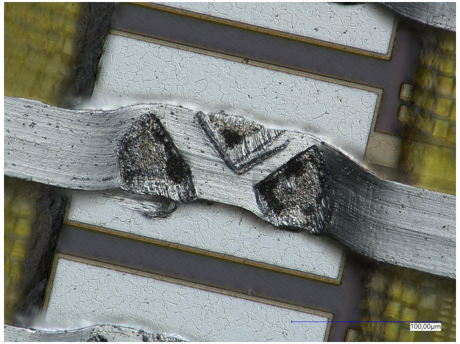




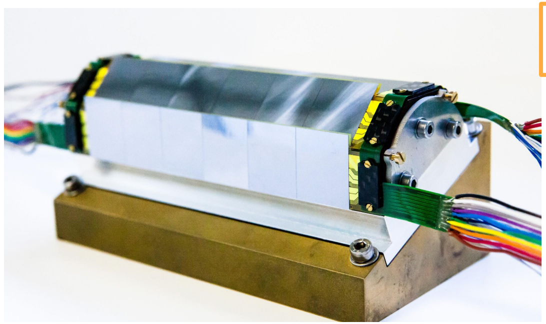
Resulting material budget



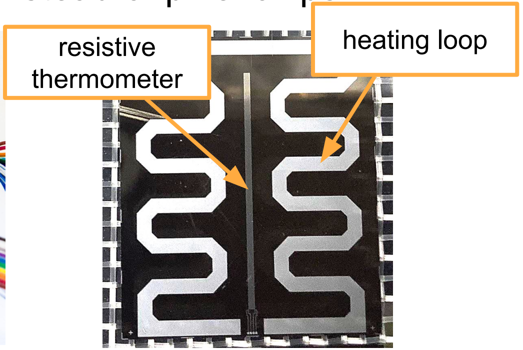
spTAB connection

Cooling studies - setup

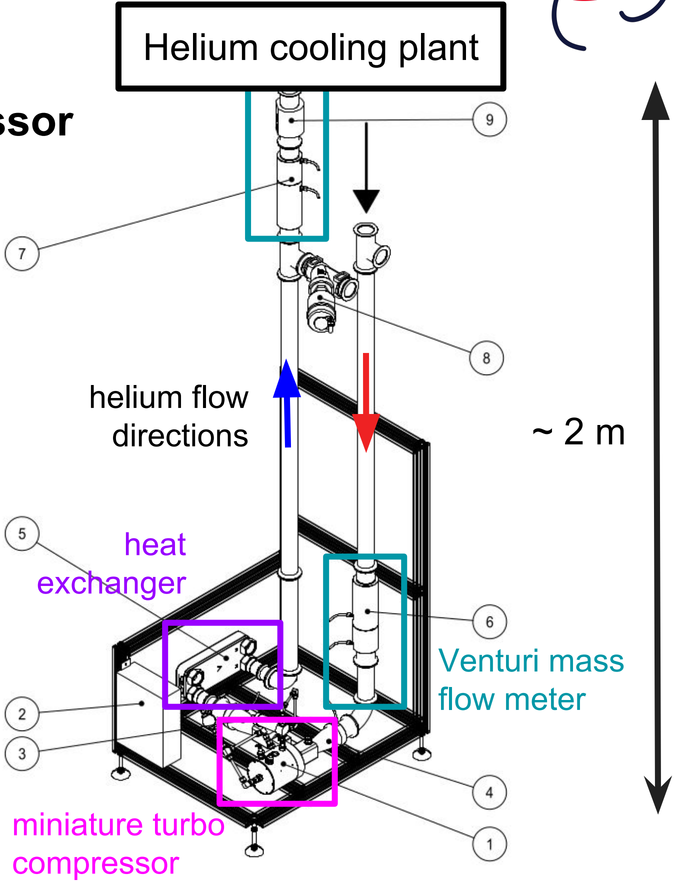
- Pumping 2 g/s helium with **miniature turbo compressor**
- Type of compressors is a **novelty** on the market
- Cooling studies
    - Prototype **helium cooling plant**
    - **Thermal-mechanical** detector **mock-up**
    - **Silicon heater chips** instead of pixel chips



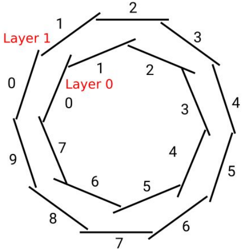
silicon heater module



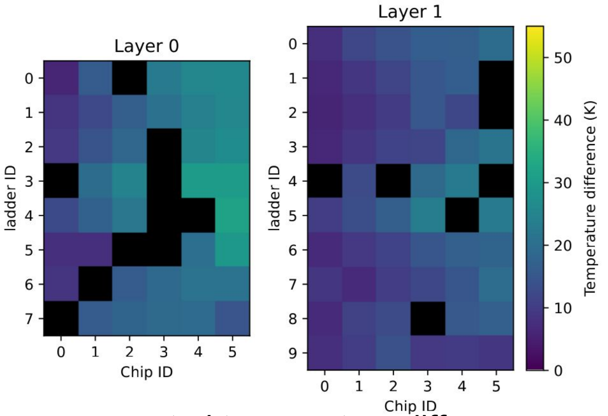
Silicon heater chip



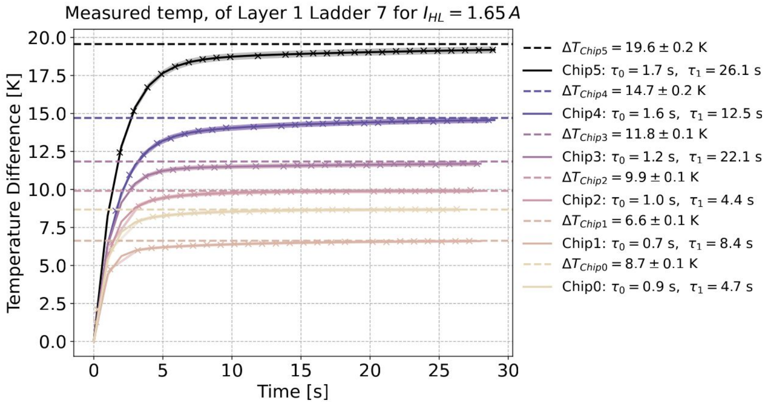
Cooling studies - measurement



- Chip temperatures required to be < 70°C
  - Glass transition temperature of epoxy used
- Temperature measurements given as **difference to gas inlet temperature**



raw uncorrected temperature difference maps for ~ 215 mW/cm²



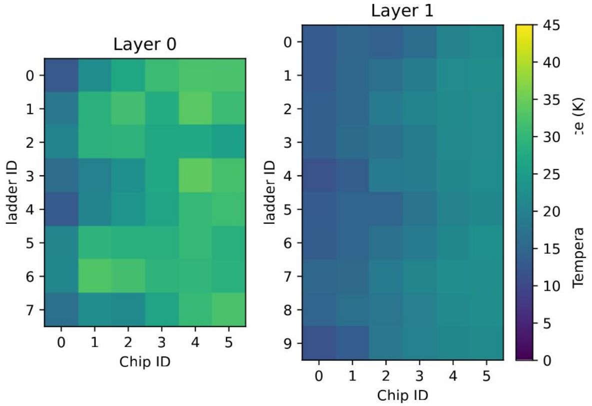
transient temperature curve along a 6-chip ladder

Analysis:
- Estimate missing temperatures readings
- Correct for temperature-dependent resistances

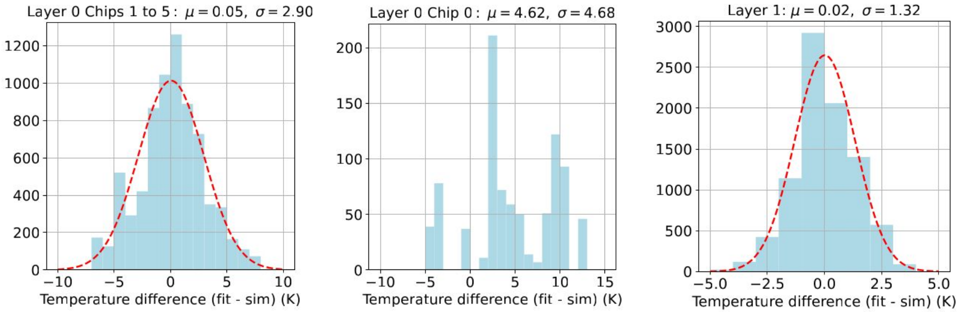
Cooling studies - analysis

Step 1:
Missing temperature reading

- Simulated temperature maps (uniformly heated mock-up implemented in Ansys CFX 18.2)
- Monte-Carlo:
  - Remove 17x random temperature readings
  - 5 selection criteria to match the missing temperature pattern of the mock-up
  - Estimate missing temperatures by 2nd grade polynomial
  - Determine uncertainty of this method



simulated temperature maps



Uncertainty distributions for estimating missing temperature readings

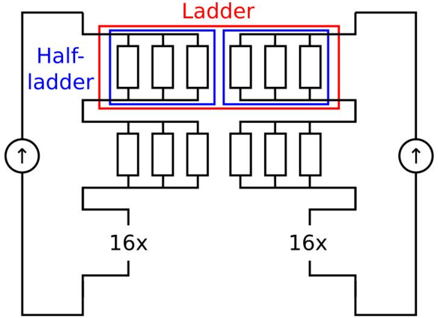
Cooling studies - analysis

Step 2:
Correct for temperature-dependent resistances

- Resistance changing linearly with temperature
- 3 chips are powered in parallel
    - Current varies due to temperature gradient
- Line resistance depends on chip position

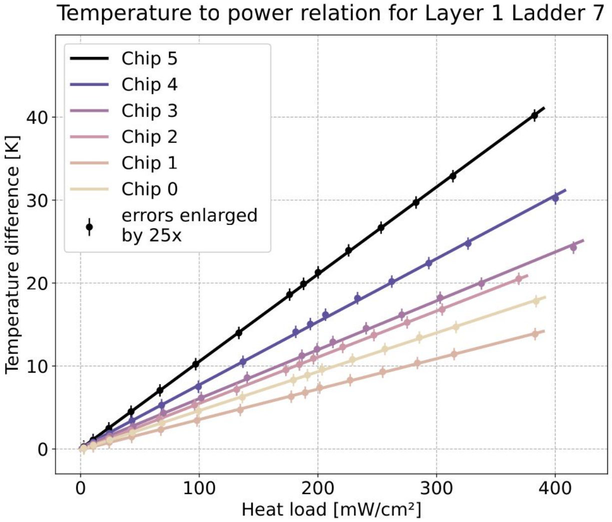
$$f_R = (1 + \alpha \Delta T_{chip})$$

$$f_I = \frac{1}{f_R + \frac{R_{chip,HDI}}{2.75\,\Omega}} \times \frac{3}{\sum \frac{1}{1 + \alpha \Delta T_i + \frac{R_{i,HDI}}{2.75\,\Omega}}}$$

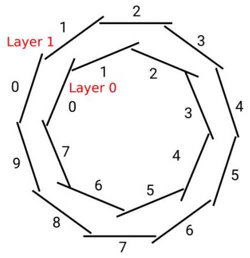


Step 3:
Re-scale to heat dissipation of interest

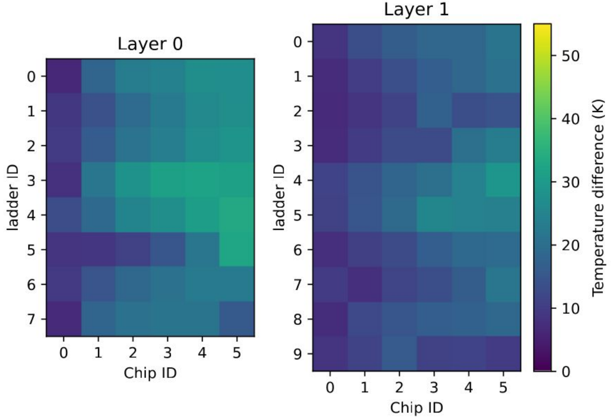
Valid due to **linear power-to-temperature** relation



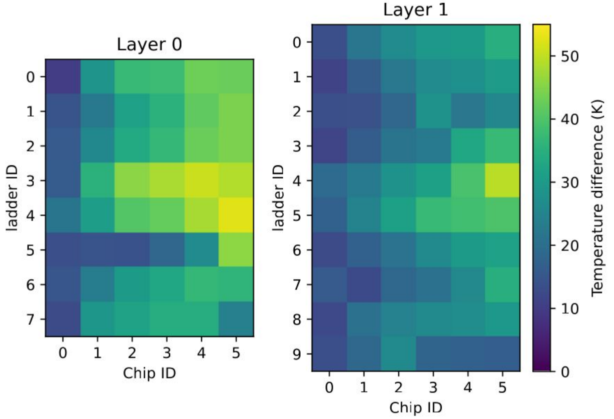
Cooling studies - results



- **Expected scenario** (215 mW/cm²)
  - Max. temperature difference < 35 K
  - Avg. temperature difference ~ 17 K
- **Conservative scenario** (350 mW/cm²)
  - Max. temperature difference < 54 K
  - Avg. temperature difference ~ 31 K
- For 2 g/s helium:
  Chip temperatures are < 70°C for gas inlet temperatures of up to 10°C even for 350 mW/cm²



temperature difference maps 215 mW/cm²
(expected scenario)



temperature difference maps 350 mW/cm²
(conservative scenario)

Experimental challenges

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- **Low-momentum** particles
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  - Electron/Positron momenta < 53 MeV/c
- Signal-to-**background** discrimination
  - μ→eeeνν (main background channel)
  - **Limited by multiple-Coulomb scattering**
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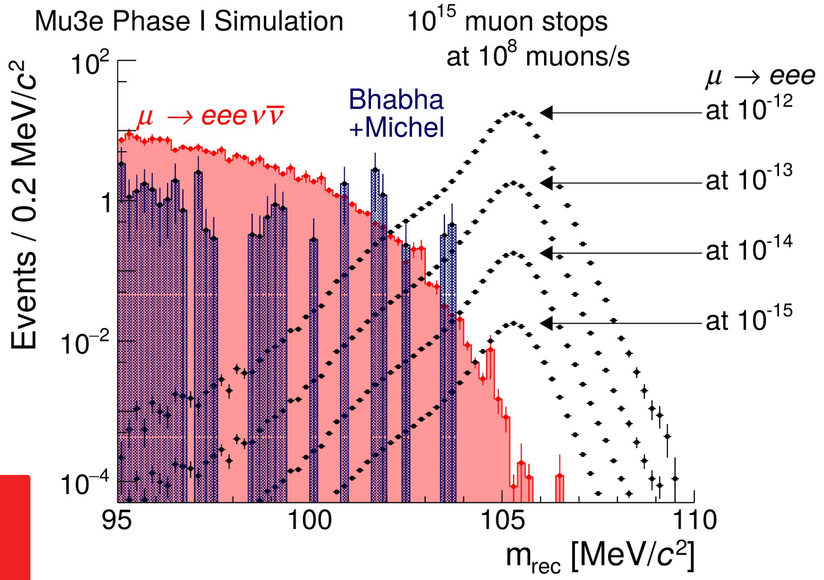
➡ **low material budget**

➡ **fast detectors**

➡ **high granularity**

Pixel sensor:
80 x 80 μm² small pixels
< 20 ns time resolution



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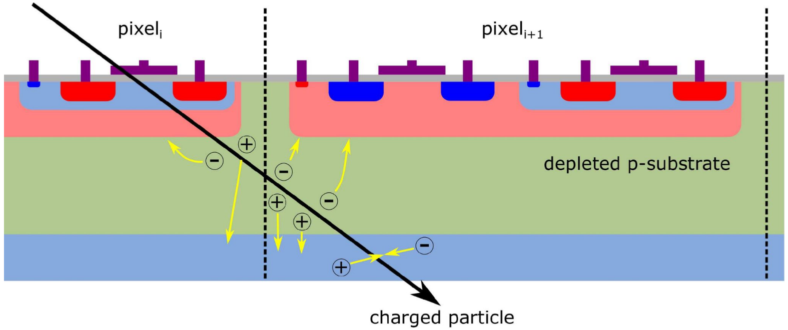
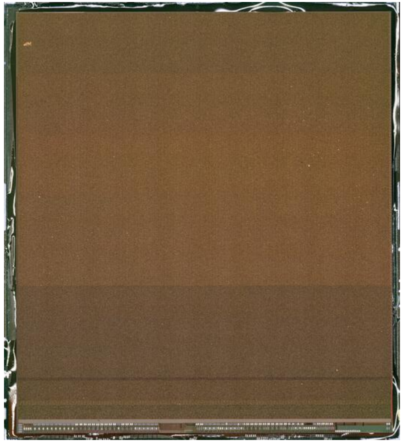
MuPix11 - the pixel chip

- HV-MAPS technology
  - Commercial 180 nm HV-CMOS process
  - Deep N-well diode
  - Fast charge collection via drift
  - **Monolithic design**: in-pixel electronics, detection & readout in one chip
- MuPix11
  - 80 x 80 μm² pixel size
  - Mu3e requirements:
    - < 20 ns time resolution
    - > 99 % efficiency (max. noise 1 Hz/pixel)
  - Thinned to 50 μm
  - Zero-suppressed continuous readout scheme





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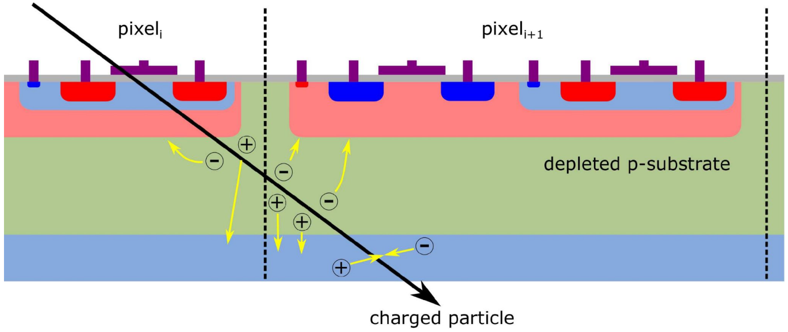
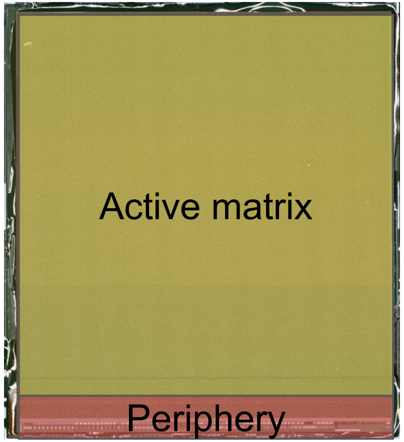
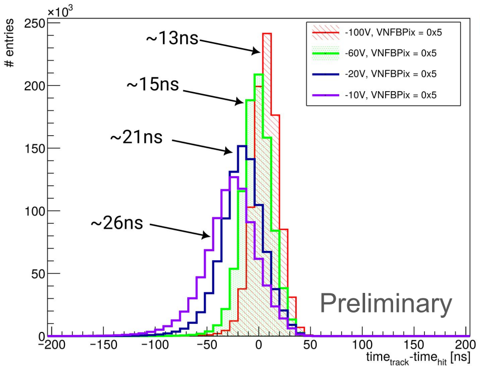




MuPix11 - results

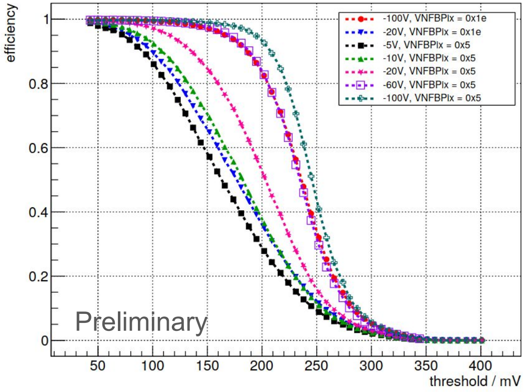
- MuPix11 (100 µm thickness) characterized
- All changes from MuPix10 successful
  - Running at full readout speed
  - Configuration via serial input
  - On-chip voltage drops minimized
- Efficiency & time resolution within specs for Mu3e
- Performance studies ongoing:
  - Thinned sensors (50 µm, 70 µm)
  - Post processing (plasma etching)



raw time resolution

offline improvements via

- time walk correction
- delay correction



MIP detection efficiency

- measured with 350 MeV $e^+/\mu^+/\pi^+$ beam
- efficiency plateau forming for HV > 10 V

Taken from Heidelberg PhD student David Maximilian Immig

Conclusion

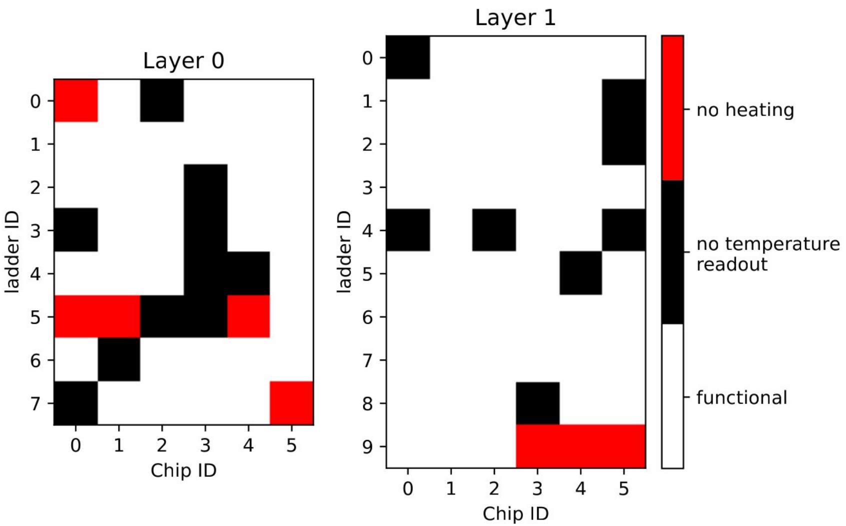
- Ultra-light helium cooled pixel detector with HV-MAPS feasible
- **Helium cooling** concept verified for the Mu3e vertex detector
- Final chip, **MuPix11**, available and performing to specs

- Characterization of 50 µm thin MuPix11 ongoing
- Full Mu3e vertex detector (v1) construction scheduled this summer
  - 1st operation with cosmics expected for late 2023
- Upscaling of helium cooling system:
  - Testing of 16 g/s sub-system ongoing for outer pixel layers
  - Construction of final helium plant about to start
  - Final commissioning Q1 2024

Backup

Pattern of functional chips in mock-up

- 8x silicon heater chips could not be powered
- 18x silicon heater chips had no functional connection to the resistive thermometer
- pattern fully disjunct



Mass flow dependence of the chip temperatures

- Measurement of a ladder in both pixel layers each
- mass flow range between 1.4 - 2.0 g/s covered
- linear dependence observed
- mass flow rate can be potentially reduced during operation if needed
- temperature can easily be estimated