Monolithic sensors for the Mu3e experiment

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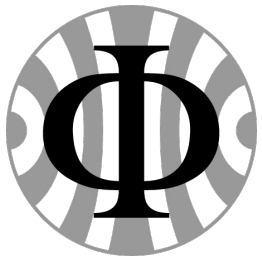
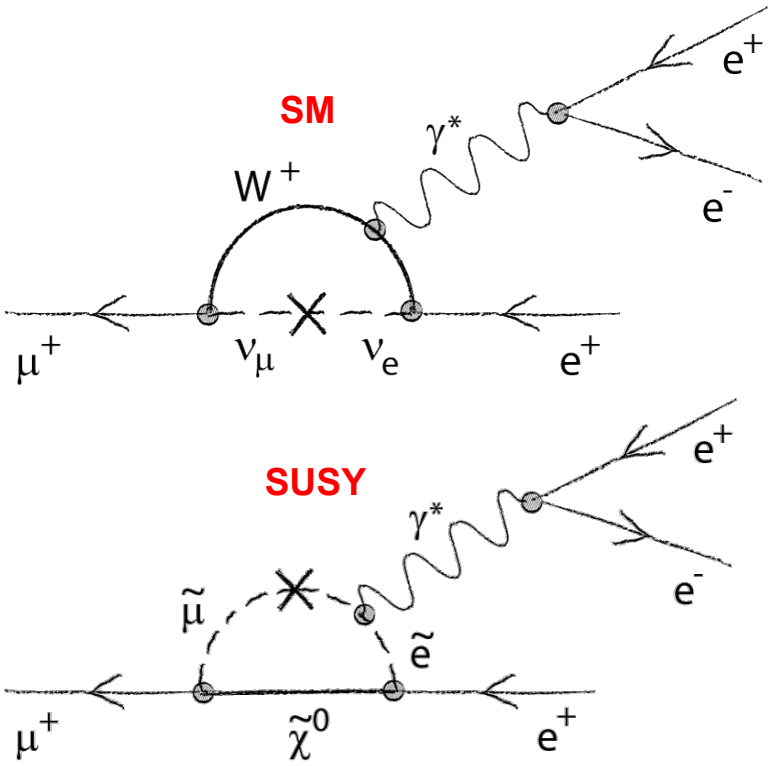
University of Heidelberg

Vertex 2021
29/09/2021



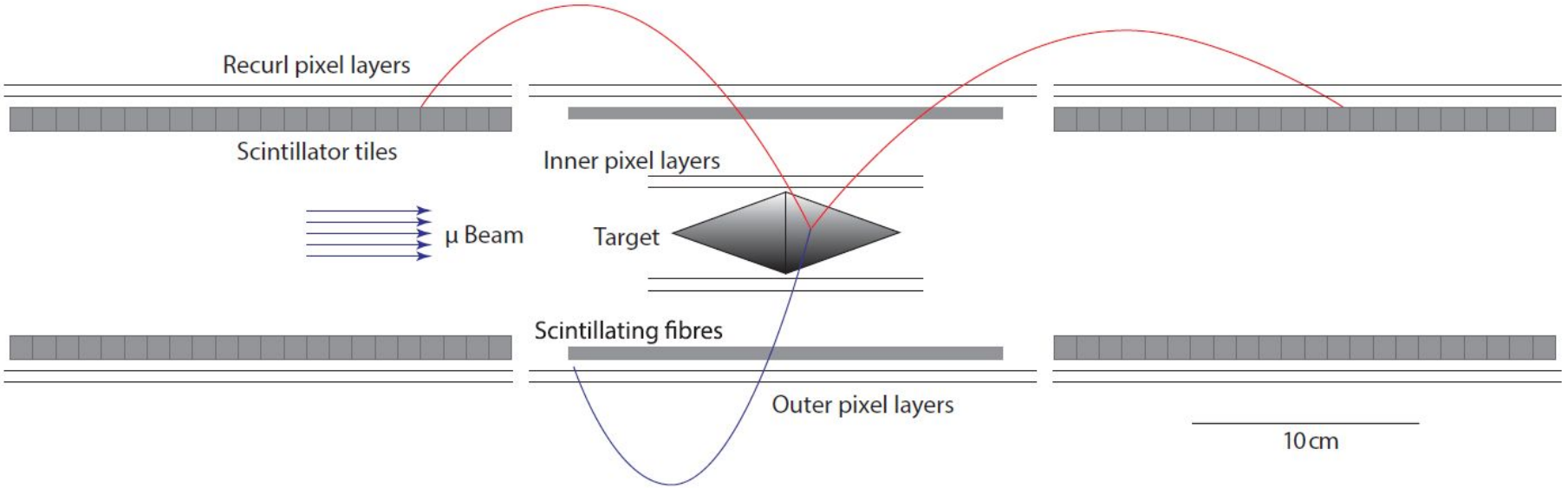
Mu3e: Physics Motivation

- Search for μ→eee
  - Standard Model: BR (μ→ eee) < 10^{-54}
- New physics might enhance BR
- Current limit:
  - BR (μ→ eee) < 10^{-12} (SINDRUM, 1988)
- Aimed single-event sensitivity:
  - BR (μ→ eee) < $2 \cdot 10^{-15}$ (Phase 1)
  - BR (μ→ eee) < 10^{-16} (Phase 2)
- PSI High Intensity Muon Beamline
- Phase 1 construction starting by beginning of next year



Experimental concept

- Tracking electrons coming from muon decays (~10^8 Hz in Phase I)
- Magnetic field (1 T)



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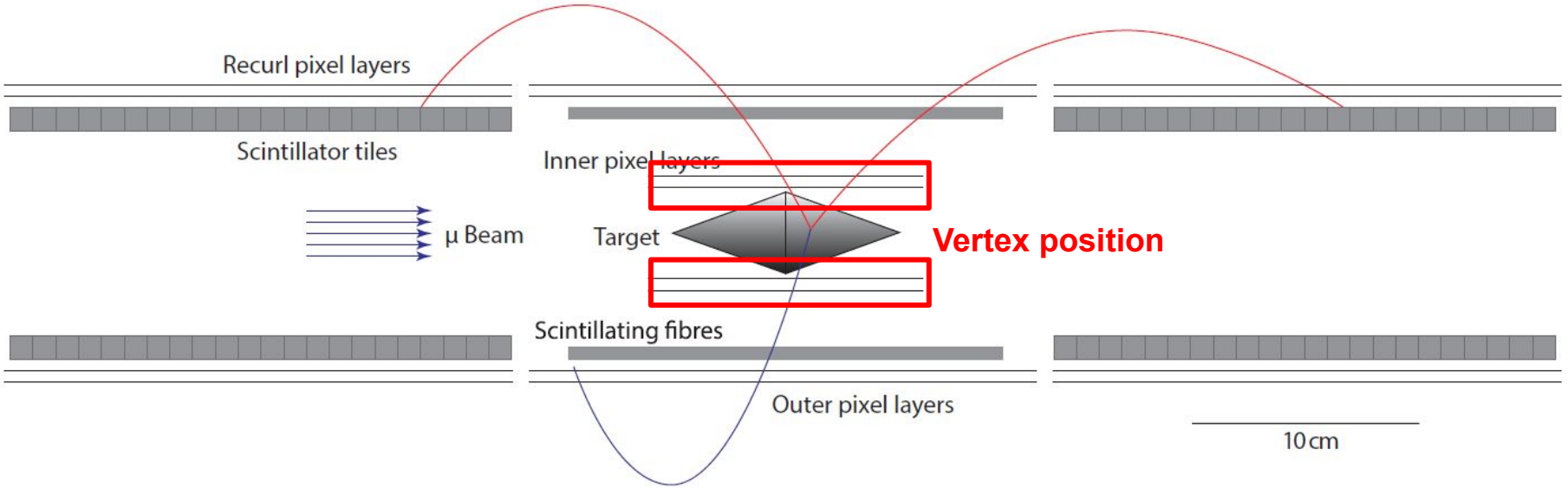

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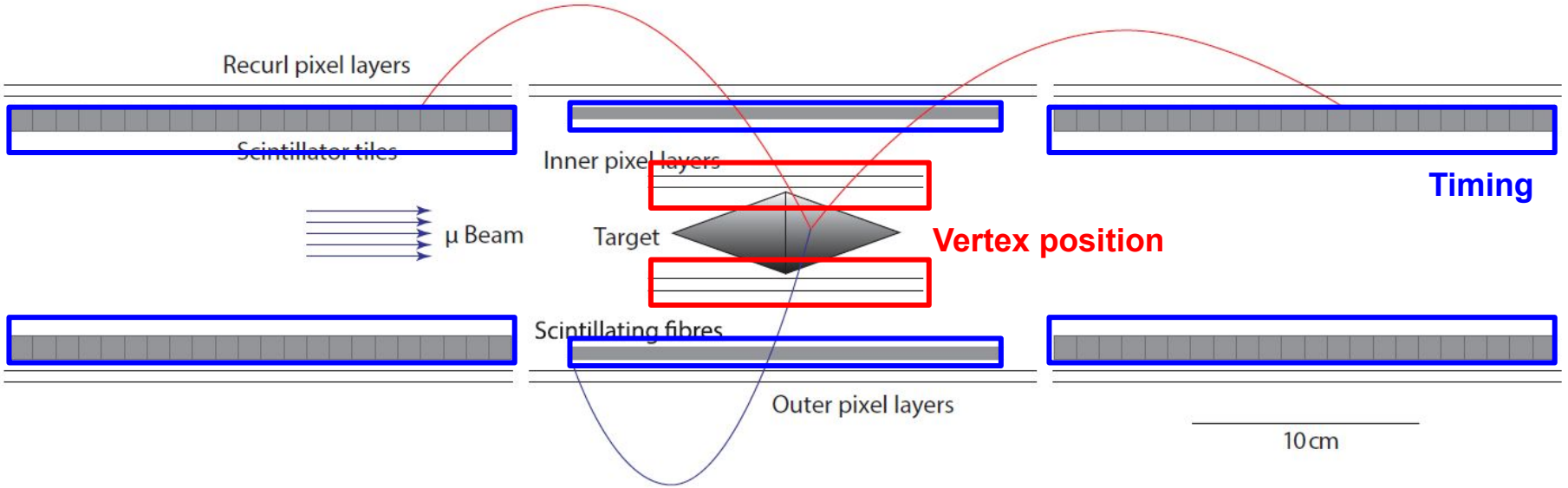

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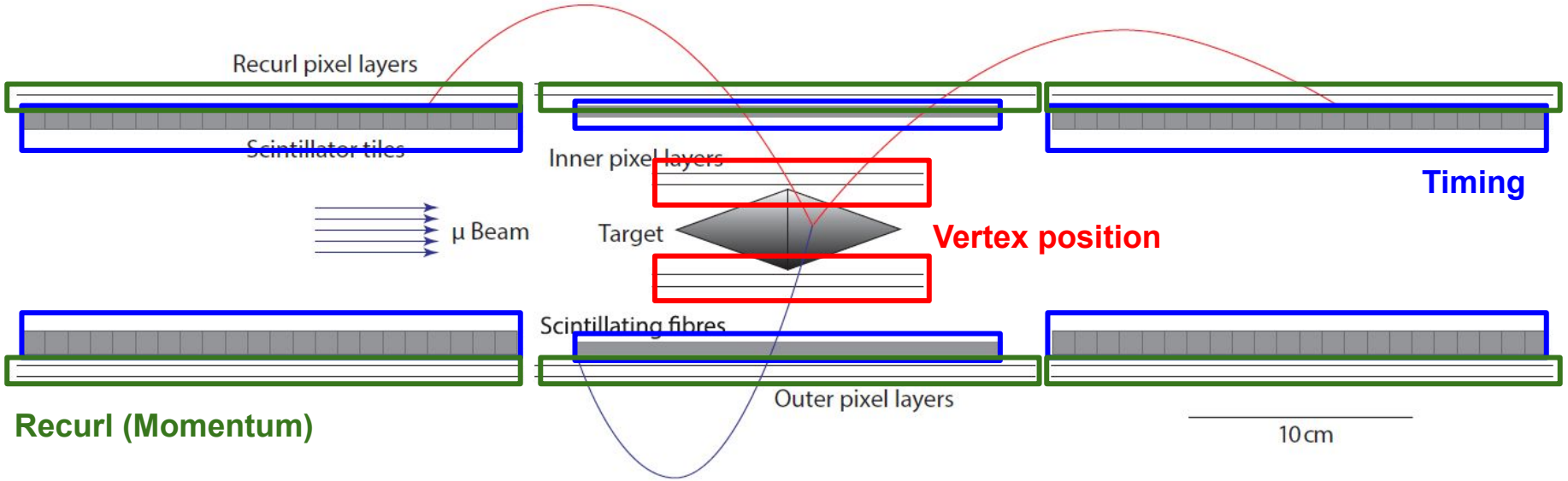

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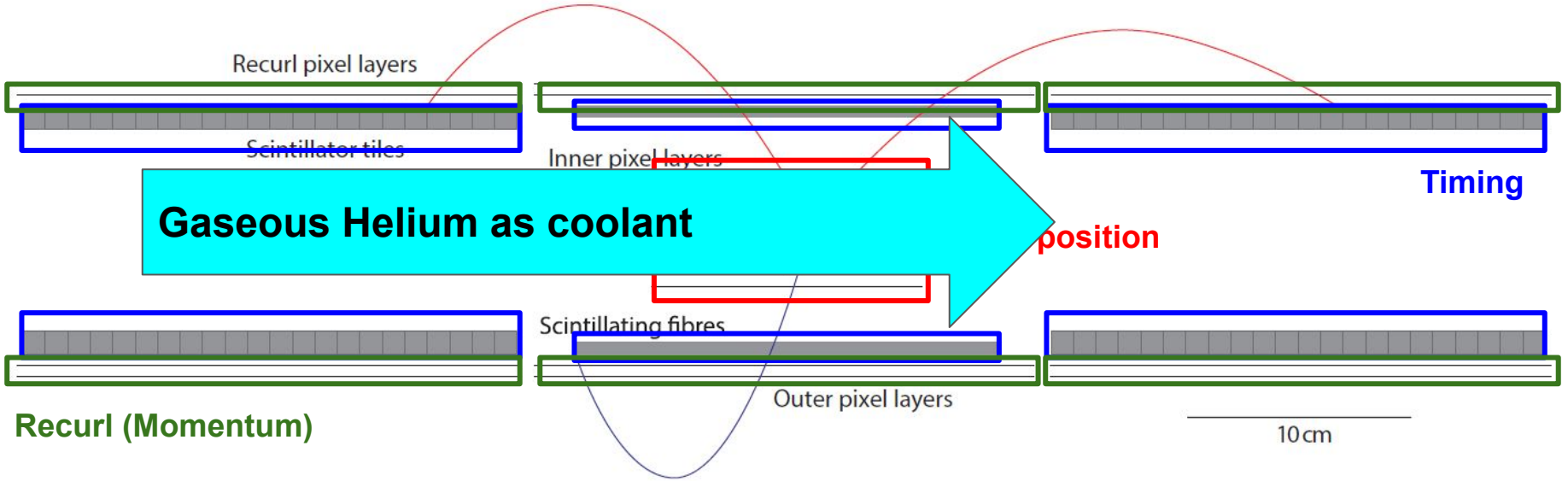

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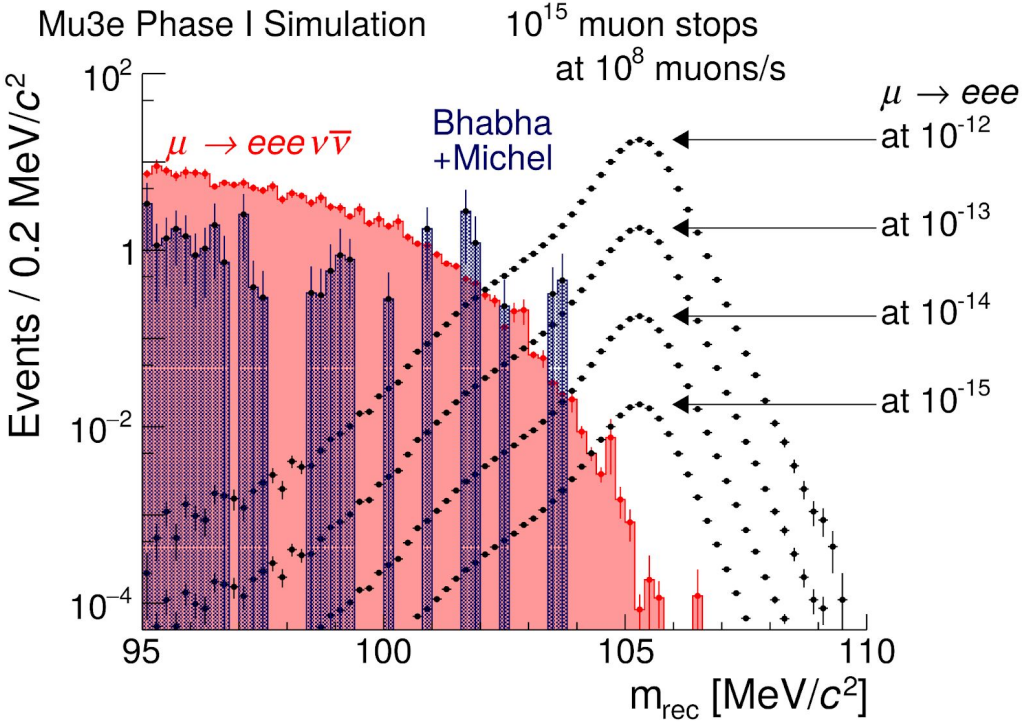


Invariant mass of signal decay, radiative decay and accidental background (Bhaba+Michel) [Mu3e TDR]

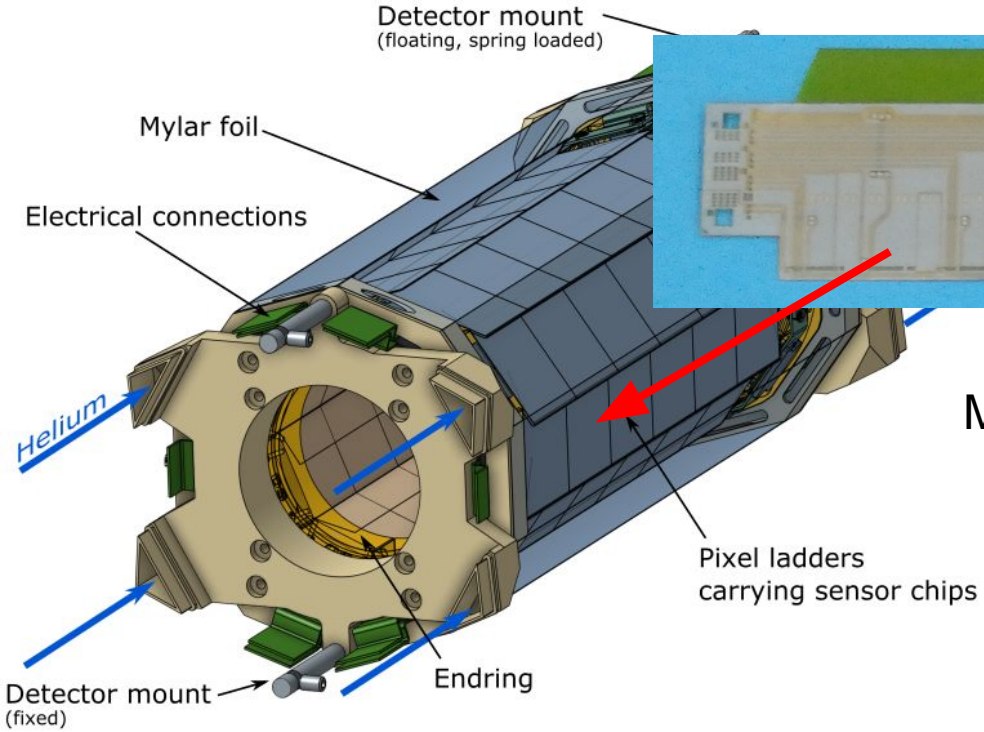
Momentum resolution crucial for detecting the peak at muon mass…

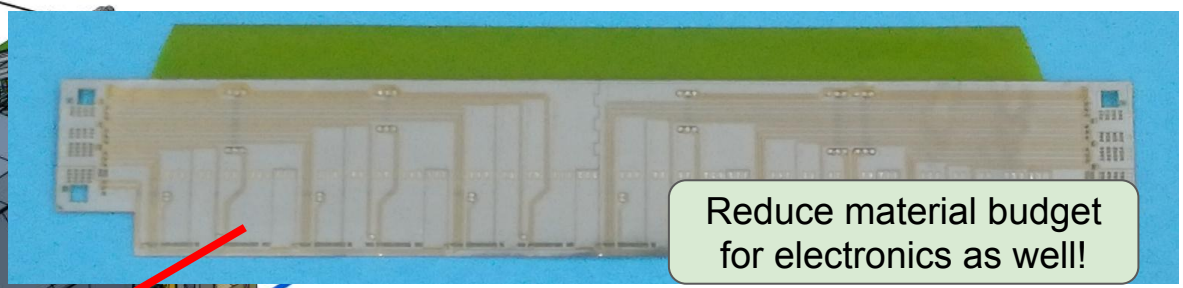
Material budget is key factor!

1 MeV resolution with 0.1% X/X_0 per layer

Tracking System

Layer 1/2



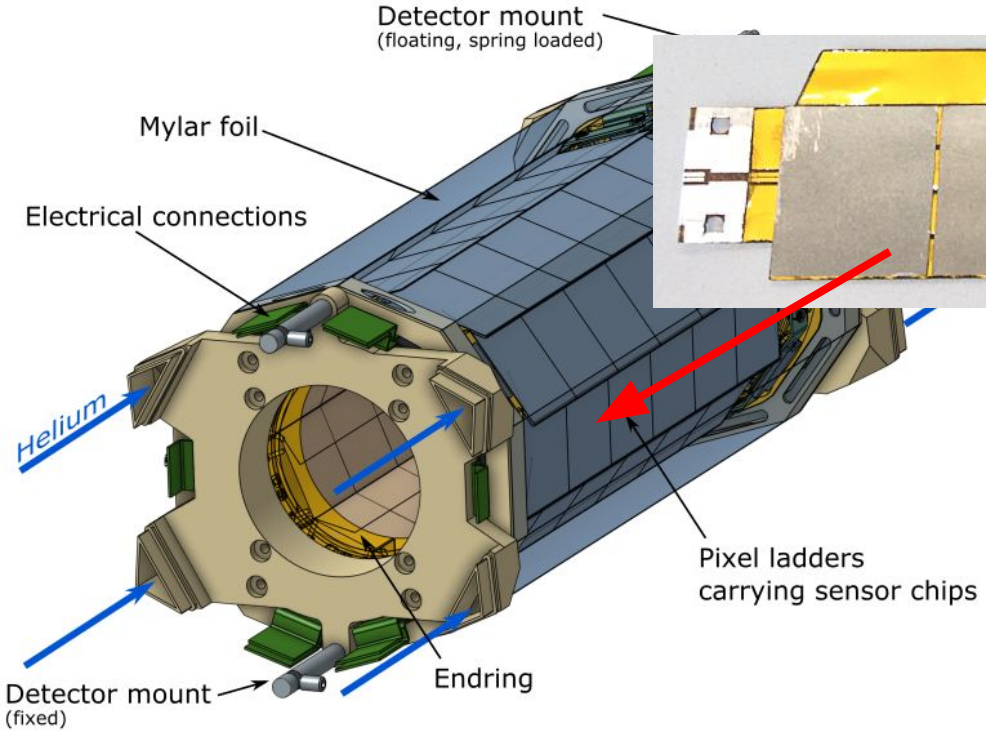


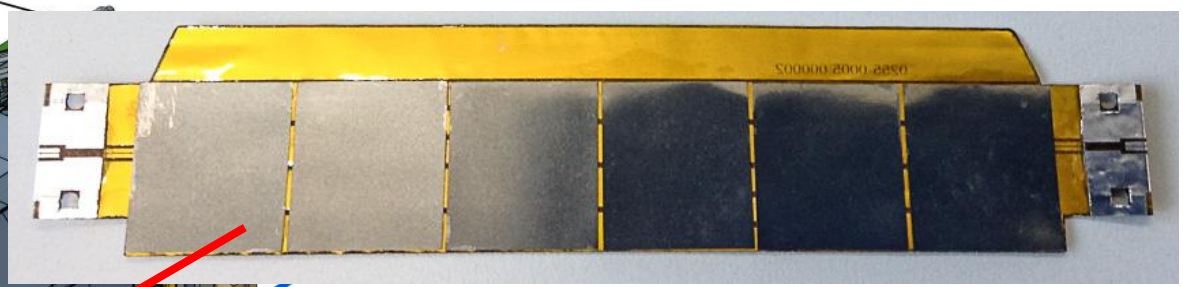
Mechanical units: Ladders

- High Density Interconnects (HDIs)
- Kapton/Aluminum foils
- Mechanical support
- Electrical traces
- Produced by LTU (Ukraine)
- No extra components

Tracking System

Layer 1/2





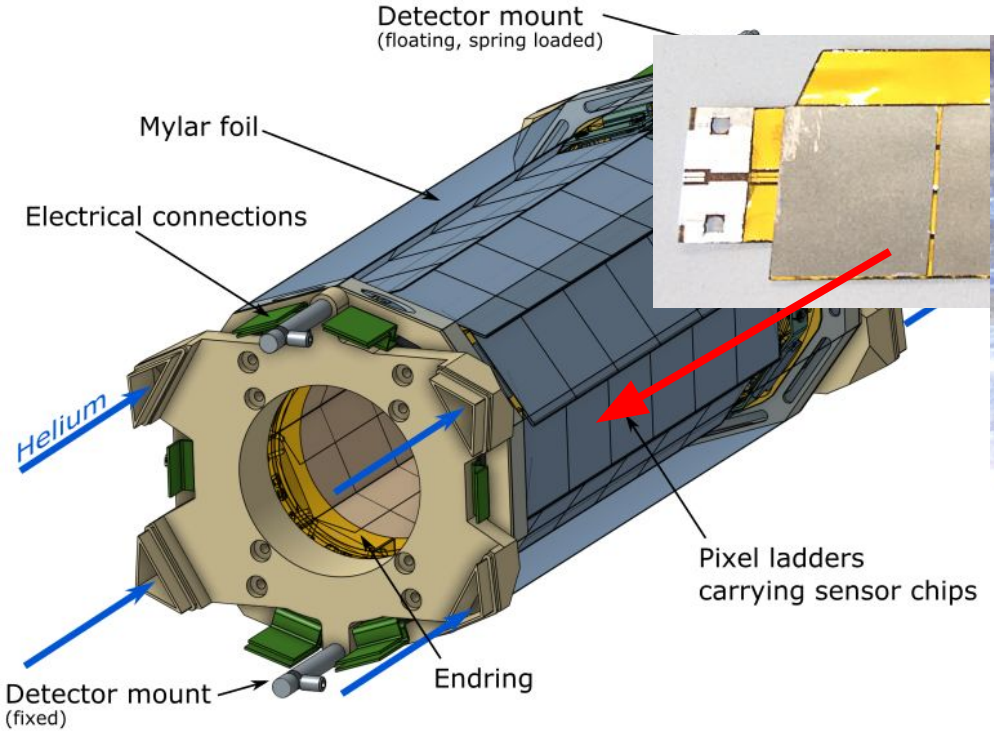
(Aliminum mockup)

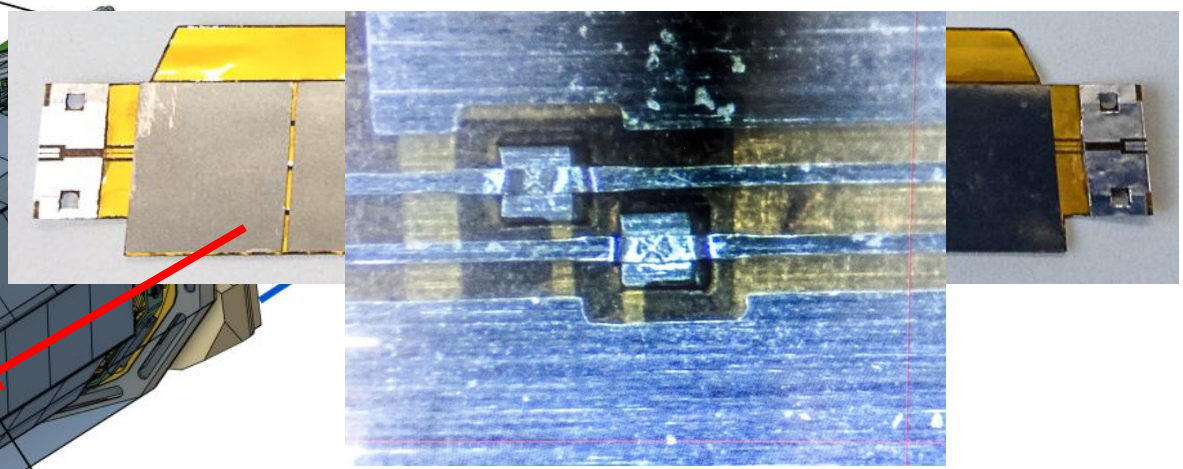
Chips glued on top

- 6 for layer 1 and 2
- 17/18 for layer 3/4

Tracking System

Layer 1/2

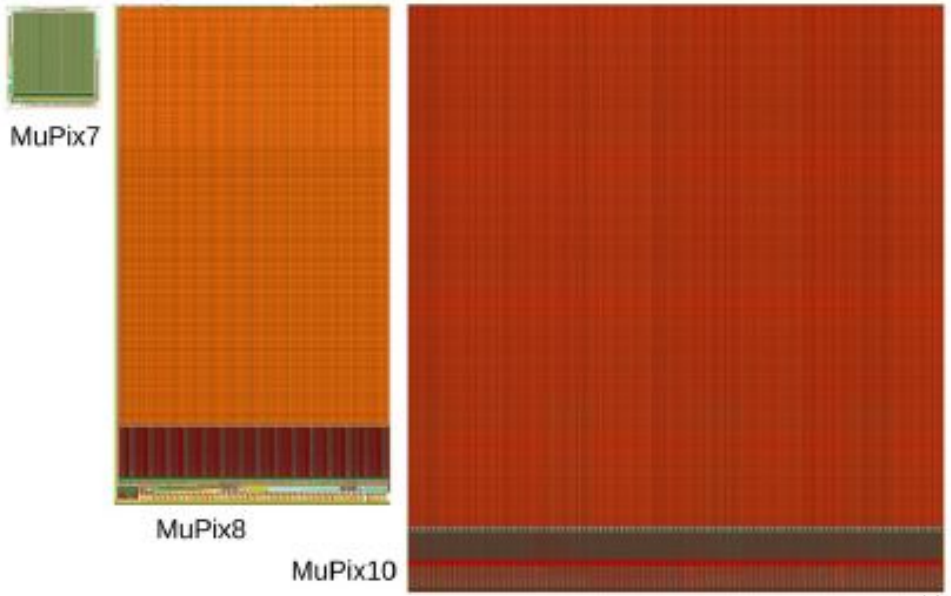




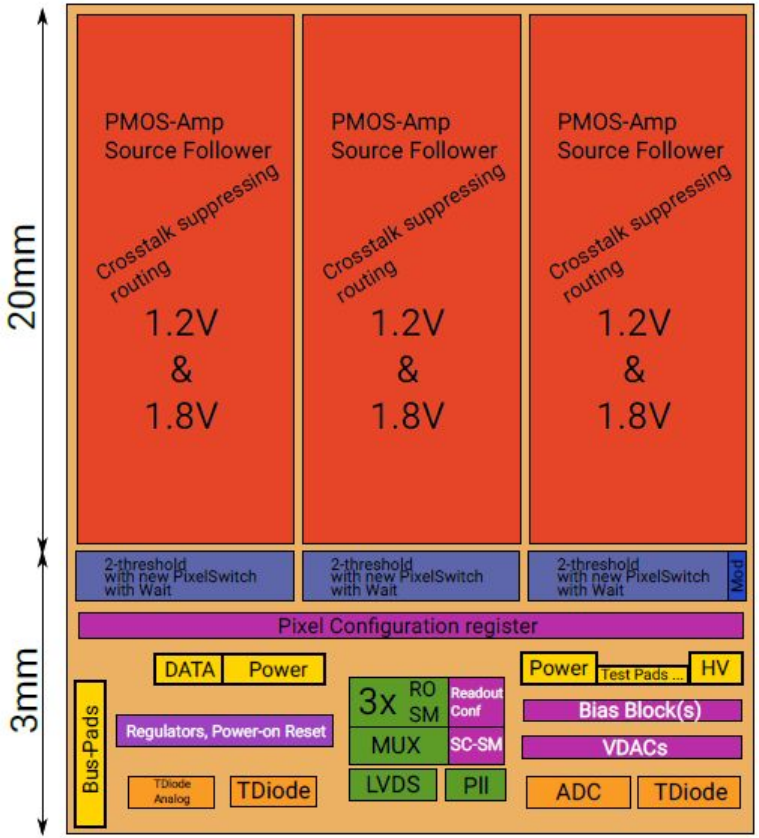
Electrical connections with Singe Point Tape Automated Bonding (SpTAB)

MuPix sensors

- Monolithic HV-CMOS
  - Super thin with high performance
- 180 nm H18 technology derived from IBM
  - AMS until 2018
  - TSI afterwards
- Long R&D campaign
  - Mupix7 first fully monolithic
  - Mupix8 larger
  - Mupix9 implemented slow control
  - Mupix10 with final size
  - Expected Mupix11 soon



MuPix sensors: MuPix10



- ~2x2 cm^2 active area
- Chip periphery on bottom

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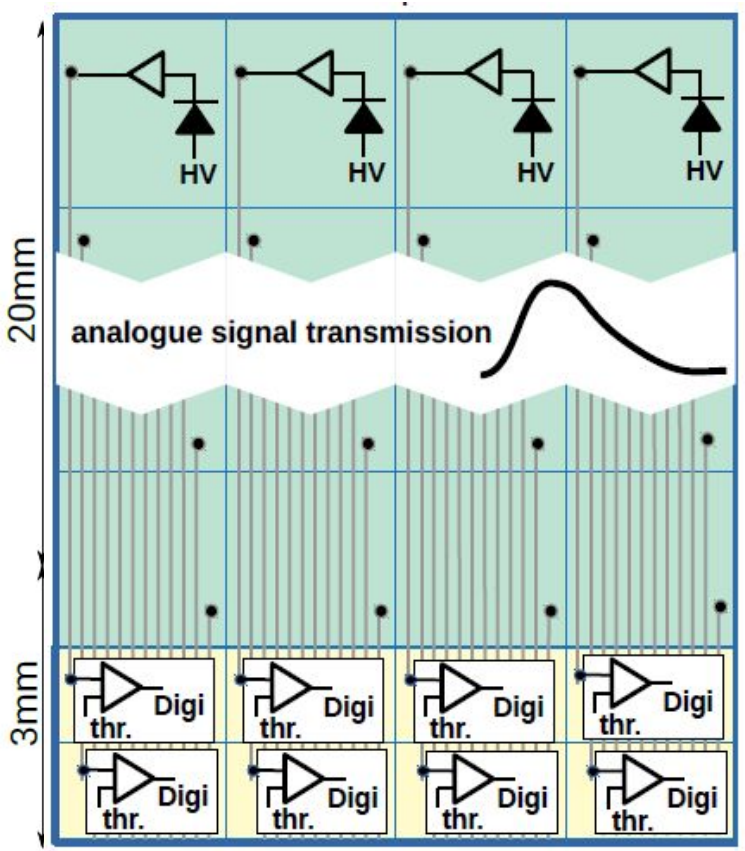
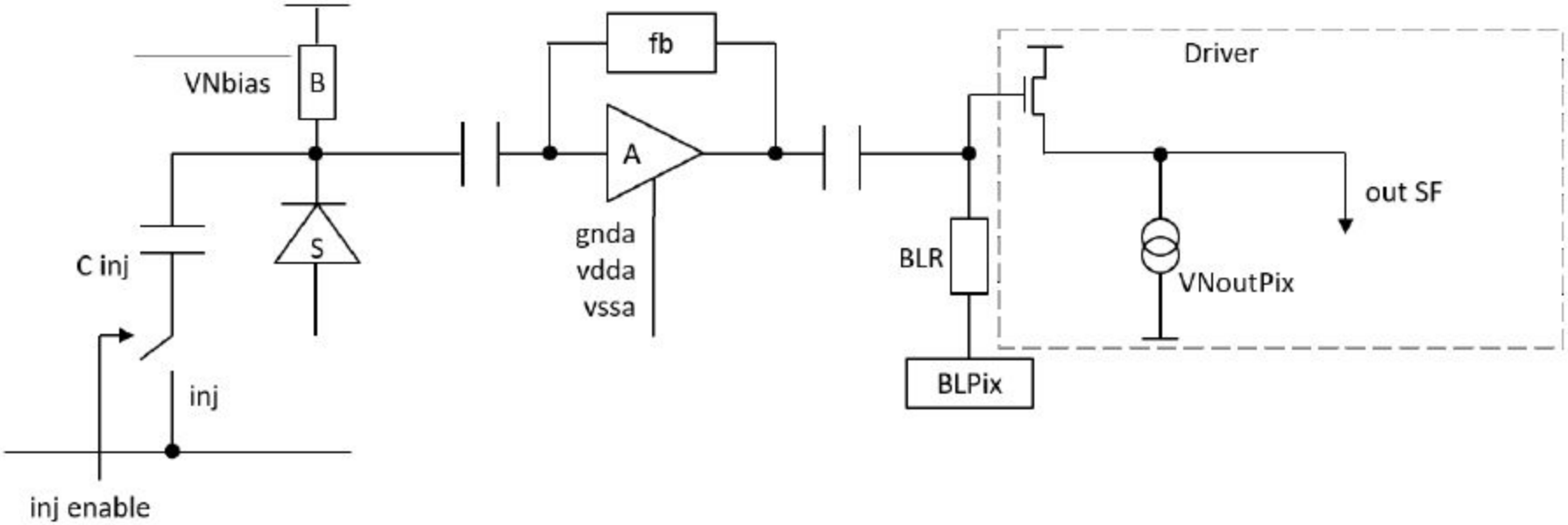


- ~2x2 cm2 active area
- Chip periphery on bottom
- Signal collected and amplified by pixels
- Analogue signal driven to periphery
- Each pixel mirrored in periphery
  - Analogue signal digitized
- State machine collects hits from double column
- Continuous read-out!
- 4 LVDS link
  - 3 per matrix (inner trackers)
  - 1 mulitplexed (outer layers)

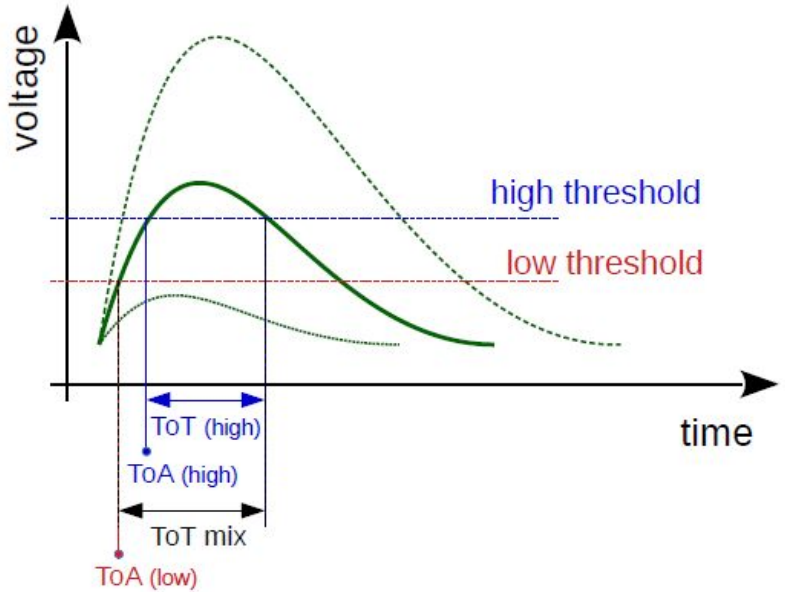
MuPix sensors: MuPix10

Single pixel read-out: in-cell



MuPix sensors: MuPix10

Single pixel read-out: periphery



Comparator in digital cell

Records Time-of-Arrival (ToA)

Records time of falling edge

Time-over-Threshold (ToT) computed

2 threshold mode:

- hit flag raised with high threshold
- ToA recorded with low threshold
- Falling edge on high threshold

Decreases time-walk

MuPix sensors: requirements

pixel size [μm^2]	80×80
sensor size [mm^2]	20×23
active area [mm^2]	20×20
active area [mm^2]	400
sensor thinned to thickness [μm]	50
LVDS links	$3 + 1$
maximum bandwidth[§] [Gbit/s]	3×1.6
timestamp clock [MHz]	≥ 50
RMS of spatial resolution [μm]	≤ 30
power consumption [mW/cm^2]	≤ 350
time resolution per pixel [ns]	≤ 20
efficiency at 20 Hz/pix noise [%]	≥ 99
noise rate at 99 % efficiency [Hz/pix]	≤ 20

MuPix sensors: special features

- 3 LVDS input lines
  - Clock
  - Sync reset
  - Serial input
- Slow control
  - ADC to read internal voltages and temperature
  - Readings sent out via data links
  - Extra temperature diode (analogue output)
- Hit-delay circuit
  - Hit recorded after a fixed delay from ToA
  - Easier time sorting procedure
  - Incidental max value on ToT

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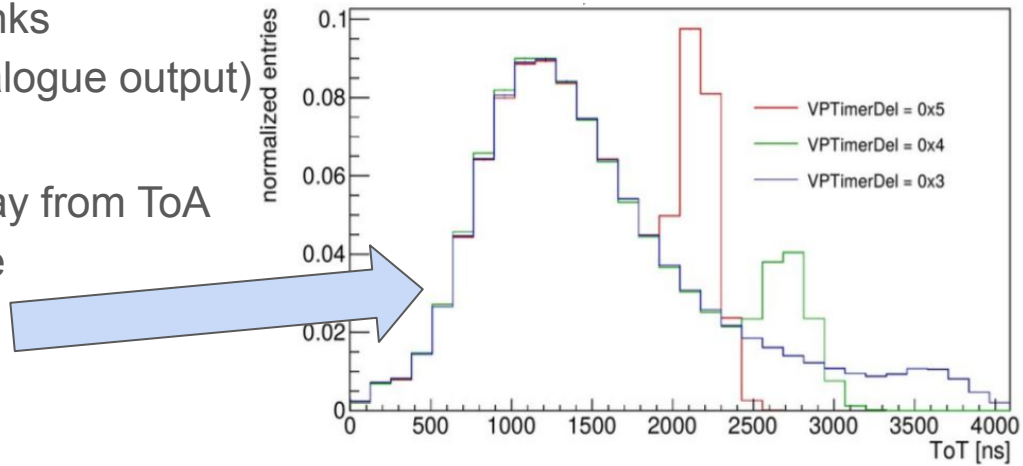
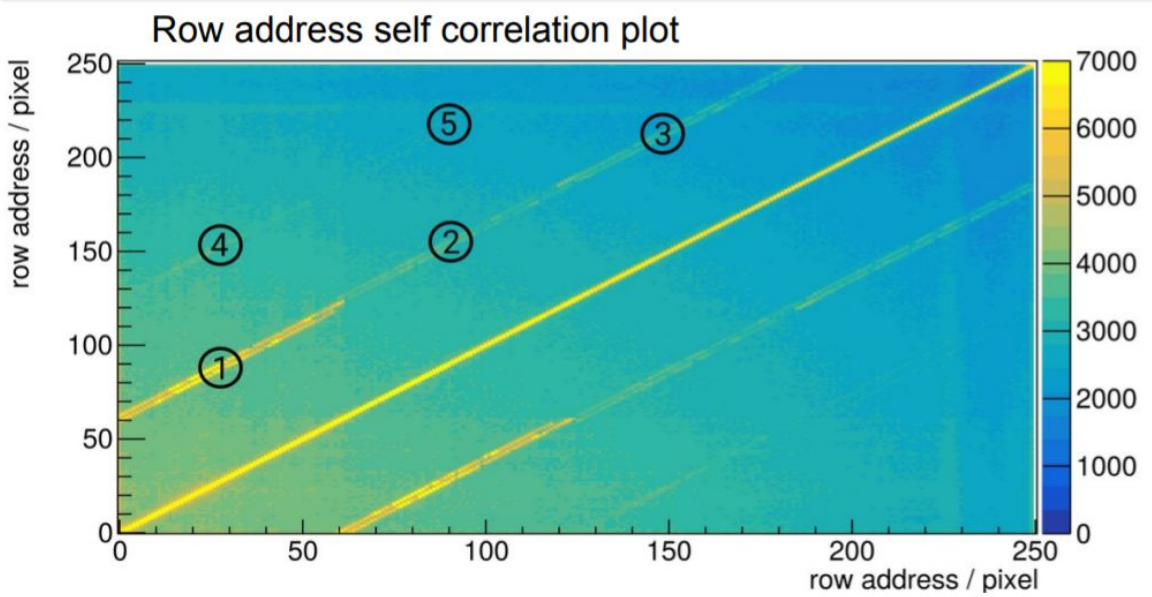


MuPix10: results

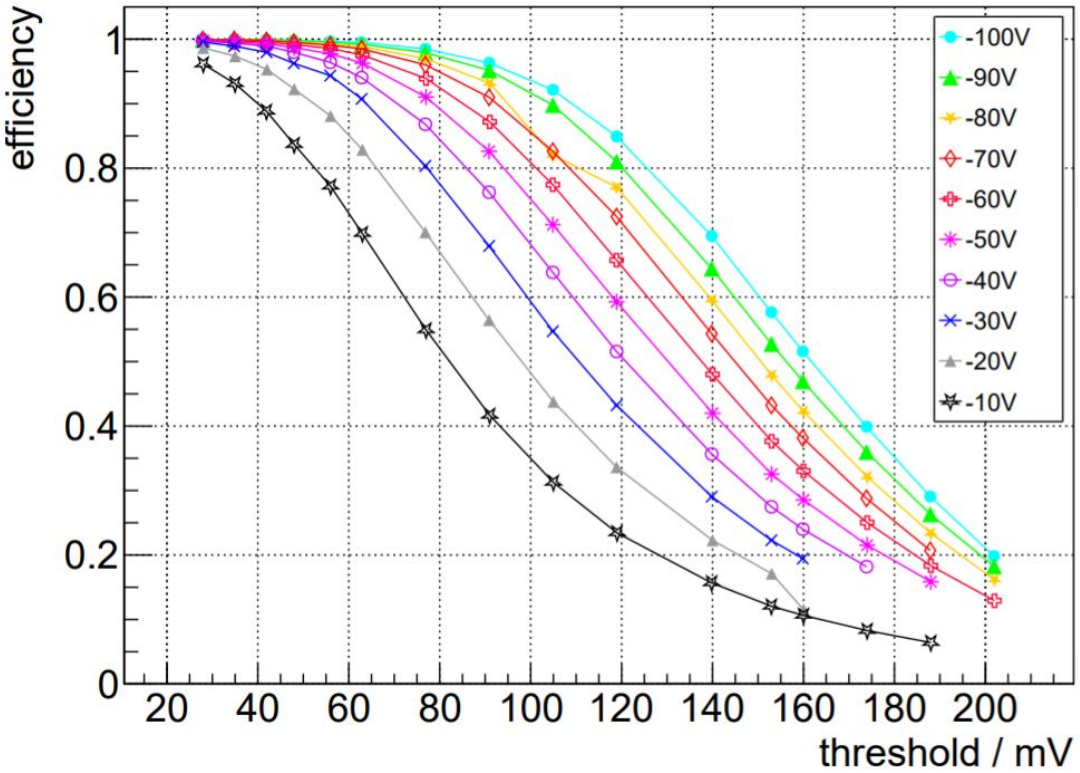
Cross-talk



Multiple metal layers (TSI specific) used to minimize inter-line capacitances. Cross-talk probability < 1.5%

Neighbouring pixels are routed on different lines: cross talk distinguishable from charge sharing

MuPix10: results

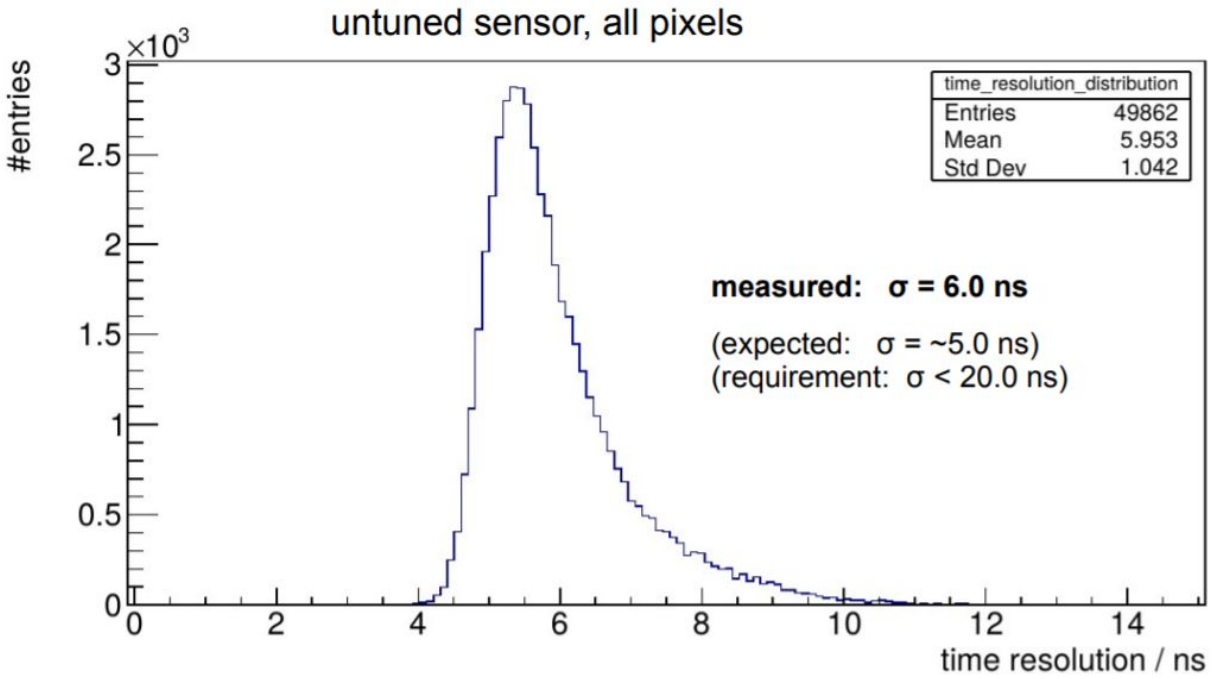


100 µm thickness

110 V breakdown

Efficiency plateau well defined above 30V

MuPix10: results

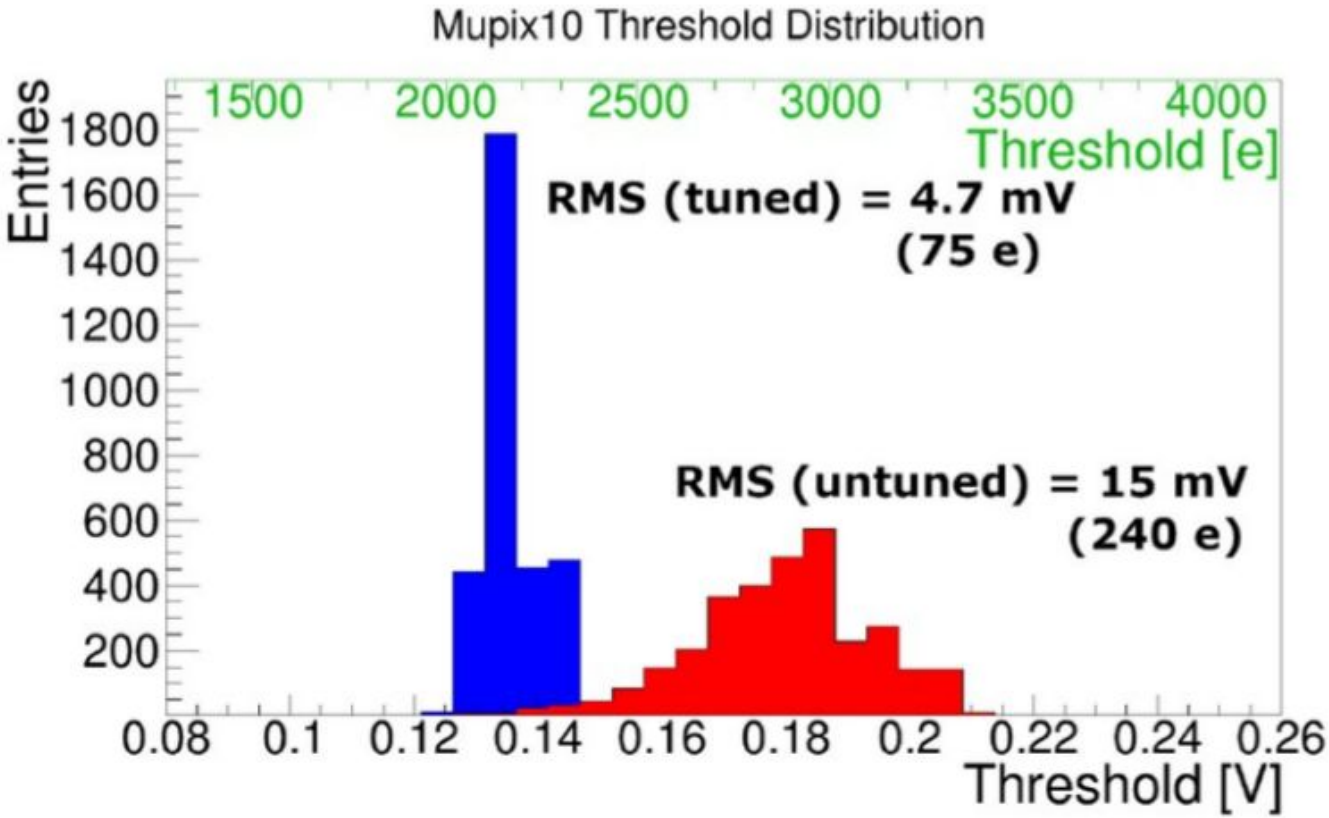


Time resolution well within specifications

~15 ns without corrections

6 ns after row and time-walk corrections

MuPix10: results



Threshold scans:

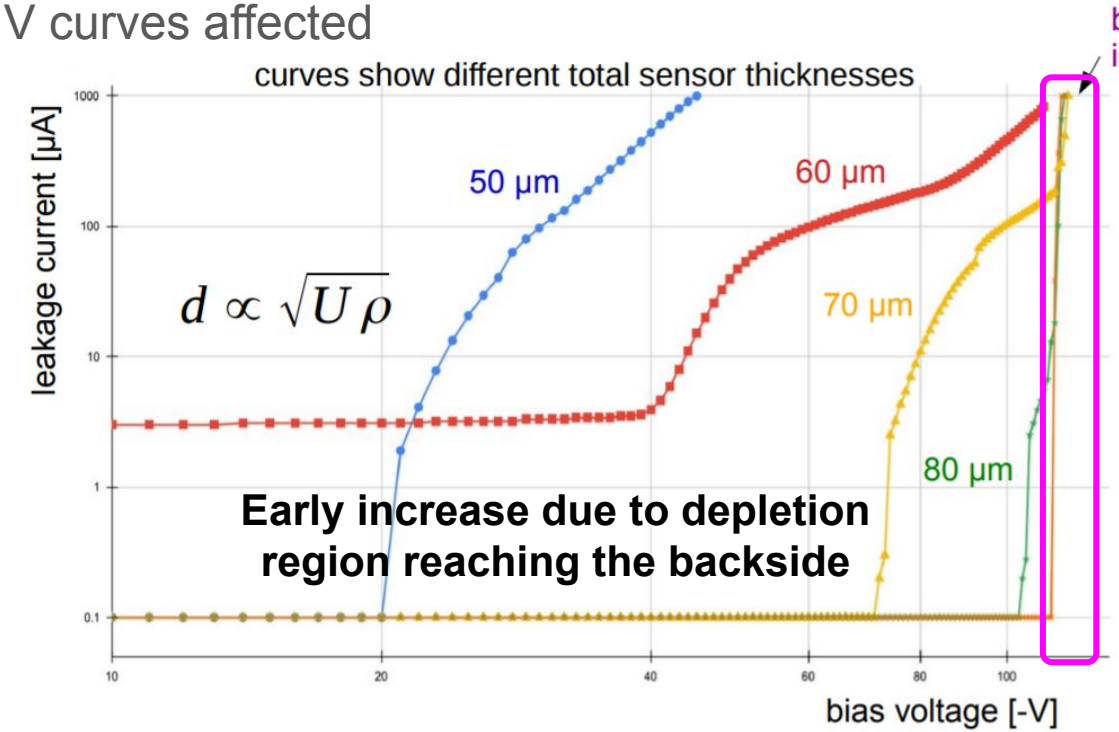
Low noise

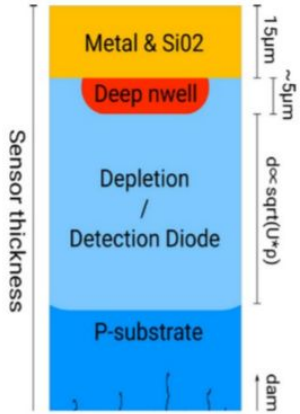
Tunable threshold

Mupix10: thinning

MuPix10 devices thinned at different thicknesses (by mechanical grinding)

ÌV curves affected





Early current increase compatible with ~300 Ωcm resistivity (nominal: 200 Ωcm)

MuPix10: thinning

Severe impact on performance

- 50 µm thin
- 200 Ωcm resistivity
- Only 25 V bias

Efficiency is low

MuPix10: thinning

Severe impact on performance

- 50 µm thin
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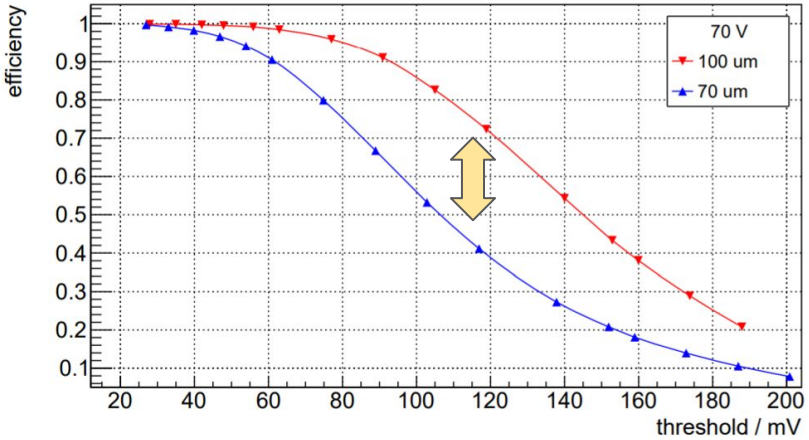
- Only 25 V bias

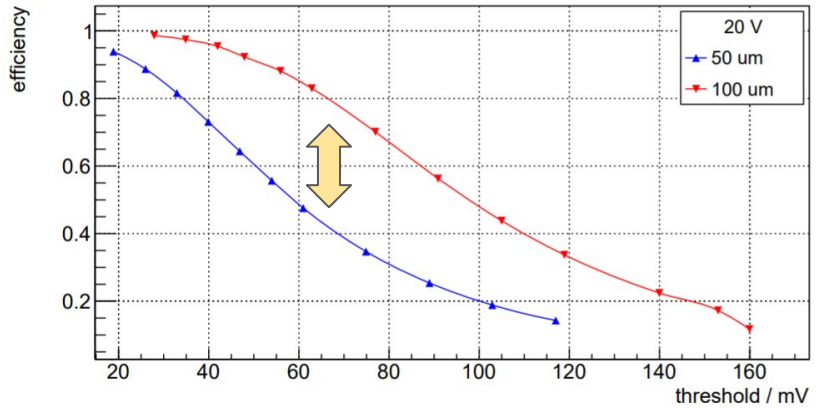
Efficiency is low

Observation: at same voltage, thicker is still better…

Diffusion? Damage in silicon bulk?

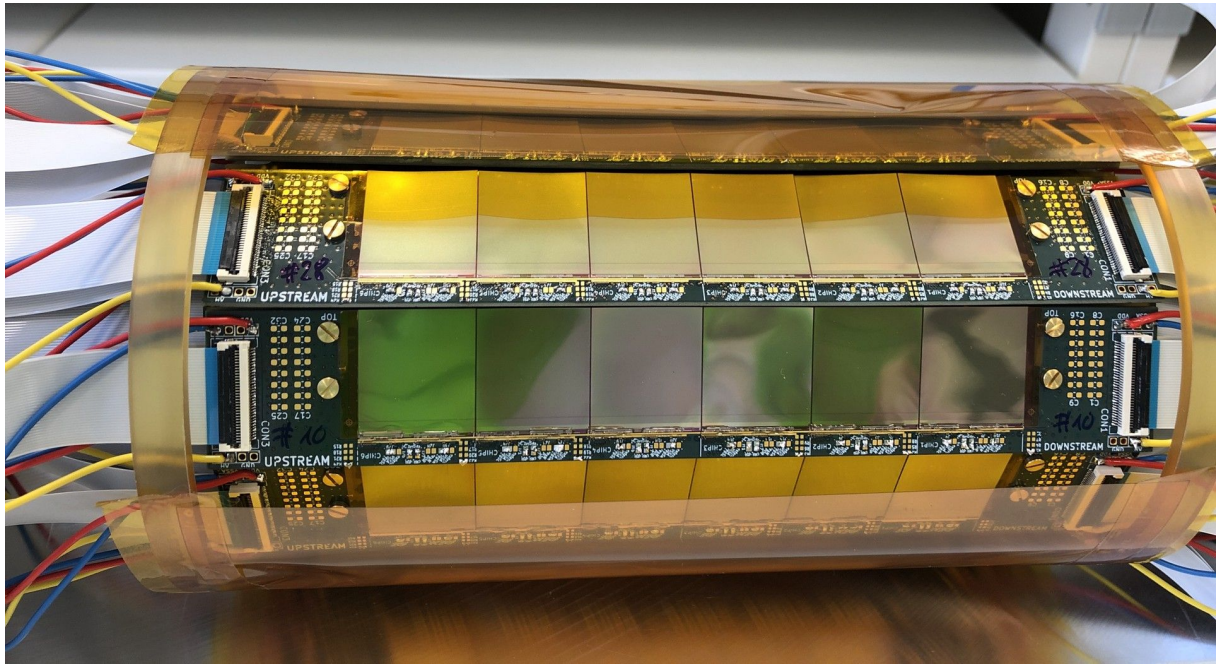
Studies ongoing (new thinning procedure, more complete data to analyze)





Prototyping

DAQ and experimental concept



Prototype of
vertex detector

Jun/Jul 2021

50 µm-thin chips mounted on katpon foils

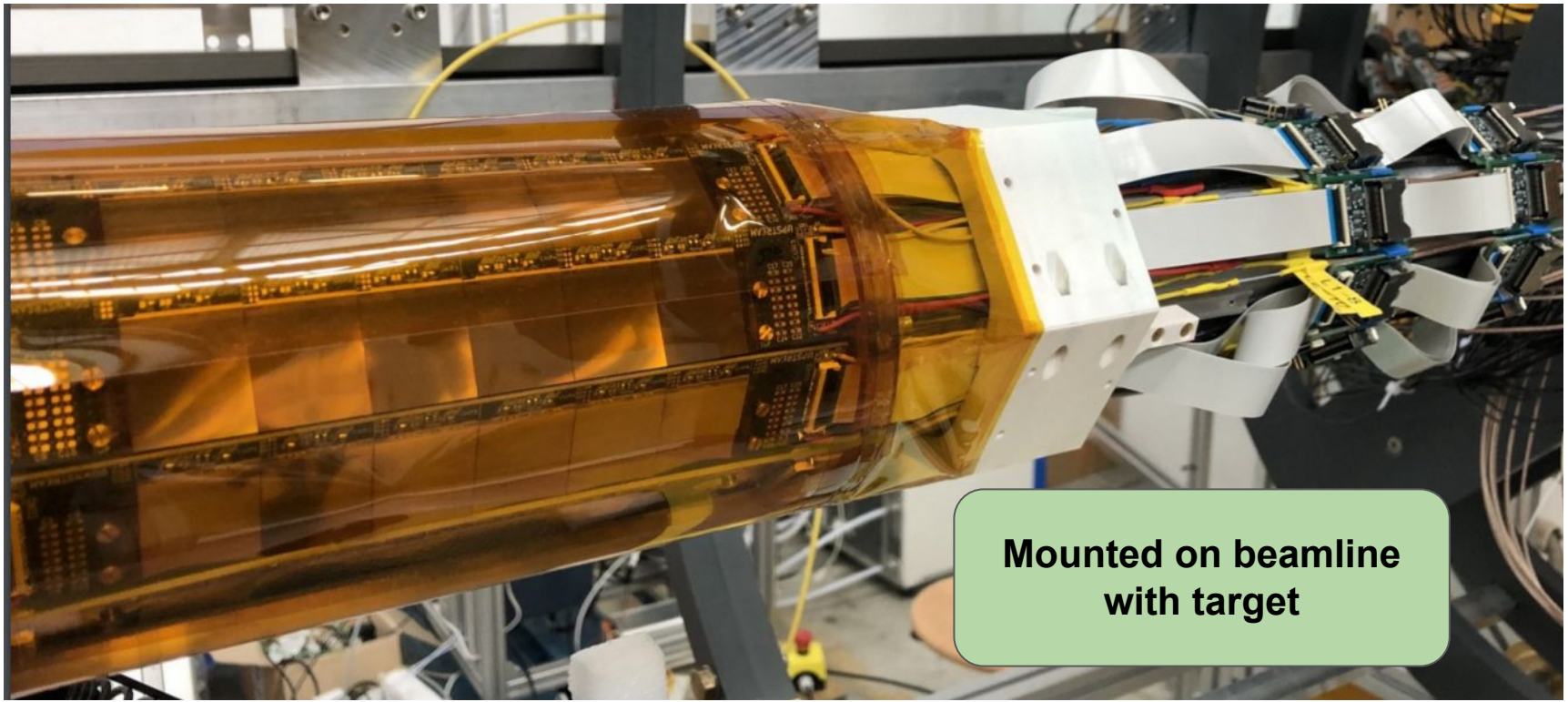
Connected to ladder-boards

Same shape as inner tracker, slightly larger

External connection with commercial cables

Prototyping

DAQ and experimental concept



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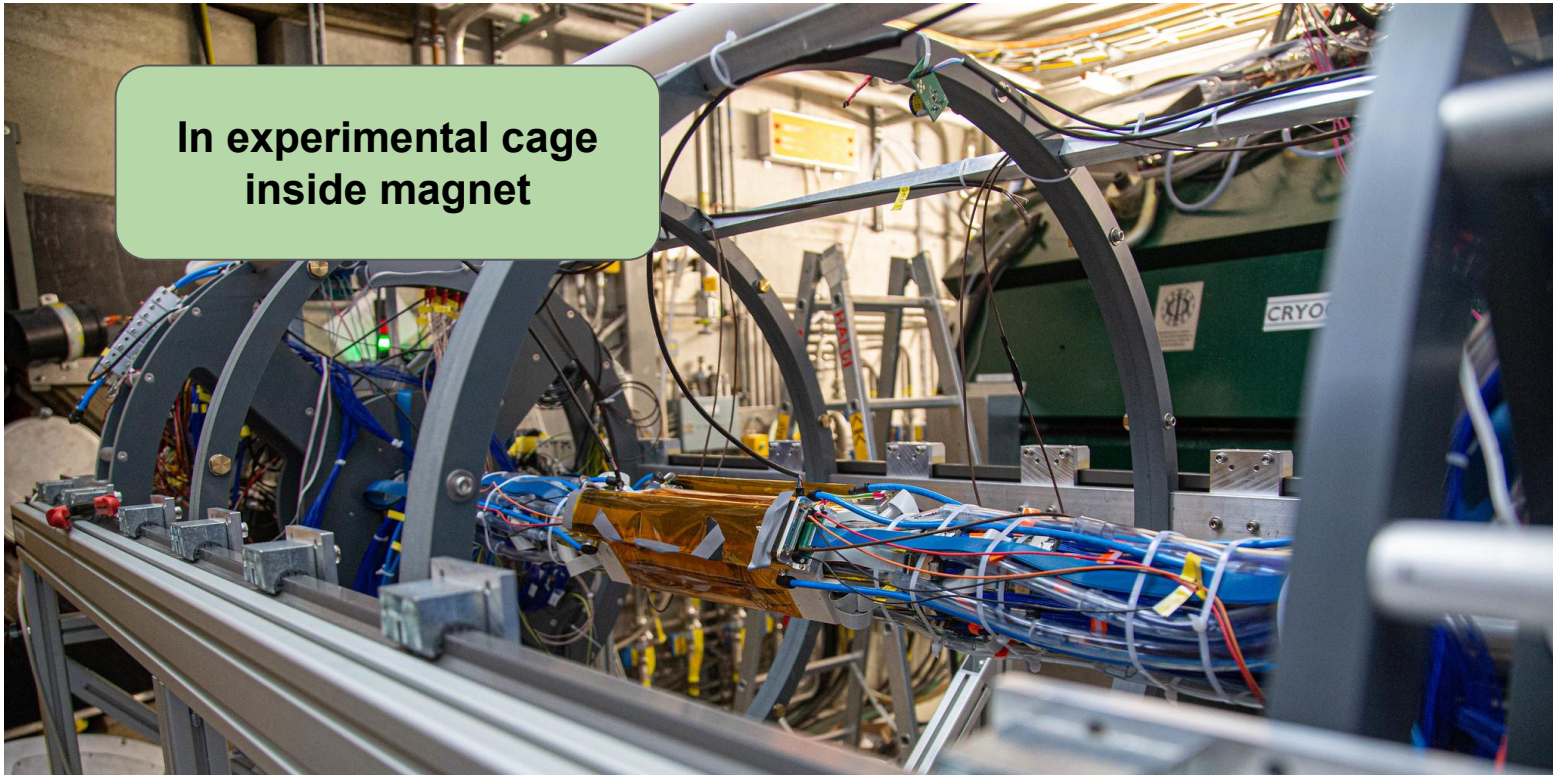
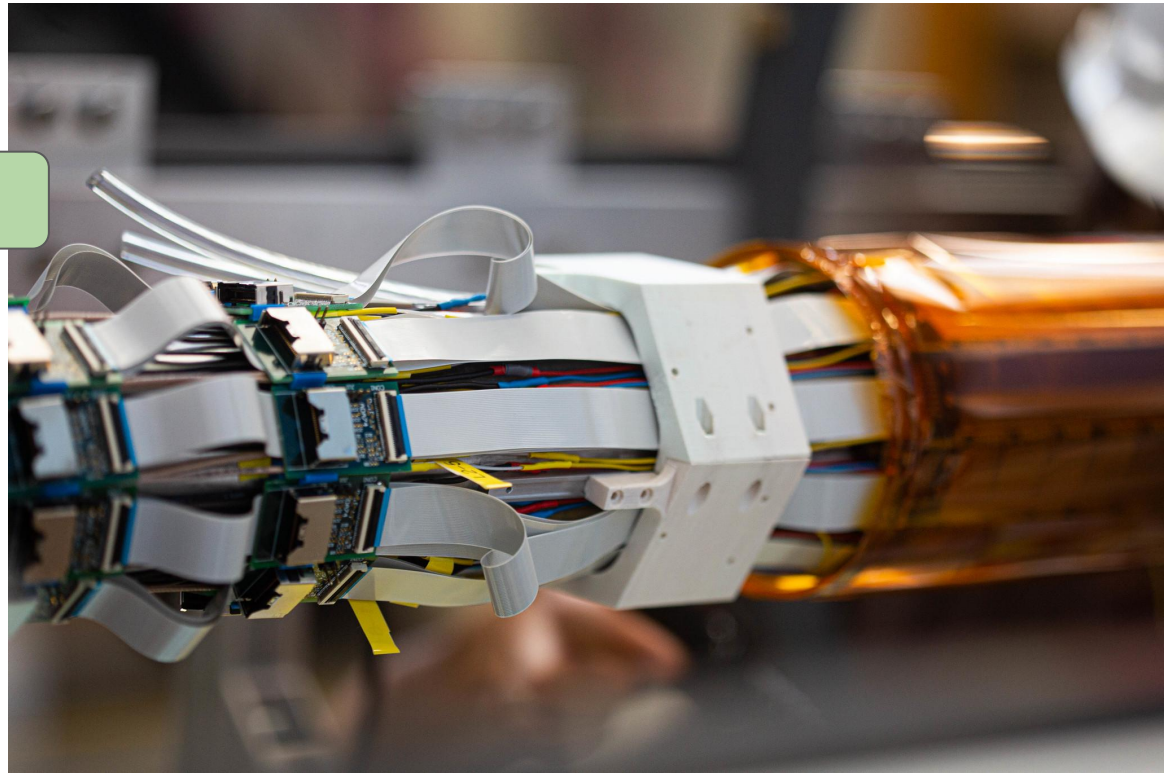


Prototyping

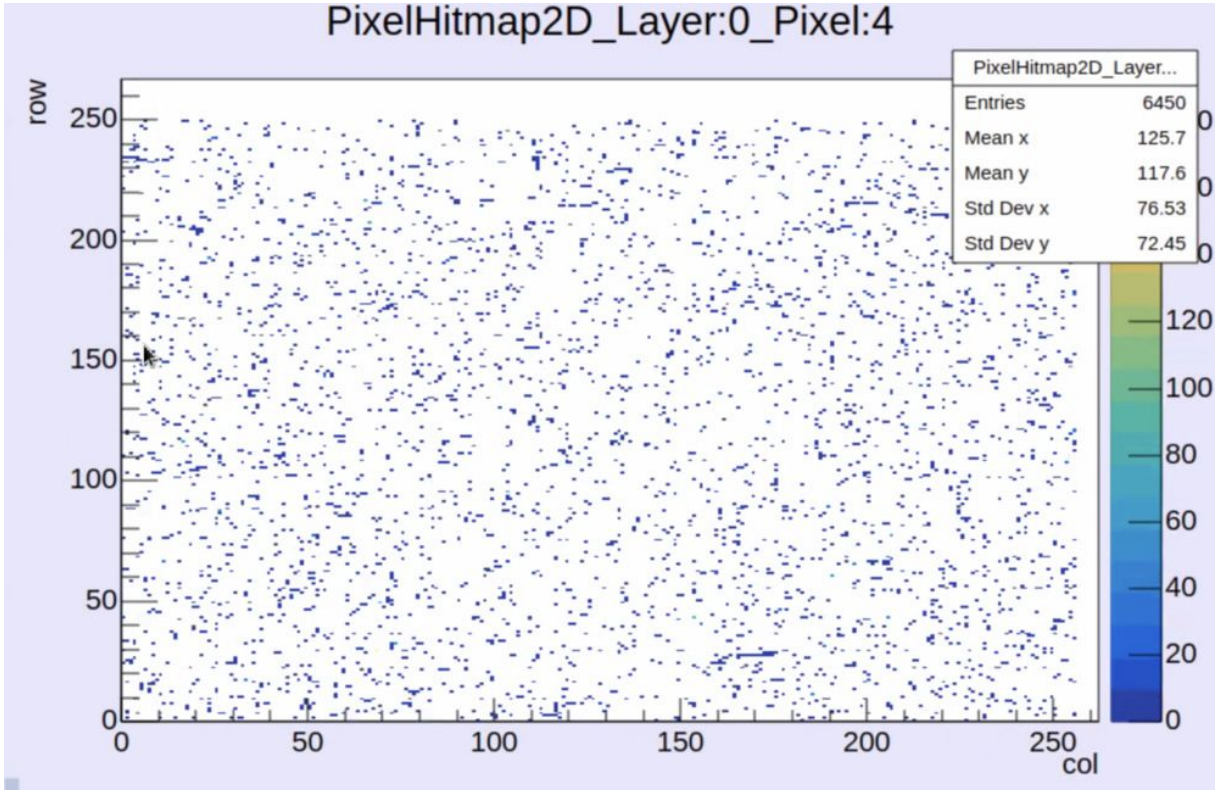
DAQ and experimental concept

Helium flow



Prototyping

DAQ and experimental concept



Prototype of vertex detector

Worked!

First hitmap ever observed for the Mu3e experiment prototype

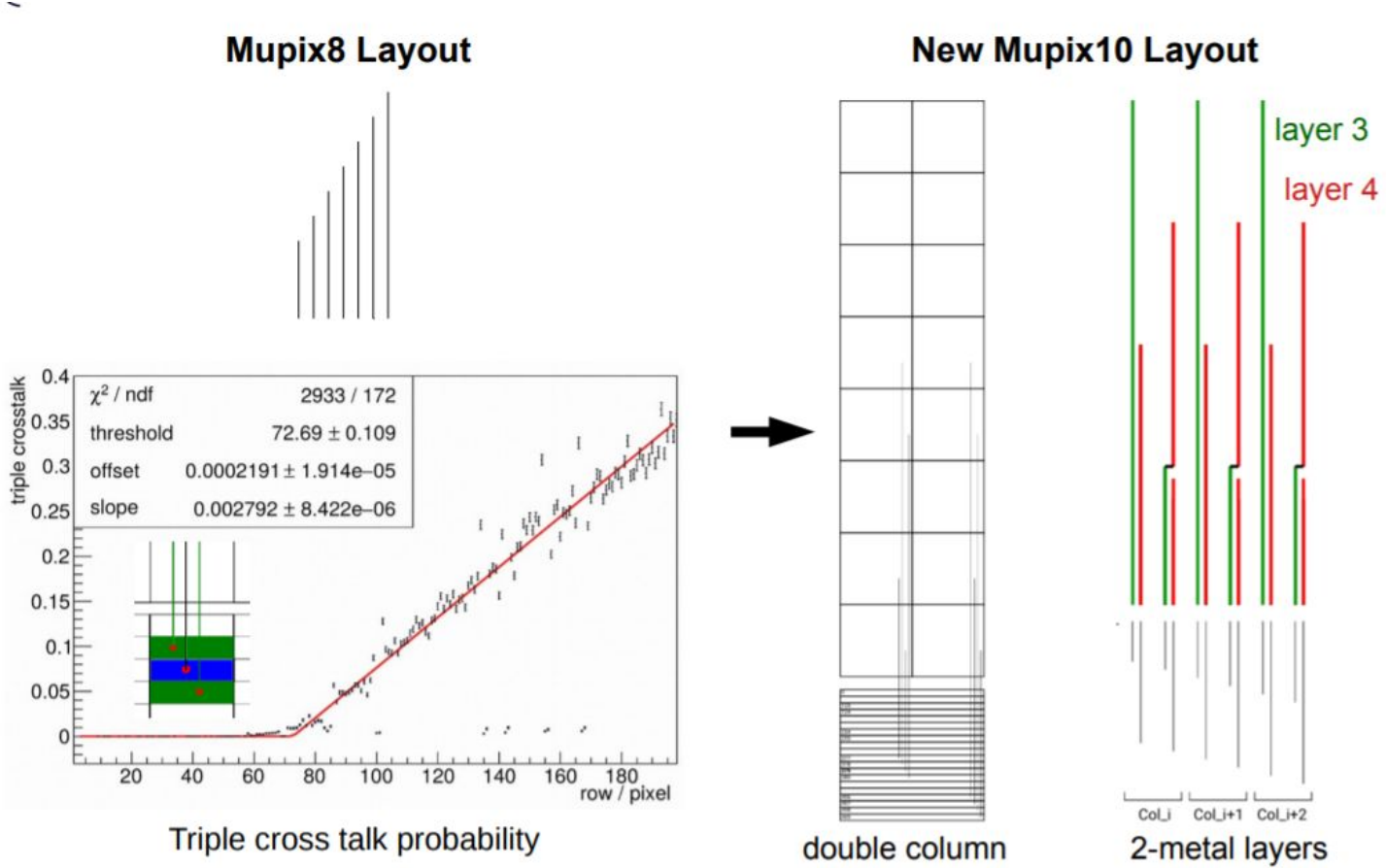
Analysis ongoing

Conclusions

- Mu3e is a CLFV experiment which uses pixel sensors to track electrons from muon decays
  - High rates
  - Low energy
- Tight experimental constraints on pixels ⟶ HV-CMOS!
- MuPix development at the forefront of HV-CMOS R&D
- MuPix10 satisfies most of experimental requirements
- Prototype of vertex detector successful
- MuPix11 underway
- Production of Mu3e starting next year

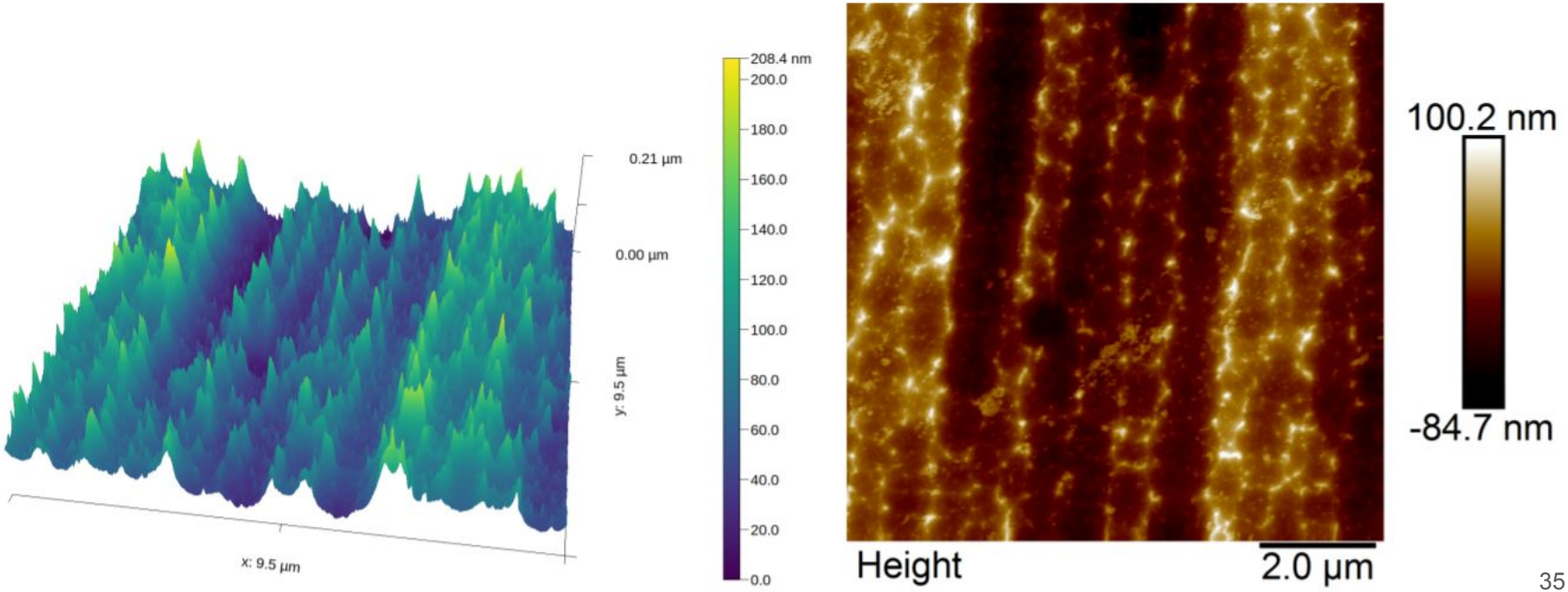
Backup

Backup: crosstalk



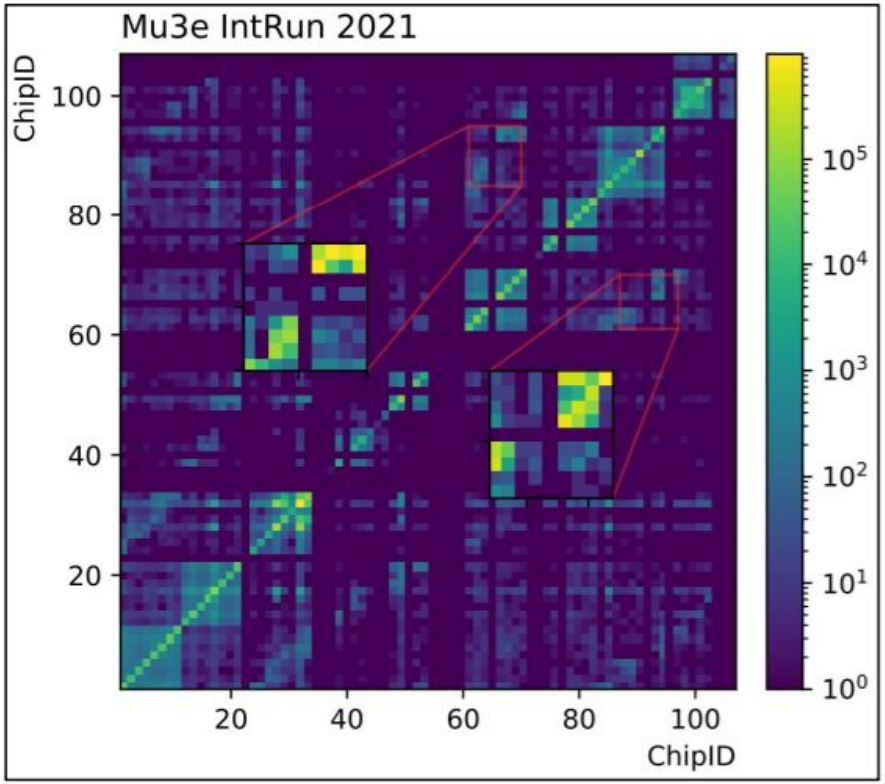
Backup: thinning issue

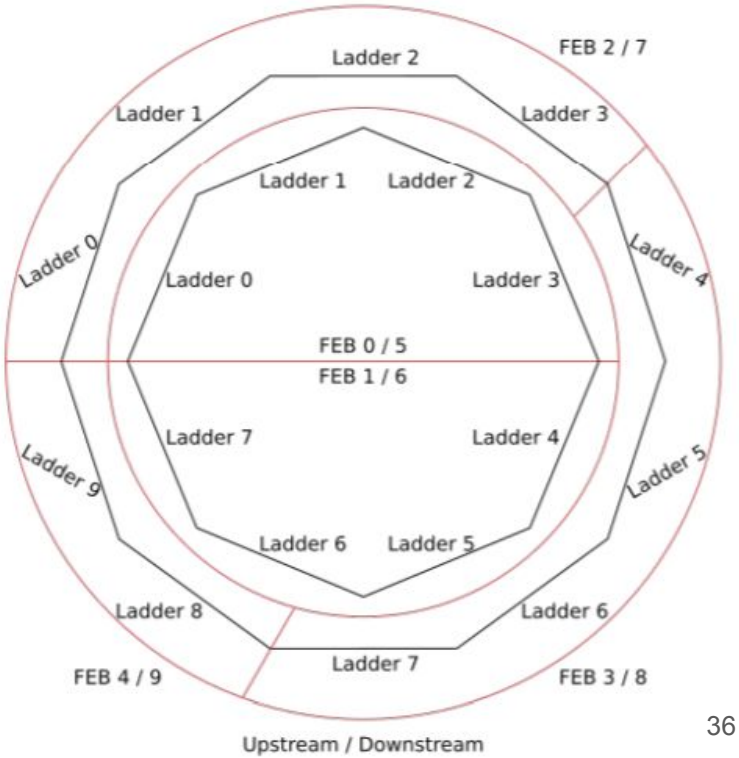
Atomic force microscopy on backside



Backup: prototype data analysis

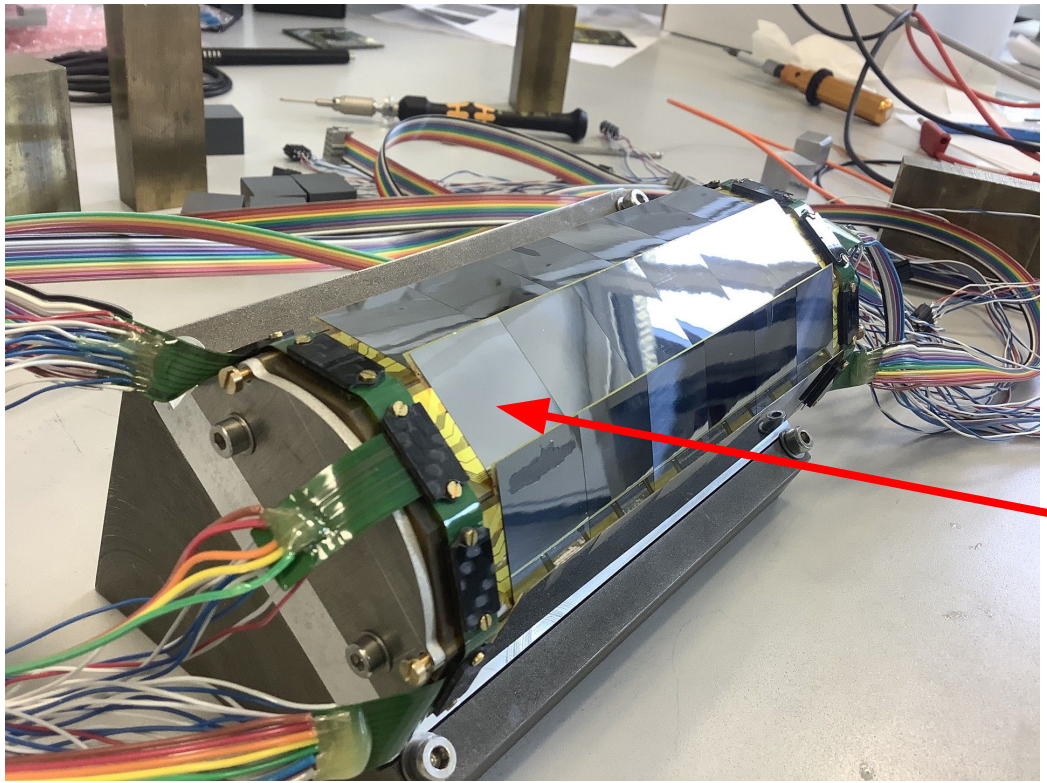
Chip-to-chip correlations





Backup: Prototyping

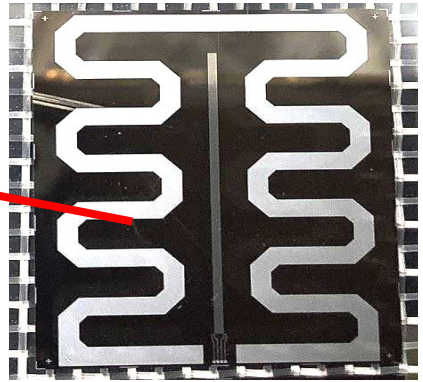
Thermo-mechanical stability



Silicon heater prototype

Reproduction of inner tracker with same materials and connections

Chips are just passive silicon heaters

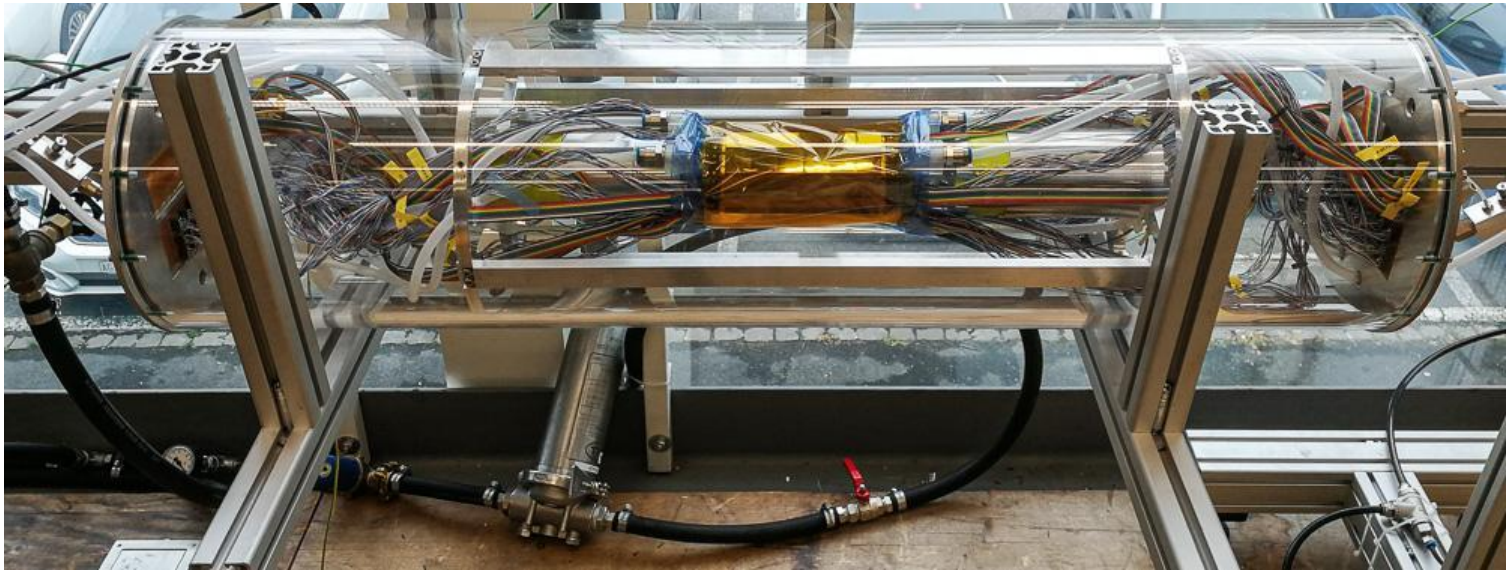


Backup: Prototyping

Thermo-mechanical stability

Silicon heater prototype

Test stand with Helium cooling system



Backup: Prototyping

Thermo-mechanical stability

- Measurement of temperature-to-power relation
- Temperature difference linearly depending on heat dissipation
- Expected ΔT < 70 K for 400 mW/cm² (conservative limit)
- Cooling concept works ✅
- More detailed studies to come

Silicon heater prototype