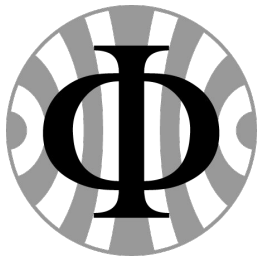
The Mu3e Detector

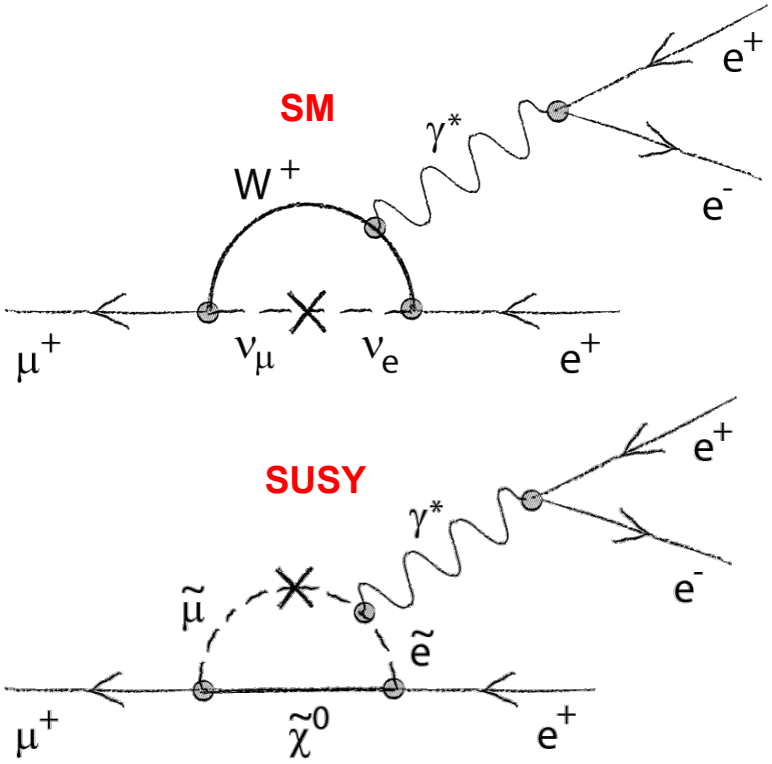
Luigi Vigani, on behalf of the Mu3e collaboration
University of Heidelberg

Twepp 2021
20/09/2021



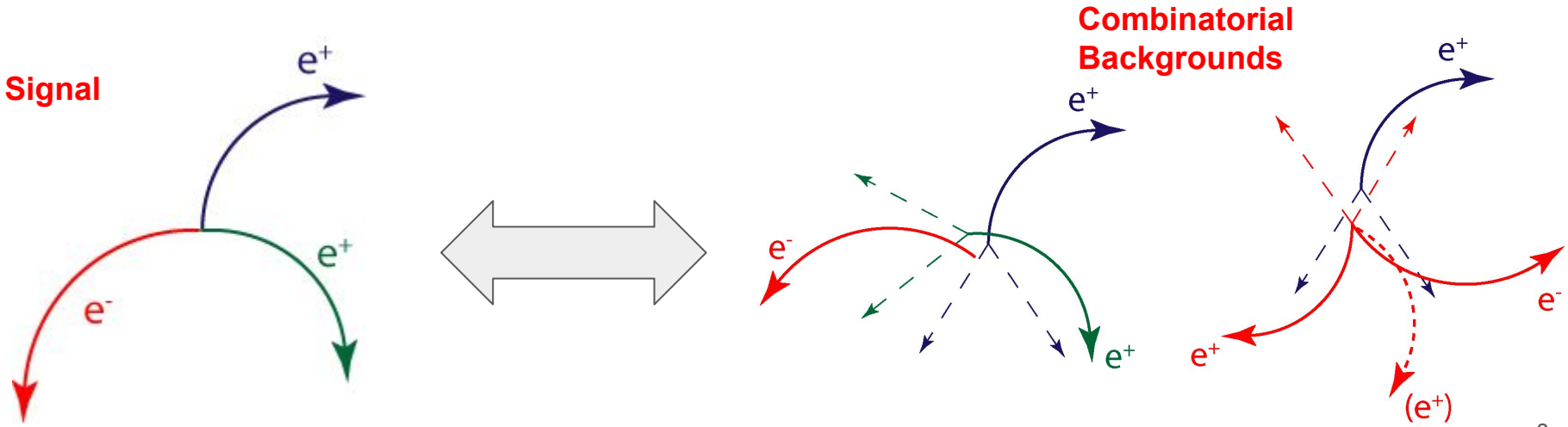
Mu3e: Physics Motivation

- 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 the end of the year



Experimental challenges

- Tracking electrons coming from muon decays
- High muon rates
  - 10^8 Hz Phase I
  - 10^9 Hz Phase II



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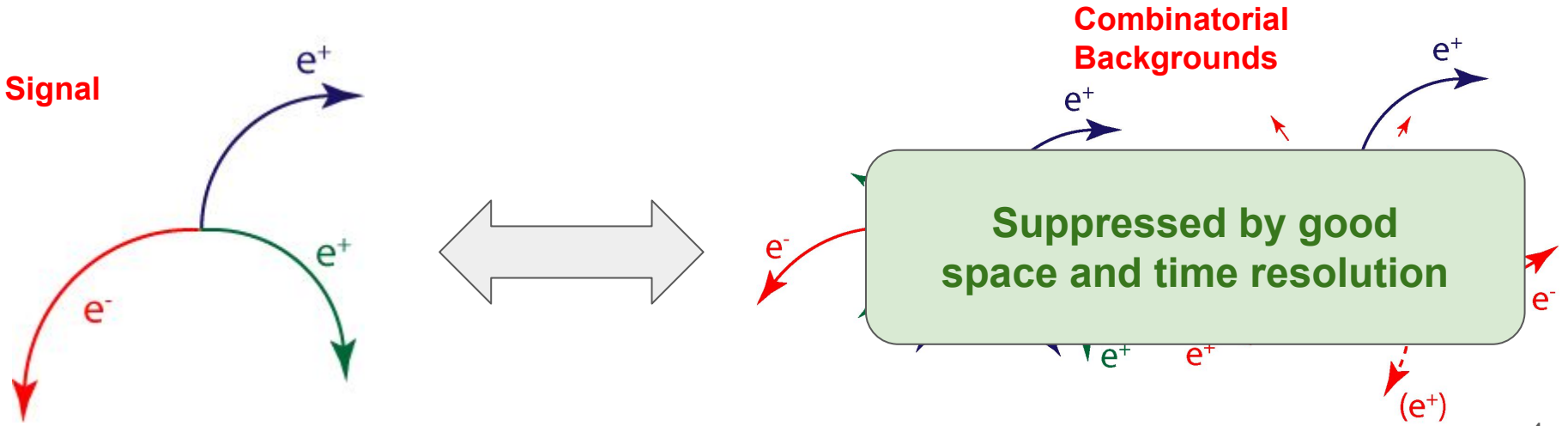

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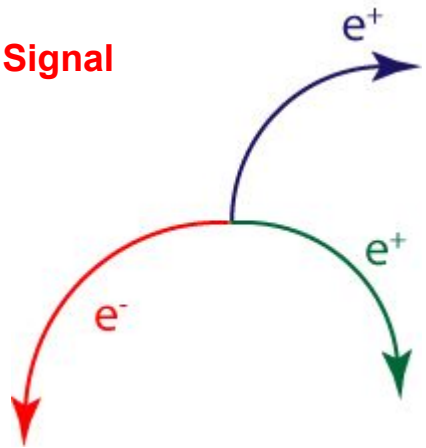
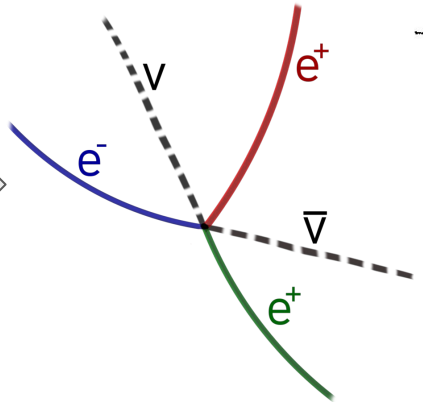
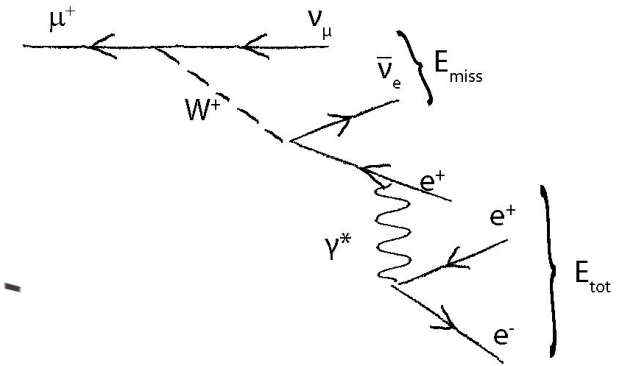
Signal



Irreducible Background



SM μ→eeevv



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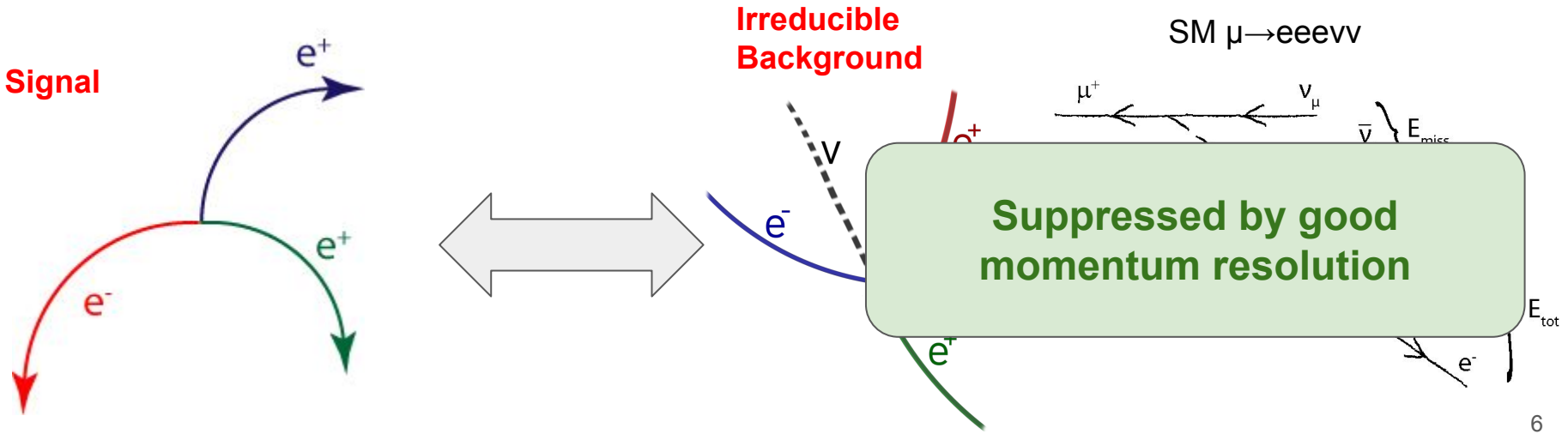
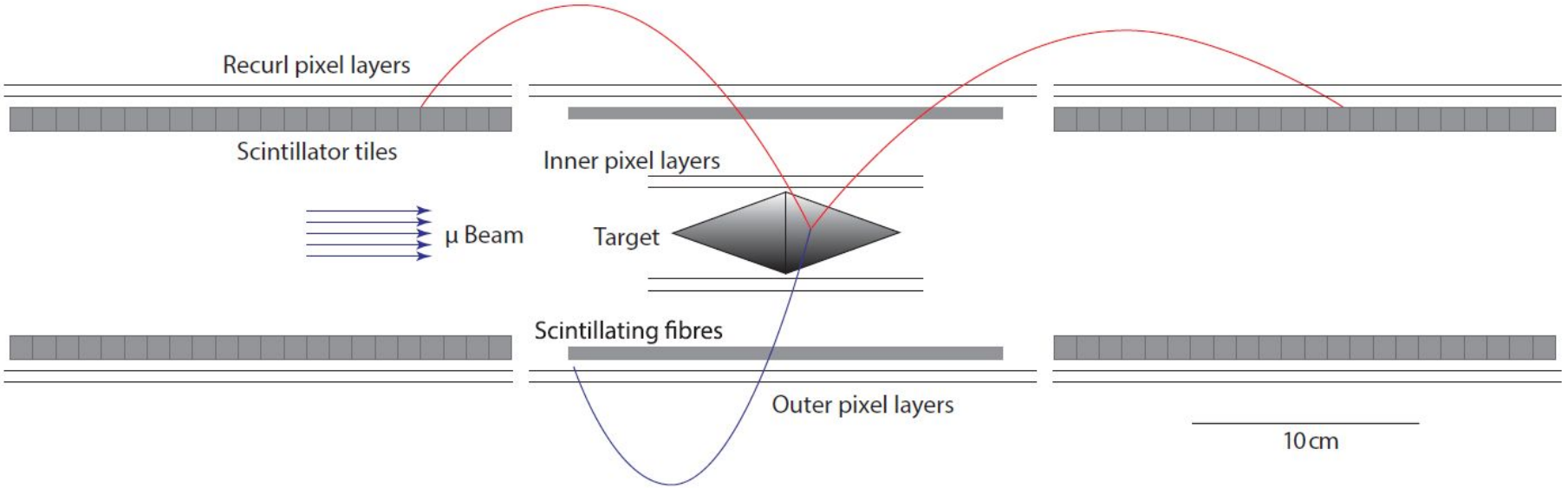


Experimental concept

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



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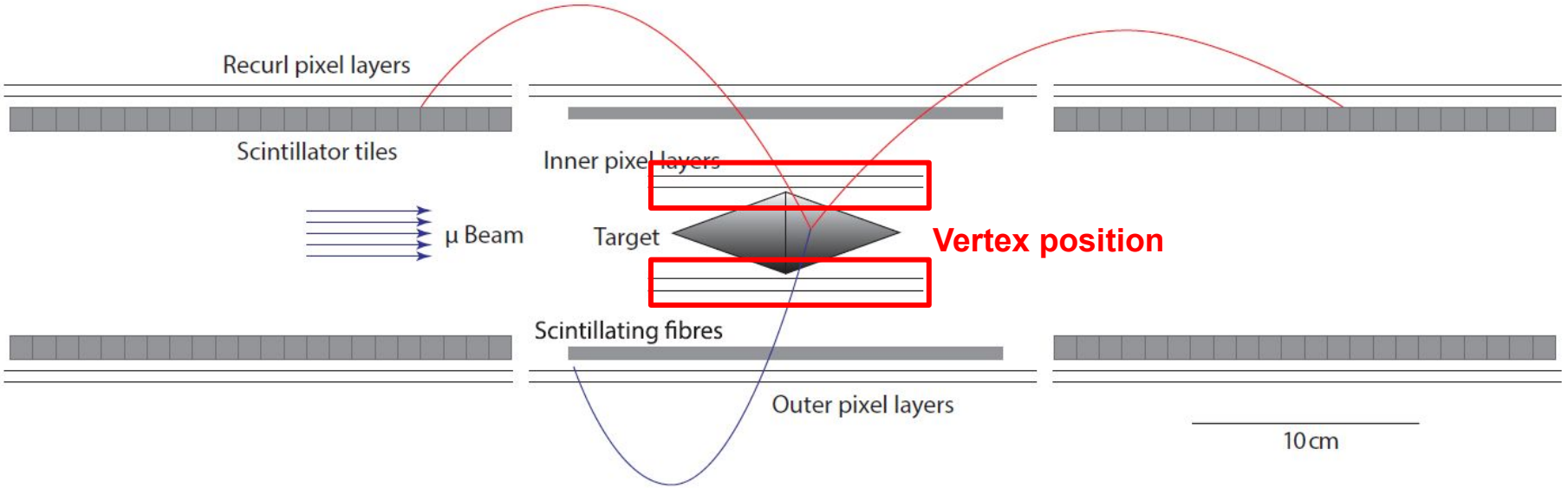

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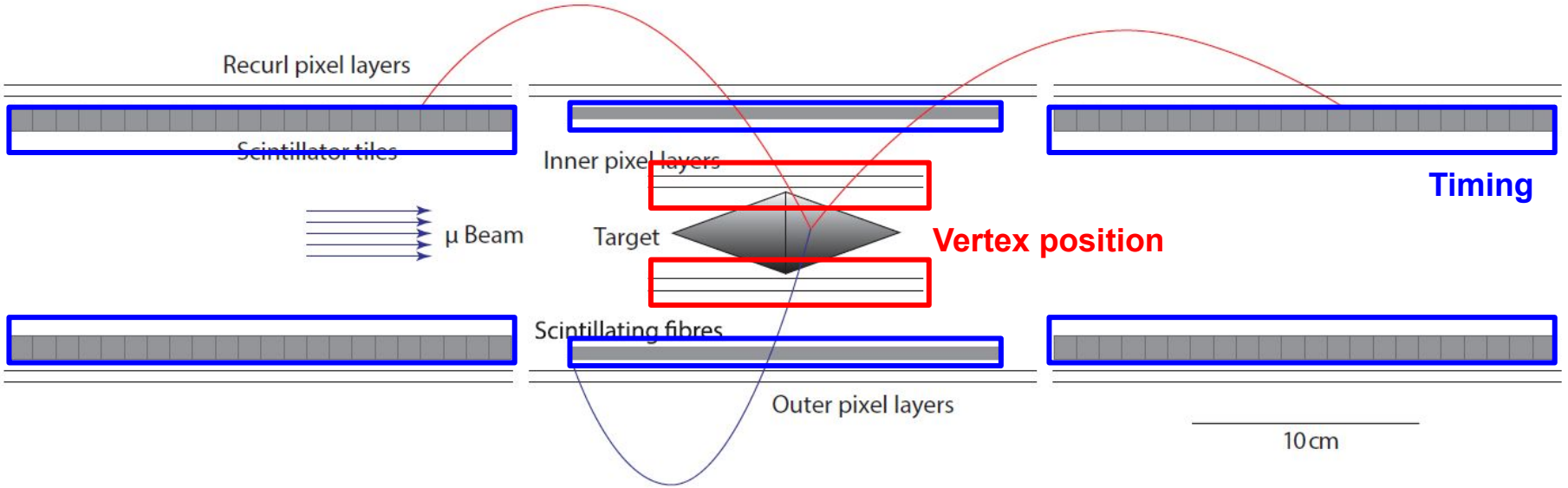

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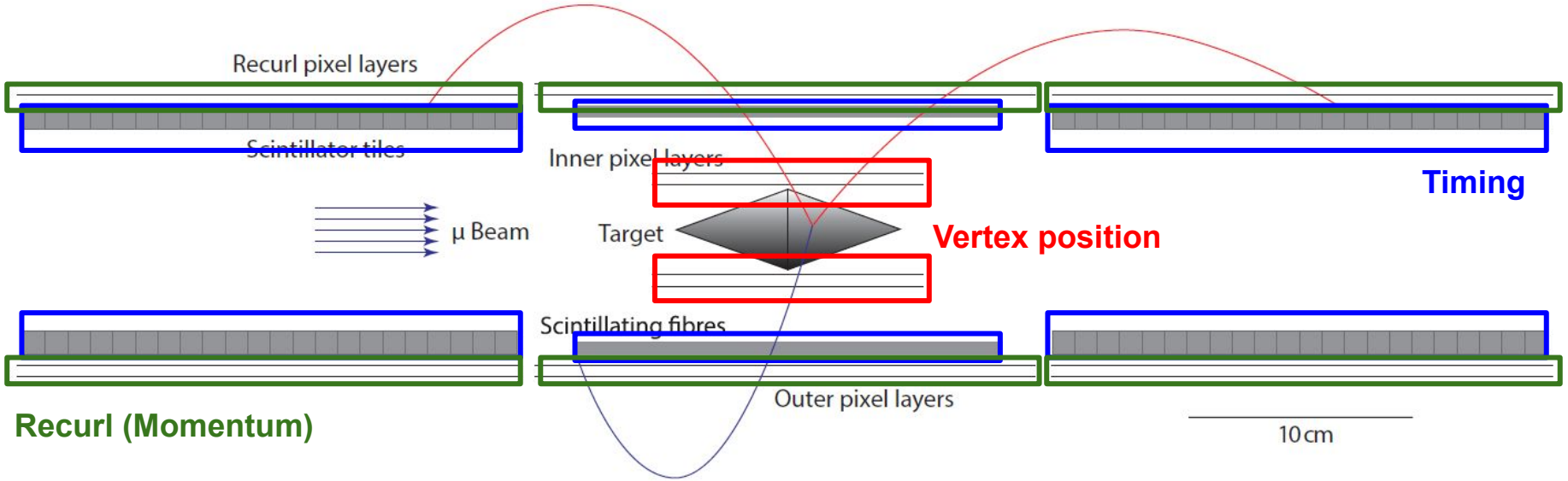

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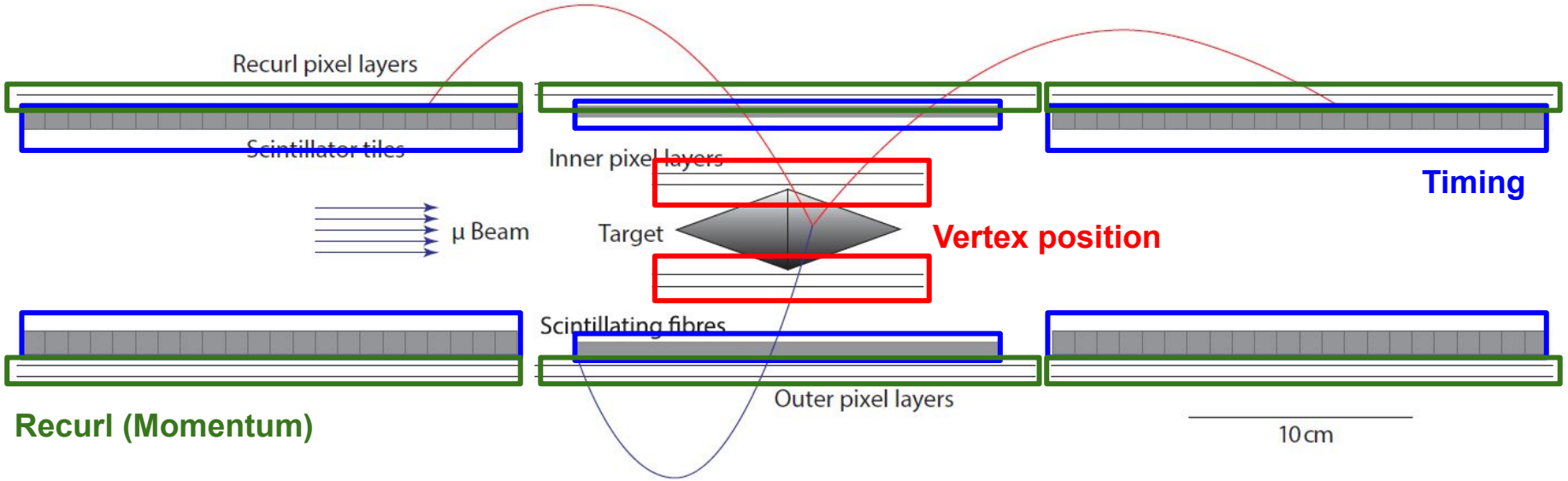
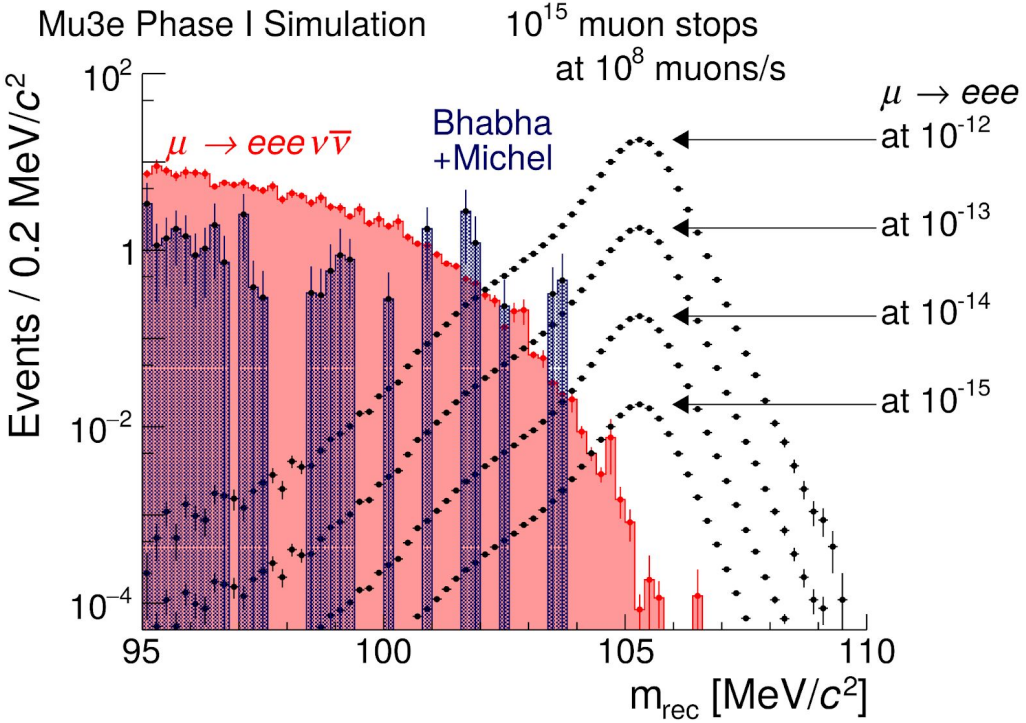


2844 pixel sensors, 3072 fibres, 5824 tiles: Highly dense environment!

Experimental concept



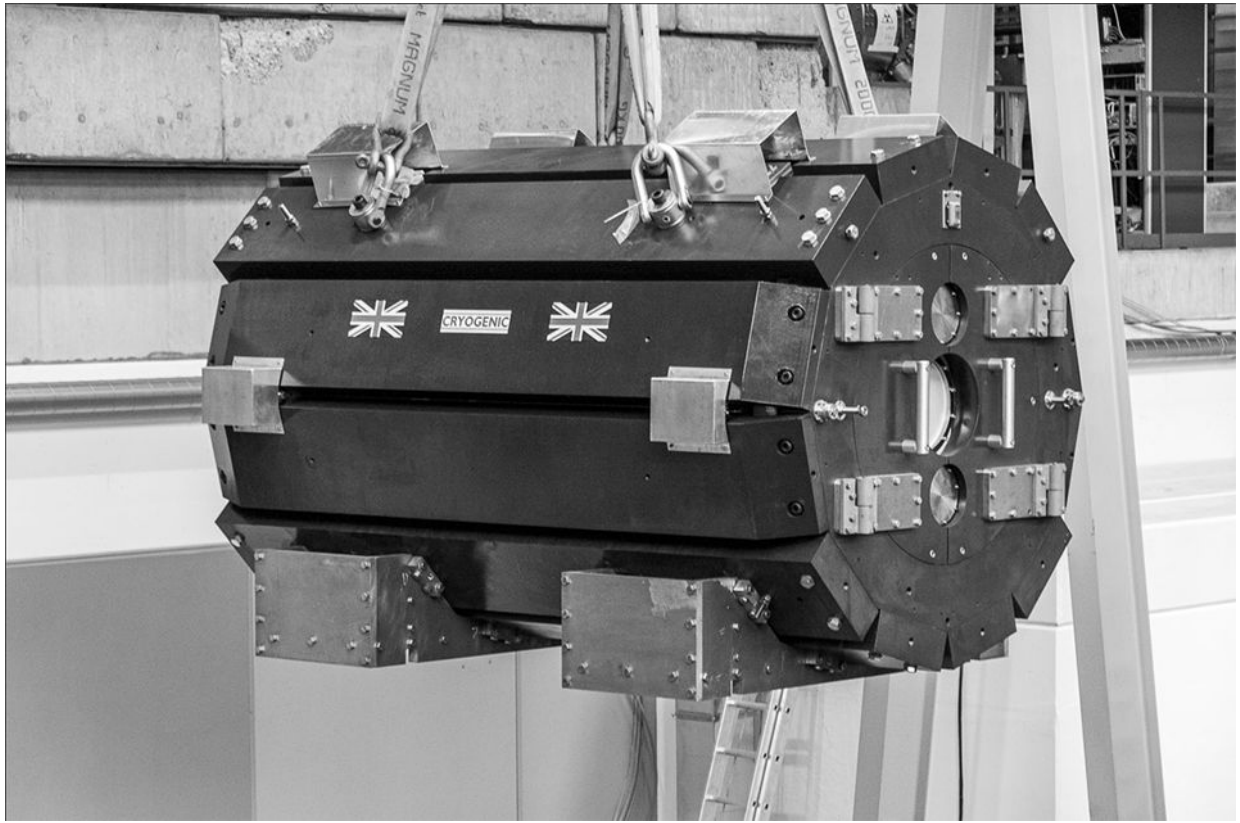
Invariant mass of signal decay, radiative decay and accidental background (Bhaba+Michel) [Mu3e TDR]

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

Magnet



Produced by Cryogenic Ltd

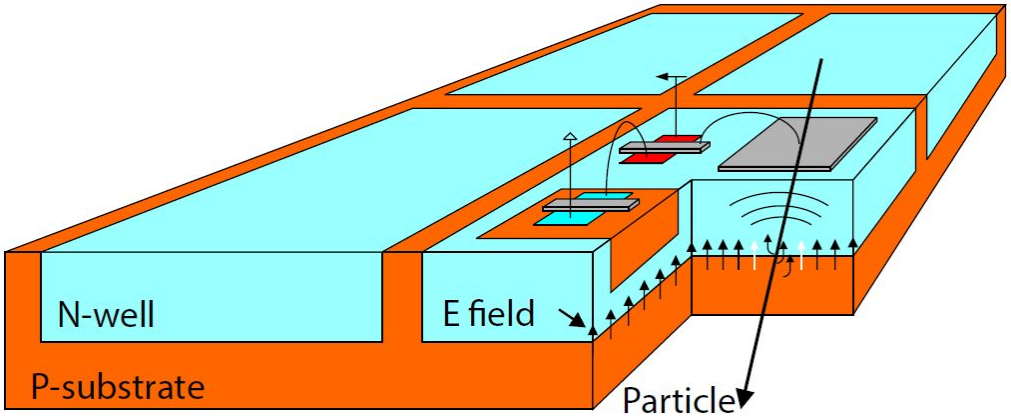
1 Tesla

Homogeneity:
10^{-4} over 1 m length

Delivered in 2020

Tracking system

Pixel Sensors



MuPix sensors: HV-CMOS

- Monolithic
- RO embedded in deep n-well
- HV applied to full depletion
- Thinned to 50 µm

Reduce material budget!

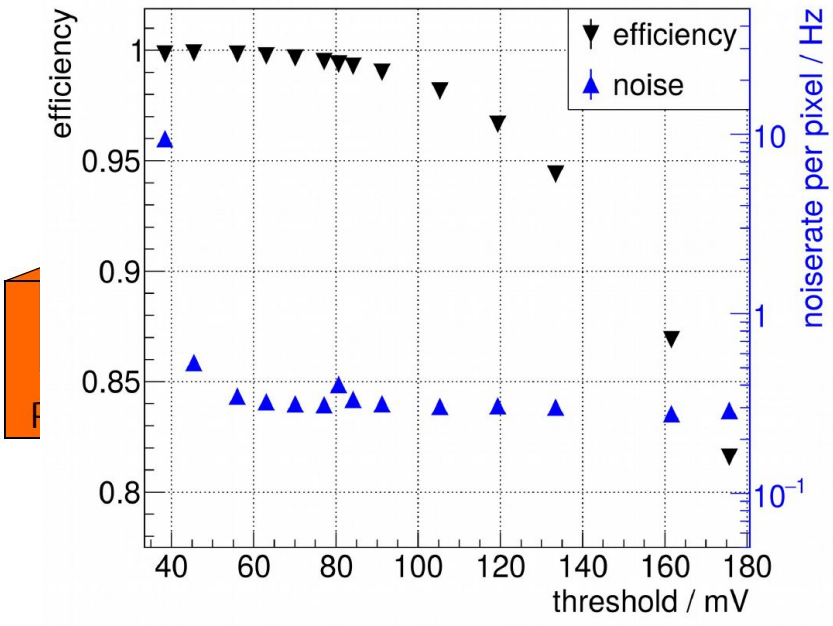
Performance requirements

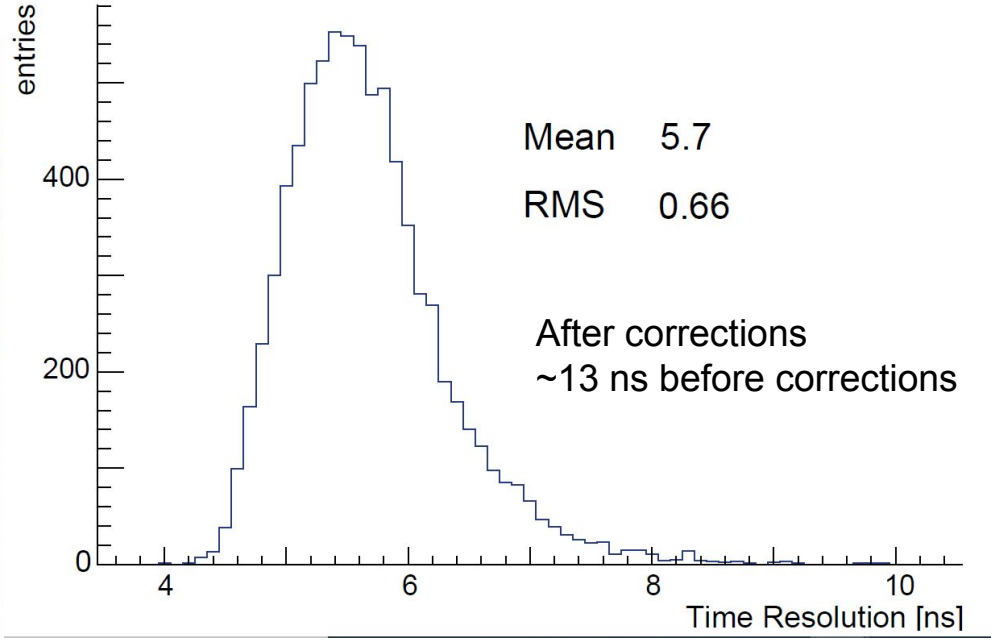
Efficiency 99.5%
Noise < 1 Hz

Time resolution < 20 ns

Tracking system

Pixel Sensors



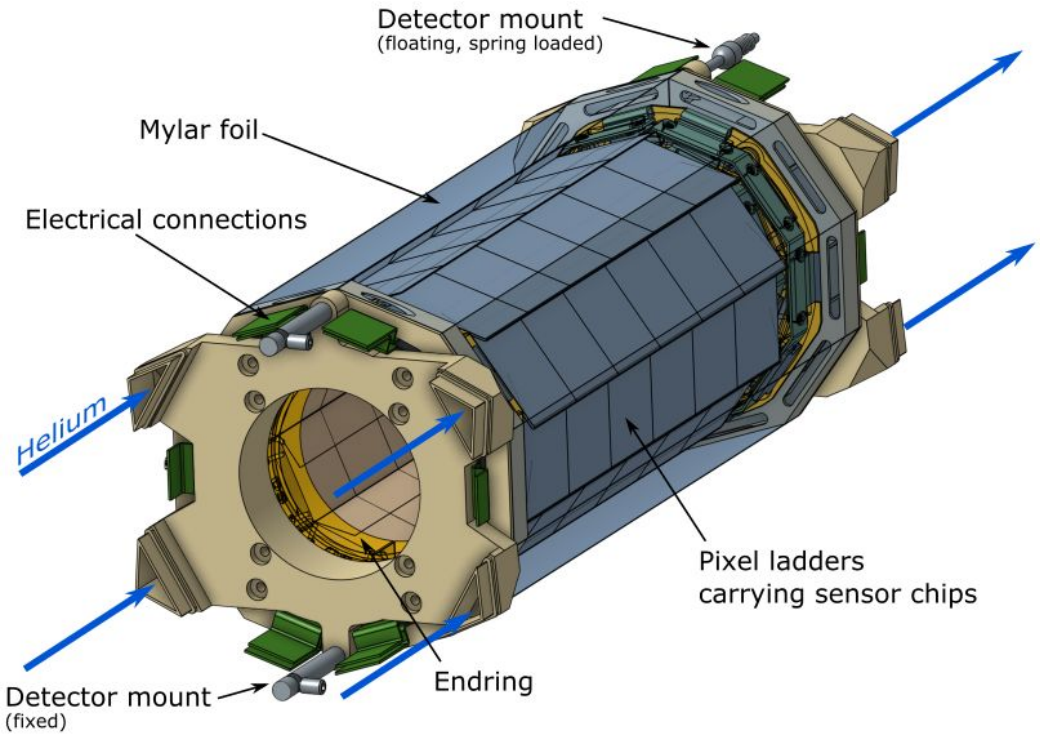


Efficiency 99.5%
Noise < 1 Hz

Time resolution < 20 ns

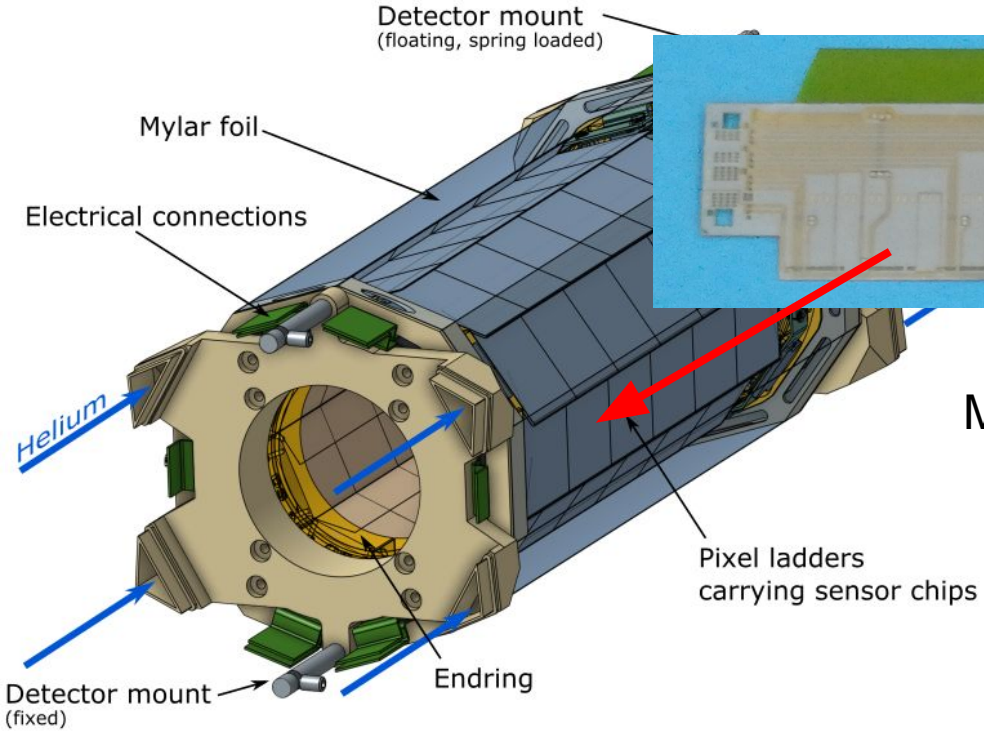
Tracking System

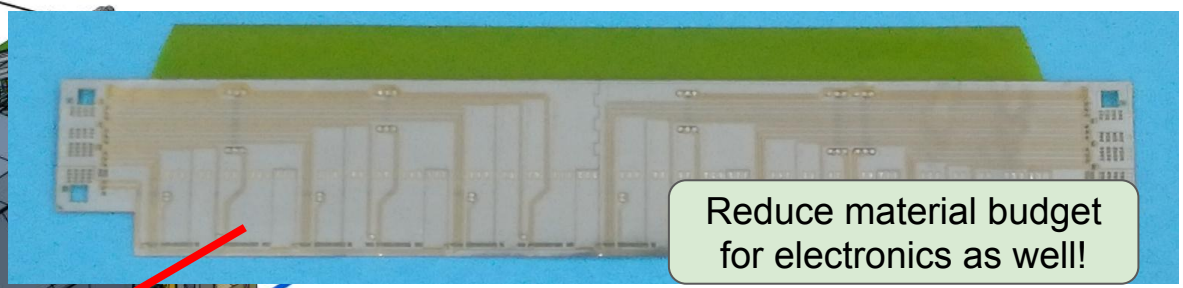
Layer 1/2



Tracking System

Layer 1/2



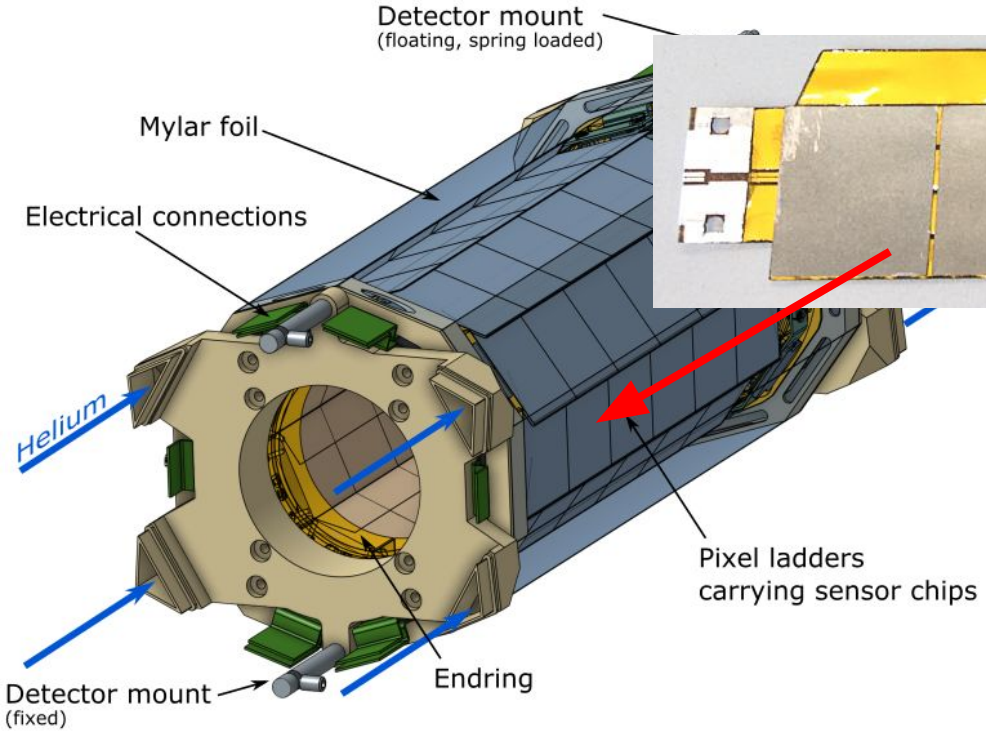


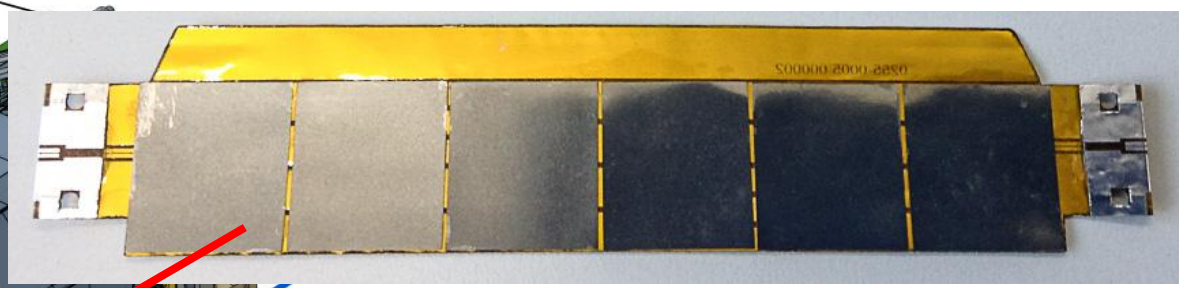
Mechanical units: Ladders

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

Tracking System

Layer 1/2





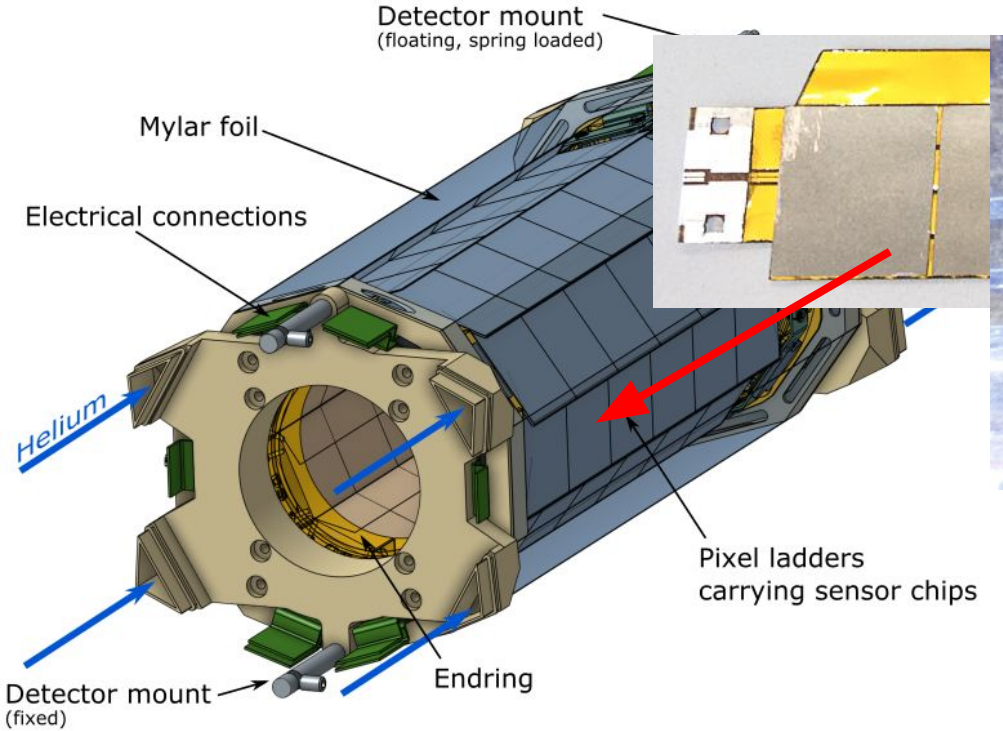
(Aliminum mockup)

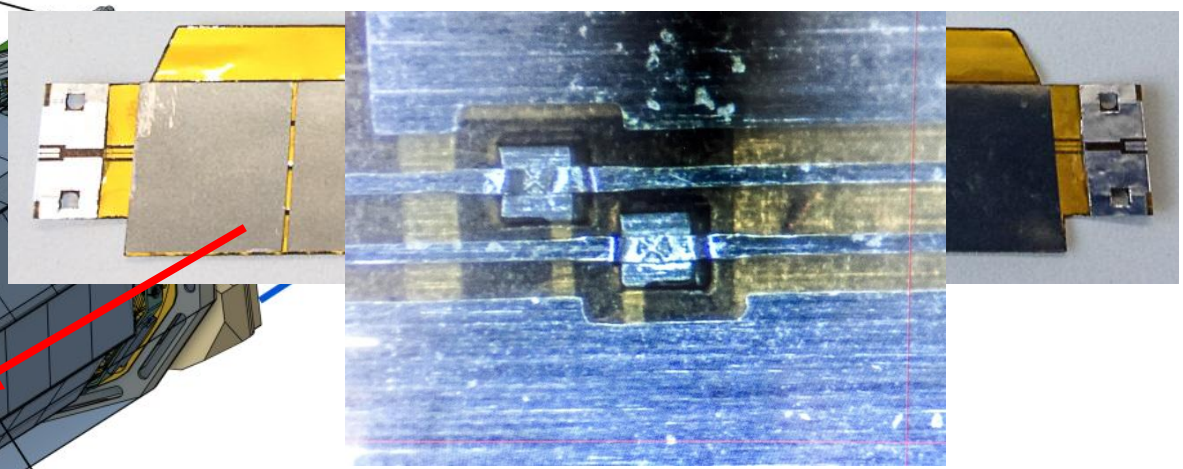
Chips glued on top

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

Tracking System

Layer 1/2

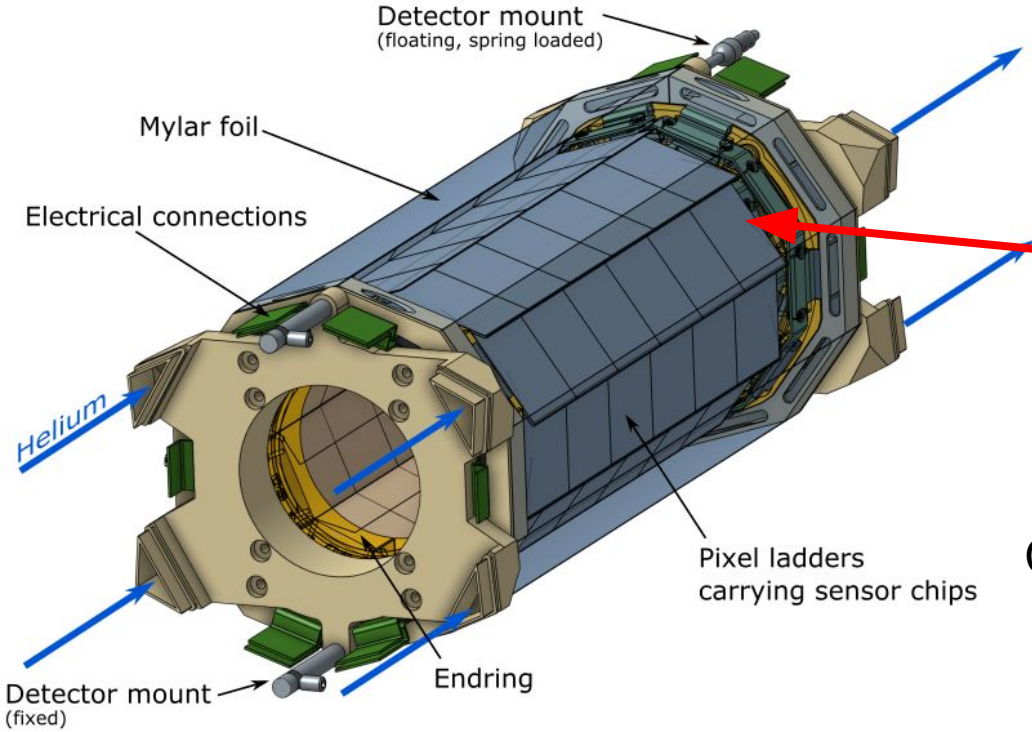


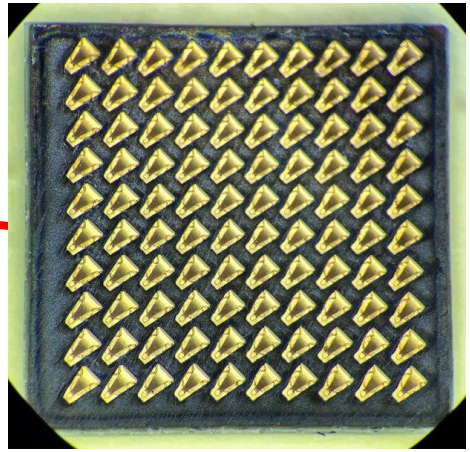


Electrical connections with Singe Point Tape Automated Bonding (SpTAB)

Tracking System

Layer 1/2

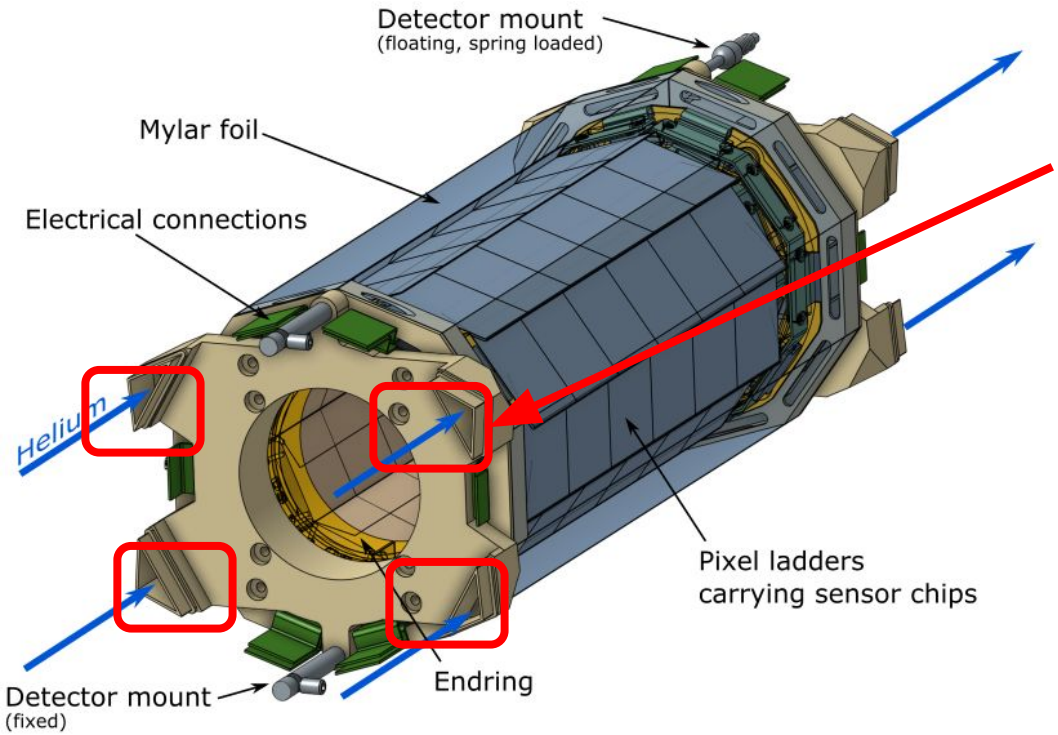




Connection to external flexes with gold ball interposers

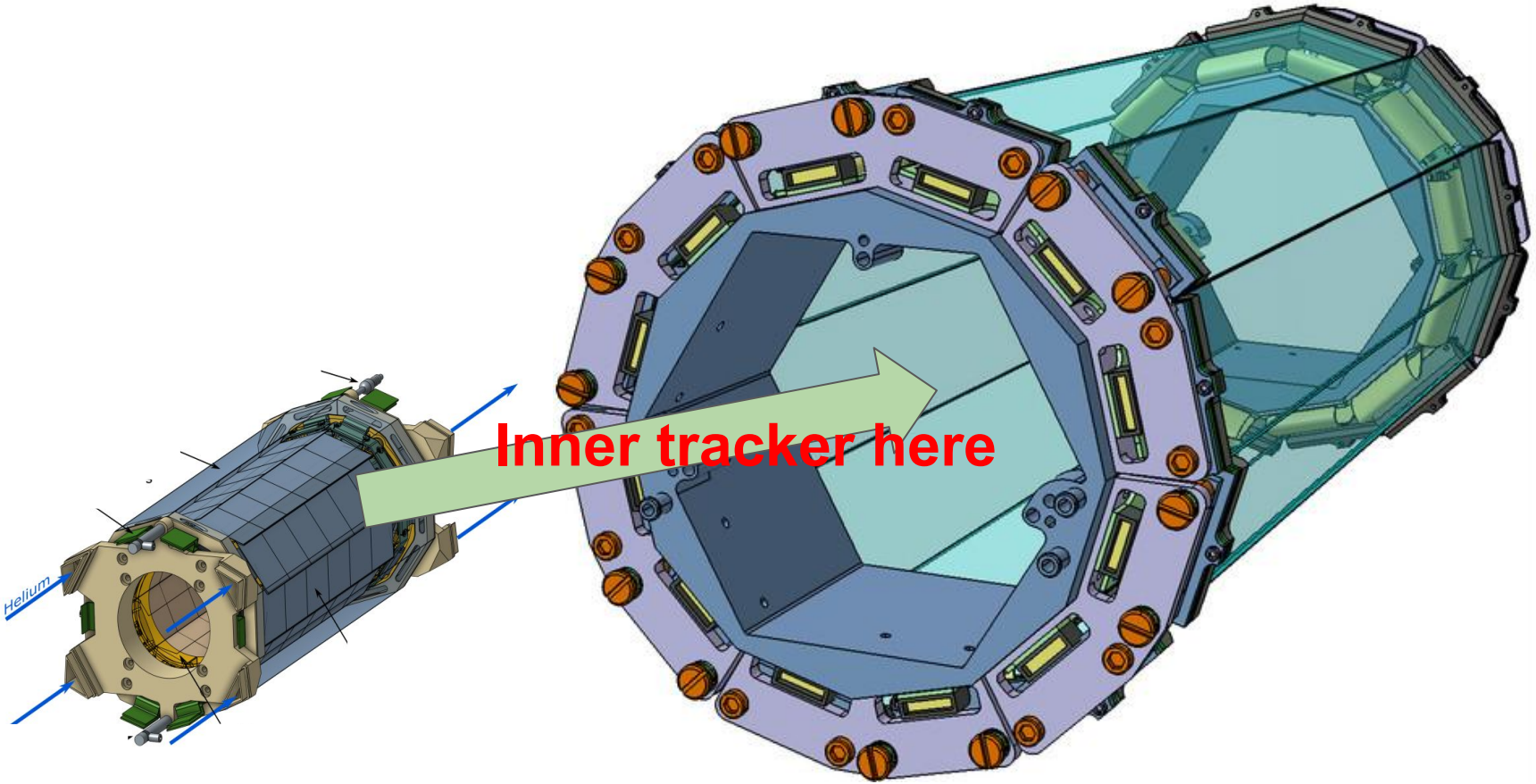
Tracking System

Layer 1/2

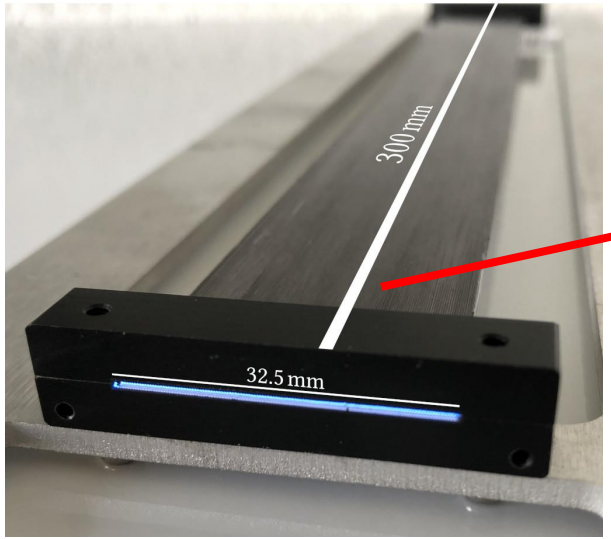


Gaseous Helium for sensors cooling system

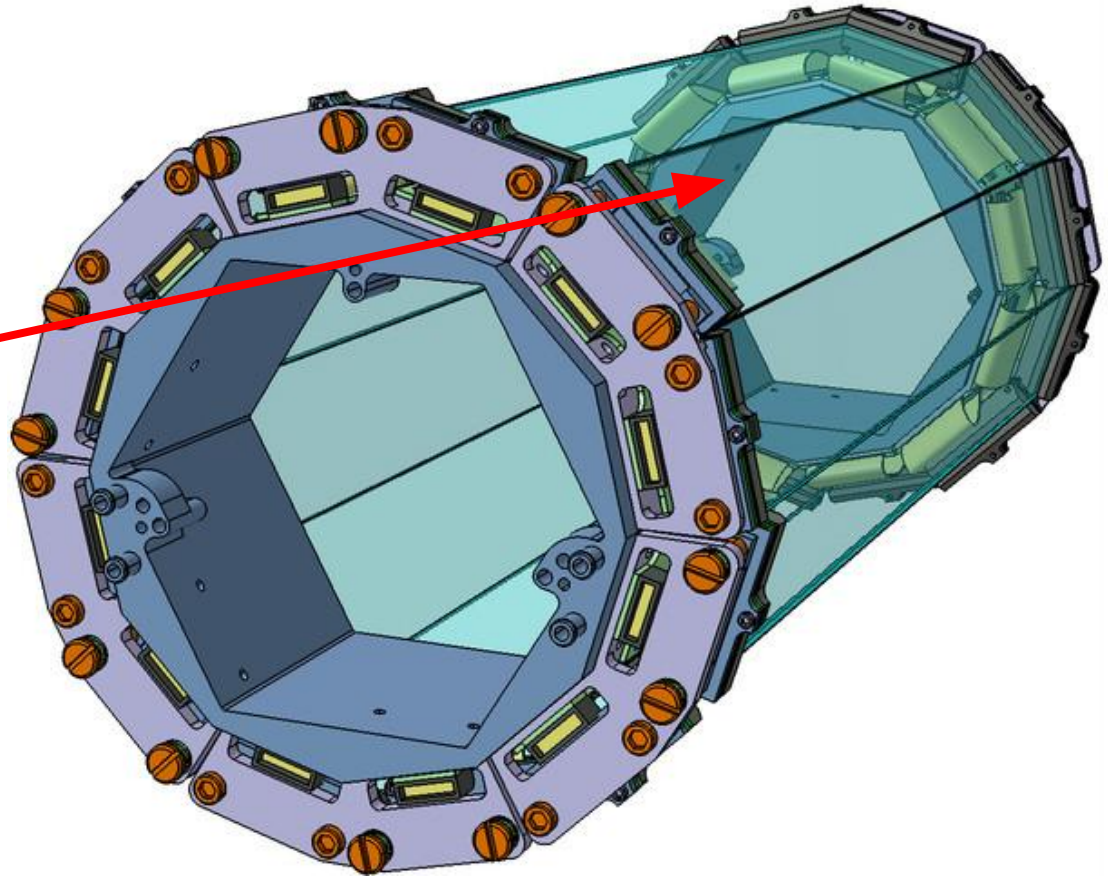
SciFi



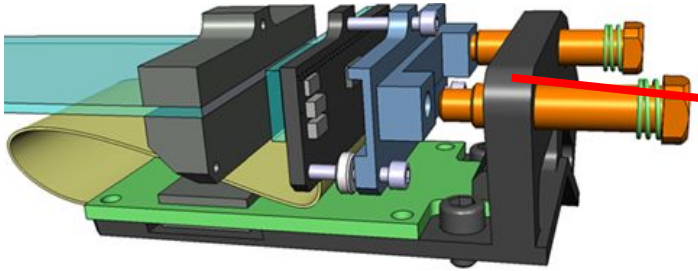
SciFi



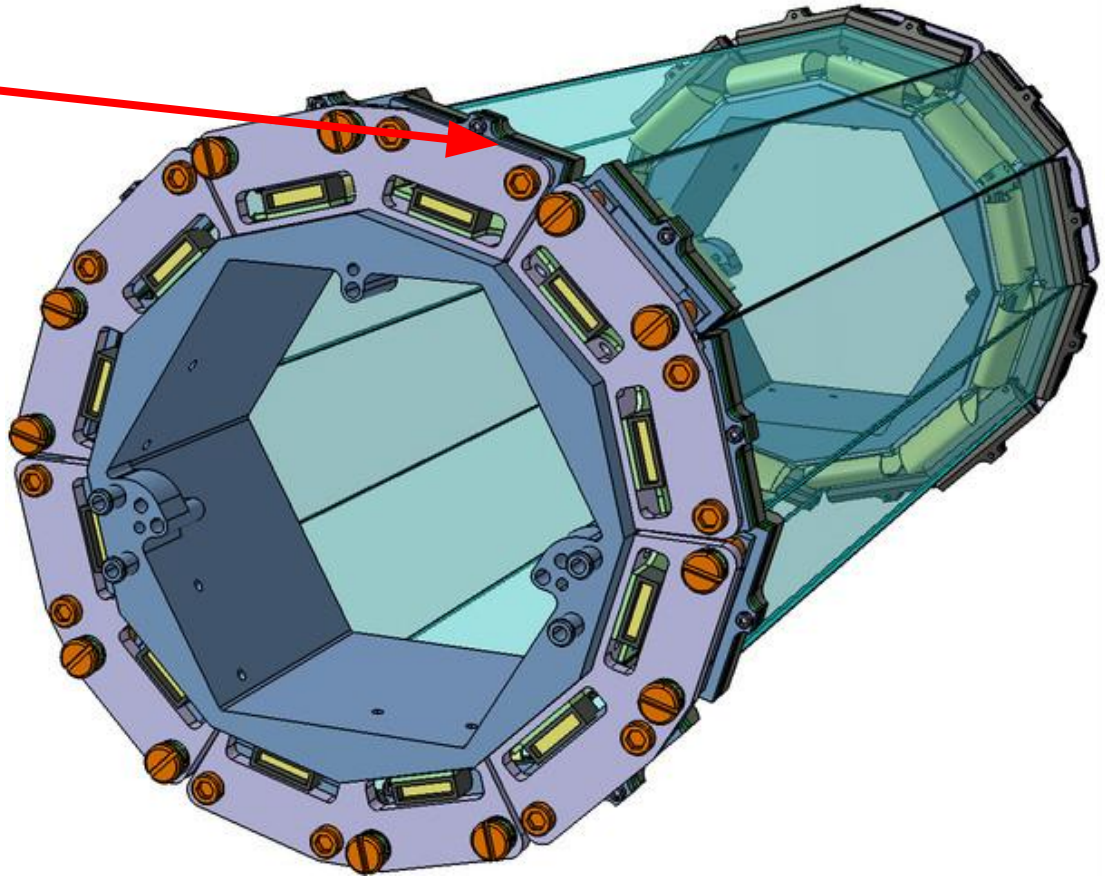
SciFi ribbons



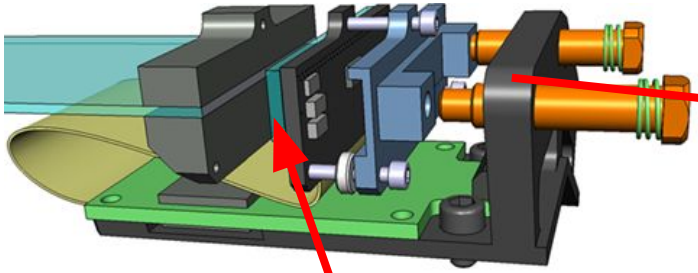
SciFi

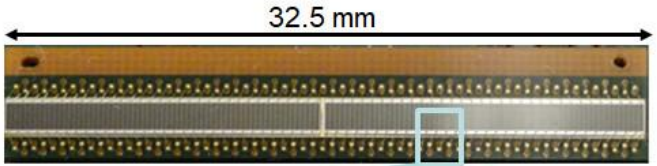


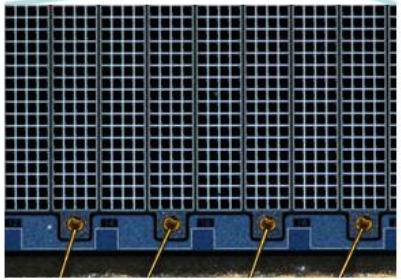
Support
structures



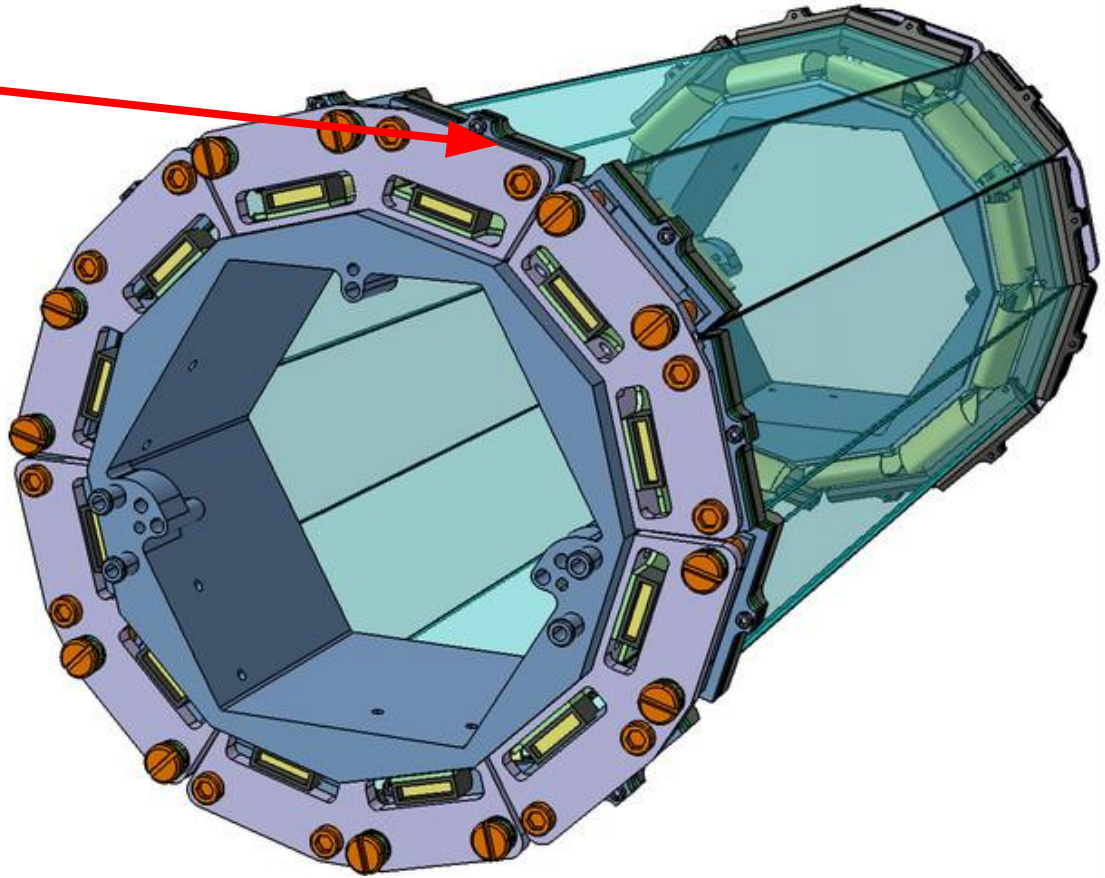
SciFi



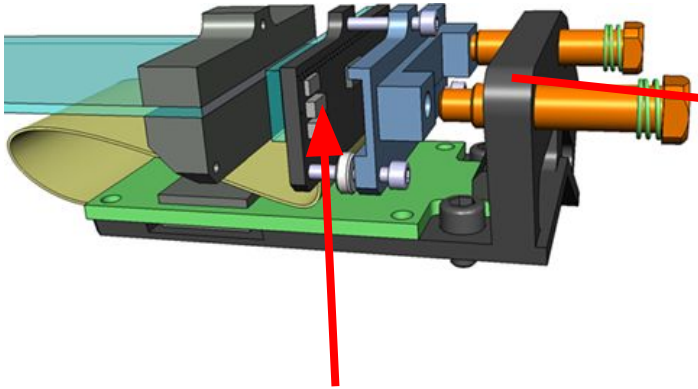




Hammamatsu SiPM

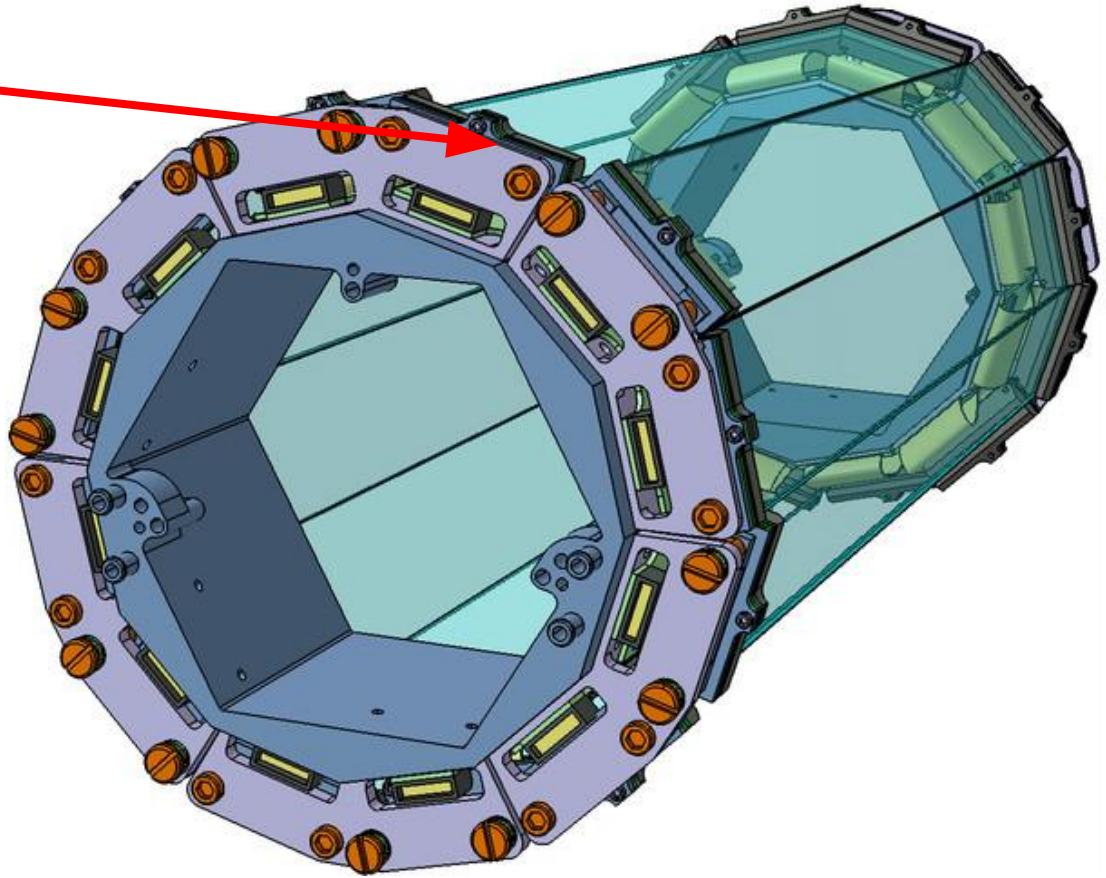


SciFi

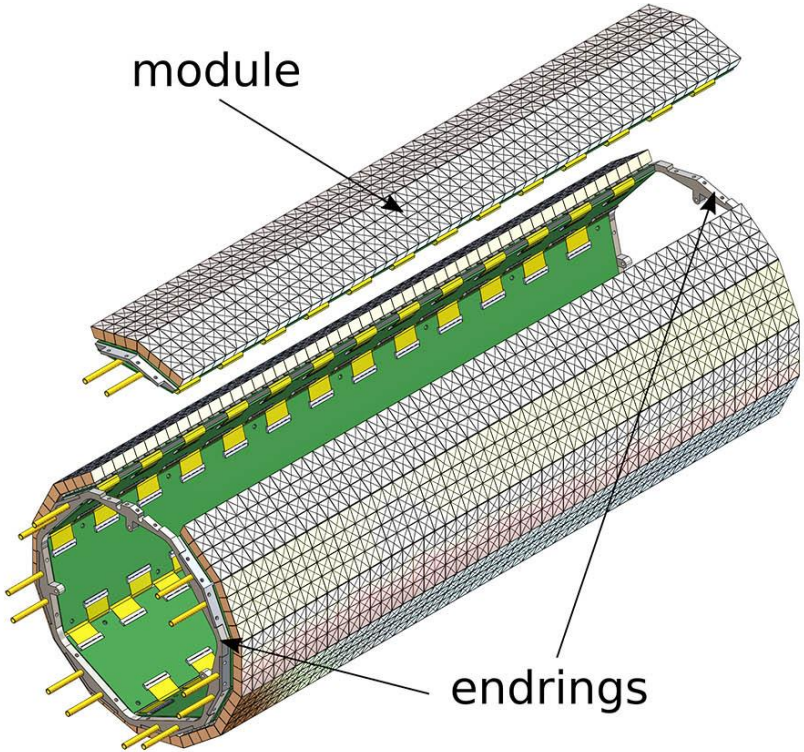


MuTRIG chip
High time resolution (50 ps)
Developed for Mu3e

Final time resolution < 1 ns

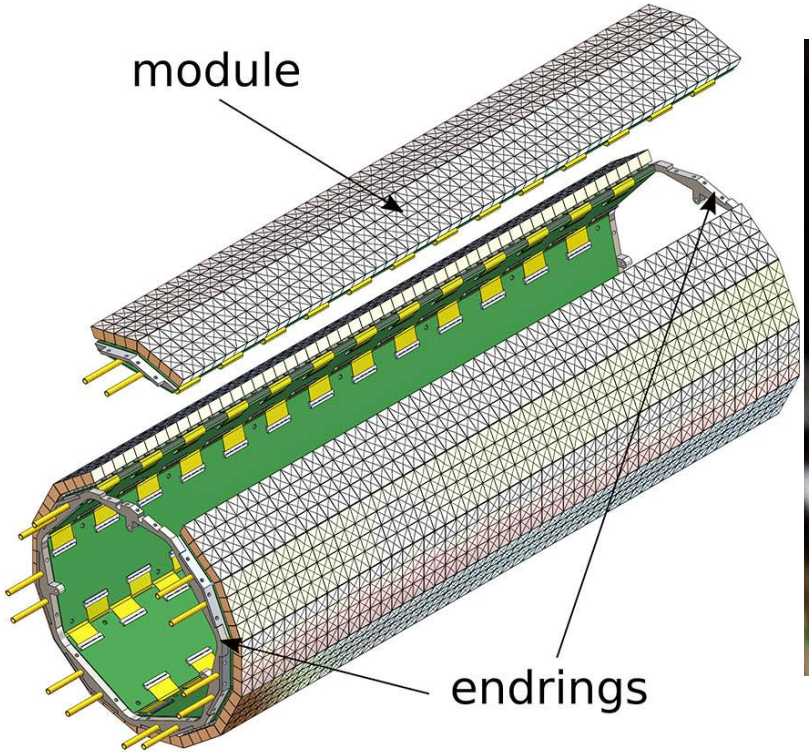


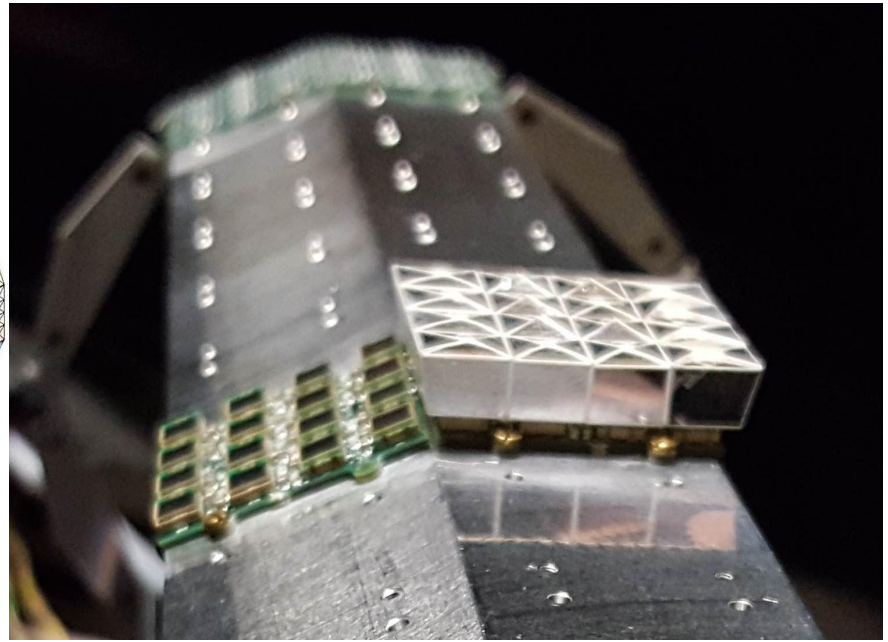
SciTiles



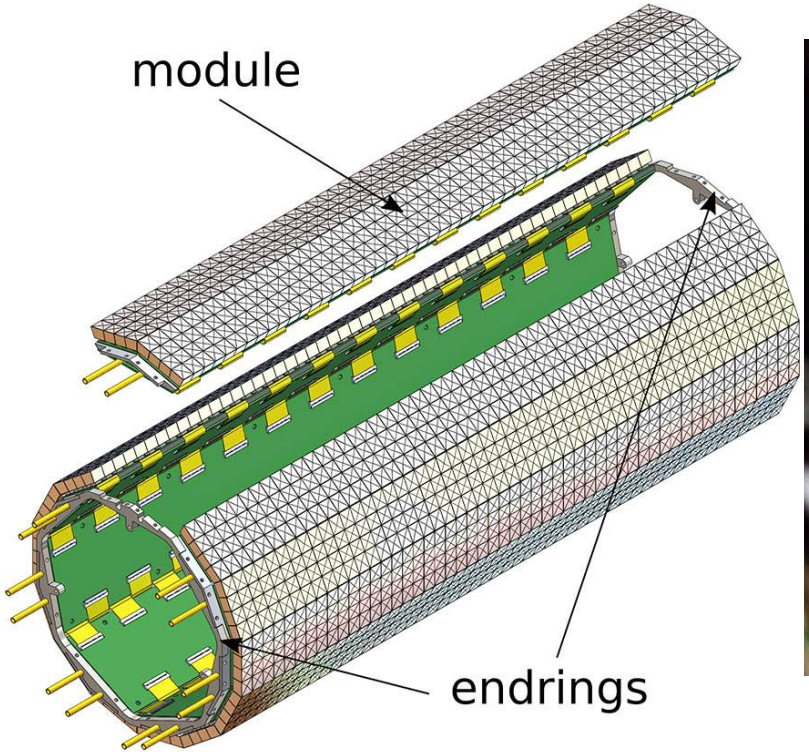
Placed on the edges
At the end of the tracks

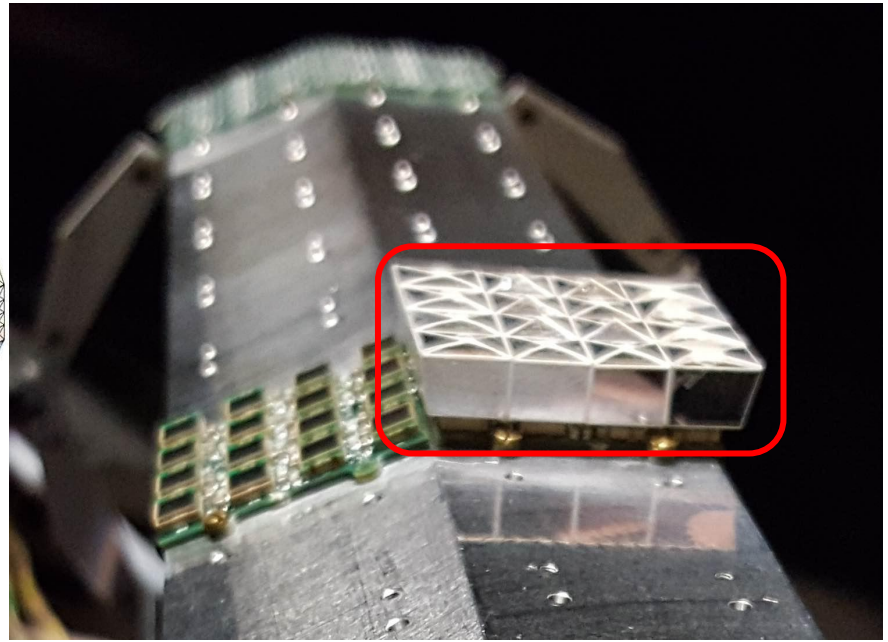
SciTiles





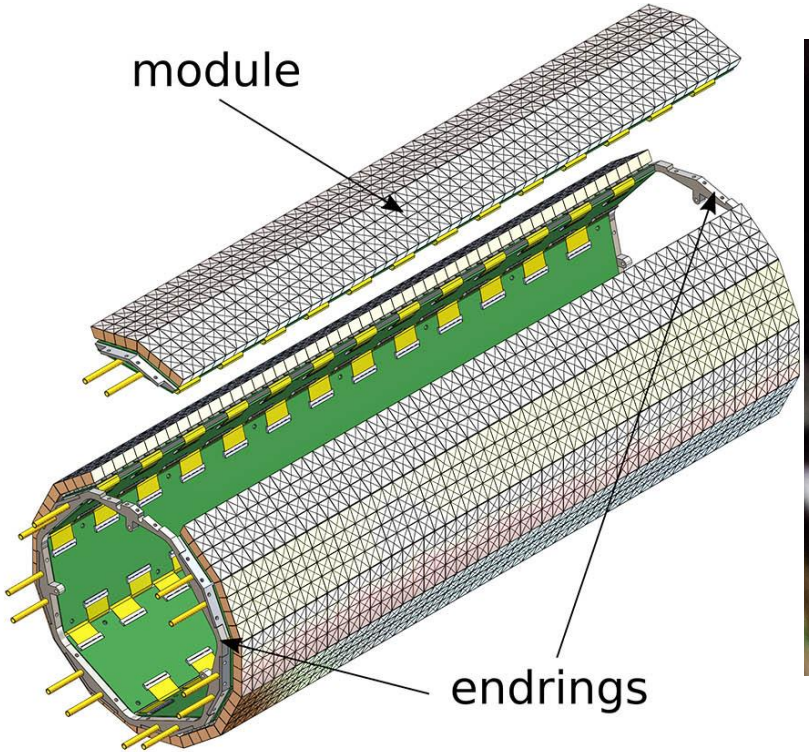
SciTiles

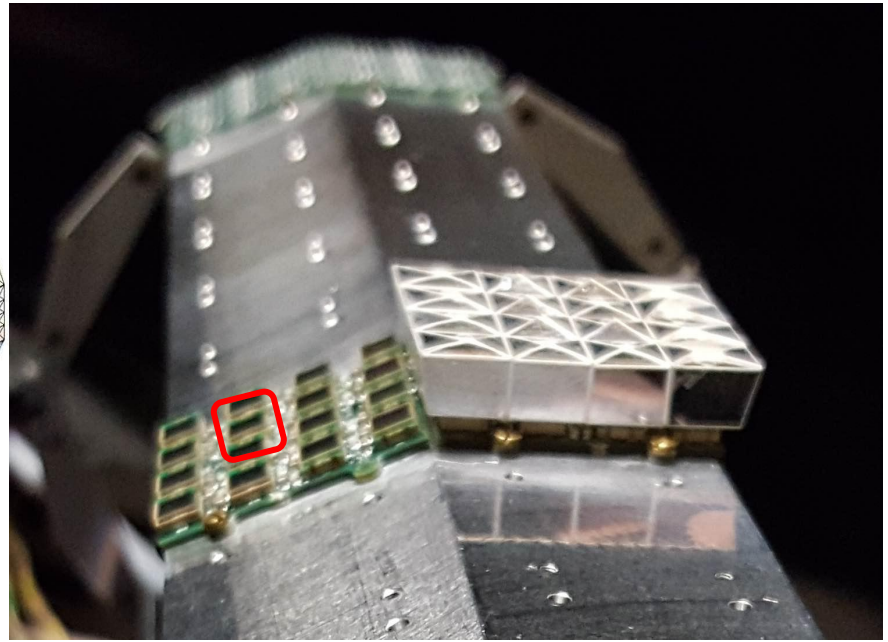




Scintillating tiles (x16)

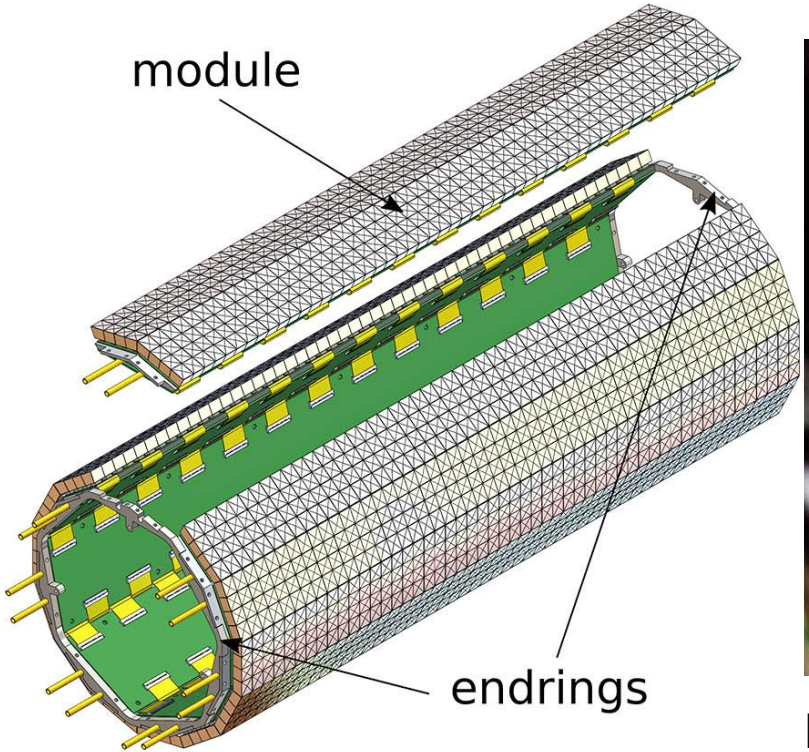
SciTiles

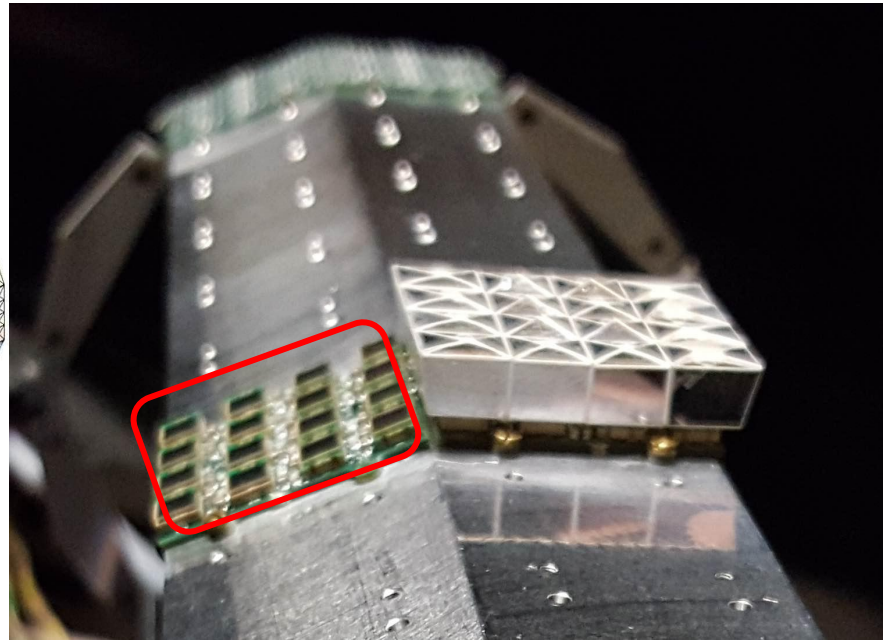




Hammamatsu SiPM (x16)

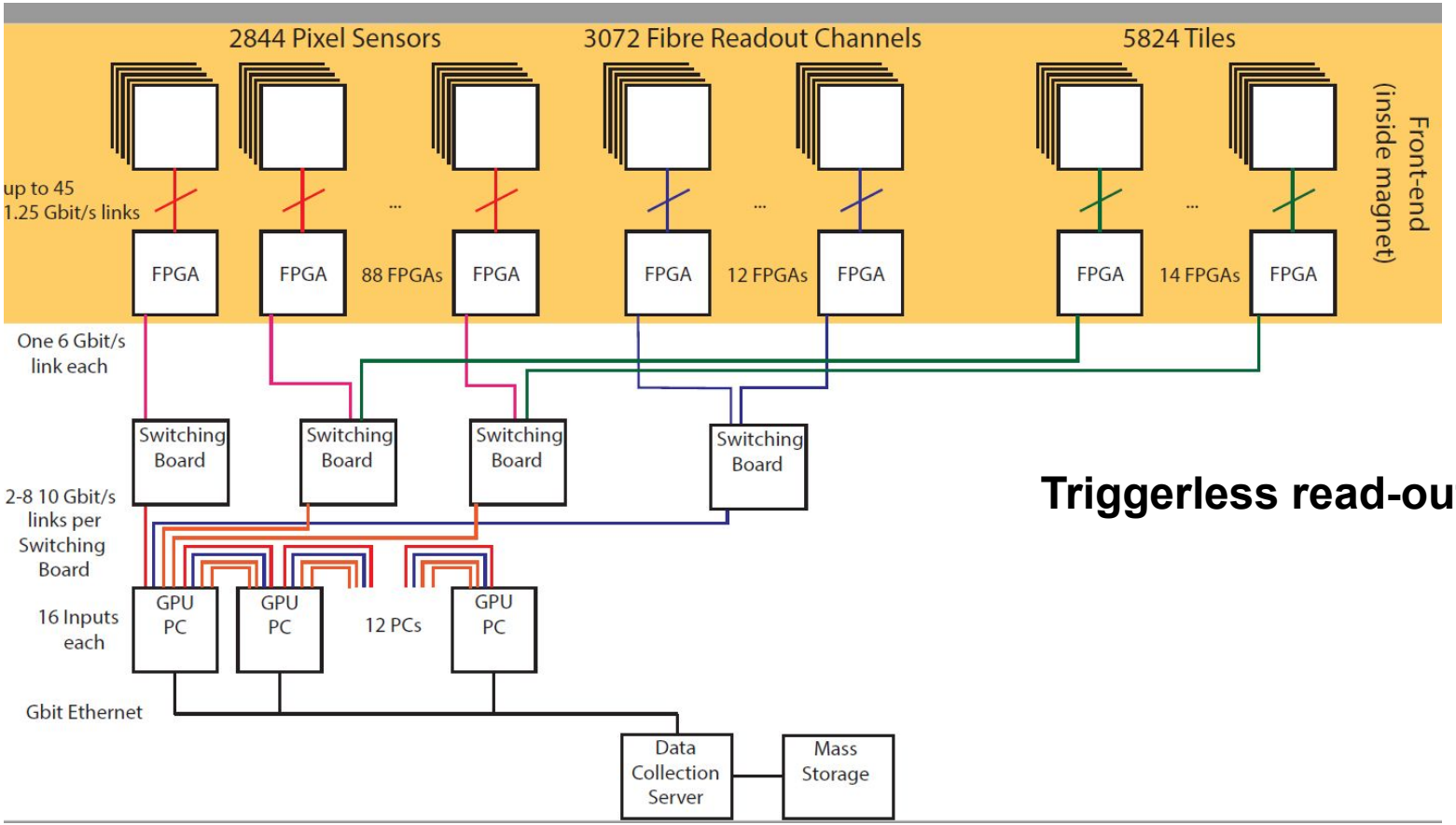
SciTiles





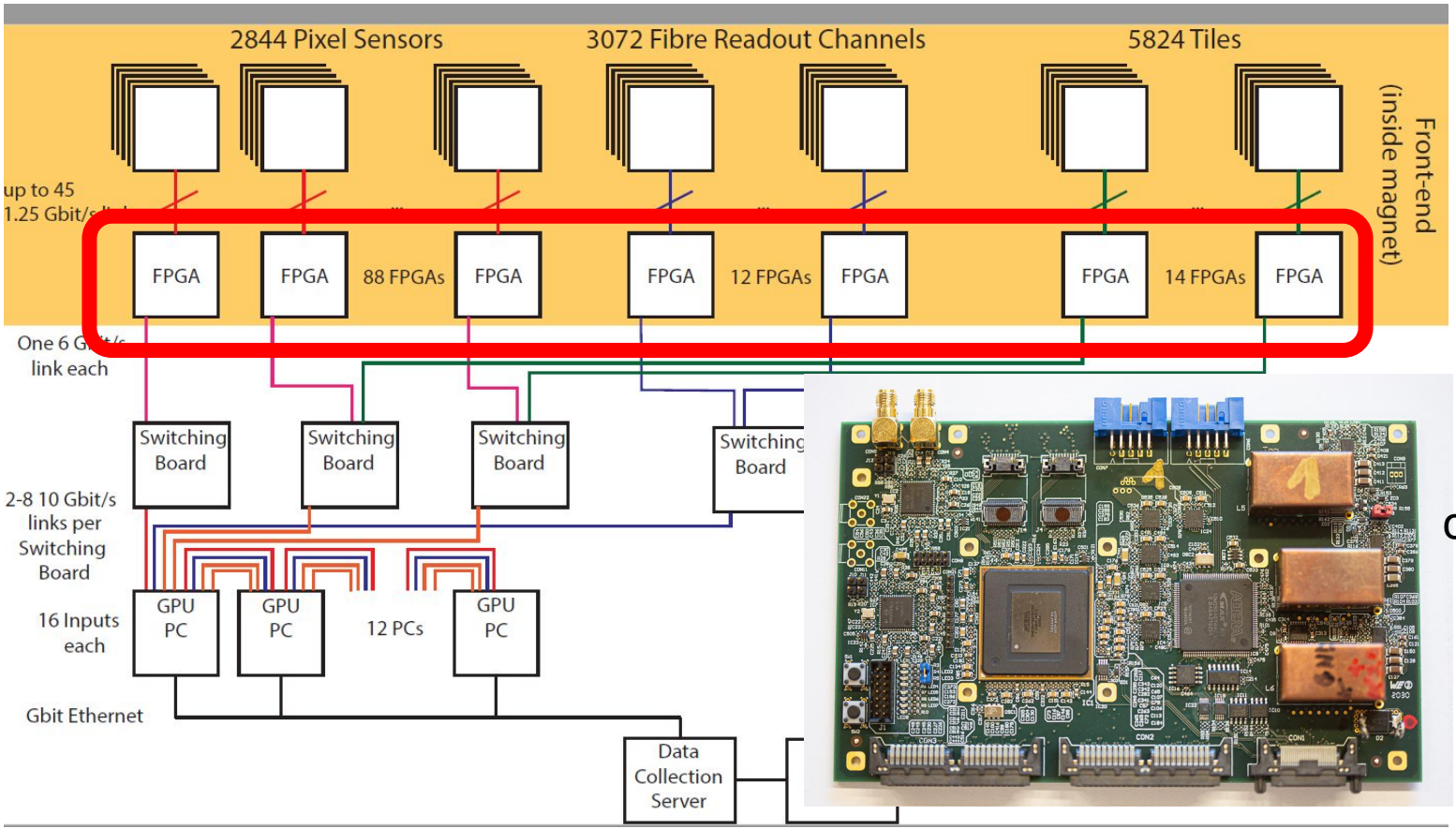
Read-out boards, MuTRIG chips underneath
Time resolution ~ 50 ps

DAQ



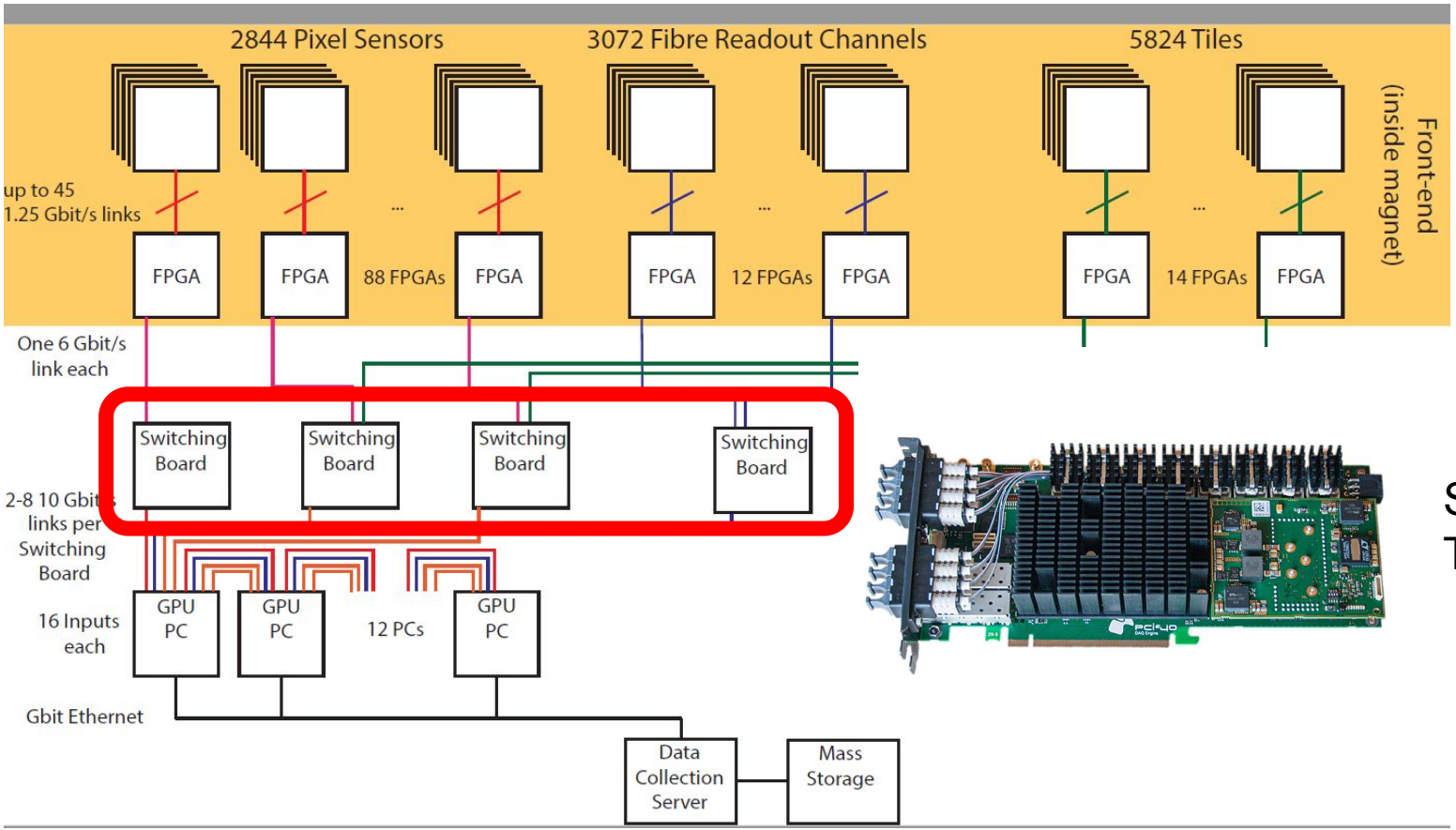
Triggerless read-out

DAQ



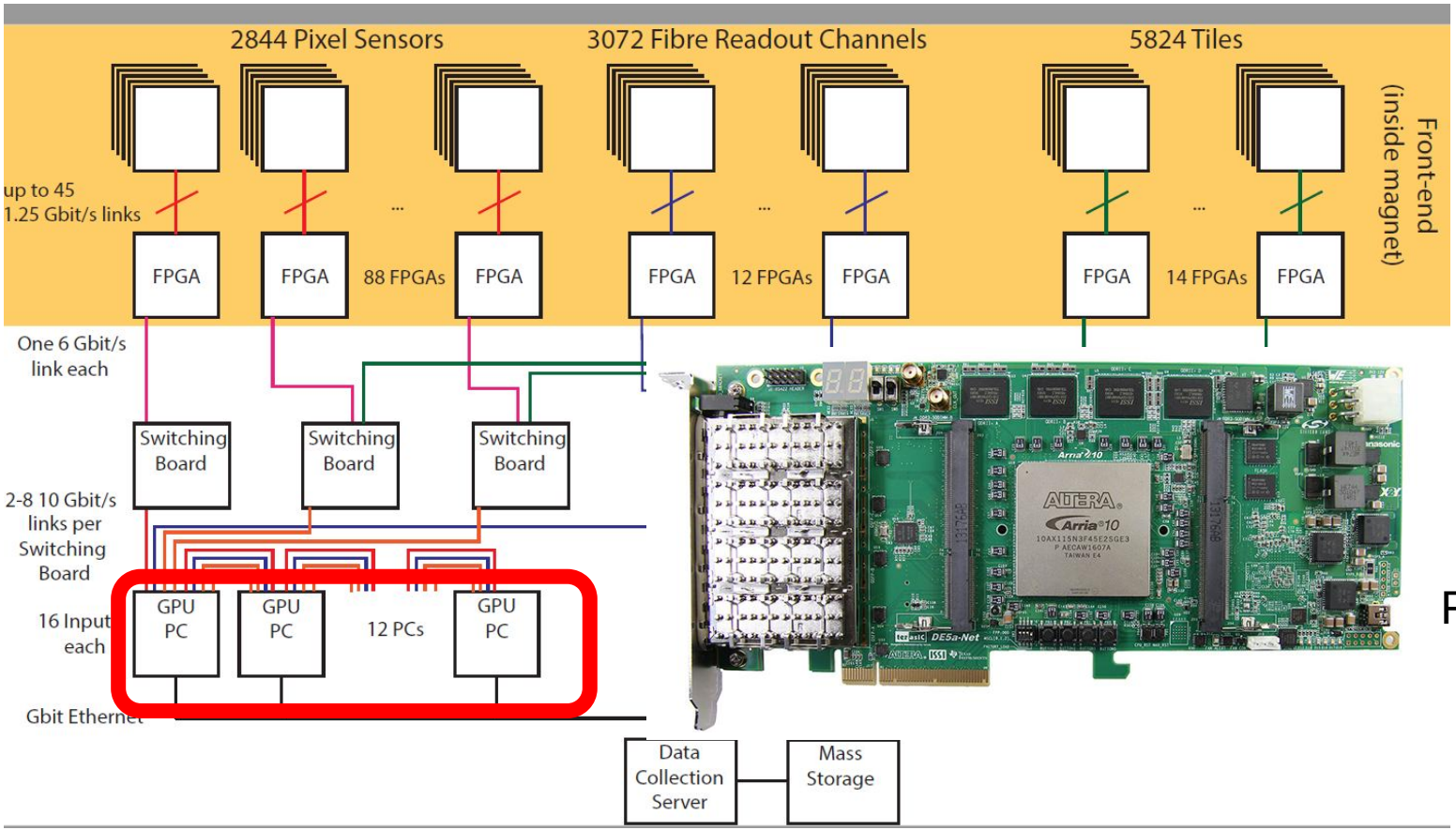
Front-end boards: Direct communication with sub-detectors (Designed for Mu3e)

DAQ



Switchin boards:
Sort data in/out
Time alignment and event building
(from LHCb)

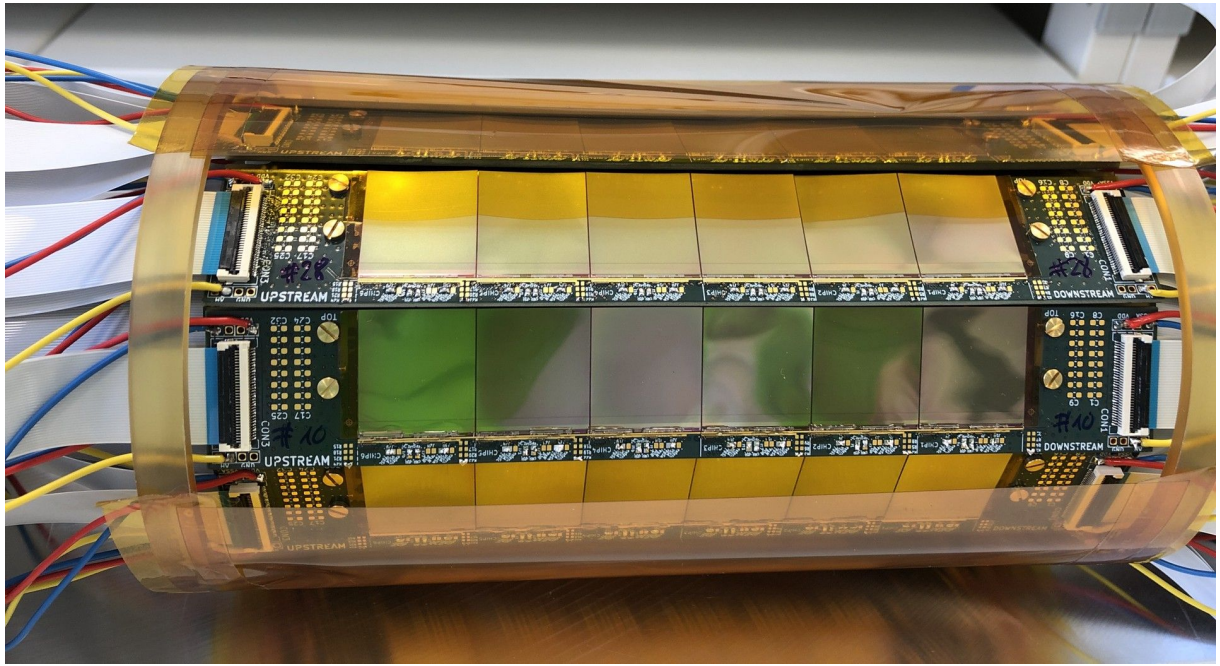
DAQ



Filter farm: Commercial FPGA cards mounted on PCs with GPUs to perform online track reconstruction

Prototyping

DAQ and experimental concept



Prototype of
vertex detector

Jun/Jul 2021

50 µm-thin chips mounted on katpon foils

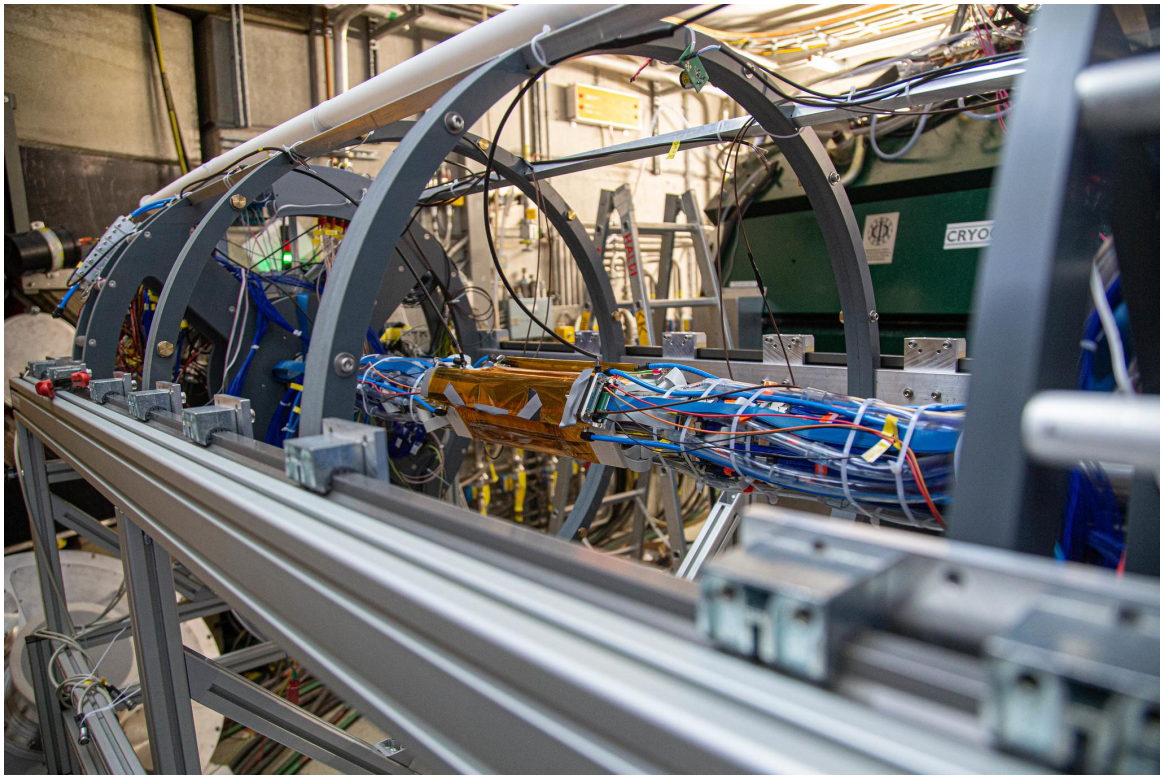
Connected to ladder-boards

Same shape as inner tracker, slightly larger

External connection with commercial cables

Prototyping

DAQ and experimental concept



Prototype of vertex detector

Mounted in cage

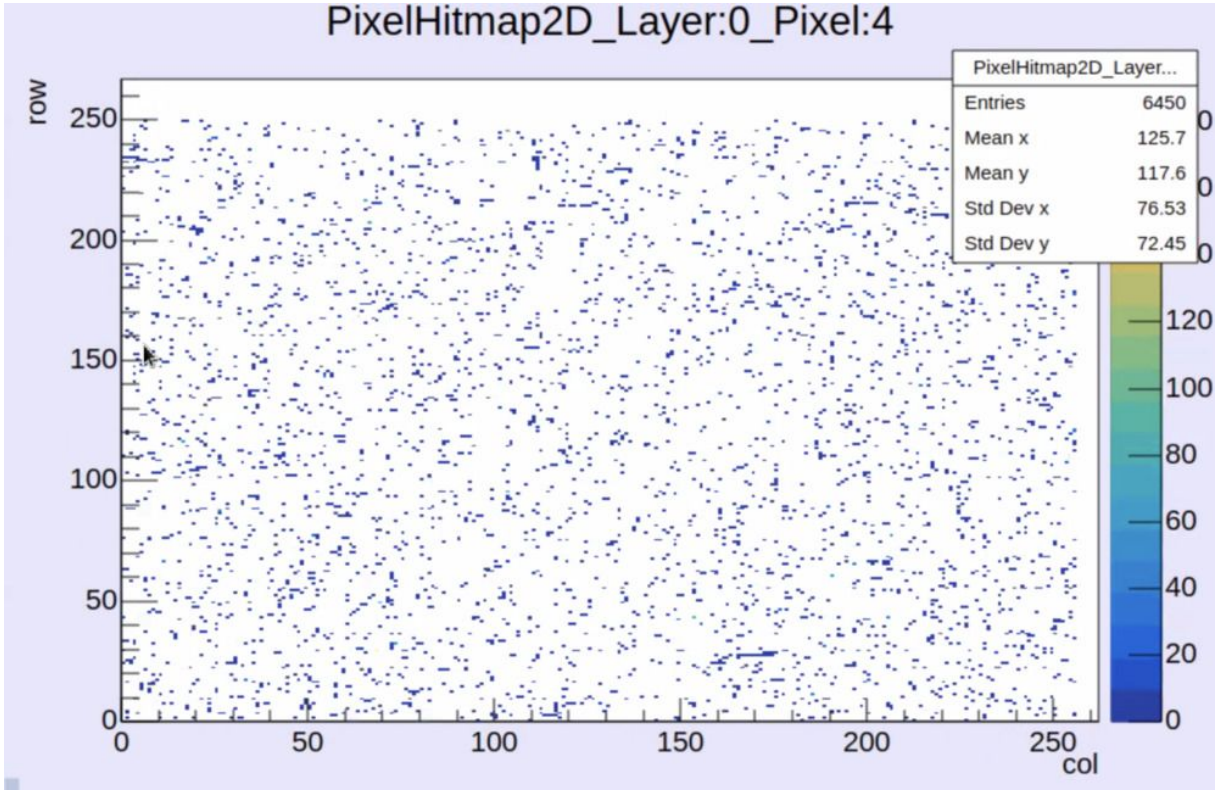
Helium flow as coolant

Inside magnet

Beam and target same as designed for the experiment

Prototyping

DAQ and experimental concept



Prototype of vertex detector

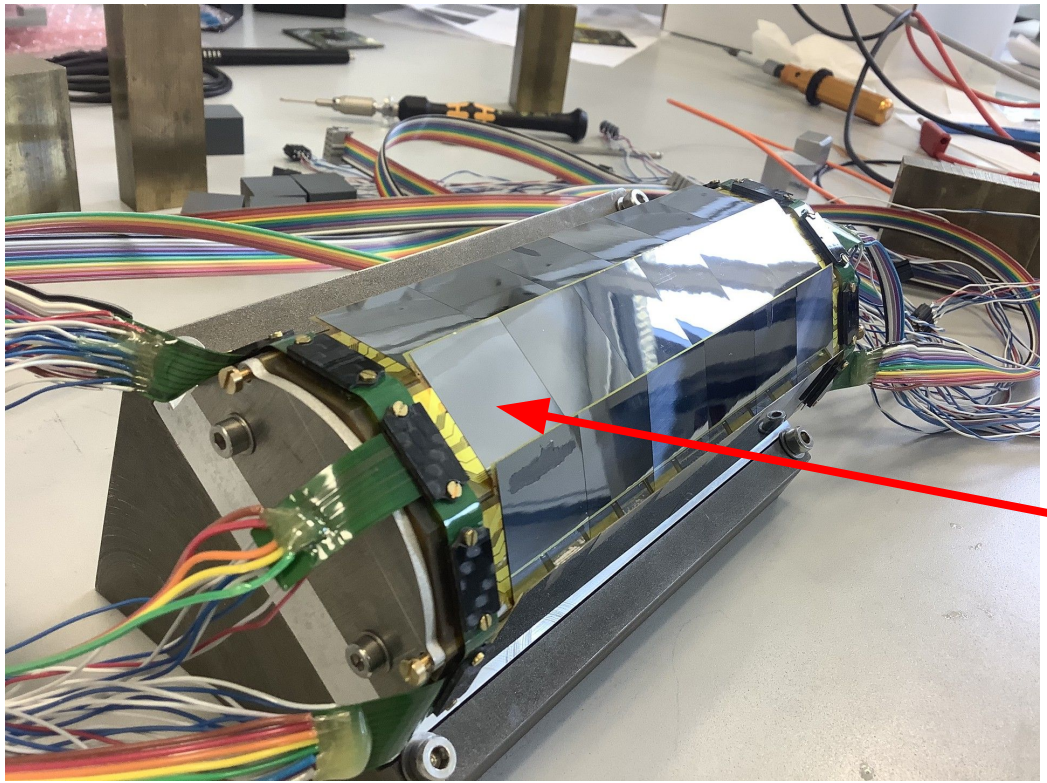
Worked!

First hitmap ever observed for the Mu3e experiment prototype

Analysis ongoing

Prototyping

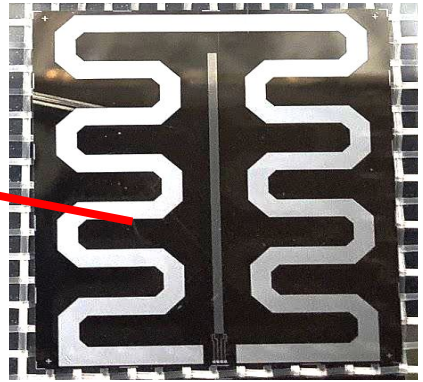
Thermo-mechanical stability



Silicon heater prototype

Reproduction of inner tracker with same materials and connections

Chips are just passive silicon heaters

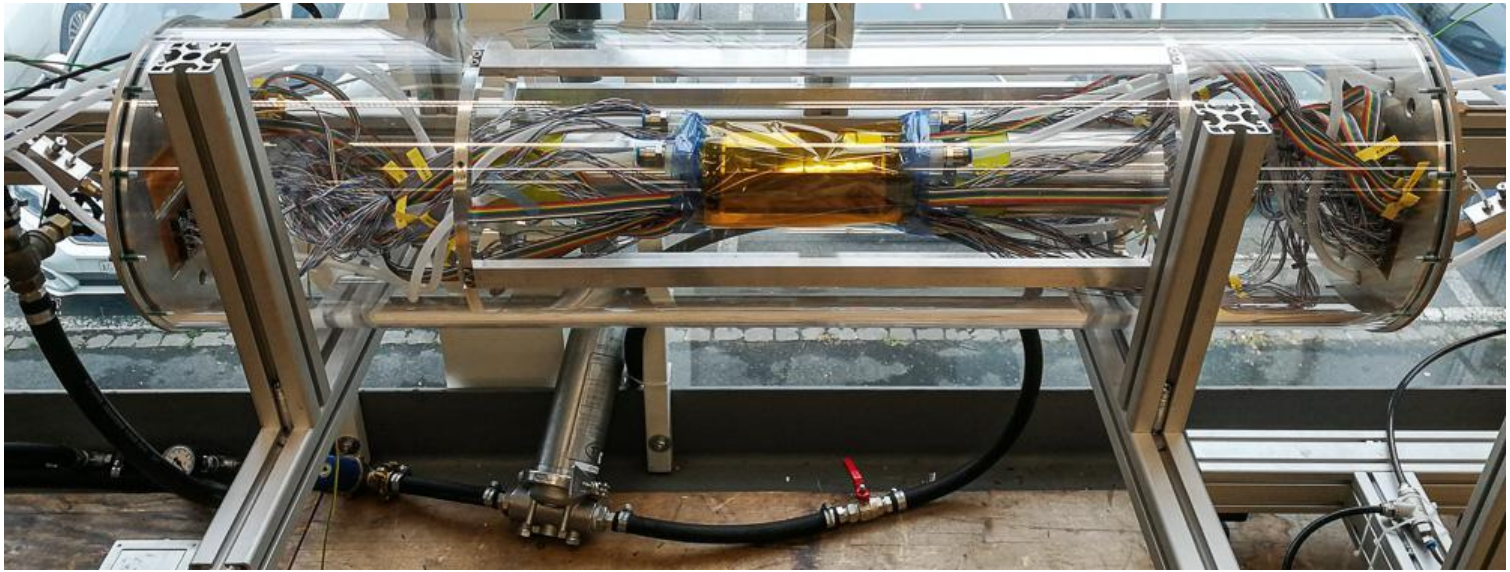


Prototyping

Thermo-mechanical stability

Silicon heater prototype

Test stand with Helium cooling system

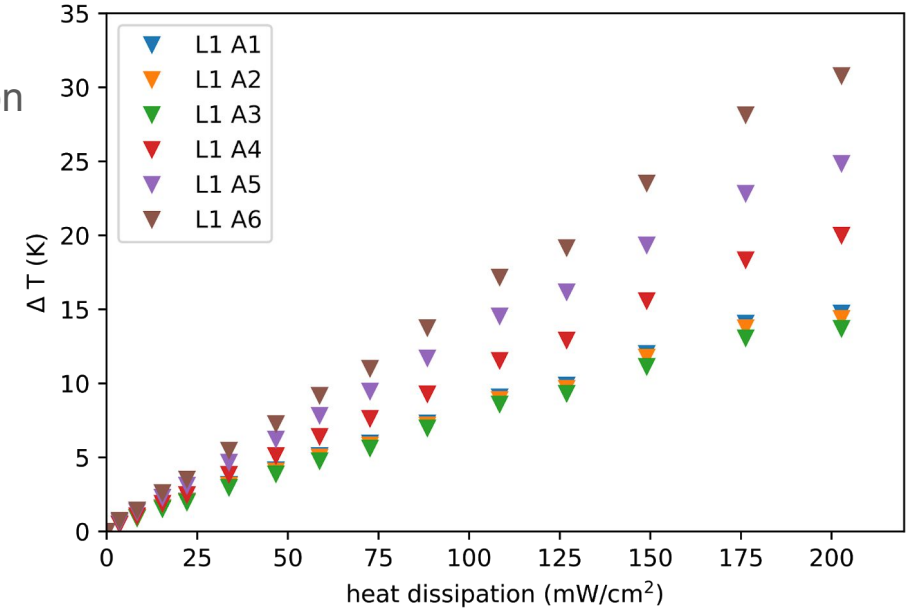


Prototyping

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

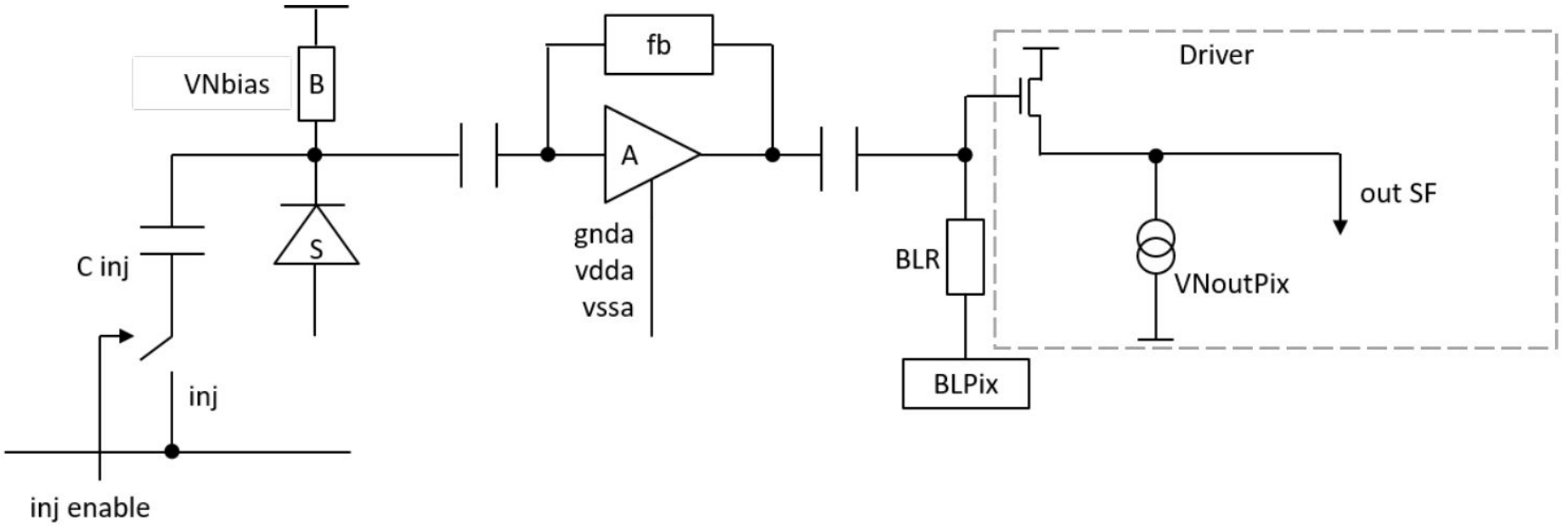
Silicon heater prototype



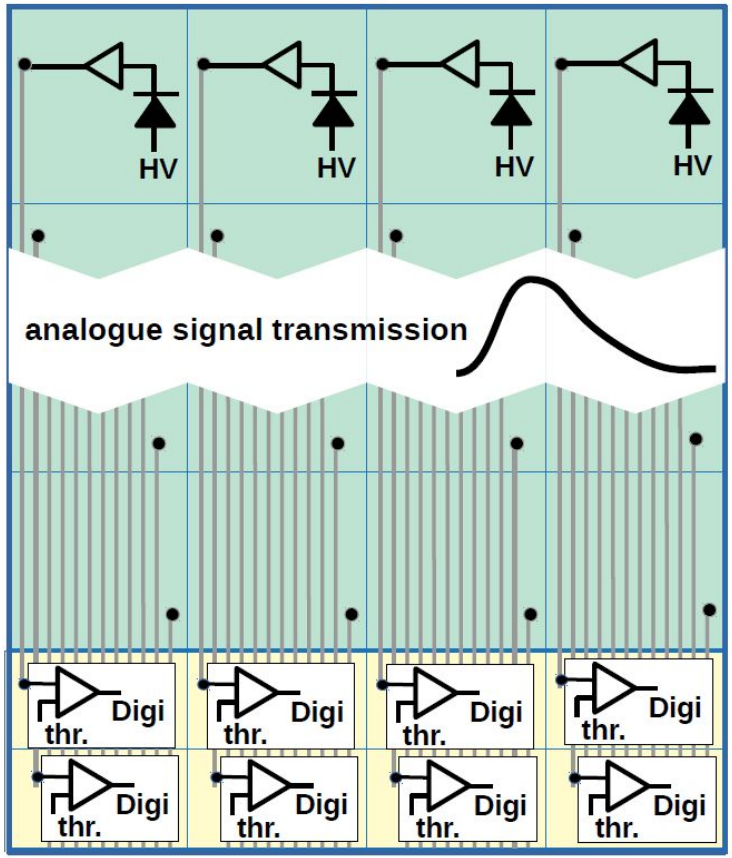
Conclusions

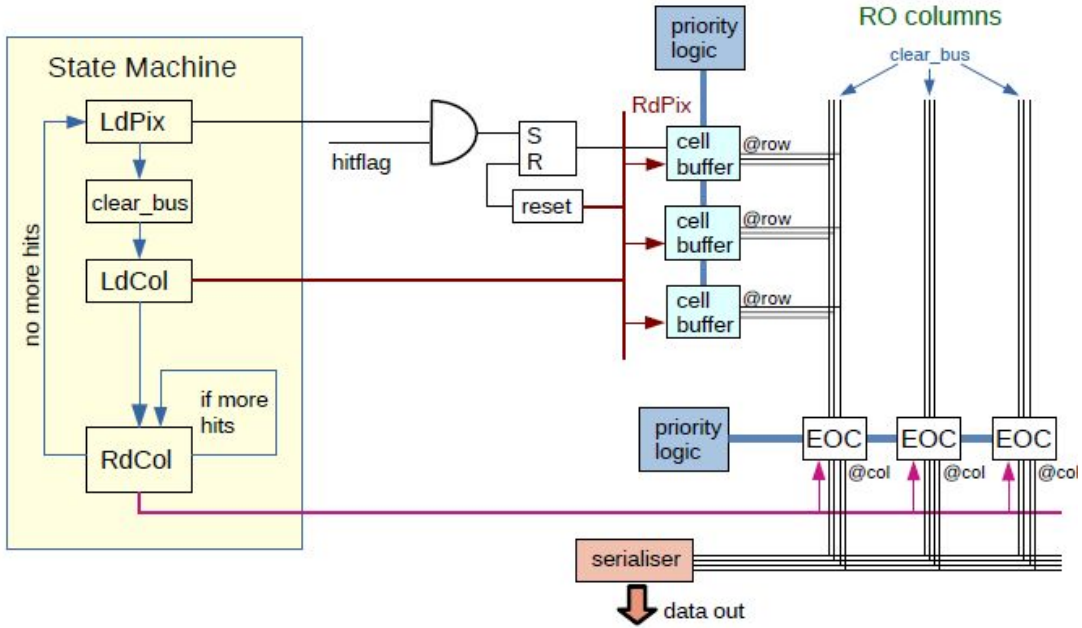
- Mu3e is a CFLV experiment under construction at PSI
- Investigation of $\mu \rightarrow eee$ decay channel with unprecedented sensitivity
- Challenging for the system design
  - Reduce material budget
  - High detector performance
  - Highly dense environment
  - Continuous read-out with online track reconstruction
- Several solutions implemented
  - Cutting-edge technologies
  - Custom made parts
- Prototyping phase successful
- Construction starting soon

Backup: Mupix10 readout scheme



Backup: Mupix10 readout scheme





Backup: Mupix10 readout scheme