The Search for Charged Lepton Flavour Violation with the Mu3e detector

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18th May 2025, Muon Physics at the Intensity and Precision Frontiers

University of
BRISTOL

Mu3e overview

- Based at the Paul Scherrer Institute (PSI) near Zurich, Switzerland.
- 3 countries - Switzerland, Germany and UK.
- 12 institutes.
- ~78 collaborators, although most not full time.

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Mu3e

- Measure the $\mu^+ \rightarrow e^+ e^- e^+$ interaction.
- Standard Model vanishingly small. Any observation clear indication of new physics.
- Previous best set by SINDRUM as 1.0×10^{-12} at 90% confidence level in 1988.

Muon sources

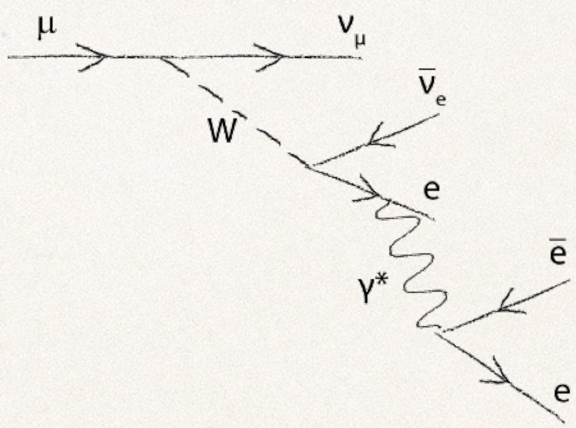
- Compact Muon Beam Line (CMBL)
  - Running until late 2026. Shared with MEG-II ($\mu^+ \rightarrow e^+ \gamma$).
  - 10^8 low energy μ^+ per second.
  - Hope to see or achieve worlds best upper limit on the branching fraction.
- High intensity Muon Beam (HiMB)
  - Operational mid 2029.
  - 10^{10} low energy μ^+ per second.
  - Expect Mu3e could achieve 10^{-16} upper limit.
  - Will require significant detector redesigns.
  - Not covered here.

Signal event characteristics

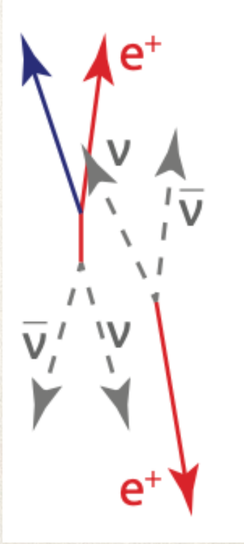
- Muons decay at rest.
- 2 positive tracks, 1 negative originating at the same point at the same time.
- Total momentum is zero.
- Invariant mass of the decay products equal to the muon mass.

Backgrounds

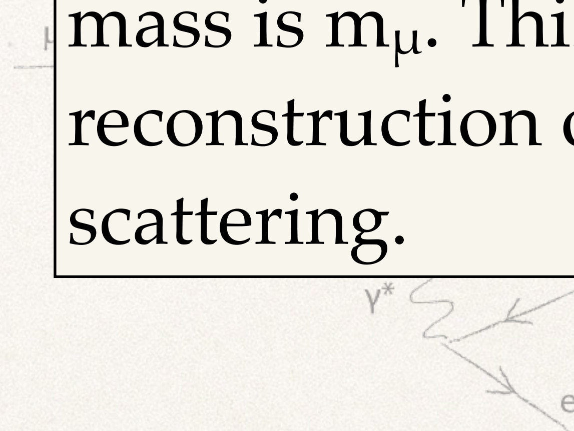
- Two classes of backgrounds:
  - radiative decay with internal conversion.



  - combinatorial
    - Michels plus incorrectly reconstructed track.
    - $\mu^+ \rightarrow e^+\gamma\nu\nu$ plus converted photon
    - Bhabha scattering plus Michel(s)

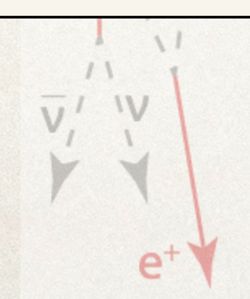


Backgrounds



Require zero momentum sum and invariant mass is m_μ. This needs excellent momentum reconstruction of individual tracks and minimal scattering.

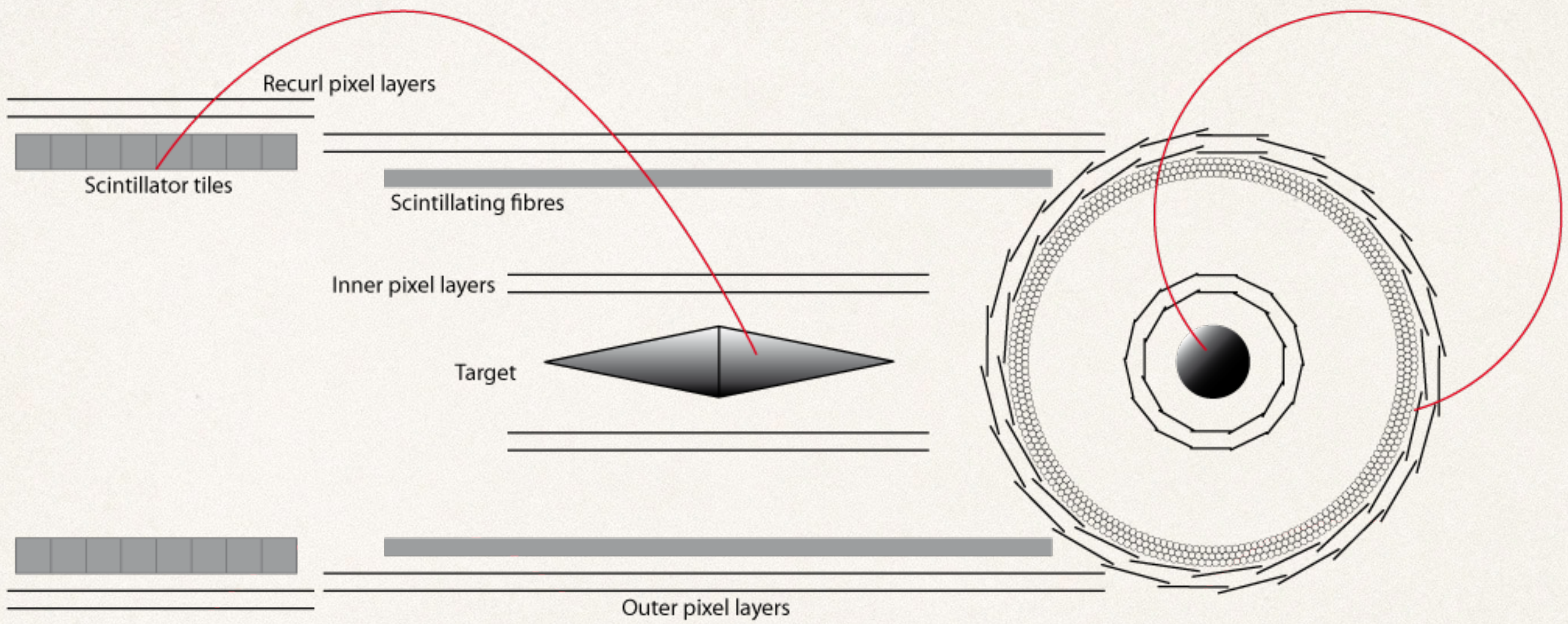
Accurately reconstruct direction of travel (and hence charge) from timing. Differentiate decays using reconstructed vertex position and time.



Requirements

- Excellent track momentum resolution.
- Light detectors to minimise multiple scattering.
- Good timing for time of flight measurement - distinguish direction of travel.
- Good vertex resolution to distinguish coincident muon decays.
- High rate.

Detector design

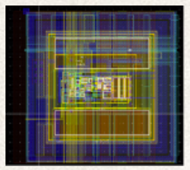


- Silicon trackers, very light. Good position resolution. Multiple scattering dominated.
- Scintillating Fibre for timing.
- Recurl stations upstream and down stream
  - outer pixel layers. Long lever arm to measure momentum with minimal material beforehand.
  - tiles for timing.
- All running inside a 1T magnetic field.
- No hardware trigger with online selection on a GPU farm.

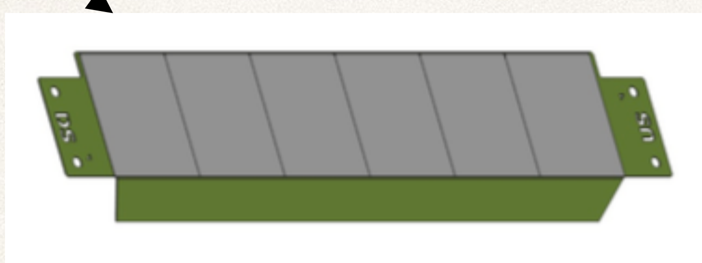
Pixel detector

- Mupix11 High Voltage Monolithic Active Pixel Sensor (HVMAPS). 80x80μm^2 pixels. This puts us firmly in the multiple scattering dominated domain.
- O(ns) timing.
- 50μm thick for the inner layers, 70μm for the outer.
- Attached to High Density Interconnect circuits, with aluminium traces on a thin substrate.
- Outer layers have additional carbon fibre stiffeners.

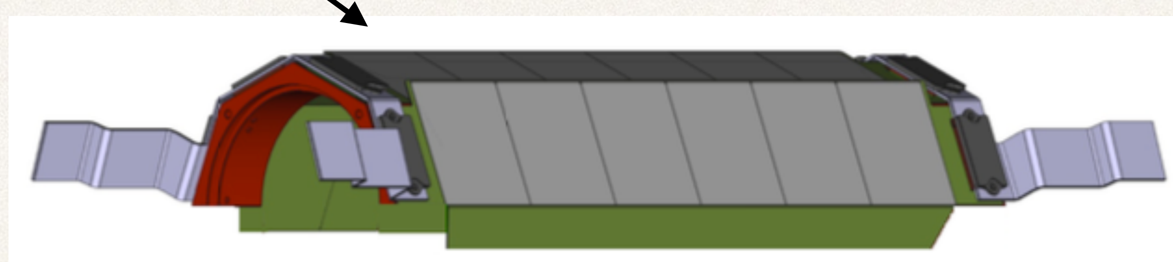
Pixel detector



Mupix11 chip



ladder



module

layer

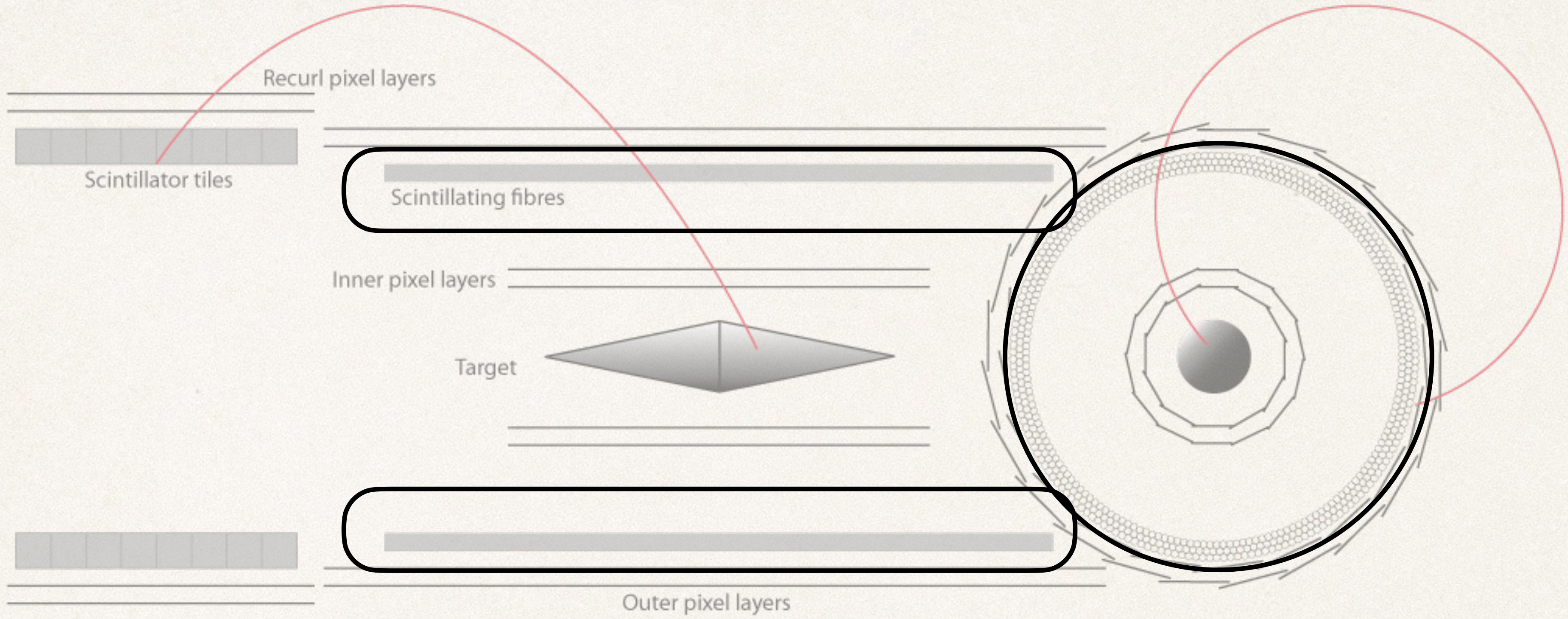
Pixel detector

	Layer 1	Layer 2	Layer 3	Layer 4
#sensors	48	60	408	504
Length(mm	124.7	124.7	351.9	372.6
Radius(mm	23.3	29.8	73.9	86.3

	Central	Upstream recurl	Downstream recurl	Total
#sensors	1020	912	912	2844

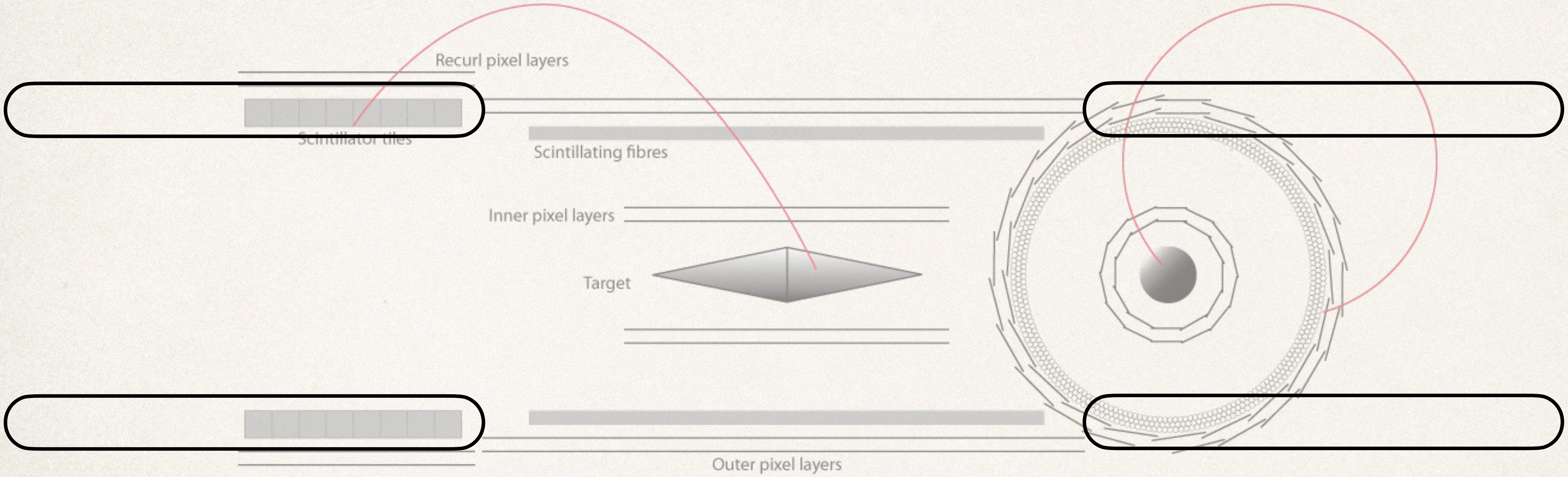
- Assuming ~1.6W/chip → need to dissipate ~4.6 kW of heat.
- Require minimal material → gaseous helium cooling.

Scintillating fibre detector



- Time resolution of 250 ps.
- Spatial resolution ~250 μm.
- $X/X_0 < 0.2\%$.
- Read out by silicon photomultipliers.

Scintillating tile detector



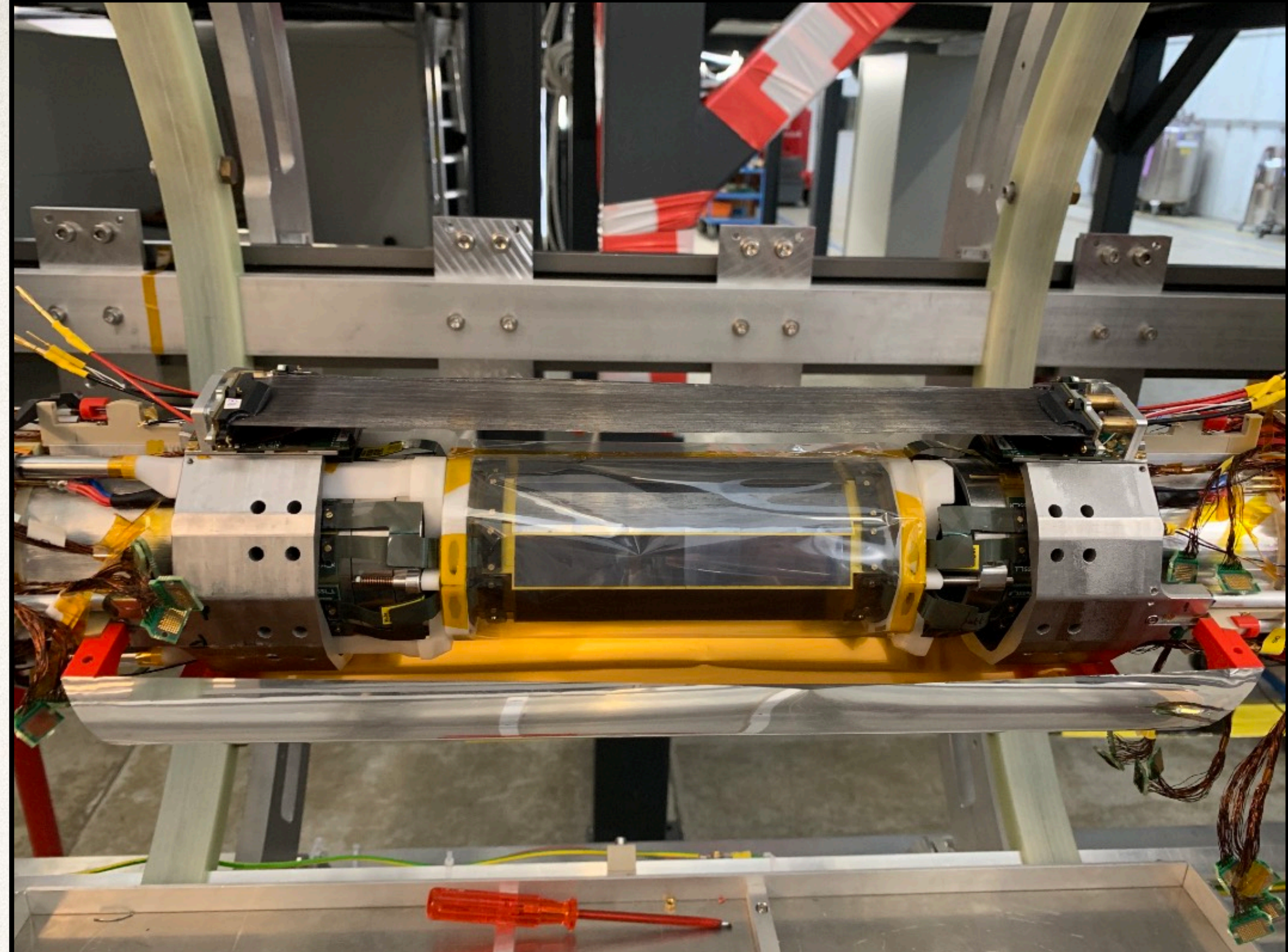
- Aim to achieve 100 ps time resolution.
- At the end of track trajectories - no constraints on material budget.
- 2912 tiles per station, 6.3x6.2x5 mm in size.
- Read out by silicon photomultipliers.

Time line

- 3 weeks of beam time starting 2nd June.
  - Operational experience only, no physics.
- Outer pixel layers to be installed in 2026.
- Aim for physics at CMBL 2nd half of 2026.
- HIPA shutdown end of 2026, detector redesign before running in HiMB 2029.

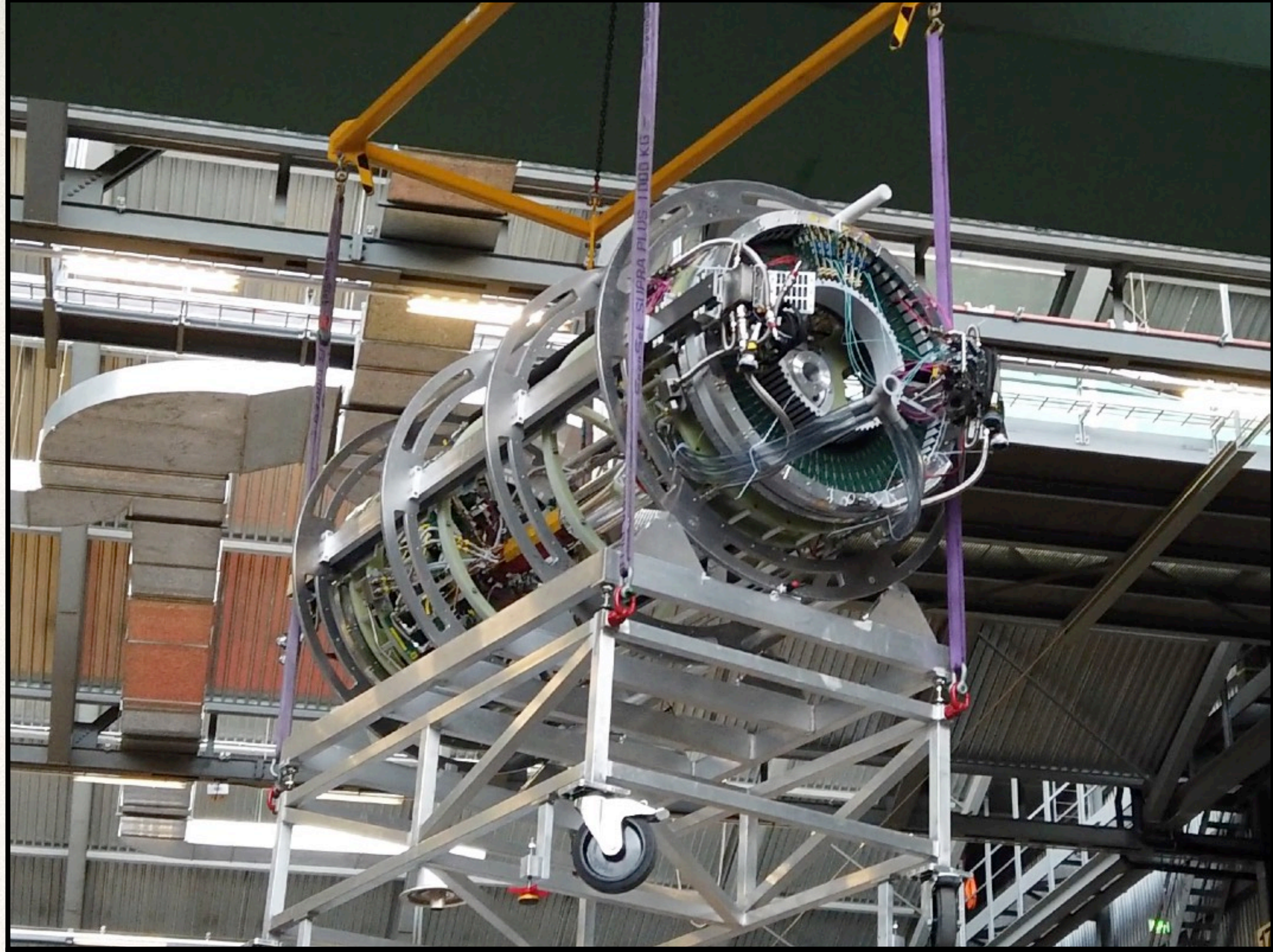
Current status

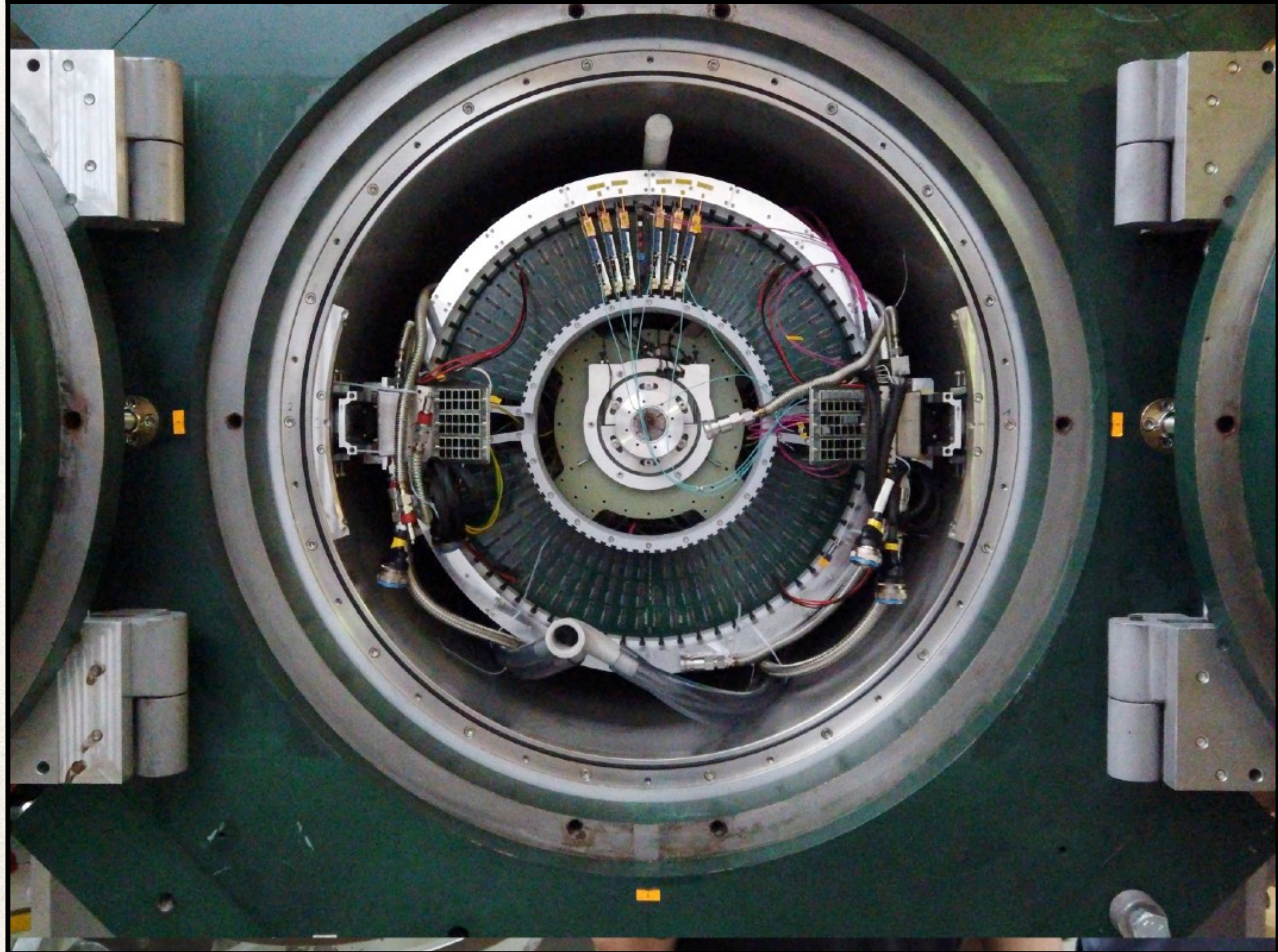
- Installed:
  - 2 inner vertex pixel layers.
  - 2 scintillating fibre modules.
  - 3 tile modules.



Current status

- Detector craned from the staging area into the πE5 beam line area and installed into the magnet last week.



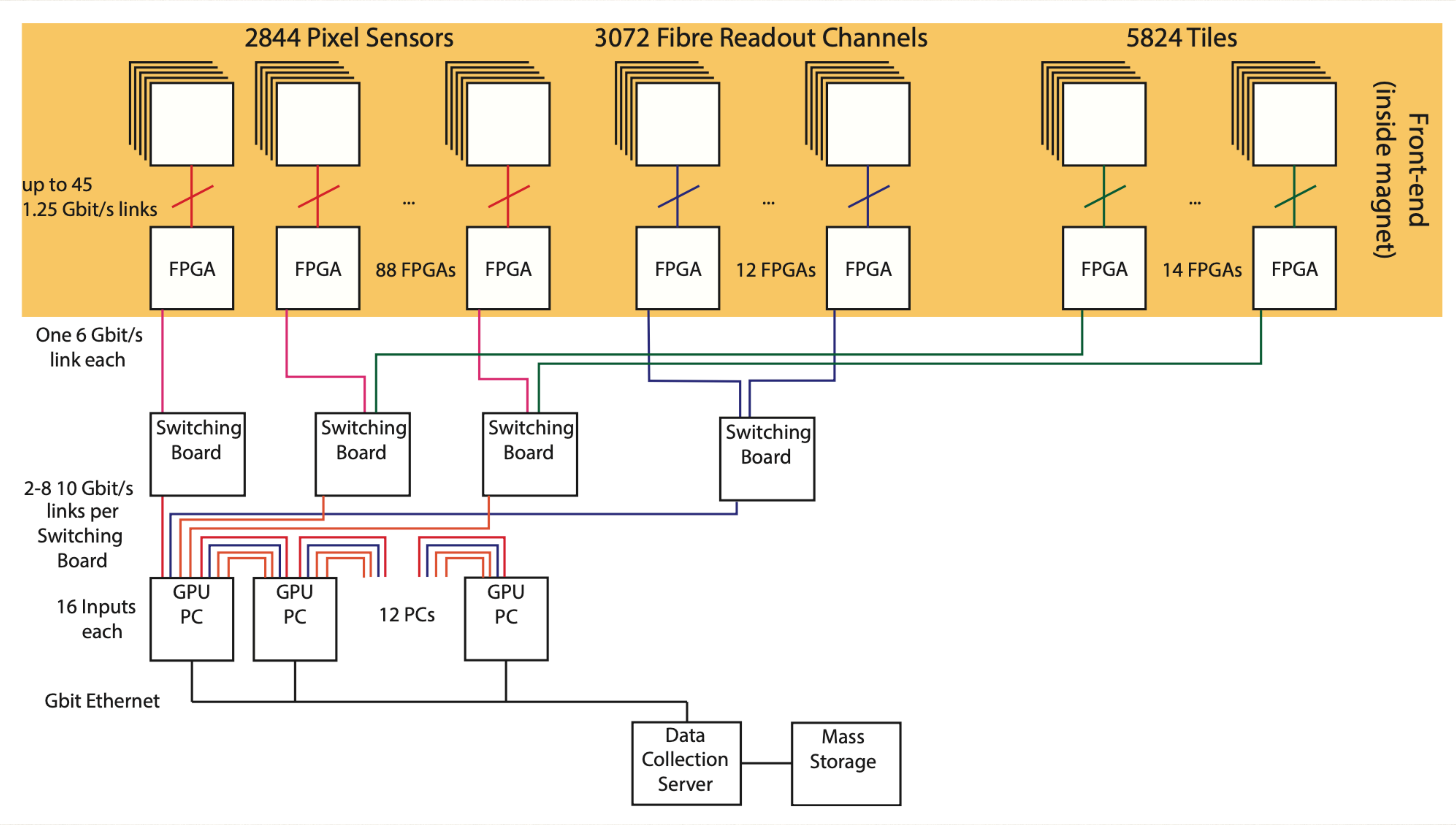


Summary

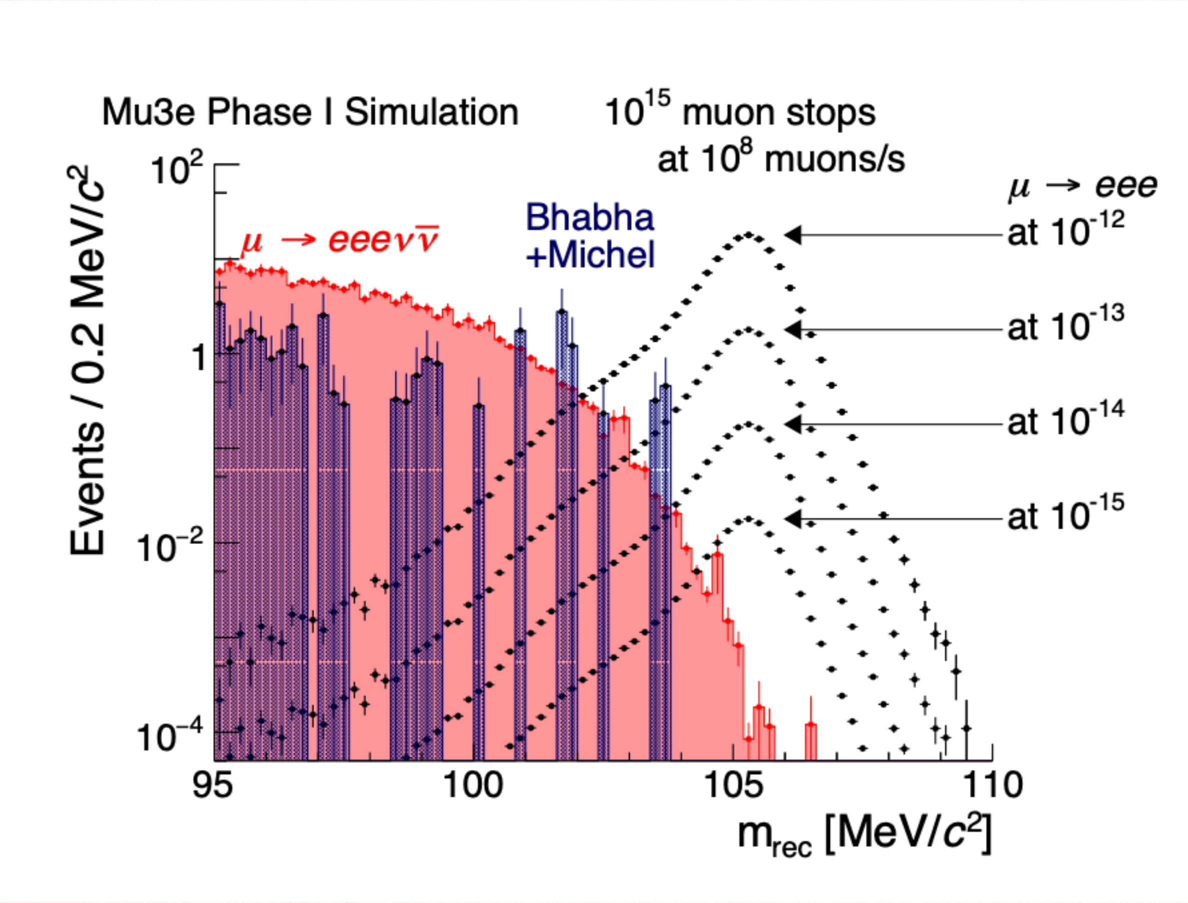
- Aim to see or set a world's best upper limit on the $\mu^+ \rightarrow e^+ e^- e^+$ branching fraction running at the CMBL. Later running at the HiMB requires extensive redesign to reach 10^{-16} at 90% confidence level.
- Many novel detector firsts.
  - Ultra light detectors
  - Helium cooling
  - ...

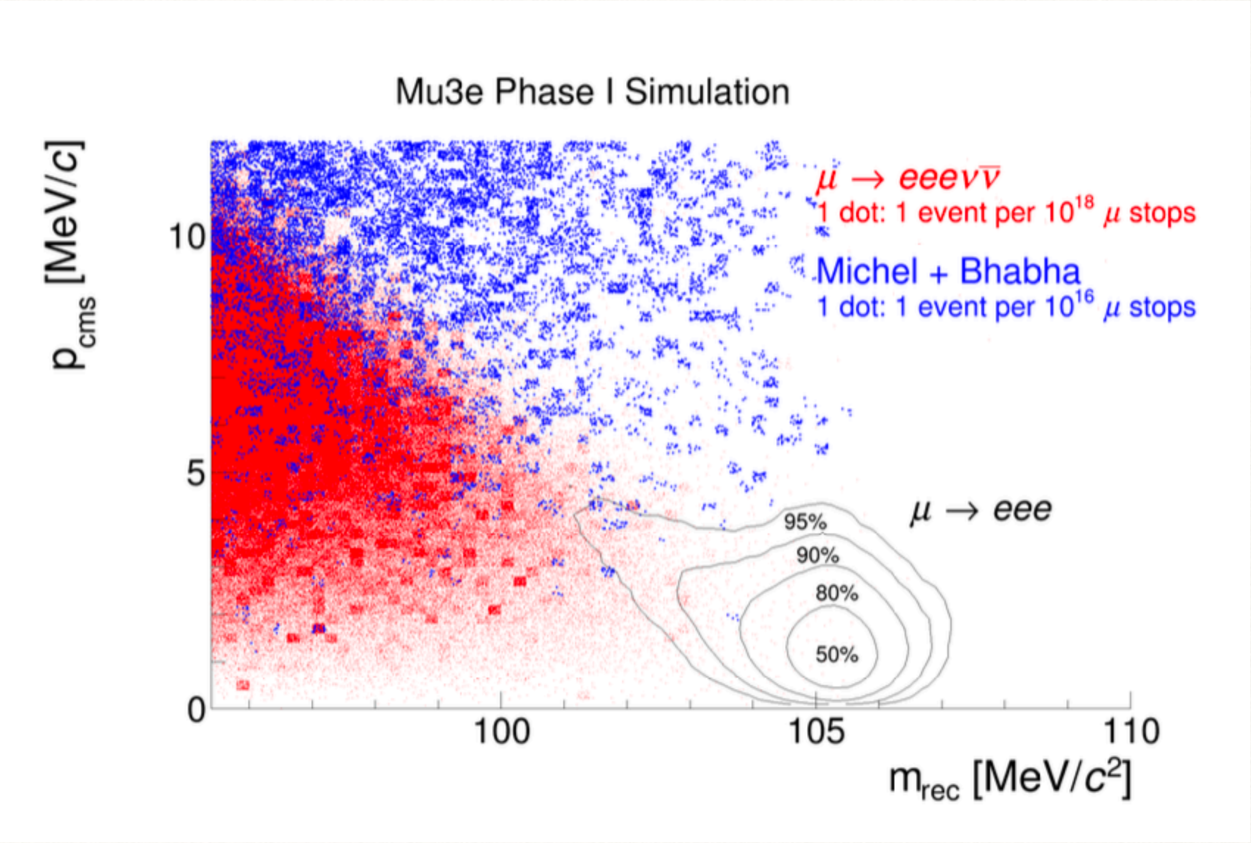
Backup

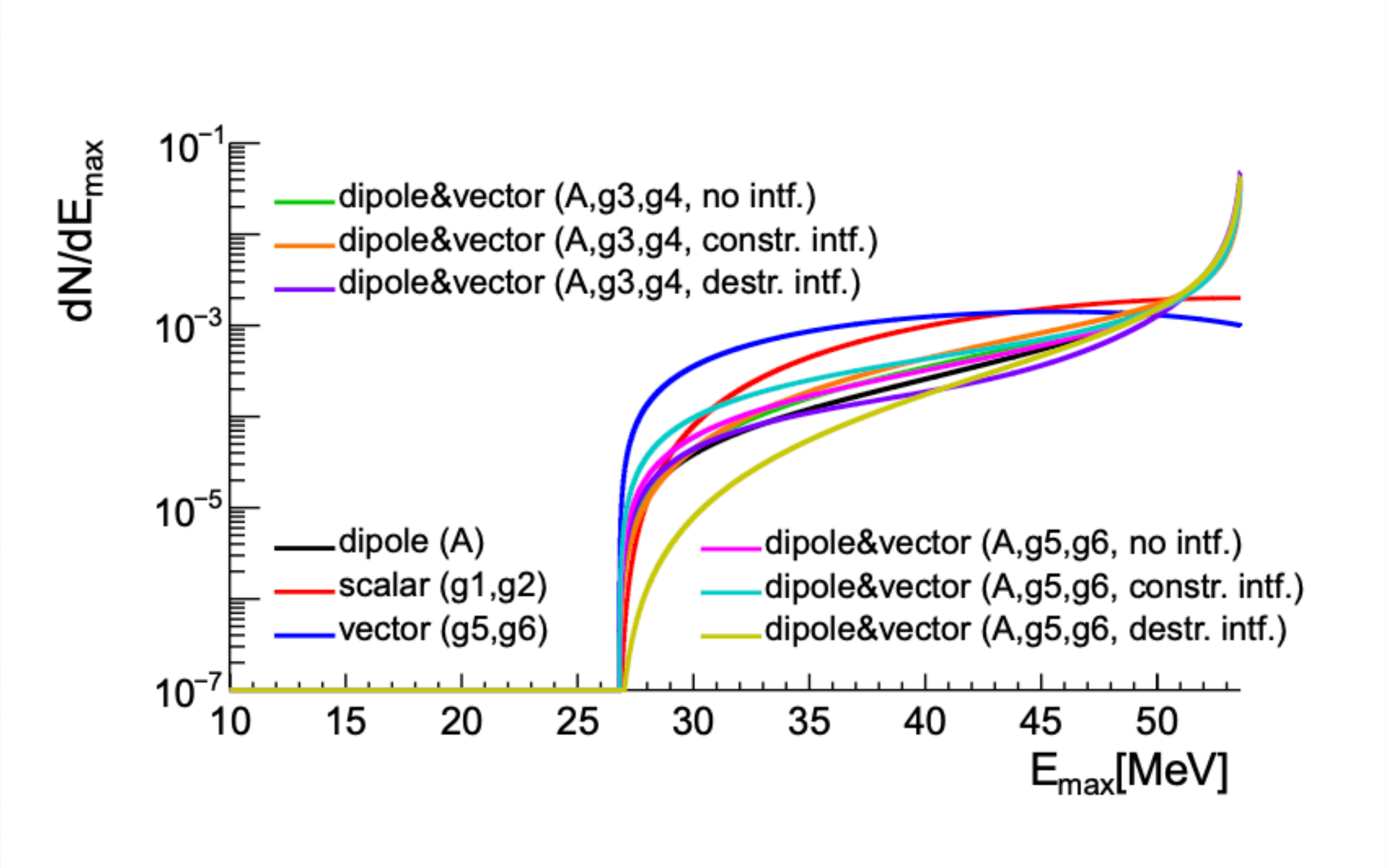
Data Acquisition



Physics performance







dN/dE_max
E_max[MeV]
dipole&vector (A,g3,g4, no intf.)
dipole&vector (A,g3,g4, constr. intf.)
dipole&vector (A,g3,g4, destr. intf.)
dipole (A)
scalar (g1,g2)
vector (g5,g6)
dipole&vector (A,g5,g6, no intf.)
dipole&vector (A,g5,g6, constr. intf.)
dipole&vector (A,g5,g6, destr. intf.)