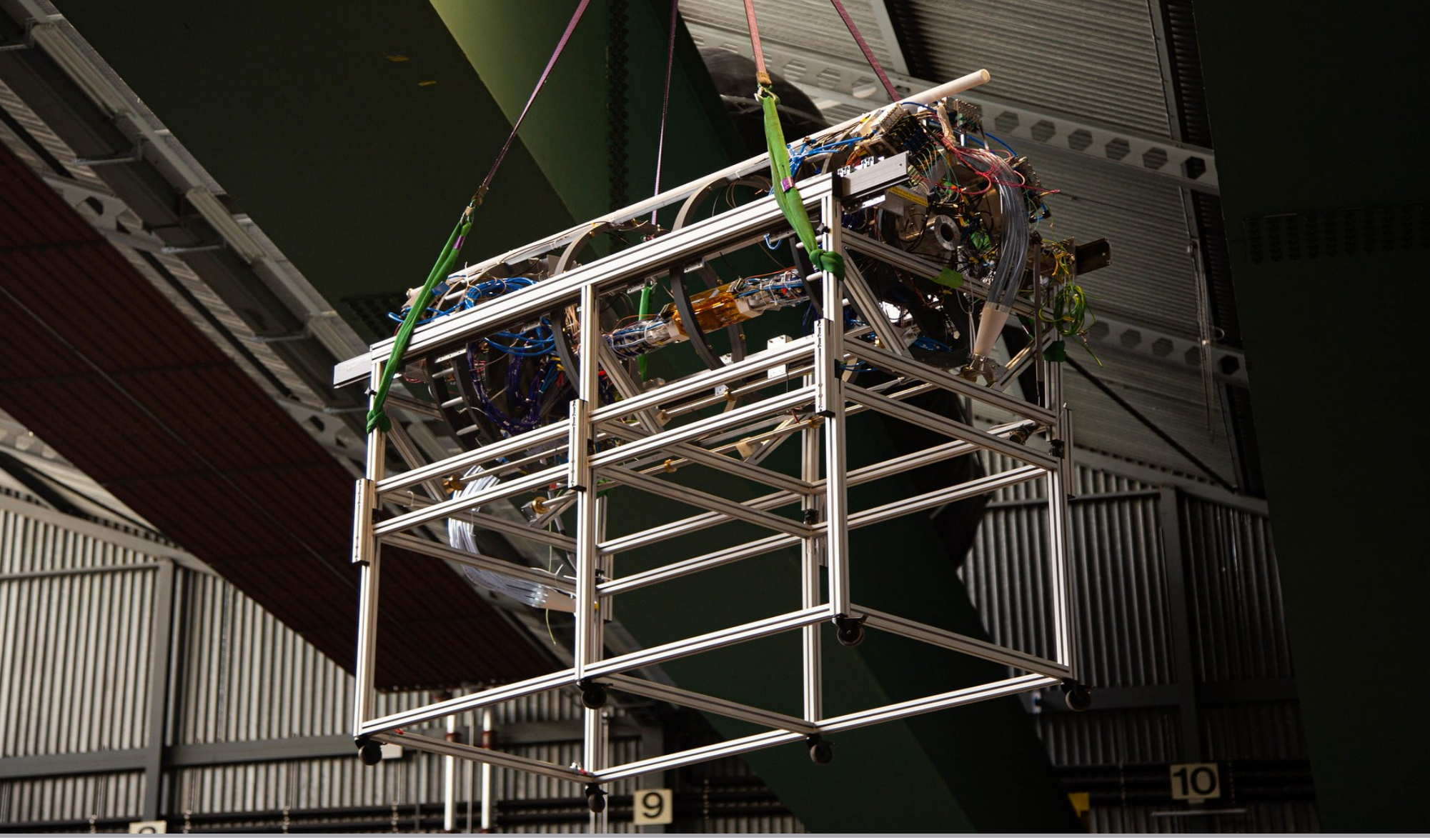


JG|U

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Status of Mu3e Phase I

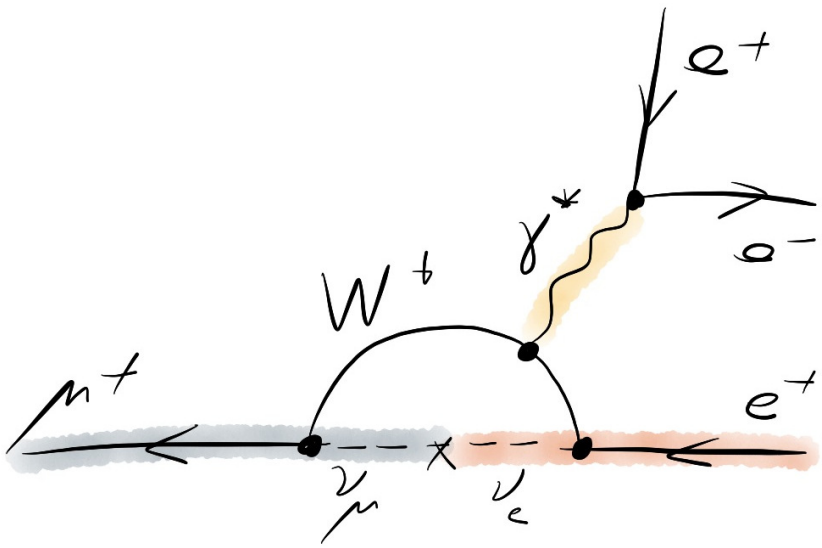
Martin Müller for the Mu3e Collaboration

NuFact 2023

Charged Lepton Flavour Violation (CLFV)

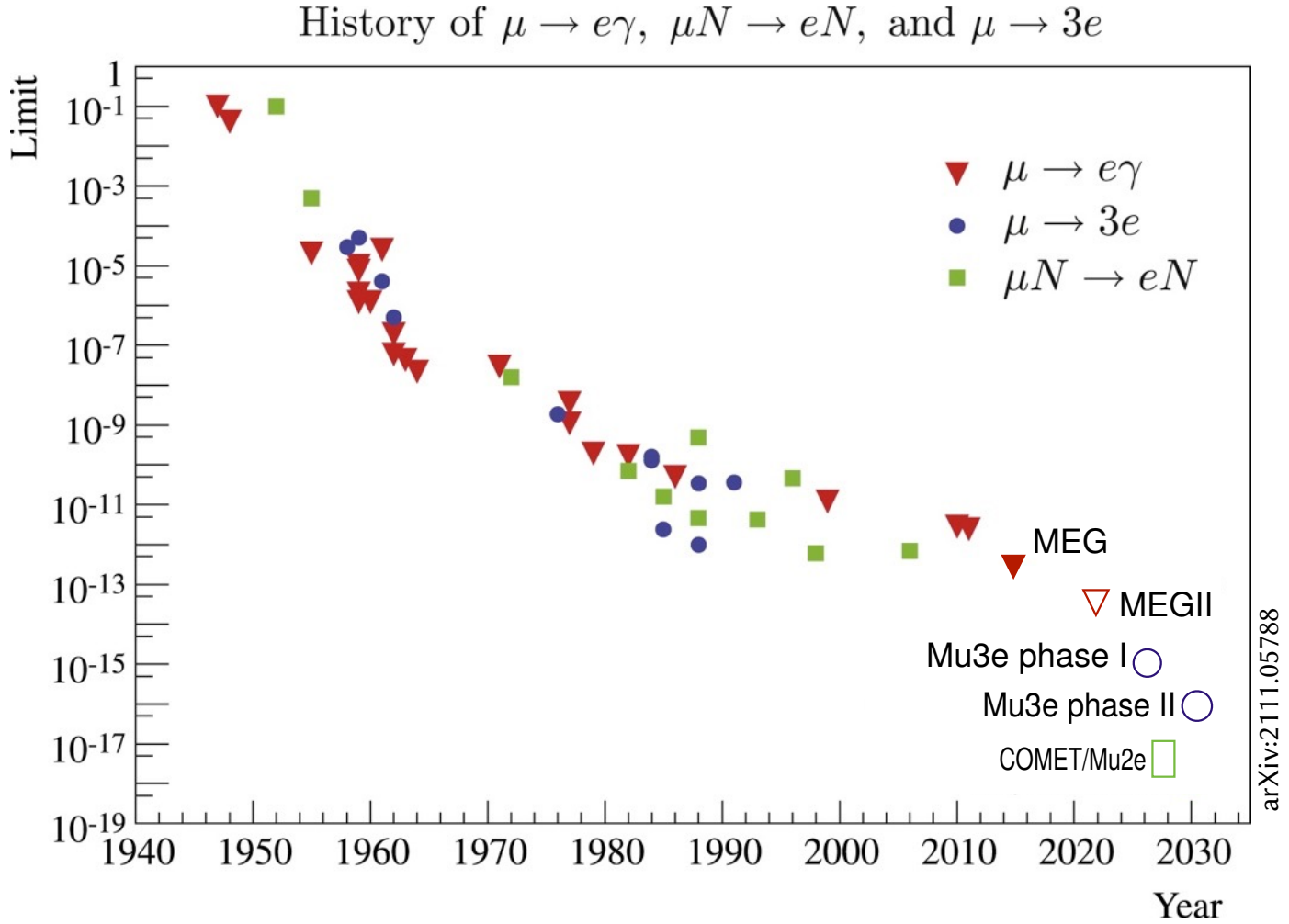
$\mu^+ \to e^+ e^- e^+$

- Mu3e will measure the BR of $\boldsymbol{\mu^+ \to e^+ e^- e^+}$ with a sensitivity goal of $2 \cdot 10^{-15}$ (Phase I) and 10^{-16} (Phase II).
- **Neutral** lepton flavour violation was observed with neutrino oscillations
- **Charged** lepton flavour violation (CLFV) is therefore also possible, but with a highly suppressed branching ratio



- BR < 10^{-54}
- $\to$ any observation of $\mu^+ \to e^+ e^- e^+$ would be a clear sign for new Physics
- many BSM physics models suggest the enhancement of CLFV

- 3 ”golden” Channels for CLFV searches in muon decays
- limit for $\mu^+ \to e^+ e^- e^+$ is at 10^{-12} and was measured in 1988 by the SINDRUM experiment



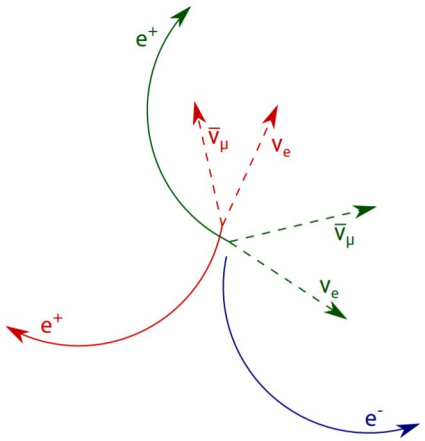
Internal conversion:

- $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu e^+ e^-$

- suppressed by good momentum reconstruction
- independent of rate

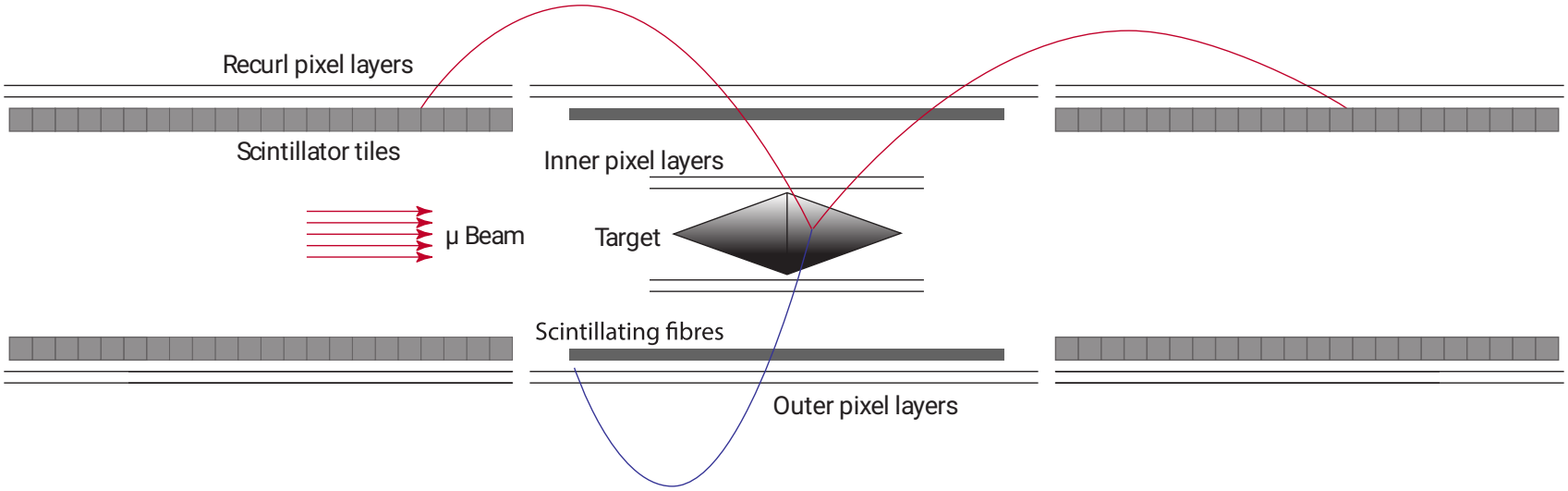
Accidentials:

- $2x(\mu^+ \to e^+ \nu_e \overline{\nu}_\mu)$ + scattering e^-

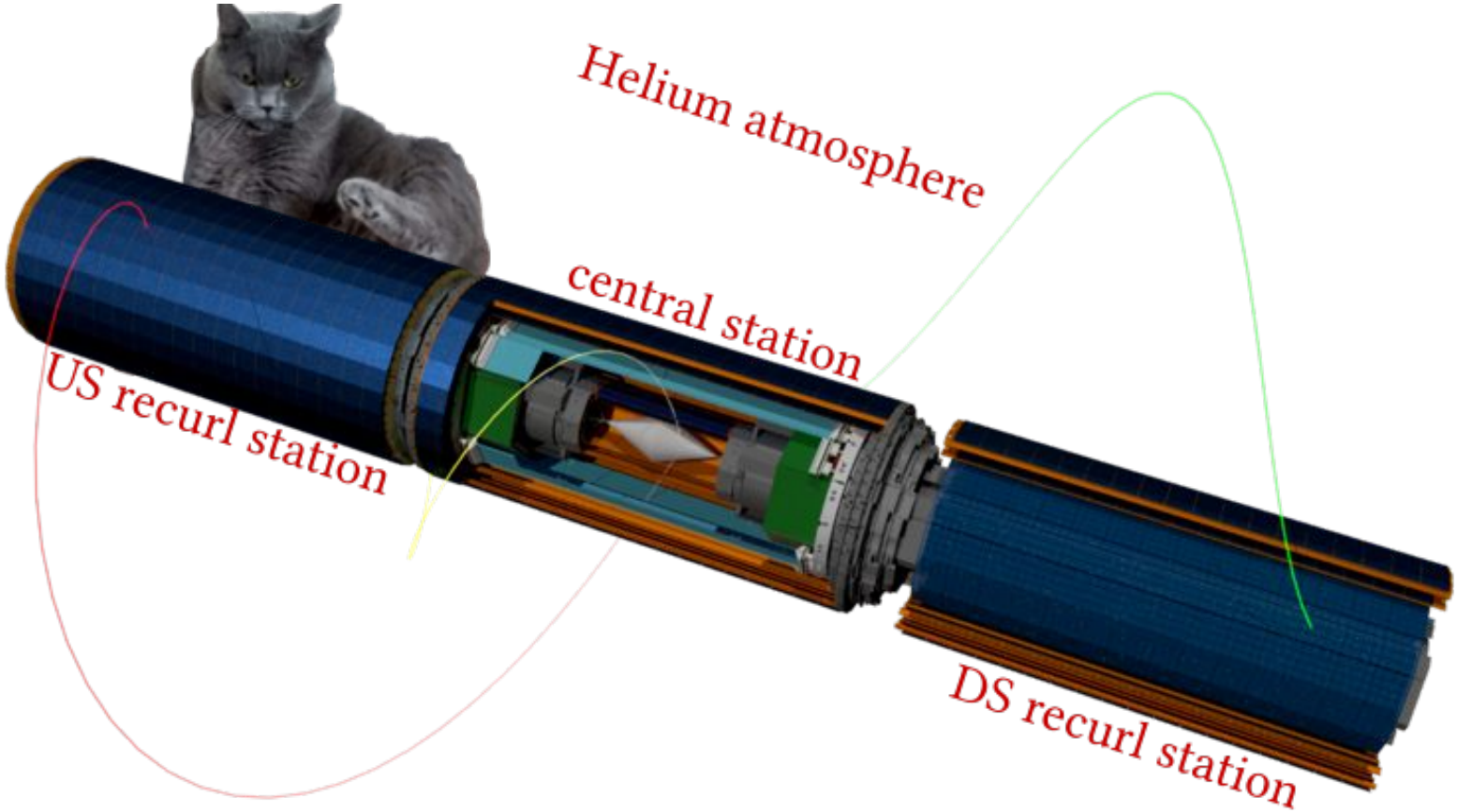


- Overlapping events
  $\to$ suppressed by time and vertex resolution
- relevant at higher rates ($\propto N^2$)

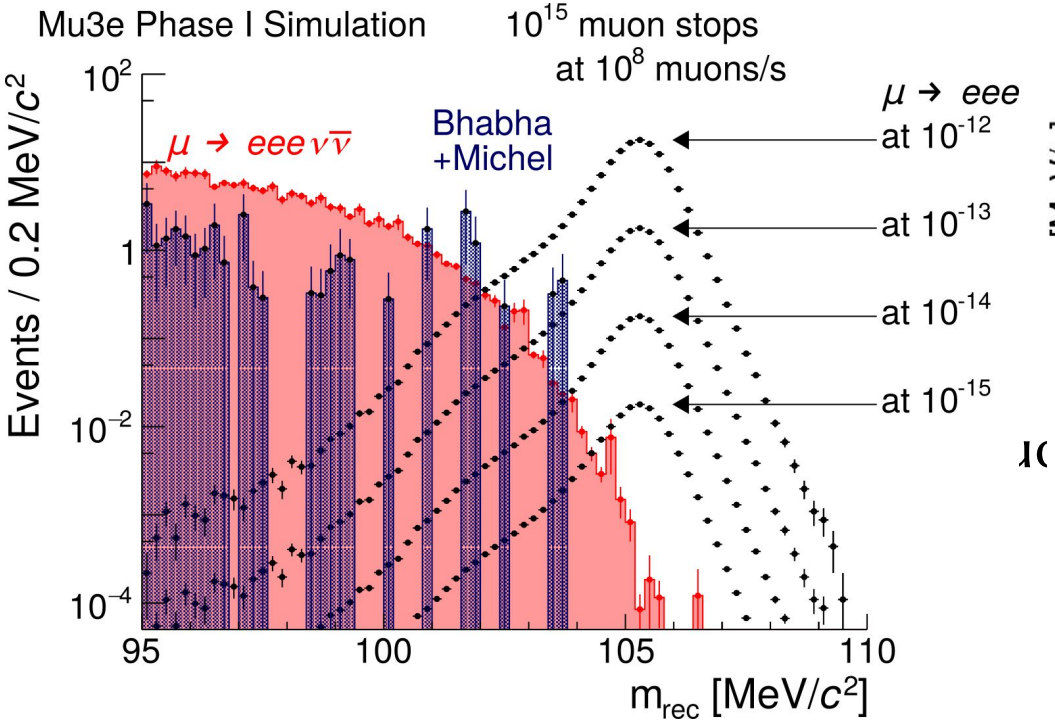
$\to$For **signal** events: $\sum \vec{p} = 0$, $\sum E = m_\mu$, $\Delta t = 0$, same vertex

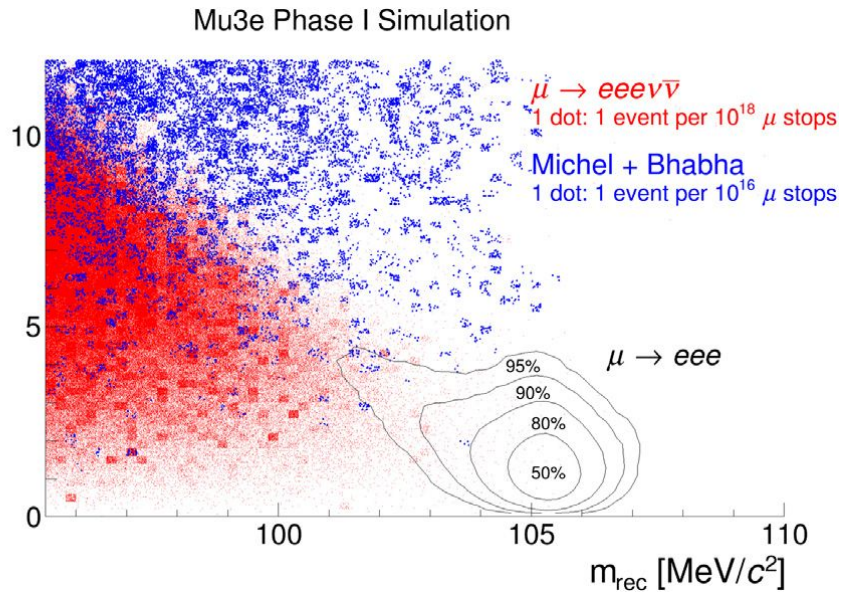


- 6 layers of pixel sensors ($t_\sigma < 15$ ns)
- 1 T magnetic field in beam direction
- scintillating fibres (t_σ =500 ps) & tiles (t_σ =70 ps) to increase timing precision
- 10^8 Muons/s decaying at rest in the target
- expected data rate of up to 100 GBit/s


Helium atmosphere
central station
US recurl station
DS recurl station

Mu3e
Sensitivity

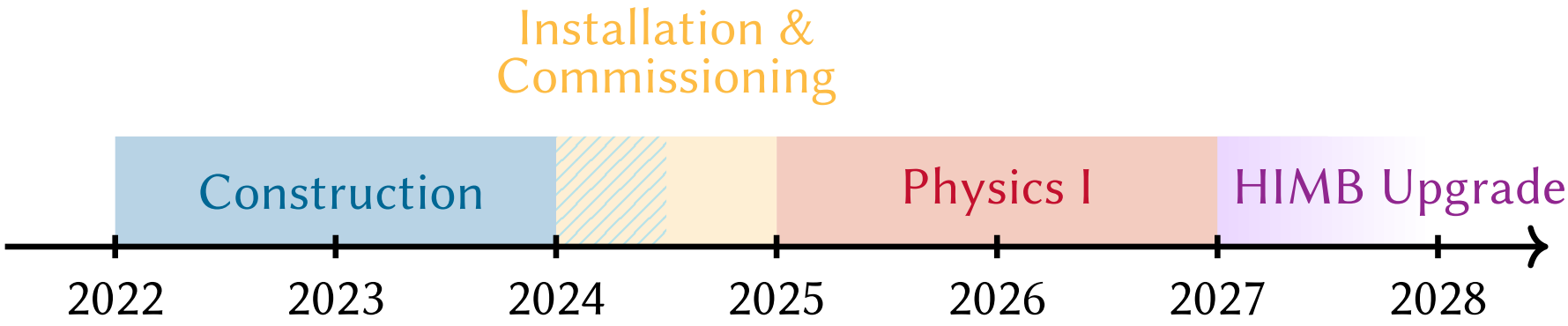




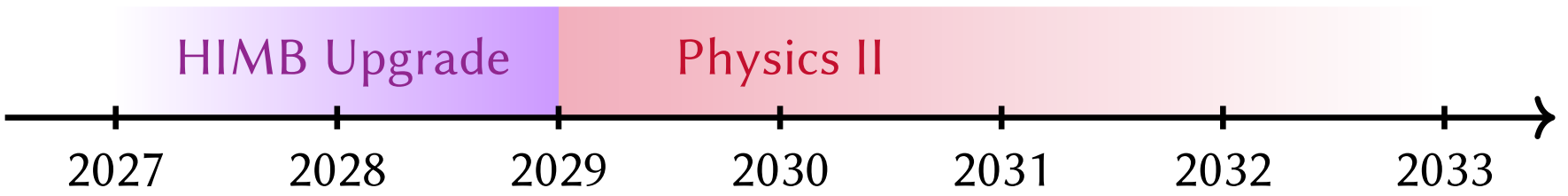
- Phase I simulations for 10^{15} muon stops
- Vertex resolution ~0.5 mm
- Momentum resolution < 1 MeV

Timeline

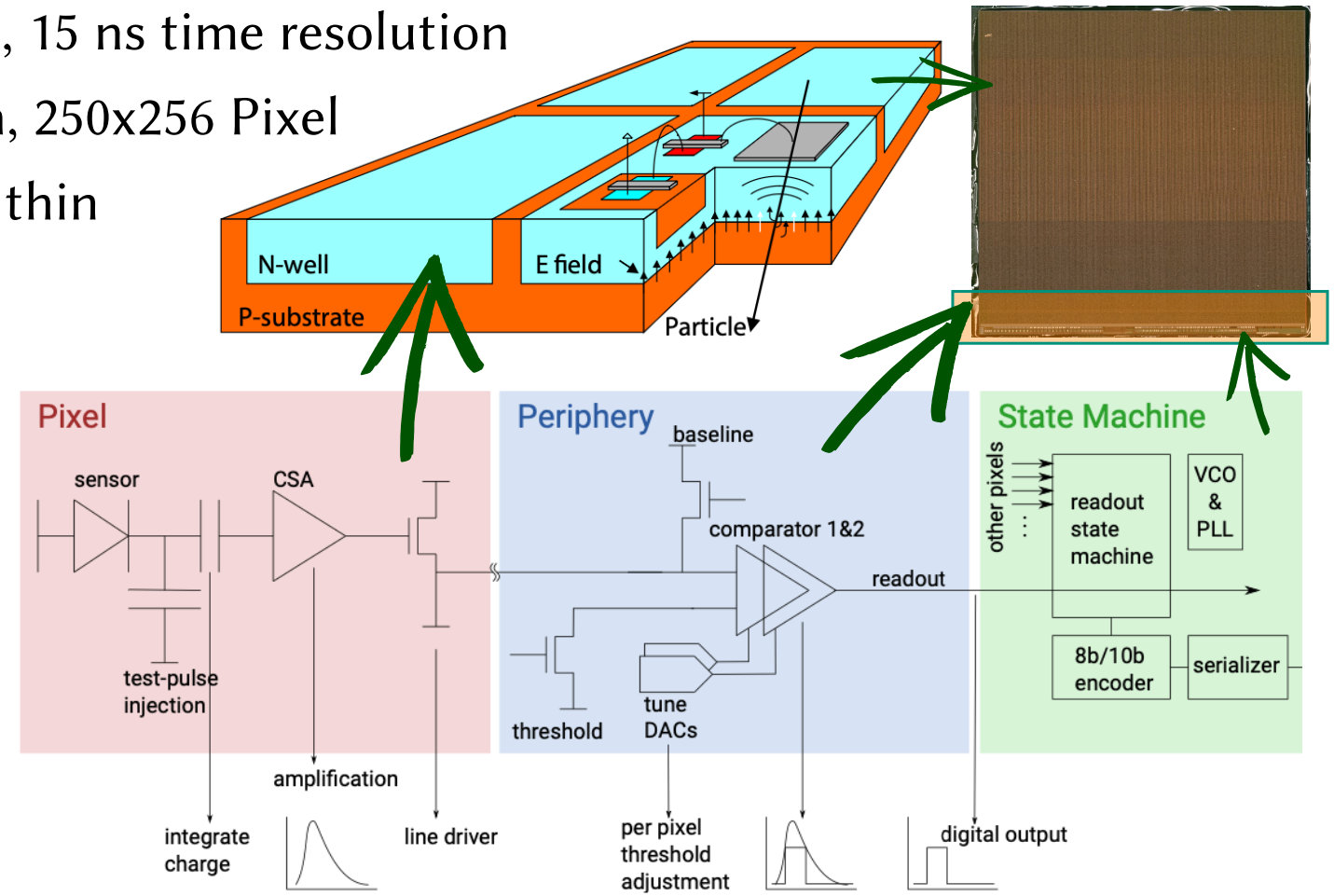
- Detector development for Phase I has finished, we are **now constructing detector modules**



- Upgrade of the Beamline to $10^9 \mu/s$ on target starting 2027
- Redesign of the Mu3e detector during beamline construction, Mu3e Phase II:



- Novel HV-MAPS pixel sensor (MUPIX), 10 years of R&D
- Fully digital 1.25 Gbit/s LVDS output, 15 ns time resolution
- 2x2 cm, 250x256 Pixel
- 70 μm thin
- amplification in each pixel cell
- individual threshold for each pixel



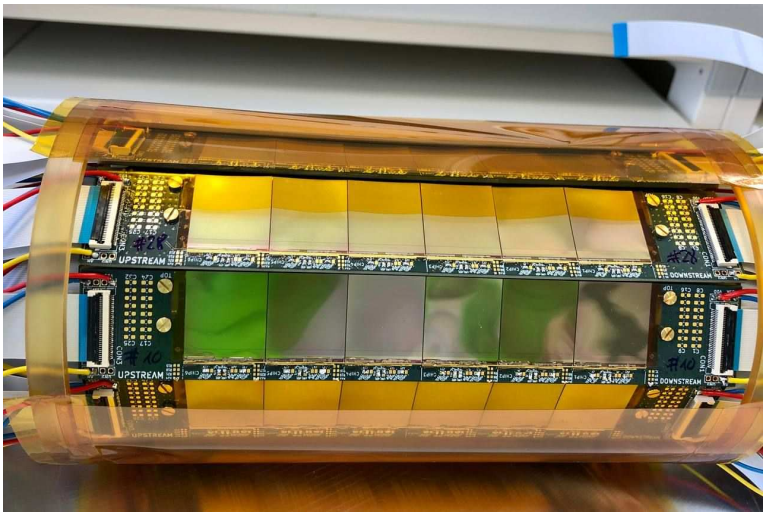
Subdetectors for Phase I

Mupix Pixel Sensor

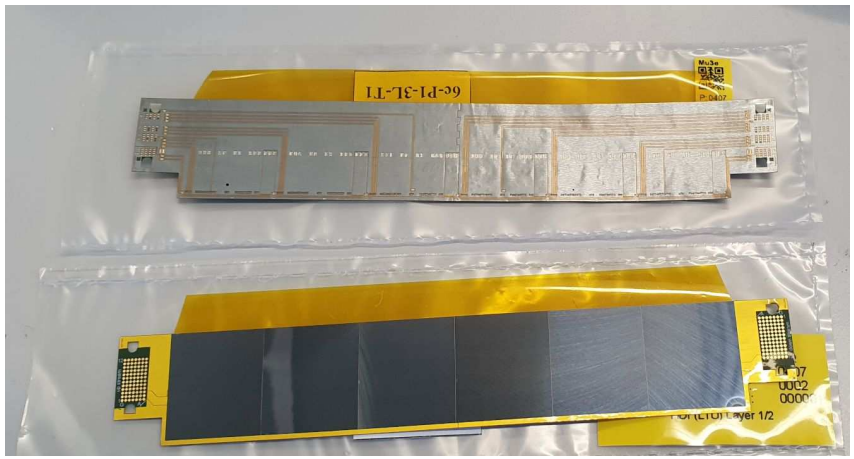
- 6 layers of thin ($\leq 70\ \mu m$) Mupix Pixel sensors (HV-MAPS)
- glued on kapton flexprints
- provides precise vertex and momentum reconstruction
- production of inner layer modules has started

- outer layer production will follow soon

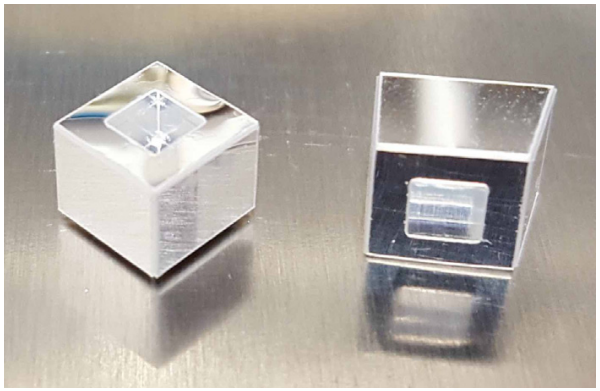
Prototype of the vertex detector with solid PCBs:



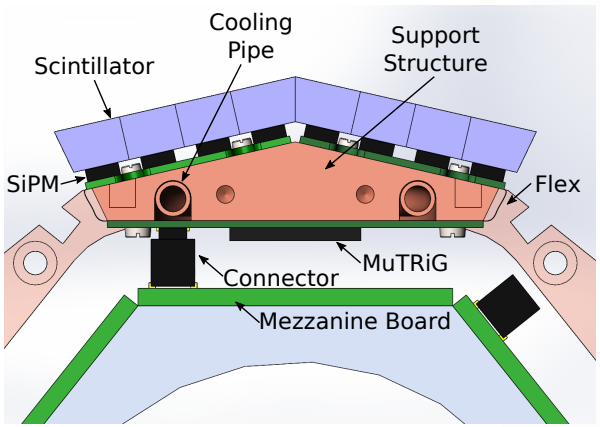
Final design with kapton flexprints:

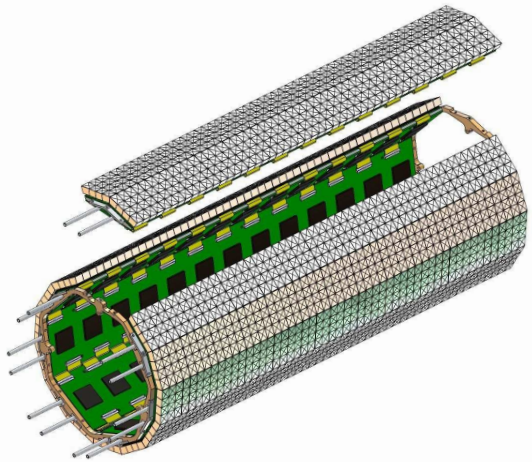


Subdetectors for Phase I
Scintillating Tiles

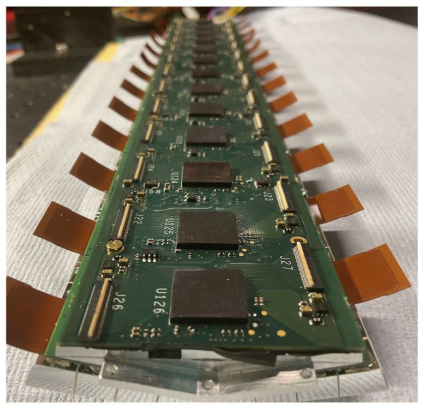


- 6272 $(0.5cm)^3$ Scintillator blocks
- coupled to SiPMs
- read out by custom ASIC (Mutrig)
- time resolution of $t_\sigma = 70$ ps

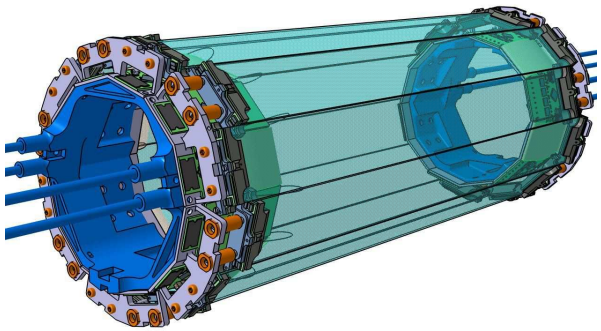




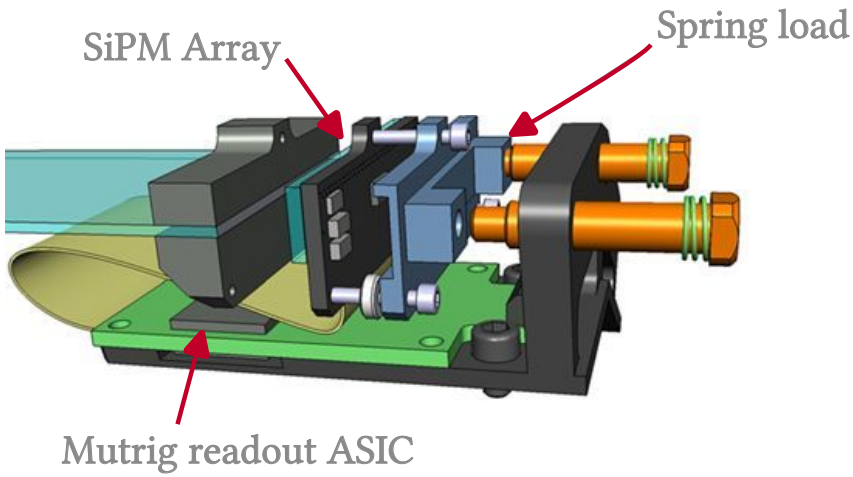
- innermost layer of recurl stations
- each tile wrapped in reflector foil to increase light yield and for optical channel isolation



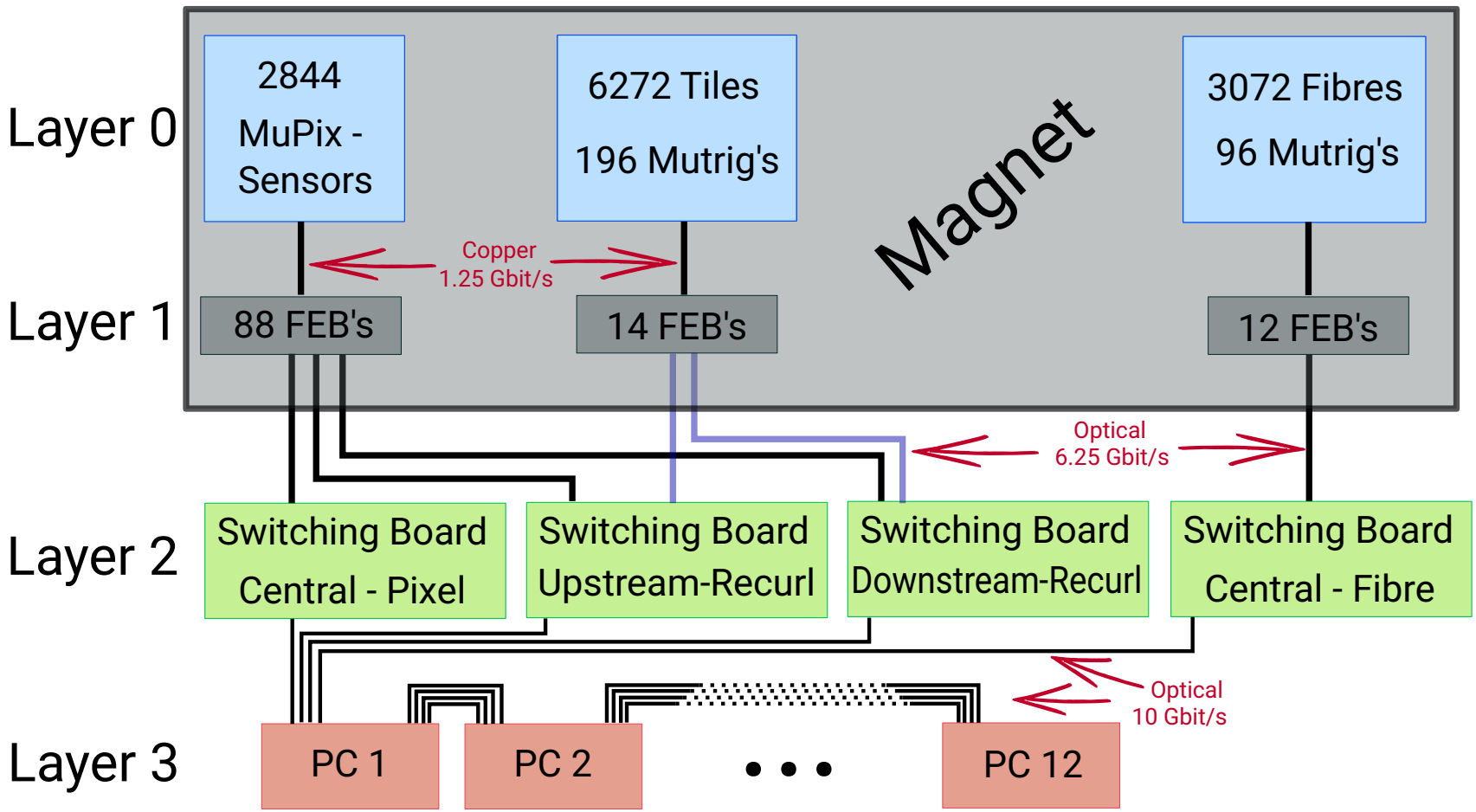
Subdetectors for Phase I
Scintillating Fibres

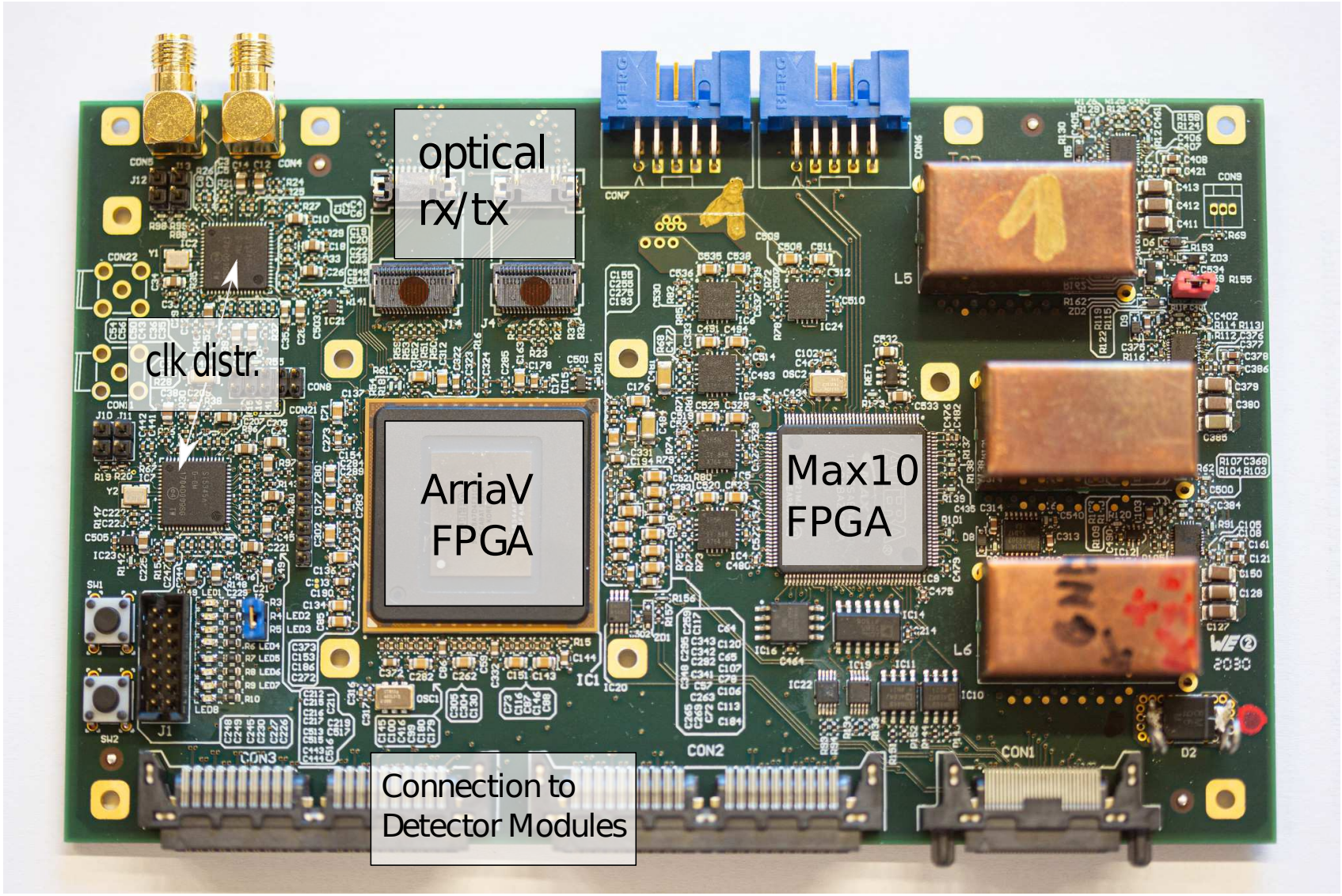


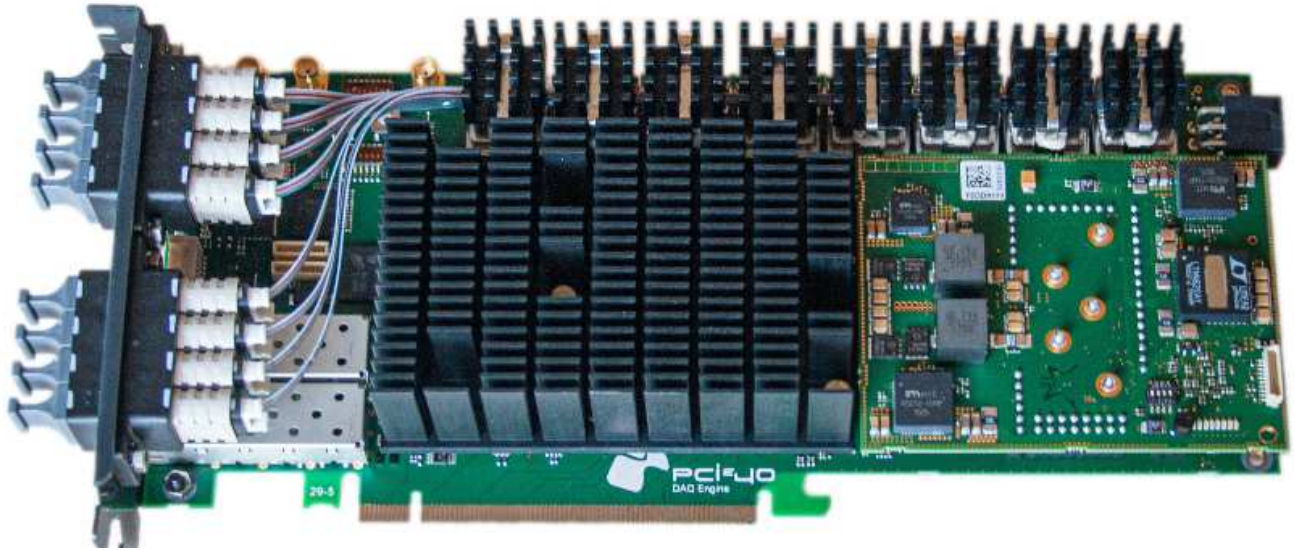
- three layer ribbons of scintillating fibres, diameter of 250 μm
- coupled to SiPM arrays
- read out by custom ASIC (Mutrig)
- time resolution of $t_\sigma = 500$ ps



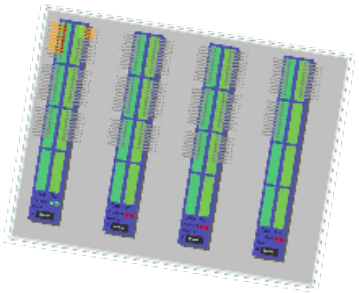
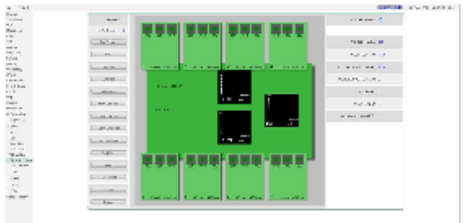
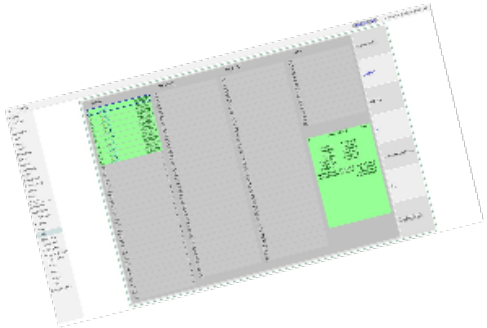
- suppression of accidental + Bhabha scattering background
- charge identification by ToF for particles with low z-momentum (recurling in central station)


Layer 0
Layer 1
Layer 2
Layer 3
2844
MuPix -
Sensors
6272 Tiles
196 Mutrig's
3072 Fibres
96 Mutrig's
Magnet
Copper
1.25 Gbit/s
88 FEB's
14 FEB's
12 FEB's
Optical
6.25 Gbit/s
Switching Board
Central - Pixel
Switching Board
Upstream-Recurl
Switching Board
Downstream-Recurl
Switching Board
Central - Fibre
Optical
10 Gbit/s
PC 1
PC 2
PC 12

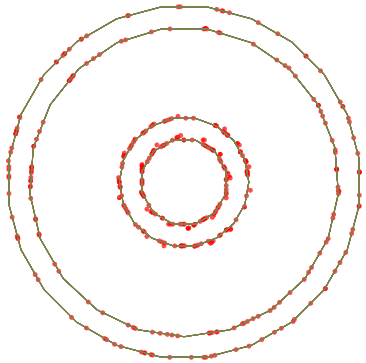

optical
rx/tx
clk distr.
ArriaV
FPGA
Max10
FPGA
Connection to
Detector Modules

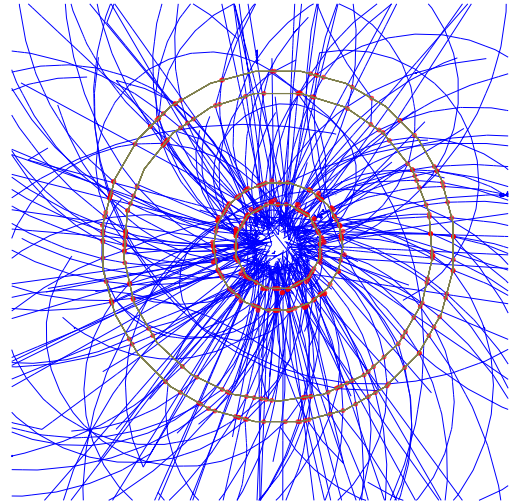


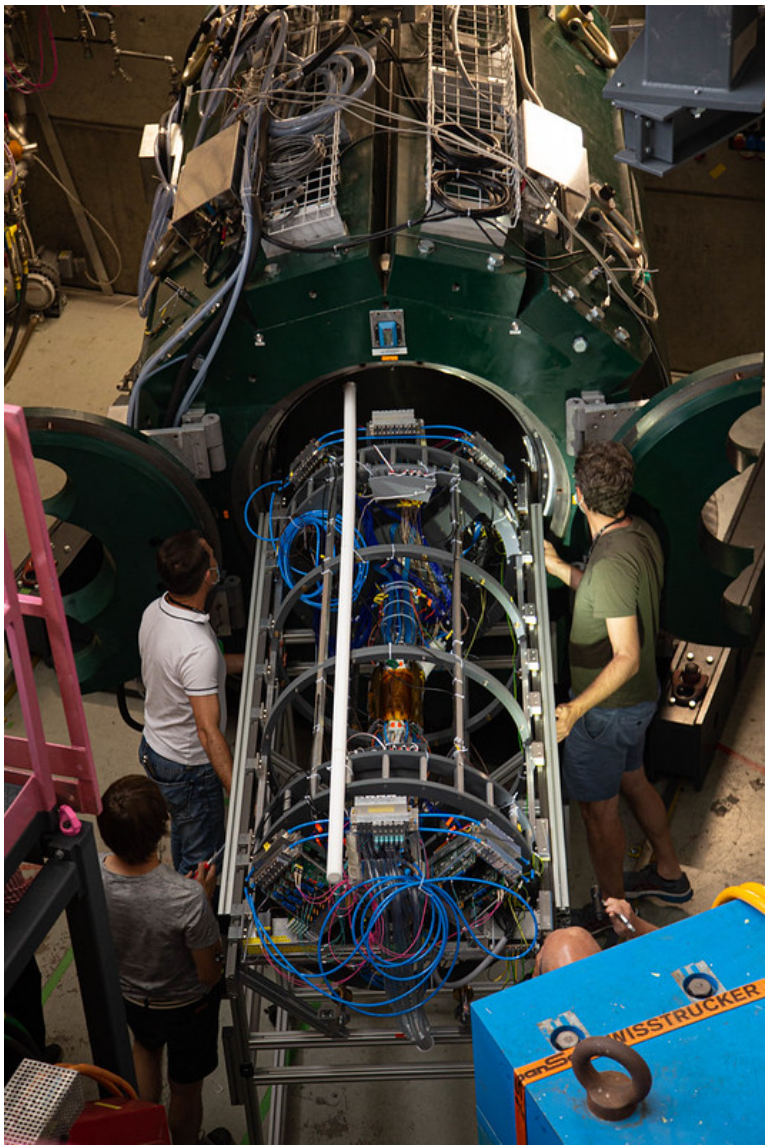
- PCie40 Board for the LHCb / Alice collaboration
- 48 optical in- and outputs
- Control and configuration link to the DAQ software (MIDAS)

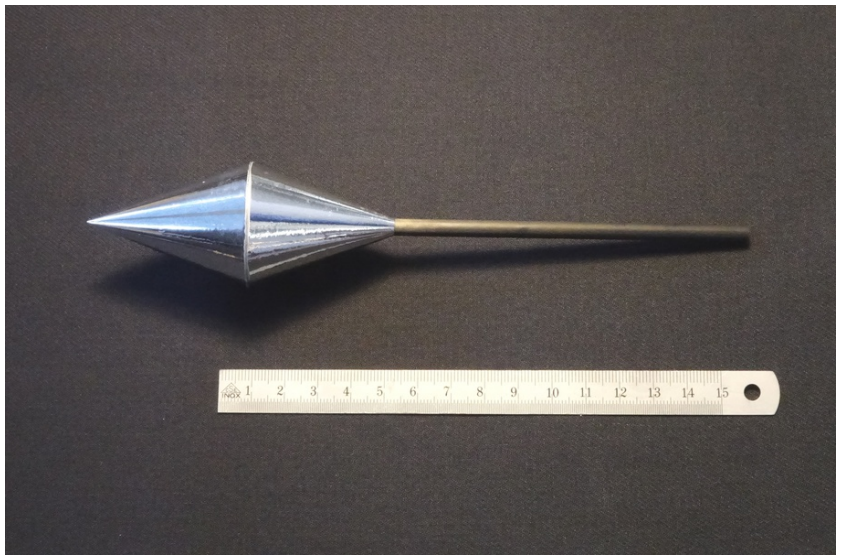
- Farm of 12 servers using only commercial hardware
- GPUs to run the track reconstruction
- Fully streaming, no trigger involved before the GPU
- Event selection based on tracker data from the inner station
- Further offline analysis of the full data of the selected time slices



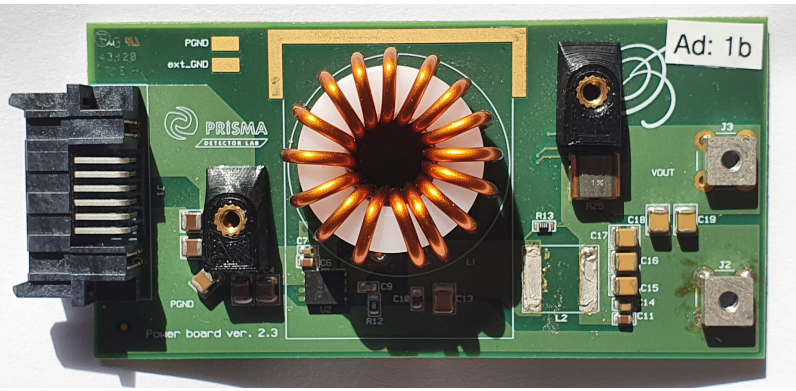




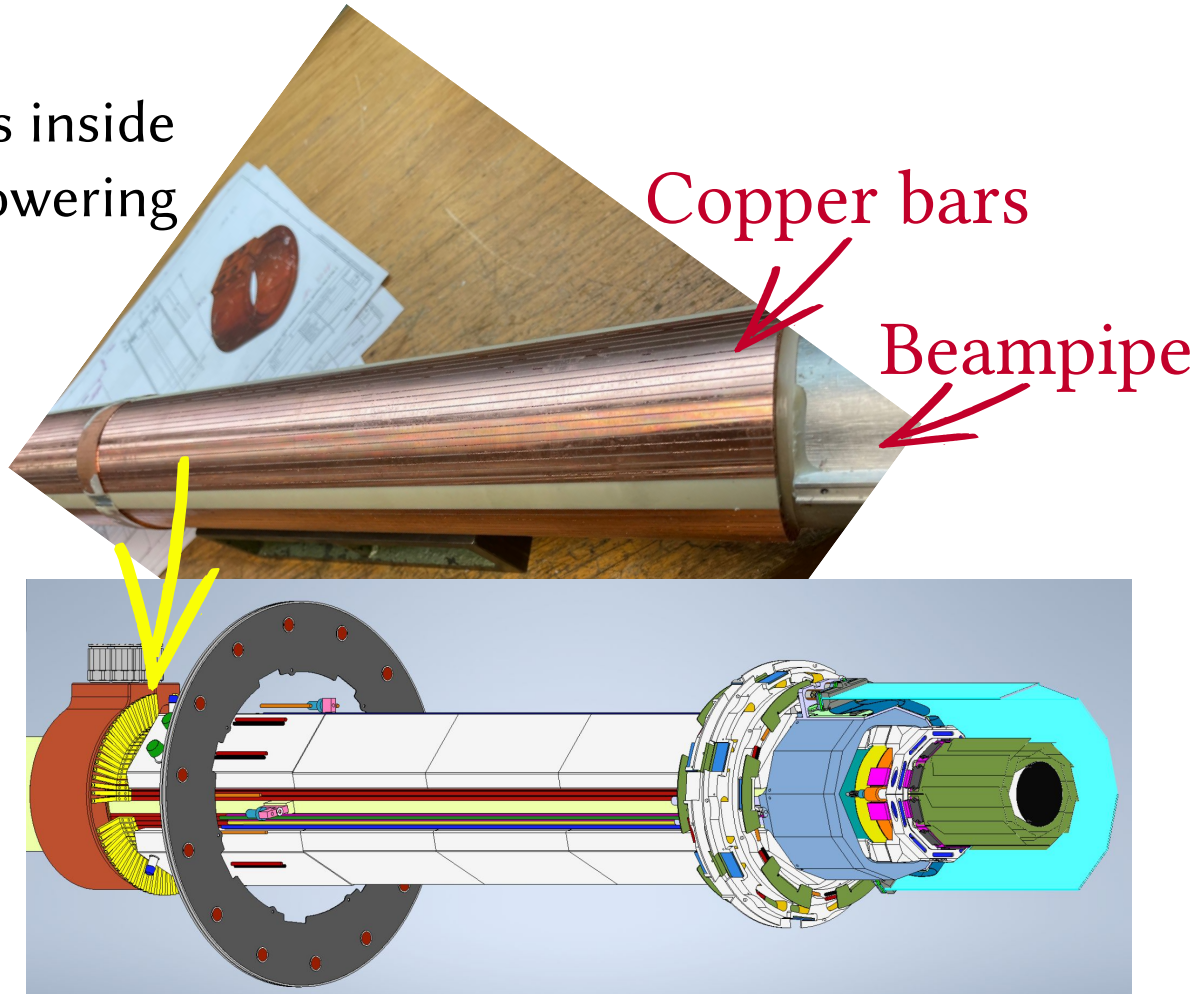
- Superconducting Mu3e solenoid Magnet was delivered in July 2020
- fully operational
- homogeneous, stable and precise magnetic field of 1 T is needed for exact momentum reconstruction
- 70 μm thin double cone Mylar target is produced and ready

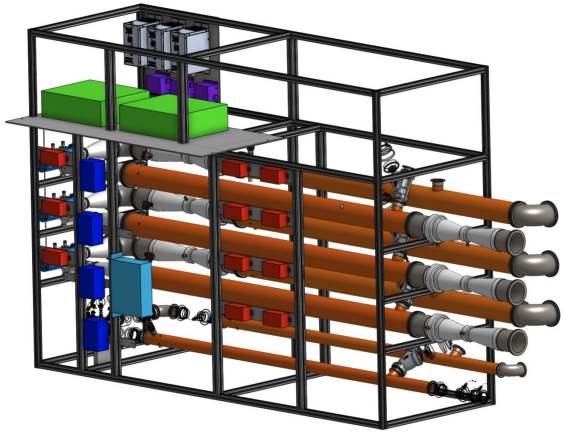


- 12 kW of Power is needed for the detector
- very tight space for cables and pipes in detector area
- Custom DC-DC converters inside the magnet for detector powering
- 20 A @ 2.1 V
  x 126 DC-DC converter

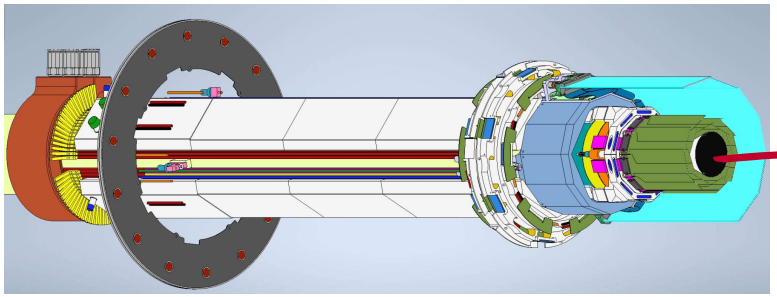


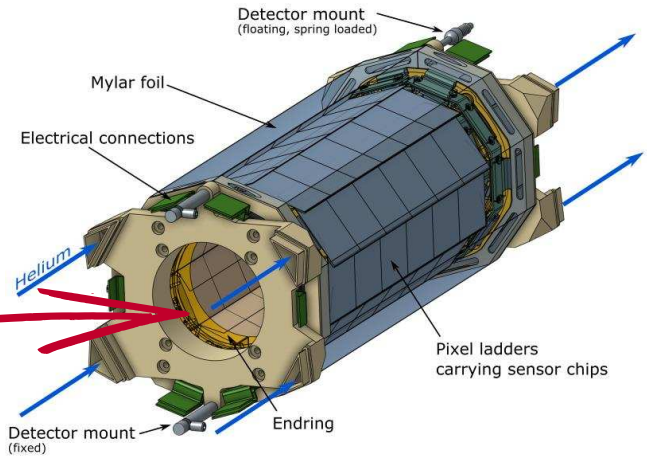
- Copper bars glued to the beampipe for space efficient power delivery



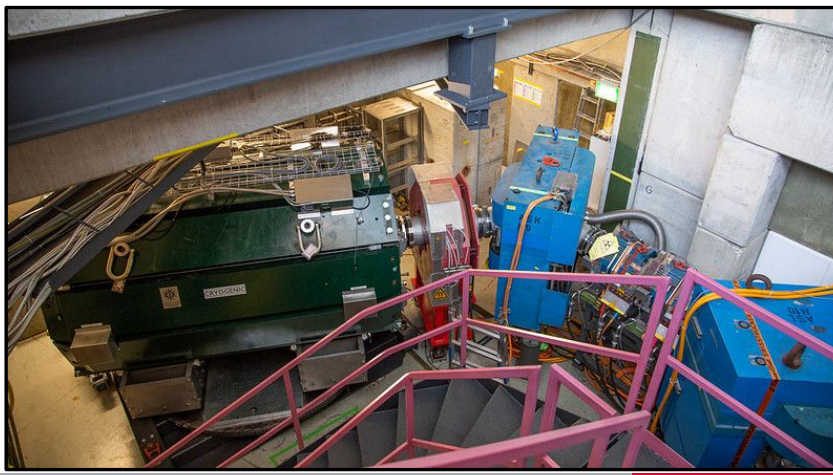


- construction of a 50 g/s helium cooling plant
- smaller version exists and was tested
- Liquid cooling for timing detectors



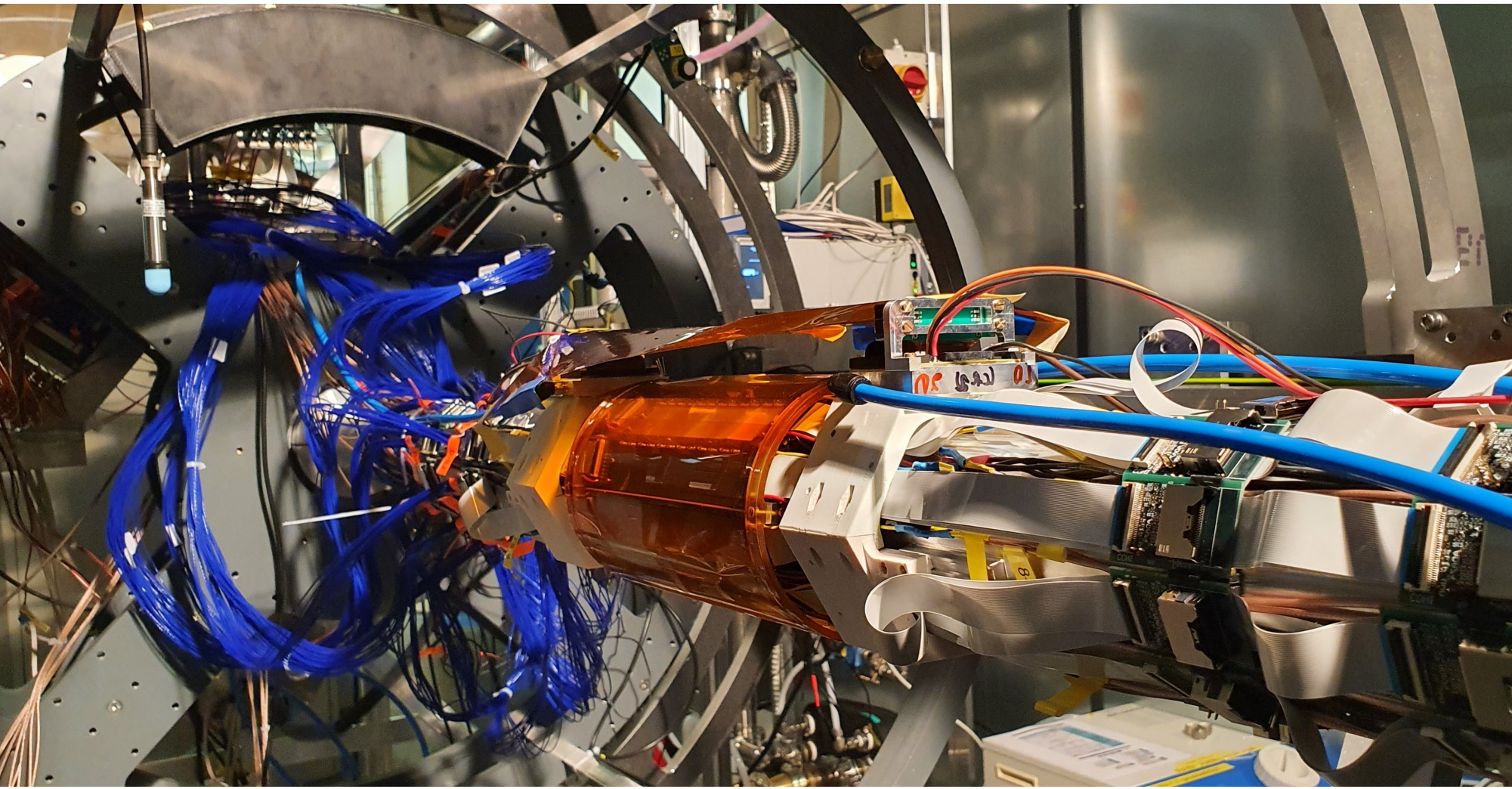


- beamline optimizations are ongoing, $7.46 \cdot 10^7\ \mu/s$ on target was achieved 2022 (goal is 10^8)



Cosmic Run 2022

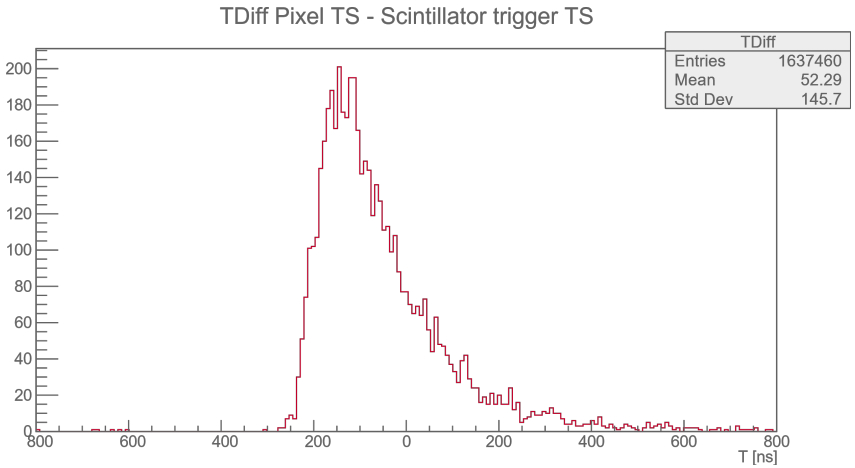
Detector Prototype

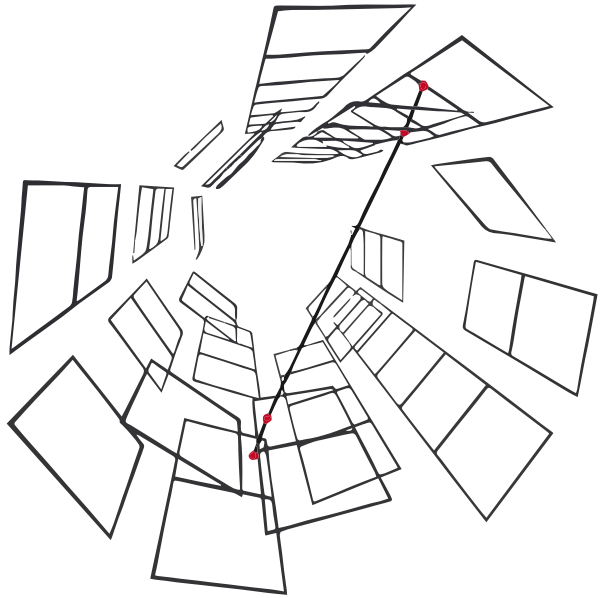


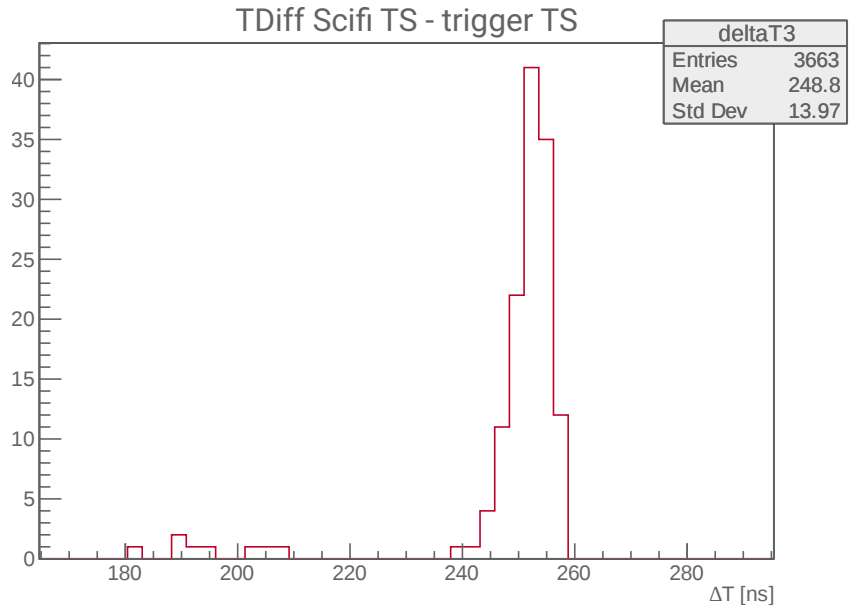
- Prototype: 2 Inner Pixel layers, 1 Scifi Module
- development of tuning procedures, QC tests, cooling tests, ...

Cosmic Run 2022

System checks



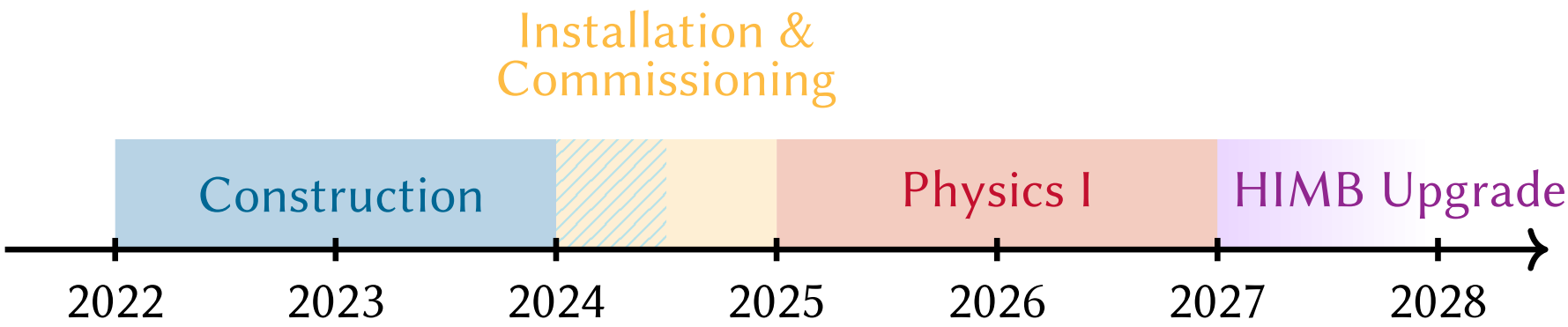




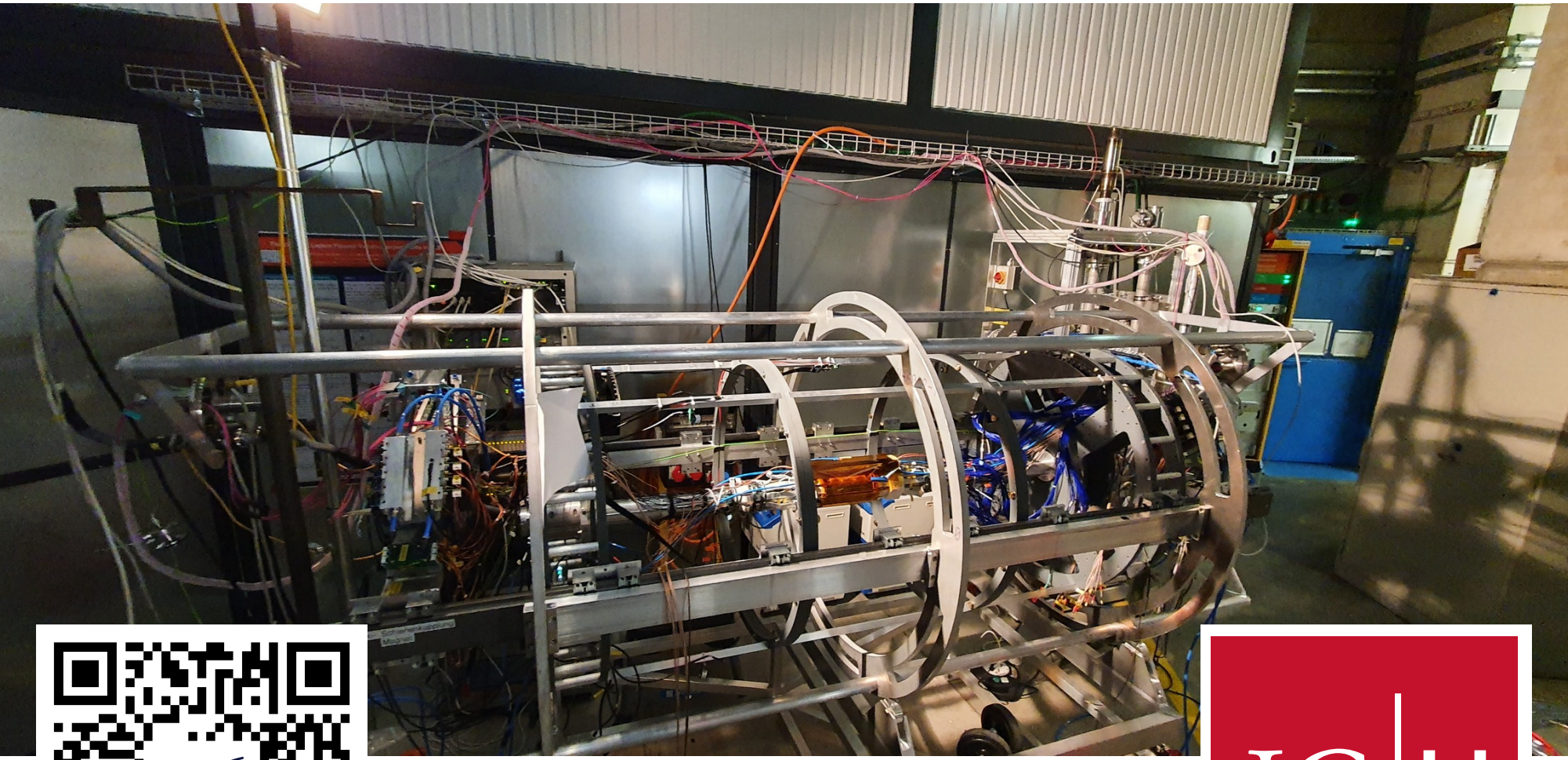
- tested synchronization of detector subsystems
- first track reconstruction in the Mu3e barrel with real data
- exercised building and operating various systems

Summary
and Outlook

- Detector development for Phase I has finished, we are **now constructing detector modules**
- A novel HV-maps pixel sensor and a fast SiPM readout ASIC were developed
- Streaming DAQ ready for 100 Gbit/s
- Infrastructure, powering and cooling systems are under construction
- 1 T Magnet delivered and operational
- Detector installation will start early next year



DFG Deutsche Forschungsgemeinschaft



Questions ?