The Mu3e Detector

Richard Plackett on behalf of the Mu3e Collaboration

1st - 4th September 20206

PSD 14

Queen Mary University of London

The Mu3e Project

The Mu3e Experiment is looking for the decay of a Muon to Three Electrons which is a Charged Lepton Favour Violating decay

Detector currently under construction on the PiE5 beamline at the Paul Scherer Institute (PSI)

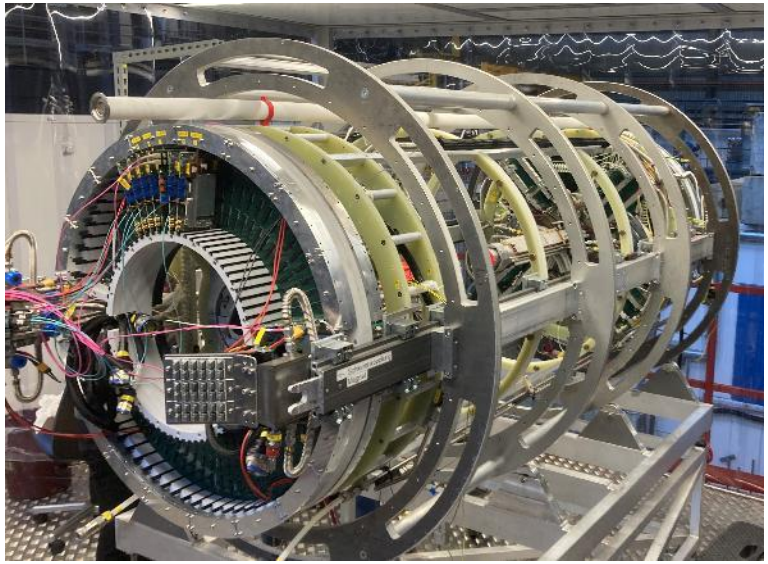
80 people from 12 institutes

Switzerland: PSI, U. Zurich, U. Geneva, ETH

Germany: Heidlberg, Mainz, KIT

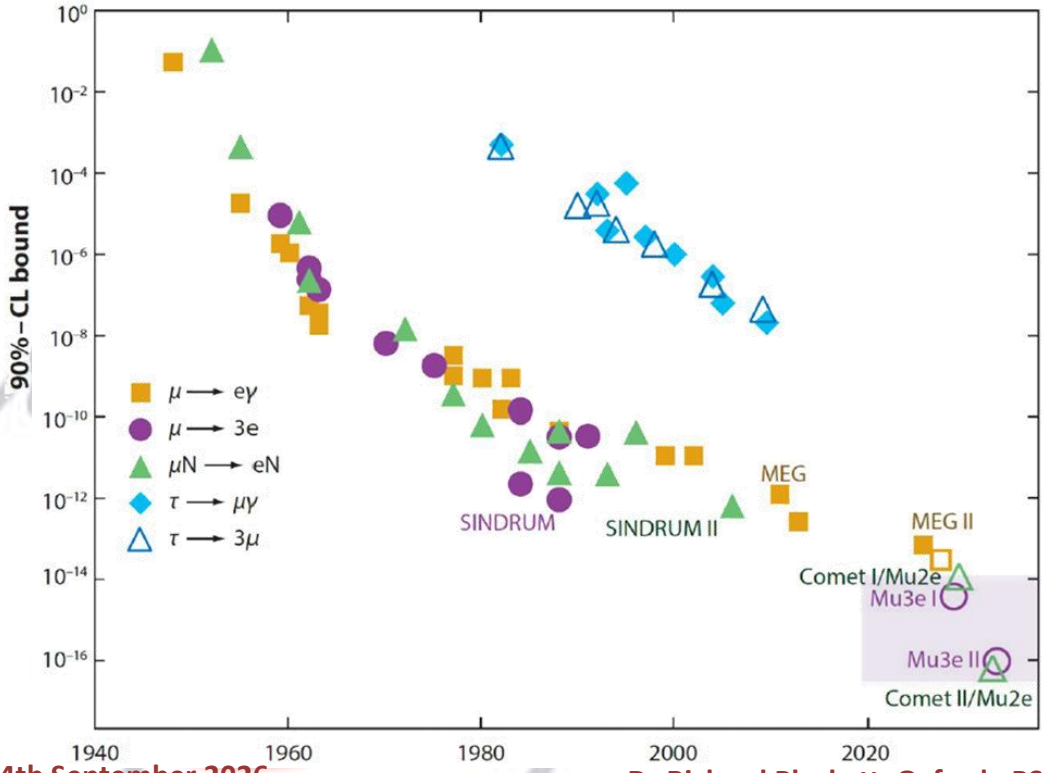
UK: Bristol, Liverpool, Oxford, UCL

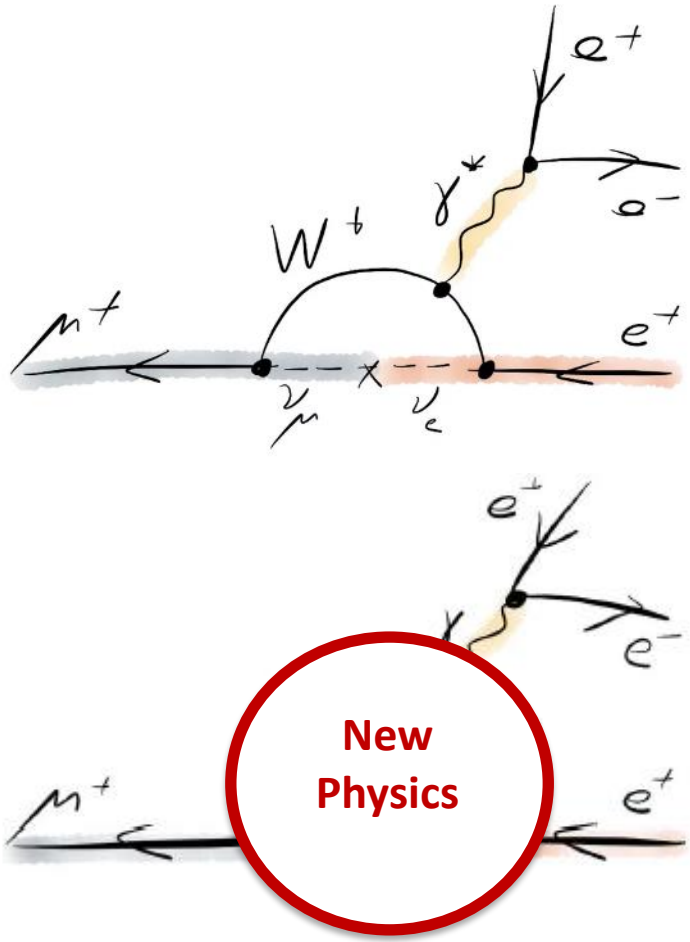
A high rate, high precision, ultra low-mass detector



Physics Motivation

- μ+ to e+ e- e+ is heavily supressed in SM
- **10^{-54}** branching ratio
- Current record is 10^{-12} (SINDRUM 1986)
- Mu3e sensitivity target is:
- **10^{-16}** Mu3e Phase1 & **10^{-17}** Mu3e Phase II
- A very clean channel to look for New Physics



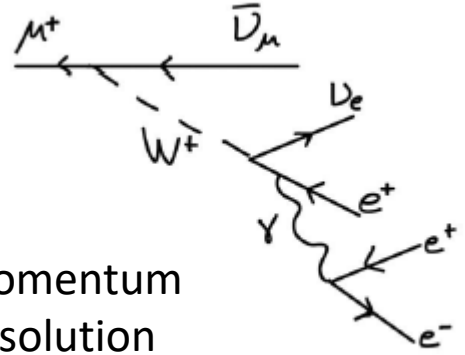


Backgrounds

When ‘signal’ is at 10^{-54} then ‘background’ is what we will actually measure

Radiative Muon Decay

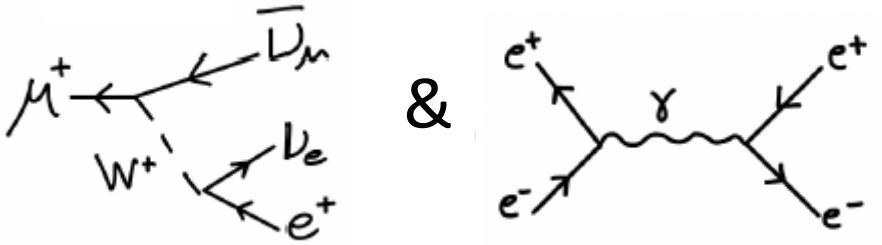
μ -> 3e + 2ν Br ~10^{-5}



Momentum Resolution

Accidental Background

Michel Decay & Bahbah Scattering Br ~0.99



Precise Vertexing and Timing

Outer Pixel System

μ -> 3e Max e- momentum ½ Muon Mass ~ 53 Mev/c

Low mass, low multiple scattering, monolithic pixels

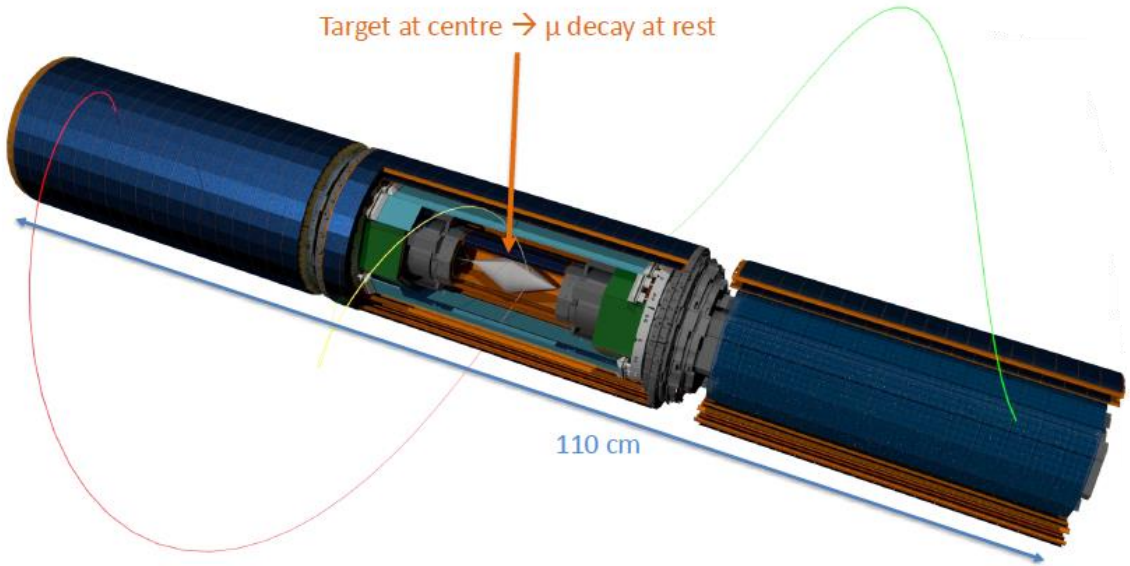
Vertex System

Low mass, low multiple scattering, monolithic pixels
25 um resolution

Scintillator Timing Systems

Scintillating Fibres 250ps
Scintillating Tiles 80 ps
High time precision on tracks

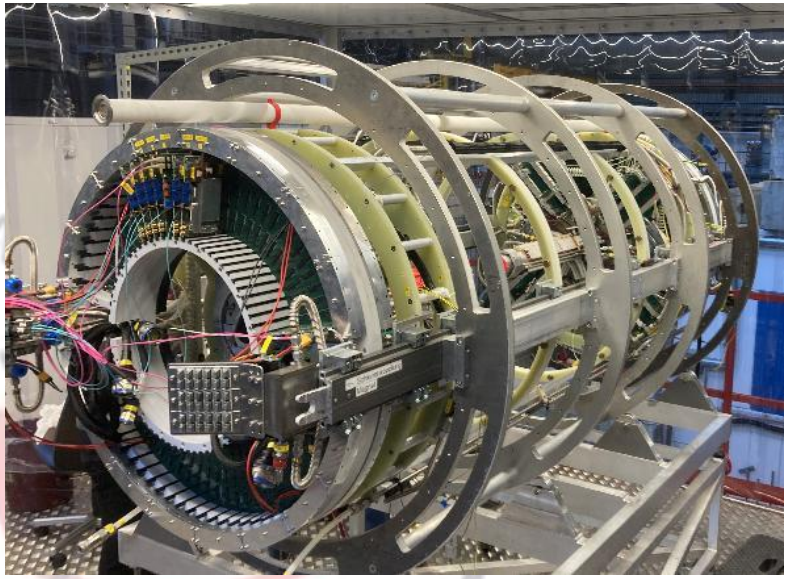
Detector Design

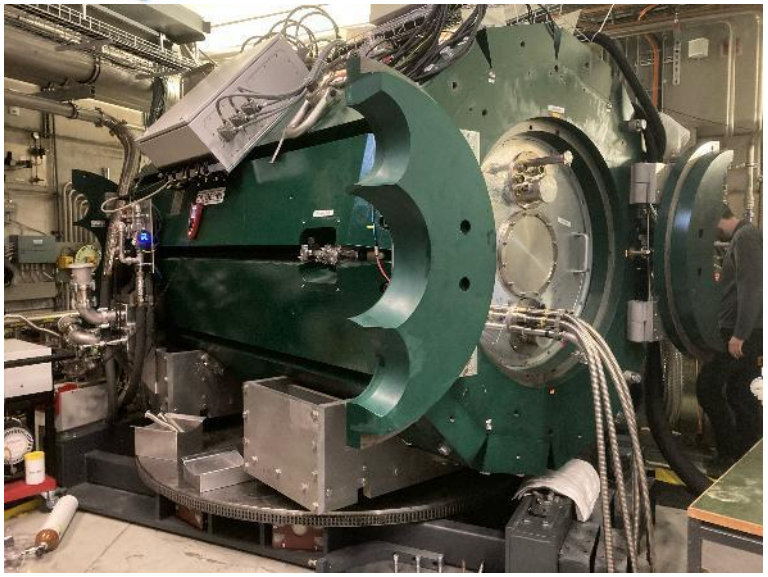


Mu3e is a low mass barrel tracker to designed to reconstruct the three electron tracks

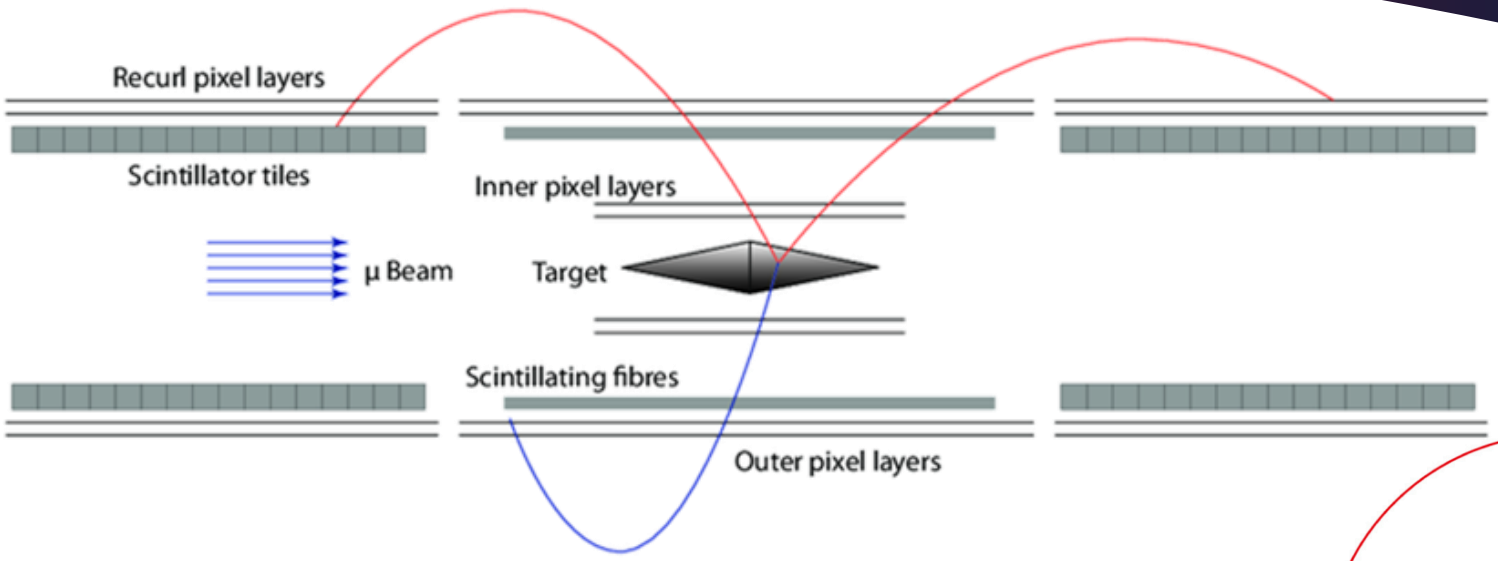
1T solenoid magnet

10^8 μ+ decays per second

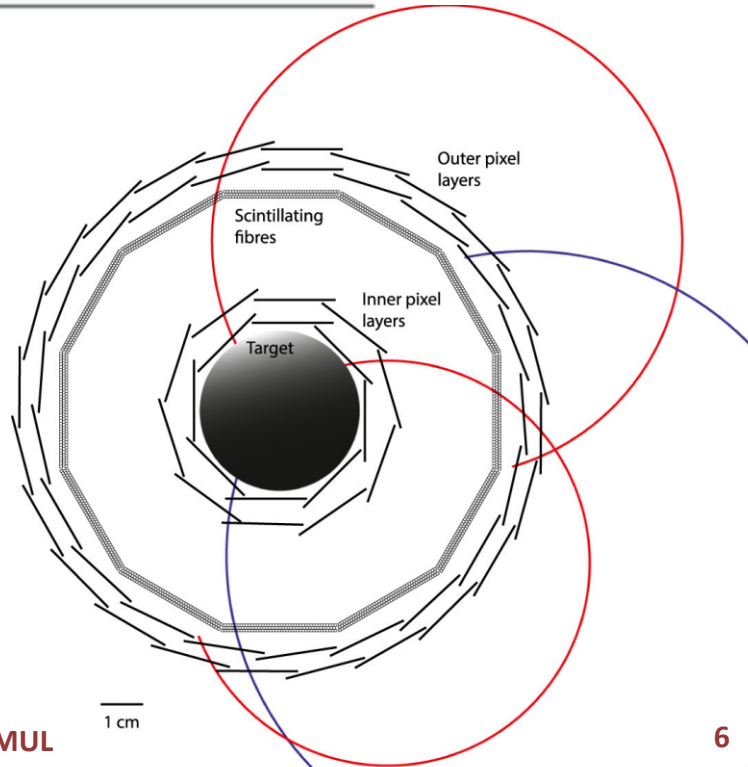




Detector Design



- Positive muons come to rest on the mylar target and decay 10^8 Hz (spreading out the muon decay positions)
- Vertex pixel detector system reconstructions the decay point
- Scintillating Fiber and Scintillating Tiles systems provide ~100 ps track timing
- Outer Pixel stations (and the magnet) provide a momentum measurement
- Pixel systems are multiple scattering dominated

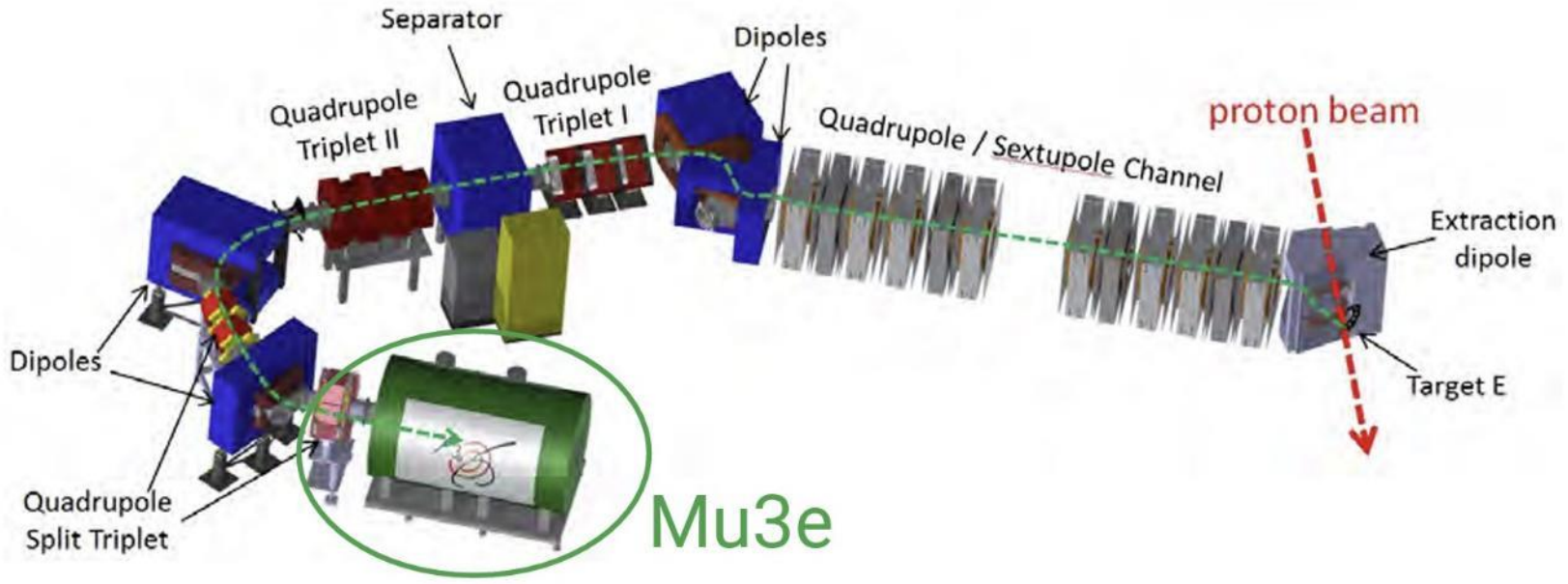


πE5 Beamline

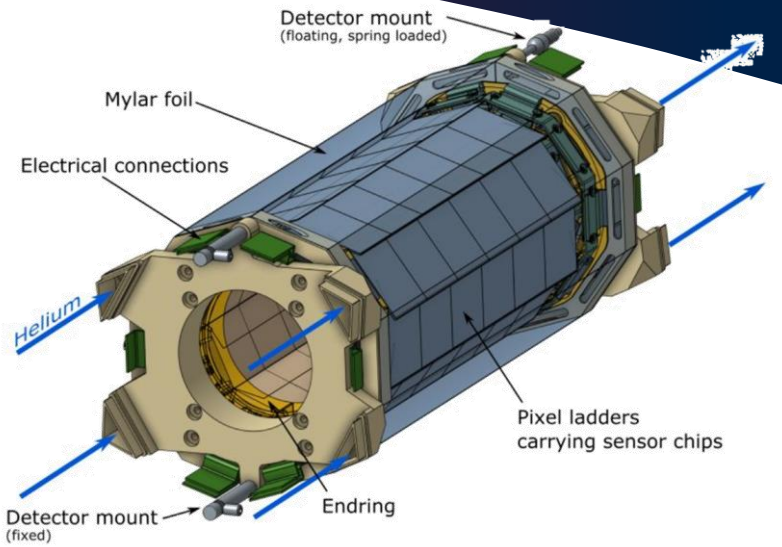
- The πE5 beam line is a low energy (10-120 MeV/c) pion and muon beam line part of the High Intensity Proton Accelerator Complex at PSI

Mu3e shares the beamline with other Experiments

- **MEG / MEG II:** Currently running MEGII uses πE5 for high-intensity muon beams to search for rare muon decays (μ → eγ).
- **Mu3e:** Shares the high intensity muon beam to look for the lepton-flavour violating decay μ → 3e.
- **PIONEER:** Next-generation experiment planned to utilize πE5's high-intensity pion stopping capabilities to measure rare pion branching ratios and test lepton flavour universality

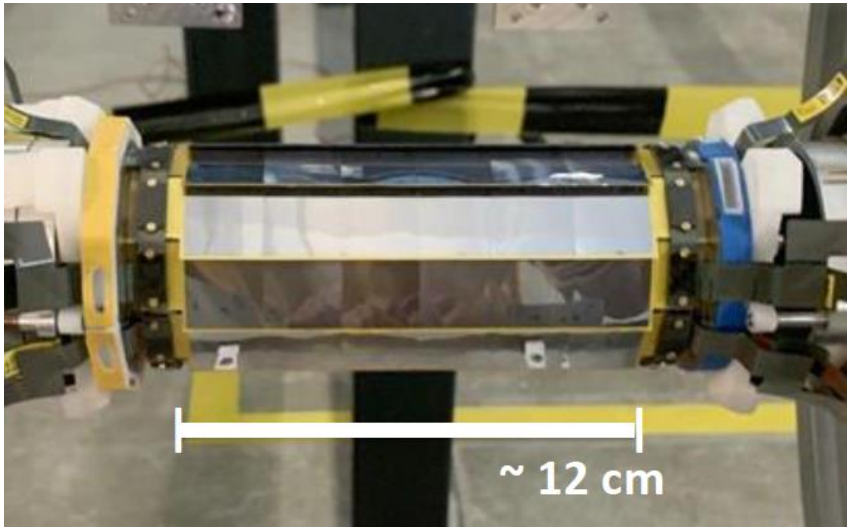


Vertex Sub-Detector

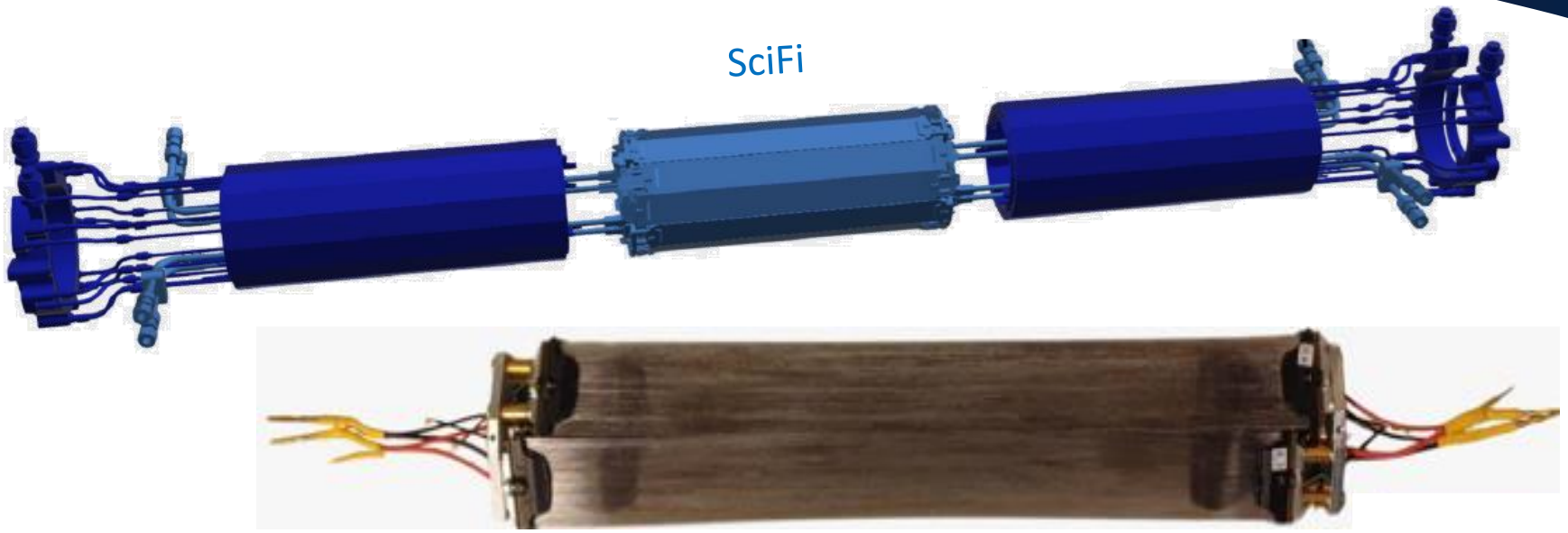


Required for vertex separation of accidental backgrounds

- 108 Mupix11 sensors
- 6 chip ladders as sub-unit
- 2 layers – eight and ten ladders for L1 and L2
- 23um resolution
- 0.1% Xo radiation length
- Gaseous helium cooling



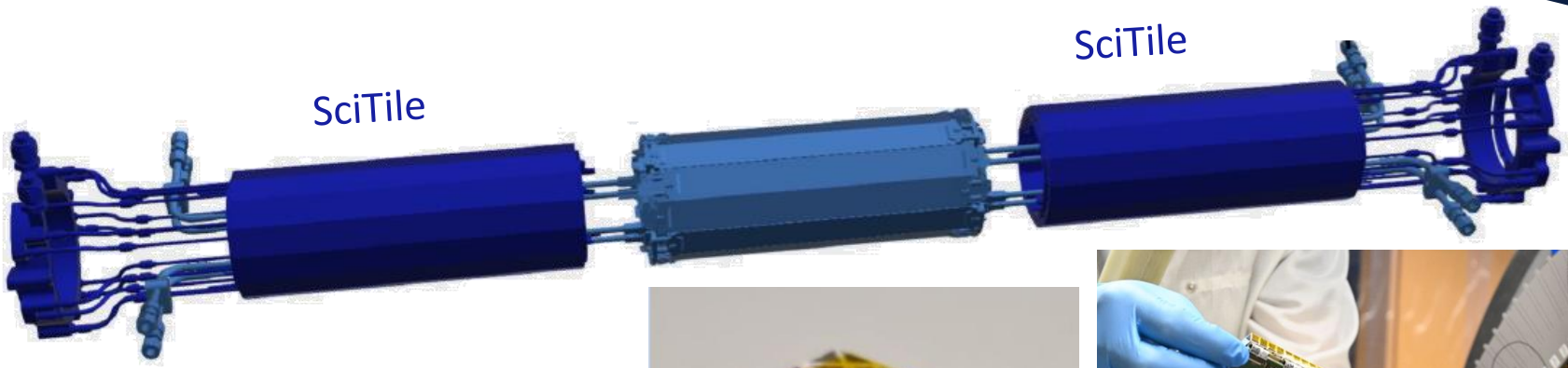
SciFi Sub-Detector

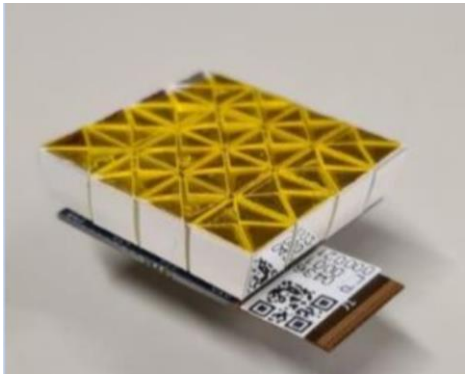


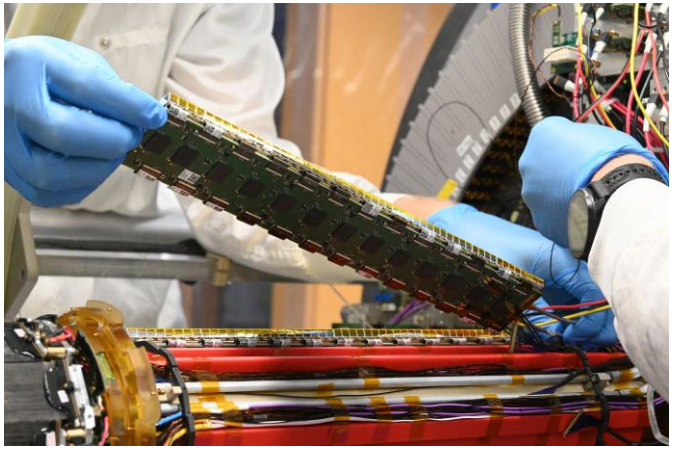
Timing System required for ‘Accidental Background’ discrimination

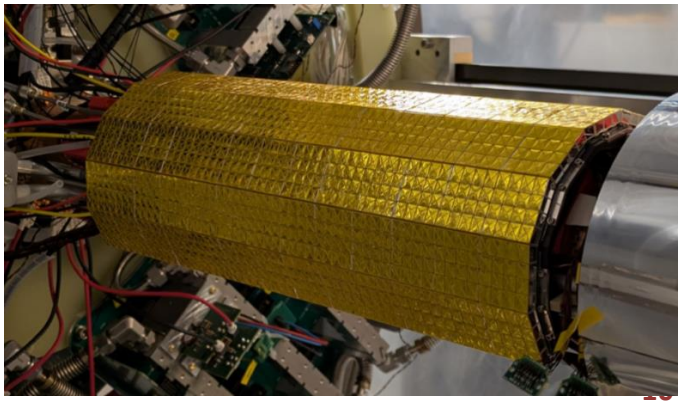
- SciFi is mounted in the central station between Vertex and Outer Pixels
- Scintillating fibres (Kuraray SCSF-78) giving 250 ps timing resolution
- 12 ribbons arranged in 6 modules
- Double ended readout by 128 channel SIPM array (Hamamatsu S13552) coupled to custom MuTrig timing ASIC.
- 1MHz per channel readout
- 0.2% Xo radiation length in acceptance
- Silicon oil liquid cooling of SIPMs for low dark noise

SciTile Sub-Detector









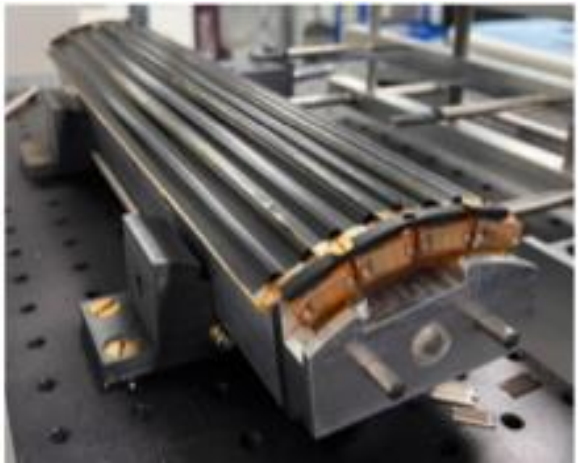
Timing System required for 'Accidental Background' discrimination

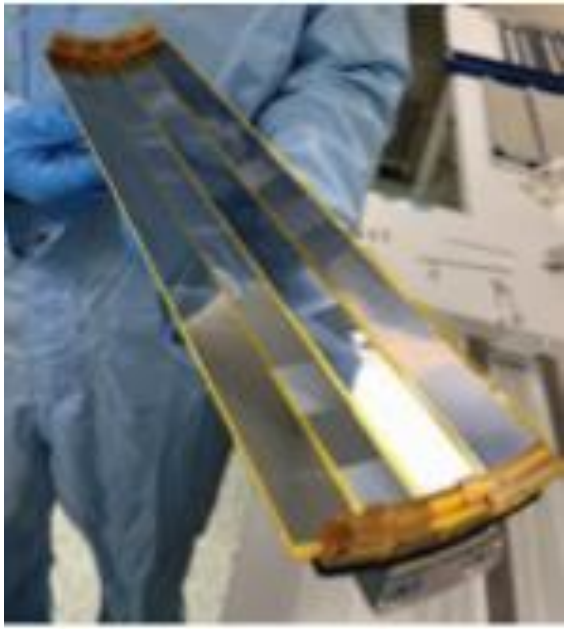
- Scintillating Tile detectors Mounted in Recurl stations around the beampipe
- ~80 ps Timing resolution
- Array of 5mm square tiles of plastic scintillator each individually wrapped and read by an single channel SIPM (Hamamatsu S13360-3050VE)
- ~2900 tiles/station ~5800 tile/SiPM channels for the two stations
- Also uses the MuTrig readout ASIC

Outer Pixel Sub-Detector

Needed for Radiative Muon Decay Background

- Reconstruct electron momentum to exclude neutrino production
- Needed for momentum resolution: $\sigma\ (p)$ ~200 keV/c
- Mupix11 pixel sensors, 25 µm carbon fibre supports
- ~ 1m^2 silicon, 2736 MuPix11
- 2 layers in three outer stations
- Helium cooling of each station ~900W

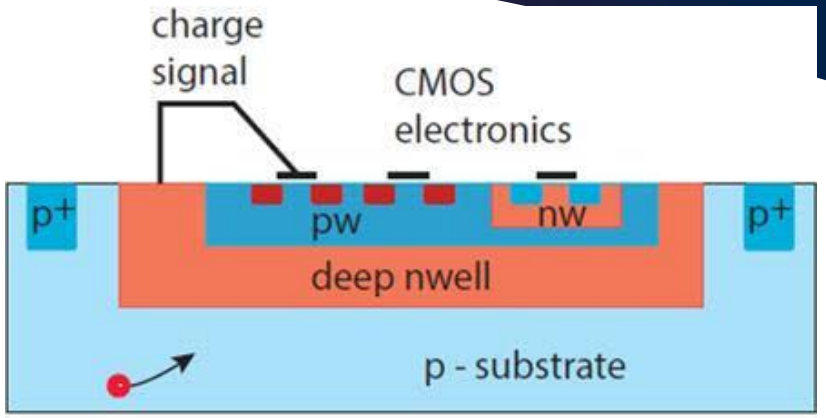


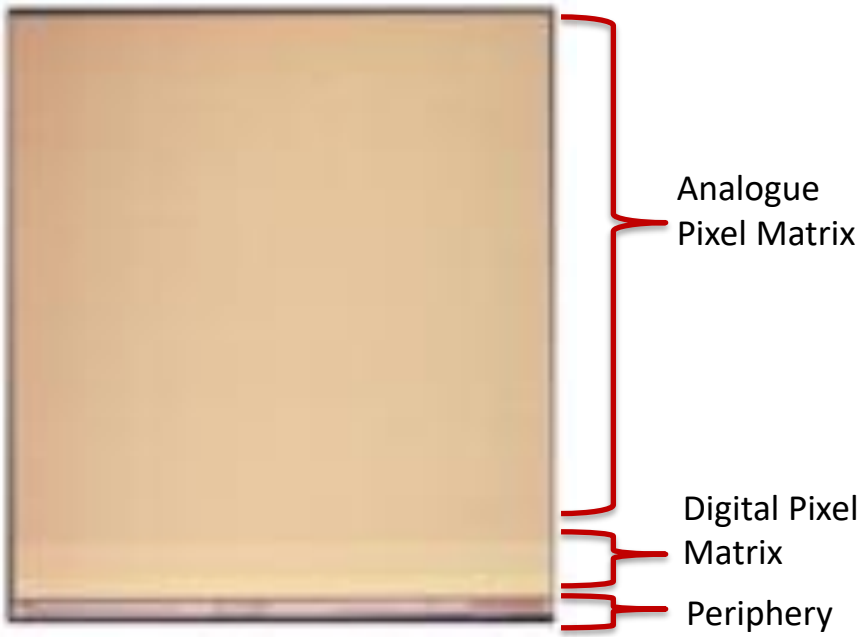


Mupix11

- High-Voltage Monolithic Active Pixel Sensor (HV-MAPS) using commercial high-voltage CMOS technology. Bosch/TSI
- Performance: Over 99% hit detection efficiency with time resolution ~25 ns
- 80 µm square pixels 2cm by 2cm array
- 256 by 250 pixels
- Designed to be thinned to 50–70 µm to reduce multiple scattering. Backside stress compensation by plasma etching.
- Continuous, trigger-less data readout, at high rate.
- Three 1.25Gb data links per chip (Vetex)
- Single multiplexed 1.25Gb link (Outer Pixels)
- 250mW/cm^2 -> 1W per chip

- High speed digital pixel structures are physically outside the analogue pixel matric to allow lower thresholds.
- Bosch 180nm process ended leaving us with a limited number of wafers and a worrying total yield requirement of ~35-40%

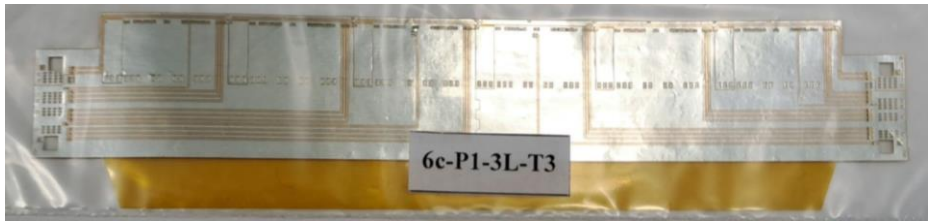


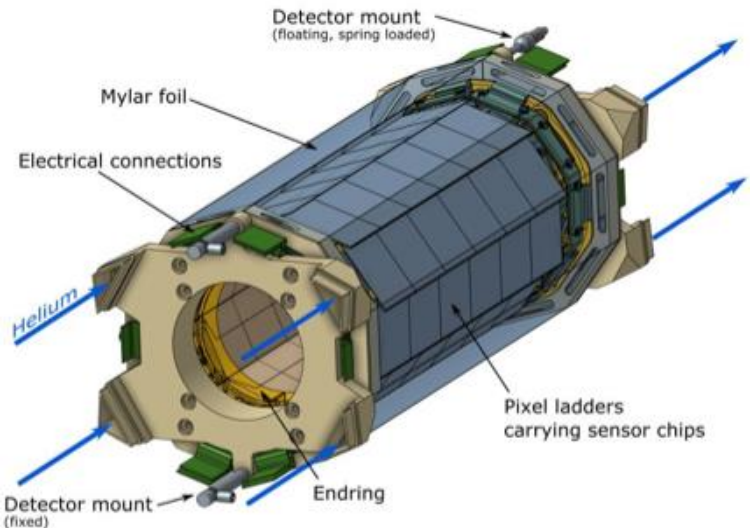


Vertex Detector Construction

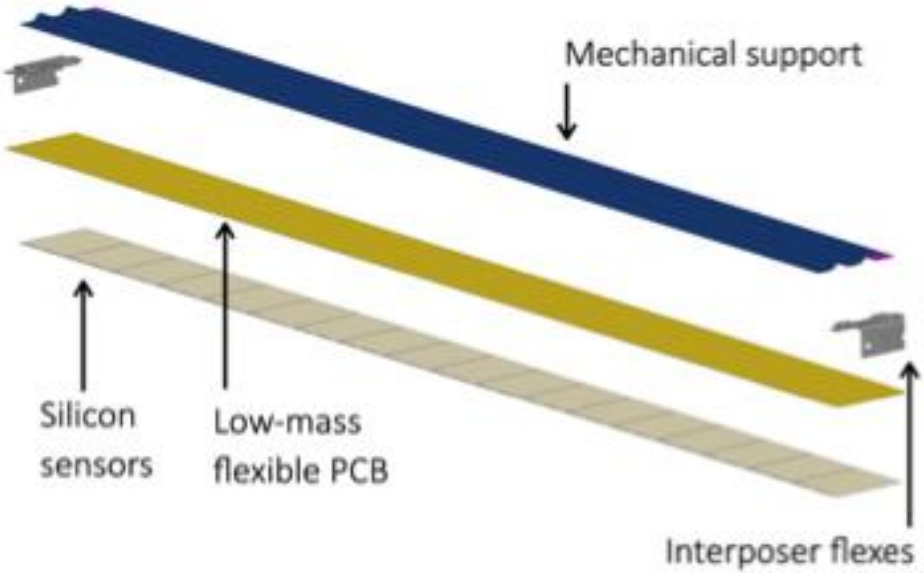
Vertex Detector assembly at Heidelberg & PSI

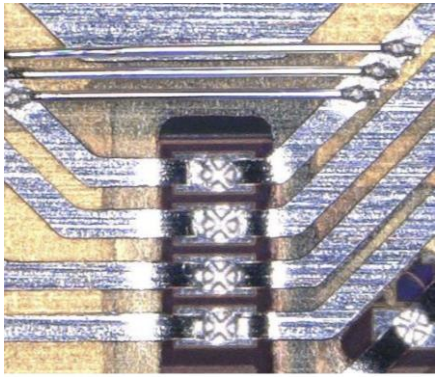
- 0.1% Xo per layer
- 50 µm / 70 µm silicon
- 75 µm two-layer Al Kapton flex
- Jig based chip placement with vacuum tools
- spTAB bonding between chip and flex
- Ladders glued together into half cylinder modules
- Flaps between ladders connected to enclose helium cooling flow volumes

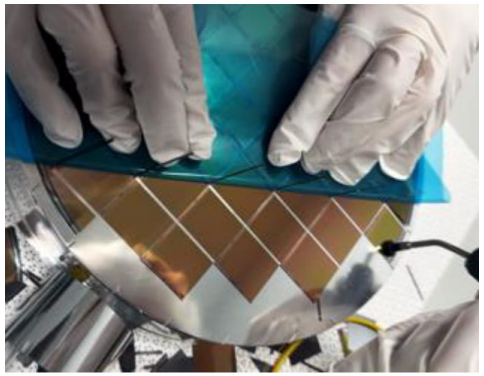




Outer Pixel Construction

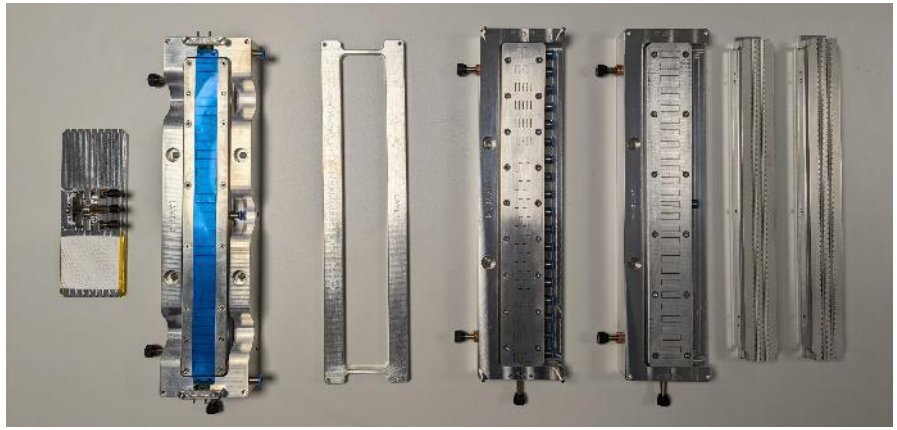






Mupix11 ASIC testing and Ladder Assembly at Oxford

- Tape removal and QC testing of 4500 70 um Mupix11 ASICs
- Robotic assembly of 17 and 18 chip ladders with 10µm precision (20 µm gap between chip)
- SpTAB bonding to Al/kapton flex
- Gluing to 25um carbon fibre support structures
- Ladder electrical QC testing



Outer Pixel Construction

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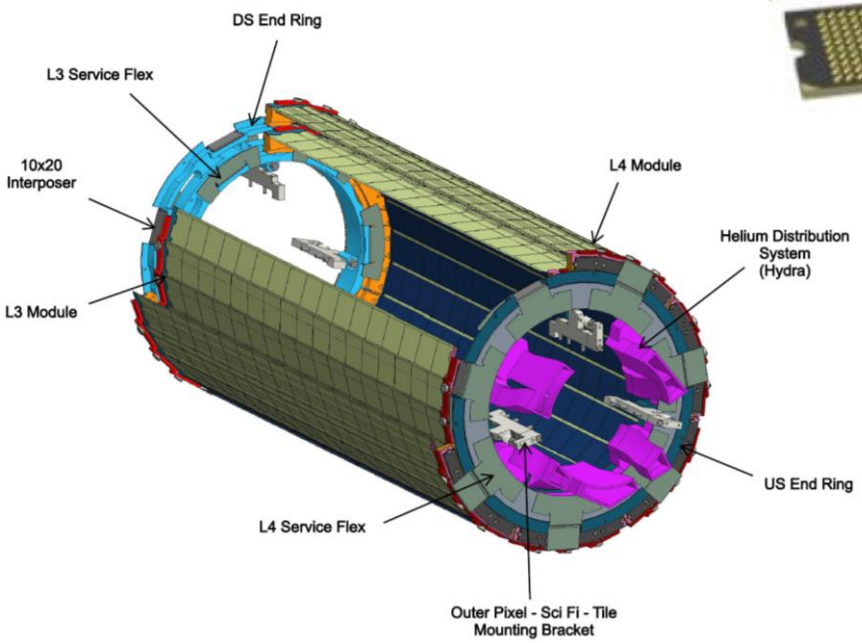
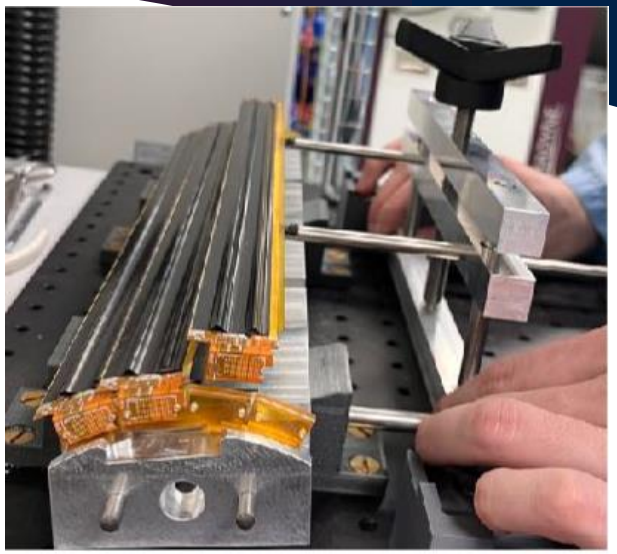
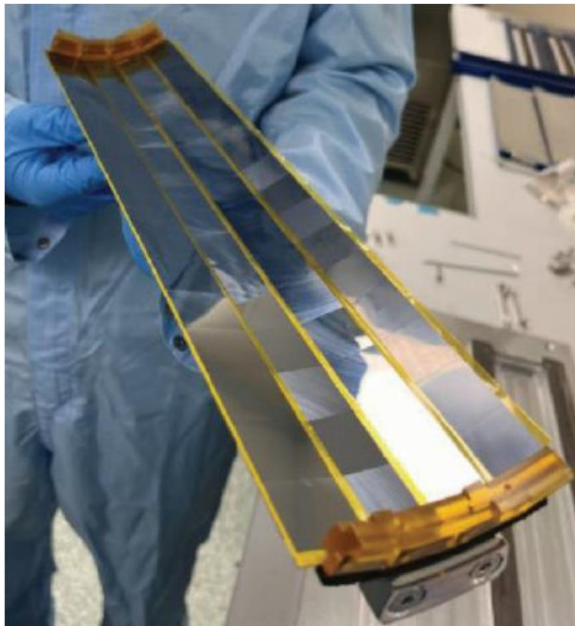
Module Assembly at Liverpool

- Four ladders tested and assembled into a module
- Ladders are clamped so can be removed for rework
- Dedicated specialist tooling to handle fragile ladders
- Modules also include PIE end pieces, interposers and Service flex parts
- Modules fit into end rings and connect with interposers







2025 Operation

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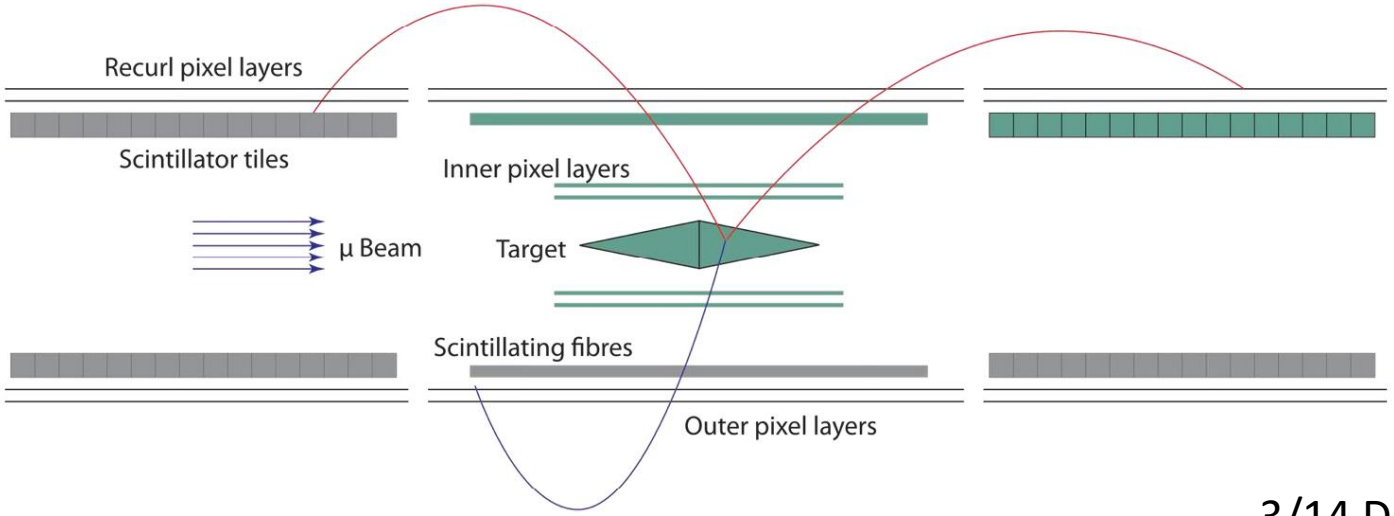
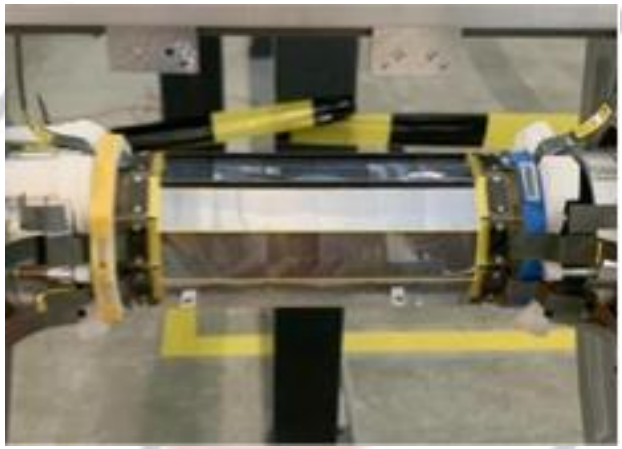
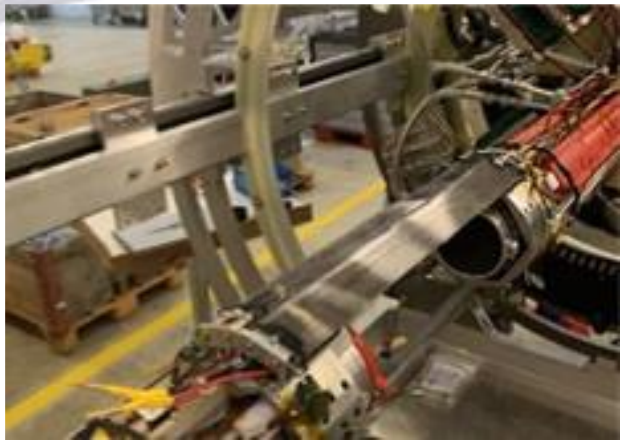
3 weeks operation with a minimal commissioning setup



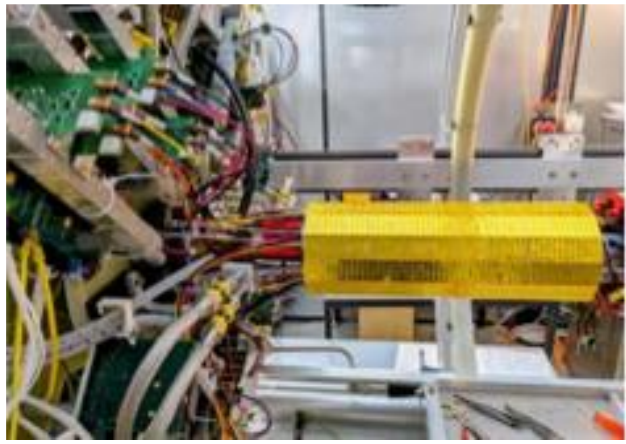
Vertex V1 detector



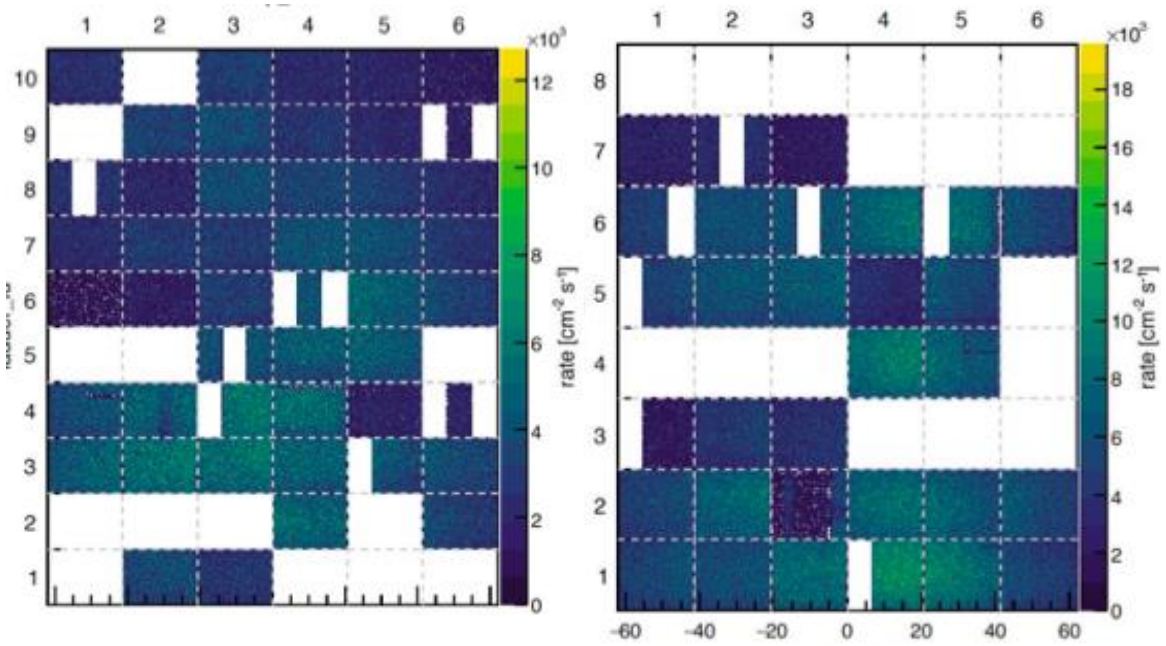
1/6 SciFi modules

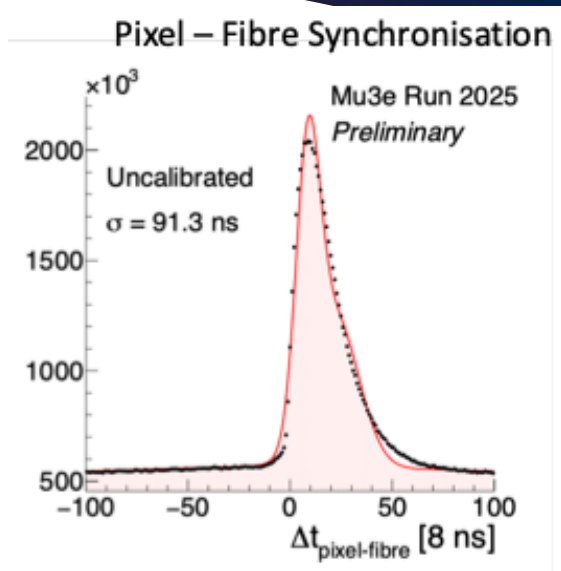


3/14 Downstream SciTile modules



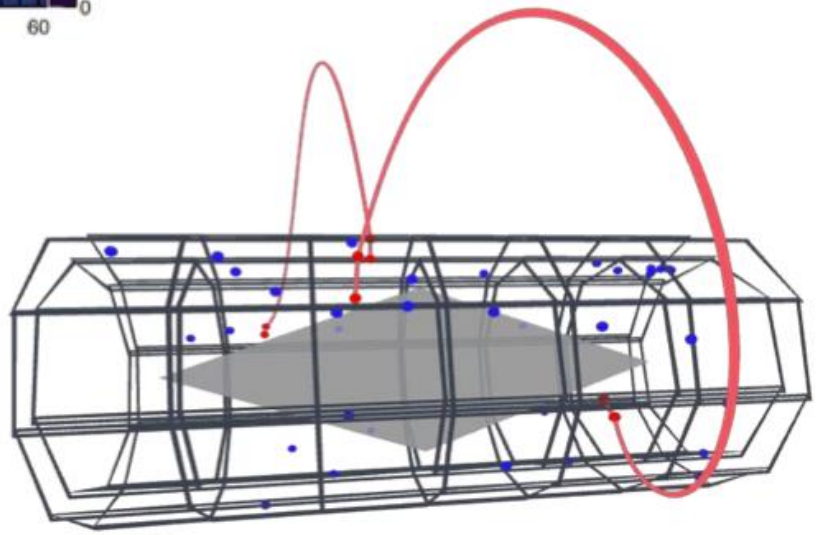
2025 Results



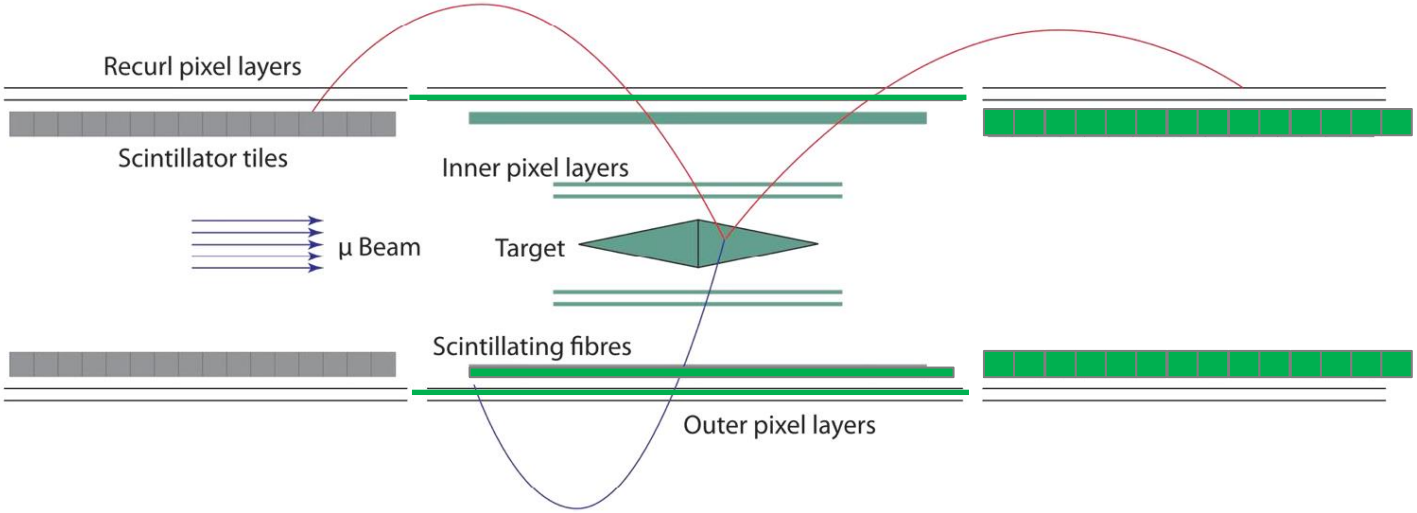


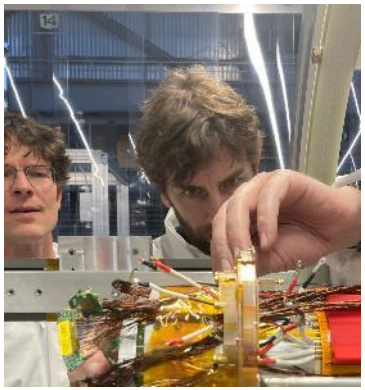
Three Weeks Beamtime in 2025

- First operation of Vertex sub-detector
- Curved Electron tracks reconstructed
- Sub-Detector timing integration successful
- Many Vertex channels missing due to mechanical and bonding issues
- Helium cooling system successfully operated at 2g/s



2026 Status





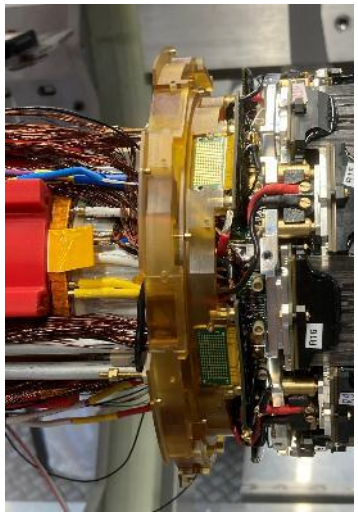
Eight weeks planned running with:

- Rebuilt Vertex V2
- Full SciFi detector **<- First full detector operation**
- Downstream SciTile detector **<- First full detector operation**
- Layer3 Outer Pixel Central Detector **<- First Operation**
- Full helium cooling system **<- First Operation**
- Full Filter Farm trigger system **<- First Operation**
- **First Integration of full systems**

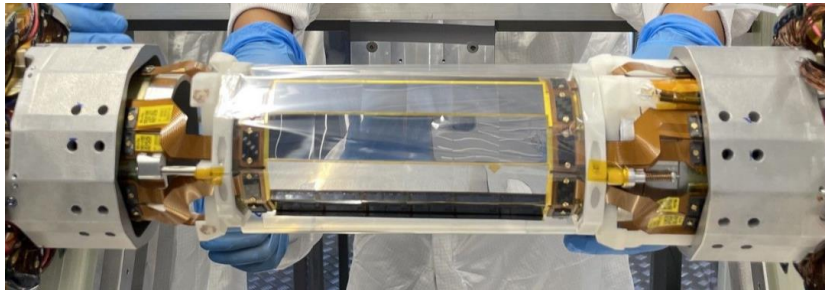
Starting in October!!

2026 Status

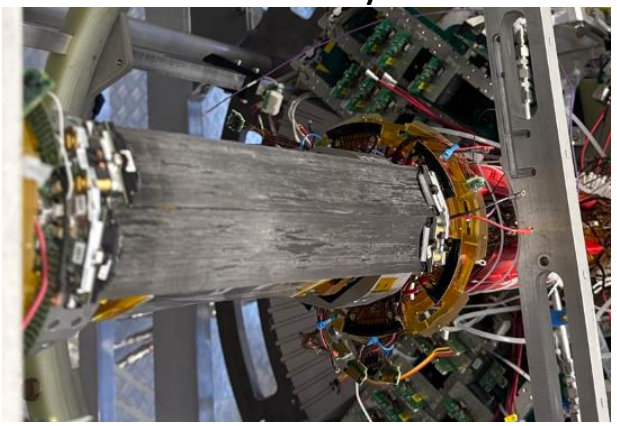
Services: Installed April-May 2026



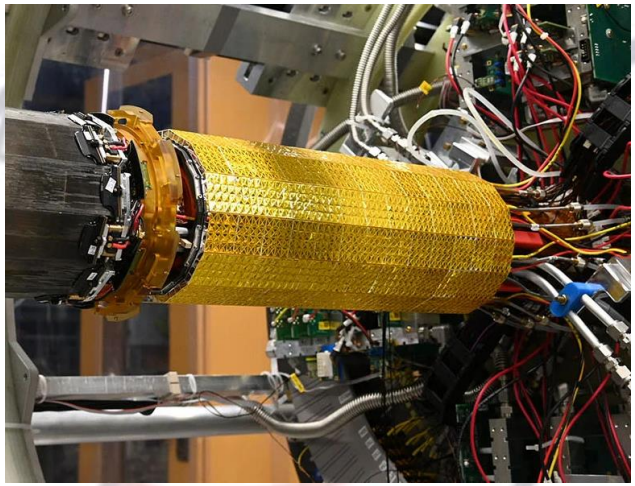
Vertex V2: Installed June-July 2026



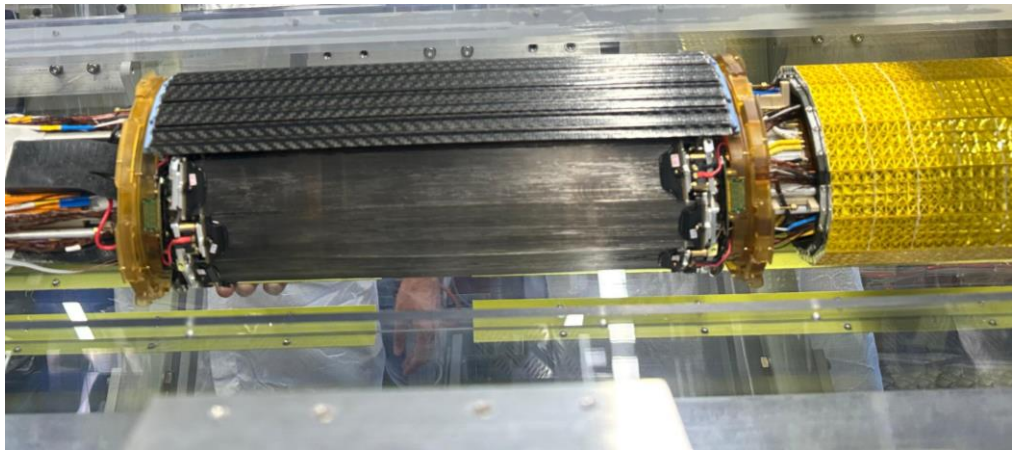
SciFi: Installed July 2026



SciTile DS: Installed Aug 2026



Outer Pixel L3: Installing now



2027 and Beyond

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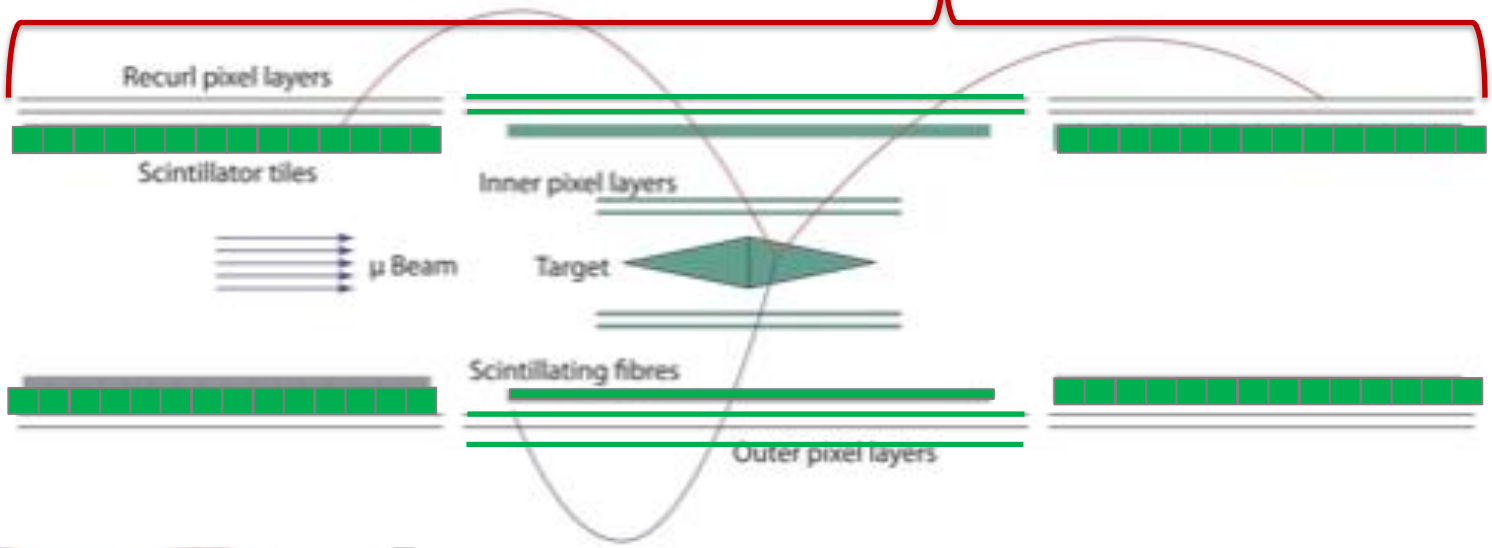
2013 - 2024	2025	2026	2027	2028 - 2029	2030 ->
R&D and Preparation	First Commissioning Vertex V1 SciFi Sci Tile	Initial Operation Vertex V2 Full Sci Fi ½ Sci Tile Outer Pixel L3	Phase 0 Running Vertex V3 Full SciFi Full SciTile Outer Central	Shutdown Beamline HIMB upgrade	Full Phase 1 Running



Summary

Mu3e has firmly left the R&D phase and is now under construction.

The pixel detectors have been designed for: ultra-low mass, high resolution, gaseous cooling and are based on the Mupix11 chip.

Interesting techniques are used in the pixel detector construction including theMupix11, Al/Kapton spTAB bonded flexes and the 25um composite supports

Three weeks commissioning beam time in 2025 is being followed by eight weeks starting in October this year.

We have a chance of a first physics measurement this year, depending on commissioning, but realistically we expect our first result in 2027 with a more complete detector.

HIMB accelerator upgrade lets us reach our final Phase I sensitivity in 2030

Thank you

UNIVERSITY OF OXFORD

Switzerland: PSI, ETH, University of Zurich, University of Geneva

Germany: Heidlberg Physics Institute, Heidlberg Kirchoff Institute, Karlsruhe Institute of Technology, University of Mainz

United Kingdon: University of Bristol, University of Oxford, University of Liverpool, University College London

Backup