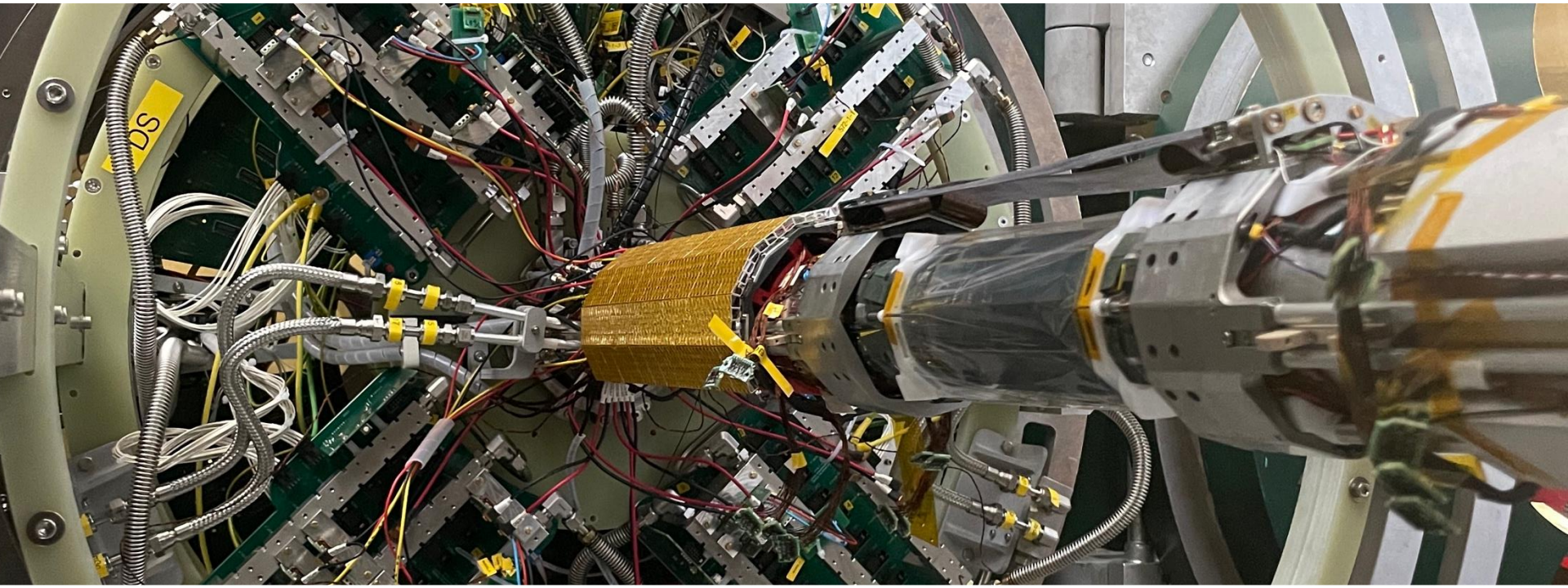
The Mu3e Experiment:
Ultra-light detectors for ultra-rare signatures



Aliki Sofia Rotelli

Les Rencontres de Noirmoutier

1st June 2026

The Mu3e Experiment

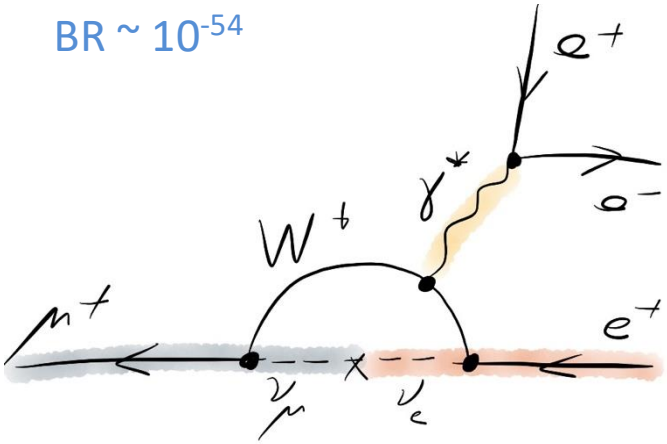
What is Mu3e?

- Detector under construction at the Paul Scherrer Institute
- Looking for the decay of a muon into three electrons → **cLFV** decay
- ~80 people from 12 institutes

https://www.psi.ch/en/sls/about-sls

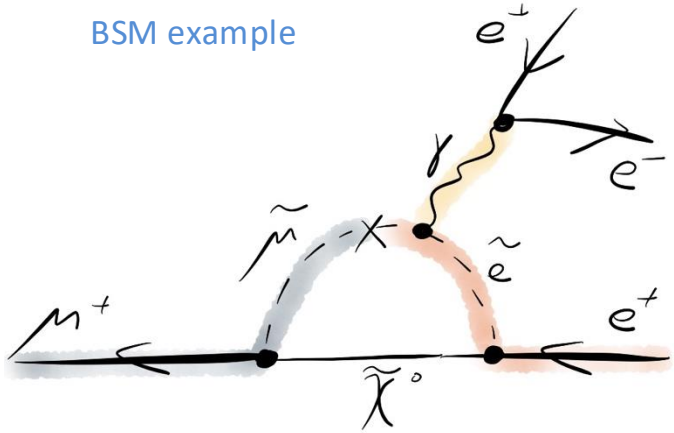
SM μ → eee diagram via neutrino oscillation

BR ~ 10^{-54}



SUSY μ → eee diagram via slepton mixing

BSM example

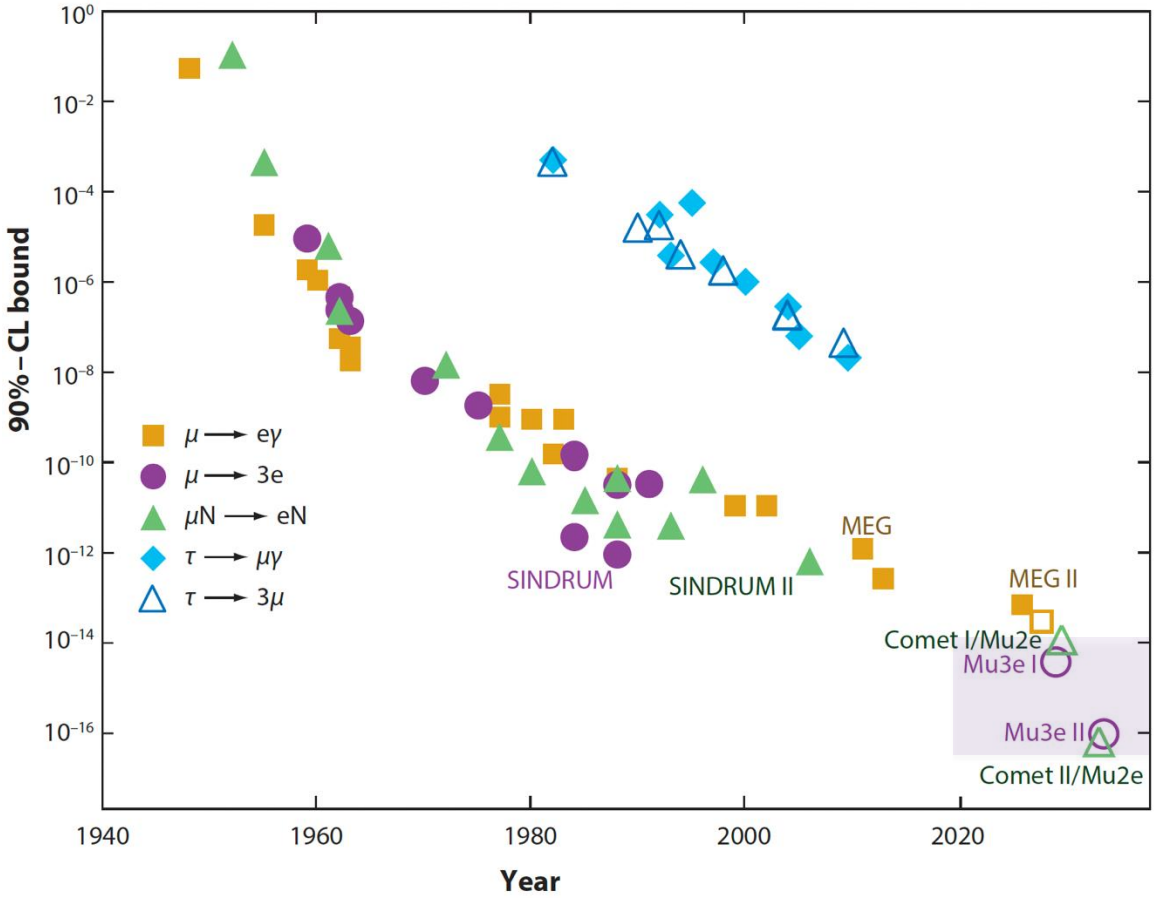


Charged lepton flavour violation:

- Charged lepton transforms into a different lepton without conserving lepton flavour.
- cLFV with muons: Promising window to BSM; clean signatures, complementary to other searches

Physics Motivation for Mu3e

History of μ charged lepton flavour violation (CLFV) searches



SINDRUM (1983 - 1986)
Set upper limit 10^{-12} for the BR[1]

[1] W Bertl et al. "Search for the decay μ →e+e+e−". en. In: Nuclear Physics B (Oct. 1987).

Physics Motivation for Mu3e

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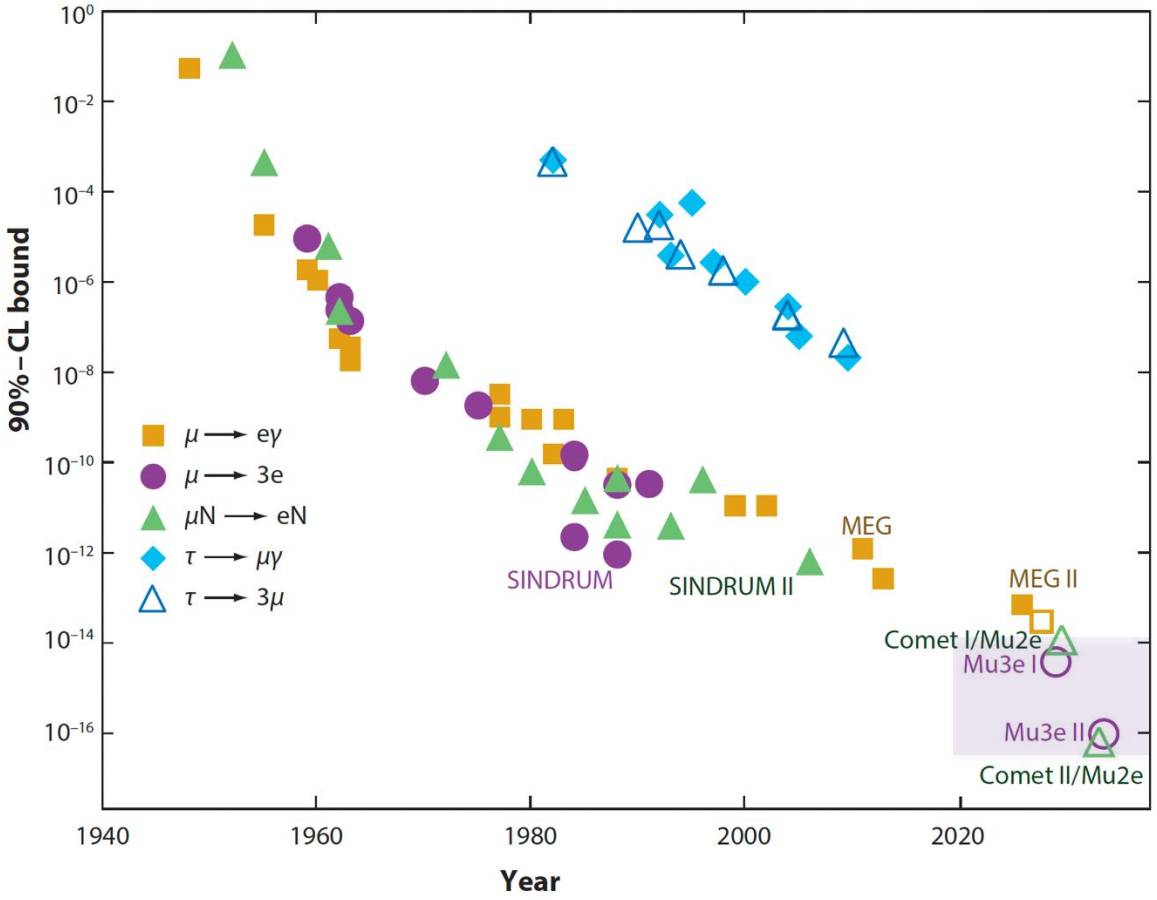


SINDRUM (1983 - 1986)
Set upper limit 10^{-12} for the BR[1]

Mu3e aim

SES corresponding to BR[2]:

Phase I : $2 \cdot 10^{-15}$

Phase II : 10^{-16}

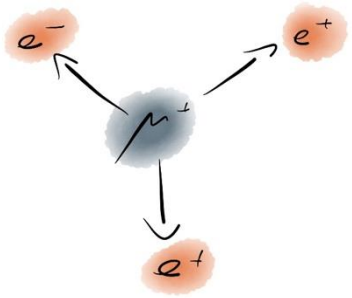
[1] W Bertl et al. "Search for the decay μ →e+e+e−". en. In: Nuclear Physics B (Oct. 1987).
[2] K. Arndt et al. "Technical design of the phase I Mu3e experiment". In: Nuclear Instruments and Methods in Physics Research Section A, 1014 (Oct. 2021).

Signal and Backgrounds

Muons are stopped by target and decay at rest, Therefore we expect:

Signal:

- 3 decay products ($e^+e^+e^-$) with:
  - $\sum E = m_\mu$
  - $\sum p_e = 0$
  - $p_{max} = \frac{1}{2} m_\mu = 53\ MeV/c$
- Simultaneous, common vertex



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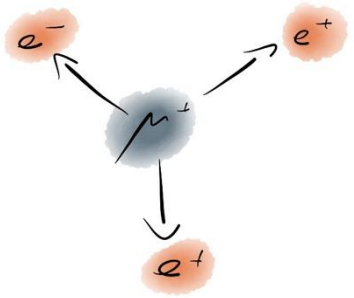
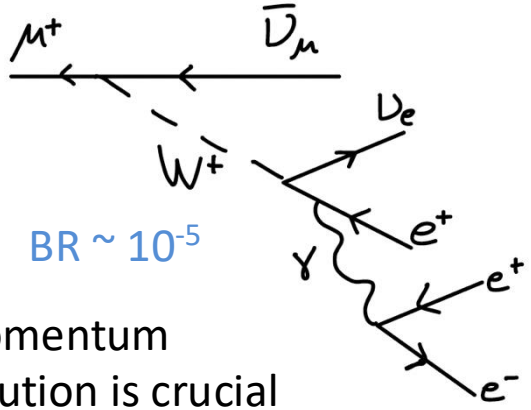


Main background channels:

Radiative muon decay with **Internal Conversion**

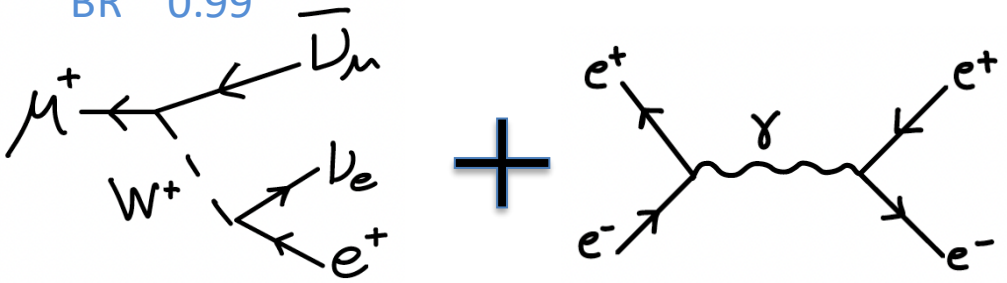


BR ~ 10^{-5}

∴ momentum resolution is crucial

Accidental e.g. Michel Decay + Bhabha Scattering

BR ~ 0.99



∴ need precise vertexing & excellent timing resolution

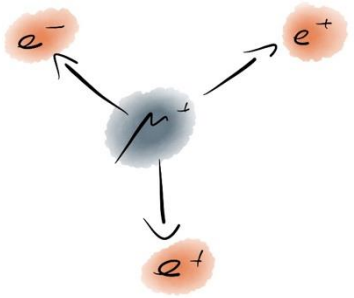
Signal and Backgrounds

Muons are stopped by target and decay at rest, Therefore we expect:

Signal:

MeV region:
Multiple scattering dominant regime!

- 3 decay products ($e^+e^+e^-$) with:
  - $\sum E = m_\mu$
  - $\sum p_e = 0$
  - $p_{max} = \frac{1}{2} m_\mu = 53\ MeV/c$
- Simultaneous, common vertex



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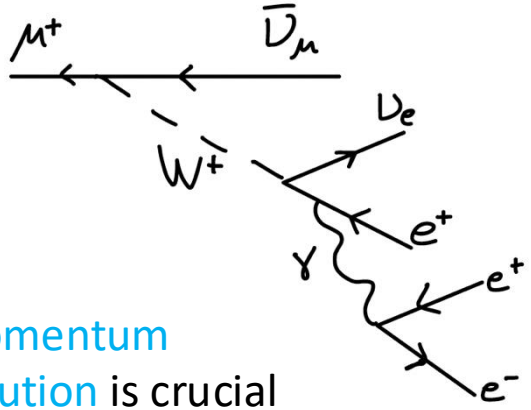

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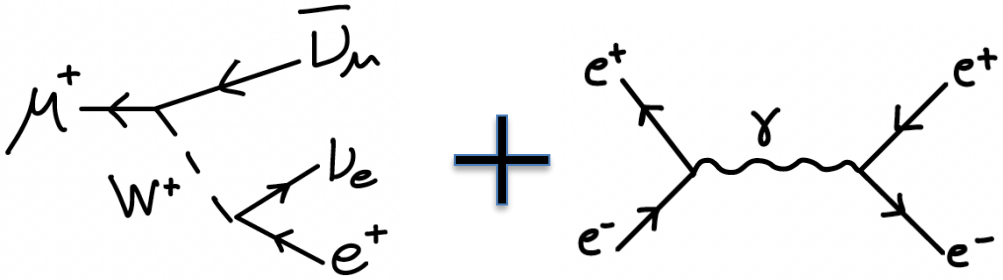
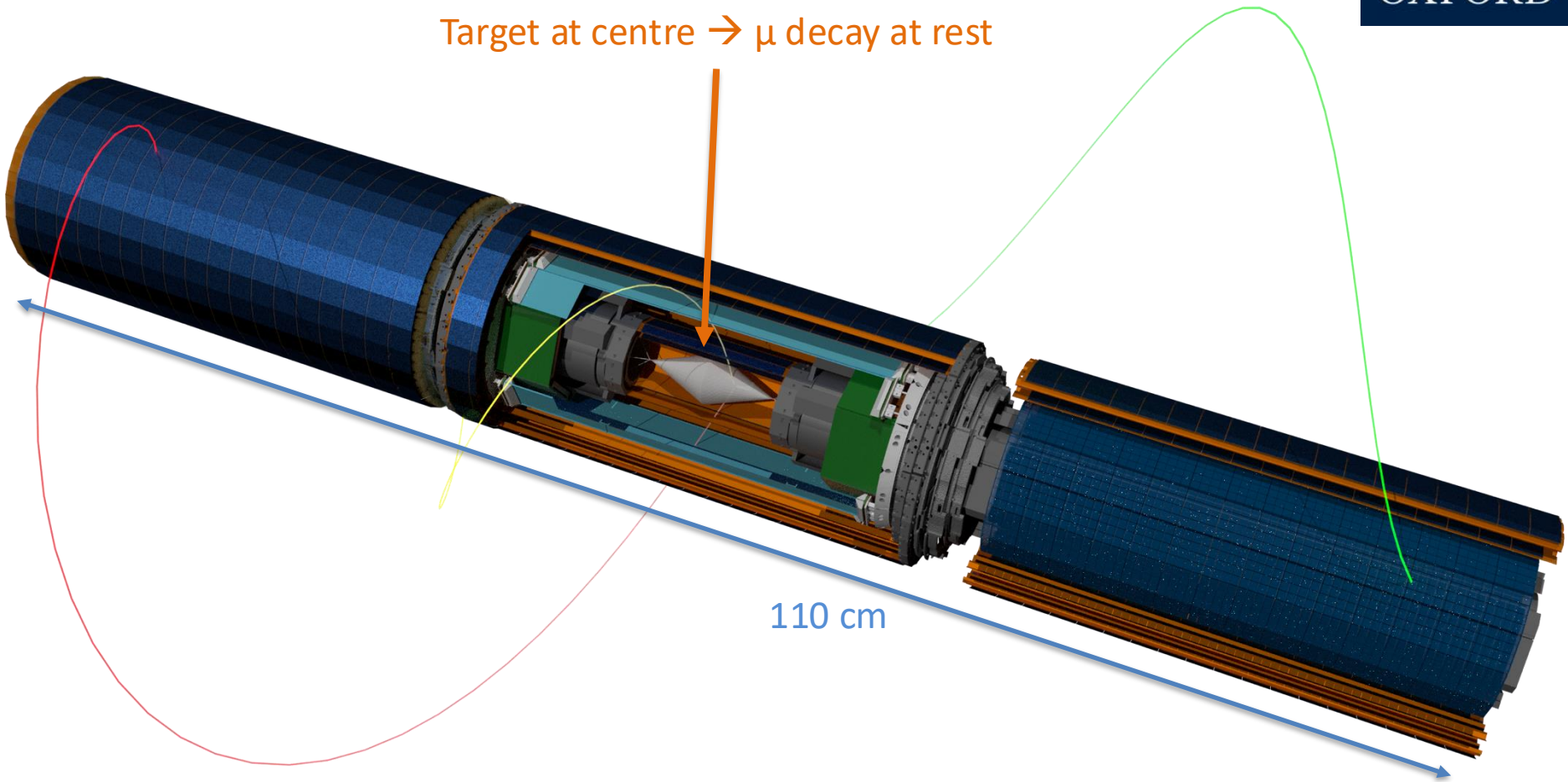


∴ need precise vertexing & excellent timing resolution

…must fulfil all three requirements while keeping multiple scattering to a minimum

Full Phase I Mu3e Detector



1T magnetic field → Tracks recurl

Compact Muon Beam Line (CMBL) setup at πE5

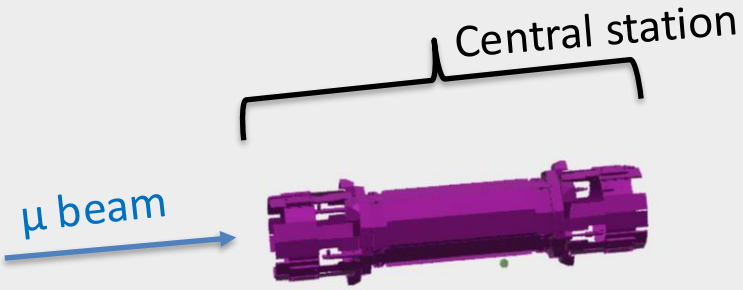
Rate $< 6 \cdot 10^7\,\mu/sec$

$p_\mu = 28\,MeV/c$

Anatomy of Mu3e

Vertex Detector

1T magnetic field

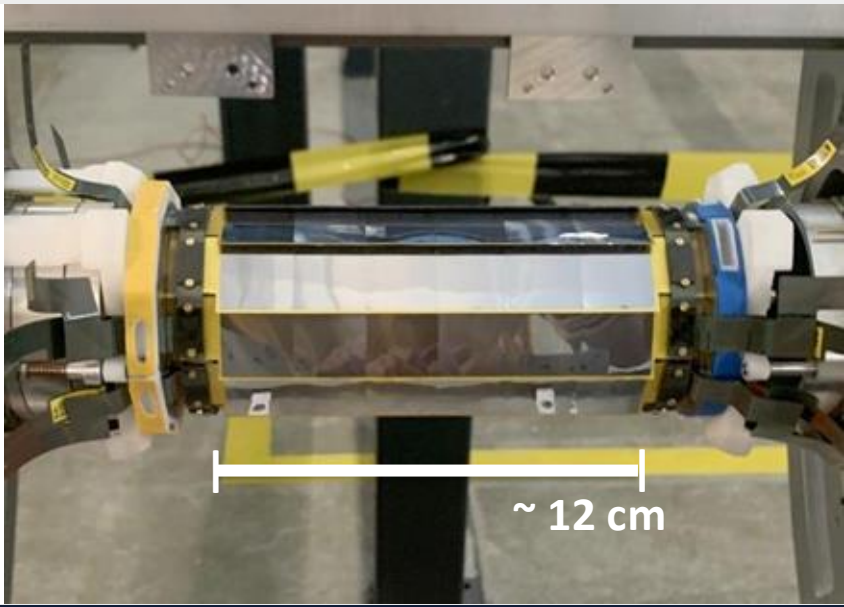


Needed for **position resolution**:
Requirement $\sigma(x) < 25\mu m$

Silicon Pixel Detector

- 108 MuPix11: HV monolithic sensors
- Six chips → "ladder", organised concentrically into two layers around target
- Gaseous He cooling

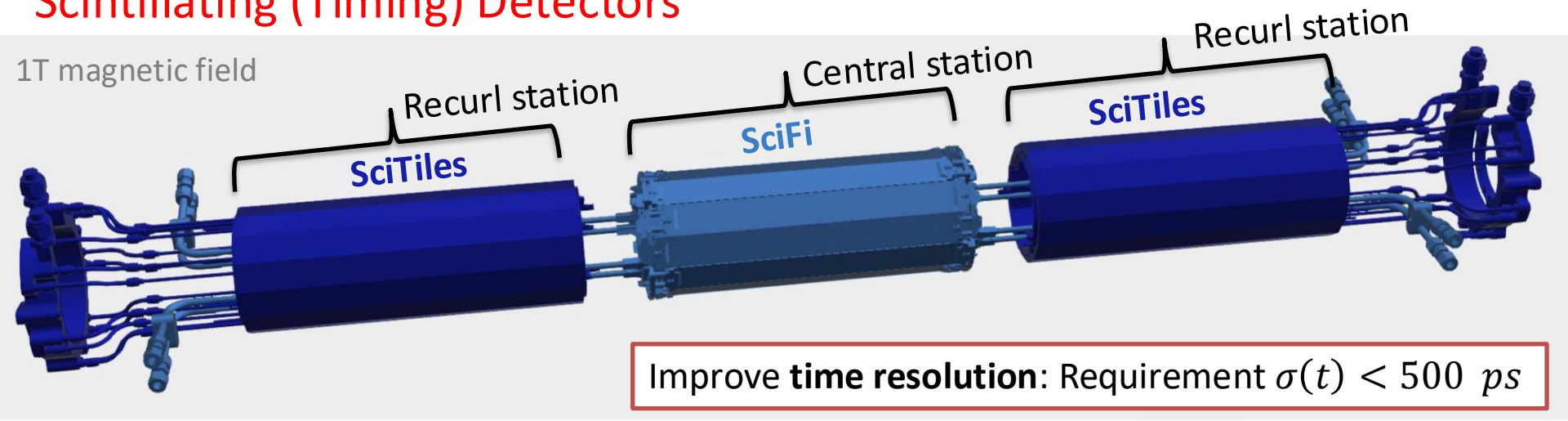
$$\sigma(x) = 23\mu m$$



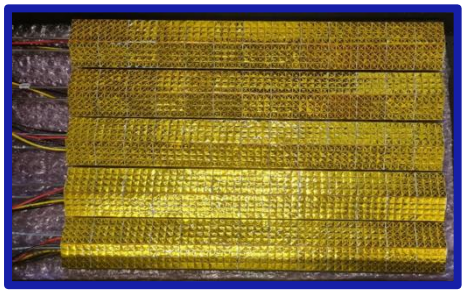
Anatomy of Mu3e

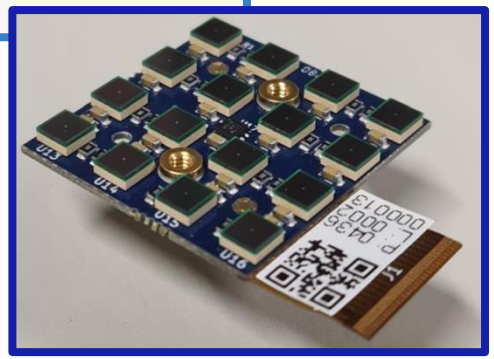
UNIVERSITY OF OXFORD

Scintillating (Timing) Detectors



Improve **time resolution**: Requirement $\sigma(t) < 500\ ps$



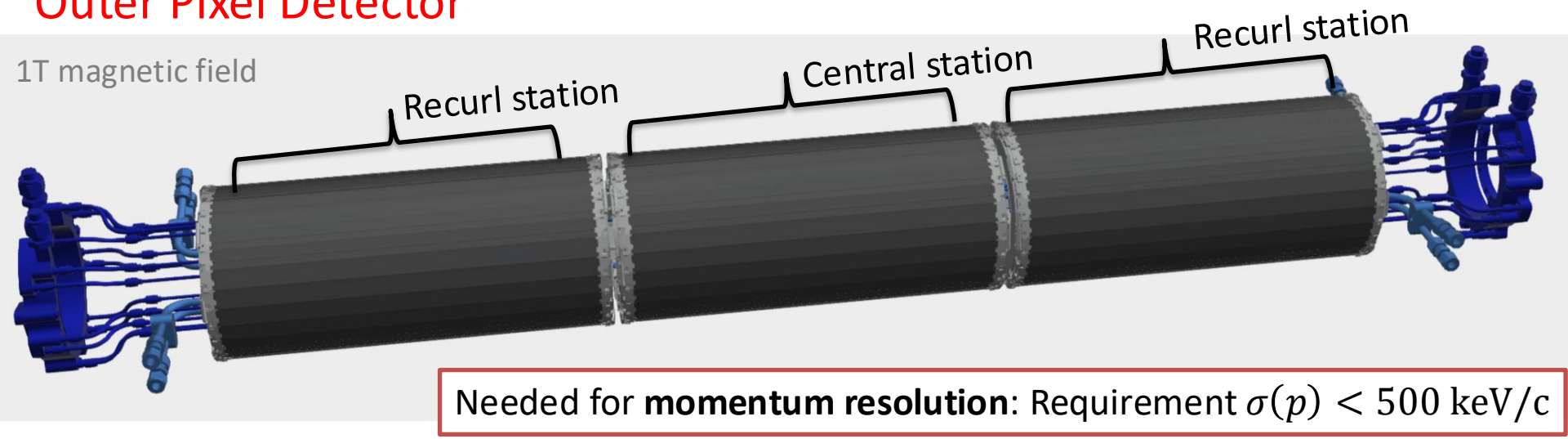


Scintillating fibres (central station) ~250ps
Scintillating tiles (recurl stations) ~80ps

both use custom ASIC MuTRiG

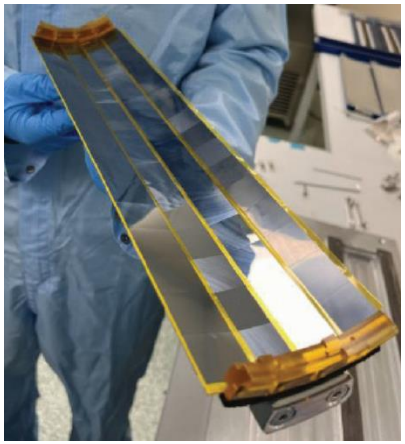
Anatomy of Mu3e

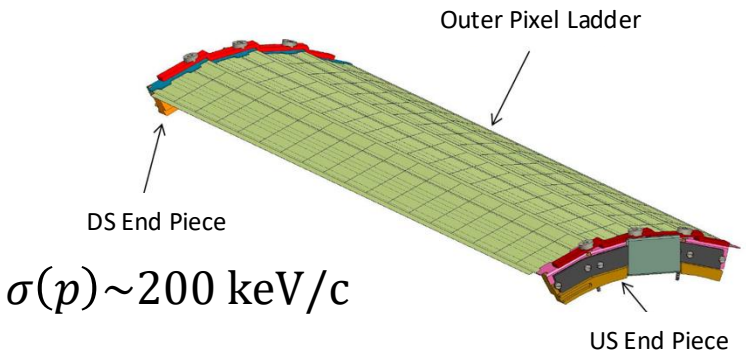
Outer Pixel Detector



Needed for **momentum resolution**: Requirement $\sigma(p) < 500\ \mathrm{keV/c}$

Same technology as Vertex detector but larger scale, ~ $1\mathrm{m}^2$ silicon, 2736 MuPix11



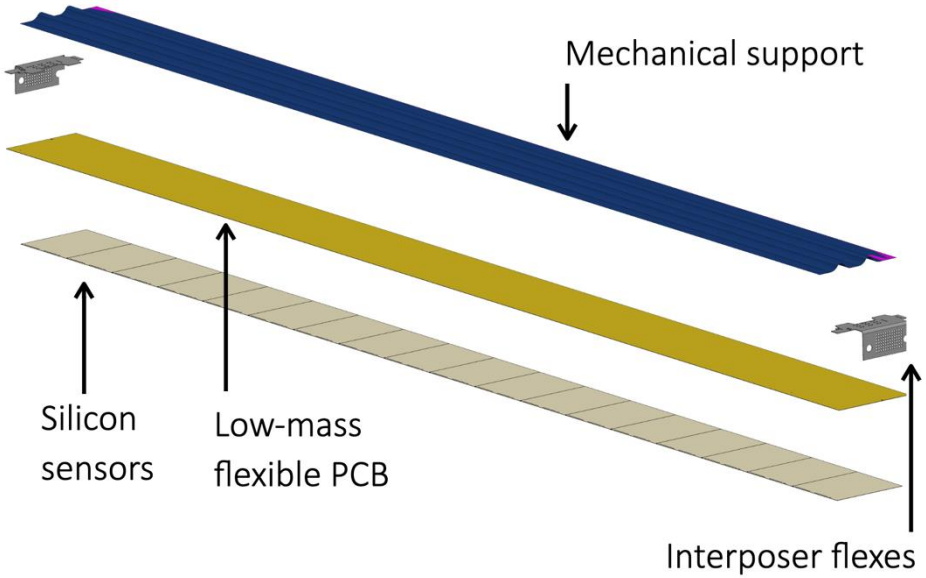


$\sigma(p) \sim 200\ \mathrm{keV/c}$

Minimising Multiple Scattering

Multiple scattering is minimised in various ways; He cooling, ultra-light structures…

Case study: Outer pixel ladders



Ladders:

Smallest building block of the pixel detectors

36cm long, contain 17 or 18 chips, but weigh ~2g

Each layer ~ 0.1% radiation length

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Multiple scattering is minimised in various ways; He cooling, ultra-light structures…

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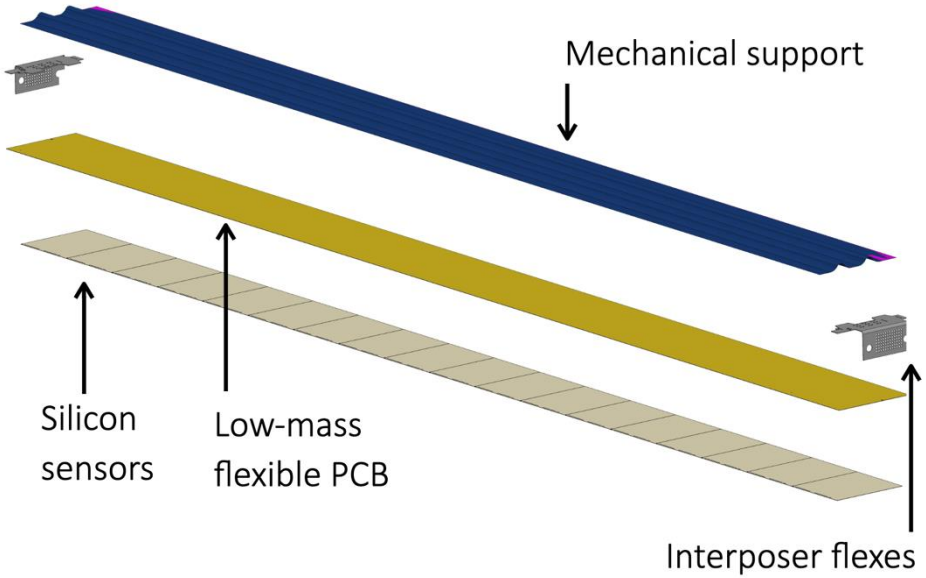
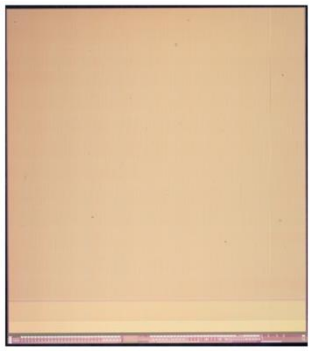


Carbon fibre stiffener, 25µm thick, 0.7g

Brick Kiln Composites/Oxford Univ.

High Density Interconnect, electrical connections

~75µm thick, 2-layer Al-Kapton LTU



MuPix11

HV-MAPS
50-70µm thick
80µm pixel pitch
< 20ns time res.
> 99% efficiency

Ladders:

Smallest building block of the pixel detectors
36cm long, contain 17 or 18 chips, but weigh ~2g

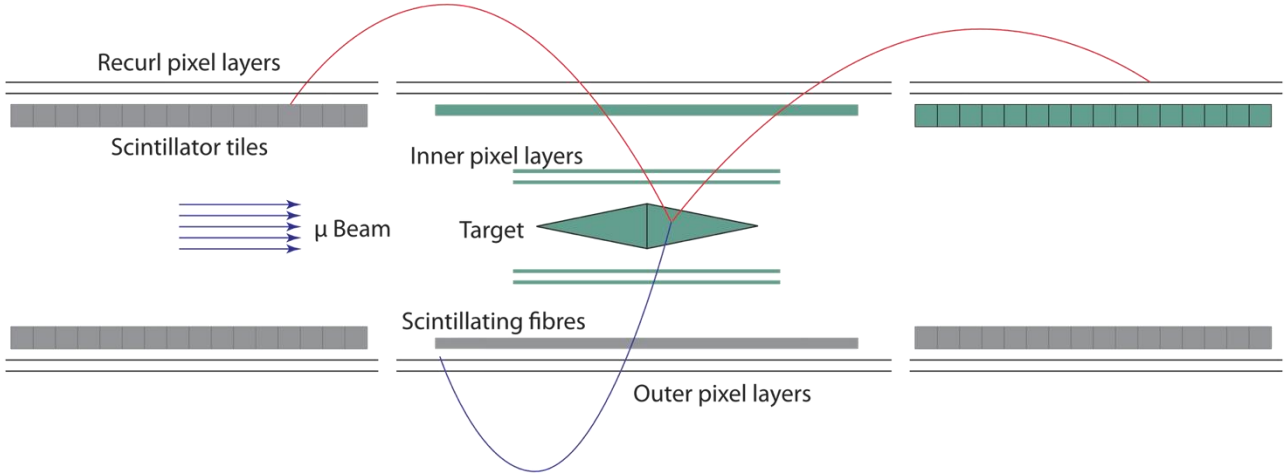
Each layer ~ 0.1% radiation length

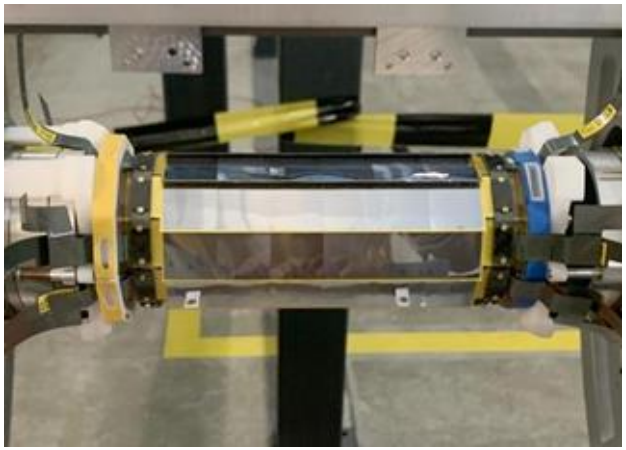
2025 Run: Detector Configuration

June 2025

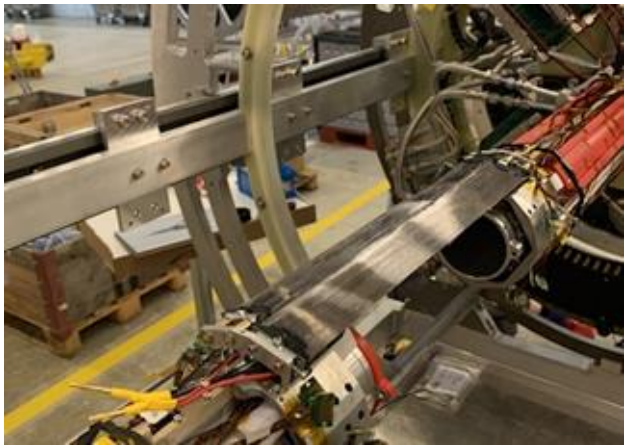
3-week Commissioning run

"Minimal configuration"

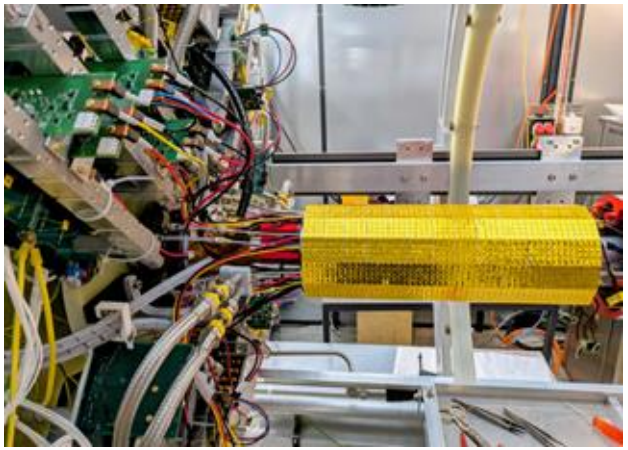




Vertex V1

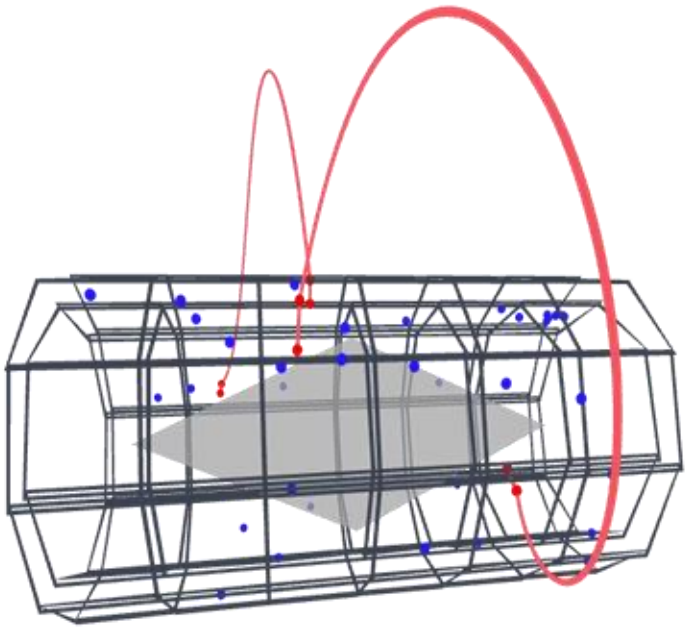


1/6 SciFi Modules



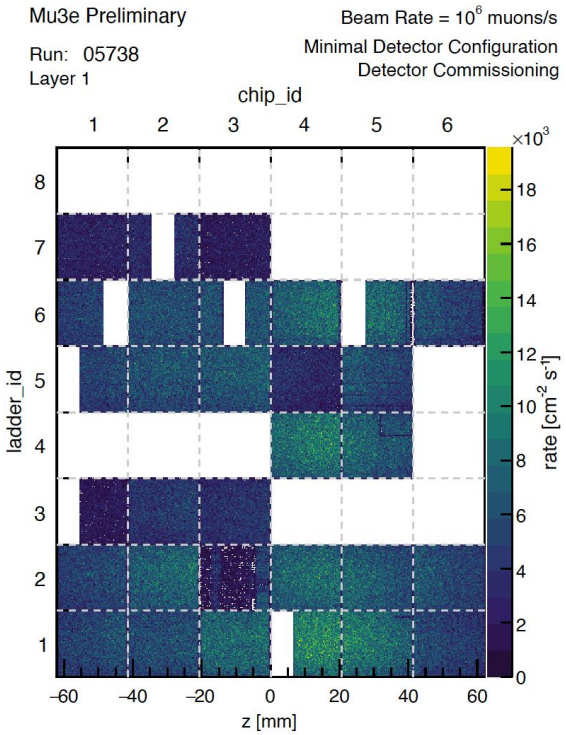
3/14 SciTile Modules

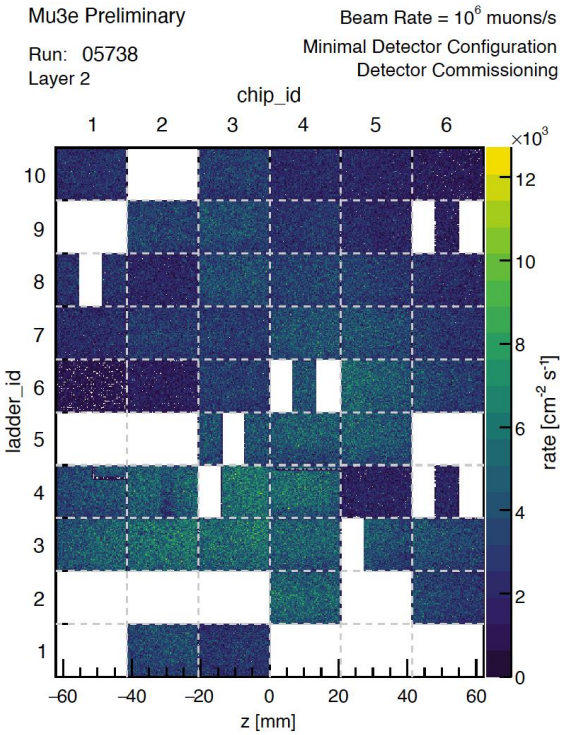
2025 Run: Preliminary Results



3D event reconstruction

Vertex detector hitmap

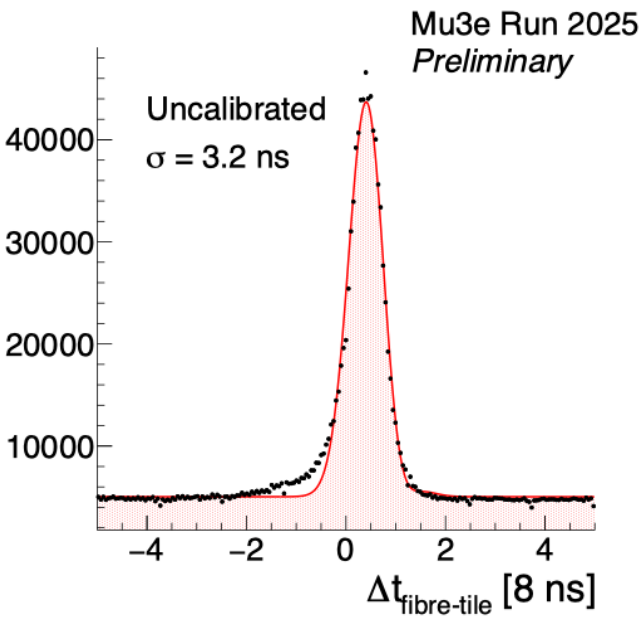




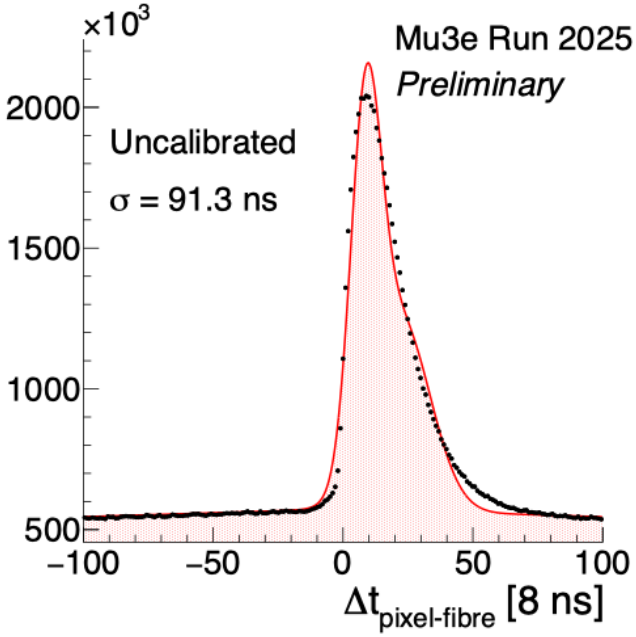
2025 Run: Preliminary Results

Subsystem synchronisation plots

Tile – Fibre Synchronisation



Pixel – Fibre Synchronisation



Milestones:

- Successful Vertex operation and tuning
- 2 g/s He cooling for Vertex commissioned
- Subsystem synchronisation

Ultra-thin Detector Challenges:

- 30% Vertex not operational
  - Mechanical damage
  - Bonding issues

Mu3e Timeline

June 2025

October- November 2026

2027

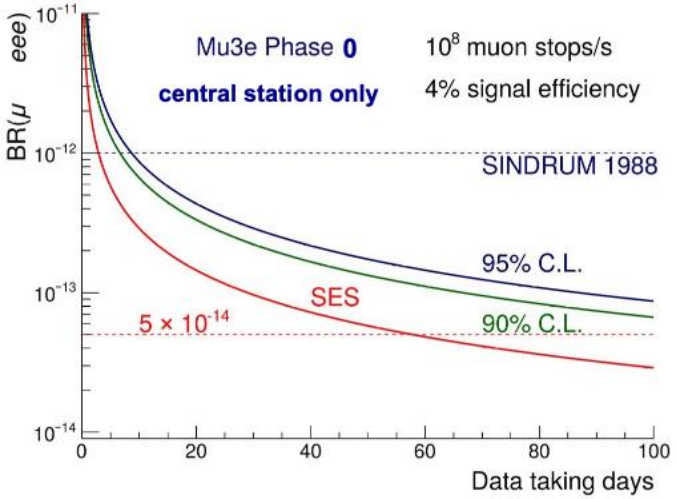
Status:
Services installed

Detector QC
&
Installation

8-week Commissioning Run
Detector configuration:
Full: Vertex (V2) & SciFi
Partial: SciTile & Outer Pixel Central Station
Targets:
Operation and integration of OP detector
Commissioning of GPU filter farm
Measurement of main backgrounds

Data Run:
Detector configuration:
Full: Vertex, SciFi, SciTile,
Outer Pixel Central Station

Targets:
Physics data taking
Improve SINDRUM limit



Conclusion

Detecting **low momentum** particles in the multiple scattering regime is challenging → ultra-low mass detectors.

Mu3e Vertex is the **most lightweight** pixel detector that has ever been operated

Looking ahead:

- Beamline shutdown (2028-2029)
  - HIMB beamline → $>10^9$ muons/second
- Post-shutdown:
  - Operate with full outer pixel recurl stations installed (Phase I)
  - Aim to reach sensitivity below 10^{-15} in Phase I

Thank you!!

BACKUP

Outer Pixel Construction

UNIVERSITY OF OXFORD

Chip Design Karlsruhe Institute of Technology

Wafer Production TSI/Bosch

Thinning and Dicing OPTIM

Wafer Reception University of Oxford

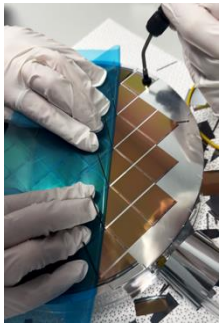
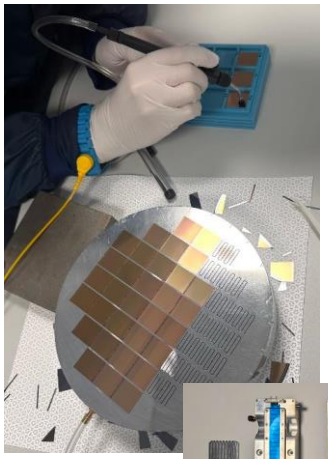
QC Firmware development University of Bristol

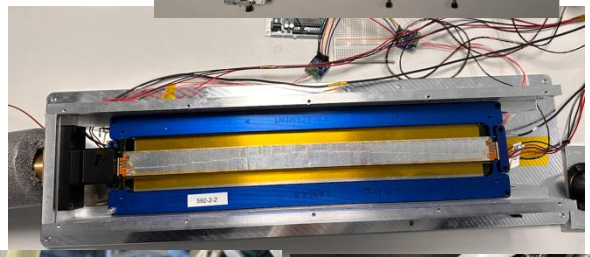
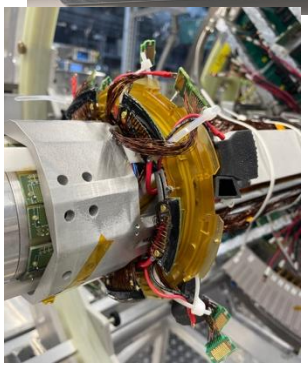
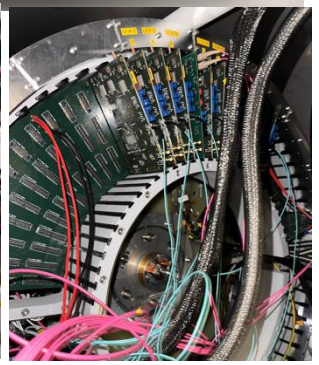
Single Chip QC University of Oxford

Ladder Construction & QC University of Oxford

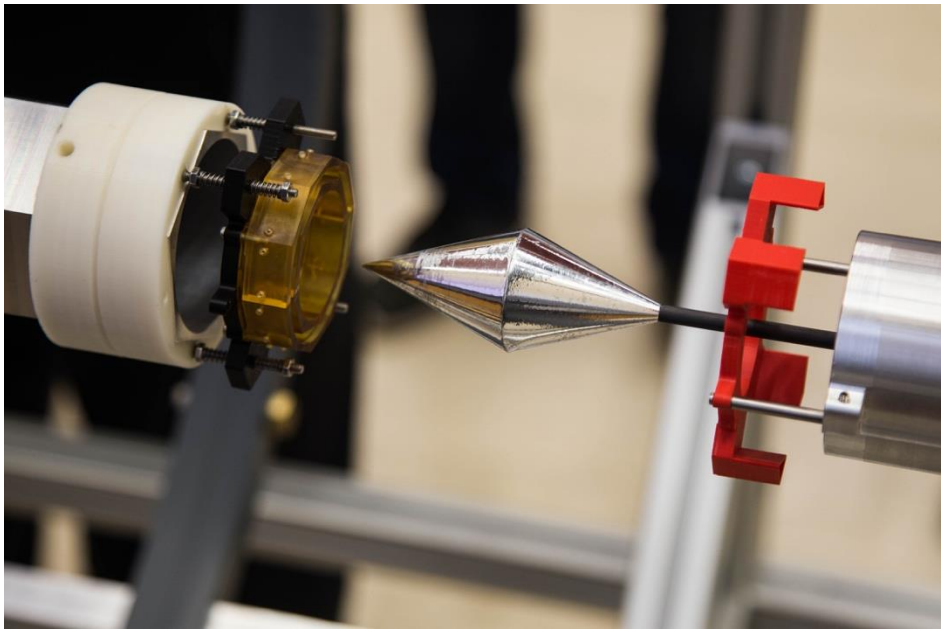
Module Assembly & QC University of Liverpool

Detector Installation and commissioning PSI

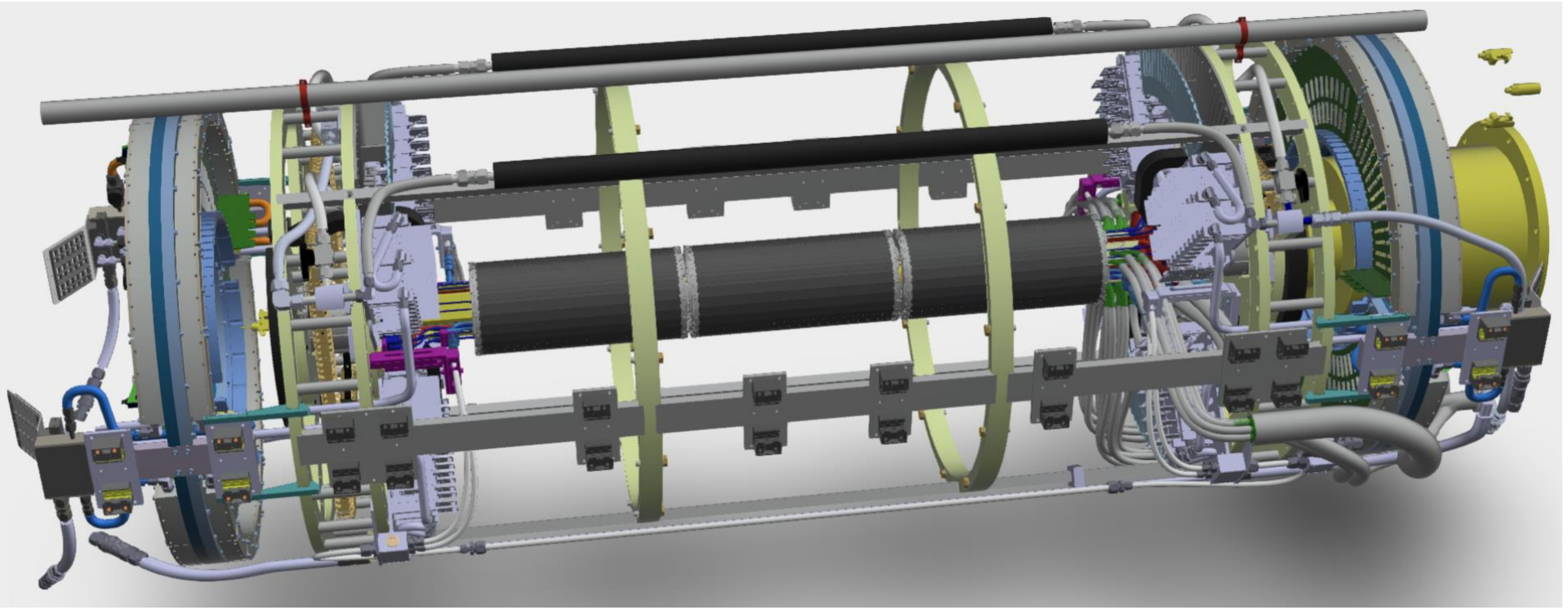



Backup: Area, Magnet and Target



Backup: “The Cage”



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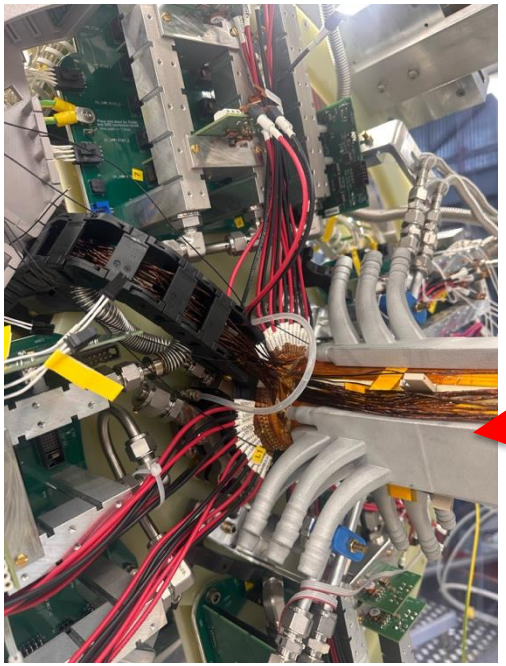
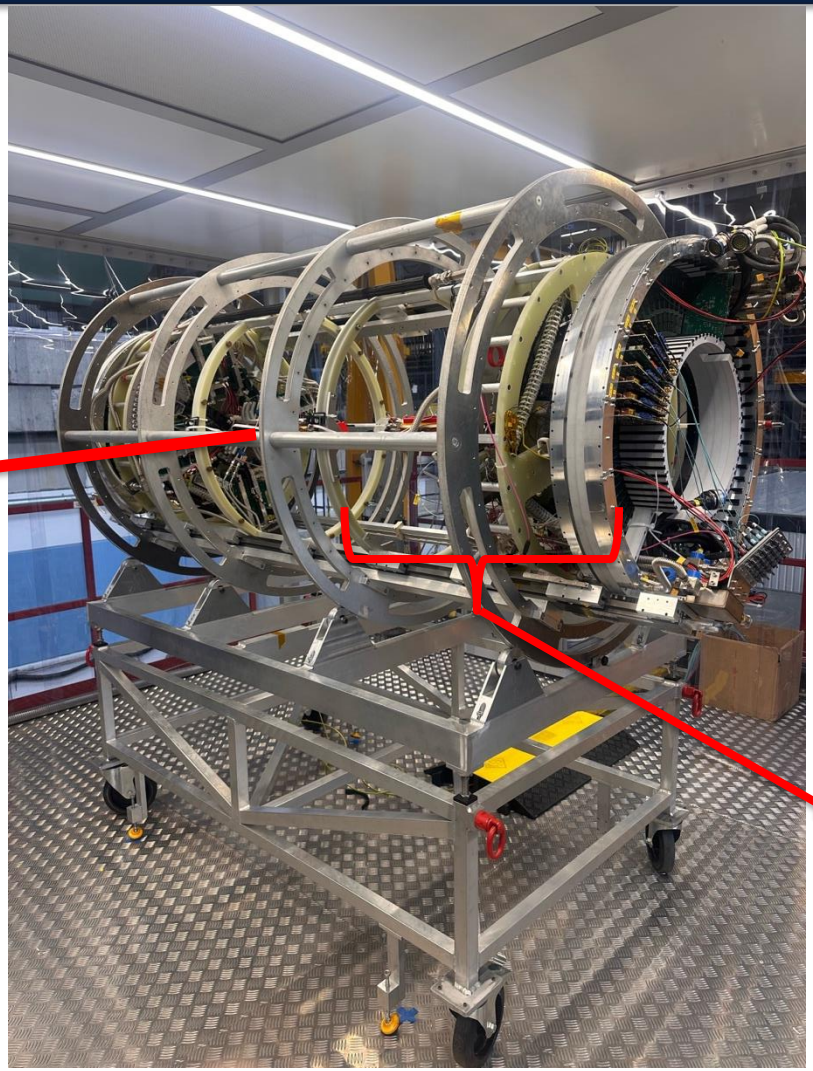
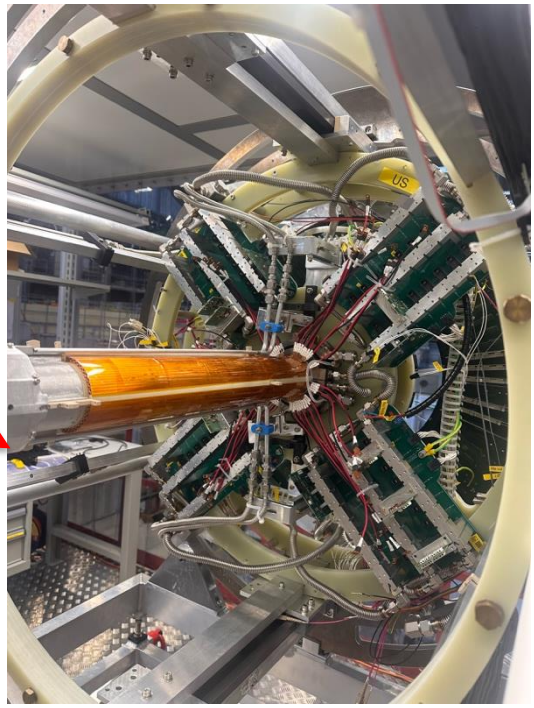


Upstream Service Support Wheel



Downstream Beampipe & Service Support Wheel



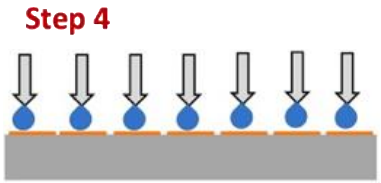
Once detector installation is complete the cage will be inserted into the Mu3e magnet in πe5 beamline

Backup: Ladder Construction Sequence

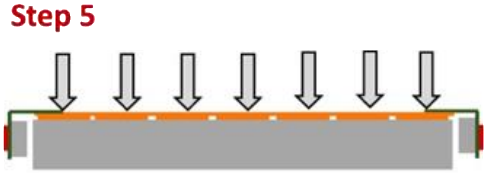
Interposer flexes are placed on precision vacuum jig. The ladder flex is vacuumed to a movable chuck in the middle and the tab bond points are aligned and locked under a microscope.

The ladder flex is removed on-chuck and glue is applied to the interposer flex using the Nordson Pro4 camera-controlled precision glue robot.

The end stops are removed and the SP-TAB bonding is performed to electrically link the interposer flexes to the ladder flex. The ladder is loaded into the ring frame and clamped so it can be removed from the chuck.

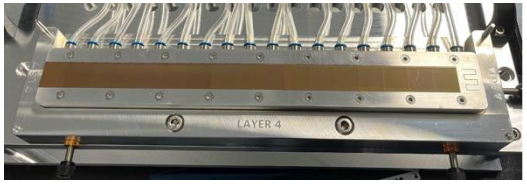


18 or 17 chips are placed with 10um accuracy and 40um separation on a vacuum chuck by the gantry positioning robot.
The chips are glued to the flex and and a fine alignment is made under a microscope.



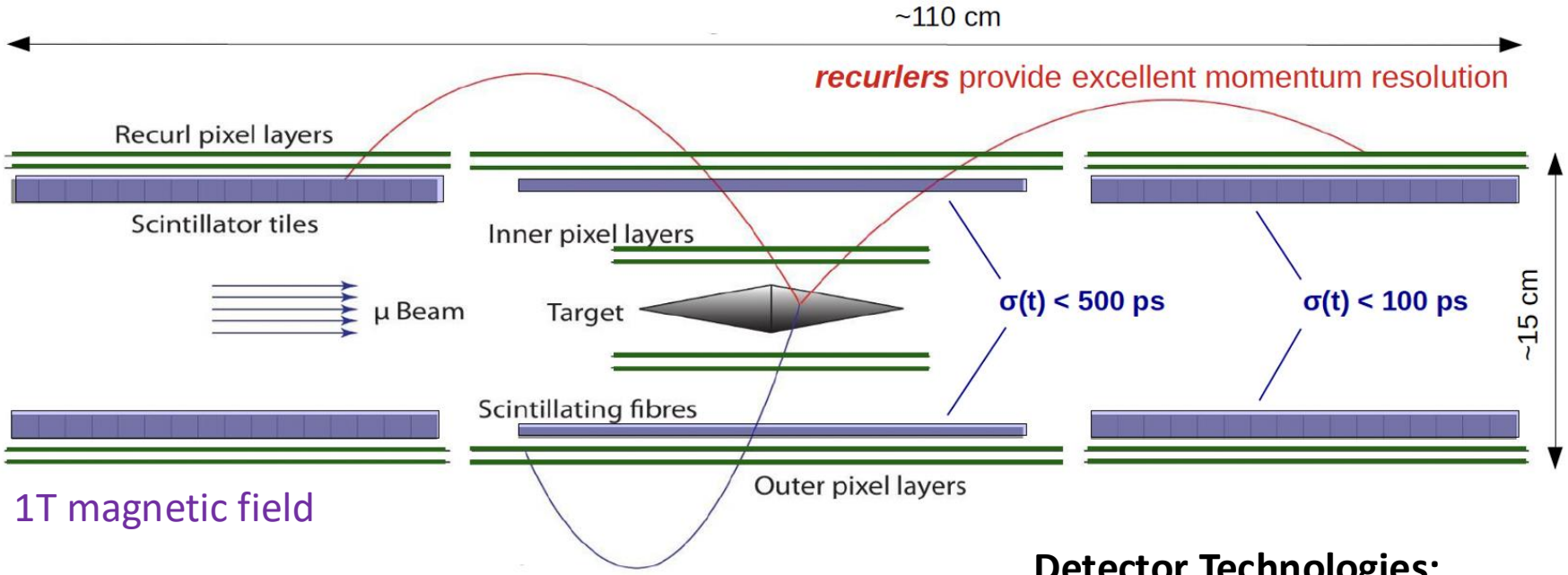
The ladder is transferred to the TAB bonder machine and the chips are SP-TAB bonded to the ladder flex. The ladder is now electrically complete. Araldite 2011 is deposited on each of the SP-TAB bonds to strengthen them.

The Kapton or Carbon Fiber V fold is lowered onto the glue and left to cure overnight. The ladder is now ready to be QC tested!



Motivation for Detector Design

PSI Muon Beam Facility → 10^8 muons/second



Mu3e Experimental Requirements:

Time Resolution: $\sigma(t) < 500\ (100)\ ps$

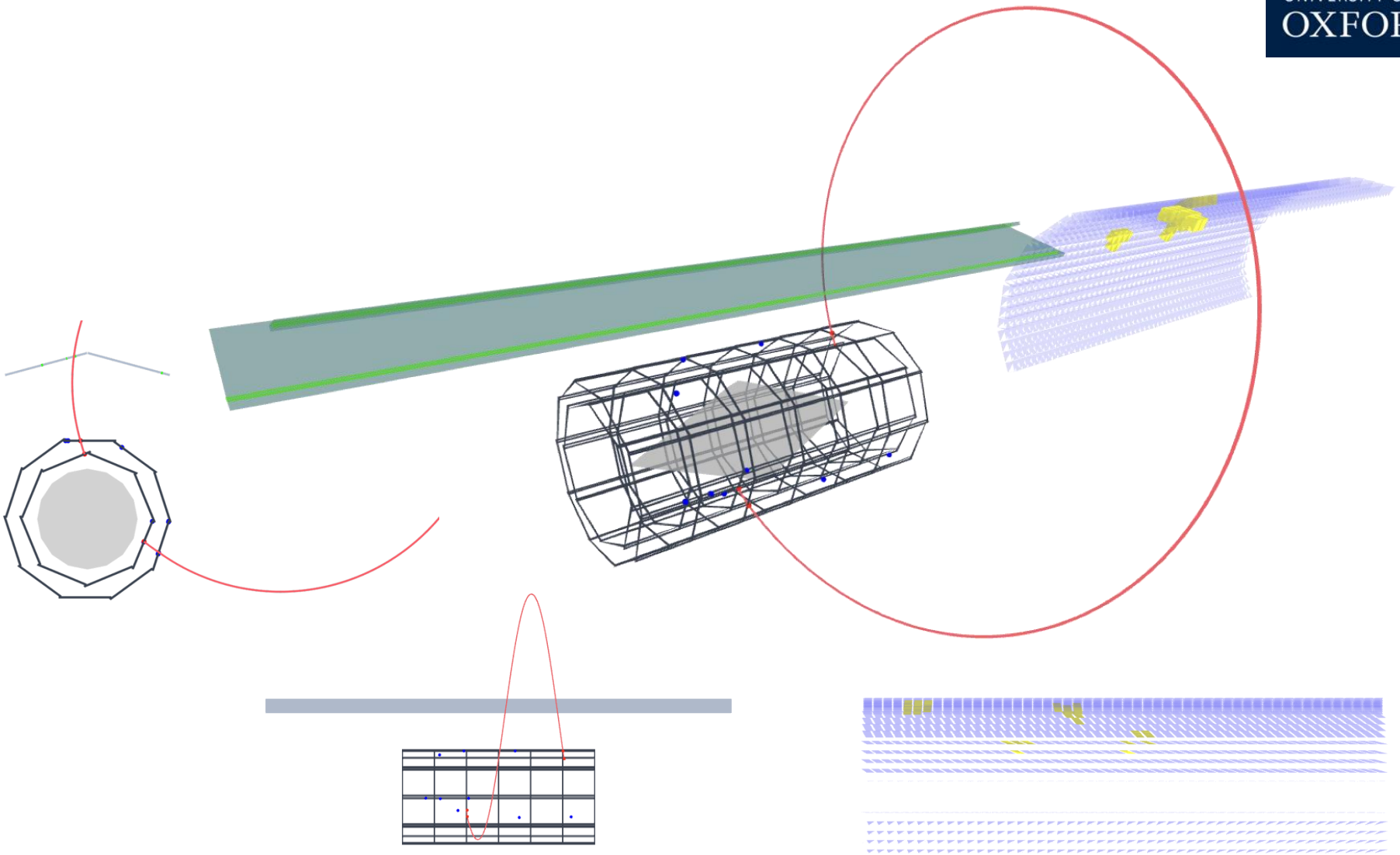
Position Resolution: $\sigma(x) < 25 \mu m$

Momentum Resolution: $\sigma(p) < 500 \frac{keV}{c}$

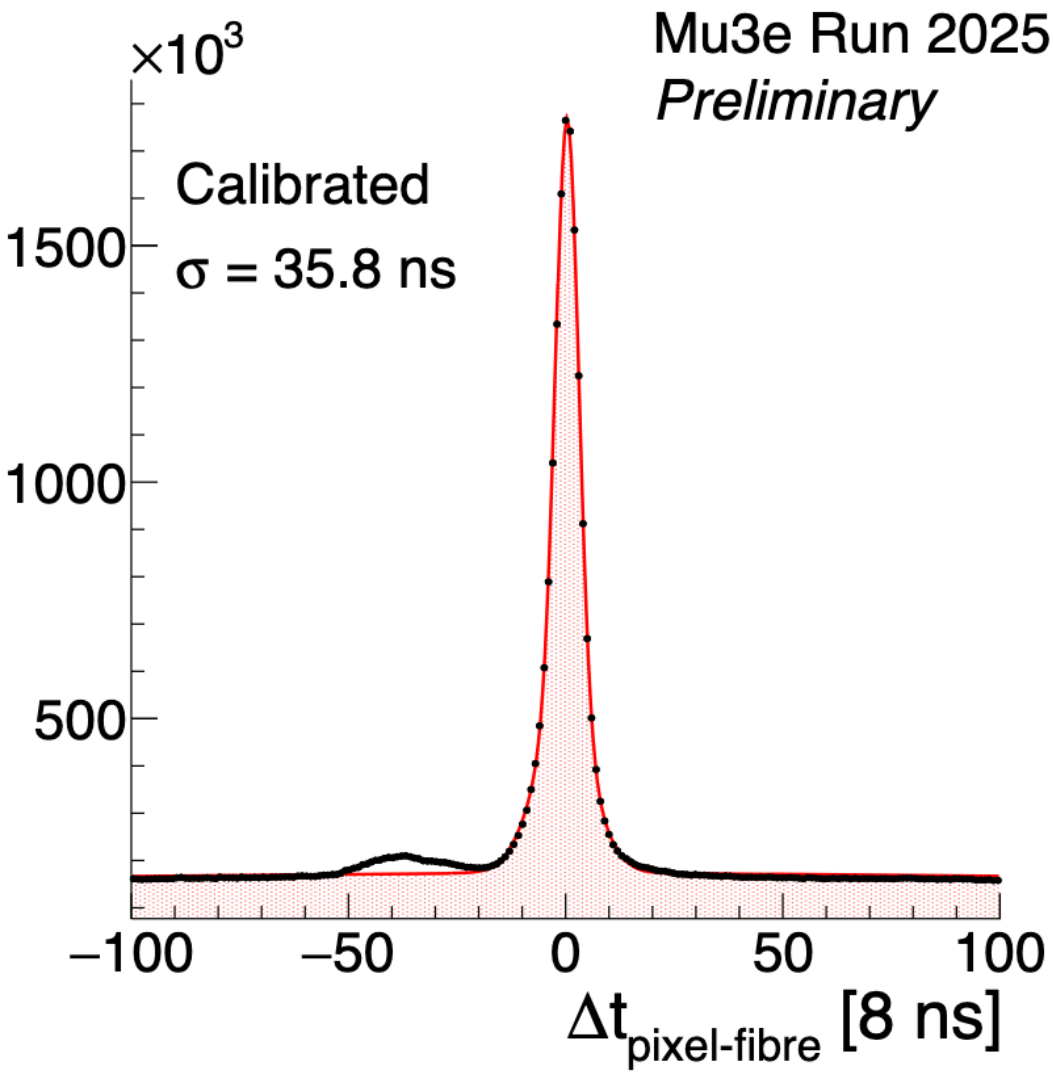
Detector Technologies:

- Silicon pixel detectors
  - Vertex
  - Outer Pixel
- Scintillating fibres
- Scintillating tiles

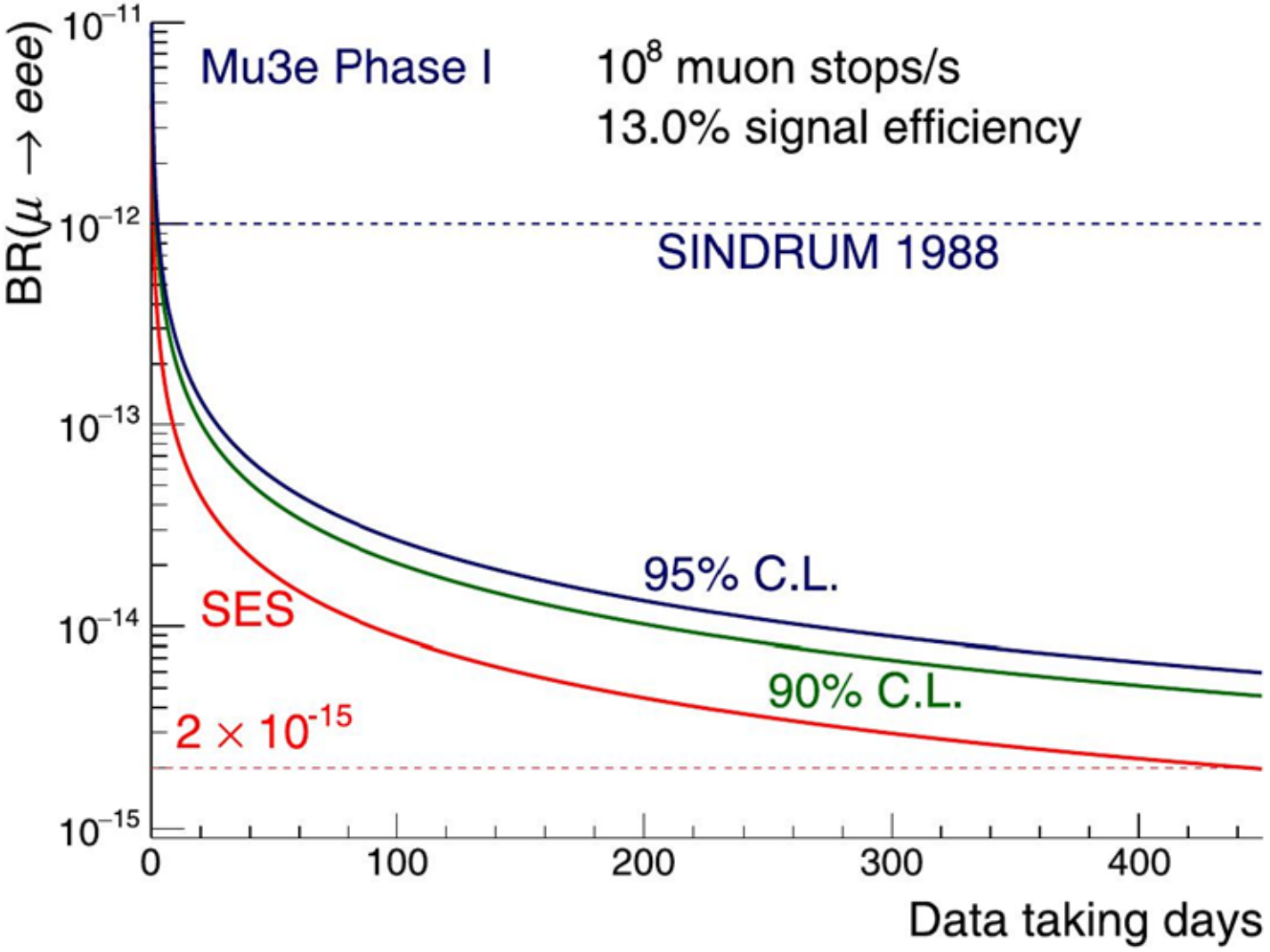
Reconstructed track



Calibrated pixel-fibre



Phase I


Mu3e Phase I
10^8 muon stops/s
13.0% signal efficiency
SINDRUM 1988
95% C.L.
90% C.L.
SES
2×10^{-15}
BR($\mu \rightarrow eee$)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
0
100
200
300
400
Data taking days