# The Mu3e experiment:
## Status and short-term plans

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# Aims:

**Design**

From theoretical motivation to experimental design.

**Construction**

Update on the construction of each subdetector.

**Short-term plans**

Cosmic run.
First physics run.

# Physics of Mu3e: Lepton Flavour Violation

Charged Lepton Flavour Violation (cLFV):

- Neutrinos ($\nu$) oscillate...
    - Consequently, lepton flavour violated...
    - Need to adapt the Standard Model (SM) to account for this → $\nu$SM.
- Implications:
    - cLFV possible through higher order processes but **highly supressed**
    - Still, cLFV impossible at tree level in $\nu$ SM.

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- Implications:
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  - Still, cLFV impossible at tree level in $\nu$ SM.

Opens "box of Pandora" for physicists...

| | |
|---|---|
| $\mu^+ \rightarrow e^+e^+e^-$ | (Mu3e @ PSI) |
| $\mu^+ \rightarrow e^+\gamma$. | (MEG @ PSI) |
| $\mu^- + N \rightarrow e^- + N$ | (Mu2e @ Fermilab, COMET @ JParc) |
| $\tau^+ \rightarrow e^+/\mu^+ \gamma$ | (Belle 2 @ KEK) |
| $\tau^+ \rightarrow \mu^+ \mu^+ \mu^-$ | (LHC @ CERN) |

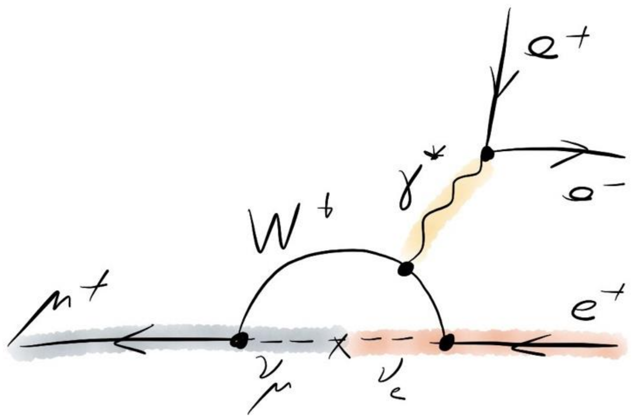
Further infos: S. Middleton Talk

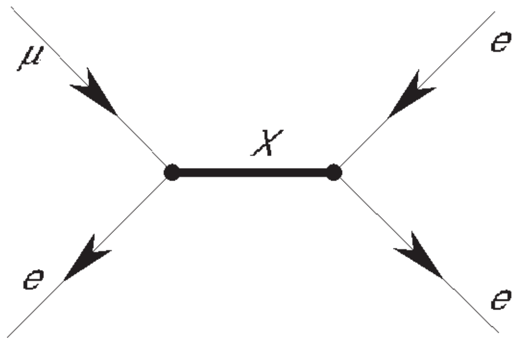
*Further infos: A. El-Khadra Talk*

# Physics of Mu3e: $\mu^+ \rightarrow e^+e^+e^-$

## Mu3e aims to look for the Charged Lepton Flavour Violation decay: $\mu^+ \rightarrow e^+e^+e^-$

- $\mu^+ \rightarrow e^+e^+e^-$ ... Technically allowed in the $\nu$SM but highly supressed ($O^{50}$)
- Any sign of $\mu^+ \rightarrow e^+e^+e^-$ would imply physics Beyond the Standard Model (BSM) as decay is strongly supressed in SM.
- Possible mechanism: Supersymmetric particles etc...




Further infos: S. Middleton Talk

*Further infos: A. El-Khadra Talk*

*Further infos: T. Menzo Talk*

# Previous attempts to measure $\mu^+ \rightarrow e^+e^+e^-$

- Processes like :
  - $\mu^+ \rightarrow e^+ \gamma$ ,
  - $\mu^- N \rightarrow e^- N$ ,
  - $\mu^+ \rightarrow e^+ e^- e^+$

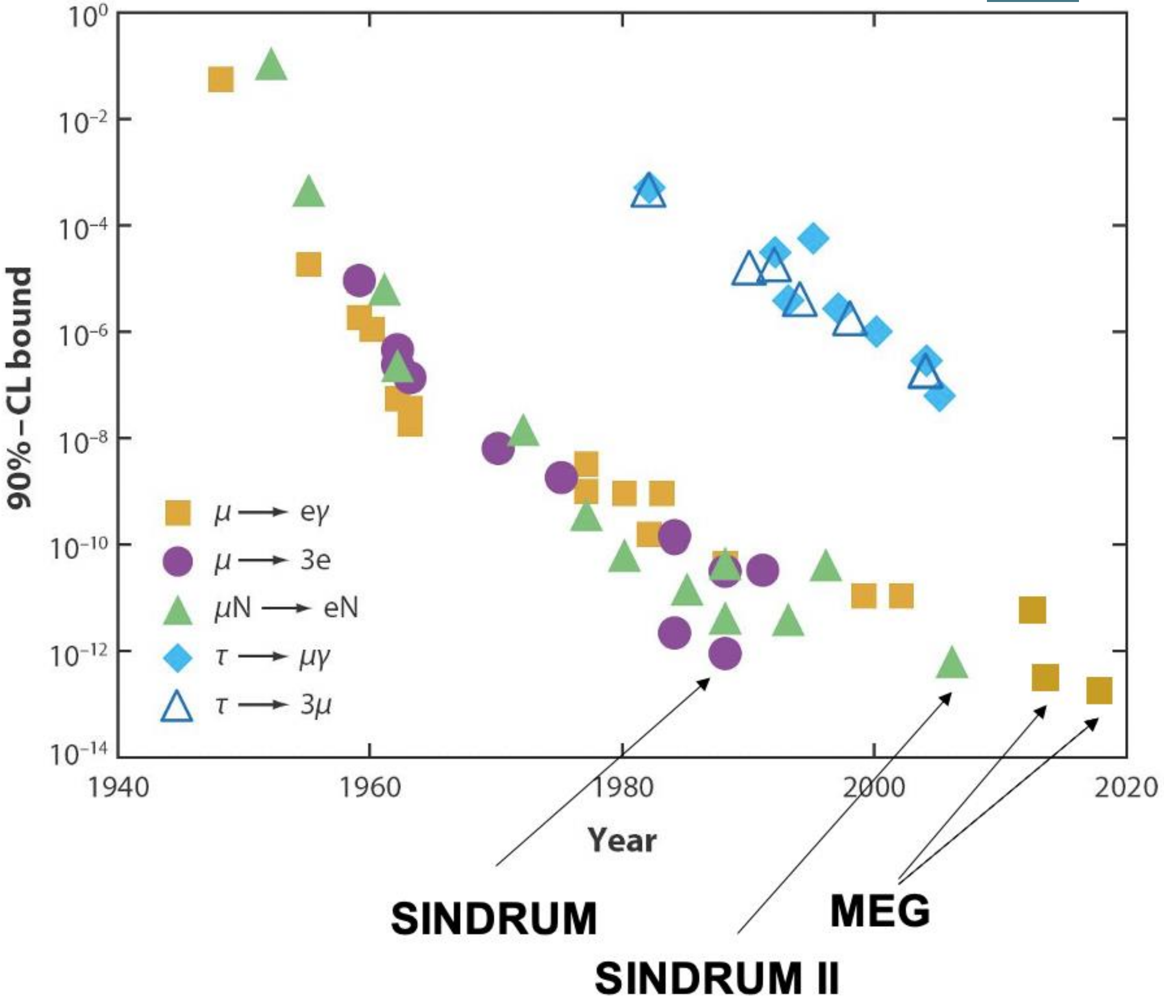
    → **not observed!**
- Best limits on LFV come from PSI muon experiments
  - $\mu^+ \rightarrow e^+ e^- e^+$

    BR < 1 x $10^{-12}$ (SINDRUM, 1988)
  - $\mu^- Au \rightarrow e^- Au$

    BR < 7 x $10^{-13}$ (SINDRUM II, 2006)
  - $\mu^+ \rightarrow e^+ \gamma$

    BR < 3.1 x $10^{-13}$ (MEG II, 2024)

See latest results from MEG 2 here

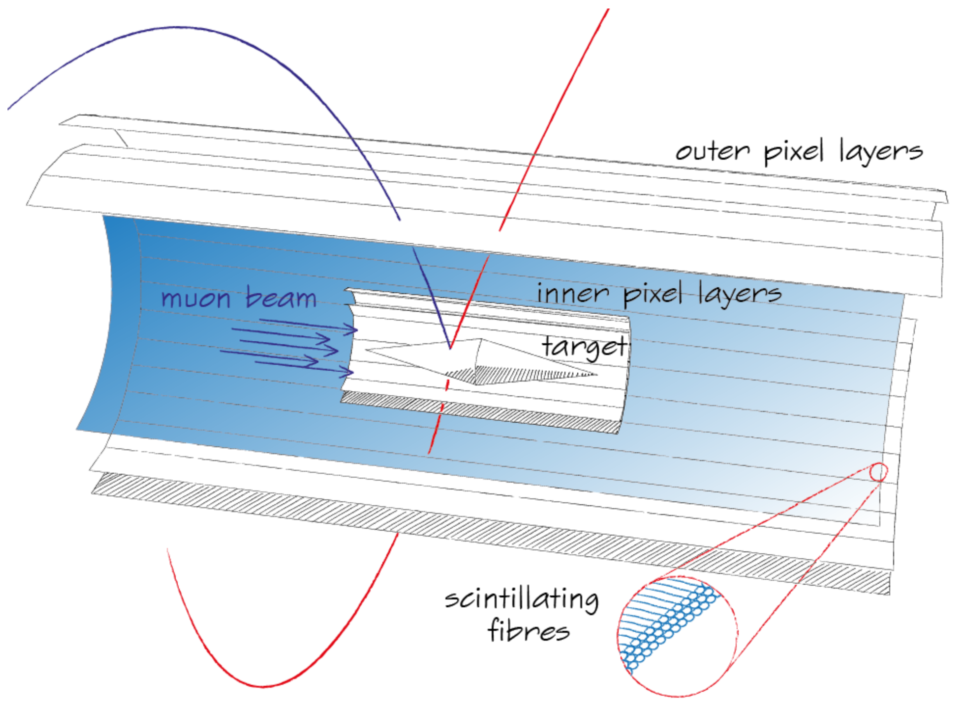


# Mu3e is going to use world's most intense muon beam to look for $\mu^+ \rightarrow e^+e^+e^-$

## Physics goals of Mu3e:

- Phase 1 goal: B(μ → eee ~ $\mathbf{10^{-15}}$)
- Phase 2 goal: B(μ → eee < $\mathbf{10^{-16}}$**)**

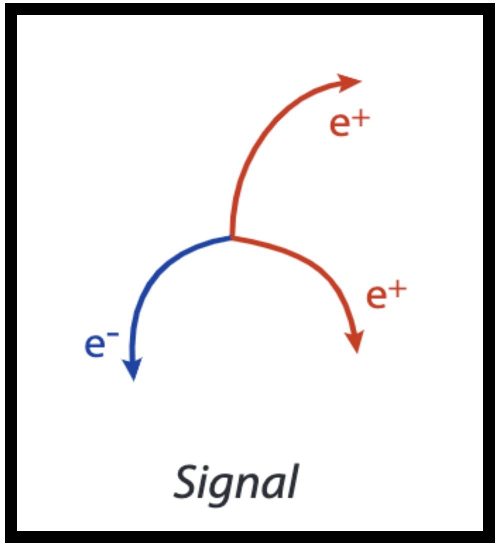
need more than $10^{17}$ muon decays…




## Only one option:

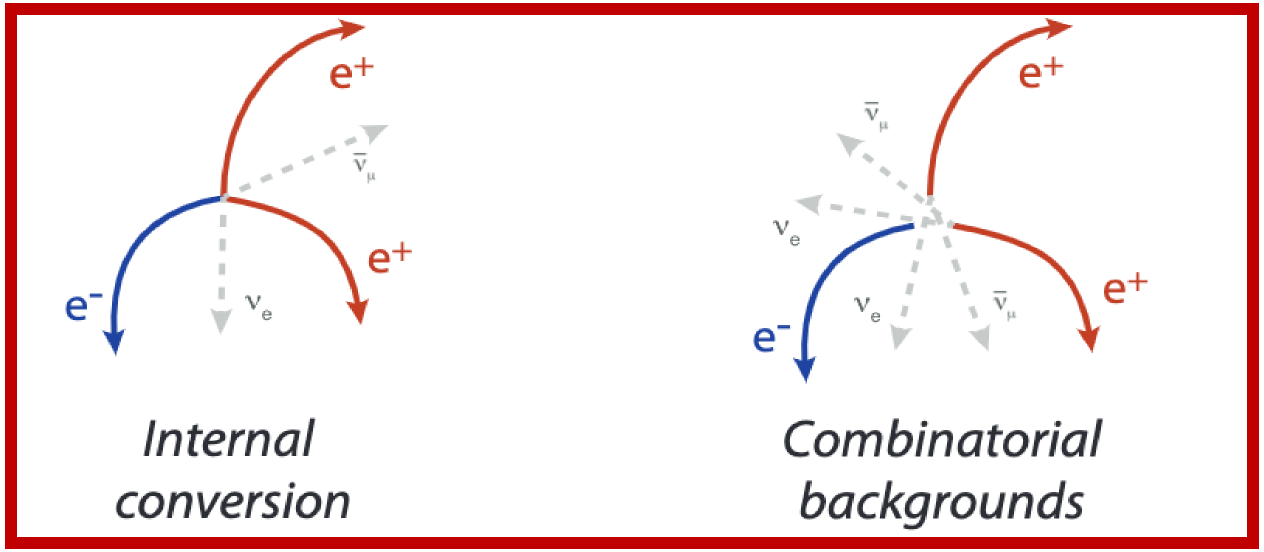
- World's highest intensity continuous muon beam ($\pi$E5 @ PSI)
  - Phase 1: ~$10^8$ muon decays/sec
  - Phase 2: >$10^9$ muon decays /sec
- Muons stopped on hollow target where they decay.

# Signal and Backgrounds




- Common vertex
- $\sum \mathbf{p}_i = 0$
- $\sum E_i = m_\mu$
- $\sum t_{eee} = 0$ (in time)

The signal of interest




- Common vertex
- **$\sum p_i \neq 0$**
- **$\sum E_i < m_\mu$**
- $\sum t_{eee} = 0$ (in time)

Need good momentum resolution

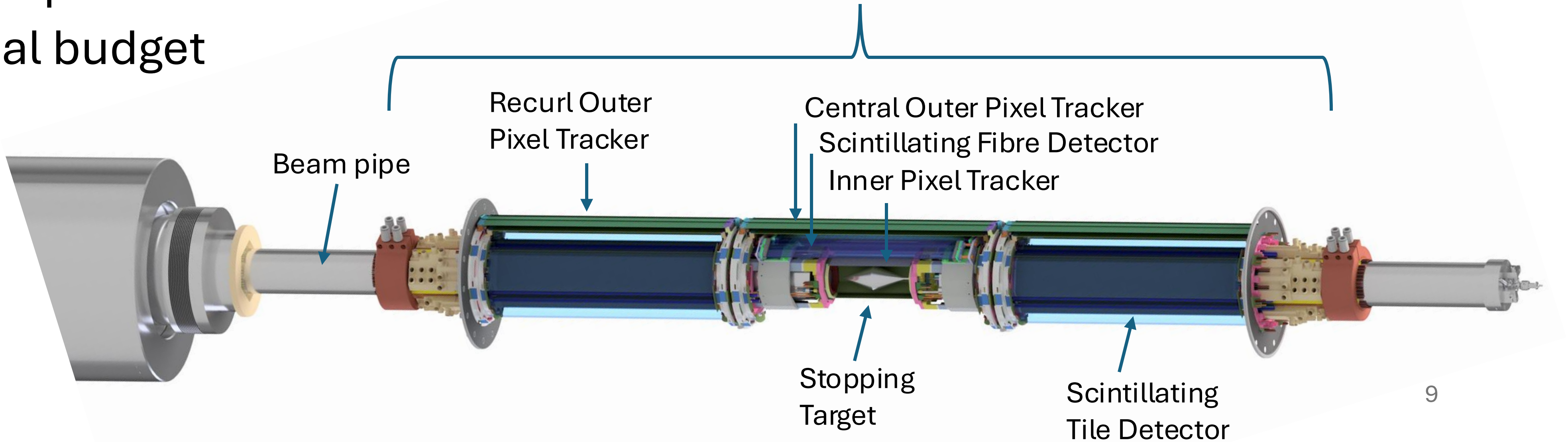
- **No common vertex**
- **$\sum p_i \neq 0$**
- **$\sum E_i \neq m_\mu$**
- **$\sum t_{eee} \neq 0$ (out of time)**

**Need very good timing**, vertex and momentum resolution

# Mu3e – General Detector Requirements

General technical requirements:

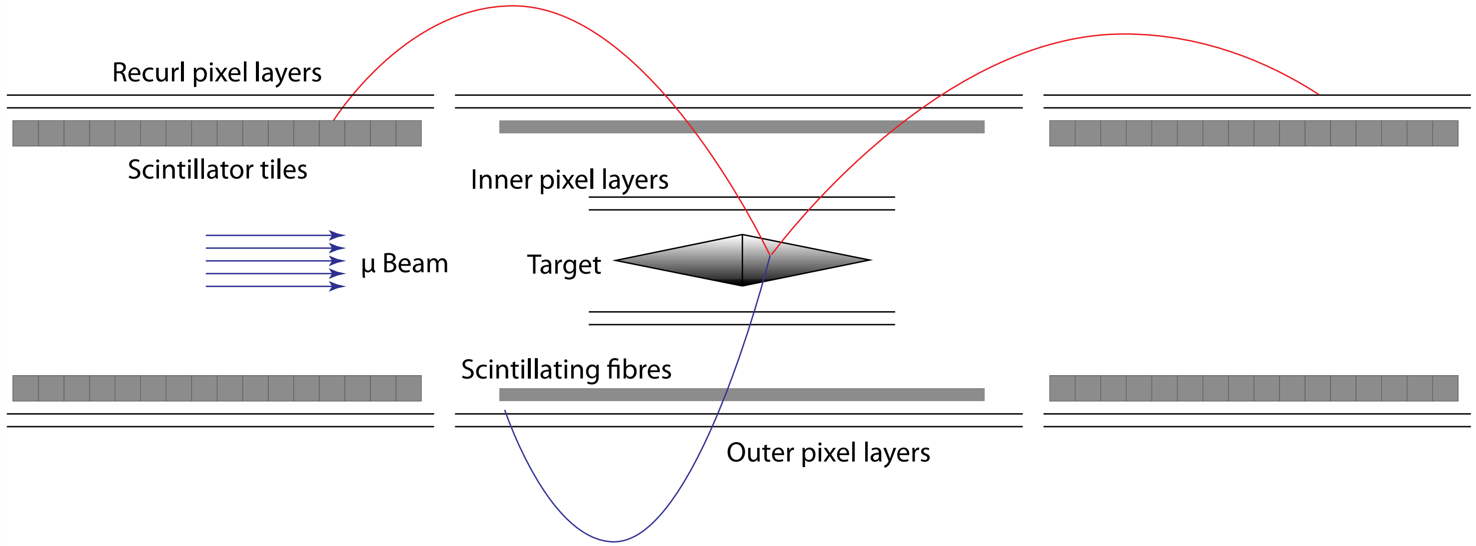
- Many muon decays needed (Phase 1+2): $10^{17}$
- Timing resolution: Better than 500 ps
- Momentum resolution: < 0.5 MeV/c
- Spatial resolution: ~ μm
- Fast data acquisition: $10^{8}$ Hz rates
- Low material budget



# Mu3e – Particle Detection Principle

Particle's direction through detector:

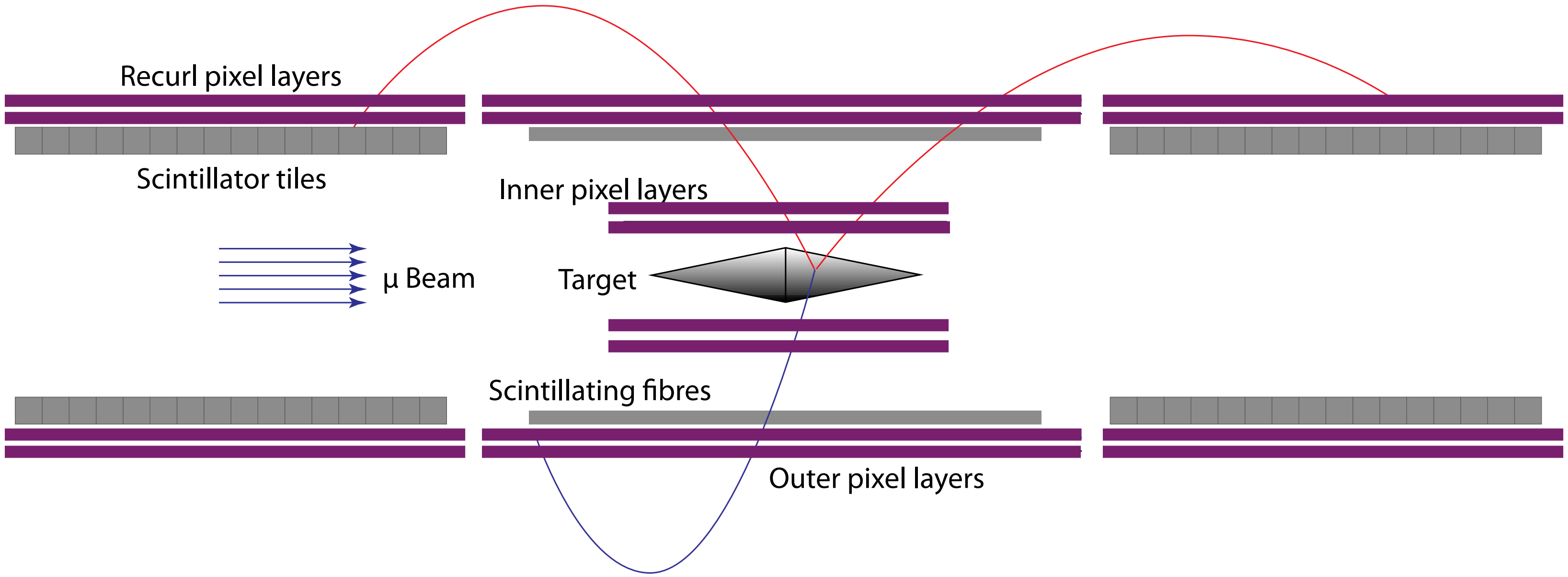
- Muons decay at rest in target
- Electrons and positrons start propagating in magnetic field
- Charged particles recurl in 1 T magnetic field → <u>$e^+/e^-$ detected a second time.</u>



# Mu3e – Subdetector roles - Pixel

## Detectors:

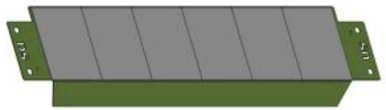
- **Pixel** detectors for tracking: vertex, outer-central, and recurl
- Thin Scintillating Fibers for timing: central
- Scintillating Tiles for timing: recurl



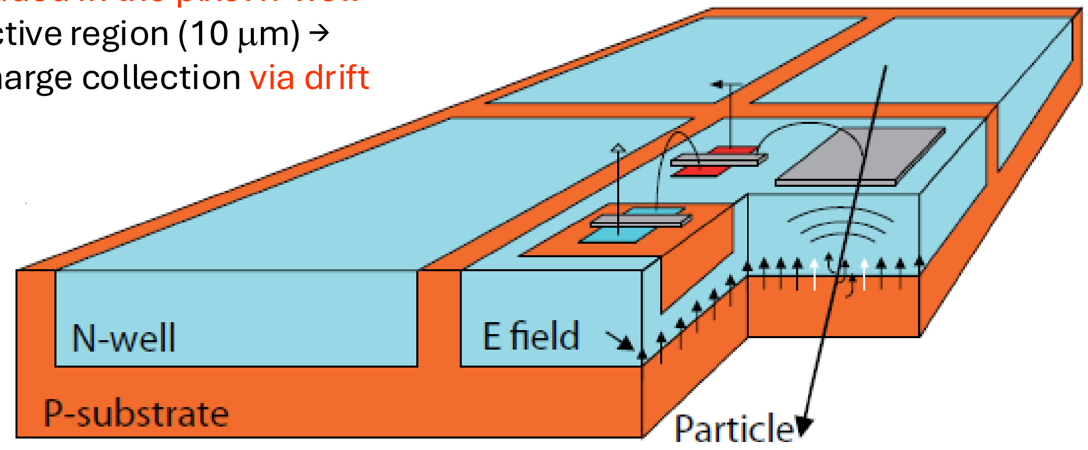
# Silicon pixel detector HV-MAPS

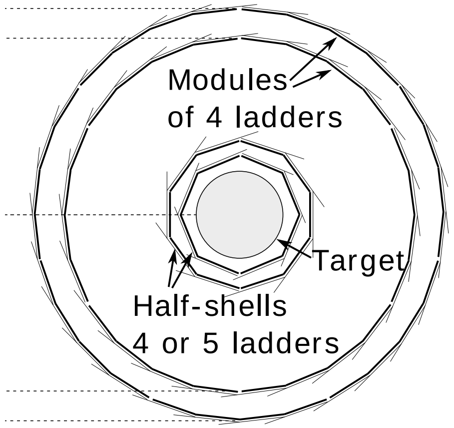
Pixel tracker – High Voltage Monolitic Active Pixel Sensors (HV-MAPS) - MuPix

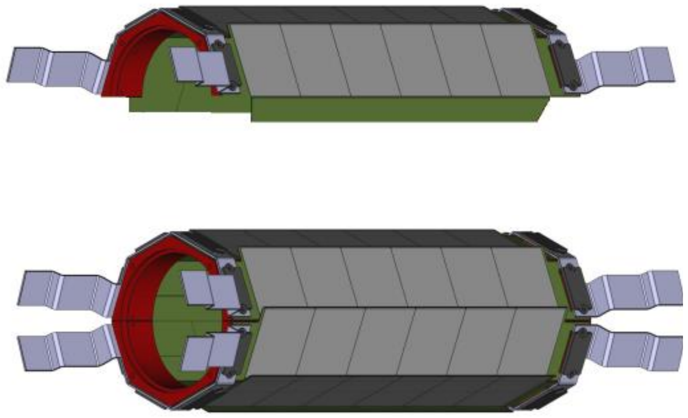
- Hits matched between two inner layers and two outer layers
- Cooled with helium gas
- Acceptance increased with recurl stations
- 50 µm thickness (vertex), 70 µm (recurl)
- Active area 20 x 20 mm$^2$ (23 mm including readout area)
- Operated with up to 70 V



- readout logic and amplifiers embedded in the pixel n-well
- thin active region (10 µm) → fast charge collection via drift



# Pixel tracker - Status

11 year R&D period over…

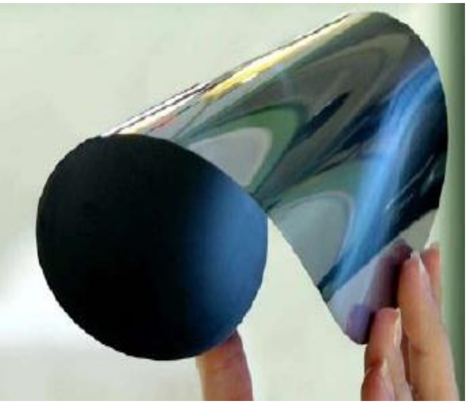
Inner pixels installation in progress

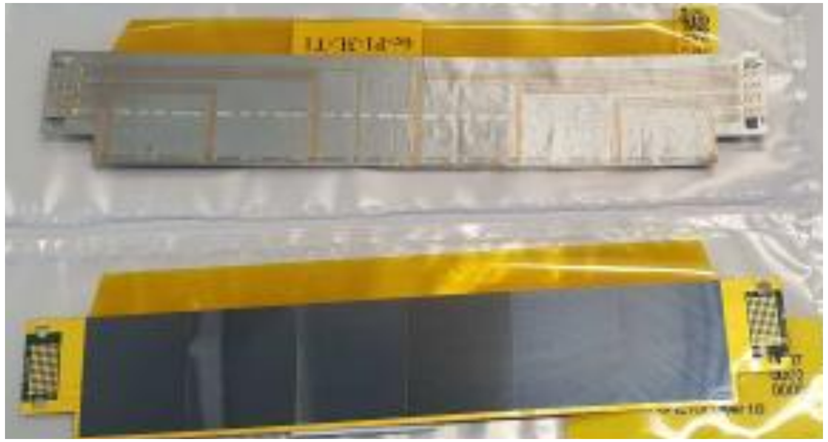
Helium gas cooling installed

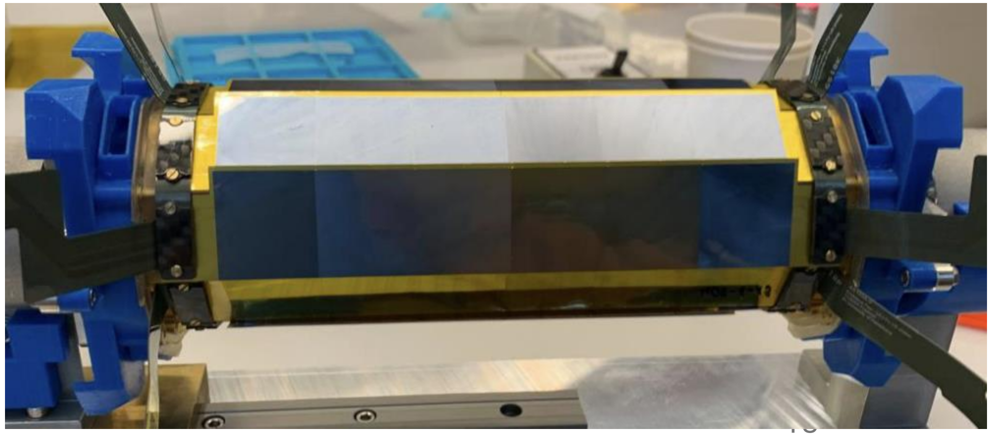
~23 µm spatial resolution, efficiency 99%*, < 20 ns time resolution

**Two layer vertex detector to be installed by November**

50 µm thick silicon wafer





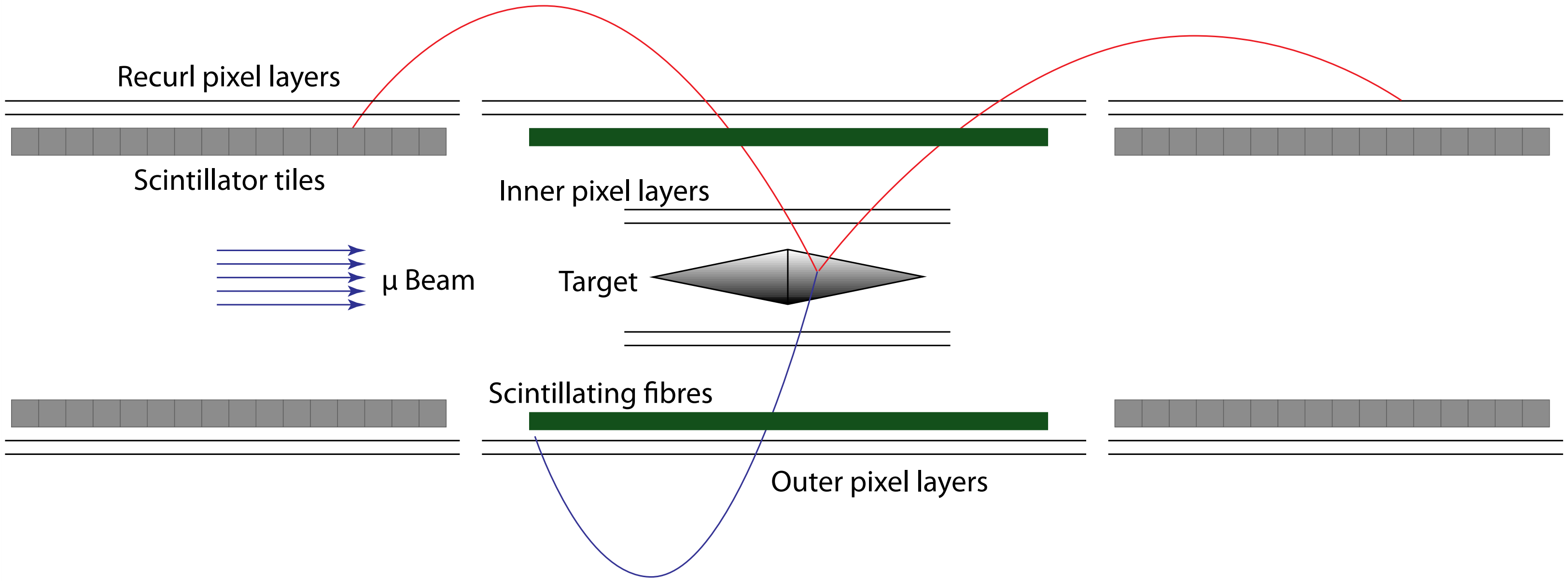


easily achievable with 70 µs, a bit more challenging with 50 µs

# Mu3e – Subdetector roles - SciFi

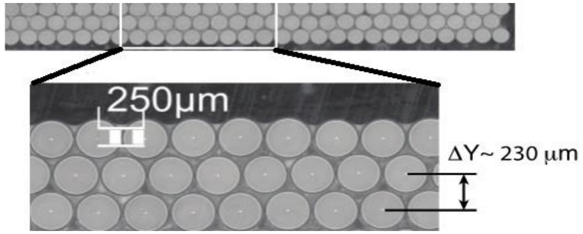
Detectors:

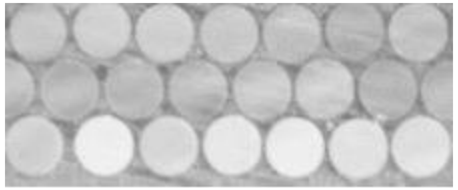
- Pixel detectors for tracking: vertex, outer, and recurl
- Thin **Scintillating Fibers (SciFi)** for timing: central
- Scintillating Tiles for timing: recurl

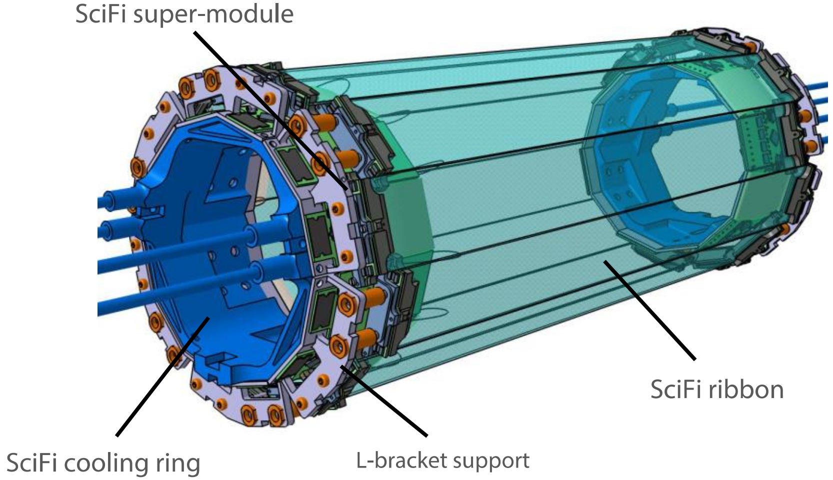


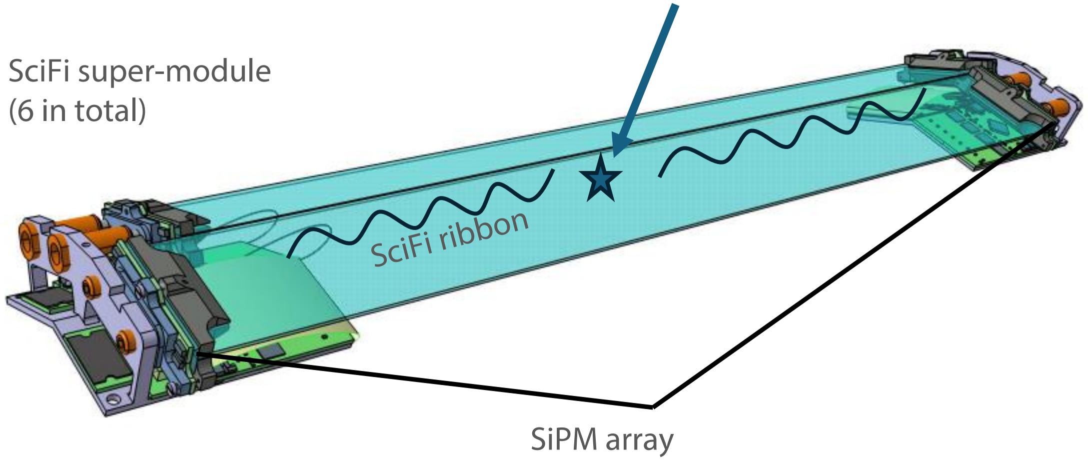
# Timing at centre: Scintillating Fibre (SciFi) detector

- SciFi basics:
  - 3 layers of 250 μm staggered fibres
  - 12 long fibre ribbons covering 4 $\pi$
  - 1 ribbon = 720 μm thick, 0.2 % radiation length
  - 300 ps time resolution
  - Liquid cooling (SilOil, -20°) through the Cooling Ring (CR).





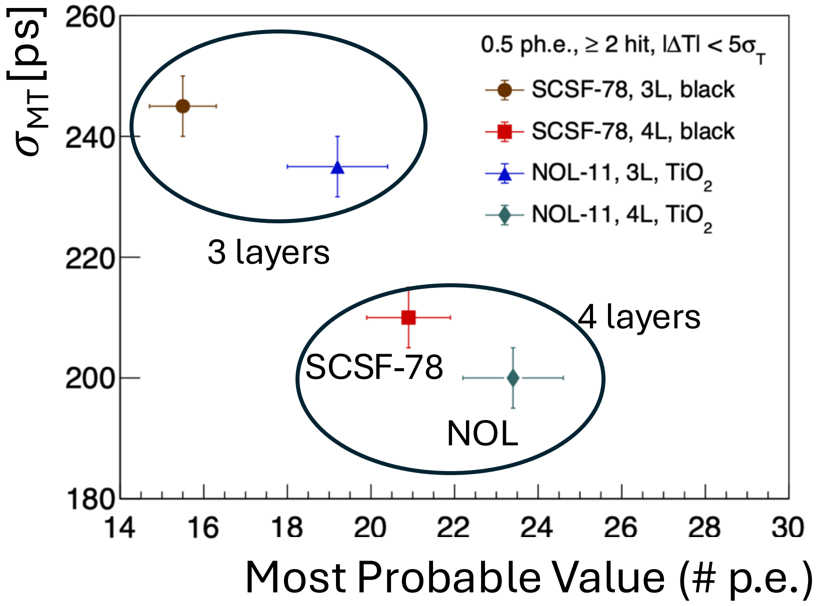



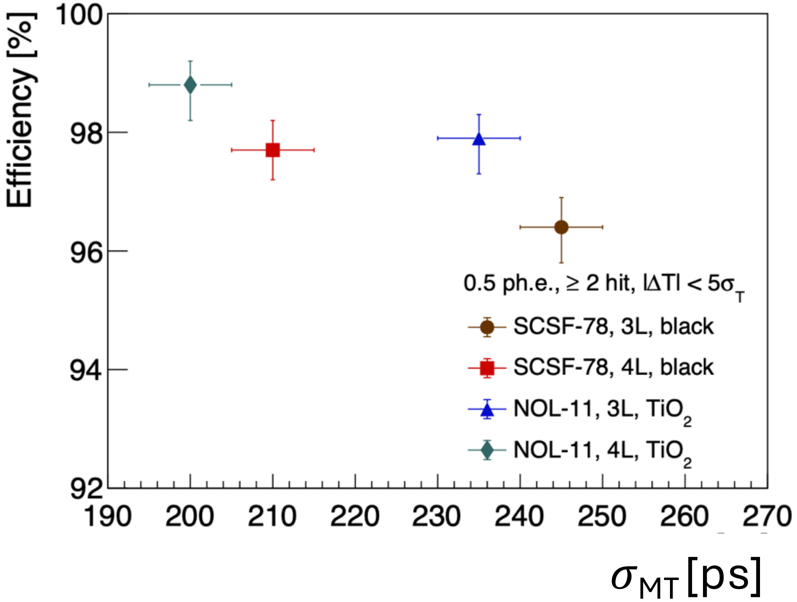

Particles produce photons which propagate towards the ends

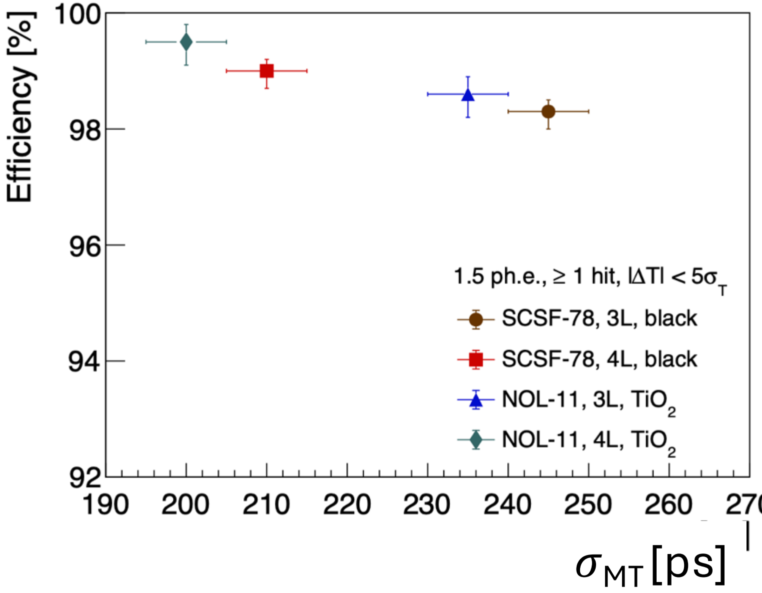
- Each ribbon has SiPM arrays at its ends
- 256 channels per ribbon, 3072 for SciFi.

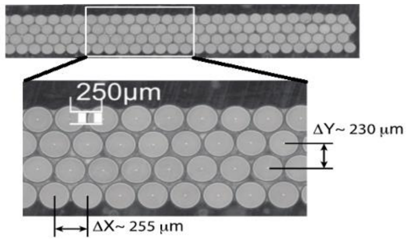
# Timing at centre: Scintillating Fibre (SciFi) detector

Performance of the SciFi detector



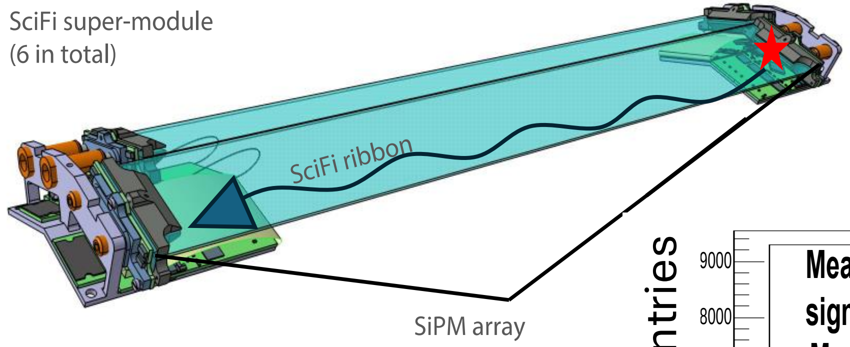




**NOL** (1.1 ns) – shorter decay time than **SCSF-78** (2.8 ns)
Not a great impact on the time resolution
→ **Photon number is the dominant contribution.**

3 layer SCSF-78 scintillator radiation length $X/X_0$ ~ 0.2%
→ Final design

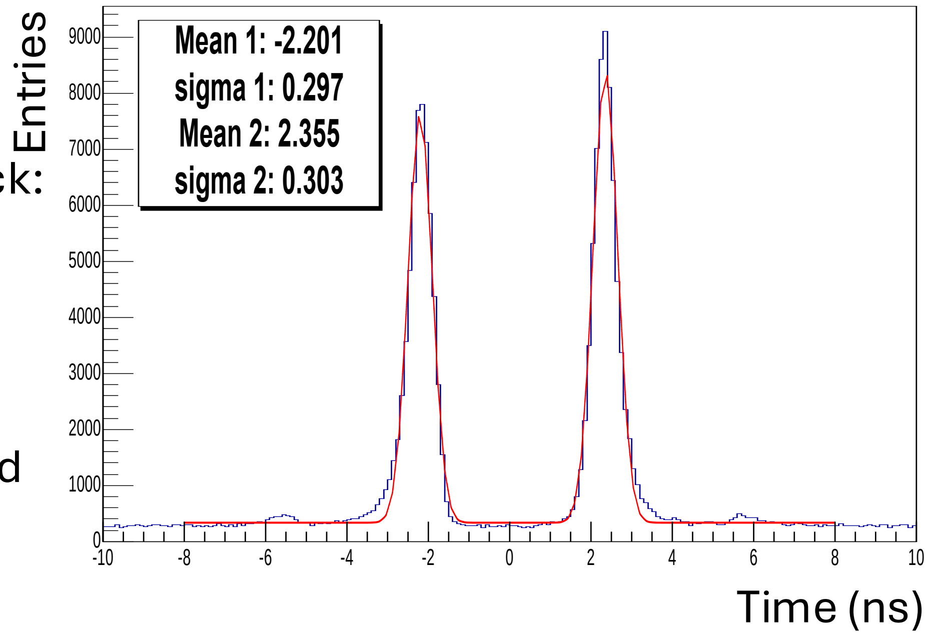
# Defining quality control methods for mass production

A dark-count photon can produce cluster both on the left or the right of the ribbon.




Double peak plot used to check:

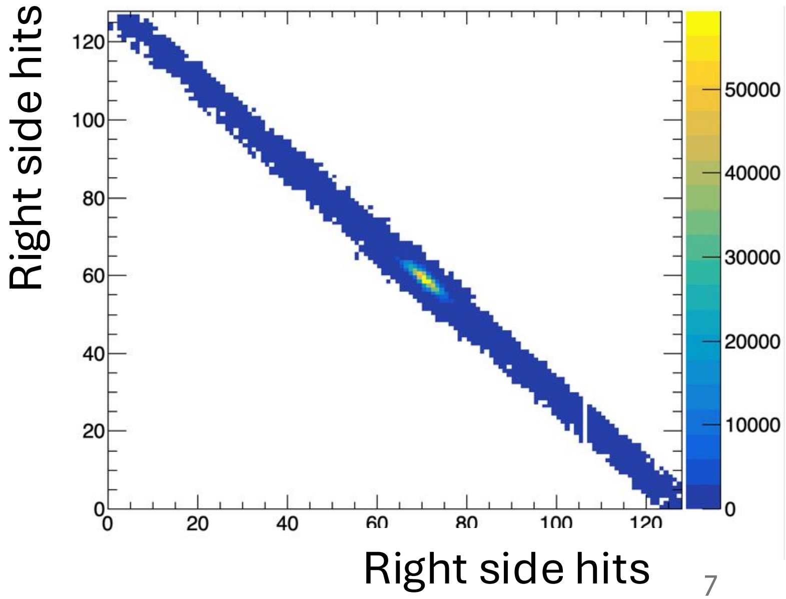
- Good overal optical properties
- Width → expected resolution ~300 ps
- Allignment at 0 → Good time sync between left and right.



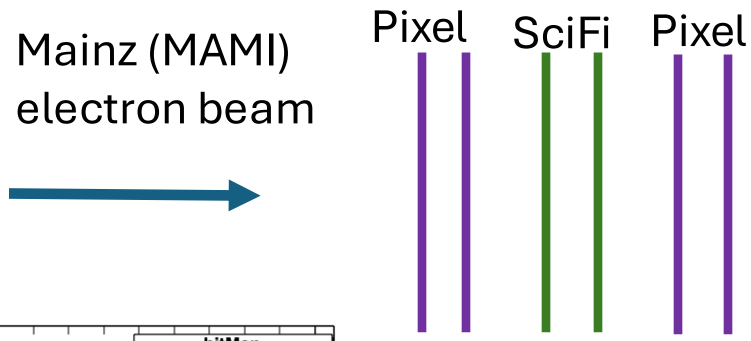

## Ribbon scan with source

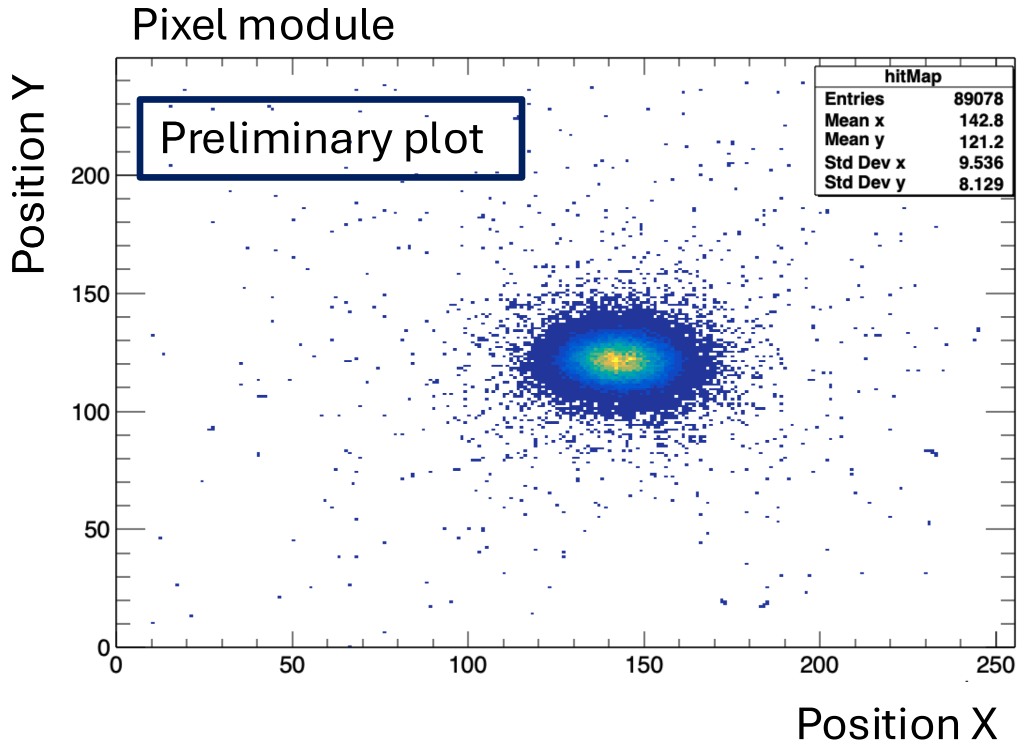
Used to check:

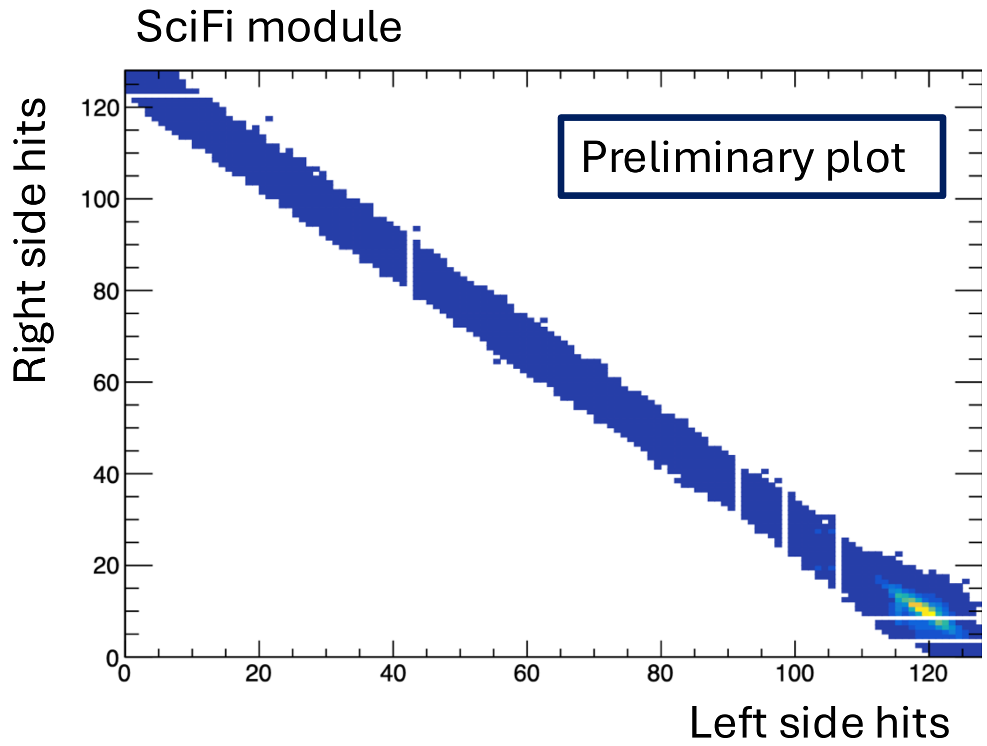
- Dead/noisy channels
- General data quality from one ribbon.



# Beam test results – SciFi qualification with MuTRiG ASICs



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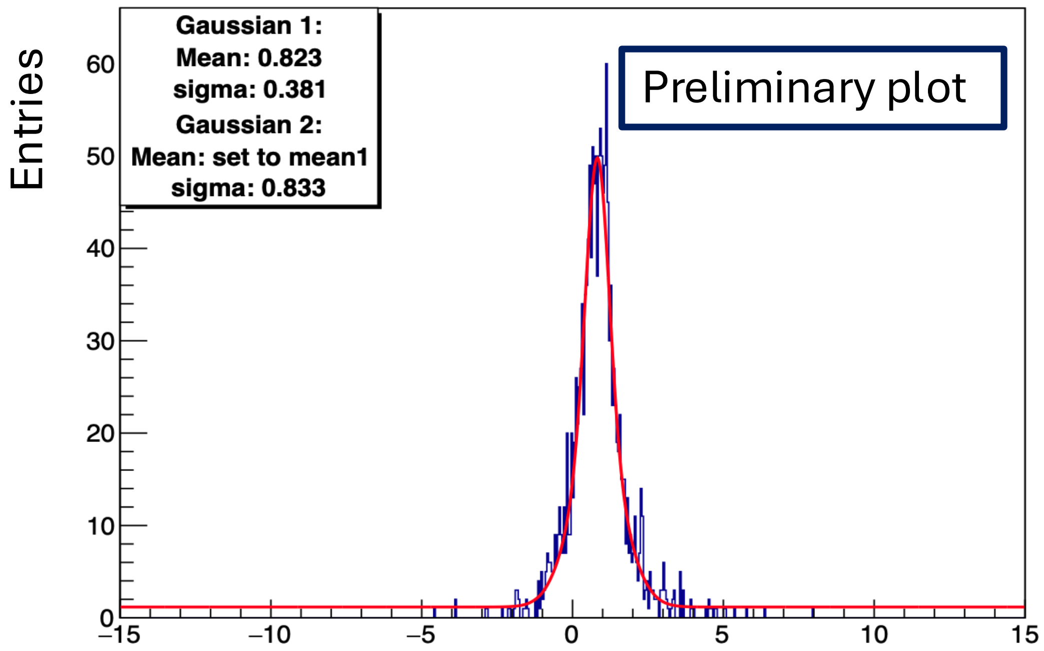
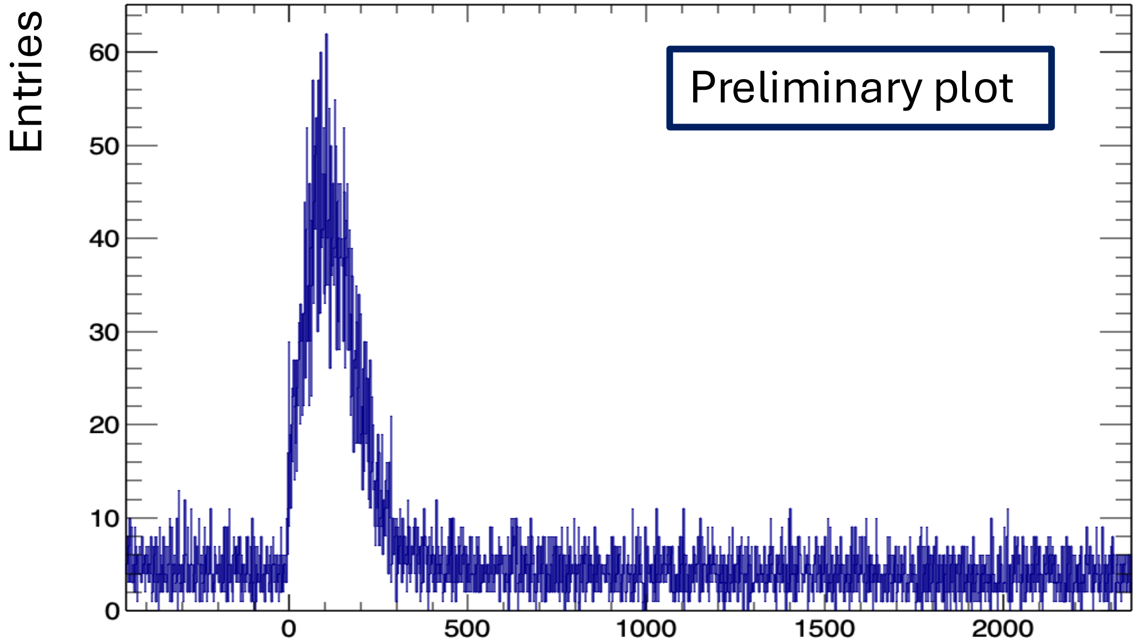



Time difference between coincidences at two ribbons (ns)



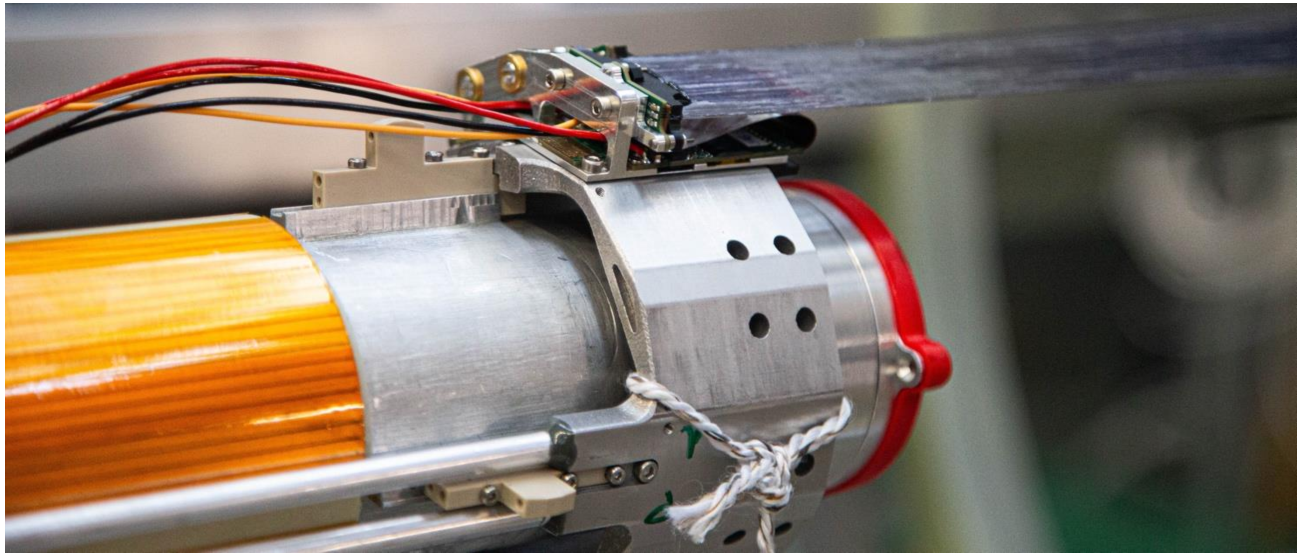

Time correlation between Pixel and SciFi (ns)

Excellent Mean Time resolution maintained for two ribbon coincidences: ~ 381 ps.

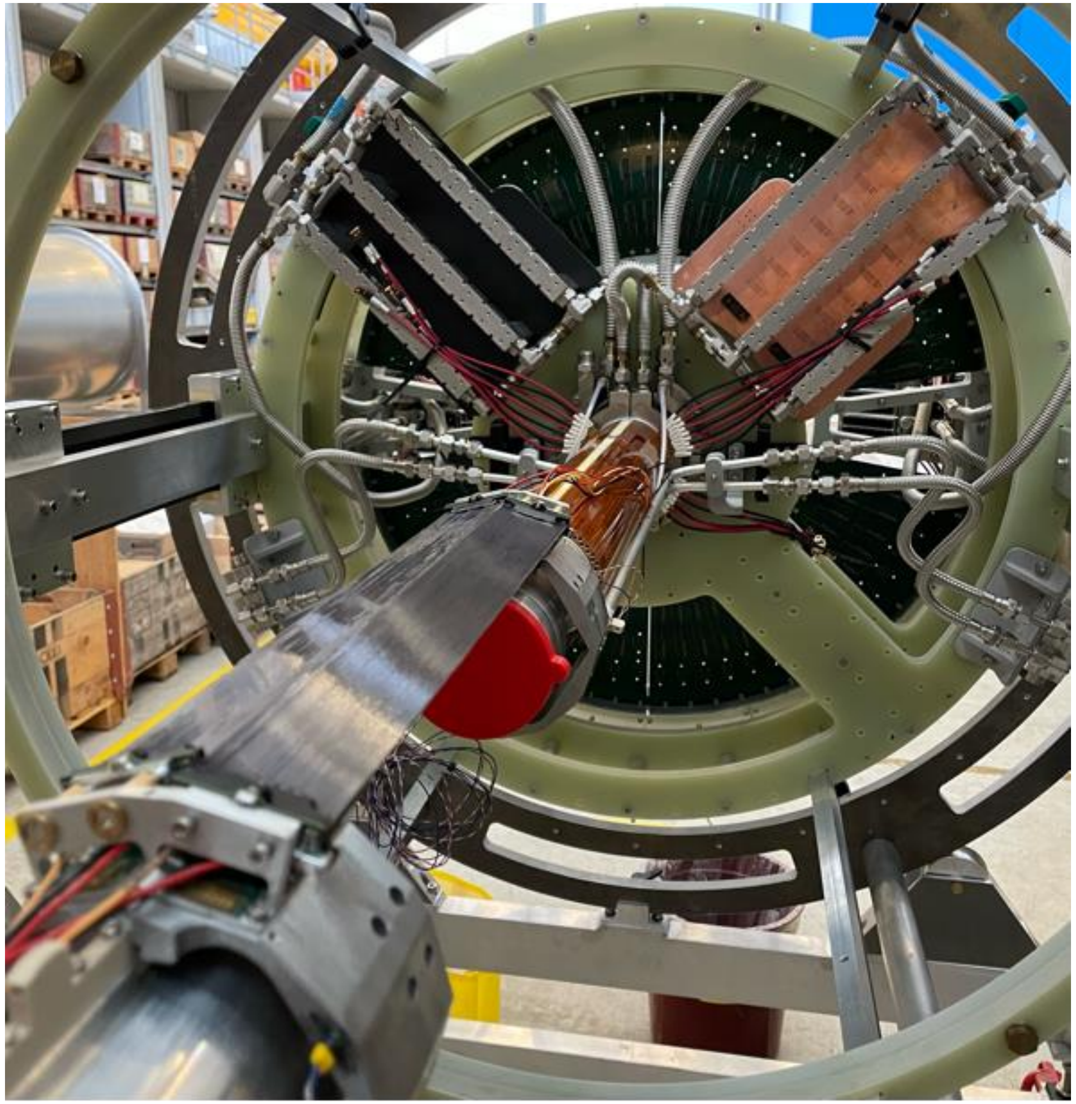
Preliminary plot: Correlation between final version of both pixel detectors and SciFi.

# SciFi detector - Status

- 6 modules produced
- To be installed by November
- Liquid cooling system installed



cc Niklaus Berger – [Flickr Mu3e]



# Mu3e – Subdetector roles - SciTile

Detectors:

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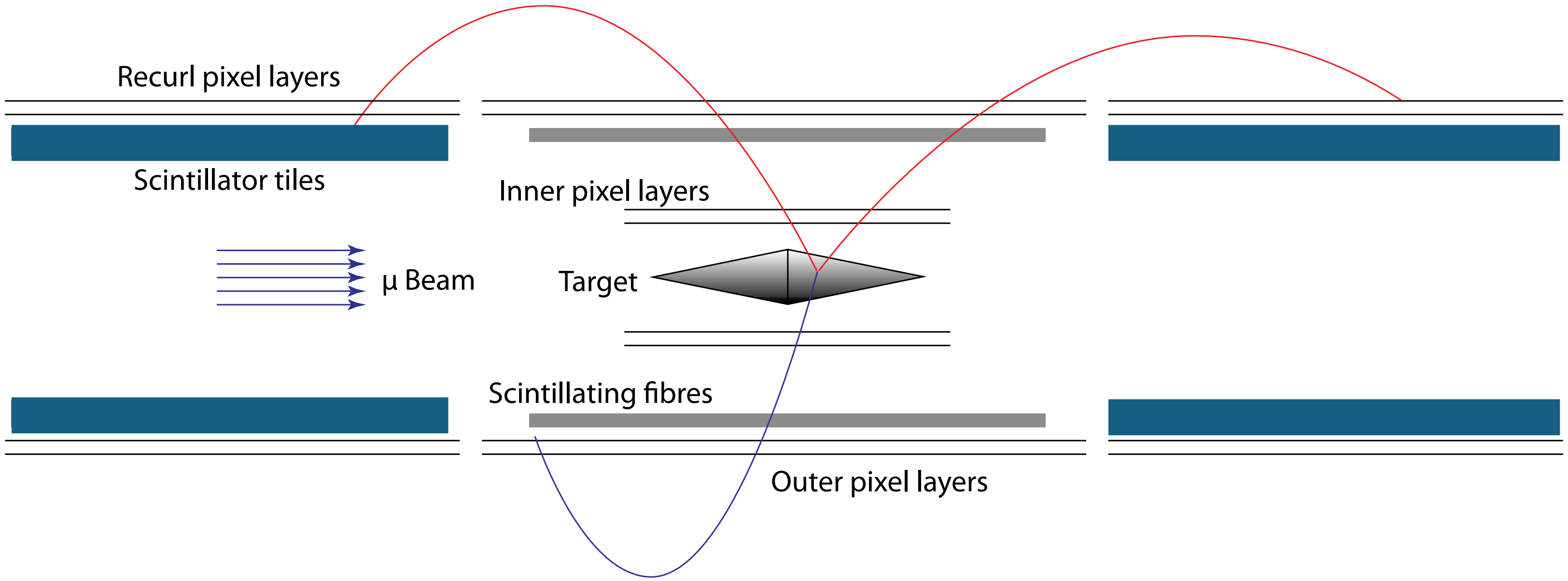
- Thin Scintillating Fibers for timing: central
- **Scintillating Tiles** (SciTi) for timing: recurl

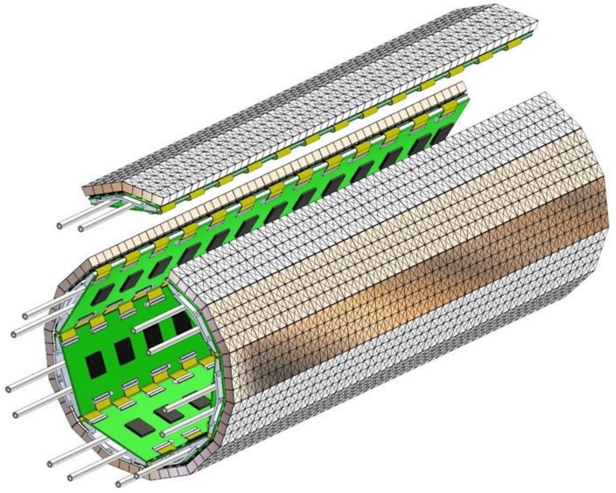


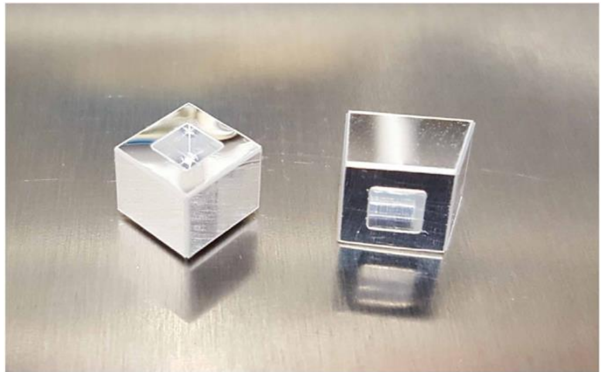
# Mu3e – Subdetector roles - SciTile

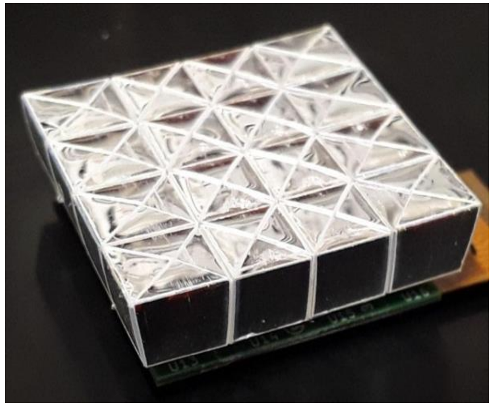
**No tight material limitation** on Detector volume → “Thick” detector
Highly segmented in ~6k tiles
Very compact design

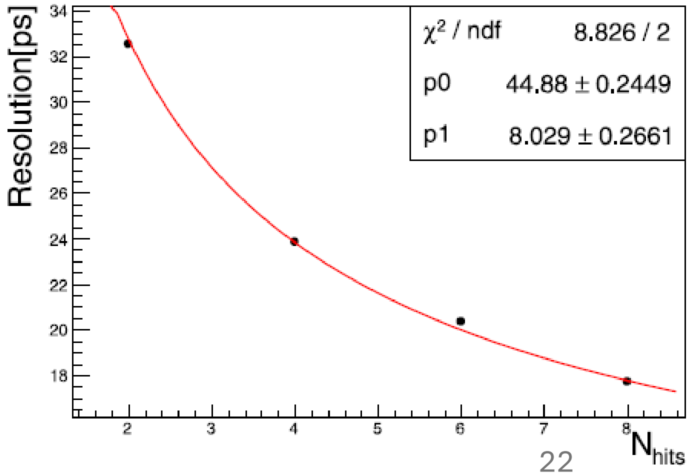
- Tiles from fast Ej-228 plastic scintillator (6 x 6 x 5 mm$^3$)
- Individually wrapped in ESR foil - Minimize crosstalk
- Coupled to Hamamatsu SiPMs read out by Mutrig ASIC (S13360-3050VE @ -10°C, Silicon oil cooling)
- Efficiency > 99%, single-channel time resolution ~ **40 ps**
- Performance validated in Demonstrator Modules

- First final modules produced









# Mu3e – Plans for 2024 and further

**Achievements so far:**

- DAQ operational with different detector types
- Cooling for detectors
- Pixel, SciFi, SciTile → First modules installed

**Aims for rest of the year:**

- Cosmic run
- Complete experimental chain
  - Detector installation
  - Data taking

Cosmic run with inner pixel and SciFi — Nov/Dec 2024

Full detector commissioning — 2025

Physics data taking — 2026

# Thank you, Argonne!

Mu3e gallery ( Nik Berger)

# Bibliography:

[1] Mu3e Letter of Intent (2012), https://www.psi.ch/sites/default/files/import/mu3e/DocumentsEN/LOI_Mu3e_PSI.p
[2] Mu3e Technical Design Report (2020), https://arxiv.org/abs/2009.11690