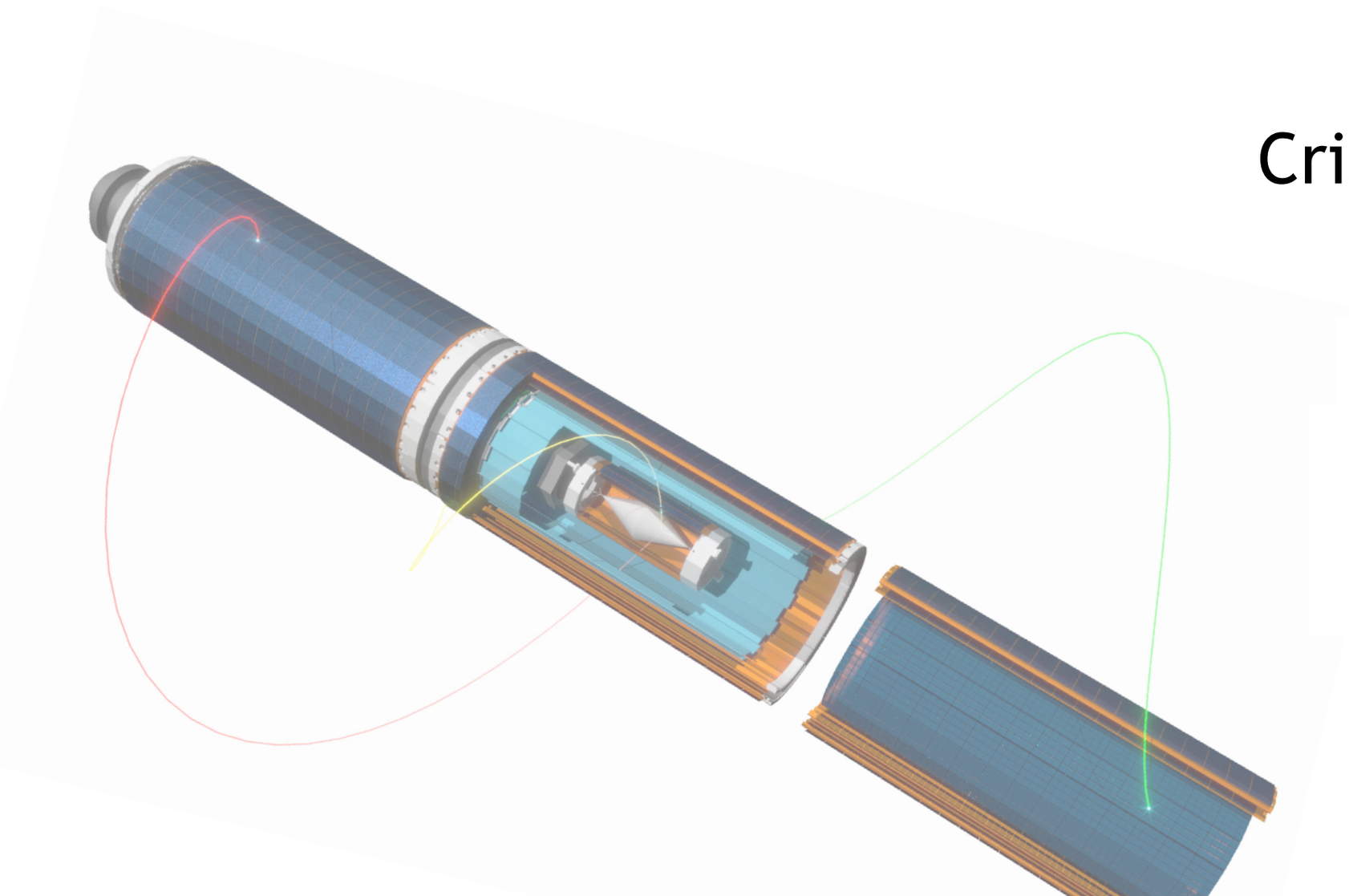
Precision timing in Mu3e towards the search for μ→eee



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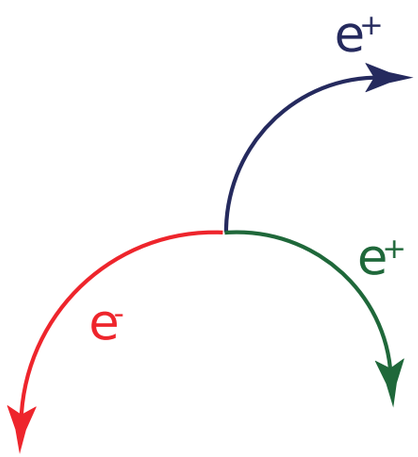
PAUL SCHERRER INSTITUT PSI

LF(U)V workshop
6 July 2022

The Mu3e experiment

- The Mu3e experiment searches for $\mu^+ \rightarrow e^+e^-e^+$:
  - evidence of of **charged LFV** → signature of New Physics
  - **sensitivity** of ~10^{-15} (Phase I) down to ~10^{-16} (Phase II)
  - world's most **intense muon beam** (10^8 muons/s) at PSI
- It is an **experimental challenge**:
  - **thin**, **fast** and high **resolution** detectors
  - signal vs. background discrimination with **energy**, **timing** and **vertexing**:

Signal



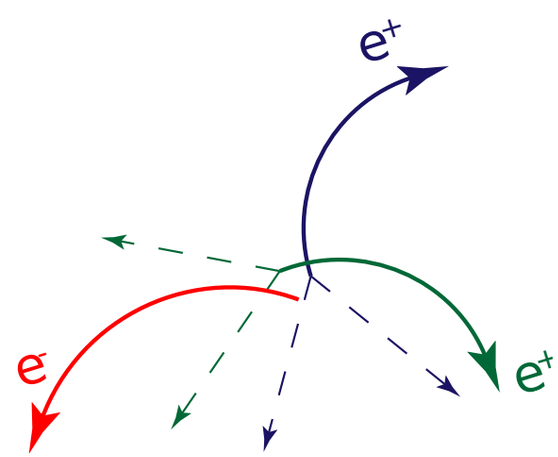
common vertex

coplanar $\Sigma\, \mathbf{p}_i = 0$

$\Sigma\, E_i = m_\mu$

$\Delta\, t_{eee} = 0$

Accidental background



no common vertex

$\Sigma\, \mathbf{p}_i \neq 0$

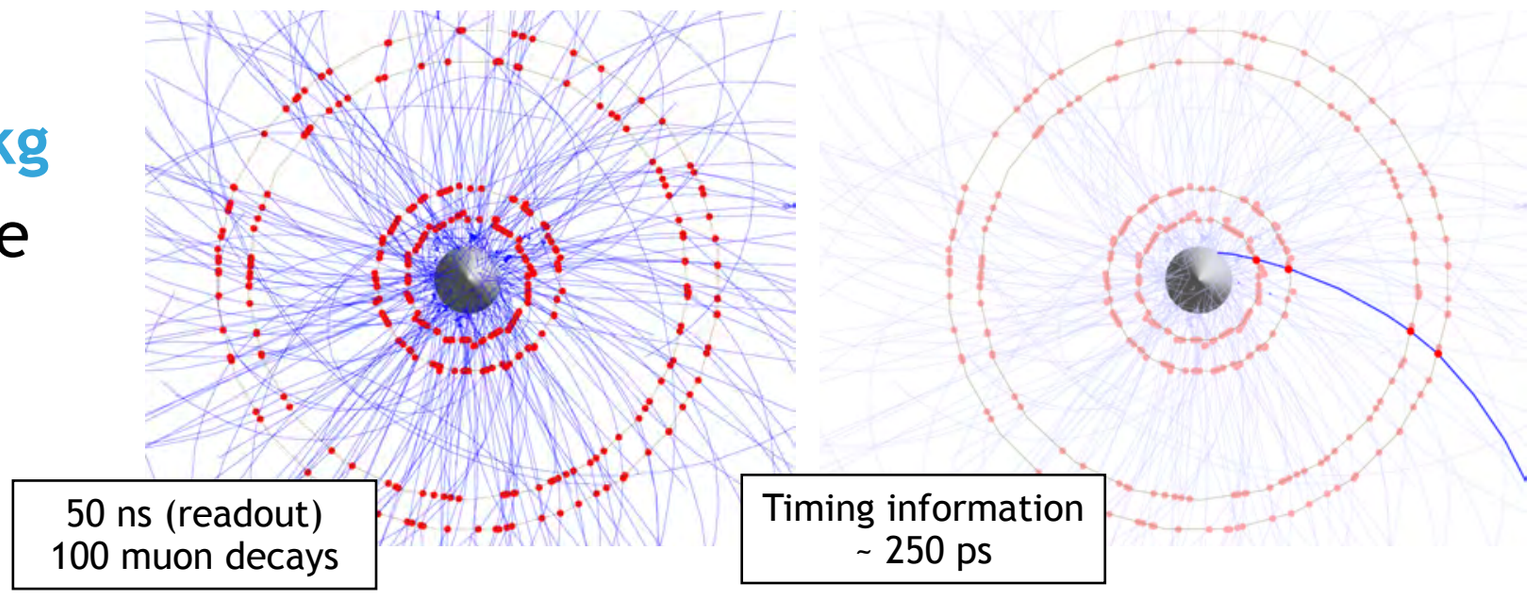
$\Sigma\, E_i \neq m_\mu$

$\Delta\, t_{eee} \neq 0$

Precise timing!

The importance of precise timing

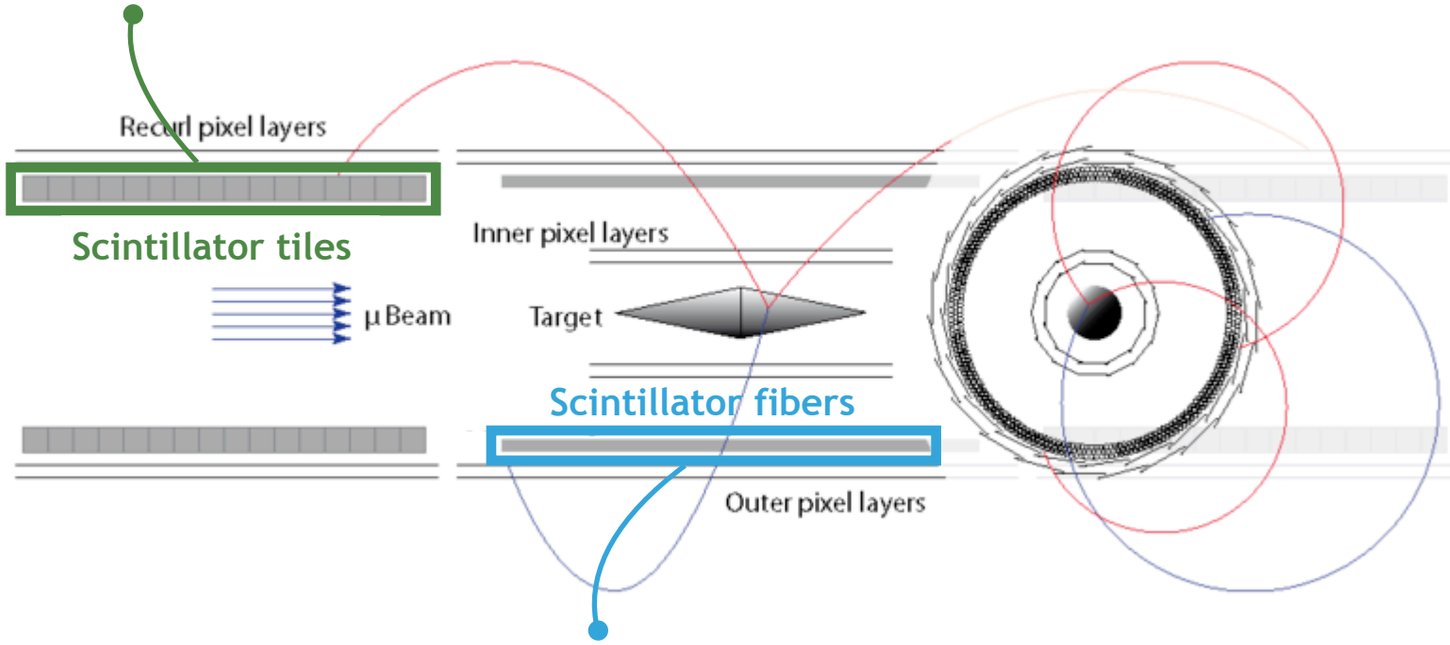
- Precise timing detectors:
  - reduction of accidental bkg
  - track identification/charge



Scintillator tiles

~70 ps resolution

>99% detection efficiency



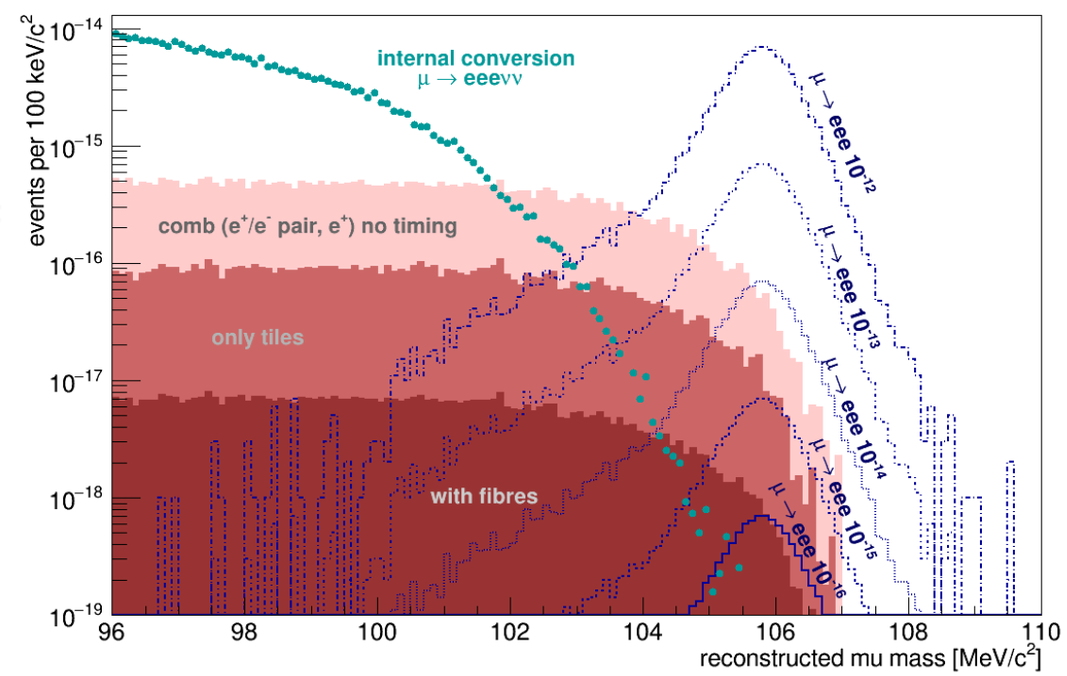
Scintillator fibers (SciFi)

~500 ps resolution

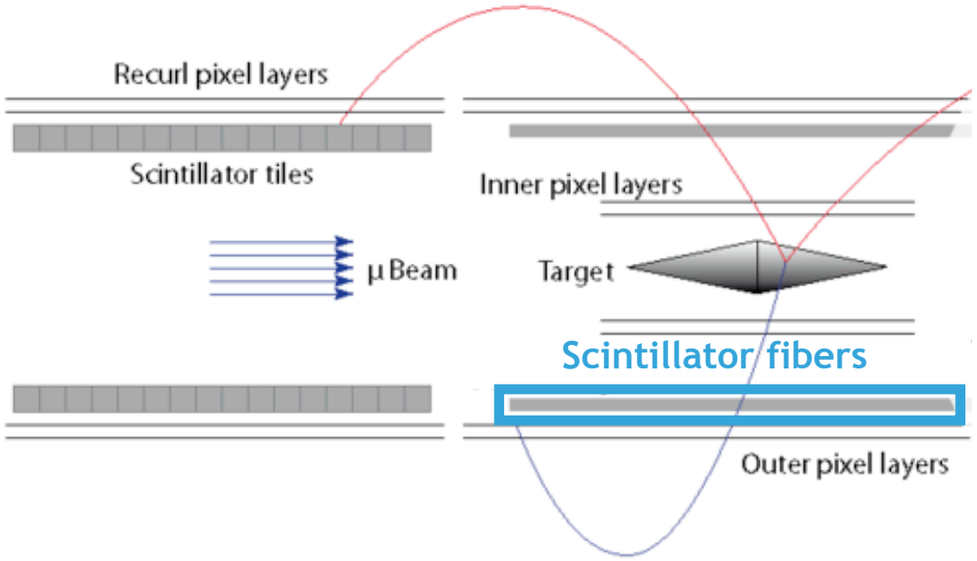
>95% detection efficiency

Tiles + fibers =

~75% accidental bkg suppression



The SciFi detector



Requirements

Time resolution < **500 ps**

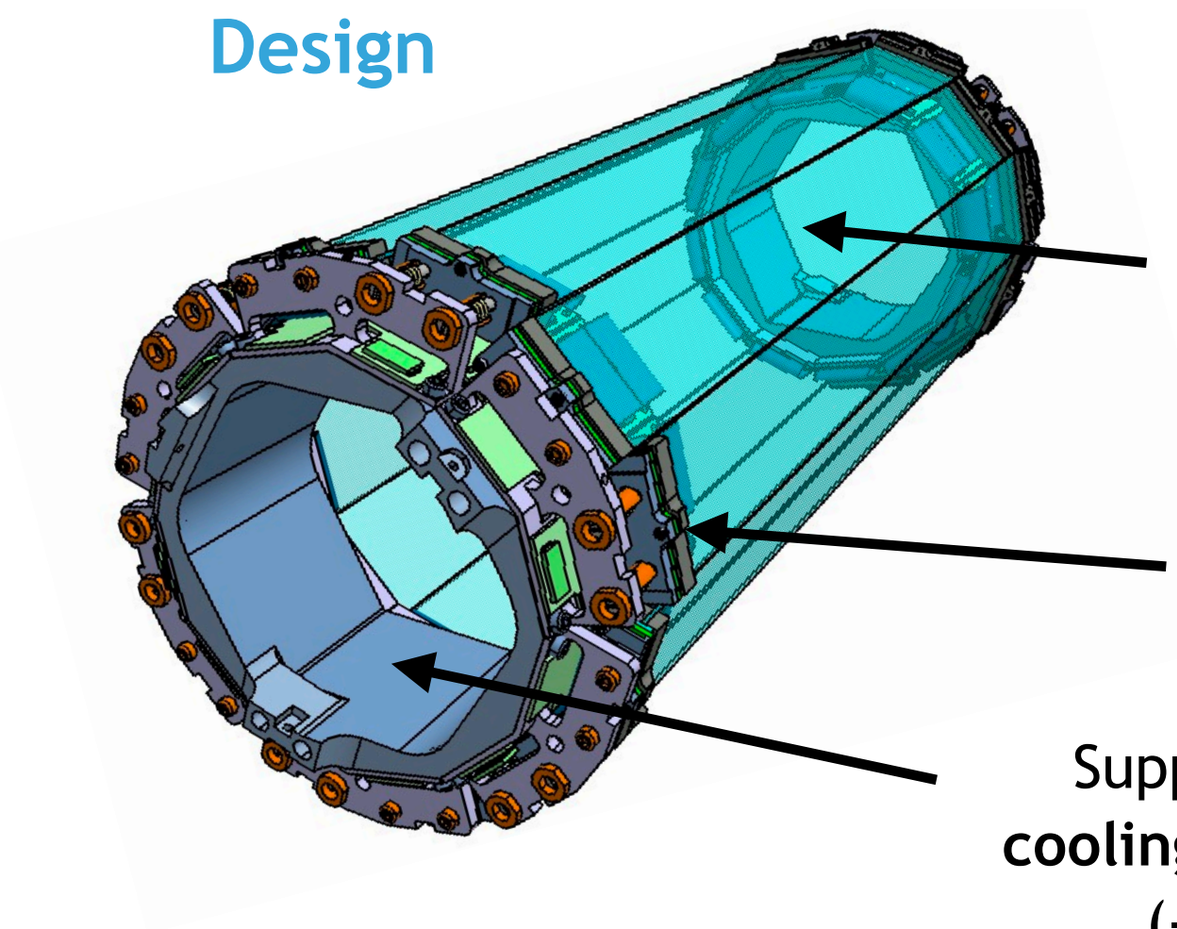
Efficiency > **95%**

Thickness x < **0.3%** x_0 (<1 mm)

High occupancy (**250 kHz/ch**)

Tight **space** (electronics, cooling)

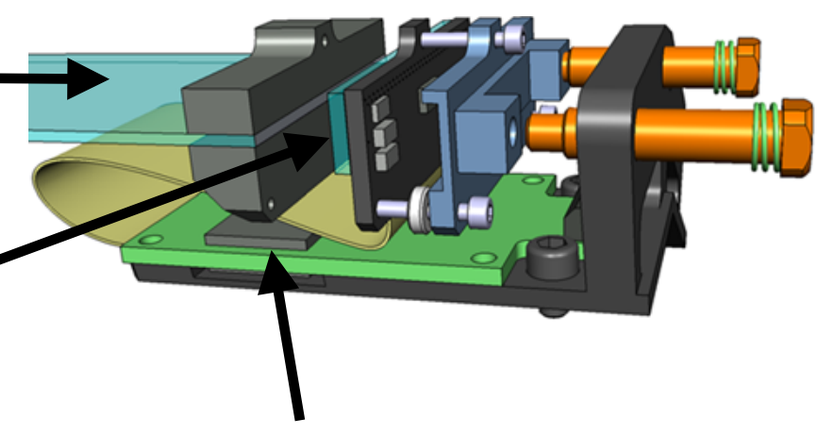
Design



12 scintillating **fiber** ribbons at ~6 cm

24 **SiPM** arrays at both ends

Support and **cooling** structure (-20°C)

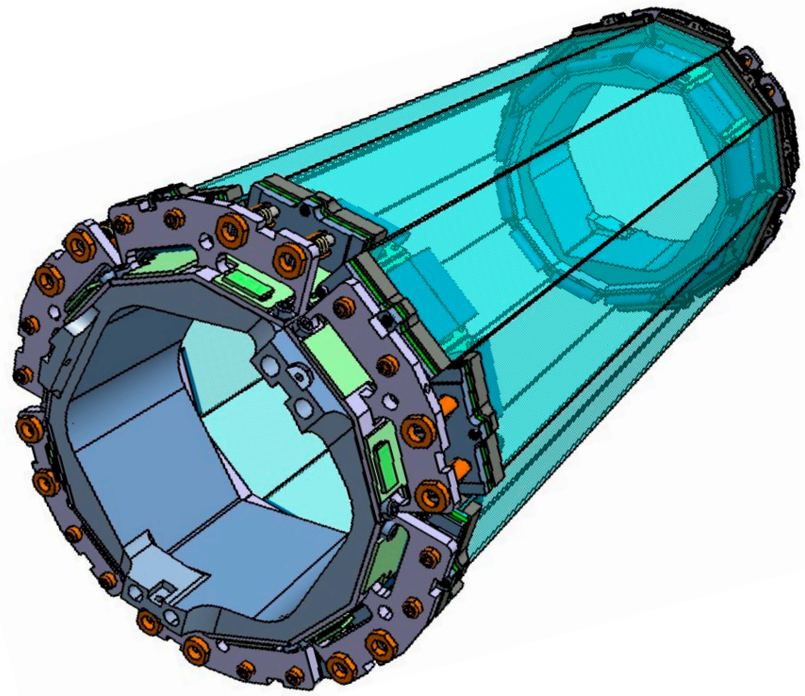


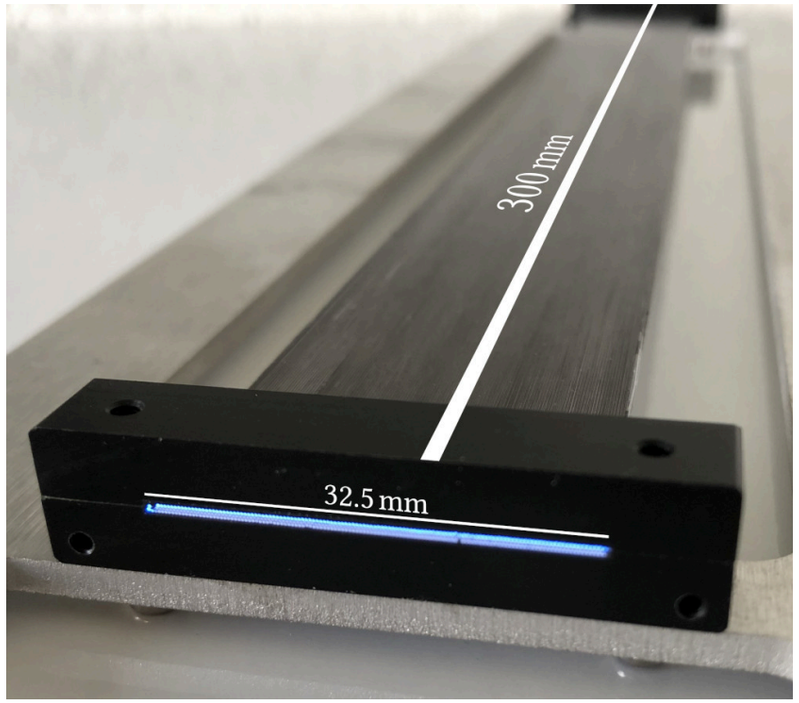
24 readout boards with dedicated **ASICs**

The fibers and the SiPMs

Scintillating fibers

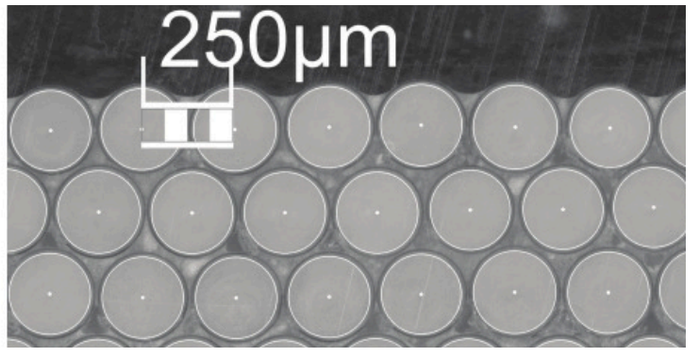
32.5 mm x 300 mm
Kuraray SCSF-78MJ
round ⌀ 250 μm
very thin ~0.2% x_0
3 staggered **layers**
black epoxy

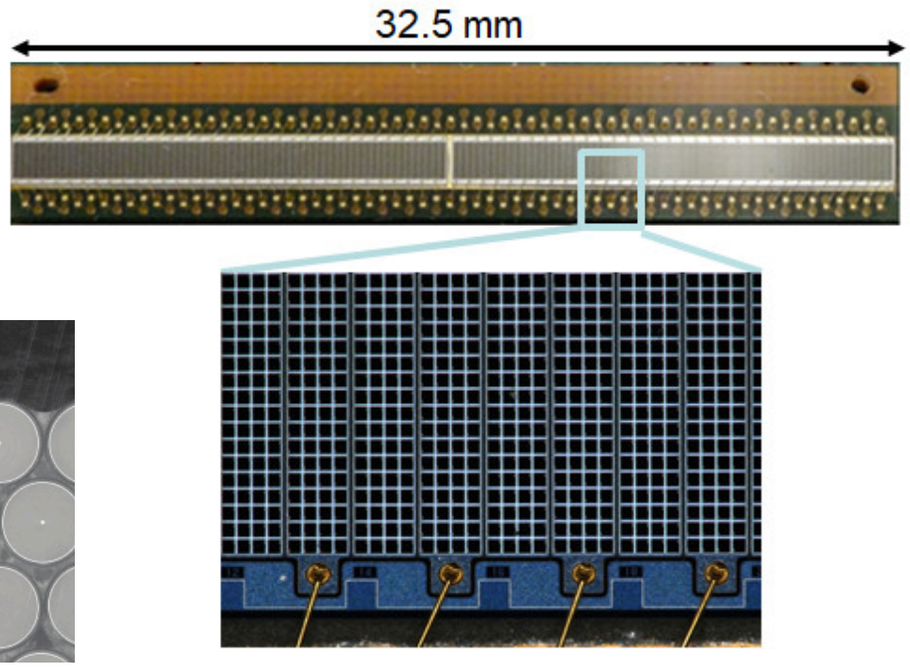




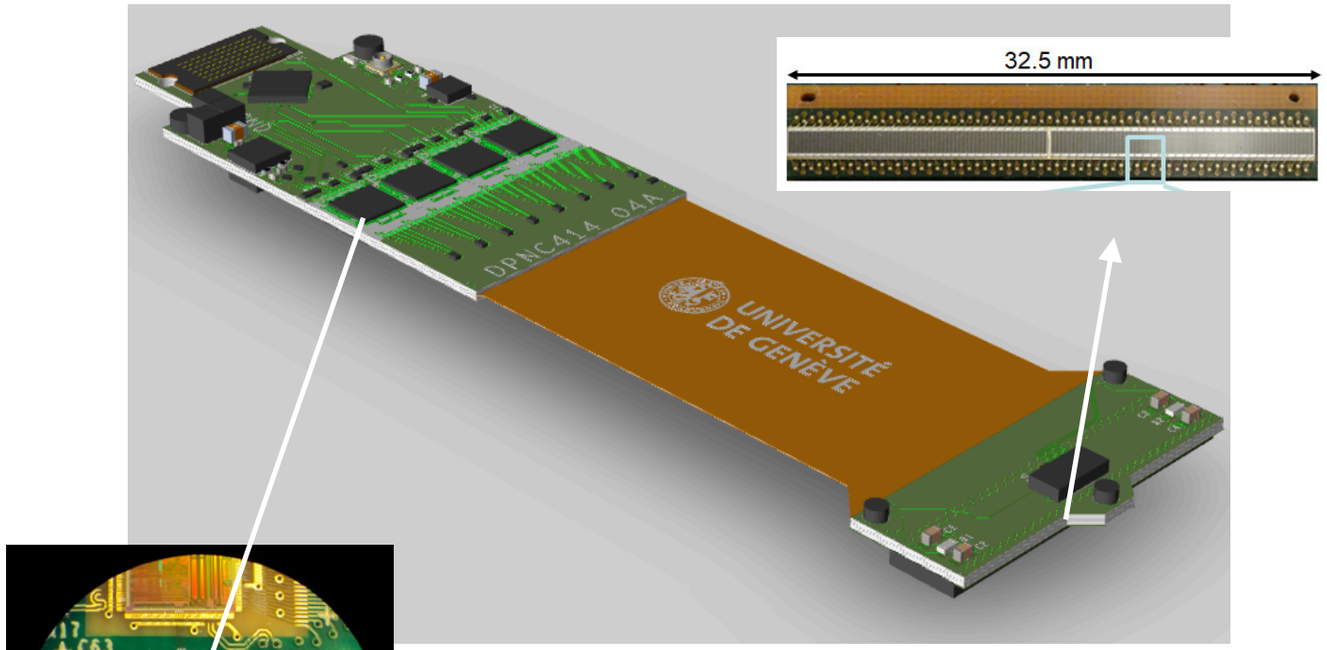
SiPM arrays

Hamamatsu S13552-HRQ
128 channels
250 μm pitch
pixel 57.5 μm x 62.5 μm
V_{break} ~52.5 V
high quenching resistor



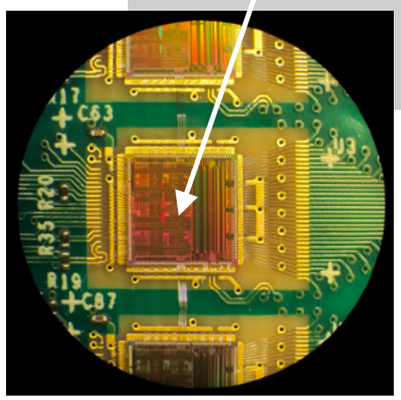


Readout electronics



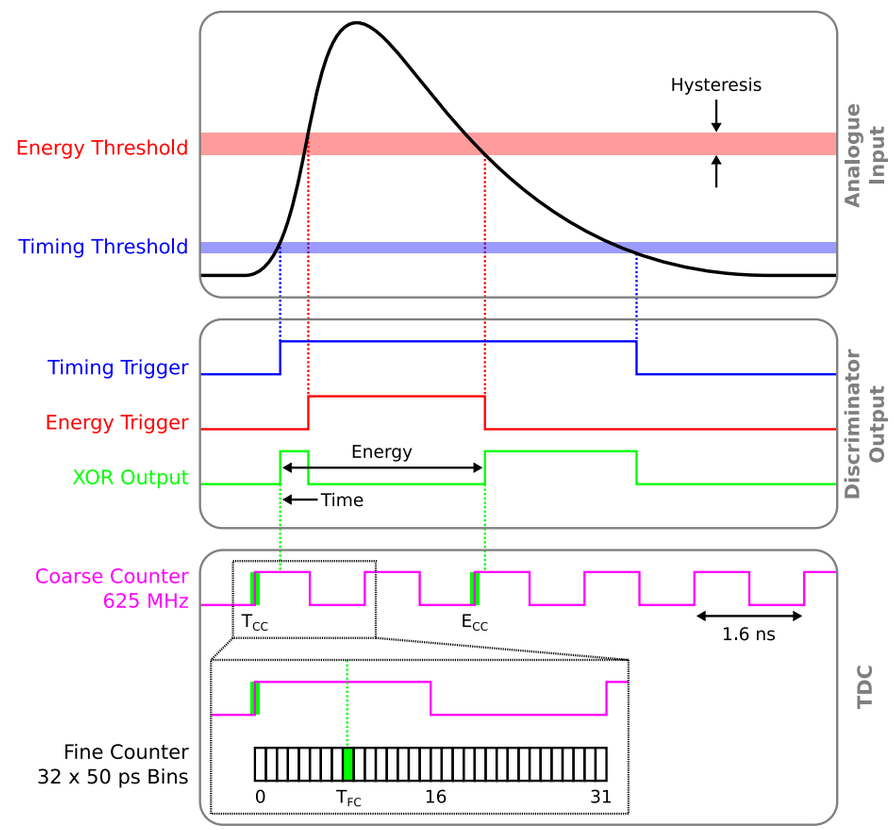
Front-end board

- SciFi Module Board (SMB)
- **128 channels** in 4 ASICs (MuTRiG)
- Clock/reset, slow control, T probes
- LVDS readout via **1.25 Gbps** data link



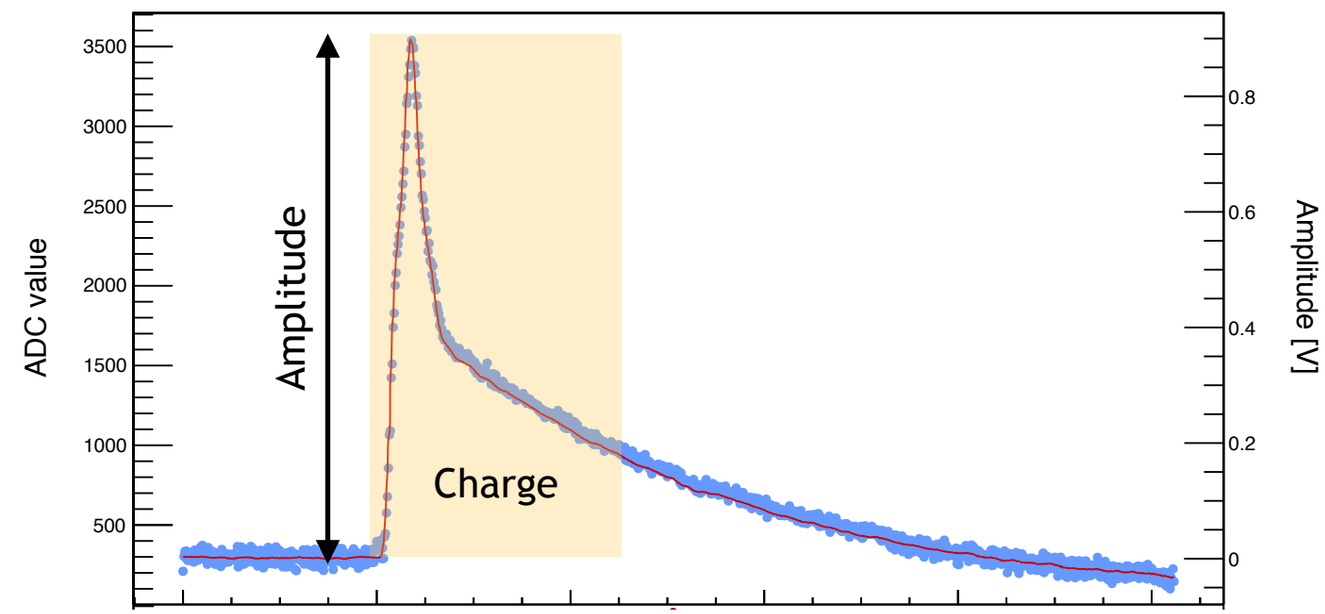
MuTRiG ASIC

- **Custom** mixed-mode ASIC for fast SiPM readout (SciFi / SciTiles)
- Rates up to 1.1 MHz/channel
- **D**ifferential analog inputs with individual SiPM bias tuning
- Separate **time** and **energy** thresholds at single-photon level
- **High resolution** TDC (50 ps)
- Clustering with **coincidence** logic

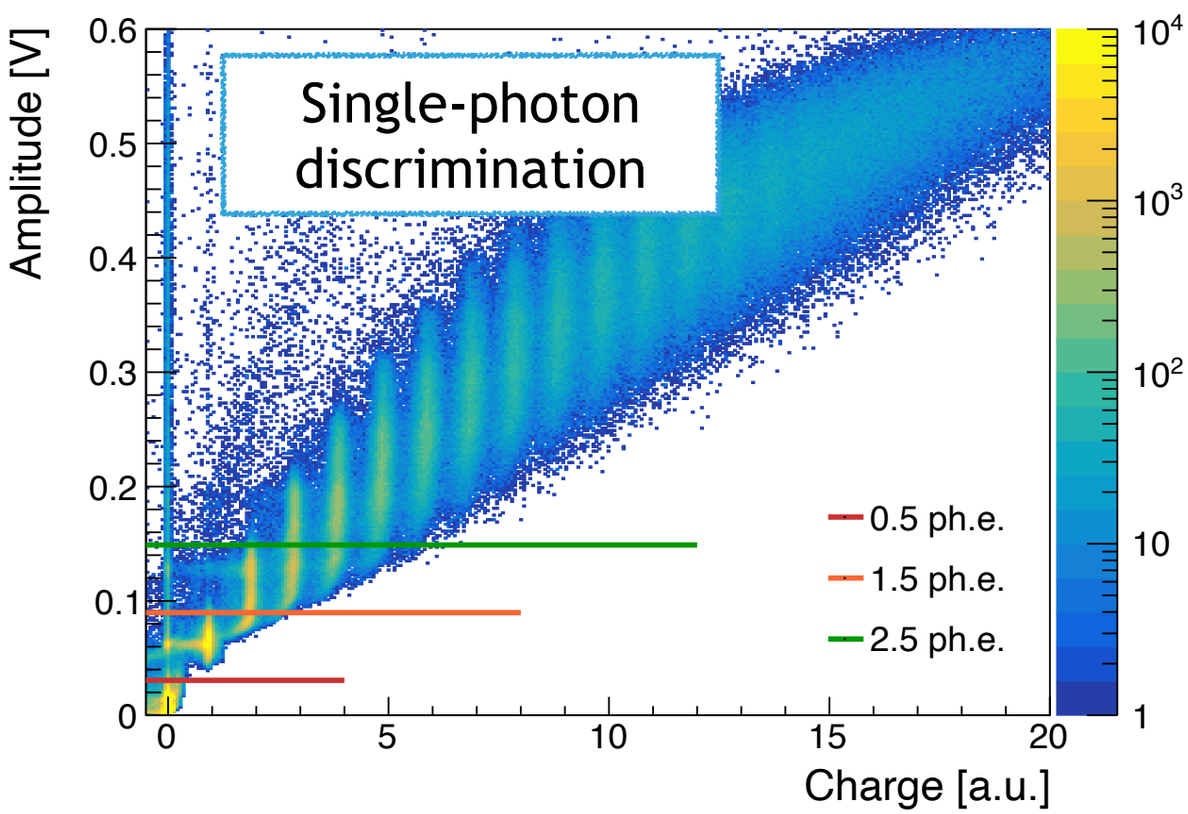


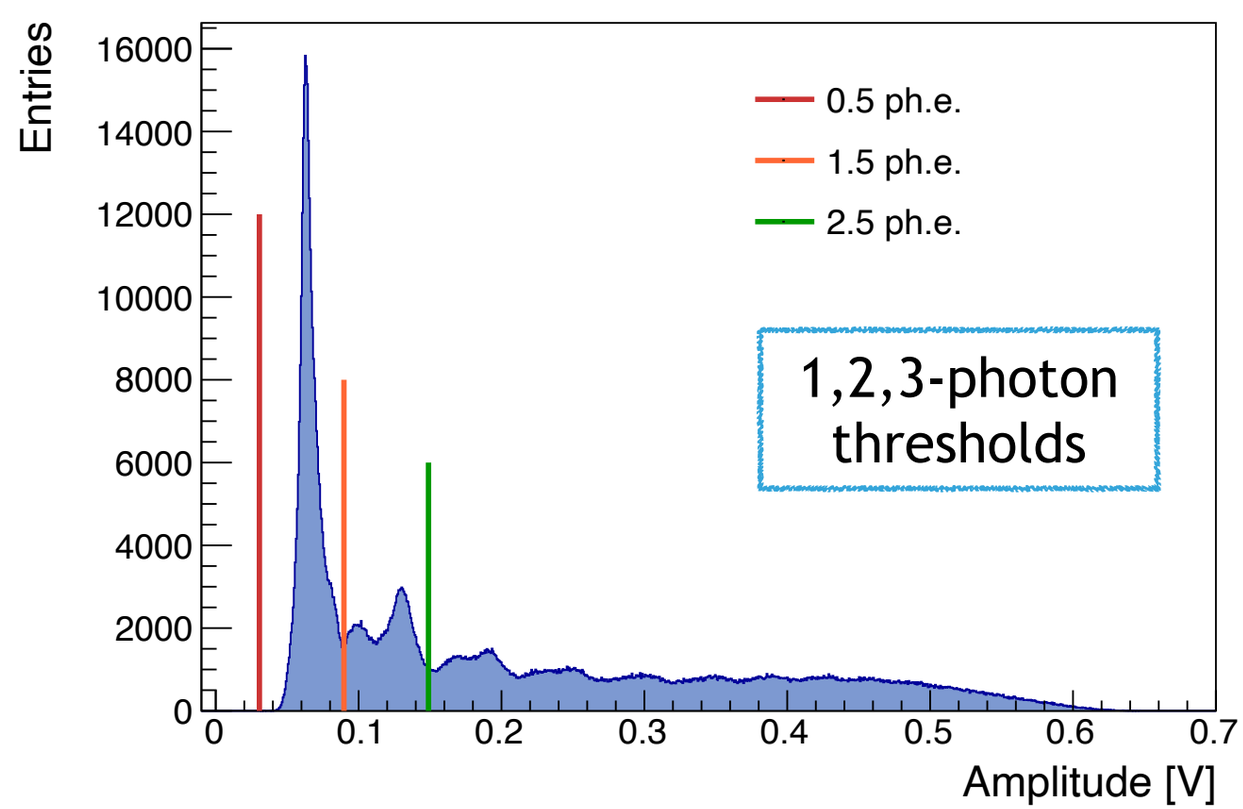
Detector performance

- Detector **characterization** in test beam campaigns (PSI, CERN)
- Waveforms recorded with DRS4 boards, analyzed with **algorithms emulating the MuTriG ASIC**



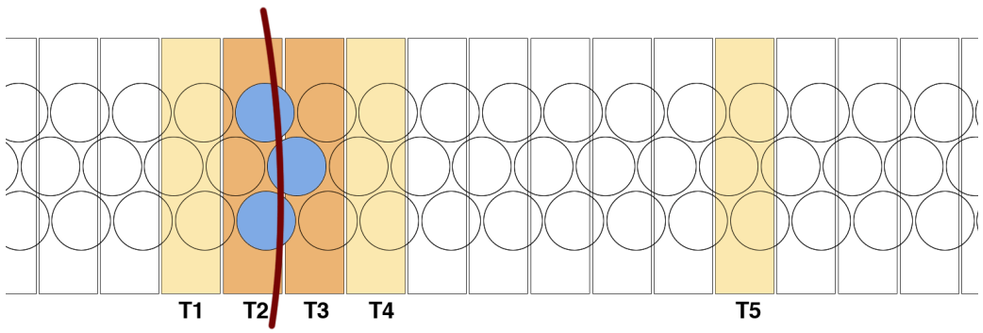
1 Photon thresholds

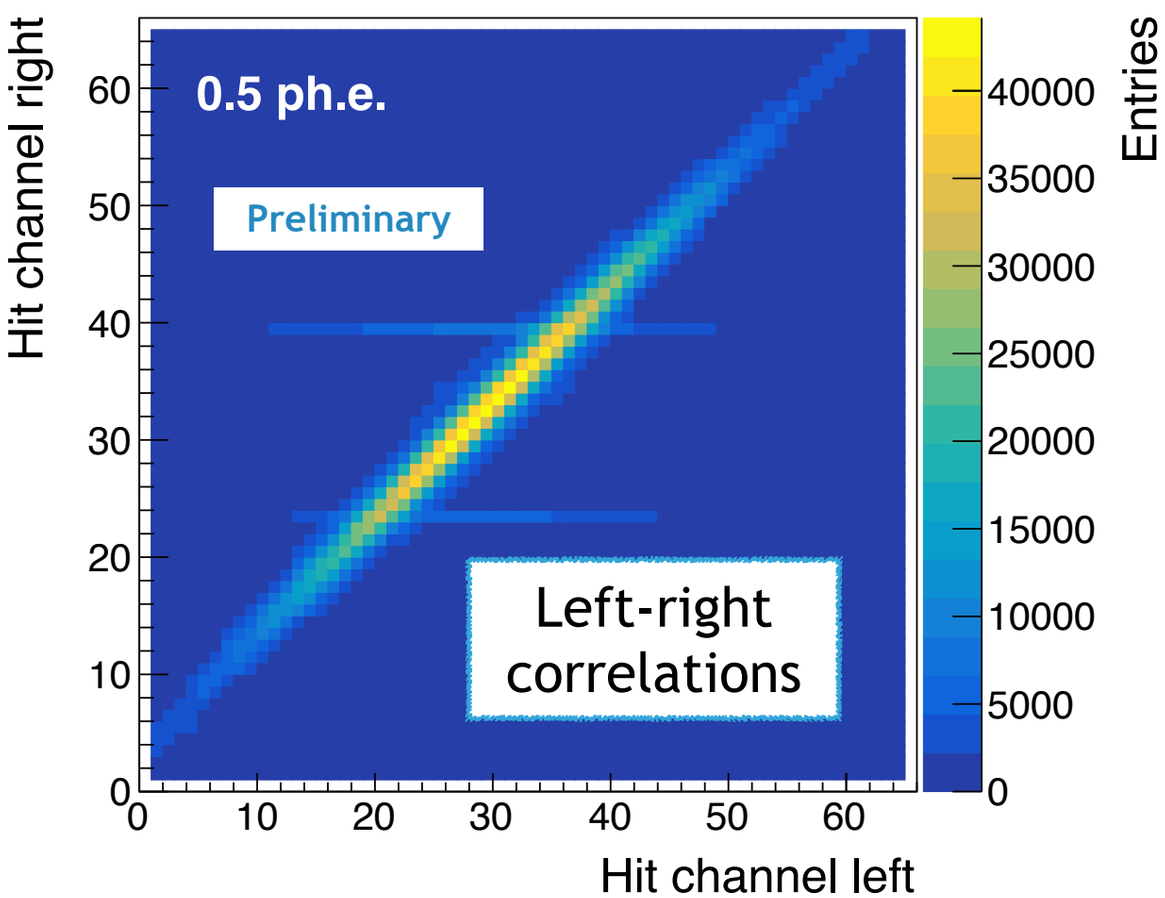


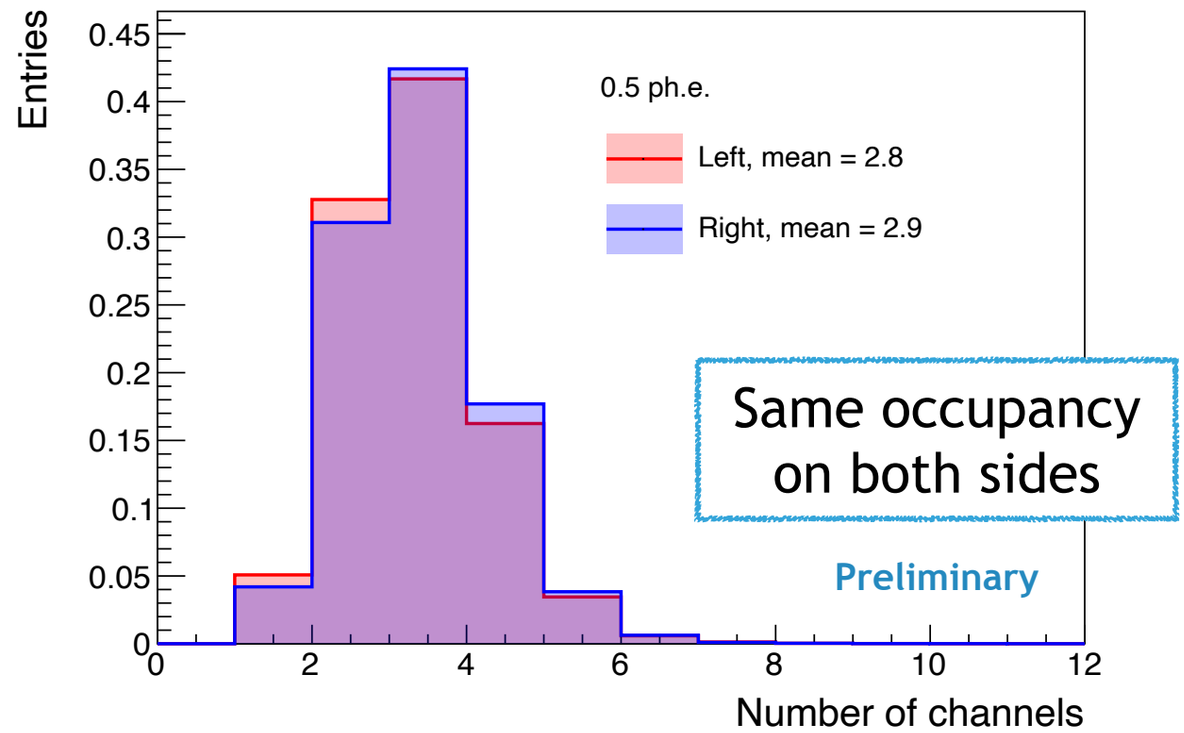


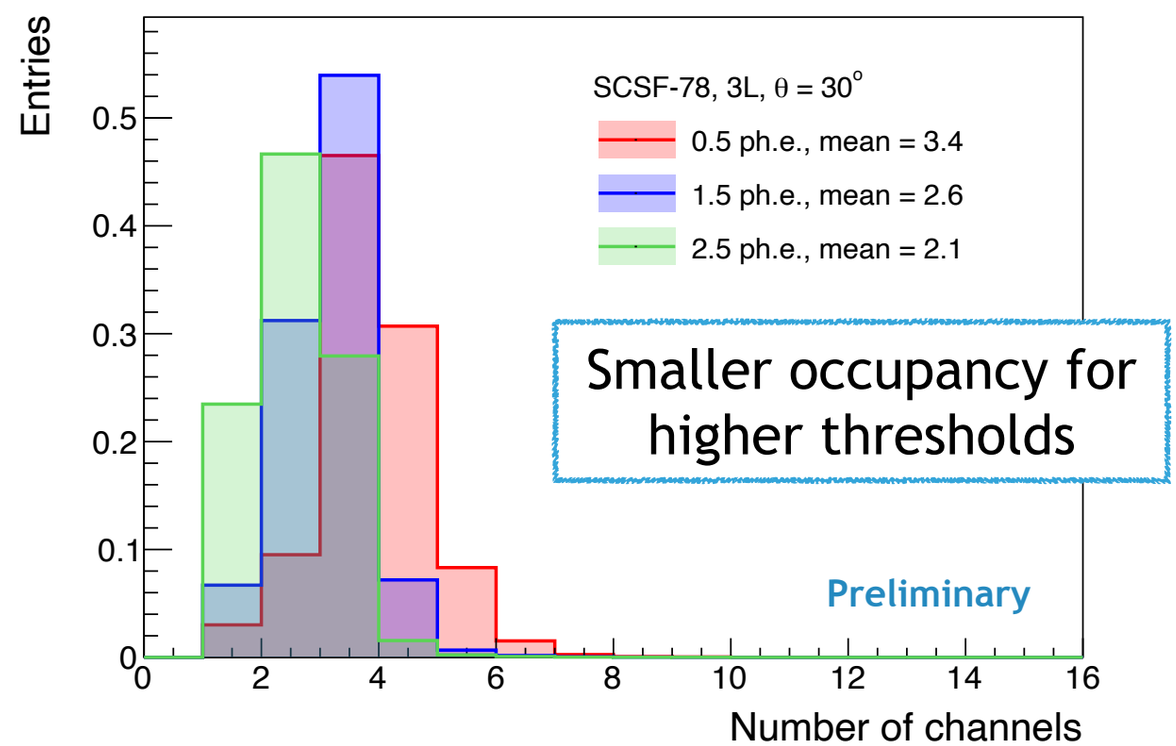
Detector performance

2 Clustering (coincidence logic)



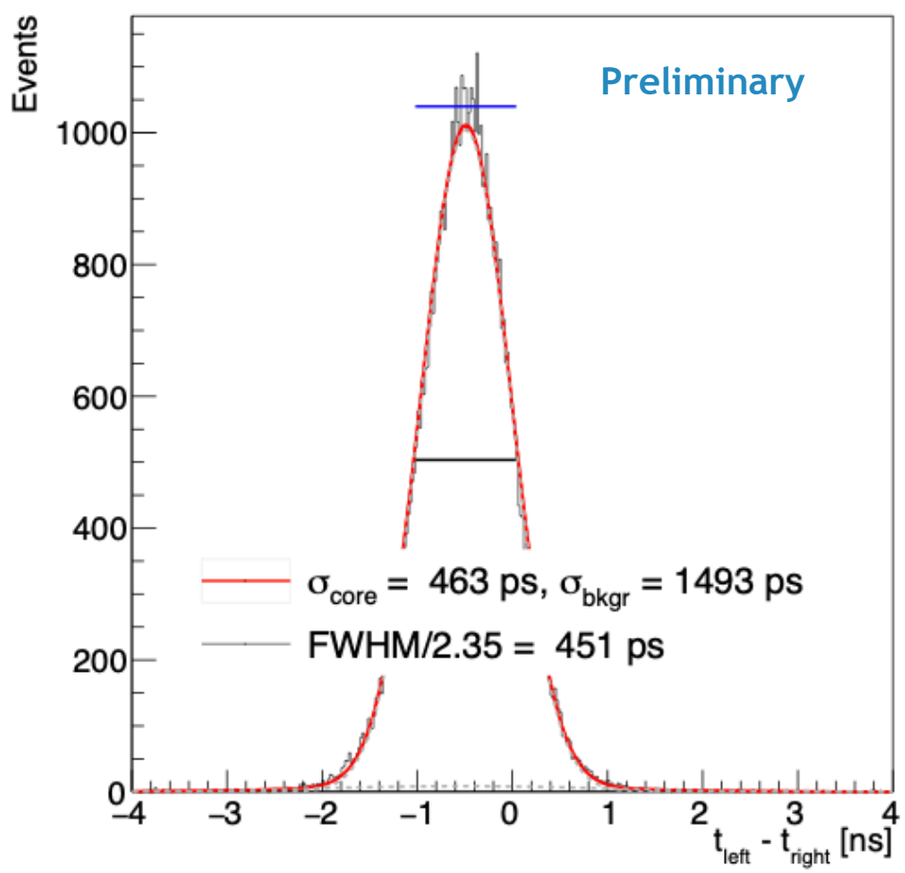






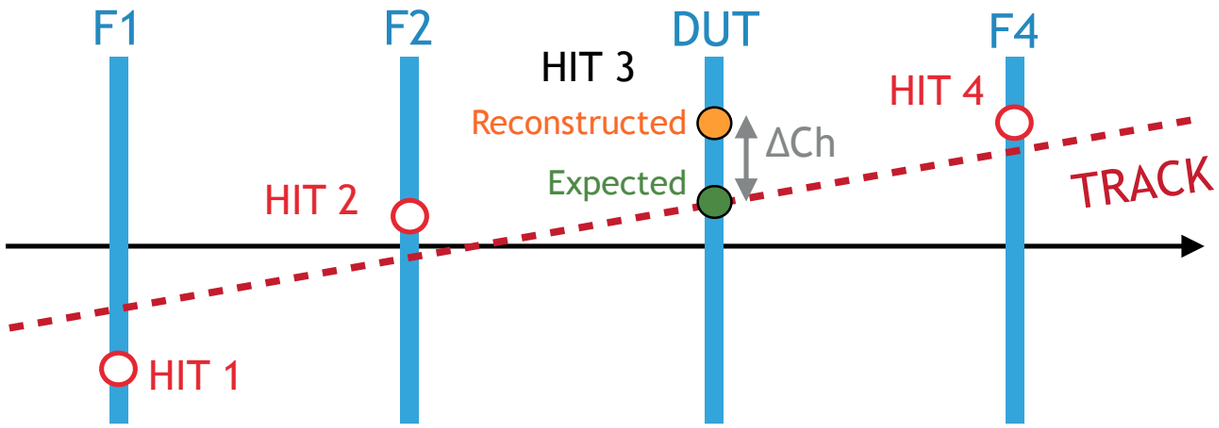
Detector performance

3 Timing algorithms



~450 ps time resolution (**without** inter-channel timing corrections)

4 Track-based efficiency



Preliminary	Hit efficiency (3σ)
1 hit (0.5 ph.e)	(99.2 ± 1.4) %
1 hit (1.5 ph.e)	(98.4 ± 1.5) %
2 hits (0.5 ph.e)	(94.9 ± 1.5) %

>95% efficiency for different hit multiplicities and thresholds

Summary and outlook

- The **SciFi** detector is composed of 3 layers of thin round **scintillating fibers**, read out with **SiPM** arrays on both sides and **fast** electronics
- It can operate at 1-2 photoelectron **thresholds**, providing a timing precision of **few 100 ps**, while keeping the limited **material budget**, and sustaining high rates at an **efficiency >95%**
- In combination with the pixel detector, it allows a full **4-dimensional reconstruction** of the muon decay products at sufficient precision to reach a sensitivity **~10^{-15}** after ~1 year running with 10^8 muons/s
- The **performance** of the detector has been proven to meet the experimental goals and its **integration** in Mu3e is being exercised in dedicated beam campaigns
- The **construction** of the SciFi detector will finalize in 2023, with the first **commissioning** runs starting in 2024, and the **physics** data-taking scheduled for 2025-2026