Scintillating Fiber Detector
for the Mu3e experiment

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Young Researchers Day
of the Physics Section

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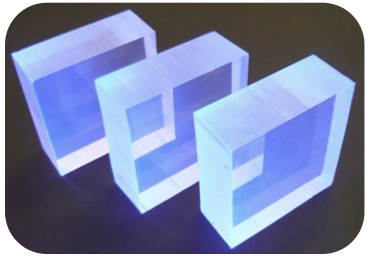
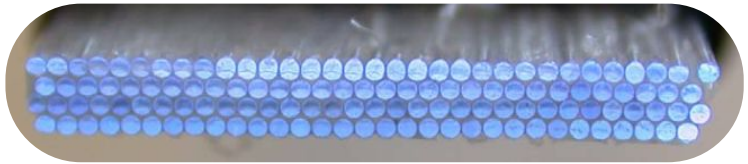
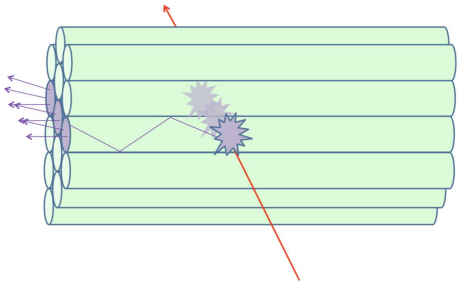
Scintillating Fibers

- Scintillators → **emit light by a passage of a particle**



- Categorised; depending the scintillation mechanism
- **Scintillating fibers (SciFi)** consists of a core **scintillating material** (plastic scintillator) surrounded by **one or more cladding layers**
- SciFi have <u>two roles</u> :
  1) act as **<u>scintillator</u>**
  2) **<u>transport the light</u>** to … a readout



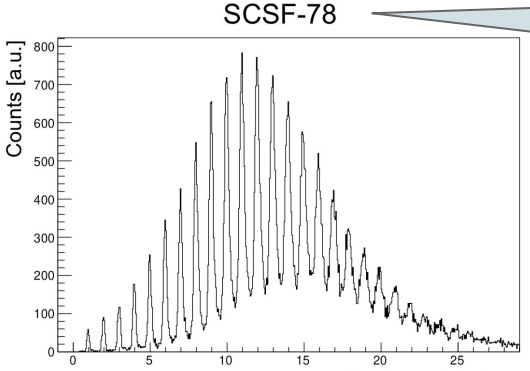


pictures taken from

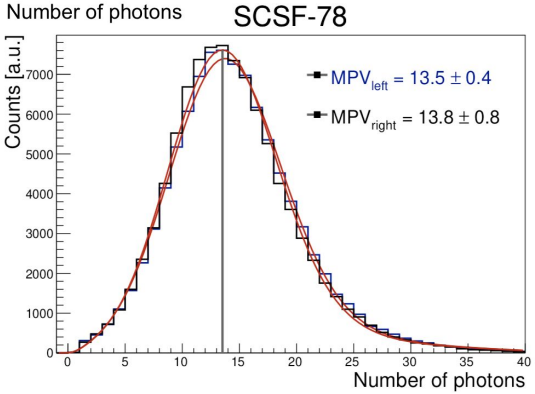
Scintillating Fibers –coupled to single photon sensitive sensors

- coupled directly to photo-sensors :
  - silicon photo-multiplier (SiPM)
- Different **properties** and **performances** to characterise fibers :
  - *Light yield* **: changed spectrum normalized** to the charge generated by **one photon**
  - *Light attenuation*
  - *Timing performances*

- But we can go further …

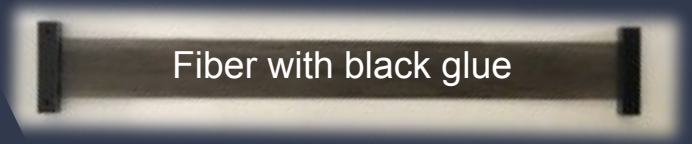


There are different types of fibers. This is one type with high light yield

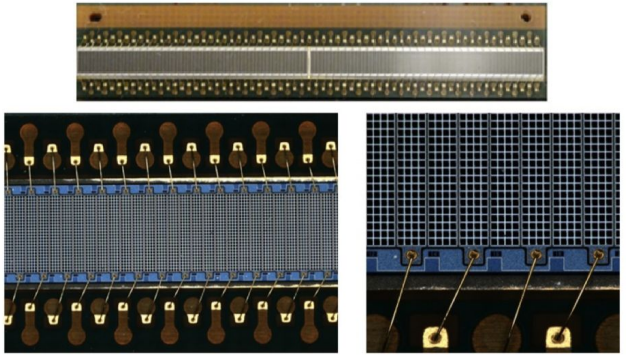


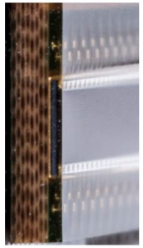
reference

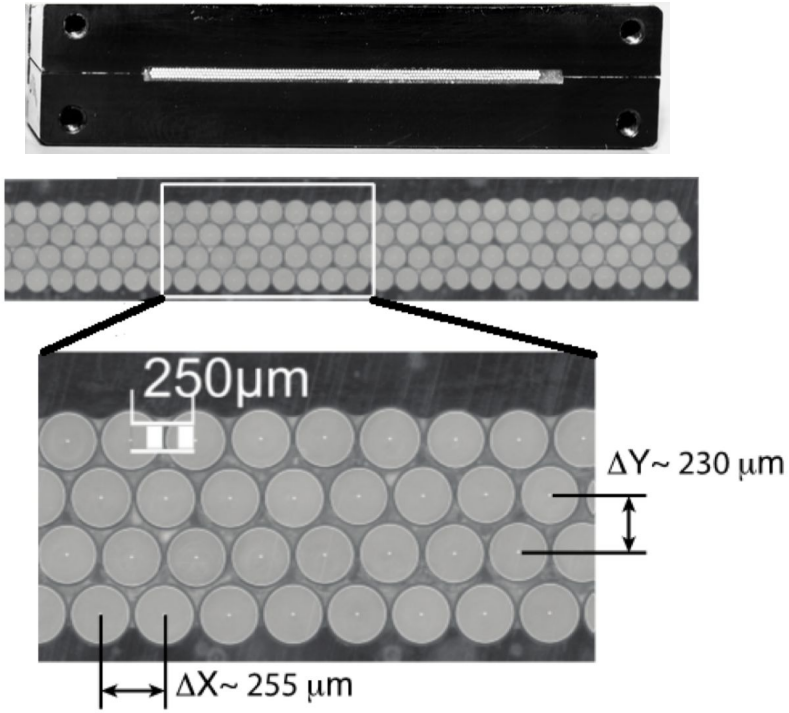
Scintillating Fiber ribbons



- Can **stagger three or more layers** scintillator fibers to make **ribbons**
- *Resulting that the thickness is still low → important, why do you think ?*
- coupled **multichannel SiPM arrays**

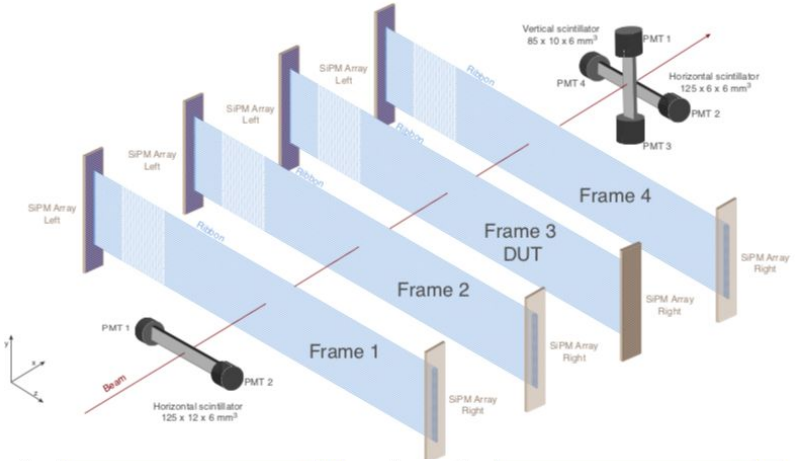


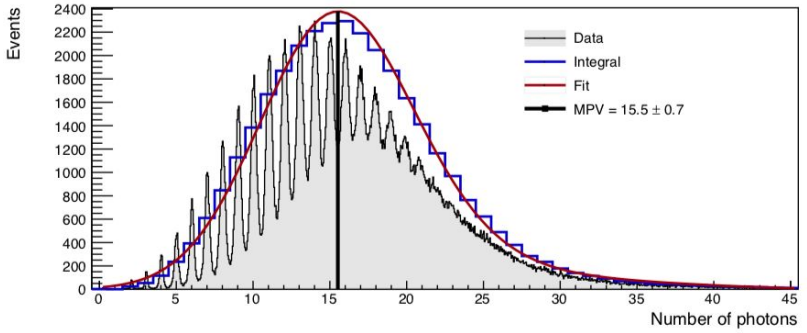


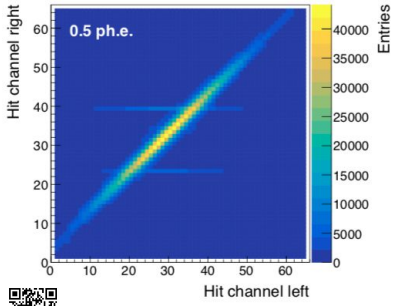


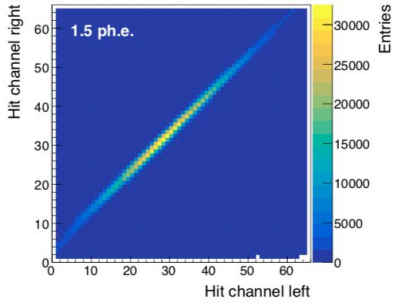
reference

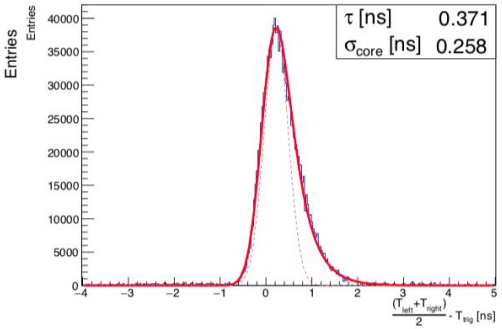
Make a particle detector – SciFi ribbons coupled with SiPM's

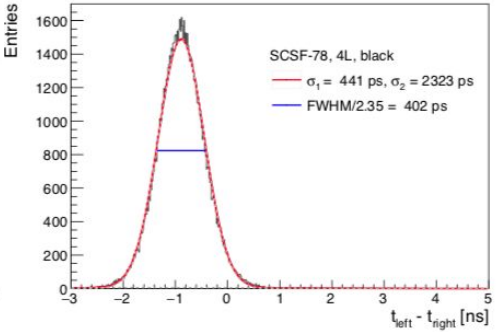








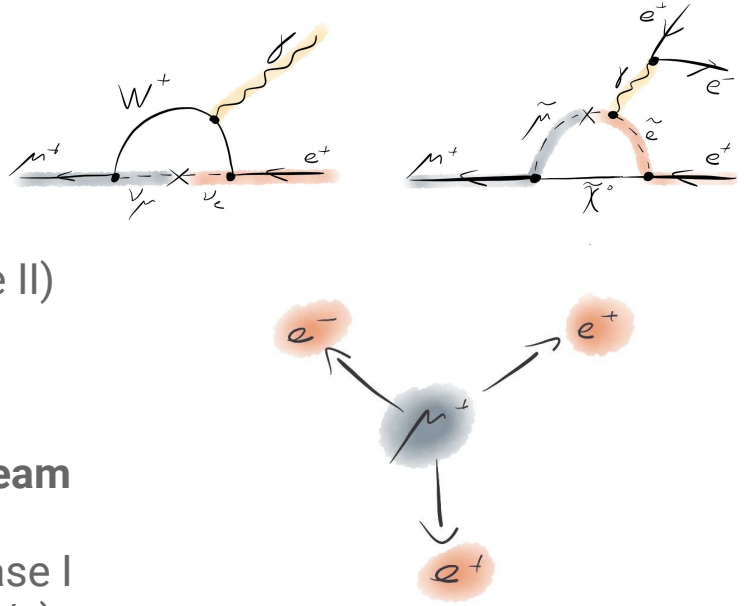




reference

Mu3e experiment

- In the **Standard Model ($m_\nu = 0$) Lepton Flavor** is **conserved** (by structure)
- **Lepton Flavor Violation** (LFV) have ***not*** *been observed yet …*
  - if observed ⇒ signature of **new physics**

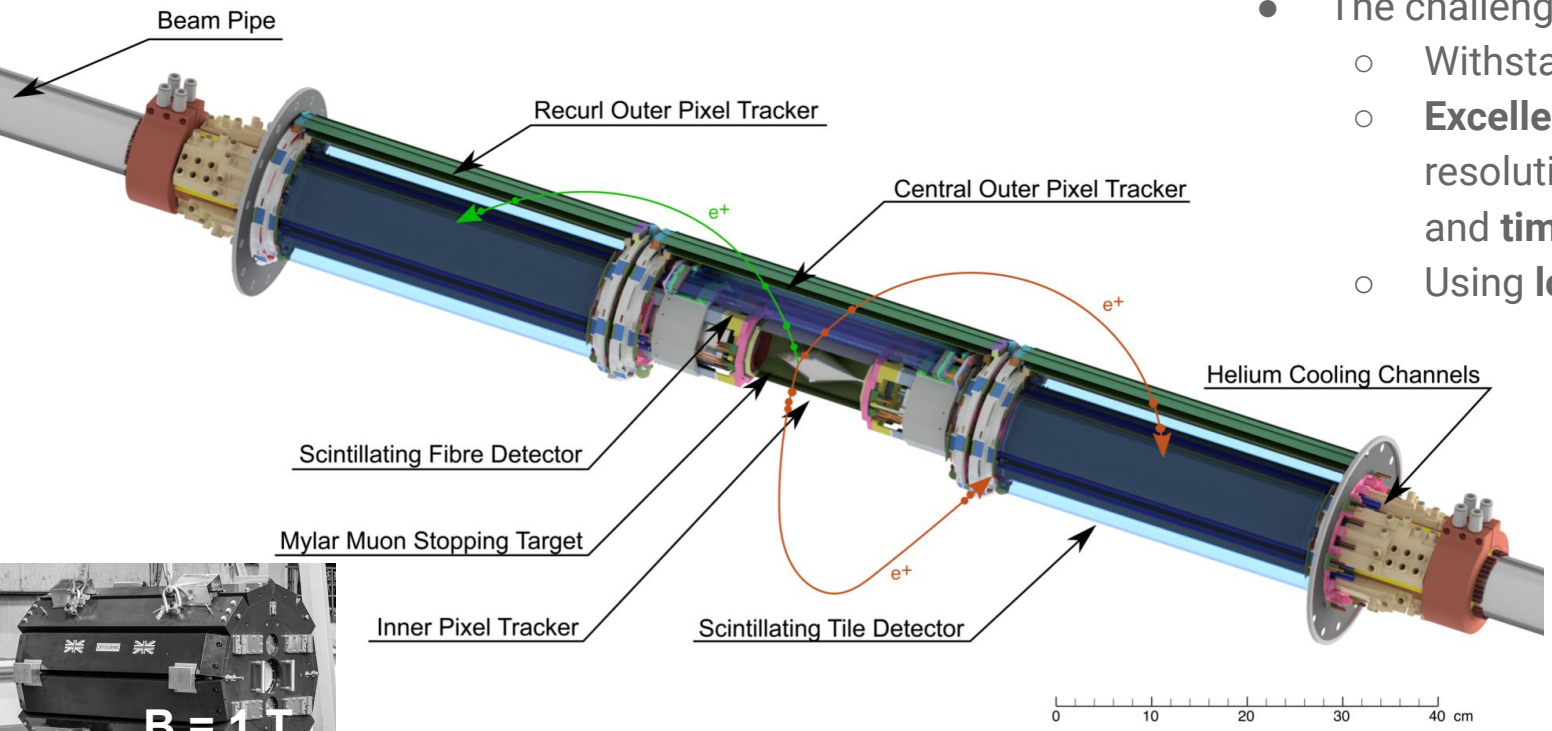


- <u>Goal of Mu3e</u> :
  - **search for $\mu \to e^+e^-e^+$** with a sensitivity of ~ 10^{-15} (Phase I) down to ~ 10^{-16} (Phase II) on the branching fraction
    ⇒ evidence of **charged LFV**

- Using the world's **most intense** surface **muon beam** (p ~ 28 Mev/c) at PSI
  ⇒ Up to **10^8 muons/s** available for Mu3e in Phase I
  (For Phase II : HiMB project with > 2.10^9 muons/s)

reference

Mu3e design

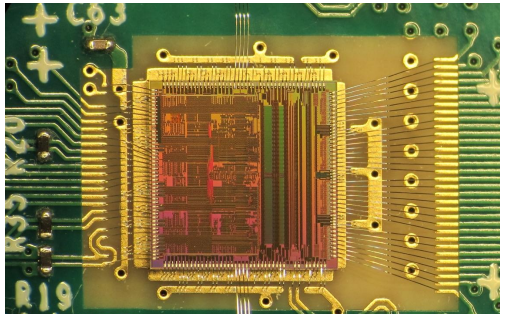


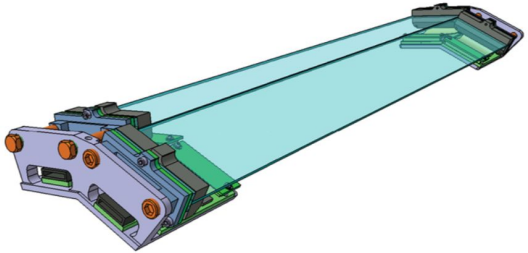
- The challenges :
  - Withstand **high rates**
  - **Excellent momentum** resolution and good vertex and **timing resolution**
  - Using **low material budget**

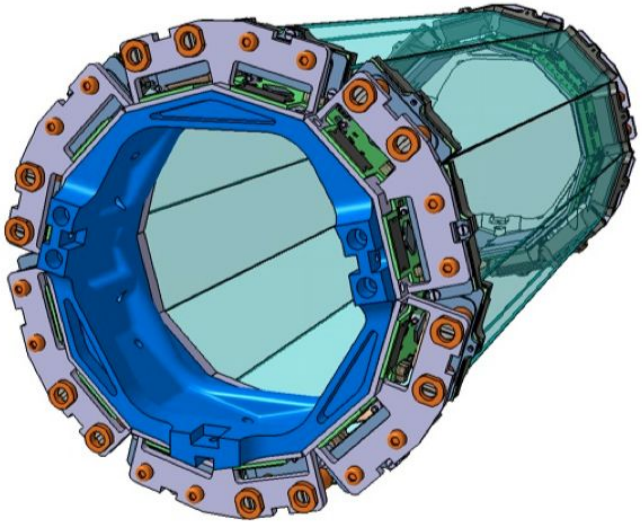
reference

SciFi detector at Mu3e

- *Mu3e requirement* : **very good timing resolution** using low material budget
  ⇒ **Goal** of the timing detectors : **very good timing measurements to suppress accidental backgrounds**
- **12 Scifi ribbons** of **250 microns diameters** fibers
- 3 staggered layers → Very thin
- Readout with multi-channel **SiPM arrays** and **custom ASIC** (MuTRiG)



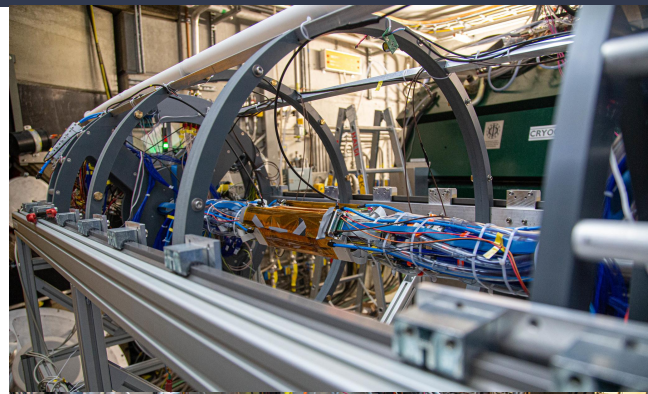


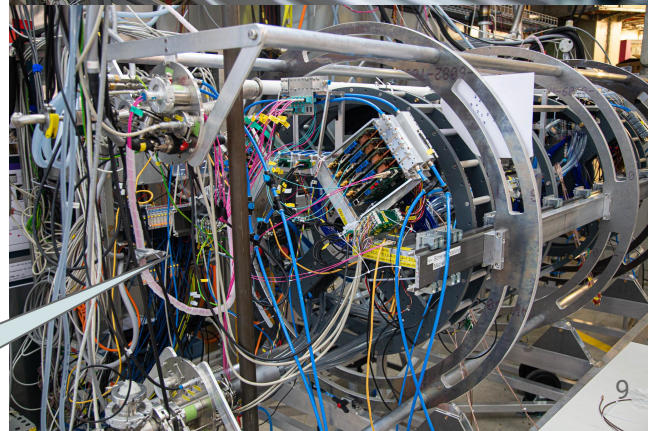


reference

Conclusion

- **Developing a very thin scintillating fiber detector**
- Can be used in **applications requiring**
  - good timing
  - good spatial resolution
  - and high efficiency with **very low material budget** capable of operating in high rates
- Used in **Mu3e experiment**
  - With the other sub-detectors allow full 4D **reconstruction** (space and time) of **$\mu^+ \rightarrow e^+e^-e^+$ decay** $\rightarrow$sensitivity ~ 10^{-15} (Phase I) down to ~ 10^{-16} (Phase II)
  - Detector prototypes integrated in dedicated campaigns at PSI
- First commissioning runs starting in 2024, and the physics data-taking scheduled for 2025-2026





It's all about good cable management … :)

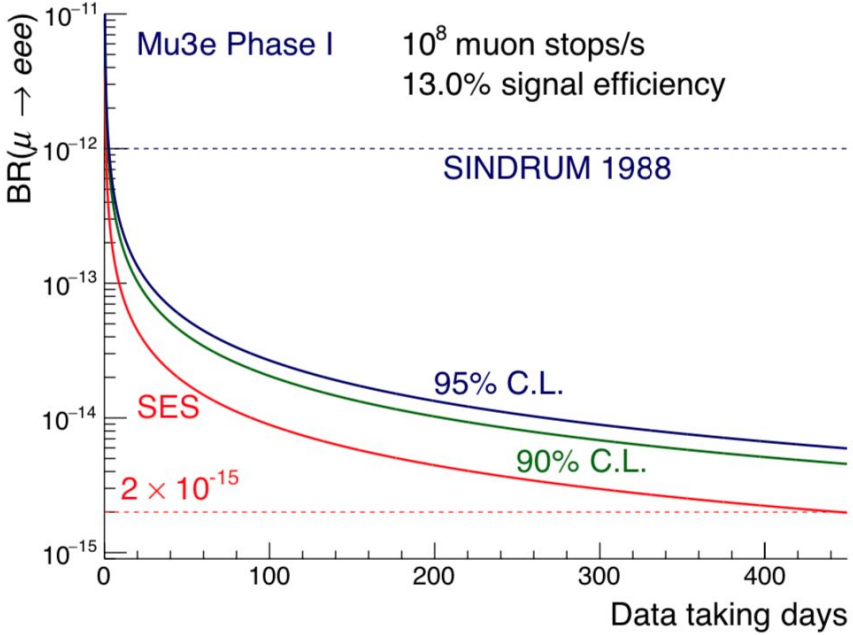
BACK UP

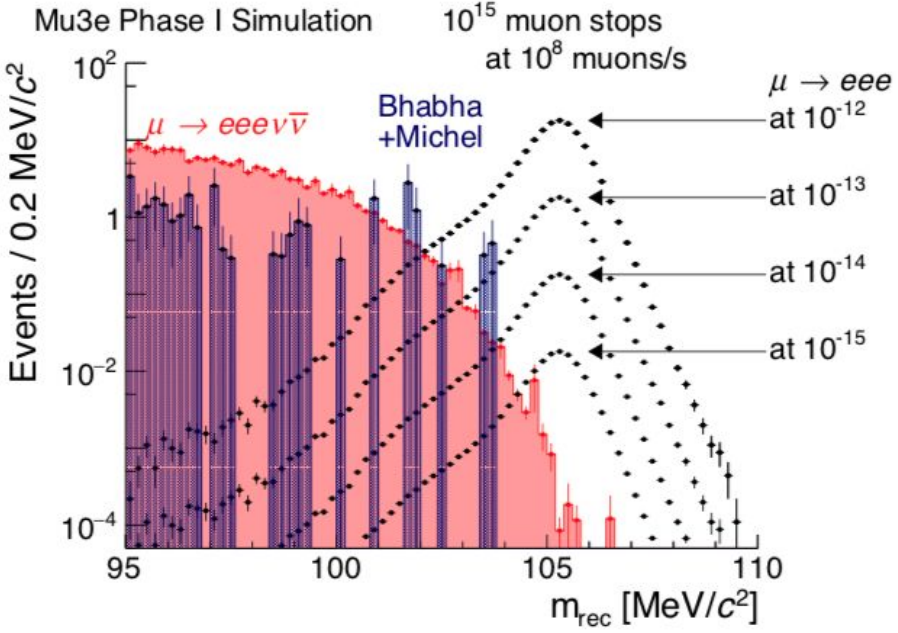
The muon beam @ PSI

- Paul Scherrer Institute in Switzerland
- 1.4 MW, 590 MeV proton accelerator
- Carbon target, produce pions, decay to muons

- Up to **10^8 muons/s** available for Mu3e (phase I)

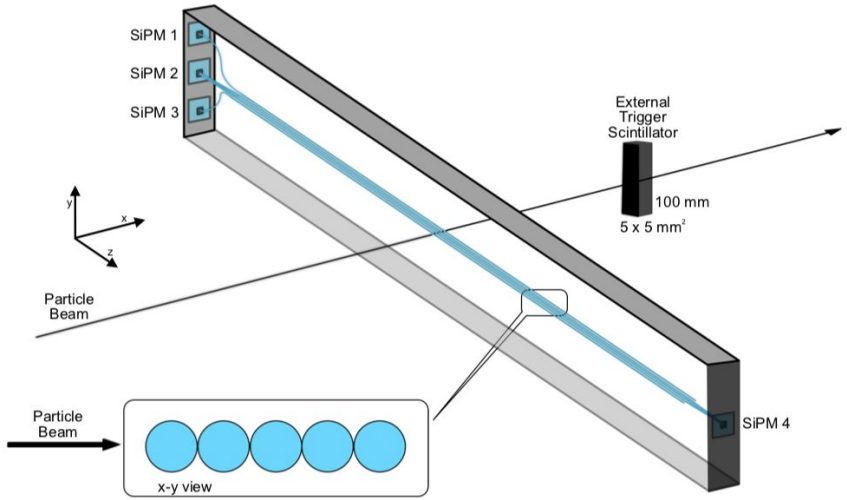
  ⇒Build a detector capable of handling such a rate


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($\mu \rightarrow eee$)
Data taking days

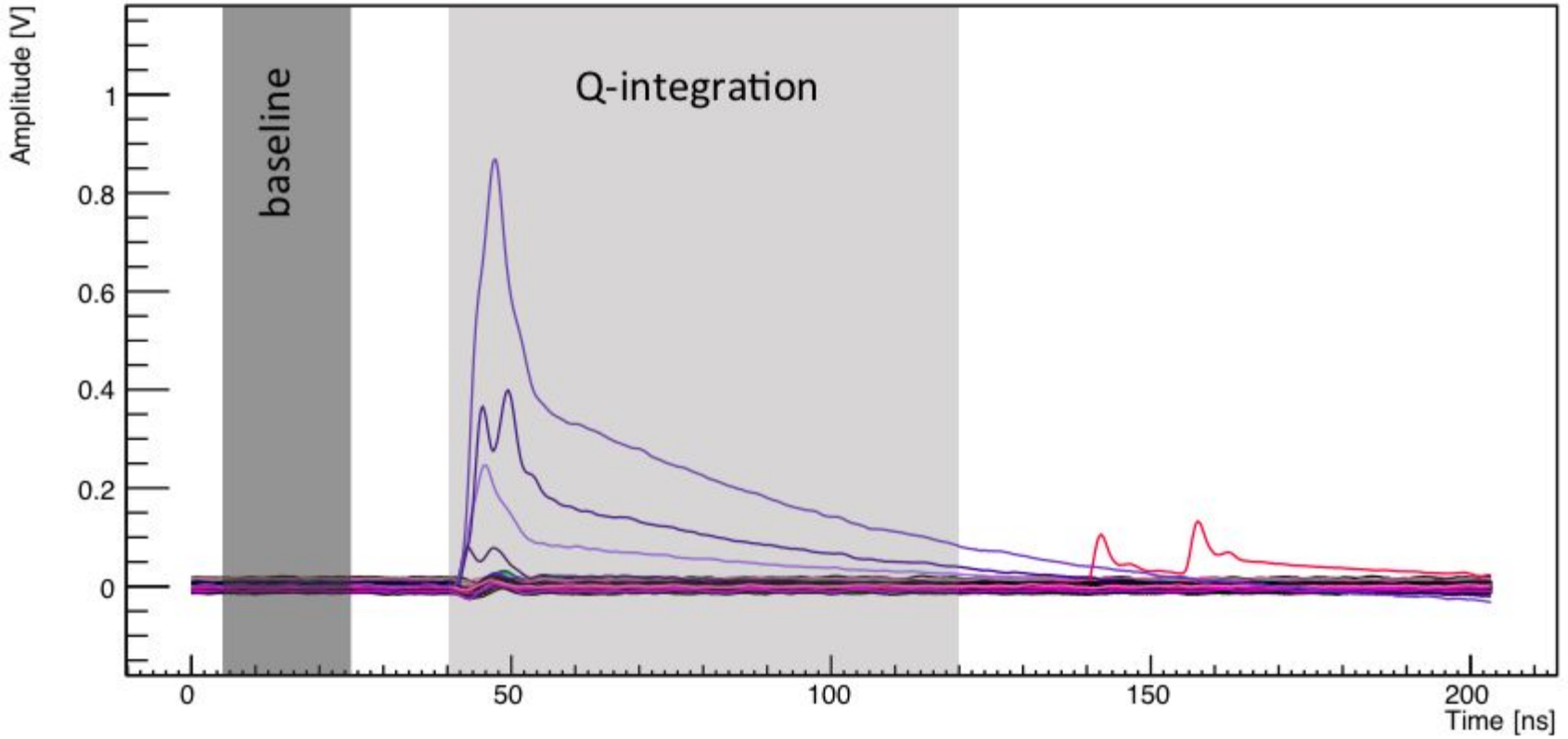

Mu3e Phase I Simulation
10^{15} muon stops
at 10^8 muons/s
$\mu \rightarrow eee\nu\bar{\nu}$
Bhabha
+Michel
$\mu \rightarrow eee$
at 10^{-12}
at 10^{-13}
at 10^{-14}
at 10^{-15}
Events / 0.2 MeV/c^2
m_{rec} [MeV/c^2]

Single fiber setup

- Fibers have been excited with ionising particles
- Measurements have been performed at PSI and in the lab with radioactive source
- Top and bottom are the triggers to guarantee the crossing and the three central fibers are grouped together and read out at each end
- Coupled and read out with 1.3 mm × 1.3 mm SiPMs with 50 μm × 50 μm pixels

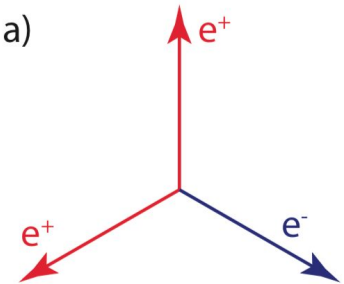


Signals with DRS4



Mu3e: the signal and backgrounds

a)



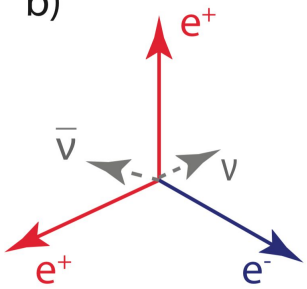
The signal of interest

- common vertex
- coplanar $\sum \mathbf{p}_i = 0$
- $\sum E_i = m_\mu$
- $\sum t_{eee} = 0$

Backgrounds:

internal conversion

b)

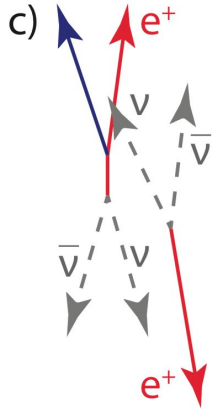


- common vertex
- $\sum \mathbf{p}_i \neq 0$
- $\sum E_i < m_\mu$
- $\sum t_{eee} = 0$

Need excellent momentum resolution

accidental

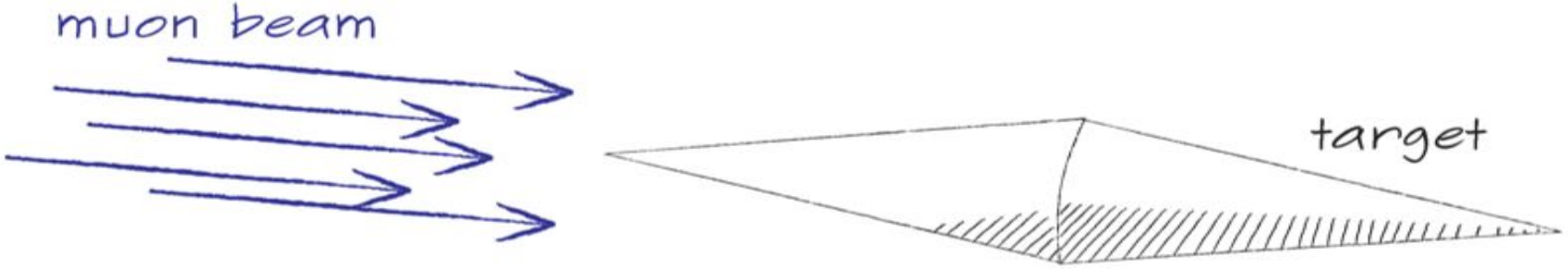
c)

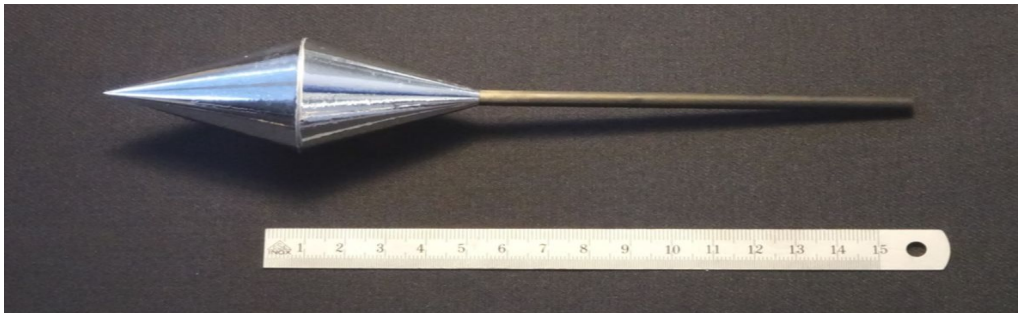


- no common vertex
- $\sum \mathbf{p}_i \neq 0$
- $\sum E_i \neq m_\mu$
- $\sum t_{eee} \neq 0$

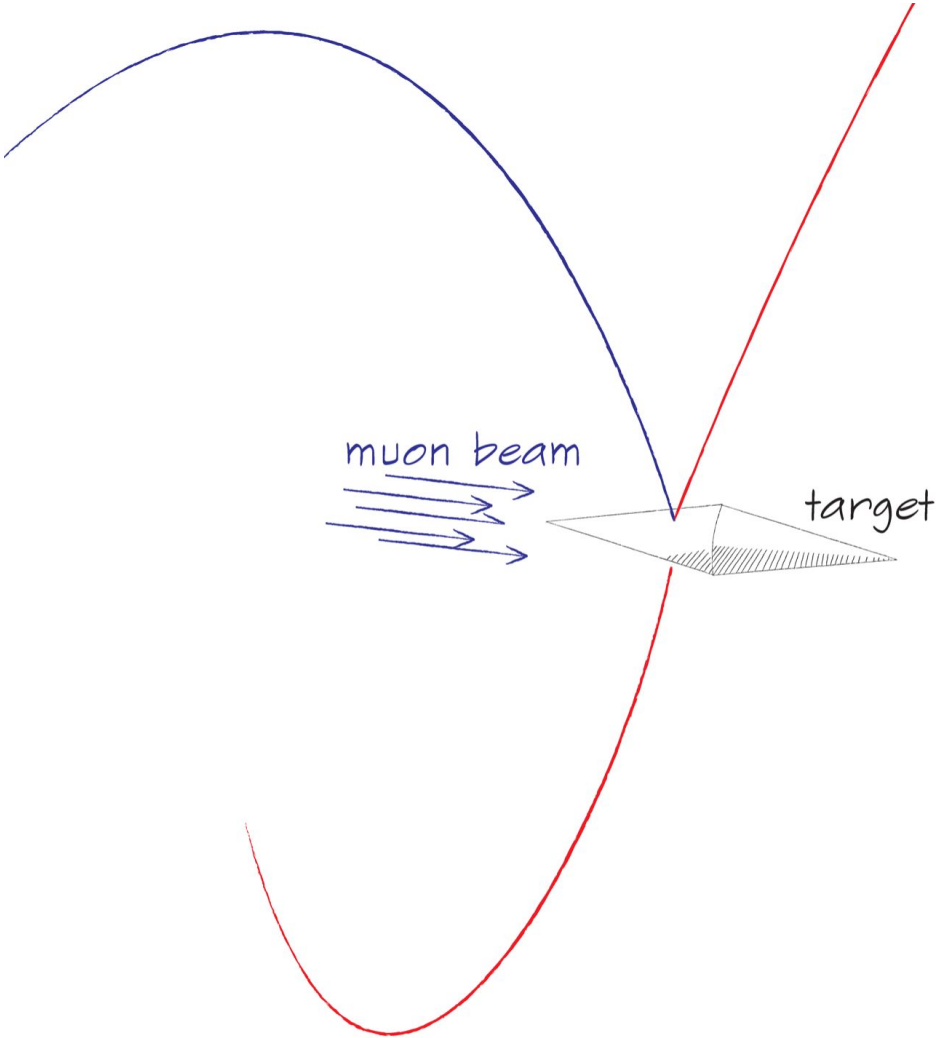
Need very good timing, vertex and momentum resolution

Mu3e design

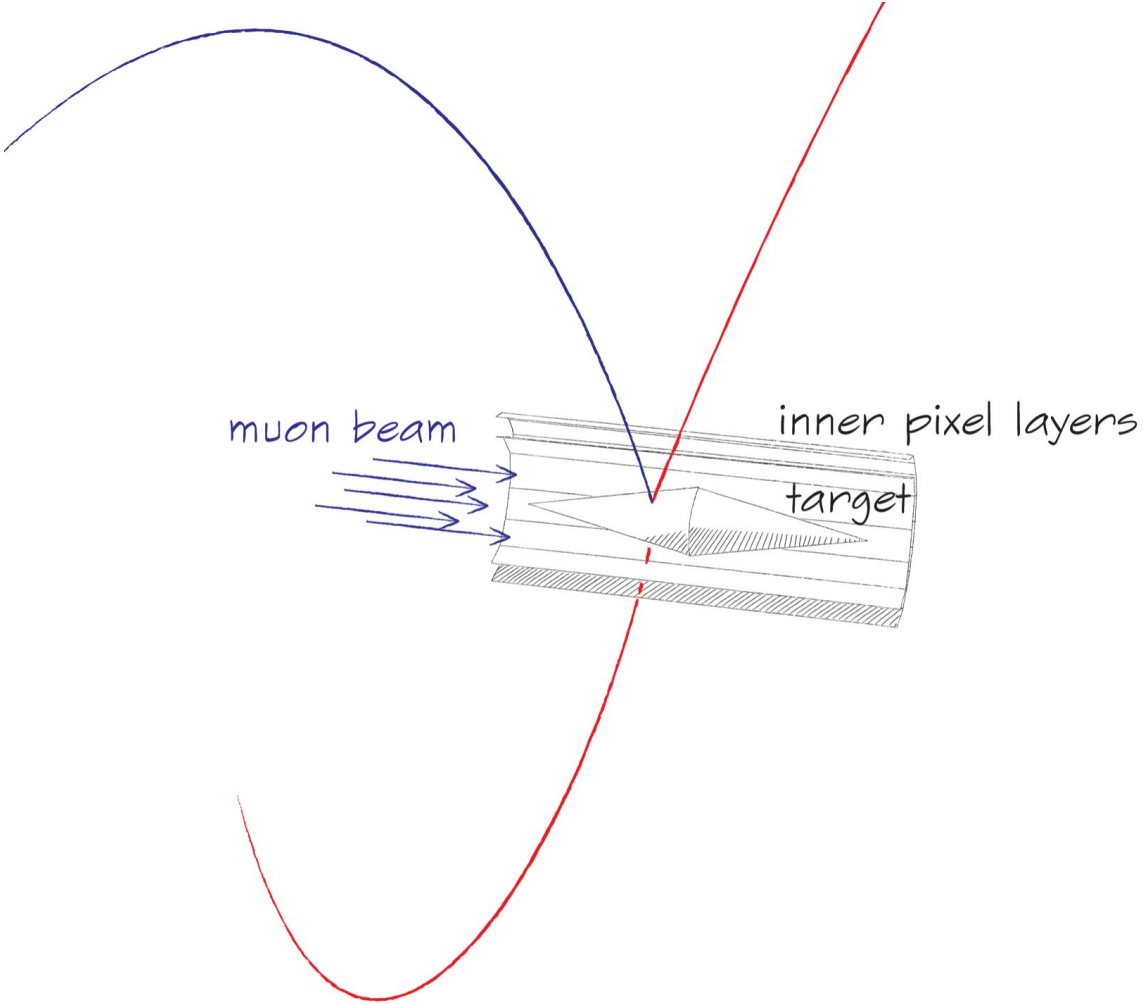




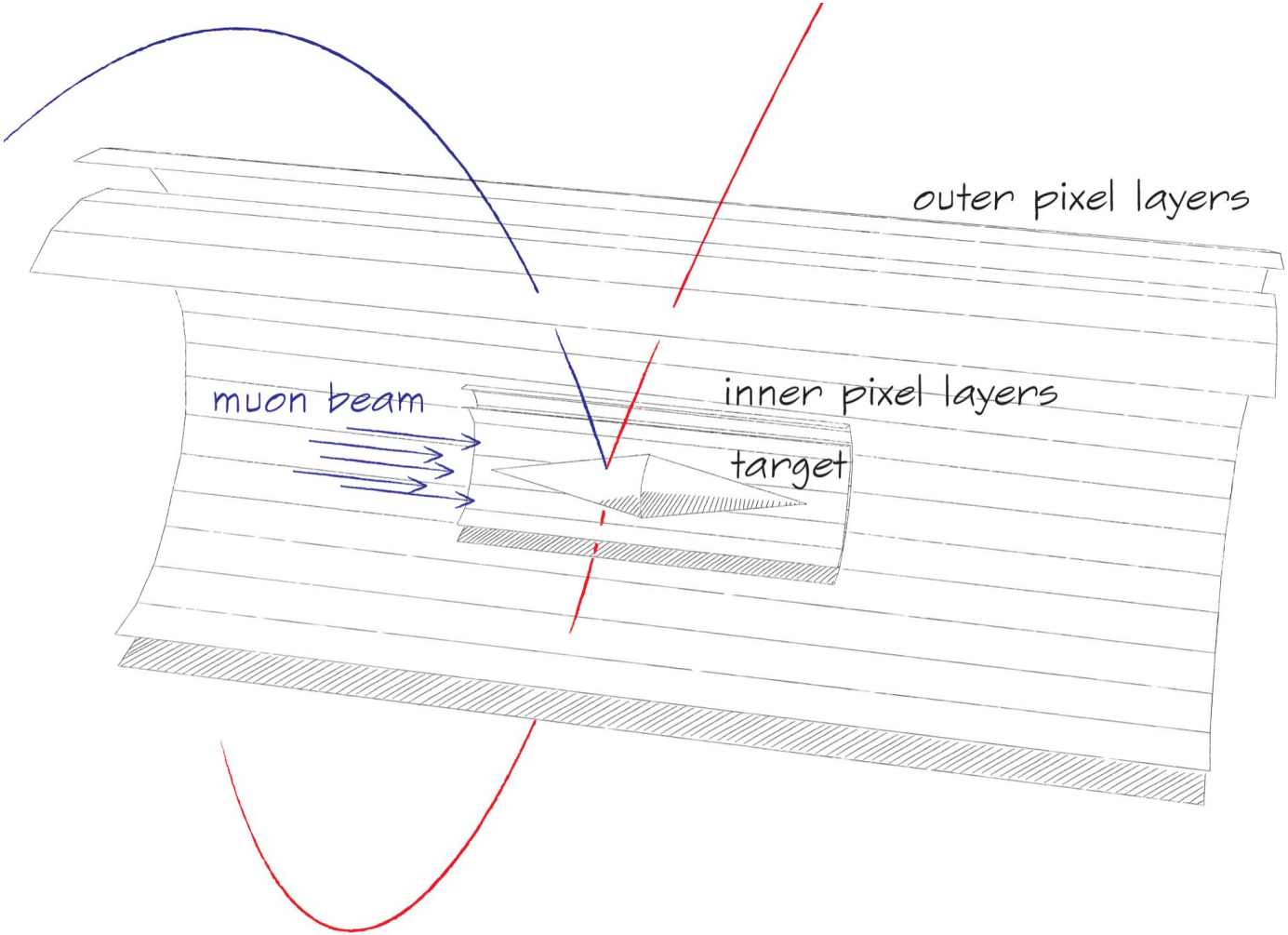
B = 1 T



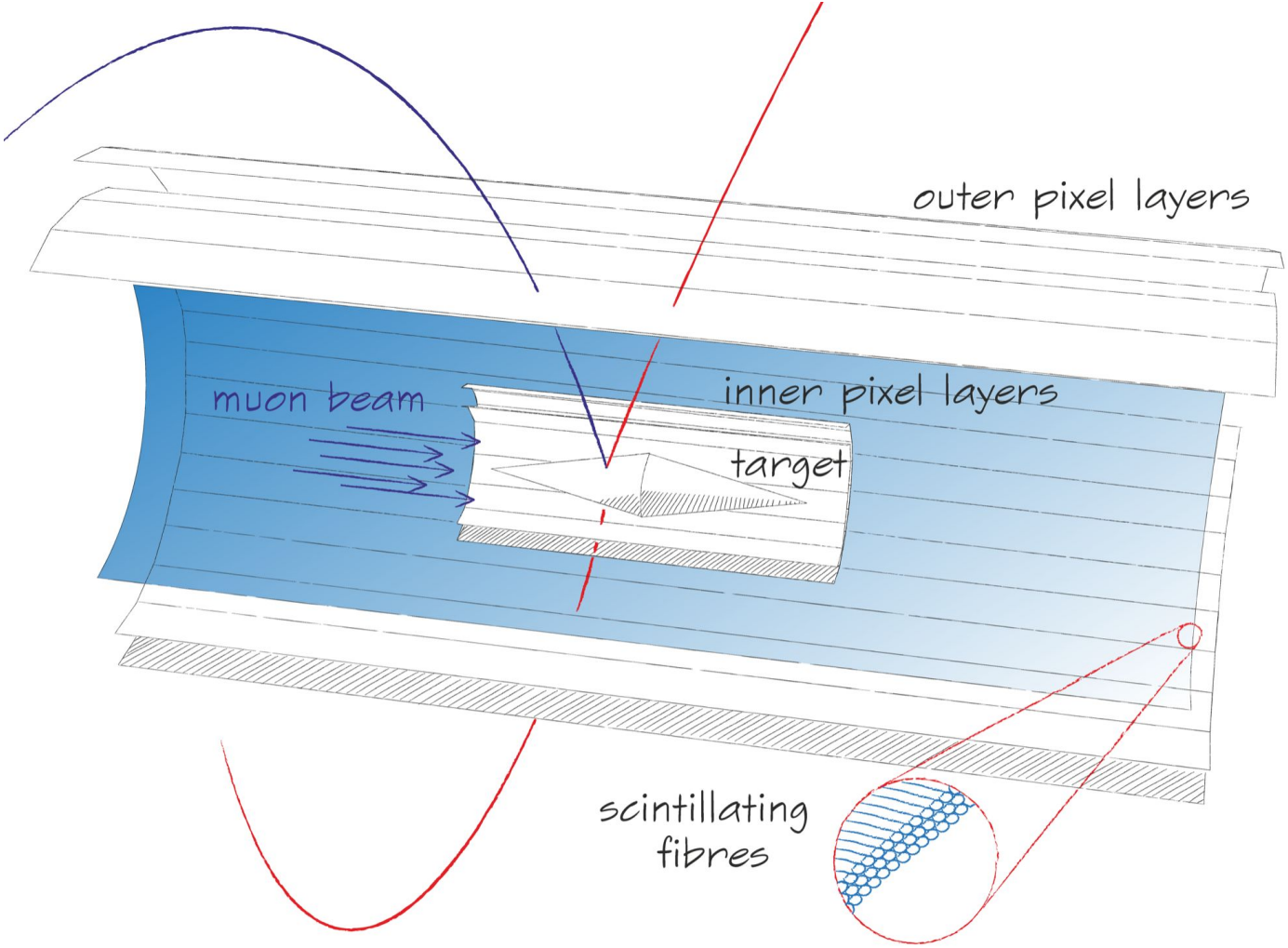
B = 1 T



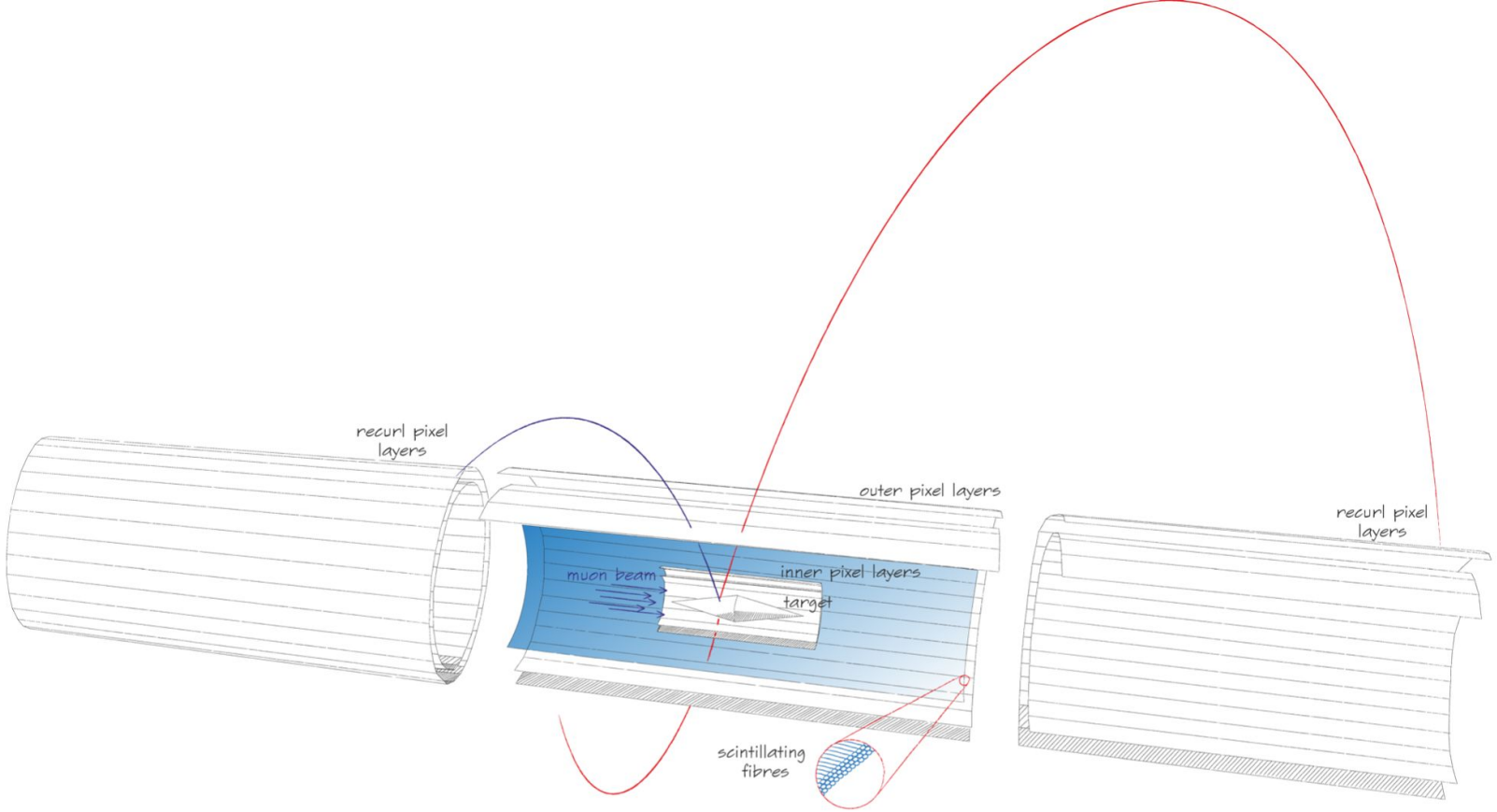
B = 1 T



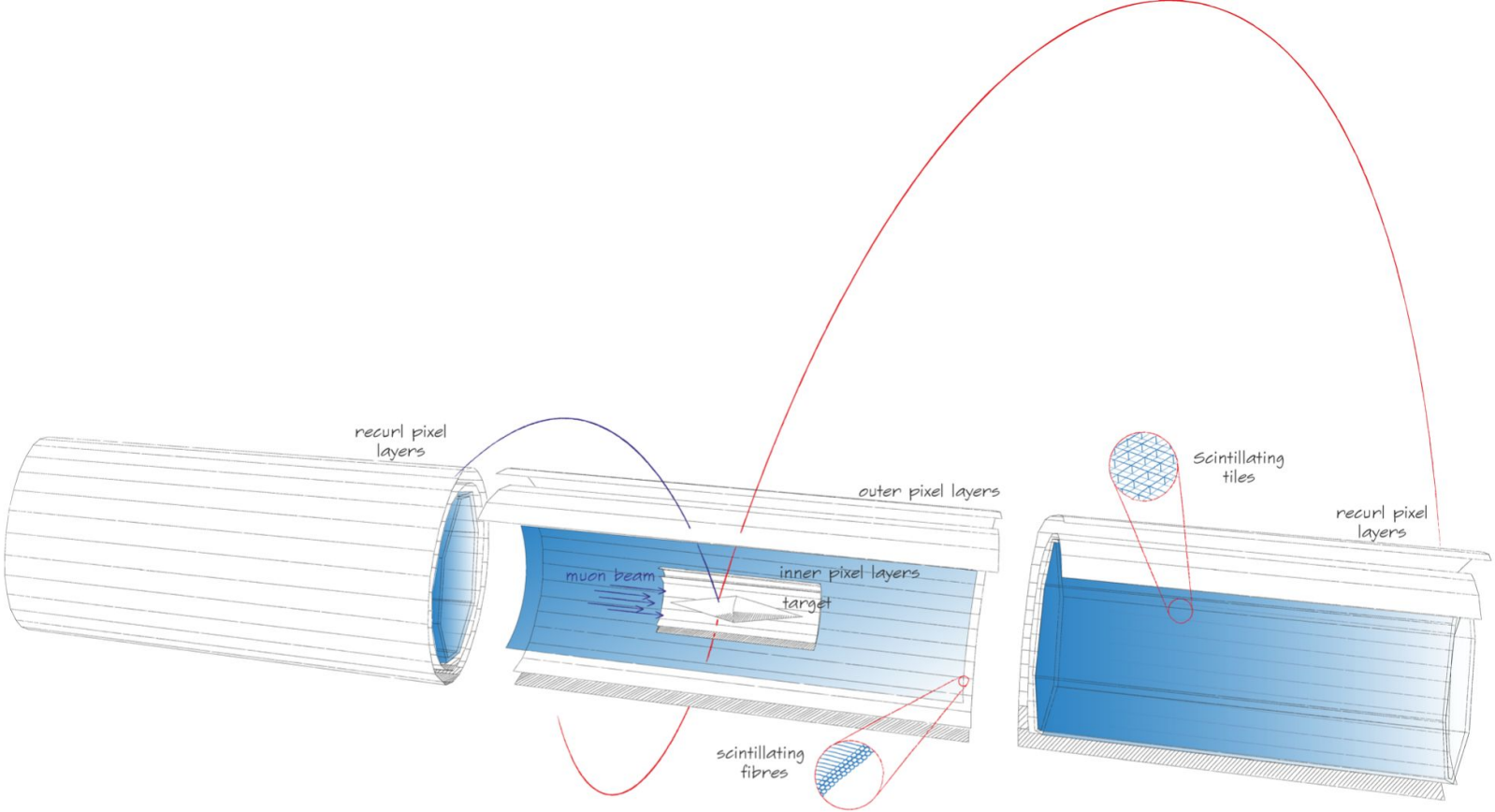
B = 1 T


outer pixel layers
muon beam
inner pixel layers
target
scintillating
fibres

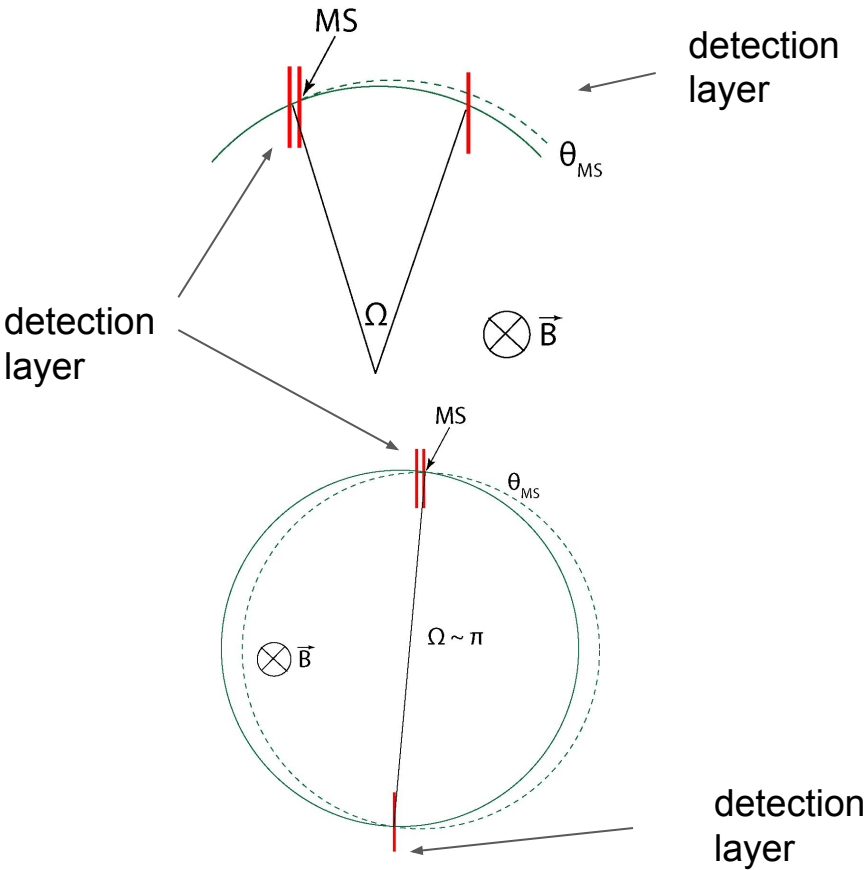
B = 1 T


recurl pixel layers
outer pixel layers
recurl pixel layers
muon beam
inner pixel layers
target
scintillating fibres

B = 1 T


recurl pixel layers
outer pixel layers
muon beam
inner pixel layers
target
scintillating fibres
Scintillating tiles
recurl pixel layers

Momentum measurement



- Using surface muons, decay at rest
- Low momentum electrons/positrons
- Resolution **dominated by multiple scattering**
- Momentum resolution at first order :

$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$

- Precision requires large lever arm (**large bending angle Ω**) and **low multiple scattering θ_{MS}**
- Particles bend back in B, and measured again

⇒ improves momentum resolution

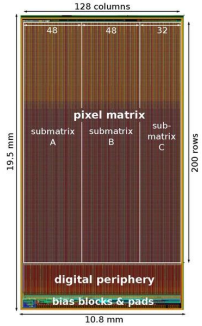
- 2 recurl stations to improve acceptance

Pixel sensors of Mu3e - MuPix

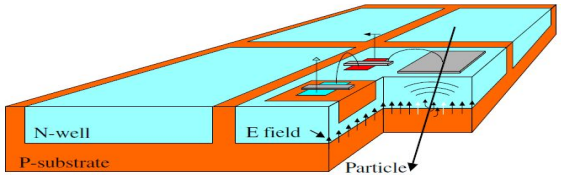
- *Mu3e requirement* : **excellent momentum resolution** using low material budget

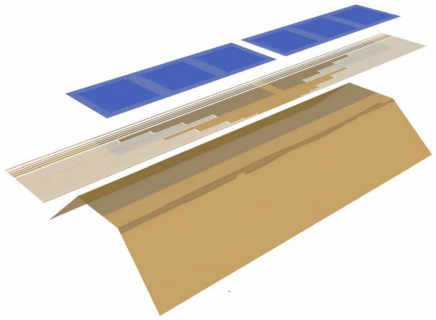
  ⇒ Goal of the pixel detectors : **excellent momentum just 50 µm silicon**

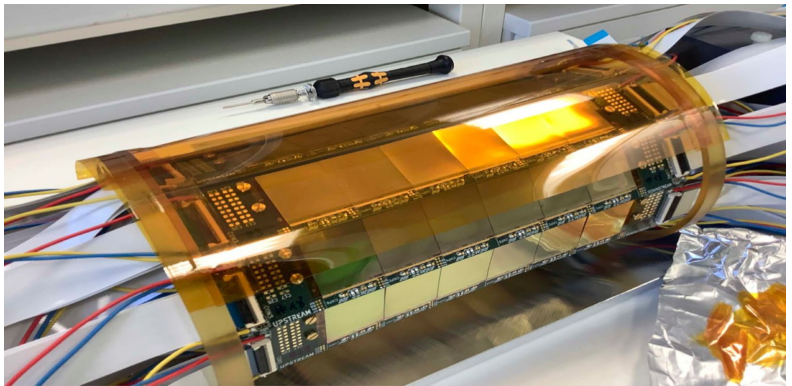
MuPix8



- **High voltage monolithic** active pixel sensors (HV-MAPS)
- **Small** active region, **fast charge collection** via drift
- **Fully integrated** digital readout
- Newest version MuPix10 (MuPix11) test ongoing
- Pixel detectors cooled with helium
- Integrated with fexpint

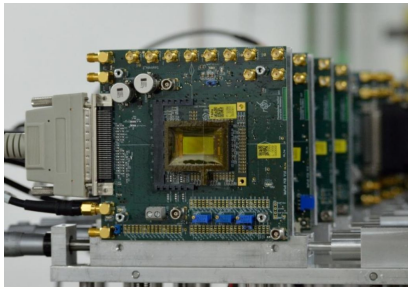


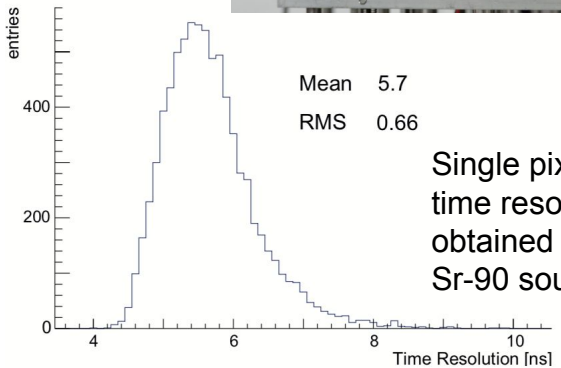




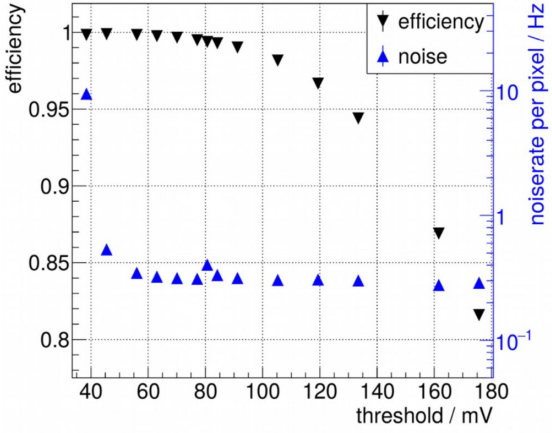
Some results of MuPix8

- Developed a series of MuPix's
- Extensif lab + testbeam characterization : Efficiency, timing,...
- Fulfill Mu3e requirements



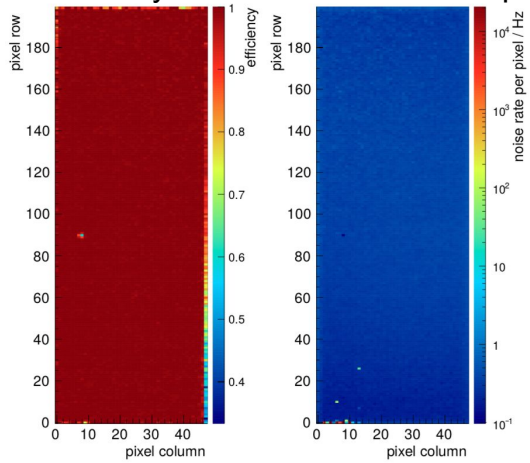


Single pixel time resolution obtained with Sr-90 source

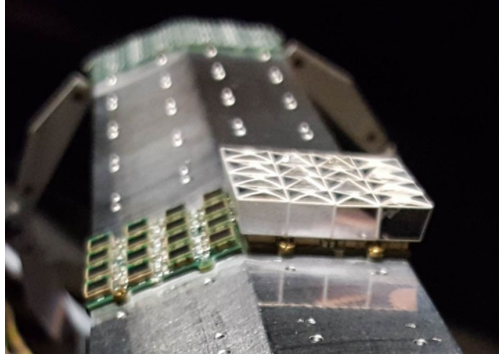


efficiency ~99%

noise ~1Hz/pixel

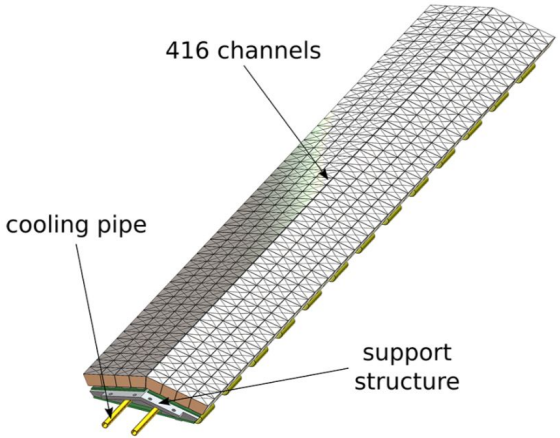


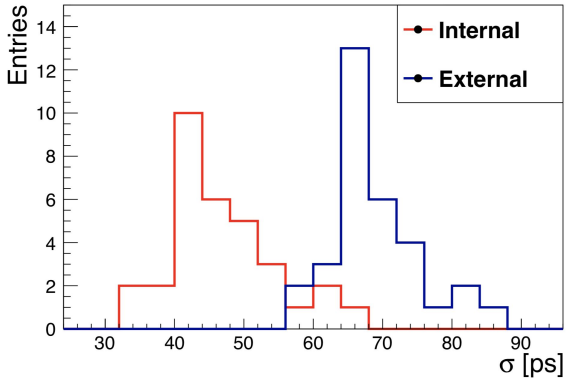
Scintillating Tiles



- ~0.5 cm^3 scintillating tiles

- Readout with silicon photomultipliers (SiPMs) and custom ASIC (MuTRiG)
- Extensif lab + testbeam characterization
- nents





internal : using channels in the same sub-module
external : using channels in the different sub-module

Readout Mu3e

- Trigger-less data, streaming readout ⇒ **Data rate of 100 Gbit/s**
- **Network of FPGAs and optical links**
- Collect **all data of a time slide** on one PC
- Reconstruct tracks, then vertices on a GPU
- Write interesting events to disk