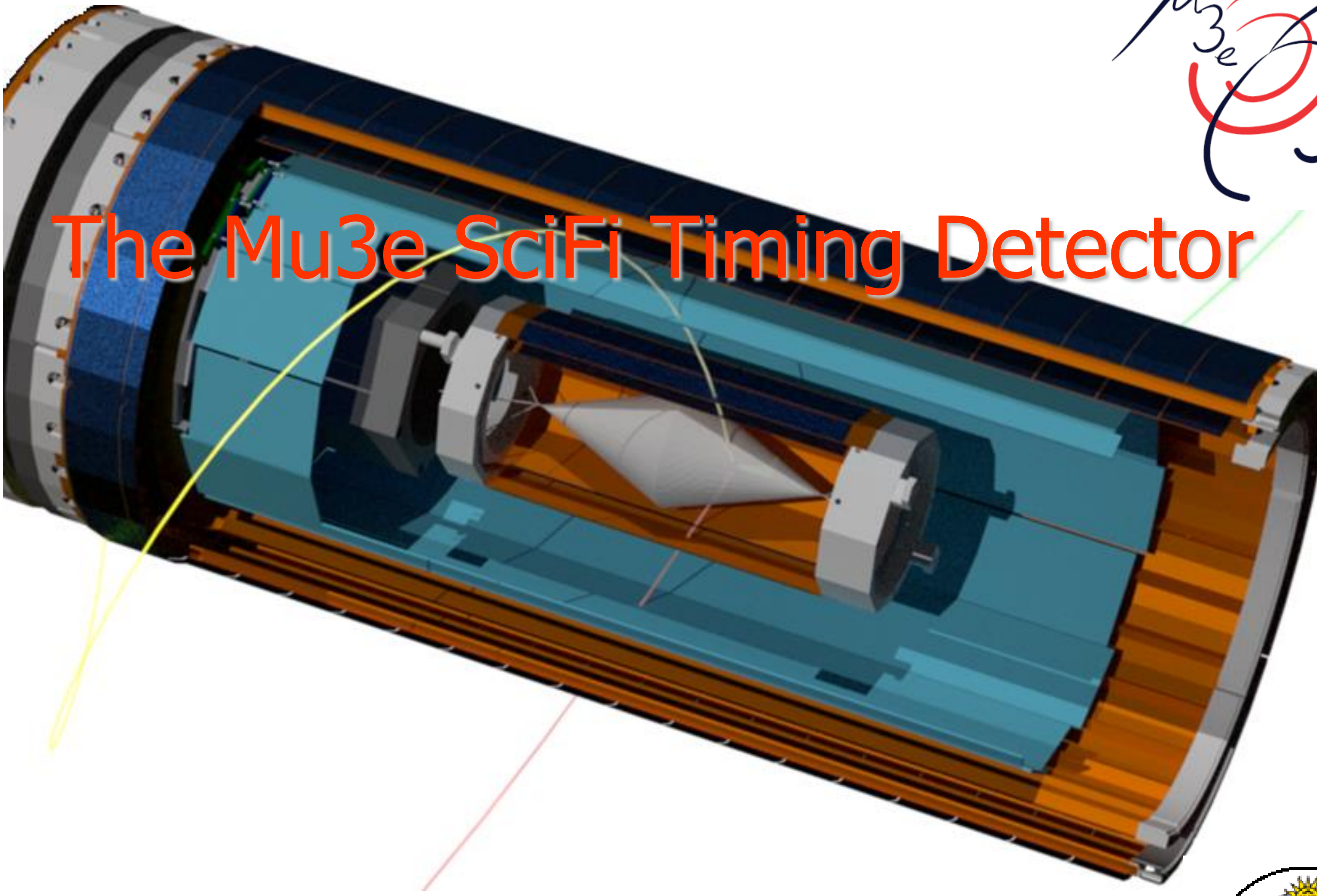
The Mu3e SciFi Timing Detector



VCI 2019
Vienna
February 21, 2019

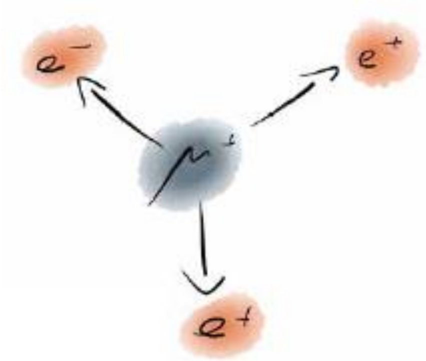
Alessandro Bravar
for the Mu3e SciFi team

Searching for the $\mu^+ \rightarrow e^+e^-e^+$ Decay

In the Standard Model ($m_\nu = 0$) Lepton Flavor is conserved absolutely
(not by principle but by structure !)

and LFV processes like $\mu \rightarrow e + \gamma$ or $\mu \rightarrow e\ e\ e$ have not been observed yet

Mu3e: search for the rare μ decay $\mu^+ \rightarrow e^+ e^- e^+$



with sensitivity BR ~ 10^{-15} to 10^{-16} (PeV scale)
$\tau_{(\mu \rightarrow eee)} > 1000$ years ($\tau_\mu = 2.2\ \mu$s)

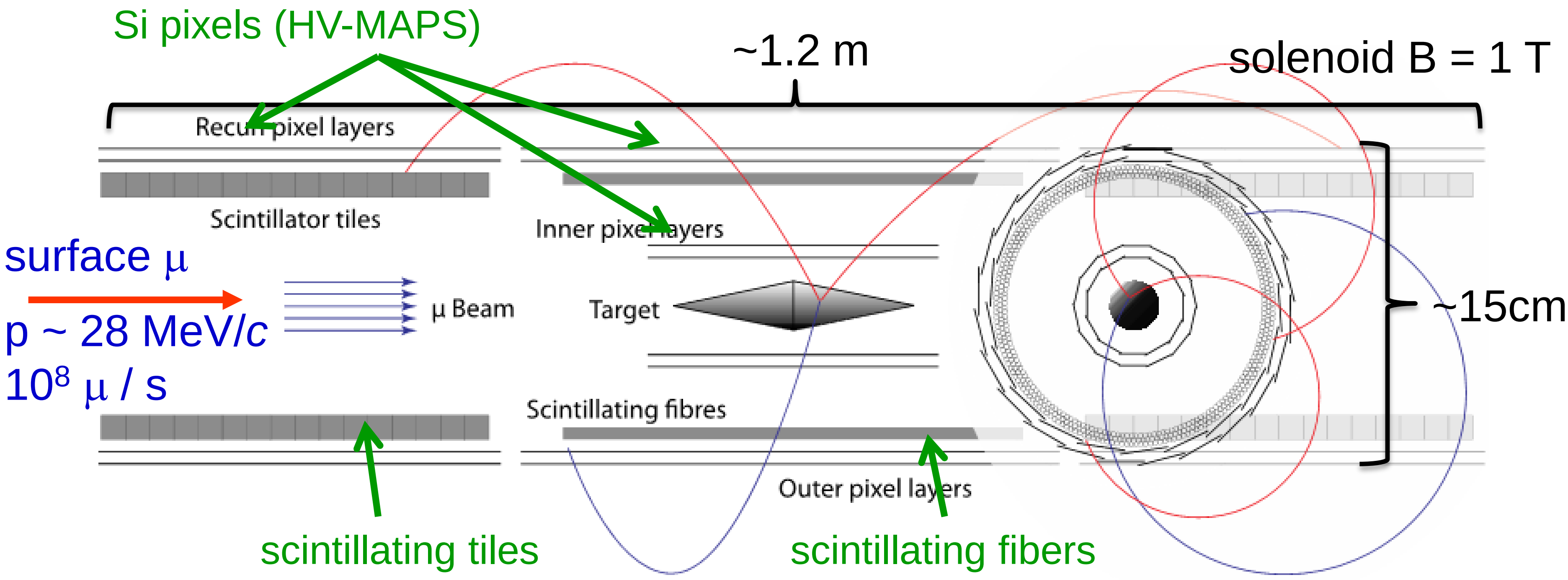
using the world's most intense DC (surface) muon beam (p ~ 28 MeV/c) at PSI

$\Rightarrow$ observe ~ 10^{16} – 10^{17} μ decays (over a reasonable time)
$\Rightarrow$ rate up to 2×10^9 μ decays / s

$\Rightarrow$ suppress all backgrounds below 10^{-16}

$\Rightarrow$ build a detector capable of measuring up to 2×10^9 μ decays / s
minimum material, maximum precision

Mu3e Baseline Design



acceptance ~ 25% for $\mu^+ \rightarrow e^+ e^- e^+$ decay (3 tracks!)

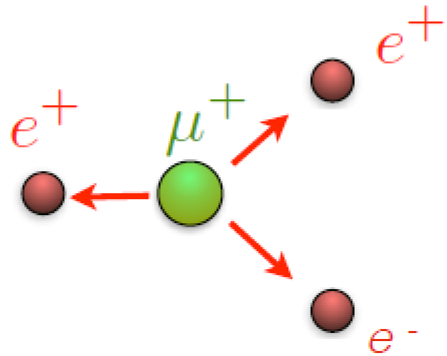
thin (< 0.1% x_0), **fast**, **high resolution** detectors
(minimum material, maximum precision)

175 M HV-MAPS channels (Si pixels w/ embedded amplifiers)

10 k ToF channels (SciFi and Tiles)

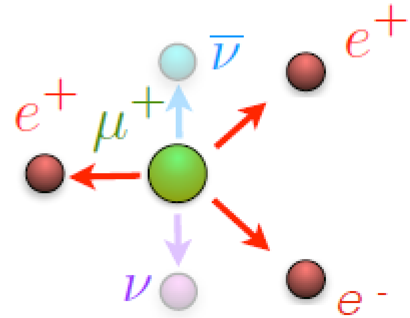
Signal and Backgrounds

signal

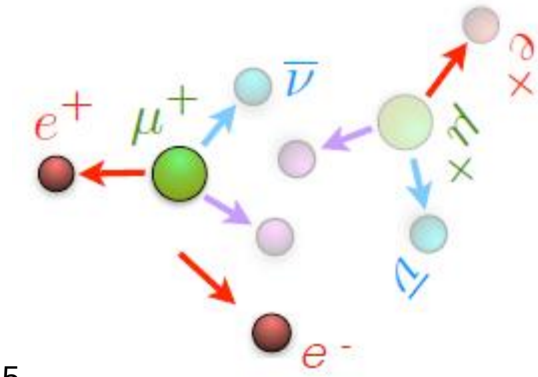


backgrounds

internal conversion



accidental



BR $(\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu) = 3.5 \times 10^{-5}$

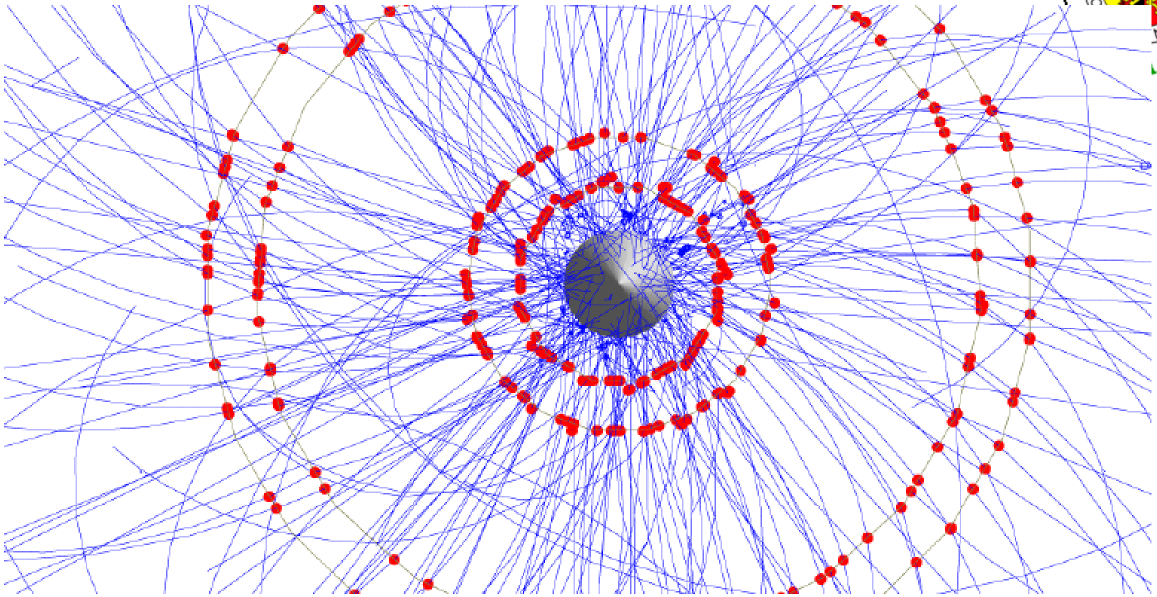
features

signal	internal conversion	accidental
common vertex	common vertex	no common vertex
coplanar $\Sigma \, \mathbf{p}_i = 0$	$\Sigma \, \mathbf{p}_i \neq 0$	$\Sigma \, \mathbf{p}_i \neq 0$
$\Sigma \, E_i = m_\mu$	$\Sigma \, E_i < m_\mu$	$\Sigma \, E_i \neq m_\mu$
$\Delta \, t_{eee} = 0$	$\Delta \, t_{eee} = 0$	$\Delta \, t_{eee} \neq 0$

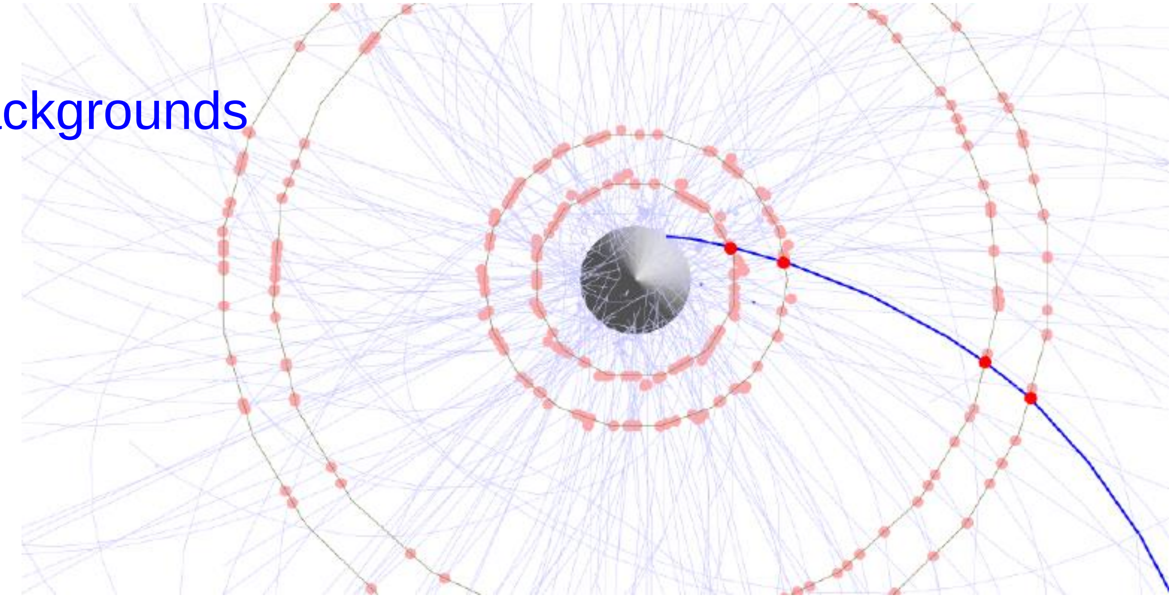
rejecting the background requires
- $\sigma_{vtx} < 300 \ \mu m$
- $\sigma_p < 0.5$ MeV/c
- $\sigma_t < 0.250$ ns

Timing

50 ns snapshot (readout frame): 100 μ decays



additional ToF information < 250 ps



to suppress accidental backgrounds
requires excellent timing

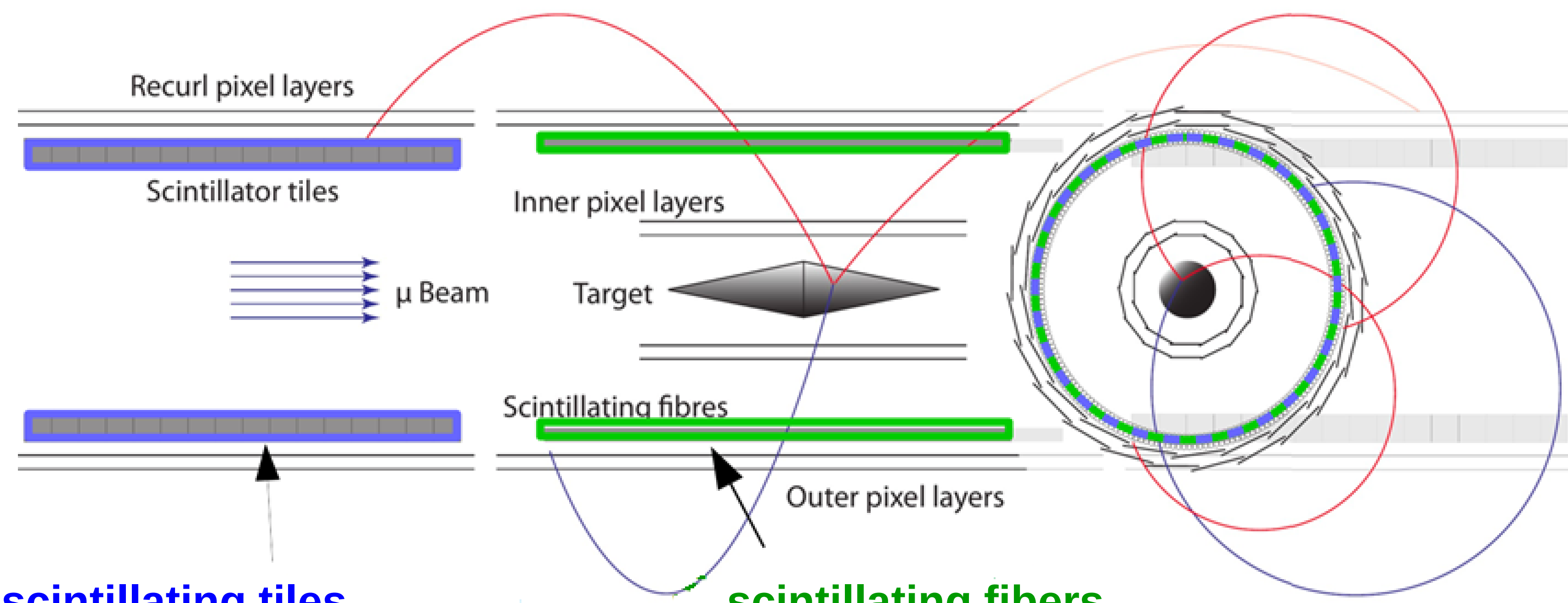
- < 250 ps SciFis
- < 100 ps scint. tiles

The Timing Detectors: Fibers and Tiles

precise timing measurement: critical to reduce accidental BKGs
determine sign of re-curling tracks (SciFi)

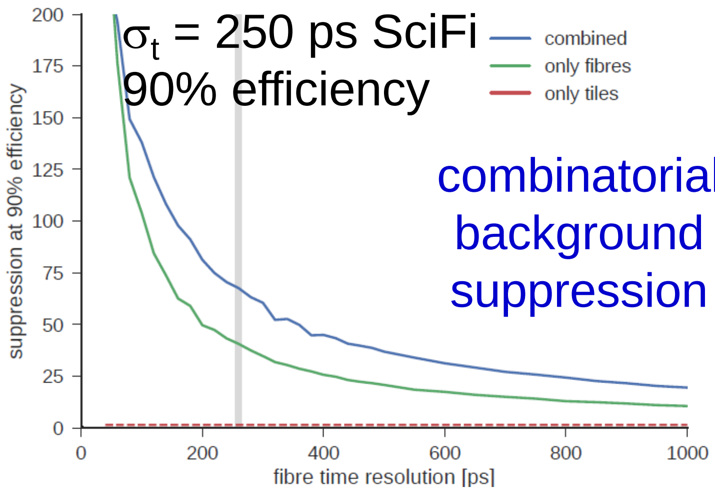
scintillating fibers (SciFi) ~250 ps, detection efficiency > 95 %

scintillating tiles ~70 ps, detection efficiency > 99 %



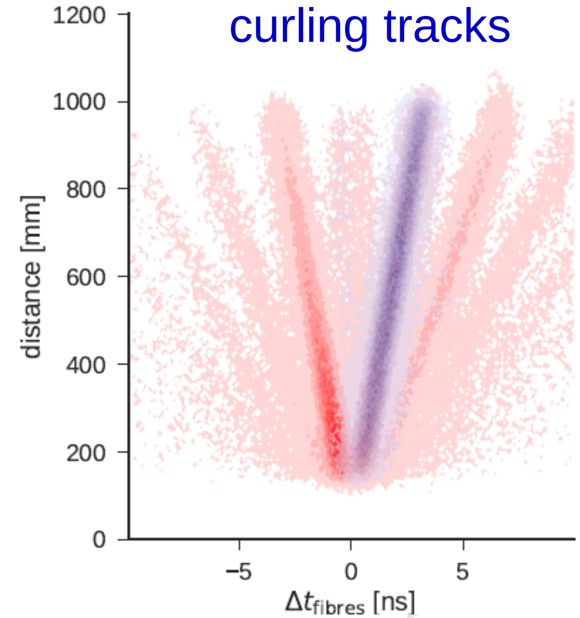
scintillating tiles **scintillating fibers**

Background Suppression

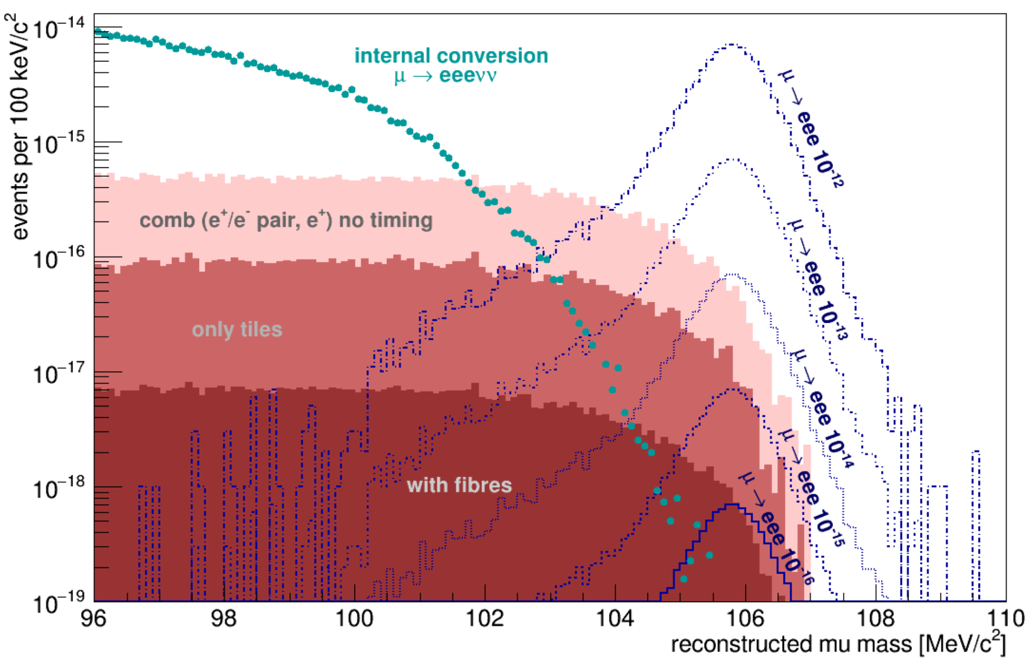


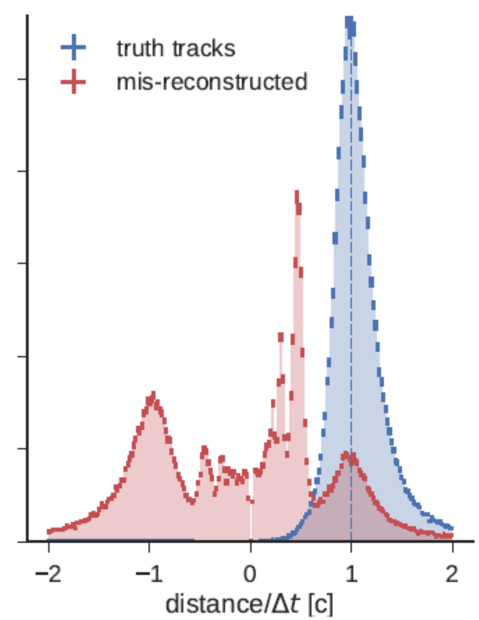
combinatorial background suppression

charge ID
curling tracks



Events per stopped μ^+





Design Parameters

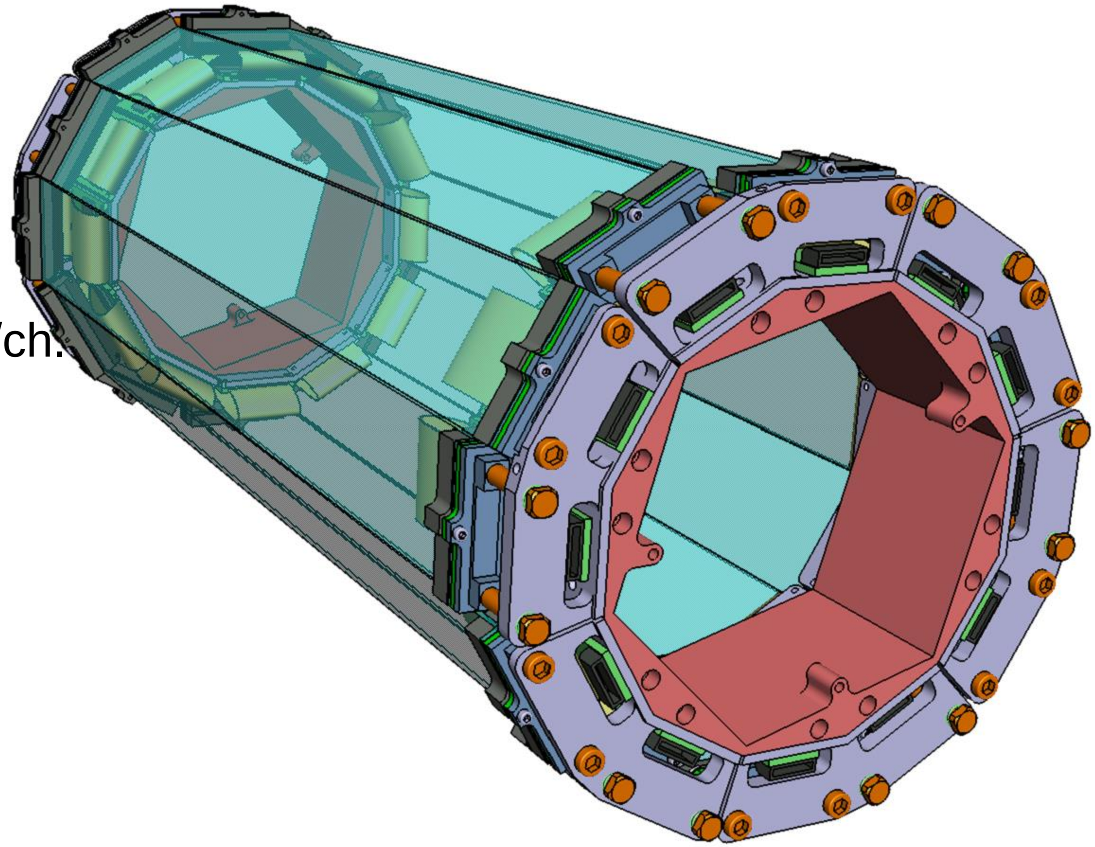
Requirements

thickness $x/x_0 < 0.3\%$ (<1 mm)
time resolution ≤ 250 ps
efficiency > 95%
limited space
high occupancy up to 250 kHz/ch.

12 SciFi ribbons at ~ 6 cm radius
32.5 mm x 300 mm
3 staggered layers
250 μm ϕ fibers
SCSF-78MJ
very thin ~0.2% x_0

Si-PM readout at both ends
128 ch SiPM array (LHCb design)
250 μm pitch

Readout
MuTRiG ASIC
~ 3000 readout channels



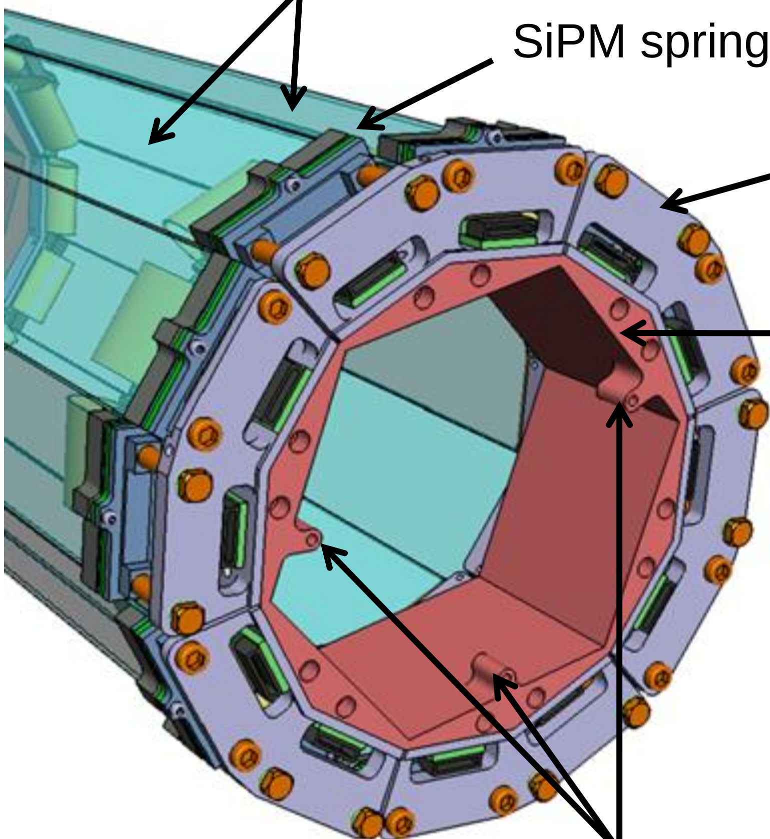
SciFi Mechanics

SciFi ribbons
longitudinally staggered to minimize dead space between ribbons

SiPM spring loaded support

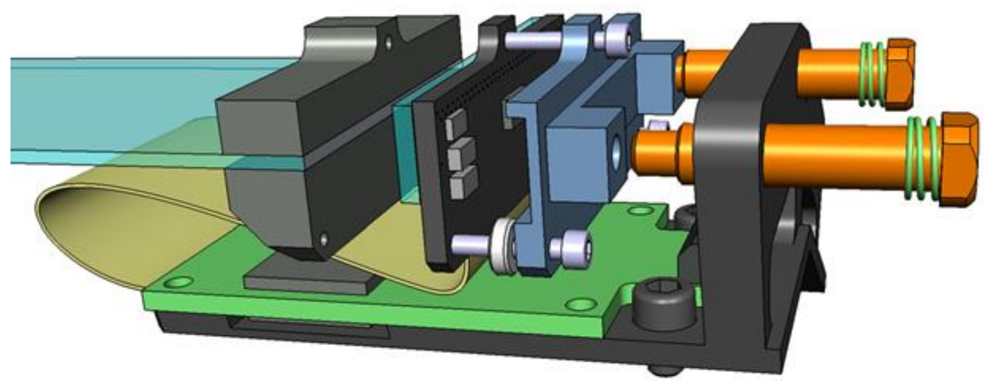
SciFi module support structure
(2 ribbons per module)

cooling ring
supports the SciFi modules



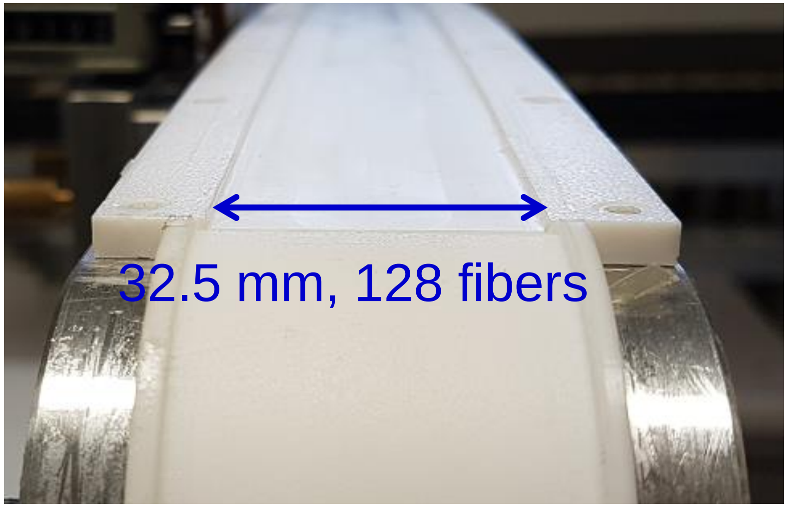
fixations to beam pipe

"expanded" view of SciFI – SiPM coupling
+ spring loaded SiPM support
+ Front End board

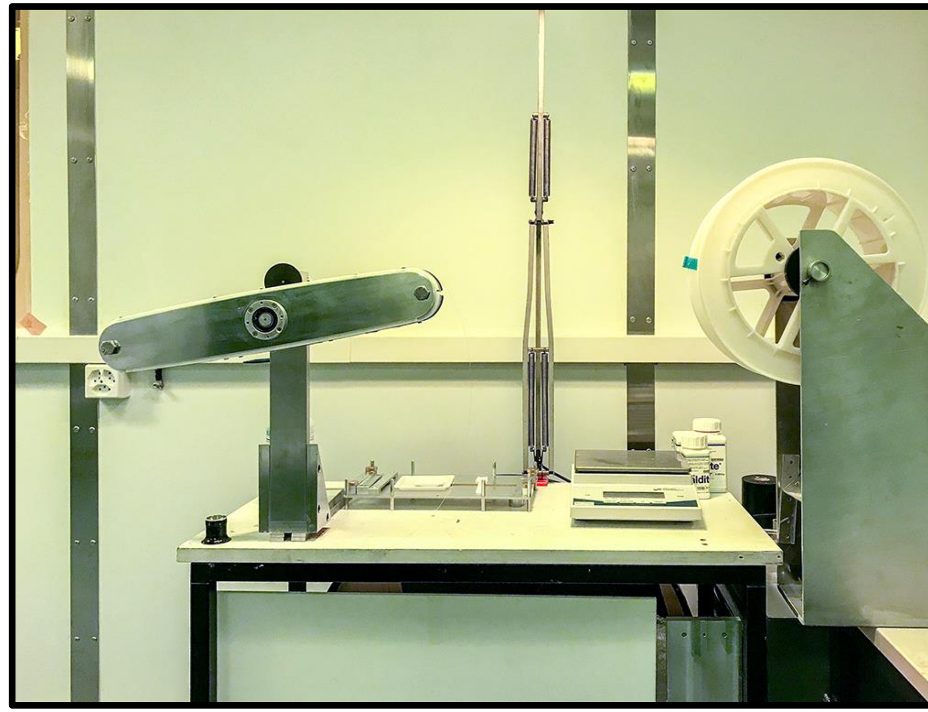


SciFi Ribbon Production

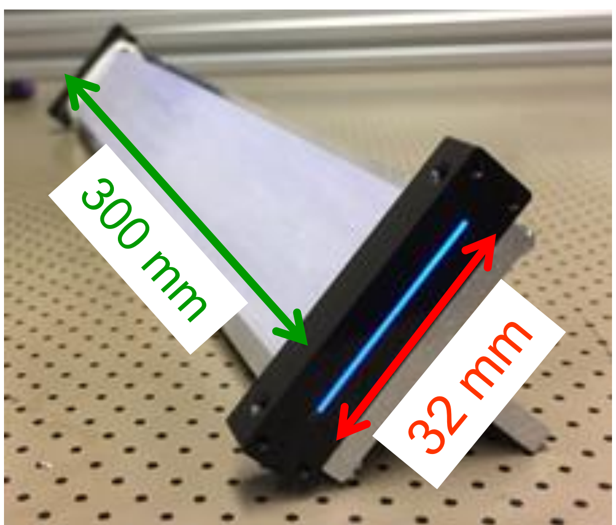
U channel



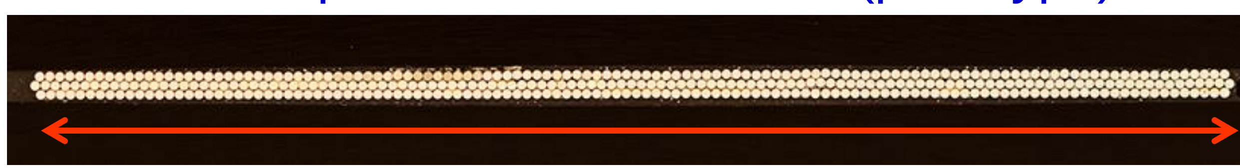
ribbon winding tool



(full size) ribbon prototype



ribbon profile: 3 x ~125 fibers (prototype)

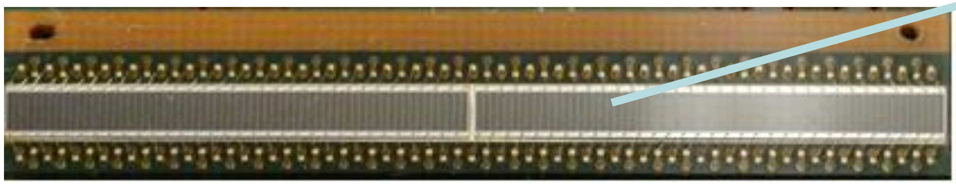


32 mm

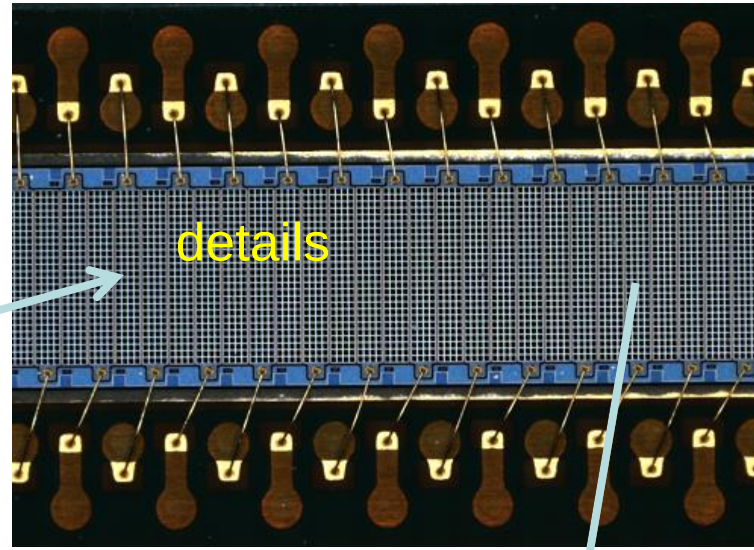
Si-PM Arrays

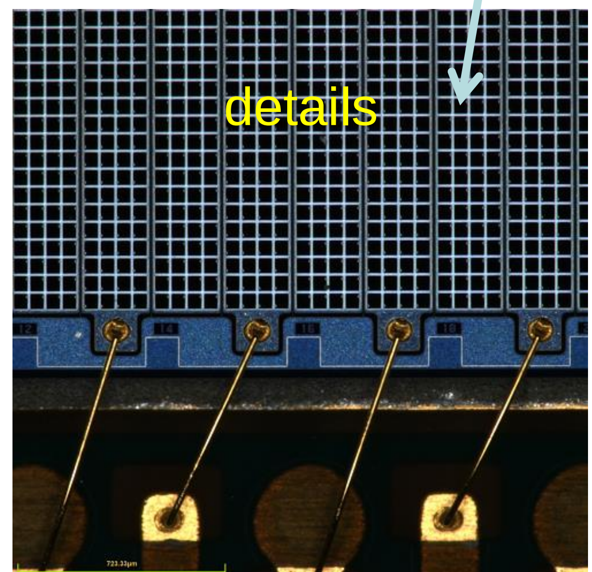
128 ch SiPM array from Hamamatsu (LHCb type) S13552HRQ

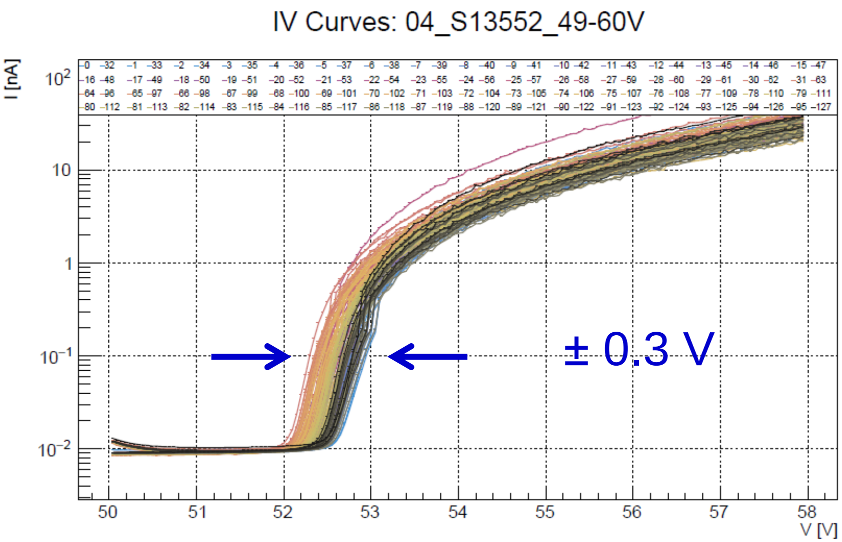
- 250 μm pitch
- pixel size 57.5 μm x 62.5 μm
- 4 x 16 pixels per column
- 230 μm x 1625 μm column area
- V_{break} ~52.5 V (± 0.3 V same array)
- high quenching resistor



32.5 mm (two 64 ch. dies)







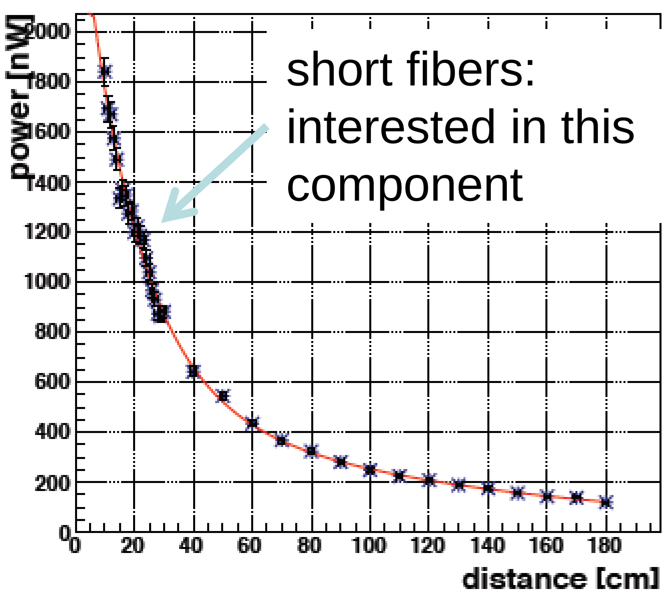
Selecting the Scintillating Fiber

criteria:

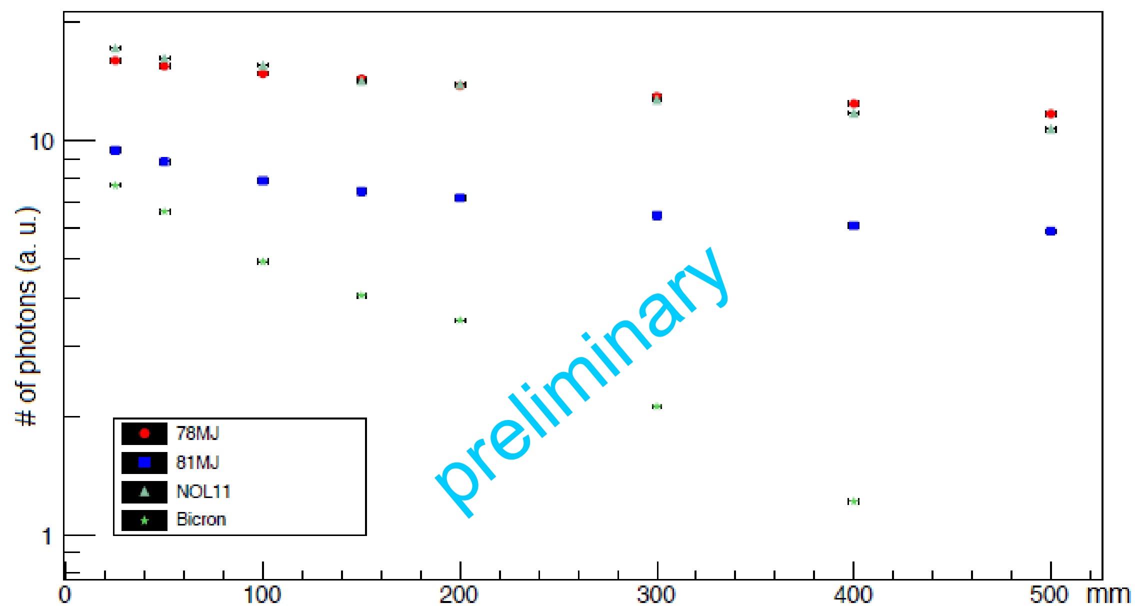
- high light yield
- best time performance

type	att. l. λ (cm)	τ_{decay} (ns)
Kuraray SCSF-78	> 400	2.8
Kuraray SCSF-81	> 350	2.4
Kuraray NOL-11	> 250	1.0
Bicron BCF-12	270	3.2

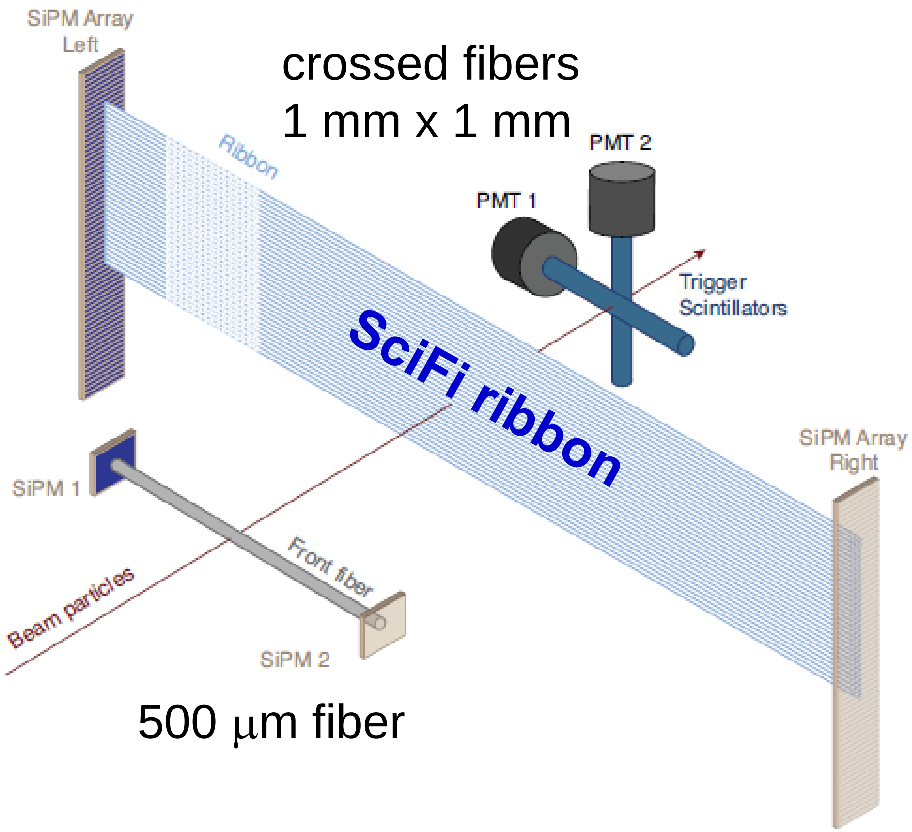
light attenuation (LED)

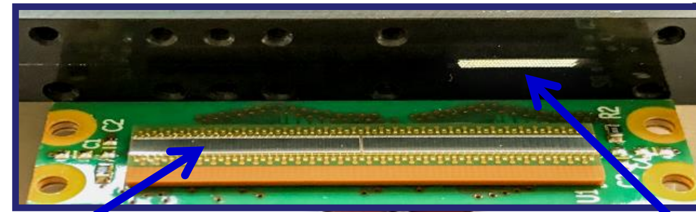


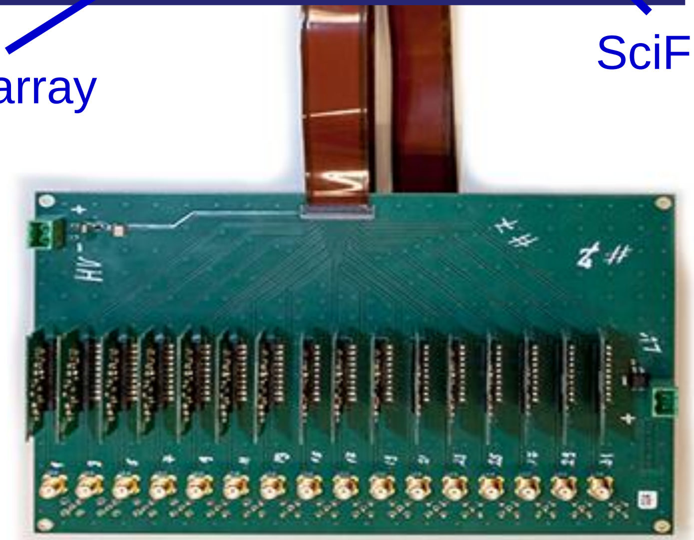
light attenuation (Sr source)



Test Beam Setup





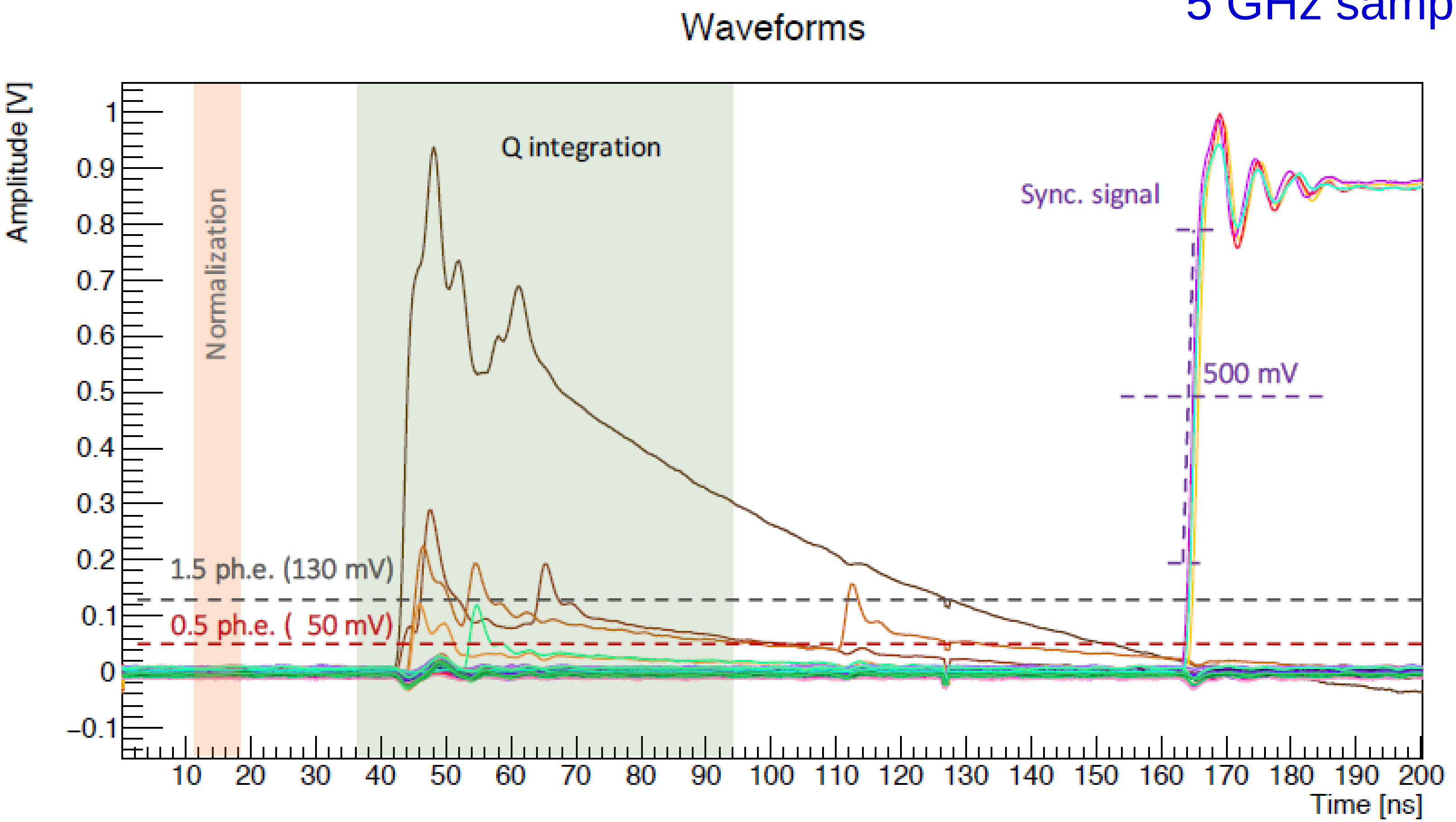


hybrid
fast amplifiers

waveform digitizer
4 x DRS4 ASIC (32 ch.)

Recorded Waveforms

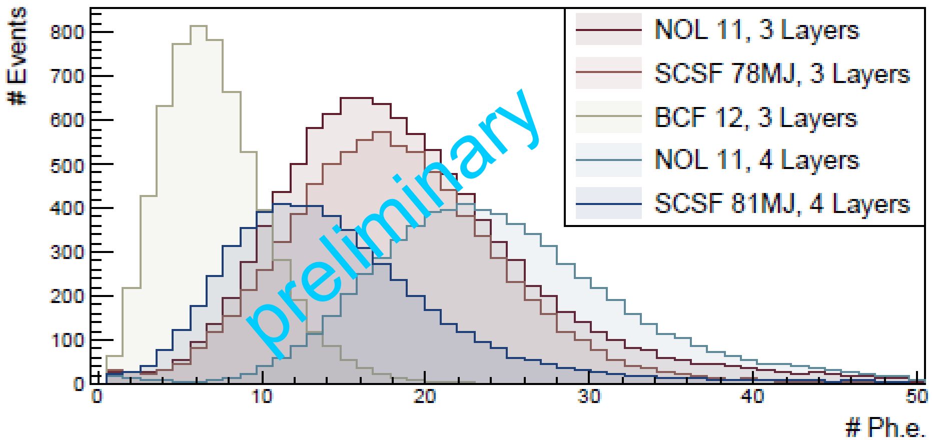
5 GHz sampling

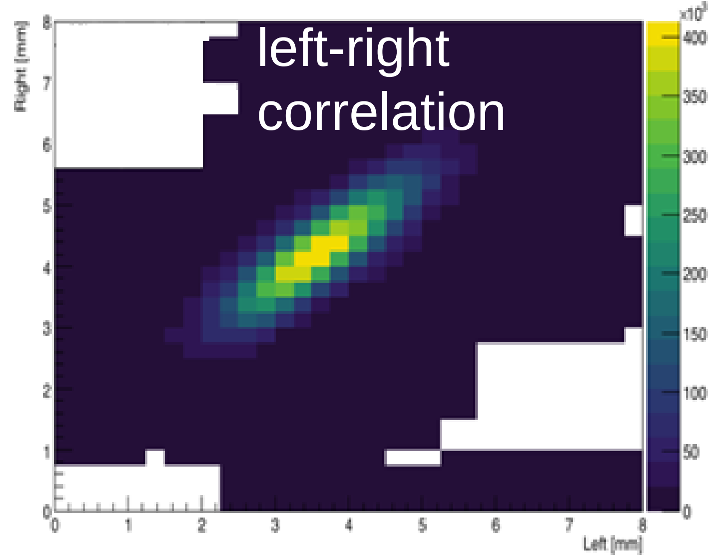


Timing: use a fixed threshold to simulate the functioning of the MuTRiG ASIC

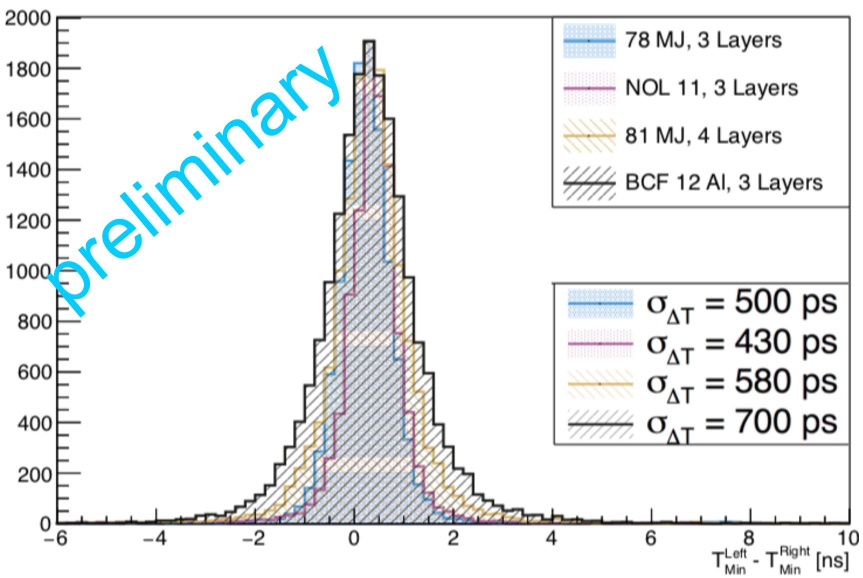
Performance of SciFi Ribbons

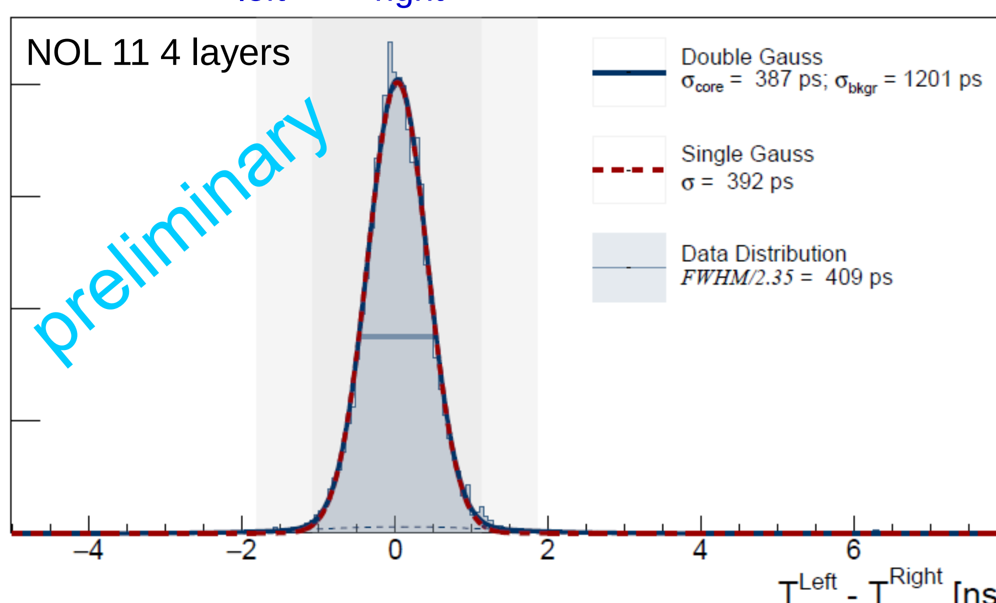
light yield





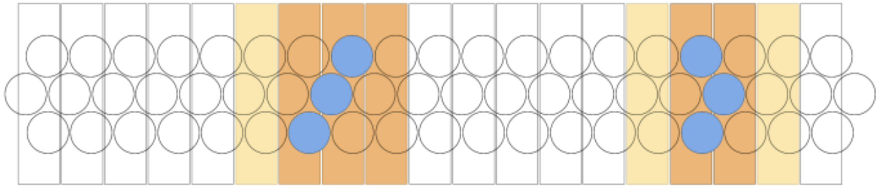
time resolution ($\Delta T = T_{left} - T_{right}$)



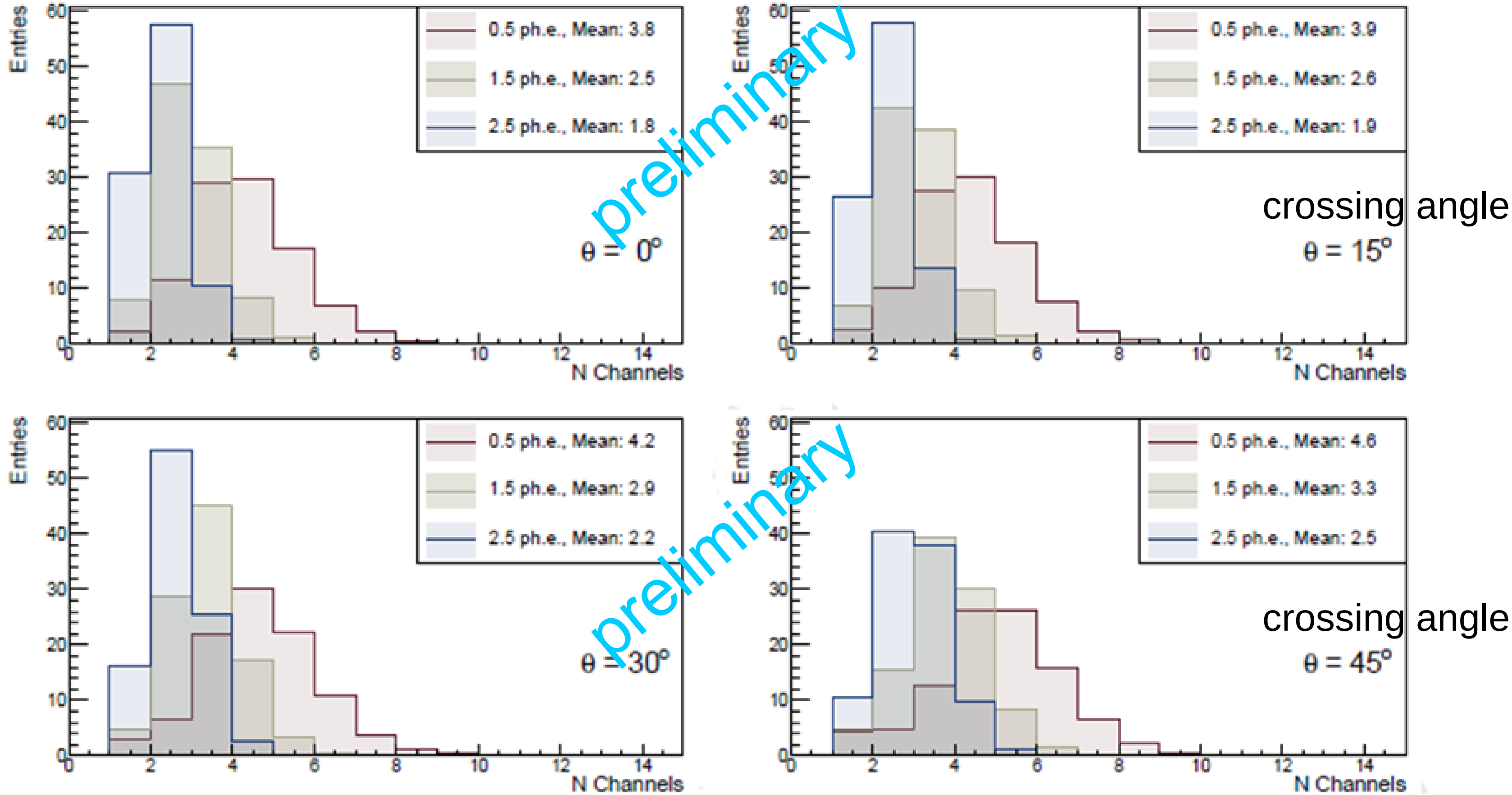


using L.E. disc. algorithm w/interpolation

Cluster Size



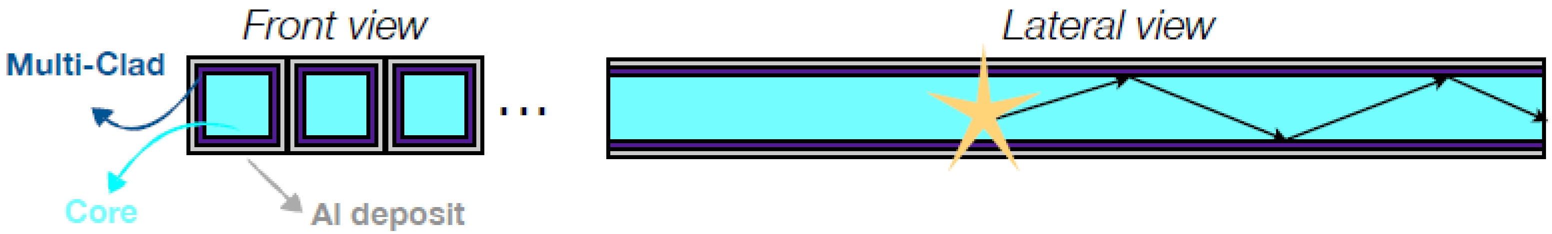
"cluster size" for different thresholds (SCSF-78MJ fiber, 3 layers)
use clear glue because of material budget



important for reducing the data rate:
lower the threshold, larger the cluster → higher the occupancy and the data rate
(lower the light yield of fibers → smaller the cluster size)

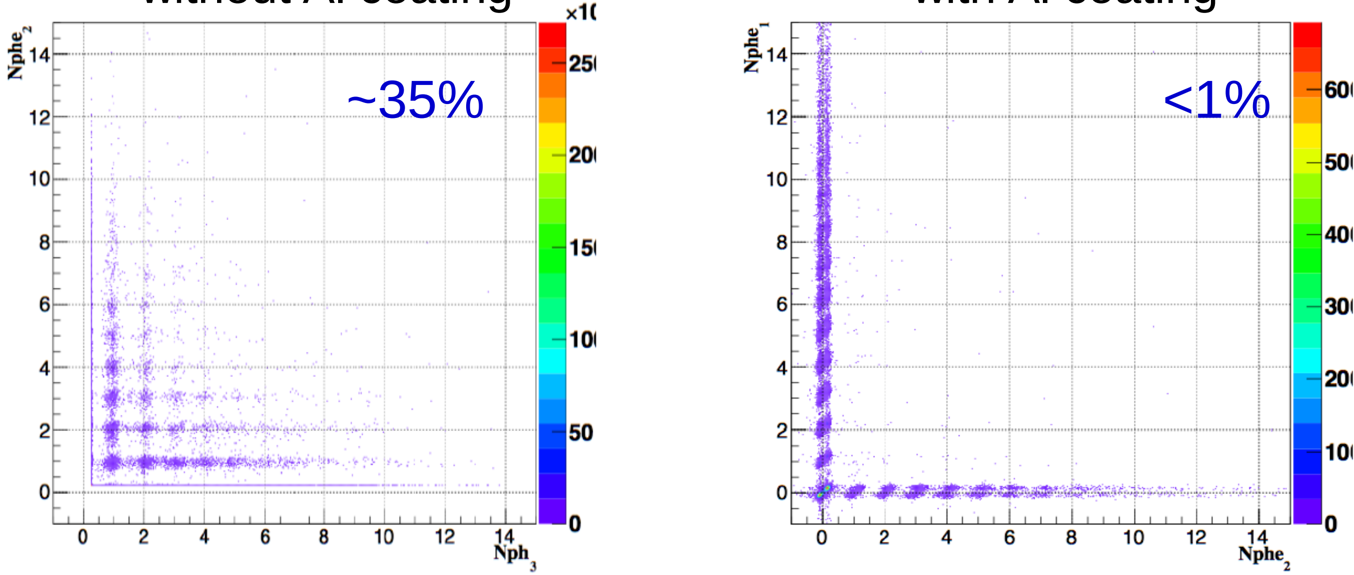
Fiber Optical Cross Talk

negligible optical cross-talk with Al coating (~100 nm): **< 1%** (w/o Al ~ 35%)



without Al coating

with Al coating



fibers (square BCF-12) readout with single channel SiPMs

however Al coating not practical: would need to coat > 10,000 fibers

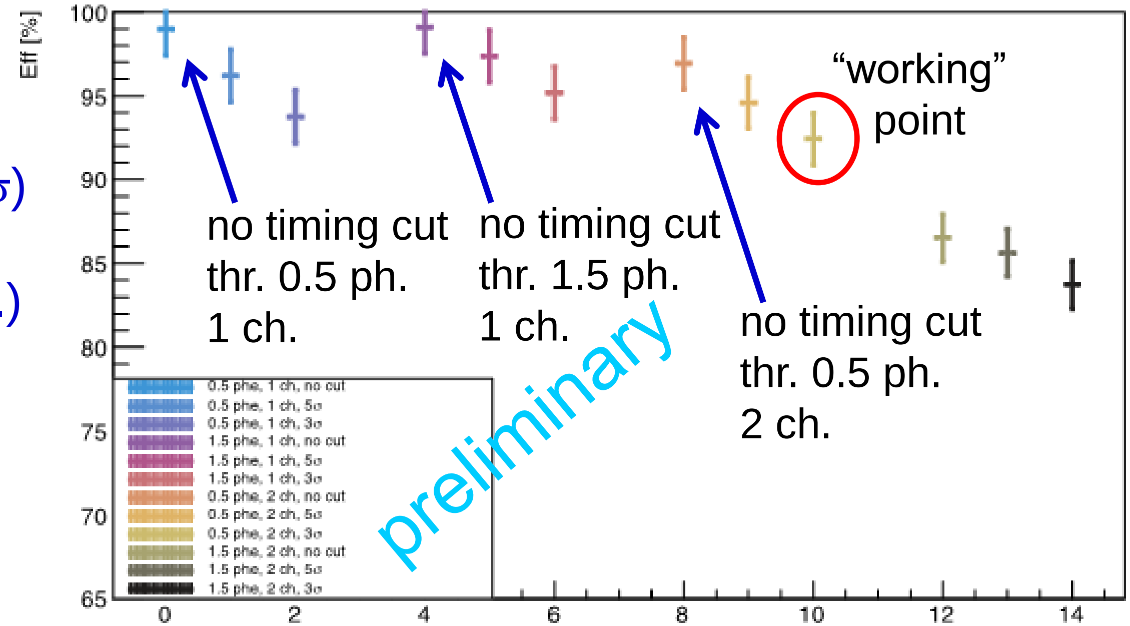
also TiO_2 not practical: would increase too much the material budget

use clear glue ⇒ cluster size increases by ~1

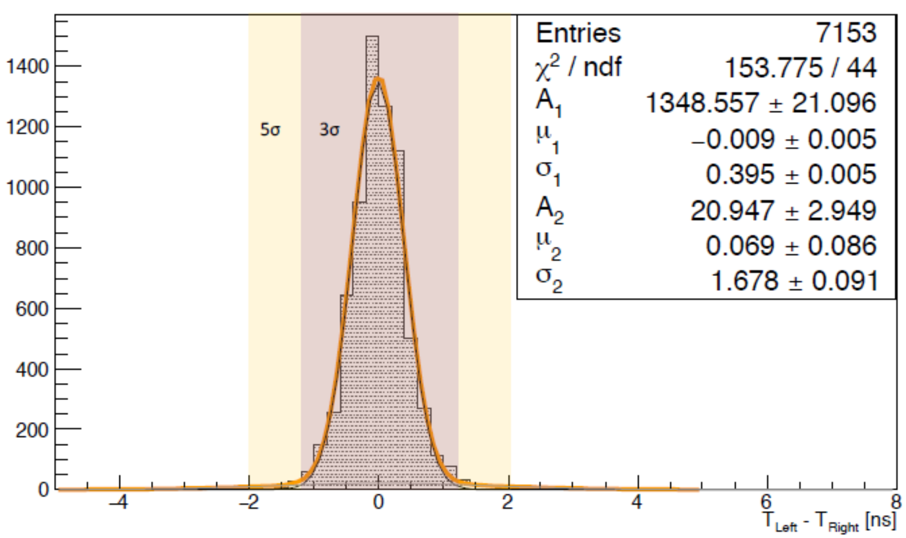
Detection Efficiency

SCSF-78MJ 3 layer ribbon efficiency for different cuts:

1. threshold (0.5, 1.5, or 2.5 ph.)
2. timing cut (no cut, +3σ, or + 5σ)
3. min. cluster size (1 ch. or 2 ch.)



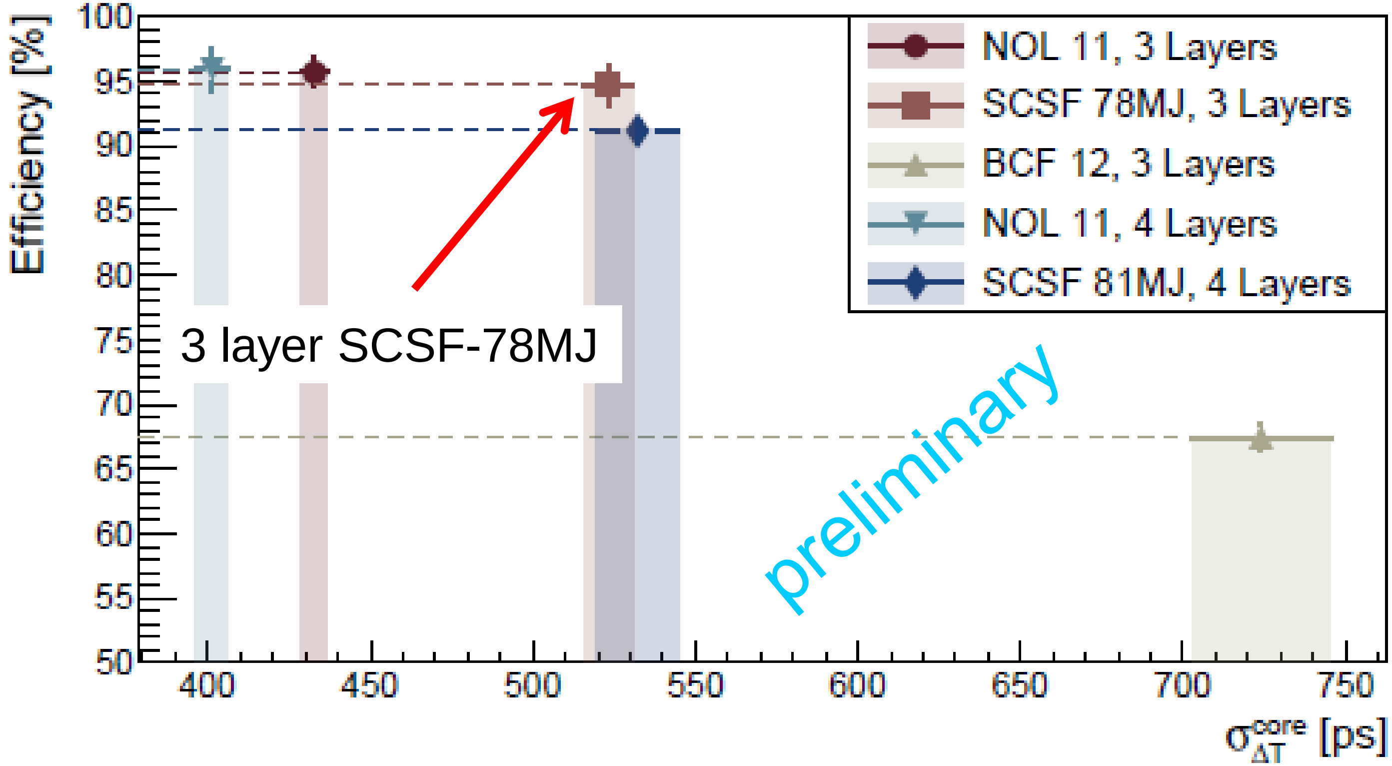
timing cut



if we drop timing cut efficiency close to 100 %

SciFi Performance Summary

comparison of different fiber ribbons: efficiency vs timing

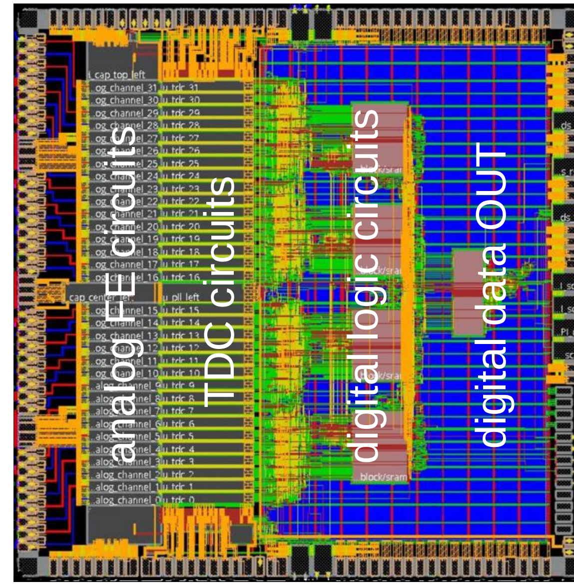


$\sigma_{\Delta T} = \sigma(T_1 - T_2)$; $\sigma_{MT} = \frac{1}{2} \sigma_{\Delta T}$

we require a cluster on each SciFi ribbon end (coincidence)
cluster: at least two adjacent SiPM channels > 0.5 ph. el. threshold
coincidence: ± 3 σ timing cut
timing with L.E. disc. algorithm w/ interpolation to simulate the MuTRiG functioning

MuTRiG ASIC

version 2.0 (01/2019)



5 x 5 mm^2

MuTRiG: Mixed-signal SiPM readout ASIC
for precise timing applications

32 differential inputs
individual SiPM bias tuning
50 ps time binning TDC (time stamps)
Gigabit serial data link (1.25 Gbps)
    up to 1.1 MHz / channel
switchable event length (48/27 bits)
(analog channel inherited from the STiC ASIC)

full chain jitter < 30 ps for charges > 480 fC (1 ph. el.)
    and rates up to 15 MHz
dominated by digitization jitter from TDC

Digital functionality

external trigger
Cyclic Redundancy Check (CRC) for transmission error detection
PLL loss-of-lock detection
clustering coincidence feature

Kirchhoff-
Institute for
Physics

Channel Diagram

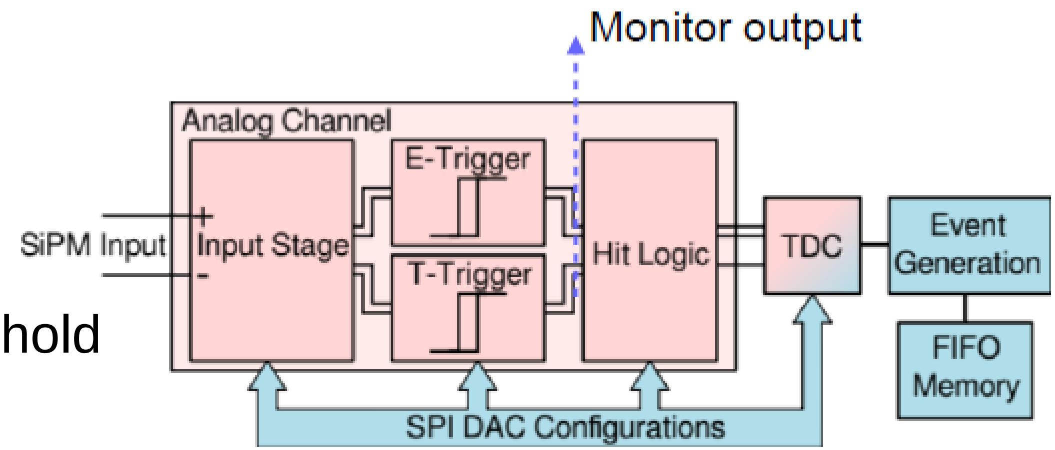
Fully-differential analog front-end
(for better noise immunity)

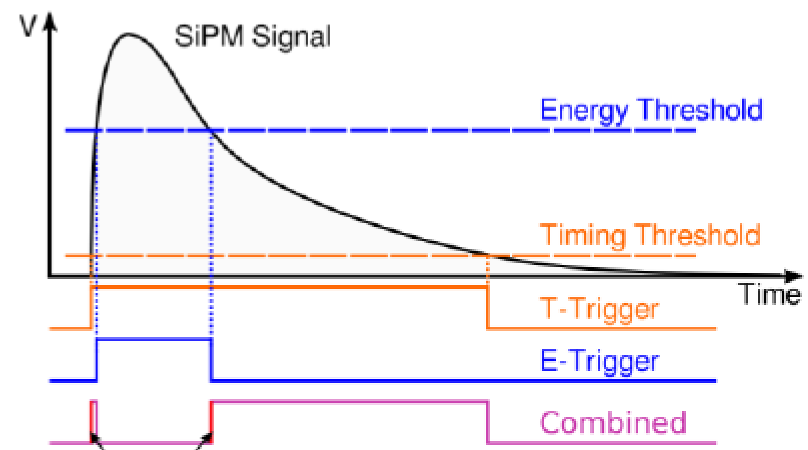
Separate timing and energy threshold

Energy measurement with
Time-over-Threshold (ToT) method

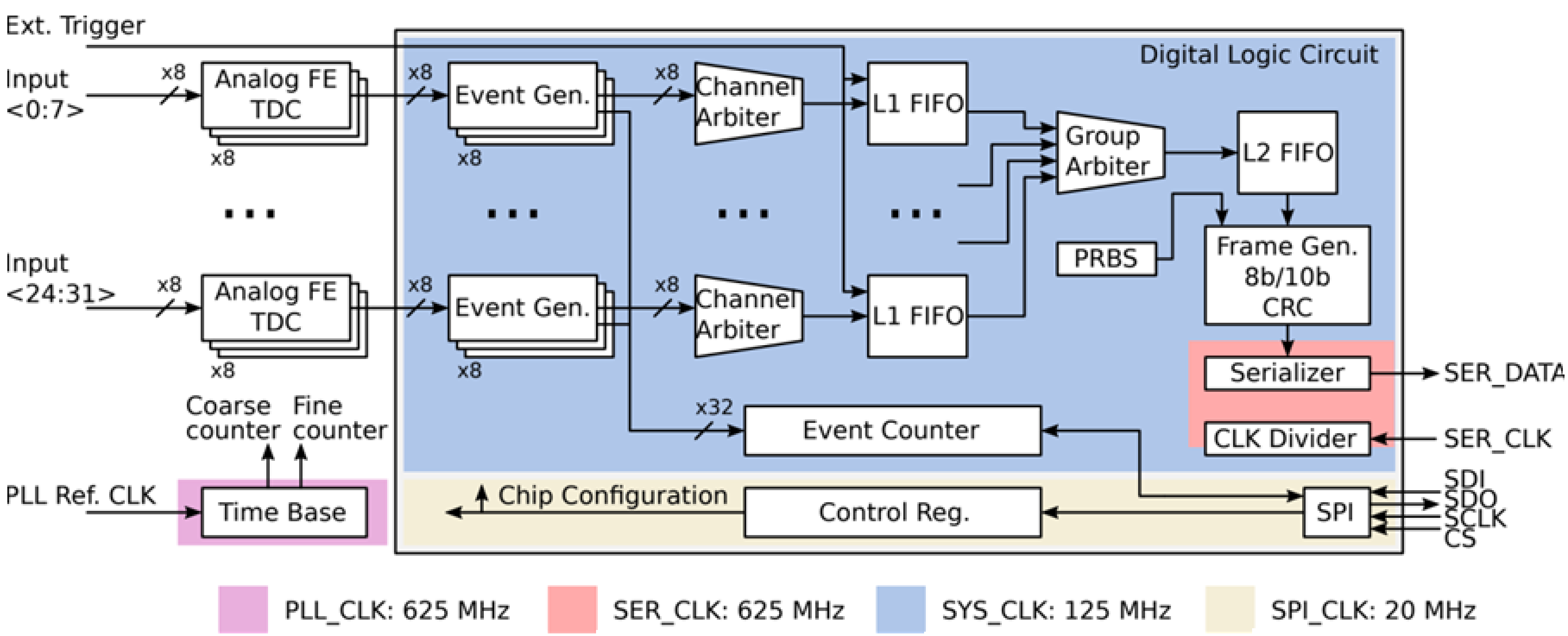
Monitor pins for debug

Encode arrival time and energy (ToT)
information into two rising edges
of the combined signal





Chip Diagram



Two data frames: **Standard (48 bits)** and **short (27 bits)** event length

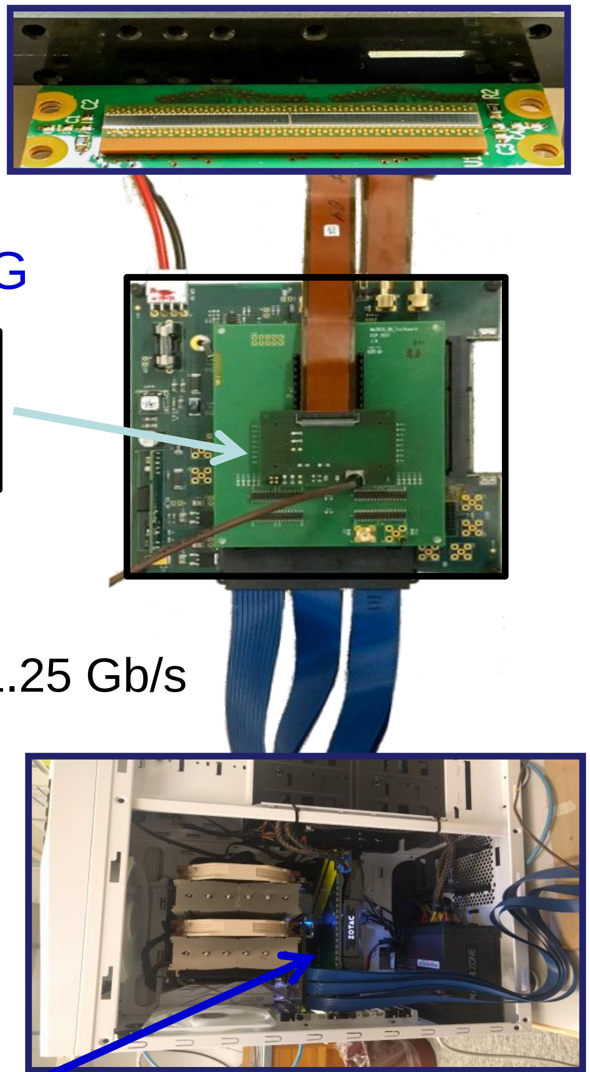
Serializer clock 625 MHz

Double data rate (DDR)

SciFi Performance with MuTRiG

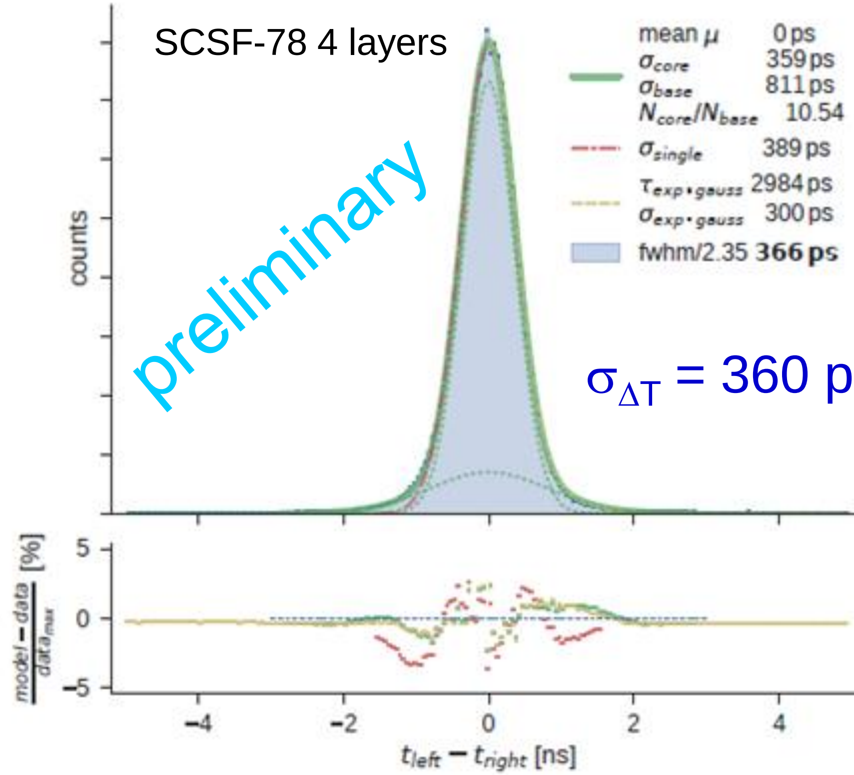
SciFi + SiPM array

MuTRiG



1.25 Gb/s

Stratix IV FPGA



SciFi timing performance w/ MuTRiG
reproduced timing resolution obtained in TB
(using only one channel at each fiber end)

SciFi Front End

4 MuTRiG ASICs per SiPM array
under development

Summary

We developed a very thin SciFi timing tracker with SiPM readout

- 3 staggered layers of 250 μm ϕ fibers SCSF-78 (Kuraray)
- thickness ~700 μm, < 0.2 % x_0
- time resolution $\leq$ 250 ps (mean time)
- efficiency > 95 % (w/ both ends coincidence measurement + timing cut)
- spatial resolution ~100 μm

MuTRiG ASIC v.1.0 fully operational

- excellent analog front-end
- full chain jitter < 30 ps (charge = 480 fC and rate < 15 MHz)
- digital functionality works well

MuTRiG ASIC v.2.0 modifications finished (higher data rate)

Construction completed by the end of 2019

Commissioning in 2020

The Team

UNIVERSITÉ DE GENÈVE

A. Bravar, A. Damyanova(*)

University of Zurich UZH

R. Gredig*, P. Owen, P. Robmann

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

S. Corrodi*, L. Gerritzen, C. Grab

PAUL SCHERRER INSTITUT PSI

M. Hildebrandt, A. Papa, G. Rutar*

PhD students (*graduated)