The Mu3e Scintillating Fiber Timing Detector

SciFi detector in Mu3e apparatus

VCI 2025
Vienna
February 20, 2025

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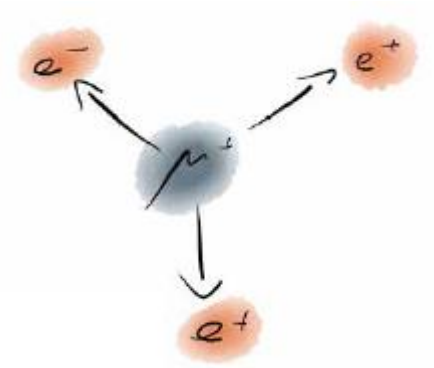
for the Mu3e SciFi team

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 (τ_μ = 2.2 μs)

using the world's most intense continuous surface muon beam at PSI

$\Rightarrow$ observe ~ 10^{16} – 10^{17} μ decays (over a reasonable time)

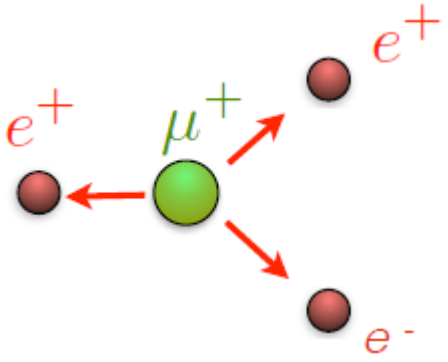
$\Rightarrow$ rate up to 2 x 10^9 μ decays / s

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

$\Rightarrow$ build a detector capable of measuring up to 2 x 10^9 μ decays / s

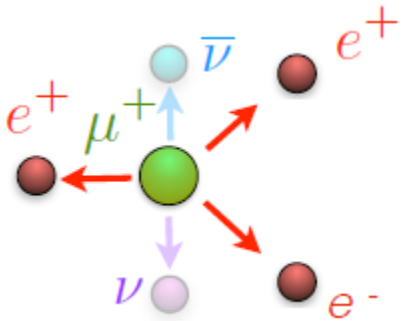
Signal and Backgrounds

signal

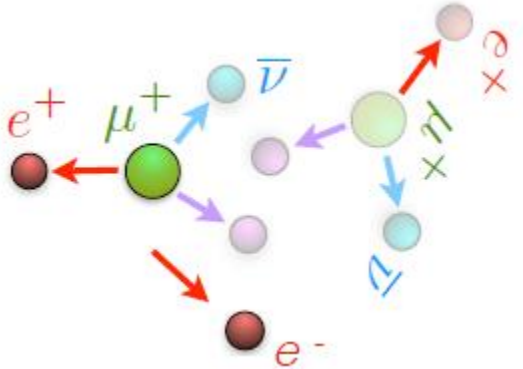


backgrounds

internal conversion



accidental



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

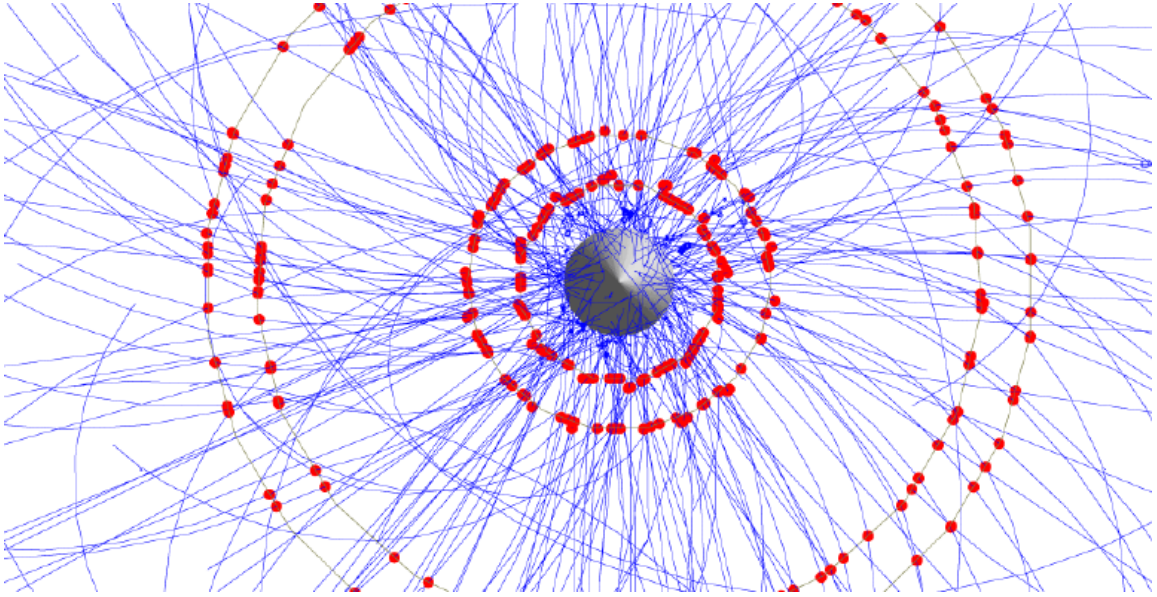
features

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 } → { minimize multiple scattering (material budget!) }

Timing

50 ns snapshot (readout frame): 100 muon decays

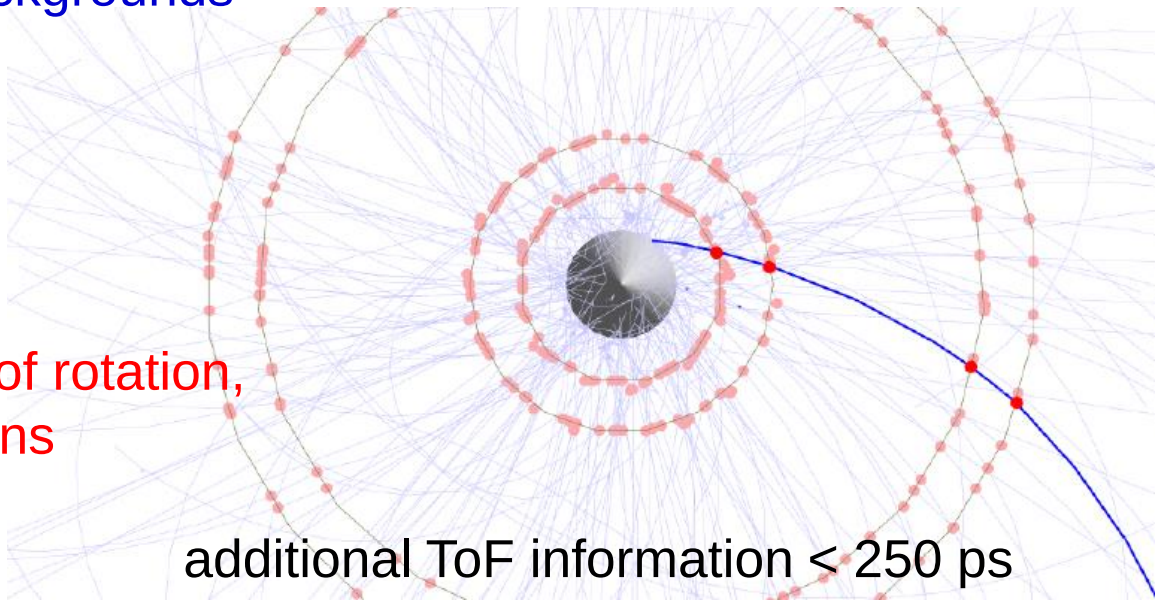


to suppress accidental backgrounds
requires excellent timing

- < 250 ps SciFi's
- < 100 ps Scint. Tiles

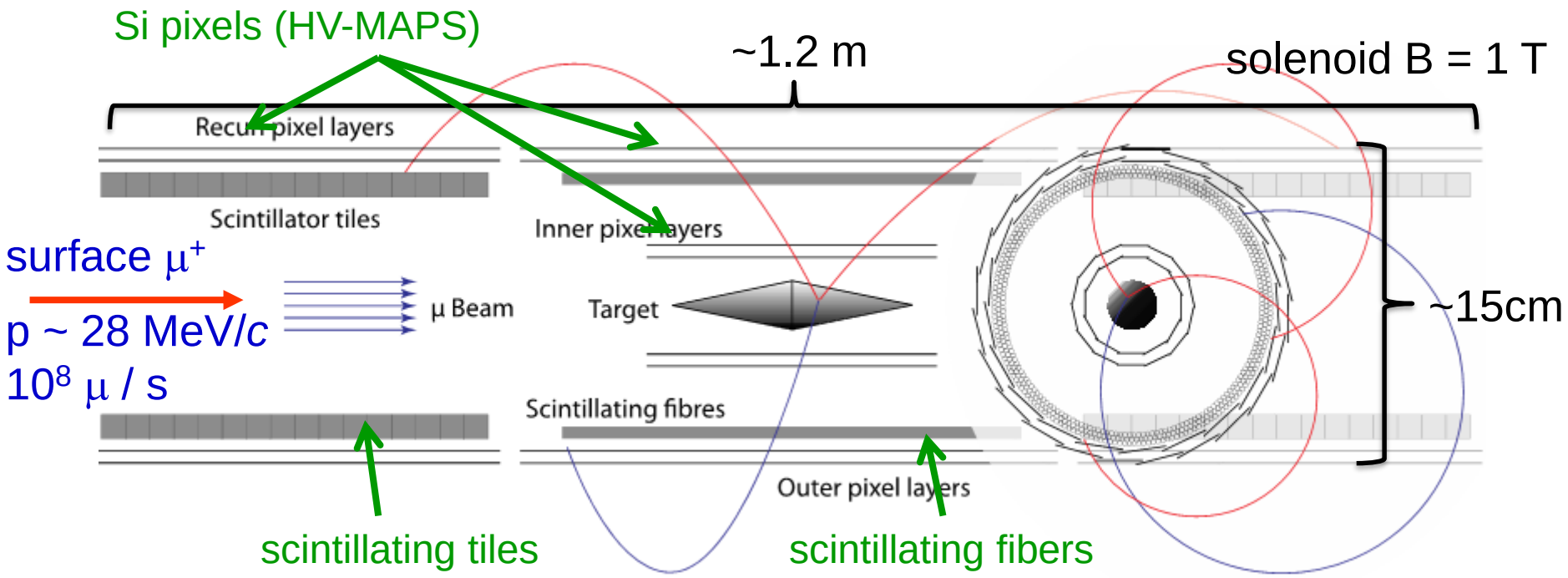
also determine the sense of rotation,
i.e. the charge of the leptons

4D reconstruction



additional ToF information < 250 ps

Mu3e Baseline Design



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

Thin, fast, high resolution detectors

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

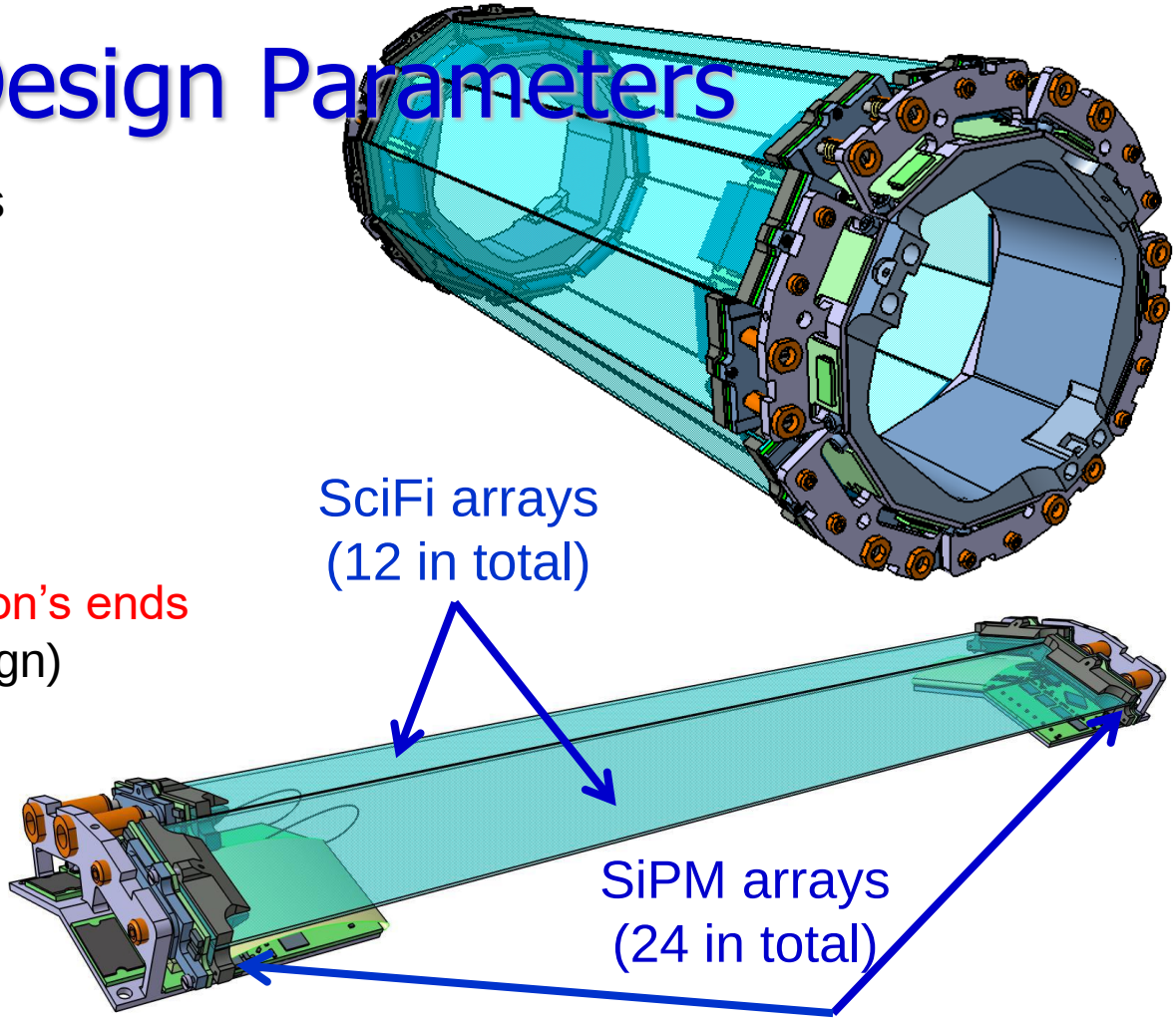
~ 3 k SciFi and ~ 7 k Tile ToF channels

SciFi Detector Design Parameters

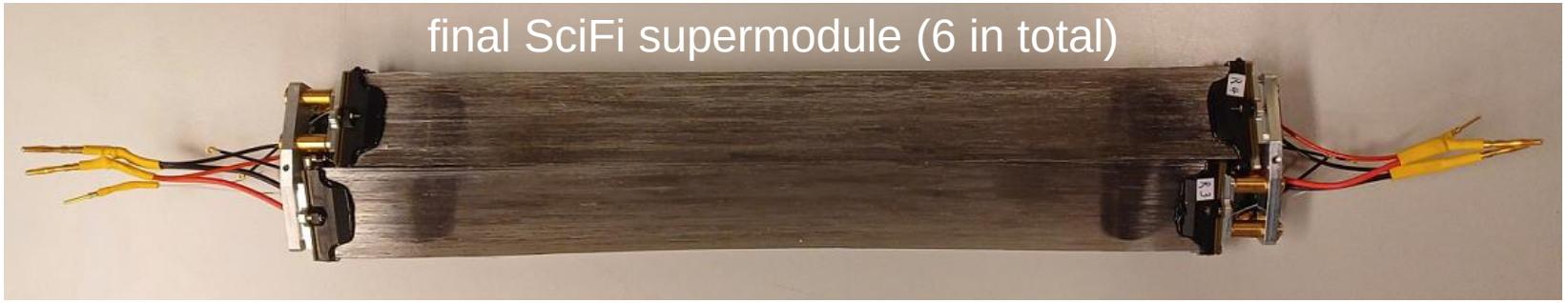
12 SciFi ribbons at ~ 6 cm radius
- 32.5 mm x 300 mm
- 3 staggered fiber layers
- 250 μm ϕ fibers
- SCSF-78MJ
- very thin ~ 0.2% x_0 (~ 700μm)

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

Readout
- MuTRiG ASIC
- ~ 3000 readout channels



Very limited space in central region of Mu3e → very compact design of SciFi detector



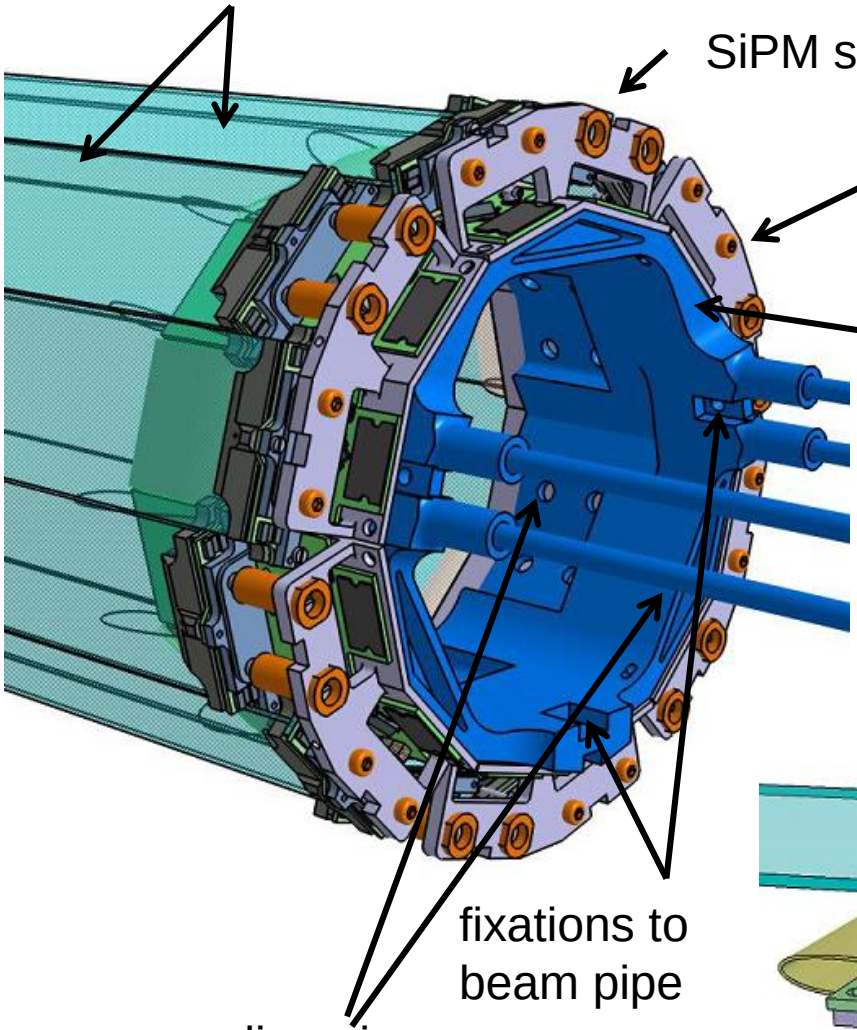
SciFi Detector Mechanics

SciFi ribbons
longitudinally staggered ~1 cm to minimize dead space between ribbons

SiPM spring loaded support

SciFi module support structure
(2 ribbons per module)

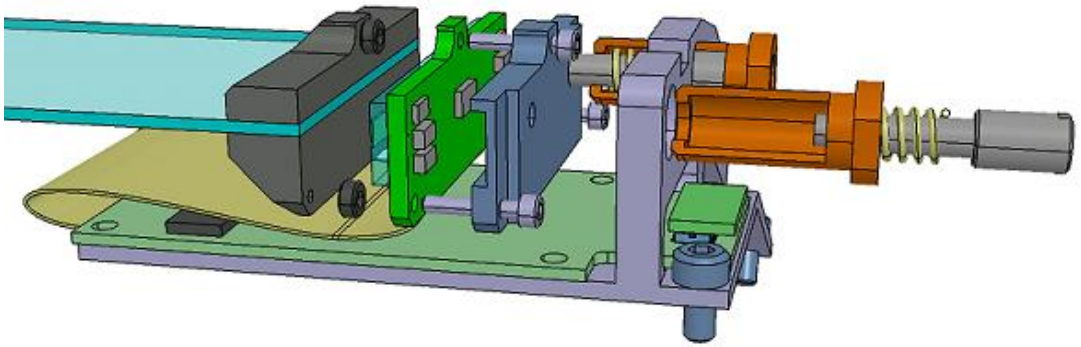
3D printed Al cooling block
it supports the SciFi modules
with embedded piping



fixations to
beam pipe

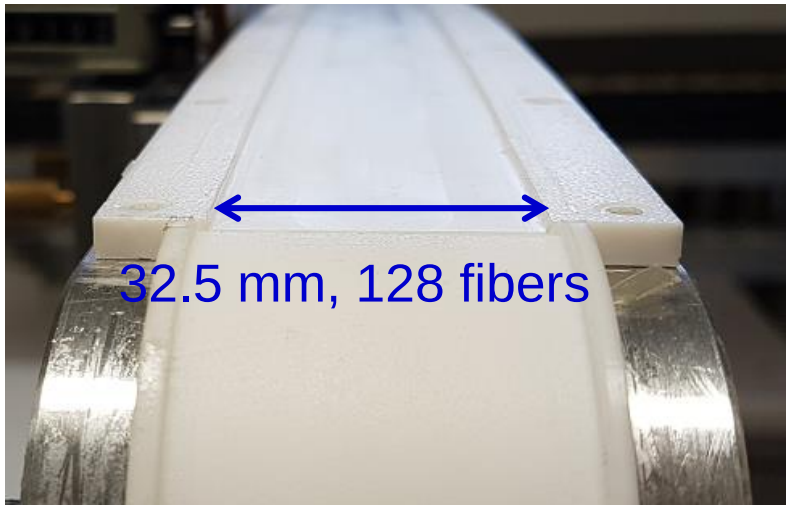
cooling pipes
(electronics + SiPM's

SciFi – SiPM coupling
+ spring loaded SiPM support
+ Front End board

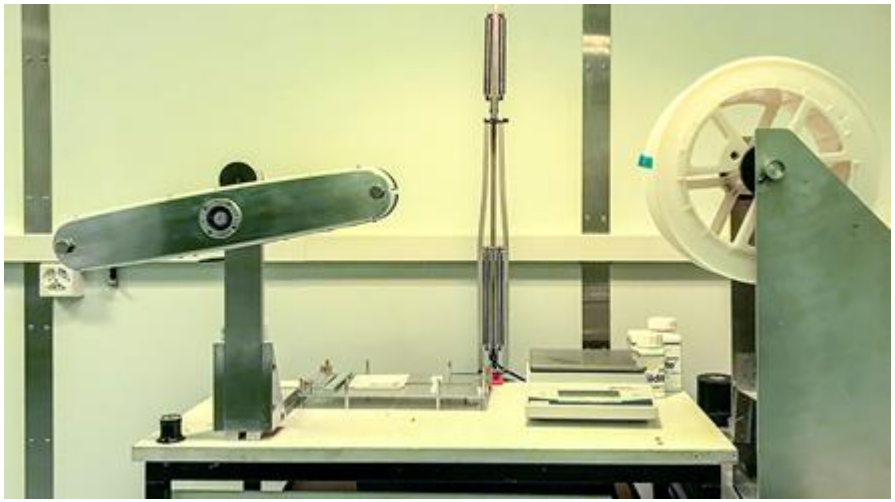


SciFi Ribbon Production

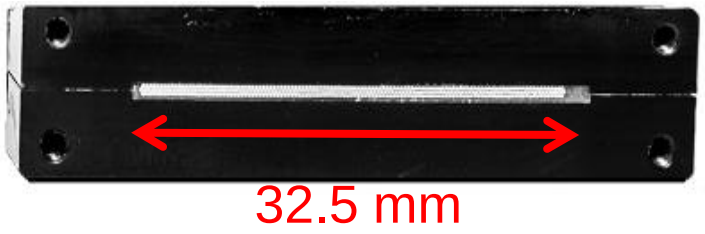
U channel



ribbon winding tool

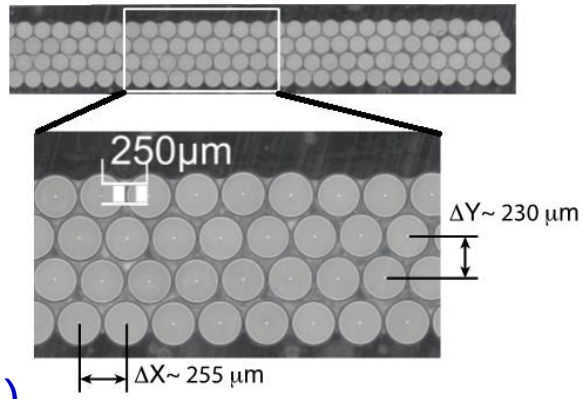


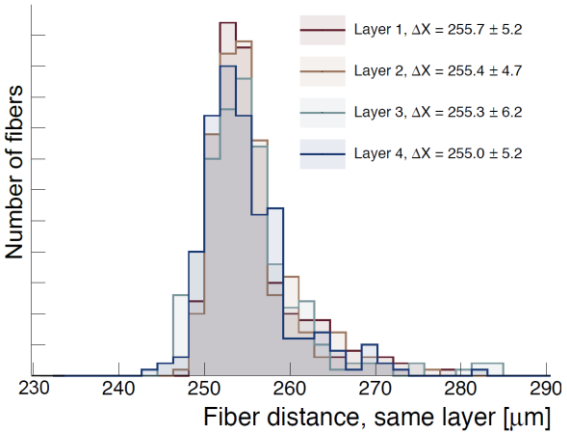
(full size) ribbon prototype



thickness ~ 700 μm (i.e. < 0.2% x_0)
for 3 staggered SciFi layers

ribbon profile: 4 x ~128 fibers (prototype)





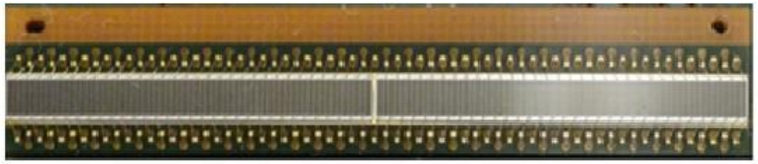
ribbon metrology

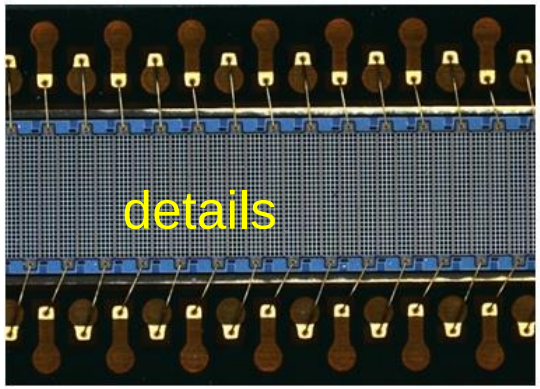
Si-PM Arrays

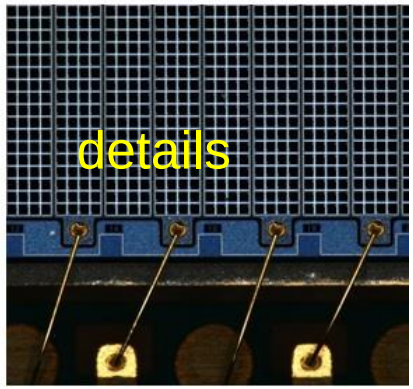
128 ch SiPM array from Hamamatsu (LHCb type) S13552HRQ

- 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

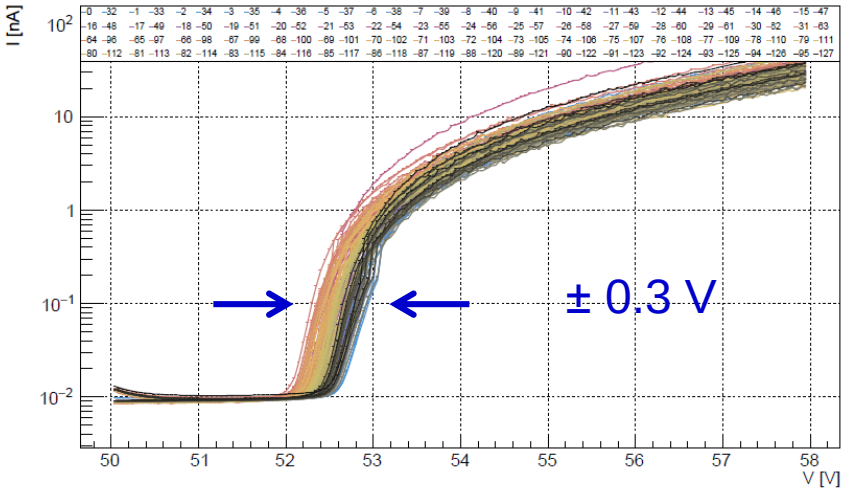
32.5 mm (two 64 ch. dies)

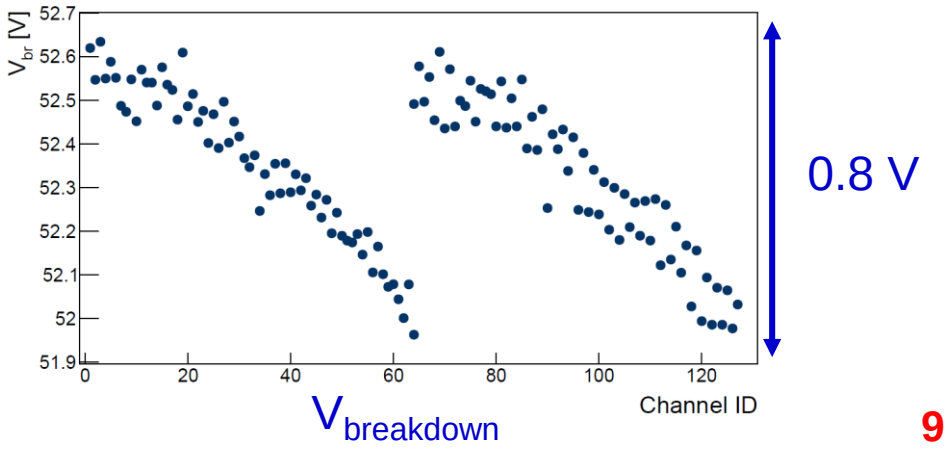






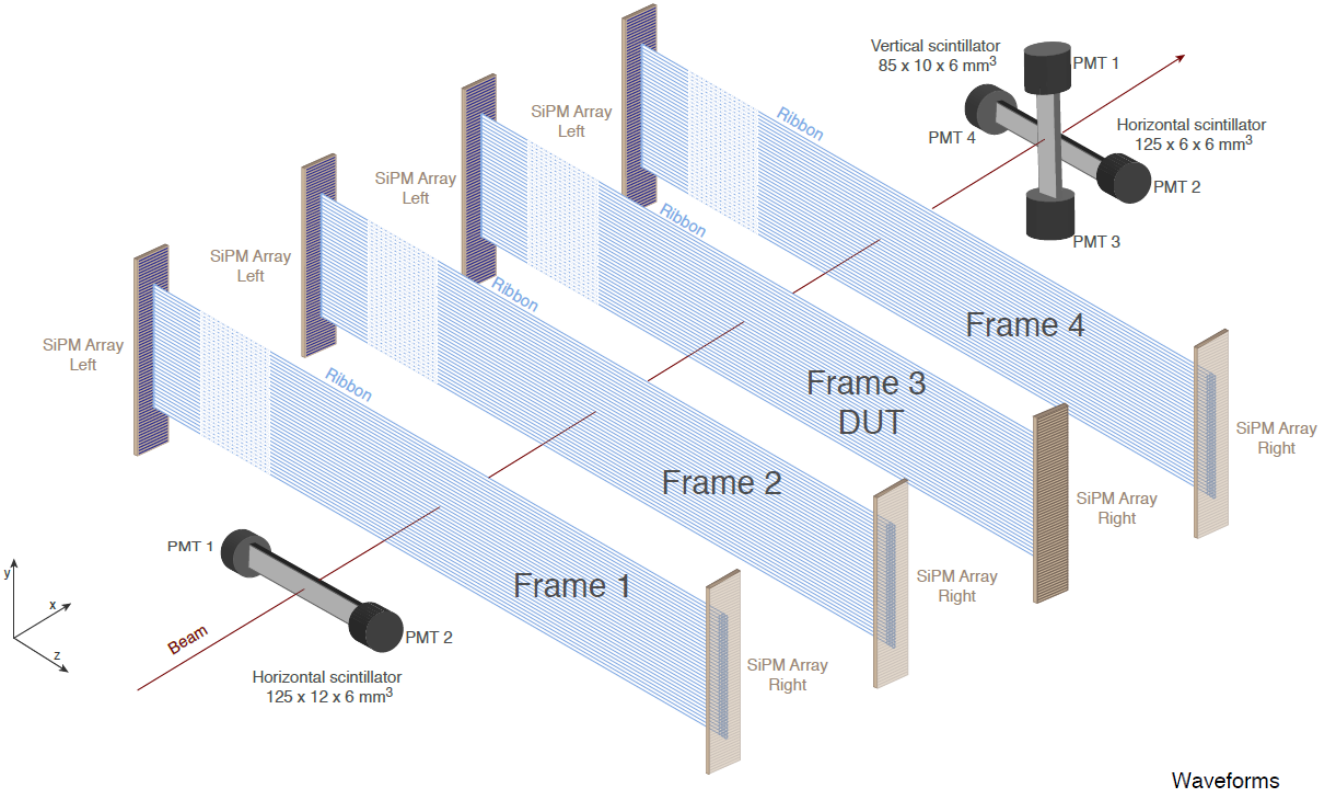
I – V curves





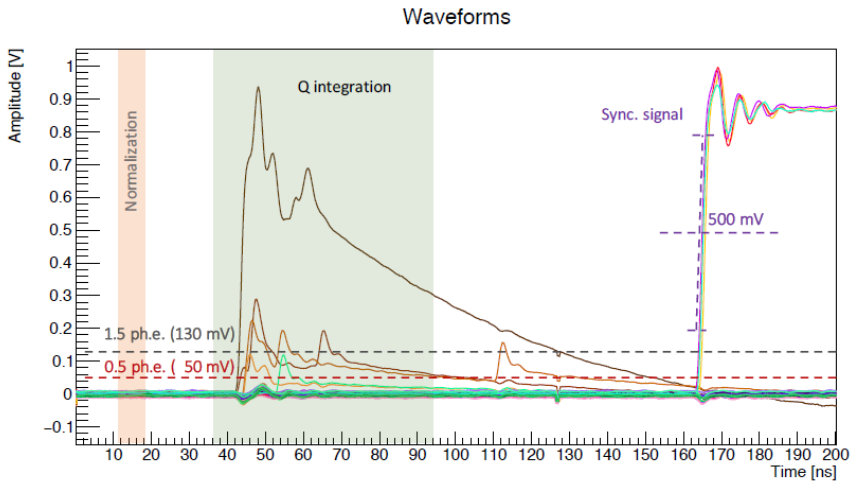
$V_{breakdown}$

Development of the SciFi Detector



4 SciFi ribbons read out at both sides

For these studies
SiPMs readout with fast hybrid amplifiers
and 5 GHz waveform digitizer
based on the DRS4 ASIC



A. B. *et al.*, NIMA1058(23)168766

Fiber Selection (Light Yield)

criteria:

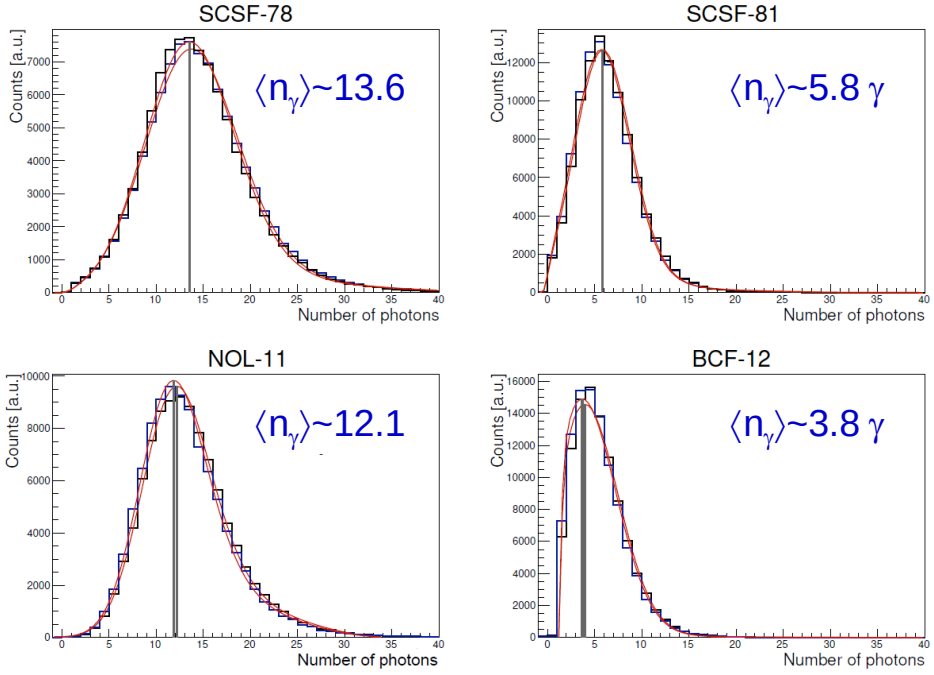
high light yield

best time performance $\sigma_t \approx \sqrt{\frac{\tau_R \tau_D}{n_\gamma}}$

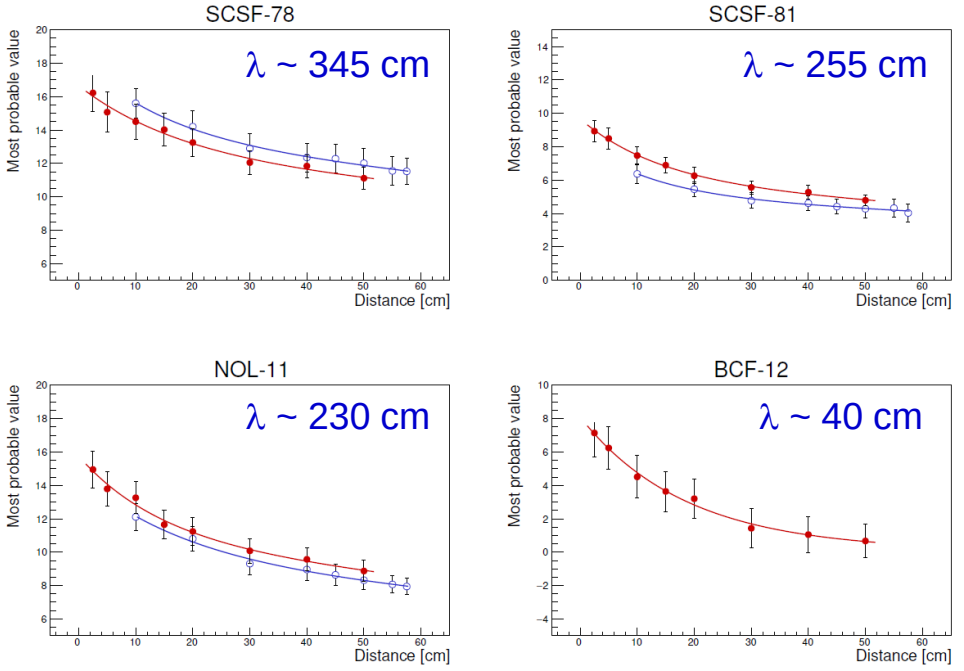
commercially available 250 μm ϕ fibers

type	att. 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 yield @ 30 cm
[thickness ~ 2 fiber ϕ]



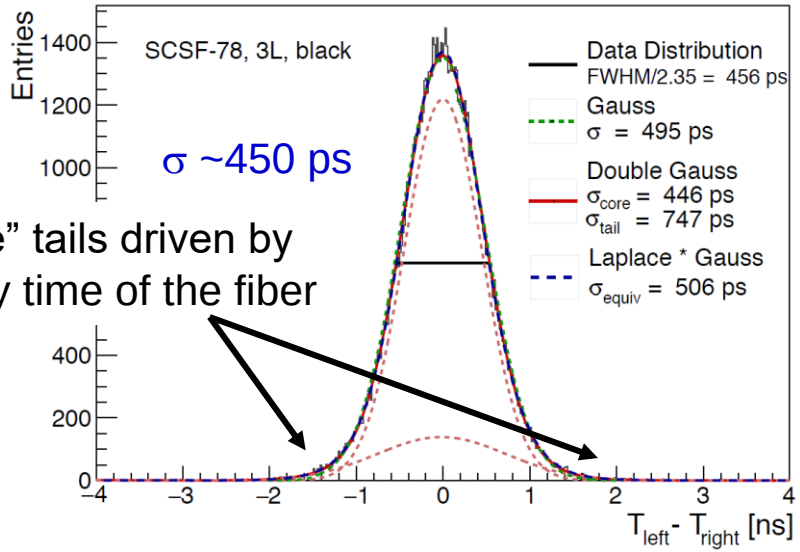
attenuation



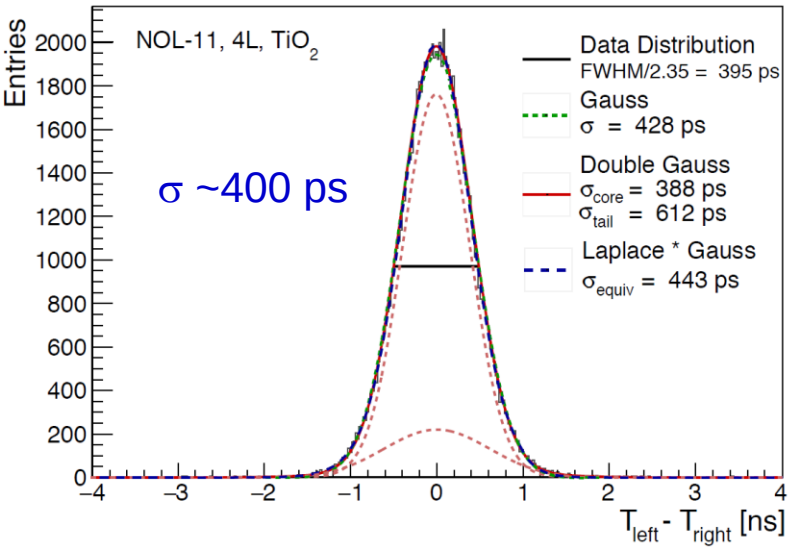
A. B. and Y. Demets, JINST17(22)P12020

T_{Left} - T_{Right} (ΔT Time Resolution)

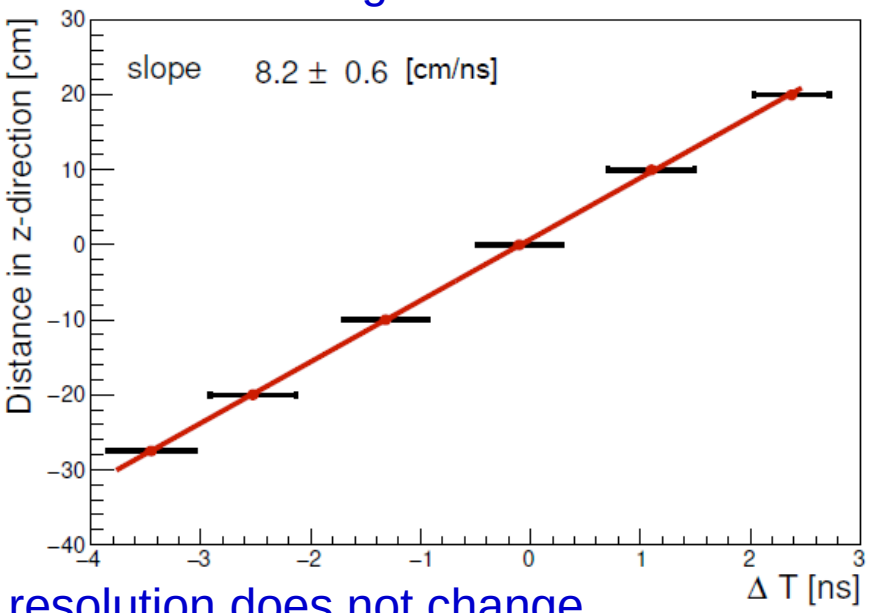
Measure intrinsic resolution of SciFi detector,
however cannot determine the crossing time



"large" tails driven by
decay time of the fiber



ΔT along the SciFi ribbon



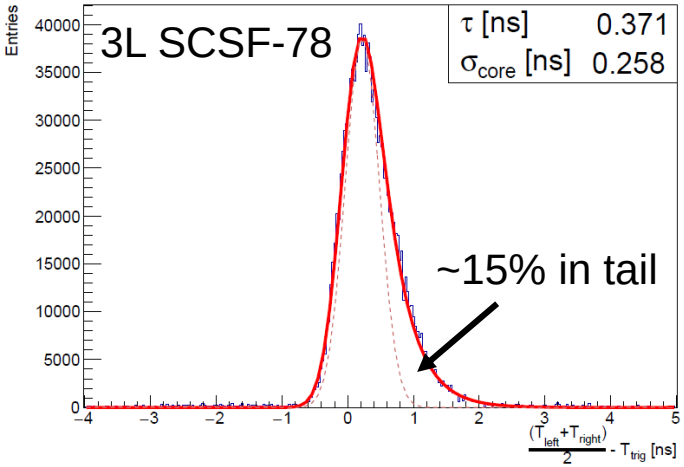
resolution does not change
with impact position (no edge effects)

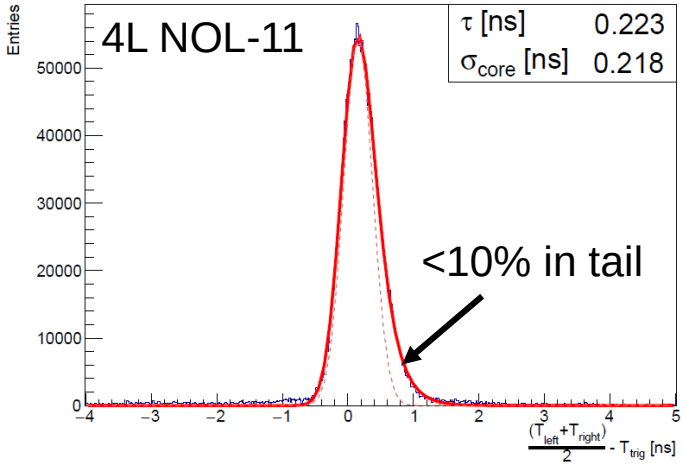
can determine effective speed of light propagation in the fiber → ~ 0.5 *c* (< *c* / n)
(effective path is longer because of
Internal reflections)

Mean Time

Combine measurements from both SciFi ribbon's ends: $MT = \frac{T_{\text{Left}} - T_{\text{Right}}}{2} + T_0$

Naively expect $\sigma_{MT} = ½\ \sigma_{\Delta T}$





σ_{MT} significantly affected by the τ_{Decay}.

Data is well described by the EMG dist.

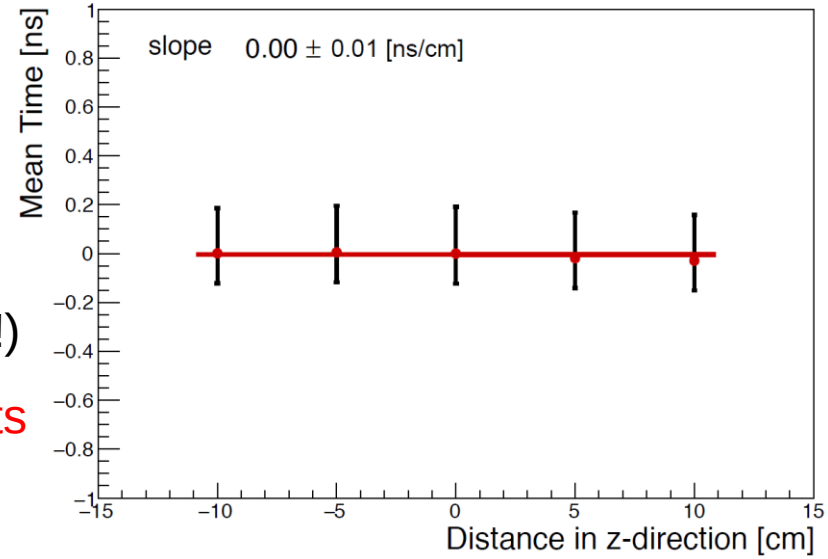
MT does not depend on the hit position

σ_{MT} ~ constant along the fiber

No edge effects (light is channeled in the fibers!)

MT is a good observable for time measurements

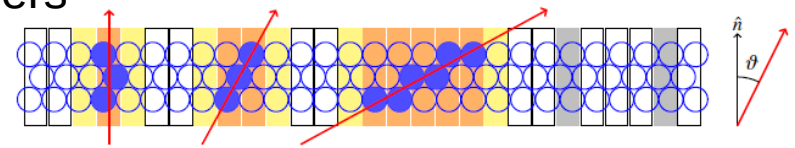
MT along the fiber



Detection Efficiency

Issues:

limited material budget of 3 SciFi staggered layers
SciFi ribbon's geometry

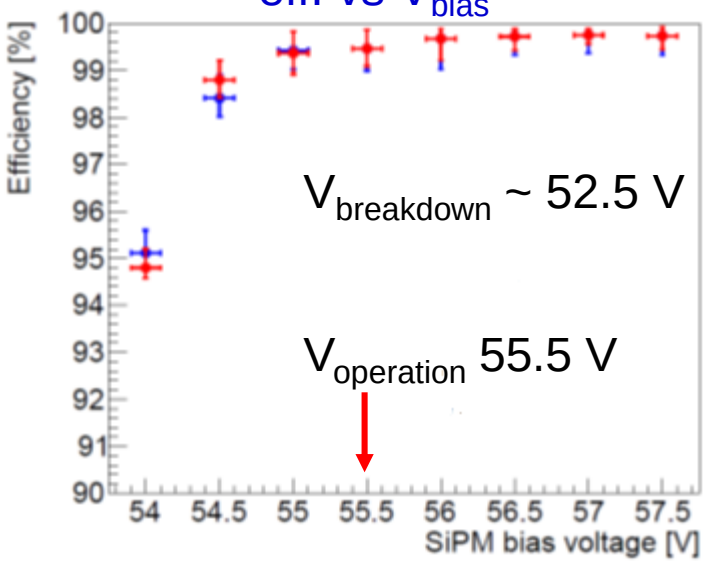


→ some events with very low light yield
→ very low thresholds of 0.5 or 1.5 ph.e. & small clusters

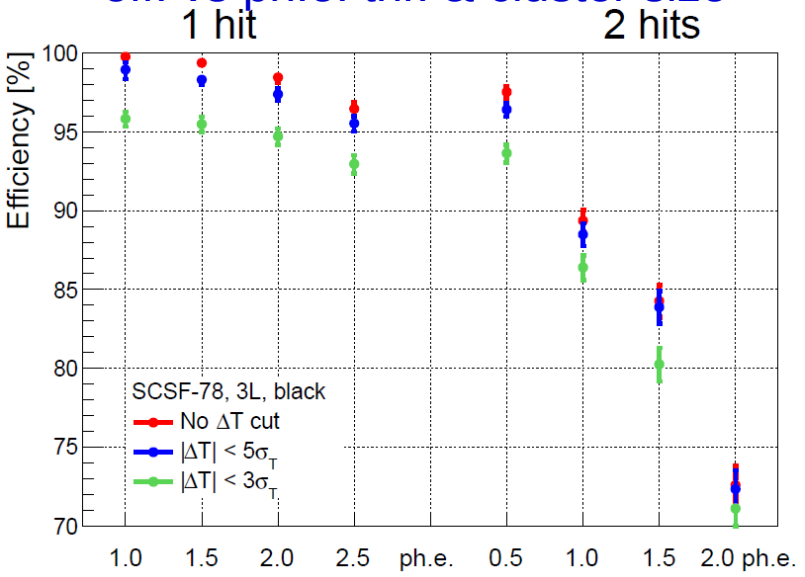
require *left / right* matched clusters → timing cut $\Delta T < n\ \sigma_{\Delta T}$

→ inefficiency

eff. vs V_{bias}



eff. vs ph.e. thr. & cluster size



Have identified 2 viable working points:

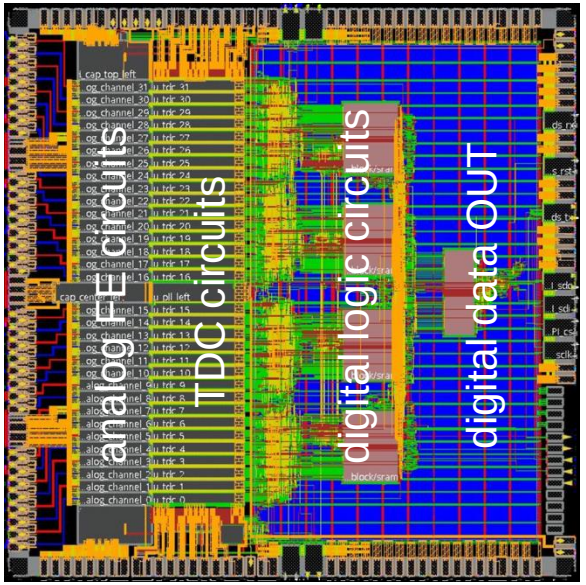
1) 0.5 ph.e. thr. & clusters ≥ 2 → ~ 97% eff.
2) 1.5 ph.e. thr. & cluster ≥ 1 → ~ 98 % eff.

Readout Electronics

Readout based on the MuTRiG ASIC

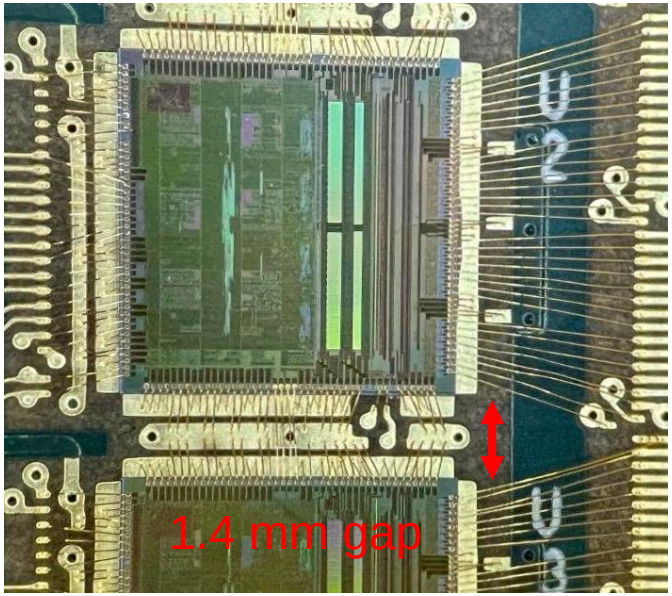
Muon Timing Resolver with Gigabit link

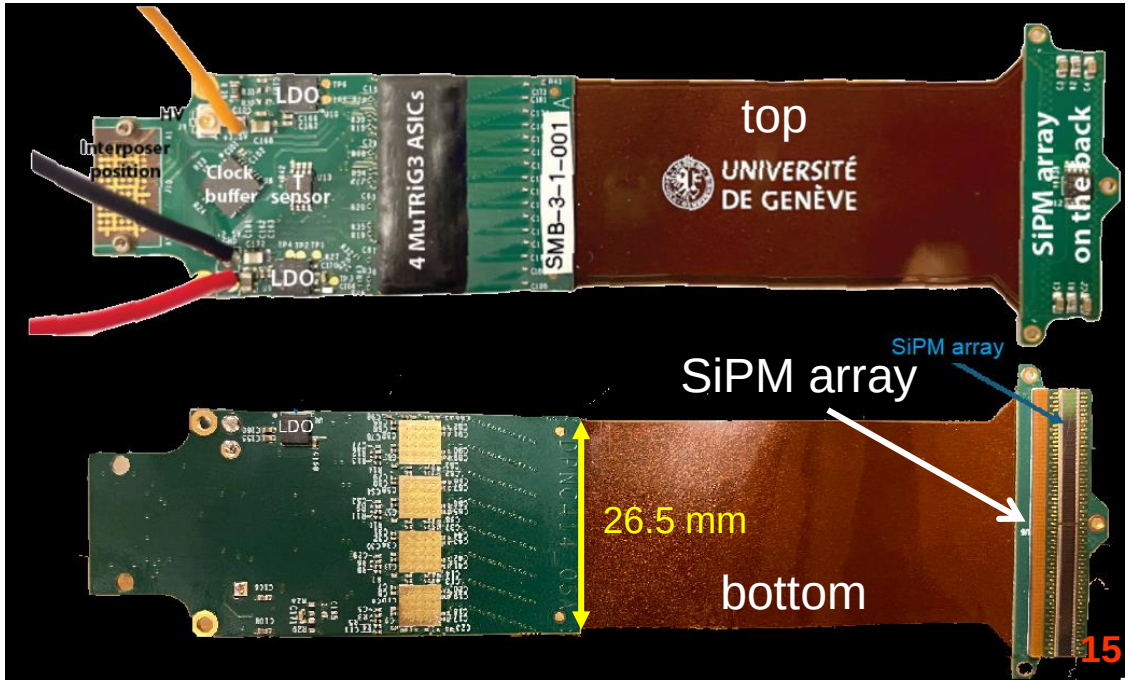
- 625 MHz serializer clock
- 32 differential inputs / chip
- 50 ps time bin
- Gigabit serial data link (1.25 Gbps) (1 MHz / ch)



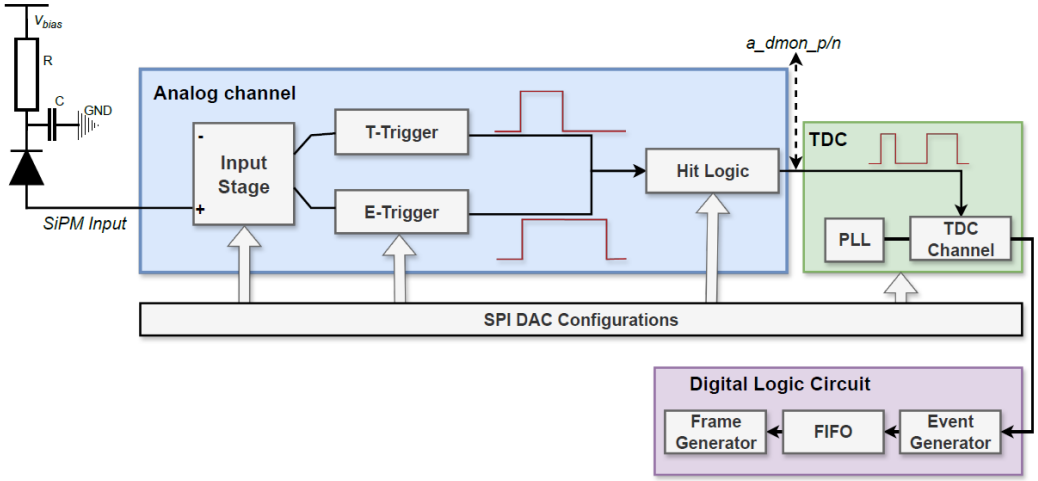
4 MuTRiG chips are required to read out one SiPM array (128 ch.) 5 x 5 mm^2

- directly wire bonded to the front-end board
- gap between ASICs 1.4 mm!





Channel Diagram



Fully-differential analog front-end.
However,
common cathode, single ended inputs

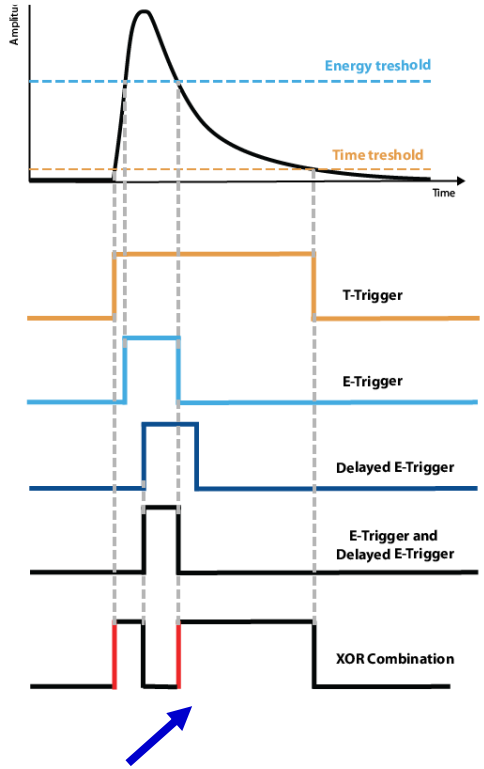
All “controls” fully differential.

Threshold set individually for each channel
Separate timing and energy threshold

No external trigger:
all hits crossing the thresholds are digitized
Possibility of clustering in the ASIC

No ADC:
Energy measurement in principle possible with
Time-over-Threshold (ToT) method

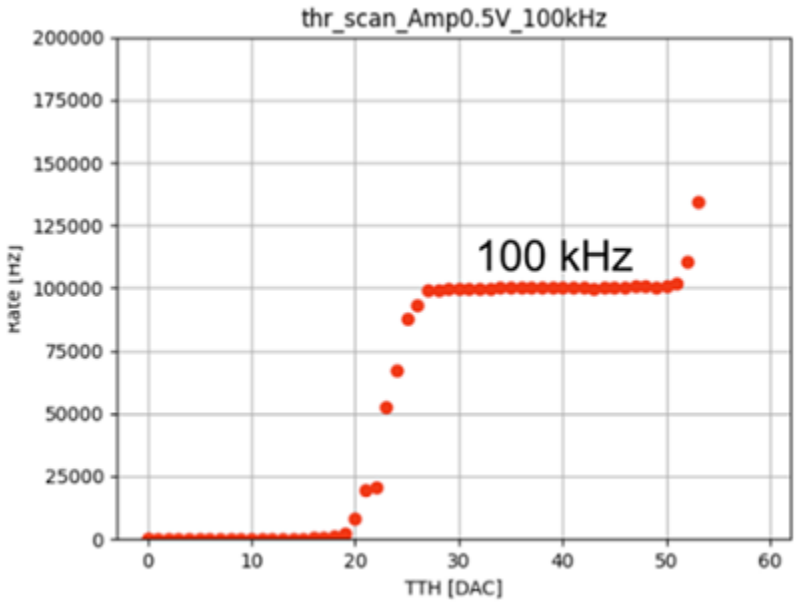
SiPM bias tunable for each channel individually.

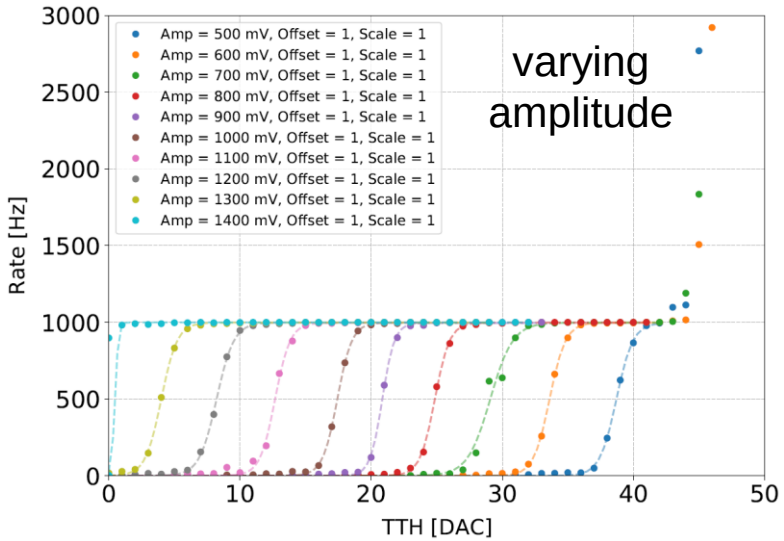


Encode arrival time and energy (ToT) information into rising edges of the combined signal

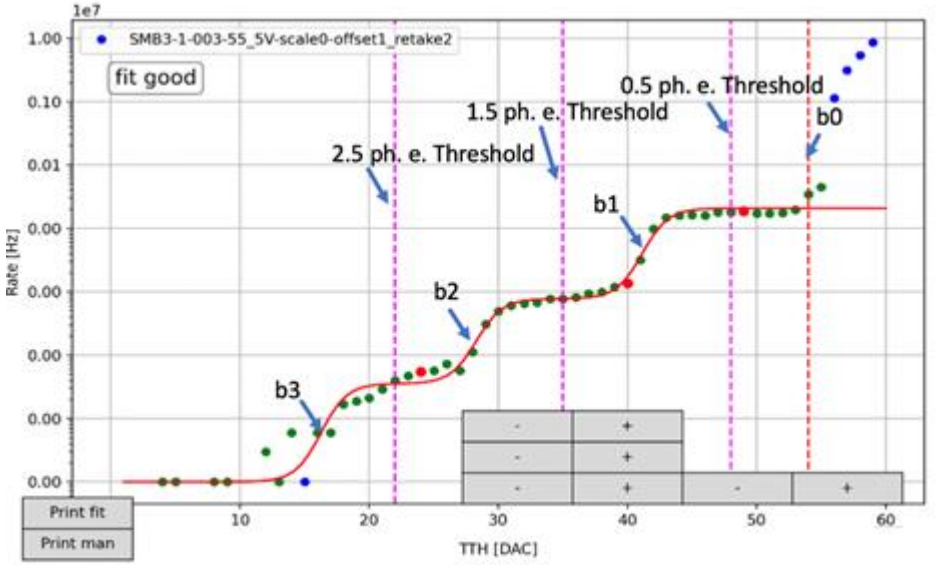
Tuning the MuTRiG

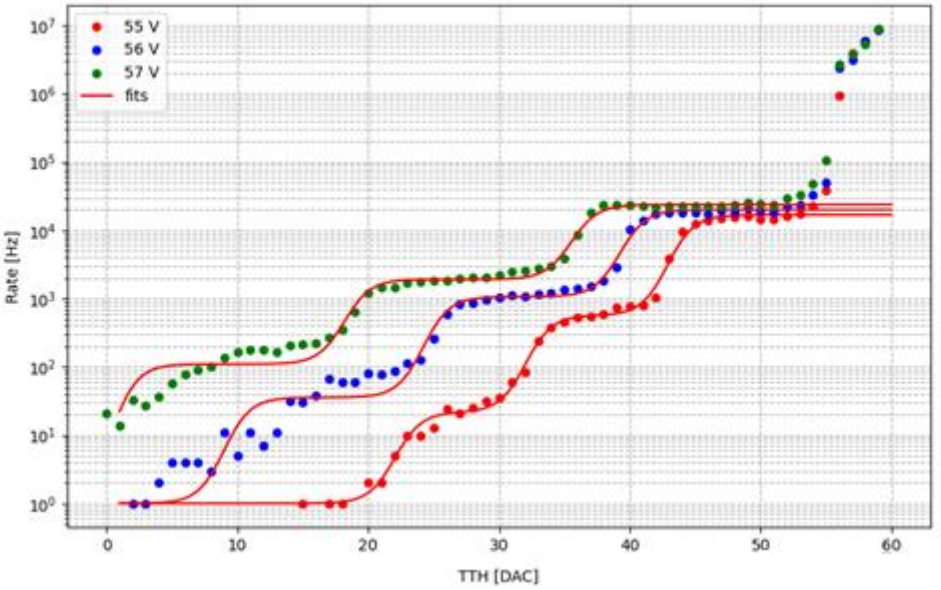
Threshold scans with charge injections





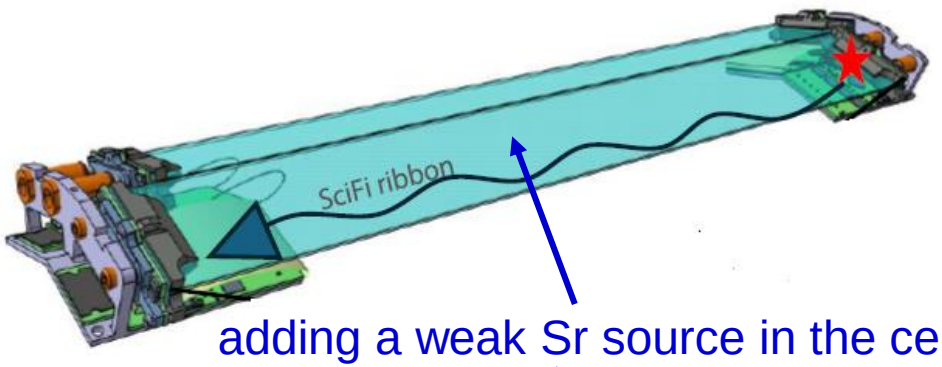
Threshold scans with dark count





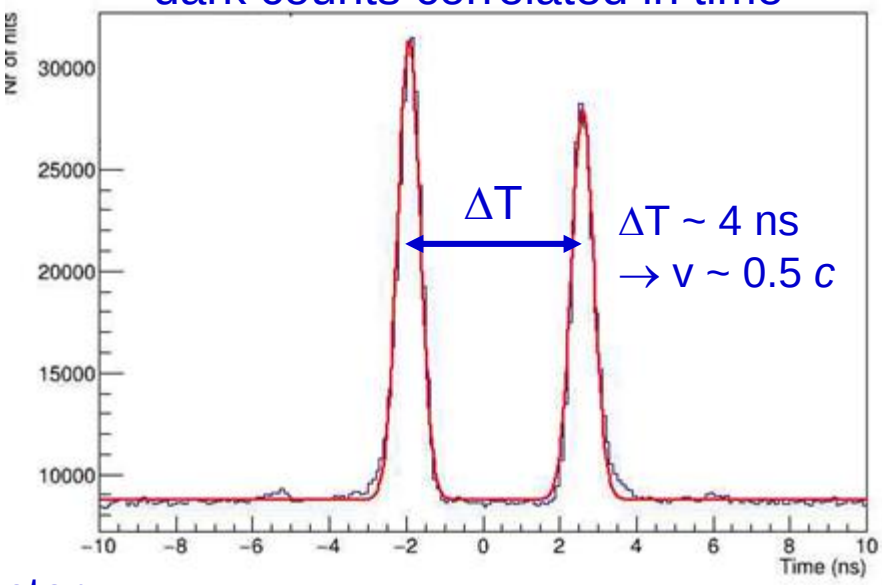
Correlated Dark Counts

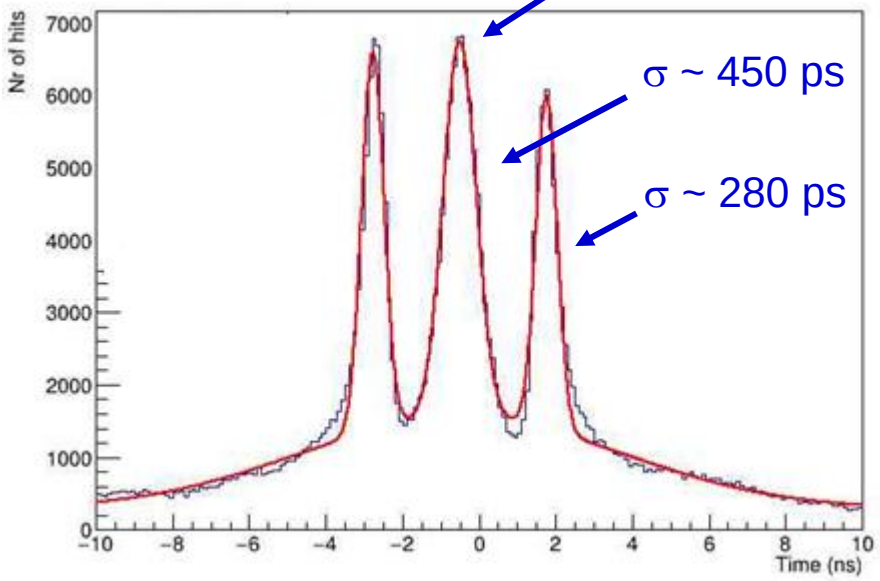
When a SiPM cell discharges,
it generates light that can escape the SiPM,
be captured and transported to the other end,
and trigger a discharge at the opposite end.
Probability for such correlated events ~ 10^{-4}.



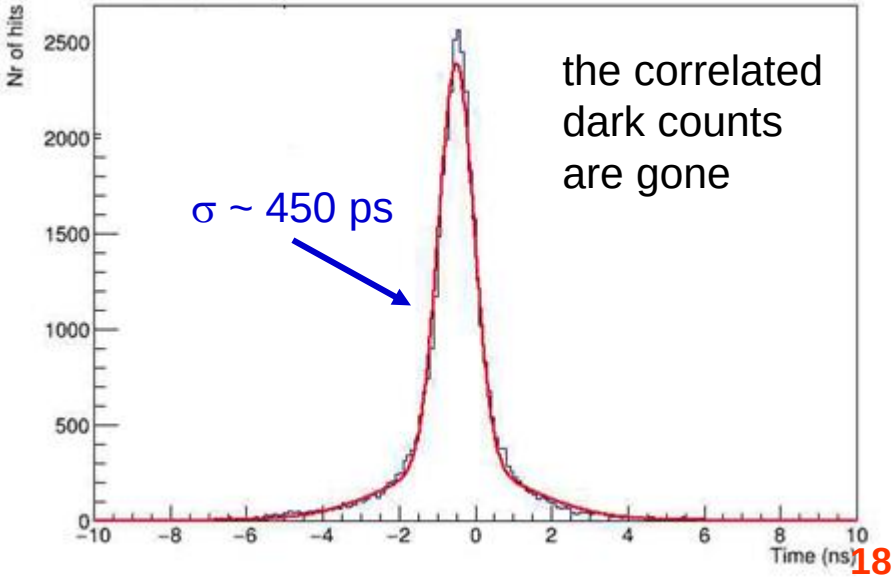
adding a weak Sr source in the center

dark counts correlated in time





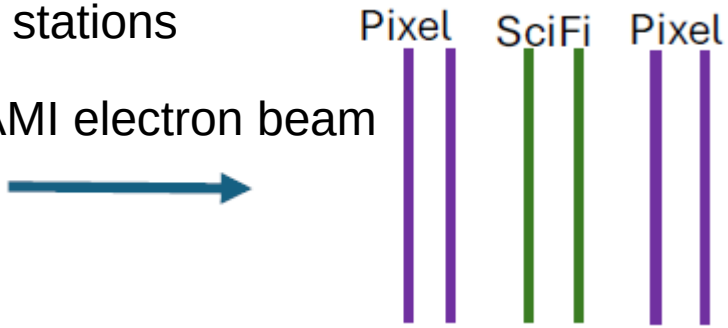
cluster size ≥ 2 or higher threshold



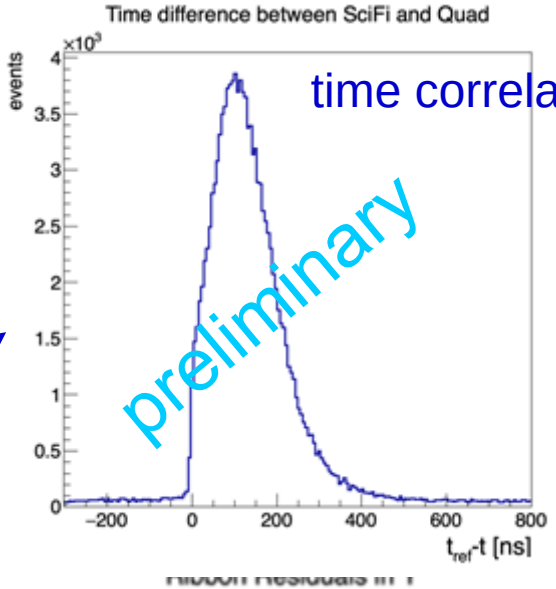
Performance with MuTRiG Readout

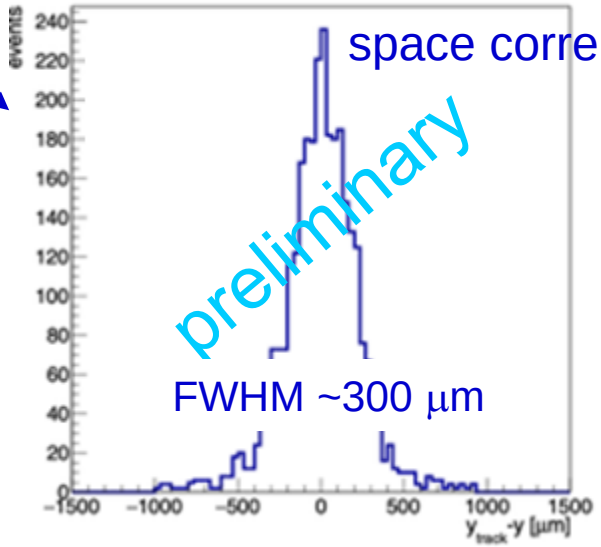
Test beam results with a telescope consisting of 4 MuPiX stations

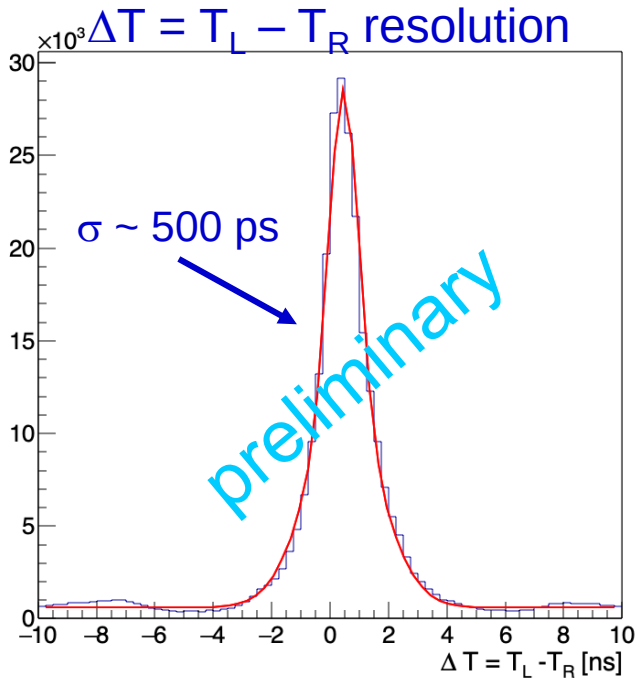
MAMI electron beam



Nice correlations between hits in the MuPiX and SciFi

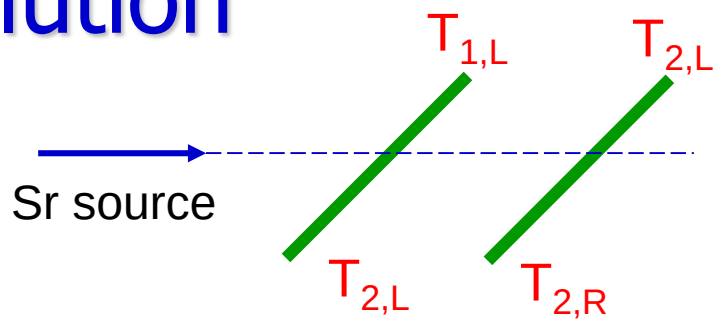






no ADC info,
with ADC info σ ~100 μm

Time Resolution



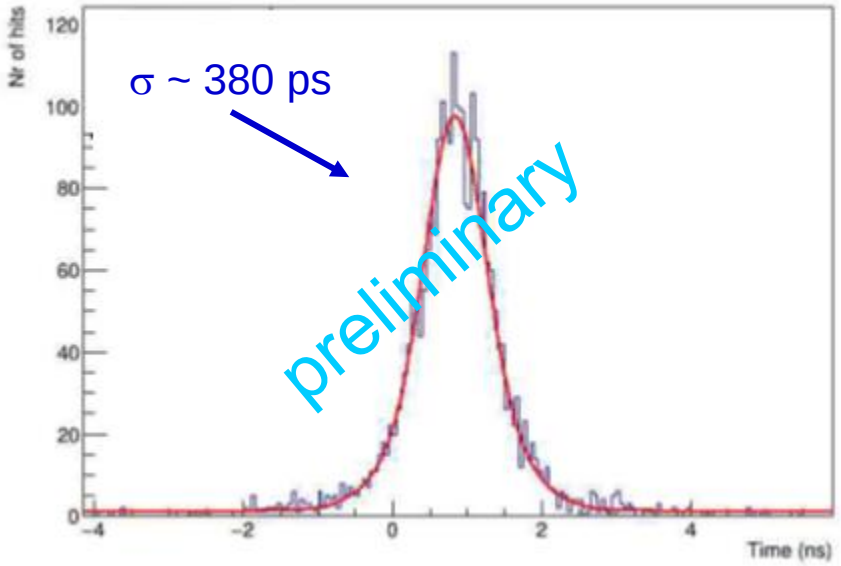
2 SciFi modules
4 MuTRiG front-end boards

All time measurements performed w.r.t. the system clock.

Form $$\Delta(MT) = MT_1 - MT_2 = \frac{\left(T_{1,\mathrm{Left}} + T_{1,\mathrm{Right}}\right) + 2T_{clock}}{2} - \frac{\left(T_{2,\mathrm{Left}} + T_{2,\mathrm{Right}}\right) + 2T_{clock}}{2}$$

with the four time measurements.
The T_0 dependence cancels in the *MT* differences

Δ(MT)



Time resolution of a single SciFi module

$$\sigma_{MT} = \frac{\sigma_{\Delta(MT)}}{\sqrt{2}} \approx 270\,ps$$

All 4 muTRiG front-end boards
nicely synchronized to the system clock.

Outlook

We developed a SciFi timing tracker with SiPM readout at both ends for the Mu3e experiment

- 3 staggered layers of 250 μm ϕ fibers SCSF-78 (Kuraray)
- thickness ~700 μm, < 0.2 % x_0
- time resolution ~ 250 ps (mean time)
- efficiency > 97 % (matched clusters with timing cut)
- spatial resolution ~ 140 μm (~100 μm with ADC readout)

In conjunction with HV-MPAS Si-pixels → full 4D track reconstruction

Limiting factor: material budget (3 staggered SciFi layers)

→ low light yield

Readout based on the mixed mode MuTRiG ASIC

SciFi sub-detector ready for installation and commissioning in Mu3e