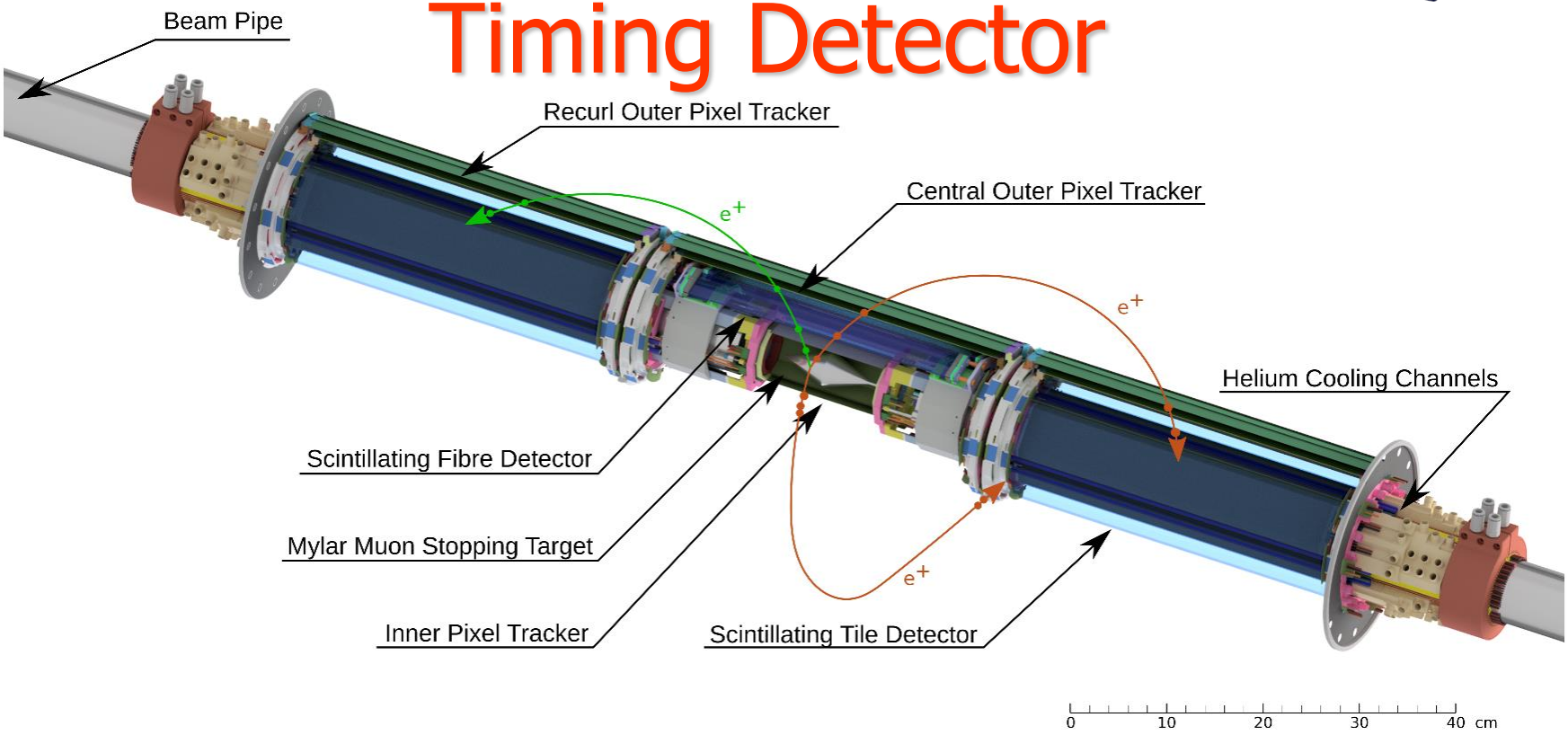
The Mu3e Scintillating Fiber Timing Detector



ICHEP 2024
Praha
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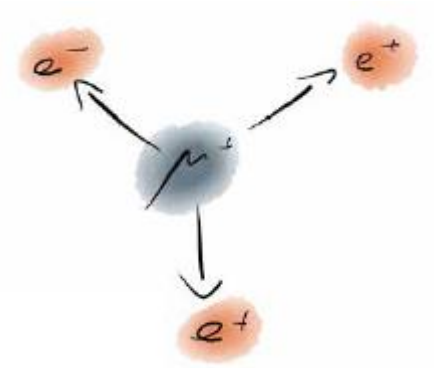
Alessandro Bravar
for the Mu3e SciFi team

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 (τ_μ = 2.2 μs)

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

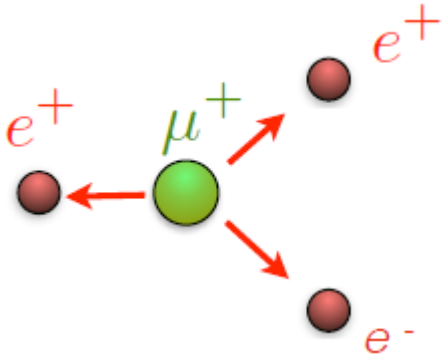
$\Rightarrow$ observe ~ 10^{16} – 10^{17} μ decays (over a reasonable time)
$\Rightarrow$ rate up to 2 x 10^9 μ decays / s

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

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

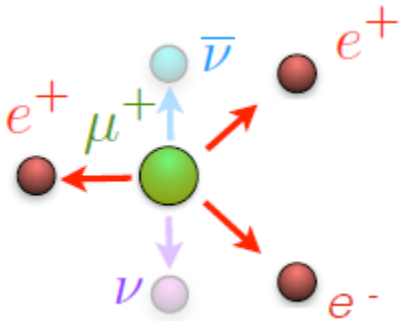
Signal and Backgrounds

signal

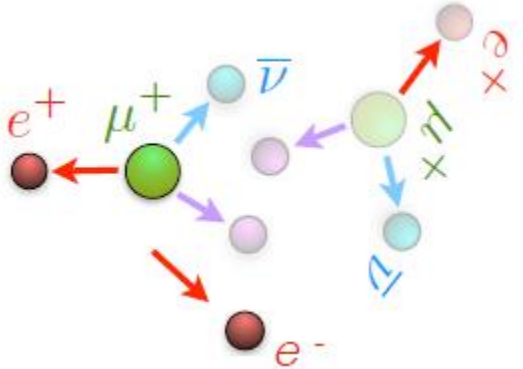


backgrounds

internal conversion



accidental



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

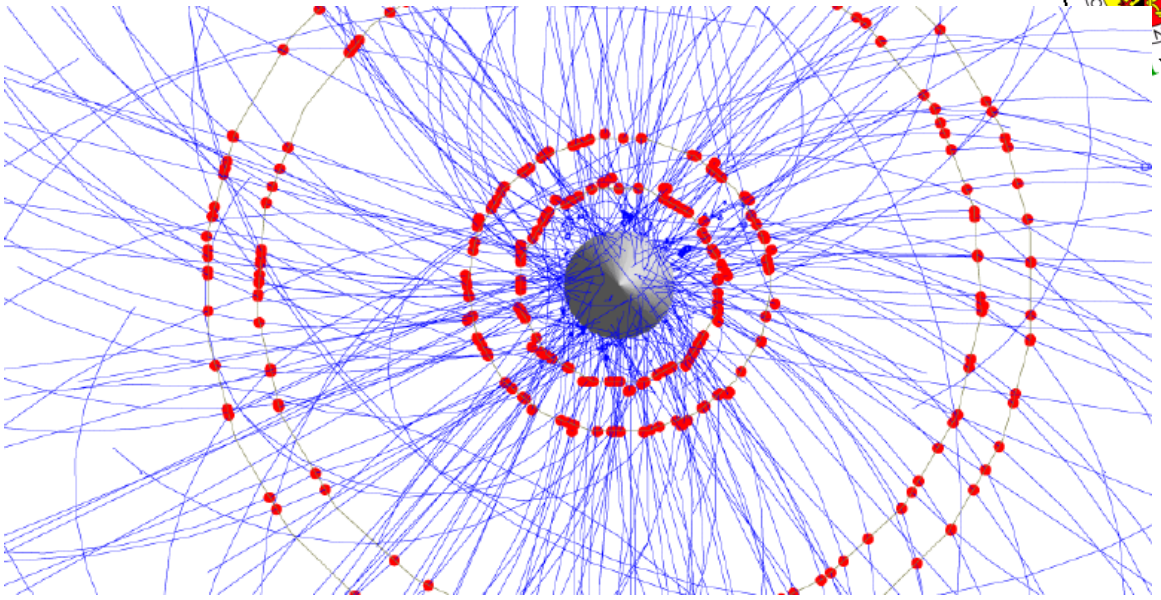
features

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 } $\rightarrow$ minimize multiple scattering

Timing

50 ns snapshot (readout frame): 100 muon decays

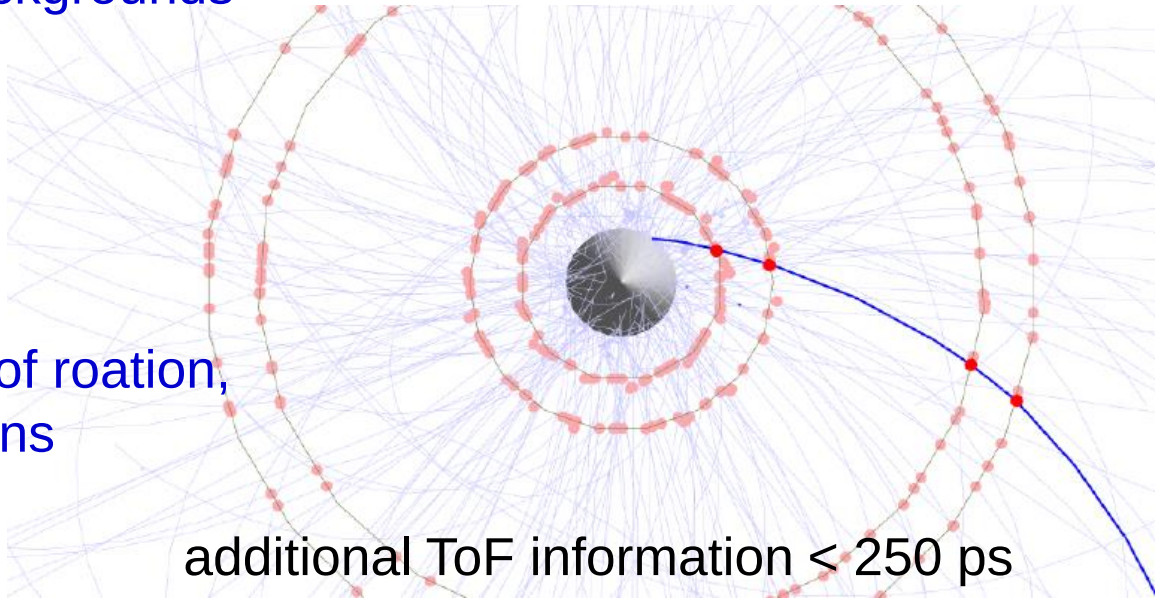


4D reconstruction

to suppress accidental backgrounds
requires excellent timing

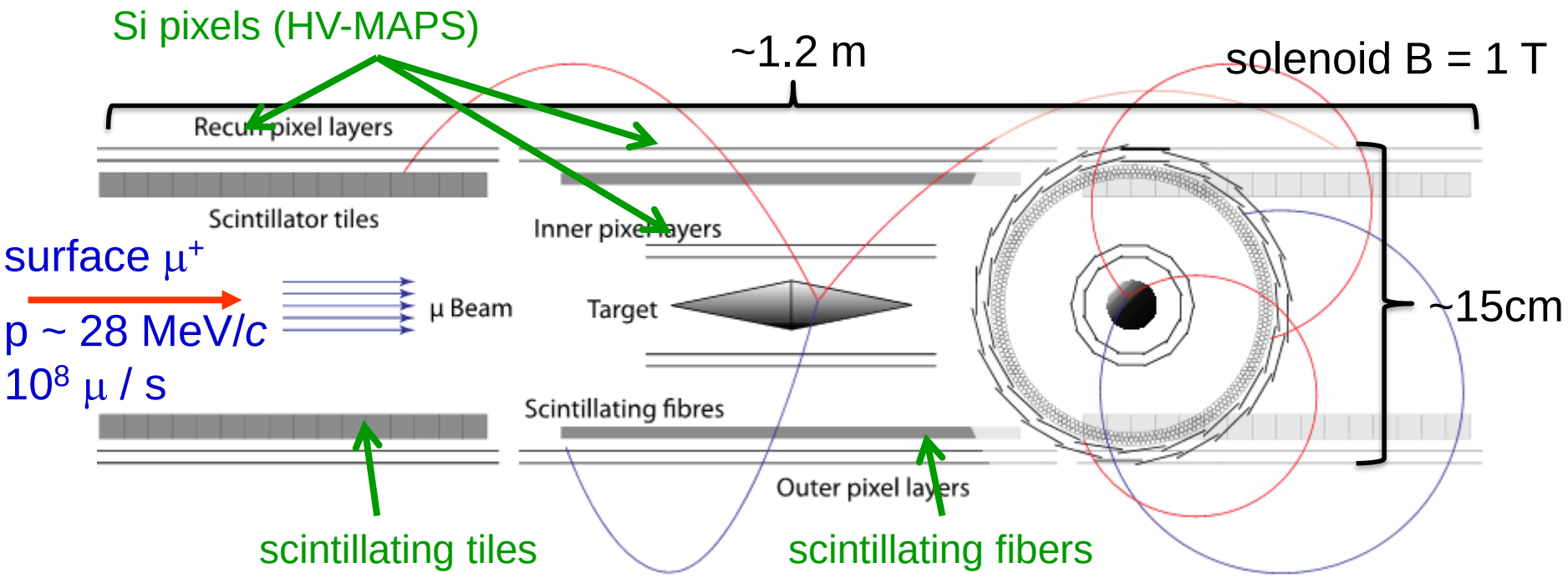
- < 250 ps SciFi's
- < 100 ps scint. Tiles

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



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

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

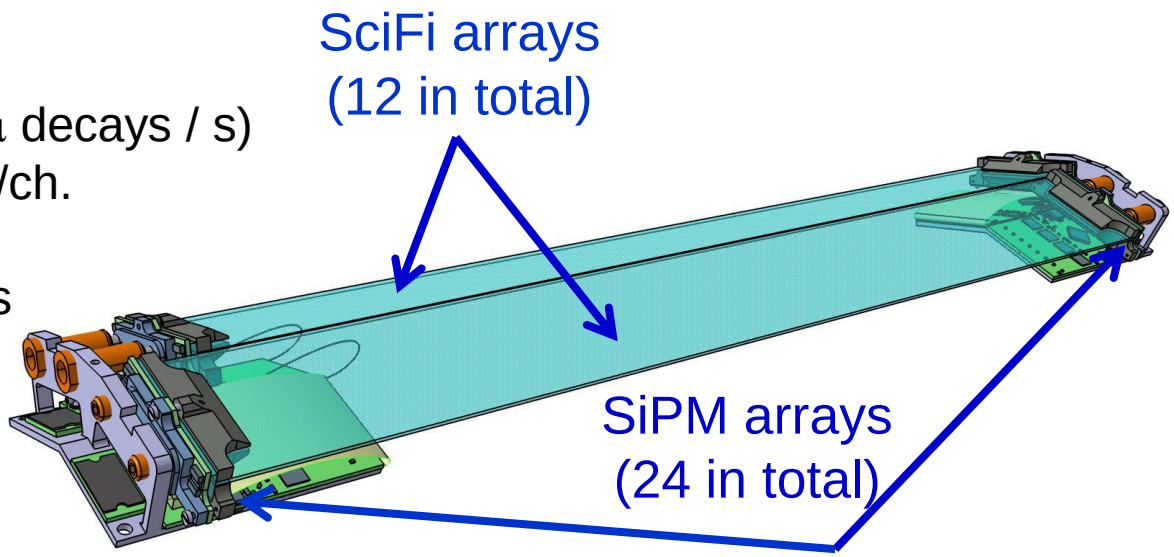
SciFi Detector Design Parameters

Requirements

thickness $x/x_0 < 0.3\%$ (< 1 mm)
time resolution $\leq$ 250 ps
efficiency > 95%
limited space
handle very high rates (> 10^8 μ decays / s)
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 (< 800μm)



Si-PM readout at both ends

128 ch SiPM array (LHCb design)
250 μm pitch

Readout

MuTRiG ASIC
~ 3000 readout channels

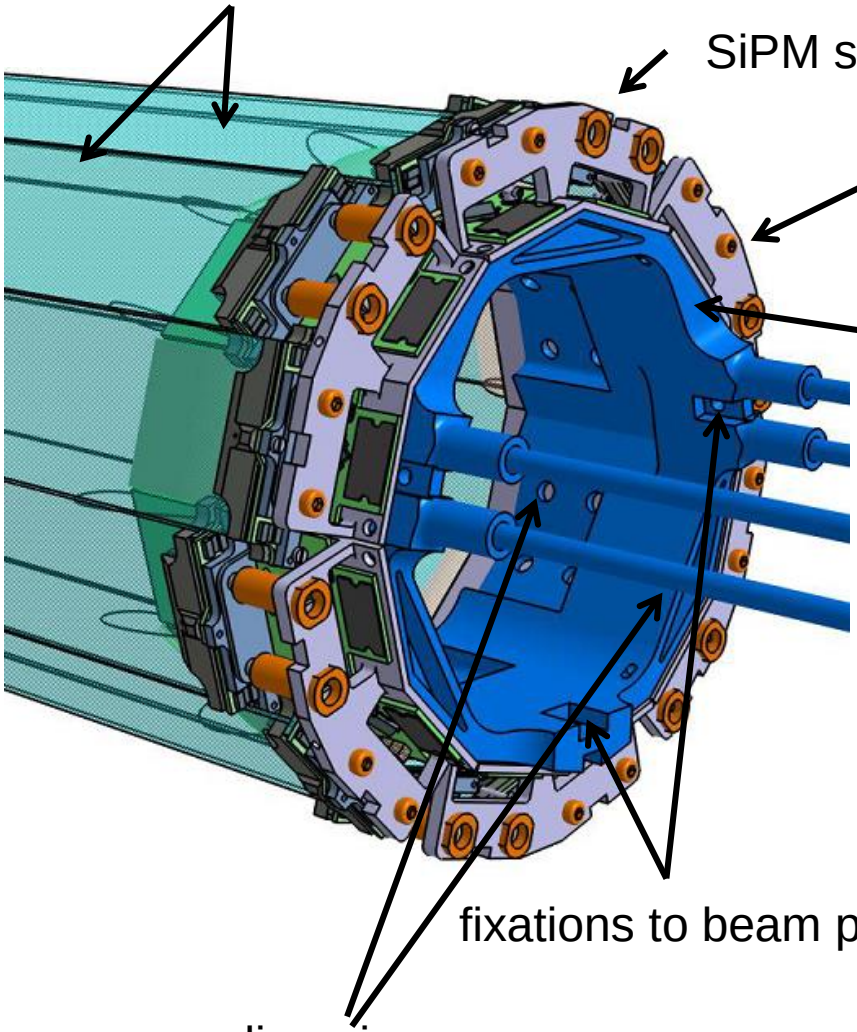
SciFi Detector Mechanics

SciFi ribbons
longitudinally staggered to minimize dead space between ribbons

SiPM spring loaded support

SciFi module support structure
(2 ribbons per module)

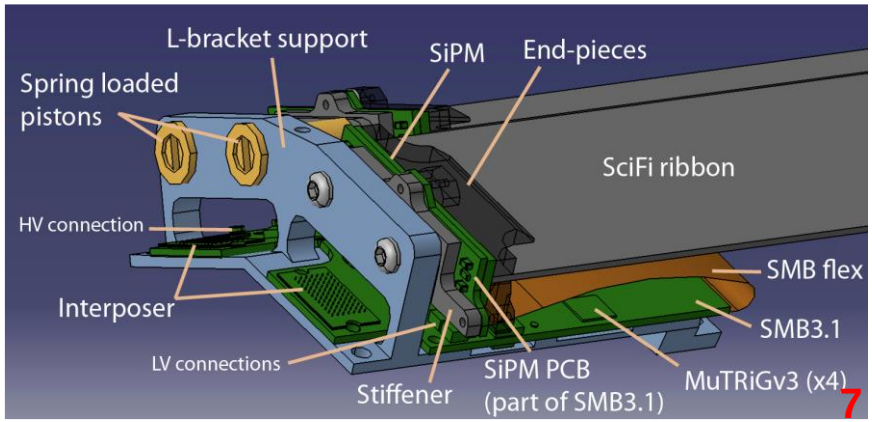
3D printed Al cooling block
it supports the SciFi modules
with embedded piping



fixations to beam pipe

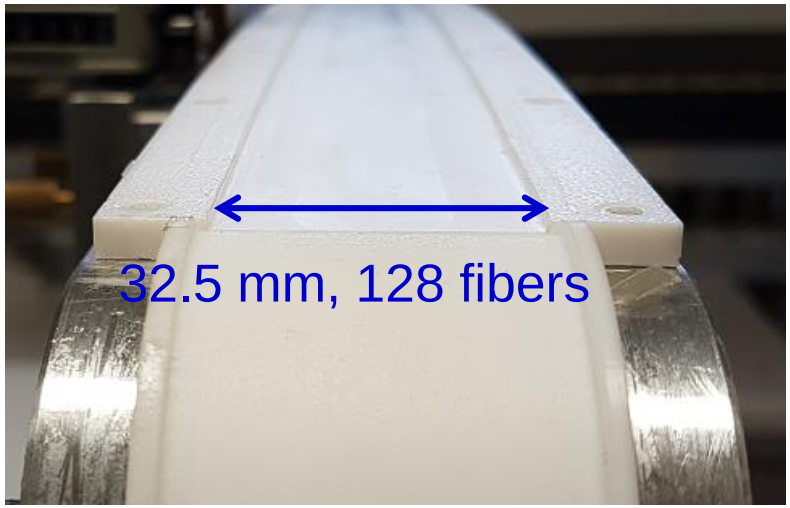
cooling pipes
(electronics + SiPM's

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

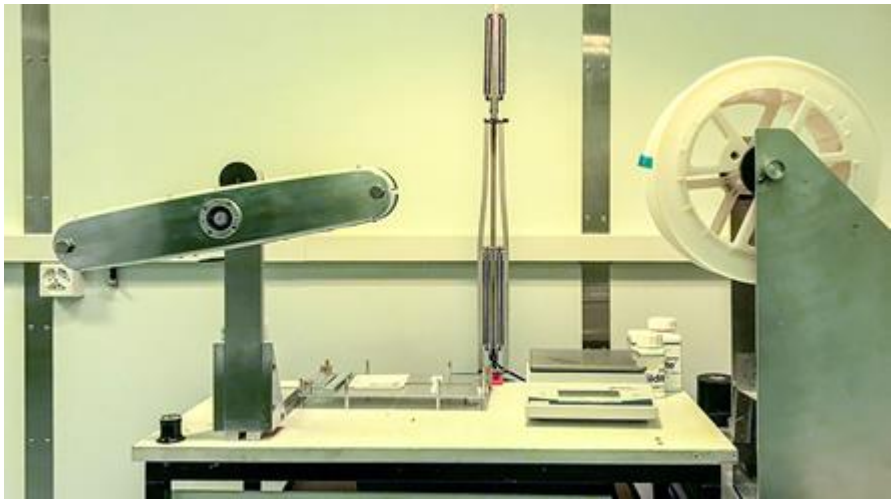


SciFi Ribbon Production

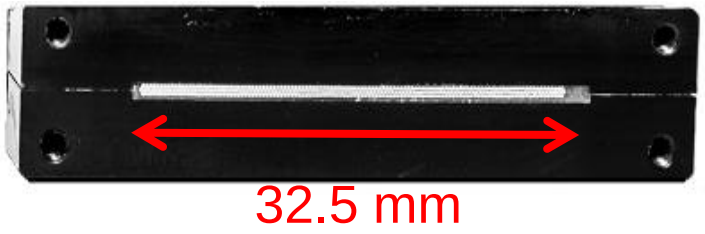
U channel



ribbon winding tool

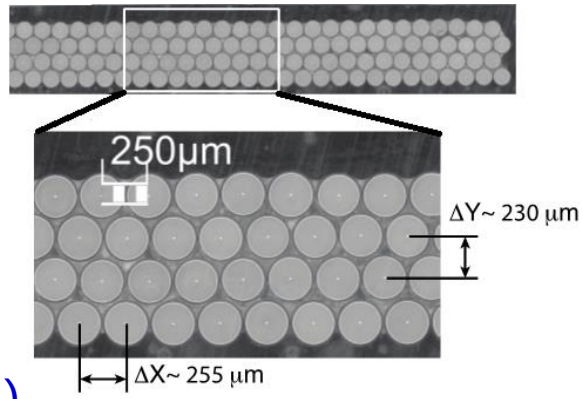


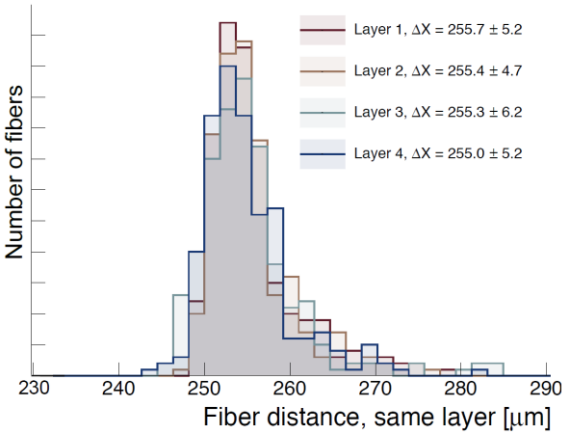
(full size) ribbon prototype



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

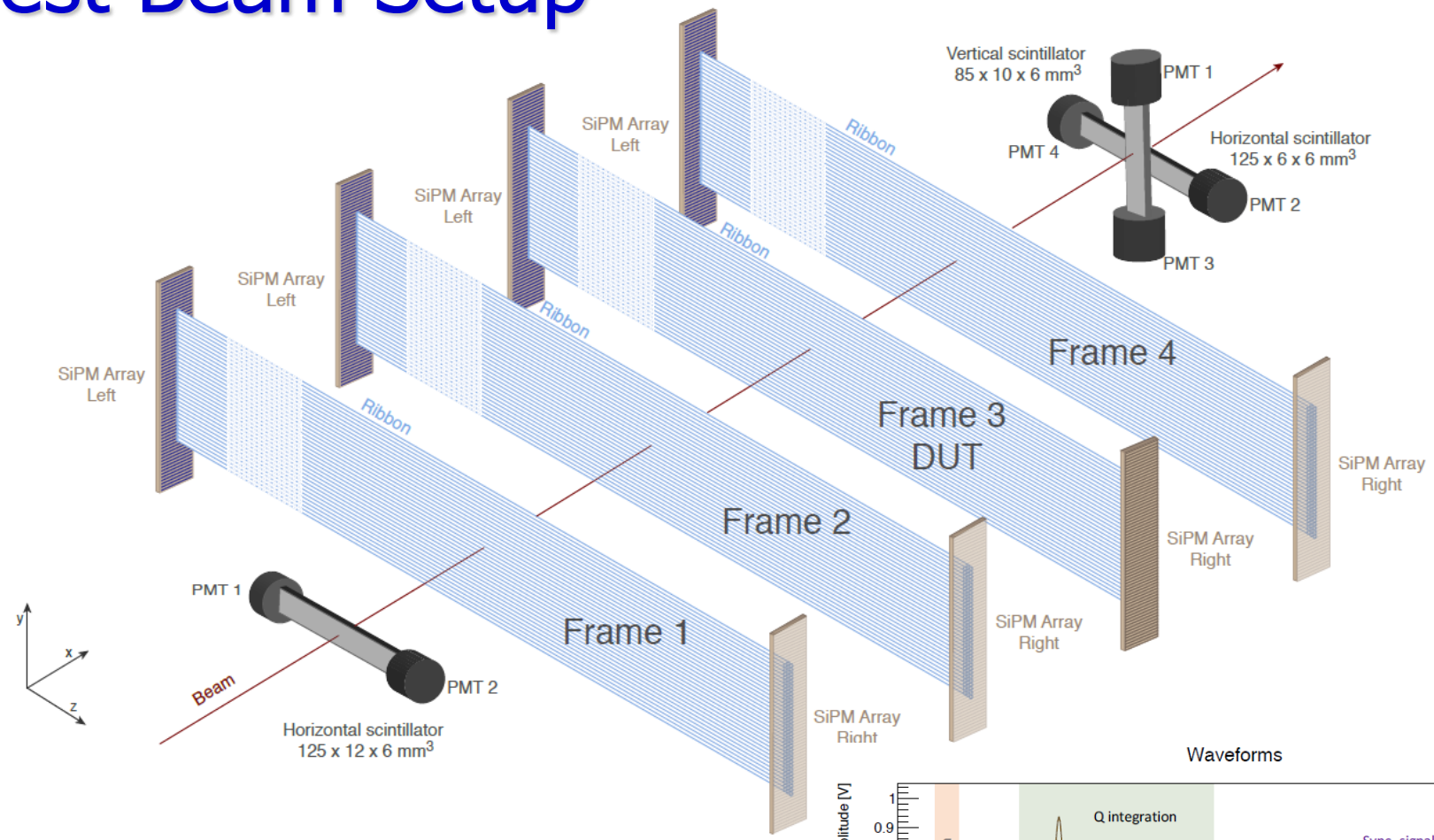
ribbon profile: 4 x ~128 fibers (prototype)





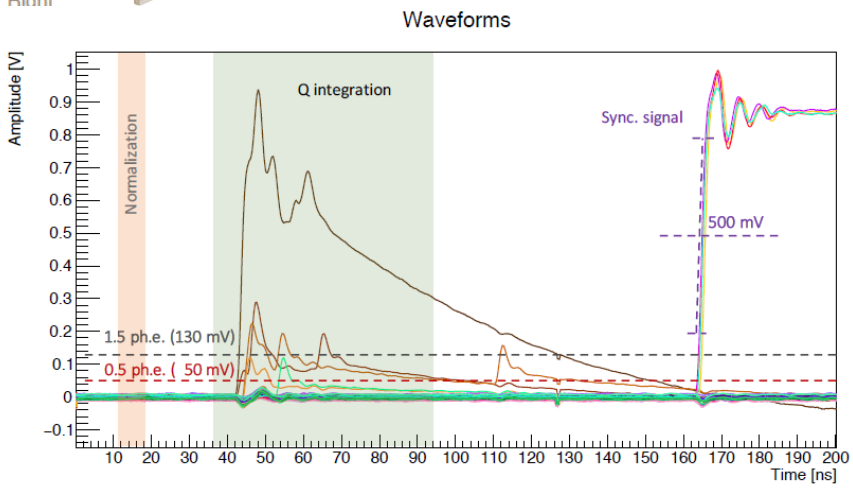
ribbon metrology

Test Beam Setup



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



Fiber Selection (Light Yield)

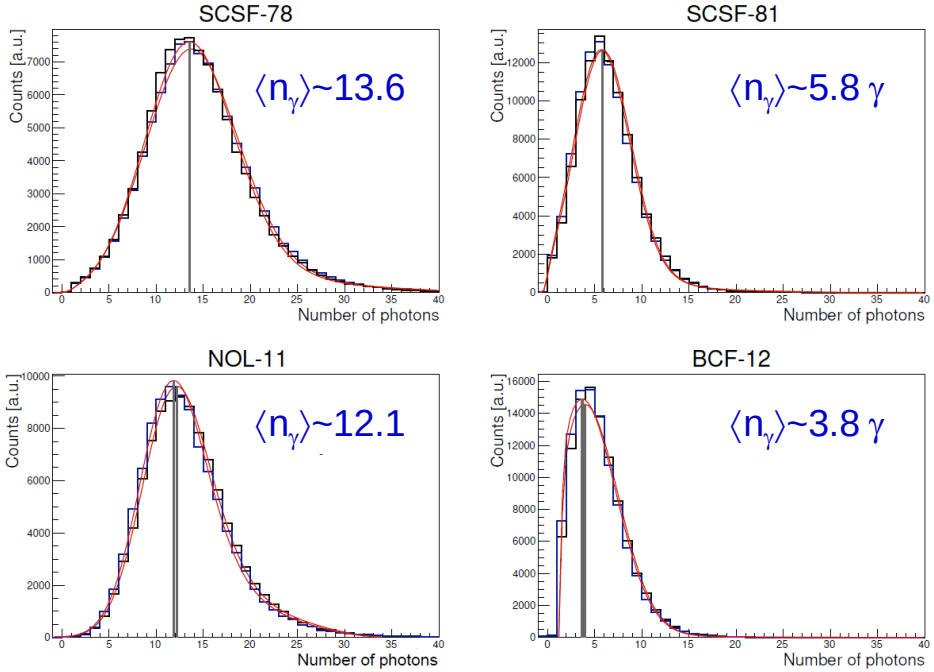
criteria:

- high light yield
- best time performance $\sigma_t \approx \sqrt{\frac{\tau_R \tau_D}{n_\gamma^2}}$

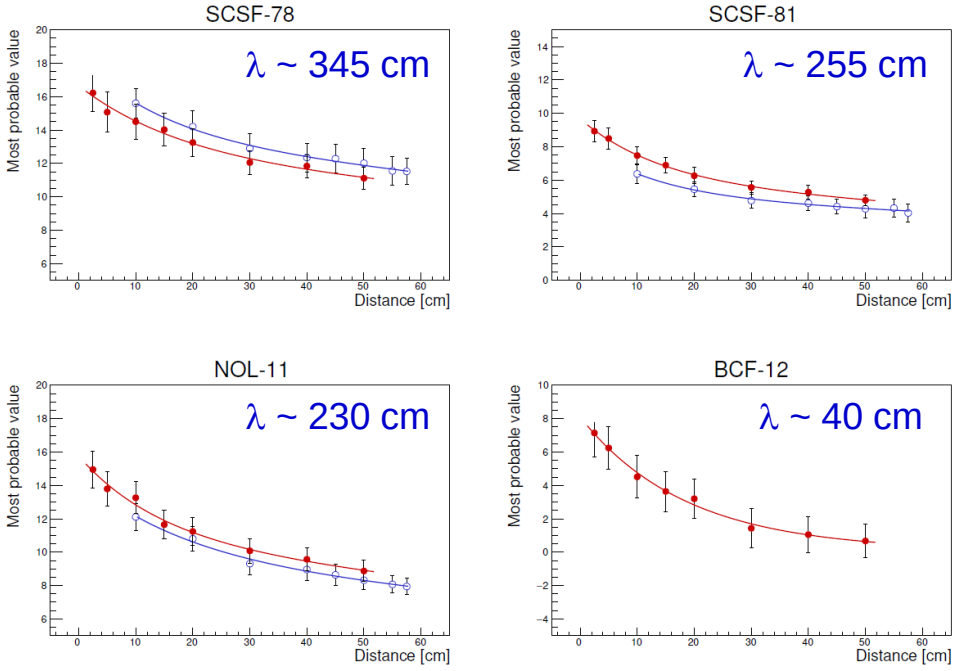
commercially available 250 μm ϕ fibers

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]



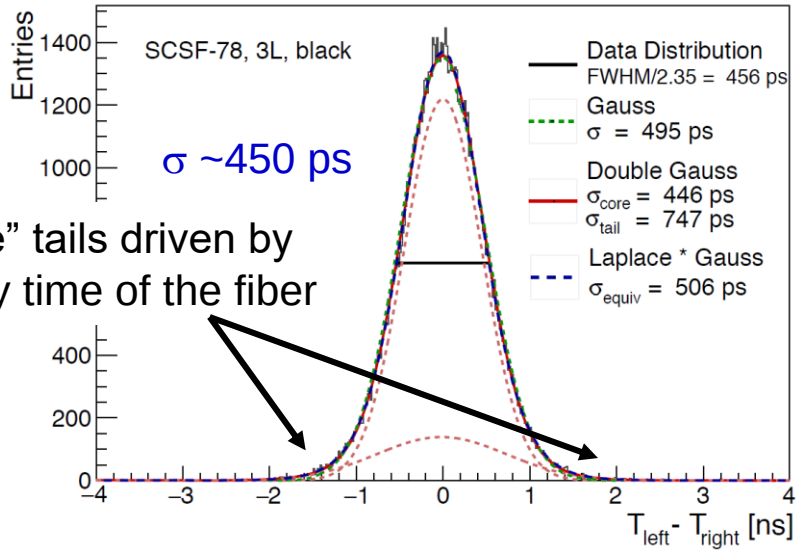
attenuation



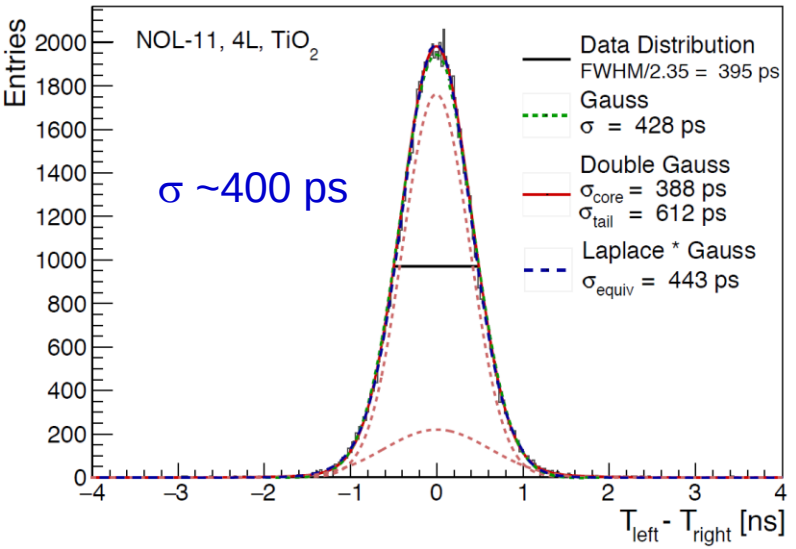
A. B. and Y. Demets, JINST17(22)P12020

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

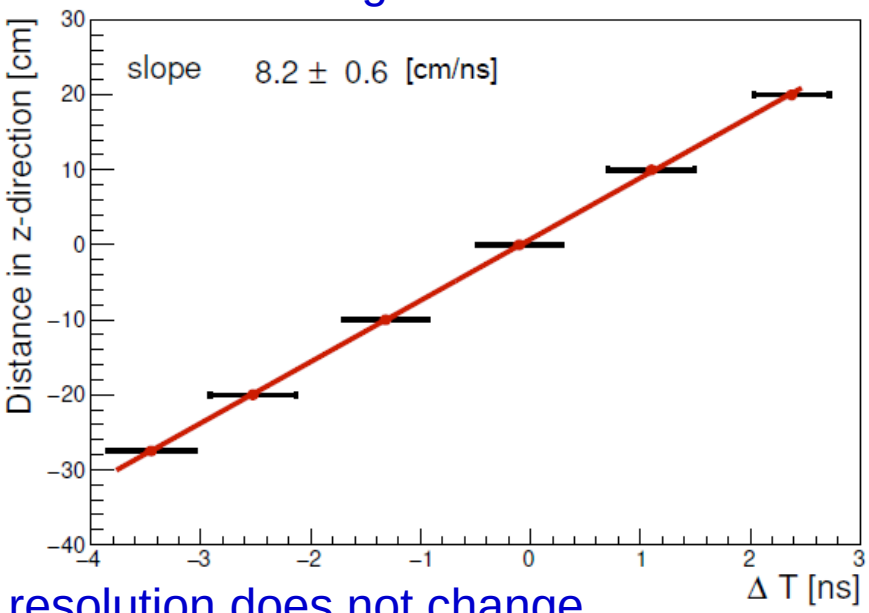
Measure intrinsic resolution of SciFi detector,
however cannot determine the crossing time



"large" tails driven by
decay time of the fiber



ΔT along the SciFi ribbon



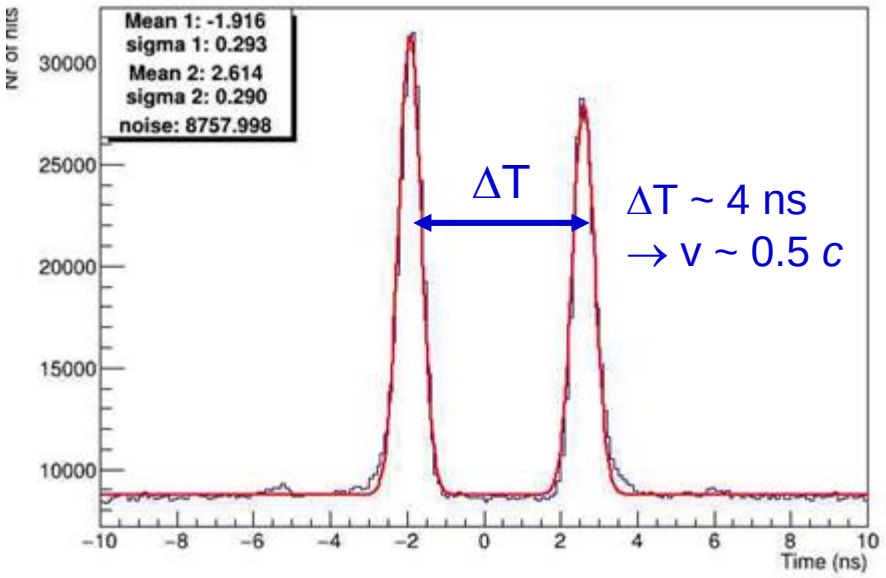
resolution does not change
with impact position (no edge effects)

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

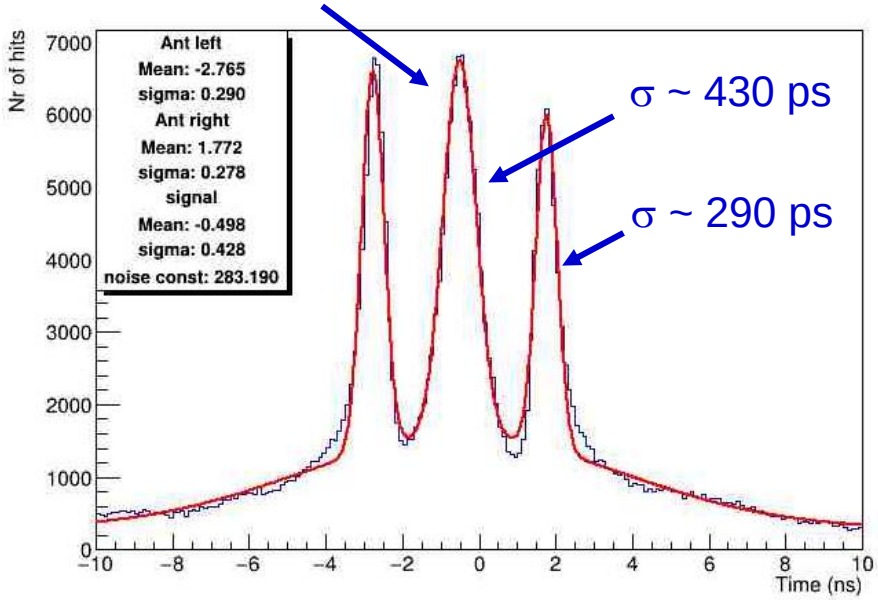
Correlated Dark Counts

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}.

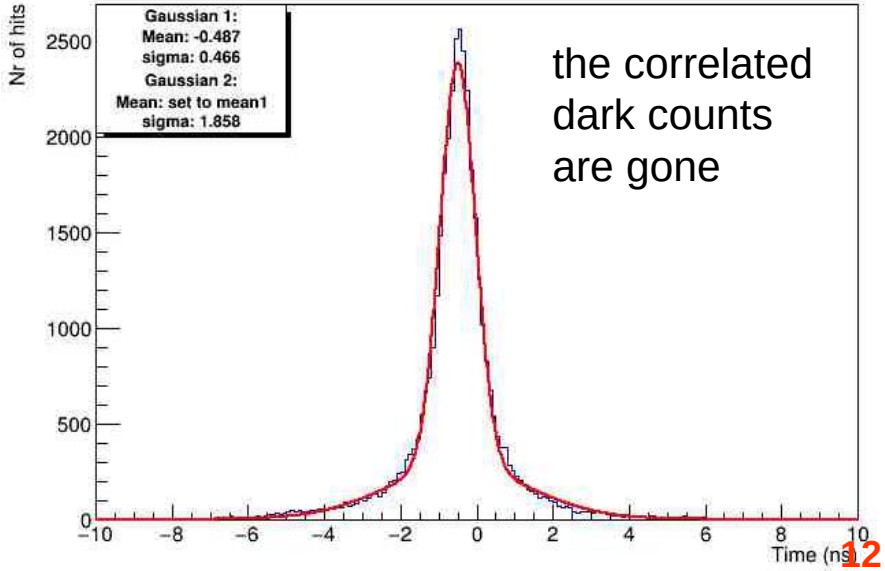
dark counts correlated in time



adding a weak Sr source in the center



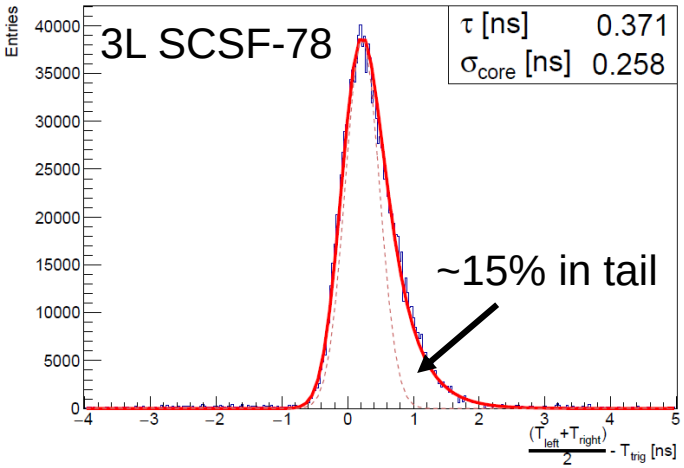
cluster size ≥ 2 or higher threshold

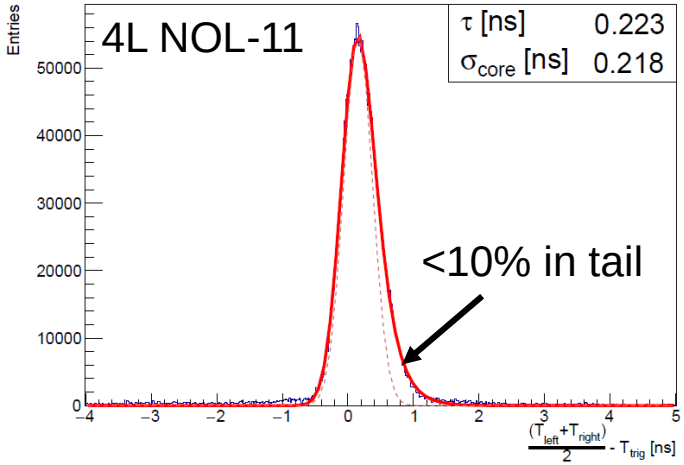


Mean Time

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.

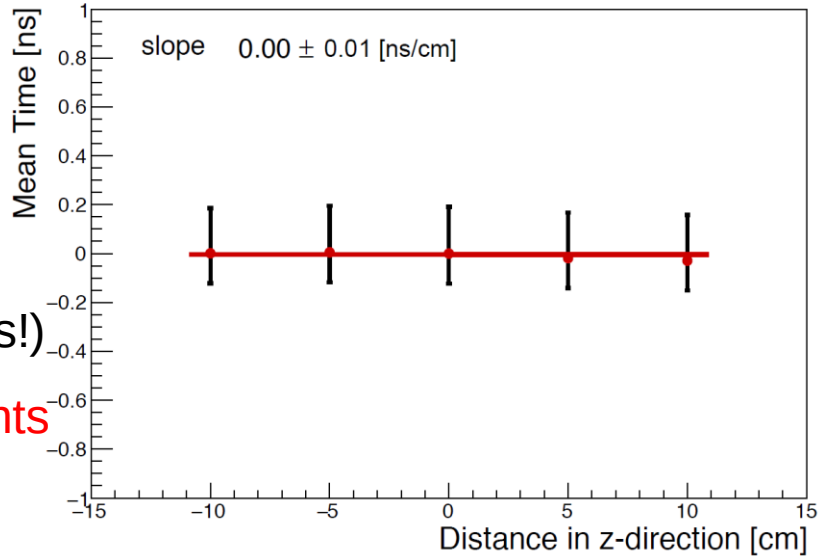
MT does not depend on the hit position

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

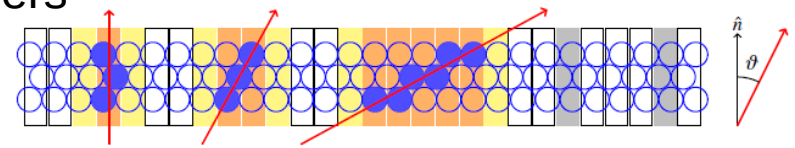


A. B. *et al.*, NIMA1058(23)168766

Detection Efficiency

Issues:

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

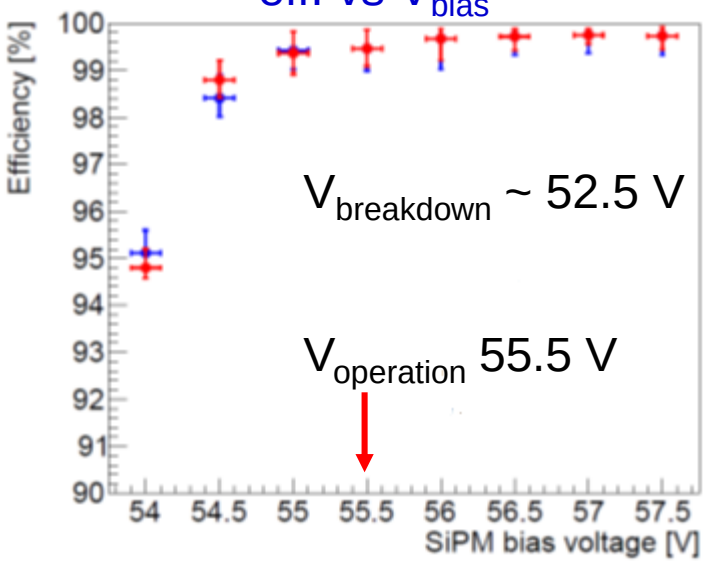


→ some events with very low light yield
→ very low thresholds of 0.5 or 1.5 ph.e. & small clusters

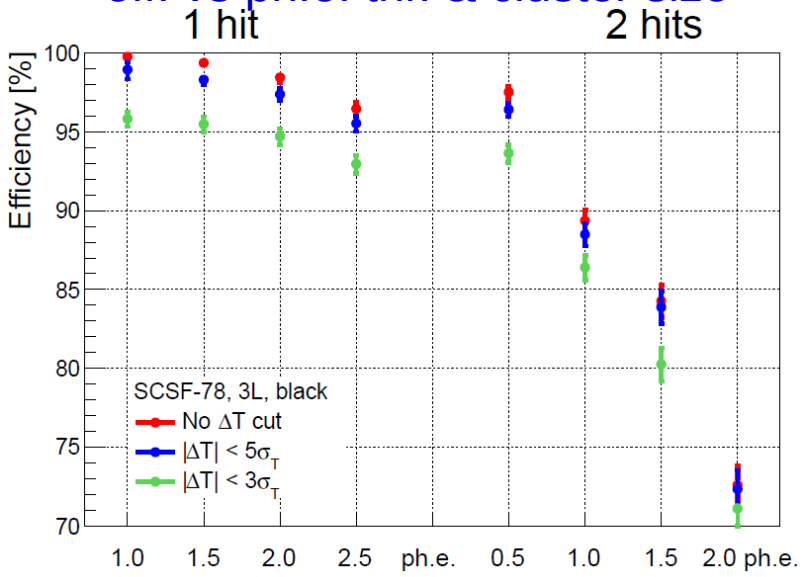
require *left / right* matched clusters → timing cut $\Delta T < n\ \sigma_{\Delta T}$

→ 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.

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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 ~100 μm

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

Limiting factor: material budget (3 staggered SciFi layers)

→ low light yield

→ not perfect (i.e. 100%) efficiency and limited time resolution

Readout based on the mixed mode MuTRiG ASIC (w/ Gigabit link)

- no time to discuss this ASIC, sorry ☹

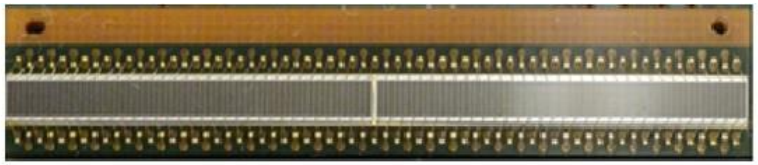
SciFi sub-detector ready for installation and commissioning in Mu3e

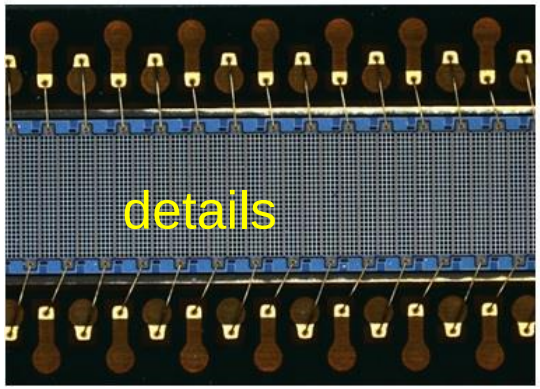
Si-PM Arrays

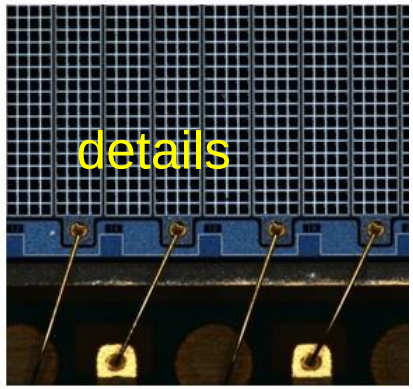
128 ch SiPM array from Hamamatsu (LHCb type) S13552HRQ

- 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

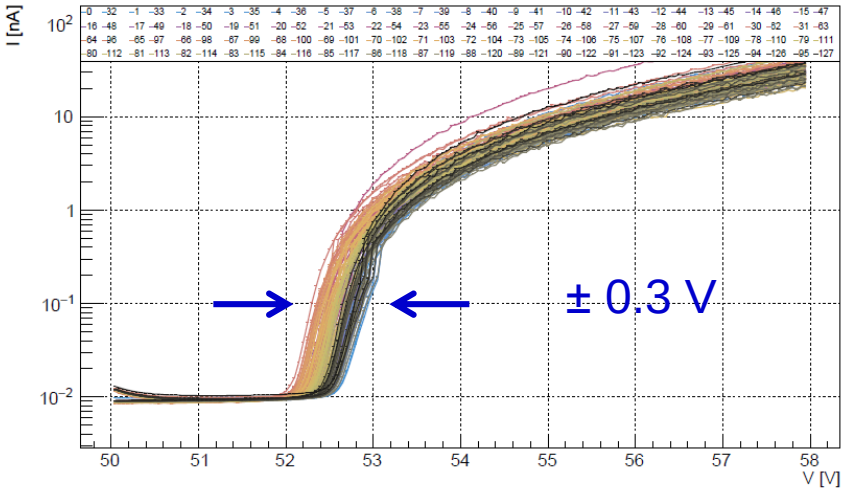
32.5 mm (two 64 ch. dies)

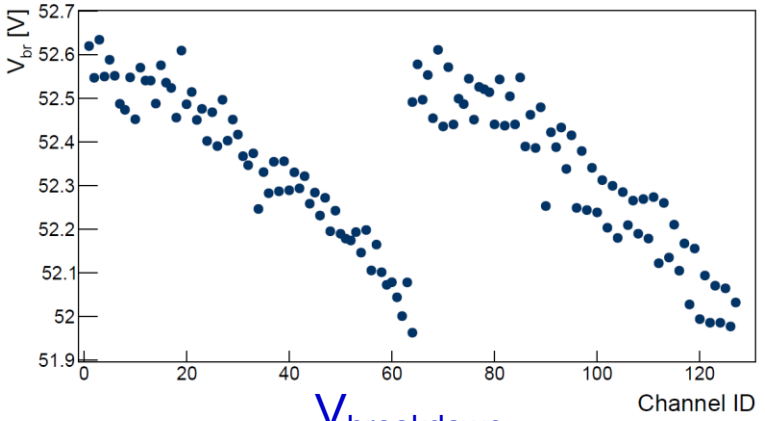






I – V curves





$V_{breakdown}$