Summary of R&D Activities
Squared Scintillating Fibers

Giada and Angela for the SciFi Group

February 8th 2017

Mu3e Meeting @ PSI

The Challenge

Detect minimum ionizing particles at high efficiency and good timing with so little scintillating material

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Back-of-the-envelope calculation **for a 30 cm long 250 μm multiclad fiber**

$$\langle N_{Phe} \rangle = \langle S \rangle \langle Q \rangle \langle T \rangle$$

Source term <S>

$$\frac{8000\ \text{photons}}{\text{MeV}} \times \frac{2\ \text{MeV cm}^2}{\text{g}} \times 1.05\ \frac{\text{g}}{\text{cm}^2} \times 250\ \mu\text{m}$$

≈ 420 photons

Transmission term <T>

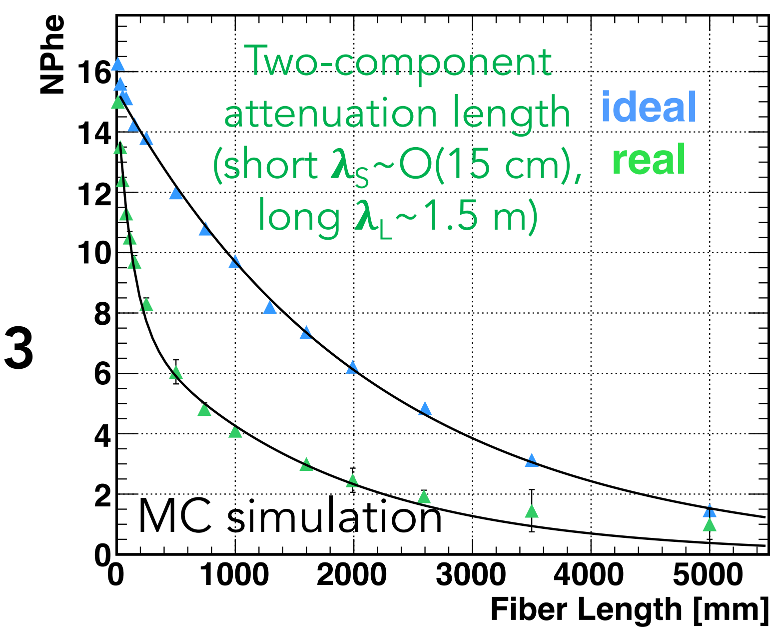
$$\frac{\delta\Omega}{4\pi} \times e^{-L/L_{att}}$$

≈ 2.6%

Quantum efficiency <Q>

≈ 40%

$\langle N_{Phe} \rangle \approx 4.3$ photons



The Challenge

Detect minimum ionizing particles at high efficiency and good timing with so little scintillating material

Ingredients for maximum performance (from our experience):

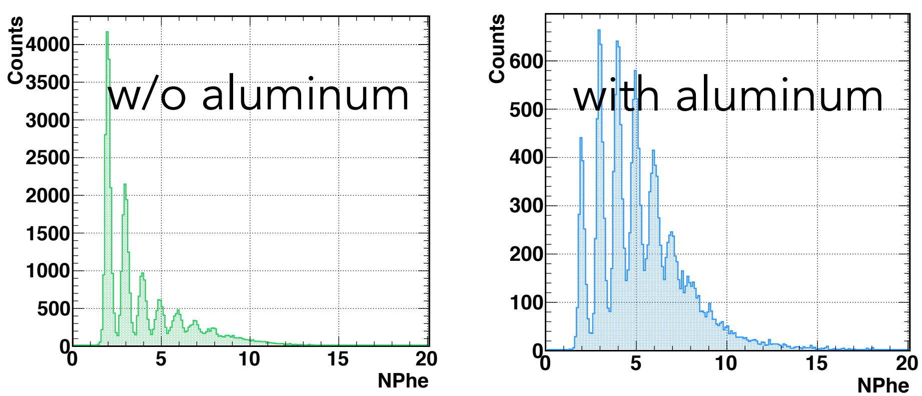
- Fiber end polishing
- Optical isolation of the fiber
- Good fiber-SiPM-alignment

Optical Isolation

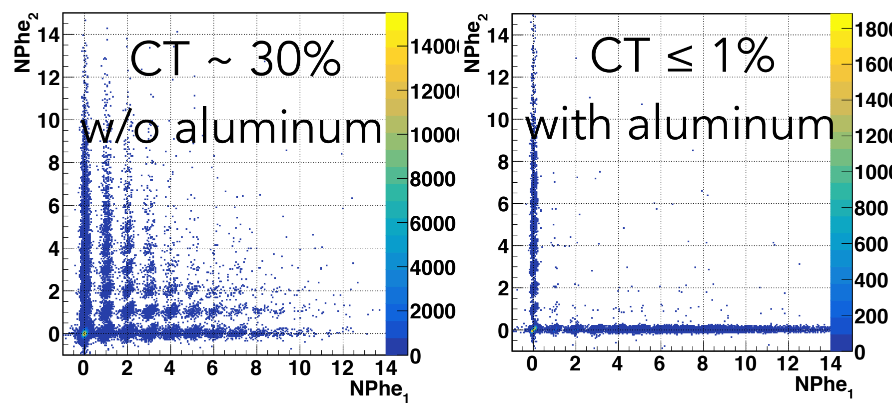
c.f. Mu3e Meeting Dec '16

Fibers w/o optical isolation are subject to substantial light losses and fiber crosstalk

Light yield (Sr90 measurements)

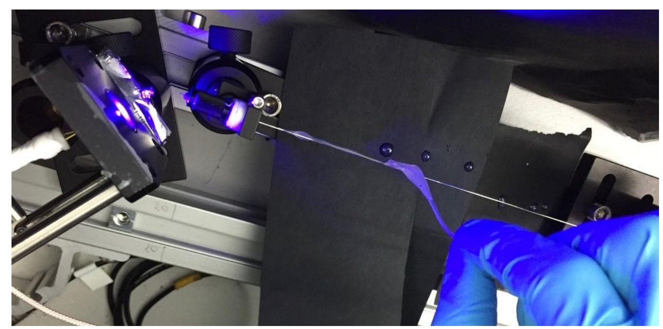


Fiber crosstalk (Sr90 measurements)



"In situ" light loss measurements

Material	n	Light loss bare	Light loss alum.
Optical cement (BC600)	1.56	40 %	$\leq$ 1 %
Araldite®	$\approx$ 1.5	30 %	$\leq$ 1 %
Optical grease (BC630)	1.47	20 %	$\leq$ 1 %



Fiber-SiPM Alignment

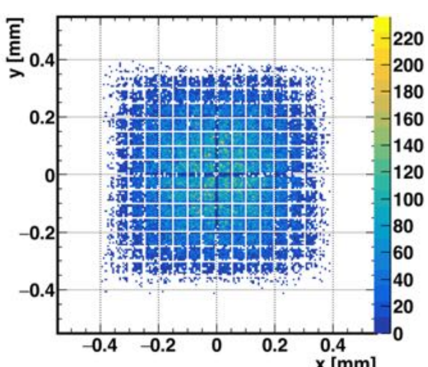
c.f. Mu3e Meeting Oct '14

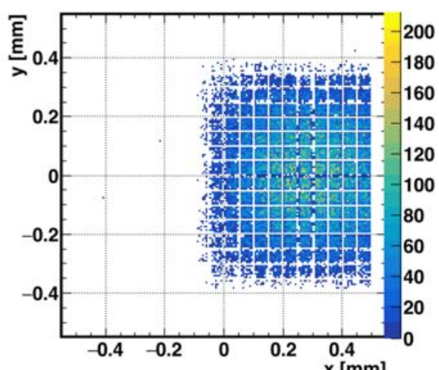
Aligned every individual SiPM on the PCB prior to soldering

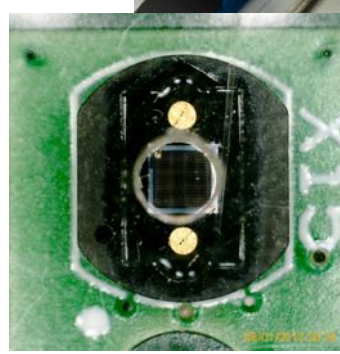
Overall alignment precision: 250-300 μm

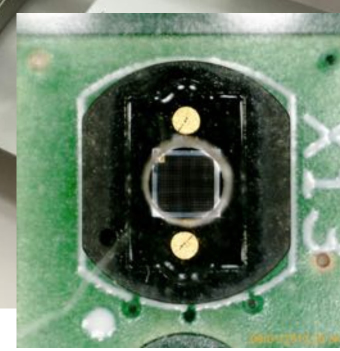
- Groove/ hole precision on plexiglass: 50-100 μm
- Precision Hole: 50 μm
- Pin holes on the SiPM PCB: 150 μm
- SiPM active area w.r.t. packaging: 200 μm

From MC simulations: Shifts up to 300 μm in both transverse directions affordable for 1.3 x 1.3 mm^2 SiPMs





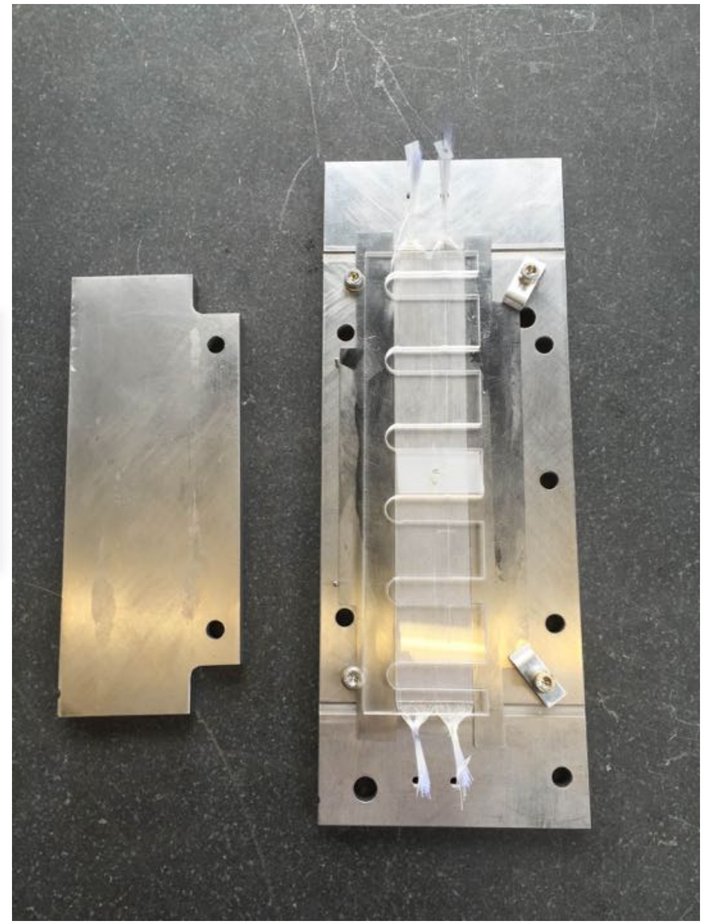




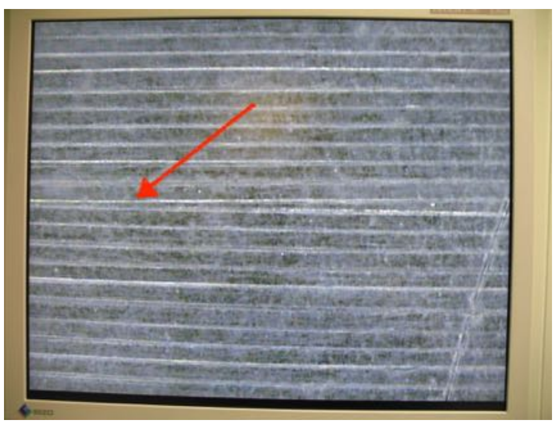
Squared Fiber Ribbons

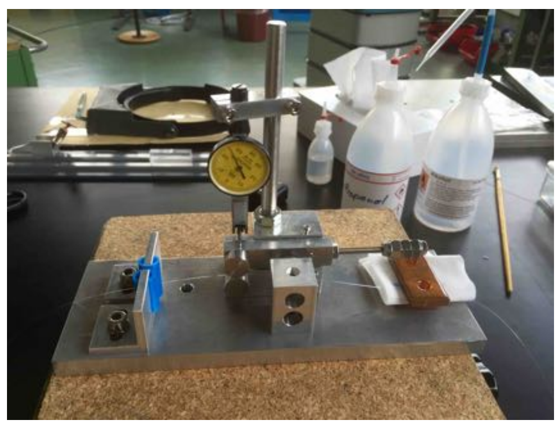
c.f. Mu3e Meeting Nov '15

- Quality control (blobs, thickness variations, cladding damage, …)
- Fiber size: 240 x 260 μm² → took special care about fiber orientation (240 μm along beam)



Measured thickness and uniformity across a single fiber layer (256 fibers): 265 ± 5 μm





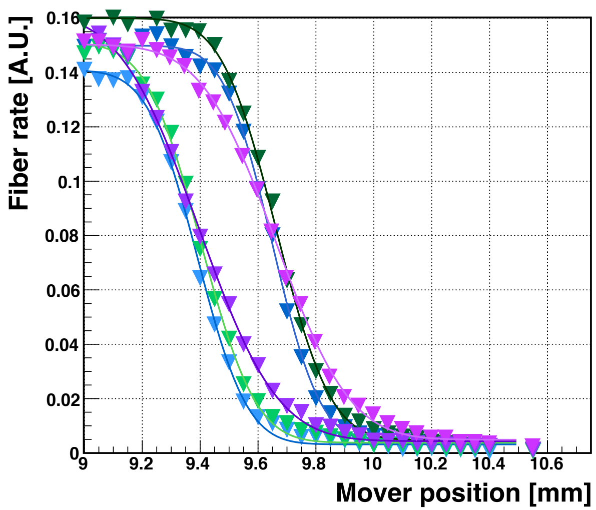
Fiber Alignment

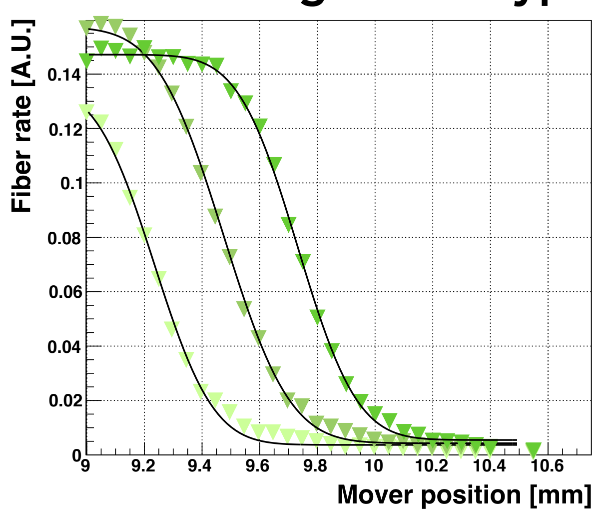
c.f. Mu3e Meeting May ‘16

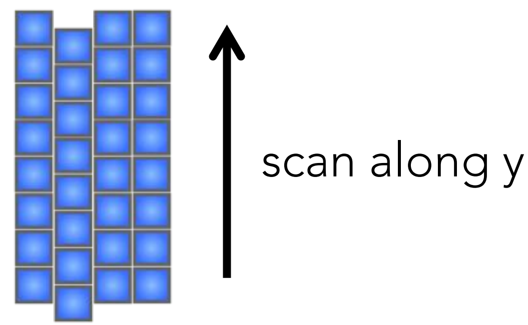
Fiber alignment both within an individual and among several layers is already at a good level, could most probably be improved by further efforts

- Distances between fibers in y- direction 260-270 μm, consistent with fiber size
- 1st, 2nd and 4th layer aligned within 10-20 μm
- 3rd layer shifted by ≈55 μm compared to perfect staggering by half a cell

Collimated Sr90 source scans with Large Prototype



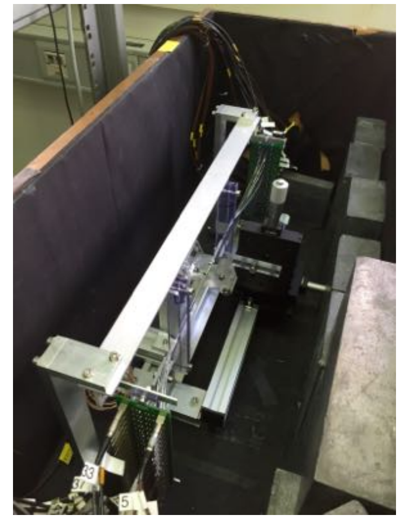




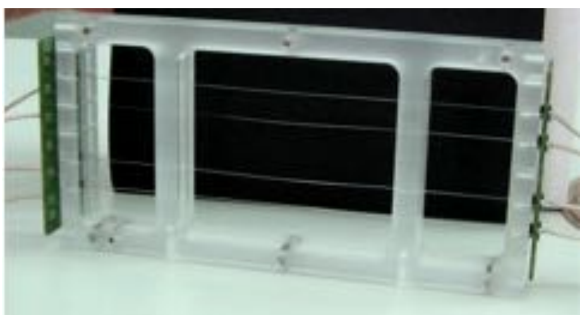
R&D History

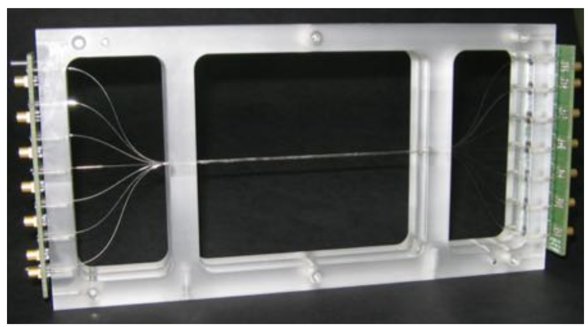
Bottom-up-approach

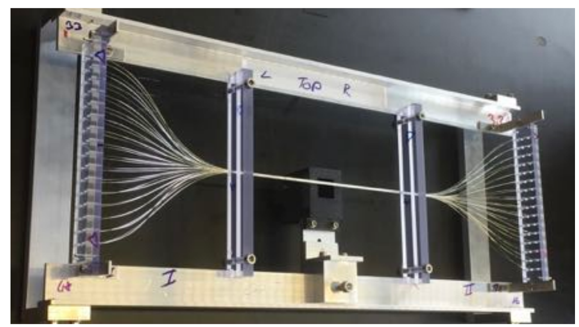
Single fiber ➠ telescope structures

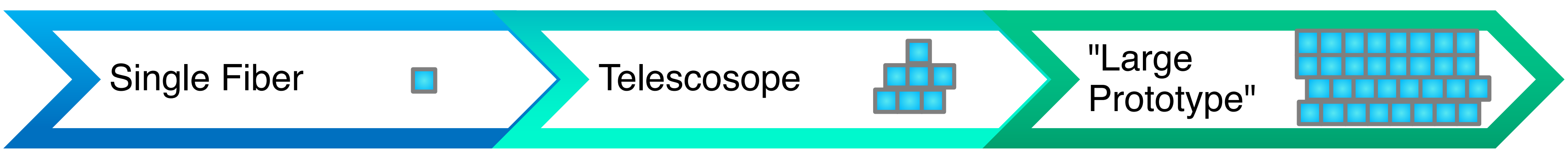


Extensive tests in the laboratory and at (mostly PSI) beam lines





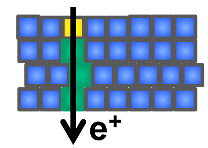


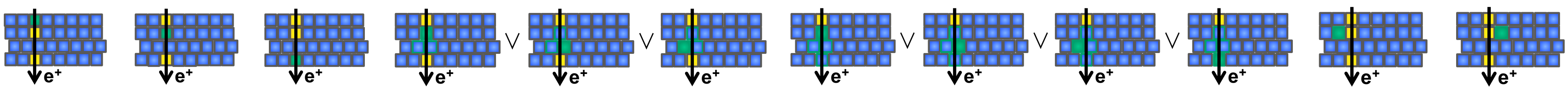


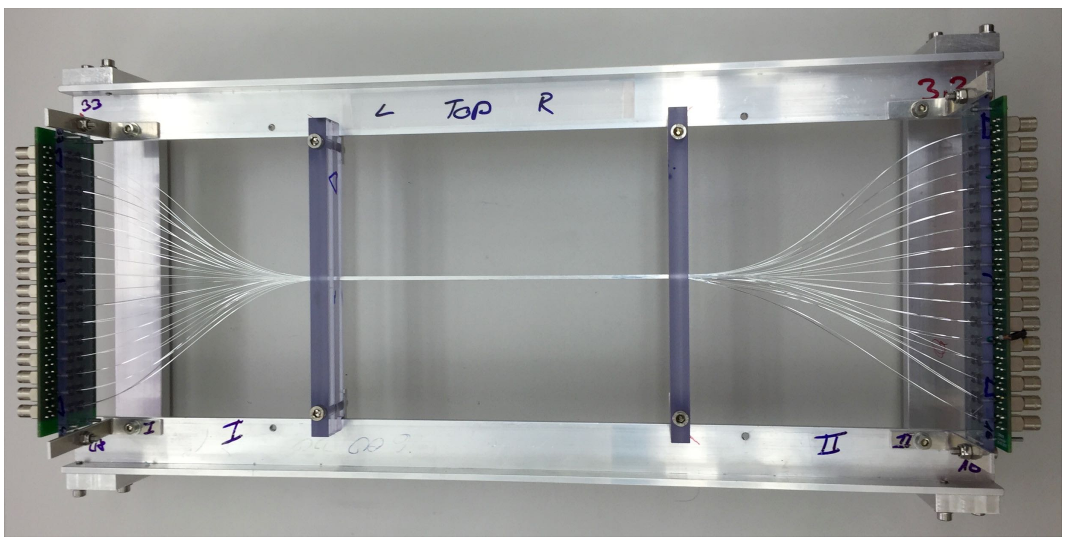
The Large Prototype

c.f. Mu3e Meeting Nov '15

The Large Prototype allowed to assess **single- and multilayer efficiencies and timing resolutions**, and to combine channels offline to **emulate the SiPM array readout**







Key Features

- 32 squared, 250 µm thin fibers with individual readout
- Aligned SiPMs
- Aluminum coating (100 nm)

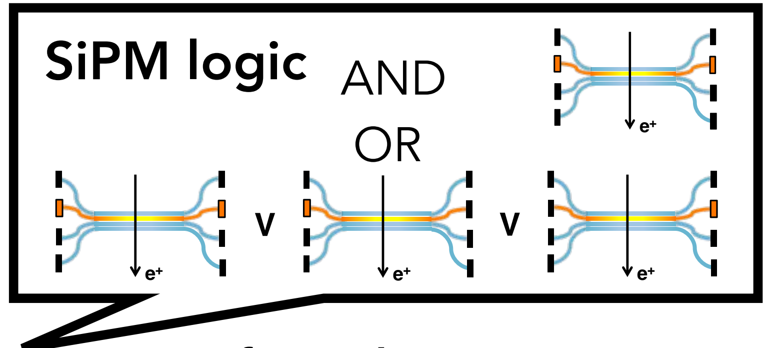
Light Yield – Straight Tracks

c.f. Mu3e Meeting
Nov '15

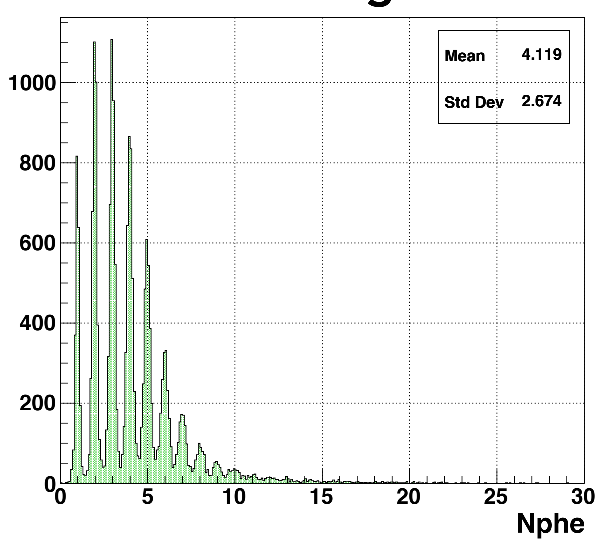
Single Fiber Light Yield (Beam Test @ πM1)

Positrons @ 115 MeV/c

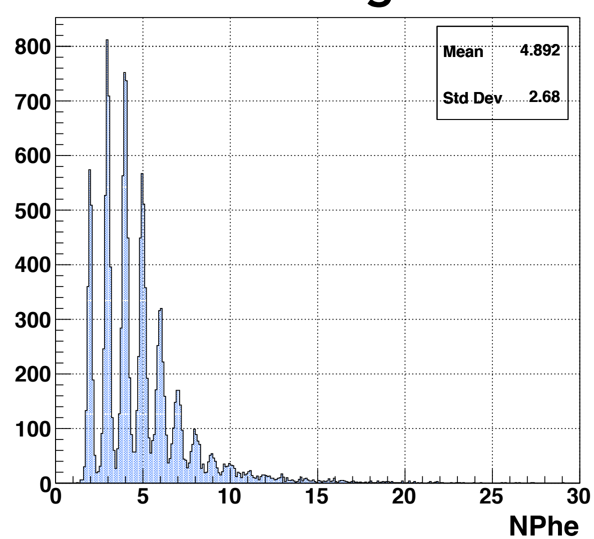
Mean $\mathbf{N_{Phe}} \approx$ **4.6 (AND)** and **3.7 (OR)** with a threshold 0.5 N_{Phe}



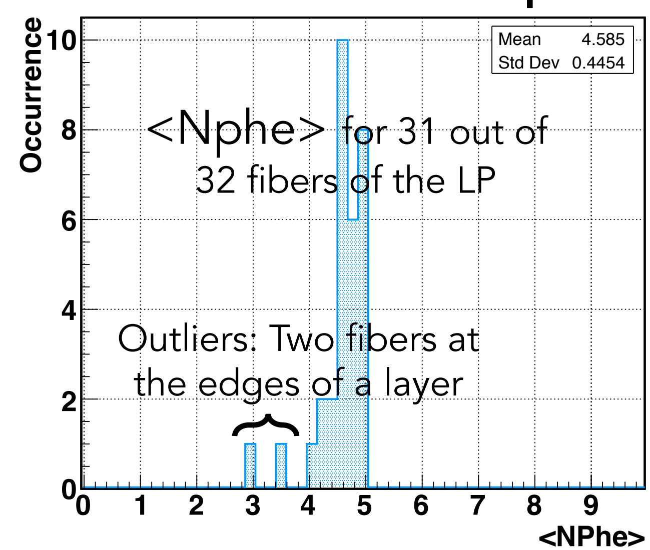
OR logic



AND logic



Uniform detector response

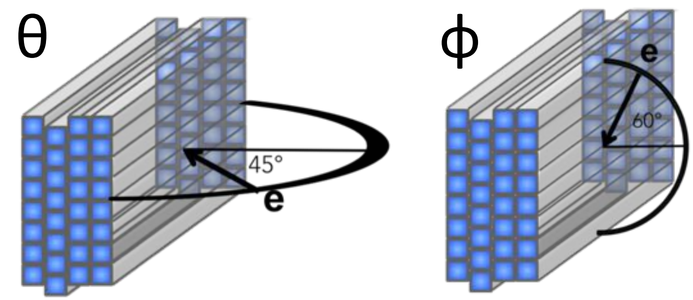


Light Yield – Inclined Tracks

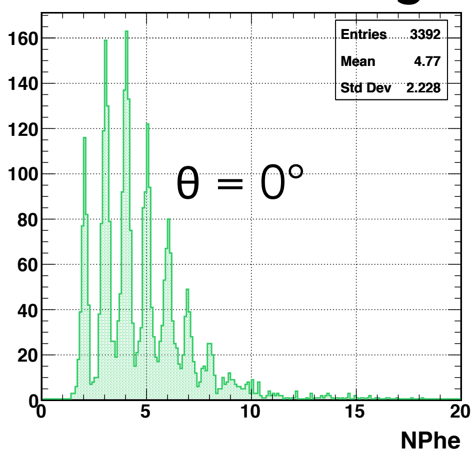
c.f. Mu3e Meeting
May '16

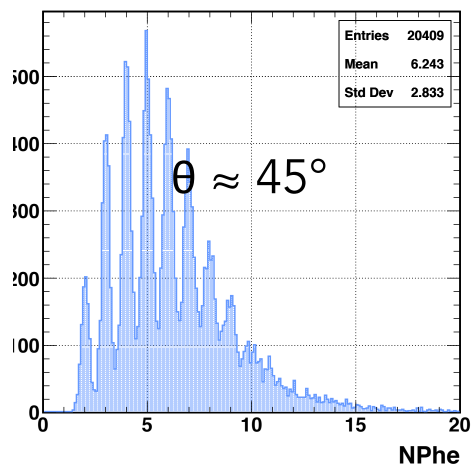
Sr90 Laboratory Measurement

Increased light yield / inclination of tracks clearly visible and consistent with expectations



Theta Angle Measurements

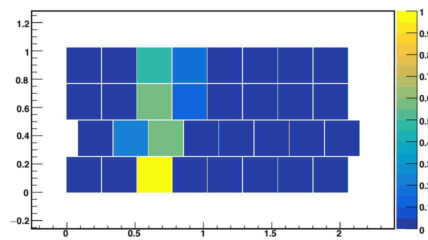




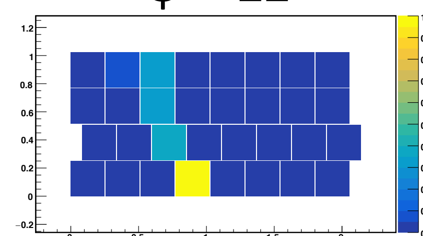
Estimated single fiber detection efficiency @ θ = 45°: ε ≈ 85%

Phi Angle Measurements

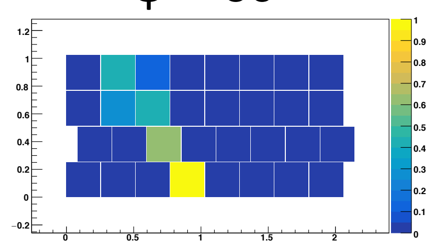
ϕ = 0°



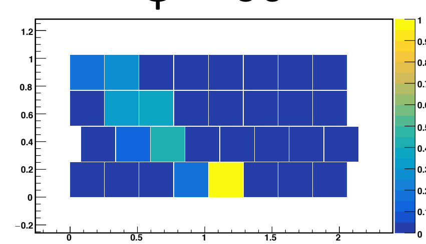
ϕ = 22°



ϕ = 35°



ϕ = 60°



Detection Efficiency

c.f. Mu3e Meeting Nov '15

Single and Multilayer Efficiency (Beam Test @ πM1)

Positrons @ 115 MeV/c

	Single Layer	Double Layer	Triple Layer
ε_{AND} [%] (0.5 NPhe)	72 ± 1	89 ± 1	95 ± 2
ε_{OR} [%] (0.5 NPhe)	96 ± 1	99 ± 1	98 ± 1
ε_{AND} [%] (1.5 NPhe)	34 ± 1	52 ± 1	67 ± 1
ε_{OR} [%] (1.5 NPhe)	79 ± 1	93 ± 1	97 ± 1

*

Extrapolated
Double
$\varepsilon_{AND} \approx 92\%$
Triple
$\varepsilon_{AND} \approx 98\%$

Measured a detection efficiency for MIP of
$\gtrsim$ 95% for three layers
of 250 x 250 μm^2 squared multiclad scintillating fibers
at a threshold of 0.5 NPhe

*The double and triple layer numbers represent **lower limits** to the detection efficiency

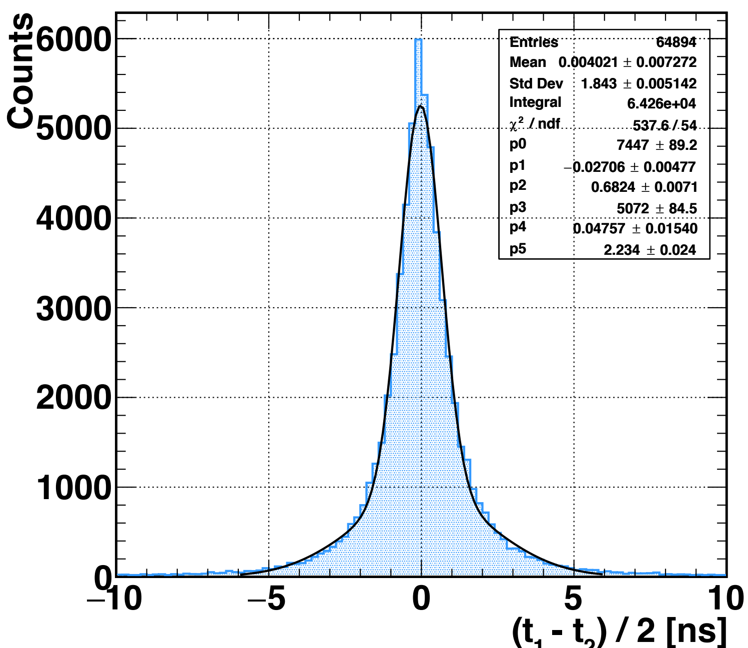
Timing Resolution

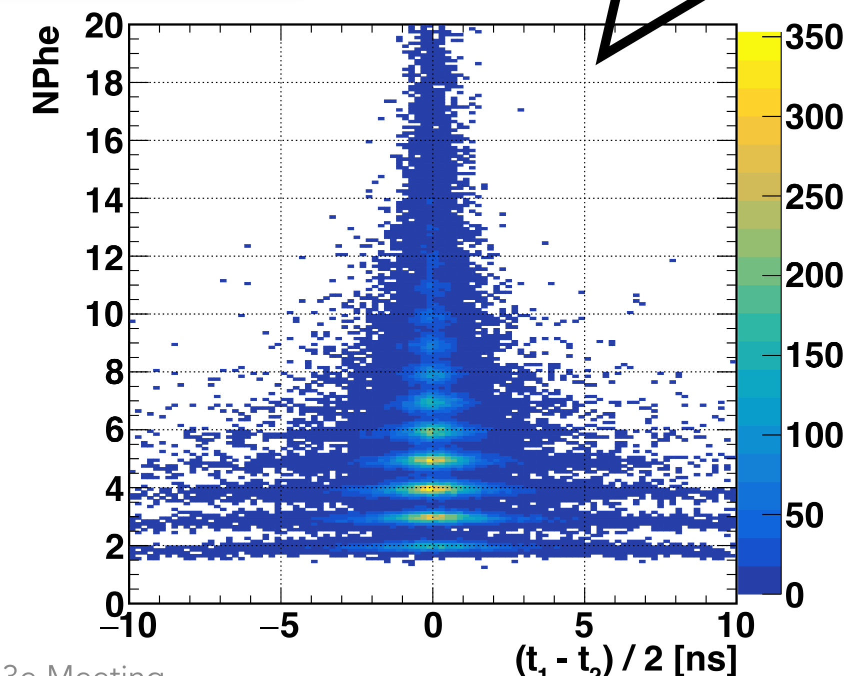
Single fiber timing resolution (Beam Test @ πM1)

- Positrons @ 115 MeV/c
- Offline constant fraction discrimination (20%), threshold 0.5 N_{Phe}
- 30 dB preamplifiers

$\sigma_{core} \approx$ 680 ps
$\sigma_{tail} \approx$ 2.23 ns
$f_{core} \approx$ 60%

Tails are mainly due to single-photon-events!





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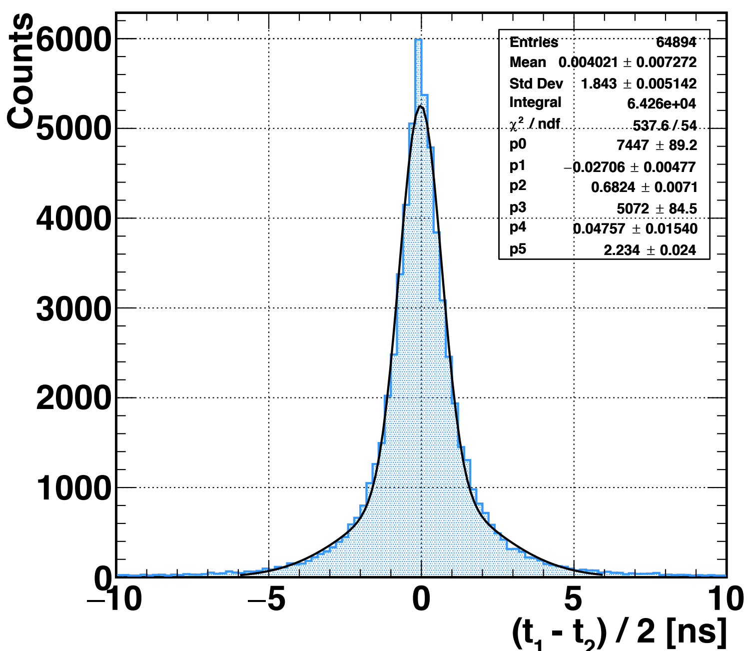
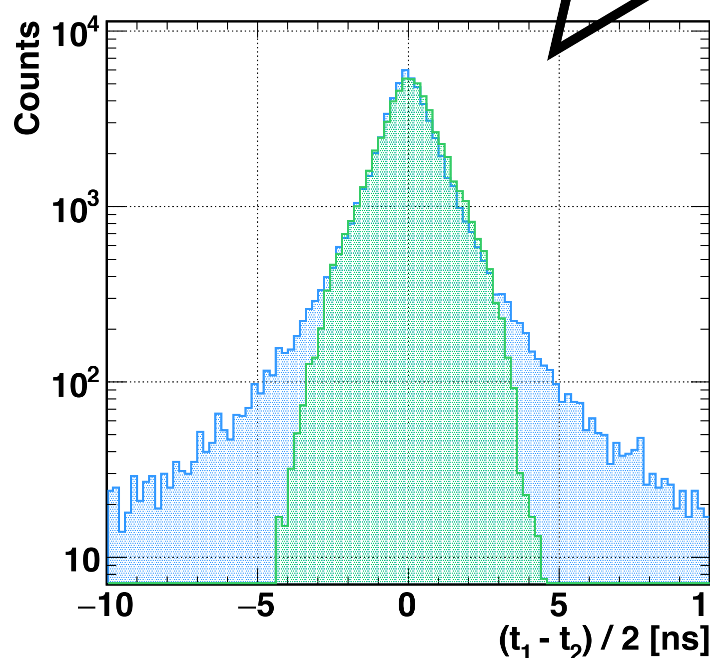
$\sigma_{core} \approx 680$ ps
$\sigma_{tail} \approx 2.23$ ns
$f_{core} \approx 60\%$

40 dB preamplifiers (lab measurement)





Timing Resolution

Single fiber timing resolution (Laboratory Test)

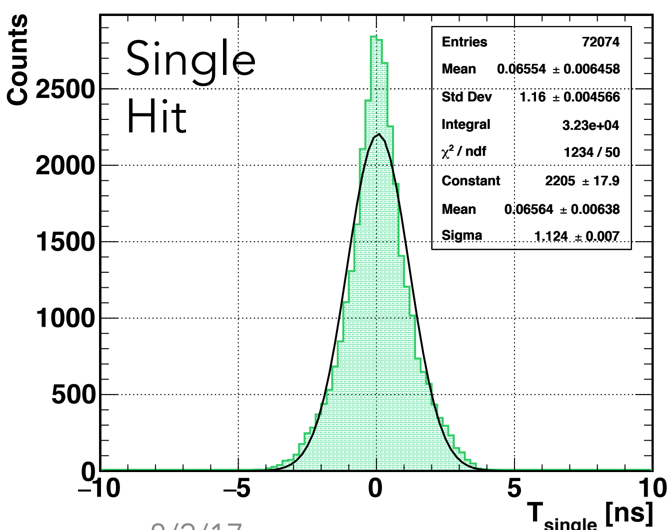
- MI electrons from Sr90
- Offline constant fraction discrimination (20%), threshold 0.5 N_{Phe}
- 40 dB preamplifiers

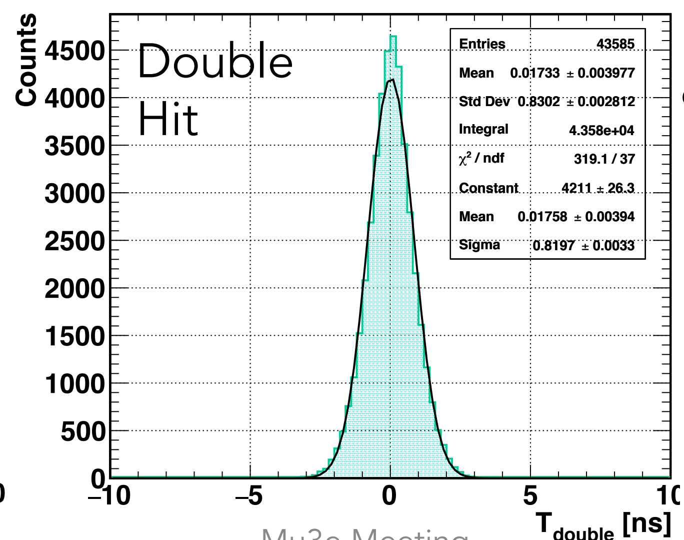
Using the 40 dB preamplifiers **the tails are gone**

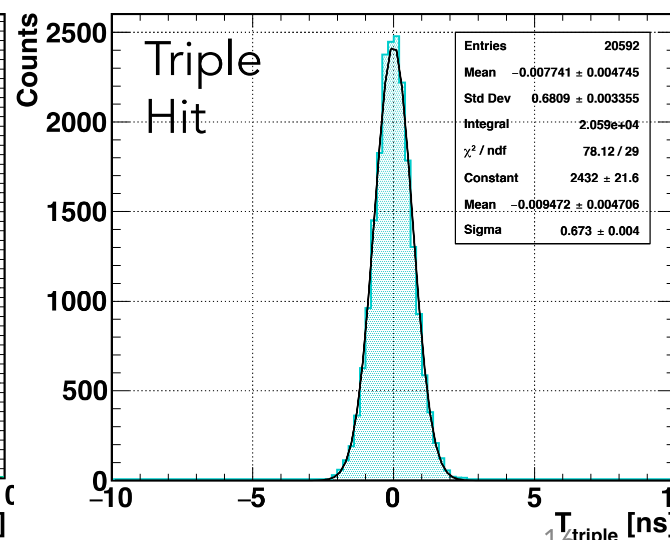
σ_{single} = 1120 ± 10 ps
RMS_{single} = 1160 ± 5 ps

σ_{double} = 820 ± 3 ps

σ_{triple} = 673 ± 4 ps







Timing Resolution

Single fiber timing resolution (Laboratory Test)

- MI electrons from Sr90
- Offline constant fraction discrimination (20%), threshold 0.5 N_{Phe}
- 40 dB preamplifiers

> Using the 40 dB preamplifiers **the tails are gone** and we observe the **correct scaling of the timing resolution** with number of fiber hits

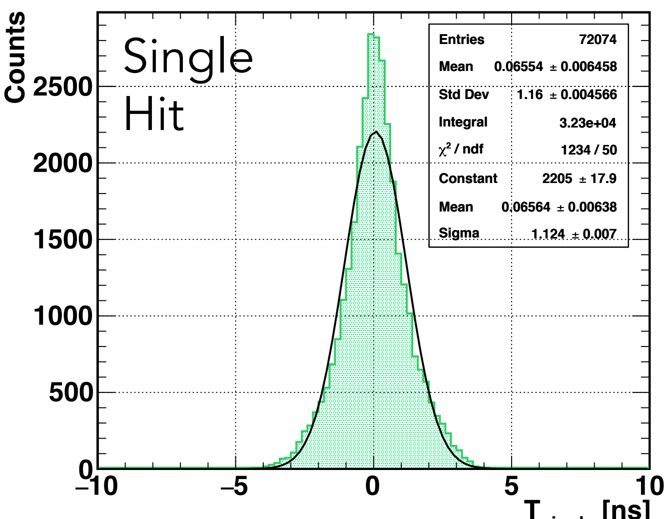
σ_{single} = 1120 ± 10 ps
RMS_{single} = 1160 ± 5 ps

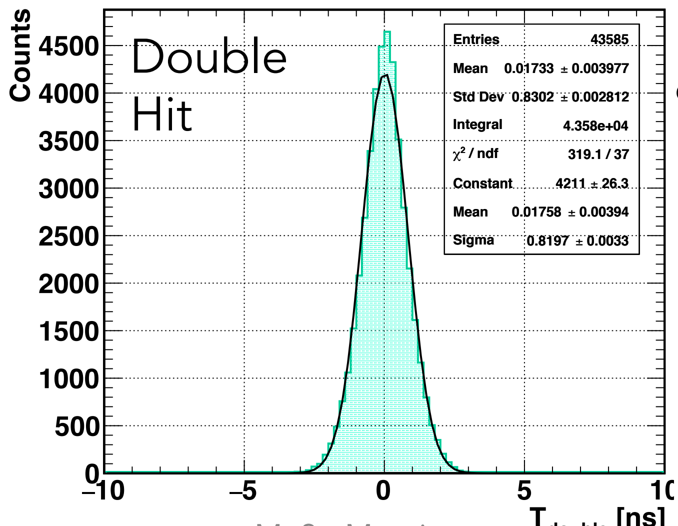
$RMS_{single}/\sqrt{2}$ = 820 ps

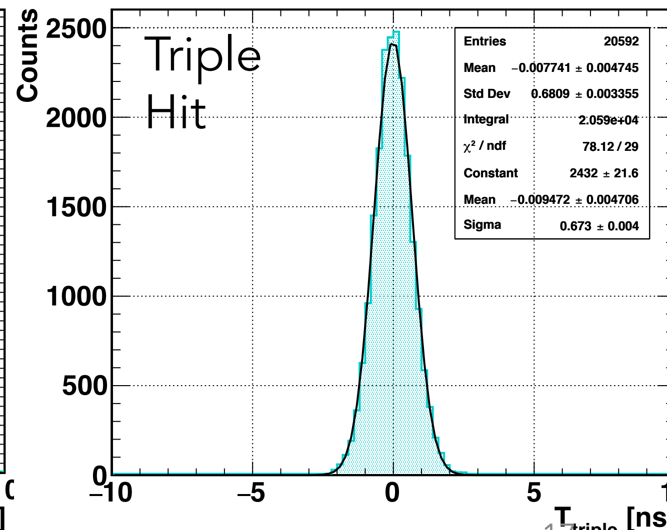
σ_{double} = 820 ± 3 ps

$RMS_{single}/\sqrt{3}$ = 670 ps

σ_{triple} = 673 ± 4 ps



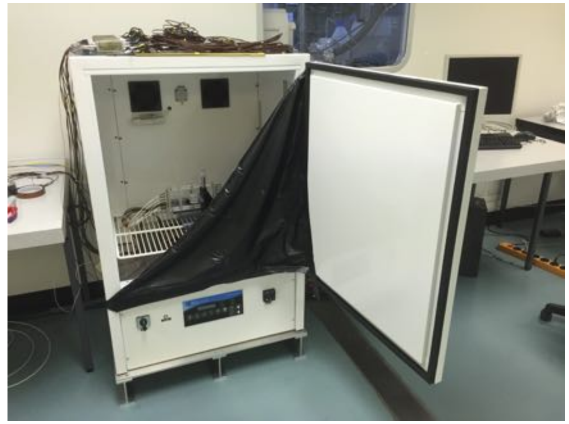




Temperature Dependence

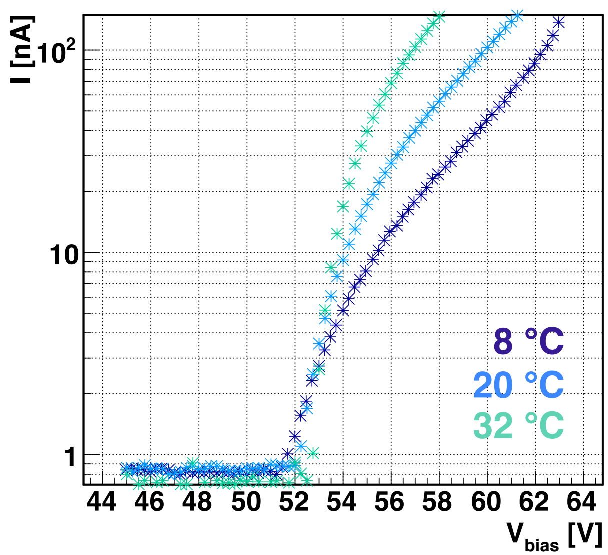
c.f. Mu3e Meeting May '15

Prototype V4.1: Temperature studies with Sr90 source and thermal chamber @ 8°C, 16°C, 24°C, 32°C, SiPM gains equalized on a hardware-level:

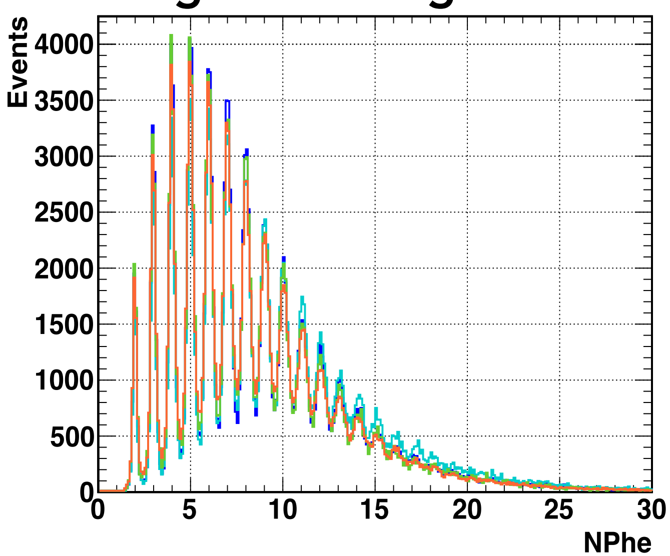


Variations in detection efficiency and timing **< 10%**

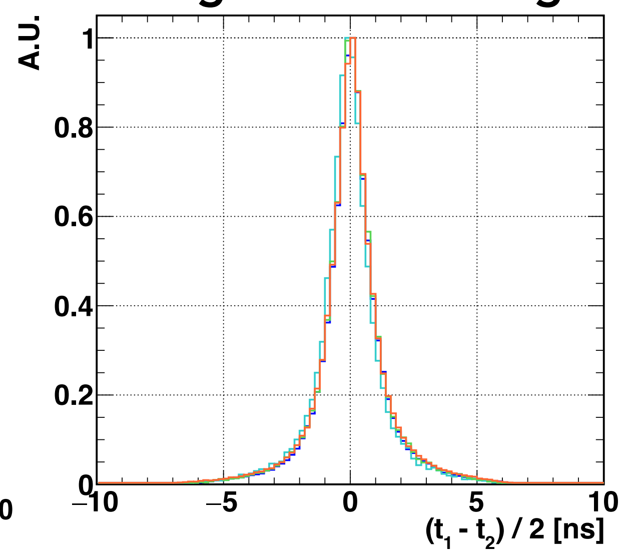
SiPM Characterization



Single Fiber Light Yield



Single Fiber Timing



Extrapolation to Final Mu3e Hodoscope Performances

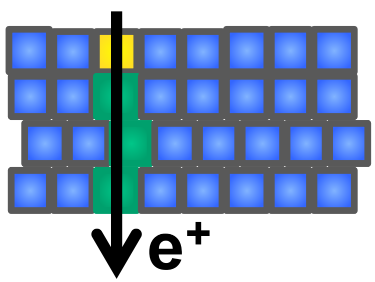
c.f. Mu3e Meeting
Nov '15

Mimic the Mu3e hodoscope by combining offline the SiPM channels of three consecutive fibers

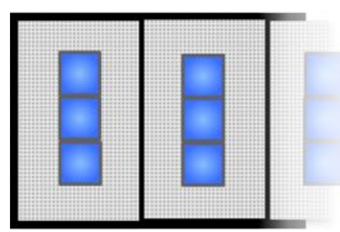
≙ "optimized" array readout

Optimized array readout:
- Good fiber-SiPM alignment
- Sufficiently large SiPM active area
- No saturation effects

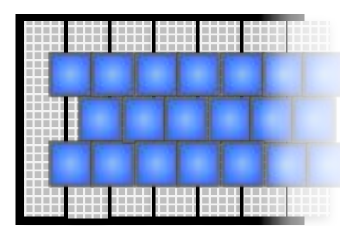
} i.e. maximum light collection capability



ideal



real



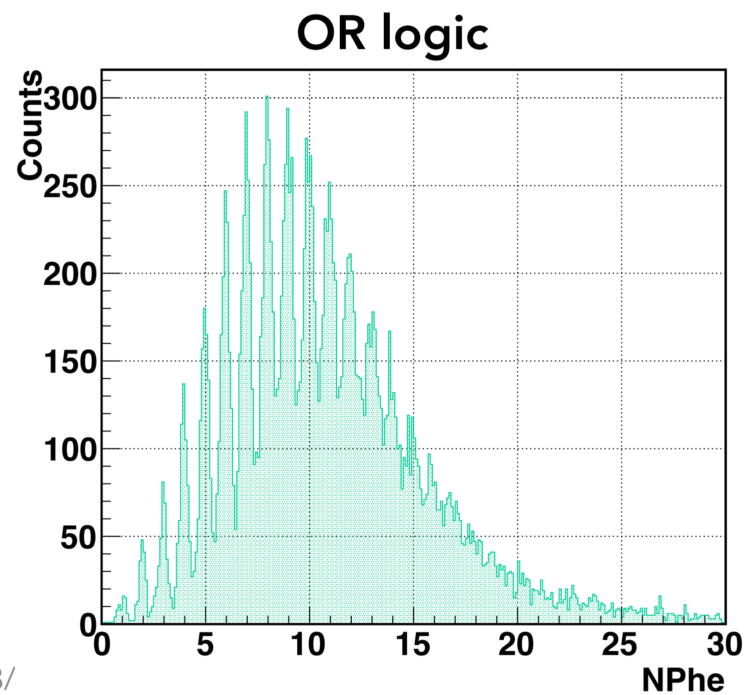
Optimized Array

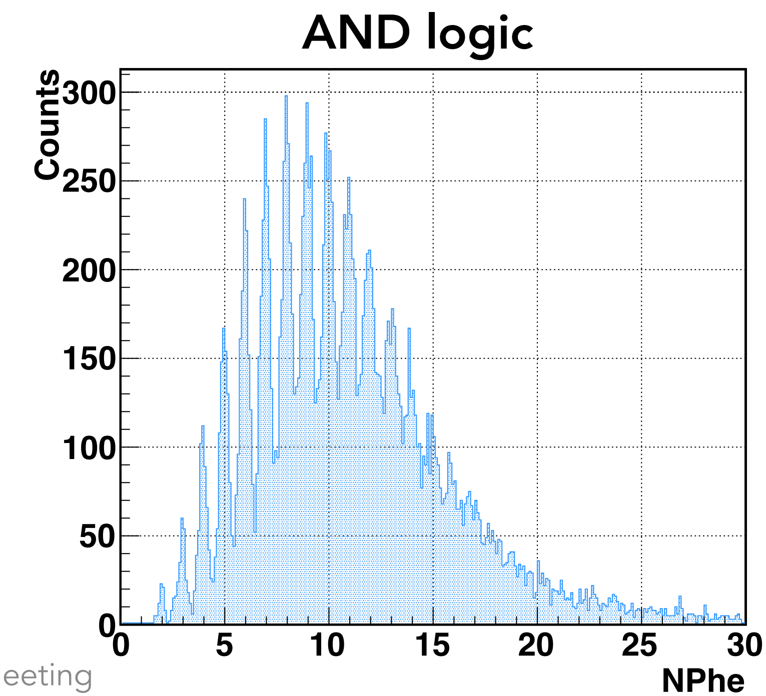
c.f. Mu3e Meeting Nov '15

Light Yield (Beam Test @ πM1)

Positrons @ 115 MeV/c

Mean $\mathbf{N_{Phe}}$ **= 10.9 ± 0.2 (AND)** and **10.6 ± 0.2 (OR)** with a threshold 0.5 N_{phe}





Optimized Array

c.f. Mu3e Meeting Nov '15

Detection Efficiency (Beam Test @ πM1)

Positrons @ 115 MeV/c

	Triple Layer
$\varepsilon_{AND}^{array}$ [%] (0.5 NPhe)	95.8 ± 0.2 (stat) %
ε_{OR}^{array} [%] (0.5 NPhe)	98.3 ± 0.2 (stat) %
$\varepsilon_{AND}^{array}$ [%] (1.5 NPhe)	88.0 ± 0.3 (stat) %
ε_{OR}^{array} [%] (1.5 NPhe)	97.5 ± 0.2 (stat) %

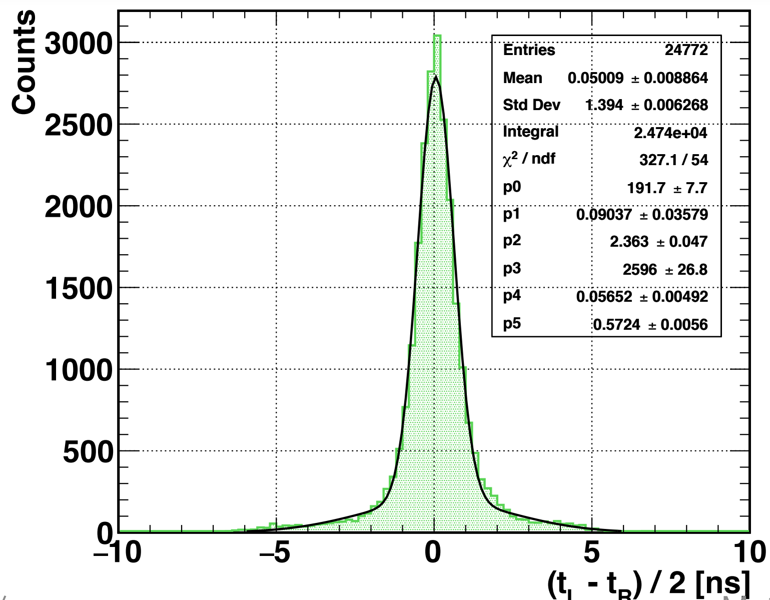
Measured a detection efficiency for MIP of
≳ 95% for three layers
of 250 x 250 μm^2 squared multiclad scintillating fibers
at a threshold of 0.5 NPhe

Optimized Array

Timing Resolution (Beam Test @ πM1)

Positrons @ 115 MeV/c

Measured a detection efficiency for MIP of ≳ **95% and a timing resolution of < 1ns for three layers** of 250 x 250 μm^2 squared multiclad scintillating fibers at a threshold of 0.5 NPhe



Double Gaussian Fit

Core fraction ≈ 75 %

		Array
σ_t [ps]	(0.5 NPhe)	572 ± 6
σ_t [ps]	(1.5 NPhe)	537 ± 4

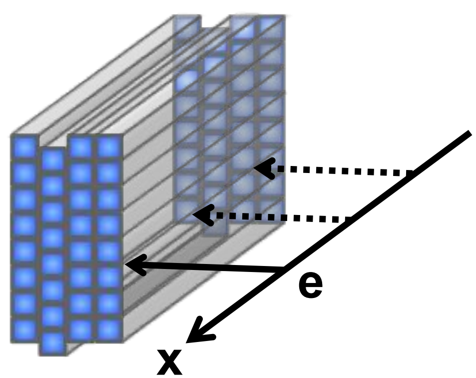
Optimized Array

Relative Detection Efficiency and Time Resolution (Laboratory Test)

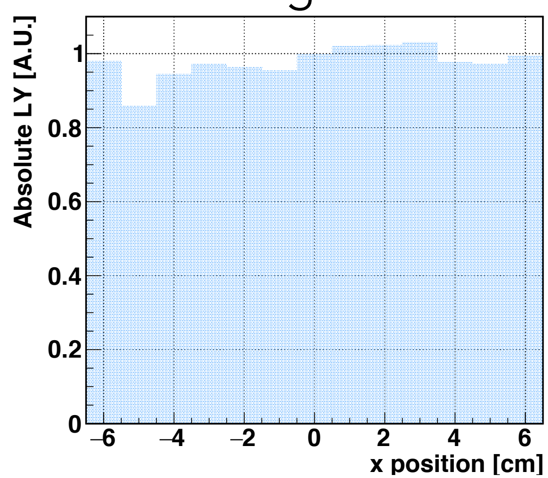
MI electrons from Sr90

Relative detection efficiencies at the most extremal (± 6 cm) positions and the central position (0 cm) agreed **within 6%.**
Timing resolution agreed **within 10%** in the scanned interval.

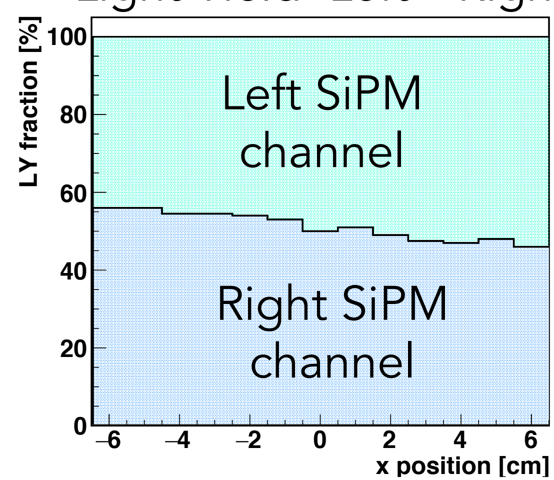
Fiber length Large Prototype: ~50 cm



Total Light Yield



Light Yield Left—Right



Conclusion

Showed that the proposed detector performances (efficiency and timing) are achievable

Extensive Studies:

- Fiber and SiPM Characterization
- Optical Isolation
- Fiber alignment, mechanics
- Light yield (straight and inclined tracks)
- Single and multilayer detection efficiencies
- Single and multilayer timing
- Extrapolated detection efficiencies and timing
- Temperature studies
- Detection efficiency vs. impact position