Scintillating Fiber Detector R&D for cLFV Experiments

Giada

LTP Seminar

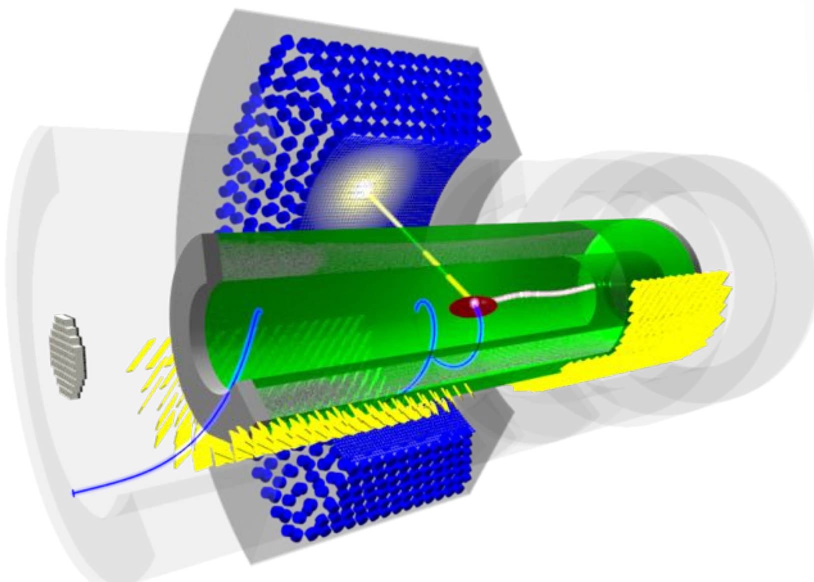
May 8th 2017

SciFis for cLFV Experiments

MEG II

$\mu^+ \rightarrow e^+ \gamma$

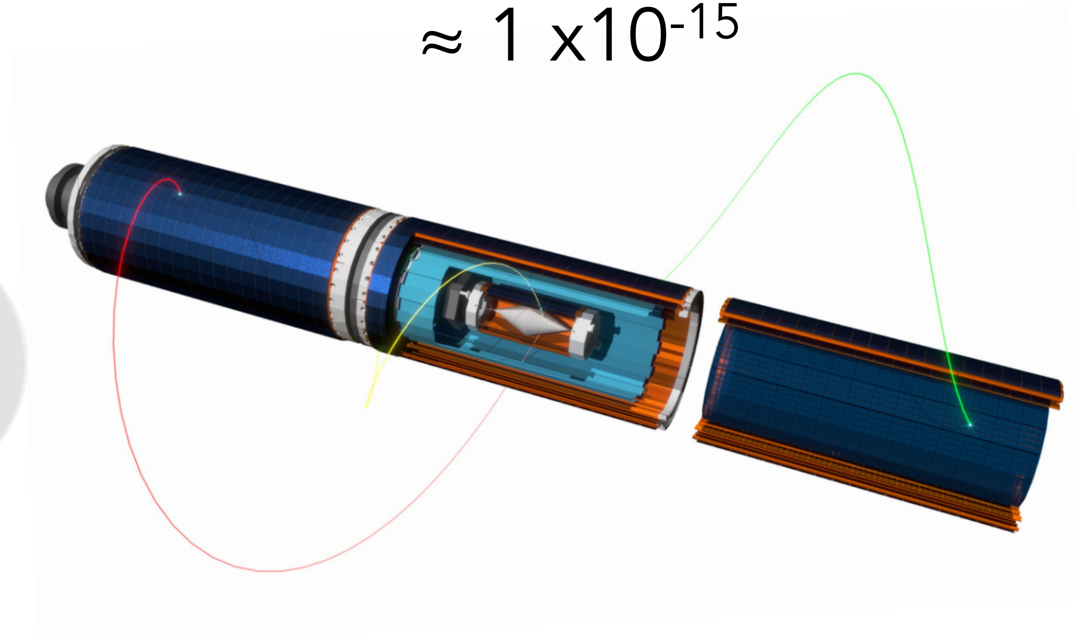
Sensitivity Goal
$\approx 4 \times 10^{-14}$



Mu3e (Phase I)

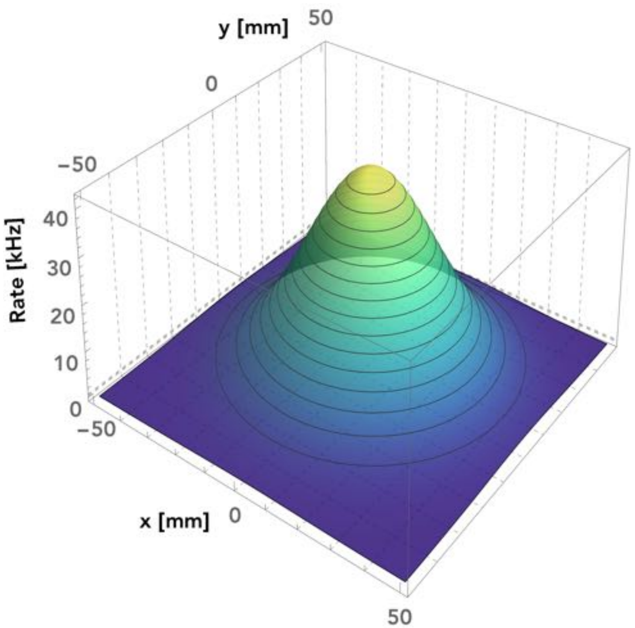
$\mu^+ \rightarrow e^+ e^- e^+$

Sensitivity Goal
$\approx 1 \times 10^{-15}$



SciFis for cLFV Experiments

Beam Monitoring



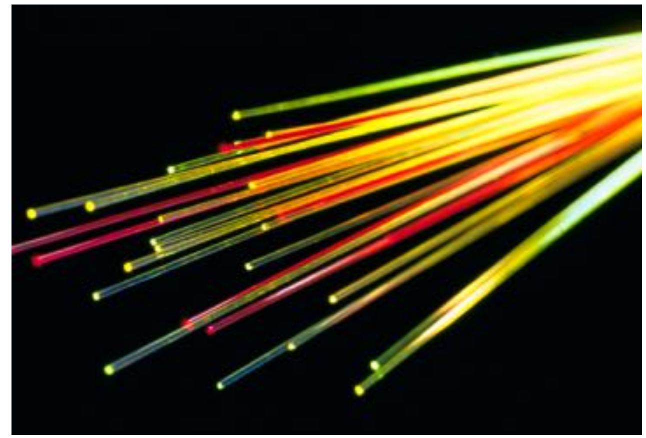
Particle Timing

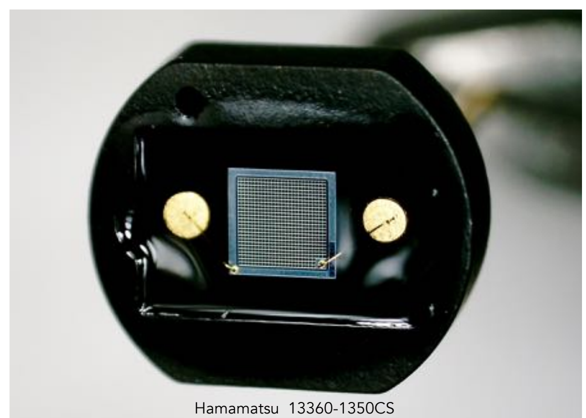
Particle Tracking

SciFis for cLFV Experiments

Why scintillating fibers + Silicon PhotoMultipliers?

- Fast (good time resolution)
- Fast (sustain high rates)
- Little material budget
- Compatible with magnetic fields
- Compatible with vacuum
- Modular, versatile
- Low cost technology



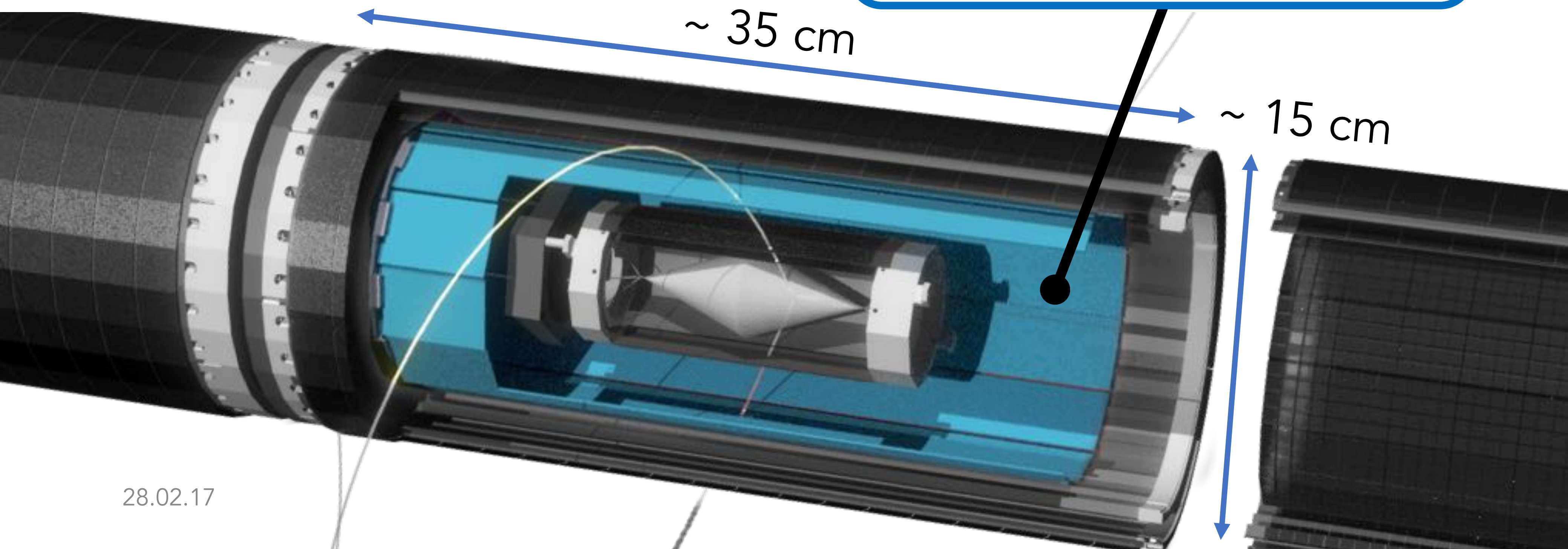


Particle Timing and Tracking (Mu3e)

Mu3e Experiment Phase I

Sensitivity Goal
$\approx 1 \times 10^{-15}$

Scintillating Fiber Detector
Suppress accidental background by a factor **~100** (together with the tile detector)



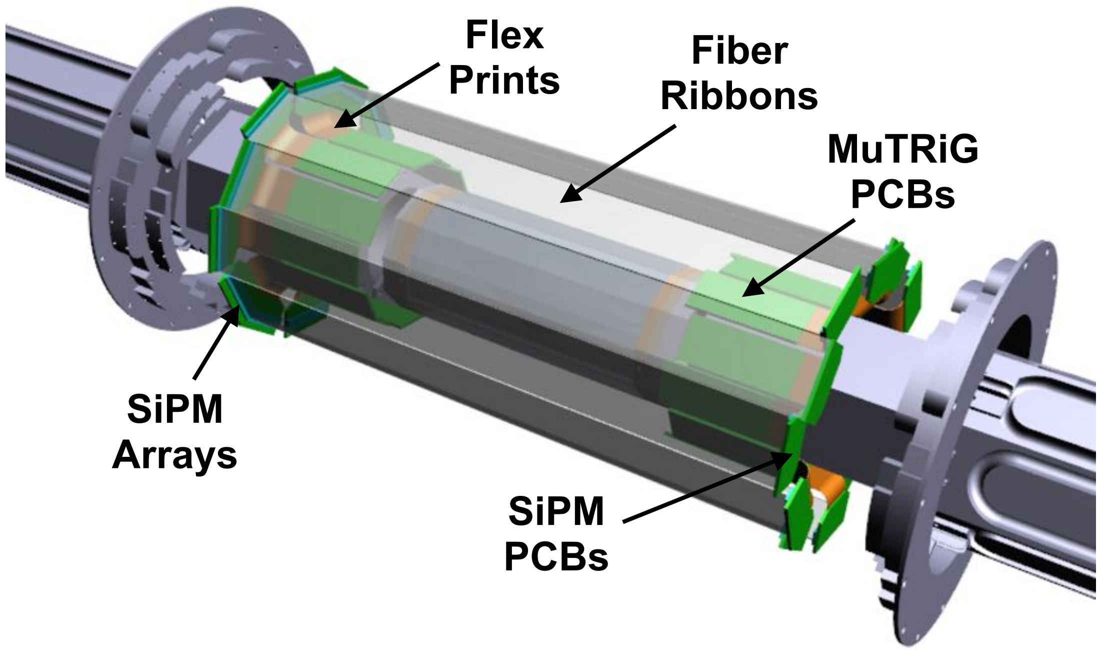
Scintillating Fiber Detector

Requirements:

- Timing resolution < 1 ns
- Detection efficiency ~100 %
- As little material as possible
- Comply with space constraints

Baseline design:

- Ribbons of scintillating plastic fibers of 250 μm thickness (12 modules à 3 layers = 4600 fibers)
- Silicon Photomultiplier (SiPM) arrays readout



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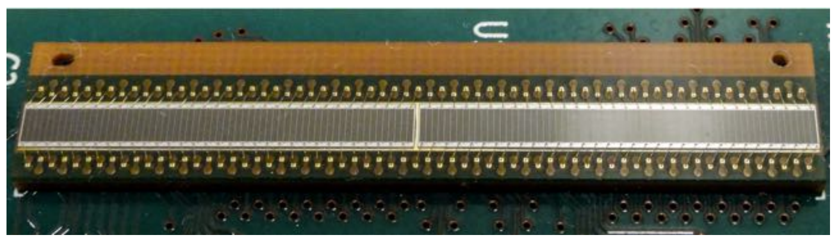

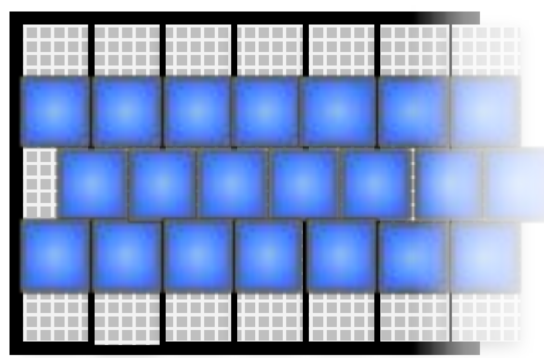

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Not trivial…

expected energy deposit (MIP)

≅

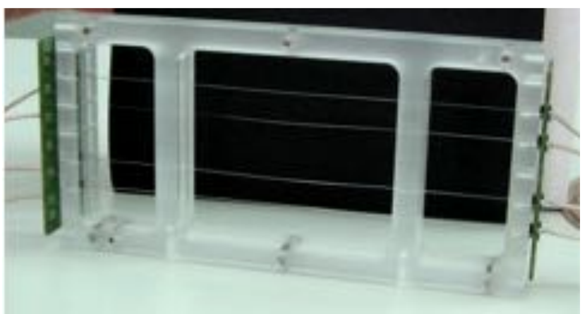
handful detected photons per 250 μm fiber!

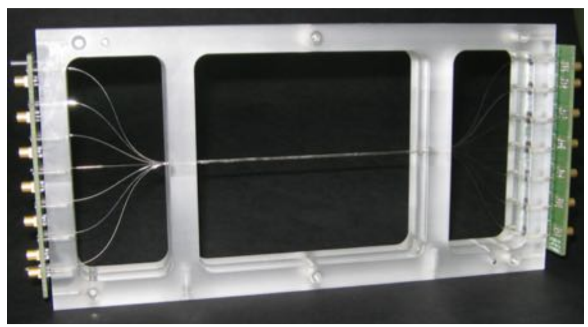
R&D History

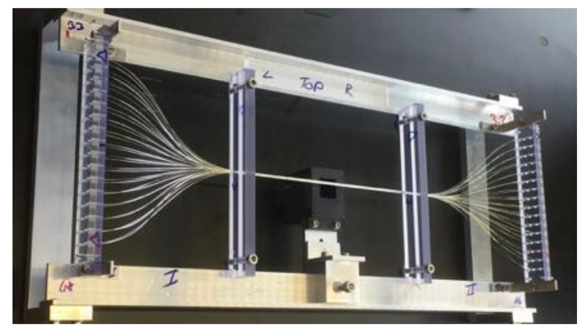
Bottom-up-approach

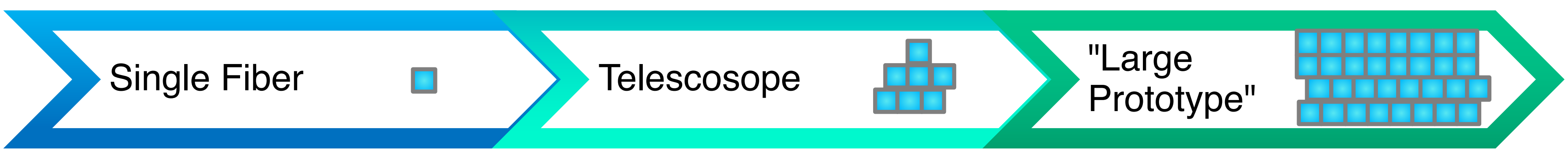
Single fiber ➠ telescope structures

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



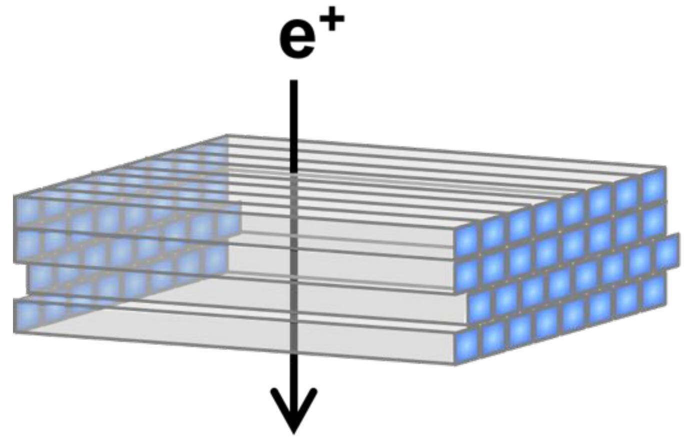


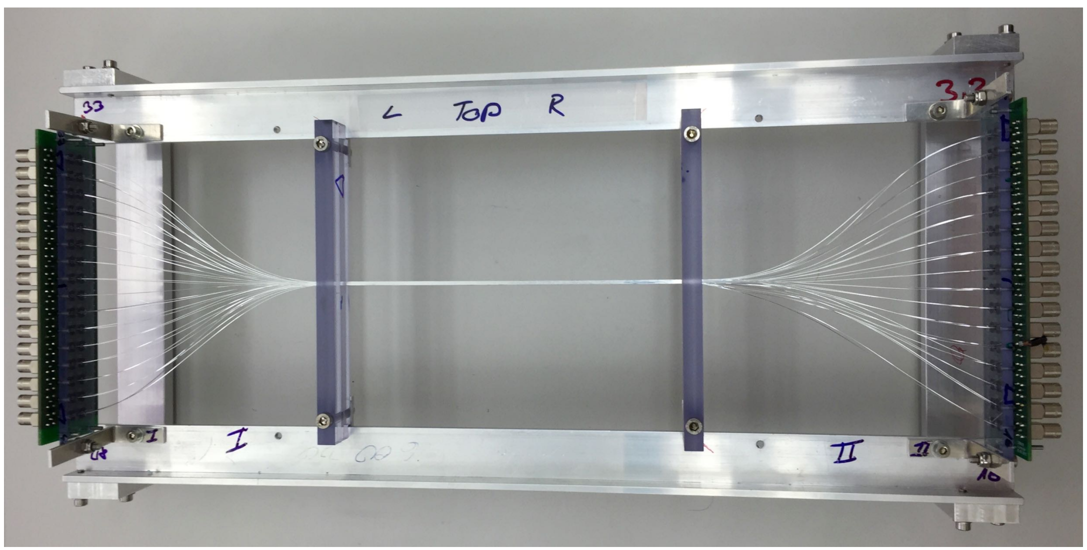




The Large Prototype

Asses **single- and multilayer efficiencies and timing resolutions,** and combine channels offline to **emulate the SiPM array readout**



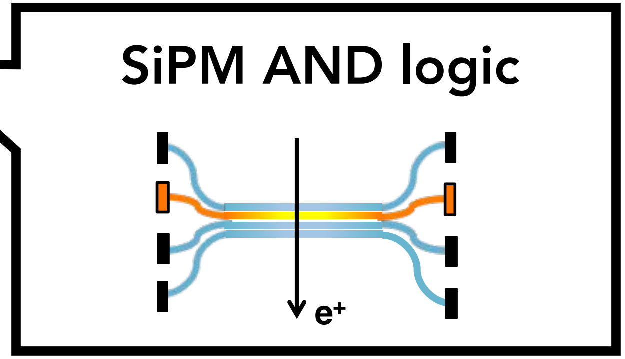


Key Features

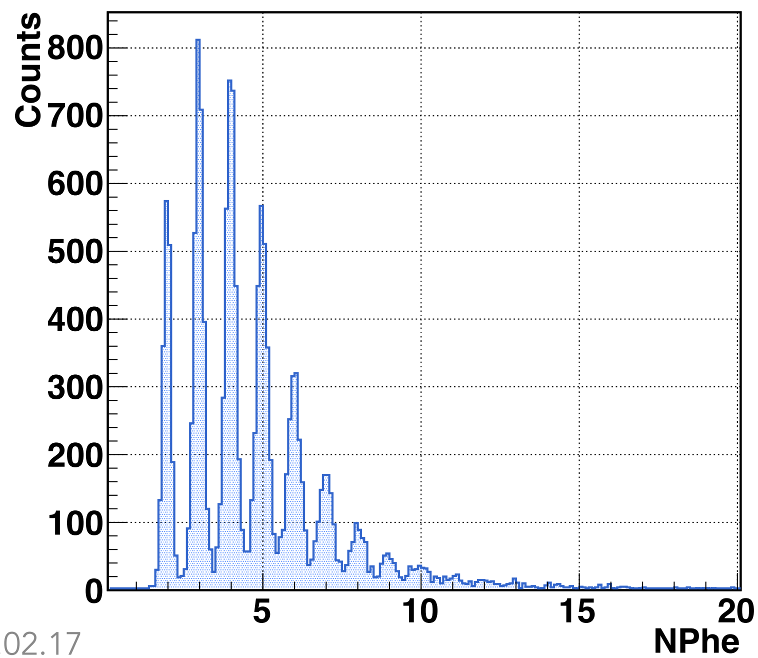
- 32 squared, 250 µm thin multiclad fibers with individual readout on both ends
- Aligned SiPMs
- Aluminum coating (100 nm)

Single Fiber – Beam Test @ πM1

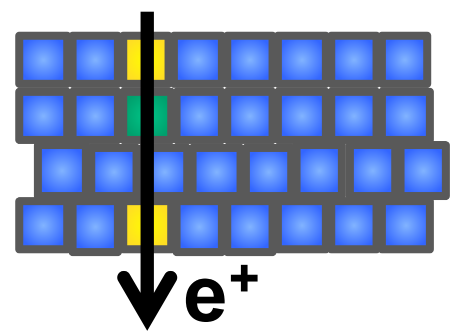
For MIP (threshold 0.5 $N_{phe,}$ AND):
Mean $\mathbf{N_{Phe}} \approx$ **4.6**



Light Yield



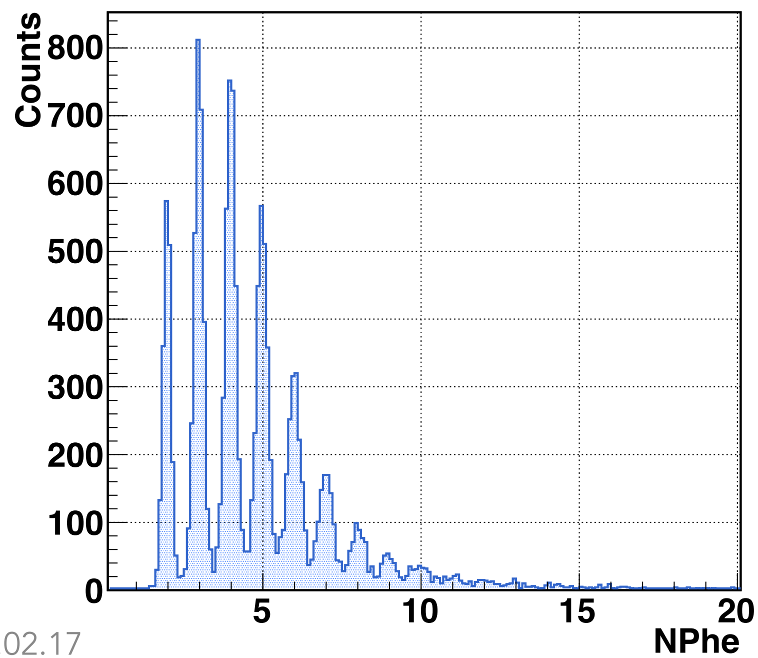
Positrons @ 115 MeV/c momentum (straight tracks)



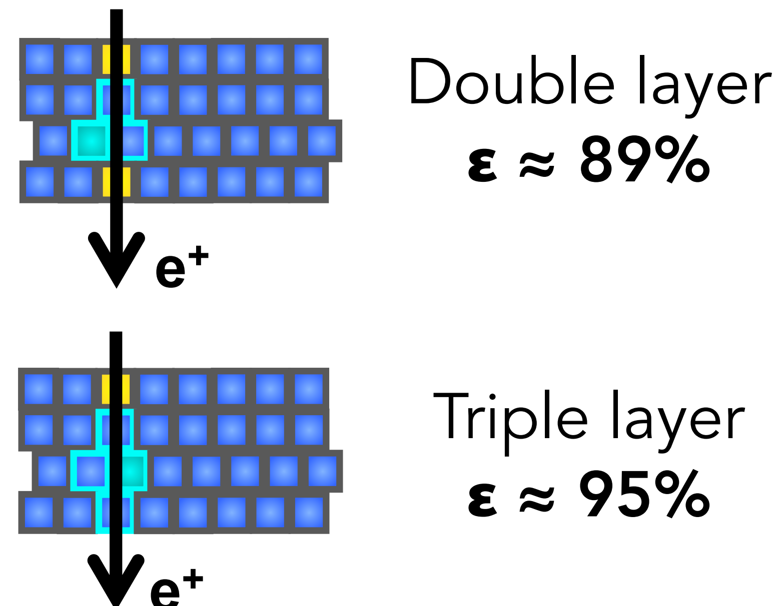
Single Fiber – Beam Test @ πM1

For MIP (threshold 0.5 $N_{phe,}$ AND):
Mean $\mathbf{N_{Phe}}$ **≈ 4.6**
Detection efficiency **ε ≈ 72%**

Light Yield



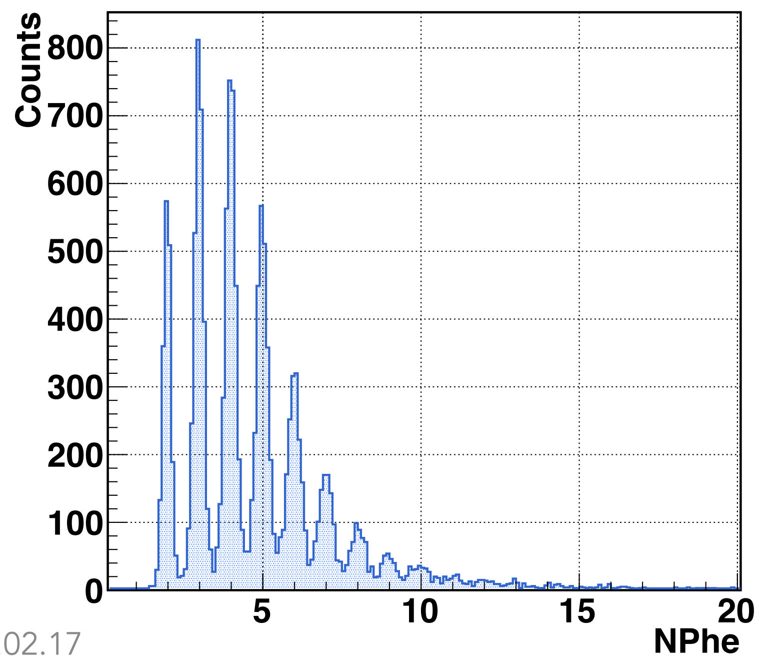
Multilayer detection efficiency



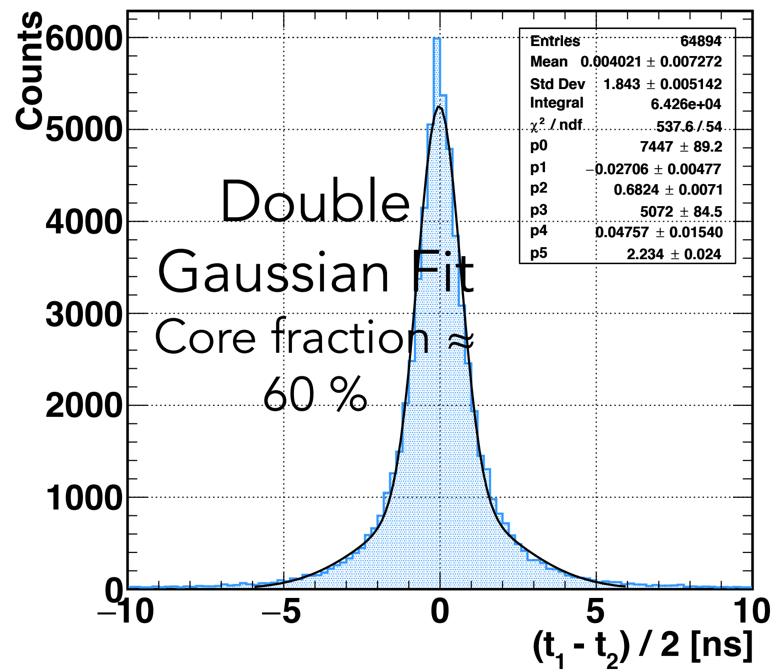
Single Fiber – Beam Test @ πM1

For MIP (threshold 0.5 $N_{phe,}$ AND):
Mean $\mathbf{N_{Phe}}$ **≈ 4.6**
Detection efficiency **ε ≈ 72%**
Timing resolution $\boldsymbol{\sigma_T^{core}}$ **≈ 680 ps**

Light Yield



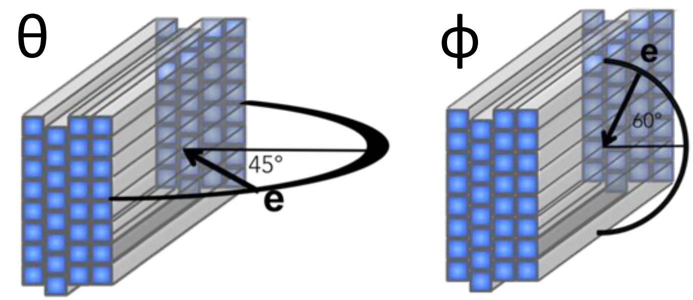
Timing Spectrum



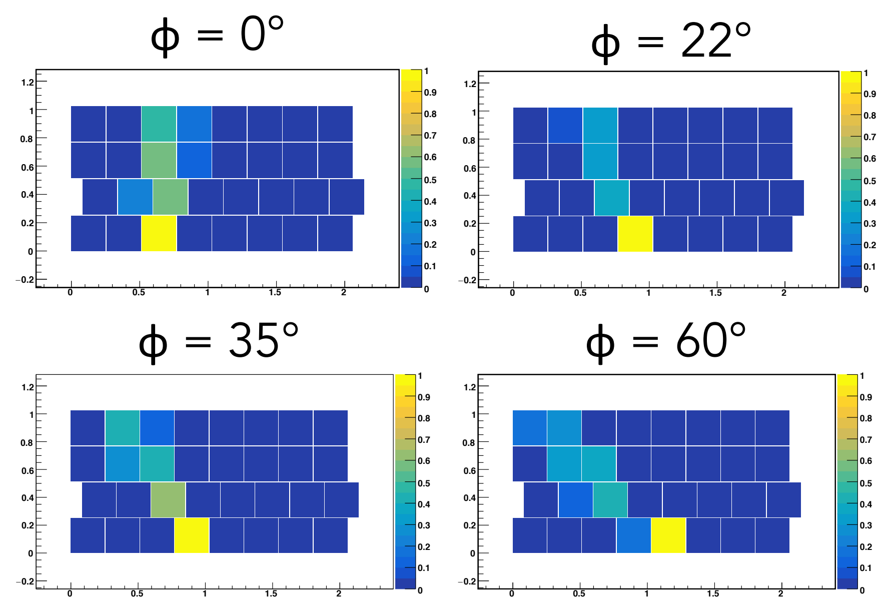
Inclined Tracks

Sr90 Laboratory Measurement

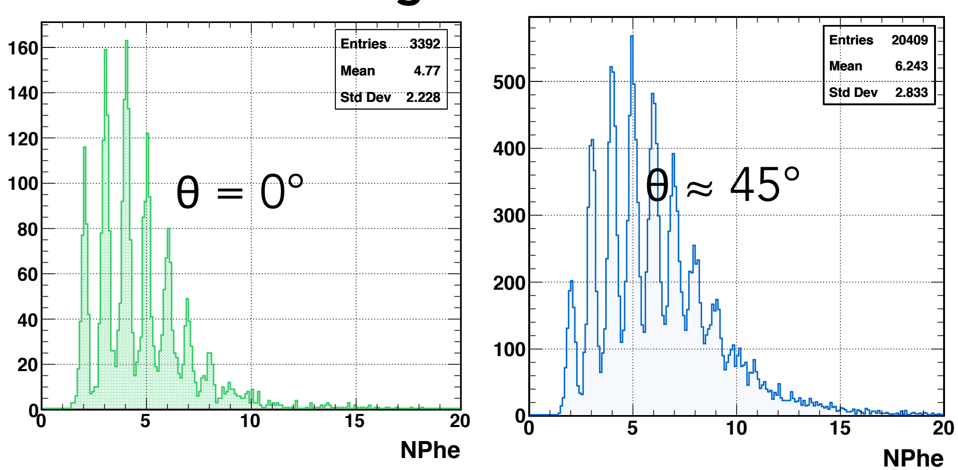
Increased light yield / inclination of tracks clearly visible and consistent with expectations



Phi Angle Measurements



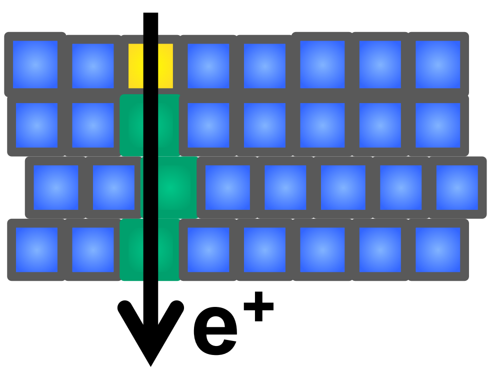
Theta Angle Measurements



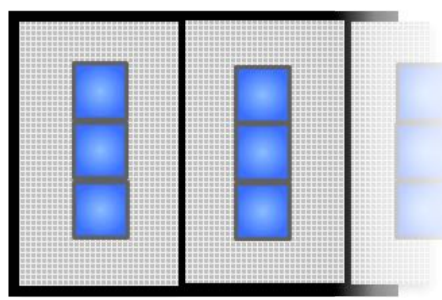
Extrapolation to Final Mu3e Hodoscope Performances

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

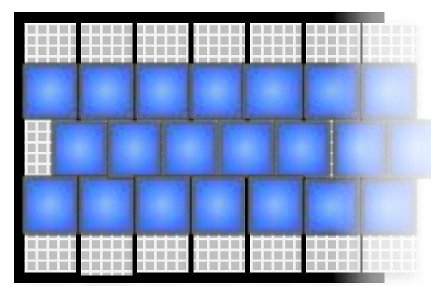
≙ "optimized" array readout



ideal



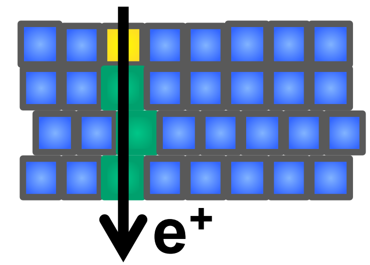
real



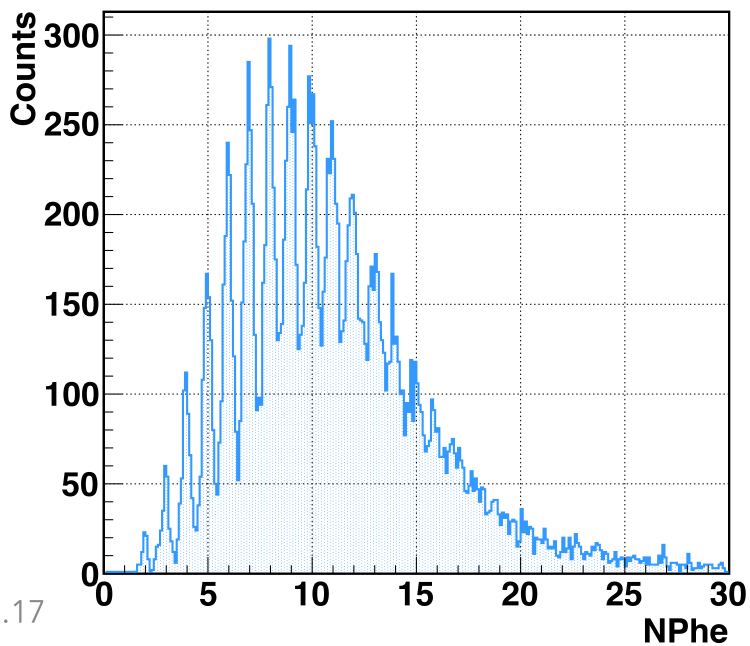
Optimized Array – Beam Test @ πM1

For MIP (threshold 0.5 $N_{phe,}$ AND):
Mean $\mathbf{N_{Phe}} \approx$ **10.9**
Detection efficiency $\boldsymbol{\varepsilon} \gtrsim$ **95%**
Timing resolution $\boldsymbol{\sigma_t}^{\mathbf{core}} \approx$ **570 ps**

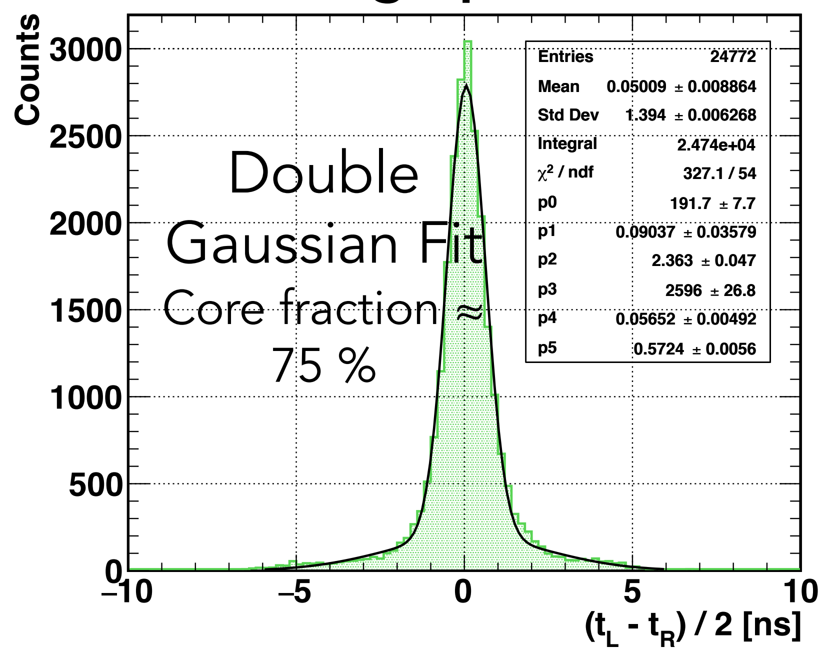
Positrons @ 115 MeV/c momentum



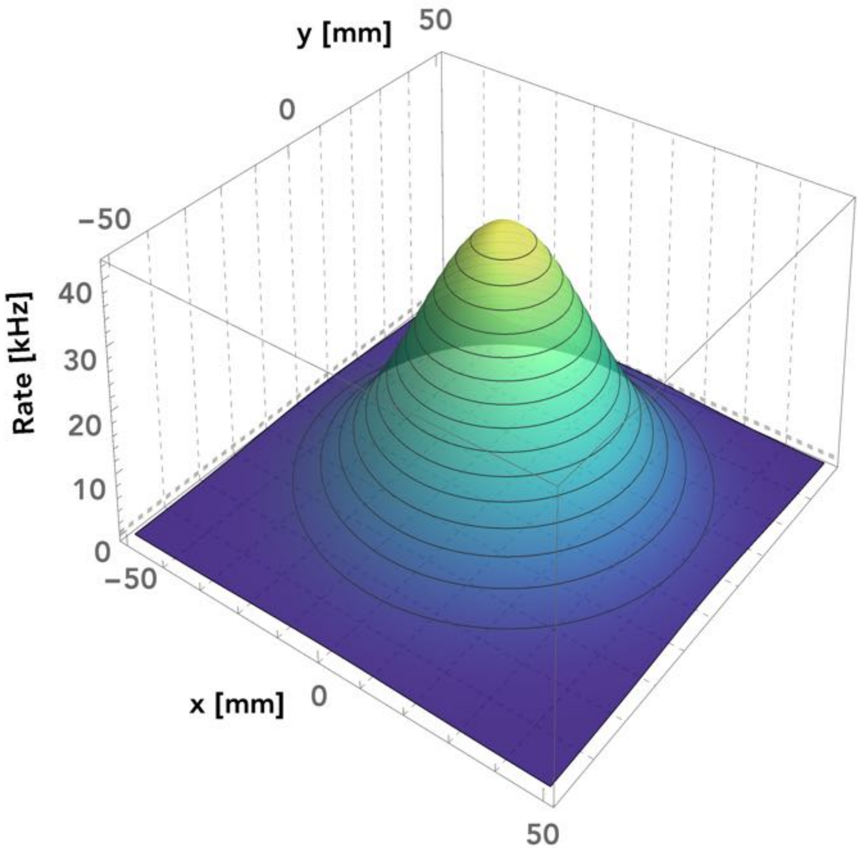
Light Yield



Timing Spectrum



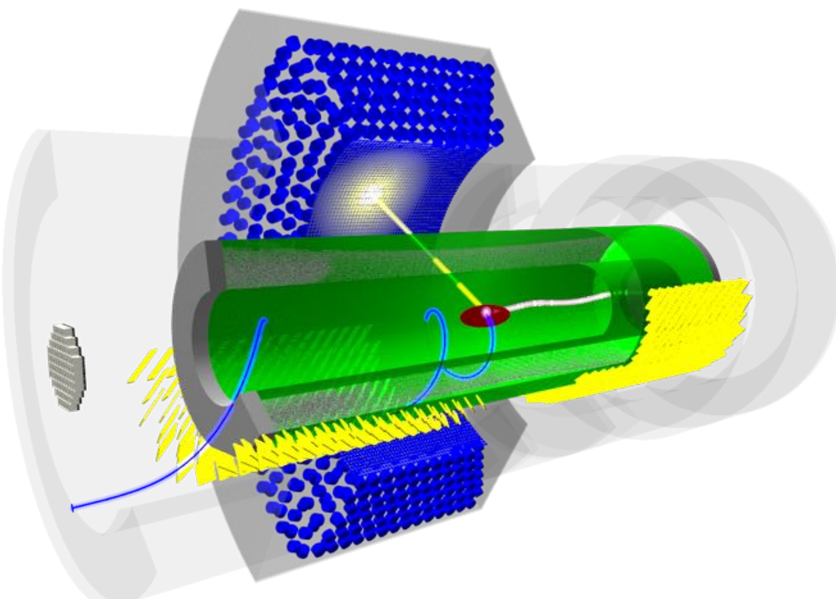
Beam Monitoring (MEGII and Mu3e)



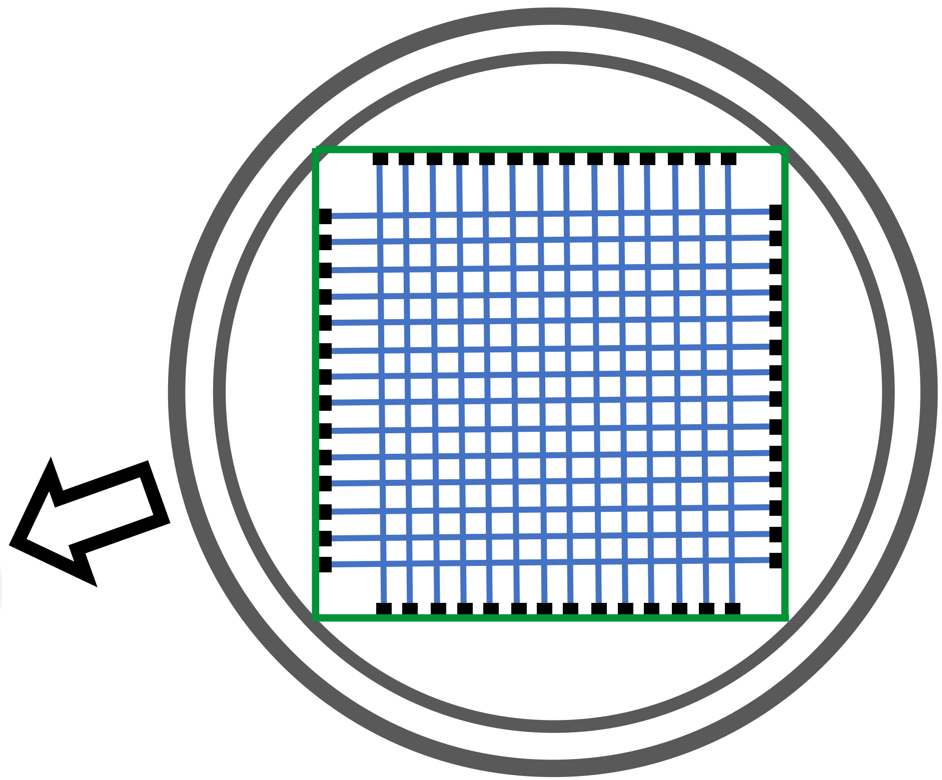
Scintillating Fiber Beam Monitor

Properties

- Fast
- Minimally invasive
- Capable of particle identification
- Compatible with magnetic fields
- Compatible with vacuum



"Rate Counter"

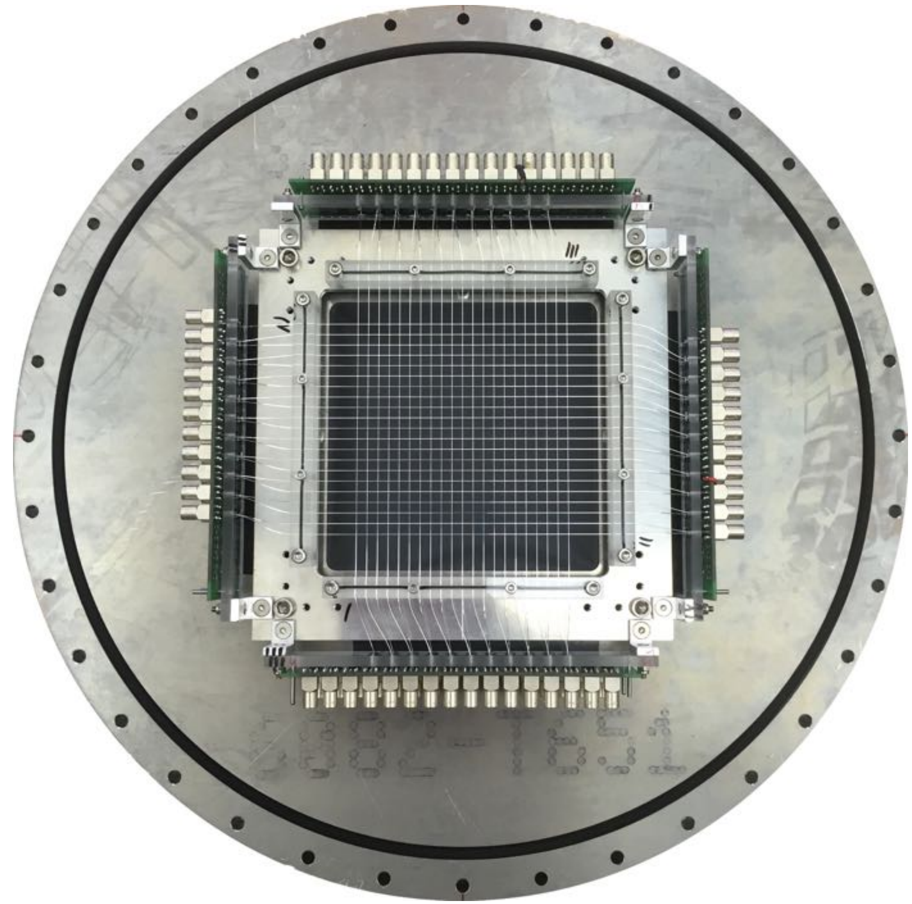


Measure muon beam size and rates also during normal MEG operation

Scintillating Fiber Beam Monitor

Properties

- Fast
- Minimally invasive
- Capable of particle identification
- Compatible with magnetic fields
- Compatible with vacuum

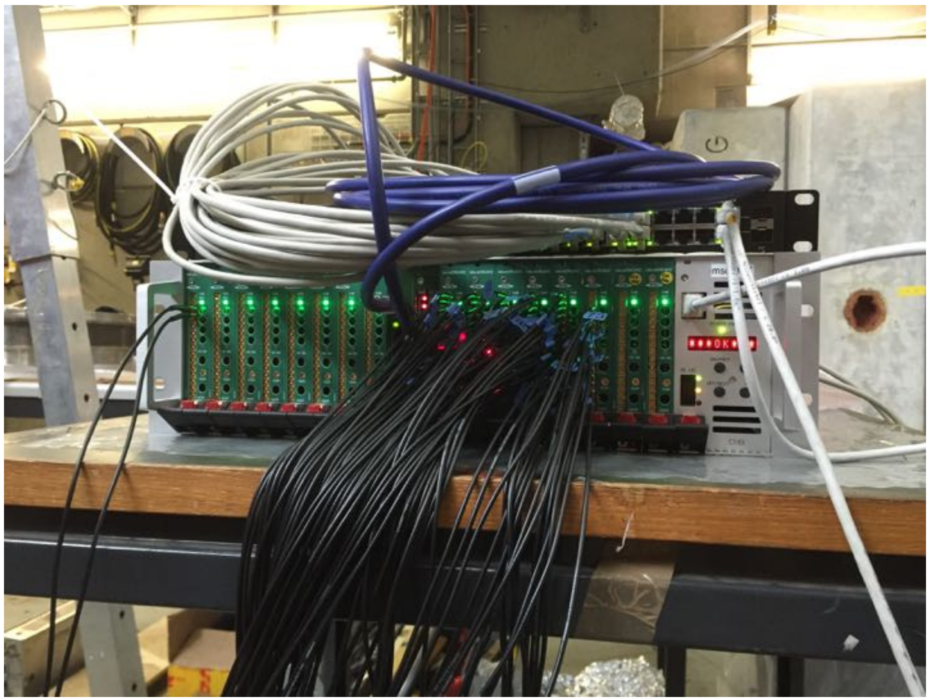


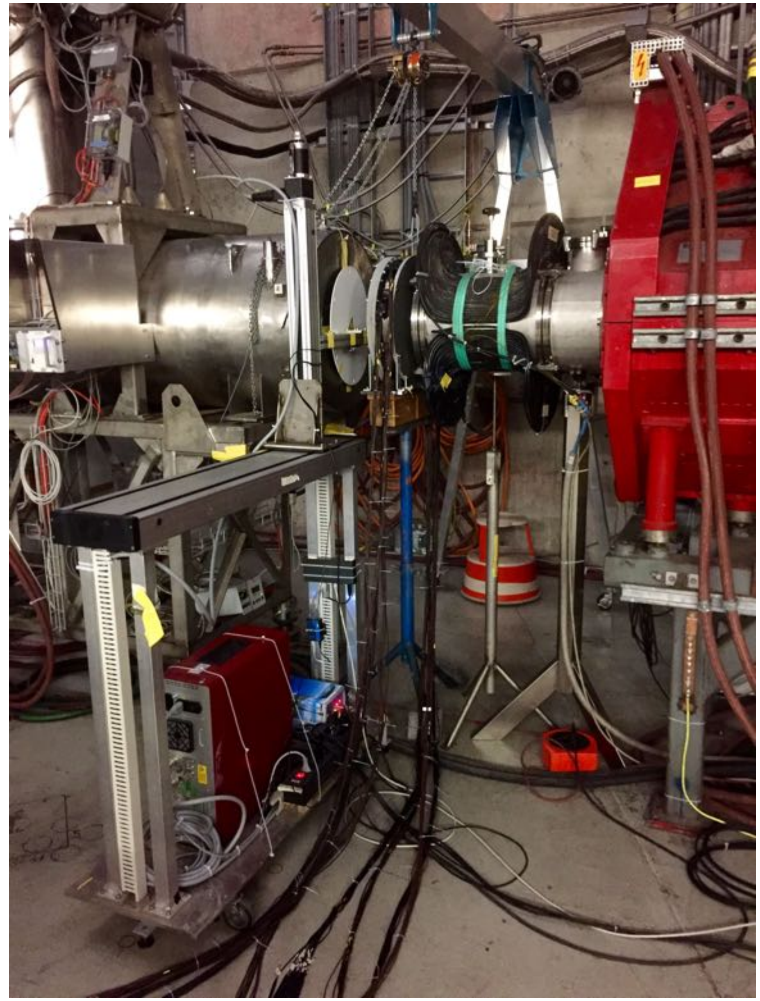
Detector Prototype

- 42 squared, 250 µm thin multiclad fibers with individual readout on both ends ➔ **84 channels**
- Aligned SiPMs
- Aluminum coating (100 nm)
- **Two grid layers (x,y)**
- Active area: 10 x 10 cm^2
- Pitch: 5 mm

Test in πE5 (MEG Beam Line)

Muon beam @ 28 MeV/c momentum
Beam rate $1.2 \times 10^{8}\ \mu^{+}/s$ (@ 2.2 mA)
MEG II prototype electronics





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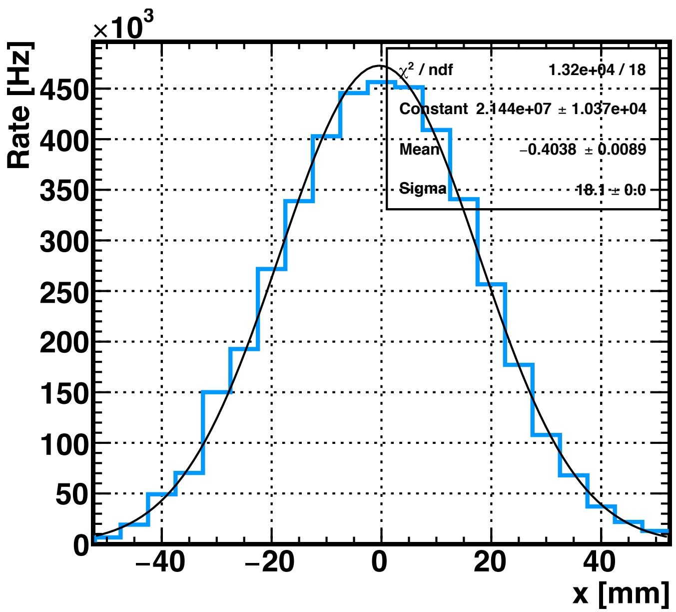
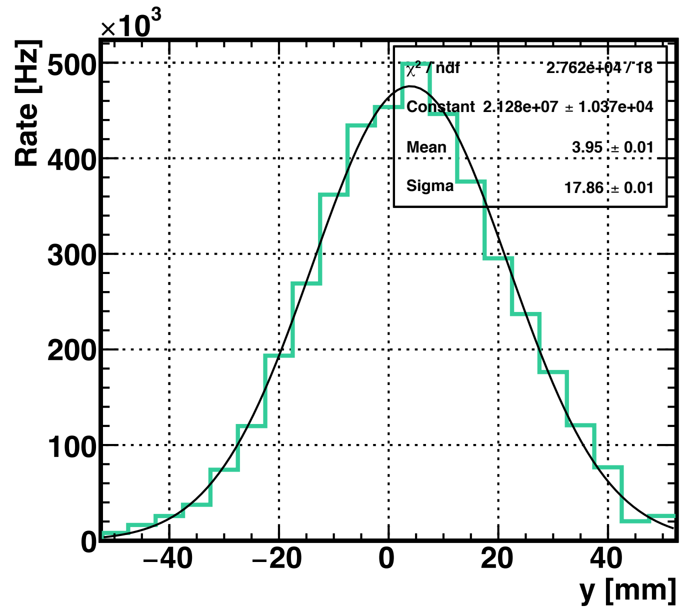
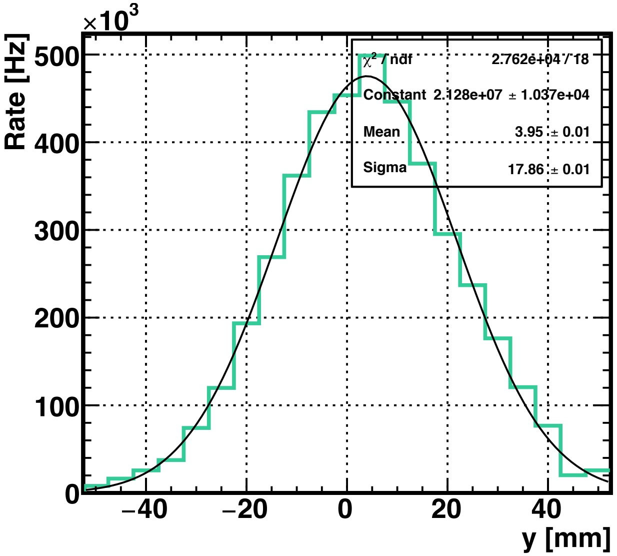




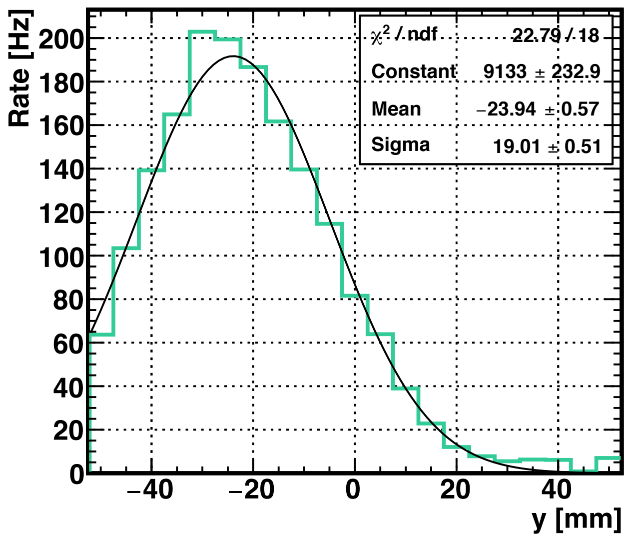
Beam sizes and rates consistent with standard beam monitoring tool

Playing Around With the Beam

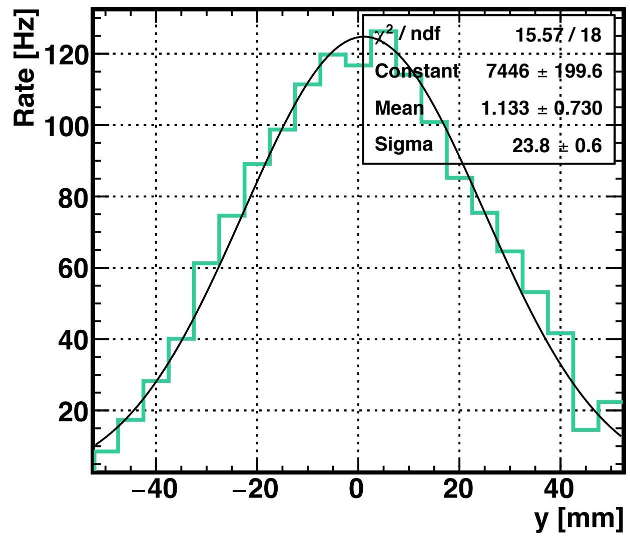
Standard



Shifted

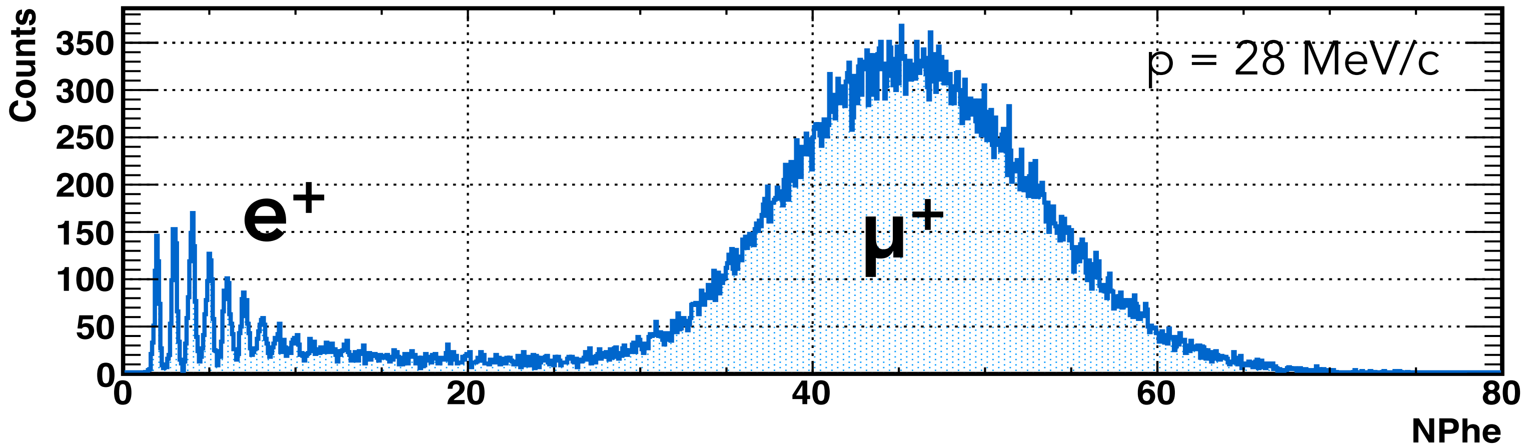


Defocused



Particle Identification

Discrimination by Charge



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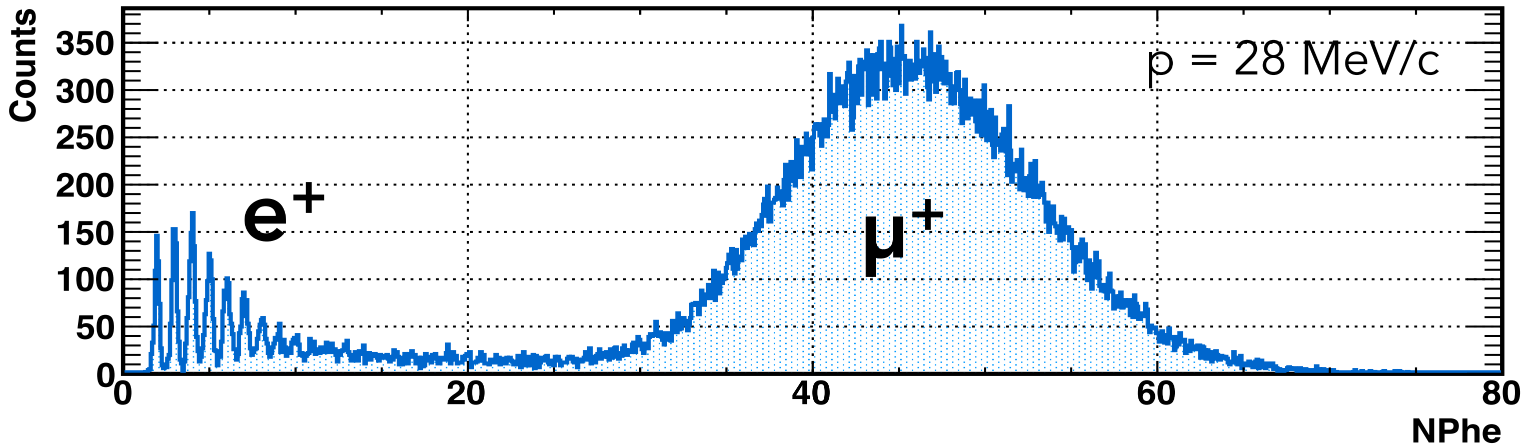
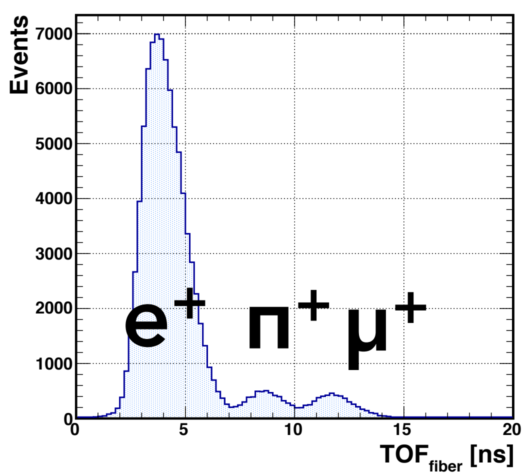
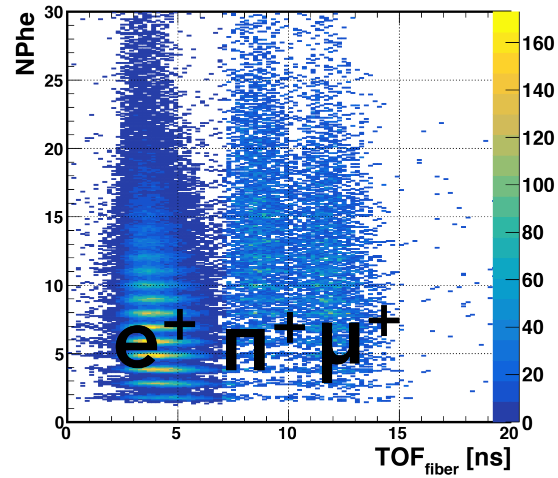


Discrimination by Time-Of-Flight

p = 115 MeV/c





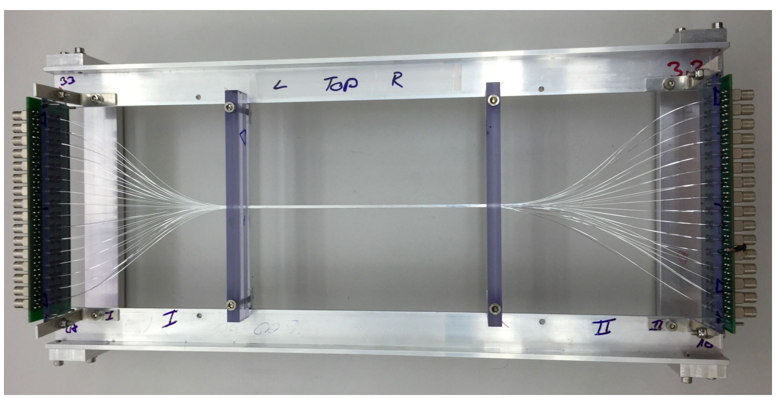
Conclusion

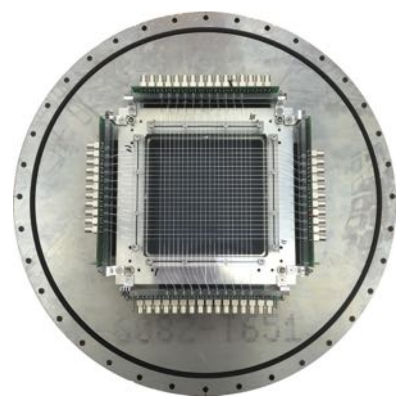
Measurements with the Large Prototype have shown that the required Mu3e detector performances can be met

Three layers of 250 µm thin, squared, multiclad fibers provide < 1 ns timing resolution at a high detection efficiency

Successful construction of a full beam monitor prototype

Minimally invasive grid of 250 µm thin, squared, multiclad fibers provides a fast rate and size measurement of high rate beams and is capable of particle identification

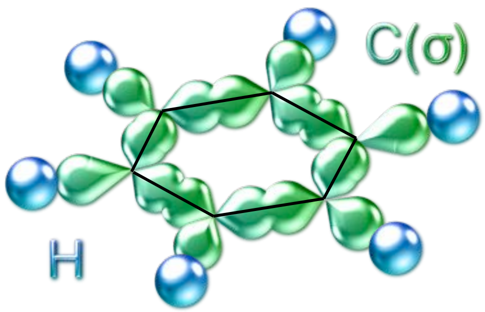


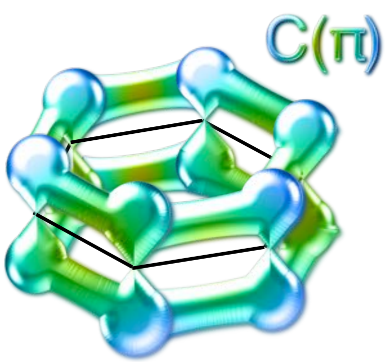


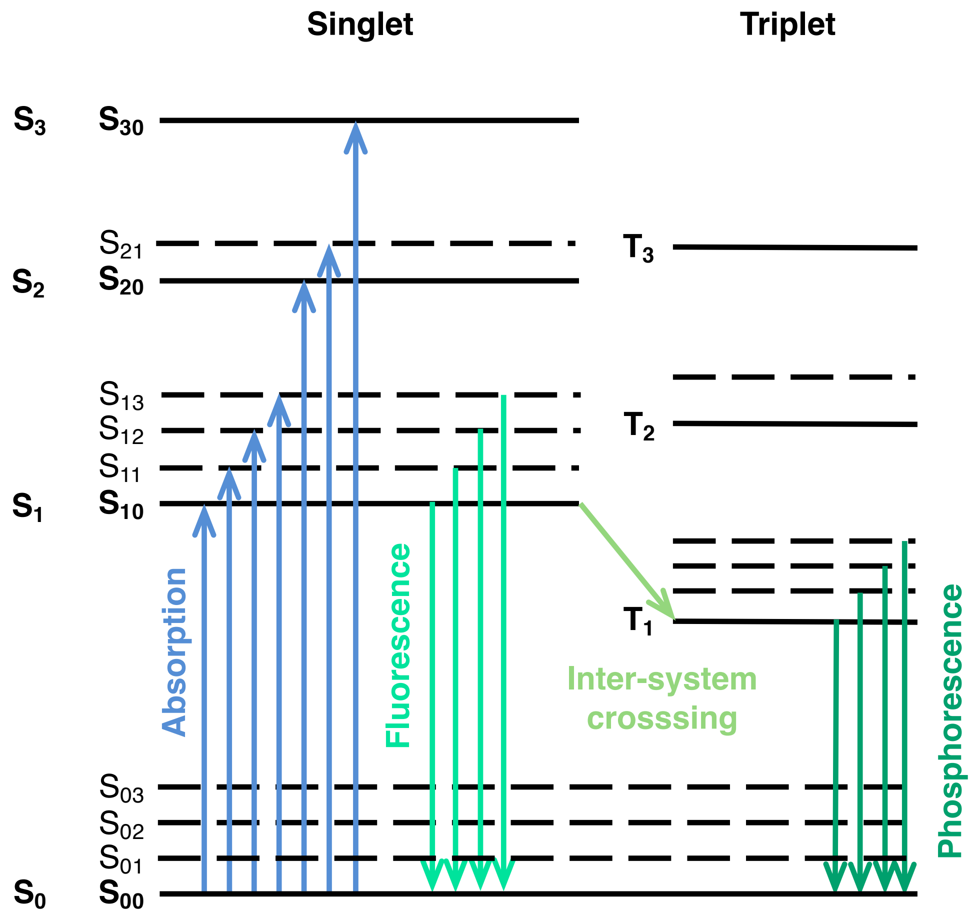
Thank you for your attention

Backup

Scintillation Mechanism

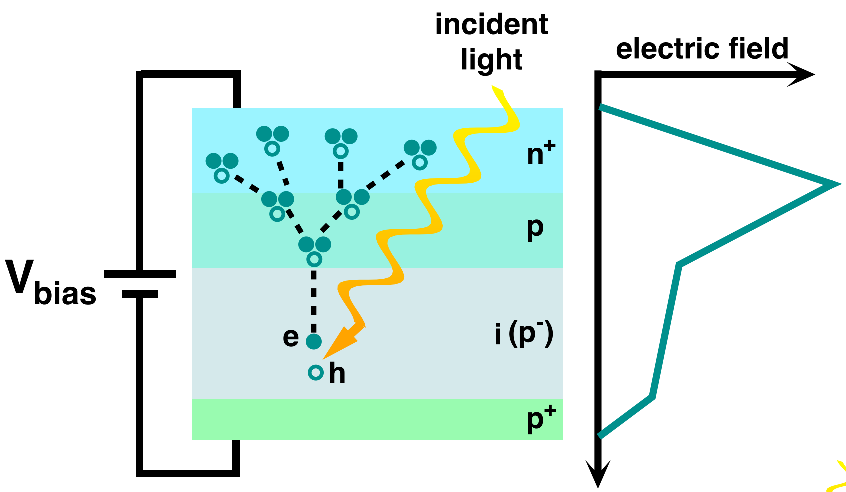




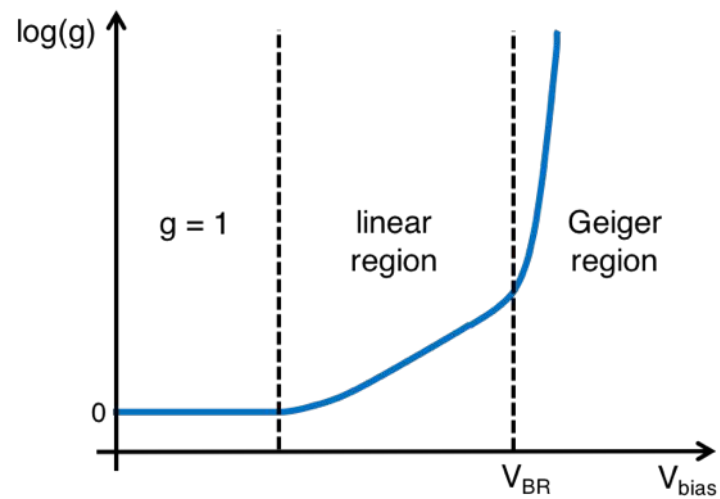


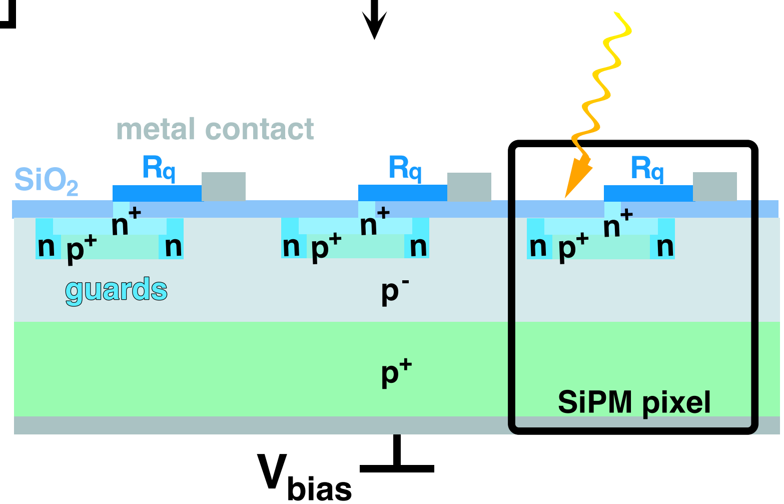
Silicon Photomultiplier

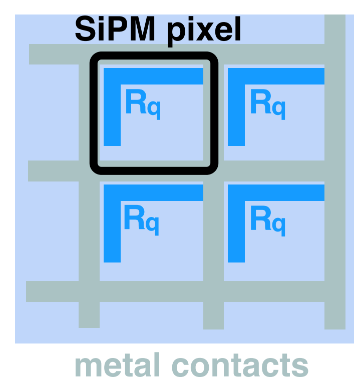
APD



Gain vs. V_{bias}

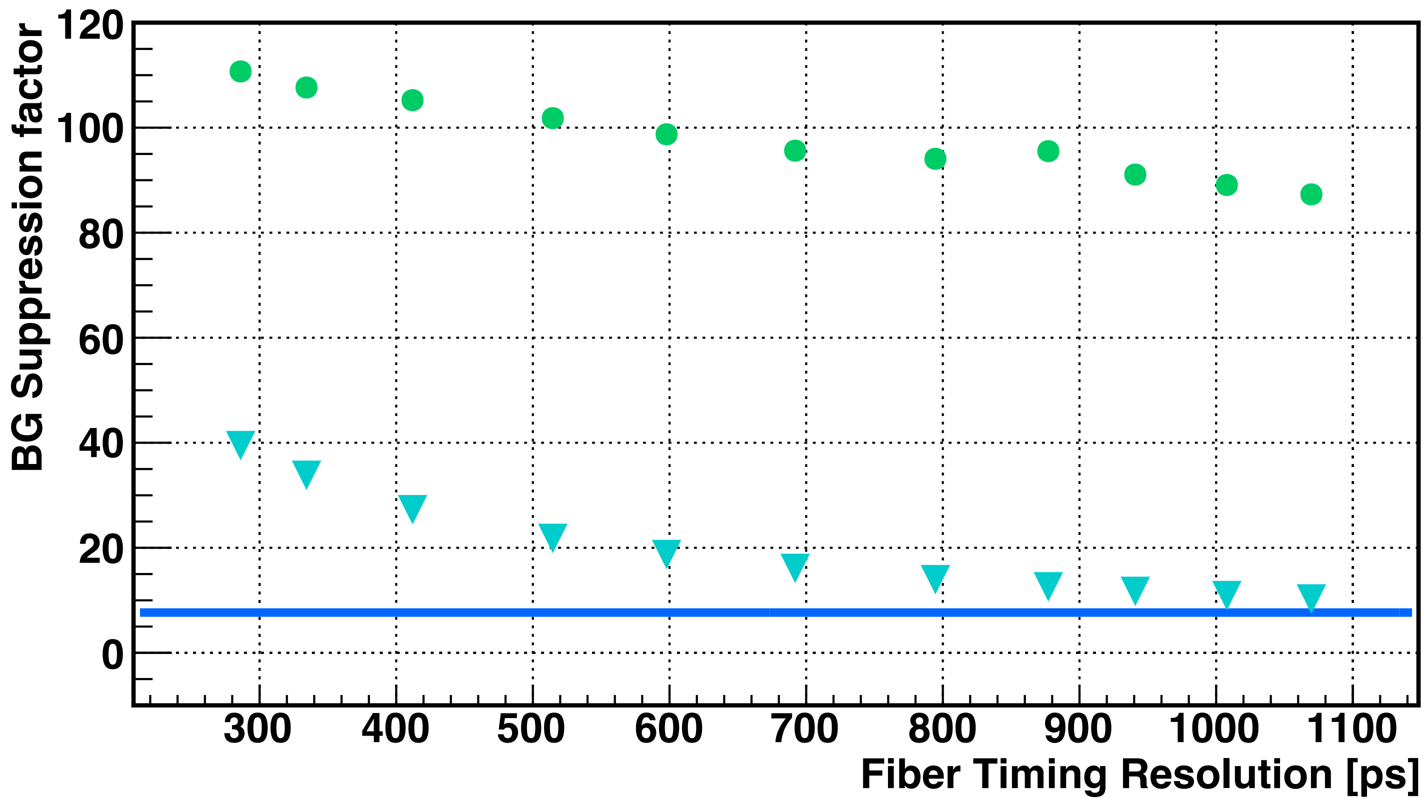






Scintillating Fiber Detector

BG suppression factor of accidental overlap Michel positron – Bhabha pair (dominant contribution)

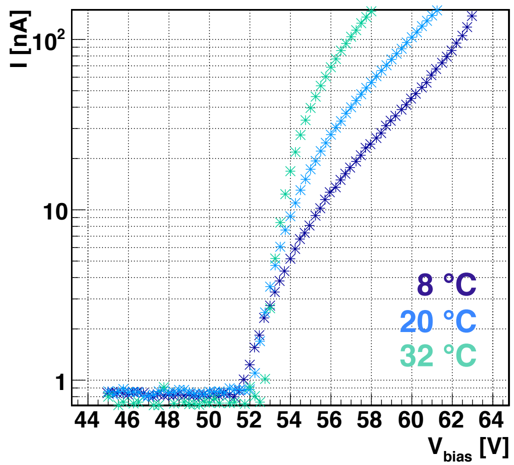


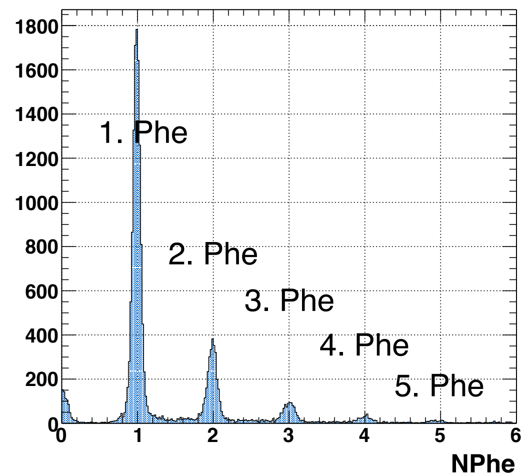
Fibers + tiles

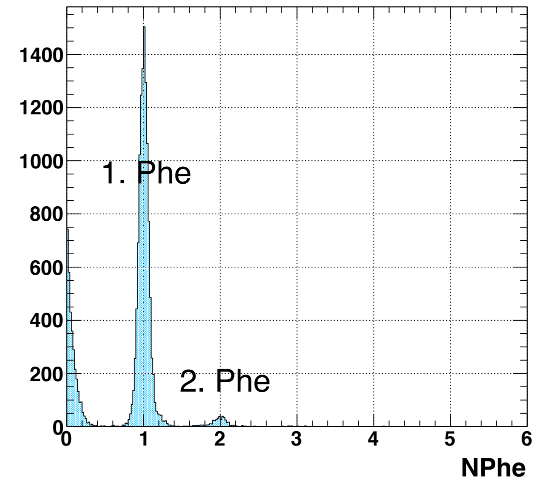
Fibers alone

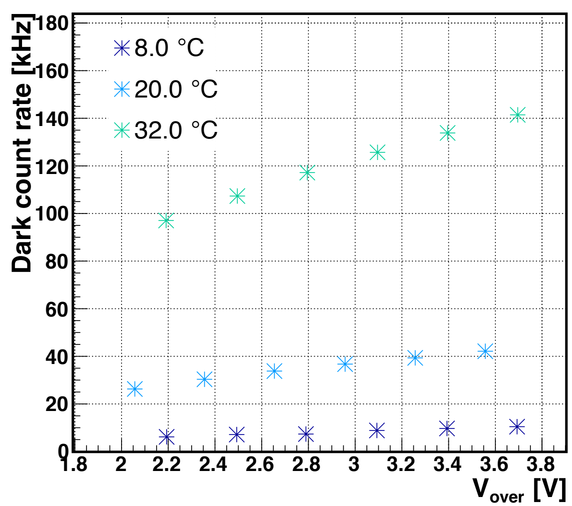
Tiles alone

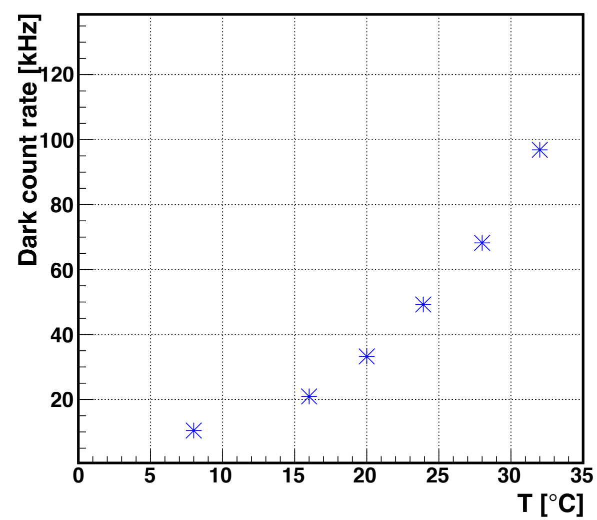
SiPM Characterization











The Challenge

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

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

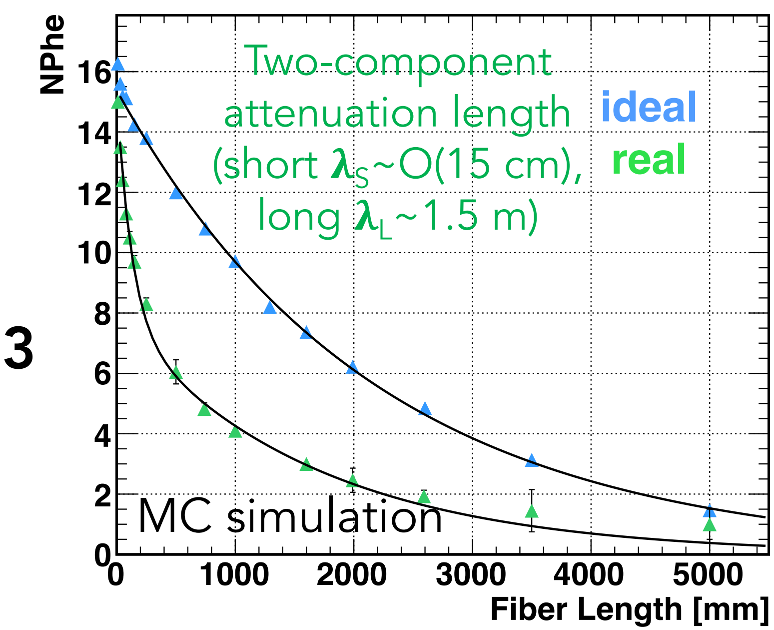
Transmission term <T>

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

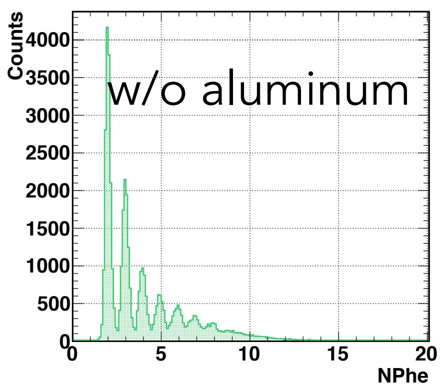
Ingredients for maximum performance (from our experience):

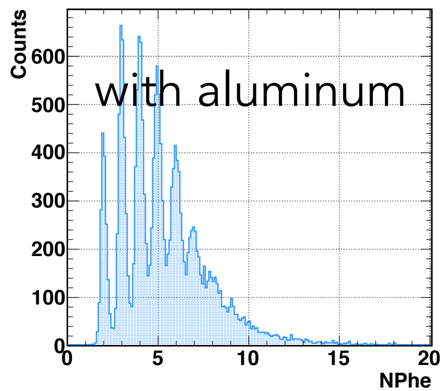
- Fiber end polishing
- Optical isolation of the fiber
- Good fiber-SiPM-alignment

Optical Isolation

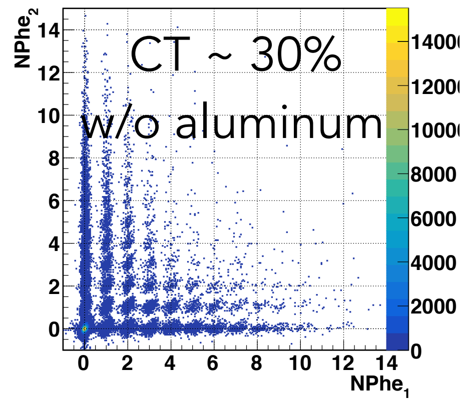
Fibers w/o optical isolation are subject to substantial light losses and fiber crosstalk

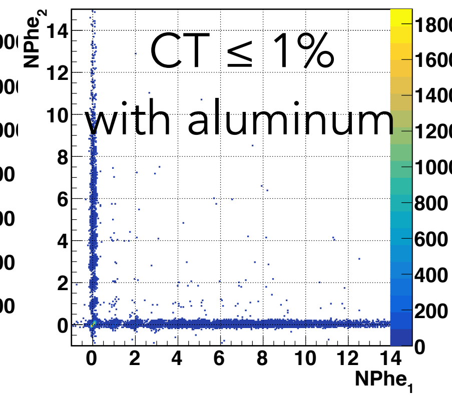
Light yield (Sr90 measurements)





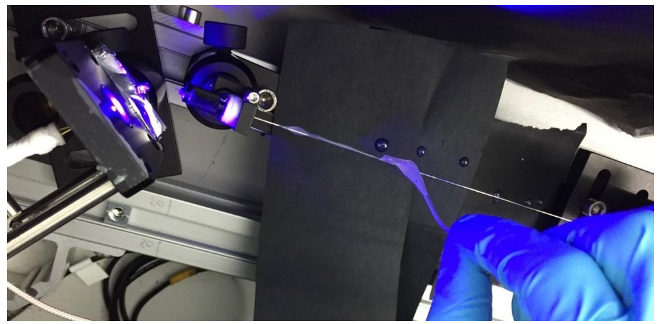
Fiber crosstalk (Sr90 measurements)





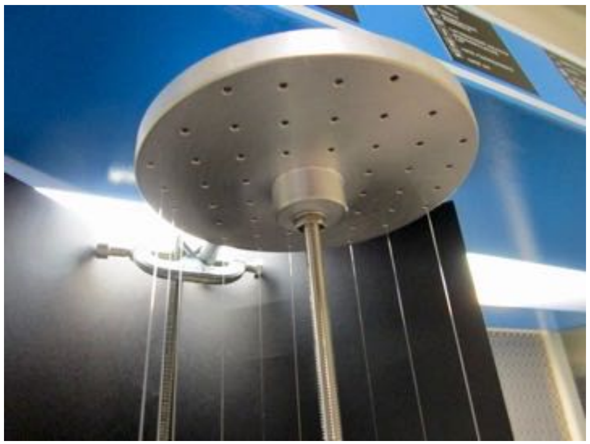
"In situ" light loss measurements

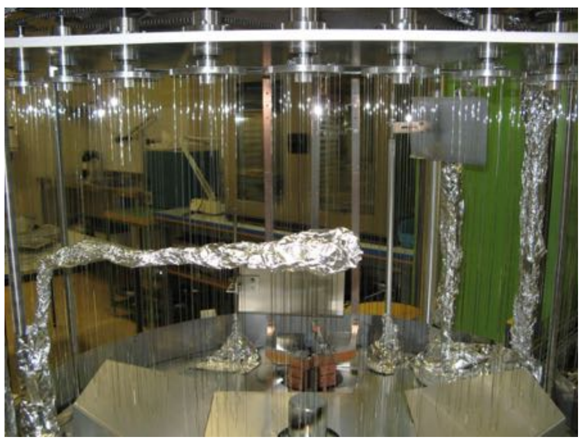
Material	n	Light loss bare	Light loss alum.
Optical cement (BC600)	1.56	40 %	≤ 1 %
Araldite®	≈ 1.5	30 %	≤ 1 %
Optical grease (BC630)	1.47	20 %	≤ 1 %



Aluminum Coating

Physical Vapor Deposition





Sputtering

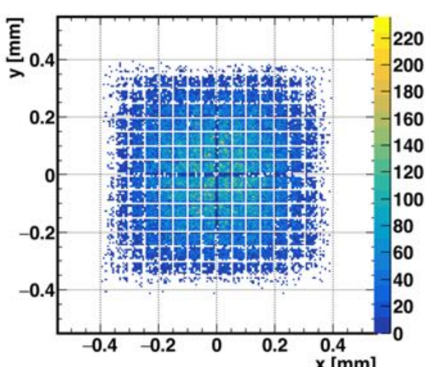
Fiber-SiPM Alignment

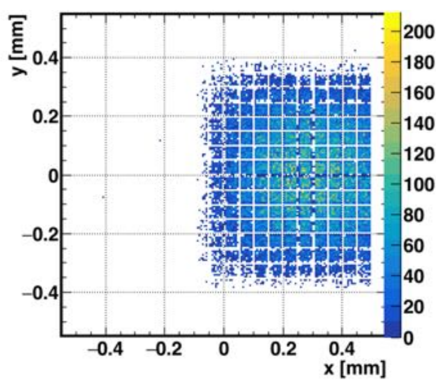
Aligned every individual SiPM on the PCB prior to soldering

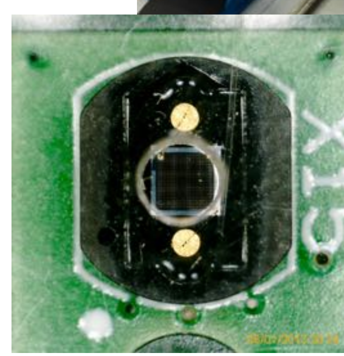
Overall alignment precision: 250-300 µm

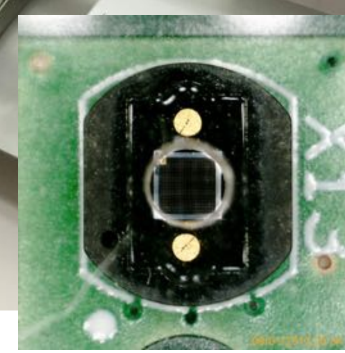
- Groove/ hole precision on plexiglass: 50-100 µm
- Precision Hole: 50 µm
- Pin holes on the SiPM PCB: 150 µm
- SiPM active area w.r.t. packaging: 200 µm

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





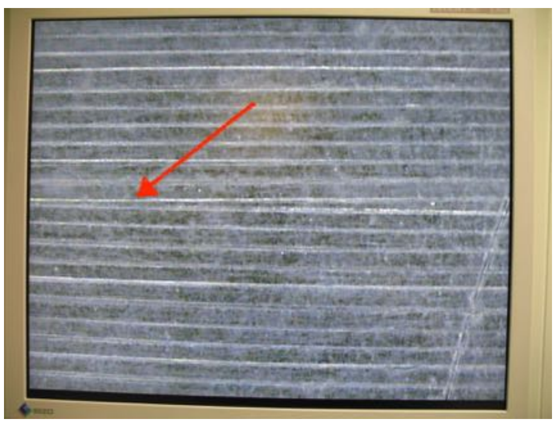


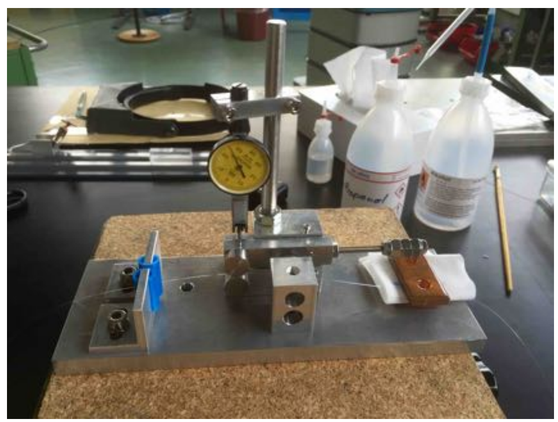


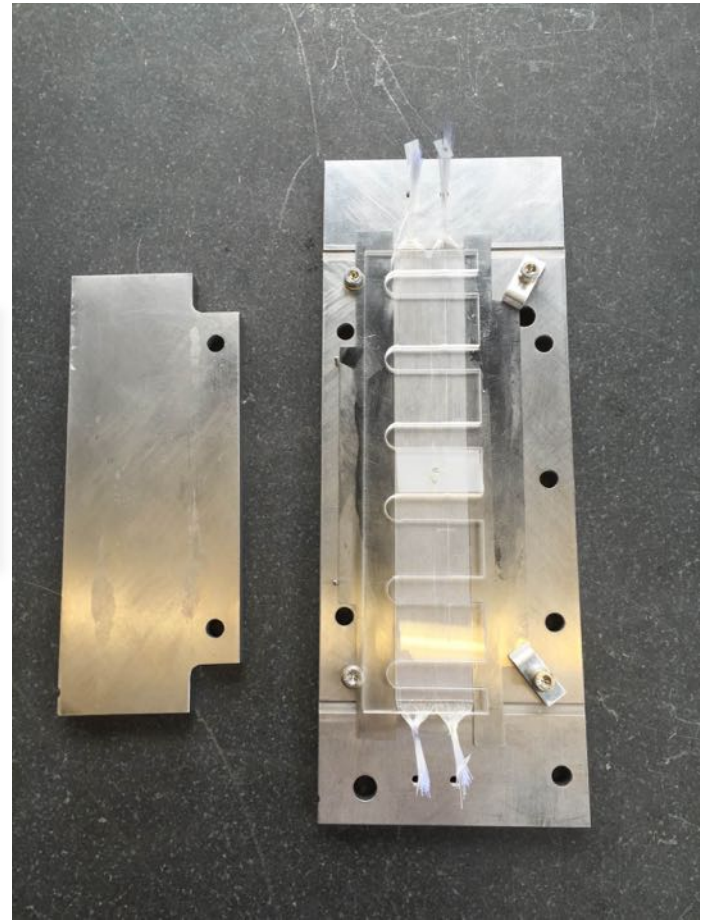
Squared Fiber Ribbons

- Quality control (blobs, thickness variations, cladding damage, …)
- Fiber size: 240 x 260 μm^2 → took special care about fiber orientation (240 μm along beam)

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





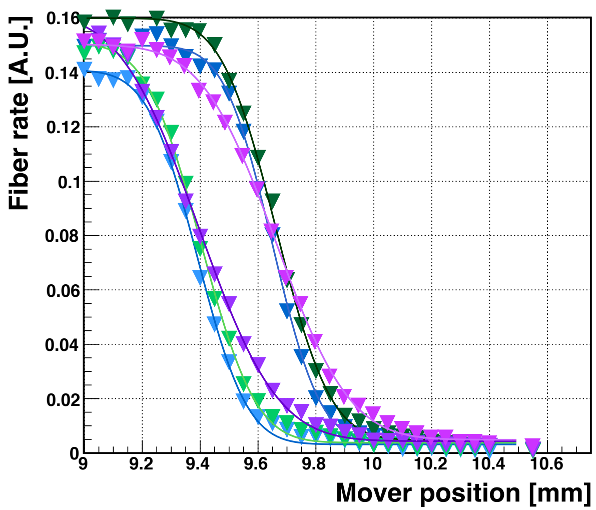


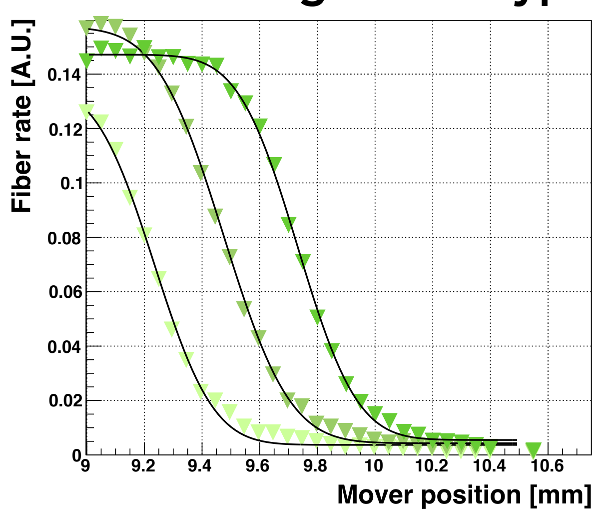
Fiber Alignment

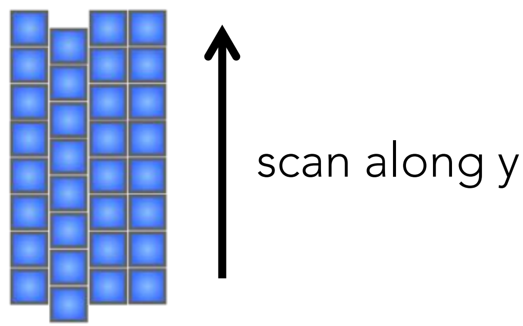
Fiber alignment both within an individual and among several layers is already at a good level, could most probably be improved by further efforts

- 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

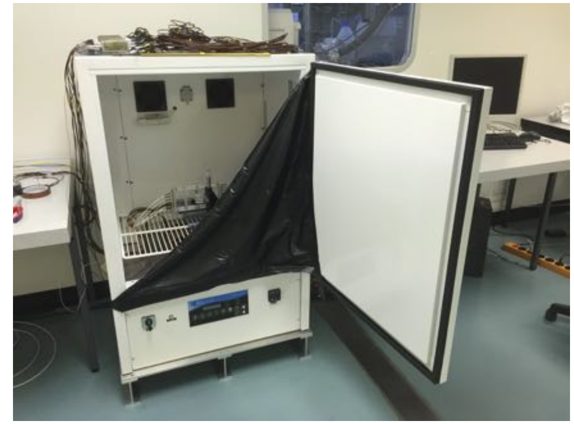






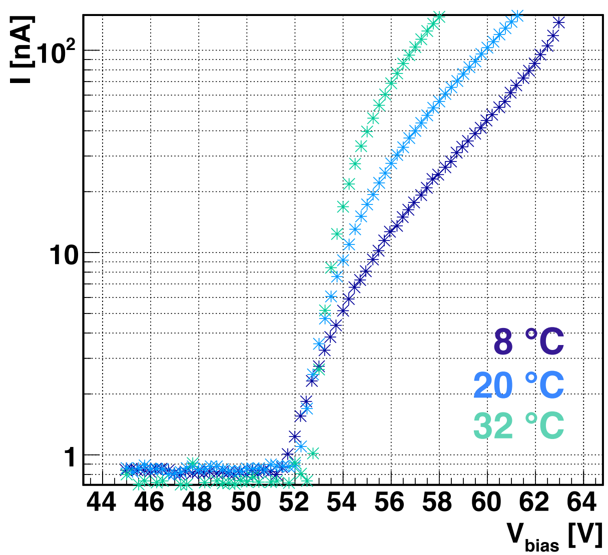
Temperature Dependence

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:

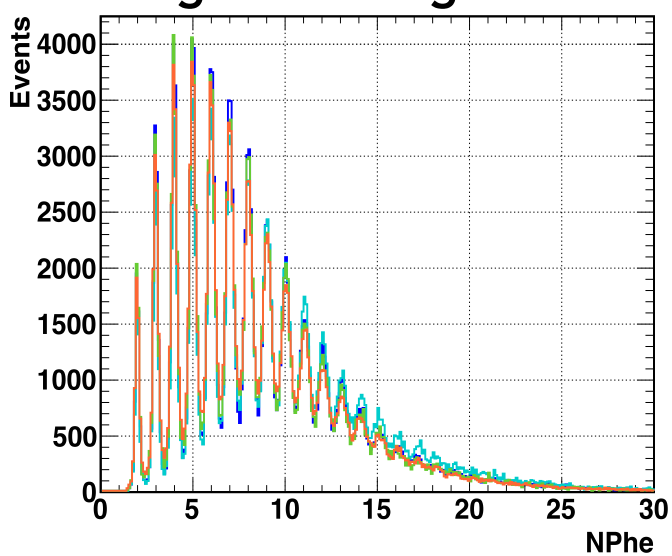


Variations in detection efficiency and timing **< 10%**

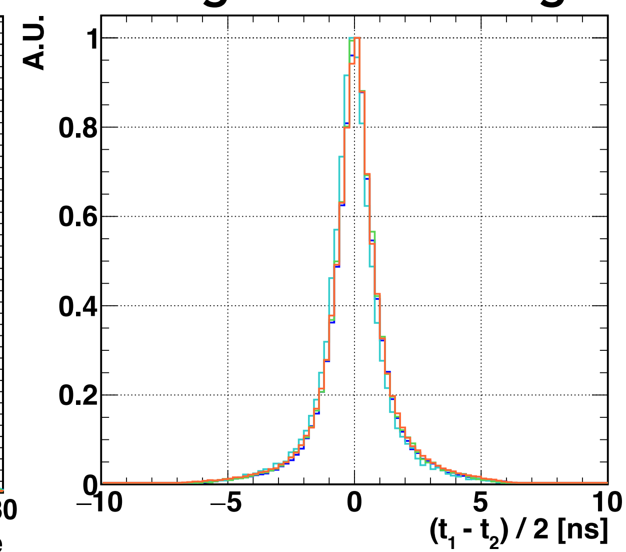
SiPM Characterization



Single Fiber Light Yield



Single Fiber Timing



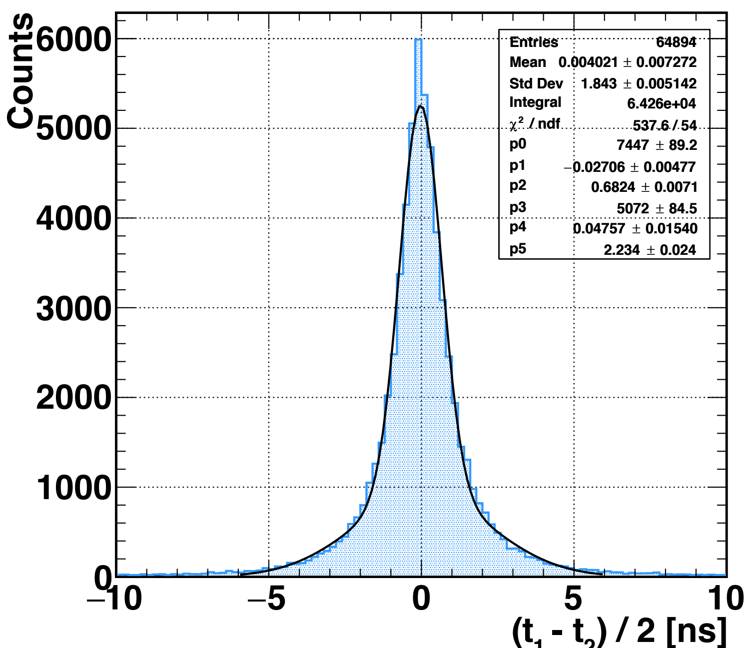
Timing Resolution

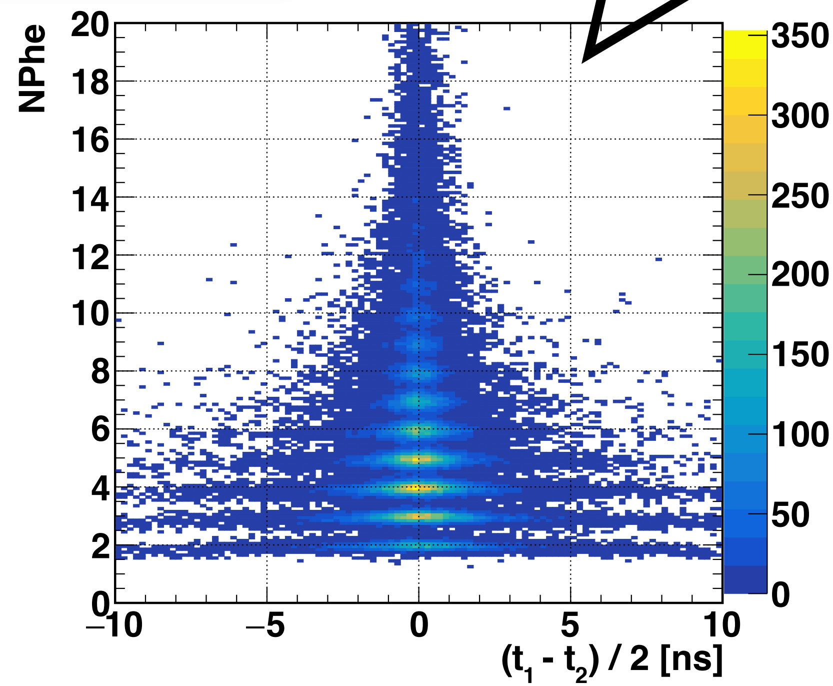
Single fiber timing resolution (Beam Test @ πM1)

- 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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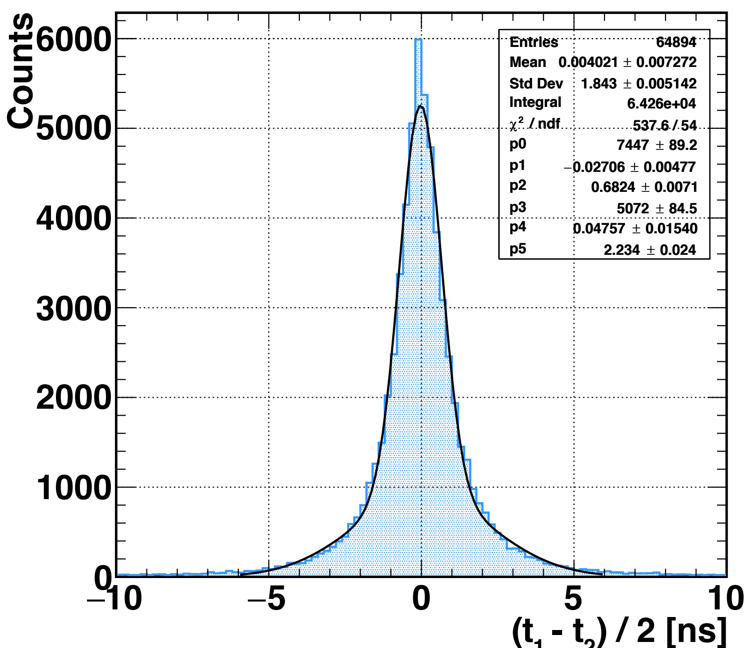
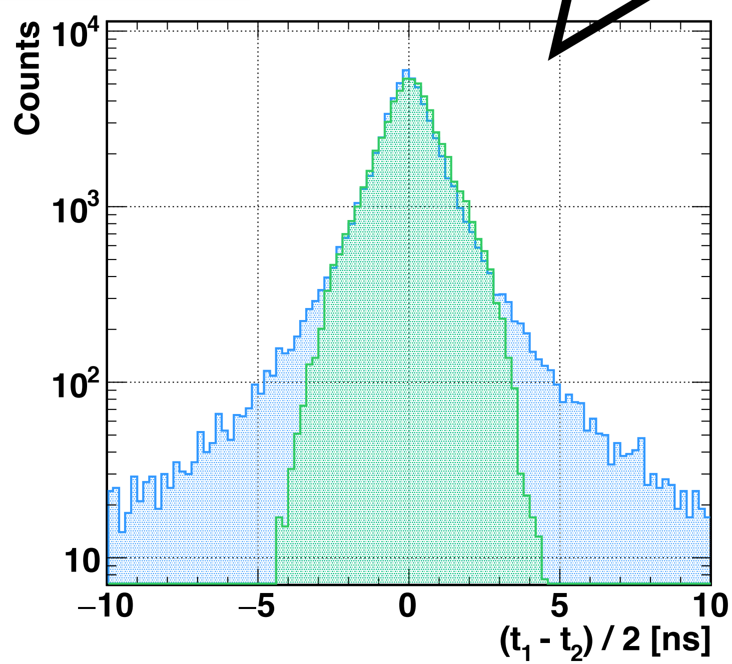
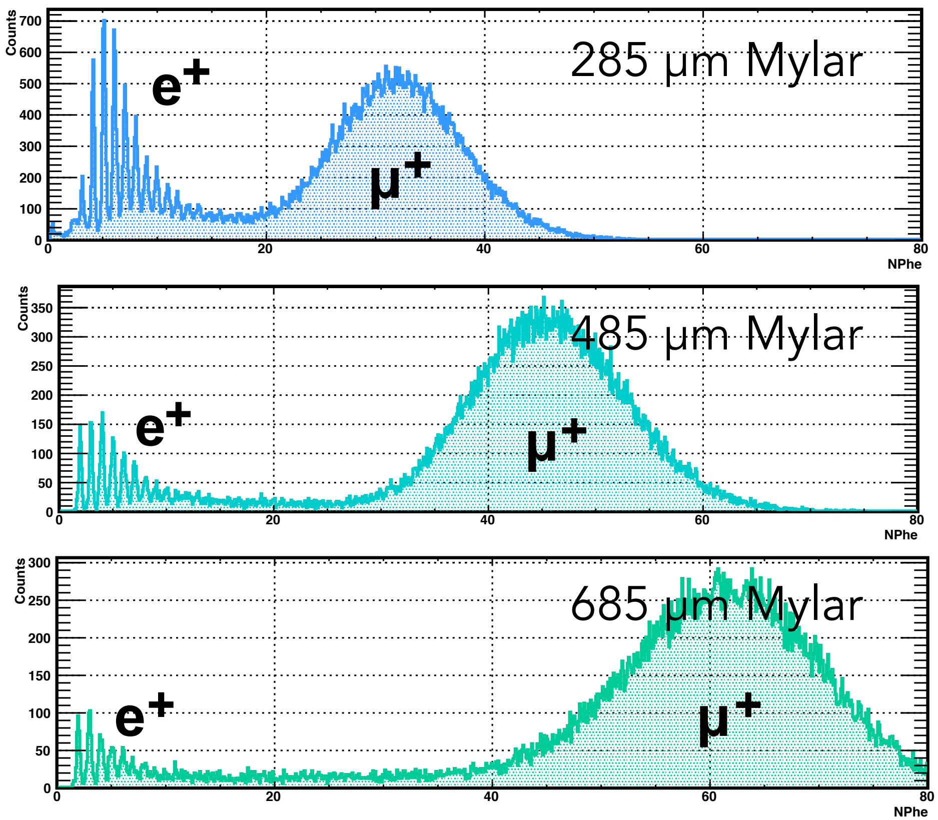
40 dB preamplifiers (lab measurement)



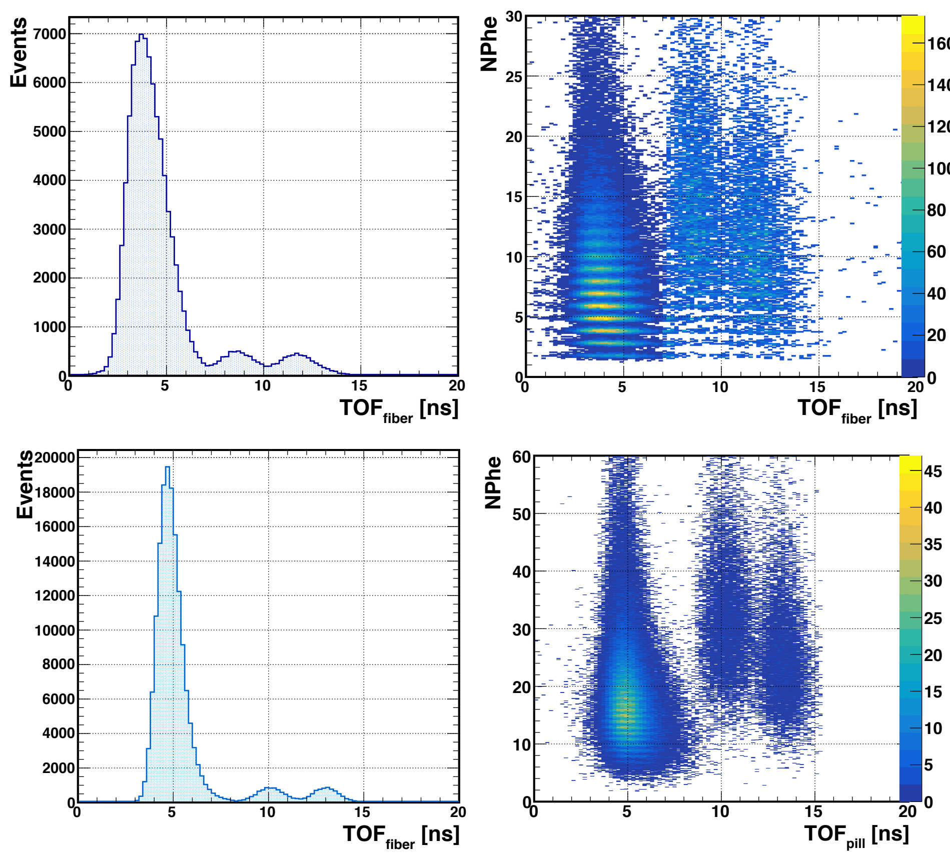


Particle Identification

Discrimination by Charge



Discrimination by time-of-flight



Fiber Beam Monitor – Range Curve