The Mu3e scintillating fiber tracker and the MEGII Beam monitoring detector

Angela Papa
University of Pisa/INFN and Paul Scherrer Institut

ICHEP Seoul (South of Korea), 4-11.July.2018

Outlook

The Mu3e experiment

- Very short introduction
- The signal to be detected by the scintillating fibre tracker

The fibre detector

- Overview
- Impact on the experiment

Results with New detector prototypes

- With squared and round fibres coupled to standalone electronics

The MEGII experiment

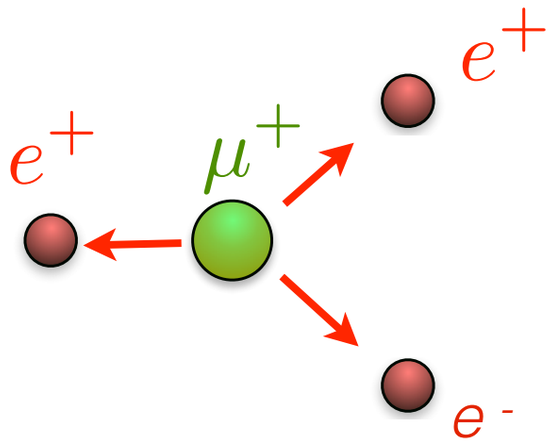
The beam fibre detector

- Overview and Results

Mu3e: The $\mu^+ \to e^+e^+e^-$ search

- Charged lepton flavour violation search: Experimental evidence would be a clear signature of New Physics
- The Mu3e experiment aims to search for $\mu^+ \to e^+ e^+ e^-$ with a sensitivity of $\sim 10^{-15}$ (Phase I) up to down $\sim 10^{-16}$ (Phase II).
- Hosting laboratory: The PSI delivering the World's most intense DC muon beam (up to 10^8 muons/s).
- Previous upper limit BR($\mu^+ \to e^+ e^+ e^-$) $\leq 1 \times 10^{-12}$ @90 C.L. by SINDRUM experiment)
- Observables (E_e, t_e, vertex) to characterize $\mu \to$ eee events

Signature

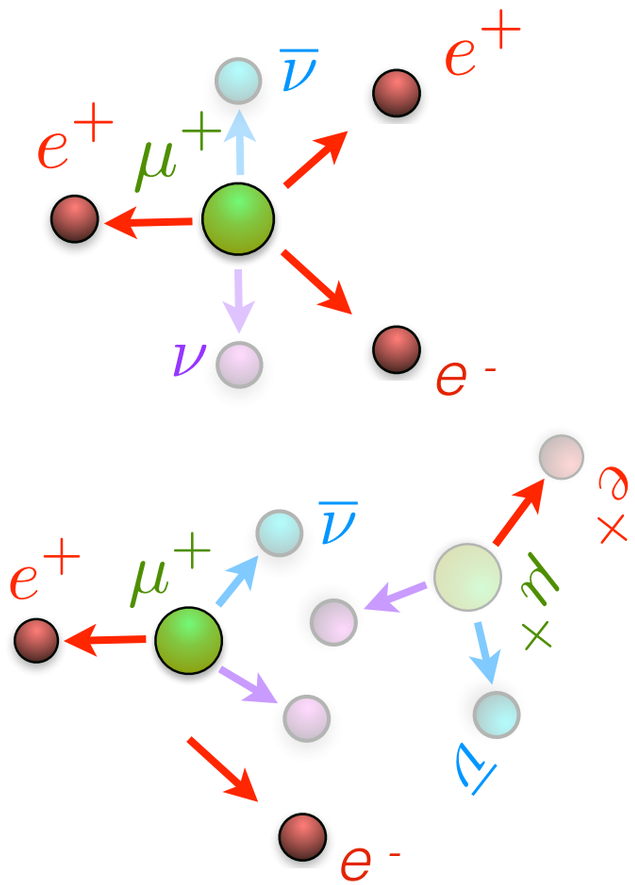


$\Delta t_{eee} = 0$

$\Sigma \vec{p}_e = 0$

$\Sigma E_e = m_\mu$

Background



Mu3e: Requirements

Signal

1. $\mu \rightarrow eee$

- Rare decay search: Intense muon beam O(10*8 muon/s) for phase I

- High occupancy: High detector granularity

- Three charged particles in the final state: allowing for high detector performances vs the case of having neutral particle

Background

1. $\mu \rightarrow eee\nu\nu$

- Missing energy: Excellent momentum resolution

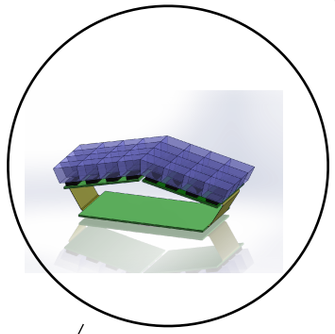
2. $\mu \rightarrow e\nu\nu, \mu \rightarrow e\nu\nu, e^+e^-$

- Coincidence and vertex: High timing and position resolutions

The Mu3e experiment: Schematic 3D

Superconducting solenoid Magnet

Homogeneous field 1T

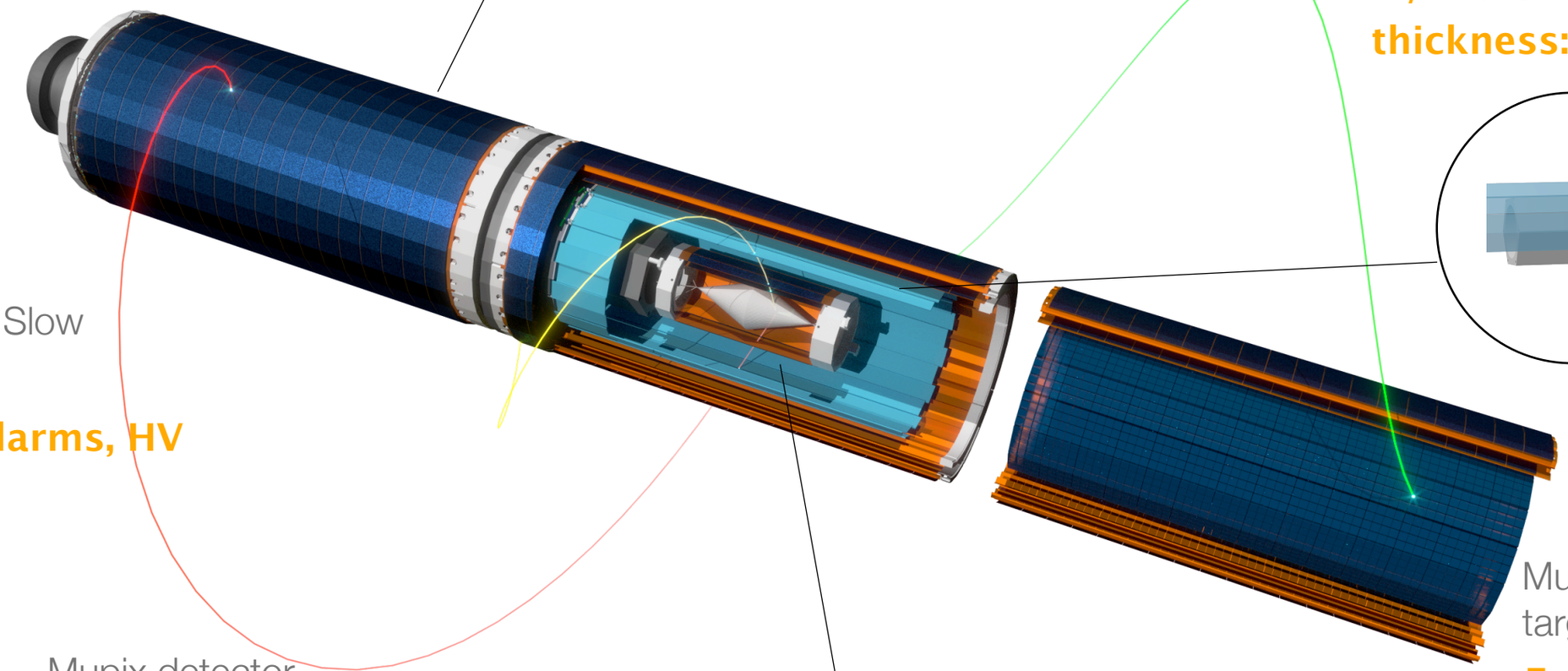


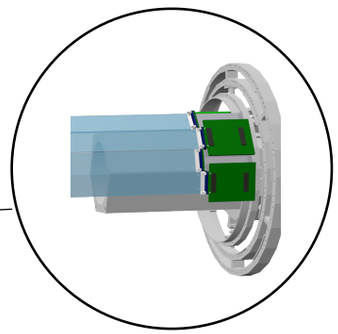
Tile detector

70 ps resolution w/ single hit

Fibre hodoscope

~ 500 ps resolution w/ multi hits thickness: < 0.3% X_0



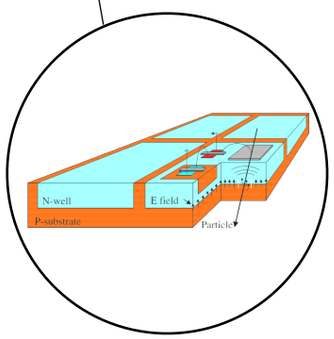


MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

Mupix detector

Tracking, integrate sensor and readout in the same device: 50 um thick
1 layer: ~ 0.1% X_0



Muon Beam and target

Full available beam intensity O(10^8)

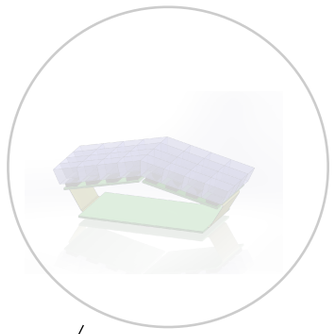
The Mu3e experiment: Focus on the SciFi tracker

Superconducting solenoid Magnet

Homogeneous field 1T

Tile detector

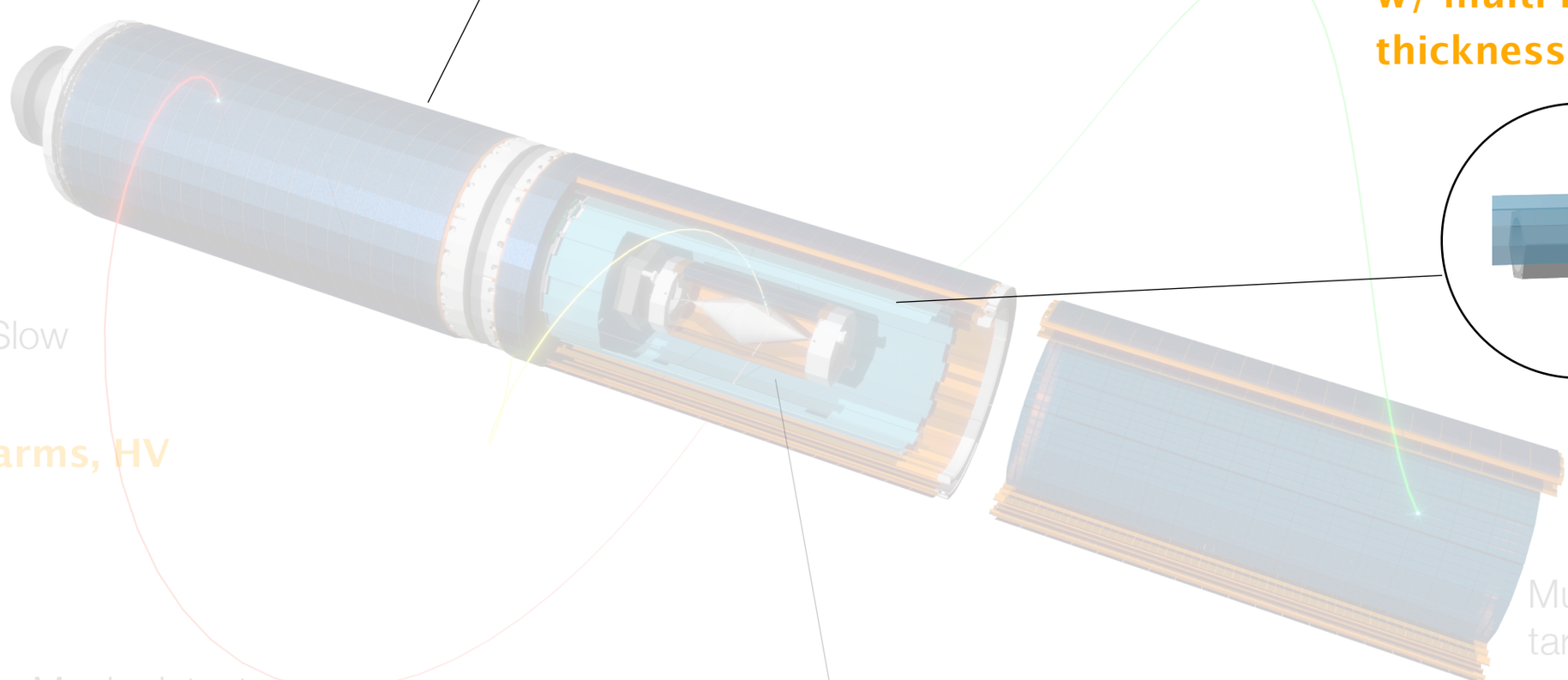
70 ps resolution w/ single hit

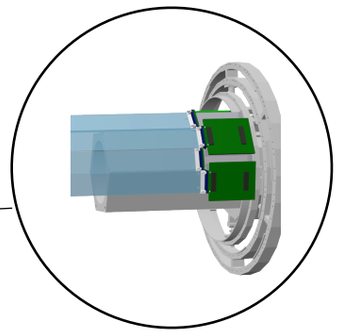


Fibre hodoscope

~ 500 ps resolution w/ multi hits

thickness: < 0.3% X_0





MIDAS DAQ and Slow Control

Run, history, alarms, HV etc.

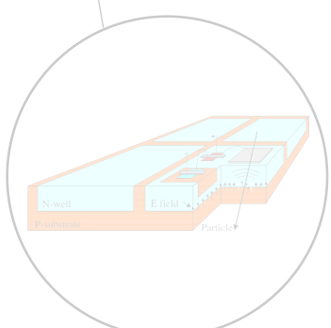
Muon Beam and target

Full available beam intensity O(10^8)

Mupix detector

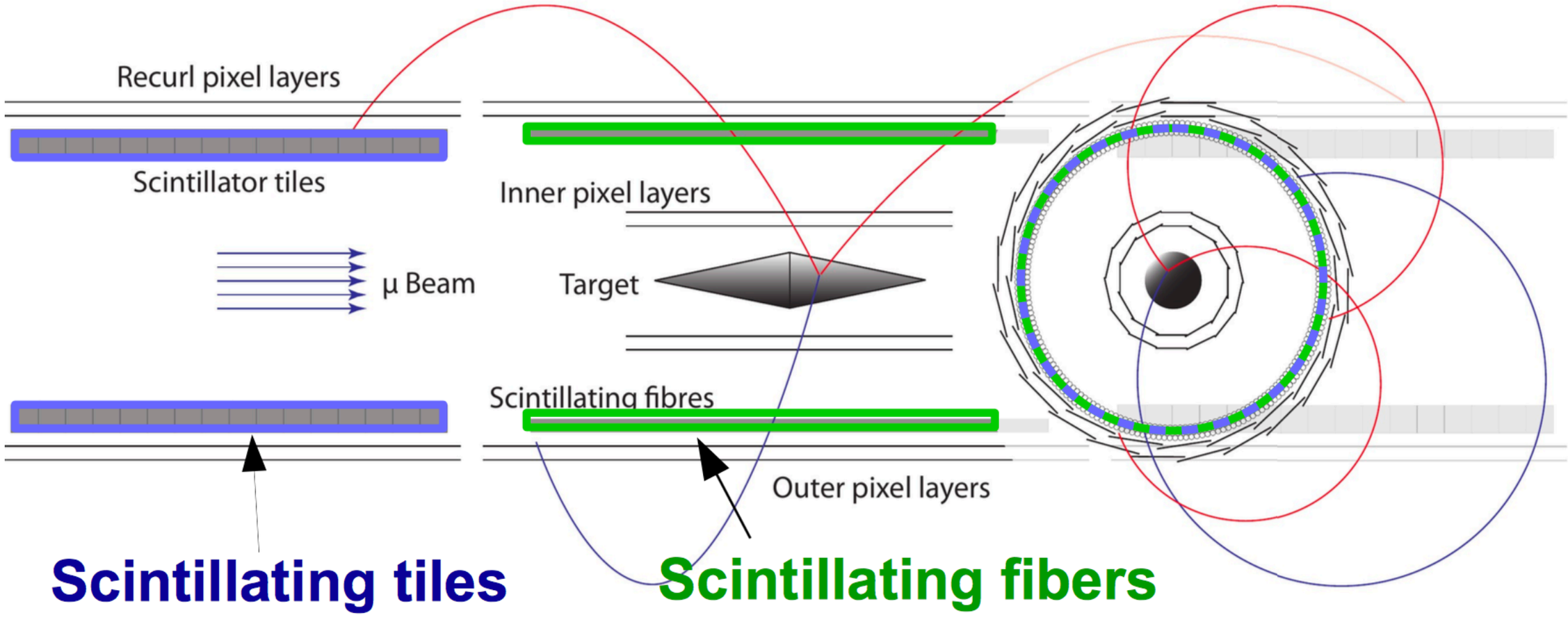
Tracking, integrate sensor and readout in the same device: 50 um thick

1 layer: ~ 0.1% X_0



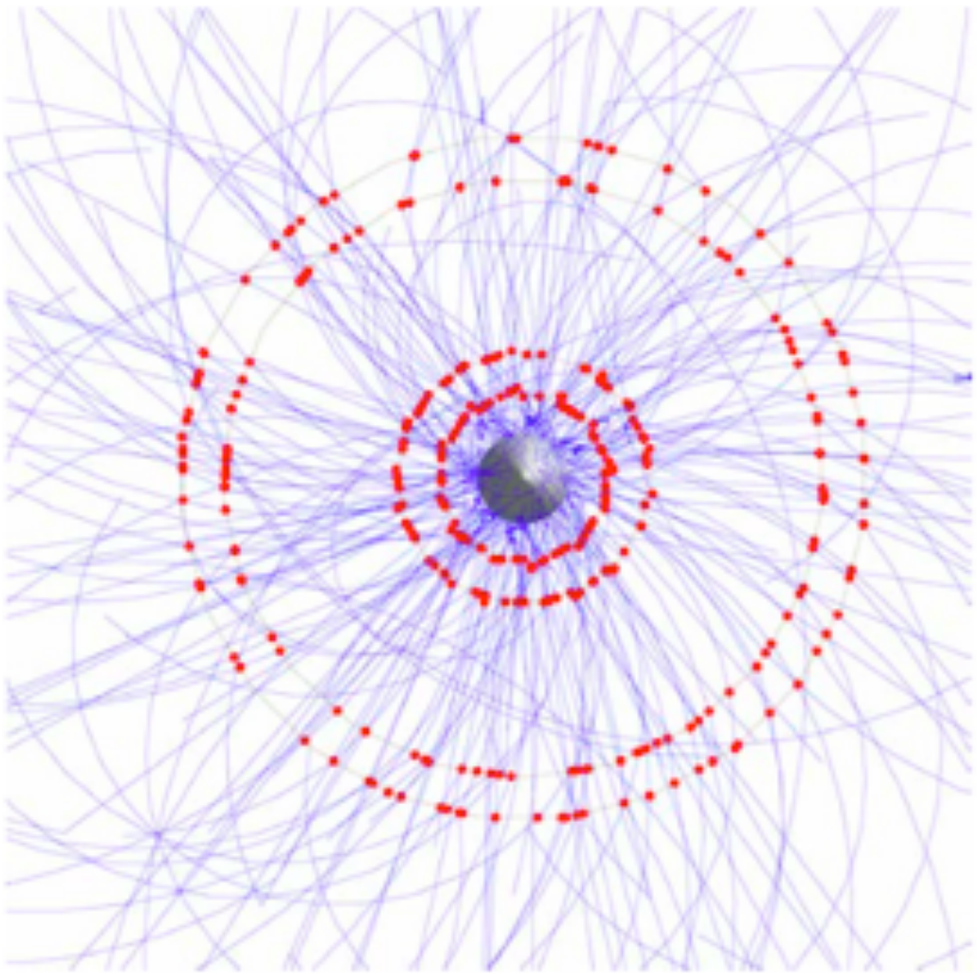
The timing detectors: Fibers and tiles

- Precise timing measurement: Critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
  - Scintillating tiles O(100 ps), full detection efficiency (>99%)

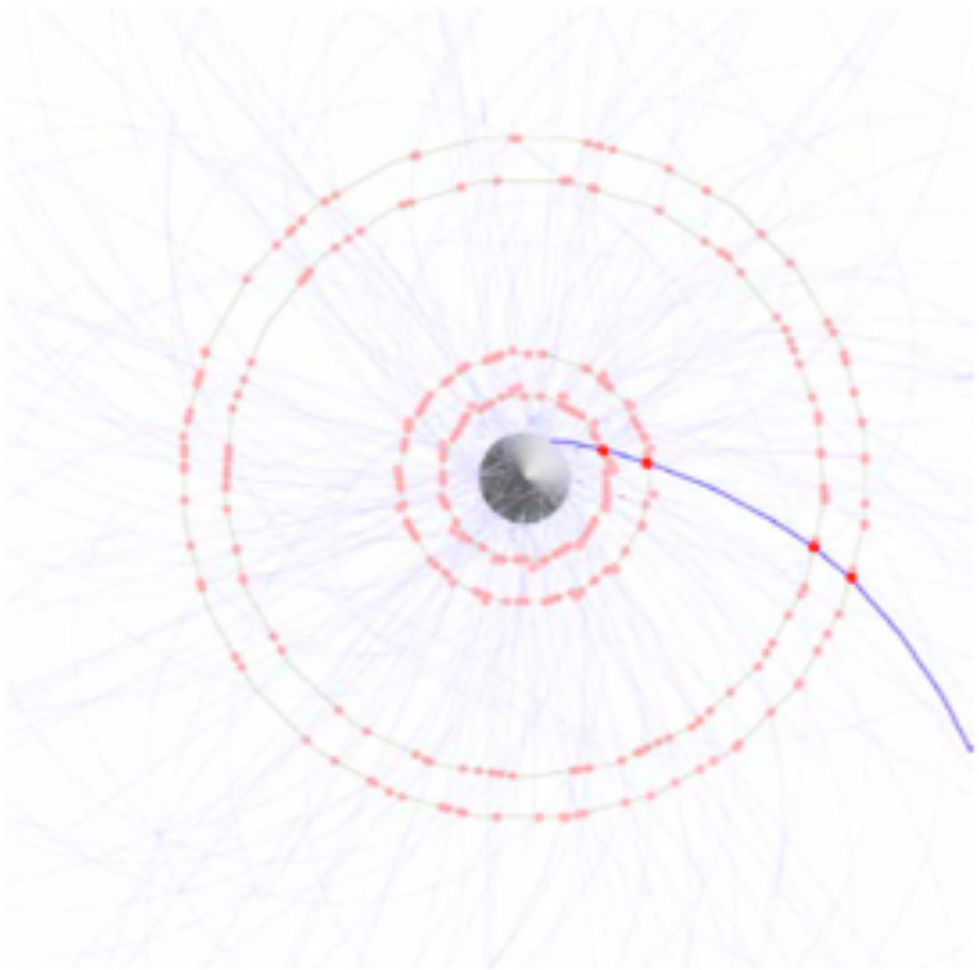


The timing detectors: Fibers and tiles

- Precise timing measurement: Critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
  - Scintillating tiles O(100 ps), full detection efficiency (>99%)



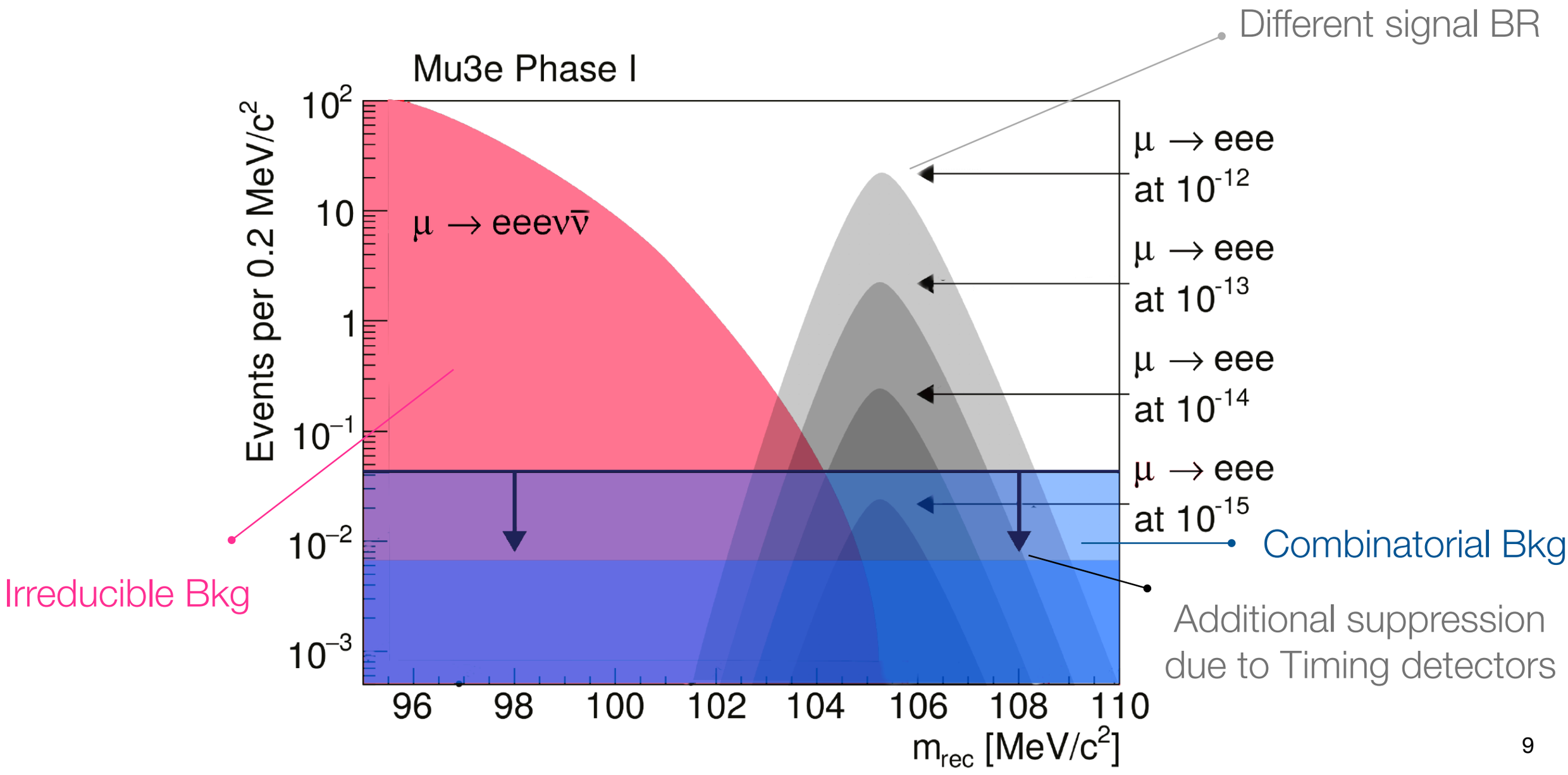
Pixels: O(50 ns)



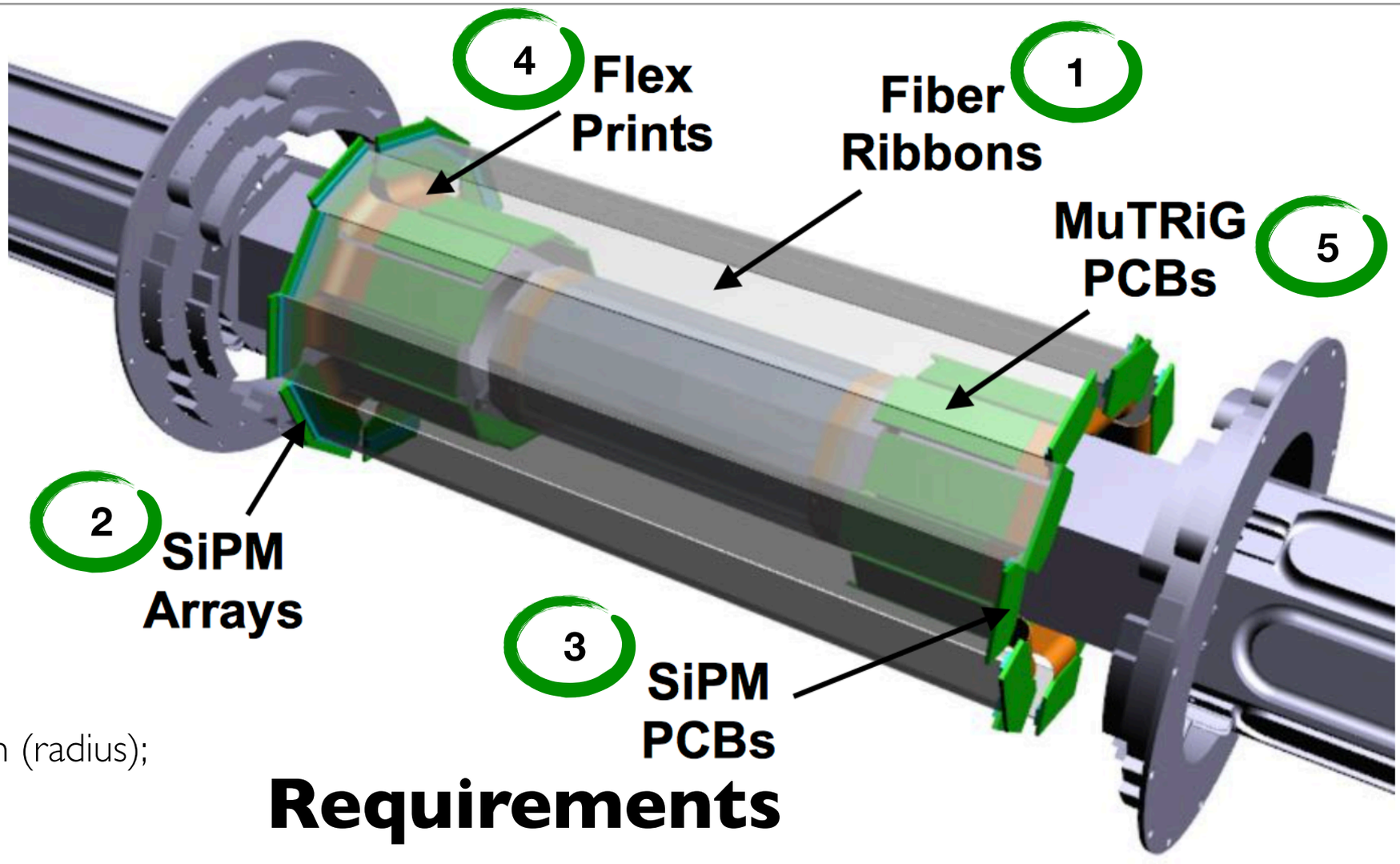
Scintillating fibres O(1 ns);
Scintillating tiles O(100 ps)

The timing detectors: Impact

- Precise timing measurement: Critical to reduce the accidental BGs
  - Scintillating fibers (SciFi) O(1 ns), full detection efficiency (>99%)
  - Scintillating tiles O(100 ps), full detection efficiency (>99%)



The Mu3e SciFi tracker



Parts

- cylindrical at ~ 6 cm (radius); length of 28-30 cm;
- 3 layers of round or square multi-clad 250 μm fibers
- fibers grouped onto SiPM array
- MuTRiG readout

Requirements

- < 900 μm total thickness
  < 0.3 % X_0
- time resolution σ < 1 ns
- rate up to 250 KHz/fiber
- very tight space for cables, electronics and cooling

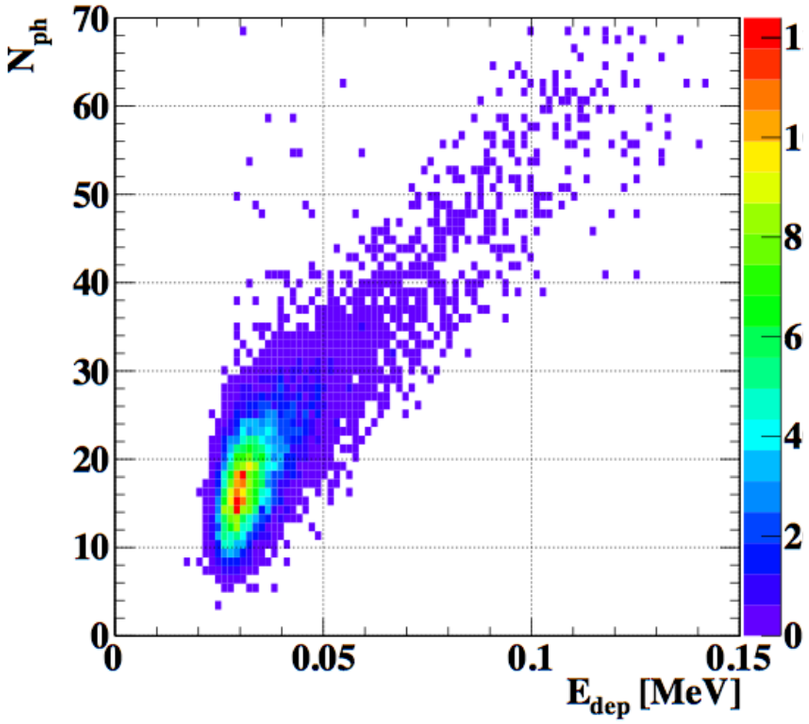
Detector

- 12 Fiber ribbons: W ~ 32 mm, L ~ 280 mm
- 24 MPPC S13552 (developed for LHCb): 128 channels/sensor, 0.25 x 1.6 mm^2
- 3072 channels read out by MuTRiG

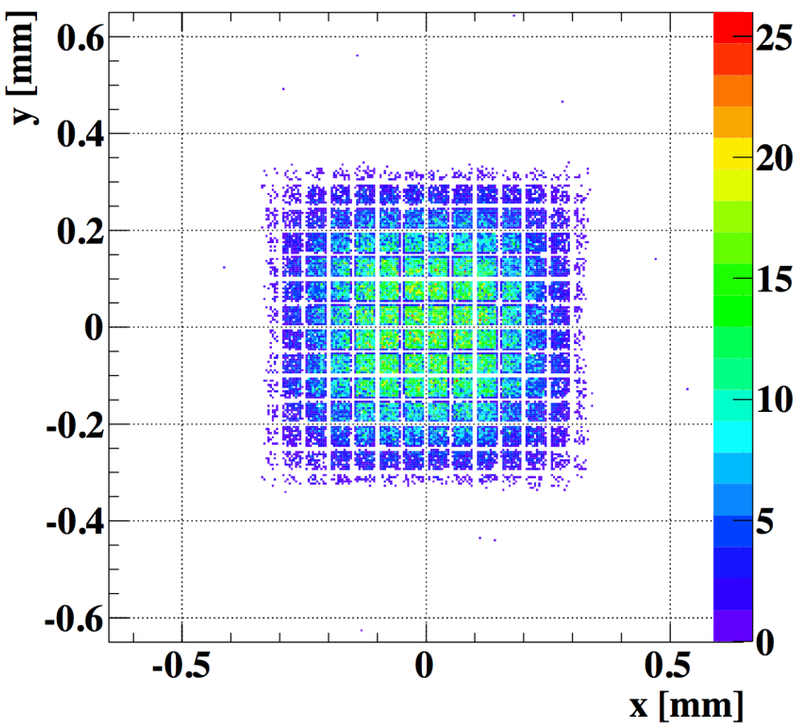
The challenge: Only few photons/fiber

- Detection of minimum ionising particle (m.i.p.)
- Only few photoelectrons/fiber (fiber thickness: 250 um)
- Coupling fiber-photosensor: polishing, alignment and optical grease
- Geant4 MC simulation framework
- Included MPPC response and DAQ response
- Plots below: SQ MC BCF 12 250 um fiber with L ~ 20 cm; MPPC 13360-1350C

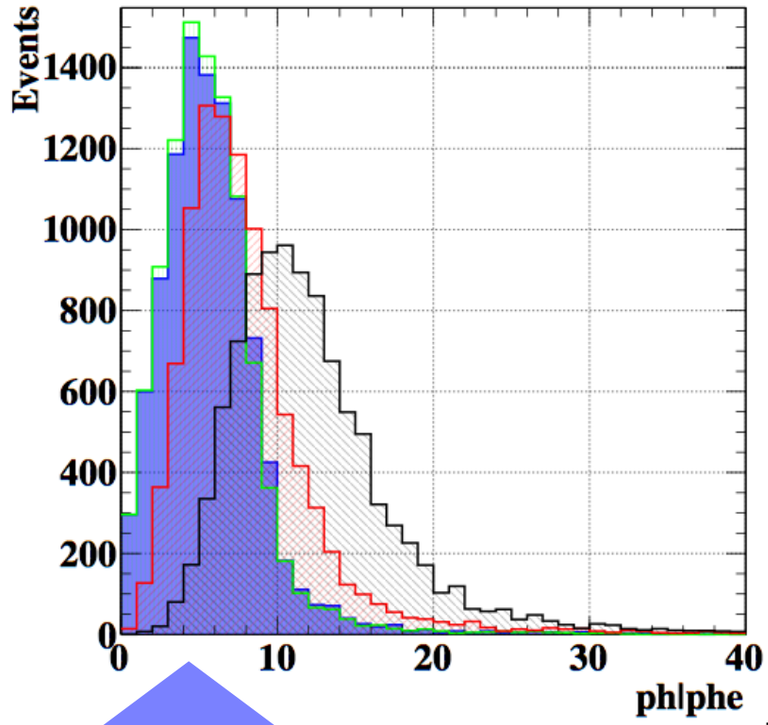
Photons vs deposited energy



Photons at the MPPC entrance window

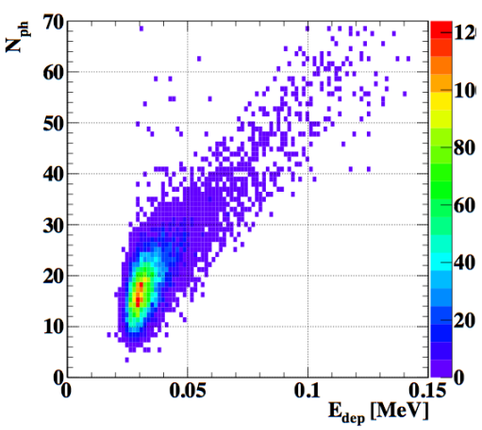


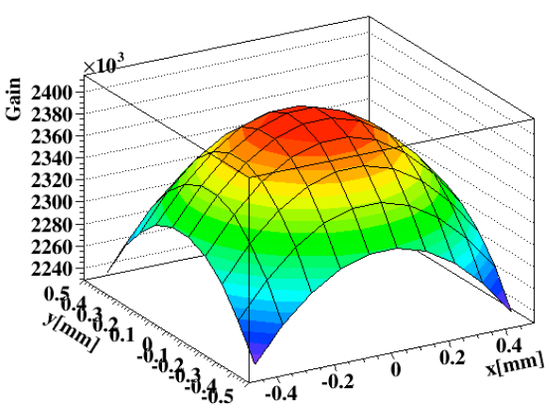
From photons to photoelectrons

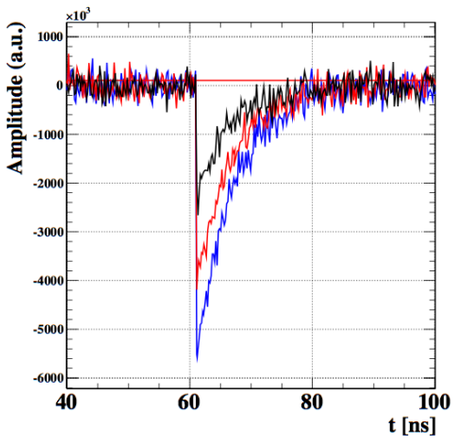


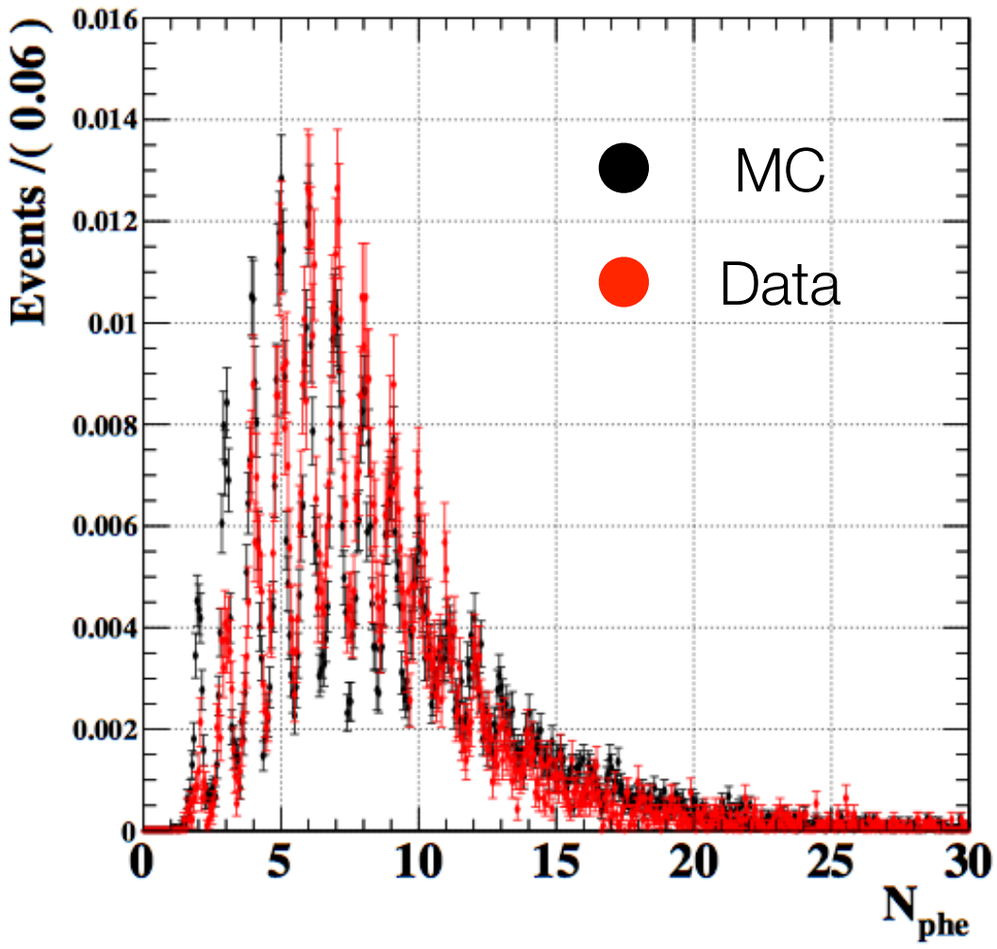
Full MC simulation chain - Standalone MC vs Data

GEANT4 MPPC DAQ Analysis: Data vs MC









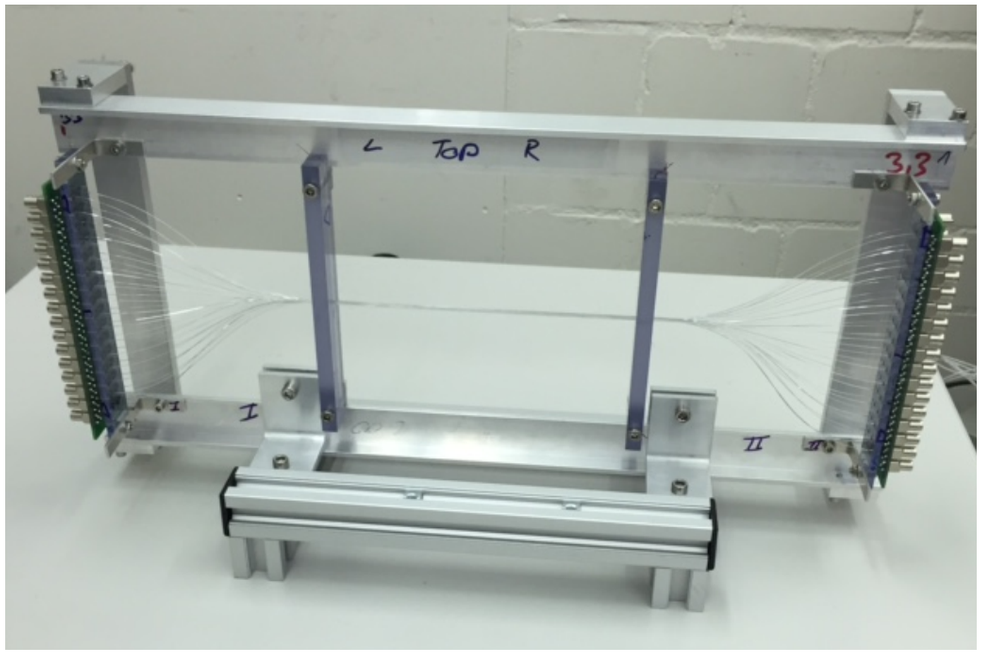
- Physical processes by GEANT4: From the first particle interaction in the medium to the photosensor

- PDE, gain/variation
- Cross-talk
- Saturation effect/ timing recovery
- Dark Counts

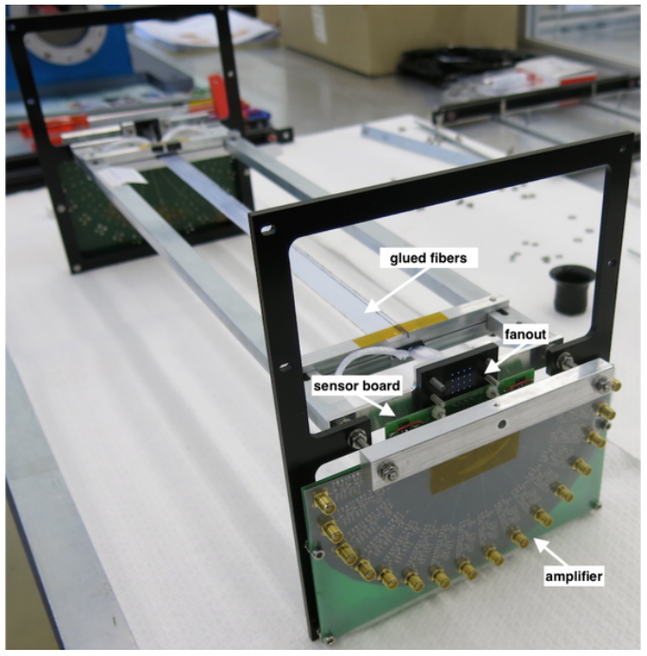
- Pre-amp gain
- Signal digitisation up to 5 GS/s
- Waveform analysis

Ribbon prototypes

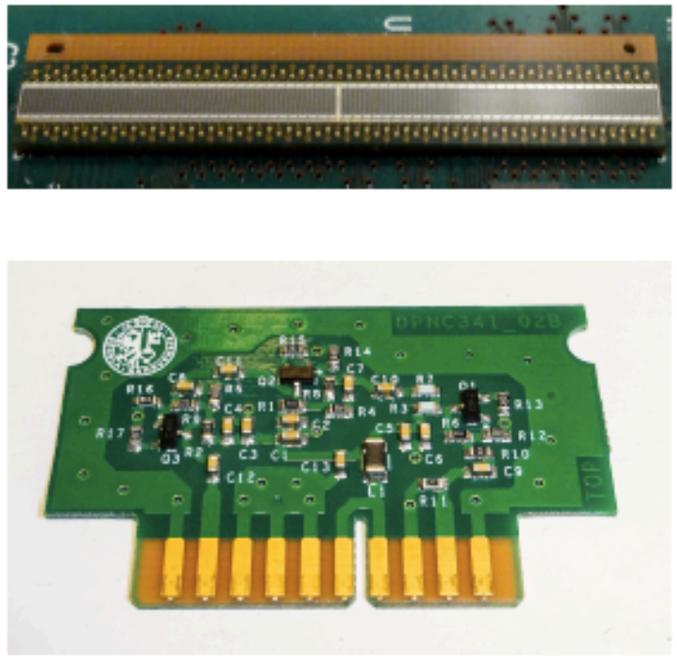
- Square and Round 250 um fibers, L ~ 50 cm
- Single and Array readout (Double readout); Channels O(64)
- Standalone DAQ and STiC readout (STiC readout predecessor of MuTRiG readout)
- Prototypes studied with Sr90 source, positrons/muon/pion with p = 115 MeV/c (PSI), SPS at CERN



- Saint Gobain MC SQ BCF12 250 um fiber
- 100 nm Al coating
- 4 fibre layers (1 trigger + 3 active layers)
- Hamamatsu S13360-1350CS
- DAQ: DRS4 evaluation boards (5 GSample/s)



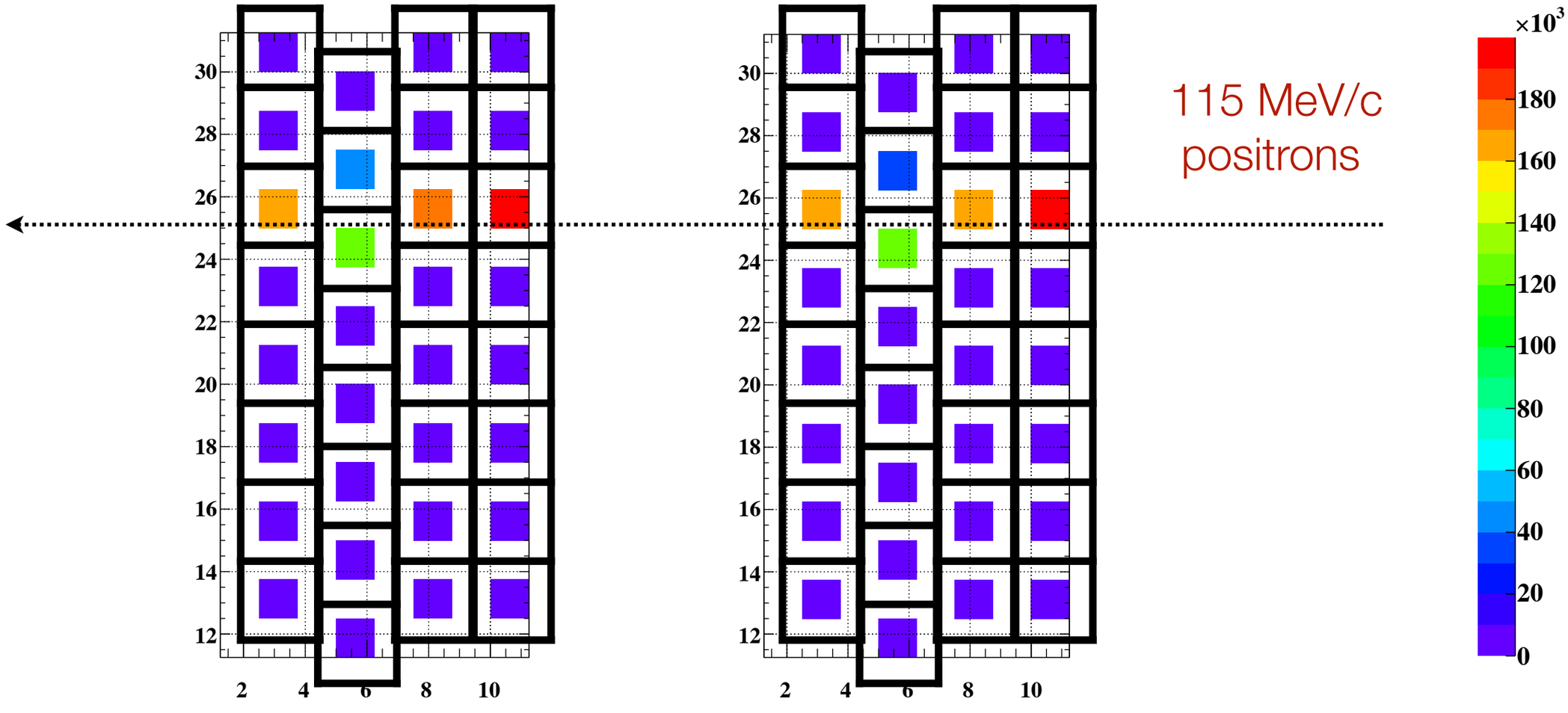
- Kuraray SCSF-81M fiber 250 um diam.
- with/out TiO_2 coating
- 4 layers
- Hamamastu S12571-050P
- Single fibre readout



- Kuraray SCSF-81M fiber 250 um diam.
- with TiO_2 coating
- 2 and 5 layers
- Hamamastu S10943-3183
- Array readout

Data: A positron track

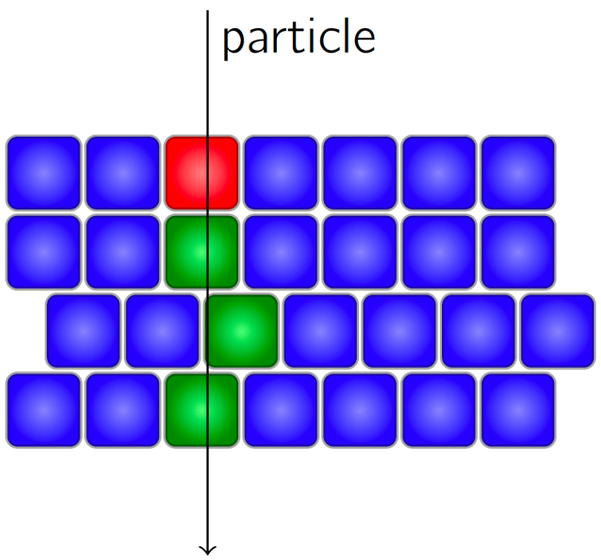
- Measurements using
  - ^{90}Sr-source (m.i.p. selection with an external thick plastic scintillator)
  - e^+ beam (e.g. πM1/PSI with p = 115 MeV/c)



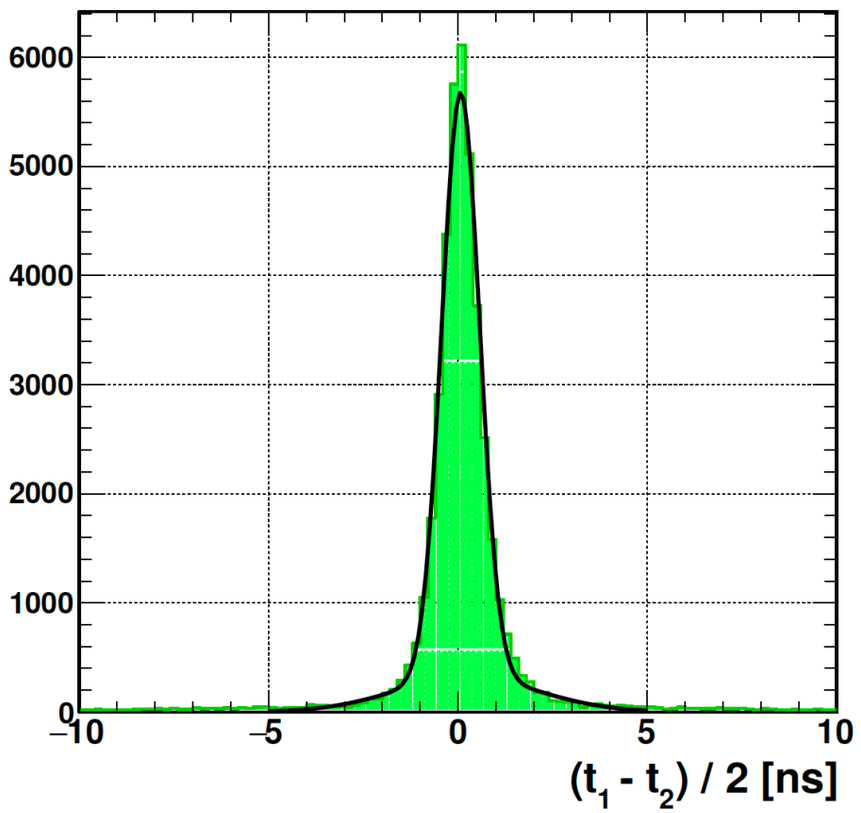
SciFi prototypes: Results

- Confirmed full detection efficiency (**> 97 % @ 0.5 thr in Nphe**) and timing performances for multi-layer configurations (square and round fibres) with several prototypes: individual and array readout with standalone and prototyping (STiC) DAQ

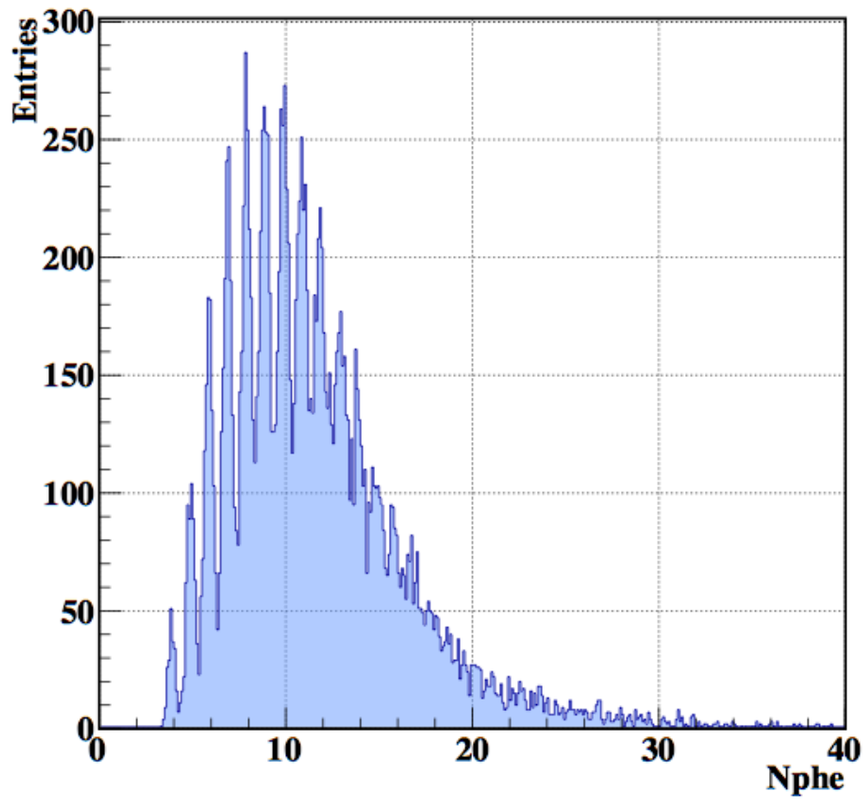
Trigger
offline selection:
hits in 3 layers



3 layer time resolution O(550) ps



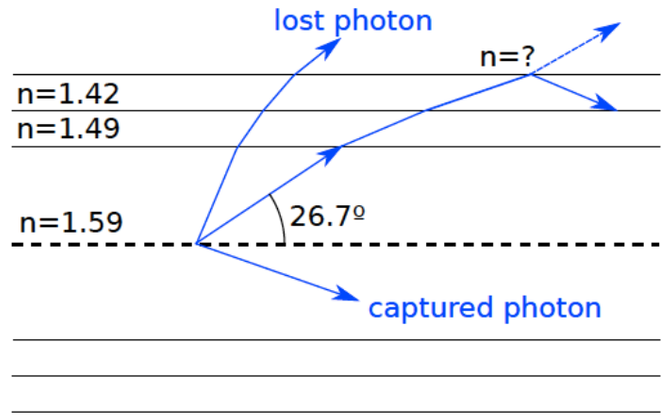
3 layer offline array charge collection (thr > 1.5 Nphe)



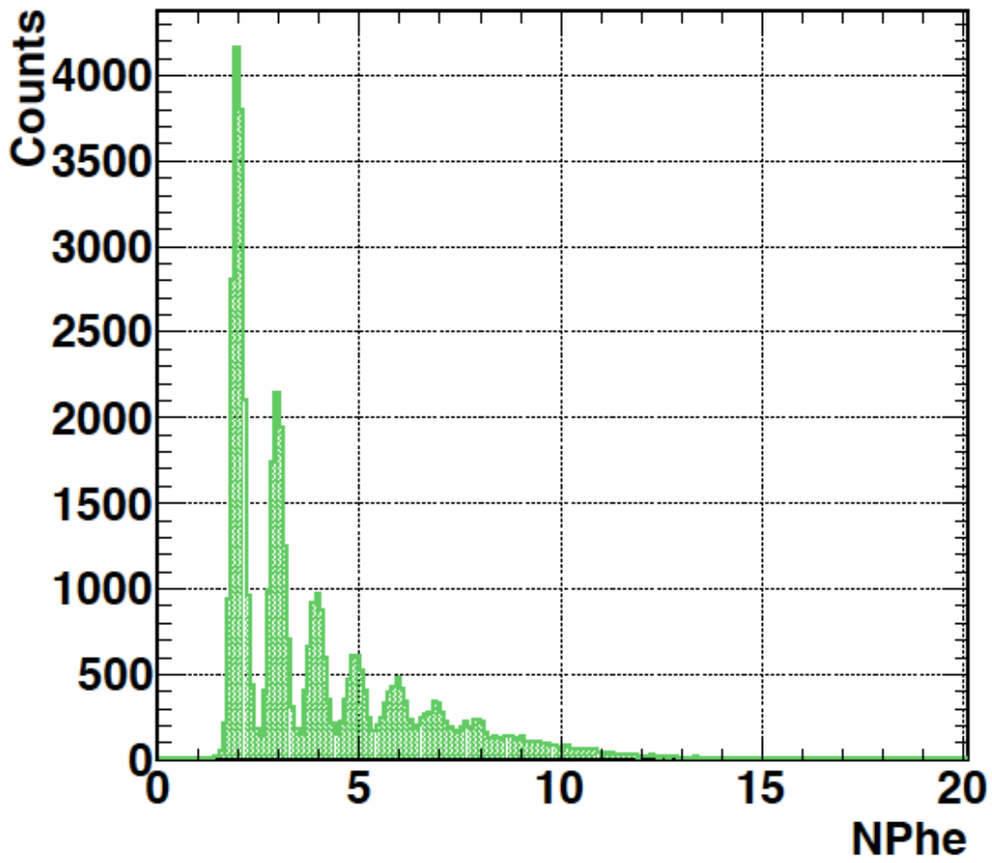
SciFi prototypes: Fiber trapping efficiency/Photon transmission

- Improved fiber trapping efficiency/photon transmission

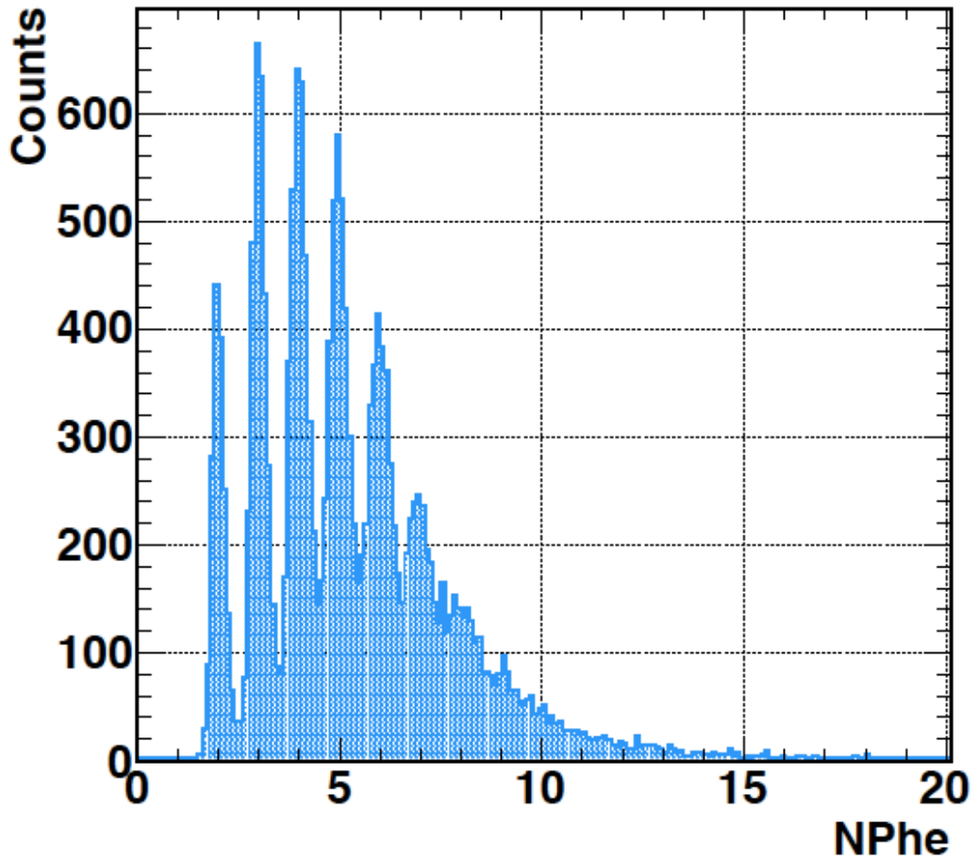
$$\Theta_{\text{total reflection}} = \arcsin\left(\frac{n_{\text{cladding}}}{n_{\text{core}}}\right)$$



Bare fiber

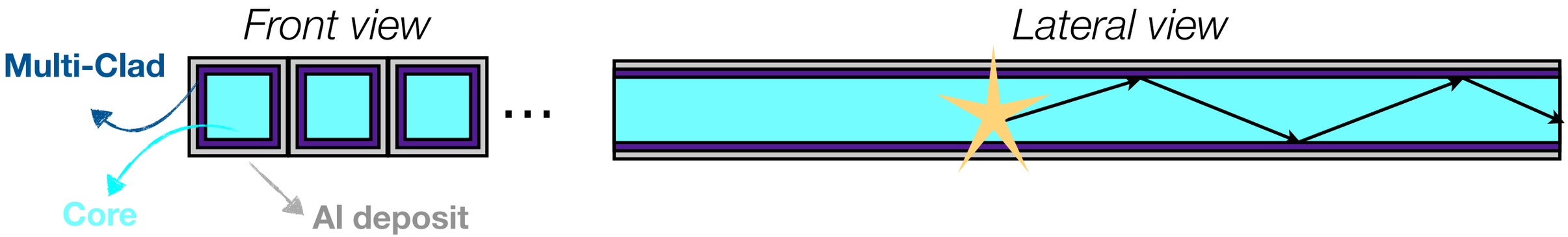


with Al

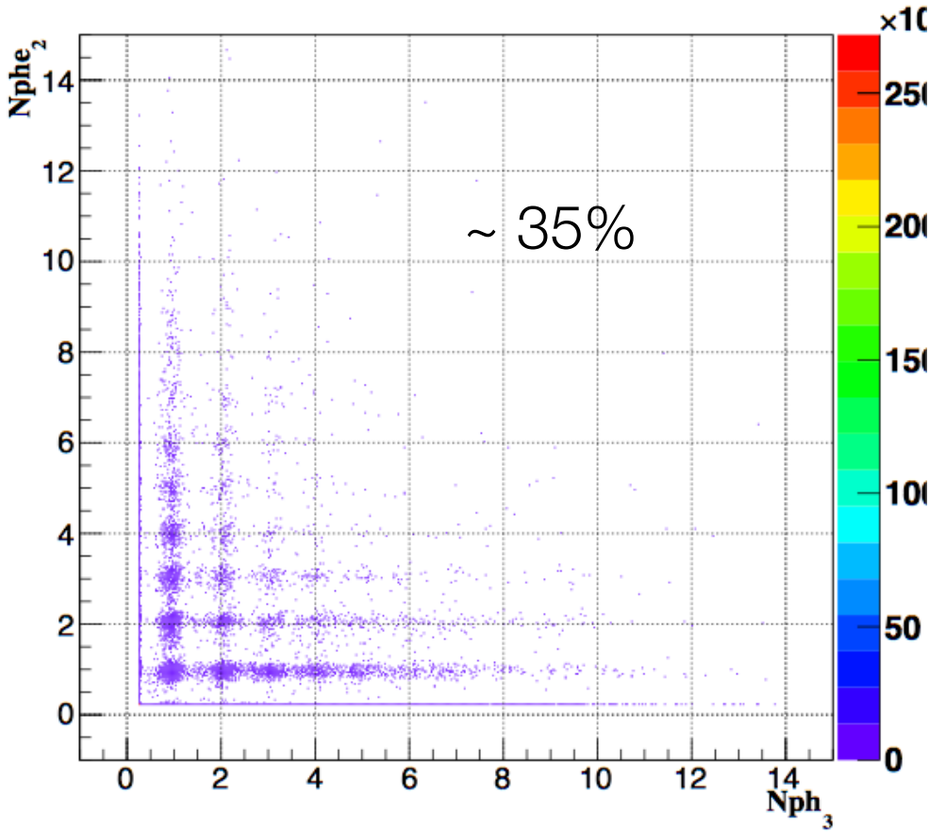


SciFi prototypes: Fiber optical cross-talk

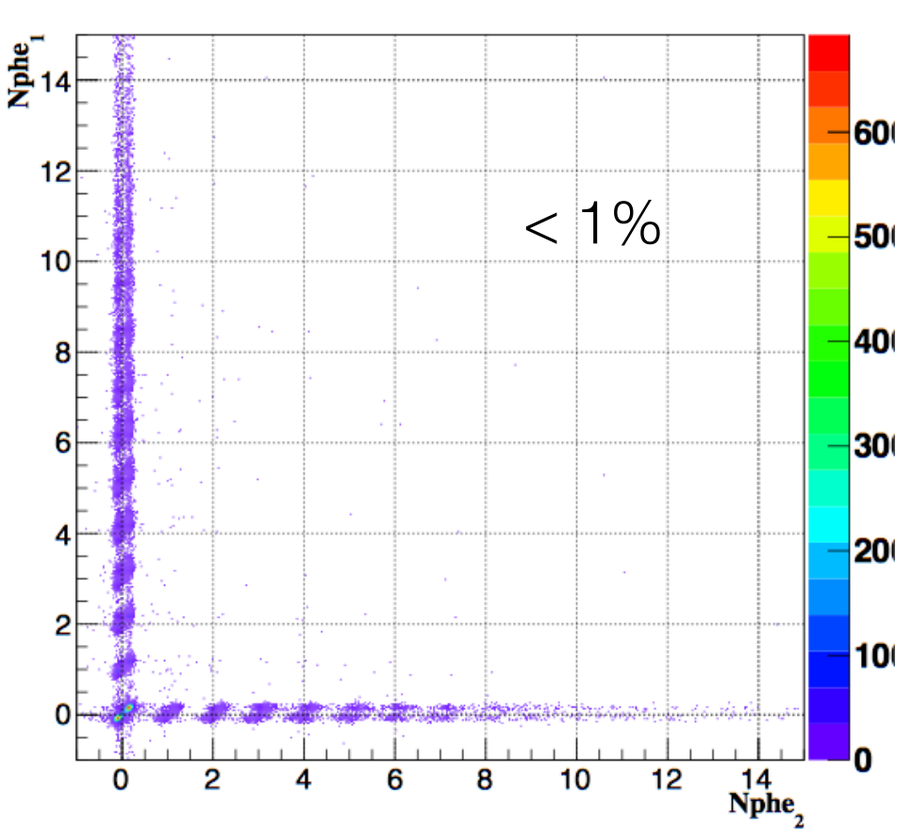
- Negligible optical cross-talk with Al deposit (100 nm): **< 1%** (without Al ~ 30%)



without Al

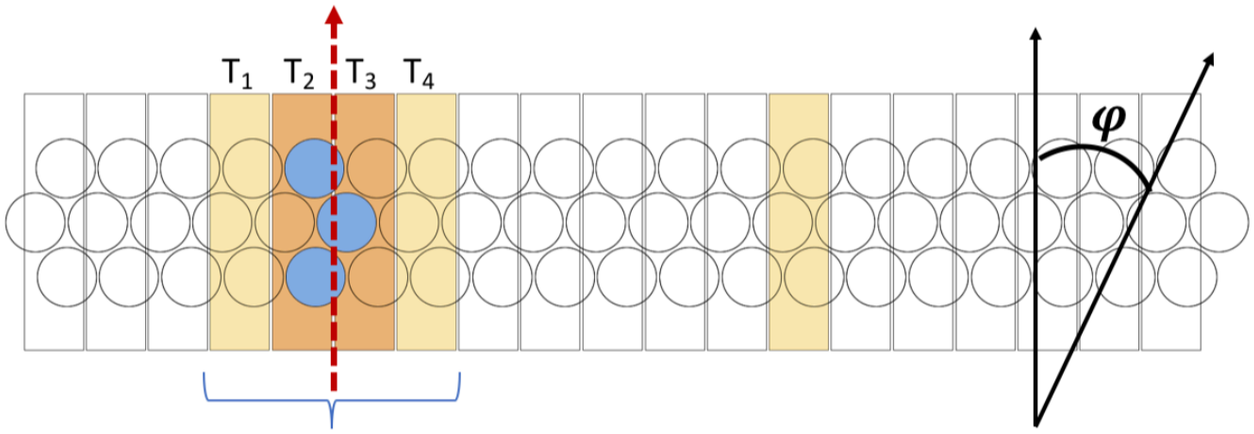


with Al

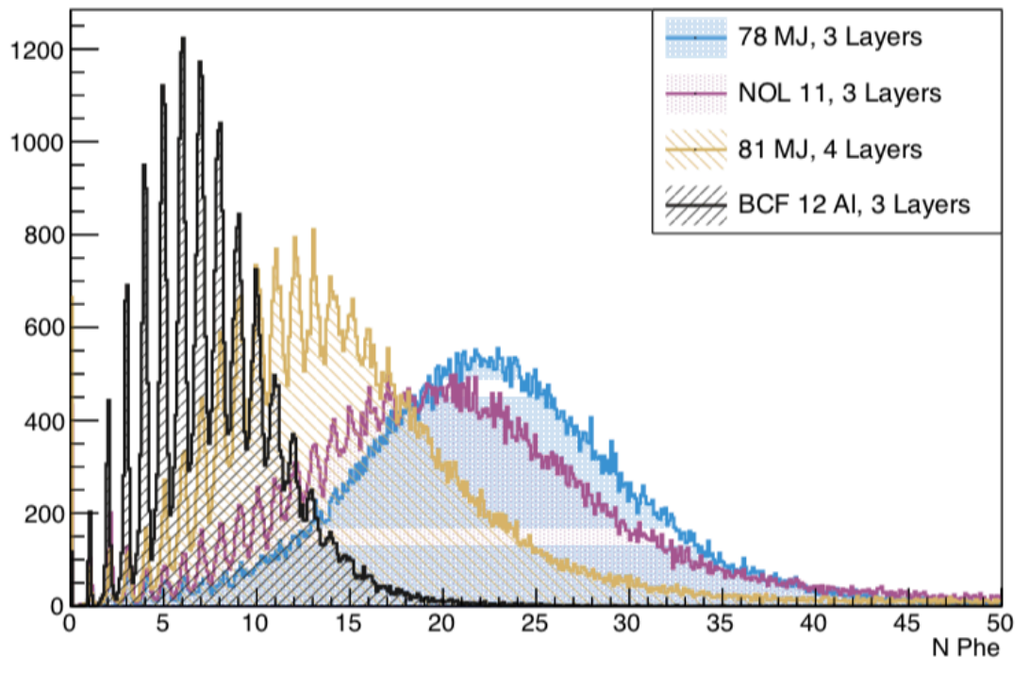


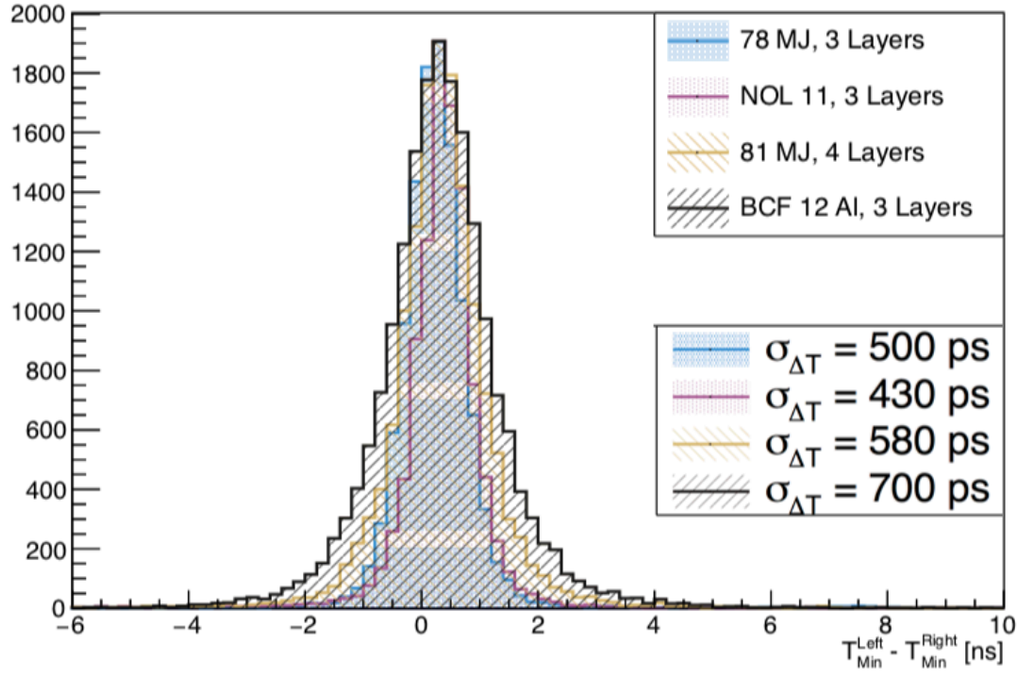
SciFi prototypes: Results

- Studied a variety of fibres (SCSF 78 MJ, clear; SCSF 78 MJ, with 20% TiO2; NOL 11, clear; NOL 11, with 20% TiO2; SCSF 81 MJ, with 20% TiO2; BCF12 clear; BCF12, with 100 nm Al deposit)
- Confirmed full detection efficiency (> 96 % @ 0.5 thr in Nphe) and timing performances for multi-layer configurations (square and round fibres) with several prototypes: individual and array readout with standalone and prototyping (STiC) DAQ



New

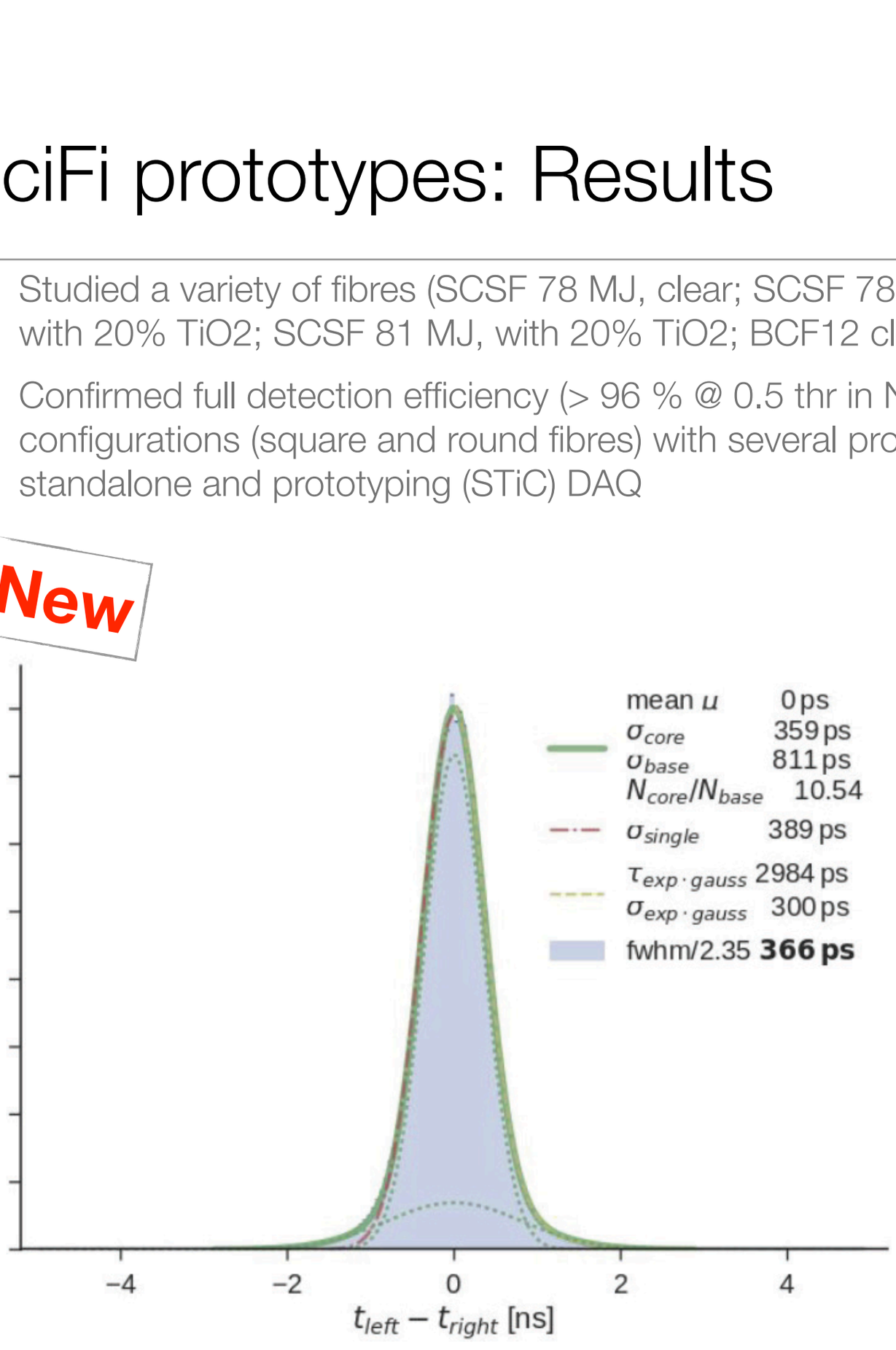




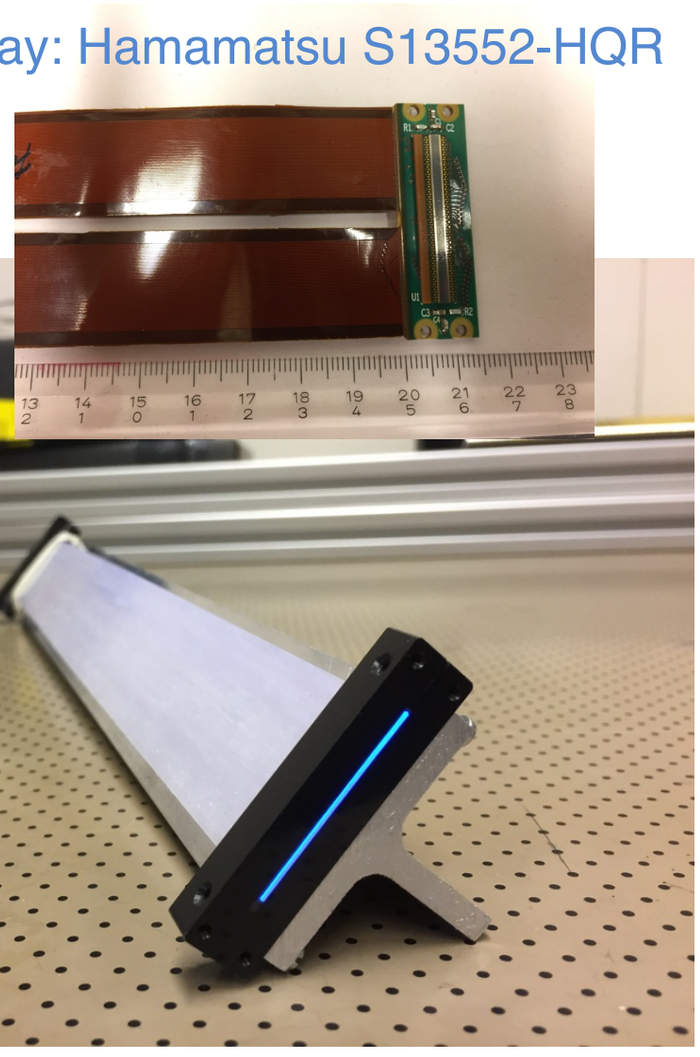
SciFi prototypes: Results

- Studied a variety of fibres (SCSF 78 MJ, clear; SCSF 78 MJ, with 20% TiO2; NOL 11, clear; NOL 11, with 20% TiO2; SCSF 81 MJ, with 20% TiO2; BCF12 clear; BCF12, with 100 nm Al deposit)
- Confirmed full detection efficiency (> 96 % @ 0.5 thr in Nphe) and timing performances for multi-layer configurations (square and round fibres) with several prototypes: individual and array readout with standalone and prototyping (STiC) DAQ

New



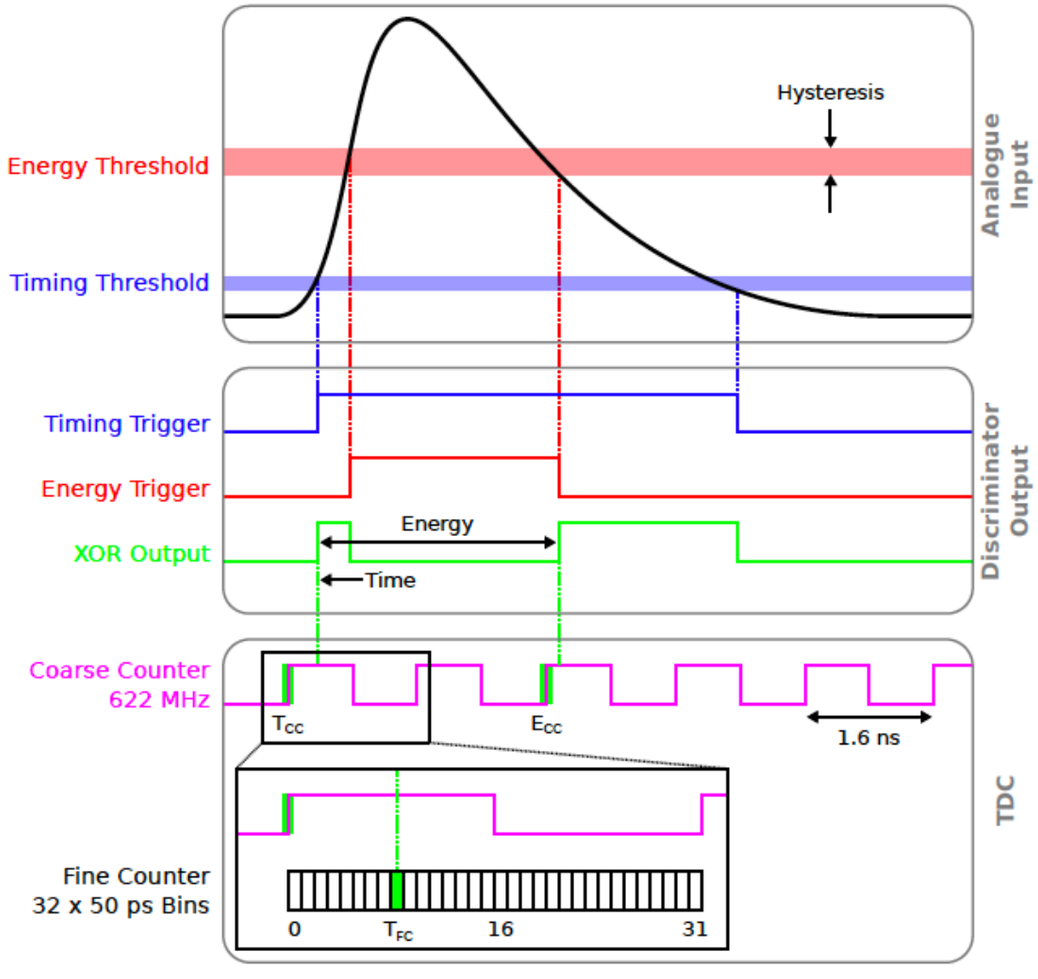
SiPM Array: Hamamatsu S13552-HQR



Fibres: Kuraray SCSF78J

Readout electronics

- Mixed mode, ~ 50 ps timestamps, high impedance, optional differential
- Fiber readout: (currently) only “Timing threshold”

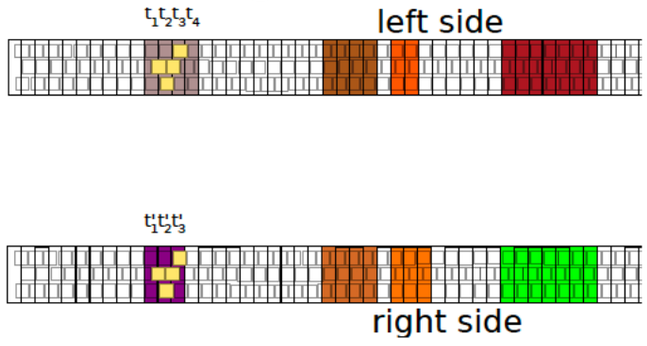


	STiC3.1 in use	**MuTRiG**
number of channels	64	32
LVDS speed [Mbit/s]	160	1250
event size [bit]	48	47
time mode	-	26
event rate / chip [MHz]	~2.6	~20
time mode	-	~38
event rate / ch [kHz]	~40	~650
time mode	-	~1200
power per channel [mW]	35	35
size [mm x mm]	5x5	5x5
number of PLLs	2	1

Data Rate and Clustering: Prospects

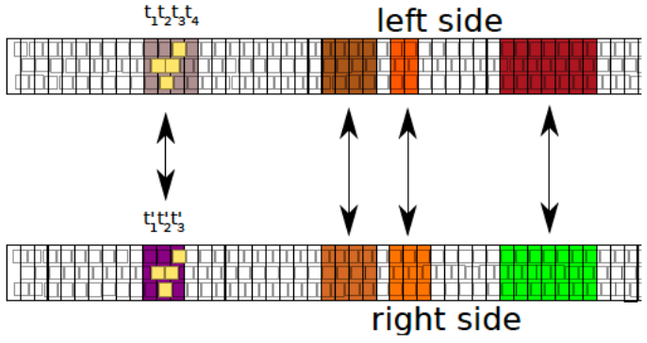
at 10^8 stopped μ/s	event rate [M/s]	data rate [Gbit/s]
SciFi detector	274	
Scintilating Fibres (235k/s/fibre)	1083	
SiPM columns signal (420 k/s/column)	1290	36.1
SiPM columns dark counts (~300 k/s/column)	922	25.8
SiPM columns total	2211	**61.9**
clustering		**20.0**

clustering per side

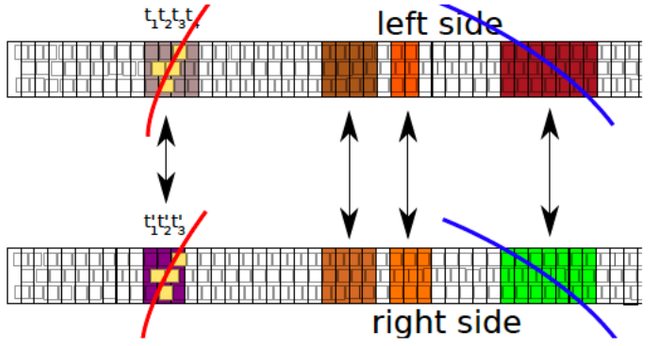


- on FPGA (FE)

match sides

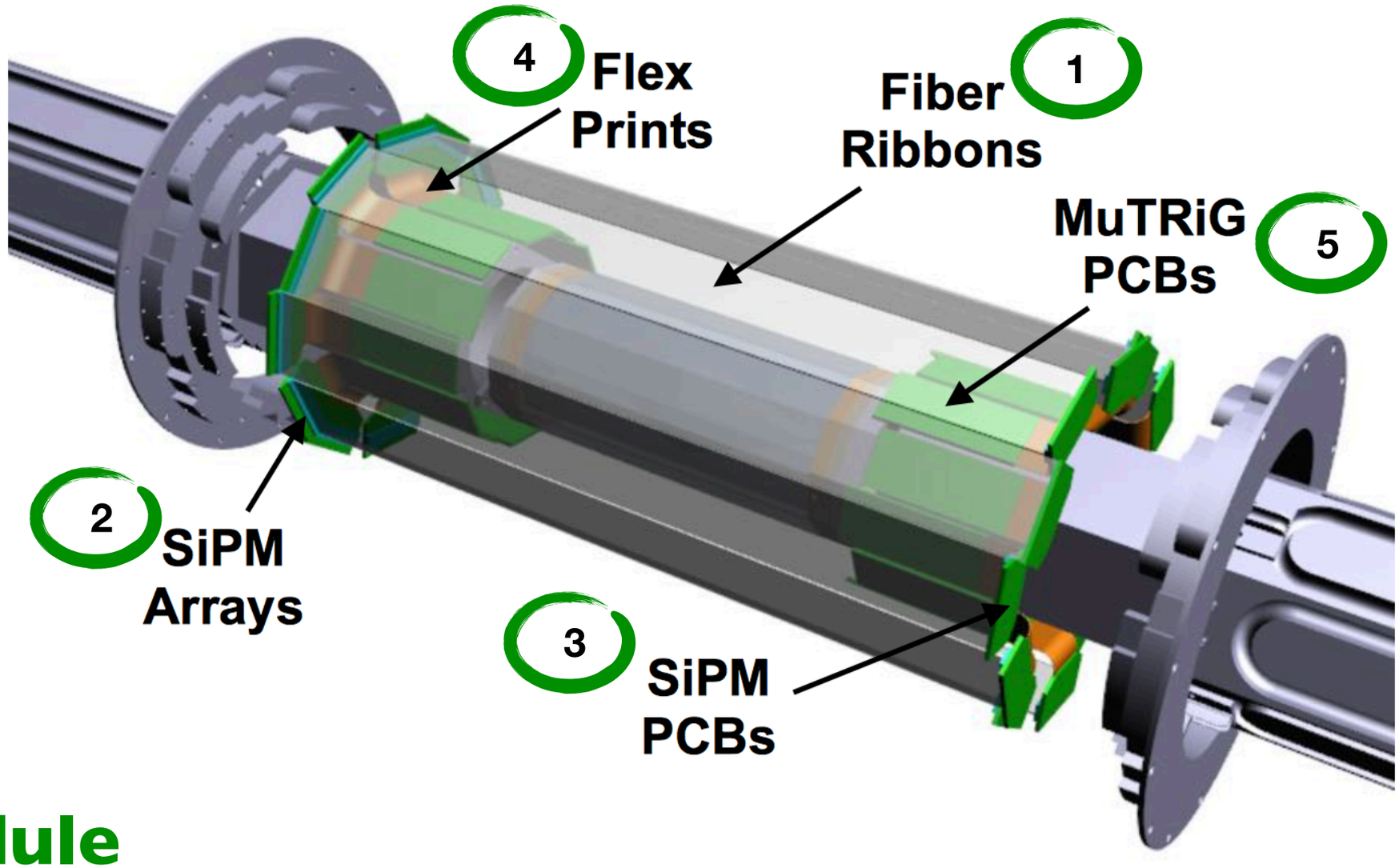


track to cluster match



- best timing: use tracking

The Mu3e SciFi Tracker: Outlook



Schedule

- Prototypes coupled to the new electronic (MuTRiG) in construction
- Full single module by the end of 2018
- SciFi tracker construction expected to start by the 2019

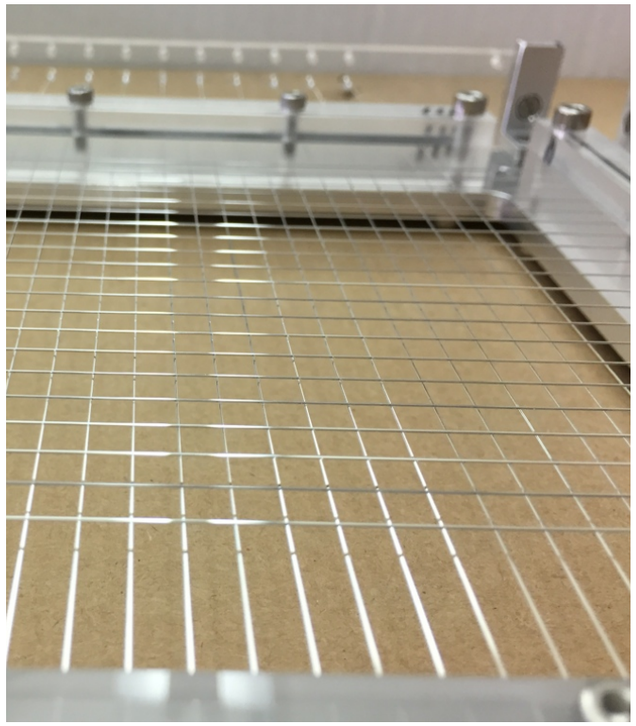
Muon Beam monitoring detector for High Intensity

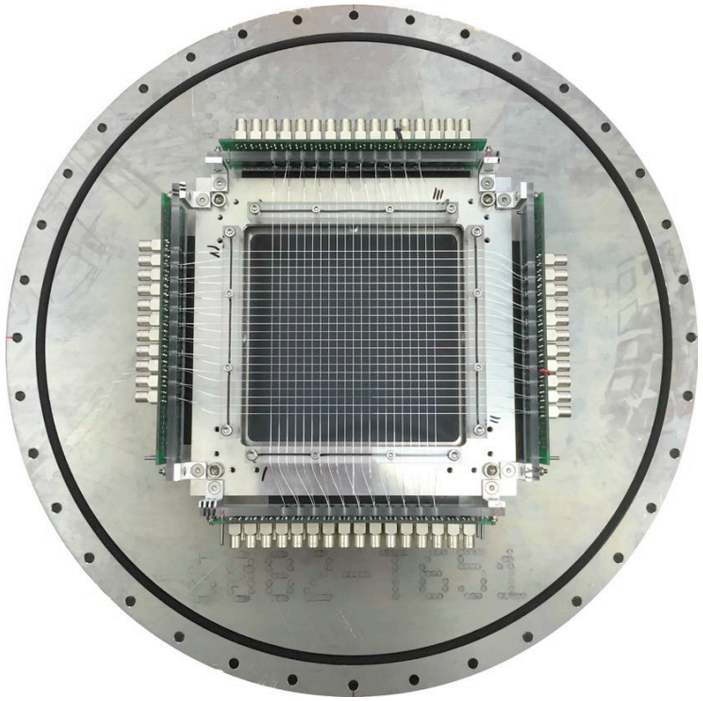
Aim

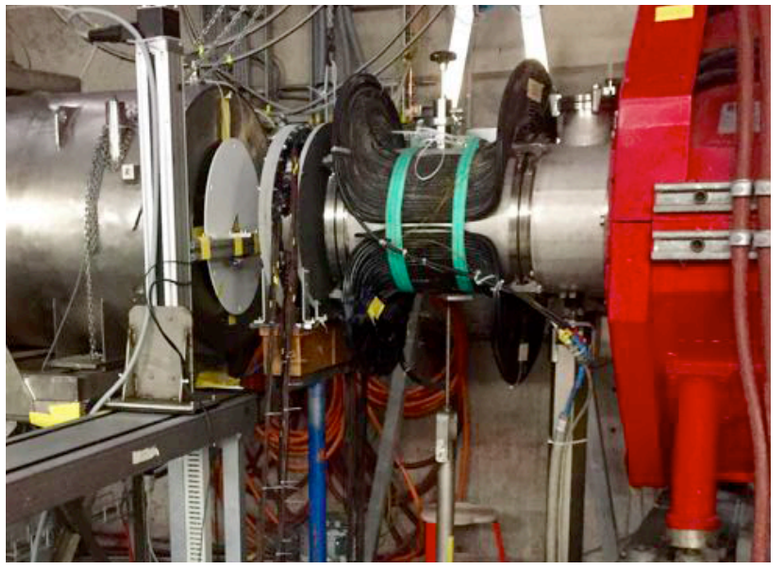
- real-time beam profiles and rates
- 2D reconstruction
- quasi-non-invasive
- high rate sustaining
- capable of particle ID
- working in magnetic fields

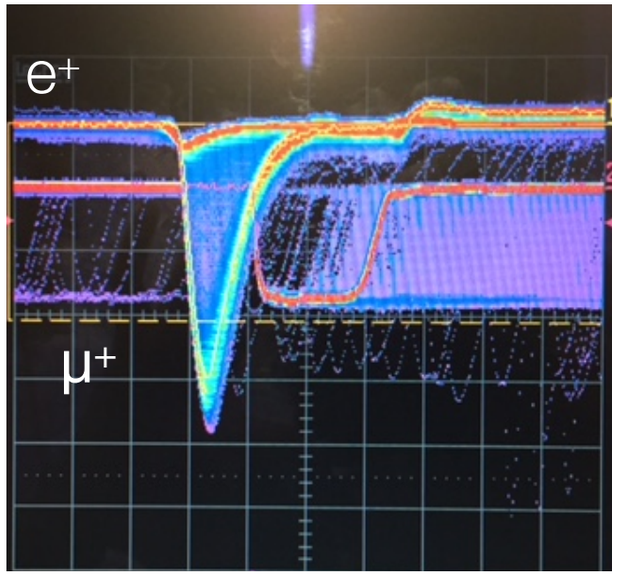
Parts

- 42 channels
- Squared 250 x 250 um^2 Saint Gobain multiclad BCF12 fibres
- 100 nm Al coating (Evaporation)
- Fibre lenght ~ 20 cm
- X and Y layers (Grid)
- Double readout
- Hamamatsu MPPC S13360-1350CS
- TDAQ: Wavedream; waveform digitizer



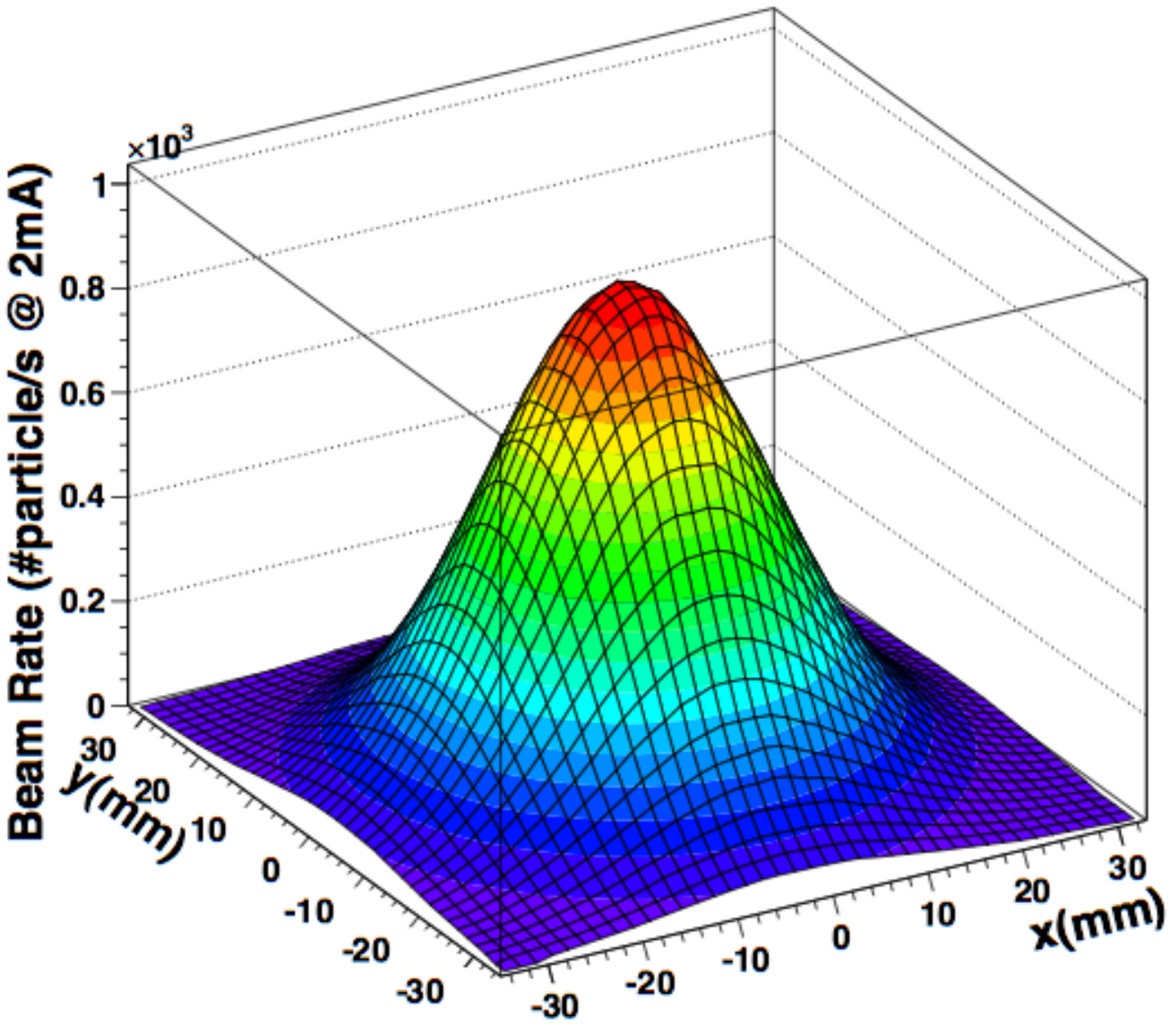






Results: beam profile and rate

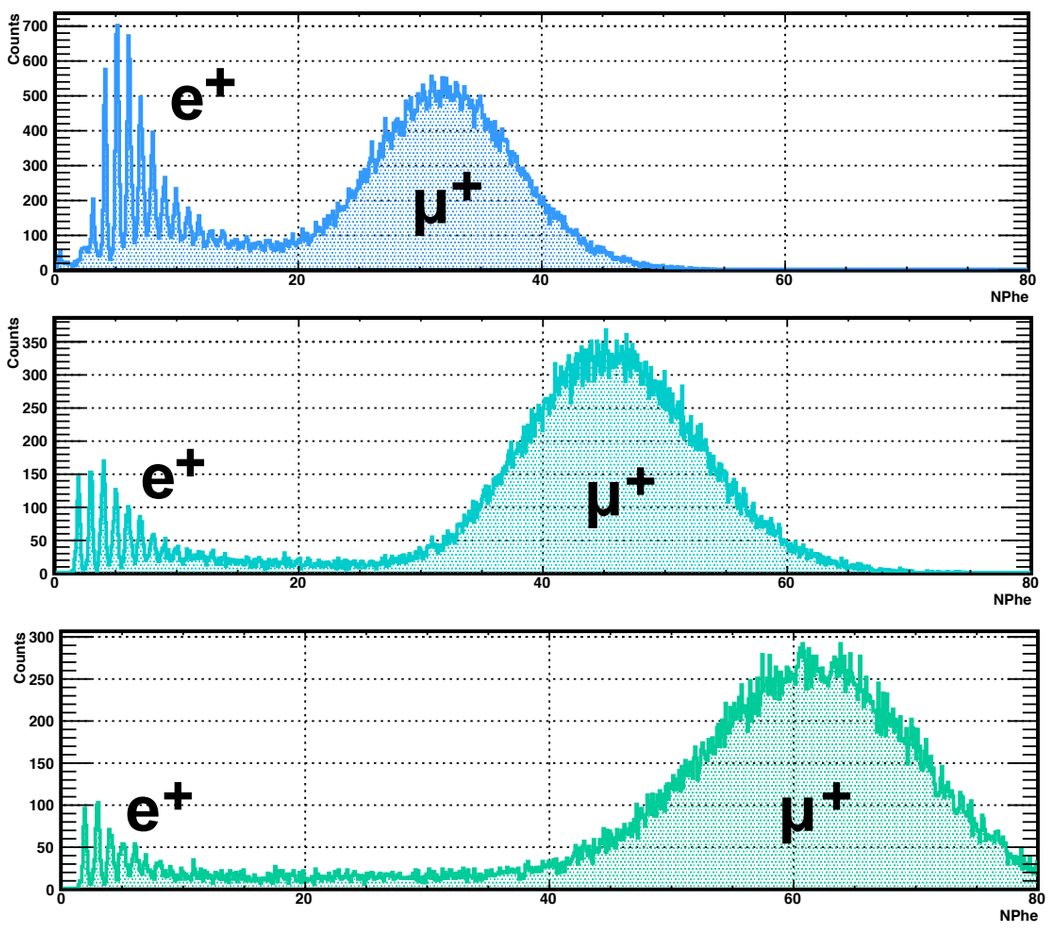
- Example of a beam profile at the **worldwide most intense** muon beamline (10^8 muon/s)
- Results in agreement with standard beam monitoring tools
- Positron beam profile too

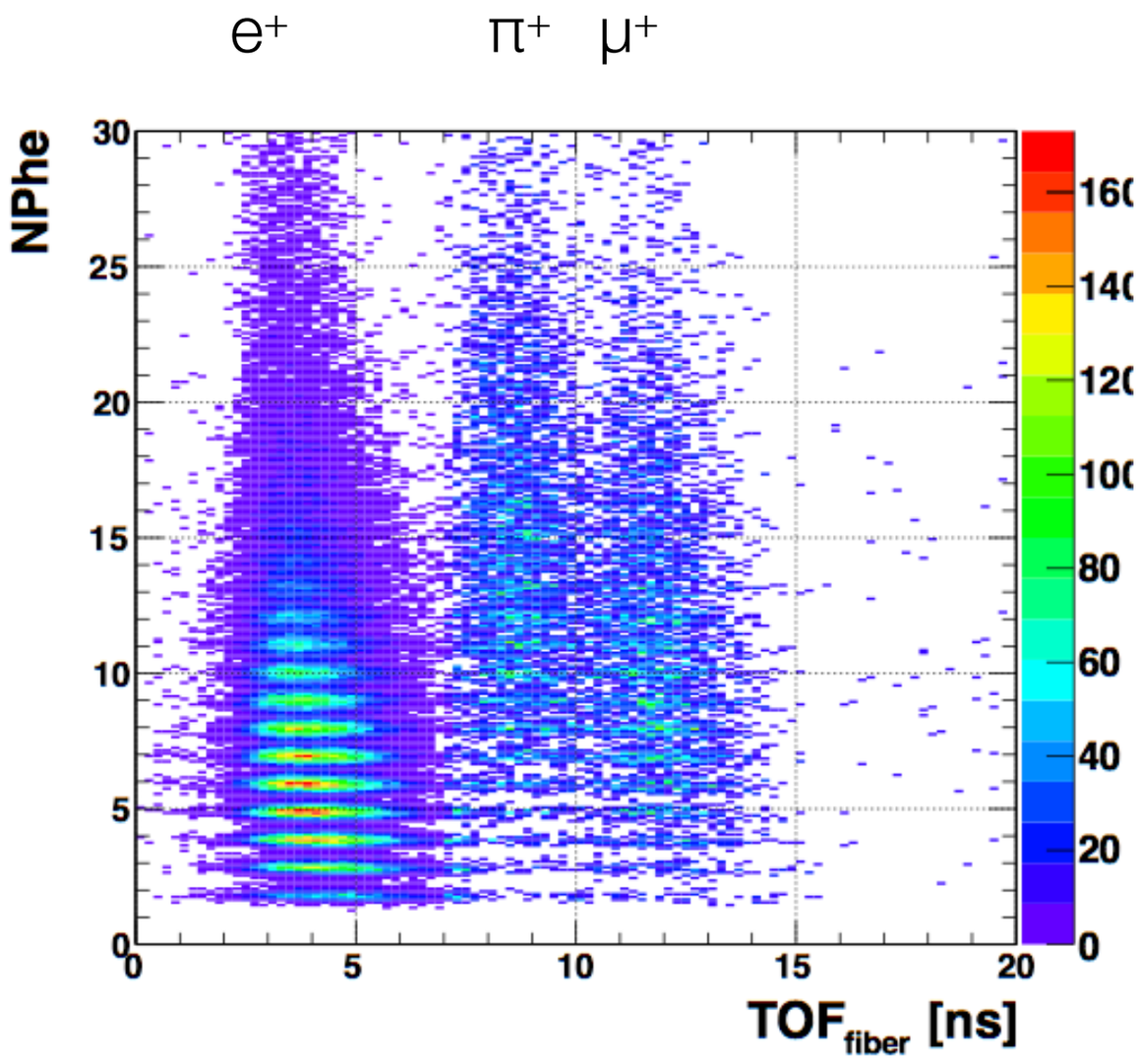


Real Data
after just ~ **few sec**

Results: particle identification

- Clear separation between highly and minimum ionising particles
- Particle identification also at 115 MeV/c (**m.i.p.**) adding the time of flight





Conclusions

- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of ~10^{-15} (Phase I) up to down ~10^{-16} (Phase II). Previous upper limit BR($\mu^+ \rightarrow e^+ e^+ e^-$) ≤ 1 x 10^{-12} @90 C.L. by SINDRUM experiment
- The MEG experiment has set a new upper limit for the branching ratio of **B(μ^+ -› e^+ γ) < 4.2 x 10^{-13}** at 90% C.L. (a factor 30 improvement with respect to the previous MEGA experiment and also the strongest bound on any forbidden decay particle)
- High granularity, relative fast and very low mass fiber tracker prototypes have been successfully built and tested, **matching the Mu3e experiment requirements**
  - High detection efficiency (also for minimum ionizing particle > 95%)
  - High position resolution (< 100 um)
  - Good timing resolution (<< 1 ns)
  - Minimal thickness (< 0.004 X_0)
  - Negligible optical cross-talk (< 1%)
  - High rate (1 MHz/fiber)
- A full MC simulation framework based on GEANT4 and integrated by the photosensor response, the DAQ and the reconstruction algorithm have been implemented with a **very good agreement between data and MC**
- The Mu3e SciFi tracker R&D has been completed: **A full module is under construction (kuraray SCSF78 J, Hamamatsu S13552-HQR MPPC array, MuTRiG readout)**
- The MEGII SciFi beam monitoring detector R&D has been completed: The main feature given by the measurements of the **full beam characteristics, particle ID and quasi non-invasive**. A first detector has been built and a movable version is under preparation

Mu3e SciFi group members

S. Corrodi and C. Grab, ETH Zurich
S. Bravar and A. Damyanova, University of Geneva
M. Hildebrandt, A. Papa and G. Rutar*, Paul Scherrer Institut
R. Gredig*, University of Zurich

(*) PhD completed

MEGII SciFi group members

D. Grigoriev[1], P.-R. Kettle[2], M. Hildebrandt[2], E. Ripiccini[3], G. Rutar[2], Y. Yudin[1]
([1]) Novosibirsk State University, 630090 Novosibirsk, Russia
([2]) Paul Scherrer Institut PSI, 5232 Villigen, Switzerland
([3]) now at CERN, 1211 Geneva, Switzerland SciFi group members