SciFi timing tracker

R&D status

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EPFL

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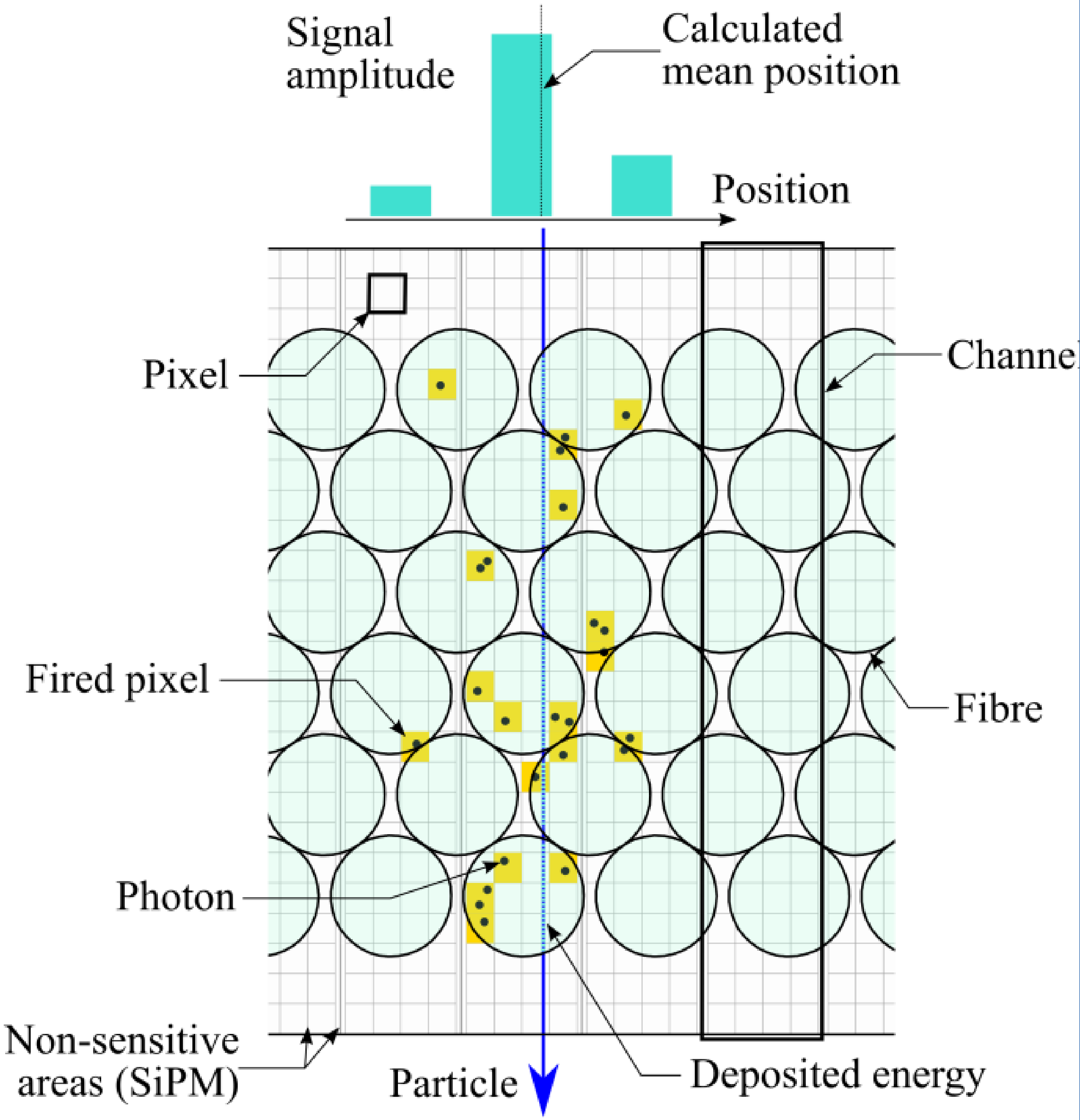
Introduction

- SciFi tracker basics, principle and limitations
- Expected performance for spatial and time resolution, efficiency
- Implementation of the readout with the STiC3 chip
- Calibration and parameter scanning for thresholds and PLL settings
- Large beam telescope with STiC3 at DESY 10.2019
- SND@LHC a SciFi timing implementation
- Discussion of the performance and characteristics
- What we learnt and outlook

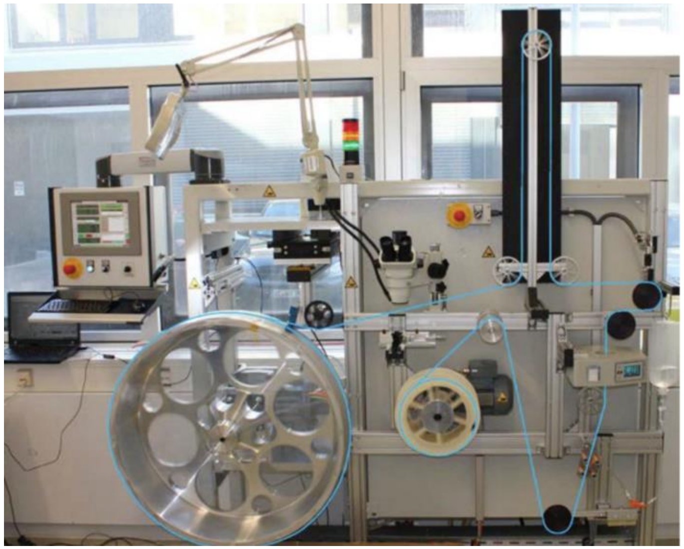
SciFi the basic principle

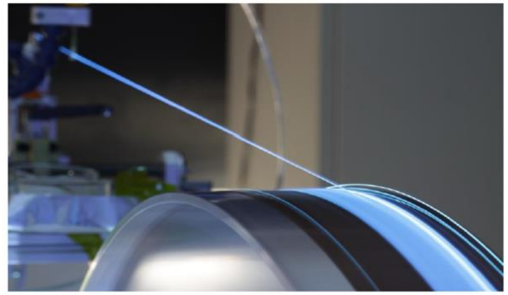


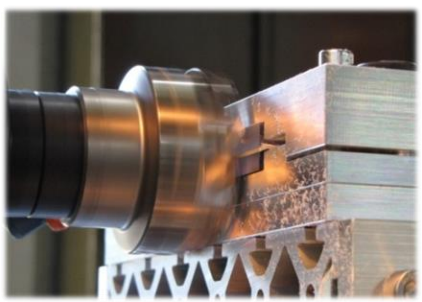
- Fibres are arranged in a tight packed array forming fibre mats
- The thickness of the fibre mat can be varied to customise the detector for different applications.
- A single type of scintillating fibre is used so far for all applications Kurraray SCSF-78MJ, a blue emitting PS fibre with high light yield (8000 ph/MeV) and fast decay time of 2.8ns.
- The signal of a single traversing particle is spread over several fibres and also several readout channels.
- The illustration shows the fibres as seen by the photo-detector and the photo-detector pixels and readout channels.

Fibre mat & module production

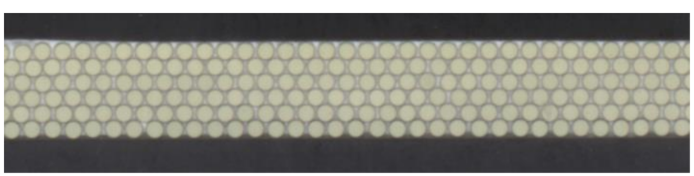
1. Fibre quality check 2. Winding 3. Unforming, lamination 4. Optical cuts and QA 5. Module production





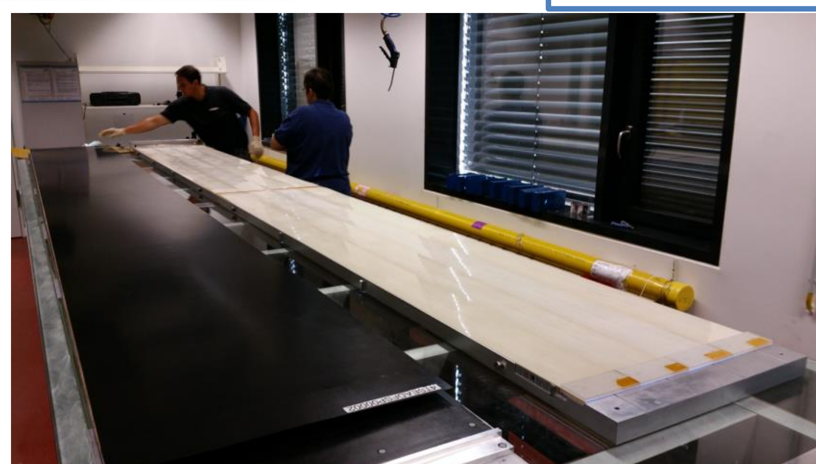


Optical cut



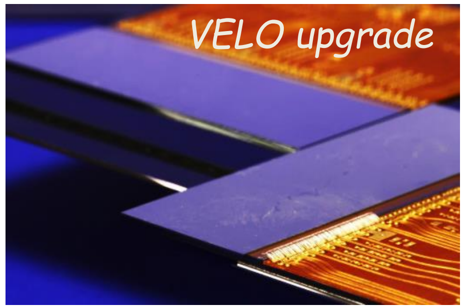
6L 1.35 mm
7L 1.55 mm

8 mats assembled into a module



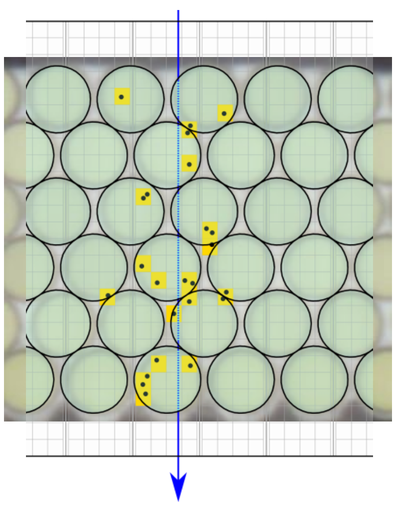
Light detection – challenge

X = 220 μm
X/X_0 = 0.23%



Signal = O(10k) e^-
Noise = O(200) e^-
} Collected on 1 pixel

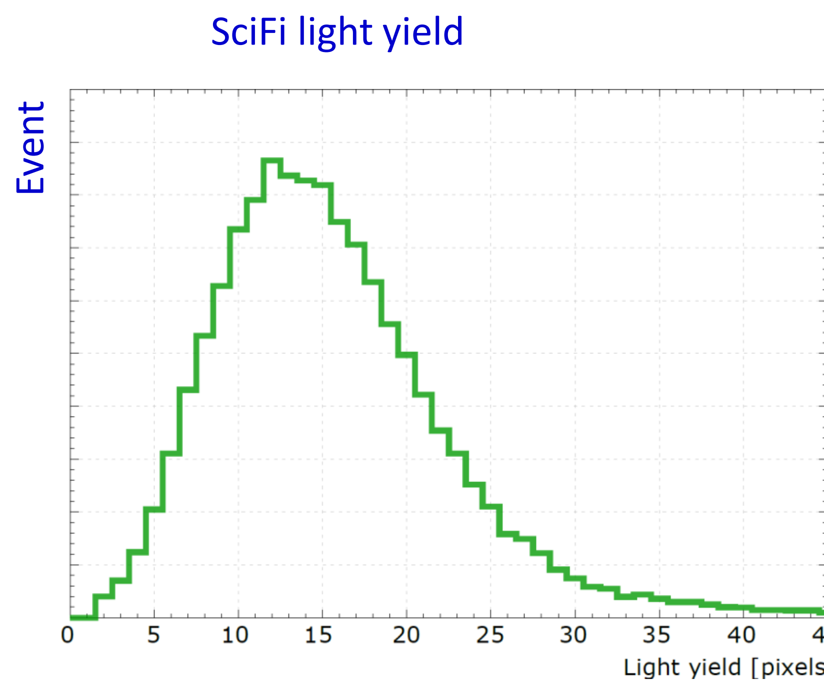
X = 1.35 mm
X/X_0 = 0.41%



Signal

Energy deposit

× scint. light yield
× light capture
× light attenuation
× photon det. eff.



Light detection – challenge

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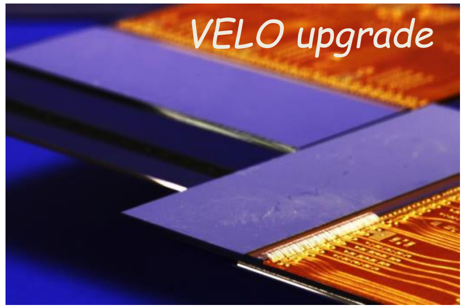
$X/X_0 = 0.23\%$



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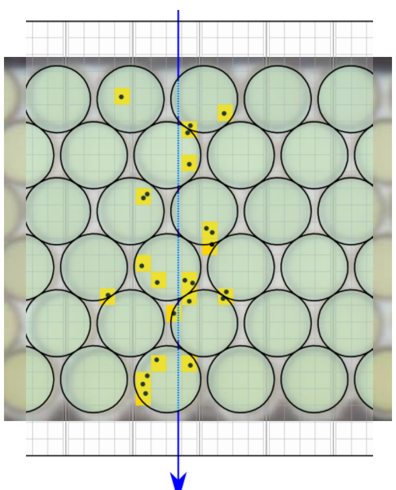

Signal

Energy deposit

× scint. light yield
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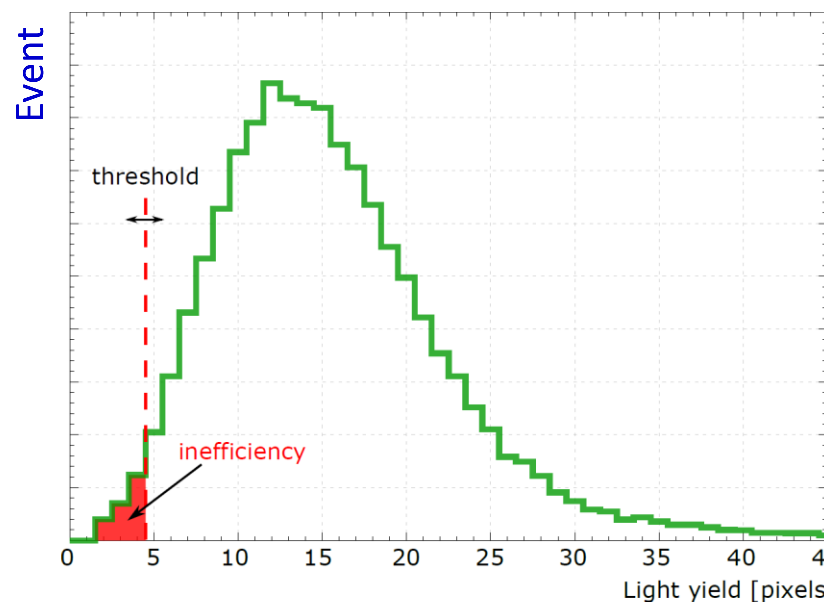
SciFi light yield



Light detection – challenge

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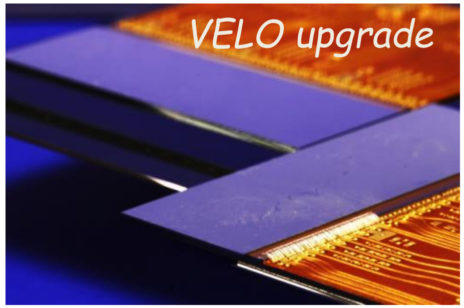

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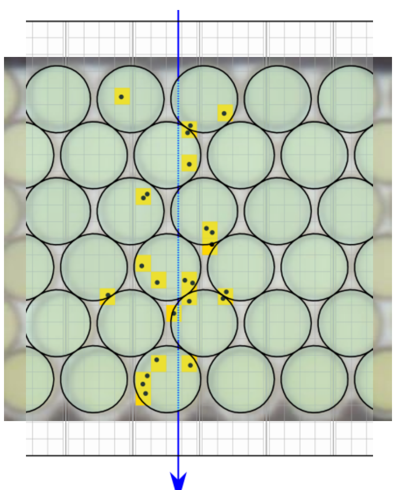


Signal

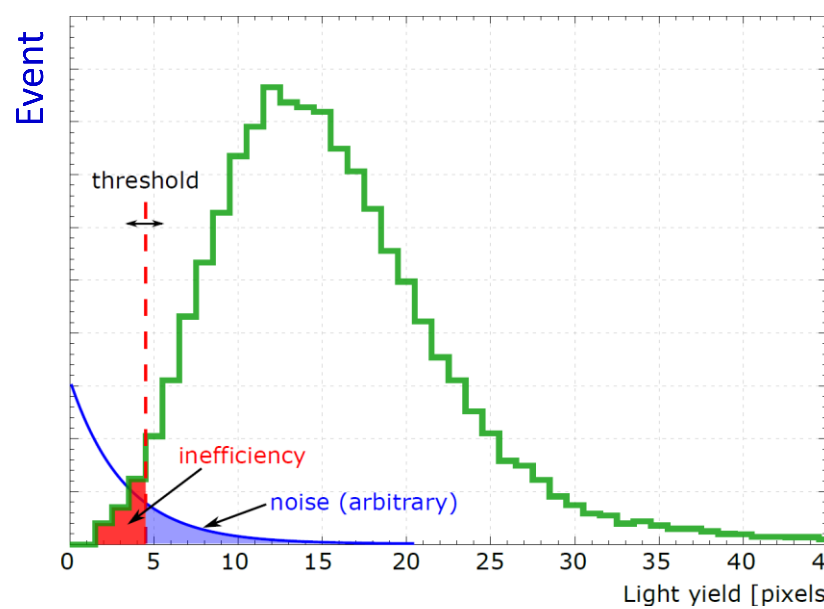
Energy deposit

× scint. light yield
× light capture
× light attenuation
× photon det. eff.

Noise

From 2-3 ch

SciFi light yield

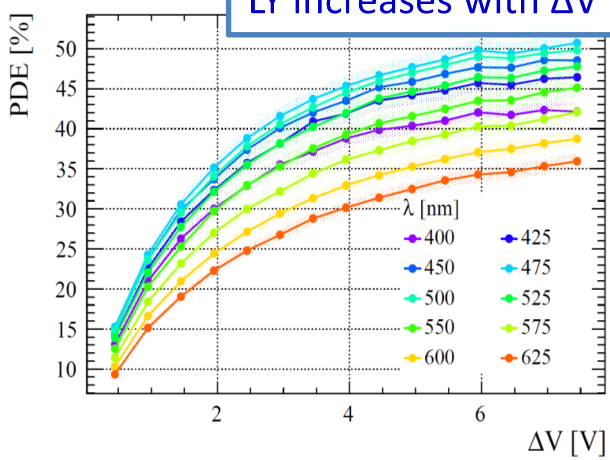


Design choices:

- Large pixels
- Optical isolation (trenches)
- Fast recovery time (70ns)
- 128 multichannel array
- 105µm thick epoxy entrance window

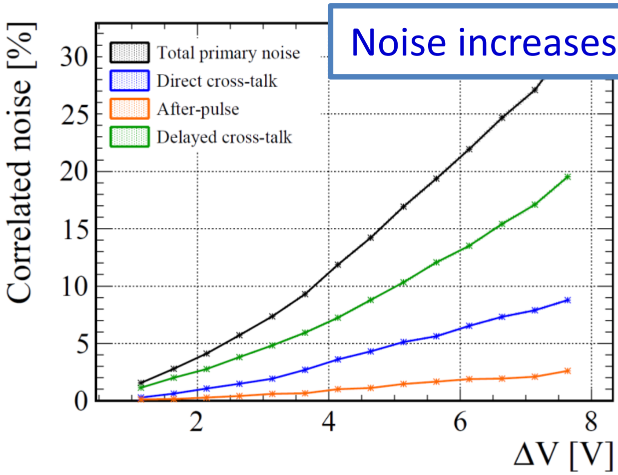
SiPM for the SciFi tracker

LY increases with ΔV



[1]

Noise increases with ΔV



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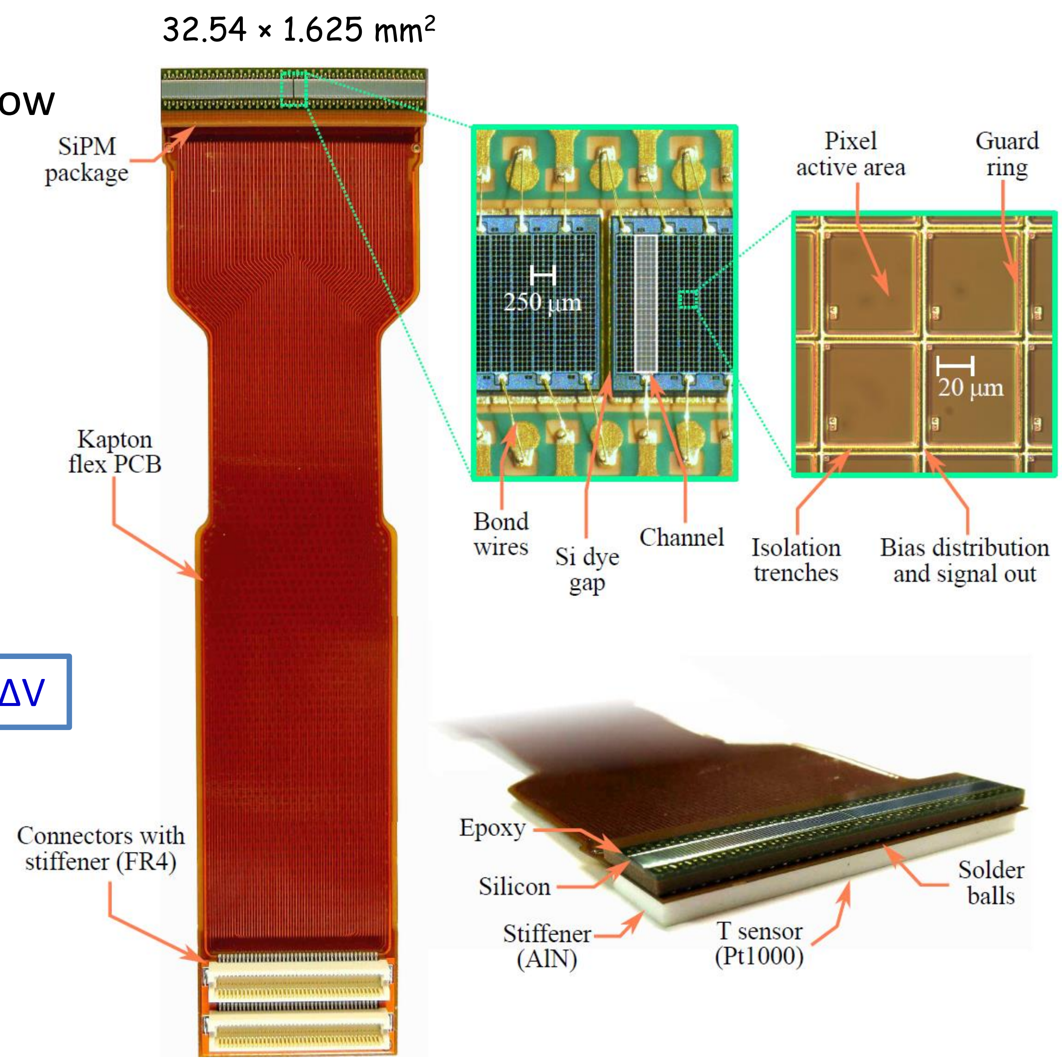
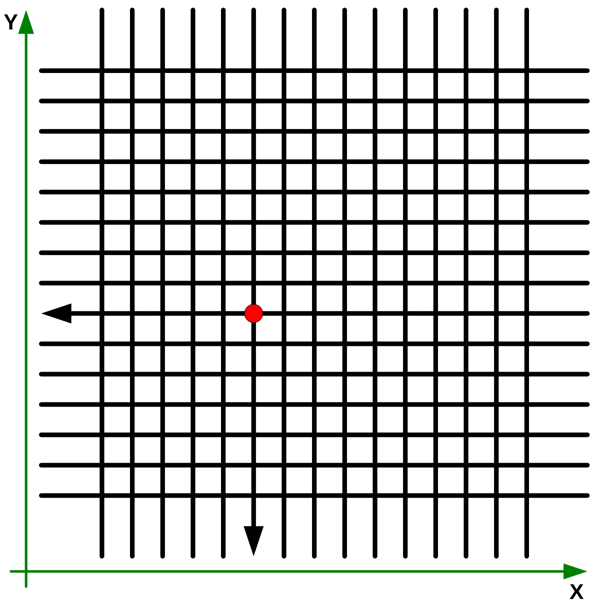
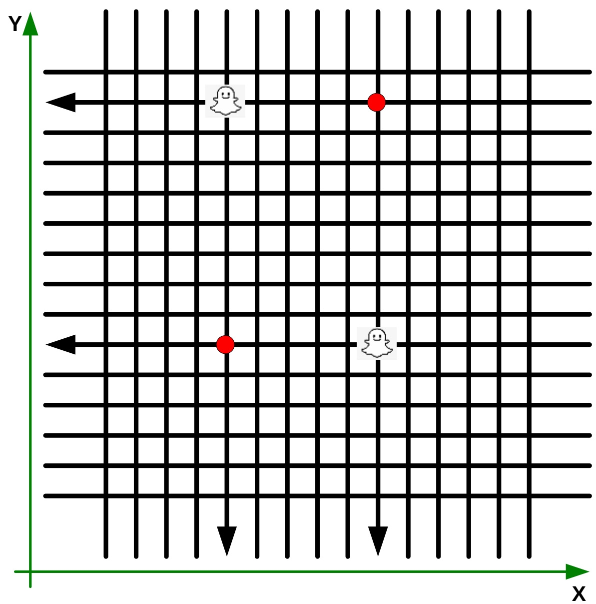
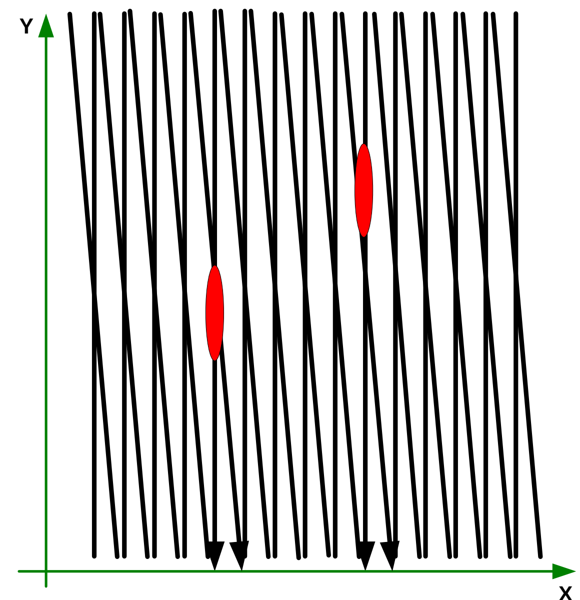


[1] O. Girard, G. Haefeli, A. Kueonen, L. Pescatore, O. Schneider, M. Stramaglia, ArXiv:1808.05775

x-y detection planes ghost problem, the SciFi is not a pixel detector!







A single hit in a x-y plane produces no ambiguities. Situation for beam telescope, and single particle cosmic rays.

Multiple hits produce ghost hits and ghost tracks. Ghost hits can be rejected by straight track condition. Ghost tracks can still be difficult to reject.

Stereo layers are used to avoid ghost hits in LHCb. Spatial resolution in y direction is bad.

Comparing the SciFi tracker technology with Si-strip or other tracking detectors

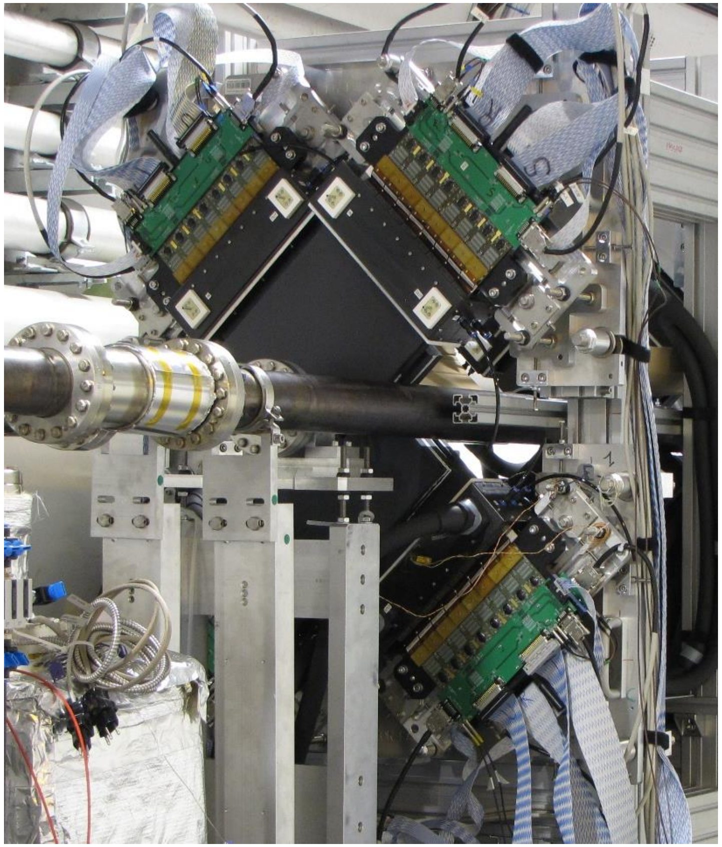
The SciFi tracker technology is in competition with Si-strip detectors but:

- ☹ They have worse spatial resolution, we achieved σ_x=32µm with short SciFi modules and analog readout but typically σ_x>50µm.
- ☹ SciFi is not radiation hard (LHCb inner region is 30kGy and at the SiPM location $4.5 \cdot 10^{11}$ n_{eq}/cm^2 which requires cooling to -40°C in LHCb.
- ☹ For long tracker modules like in LHCb (2.5m) the efficiency is at order of ~97% or lower depending on the radiation and detector region.
- ☹ Occupancy can be a problem for long modules (LHCb Uprage II).
- ☹ The fibre layers are significantly thicker than silicon (1.35mm vs 0.2mm) which is producing large clusters and high occupancy with angle tracks.
- ☺ Excellent scaling capability, readout channels increases with module "edge length" and not with surface – silicon is also limited to short modules.
- ☺ Good spatial resolution large surface is the best application.
- ☺ Low cost, easy handling, only low voltage, no gas, no service in the active area needed.
- ☺ The fibres are at the same time detection and transport medium in the active region, allows to detect in B-field environment (medical applications with MRI)
- ☺ Timing helps to get more applications for SciFi and can be perfect to suppress noise.

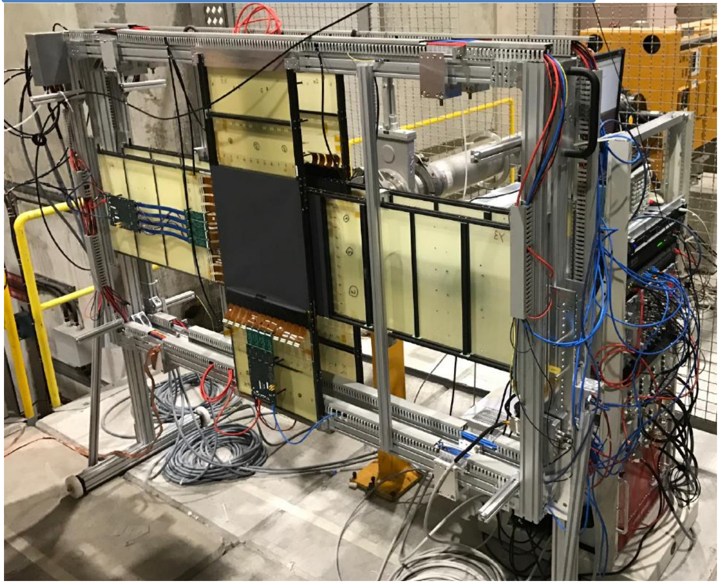
SciFi detectors with stereo layers

LHCb (0.6Mchannels

BGV at LHC (14Kchannels)



SHiP Charm @ SPS (6Kchannels



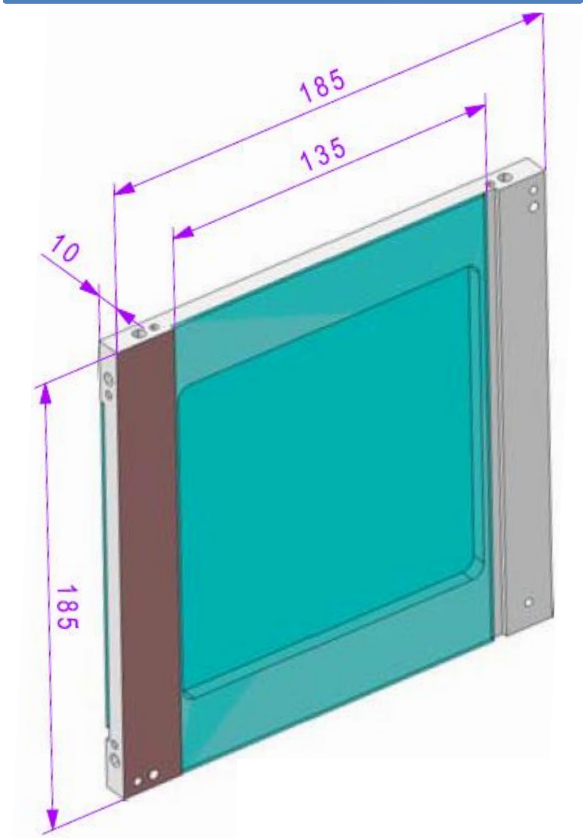
2^{nd} generation SciFi beam telescope with timing

7 layer fibre mats

25 direct photons detected

No mirror but a light injection system

X/X_0=1%

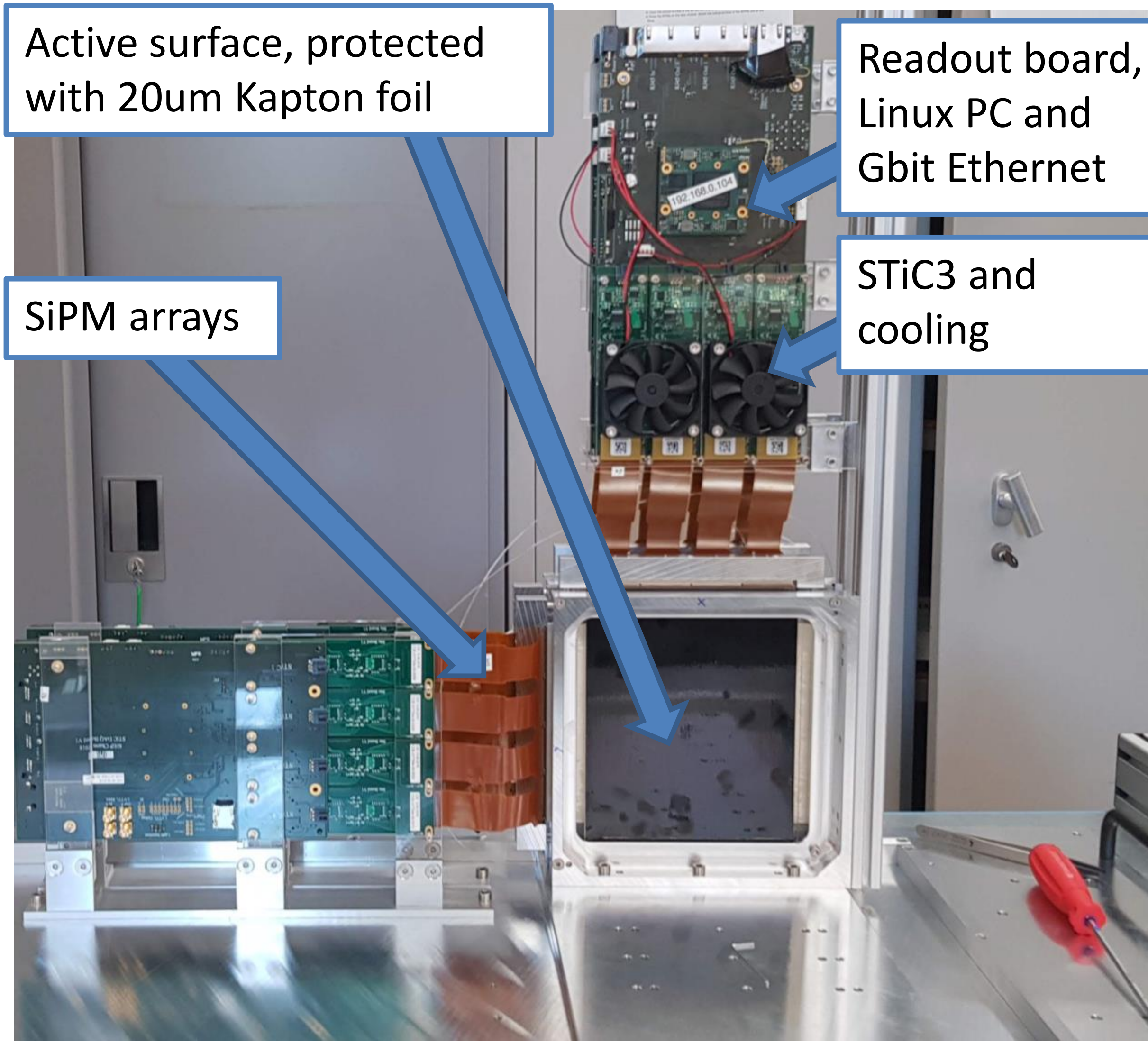


Active surface, protected with 20um Kapton foil

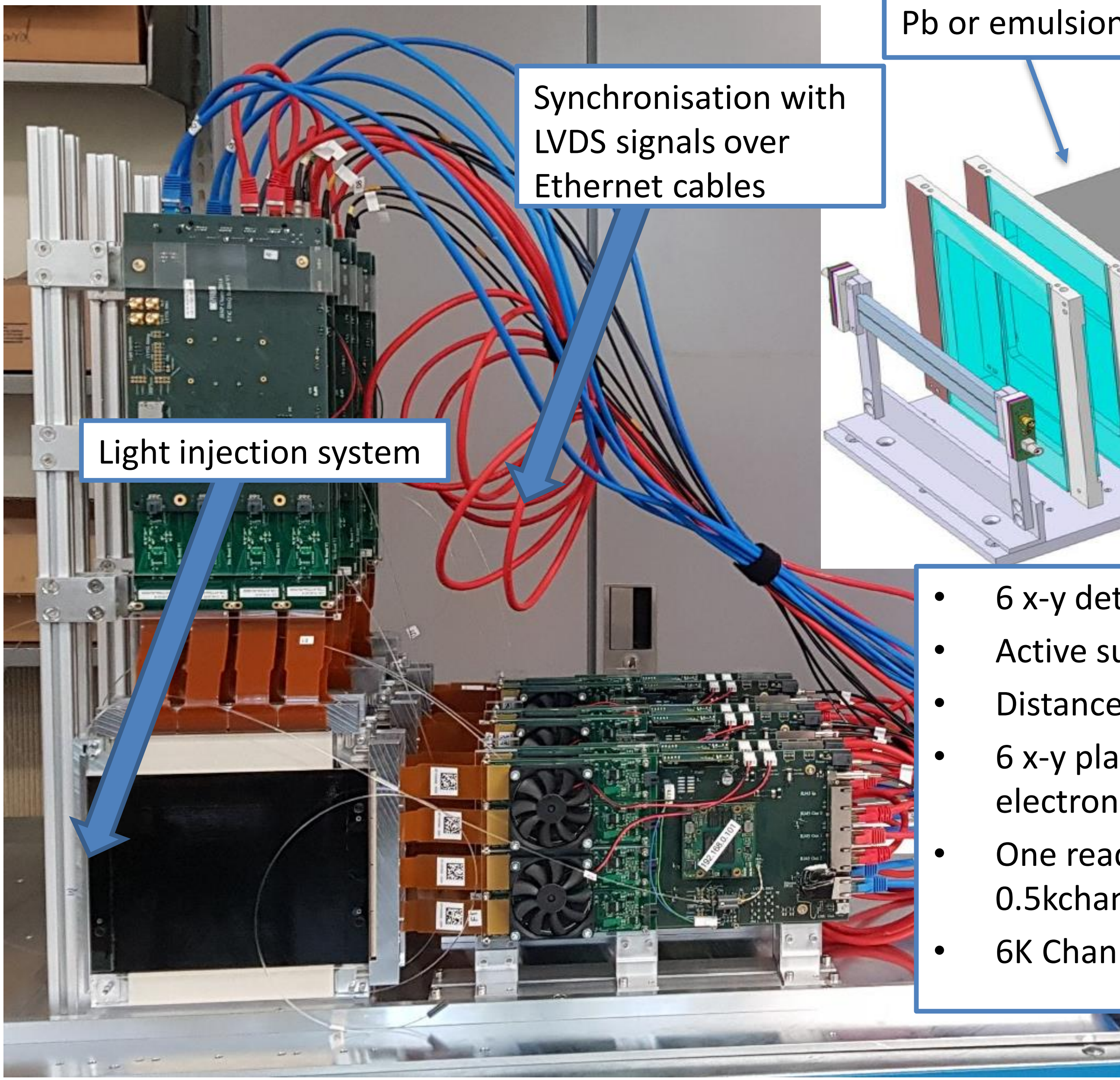
SiPM arrays

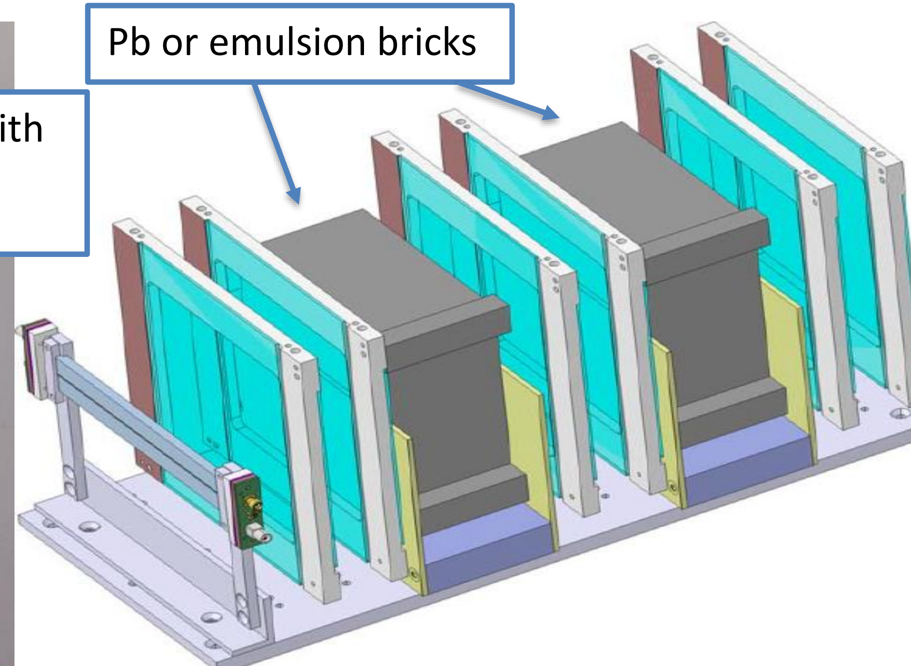
Readout board, Linux PC and Gbit Ethernet

STiC3 and cooling

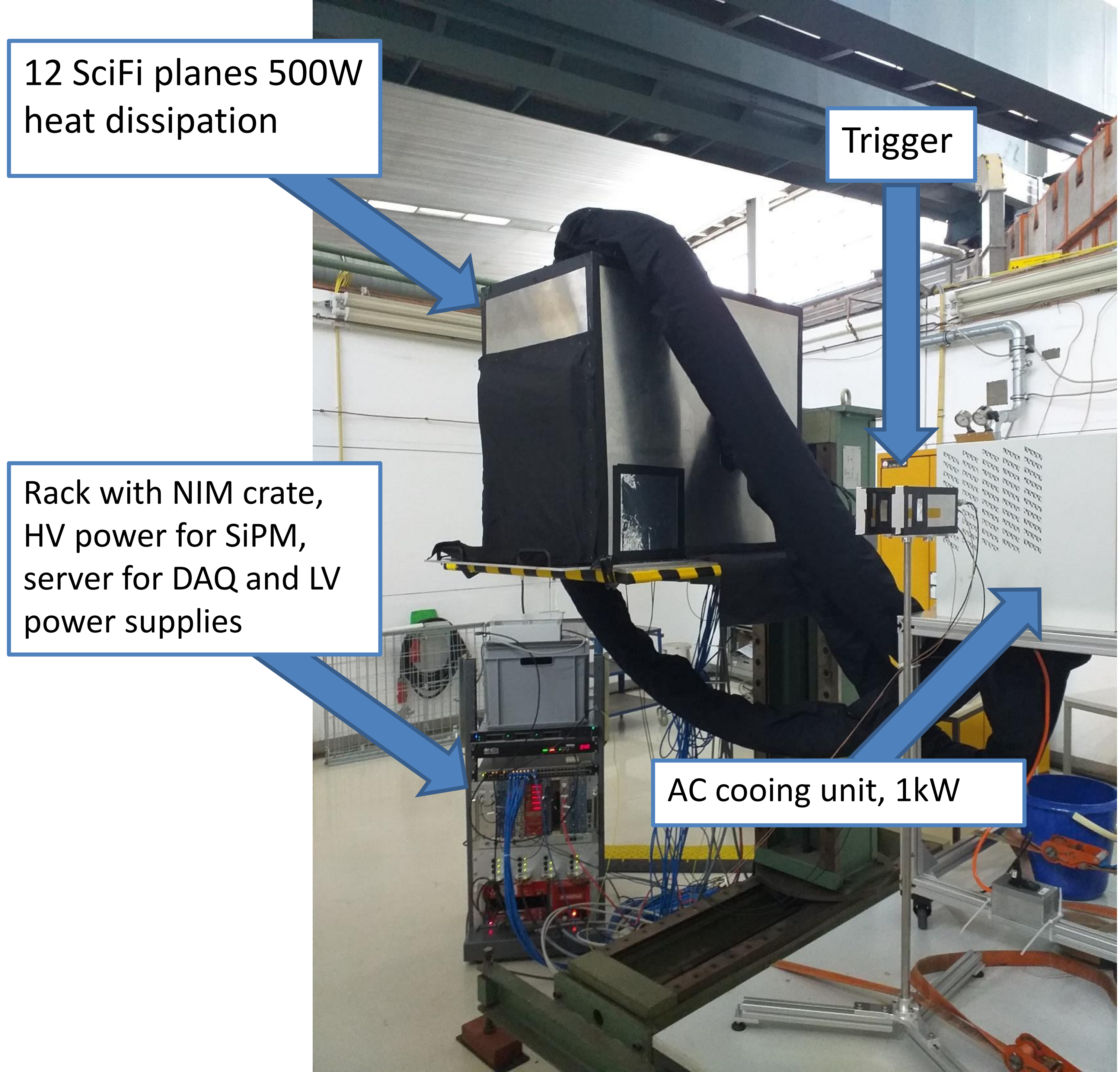


Telescope for timing R&D with SciFi tested at DESY





- 6 x-y detetion planes
- Active surface 133mm x 133mm
- Distance between x-y layers is 9mm
- 6 x-y planes are equipped with electronics
- One readout board acquires 0.5kchannels from (4 SiPM arrays)
- 6K Channels in total


12 SciFi planes 500W heat dissipation
Trigger
Rack with NIM crate, HV power for SiPM, server for DAQ and LV power supplies
AC cooing unit, 1kW

Time measurement with SciFi

Coincidence Time Resolution CTR for a system measuring the 1st arriving photon in two identical scintillators:

1. $$CTR_{1st} = 2.18\sqrt{\frac{\tau_r \cdot \tau_d}{N_{ph}}} = 2.18\sqrt{\frac{0.2ns \cdot 2.8ns}{25}} = 326\text{ps}$$ [2]

τ_r : Scintillator rise time (200ps, estimated value)

τ_d : Scintillator decay time (2.8ns for the SCSF-78)

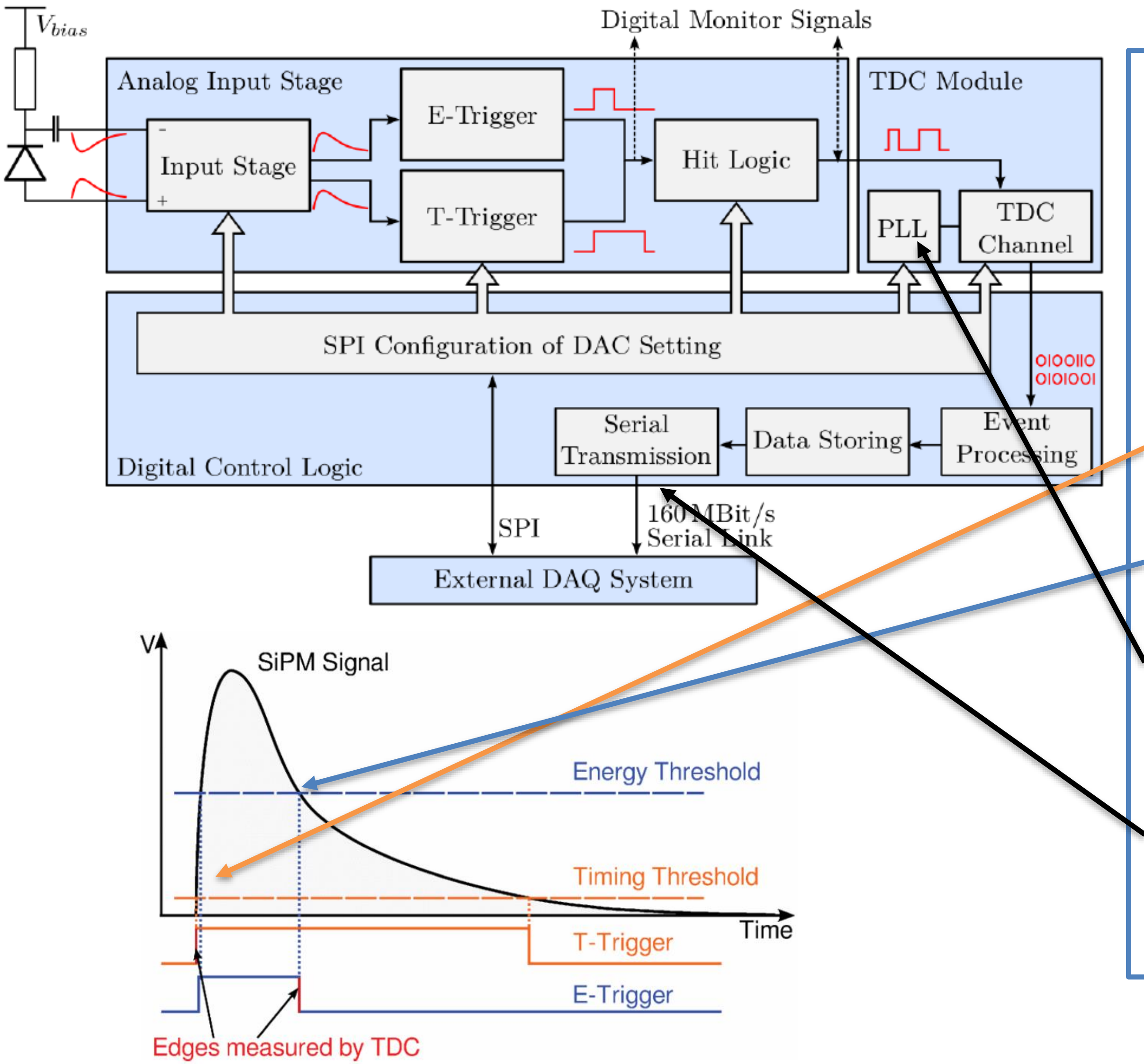
N_{ph} : Number of detected photons (Light yield for direct photons in a SciFi tracker 25 for the telescope planes)

Approximation with the condition that: $\tau_d \ll \tau_r \cdot N_{ph}$

2. $$CTR_{1st} = 3.33\,\frac{\tau_d}{N_{ph}} = 3.33\,\frac{2.8ns}{25} = 373\text{ps}$$ [2]

[2] S.Gundacker, R.M. Turtos, E. Auffray, P. Lecoq. Nuclear inst. and Methods in Physiscs Research, A 891 (2018) 42-52

STiC3[3] readout chip integrated for SciFi readout



- Optimised for ToF-PET applications (large SiPMs with order of 100 times more signal than SciFi trackers)
- Time measurement 57.5ps fine time steps
- Time measurement with T-threshold (0.5ph)
- Amplitude measurement with E-threshold (4-7ph), ToT
- PLL for synchronisation and time measurement using 1.84ns course time steps
- Fast data interface with max hit rate of 2.8MHz

[3] T. Harion, K Briggl, H Chen, P Fischer, A Gil, V Kiworra, M Ritzert, H-C Schultz-Coulon, W Shen and V Stankova, 2014 JINST 9 C02003

Challenges to use STiC3 for SciFi tracker readout

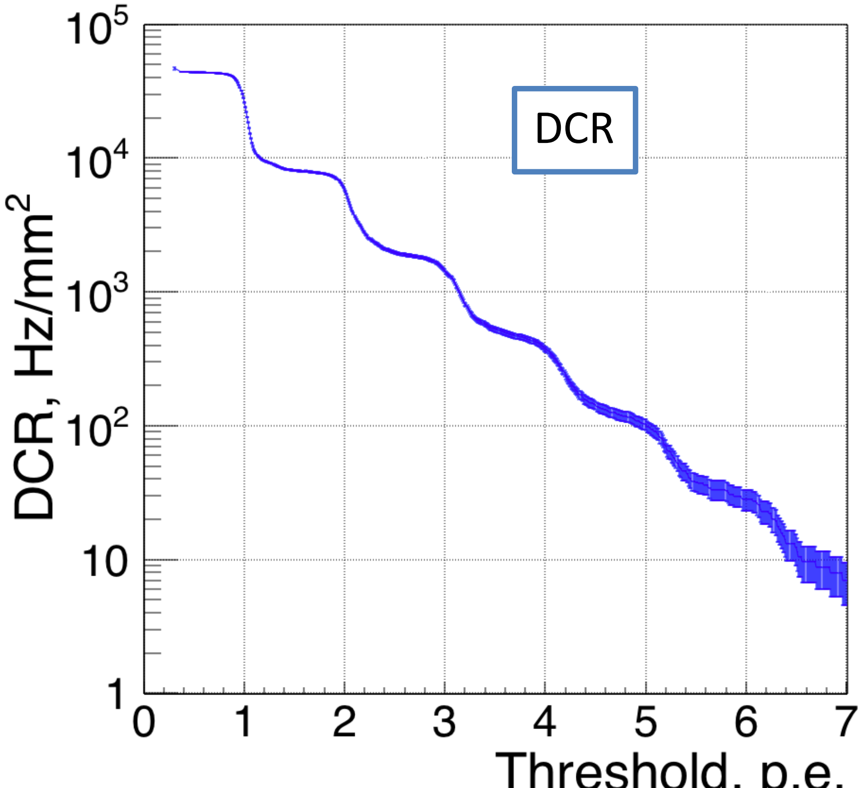
- The large number and high density of detector channels compared to the original purpose (ToF-PET). The high power consumption requires active cooling (84mW per channel, 43W per board).

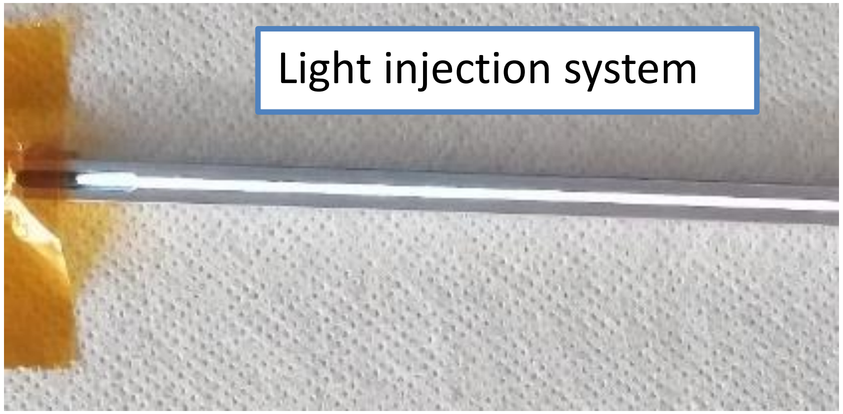
  (note that part of the power consumption is also due to the large FPGA on each readout board)
- Low signal compared to ToT-PET LYSO from 512keV photons (1500 photons vs 25 for a SciFi tracker), E-threshold dynamic range is not adapted, threshold steps about 1pe. Getting high hit efficiency requires low noise cut for the E-threshold.
- Noise suppression in FPGA desired but difficult (decoding of the time stamp data almost needs a CPU, LSFR)
- Large channel to channel variations (amplifier gain)
- PLL characteristics variations, variable time offsets after reset
- Missing on chip electrical injection system for time calibration

Calibration

The calibration procedure should not required any special lab equipment as x-y table for scanning or laser system such that it can be performed in situ.

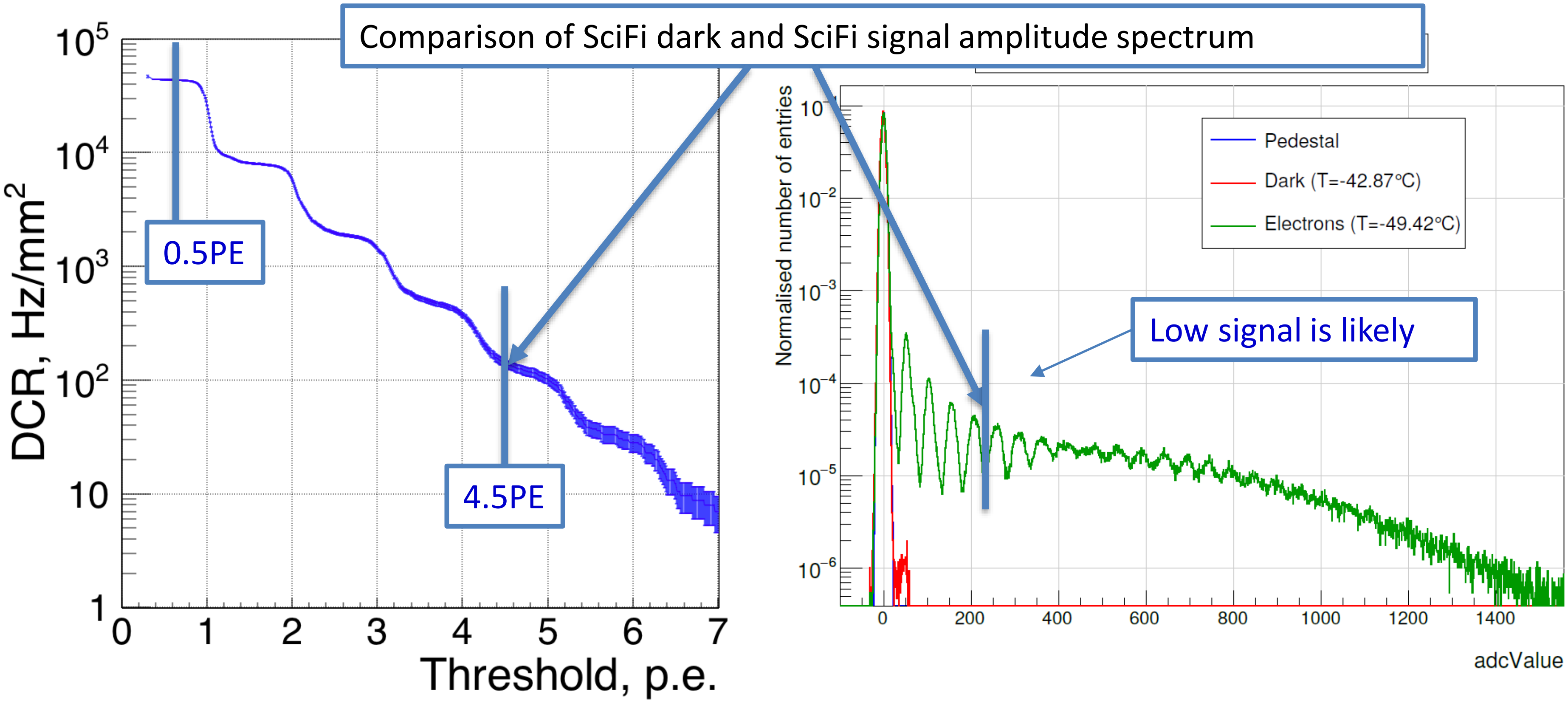
- Use DCR of the SiPM as "electrical" signal generator
- Use VCSEL light injection system for periodic injection of light pulses for PLL and delay calibration



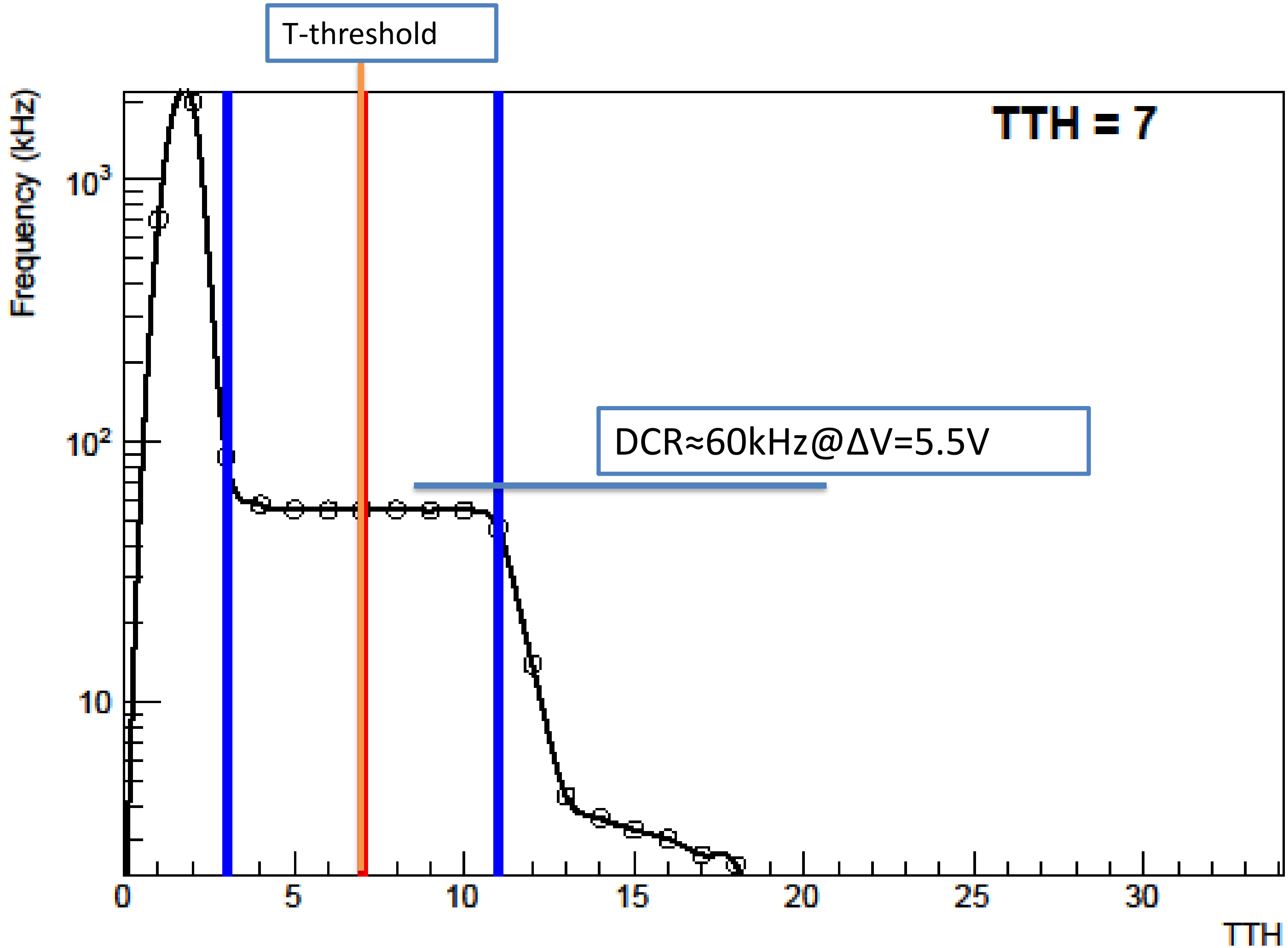


Threshold scan

- The dark noise (DCR) from the SiPM can be used for the T-threshold and E-threshold adjustment.
- The signal amplitude depend on SiPM V_{bias} and T, channel to channel variations are small $\approx \pm 10\%$ due to V_{bd} variations.



T-threshold scan

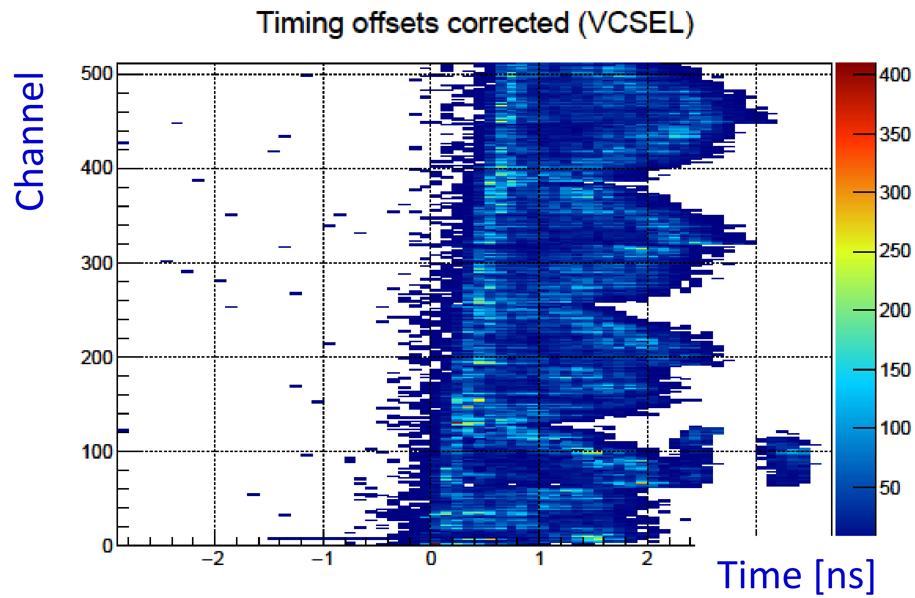


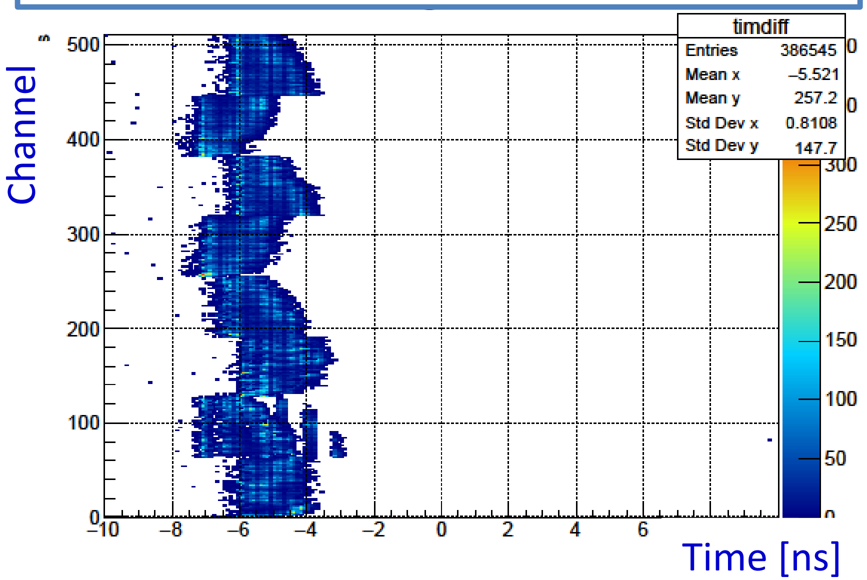
Calibration with VCSEL light injection system

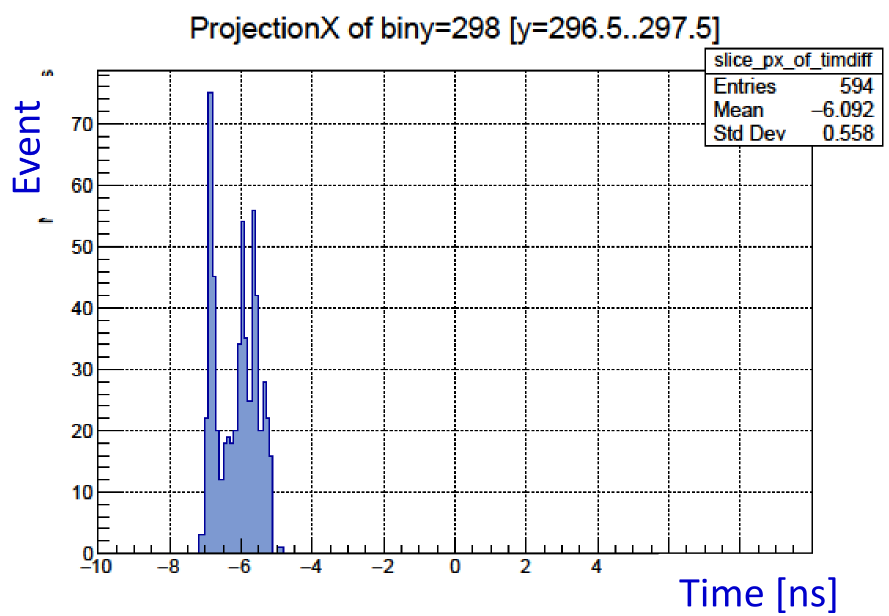
- The “leaking fibre” light injection system for SciFi trackers (used and developed for LHCb) injects light into all channels at the same time.
- No mirror, only direct photons can give good timing information.
- A large signal on all channels simultaneously produces bias voltage transients, saturation of FE-chip DAQ.
- A VCSEL laser is used in On/OFF mode to inject a fast light pulse.

Calibration with VCSEL light injection system

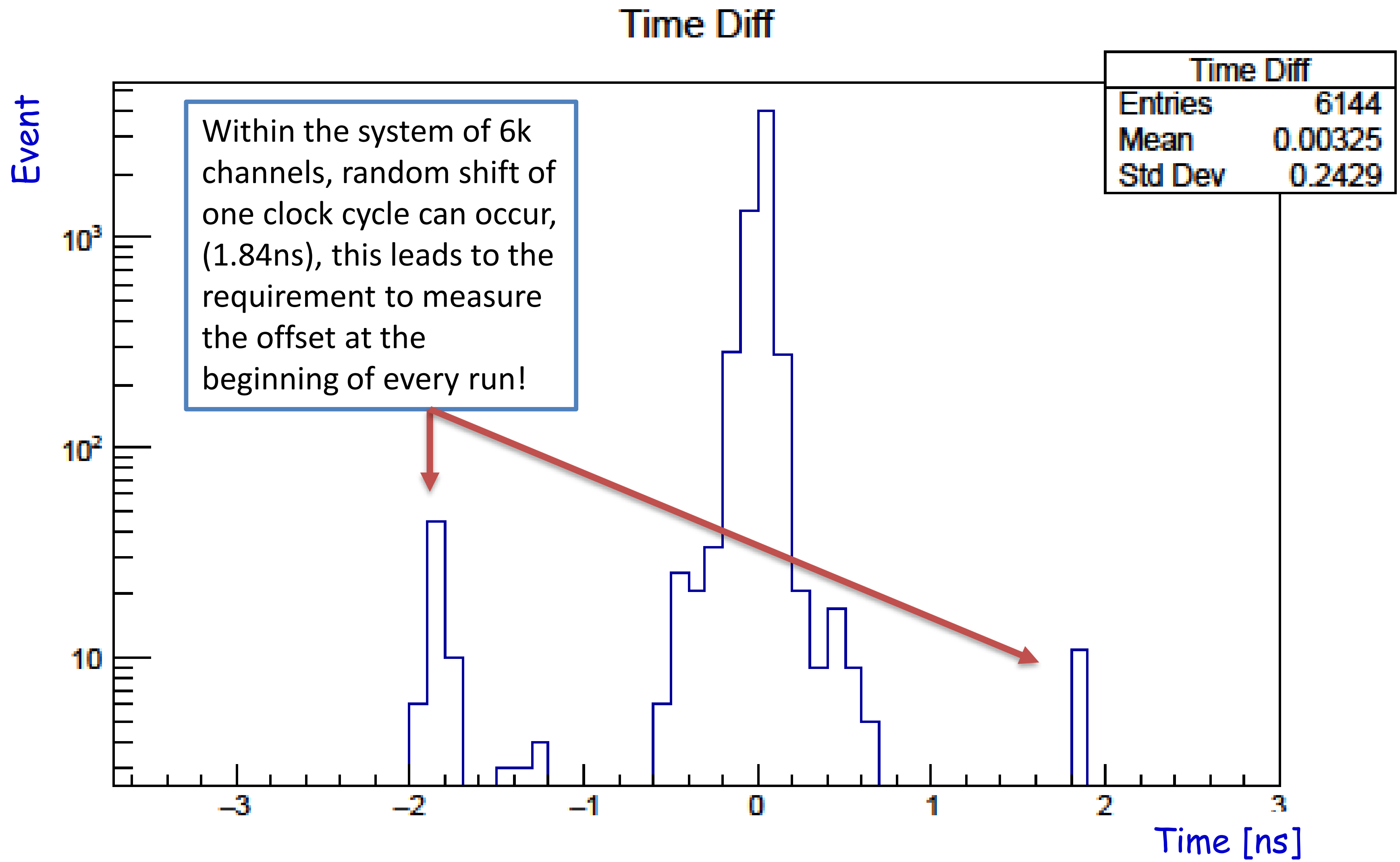
- Time offset for each channel has to be compensated with the light propagation delay in the fibre.
- Rising edge detection of the $t_{hit} - t_{trigger}$ distribution
- A fixed interval light injection allows to measure the time between two consecutive hits in a channel. The time difference has to correspond to the injection interval and allows to scan and verify the PLL adjustment.







Comparison the time offsets between Runs (reset)



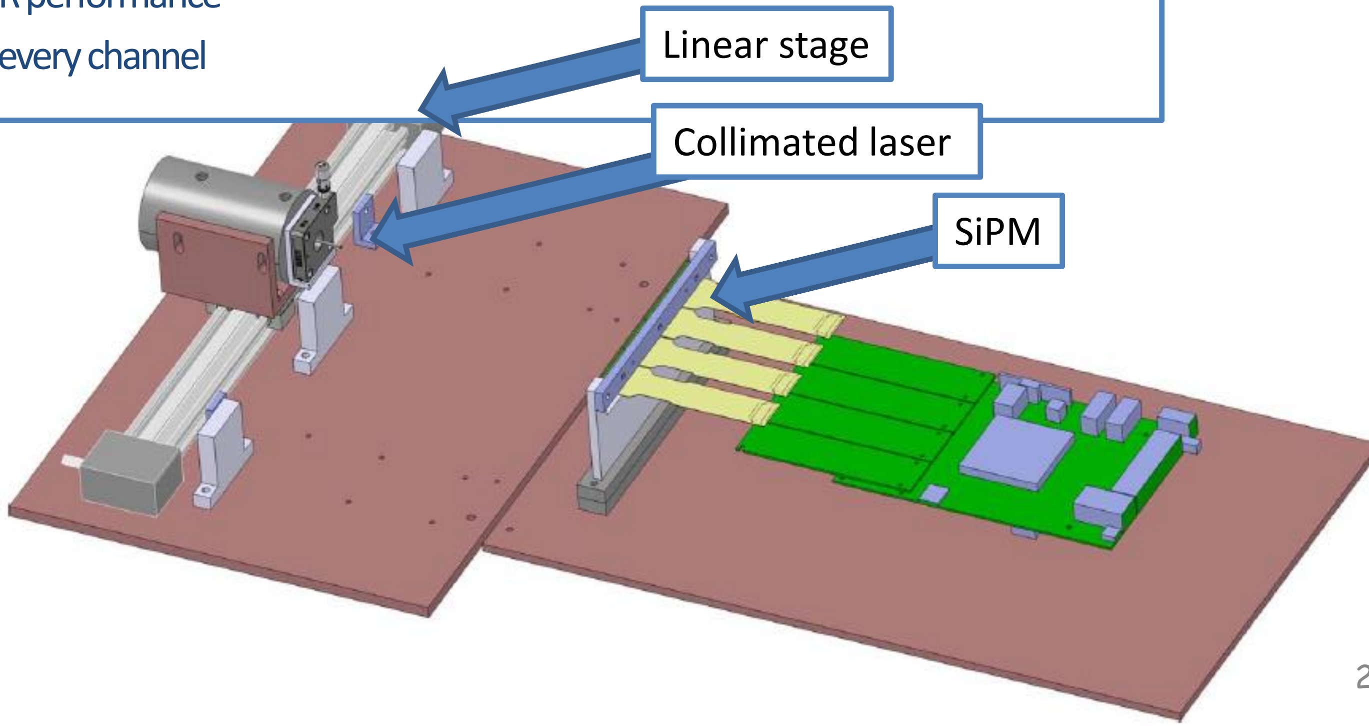
Test the electronics performance with a laser injection system

Setup and procedure:

- Synchronous pulsed laser (trigger and fast pulse)
- Measure trigger to light detection delay for every channel
- No Scintillator that slows down the response
- Inject only 2 channels at a time, scan over the full plane of 133mm (512 channels) with linear stage

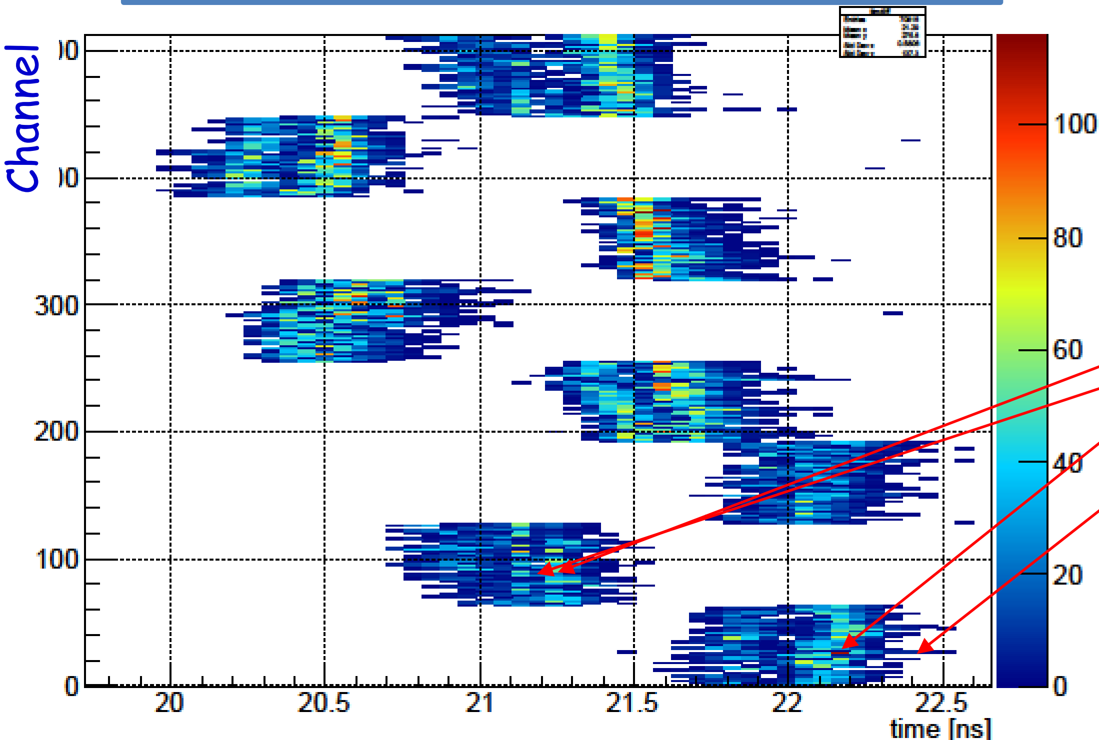
This allows:

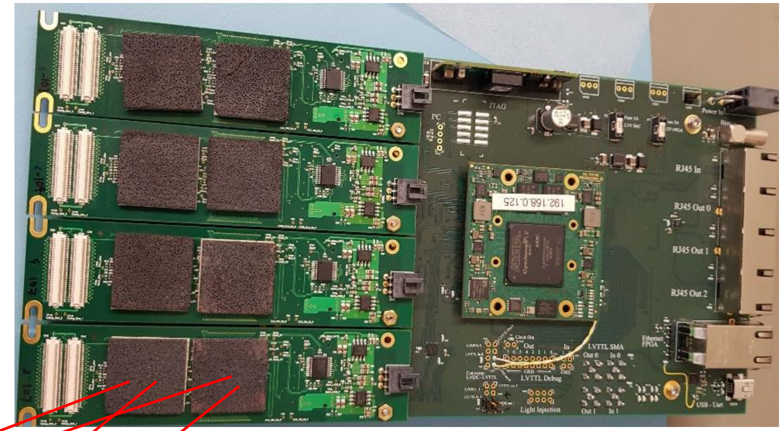
- Evaluate the system CTR performance
- Extract time offsets for every channel



Timing performance of the electronics with the laser injection system

$t_{Hit} - t_{Trigger}$: 512 channels Laser injection calibration

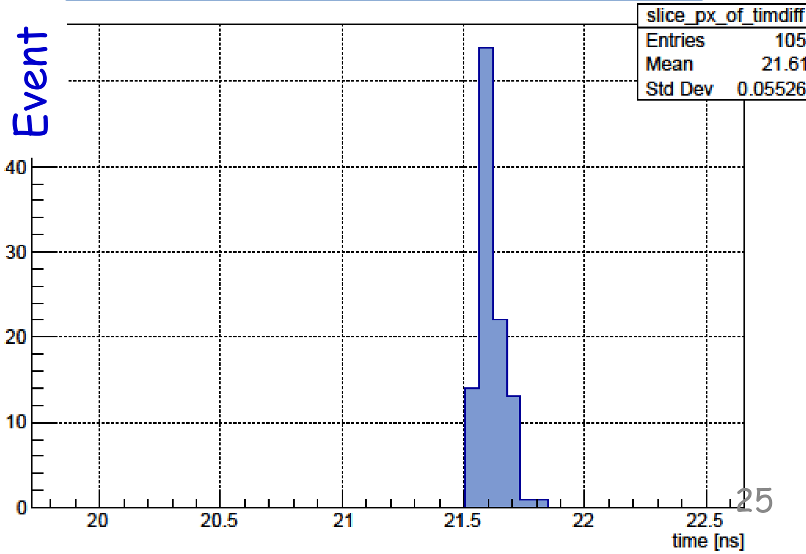




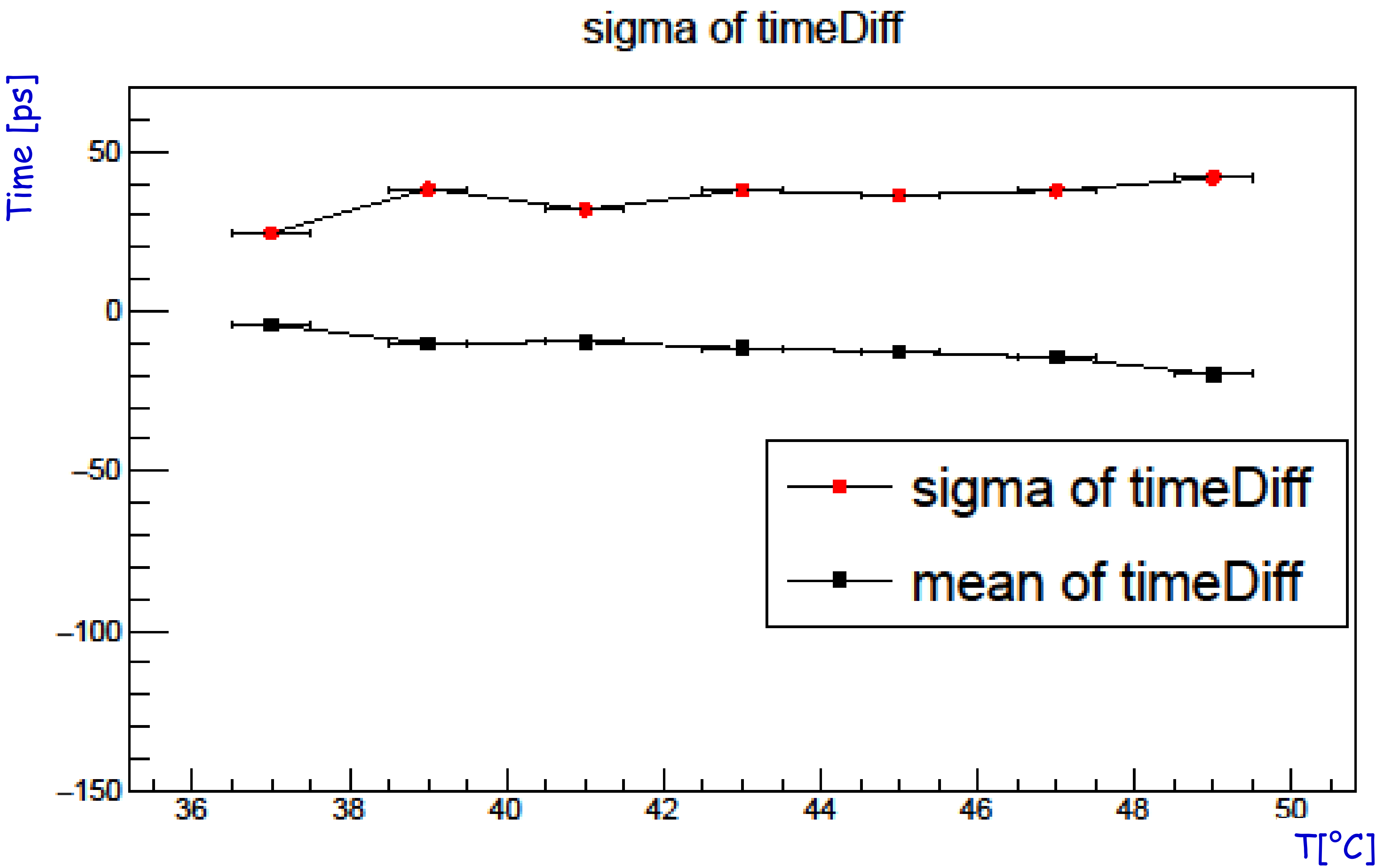
Different half chips and also every channel reveals different delays!

Is probably better if fine time bin size calibration is performed!

$t_{Hit} - t_{Trigger}$: single channel σ_{time}=55ps

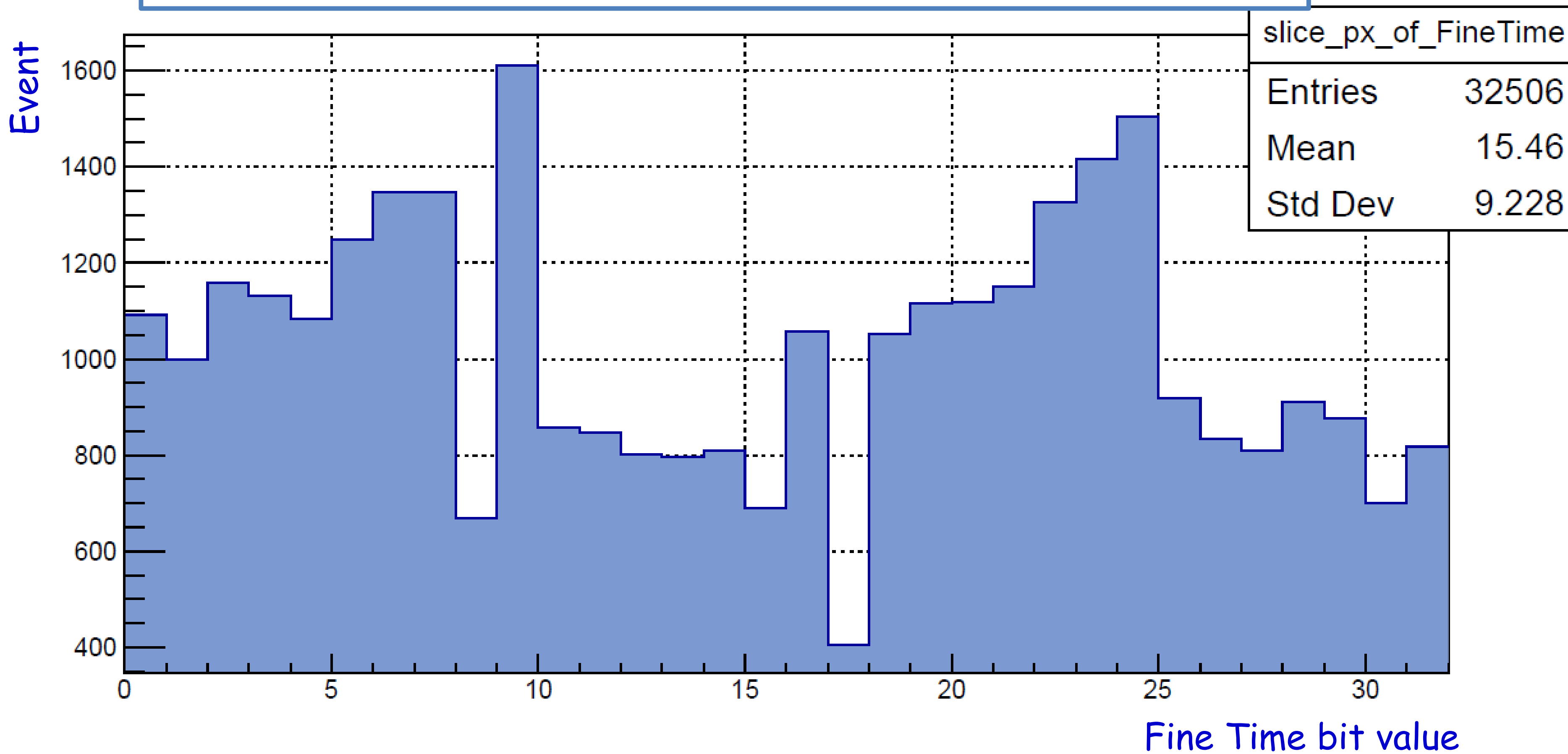


Comparison the time offsets between Runs for different temperature



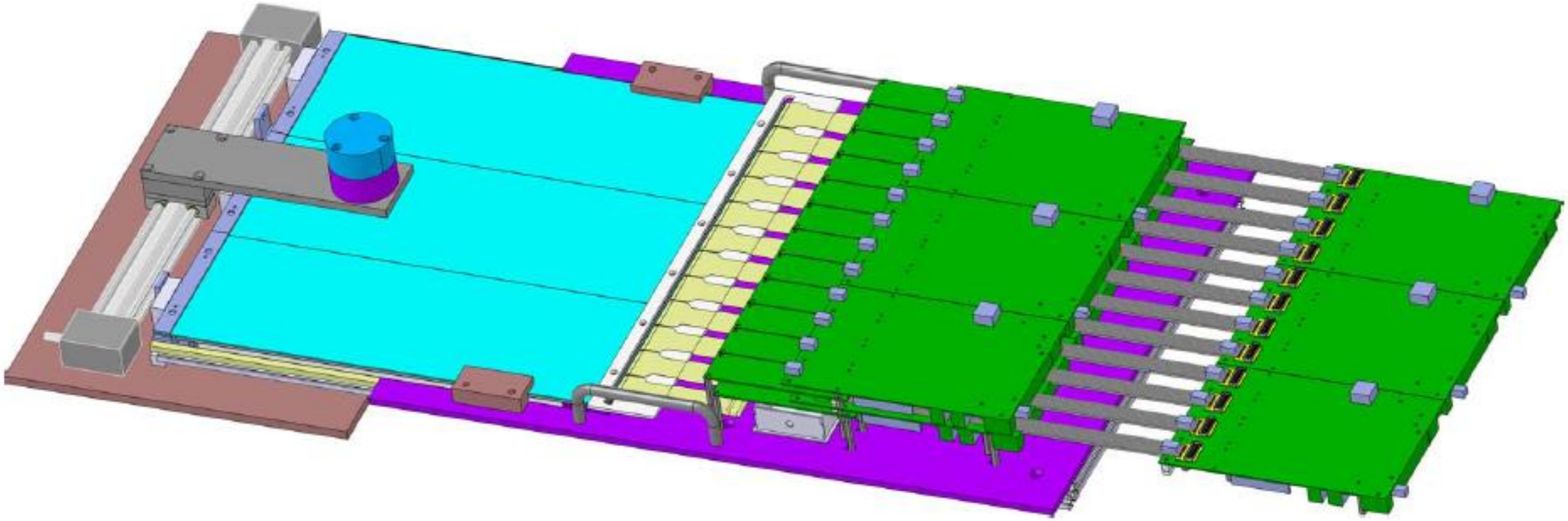
Fine time distribution (random signal)

The expected distribution is flat if the fine time bins have equal width in time.
A renormalisation can be applied



Signal injection with Sr-90 source

- Setup used to produce “MIP like” signal injection
- A trigger is placed on the back side of the fibre module and allows for a “test beam like” setup
- CTR measurement can be made between two channels in the same cluster



Measurements with the beam telescope

@DESY e at E=2-6 GeV

Trigger rate 1Hz-50kHz

Good tracks 70% ,multiple particles in events in 30%

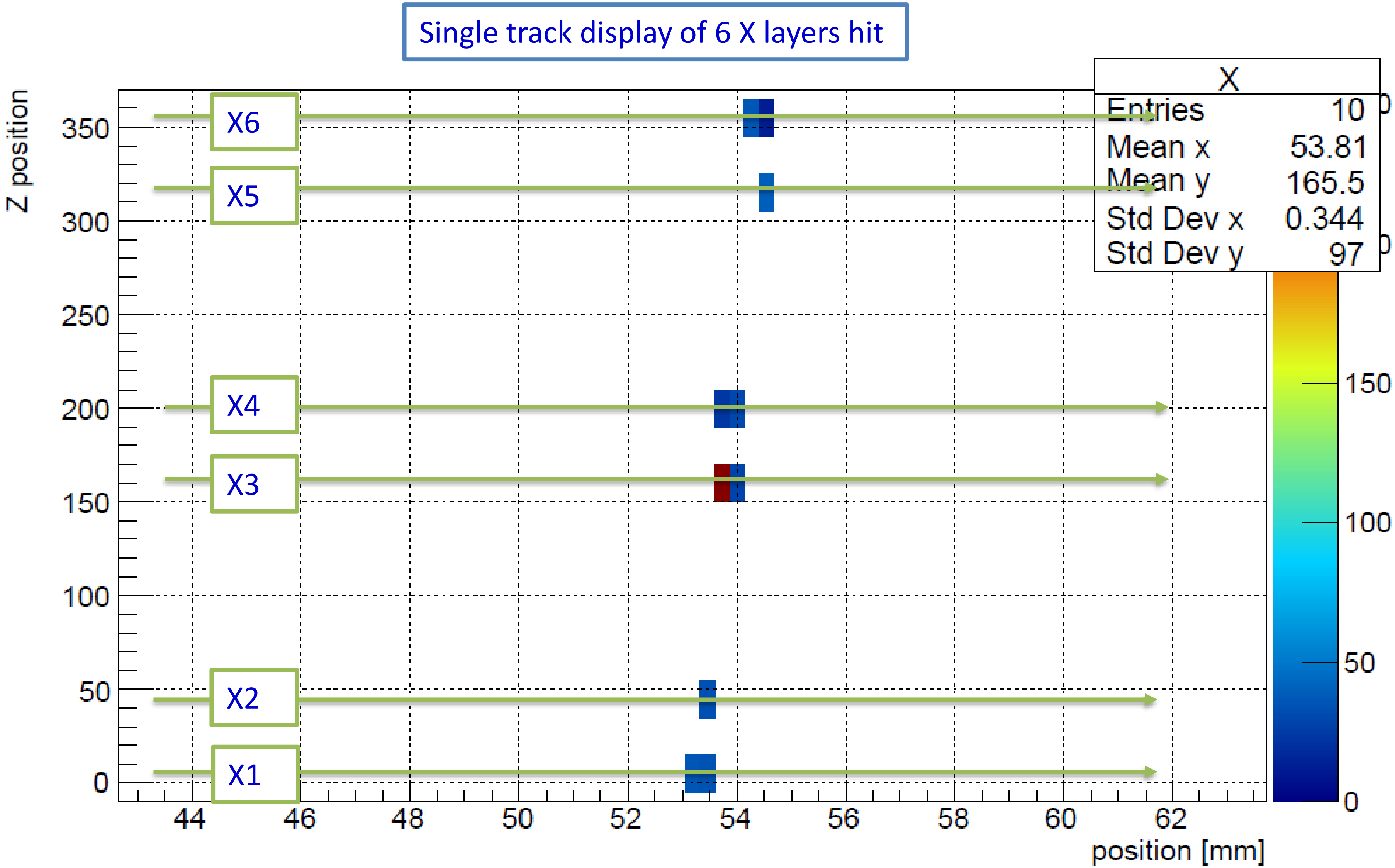
Cosmic rays muons 2-3 GeV

(use two large scintillators for trigger, rotate the system in the vertical position)

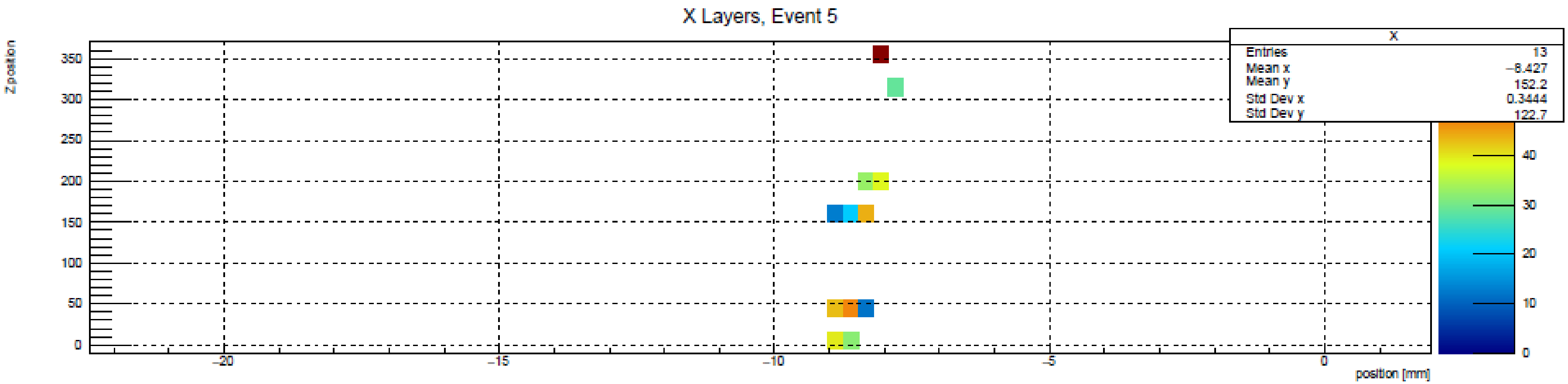
Trigger rate 1Hz

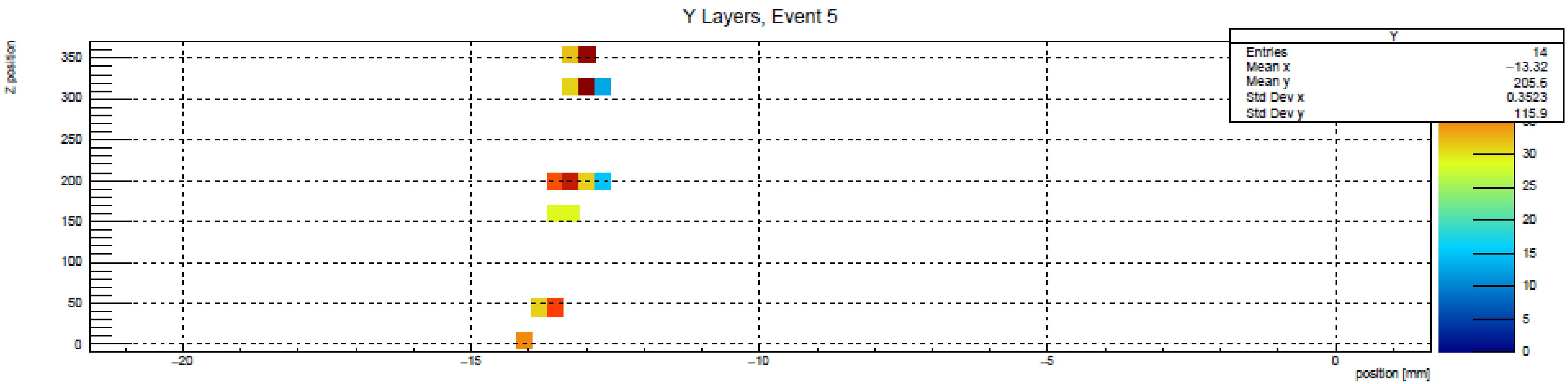
Good tracks 20% (80% large angle or conversion in concrete ceiling producing showers)

Single event display

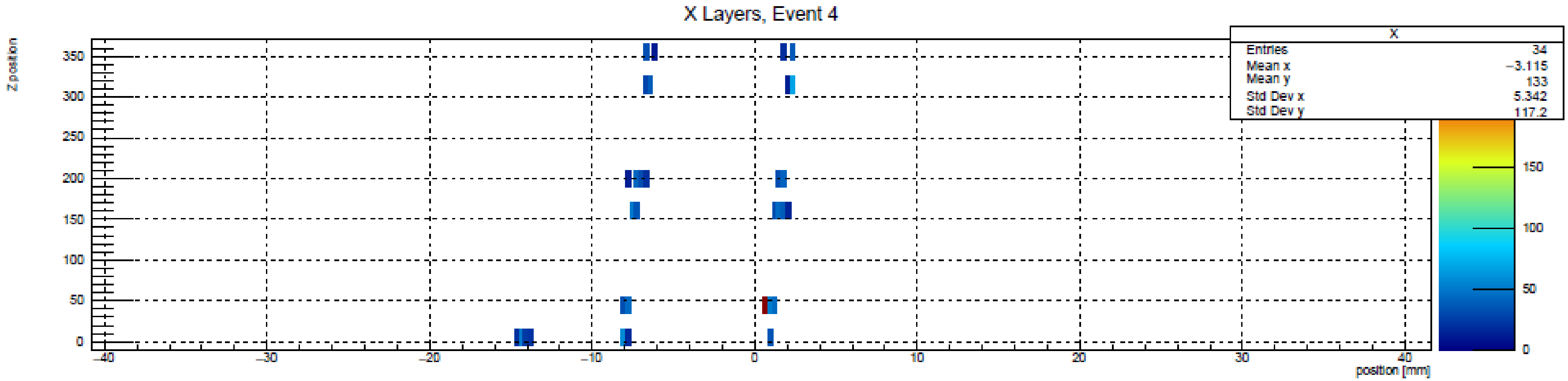


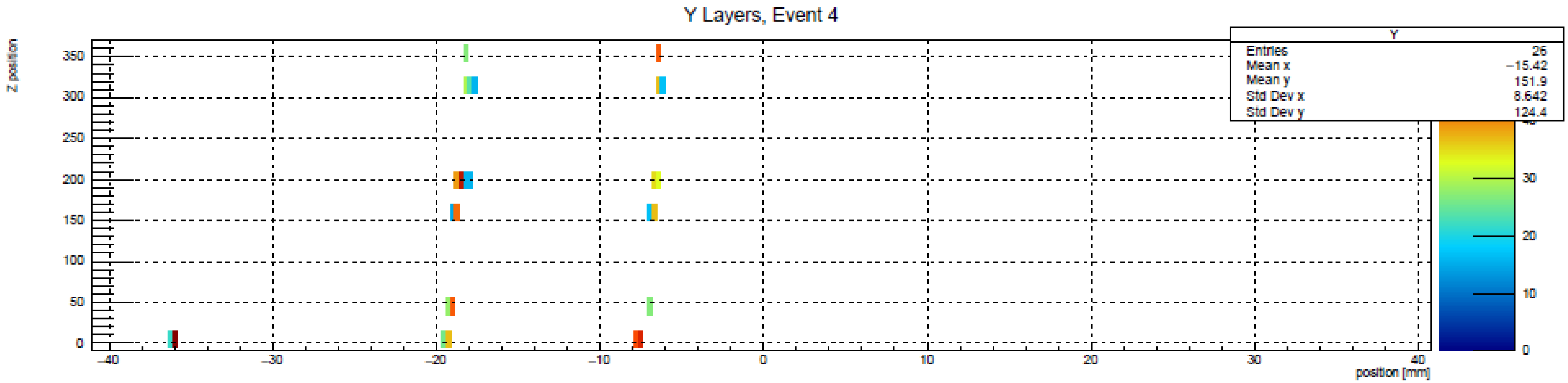
Single event display in X and Y



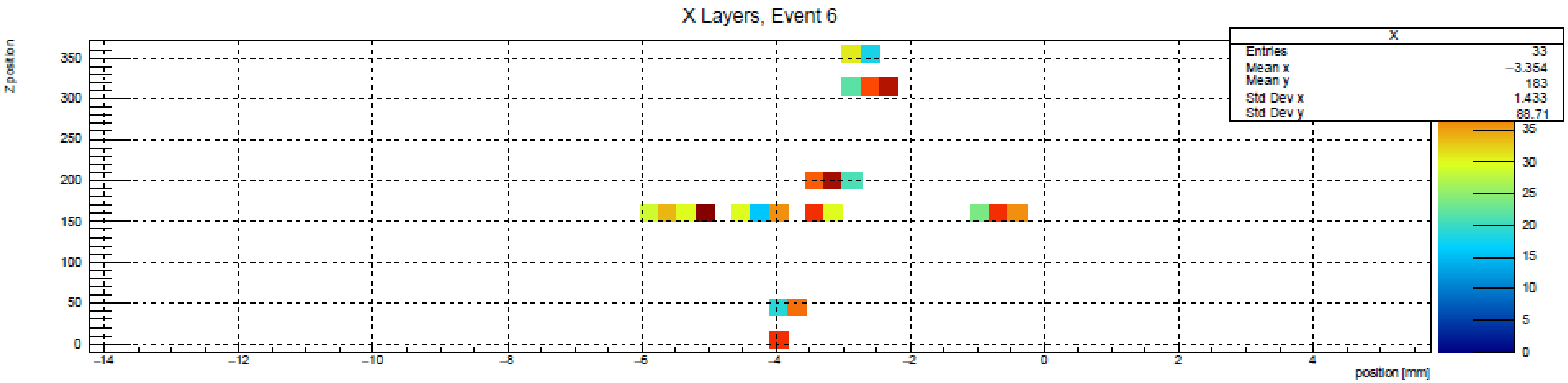


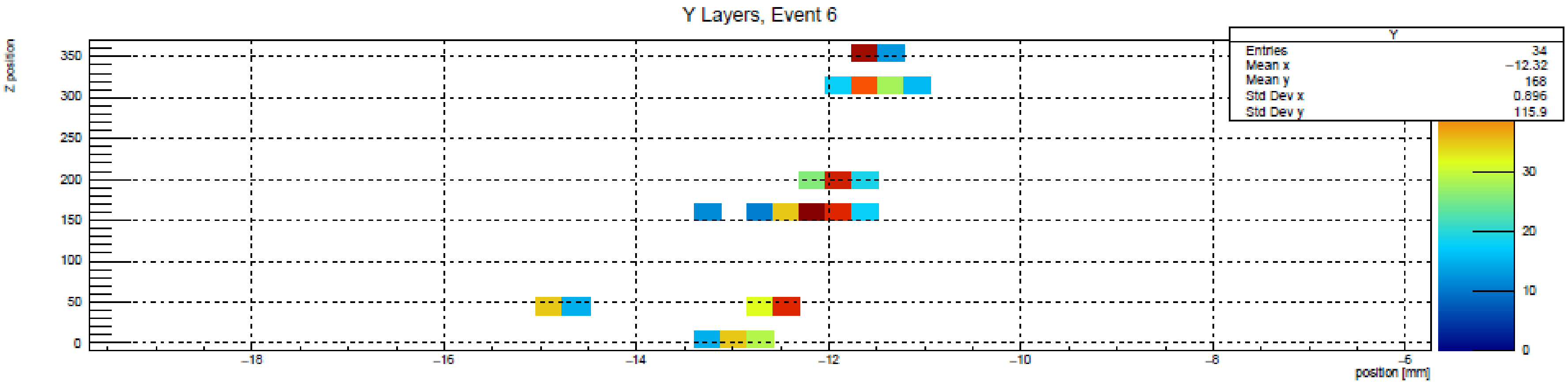
Single event display two tracks



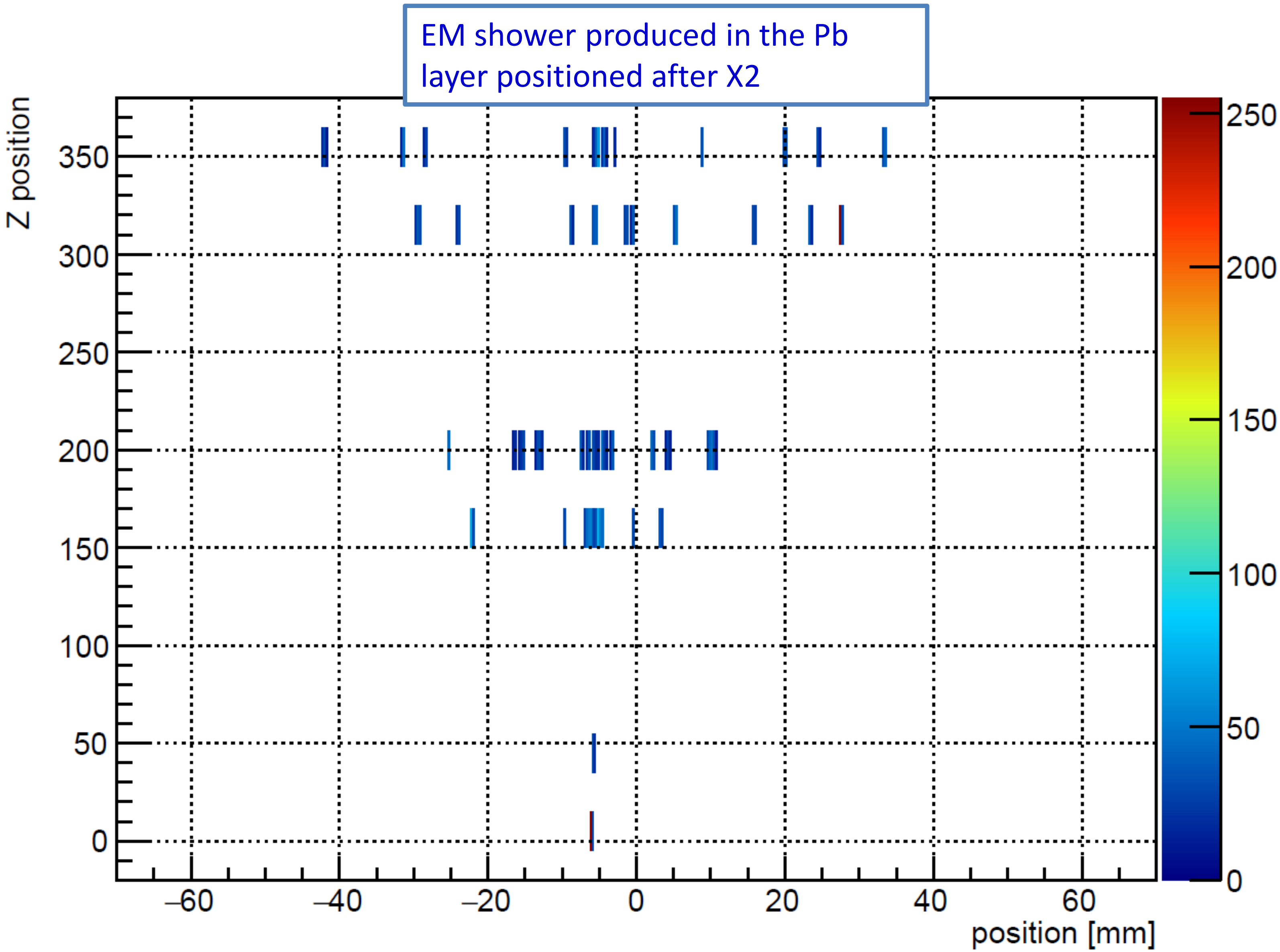


Single event display noise due to secondary tracks

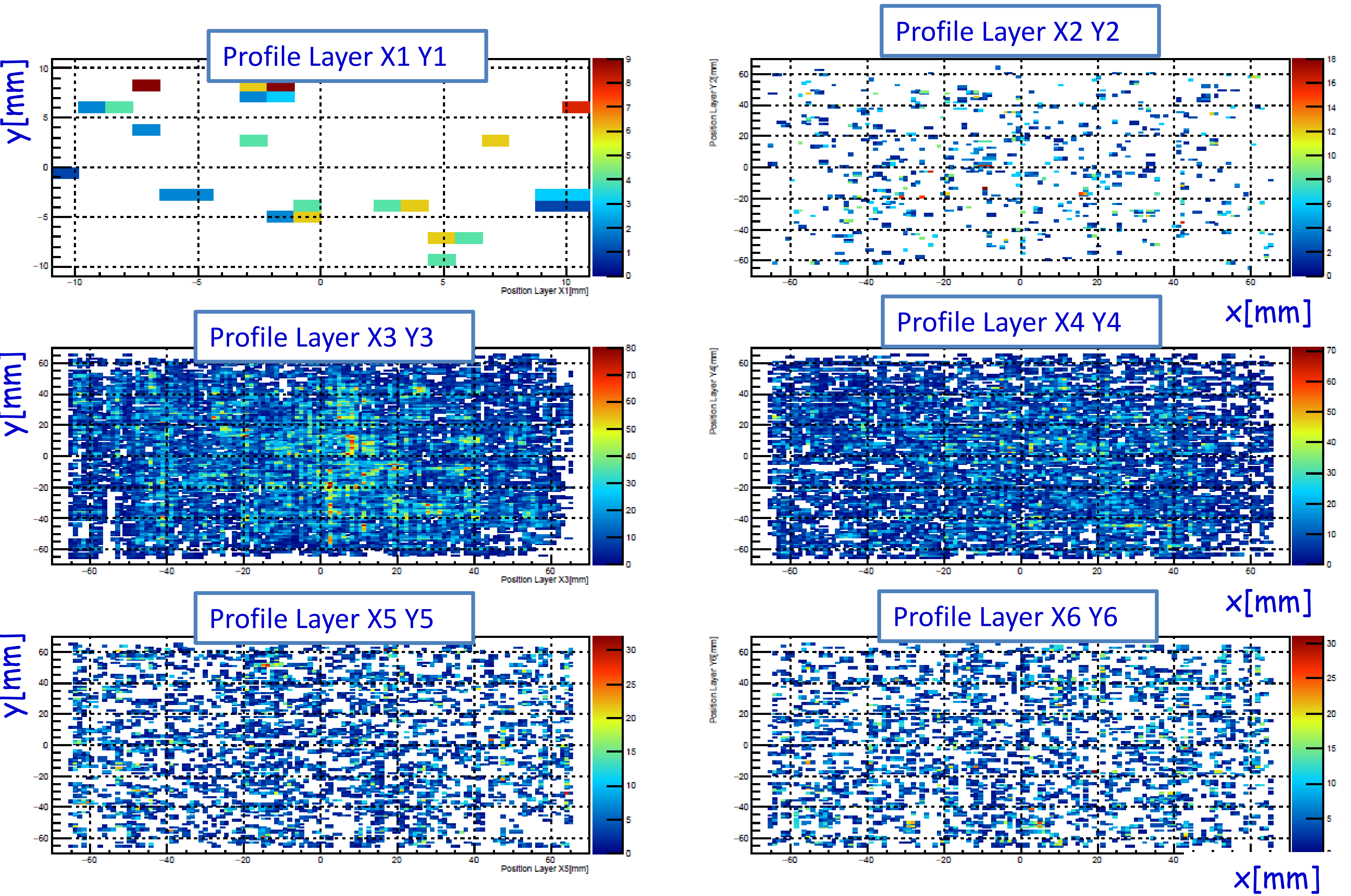




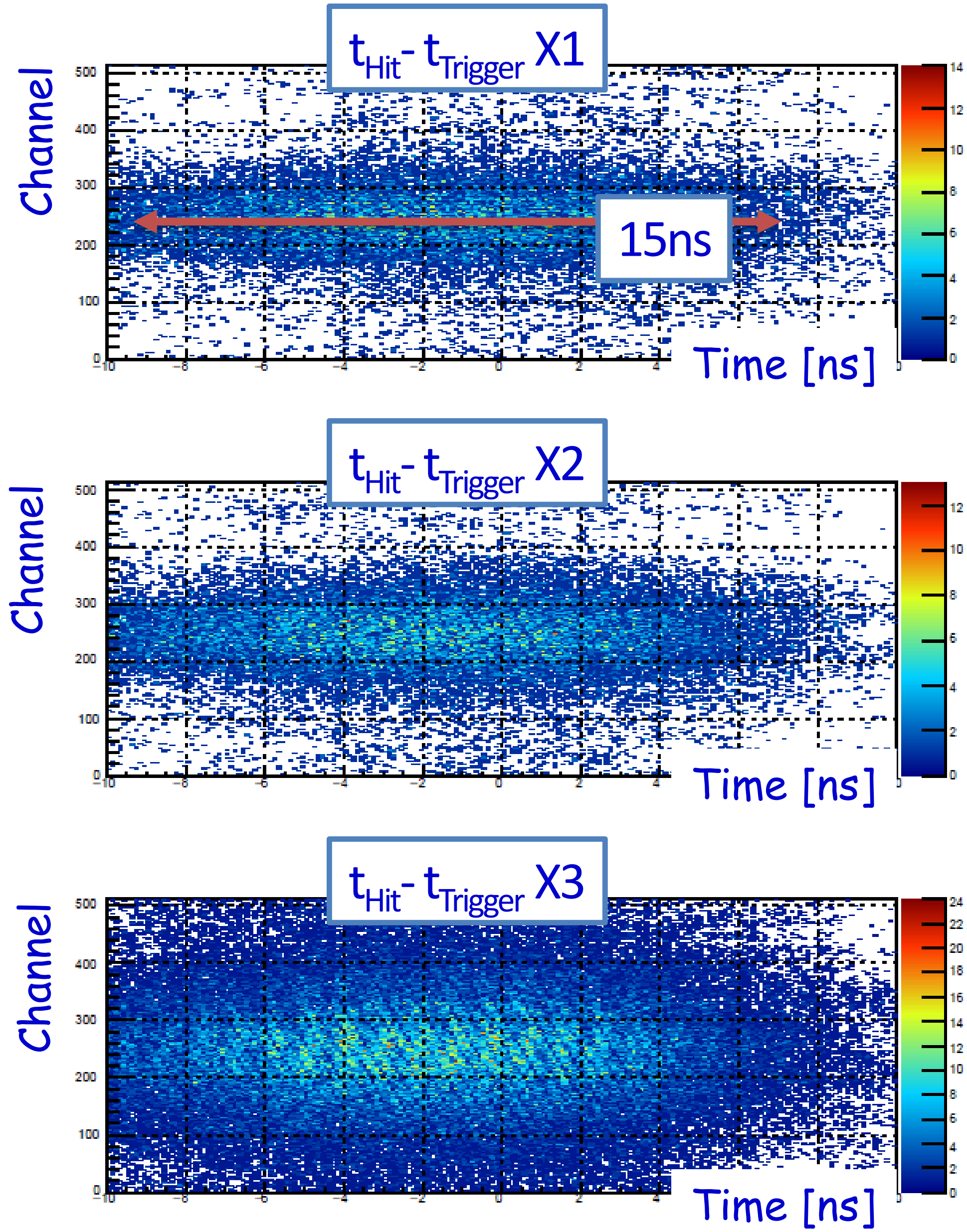
Single event display



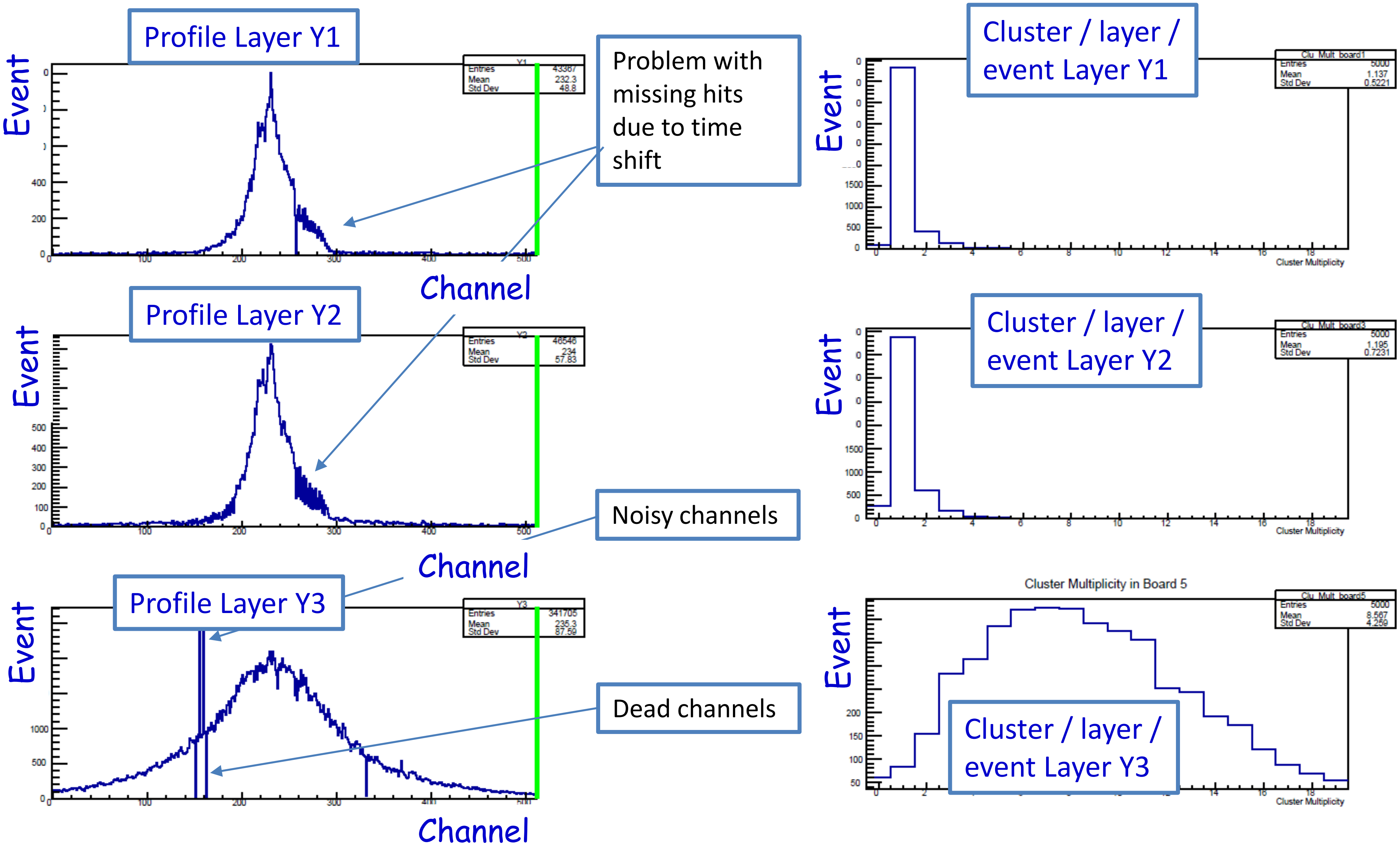
SciFi with Emulsion (with Pb) uniform illumination



Hit time – trigger time (electrons with Pb after M2)

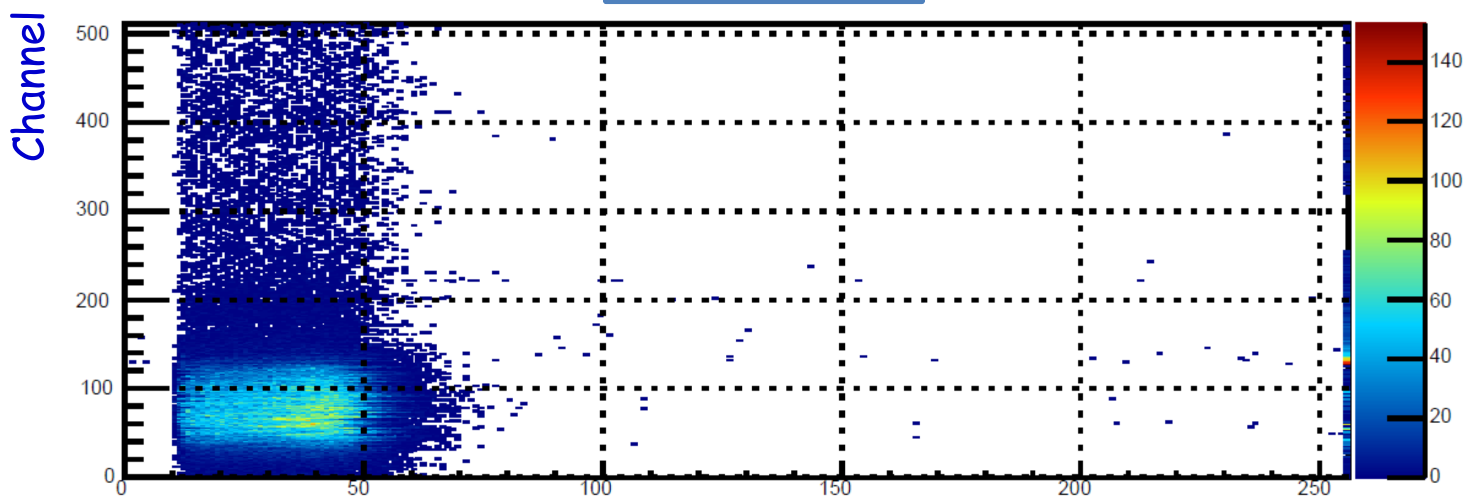


Beam profile (e beam DESY, E=2GeV, Pb d=1cm after Y2)

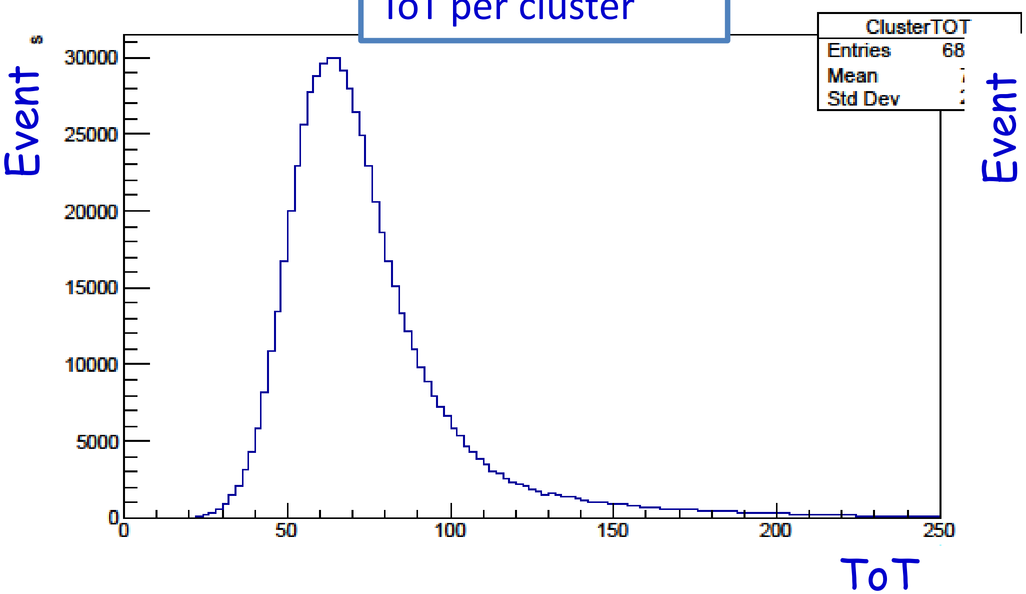


Amplitude of signal

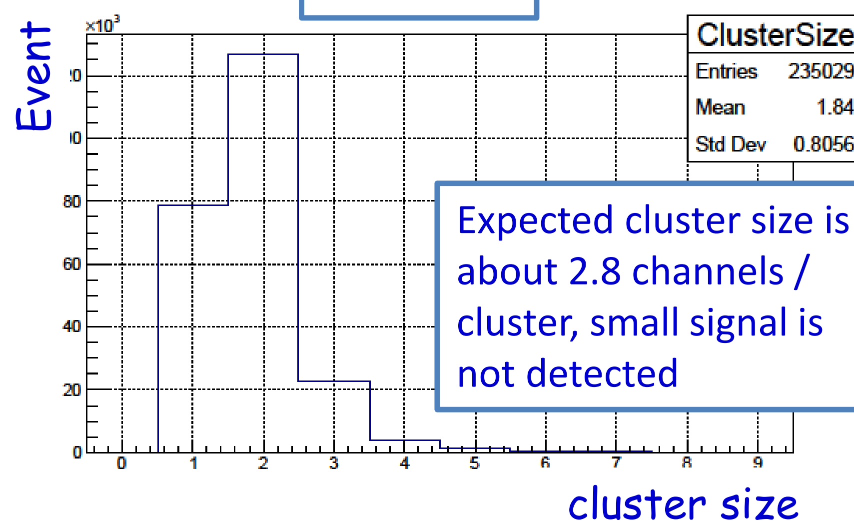
ToT per channel



ToT per cluster



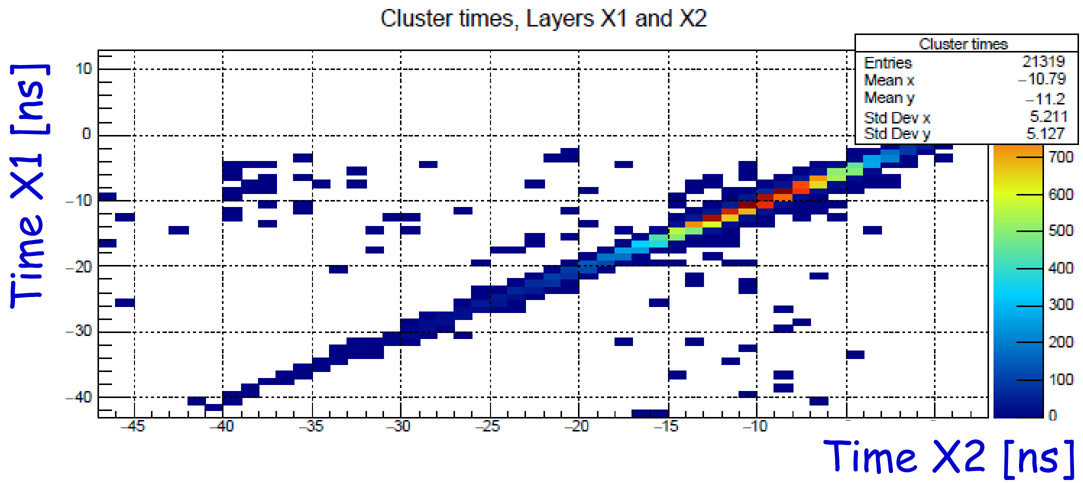
Cluster size

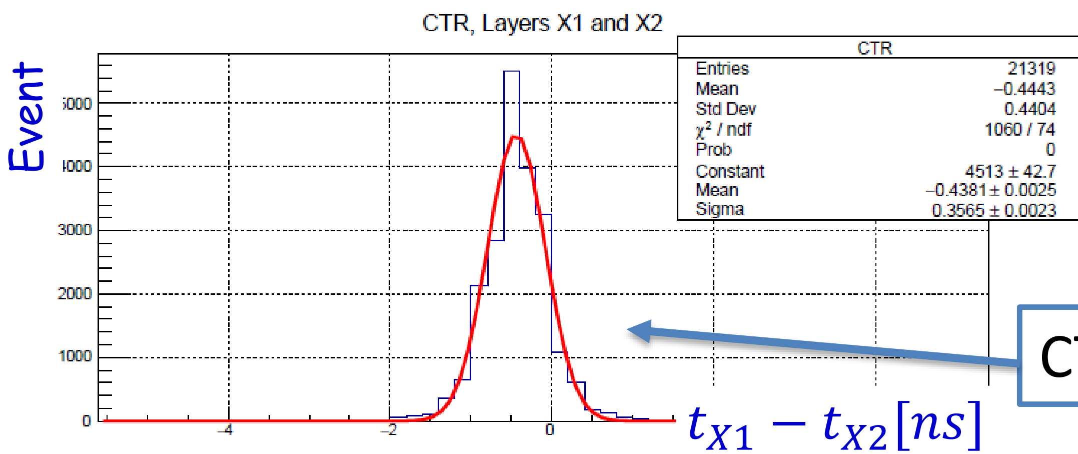


Expected cluster size is about 2.8 channels / cluster, small signal is not detected

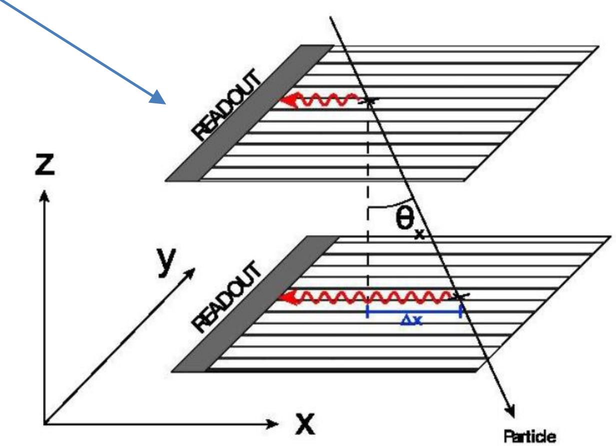
CTR calibration and corrections

1. Every board (detection plane) has a global board offset
2. Every channel for every run has a channel offset
3. Every hit has an offset to compensate the light propagation delay





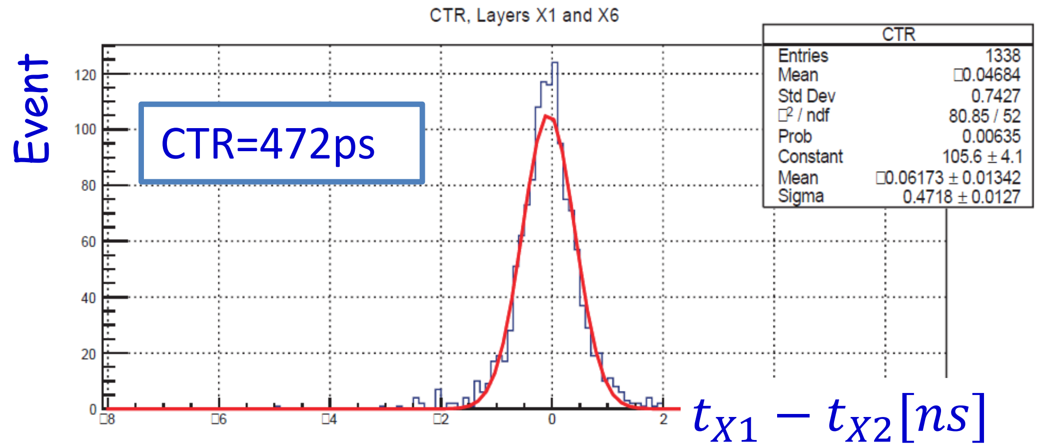
Light propagation delay



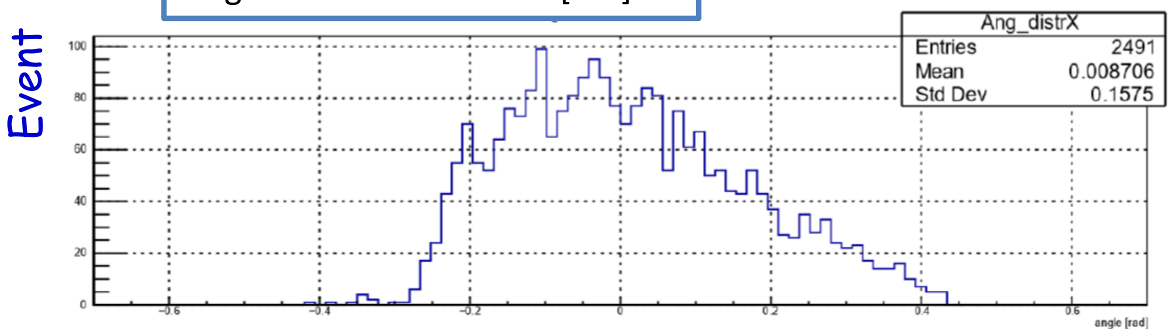
CTR=357ps

CTR with cosmic rays

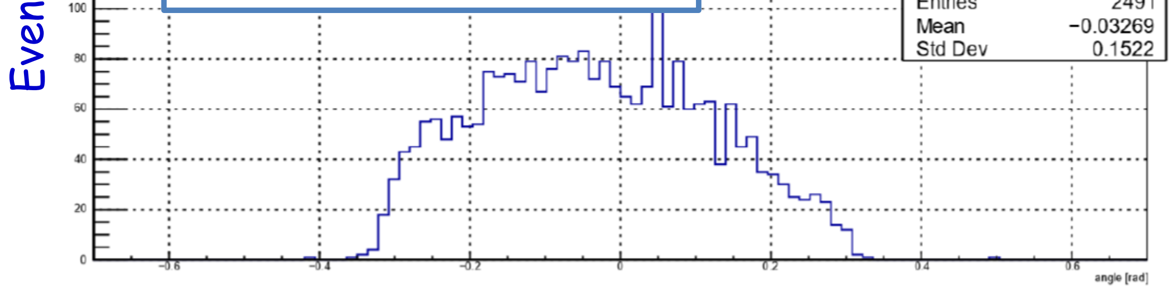
The CTR measured with cosmic rays is higher, multiple particle events with “slow” particles are observed.



Angular distribution in X [rad]



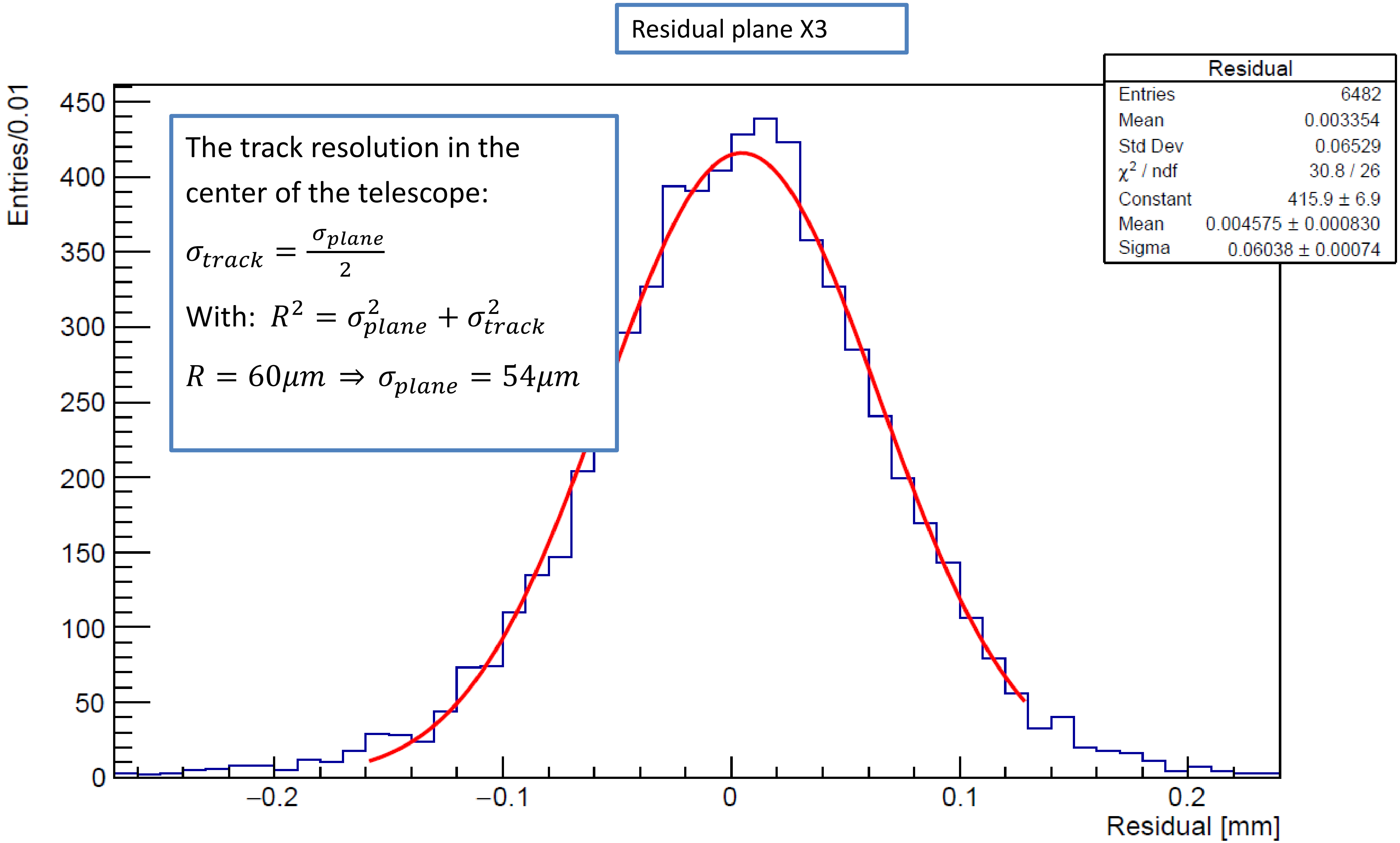
Angular distribution in X [rad]



CTR comparison between beam and cosmic ray test
All combinations in Y

		Beam $[ns]$		Cosmic rays $[ns]$	
Layer 1	**Layer 2**	**CTR**	σ_{CTR}	**CTR**	σ_{CTR}
Y1	Y2	0,3856	0,0020	0,3646	0,0073
Y1	Y3	0,3738	0,0018	0,3741	0,0077
Y1	Y4	0,3849	0,0019	0,3874	0,0081
Y1	Y5	0,3878	0,0019	0,410	0,010
Y1	Y6	0,4034	0,0022	0,4188	0,0099
Y2	Y3	0,3845	0,0020	0,3745	0,0080
Y2	Y4	0,4006	0,0021	0,3950	0,0076
Y2	Y5	0,4060	0,0022	0,4039	0,0096
Y2	Y6	0,4174	0,0024	0,414	0,011
Y3	Y4	0,3738	0,0019	0,3539	0,0071
Y3	Y5	0,3880	0,0020	0,3756	0,0082
Y3	Y6	0,4020	0,0023	0,400	0,010
Y4	Y5	0,4029	0,0020	0,3987	0,0090
Y4	Y6	0,4067	0,0022	0,397	0,011
Y5	Y6	0,4001	0,0023	0,387	0,010

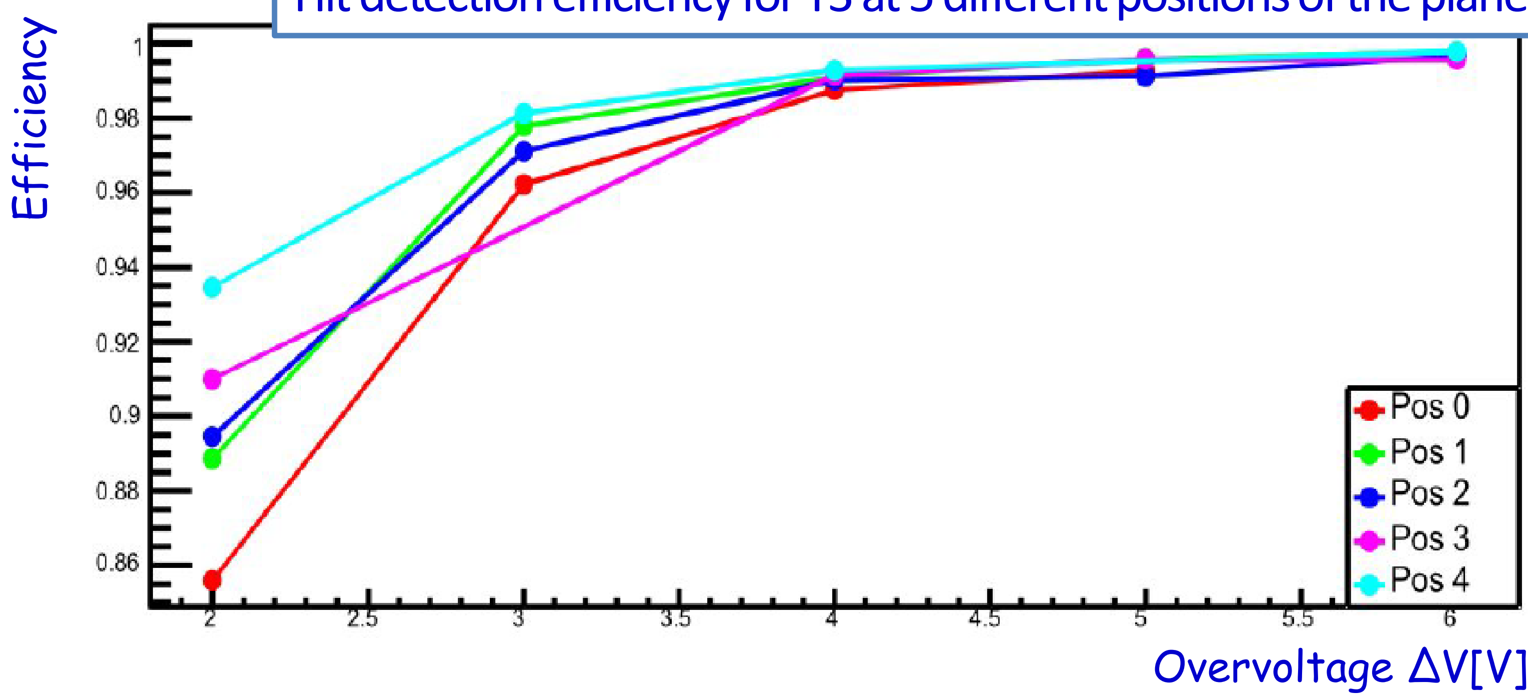
Spatial residual



Hit detection efficiency

- The beam telescope allows to measure the hit detection efficiency of every plane, with cosmic rays and beam particles.
- Tracking is performed among all but the test plane, events with more than one track or noise clusters are excluded.
- The hit detection efficiency increases with ΔV and reaches 99% at ΔV=5V, (short fibre modules without mirror, LY is about 28PE at ΔV=5V).

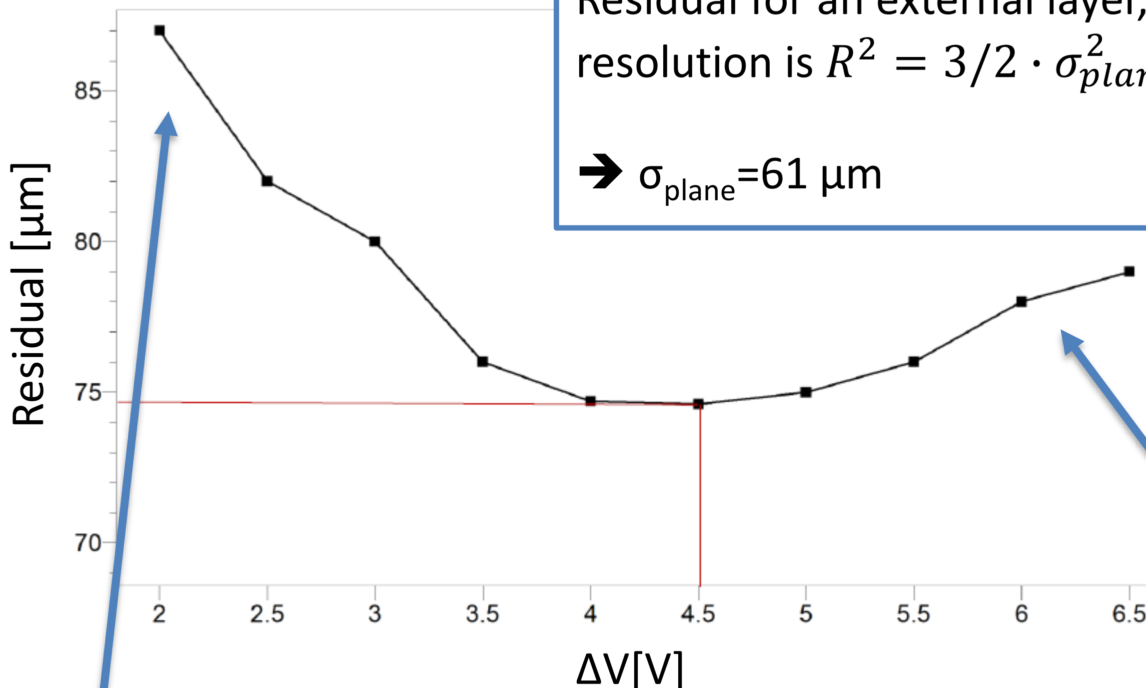
Hit detection efficiency for Y3 at 5 different positions of the plane

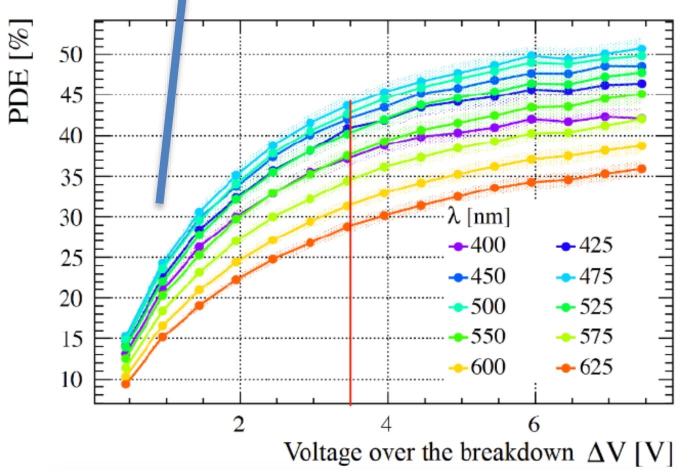


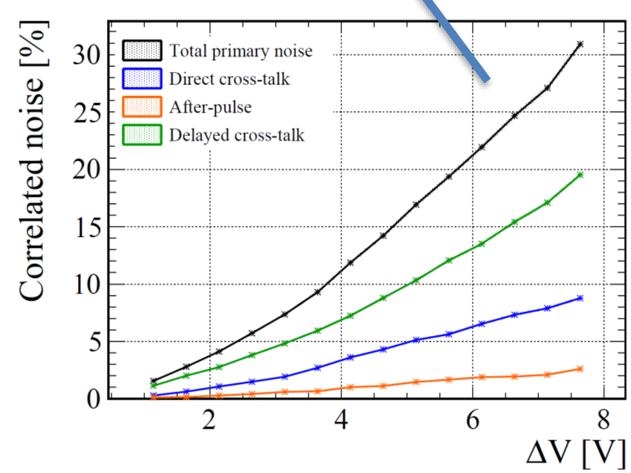
Spatial resolution as a function of ΔV

Residual for an external layer, resolution is $R^2 = 3/2 \cdot \sigma_{plane}^2$

➔ σ_{plane}=61 µm



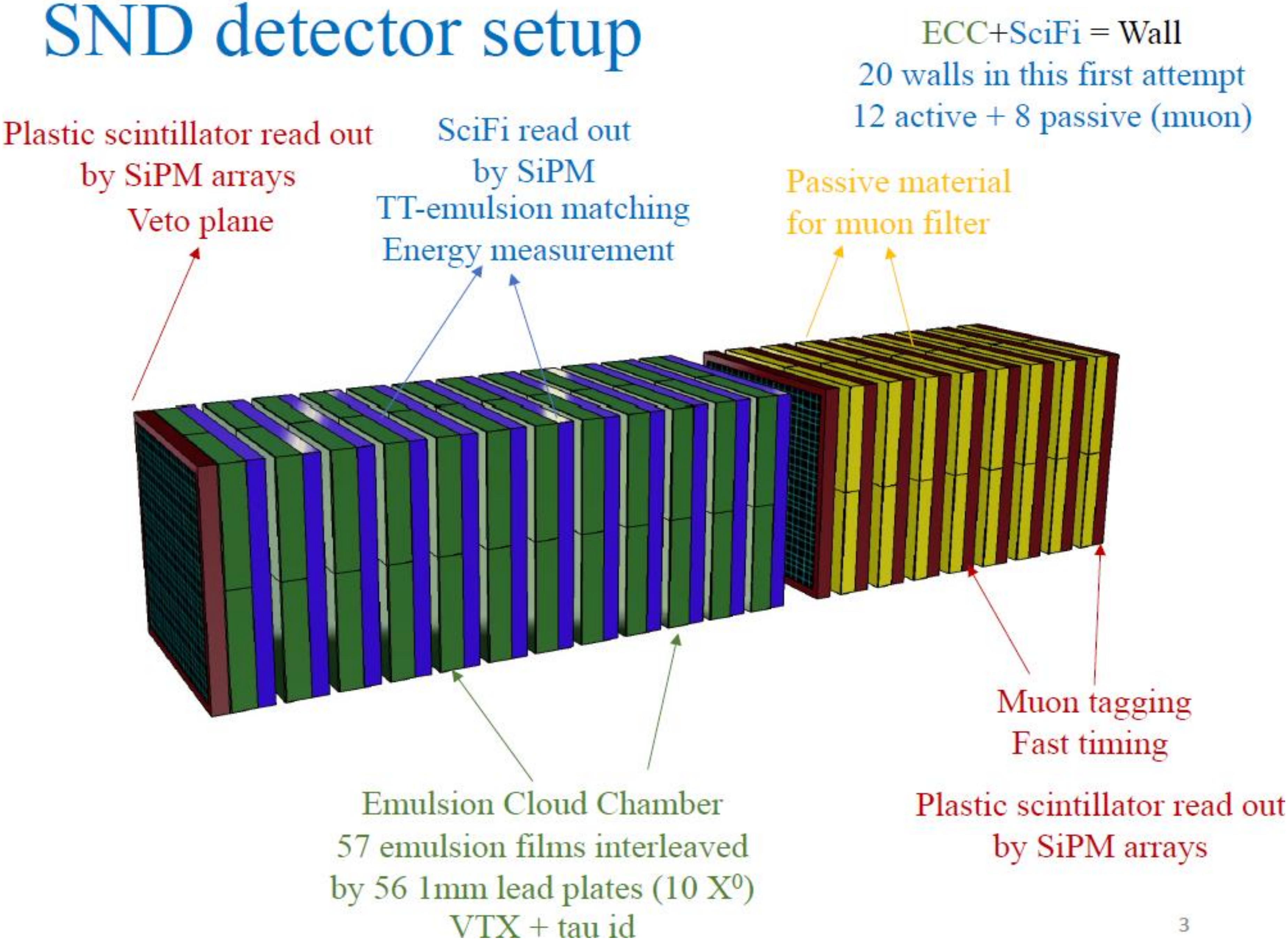




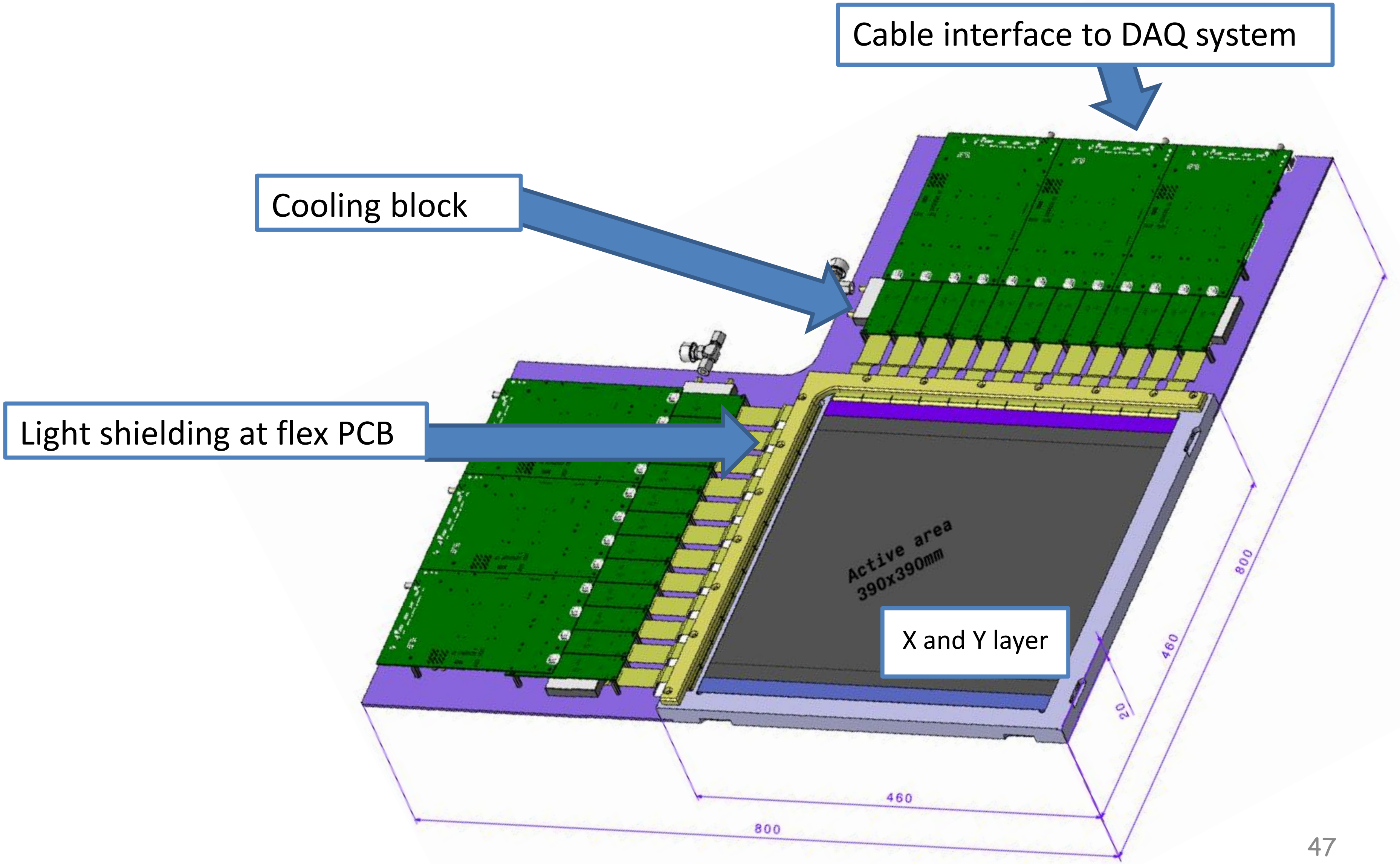
SciFi with timing application
Scattering and Neutrino Detector in TI18 (LHC) SND@LHC

- Neutrino scattering at LHC energies produced at the ATLAS interaction point + dark matter observation.
- Emulsion bricks consist of 56 active emulsion layers interleafed with Pb absorber layers.
- SciFi combined with emulsion detectors are used to merge and time tag events between consecutive emulsion bricks.
- SciFi is used in a high granular sampling calorimeter mode.
- The design of modules (X-Y) with 390x390mm^2 active surface has been started.
- Modular design with stackable X-Y layer planes are proposed.

SND detector setup



SciFi timing tracker for SND@LHC



Characteristics

- Independent x-y module, no additional light shielding or cooling enclosure required
- Thickness of the module is 20mm, two edges are used for the readout electronics which are 40mm.
- 250W power dissipation per module
- Expected timing performance: σ_{CTR}=400ps for one layer time resolution for an x-y module is σ_t=200ps
- 50μm spatial resolution
- 99% detection efficiency per layer

Development of modules with faster fibres and potentially higher LY

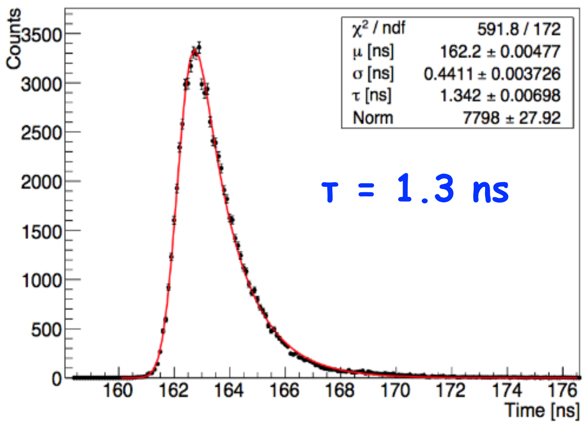
The limitation of the CTR to about 350ps in the current configuration can only be overcome by:

- Increasing the LY of the module, thicker fiber layers (1mm fibres) but this introduces many difficult design changes
  - SiPM active surface increase
  - Winding wheel and many tools
- Decrease the decay time of the scintillator without decreasing significantly the LY
  - Fibres based on NOL have been tested and produced decreasing the decay time by about 2 to 2.5

NOL prototype fibre performance

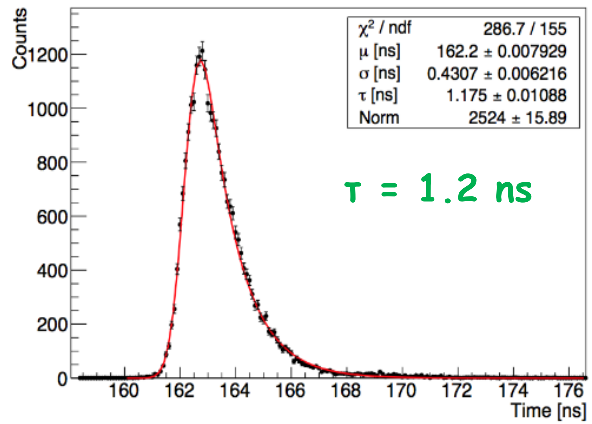
O. Borshchev et al., 2017 JINST 12 P05013

Best blue NOL fibre



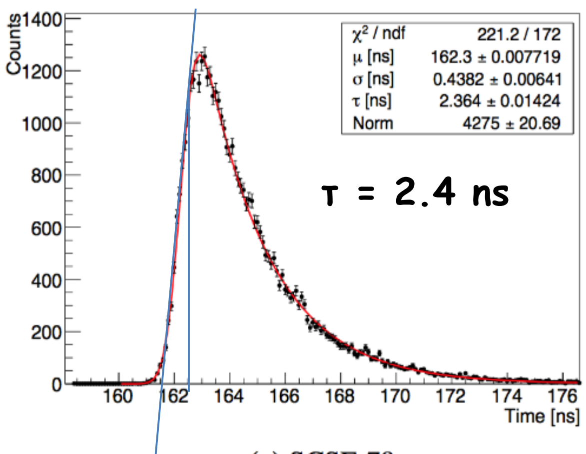
(a) BPF-11-1

Best green NOL fibre



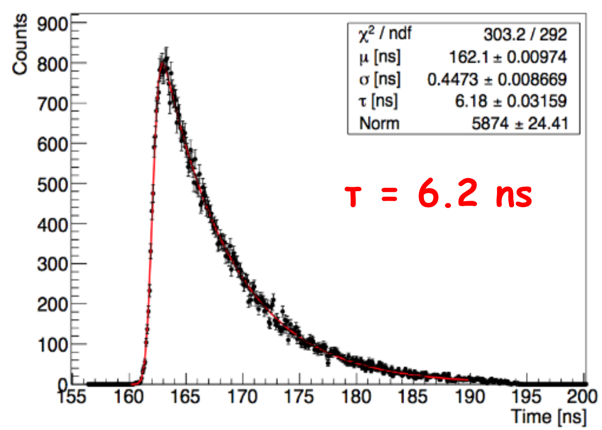
(b) GPF-19-1

Best blue standard fibre



(c) SCSF-78

Best green standard fibre

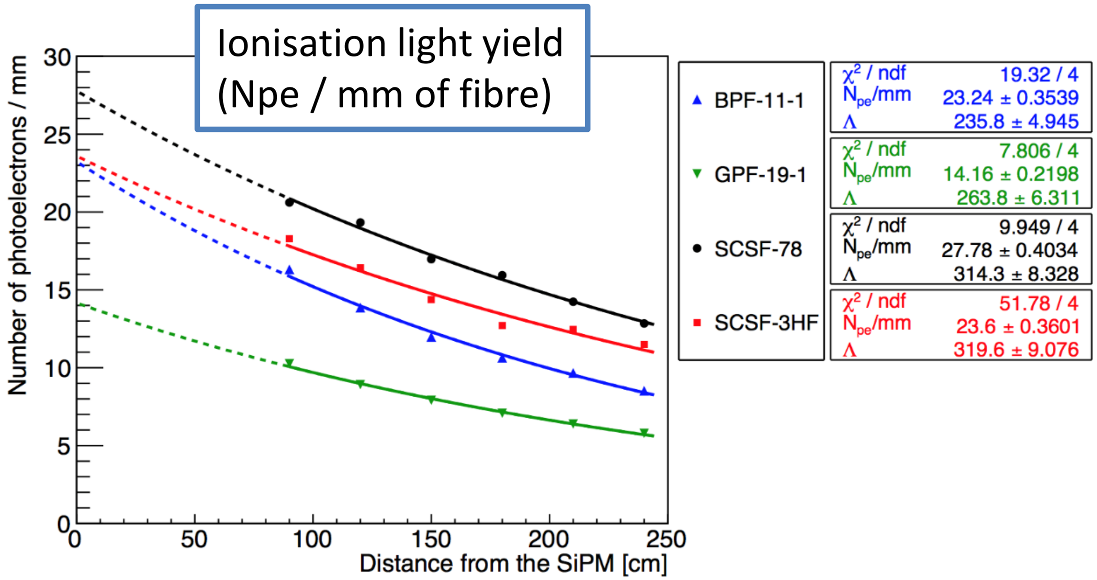


(d) SCSF-3HF

Decay time: NOL fibres are almost a factor 2 (6) faster than the best blue (green) standard fibres, which makes them already very interesting for time critical applications!

NOL prototype fibre performance

O. Borshchev et al., 2017 JINST 12 P05013



Best blue NOL prototype fibre

Best green NOL prototype fibre

Best blue standard fibre

Best green standard fibre

- After 8 iterations NOL fibres clearly improved but still a bit behind in terms of light yield and attenuation length
- 250 cm < Λ(NOL) < 300 cm
  Λ(standard) > 300 cm
- **Self absorption, i.e. choice of materials, contents and purity are key issues**

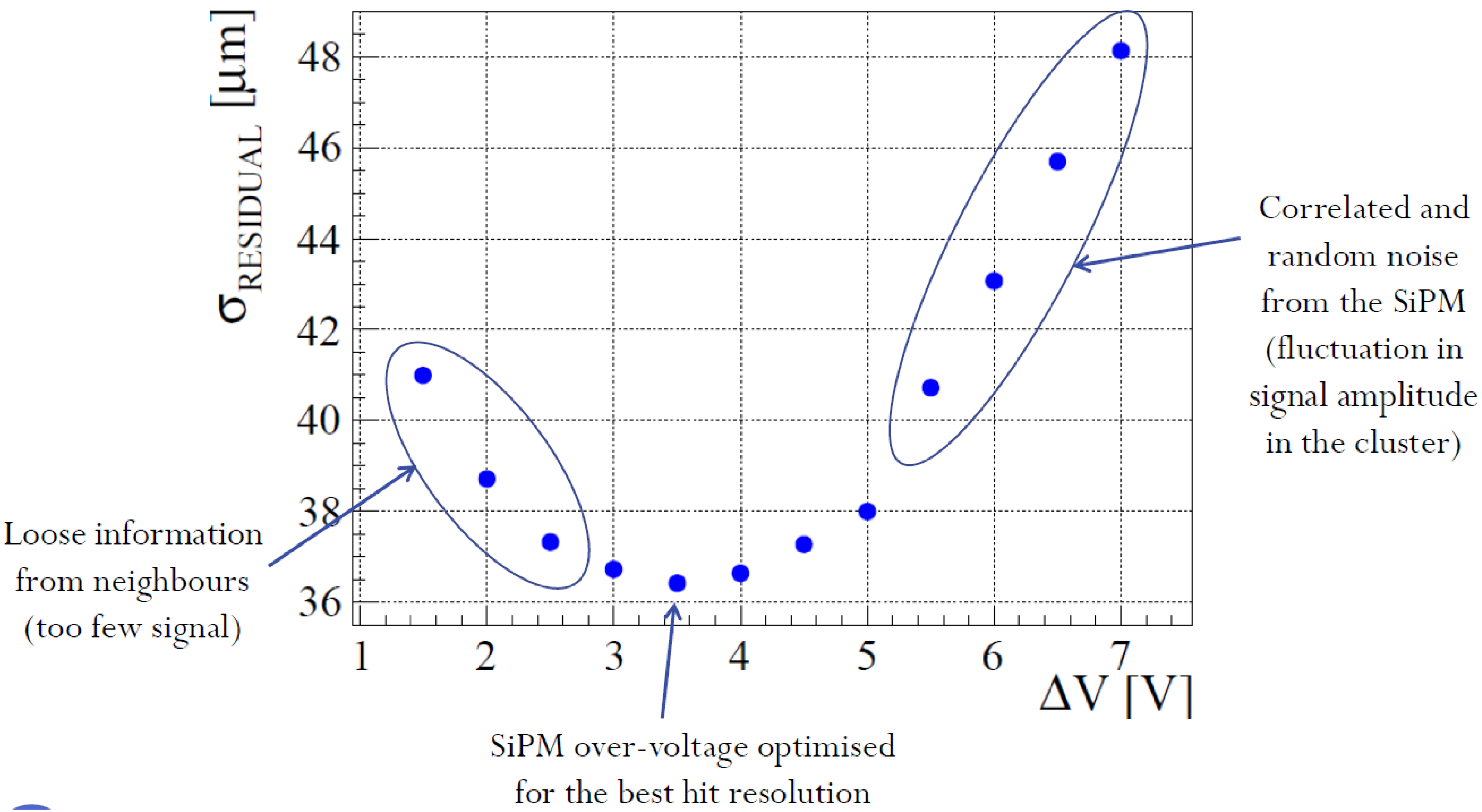
Outlook for better timing

- Fibre tracker modules of the size 40x40cm^2 can potentially reach a CTR of 150ps with faster fibres.
- Optimise the FE electronics for better performance with the low SciFi signal
  - Improved light injection system
  - Lower E-threshold cuts and higher amplification desired
  - Calibrate the timing with tracks

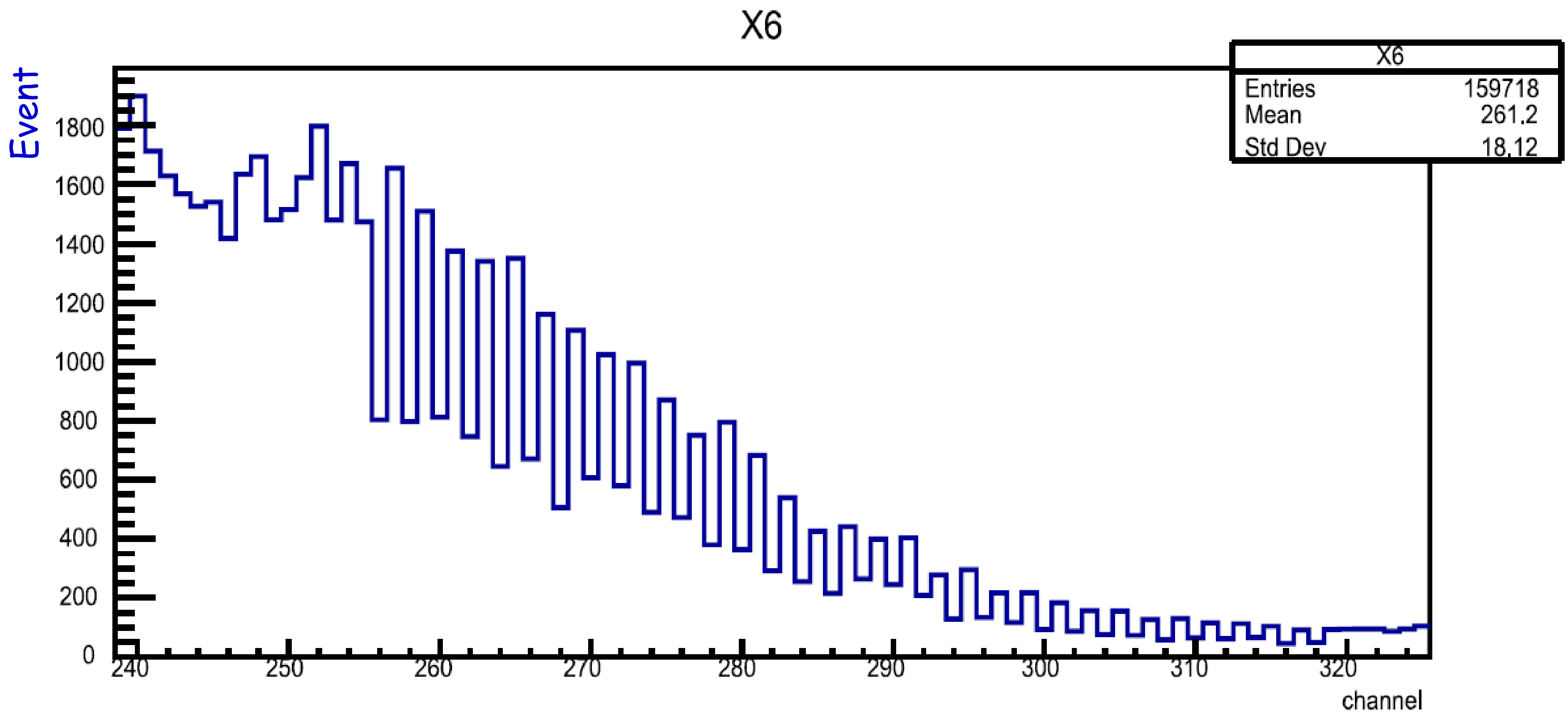
Important lessens for SciFi with timing

- Time calibration is required before every data run. A precise in situ calibration system that allows to extract time offsets and adjust parameters is required!
- Threshold and PLL parameter settings, temperature variation, PCB trace length and the reset procedure introduce channel to channel offsets that can change in time.
- The lab characterisation with fast and collimated laser pulses allow to characterise the electronics system and helps to disentangle the effects of the LY, decay time and electronics limitations.
- Every signal source has advantages and disadvantages:
  - Synchronous laser pulse vs random particle injection
  - Single cluster particle or laser pulse vs VCSEL all channel injection
  - Fast laser pulse vs delayed scintillation light detection

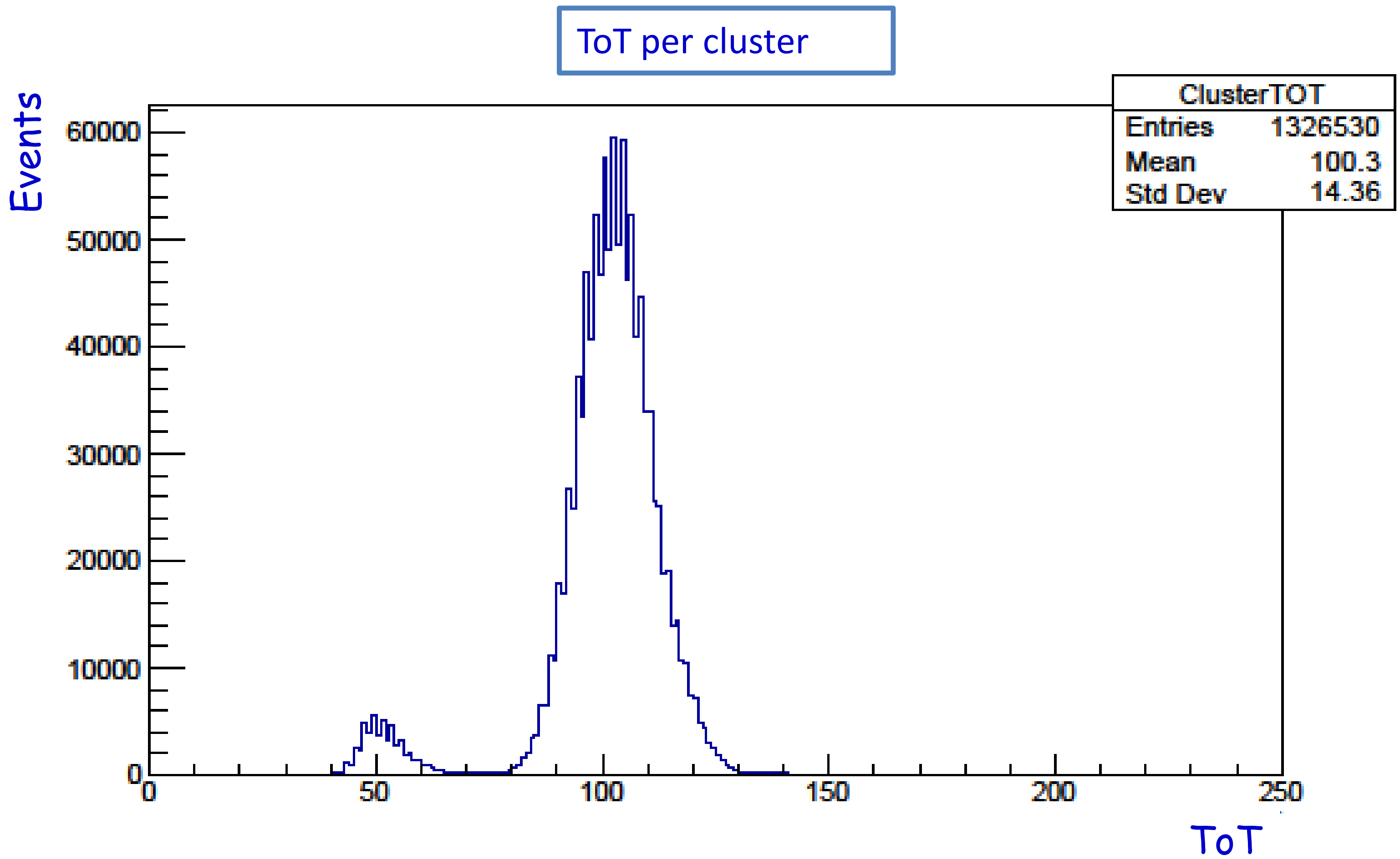
Telescope optimisation (ΔV)



Some defect region, only one hit in two is send to the DAQ, jump in time stamp observed



Amplitude light injection



Hit time – trigger time (electrons with Pb after M2)