High **G**ranularity **N**eutron detector prototype test in Xe run

JINR/KCTEP/INR team

BM@N detector meeting 30 may 2023

HGN prototype layout

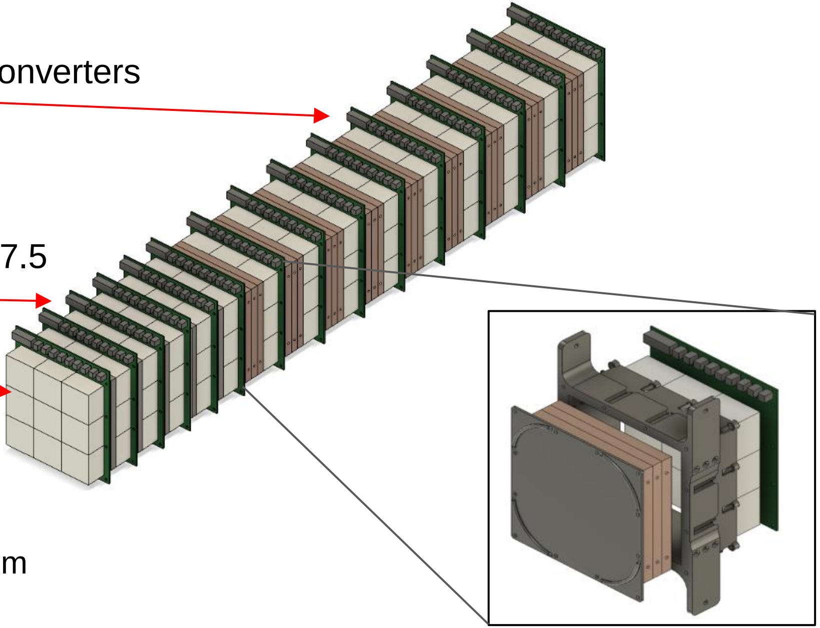
9 layers with **Cu** converters

5 layers with **Pb** converters χ_0~7.5

VETO layer (no converter)

120mm

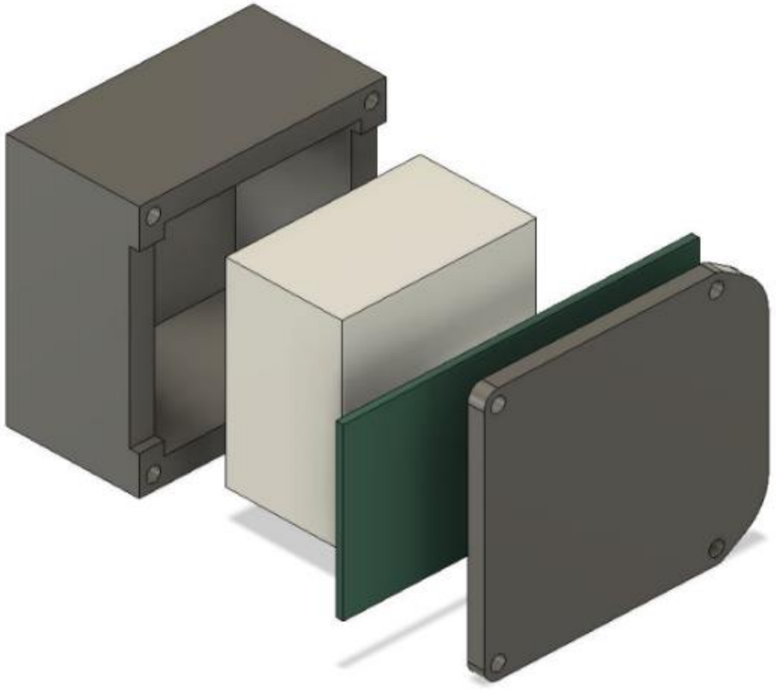
120mm



One layer consists of 3x3 cells
Scintillator cell – 40 x 40 x 25 mm^3
Total readout channels 9+45+81 = 135
Total size – 120 x 120 x 825 mm^3
Total nuclear interaction length λ~2

- 3D-printed detector casings
- Light-tight assembly
- Options for Pb, Cu and no converter

HGN prototype cell



- JINR-produced fast scintillator
  - Polystyrol + 1.5% p-terphenil and 0.01% POPOP
  - Scintillator cell – 40 x 40 x 25 mm^3
- Timing resolution evaluated with a single-channel detector and a MCP-based trigger
- Photodetector: Hamamatsu S13360-6050PE
  - $6x6mm^2$ photosensitive area
  - 14400 px per ch
  - 50 μm px size
  - $1.7x10^6$ gain
  - 40% PDE

Aim

- Optimal ratio of detector acceptance unit price and time resolution

Parameters affecting the time resolution of the detector:

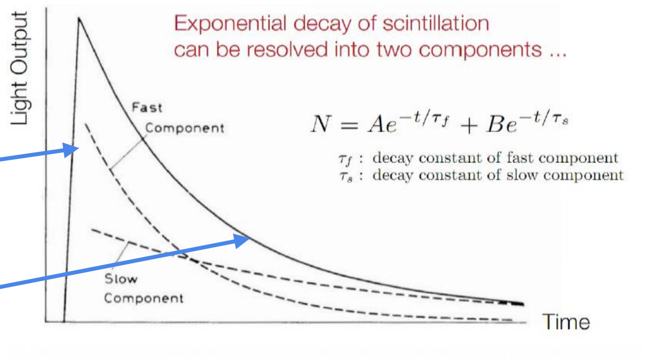
- Time properties of the scintillator
- Time properties of SiPM
- Reflective surface of the scintillator
- Method of light transmission to SiPM

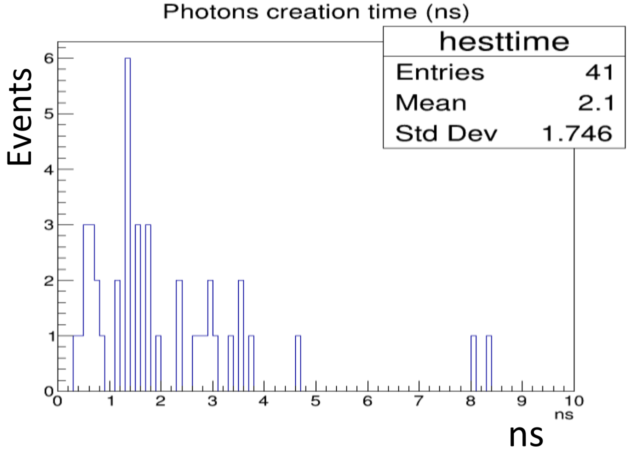
Factors determining time properties

Flashing time

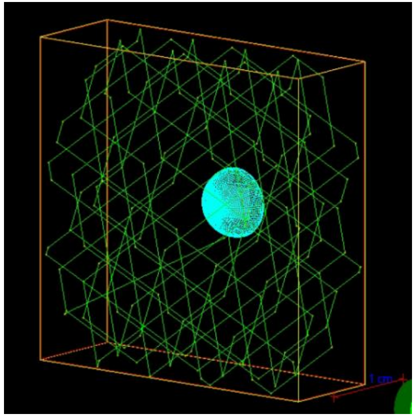
Front time

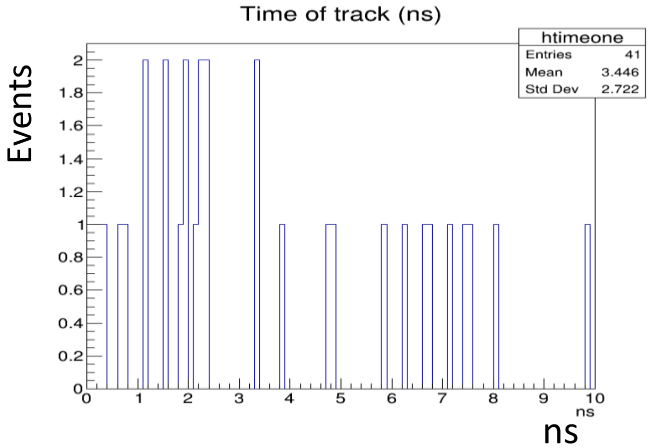
Decay time



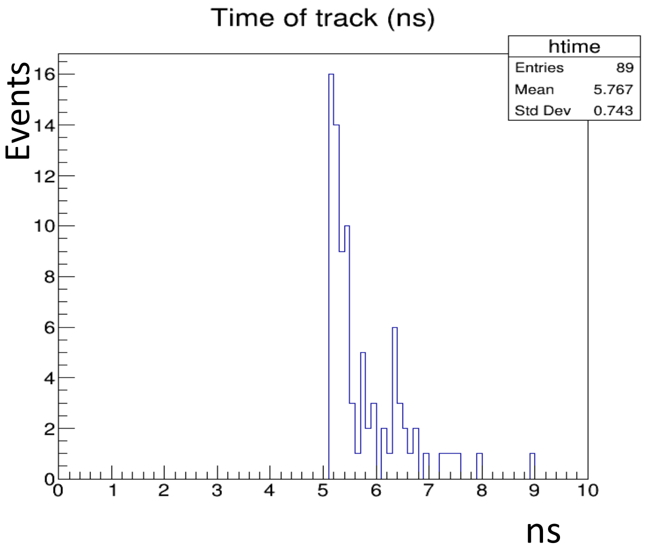


Light transportation time

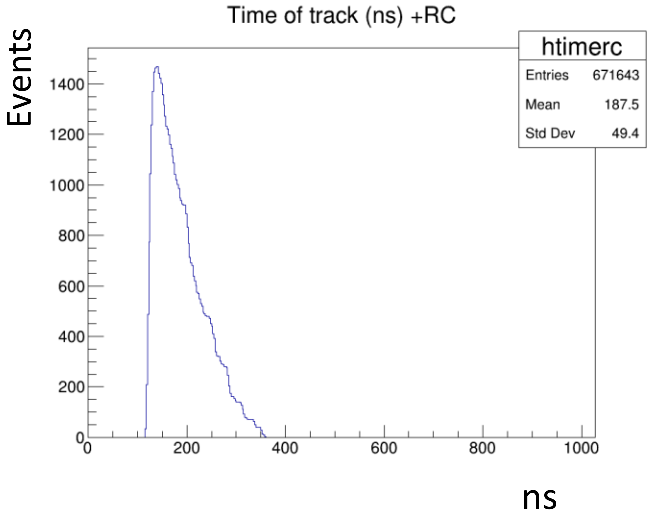




Signal generation

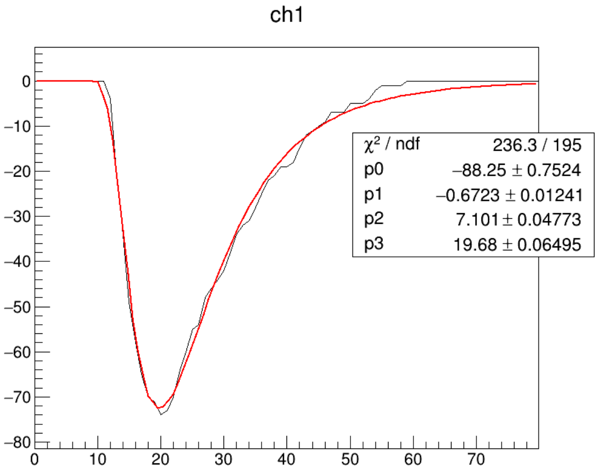


Photon transportation time



$$U_f = U_0 (1 - e^{\frac{-(t-t_0)}{R_f C_f}})$$

$$U_b = U_0 * e^{\frac{-(t-t_0)}{R_b C_b}}$$



Fitted signal by the Novosibirsk function

$$f(x) = e^{-\frac{\ln^2 q_y}{2\Lambda^2} + \Lambda^2}, \quad q_y = 1 + \frac{\Lambda(x - x_0)}{\sigma} \times \frac{\sinh(\Lambda\sqrt{\ln 4})}{\Lambda\sqrt{\ln 4}}$$

Characteristics of the scintillator and SiPM

Scintillators

Scintillators based on polyvinyltoluene **EJ-200** and **EJ-228** with the following characteristics

	EJ-200	EJ-228	EJ-230	**POPOP+p-ter.**	BC-408
Scintillator efficiency (photons/1 MeV e^-)	10000	10200	9700	**8500**	9700
Rise Time (ns)	0.9	0.5	0.5	**0.8**	0.9
Decay Time (ns)	2.1	1.4	1.4	**2.3**	2.1
Light attenuation length (cm)	380	380	120	**180**	210

SiPM

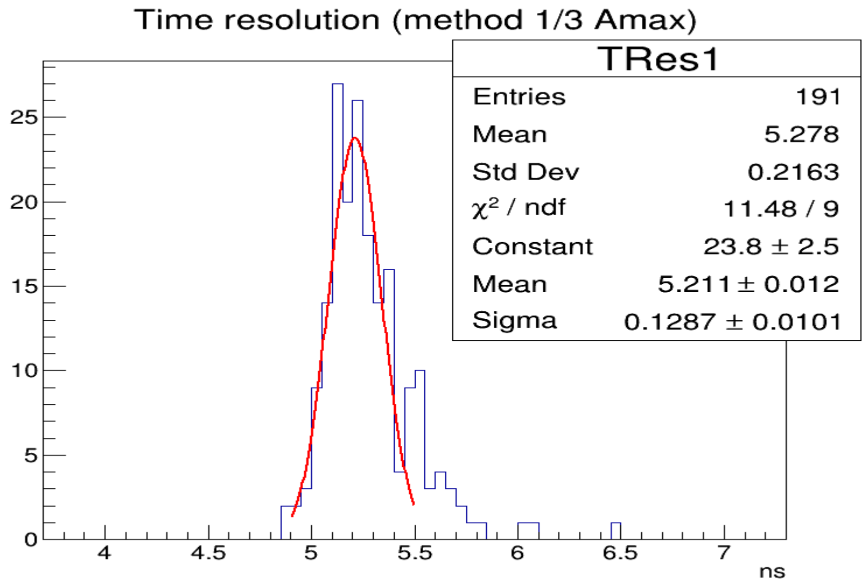
Sensl MICROFJ-30035 3x3 mm^2 and 60035 6x6 mm^2 **Hamamatsu** S12572-015P 3x3mm^2 and S13360-6050PE 6x6 mm^2

	Hamamatsu		Sensl		SQR-15
Size, mm^2	3x3	**6x6**	3x3	6x6	6x6
Front Time (ns)	3.5	**6.5**	3	5	2
Decay Time (ns)	150	**300**	120	400	10
Quantum efficiency, %	25	**40**	30	50	45

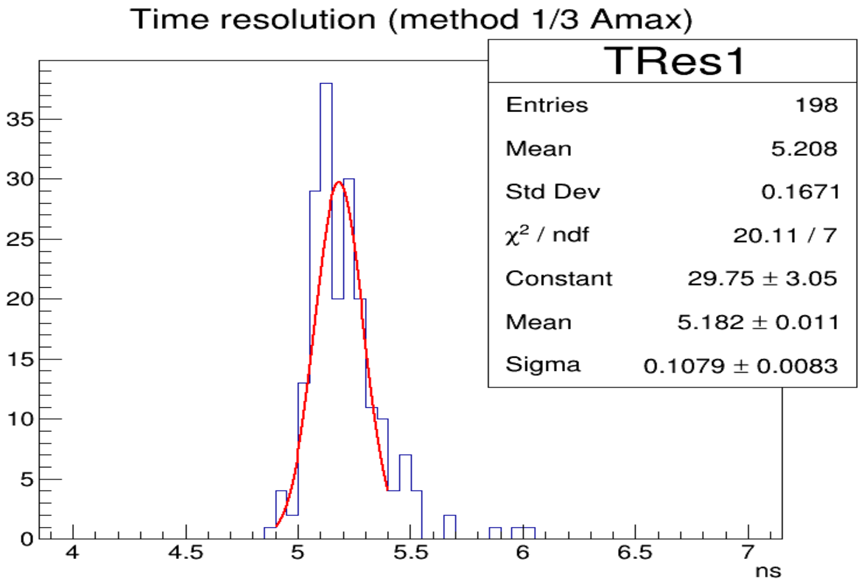
Моделирование Диффузное отражение

Временное разрешение   порог 3МэВ

40x40x38 mm^3



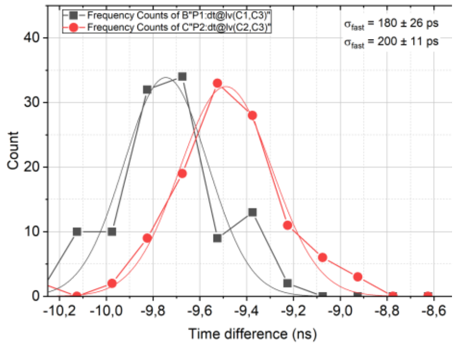
40x40x25 mm^3

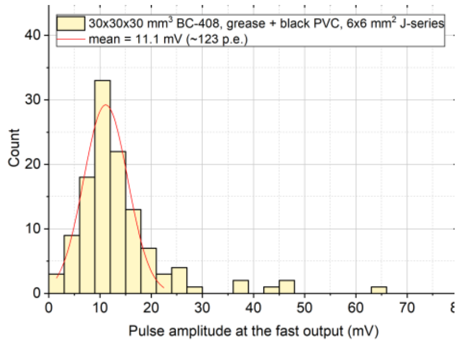


Влияние покрытия (на примере BC-408 30x30x30 мм³)

Смазка + чёрная ПВХ плёнка

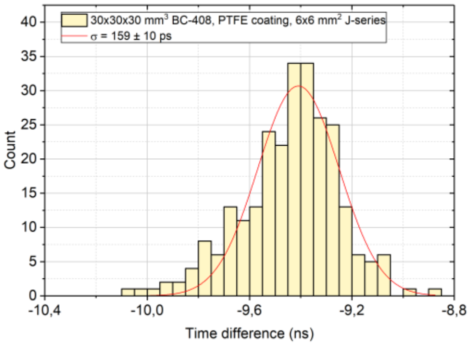
120 ф.э. | σ = 170 пс

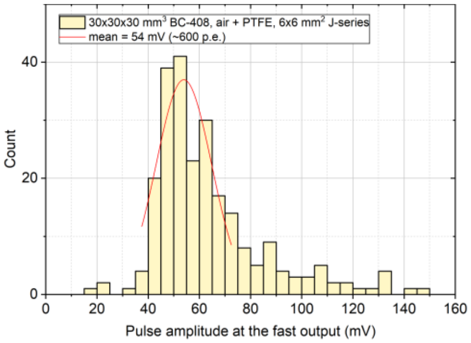




Воздух + тефлон

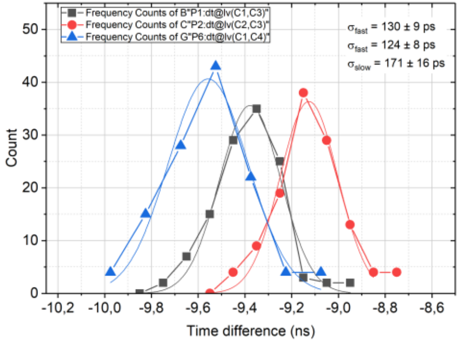
600 ф.э. | σ = 150 пс

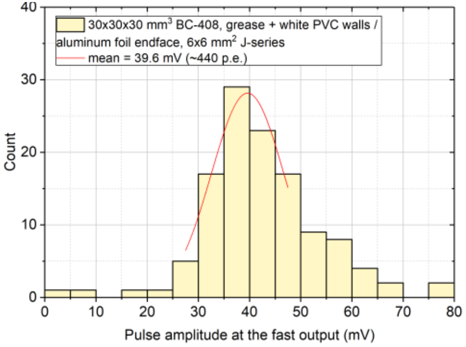




Смазка + белая ПВХ на стенках + зеркальный торец

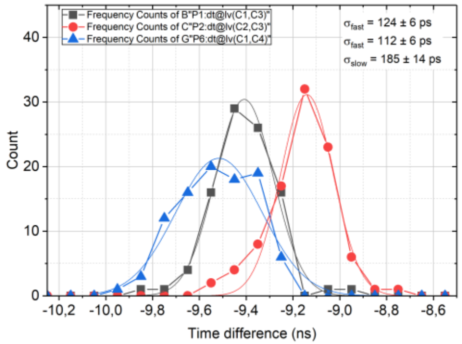
440 ф.э. | σ = 120 пс

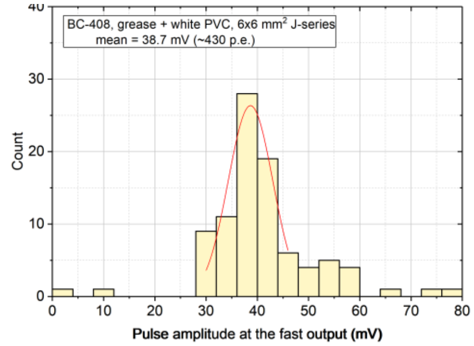


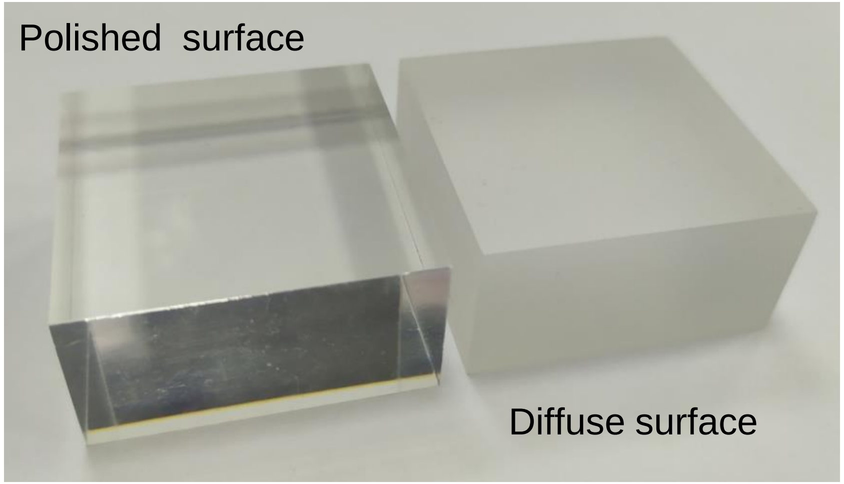


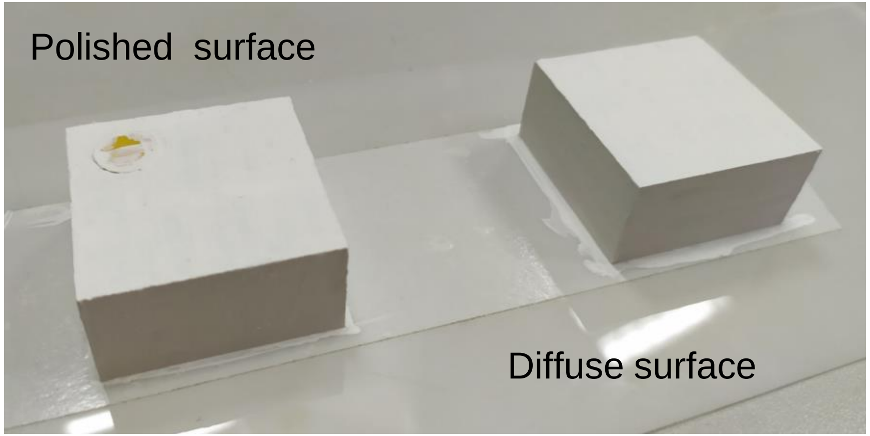
Смазка + белая ПВХ плёнка

430 ф.э. | σ = 110 пс





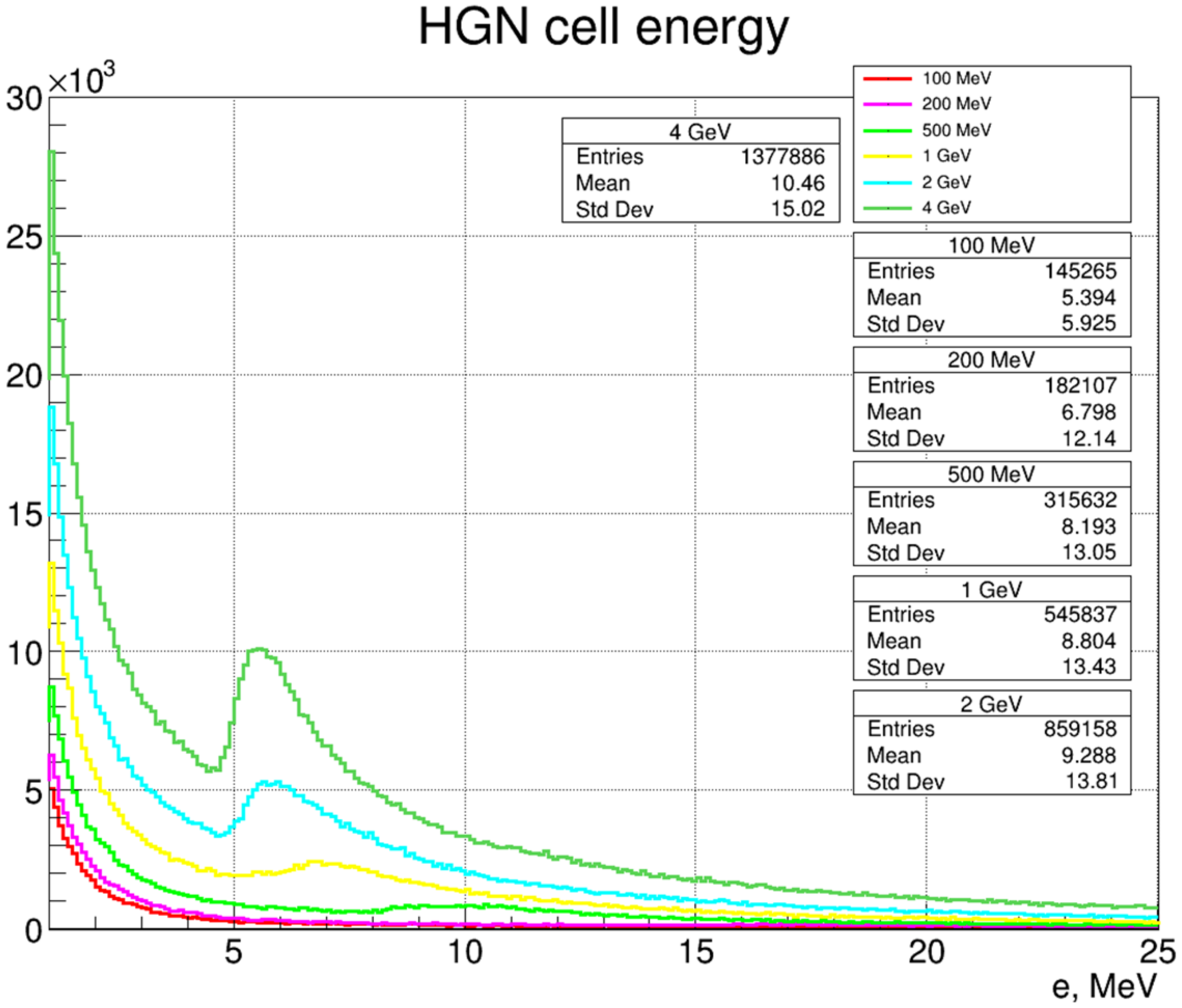




Non painted scintillators

Dimension 40x40x25 мм^3

Painted scintillators
Ej-510 reflective coating



HGN cell energy
30 ×10^3
25
20
15
10
5
0
5
10
15
20
25
e, MeV
4 GeV
Entries 1377886
Mean 10.46
Std Dev 15.02
100 MeV
200 MeV
500 MeV
1 GeV
2 GeV
4 GeV
100 MeV
Entries 145265
Mean 5.394
Std Dev 5.925
200 MeV
Entries 182107
Mean 6.798
Std Dev 12.14
500 MeV
Entries 315632
Mean 8.193
Std Dev 13.05
1 GeV
Entries 545837
Mean 8.804
Std Dev 13.43
2 GeV
Entries 859158
Mean 9.288
Std Dev 13.81

HGN

HGN neutrons energy resolution and efficiency vs kinetic energy

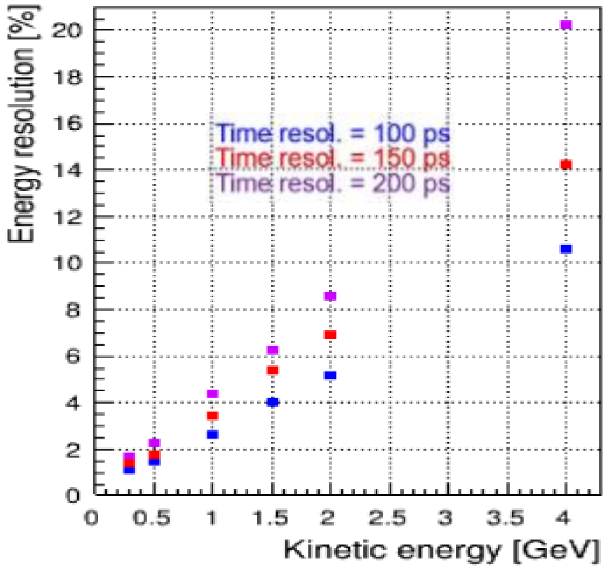
780 cm, 12x12 cm, 9 mods, 4x4 cm, 10000 ev., **w/o magnetic field, 82.5 cm**

Veto 2.5 cm + 5 slices (Pb 0.8 cm + Sc 2.5 cm + G10 0.5cm + Air 0.5 cm) **+**
9 slices (Cu 3 cm + Sc 2.5 cm + G10 0.5cm + Air 0.5 cm)

Time cut in HGN**:** time < **55** nsec (in simulations)

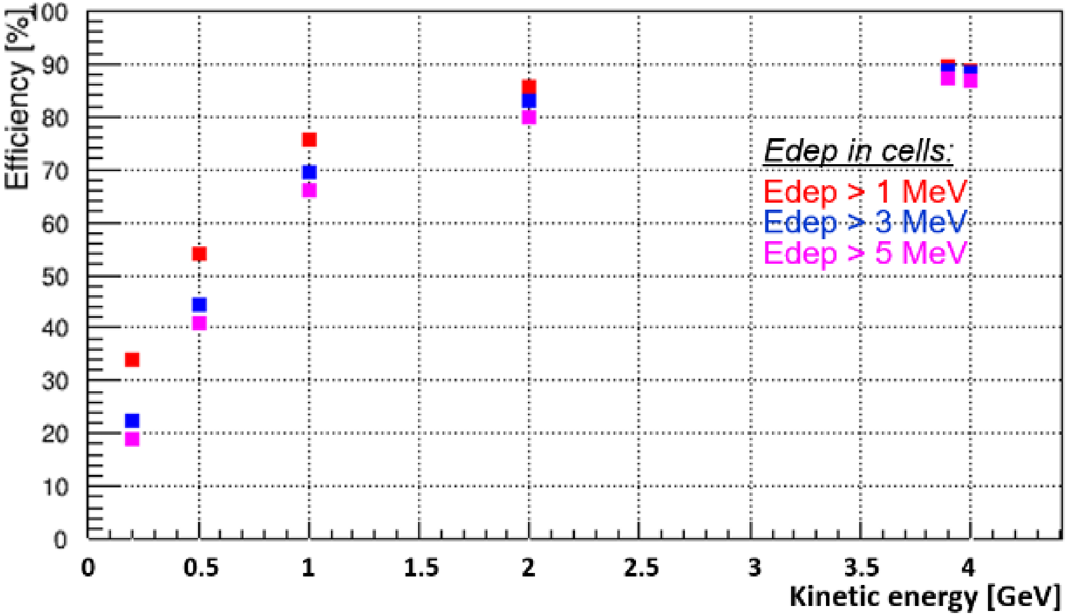
Vac. in cave, neutrons multiplicity = 1, BOX generator, "Huge" spot

Neutrons energy resolution



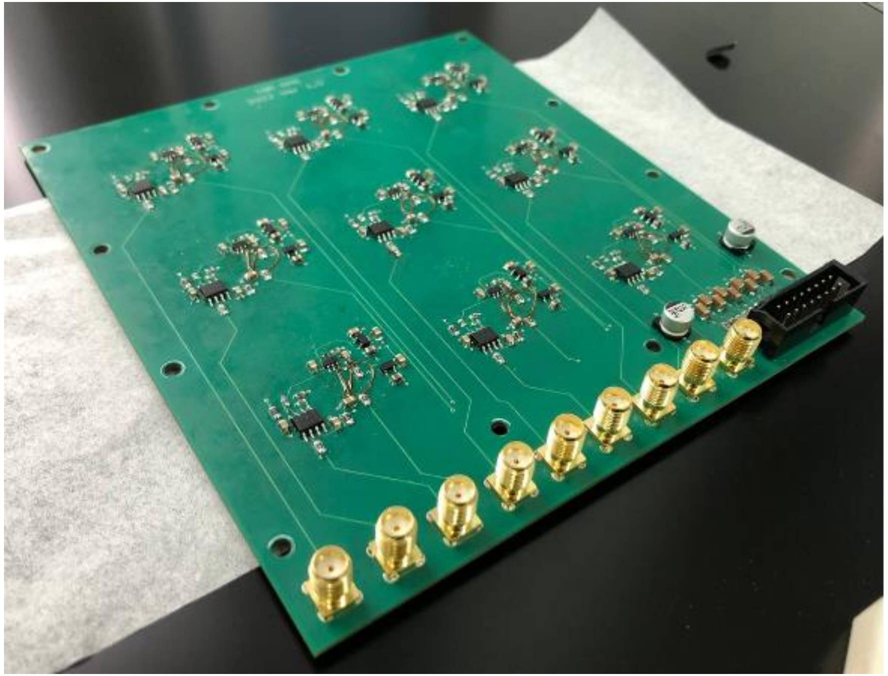
Kinetic energy is reconstructed with hit with min. time, Edep in cells > 3 MeV and w/o hits in Veto

Efficiency



Inefficiency = nb of events w/o hits in nDet / nb of analyzed events
*Efficiency [%] = (1 – Inefficiency) * 100*
Nb of slices in nZDC = 1, 2, ... 14)

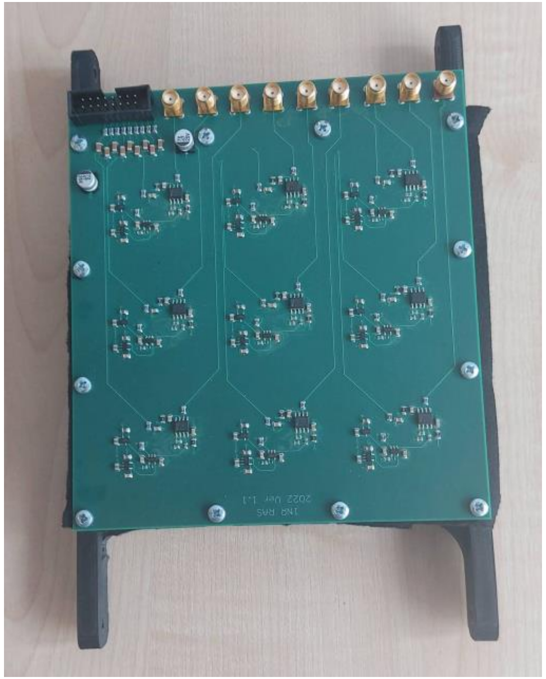
HGN prototype electronics



- **Two types of PCBs** with photodetectors were designed in INR and ITEP
  - Used 9 SiPM per board
  - INR boards are compatible with COMPASS V3 bias supplies
  - KCTEP boards are supplied by single HV source

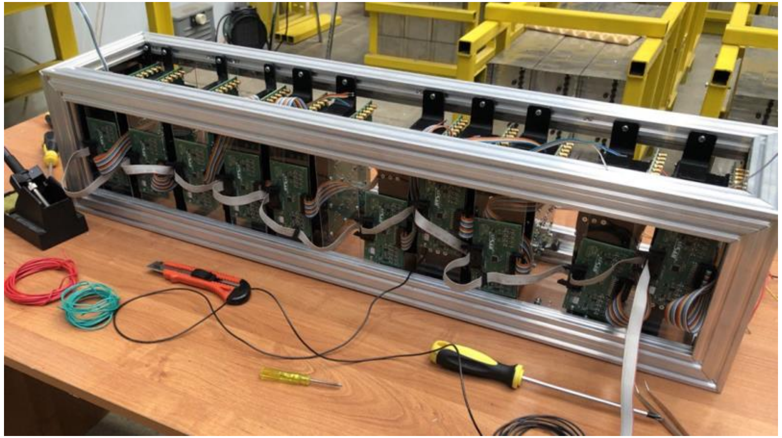
HGN prototype components

- Hamamatsu S13360-6050PE 6x6 mm^2
- P-terphenile 1.5% + POPOP 0.01%



HGN prototype mechanics

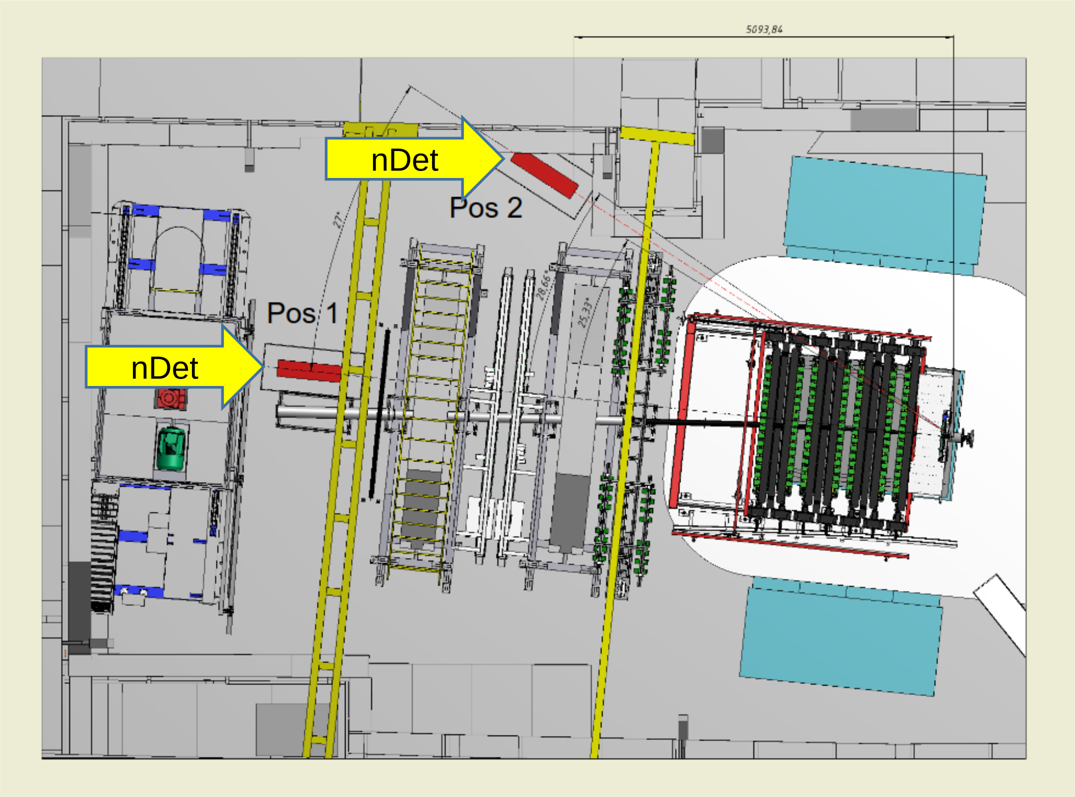
- Detector modules are independent
  - May be inserted and removed with minimal disassembly
- Bias supply system is modular with variable module count



- Support structure for HGN positioning
  - ~2m tall
  - On rollers with retractable feet
  - ~1m high shelf for readout equipment
  - Shelf for additional weight on the bottom
  - Adjustable on all 3 axes of movement and rotation
  - Built with 40x40 Bosch Rexroth profile


NKM

Objectives



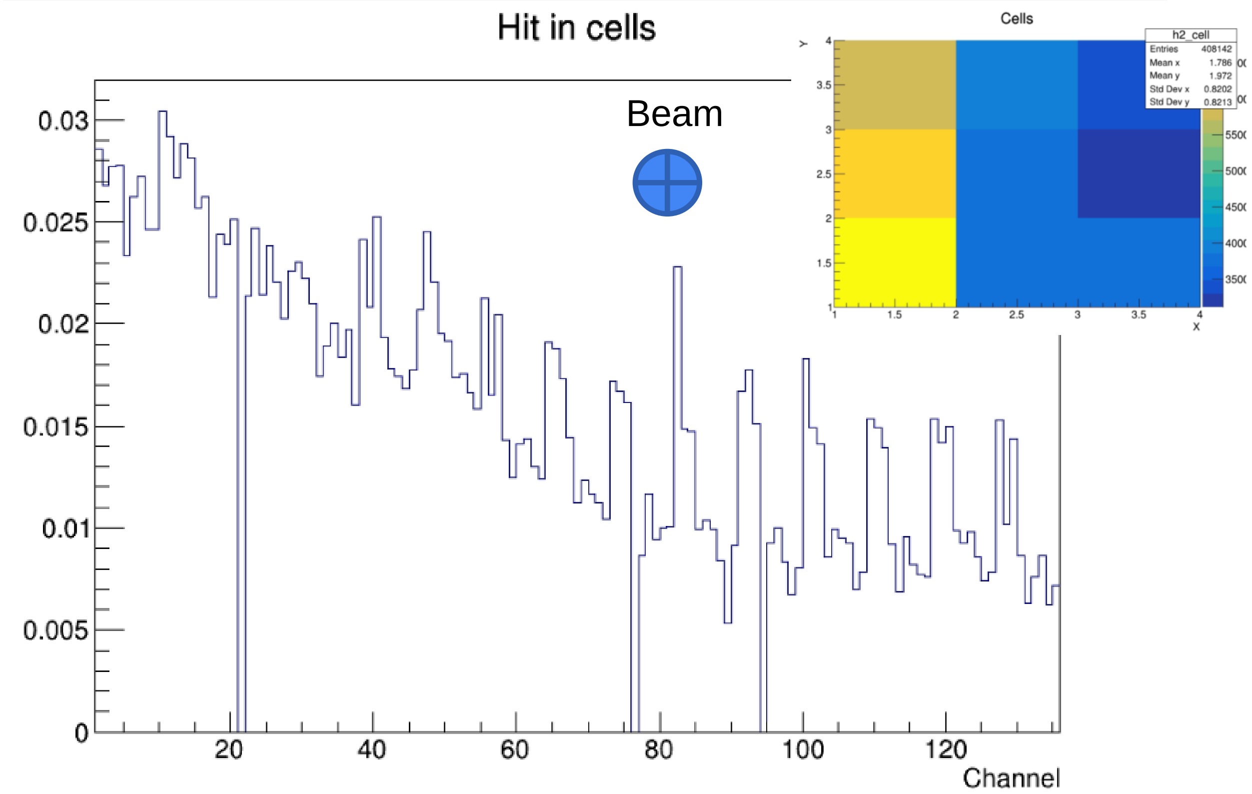
Beam test of HGN prototype for the BM@N experiment;

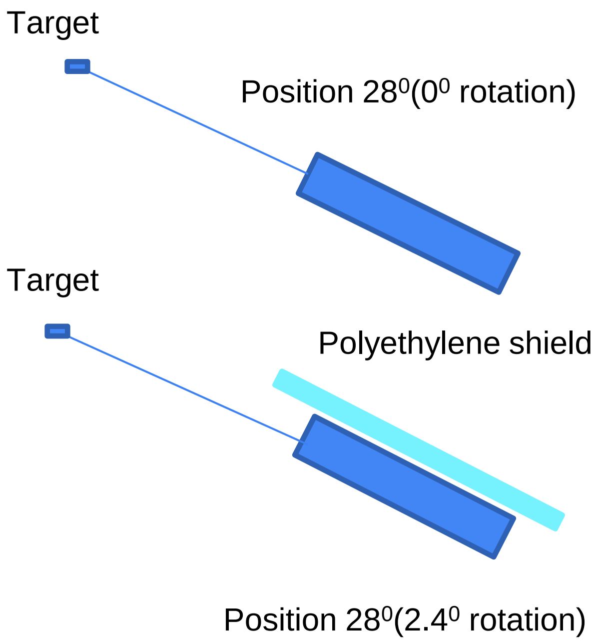
Identification and energy measurements of fast neutrons up to 4 GeV energies;

Investigation of background conditions on the setup;

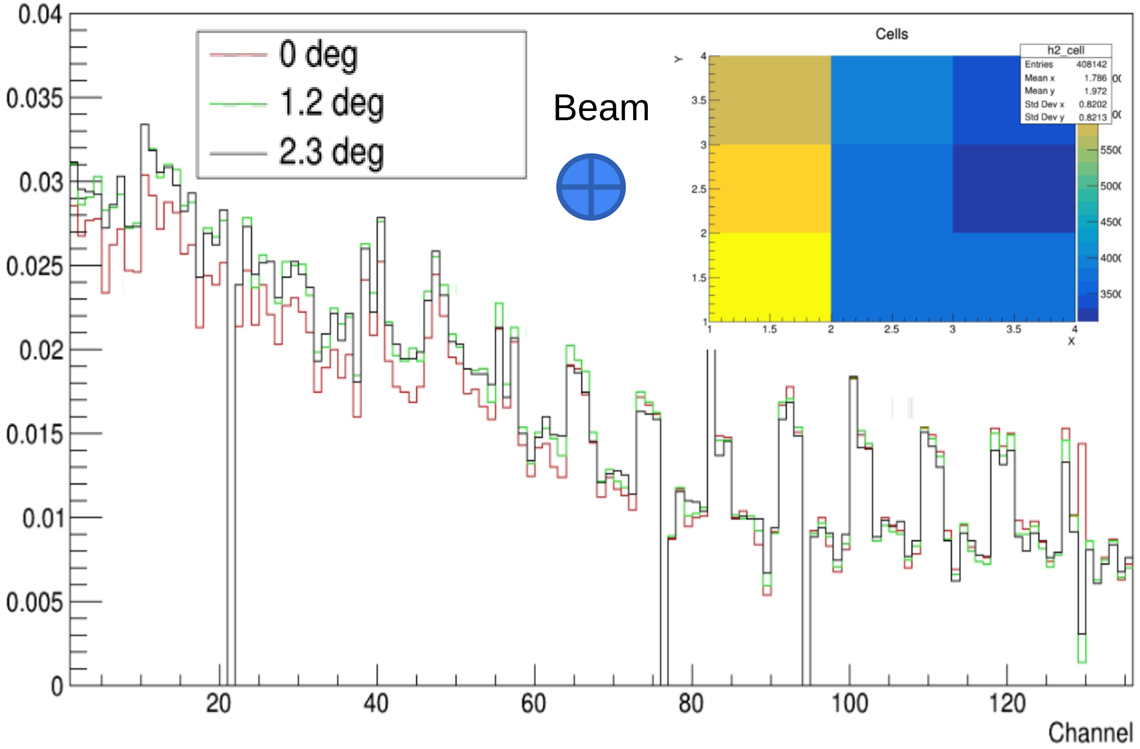
Investigation of the time resolution during neutron registration.

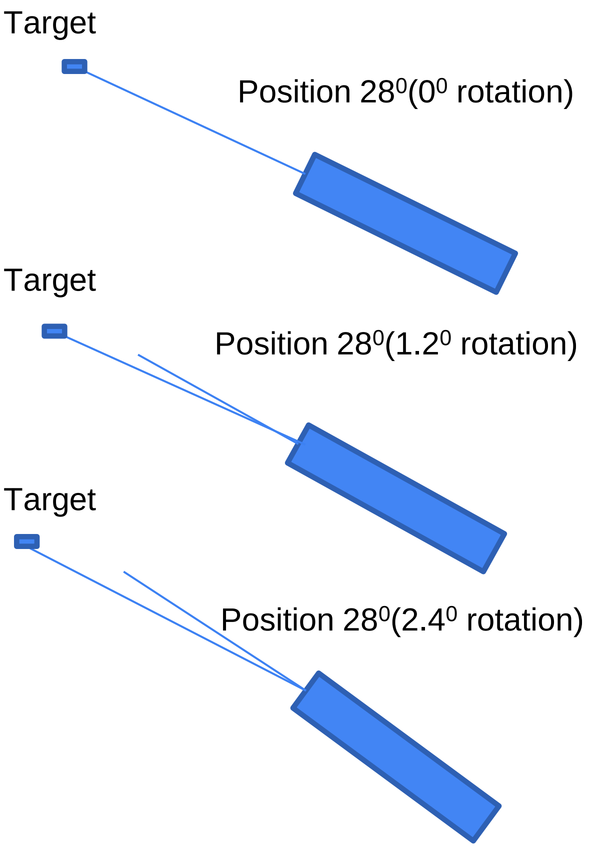
Non uniform occupancy in the cells of HGN. (position 28^0)



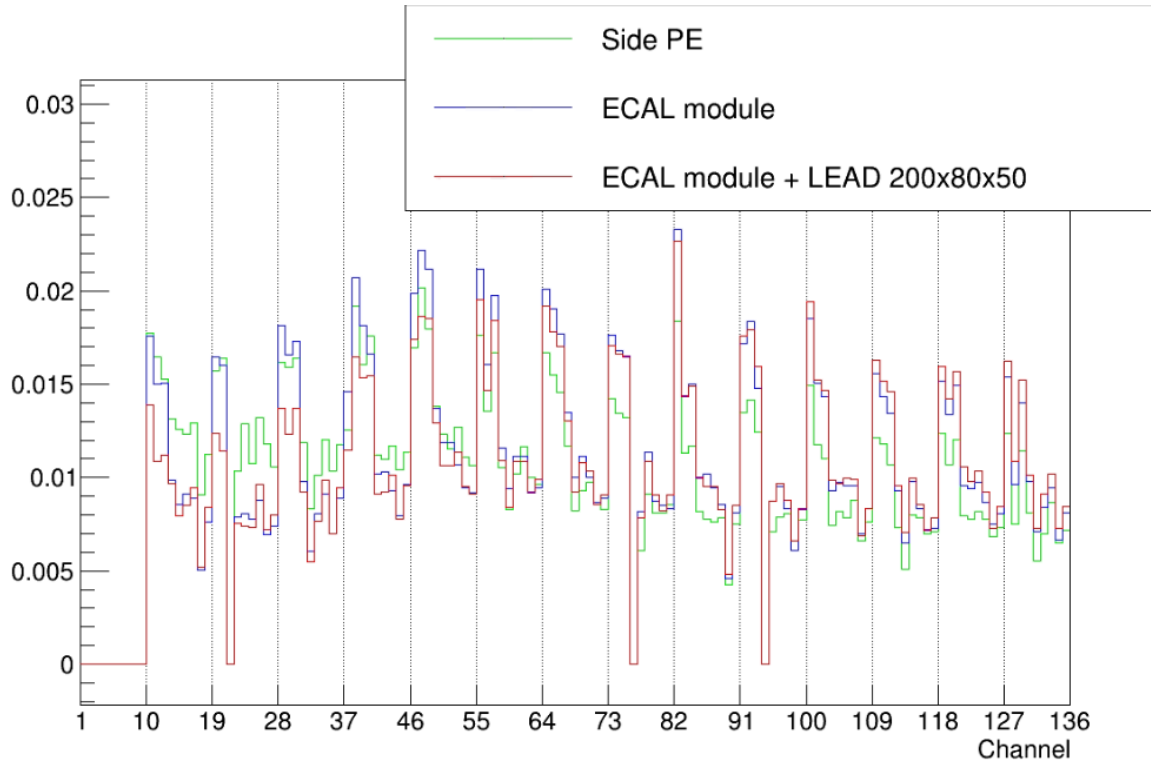


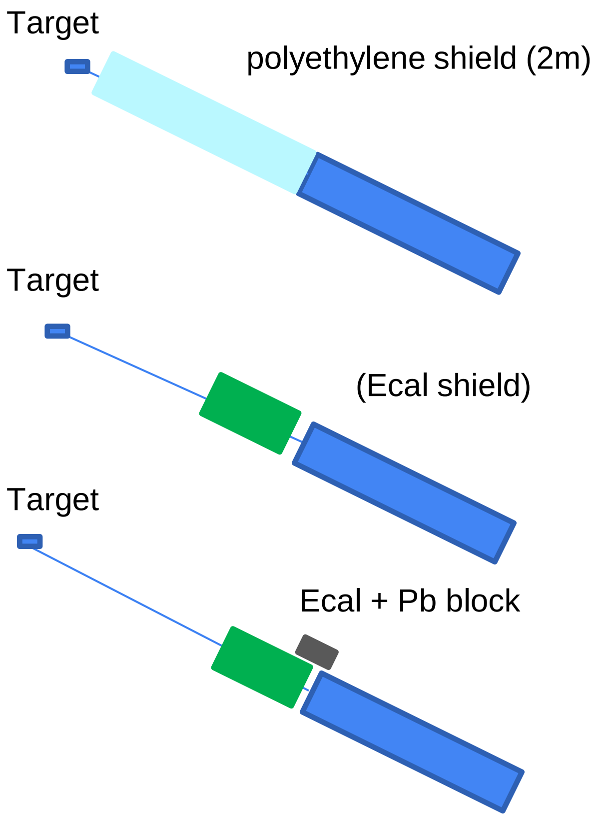
Non uniform occupancy in the cells of HGN. (position 28^0)



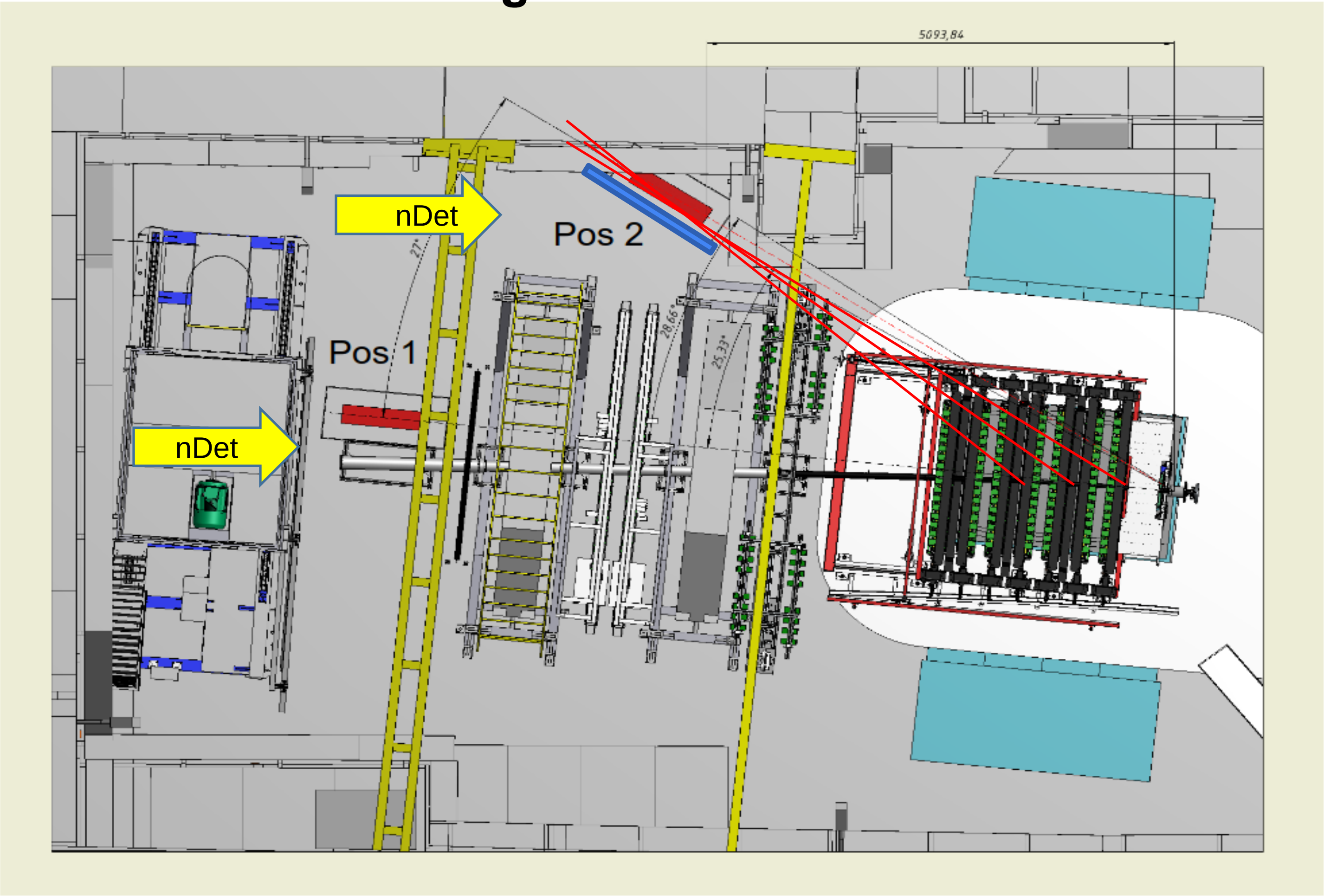


Non uniform occupancy in the cells of HGN. (position 28^0)

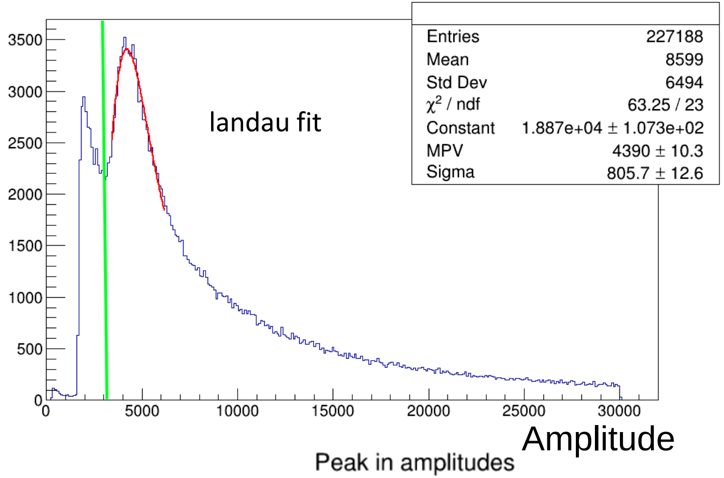




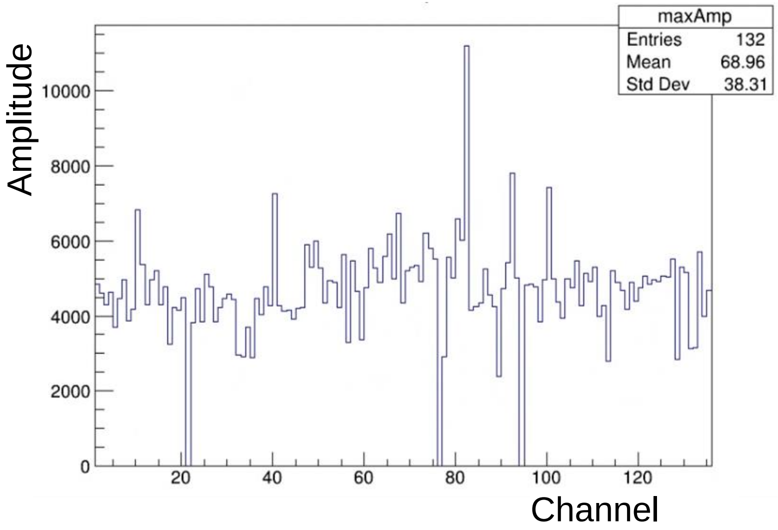
Backside background from GEM +TOF+…

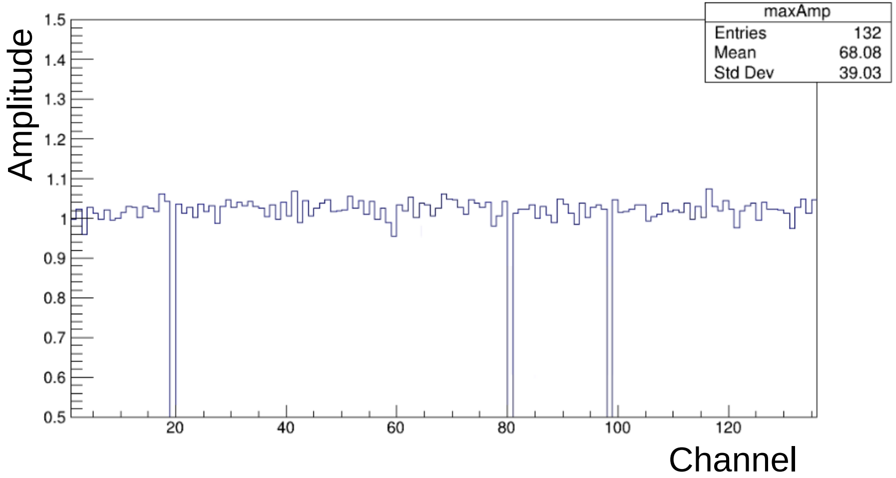


Normalization of amplitudes



C = 1/ MPV
Ampl = Ampl * C



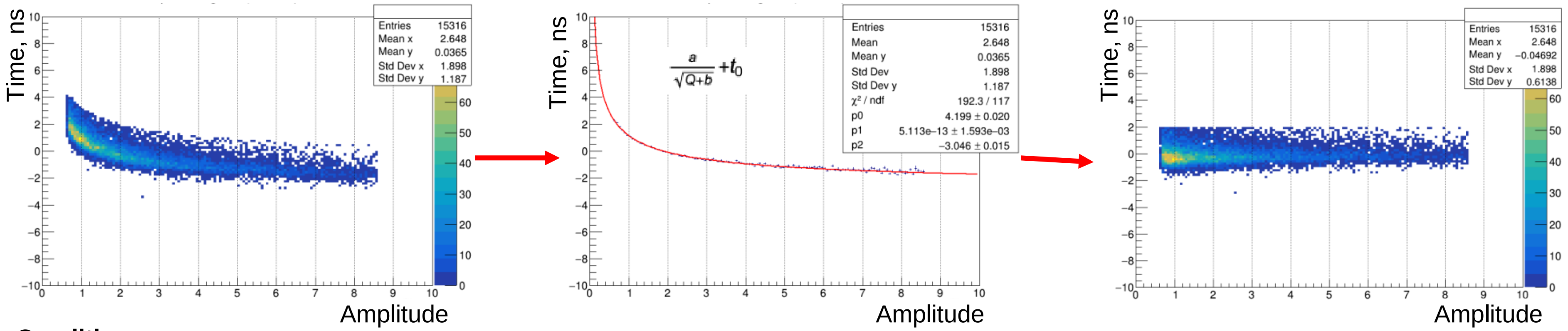


Measurement conditions

Xe+CsI interactions
Selection of events with one Xe core
Trigger CCT2
0 degree position
Energy 3.86 AGeV
No hits in the veto layer for cut off charged particles
Cell times of the first triggered layer in the event

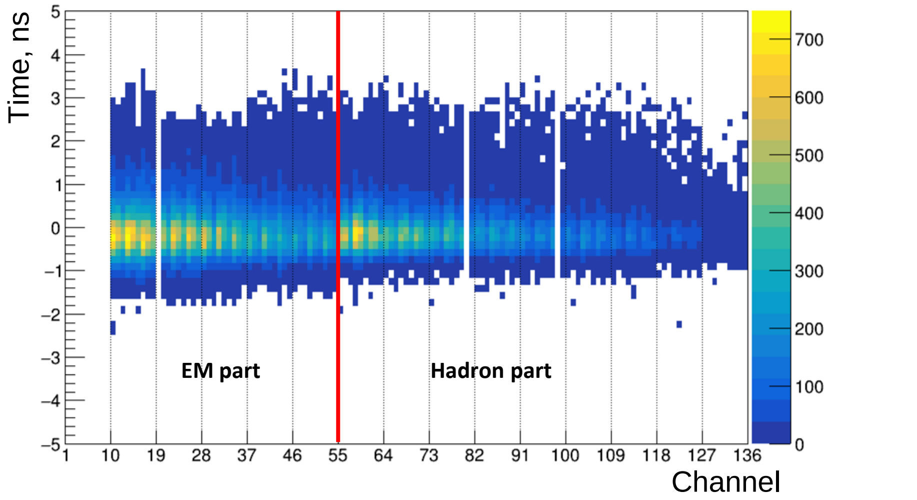
Slewing correction

Dependence between time and amplitude for one detector channel



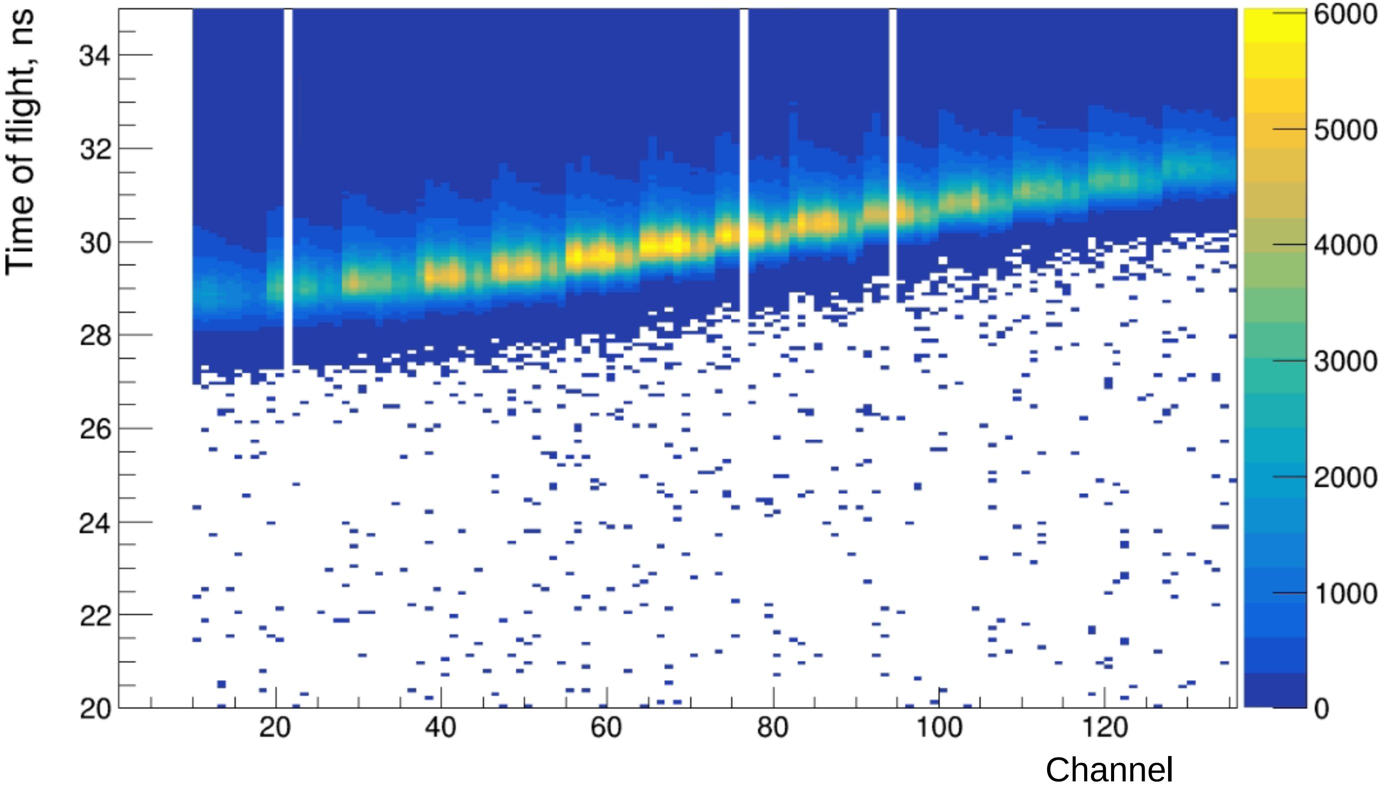
Conditions:

- Individual amplitude thresholds have been selected to cut off background events
- Amplitudes was normalized to MIP peak
- Slewing correction for start counter

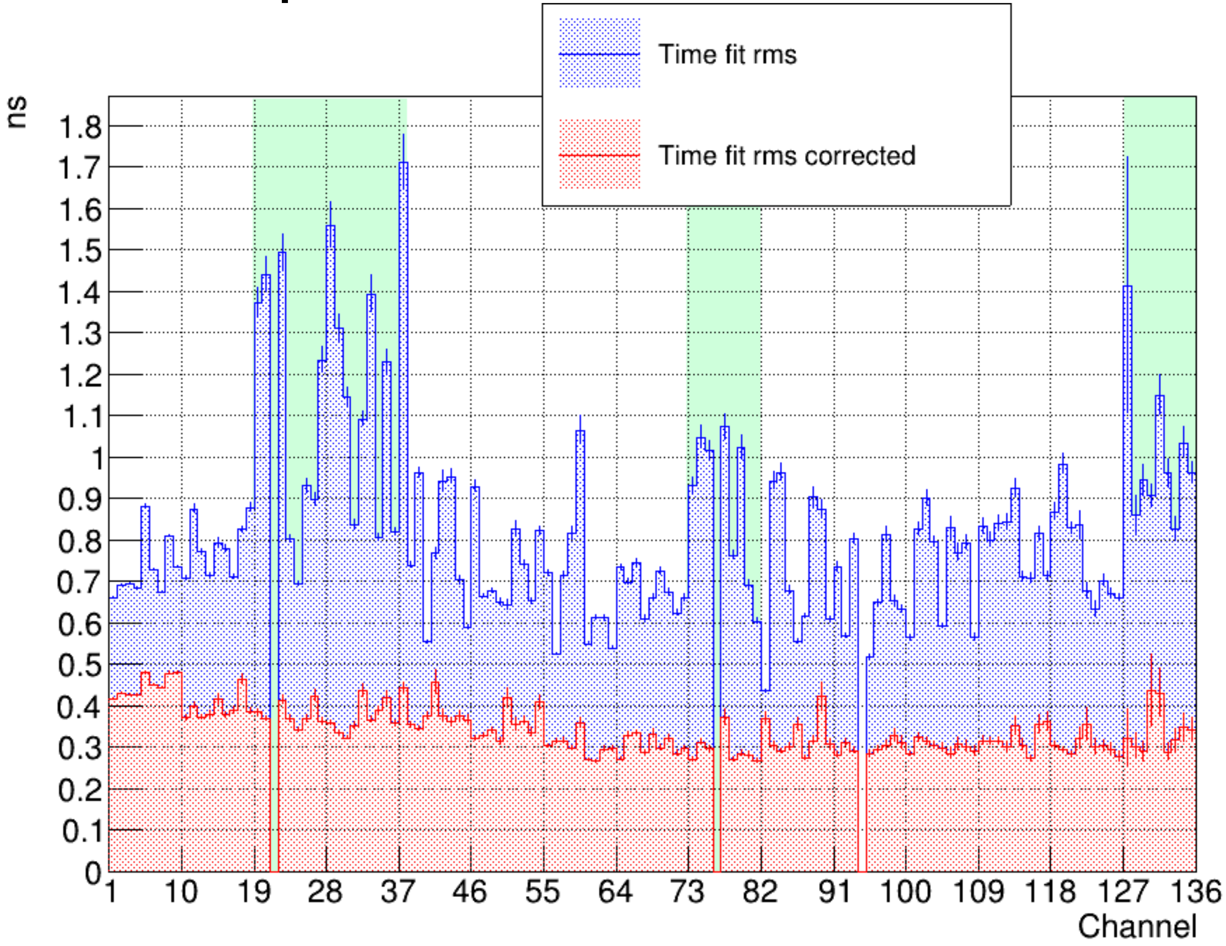


Time of flight for all detector channels

The time was calculated depending on the distance from the target to the detector layer and the neutron velocity.
The time peak corresponds to the neutron energy of 3.86 GeV



Uniformity of the time parameters



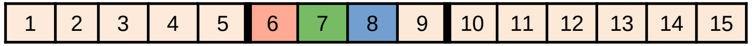
Estimation of time resolution of single cells

Cut – hits in 4 layers: (i) & (i+1) & (i+2) & (i+3)

Layers 6 – 11

Run ID	Trigger	N_ events	Ndet pos	CCT2 & BC1S ev.	Ndet ev.	Veto=0 ev.
7513-7521	Mixed	3M	0°	986k	634k	465k

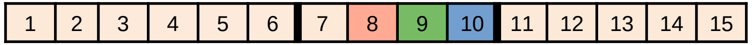
1st step 1-3 layers



1st step 2-4 layers

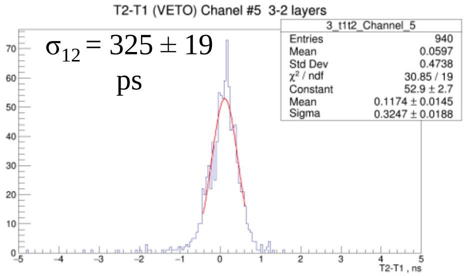
2nd step 1-3 layers

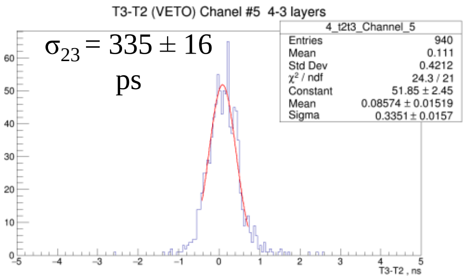
2nd step 2-4 layers

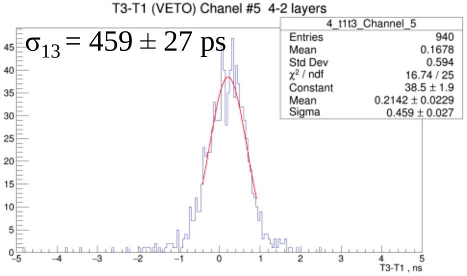


$$\sigma_1^2 + \sigma_2^2 = \sigma_{12}^2$$
$$\sigma_2^2 + \sigma_3^2 = \sigma_{23}^2$$
$$\sigma_1^2 + \sigma_3^2 = \sigma_{13}^2$$

$$\sigma_1 = \sqrt{((\sigma_{12}^2 + \sigma_{13}^2 - \sigma_{23}^2)/2)}$$
$$\sigma_2 = \sqrt{((\sigma_{12}^2 + \sigma_{23}^2 - \sigma_{13}^2)/2)}$$
$$\sigma_3 = \sqrt{((\sigma_{13}^2 + \sigma_{23}^2 - \sigma_{12}^2)/2)}$$







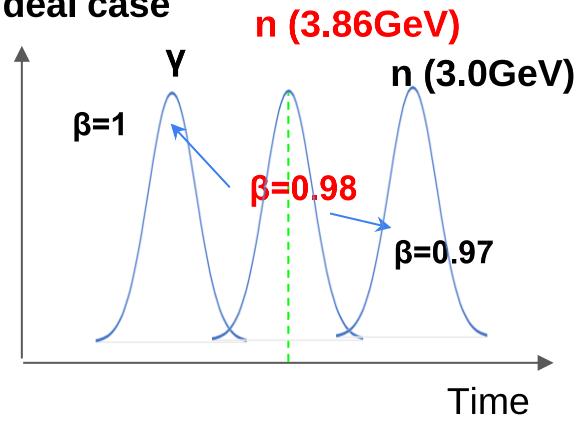
Cell 1	***Cell 2***	***Cell 3***
202±10	213±21	206±21
127±8	124±23	141±34
197±8	207±10	197±15
Cell 4	***Cell 5***	***Cell 6***
221±19	249±28	234±65
131±27	154±23	150±69
206±25	247±11	220±55
Cell 7	***Cell 8***	***Cell 9***
186±12	-	206±12
118±19	-	126±11
187±22	-	200±11

For center cell

134±27 ps

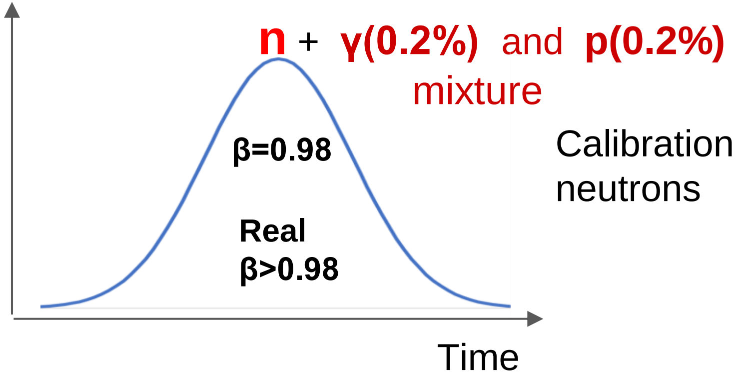
Reconstruction of neutron energy from time of flight

Ideal case

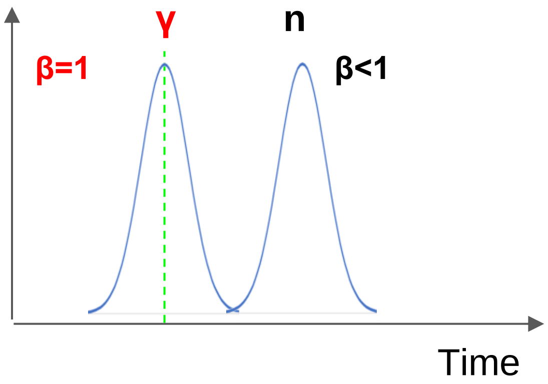


Calibration on neutrons

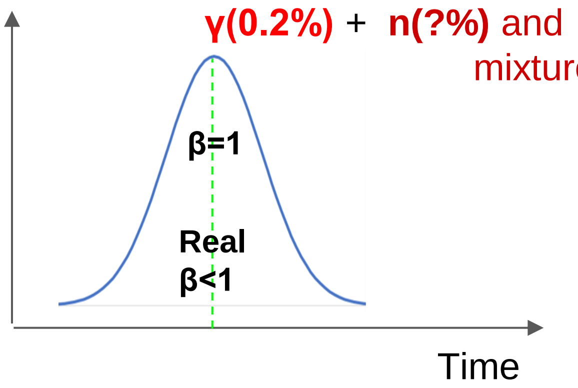
Real data



Calibration on neutrons



Calibration on photons



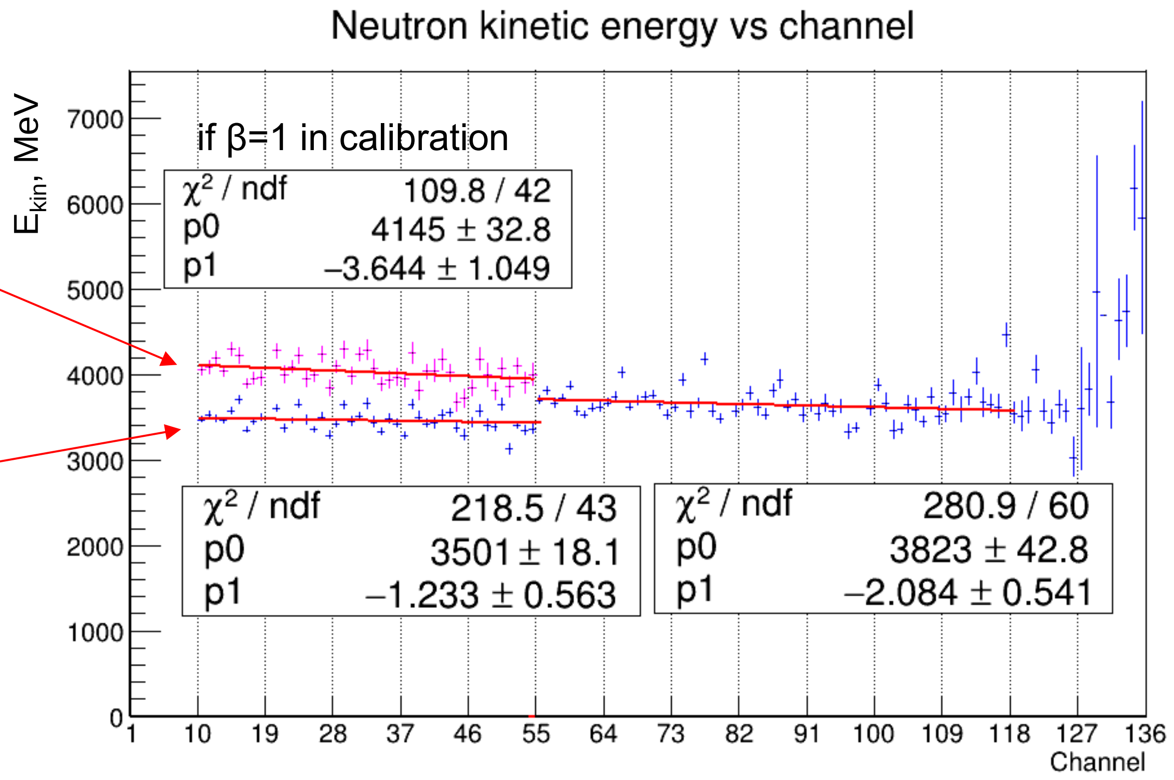
Calibration on photons is possible up to 8 layer

Reconstruction of neutron energy from time of flight

Dependence of the energy reconstruction on the calibration method based on the time spectra of photons and neutrons

Based on photon calibration

Based on neutrons calibration

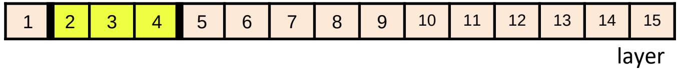


Gamma events selection

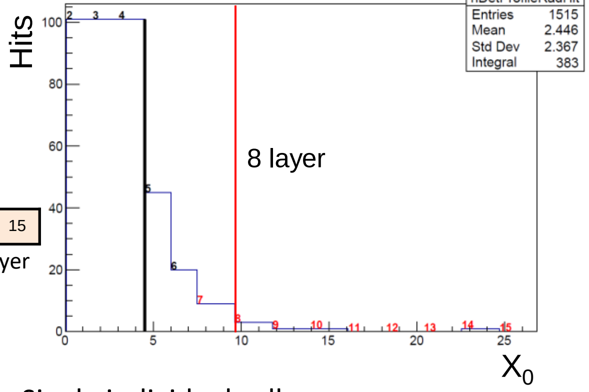
"Gamma":

- Veto == 0
- Ampl > 0.5 MIP
- Hits in layers 2 & 3 & 4 in cell

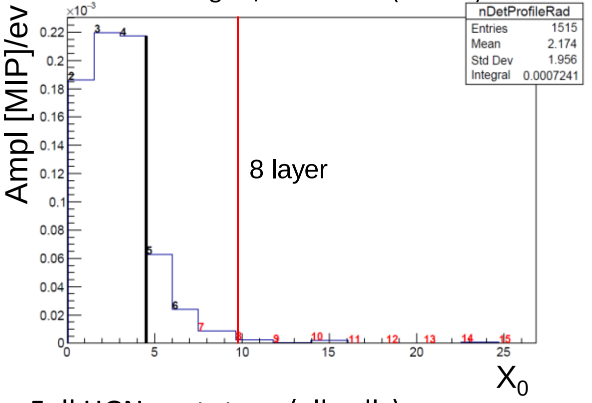
=> 4.52 X_0 or 0.266 λ_{int}



Gamma hits in cell 5 (central)



Gamma signal/ev. in cell 5 (central)



Single individual cells

Full HGN prototype (all cells)

Runs 8100-8104 (CsI 2%)
HGN 27 deg. pos.
Hit selection: Ampl > 0.5 MIP
Total number of events:
(CCT2+BC1S) – 1202k (100%)
+ Veto – 68.2k (5.67%)

Cell 1 (layer 3 didn't work)	***Cell 2*** **0.0092 %** ±0.0009 %	***Cell 3*** **0.0097 %** ±0.0009 %
Cell 4 **0.0202 %** ±0.0013 %	***Cell 5*** **0.0084 %** ±0.0008 %	***Cell 6*** **0.0099 %** ±0.0009 %
Cell 7 **0.0221 %** ±0.0014 %	***Cell 8*** **0.0118 %** ±0.0010 %	***Cell 9*** **0.0102 %** ±0.0009 %

0.17317 %
±0.00004 **%**

~15 times more then in one cell

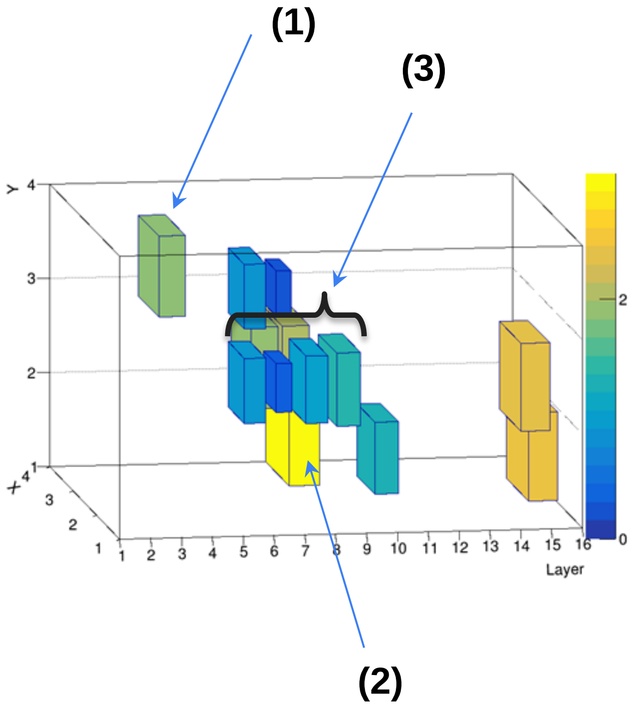
Comparable with simulation (0.1 – 0.2%)

Neutron energy determination algorithms

1. **Minimum time in first triggered layer**
   - First triggered layer on the Z axis;
   - Cell with the minimum time in this layer $\textbf{time}_{\textbf{layer}}$
   - Cut on EM shower

2. **Maximum particle speed in event**
   - Cell with the maximum particle speed in event $\textbf{time}_{\textbf{event}}$

3. **Search for neutron clusters**
   - In the first approximation, the simplest clusters containing 4 consecutive cells was considered

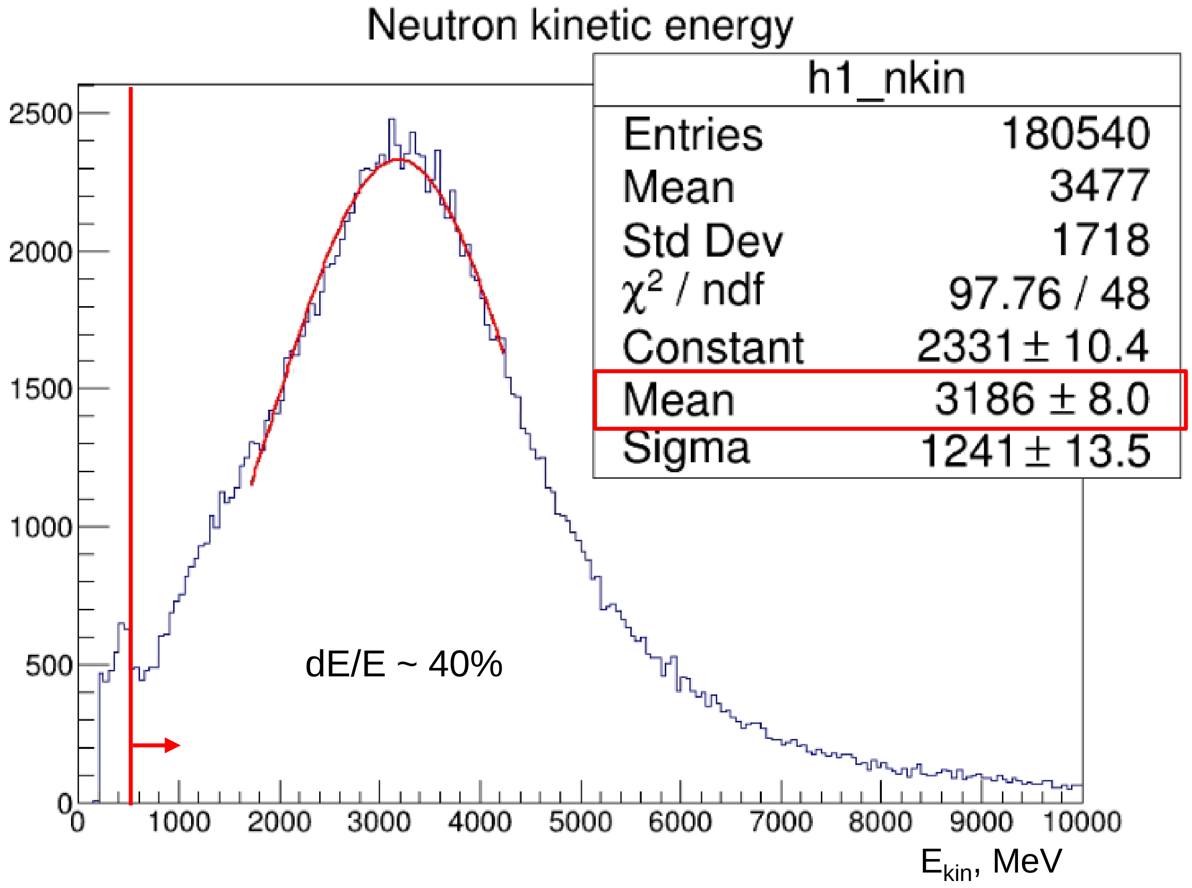


1. Minimum time in first triggered layer

Beam energy 3.86 AGeV

Search:
- First triggered layer on the Z axis;
- Cell with the minimum time in this layer **$time_{layer}$**

No signals in VETO layer;
E_{kin} > 500 MeV

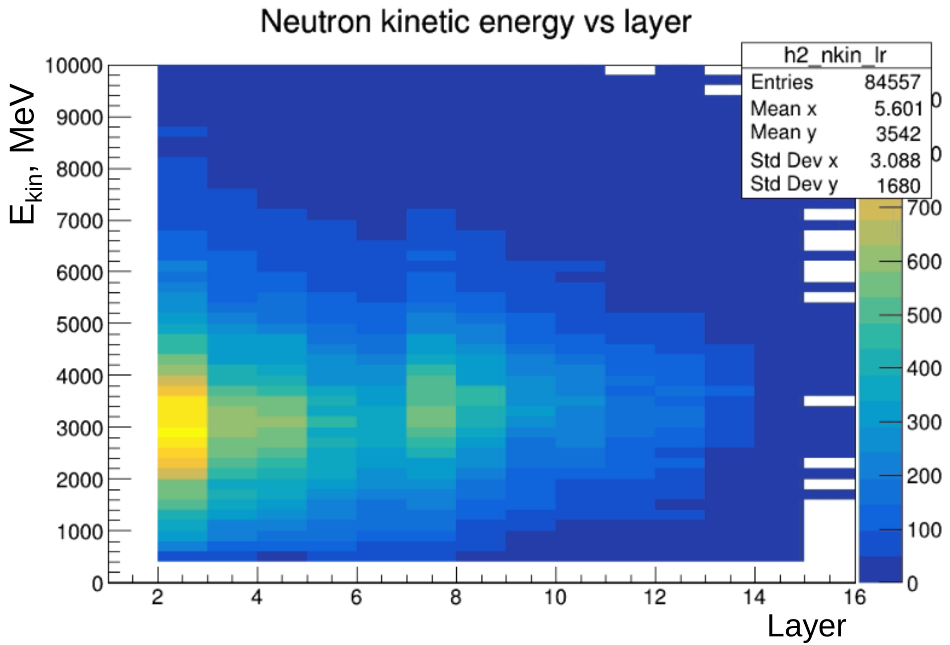


● Gamma suppression

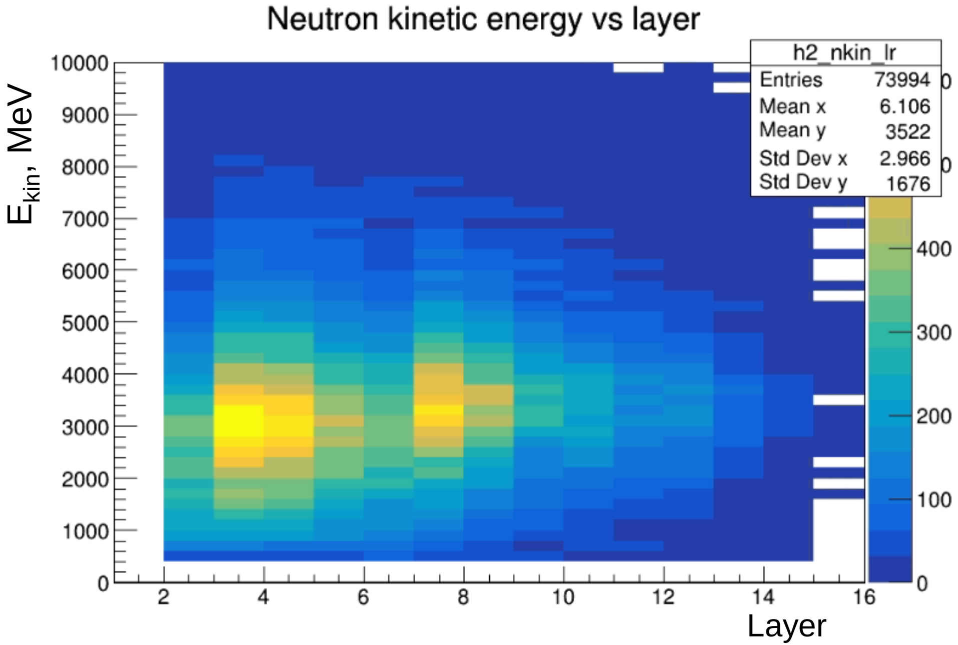
Mix of neutrons and electrons in EM part

Conditions for the selection of events without electromagnetic shower

Only VETO



NO hits in veto and in three first layers simultaneously

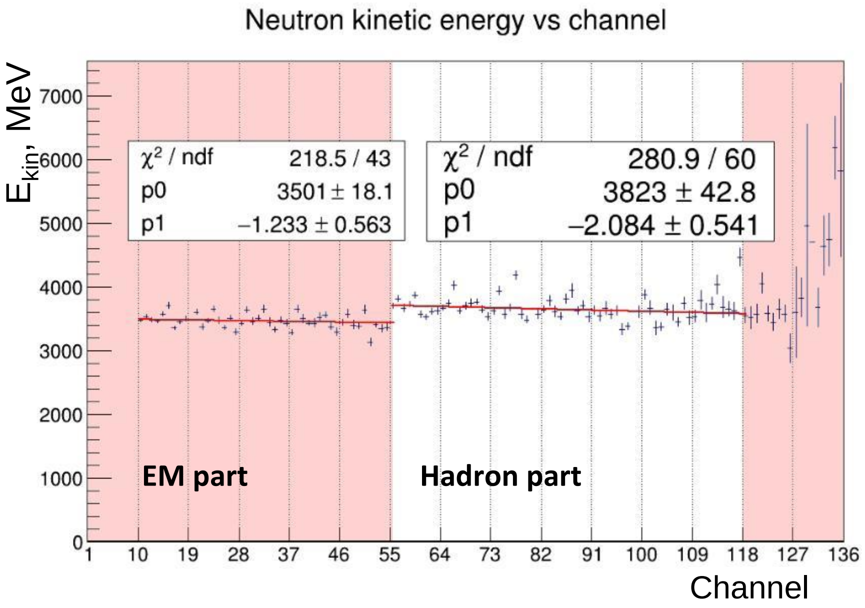


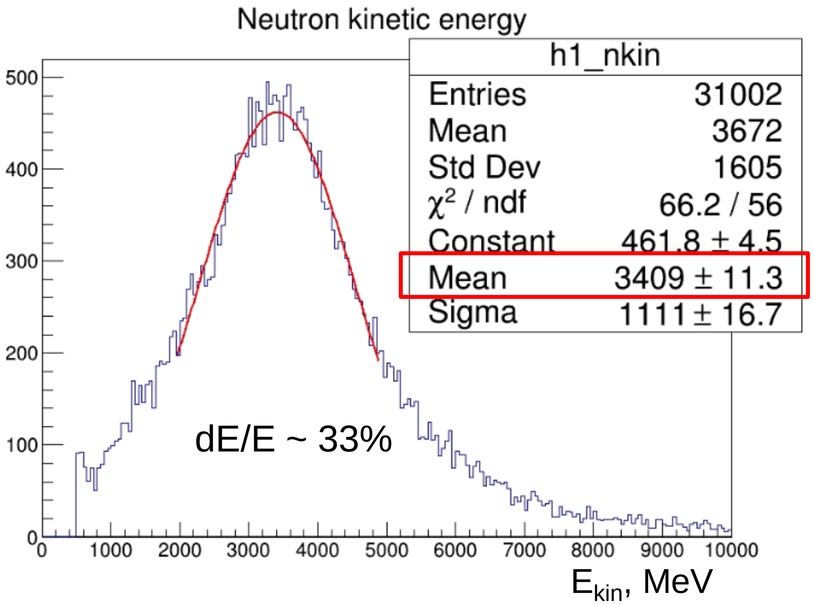
Statistics decreased by 12%

● Cut on EM part

6 < Layer $\mathbf{time}_{\mathbf{layer}}$ < 14

Applied conditions make the energy lower due to the presence of EM processes in the calibration data





2. Maximum particle speed in event

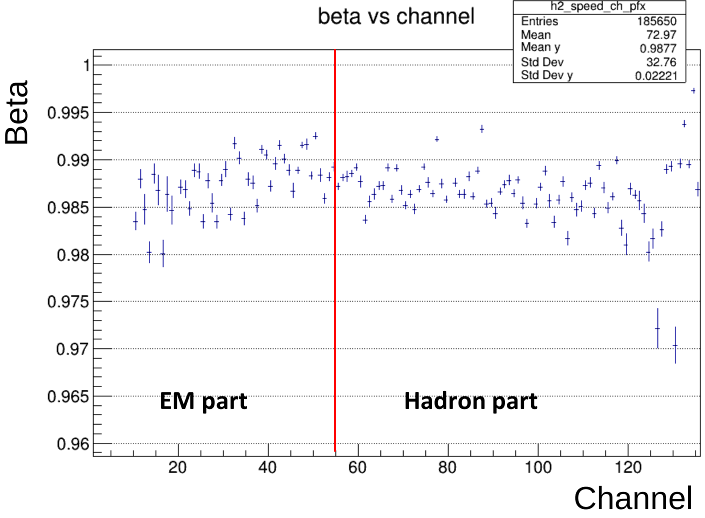
Beam energy 3.86 AGeV

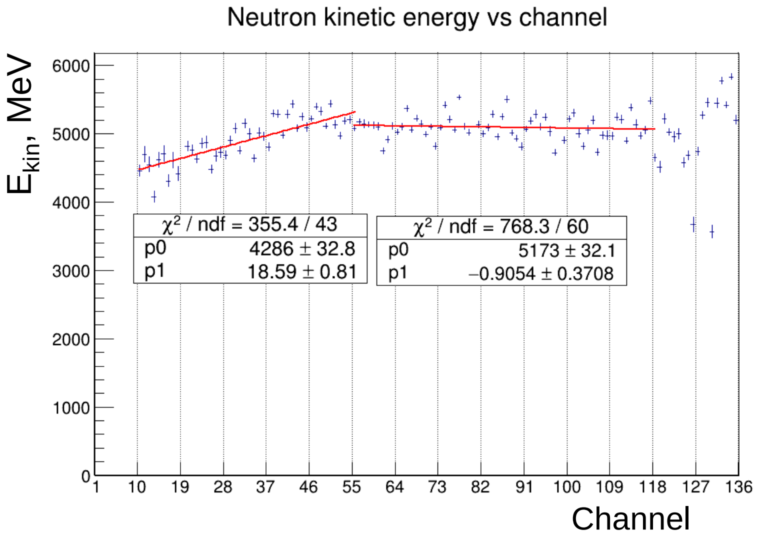
Search:

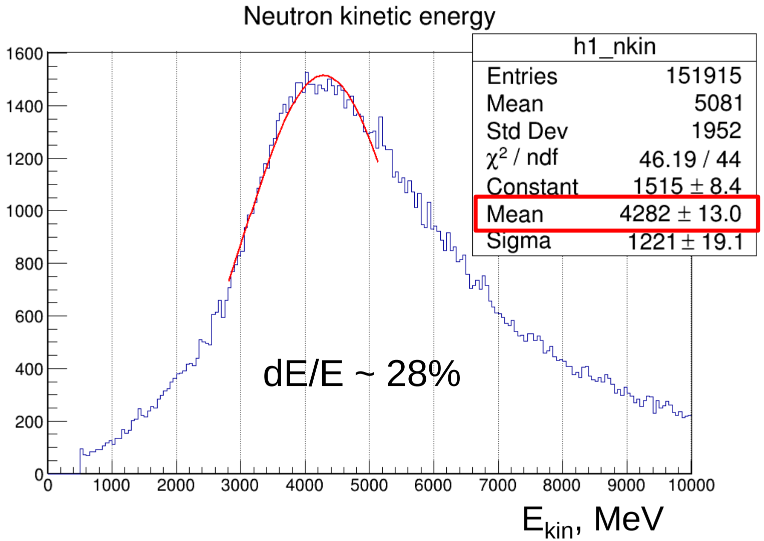
- Cell with the maximum particle speed in event **time$_{event}$**

No signals in VETO layer;

E_k > 500 MeV

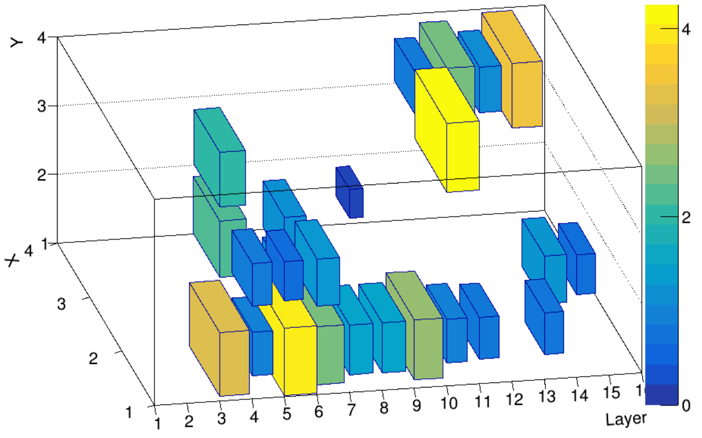






3. Clusterization

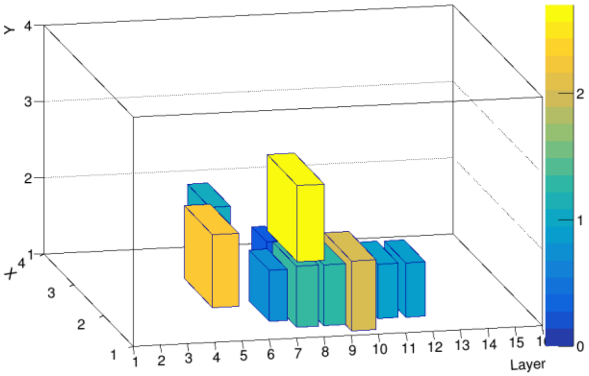
Beam energy 3.86 AGeV

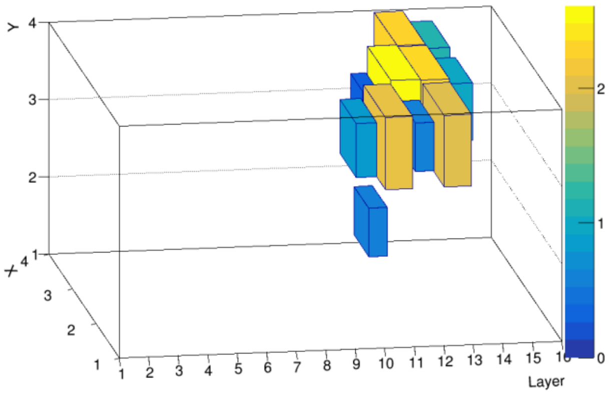


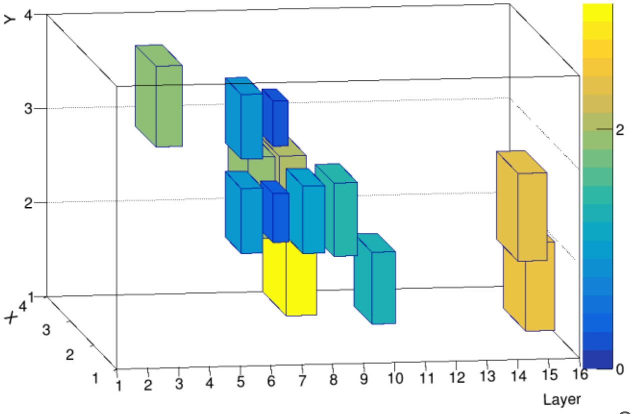
The neutron detector was designed to select clusters and analyze it for reconstruction of neutrons energy.
In the first approximation, the simplest clusters containing 4 consecutive cells was considered
Search:

- 4 layers triggered in a row along the Z axis within the boundaries of one cell
- Average cluster speed

No signals in VETO layer;
E_{kin} > 500 MeV





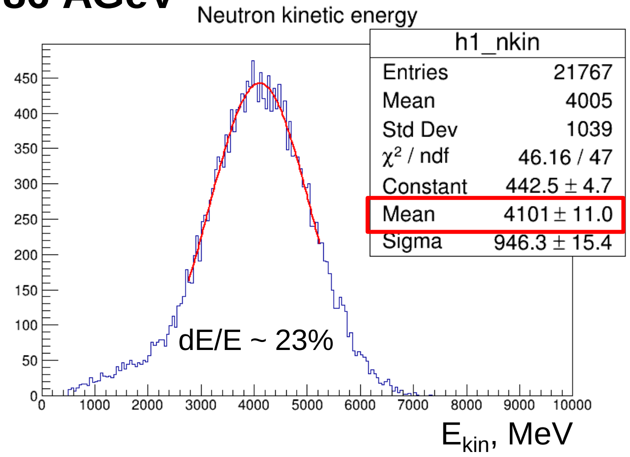


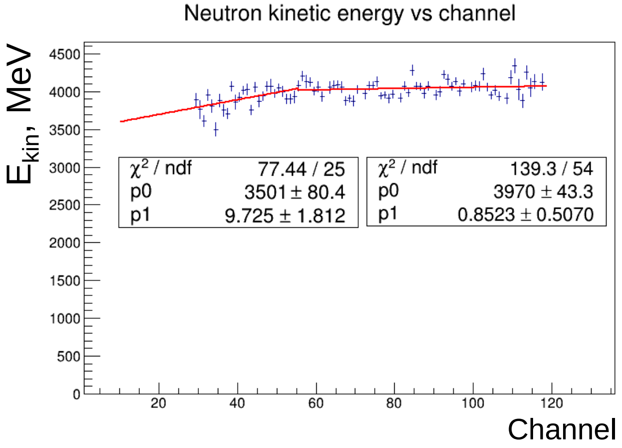
Clusterization

The neutron energy was determined by the average value of the energy measured in each cell of the cluster. Cells with energy E > Emean + 3σ was skipped

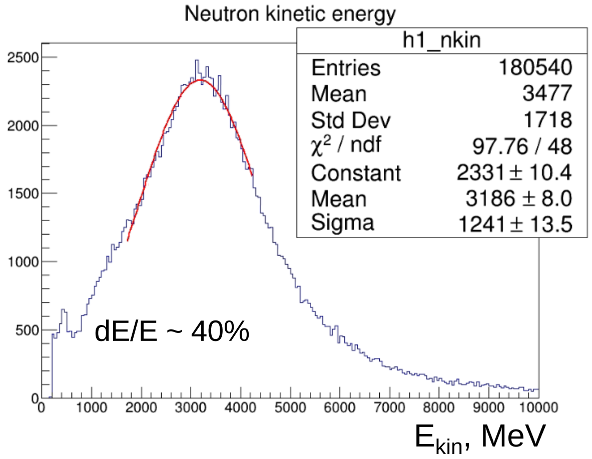
Beam energy 3.86 AGeV

With clustering (No EM shower in calibration)





W/O clustering

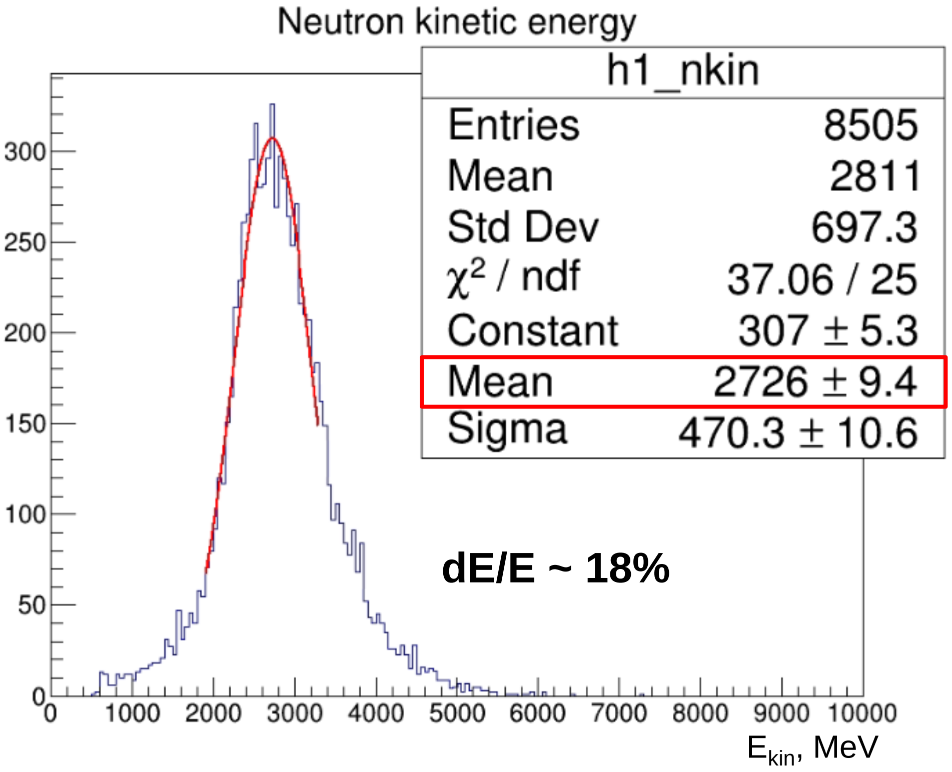


Clusterization

Beam energy 3 AGeV

$E < E_{mean} + 3\sigma$

With clustering
(No EM shower
in calibration)

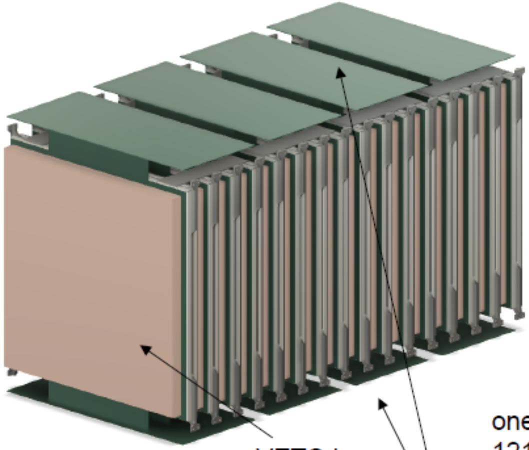


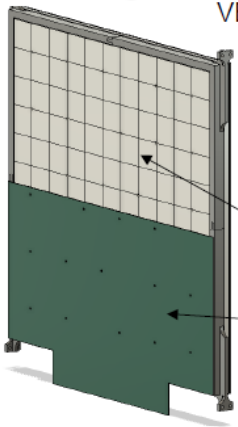
Status, conclusions and further work

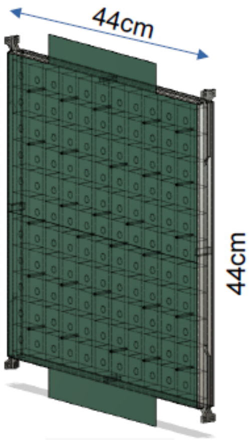
- Prototype of neutron detector based on 3.86 and 3 AGeV beams in various configurations was assembled and successfully tested;
- The time resolution of 134 ps was achieved for cells;
- 3 methods of neutron energy reconstruction was tested;
- Obtained energy resolution is comparable to simulation;
- The results will be used for development of HGN detector;
- Need to next effort for data analysis.

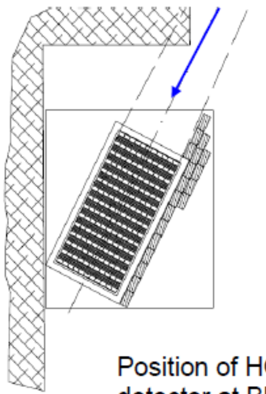
Thanks for attention

Development of HGN in progress..









Position of HGN detector at BM@N

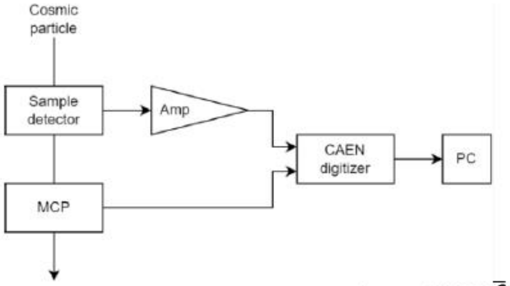
Front-End-Electronics:

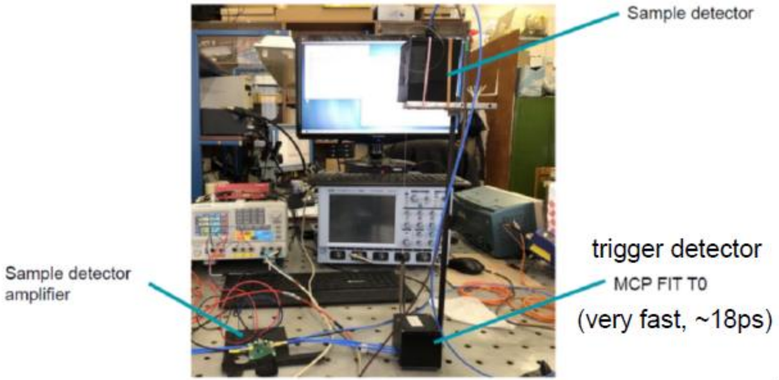
- SiPM HV power supply with temperature gain compensation
- amplification of SiPM signal with discriminators for TDC

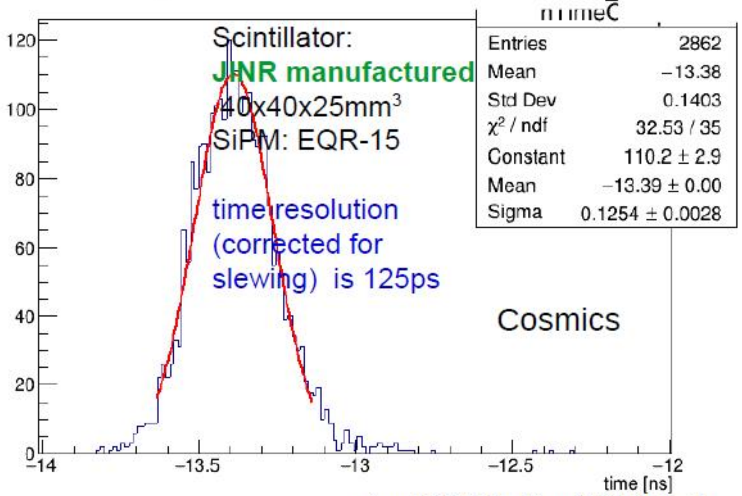
Read-out electronics:

- FPGA based TDC boards with
  1) TDC for time measurements and
  2) ToT for amplitude measurements

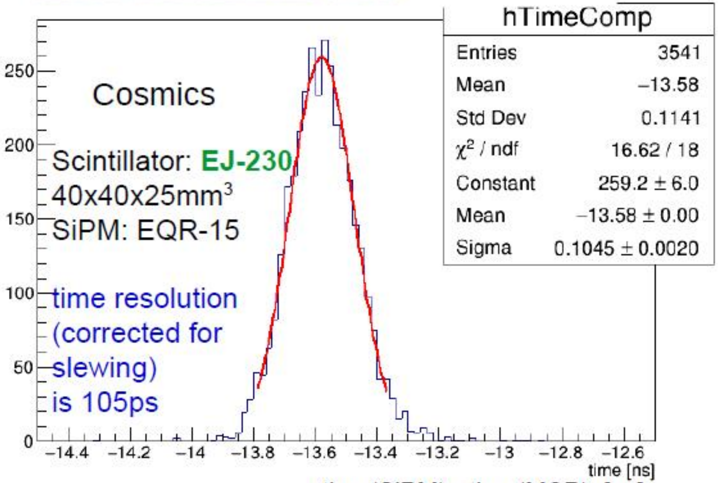
Measurements of time resolution of scintillating detector assemblies (scint + SiPM)







time(SiPM2) - time(MCP), [ns]



time(SiPM) - time(MCP), [ns]