12th Collaboration Meeting of the BM@N Experiment at the NICA Facility

Measurement of forward neutron yields with a High Granular Neutron Time-of-Flight Detector prototype from electromagnetic dissociation and nuclear interaction in Xe+CsI@3.8 AGeV collisions at the BM@N experiment

A. Zubankov on behalf of the HGND team

15.05.2024

- The High Granular Neutron Time-of-Flight Detector (HGND) at the BM@N experiment is under development for measuring the energy of neutrons produced in nucleus-nucleus collisions.
- For the first time, small prototype of the HGND was used in Xe+CsI at 3.0 and 3.8 AGeV run at the BM@N.
- The multilayer (absorber/scintillator) and high granular structure of the ToF HGND makes it possible to identify and measure the energies of neutrons.
- The purpose of the research is to investigate forward neutron yields for electromagnetic dissociation (EMD) and nuclear interaction at 0 degrees by HGND prototype

- Design of **H**igh **G**ranular **N**eutron **D**etector prototype
- Selection of neutrons from nuclear interaction and EMD
- Estimation background events from an empty target
- Estimation of the ratio of neutron yields from nuclear interaction to EMD
- Comparison with simulation

HGND prototype design

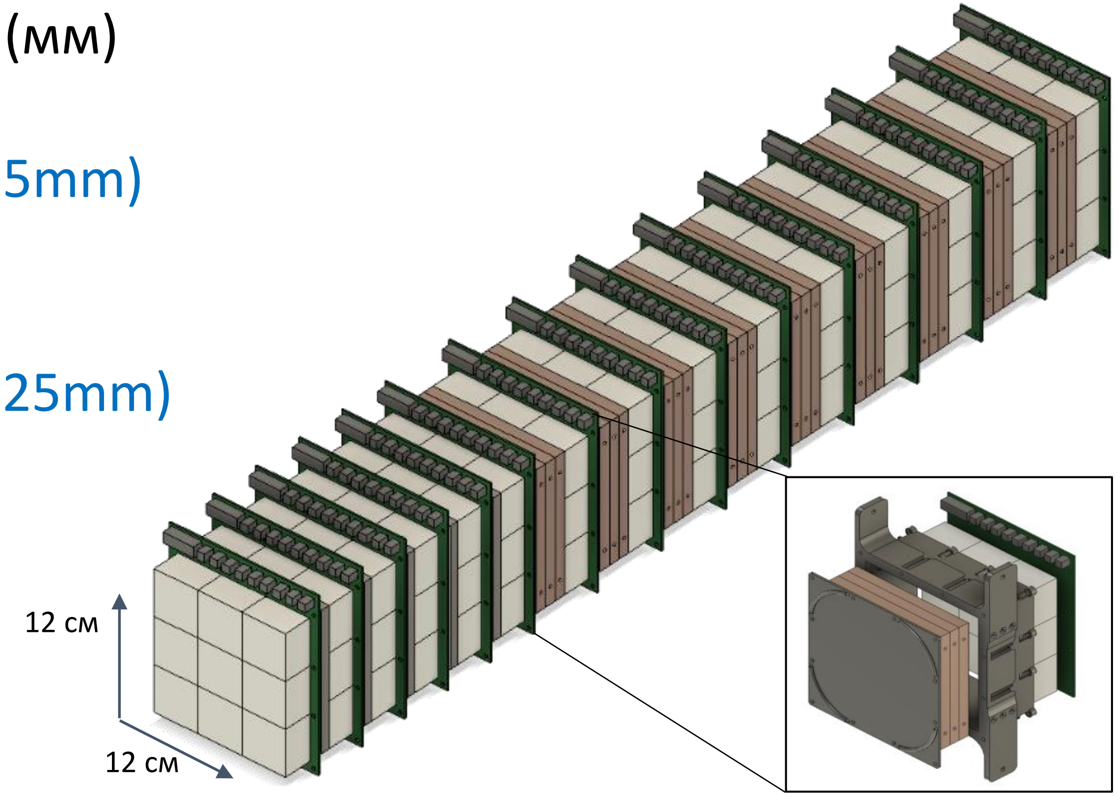
- Scint. layer **Veto** 120x120x25 (мм)
- 1^{st} (electromagnetic) part:
  5 layers: **Pb (8mm)** + Scint. (25mm)
  + PCB + air
- 2^{nd} (hadronic) part:
  9 layers: **Cu (30mm)** + Scint. (25mm)
  + PCB + air

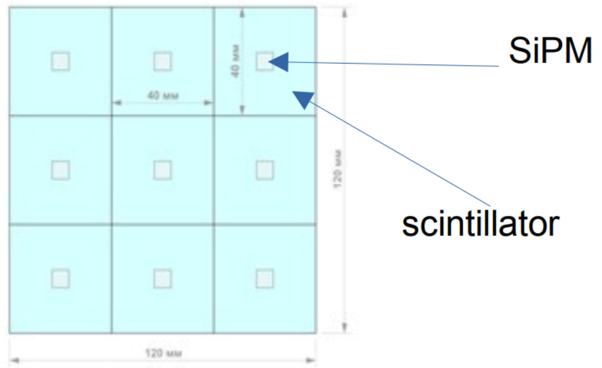
Scint. cell – 40 x 40 x 25 mm^3

Total number of cells – 135

Total size – 12 x 12 x 82.5 cm^3

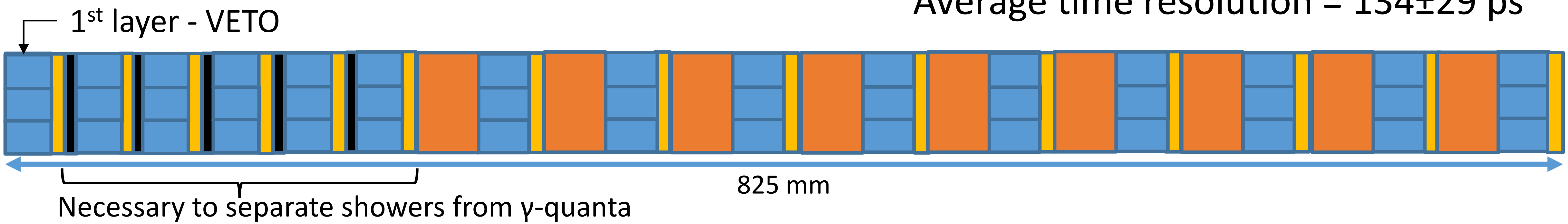
Total length ~ 2.5 λ_{int}



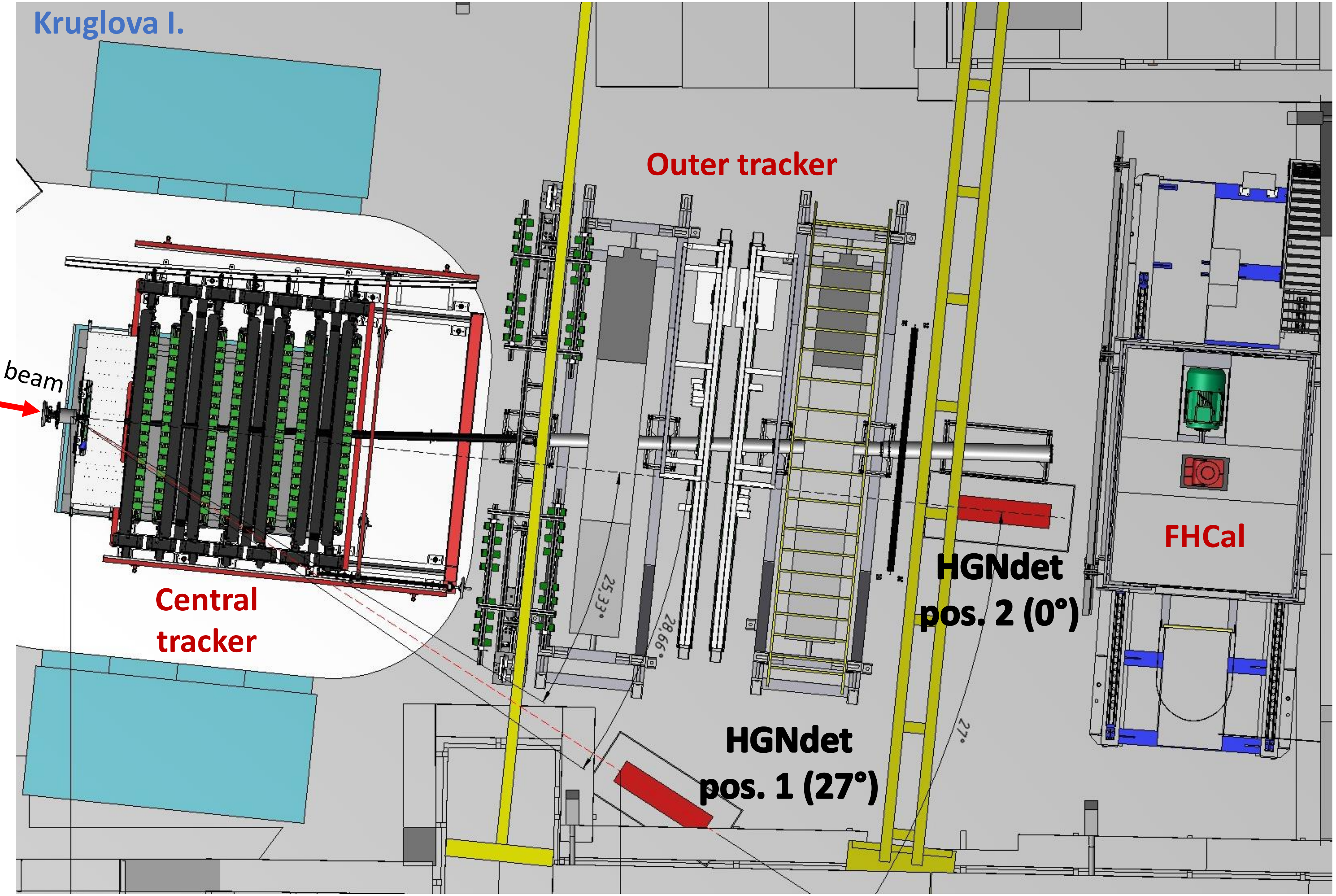


Hamamatsu S13360- 6050PE
Photosensitive area – 6x6 mm^2
Number of pixels – 14400
Pixel size – 50 µm
Gain – 1.7×10^6
PDE – 40%

Average time resolution = 134±29 ps



HGND prototype in the Xe run of BM@N on Xe ion beam



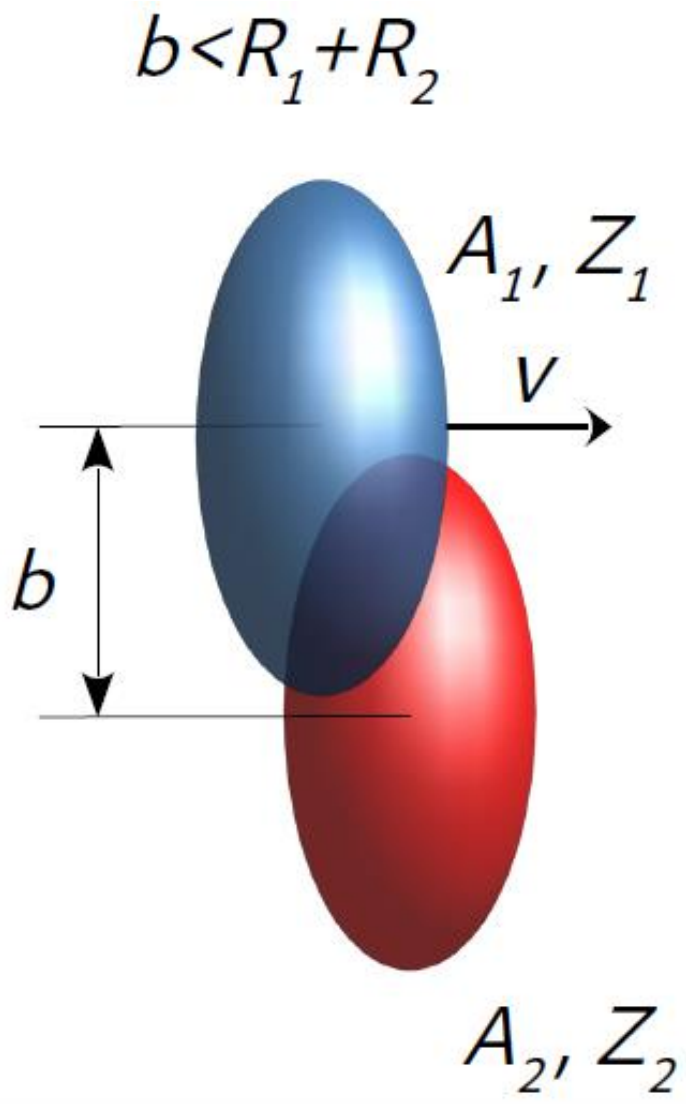
27° position:

Measurements of the neutron spectrum at ~ midrapidity.

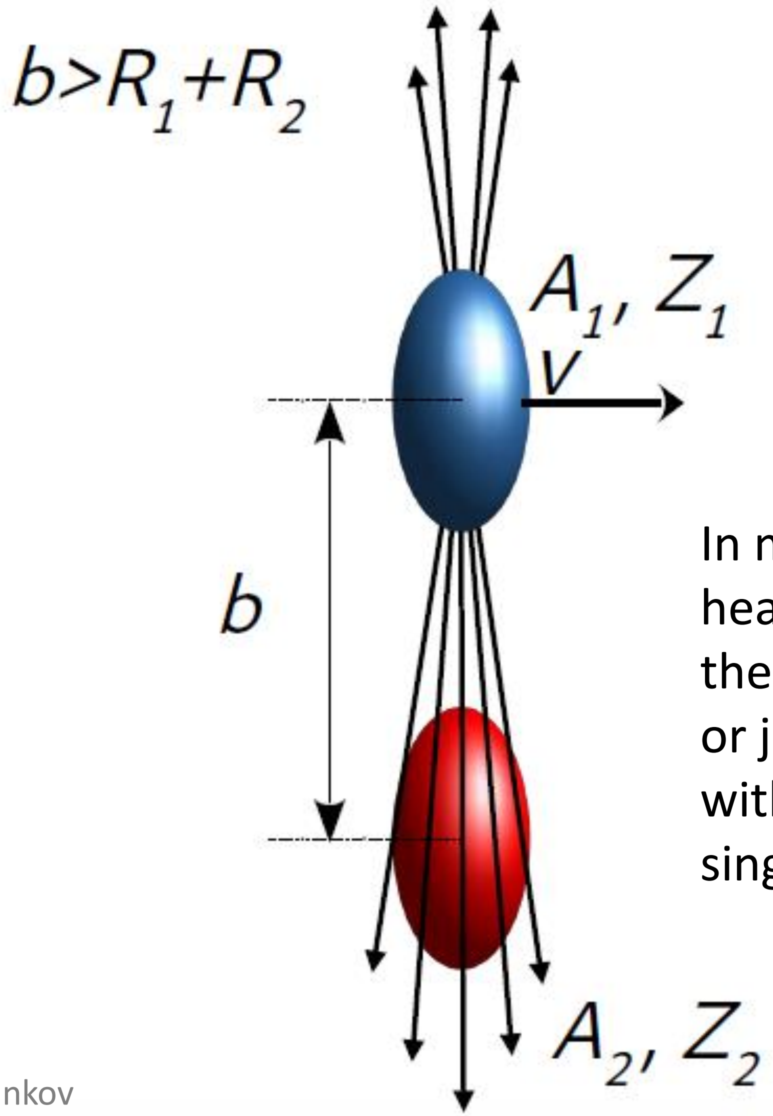
0° position:

Test and calibration with known neutron energy (energy of a beam of spectator neutrons)

Nuclear interaction:
with overlap of nuclear densities



EMD:
without overlap of nuclear densities



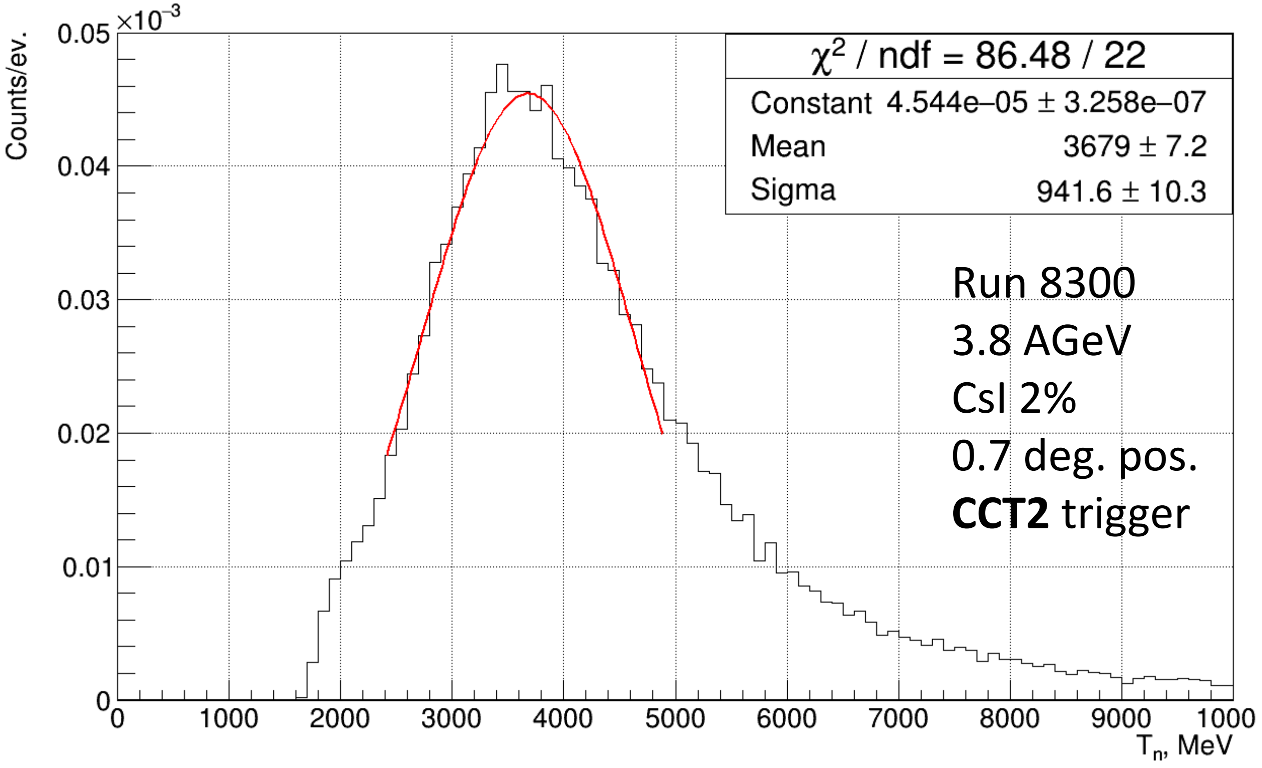
In most cases, EMD of a heavy nucleus results in the emission of a single or just few neutrons with the production of a single residual nucleus

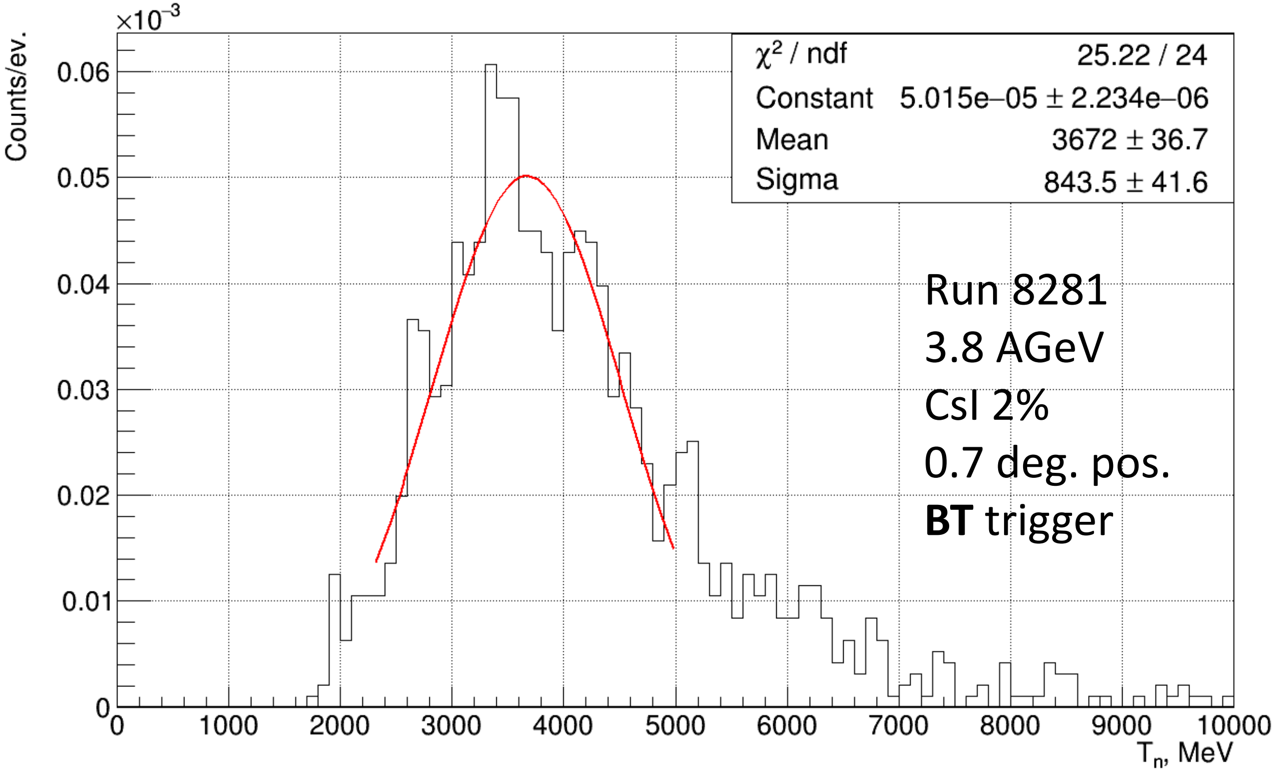
Criteria for selecting events with neutrons

Central collisions – Nuclear interaction:
- 1 Xe ion, BC1S + **CCT2** + Vertex ± 1.5 cm
- FD Ampl < 4500
- Veto cut, Ampl cut, ToF cut, γ-cut, >=2 cells in ev.

Ultra-peripheral collisions – EMD:
- 1 Xe ion, BC1S + **BT**
- Hodo $Z^2>2500$
- Veto cut, Ampl cut, ToF cut, γ-cut, >=2 cells in ev.

Reconstruction of energy by maximum velocity
(without efficiency correction)
Scaled by incident ion beam rate

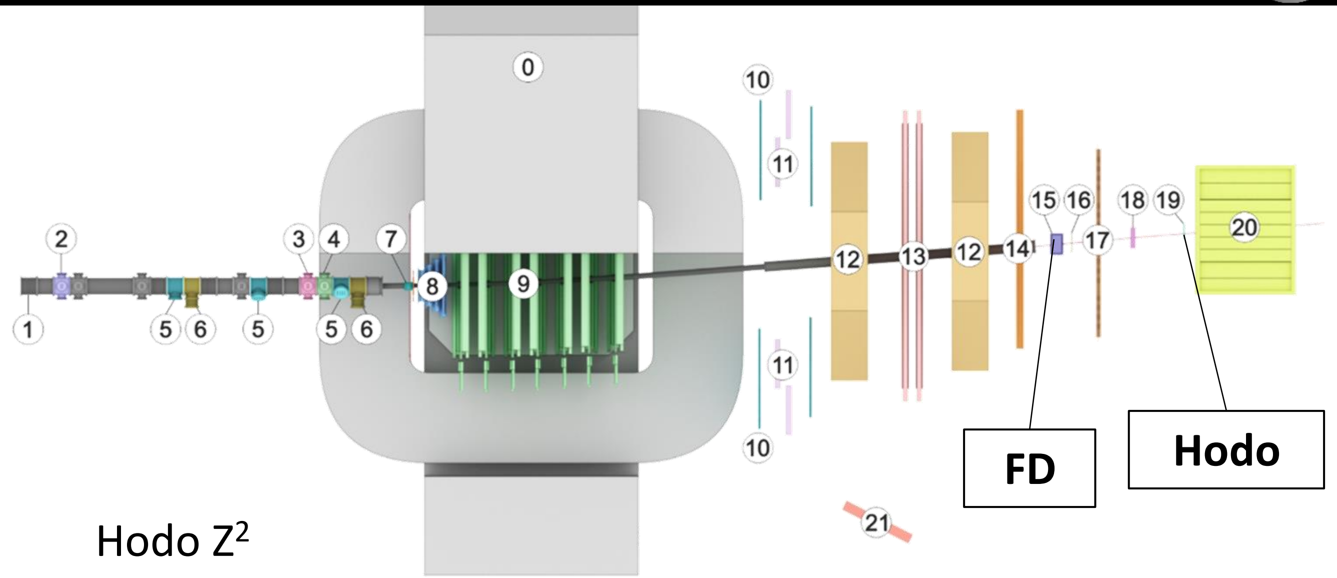




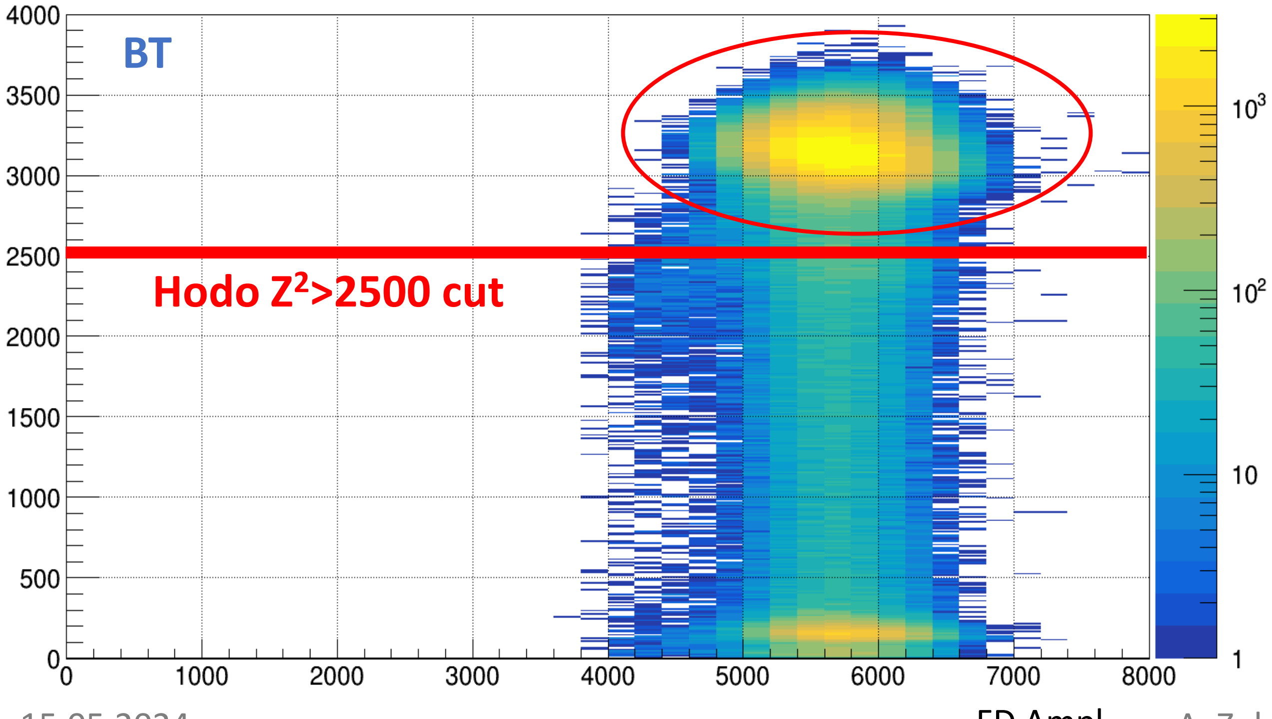
Event selection

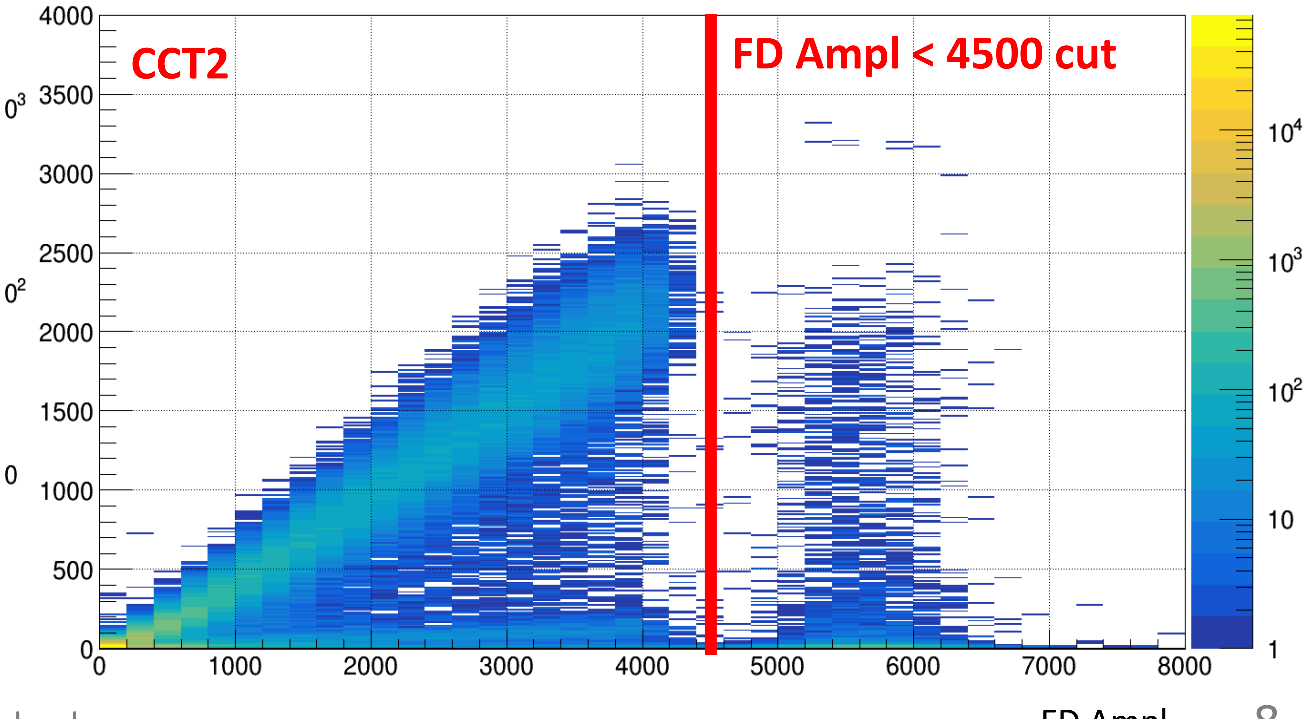
Comparison of nuclear interaction (CCT2) with electromagnetic dissociation (BT) on **Hodoscope** vs **FD**

Run **8281 (BT)** vs **8300 (CCT2)** 3.8 AGeV



Xe ions on Hodoscope around Z^2=3000 in EMD

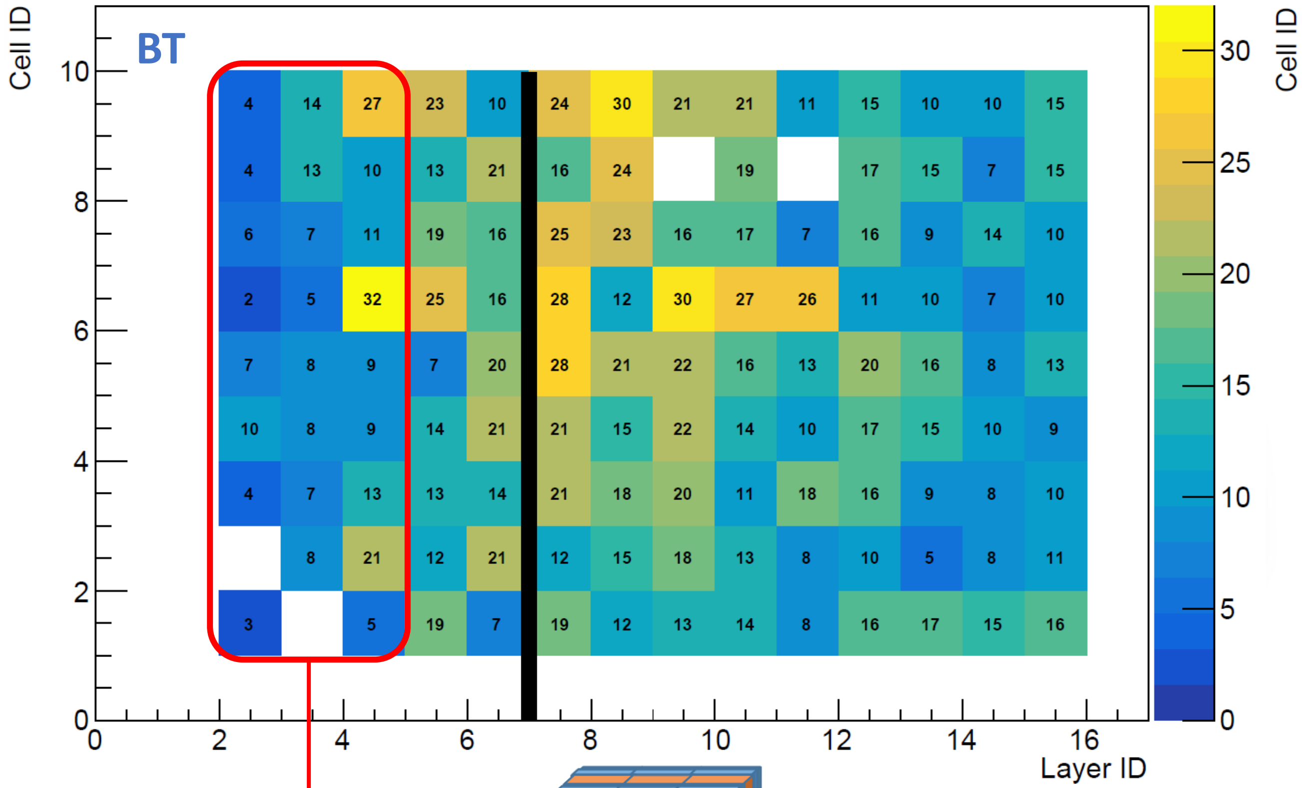


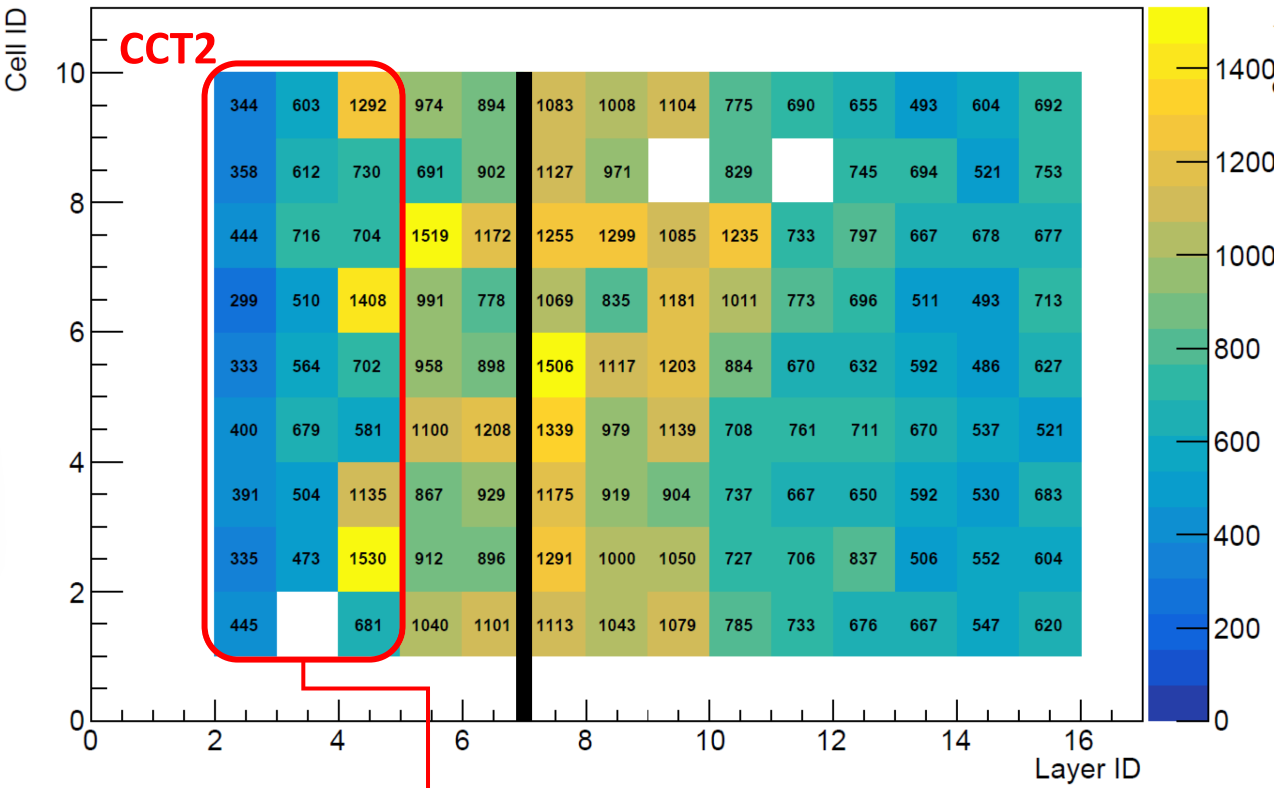


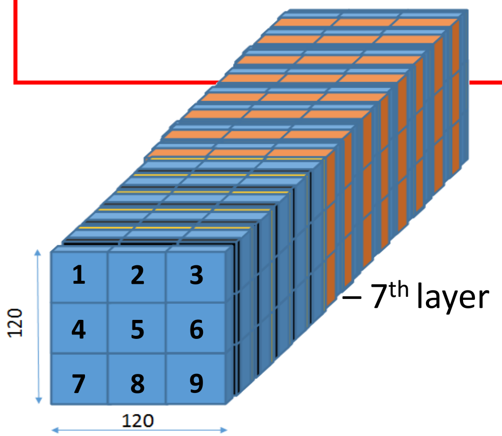
Fastest cells for EMD vs Nuclear interaction

Comparison of nuclear interaction (CCT2) with electromagnetic dissociation (BT)

Run 8281 (BT) vs 8300 (CCT2) 3.8 AGeV





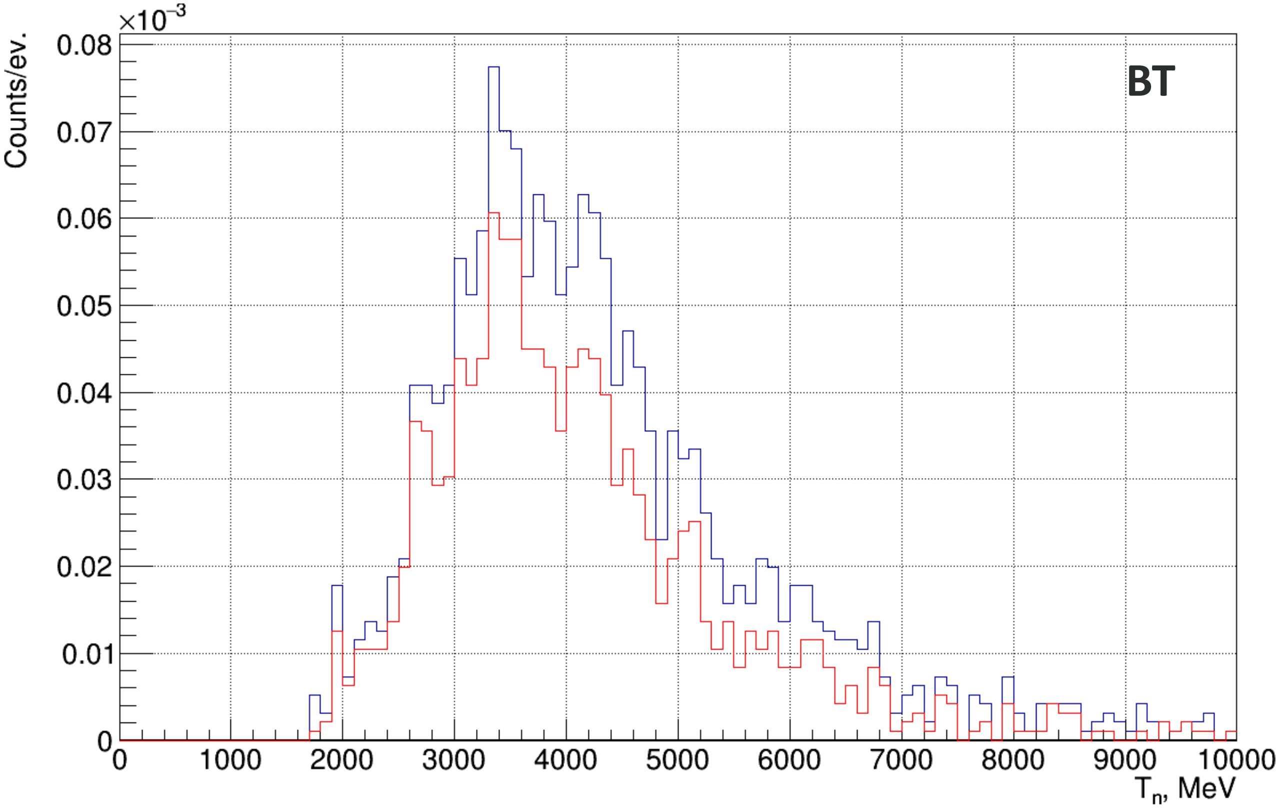


γ-quanta cut – no hits in 2 & 3 & 4 layers in module => 4.52 X_0 or 0.266 λ_{int}

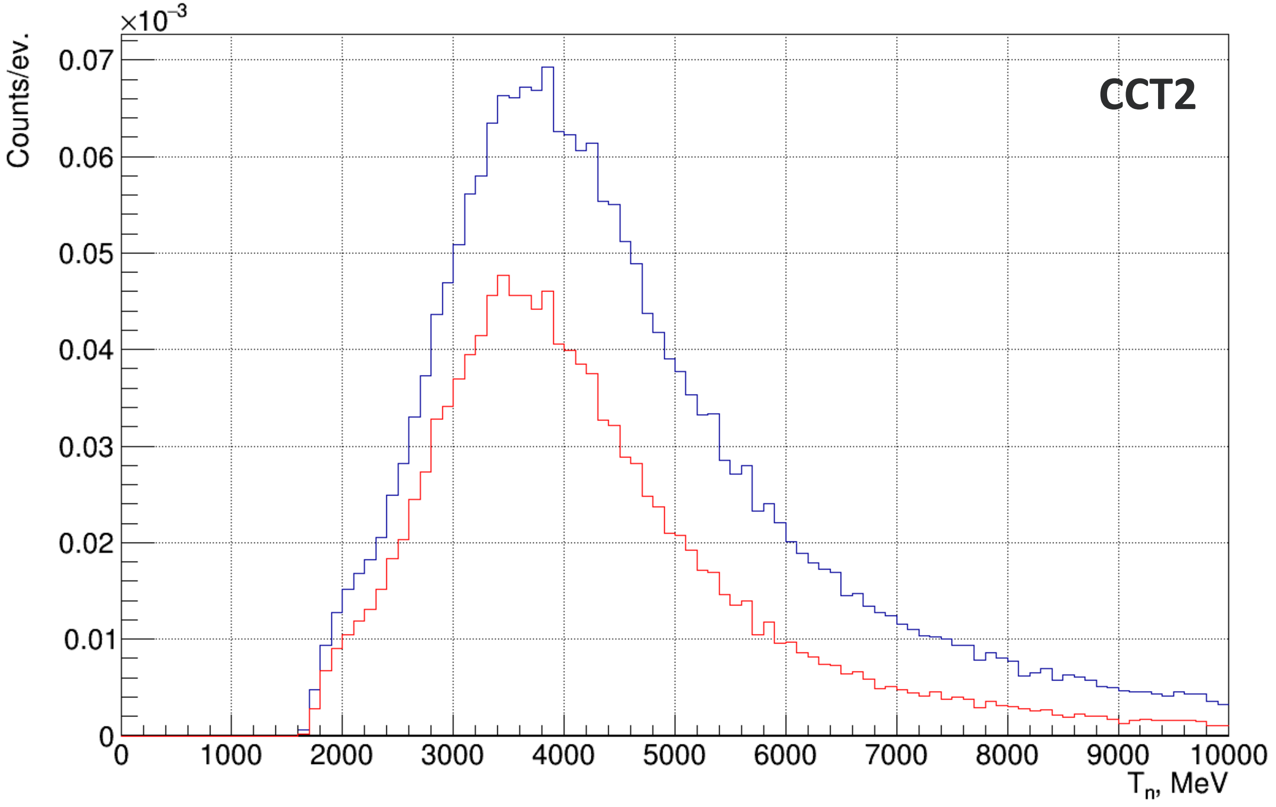
Most of the neutrons are deposited after the 7th layer for both EMD and nuclear interaction

γ-quanta cut

All – 1757 (100%)
No hits in 2-4 layers – 1236 (70%)

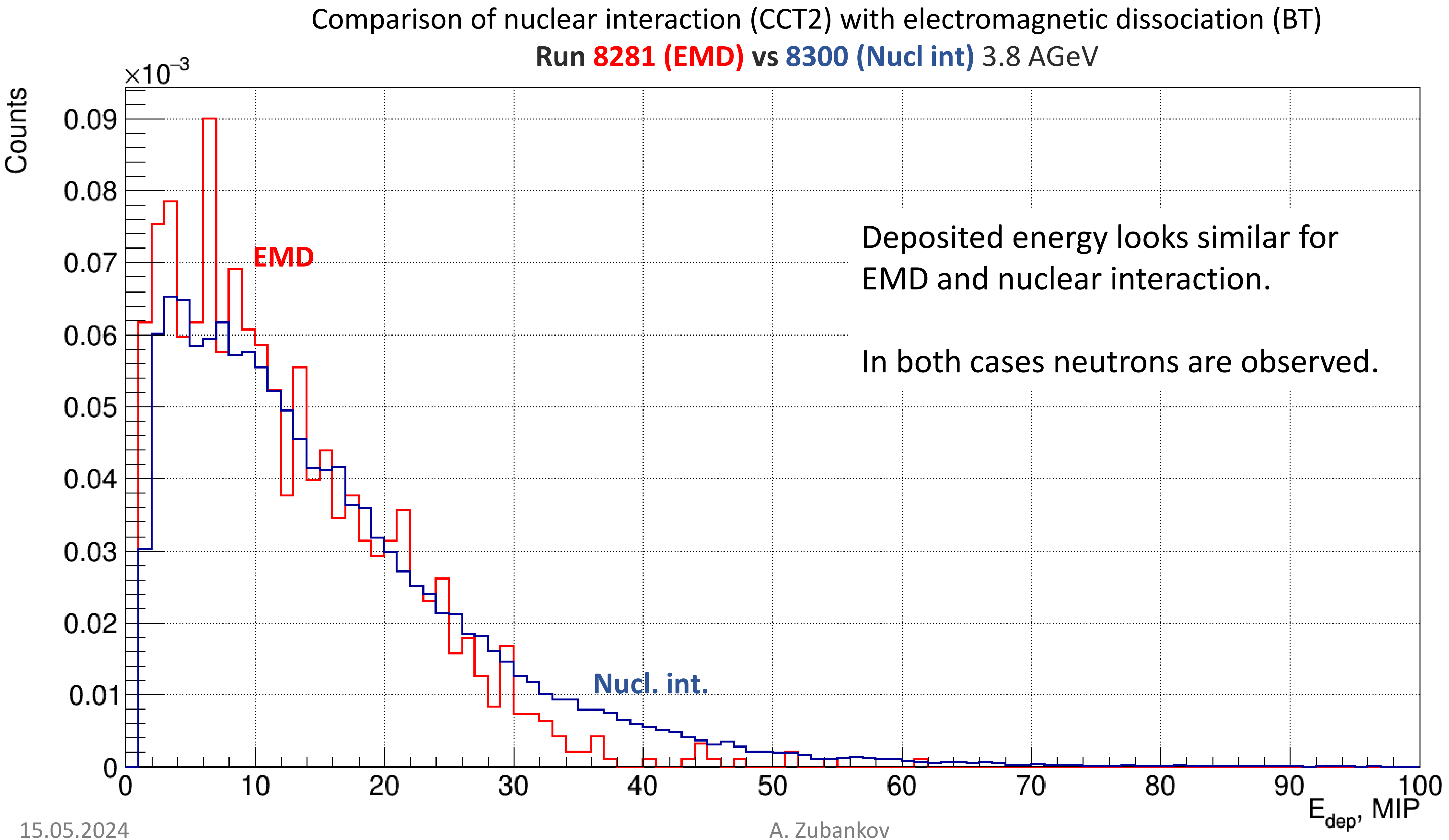


All – 99.5k (100%)
No hits in 2-4 layers – 57.2k (57%)



γ-quanta cut - no hits in 2 & 3 & 4 layers in module => 4.52 X_0 or 0.266 λ_{int}

Deposited energy for EMD vs Nuclear interaction



Deposited energy looks similar for EMD and nuclear interaction.

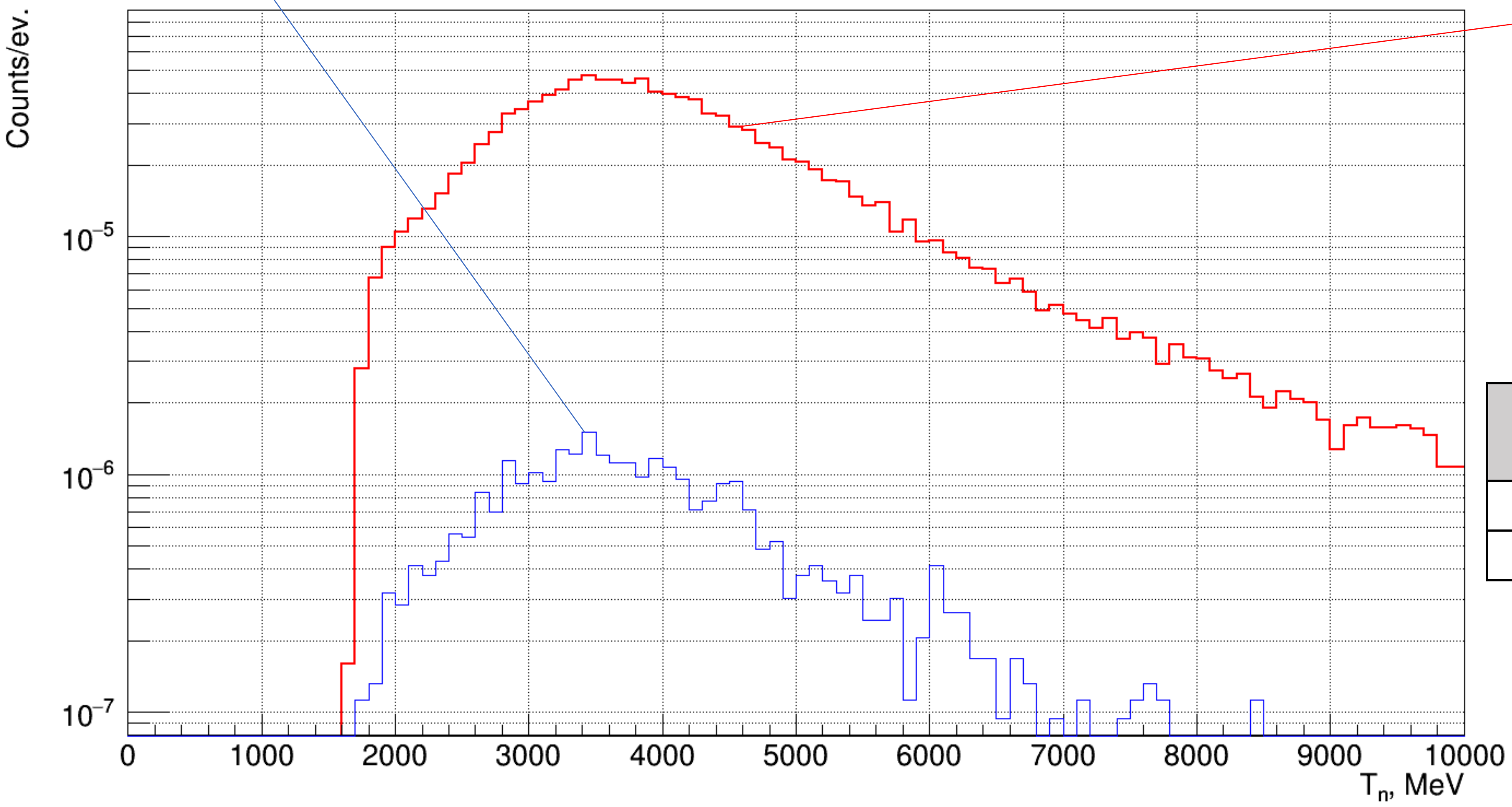
In both cases neutrons are observed.

Empty target vs CsI 2% for nuclear interaction

Total number of events – 304k
Ions – 26.6k*2k
BC1S + CCT2 – 75.5k
Vertex ± 1.5 – 7.9k
Number of neutrons – 1766

Empty vs **CsI 2%**
0.7 deg., 3.8 AGeV, **CCT2**+BC1S – **Nucl int**
Scaled by incident ion beam rate

Total number of events – 1kk
Ions – 22k*2k
BC1S + CCT2 – 364k
Vertex ± 1.5 – 268k
Number of neutrons – 57.2k



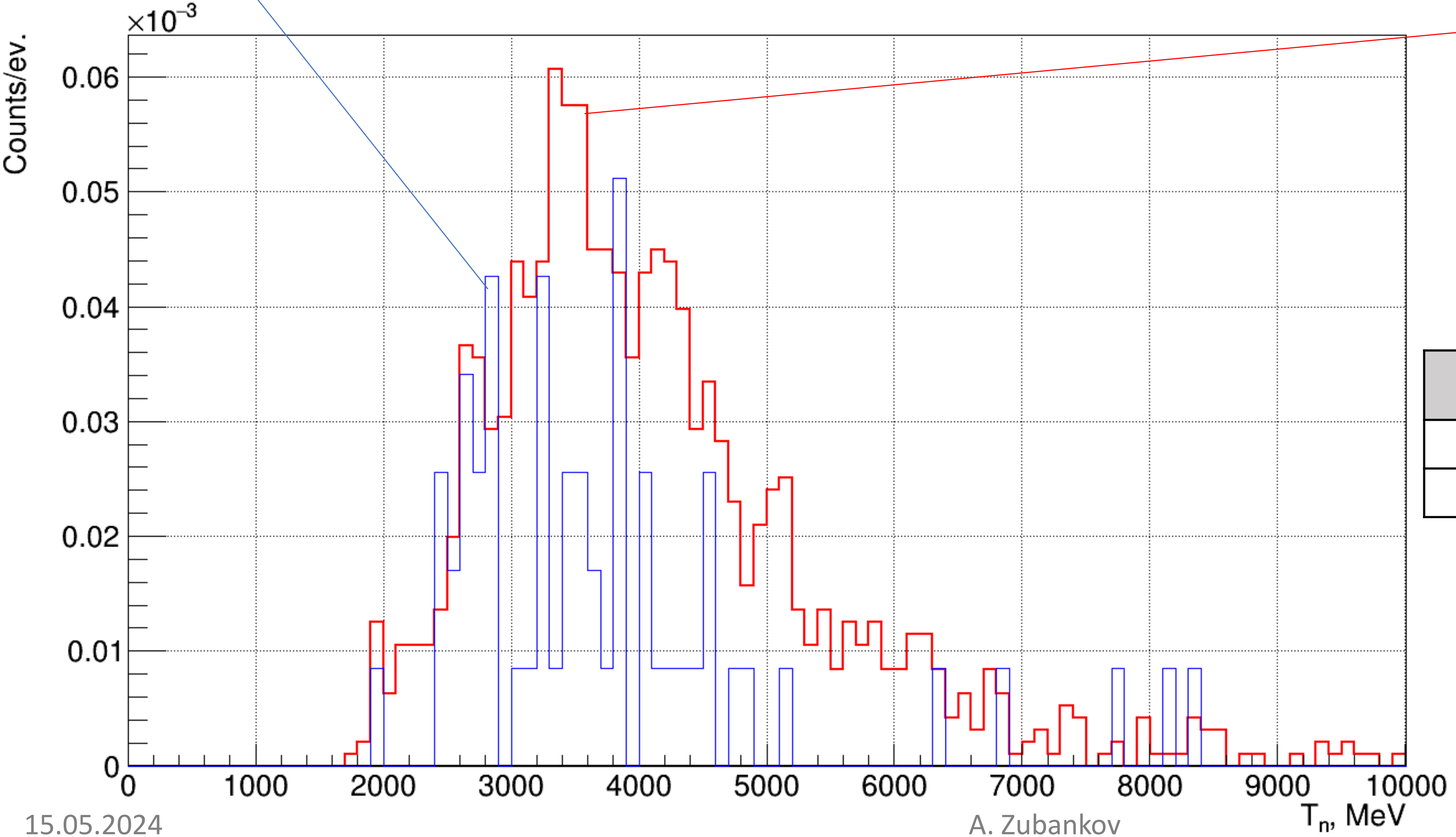
Target	*neutrons/ion, n/i*	Ratio
CsI 2%	**$1.307 \cdot 10^{-3}$**	**39.61 ± 1.12**
Empty	**$0.033 \cdot 10^{-3}$**	

Empty target vs CsI 2% for EMD

Empty
Total number of events – 121k
Ions – 117k
BT + BC1S –74k
Number of neutrons – 61

Runs 8281 CsI 2% vs 8282 Empty
0.7 deg., 3.8 AGeV, **BT**+BC1S – **EMD**
Scaled by incident ion beam rate
BT trigger, beam pos.: x=-7 mm y=-14 mm

CsI 2%
Total number of events – 994k
Ions – 956k
BT + BC1S – 496k
Number of neutrons – 1236



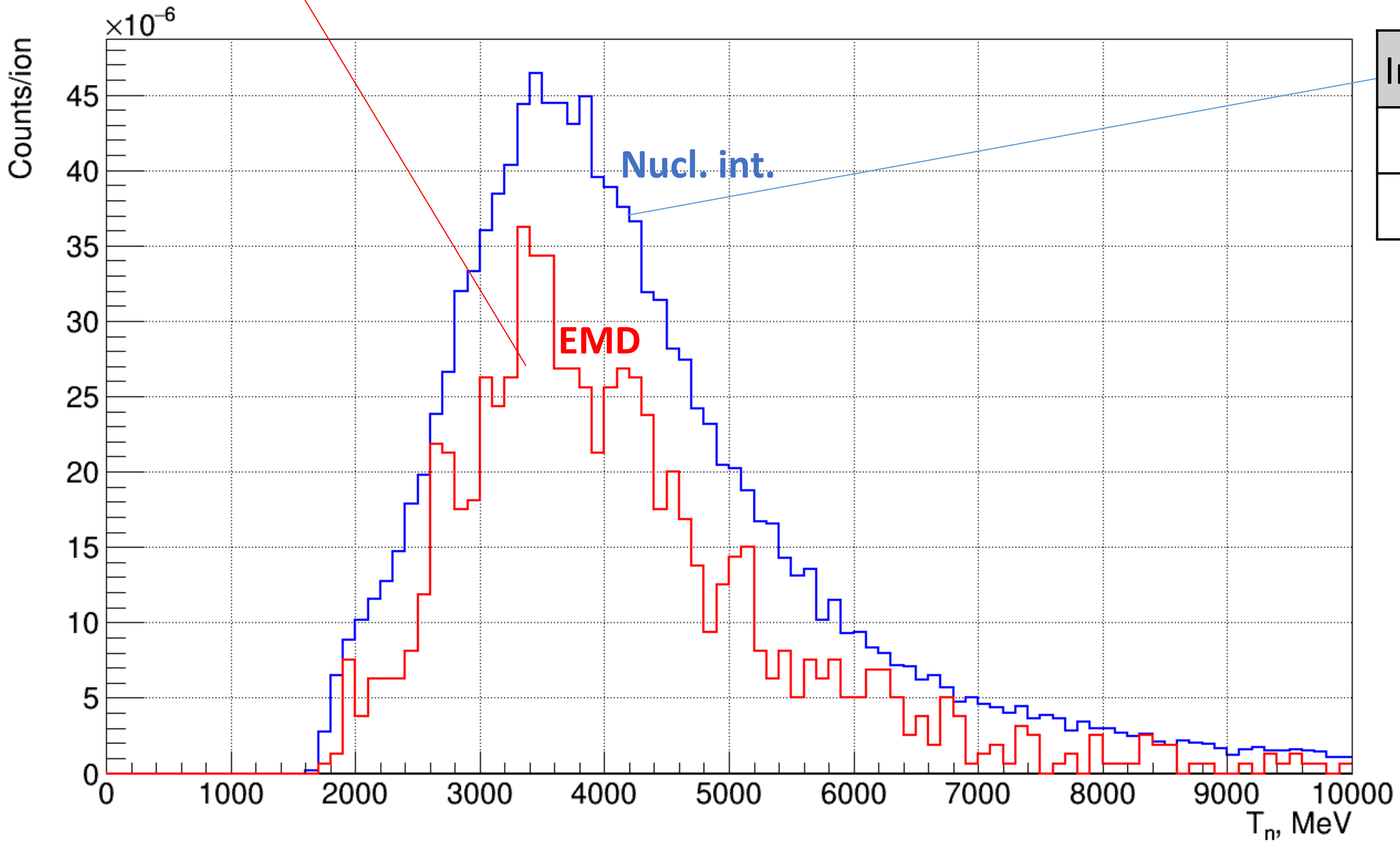
Target	*n/i*	Ratio
CsI 2%	**$1.293 \cdot 10^{-3}$**	**2.48 ± 0.40**
Empty	**$0.521 \cdot 10^{-3}$**	

EMD vs Nuclear interaction

Total number of events – 994k
Ions – 956k
BT + BC1S – 496k
Number of neutrons – 1.2k

Comparison of nuclear interaction (CCT2)
with electromagnetic dissociation (BT)
Run 8281 (EMD) vs 8300 (Nucl int)
0.7 deg., 3.8 AGeV
Scaled by incident ion beam rate

Total number of events – 1kk
Ions – 22k*2k
CCT2 + BC1S – 364k
Vertex ± 1.5 – 268k
Number of neutrons – 57.2k



Interaction	*n/i*	*n/i - n/i^empty^*
Nucl. int.	**$1.307 \cdot 10^{-3}$**	**$(1.274 \pm 0.006) \cdot 10^{-3}$**
EMD	**$1.293 \cdot 10^{-3}$**	**$(0.772 \pm 0.106) \cdot 10^{-3}$**

$$\frac{n/i_{nucl}}{n/i_{EMD}} = 1.01 \pm 0.04$$

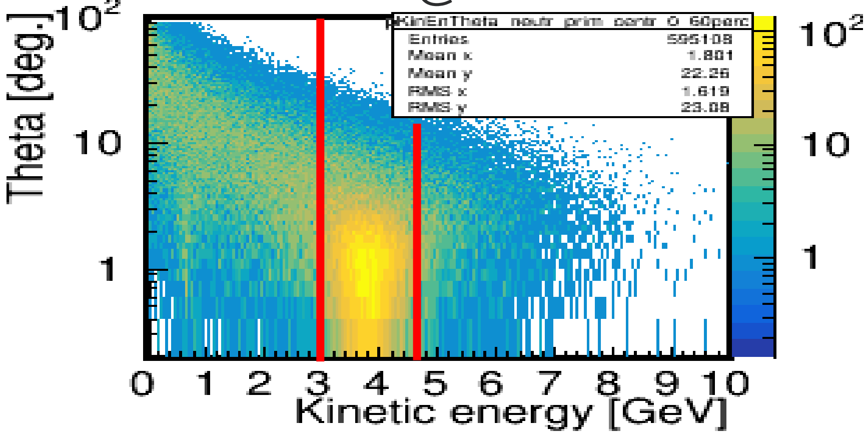
$$\frac{n/i_{nucl} - n/i^{empty}_{nucl}}{n/i_{EMD} - n/i^{empty}_{EMD}} = 1.65 \pm 0.24$$

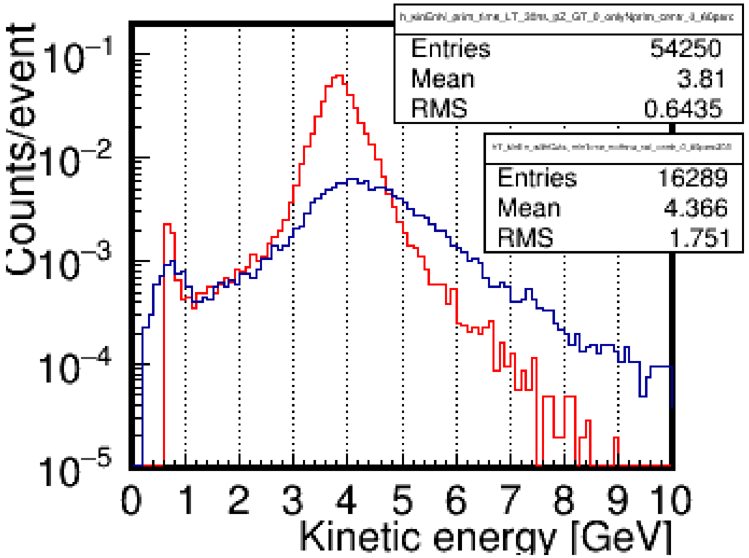
EMD vs Nuclear interaction in simulation

1. HGND prototype acceptance & selection for neutrons from nuclear interaction and EMD:

DCM-QGSM-SMM (0-60%)

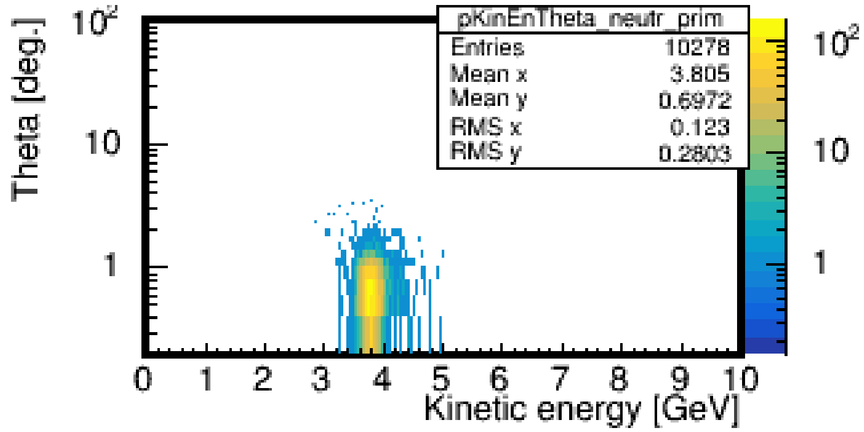
^{131}Xe + Cs @ 3.8AGeV

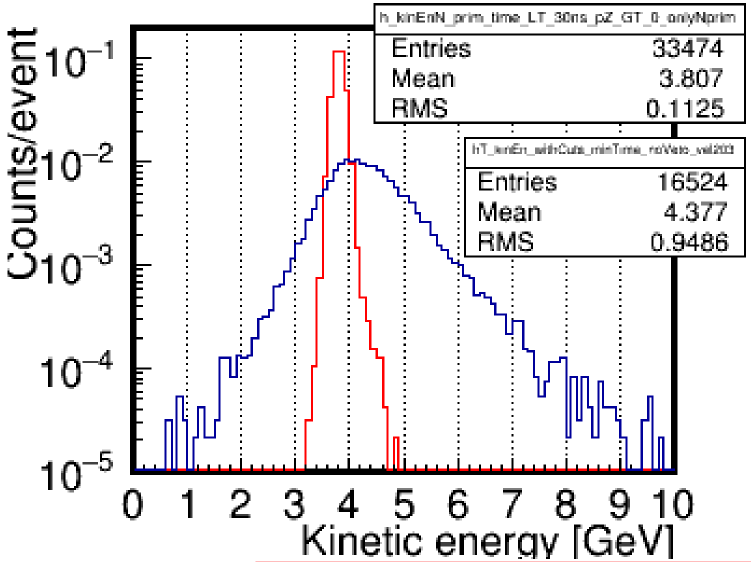




RELDIS[1]

^{124}Xe + ^{130}Xe @ 3.8 AGeV





Primary neutrons spectra at HGND entrance

Reconstructed energy spectra

$$acc = \frac{n_{selected}}{n_{total}};$$

$$acc_{nucl} = 0.558 \pm 0.005\%$$

$$acc_{EMD} = 8.039 \pm 0.080\%$$

[1]I. Pshenichnov, Electromagnetic Excitation and Fragmentation of Ultrarelativistic Nuclei. *Phys. Part. Nucl.* **2011**, 42 (2), 215-250.

EMD vs Nuclear interaction in simulation

2. Calculation of the ratio of the number of neutrons from a nuclear interaction to EMD:

Model	Cross section, σ [b]	interactions/ion, *int/i*	‹neutrons›/interaction, *‹n›/int*	*n/i*, $\cdot 10^{-3}$
DCM-QGSM-SMM (0-60%)	**3.165**	**$1.162 \cdot 10^{-2}$**	**14.61**	**1.102 ± 0.009**
RELDIS	**1.9**	**$0.695 \cdot 10^{-2}$**	**1.03**	**0.587 ± 0.006**

$$\frac{n/i_{nucl}}{n/i_{EMD}} = \frac{\left(\mathrm{int}/i \cdot \langle n \rangle/\mathrm{int} \cdot acc\right)_{nucl}}{\left(\mathrm{int}/i \cdot \langle n \rangle/\mathrm{int} \cdot acc\right)_{EMD}} = 1.65 \pm 0.03$$

VS

Experimental result:

Interaction	$n/i - n/i^{empty}$, $\cdot 10^{-3}$	Ratio
Nucl. int.	**1.274 ± 0.006**	**1.65 ± 0.24**
EMD	**0.772 ± 0.106**	

Not taken into account yet:

- Triggers efficiency
- FD cut in simulation

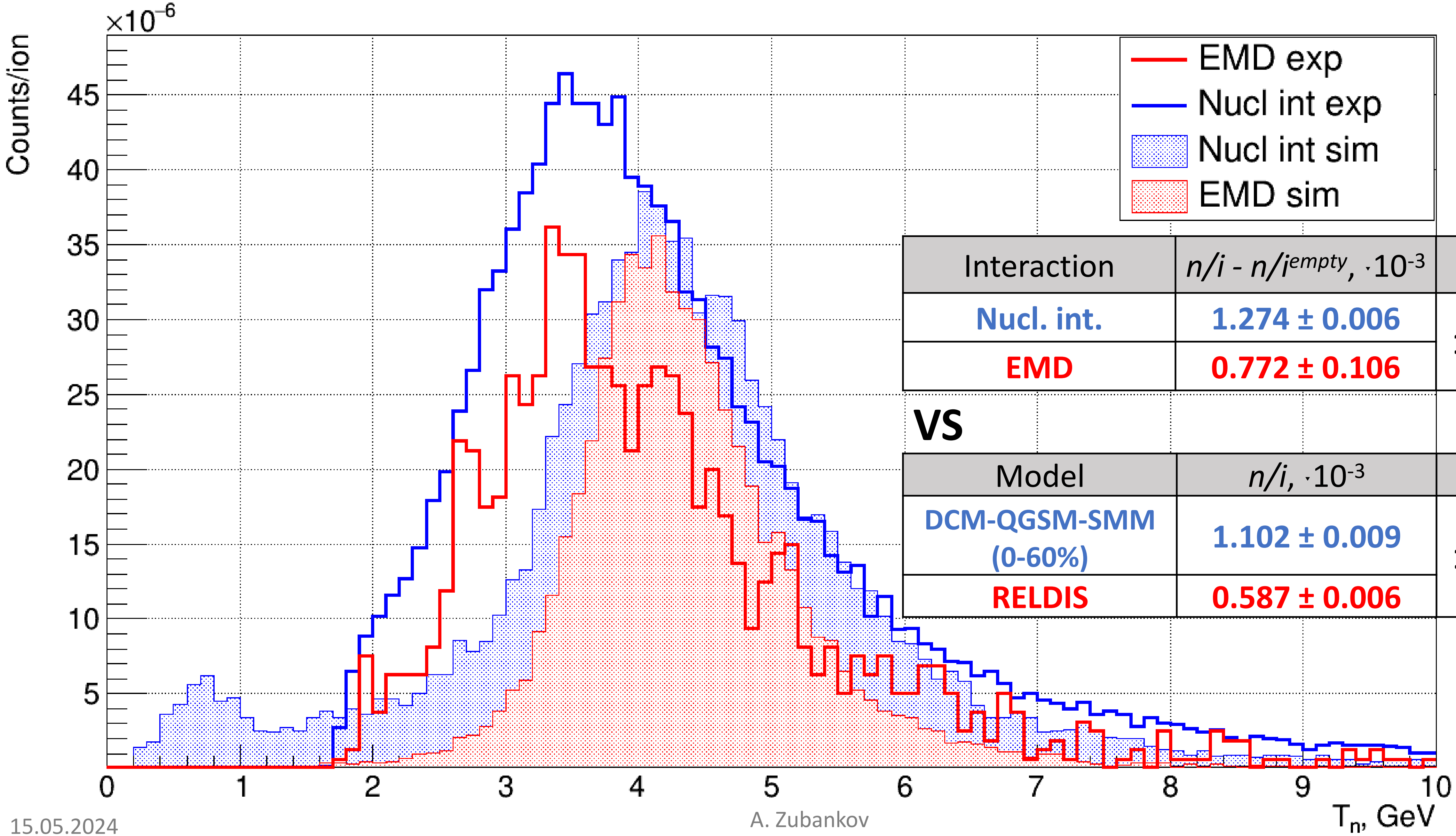
Conclusions

- The response of the HGND prototype to neutrons from the nuclear reaction and EMD was studied.
- Taking into account the acceptance and efficiency of neutron detection by the HGND prototype, the ratio of neutron yields from a nuclear reaction to EMD is 1.65±0.24, which is close to the simulation – 1.65±0.03.
- It is shown that spectator neutrons from nuclear reaction and neutrons from EMD can be used to calibrate HGND.
- EMD in the BM@N experiment can be used as a source of high energy neutrons with multiplicity $\approx$1.

Thank you for your attention!

Backup

Comparison of experimental results with simulation

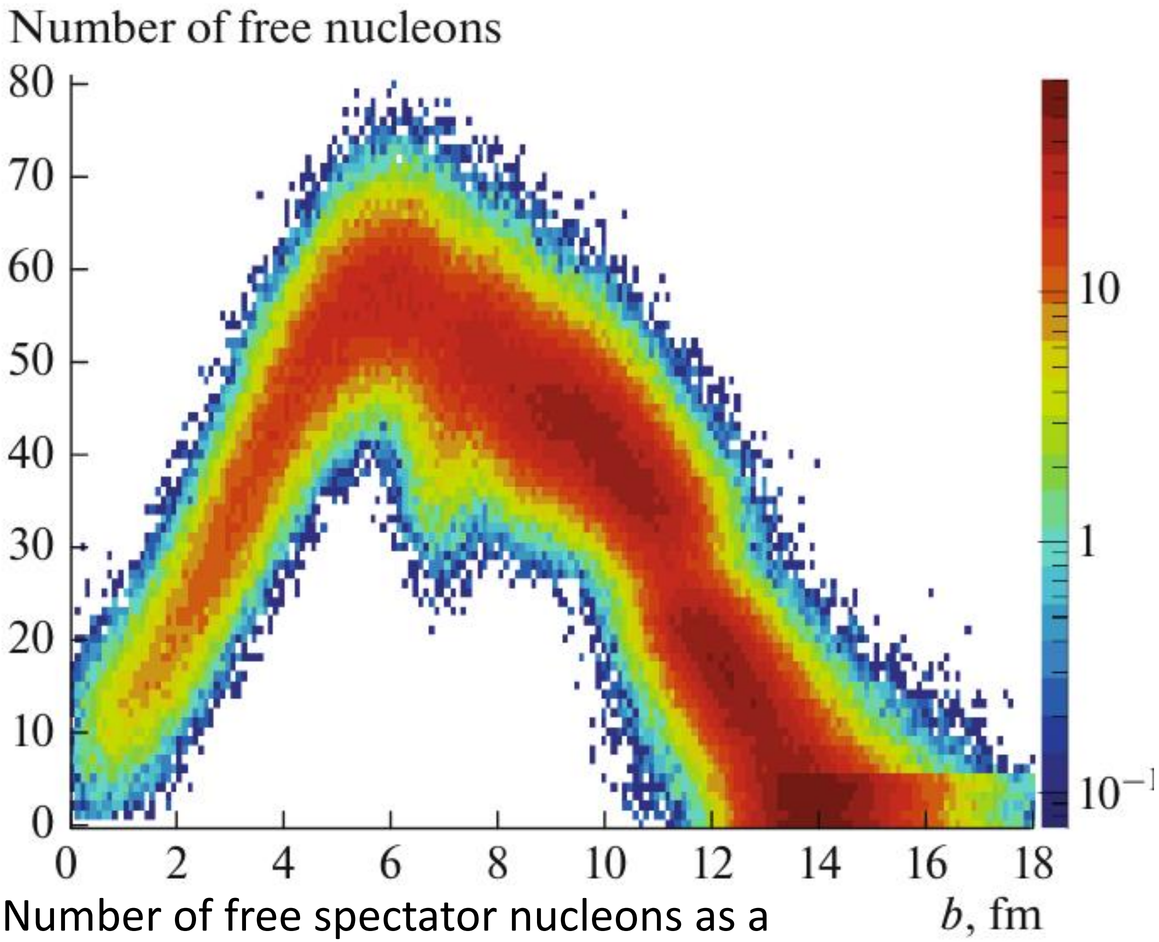


Interaction	n/i - n/i^{empty}, $\cdot 10^{-3}$	Ratio
Nucl. int.	**1.274 ± 0.006**	**1.65 ± 0.24**
EMD	**0.772 ± 0.106**	

VS

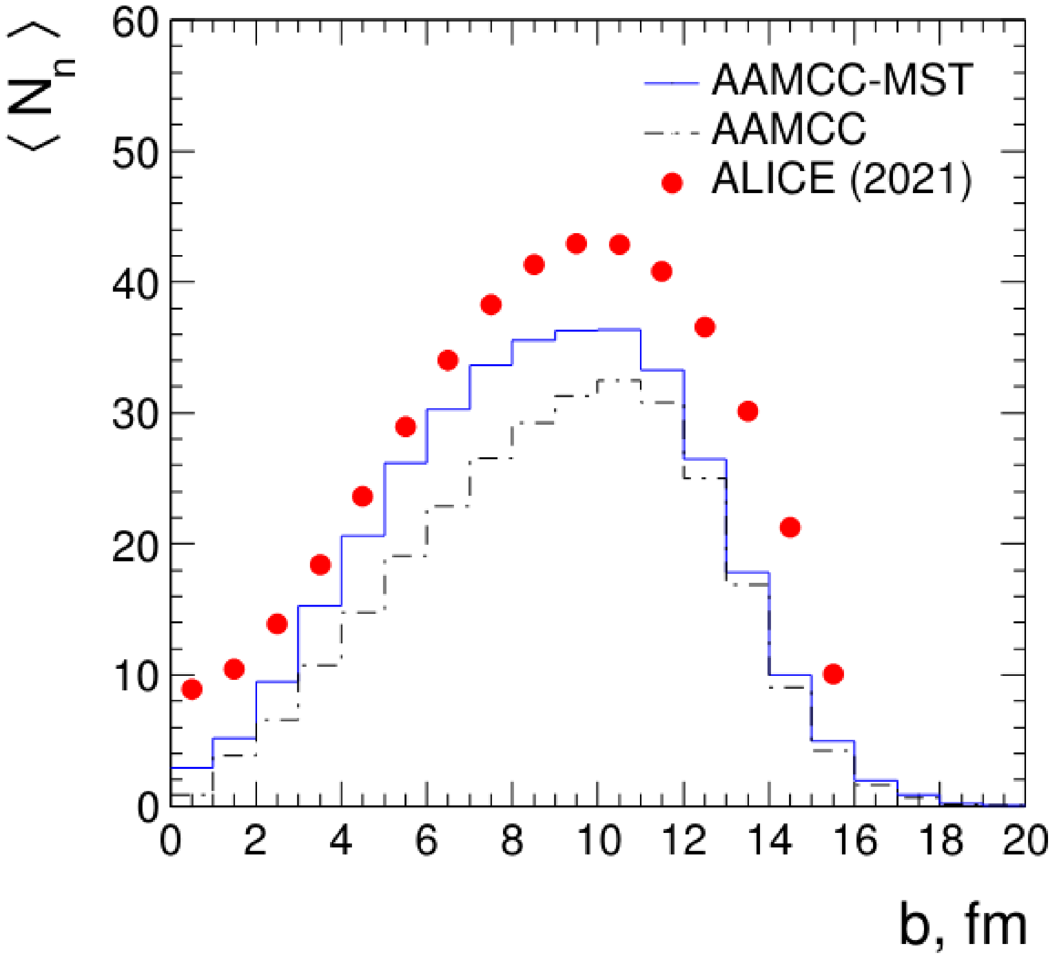
Model	n/i, $\cdot 10^{-3}$	Ratio
DCM-QGSM-SMM (0-60%)	**1.102 ± 0.009**	**1.65 ± 0.03**
RELDIS	**0.587 ± 0.006**	

Nuclear interaction



Number of free spectator nucleons as a function of the impact parameter in collisions between ^{197}Au nuclei at NICA at $\sqrt{s_{NN}}$ = 5 GeV

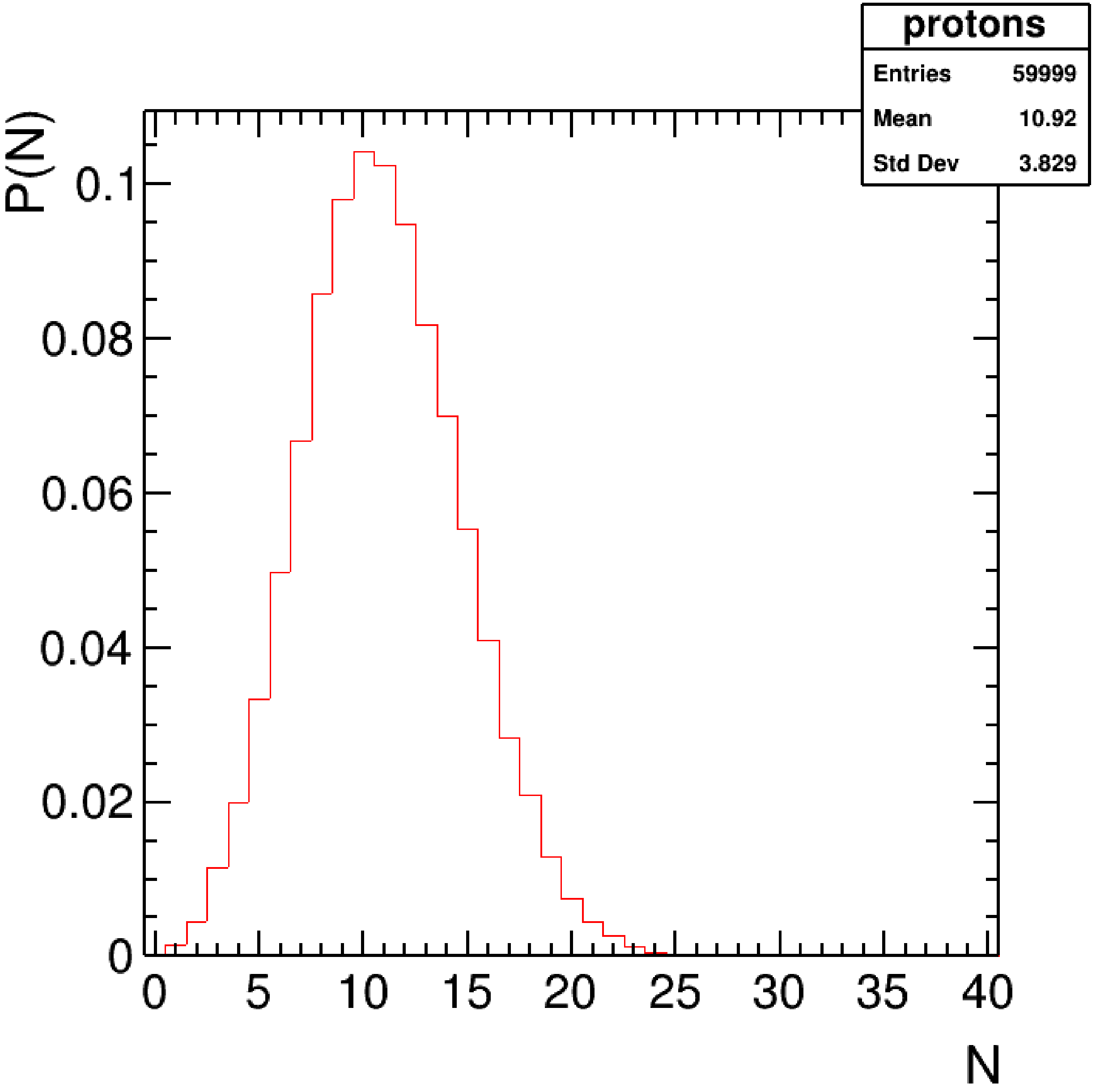
A. Svetlichnyi & I. Pshenichnov, Formation of Free and Bound Spectator Nucleons in Hadronic Interactions between Relativistic Nuclei. *Bulletin of the Russian Academy of Sciences: Physics* **2020**, 84 (8), 911–916.

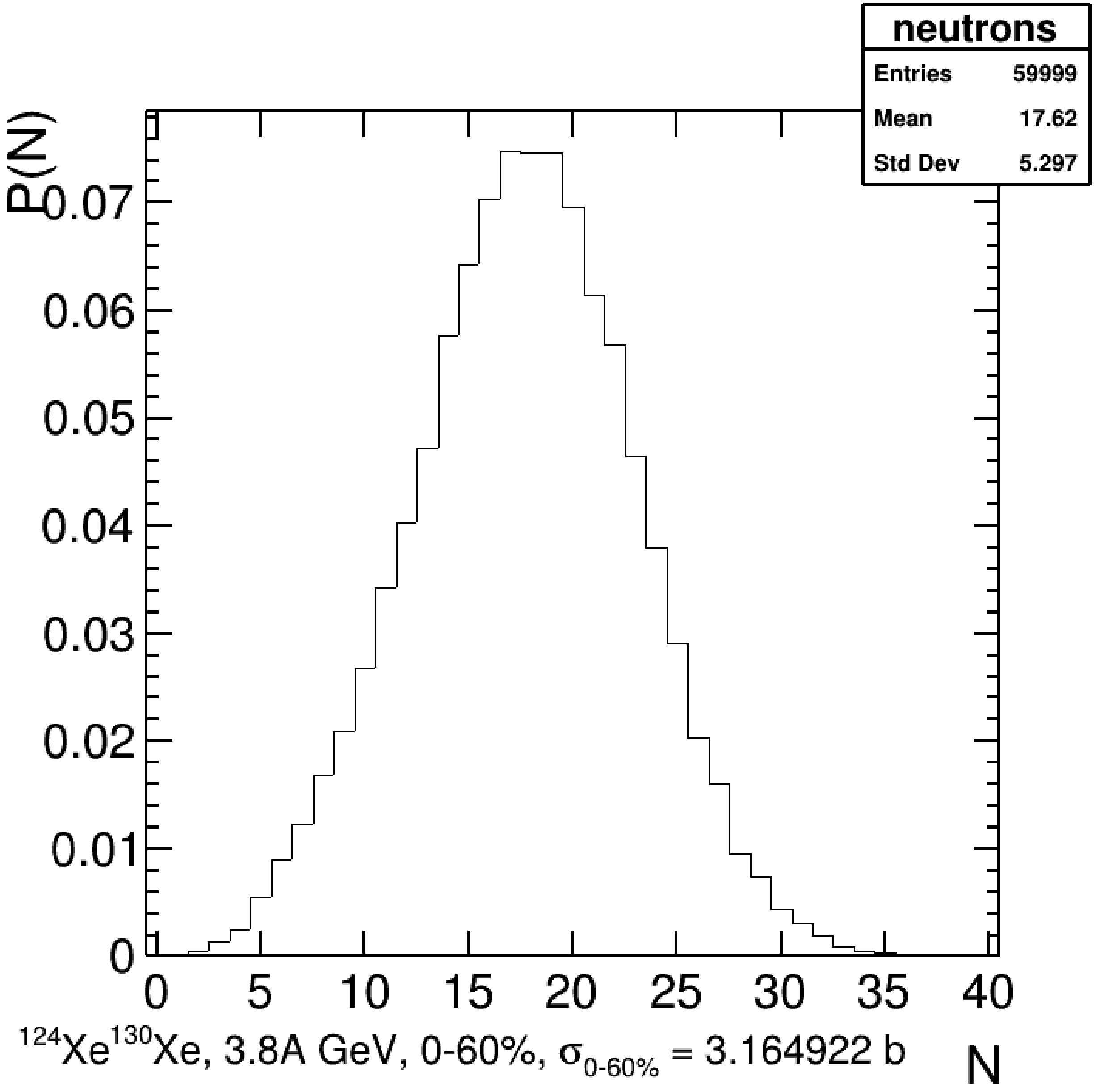


Average multiplicities of neutrons in ^{208}Pb–^{208}Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV as functions of the collision impact parameter

Nepeivoda, R. et al., Pre-Equilibrium Clustering in Production of Spectator Fragments in Collisions of Relativistic Nuclei. *Particles* **2022**, 5, 40–51.

Nuclear interaction



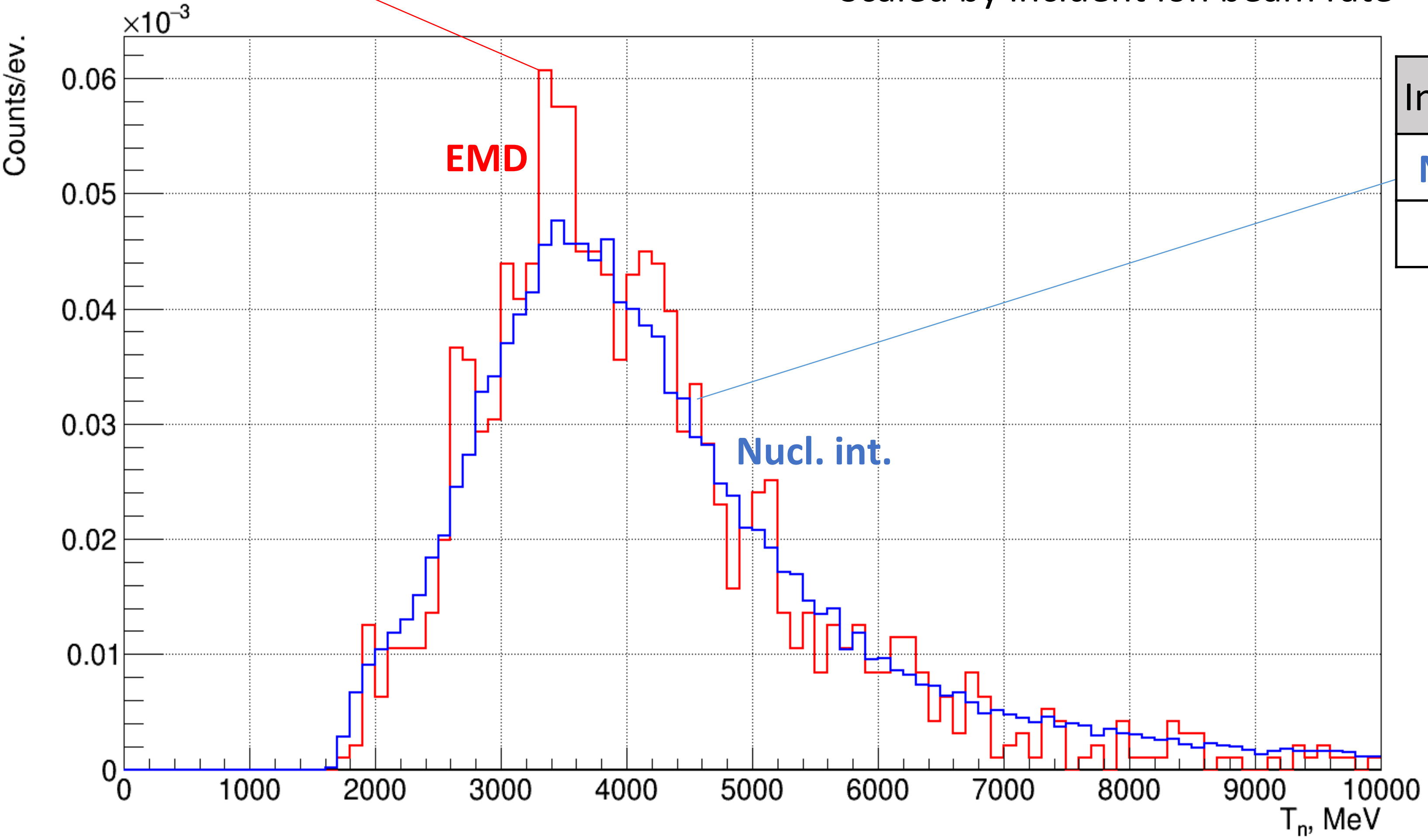


EMD vs Nuclear interaction

Total number of events – 994k
Ions – 956k
BT + BC1S – 496k
Number of neutrons – 1.2k

Comparison of nuclear interaction (CCT2)
with electromagnetic dissociation (BT)
Run 8281 (EMD) vs 8300 (Nucl int)
0.7 deg., 3.8 AGeV
Scaled by incident ion beam rate

Total number of events – 1kk
Ions – 22k*2k
CCT2 + BC1S – 364k
Vertex ± 1.5 – 268k
Number of neutrons – 57.2k



Interaction	*n/i*	*n/i - n/i^{empty}*
Nucl. int.	**$1.307 \cdot 10^{-3}$**	**$(1.274 \pm 0.006) \cdot 10^{-3}$**
EMD	**$1.293 \cdot 10^{-3}$**	**$(0.772 \pm 0.106) \cdot 10^{-3}$**

$$\frac{n/i_{nucl}}{n/i_{EMD}} = 1.01 \pm 0.04$$

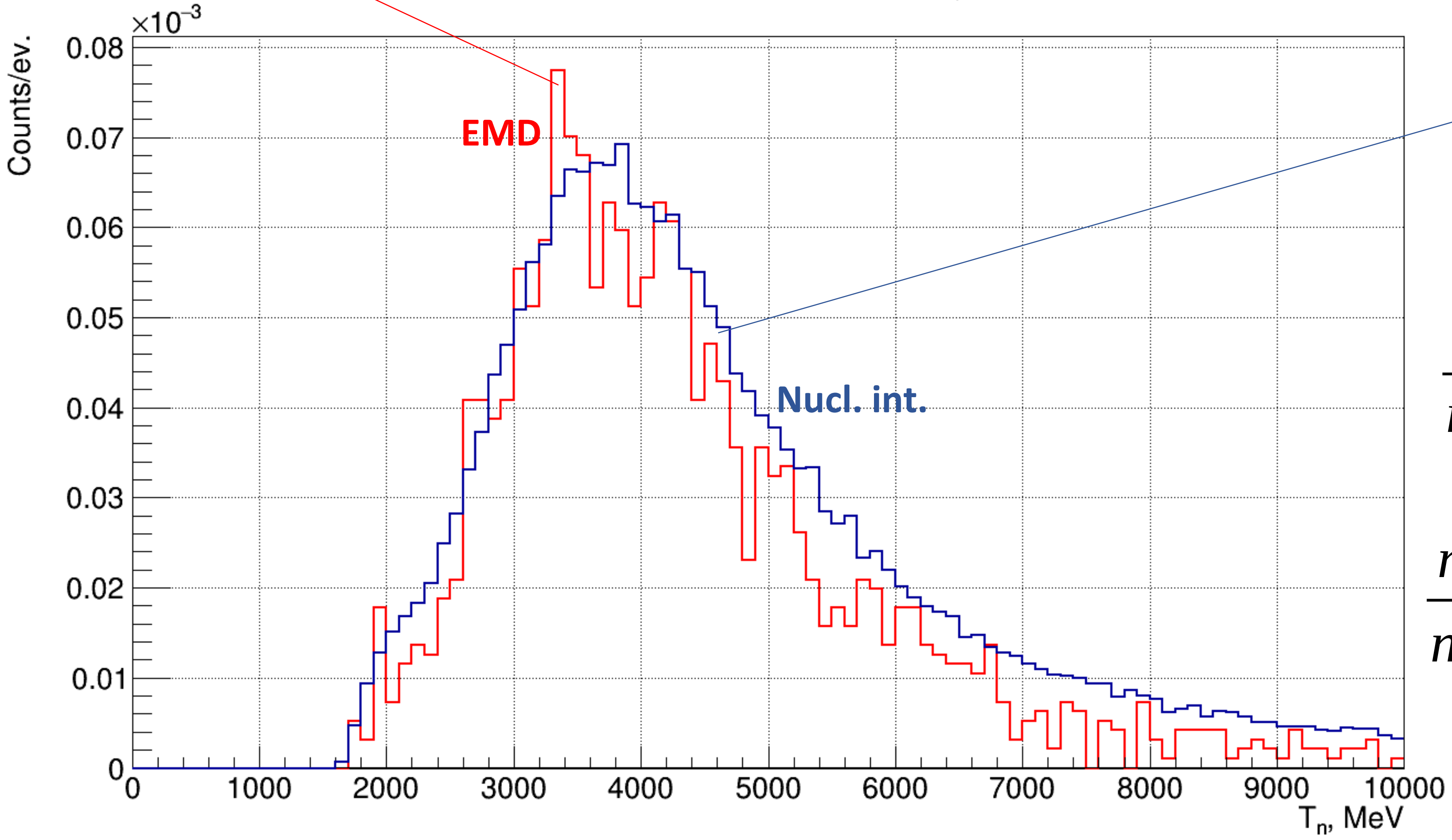
$$\frac{n/i_{nucl} - n/i^{empty}_{nucl}}{n/i_{EMD} - n/i^{empty}_{EMD}} = 1.65 \pm 0.24$$

EMD vs Nuclear interaction

Total number of events – 994k
Ions – 956k
BT + BC1S – 496k
Number of neutrons – 1757

Comparison of nuclear interaction (CCT2)
with electromagnetic dissociation (BT)
Run 8281 (EMD) vs 8300 (Nucl int)
0.7 deg., 3.8 AGeV
Scaled by incident ion beam rate

Total number of events – 1kk
Ions – 22k*2k
CCT2 + BC1S – 364k
Vertex ± 1.5 – 268k
Number of neutrons – 99.5k



Interaction	*n/i*	*n/i - n/i^empty*
Nucl. int.	**$2.261 \cdot 10^{-3}$**	**$2.205 \cdot 10^{-3}$**
EMD	**$1.838 \cdot 10^{-3}$**	**$1.206 \cdot 10^{-3}$**

$$\frac{n/i_{nucl}}{n/i_{EMD}} = 1.23 \pm 0.03$$

$$\frac{n/i_{nucl} - n/i^{empty}_{nucl}}{n/i_{EMD} - n/i^{empty}_{EMD}} = 1.83 \pm 0.19$$

2. HGND prototype acceptance for neutrons from nuclear interaction and EMD:

$$acc = \frac{n_{\text{det}}}{n_{total}} = \frac{n_{\text{det}}}{\langle n \rangle \cdot ev.};$$

$$acc_{nucl} = 3.47 \pm 0.01\%$$

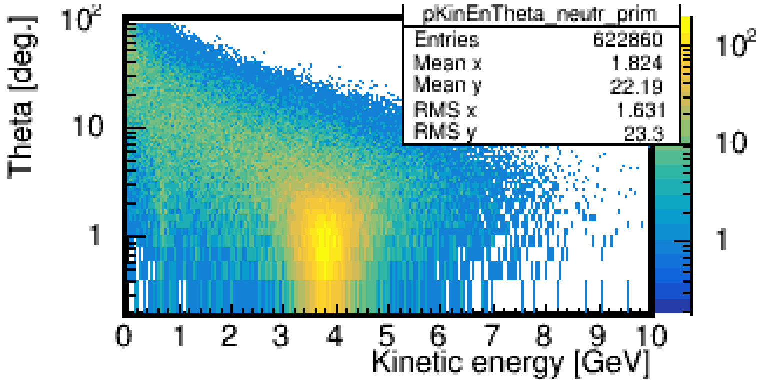
$$acc_{EMD} = 36.13 \pm 0.21\%$$

$$m = \frac{n_{select}}{n_{det}};$$

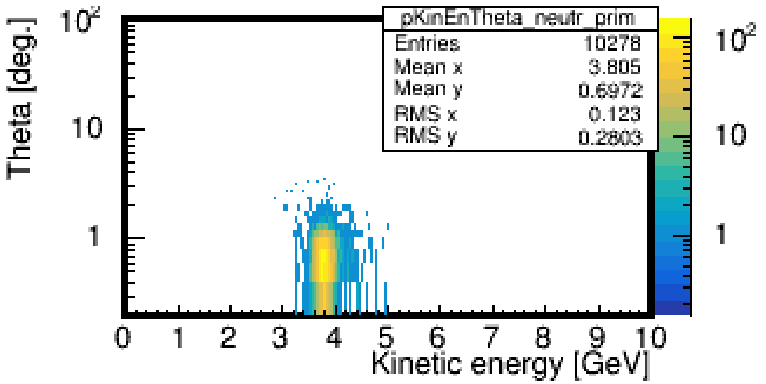
$$m_{nucl} = 52.09 \pm 0.36\%$$

$$m_{EMD} = 74.16 \pm 0.58\%$$

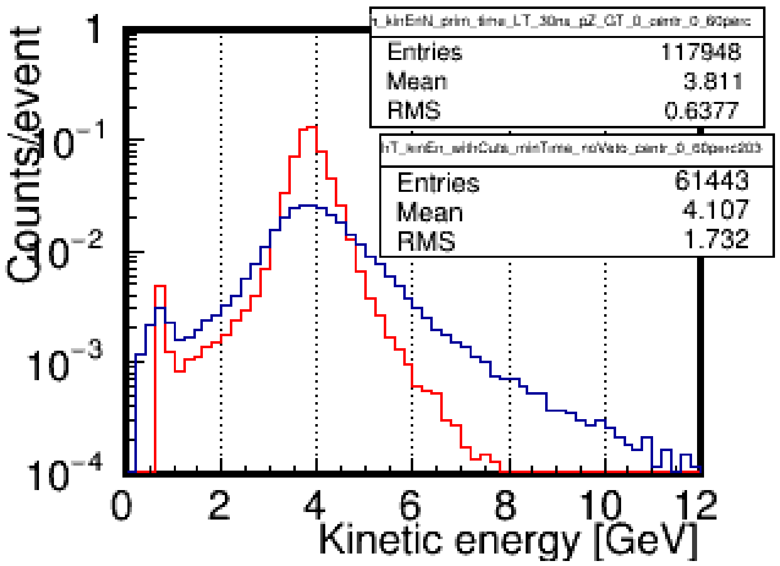
DCM-QGSM-SMM (0-60%)

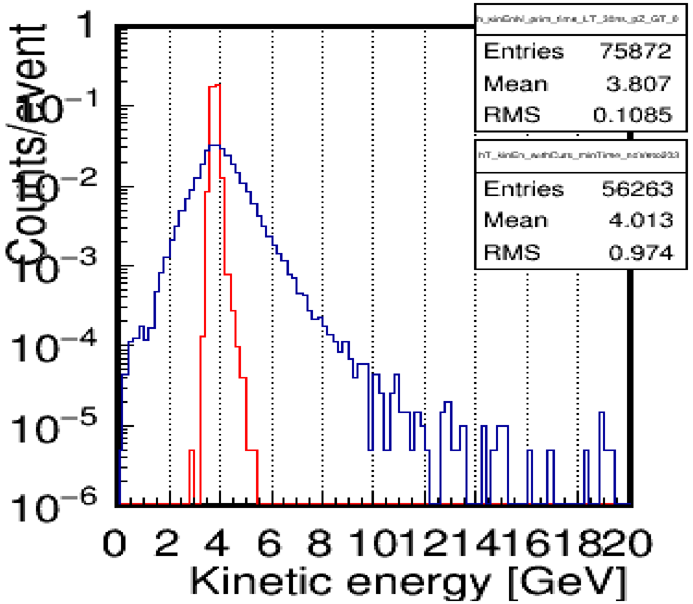


RELDIS



Primary neutrons distributions at vacuum wall before HGND prototype



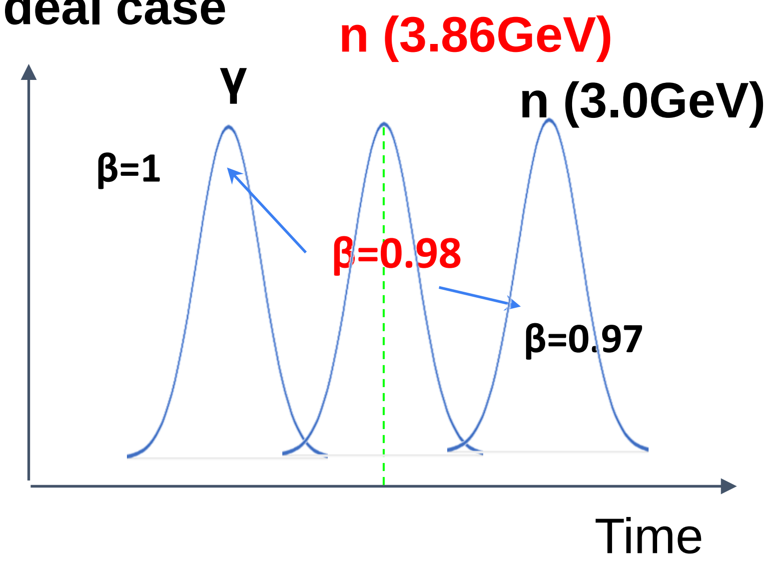


$$acc_{nucl} \cdot m_{nucl} = 1.81 \pm 0.08\%$$

$$acc_{nucl} \cdot m_{nucl} = 26.79 \pm 0.17\%$$

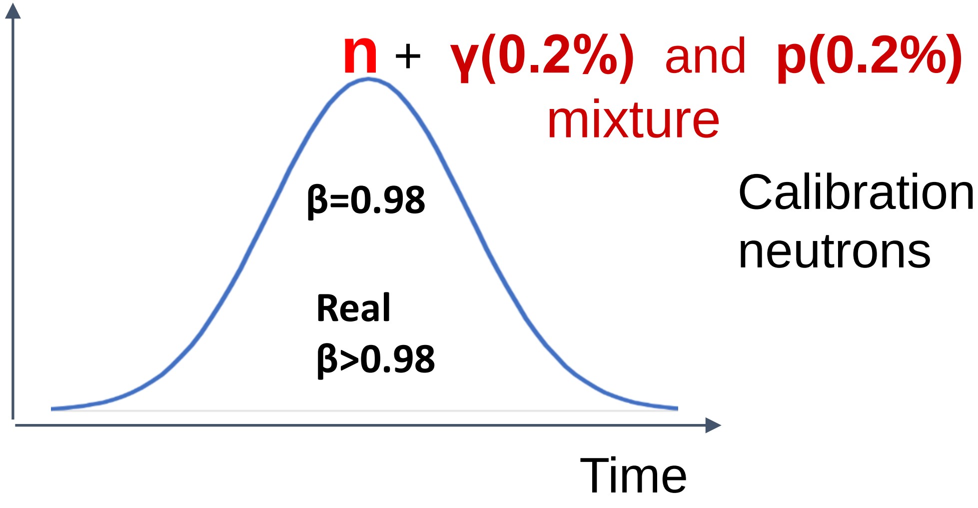
HGND calibration

Ideal case

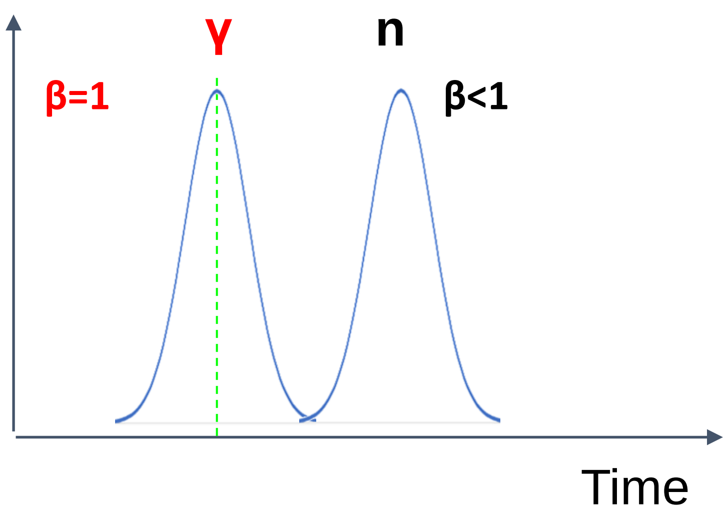


Calibration on neutrons

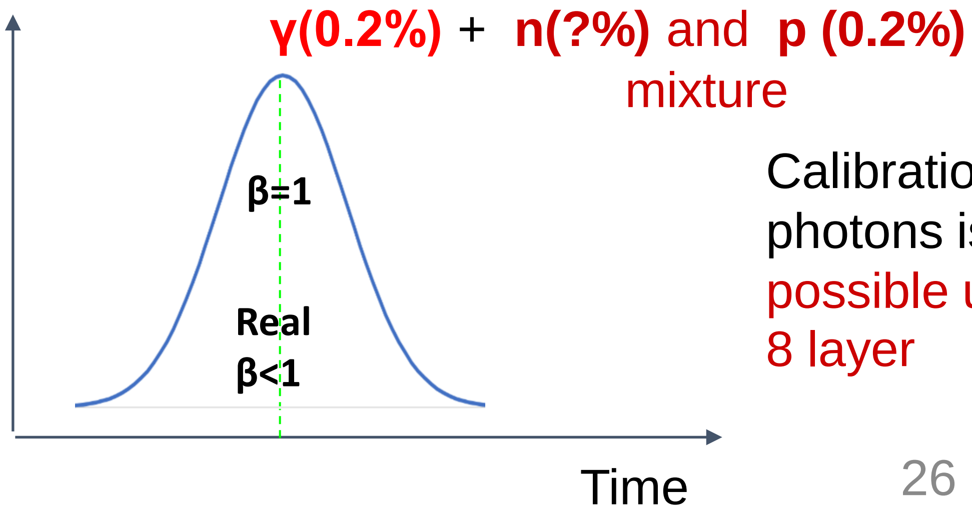
Real data



Calibration on neutrons



Calibration on photons

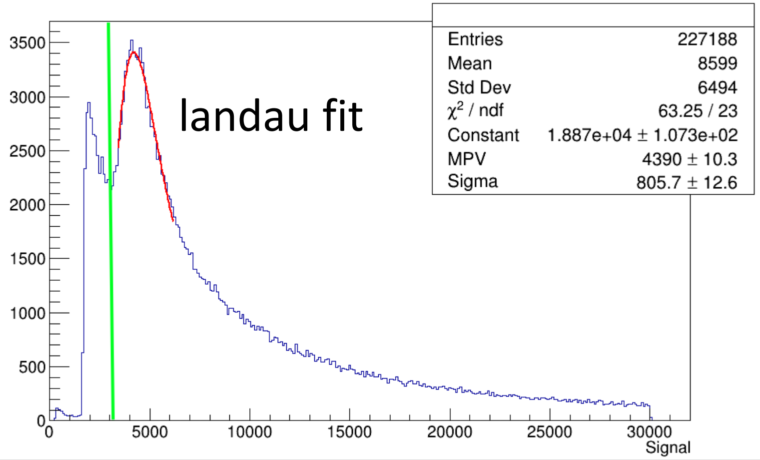


Calibration on photons is possible up to 8 layer

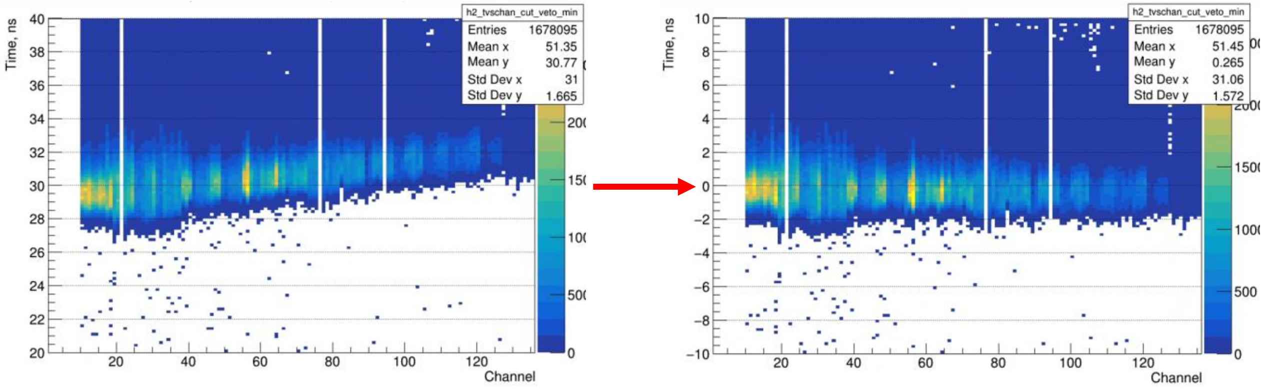
HGND calibration

1. Amplitude normalization

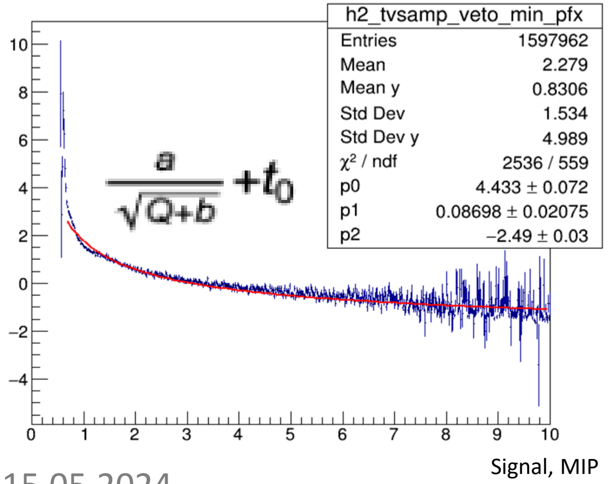
$$Ampl = Ampl \cdot \frac{1}{MPV}$$



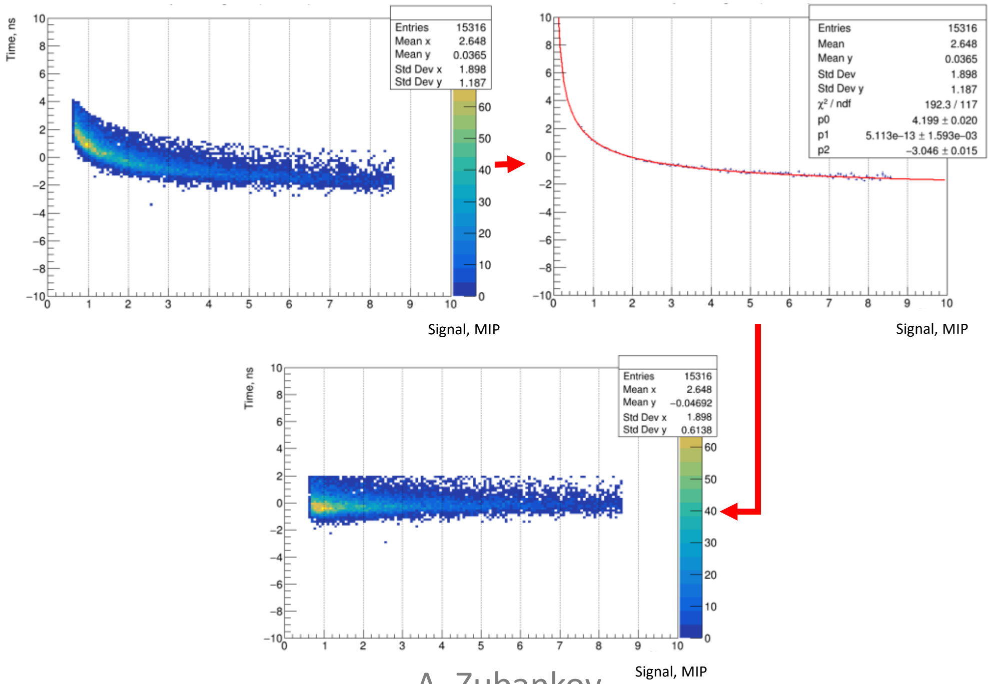
2. Time shift for all channels by the average fit value



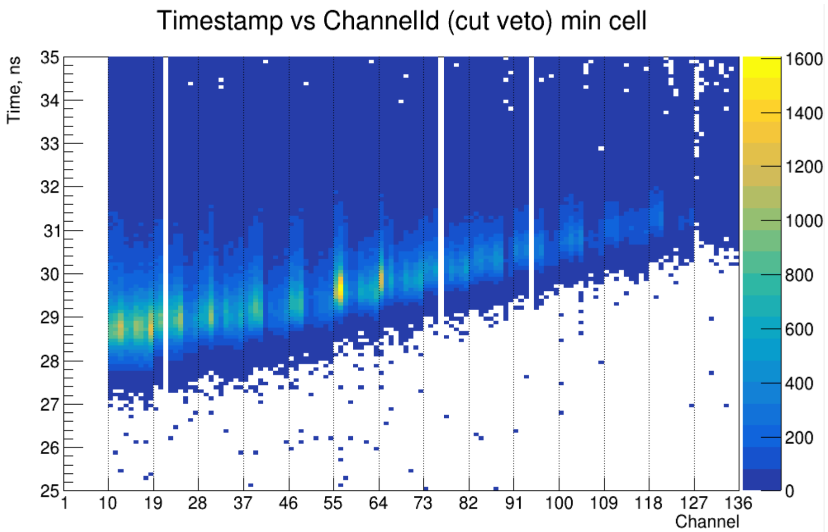
3. Determination of parameters of the approximating function for all channels & time limit



4. Time-amplitude correction

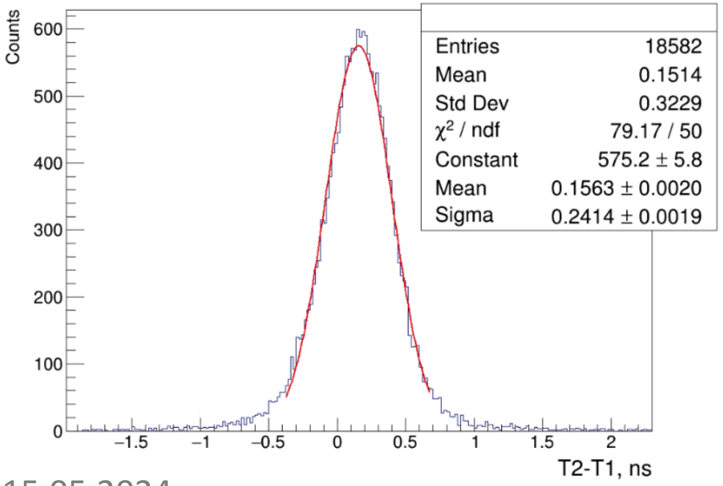


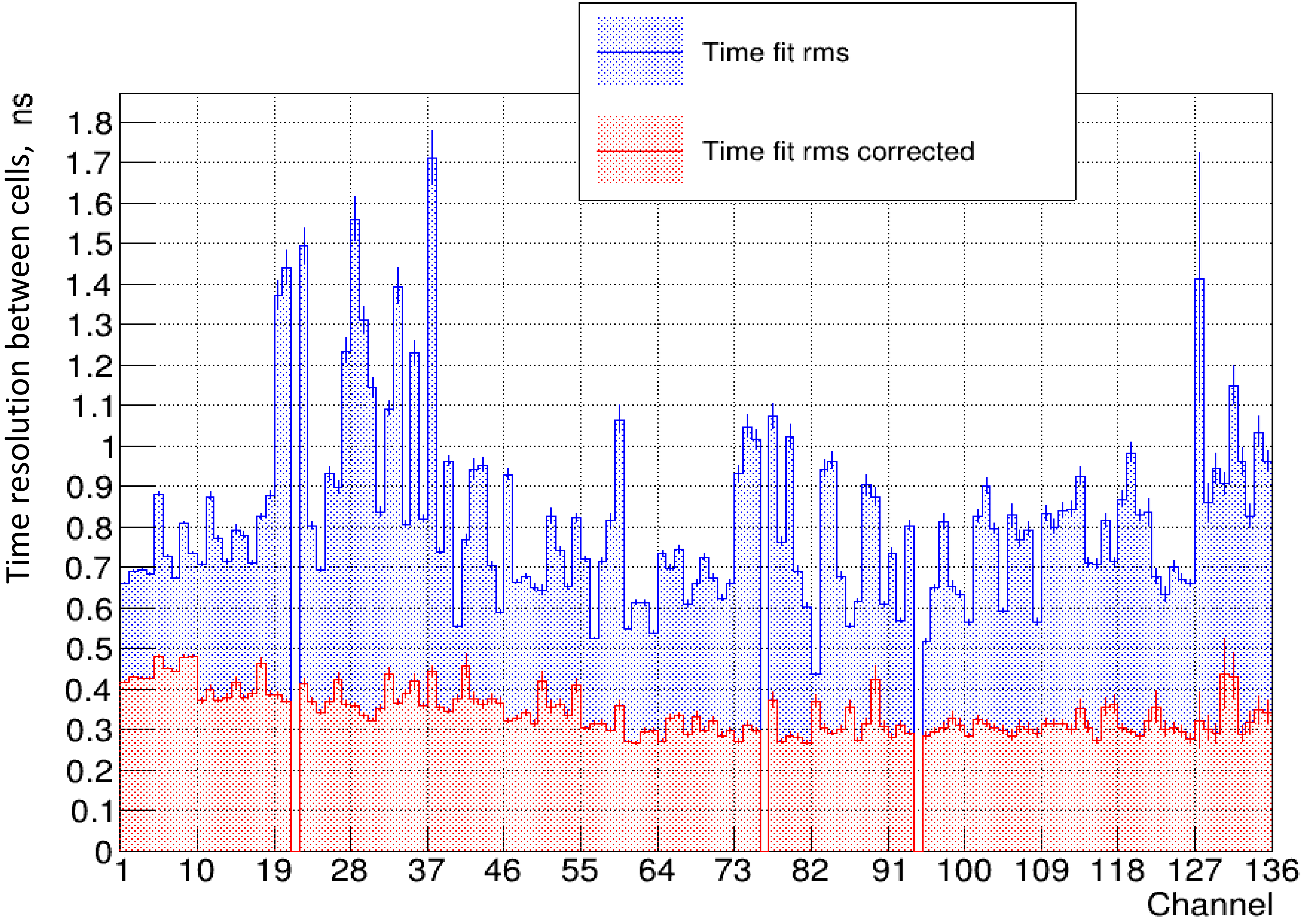
5. Time shift



HGND calibration

Time-amplitude correction of signals made it possible to get rid of the dependence of time on signal amplitude, which improved the time resolution by ~2.4 times.



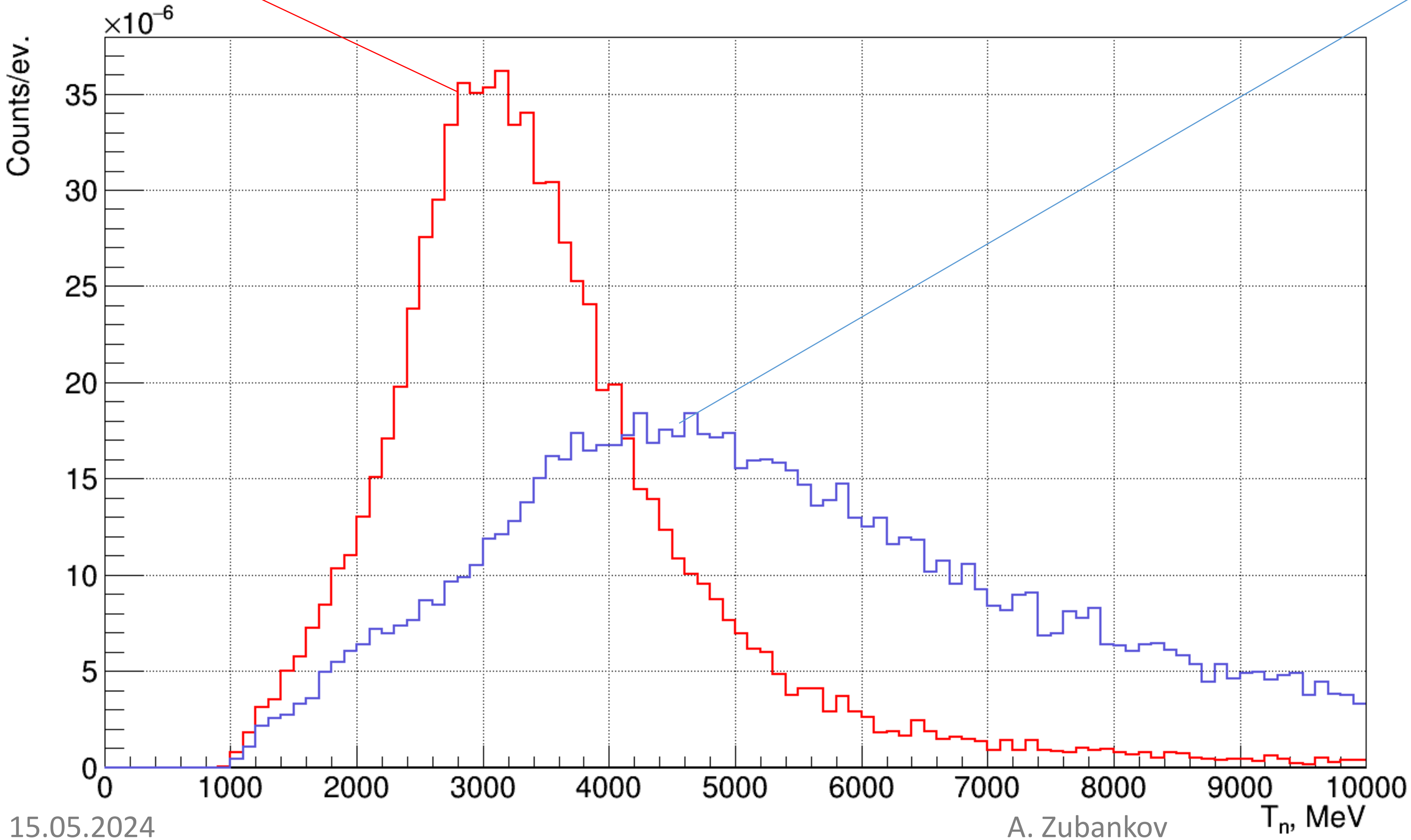


Nuclear interaction in 3.0 vs 3.8 AGeV runs

Run 8320 – **3 AGeV** CsI 2%
Total number of events – 579k
Ions – 15k*2k
BC1S + CCT2 – 212k
Vertex ± 1.5 – 166k
Number of neutrons – 30k

3 AGeV vs 3.8 AGeV
0.7 deg., CCT2+BC1S
Scaled by incident ion beam rate

Run 8300 – **3.8 AGeV** CsI 2%
Total number of events – 1kk
Ions – 22k*2k
BC1S + CCT2 – 364k
Vertex ± 1.5 – 268k
Number of neutrons – 58k



Run	n/ev. (BC1S+CCT2)	n/ions
3 AGeV	**11.8%**	**0.083%**
3.8 AGeV	**12.9%**	**0.107%**

Calibration performed on 3.8 AGeV data gives a peak in correct position for 3 AGeV runs

Estimating the time resolution of cells

Xe + CsI (2%) @ 3.8 AGeV
1 Xe ion, BC1S, CCT2
HGN 0 deg. pos., Veto cut

Selection – hits in 4 consecutive layers: (i) & (i+1) & (i+2) & (i+3),
3 of which are used to calculate the time resolution of the cell in layers 6 – 11.

1st step 1-3 layers

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

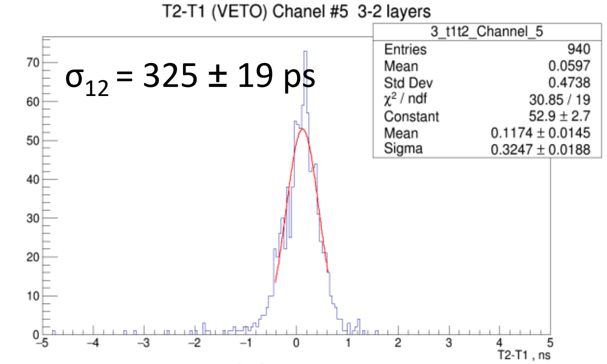
2nd step 1-3 layers

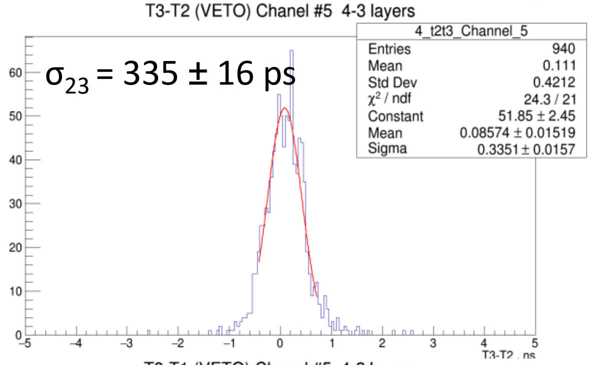
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

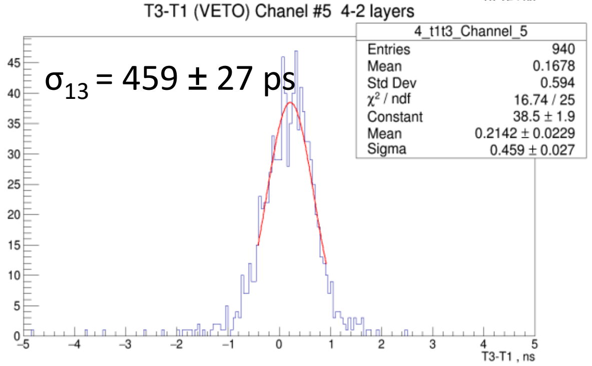
$$\sigma_1^2 + \sigma_2^2 = \sigma_{12}^2$$
$$\sigma_2^2 + \sigma_3^2 = \sigma_{23}^2$$
$$\sigma_1^2 + \sigma_3^2 = \sigma_{13}^2$$

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

Average time resolution $\overline{\sigma_2}$ = 134±29 ps







Estimation of γ-background

Criterion for selecting events with “γ-quanta”:

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

=> 4.52 X_0 or 0.266 λ_{int}

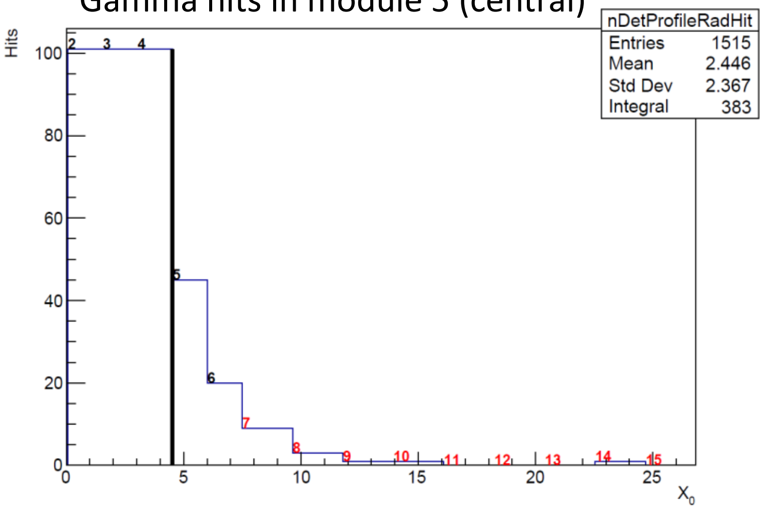
layer

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

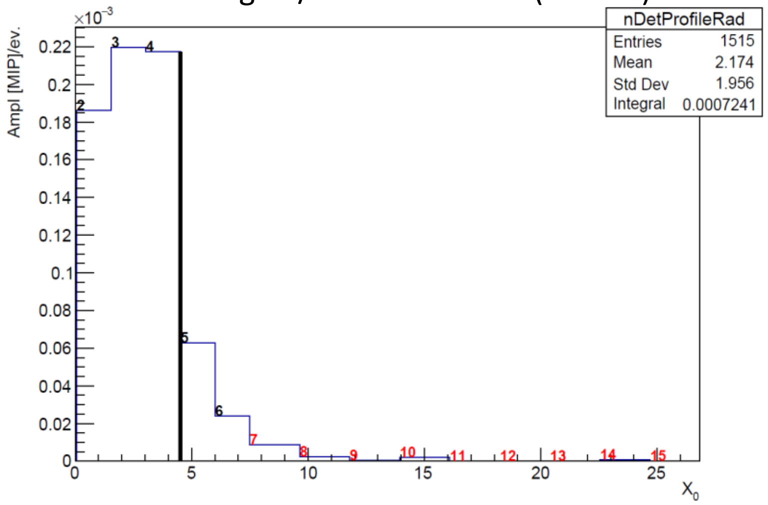
For inverted HGND prototype:

- Hits in 14 & 13 layers in module => 4.36 X_0

Gamma hits in module 5 (central)



Gamma signal/ev. in module 5 (central)



Fraction of γ-ev. in single individual cells

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%

Beam

Fraction of γ-ev. for inverted HGND prot.

Cell 3 **0.0287%** ±0.0015%	***Cell 2*** **0.0131%** ±0.0010%	***Cell 1*** **0.0117%** ±0.0010%
Cell 6 **0.0287%** ±0.0015%	***Cell 5*** **0.0131%** ±0.0010%	***Cell 4*** **0.0227%** ±0.0013%
Cell 9 **0.0340%** ±0.0016%	***Cell 8*** **0.0117%** ±0.0010%	***Cell 7*** **0.0146%** ±0.0011%

Beam

Xe + CsI (2%) @ 3.8 AGeV
HGN 27 deg. pos.
Total number of events:
1 Xe ion, BC1S + CCT2 – 1.2M (100%)
+ Veto cut – 68.2k (5.67%)

Fraction of γ-ev. in full HGND prototype (all cells):
0.173 %

Comparable to simulation (0.1–0.2%)

Gamma rejection efficiency is the same in both configurations

High granular neutron time-of-flight detector (HGND)

The EoS establishes the relationship between pressure, density, energy, temperature and the **symmetry energy**.

$$E_A(\rho,\delta) = E_A(\rho,0) + \mathbf{E_{sym}(\rho)} \cdot \delta^2 + O(\delta^4)$$

The symmetry energy term characterizes the **isospin asymmetry** of nuclear matter

$$\delta = (\rho_n - \rho_p)/\rho$$

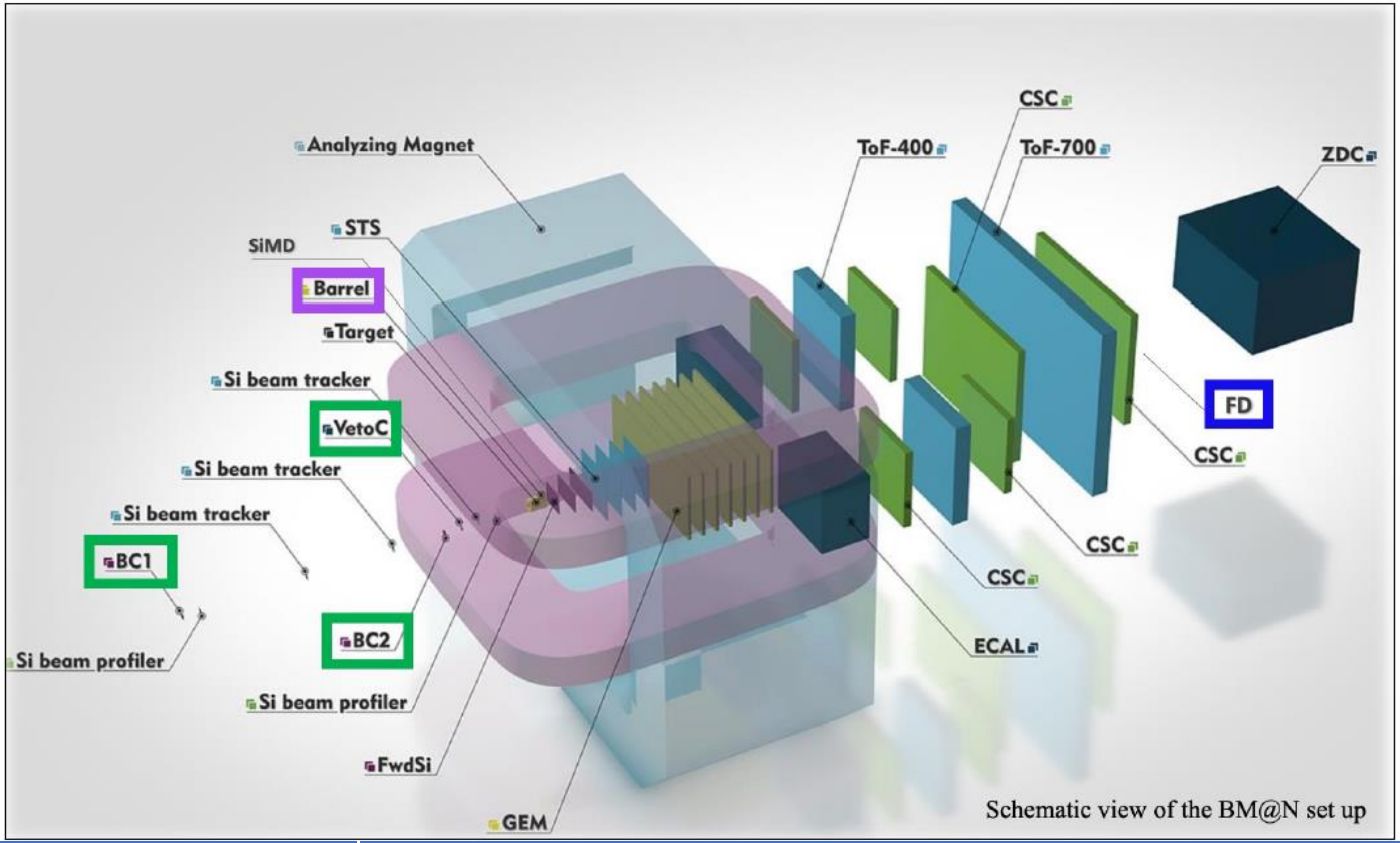
The ratio of the directed and elliptic neutron flow to corresponding flow of protons is a sensitive observable of the symmetry energy contribution to the EoS of high density nuclear matter.

To measure yields and flow of neutrons at the BM@N a new **high-granular neutron time-of-flight detector** (HGND) is now developed and constructed

BC1, VC, BC2

BD

FD



Schematic view of the BM@N set up

Trigger type	Trigger logic
Beam Trigger (BT)	BT = BC1 * BC2 * !VC
Min. Bias Trigger (MBT)	MBT = BT * !FD
Centrality Trigger 1 (CCT1)	CCT1 = BT * BD
Centrality Trigger 2 (CCT2)	CCT2 = MBT * BD

EMD vs Nuclear interaction in simulation

1. In the analysis of the experiment, only one fastest neutron in the event is identified, regardless of how many neutrons hit the detector surface:

Detection efficiency of 3.8 GeV neutrons:

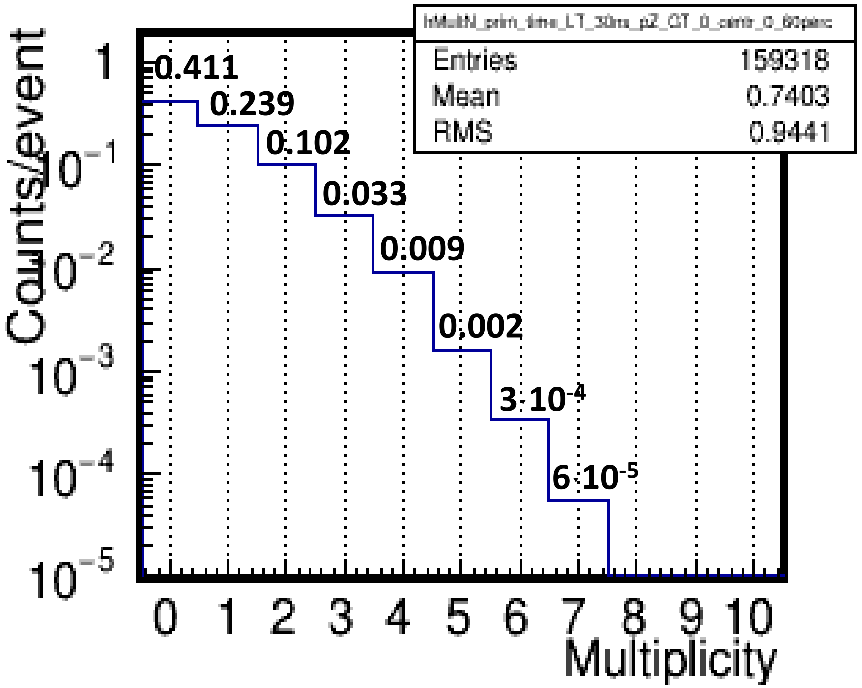
$\varepsilon = 75.1\%$

with γ-cut:

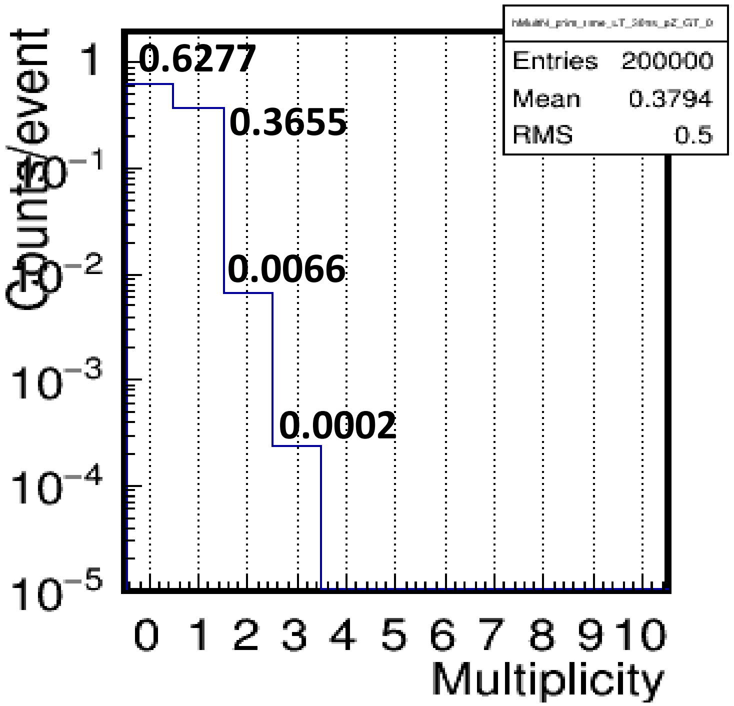
$\varepsilon_{\gamma\text{-cut}} = 52.8\%$

$$m = \frac{1 \cdot \sum_{mult=1}^{n} P_{mult} \cdot \left(1 - [1-\varepsilon]^{mult}\right)}{\sum_{mult=1}^{n} P_{mult} \cdot mult};$$

DCM-QGSM-SMM (0-60%)



RELDIS[1]



$$m_{nucl} = 54.10 \pm 0.77\% \qquad m_{EMD} = 74.04 \pm 0.64\%$$

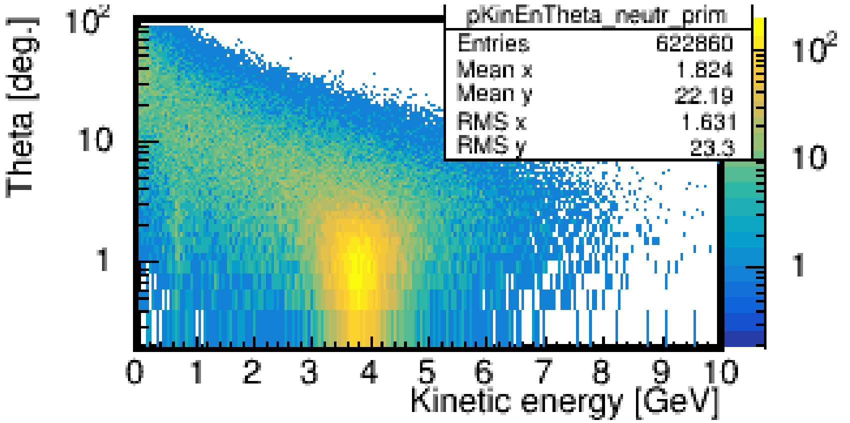
With γ-cut: $m_{nucl}^{\gamma-cut} = 41.70 \pm 0.60\%$ $\quad m_{EMD}^{\gamma-cut} = 52.27 \pm 0.45\%$

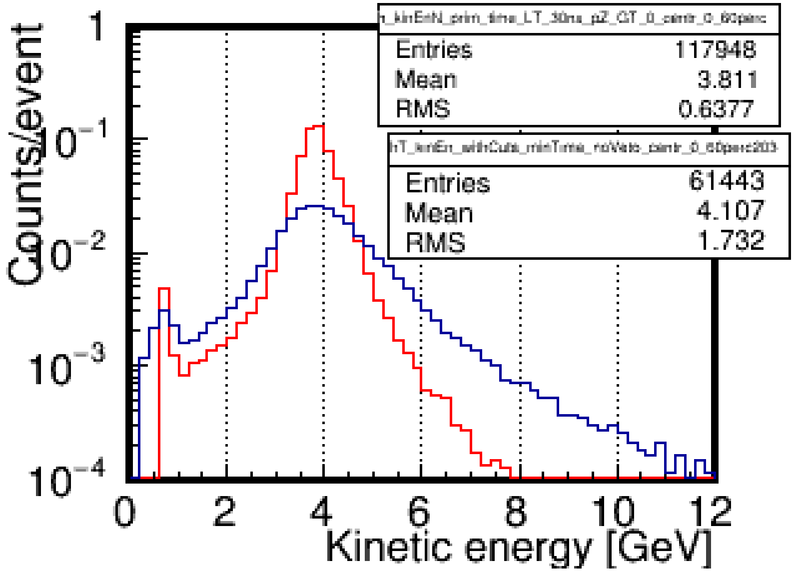
[1] I. Pshenichnov, Phys. Part. Nucl. 42, 215 (2011)

EMD vs Nuclear interaction in simulation

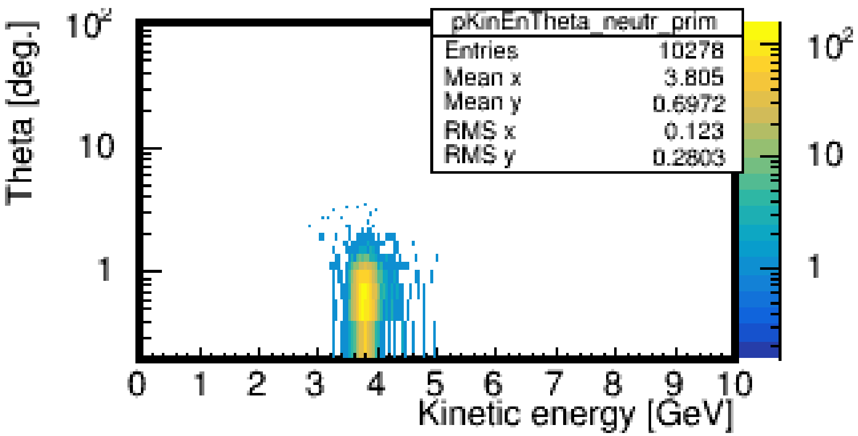
2. HGND prototype acceptance for neutrons from nuclear interaction and EMD:

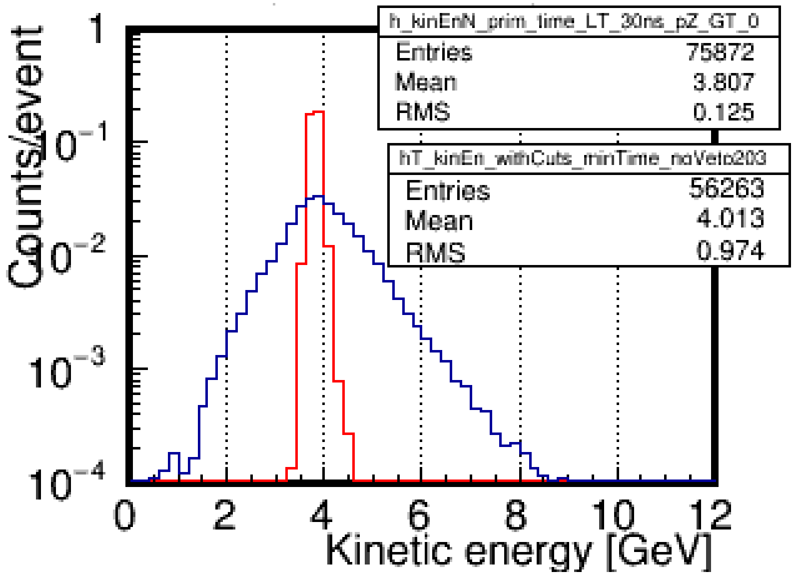
DCM-QGSM-SMM (0-60%)





RELDIS





Primary neutrons distributions at vacuum wall before HGND prototype

Reconstructed energy spectrum (without γ-cut)

$$acc = \frac{n_{\det}}{n_{total}} = \frac{n_{\det}}{\langle n \rangle \cdot ev.};$$

$$acc_{nucl} = 3.47 \pm 0.01\%$$

$$acc_{EMD} = 36.13 \pm 0.21\%$$