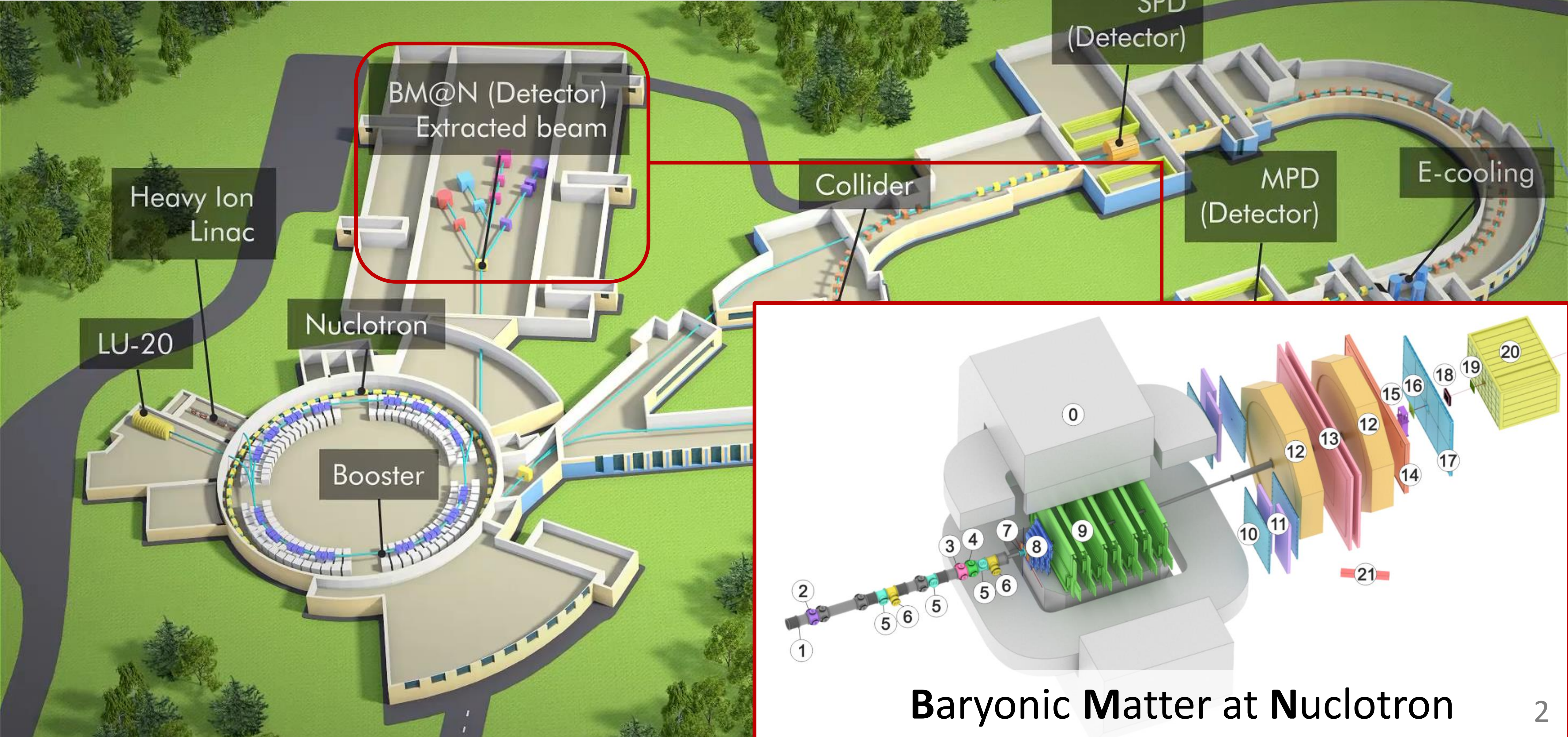
Calculations of the efficiency of the Highly Granular Neutron Detector prototype in detecting spectator neutrons in the BM@N experiment

A. Zubankov, M. Golubeva, F. Guber, N. Karpushkin, S. Morozov,
I. Pshenichnov, S. Savenkov, A. Shabanov, A. Svetlichnyi

25.10.2024

BM@N is the first operational experiment at the NICA complex

Nuclotron-based Ion Collider fAcility



Baryonic Matter at Nuclotron

Introduction

- The Highly Granular Neutron Detector (HGND) at the BM@N experiment is under development for measuring the energy of neutrons up to 4 GeV produced in nucleus-nucleus collisions.
- Neutron measurements are necessary to obtain robust information on the symmetry energy of the Equation of State for high baryon density matter.
- A compact HGND prototype has already been designed and constructed to validate the concept of the full-scale HGND.
- For the first time, small prototype of the HGND was used in Xe+CsI at 3.8A GeV run at the BM@N.
- This work presents the results of the efficiency and geometric acceptance simulation of the HGND prototype for the detection of forward spectator neutrons

Outline

- Design of **H**ighly **G**ranular **N**eutron **D**etector prototype
- HGND prototype in Xe+CsI@3.8A GeV run
- UrQMD-AMC vs DCM-QGSM-SMM
- HGND prototype efficiencies and acceptances

HGND prototype design

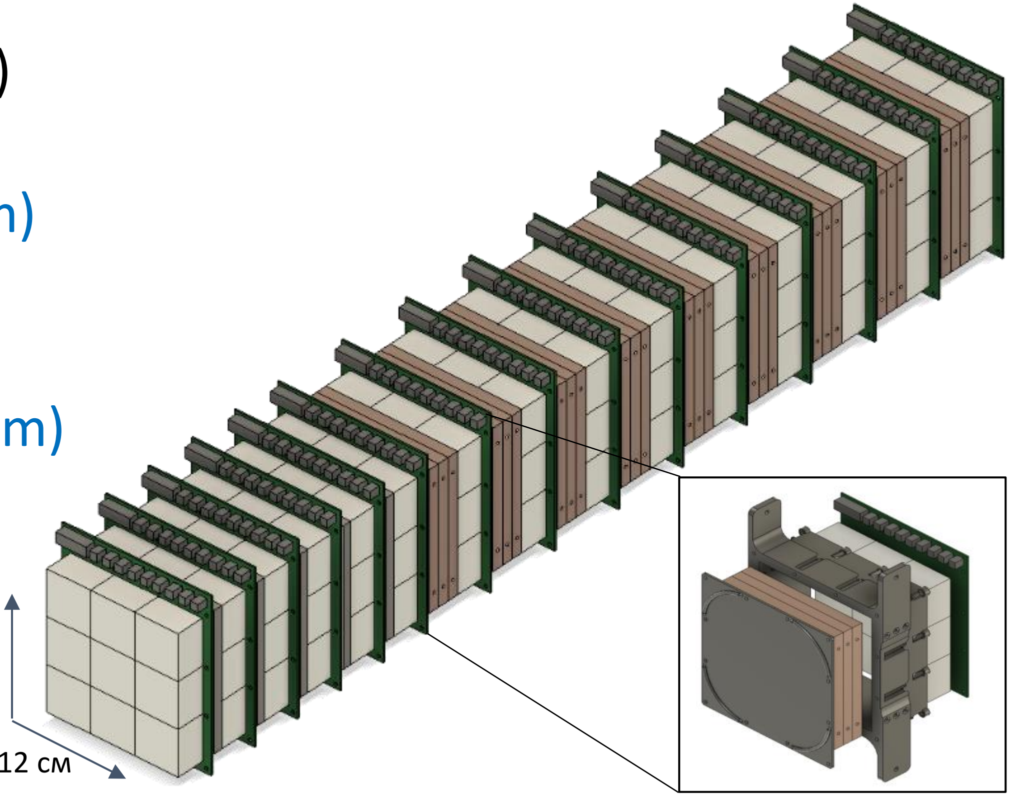
- Scint. layer **Veto** 120x120x25 (мм)
- 1^{st} (electromagnetic) part:
  5 layers: **Pb (8mm)** + Scint. (25mm) + PCB + air
- 2^{nd} (hadronic) part:
  9 layers: **Cu (30mm)** + Scint. (25mm) + PCB + air

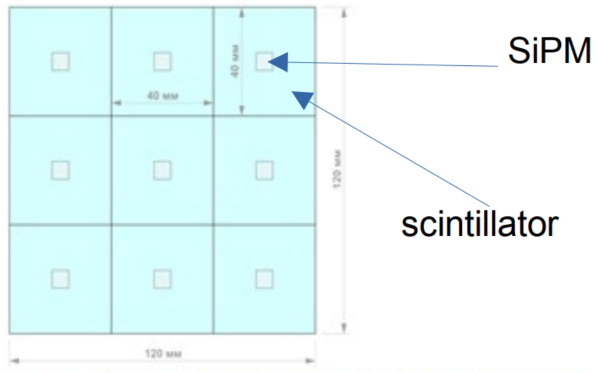
Scint. cell – 40 x 40 x 25 mm^3

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

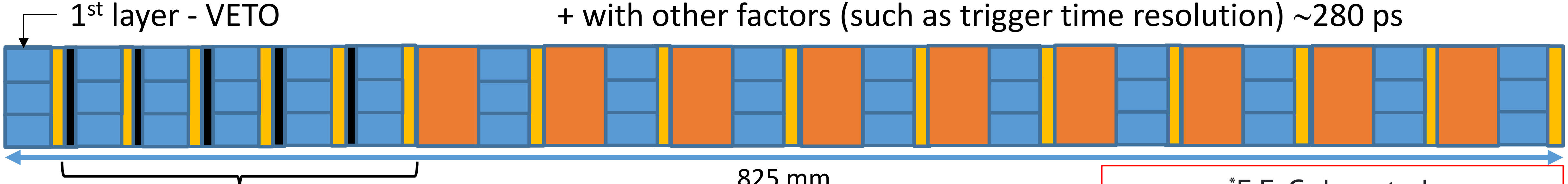
Gain – $1.7x10^6$

PDE – 40%

Time resolution of cell ~200 ps*,

+ with light collection heterogeneity ~240 ps,

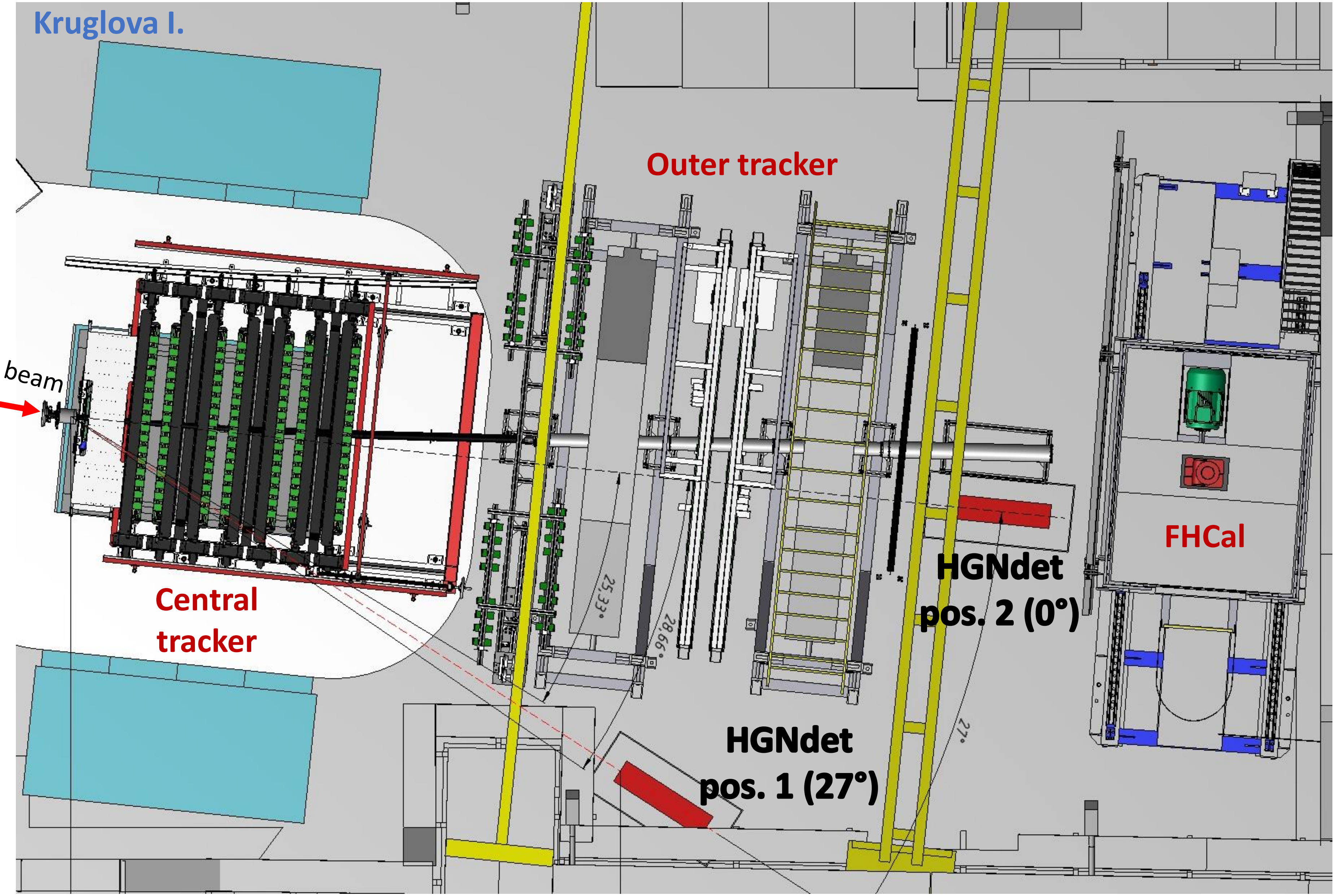
+ with other factors (such as trigger time resolution) ~280 ps



Necessary to separate showers from γ-quanta

*F.F. Guber et al. 10.1134/S0020441223030065

HGND prototype in the Xe+CsI@3.8A GeV run of BM@N



27° position:

Measurements of the neutron spectrum at ~ midrapidity.

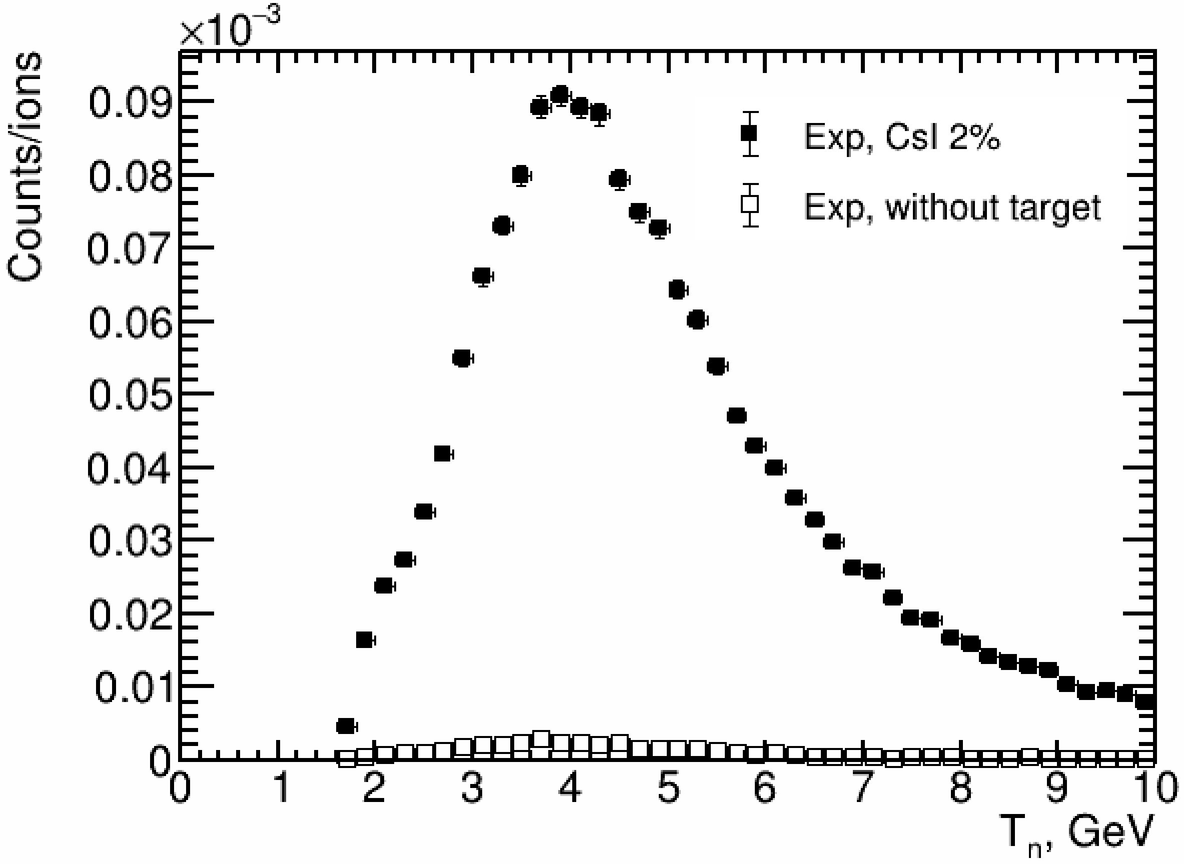
0° position:

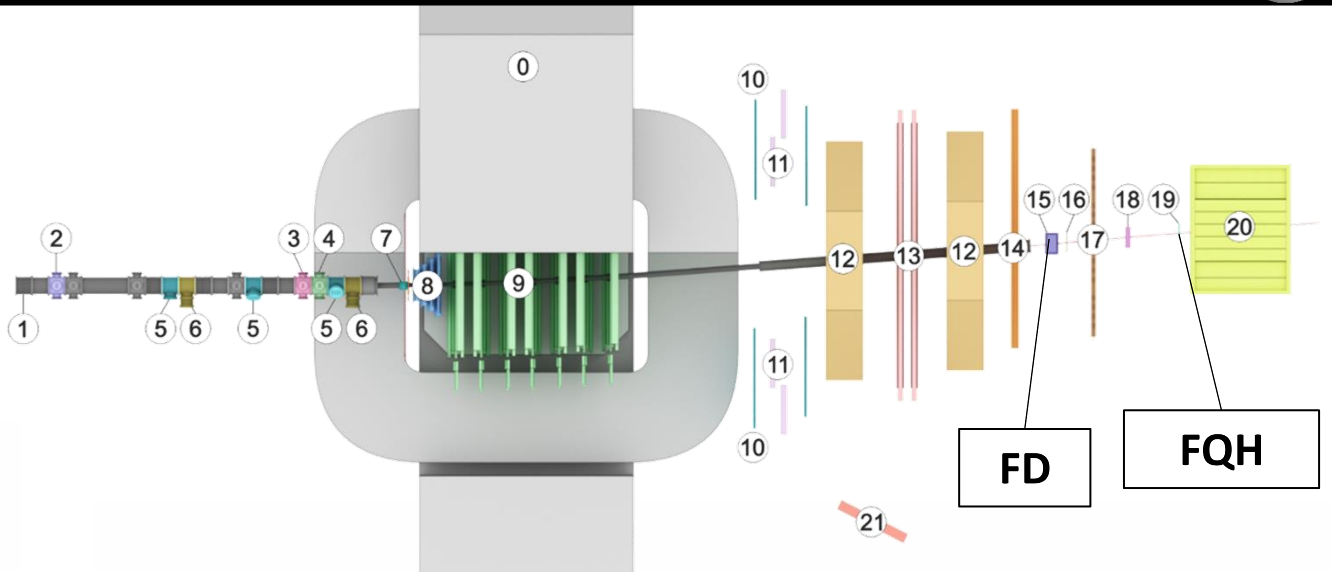
Test and calibration with known neutron energy (energy of a beam of spectator neutrons)

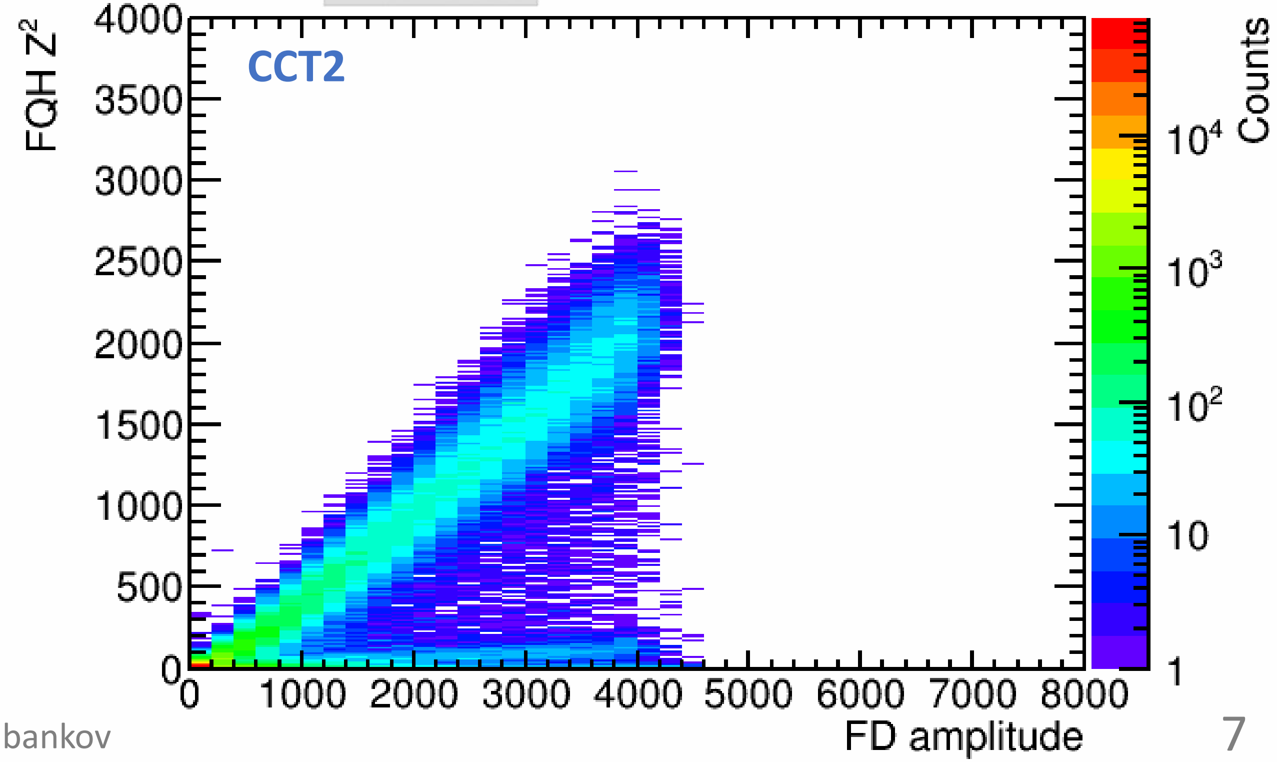
Criteria for selecting events with spectator neutrons

Central & semi-central collisions

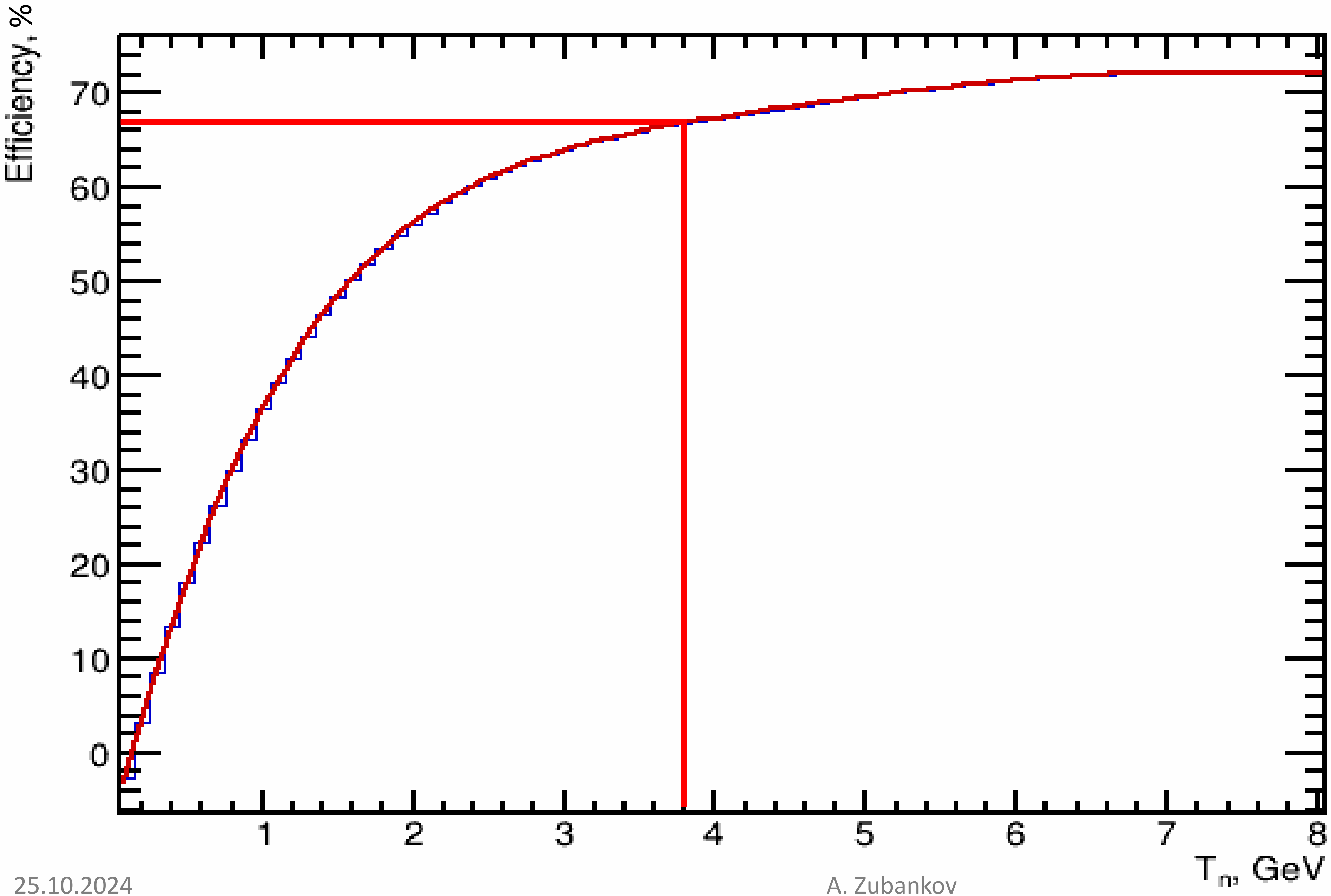
- Single Xe ion in target + **Central trigger (CCT2)**
- Forward Detector amplitude < 4500
- Selection of events without charged particles, ToF cut, γ-cut (1.55 X_0 or 0.11 λ_{int})
- Reconstruction of energy by maximum velocity







HGND prototype efficiency for neutrons



Geant4 simulation:

Box generator

Only neutrons

- VETO-cut
- γ-cut
- ToF cut

We use the DCM-QGSM-SMM* and UrQMD-AMC models to estimate the detector efficiency for hadronic interactions

*M. Baznat et al., Monte-Carlo Generator of Heavy Ion Collisions DCM-SMM, *Phys. Part. Nucl. Lett.* **2020**, 17, 303.

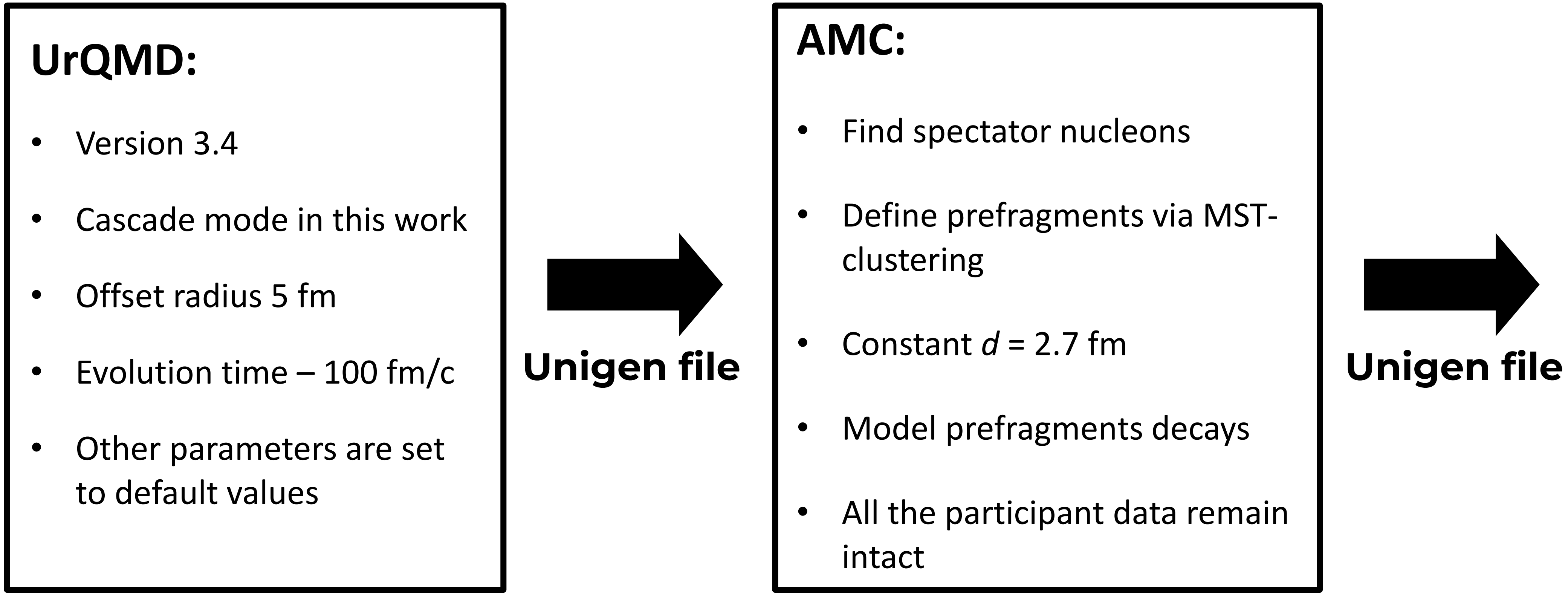
Ablation Monte Carlo: decay code from AAMCC

- The excited nuclear fragments are formed by means of MST-clusterization algorithm after UrQMD
  - A few excited nuclear prefragments can be formed, in contrast with DCM-QGSM-SMM, where all the spectator nucleon remain bound in one prefragment.
- Excitation energy of prefragment is calculated by hybrid approximation: a combination of Ericson formula for peripheral collisions and ALADIN approximation otherwise1)
- Decays of prefragments are simulated as follows:
  - Fermi break-up model from Geant4 v9.2 2)
  - Statistical Multifragmentation Model (SMM) from Geant4 v10.4 2)
  - Weisskopf-Ewing evaporation model from Geant4 v10.4 2)
- They were validated and adjusted to describe the data3).

1) R. Nepeivoda, et al., Particles **5** (2022) 40
2) J. Alison et al. Nucl. Inst. A **835** (2016) 186
3) 55th Geant4 Techical Forum
https://indico.cern.ch/event/1106118/contributions/4693132/

Combining UrQMD and AAMCC

- AMC is developed to simulate secondary decays of spectator fragments created in other models, in particular UrQMD.
- It is assumed that spectator matter is formed out of nucleons that do not undergo any collisions.



UrQMD:

- Version 3.4
- Cascade mode in this work
- Offset radius 5 fm
- Evolution time – 100 fm/c
- Other parameters are set to default values

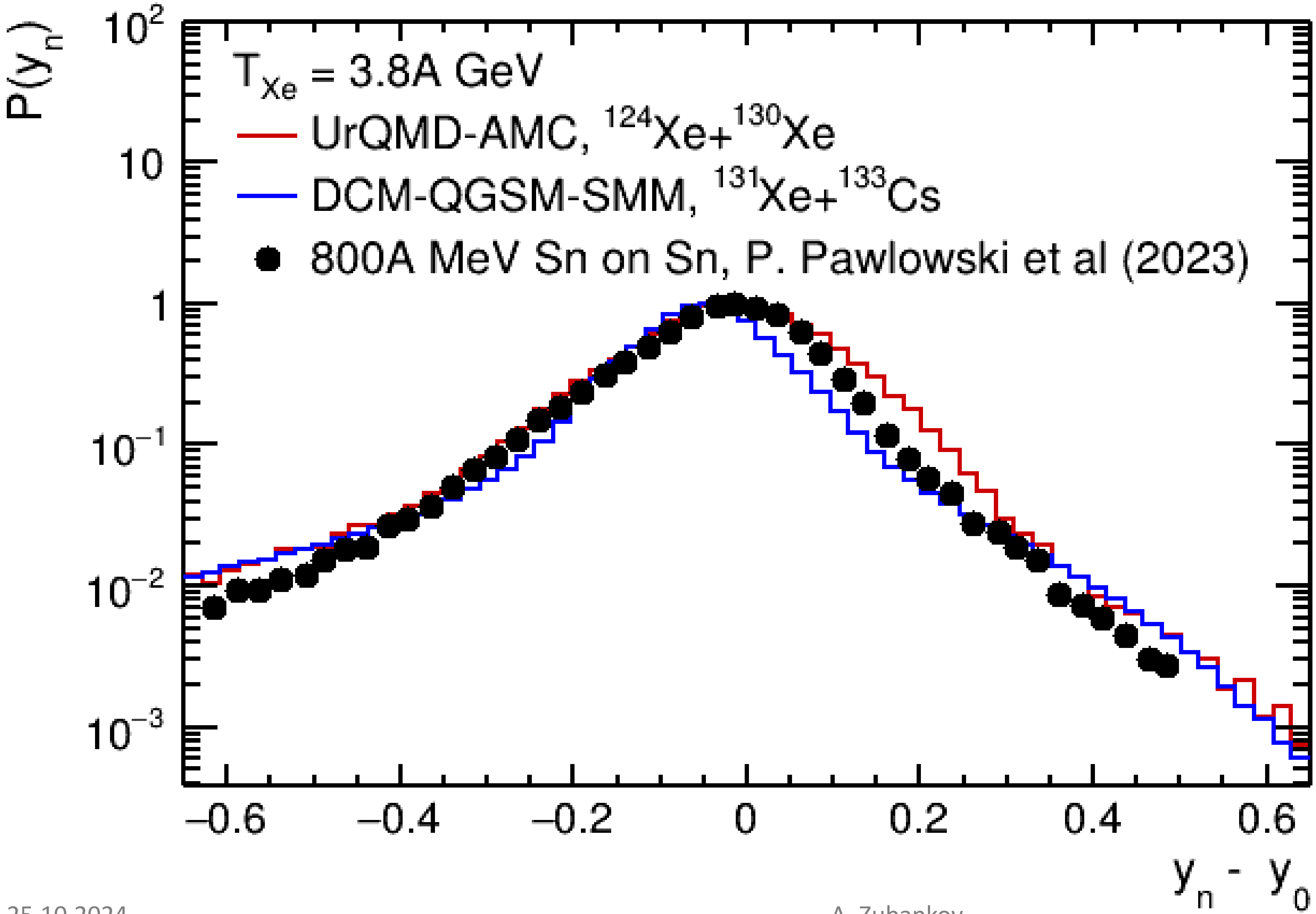
Unigen file

AMC:

- Find spectator nucleons
- Define prefragments via MST-clustering
- Constant *d* = 2.7 fm
- Model prefragments decays
- All the participant data remain intact

Unigen file

UrQMD-AMC vs DCM-QGSM-SMM



DCM-QGSM-SMM and UrQMD-AMC describe the experiment well in the rapidity region y_n-y_0<0.

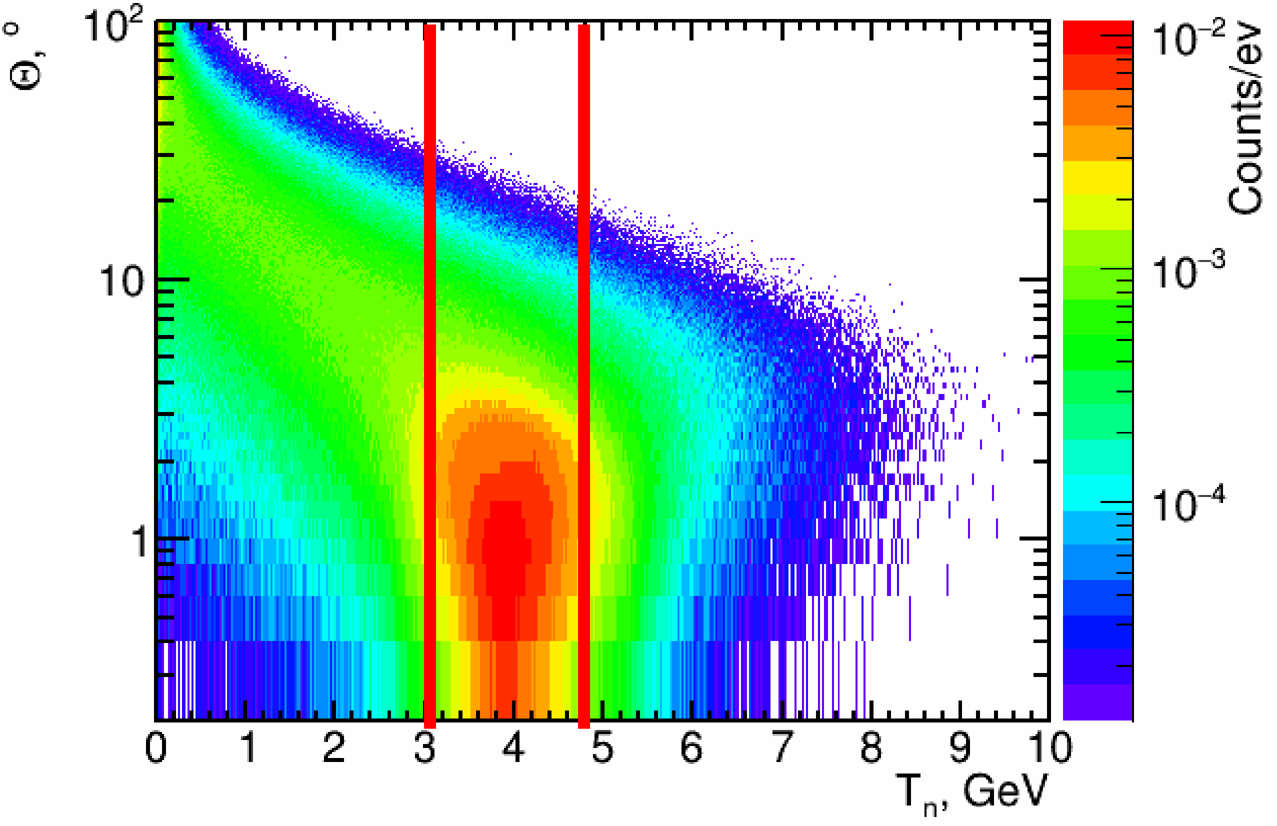
In the region y_n-y_0>0, DCM-QGSM-SMM underestimates the data whereas UrQMD-AMC overestimates.

For DCM-QGSM-SMM, there is a shift in the rapidity relative to the beam rapidity.

UrQMD-AMC vs DCM-QGSM-SMM for BM@N

UrQMD-AMC

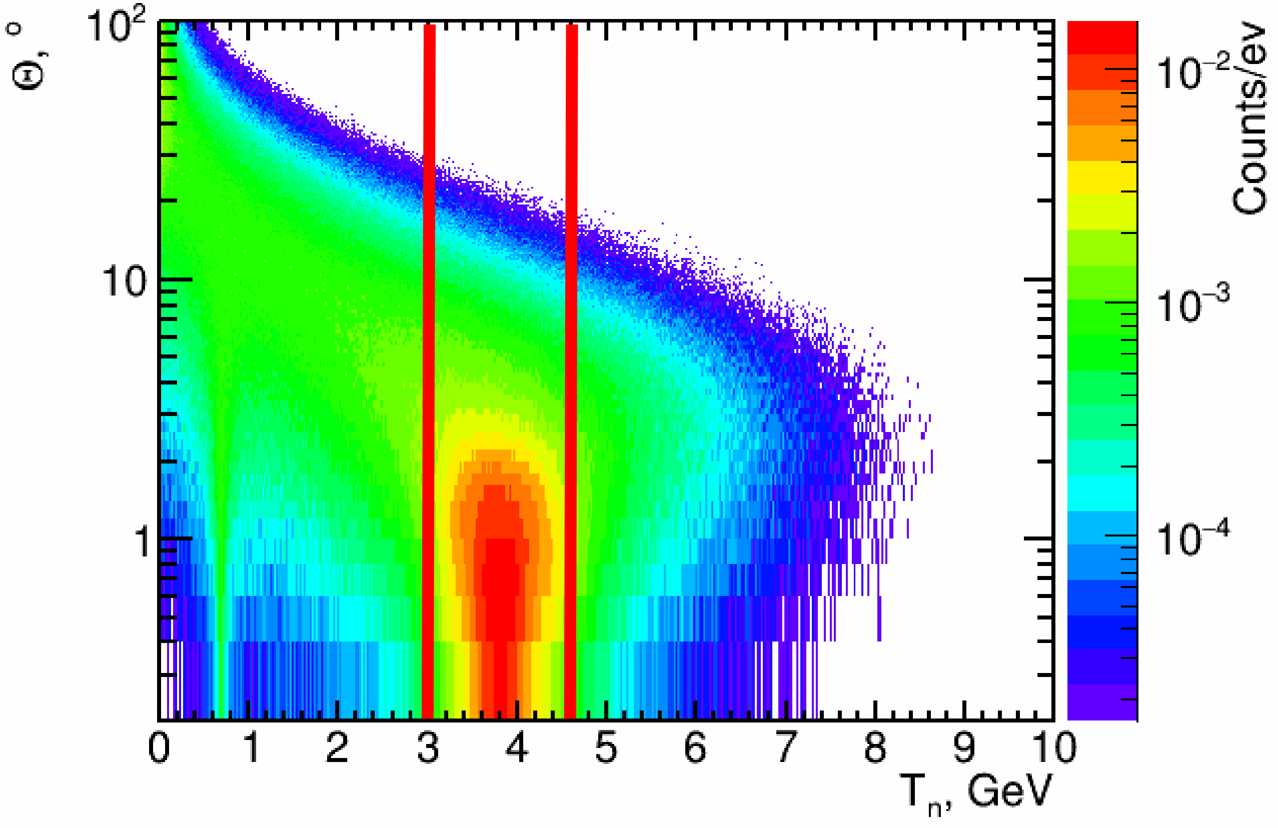
3.8A GeV ^{124}Xe + ^{130}Xe



Spectator neutron multiplicity – **17.70**

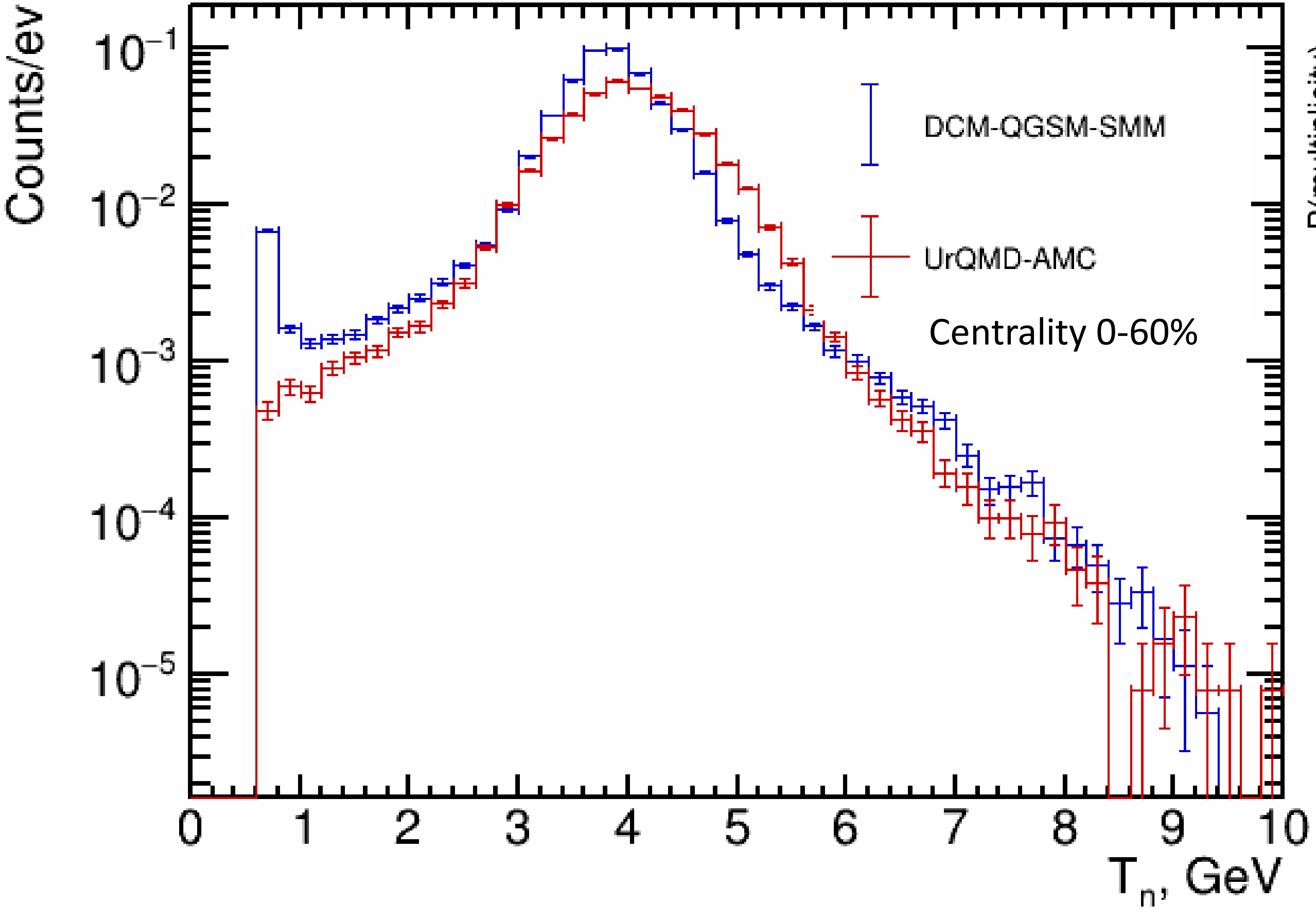
DCM-QGSM-SMM

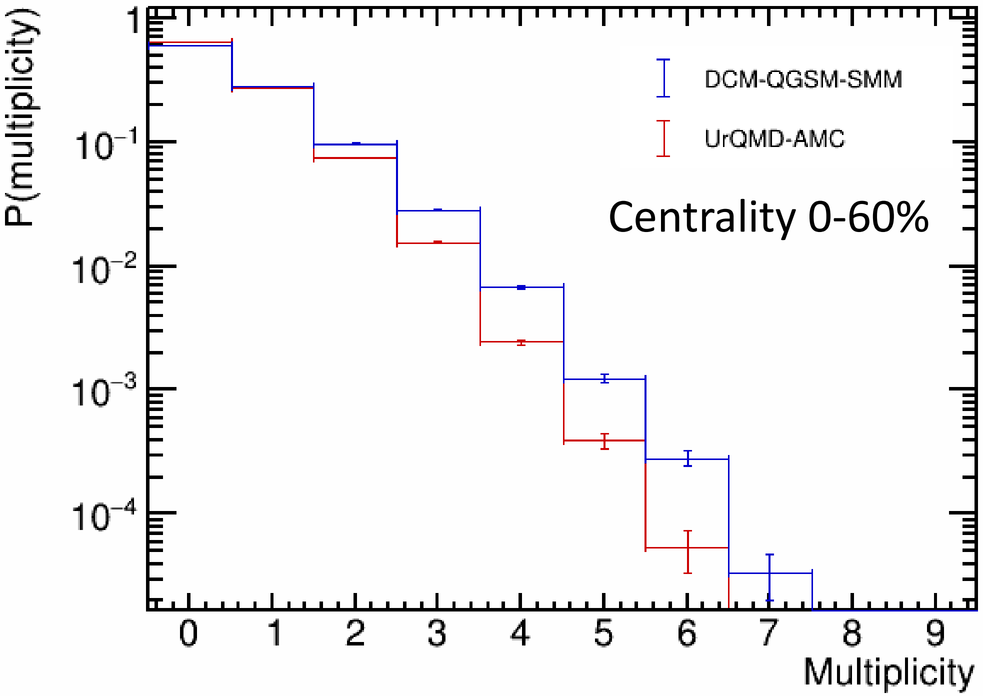
3.8A GeV ^{131}Xe + ^{133}Cs



Spectator neutron multiplicity – **16.01**

Neutrons on the surface of the HGND prototype





Neutron multiplicity on the surface

– **1.31** for **UrQMD-AMC**

– **1.44** for **DCM-QGSM-SMM**

HGND prototype efficiencies

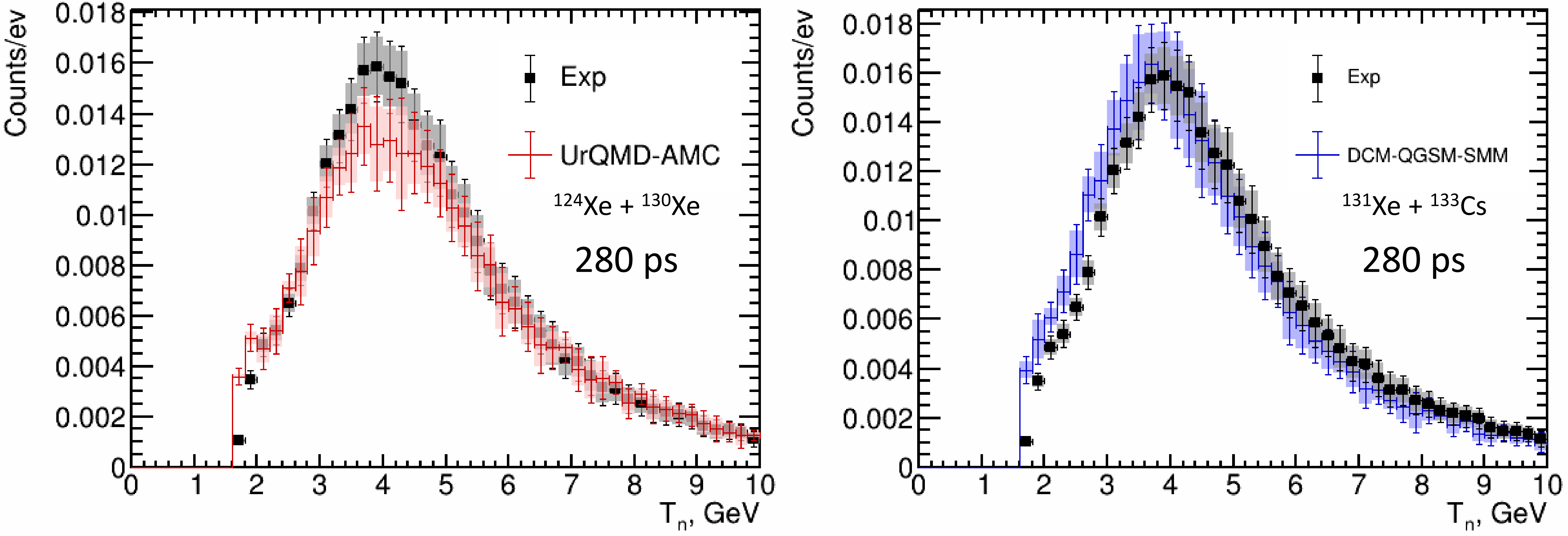
$$acc = \frac{N_{hit}}{N_{gen}} \qquad \varepsilon = \frac{N_{rec}}{N_{hit}}$$

Model	*acc*, %	*ε*, %	*acc* x *ε*, %
DCM-QGSM-SMM	3.37 ± 0.02	39.41 ± 0.20	1.328 ± 0.007
UrQMD-AMC	2.50 ± 0.02	46.47 ± 0.29	1.162 ± 0.007
Combined	2.94±0.01±0.44 (stat) (sys)	42.94±0.18±3.53 (stat) (sys)	1.245±0.005±0.083 (stat) (sys)

The difference in *acc* is explained by the differences in angular distribution of primary neutrons (17.70 vs 16.01) and in average multiplicity of neutrons hitting the detector (1.31 vs 1.44).

The difference in *ε* is due to the difference in average multiplicity of neutrons hitting the detector (1.31 vs 1.44).

Reconstructed energy spectra



The difference in the shape and peak position of the reconstructed spectra of the models is noticeable, which is also due to the difference in the mean kinetic energy of neutrons and their multiplicity.

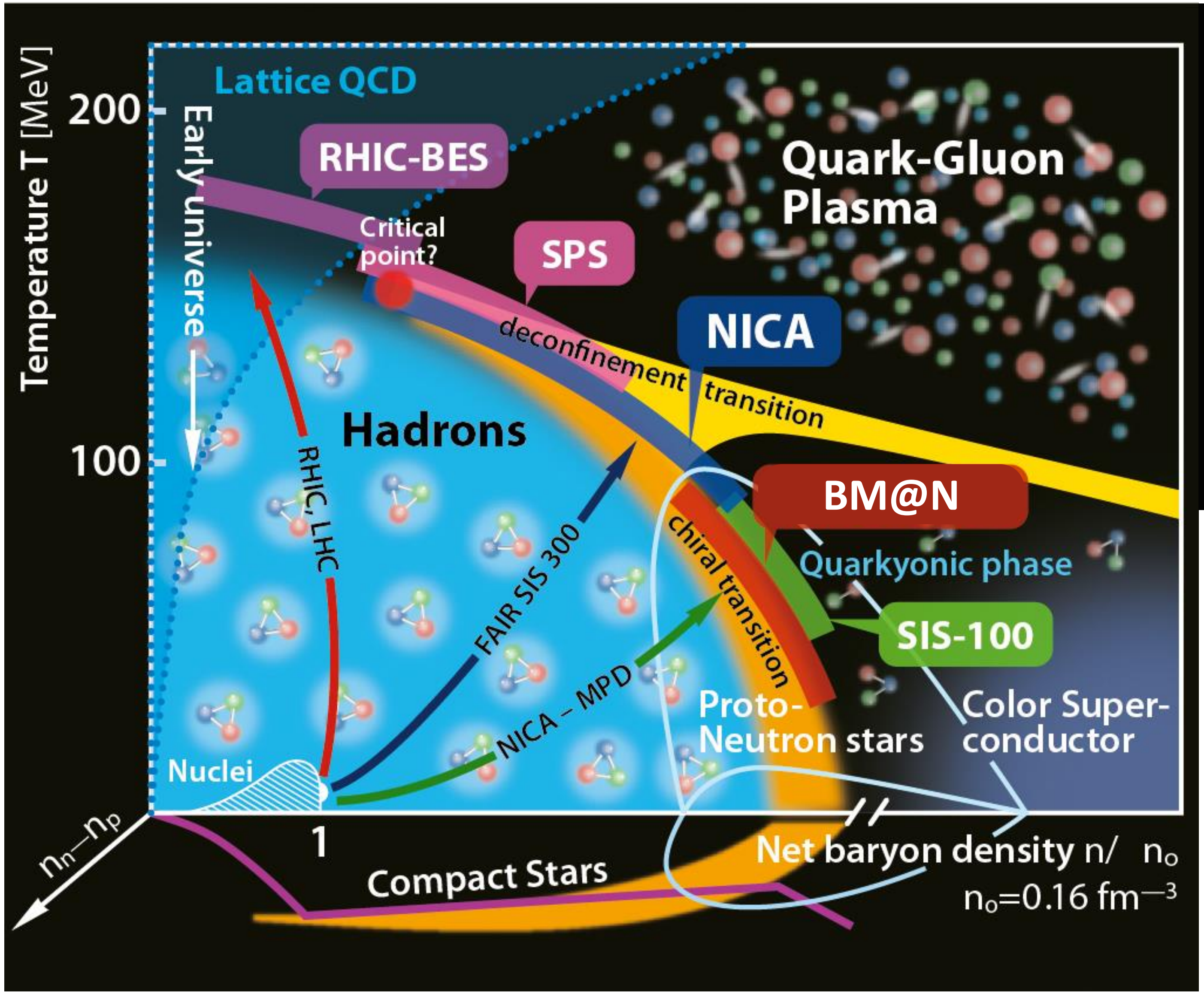
Conclusions

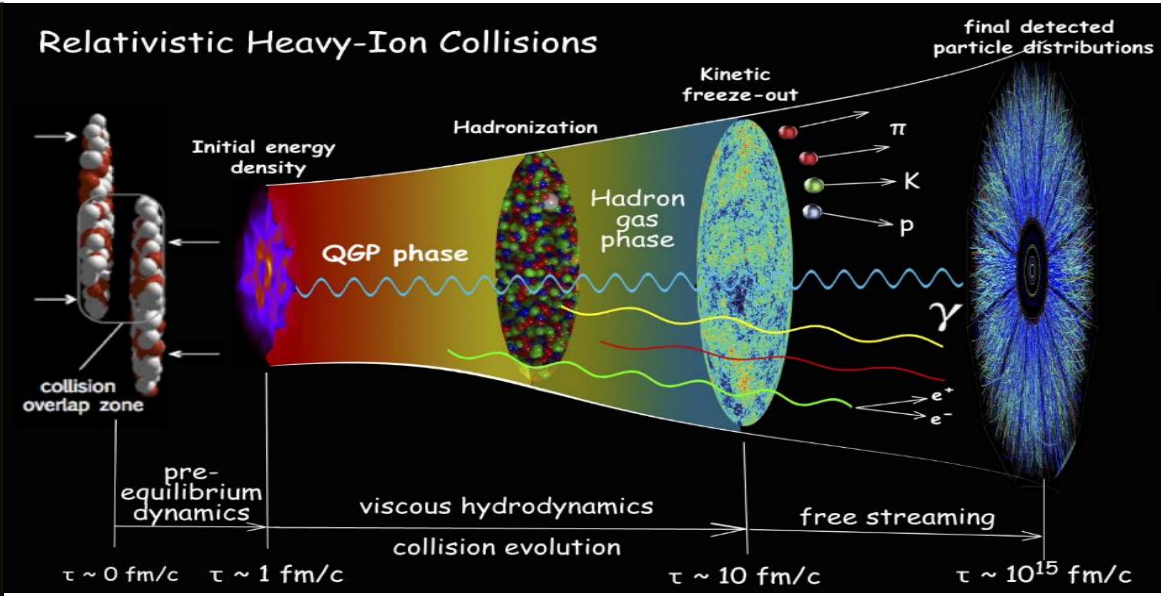
- The acceptance and efficiency of the HGND prototype to projectile spectator neutrons were studied using UrQMD-AMC and DCM-QGSM-SMM models to generate primary collisions.
- The models were validated with GSI data on neutron production in 800A MeV ^{124}Sn + ^{124}Sn reaction.
- Some difference in the multiplicity of spectator neutrons and their energy spectra are found. This difference was used to estimate the systematic uncertainties.
- The average acceptance predicted by two models is $2.94 \pm 0.01_{(stat)} \pm 0.44_{(sys)}$%.
- The average efficiency predicted by two models is $42.94 \pm 0.18_{(stat)} \pm 3.53_{(sys)}$%.

Thank you for your attention!

Backup

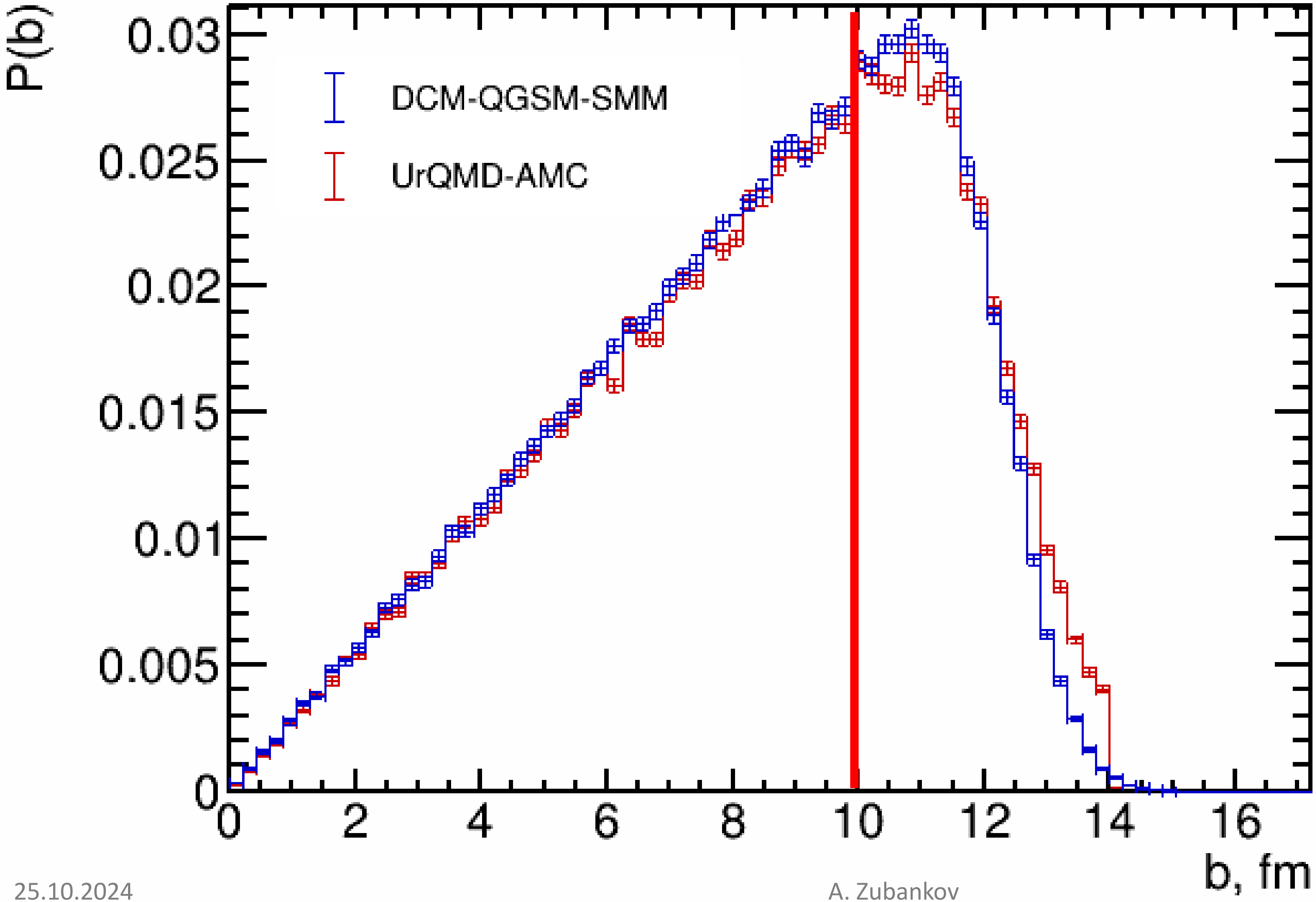
BM@N: studying the properties of dense baryonic matter





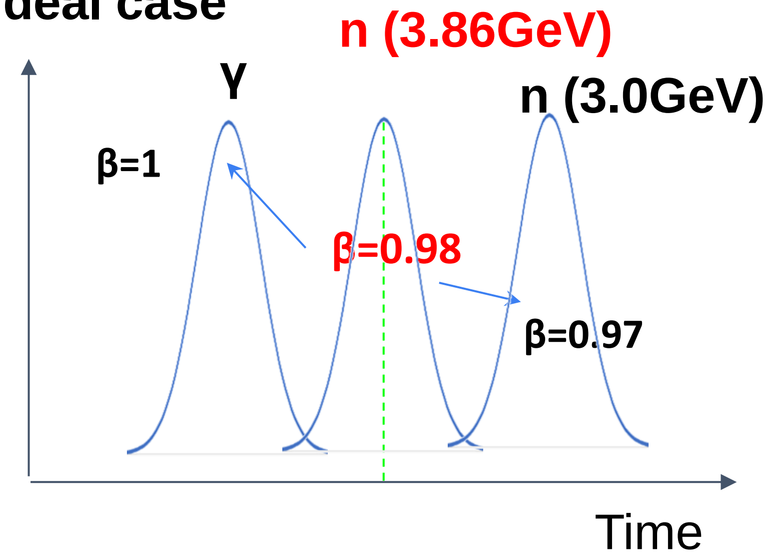
- Study of the QCD diagram at high baryon densities
- Study of the formation of multi-strange hyperons
- Search for hypernuclei in nucleus-nucleus collisions
- Study of the azimuthal asymmetry of charged particle yields in collisions of heavy nuclei.

Impact parameter distribution



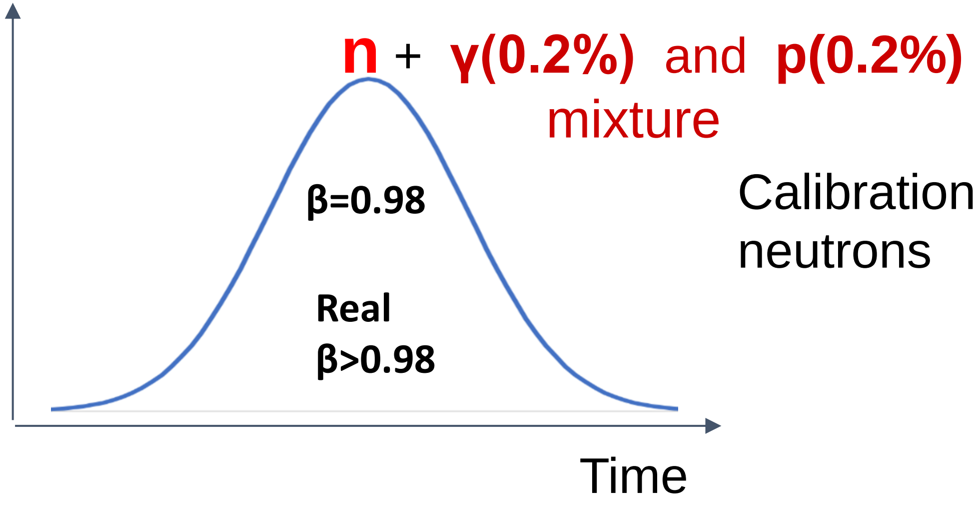
HGND calibration

Ideal case

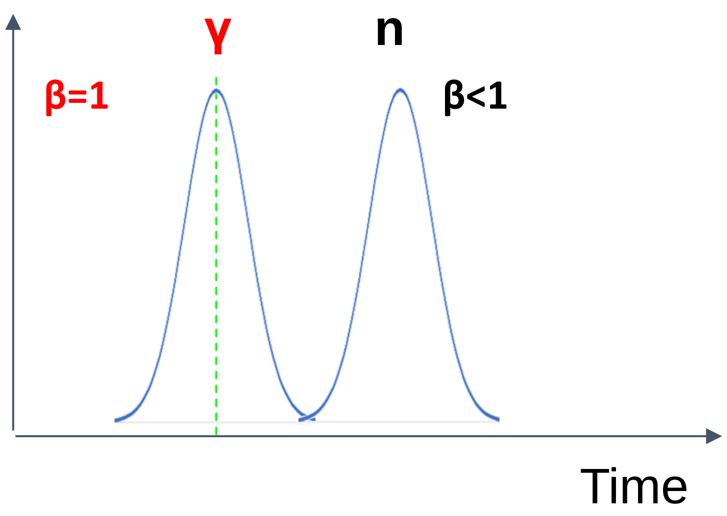


Calibration on neutrons

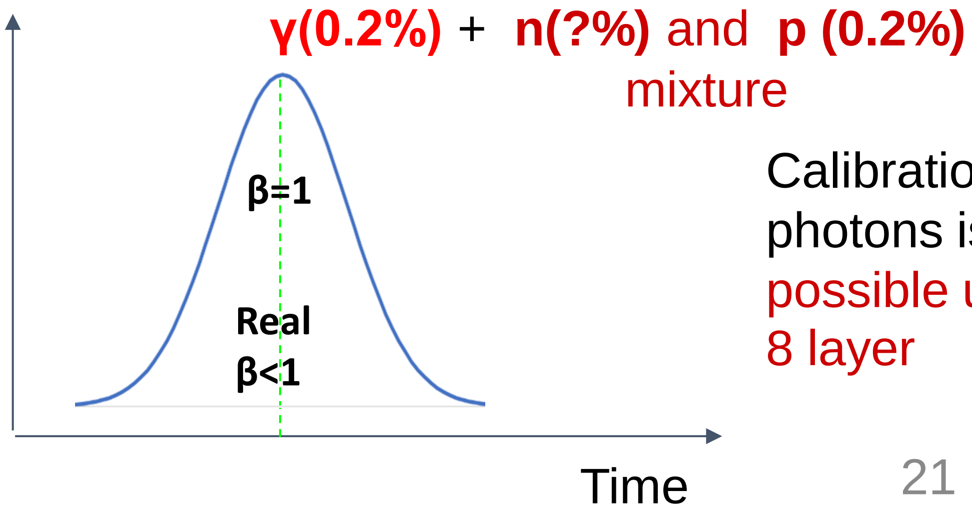
Real data



Calibration on neutrons



Calibration on photons

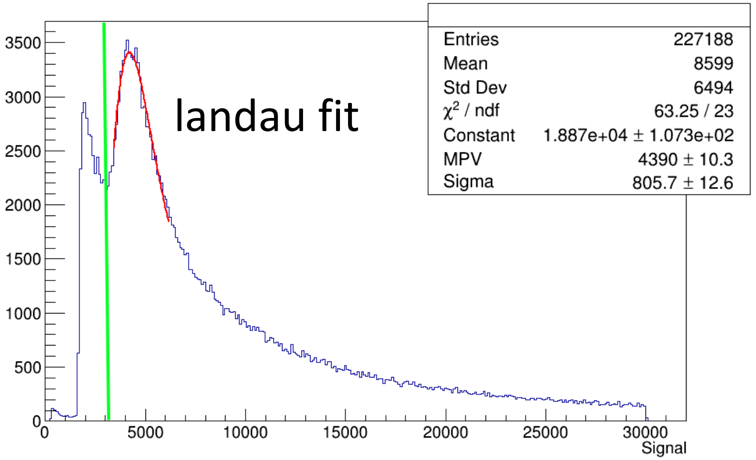


Calibration on photons is possible up to 8 layer

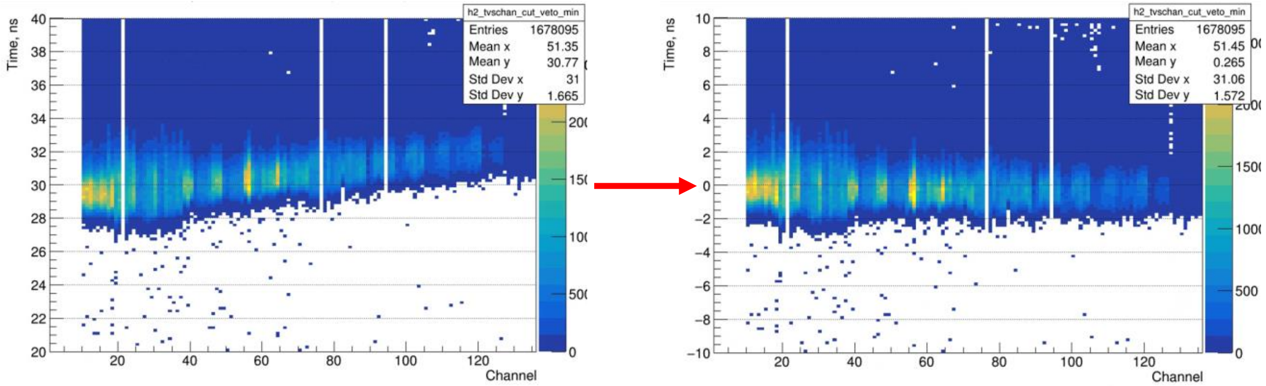
HGND calibration

1. Amplitude normalization

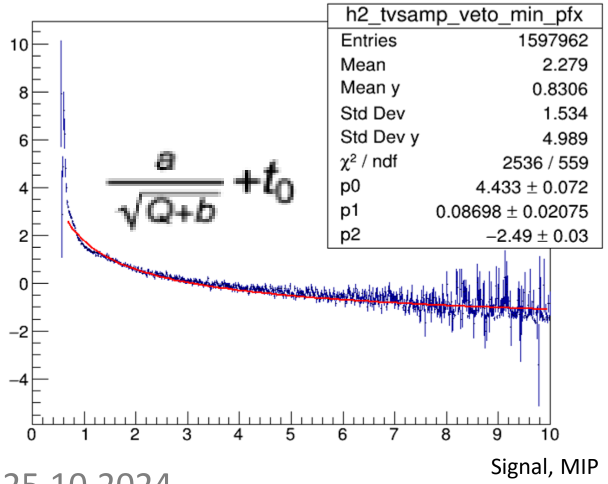
$$Ampl = Ampl \cdot \frac{1}{MPV}$$



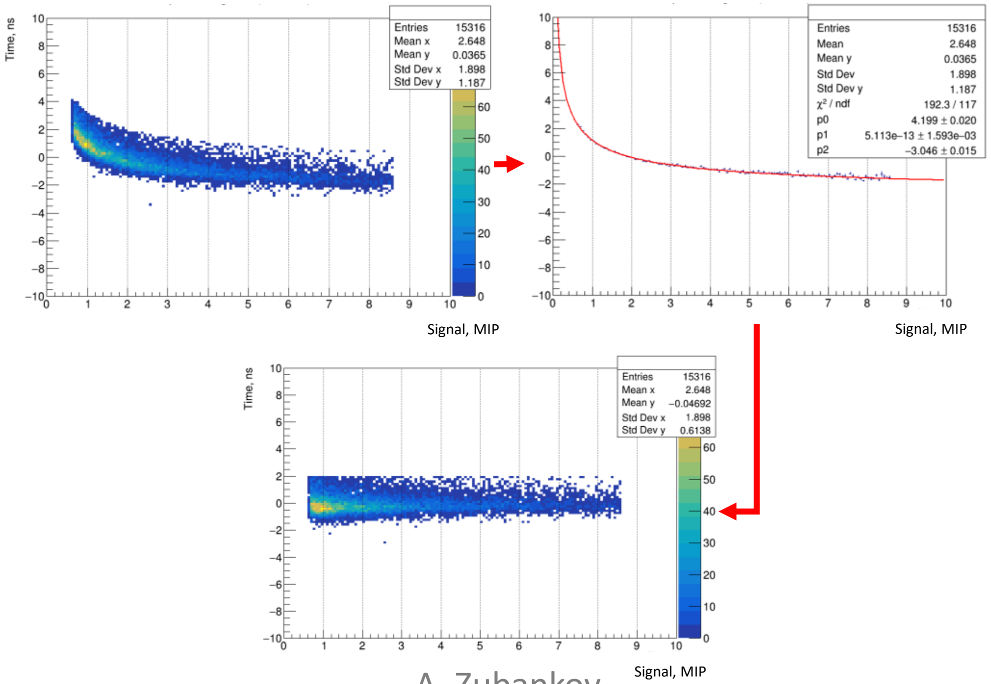
2. Time shift for all channels by the average fit value



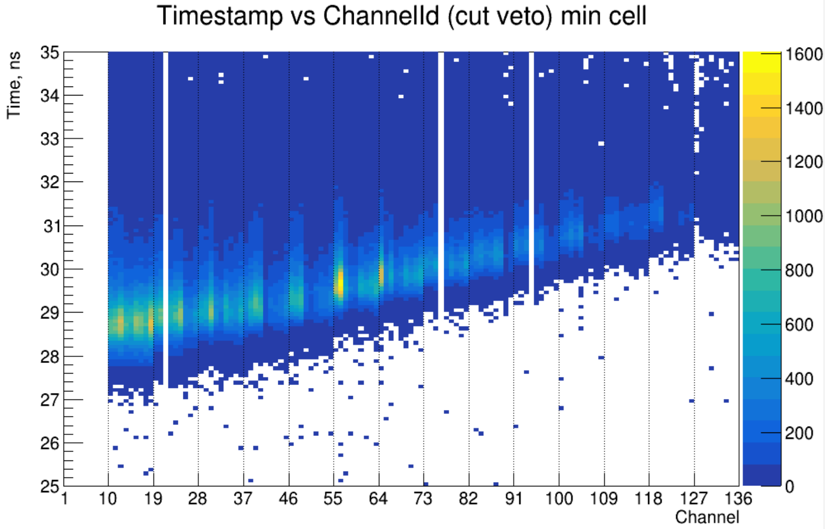
3. Determination of parameters of the approximating function for all channels & time limit



4. Time-amplitude correction

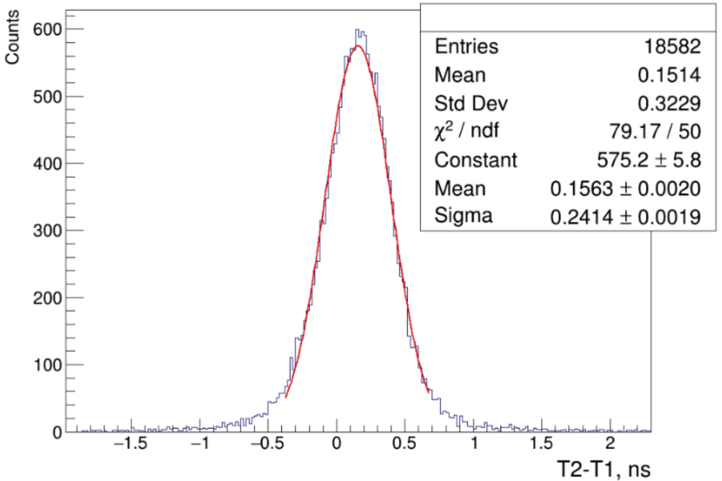


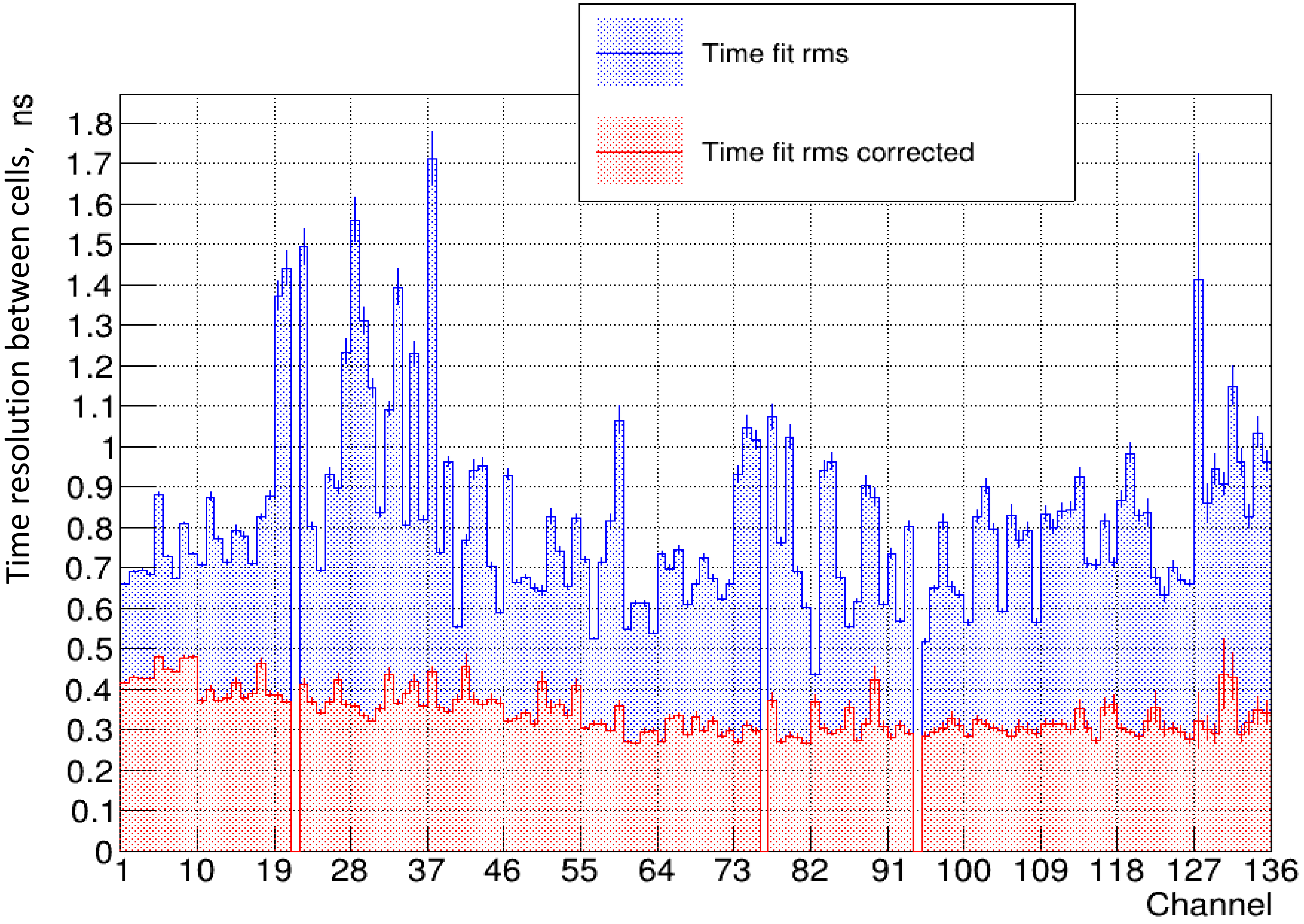
5. Time shift



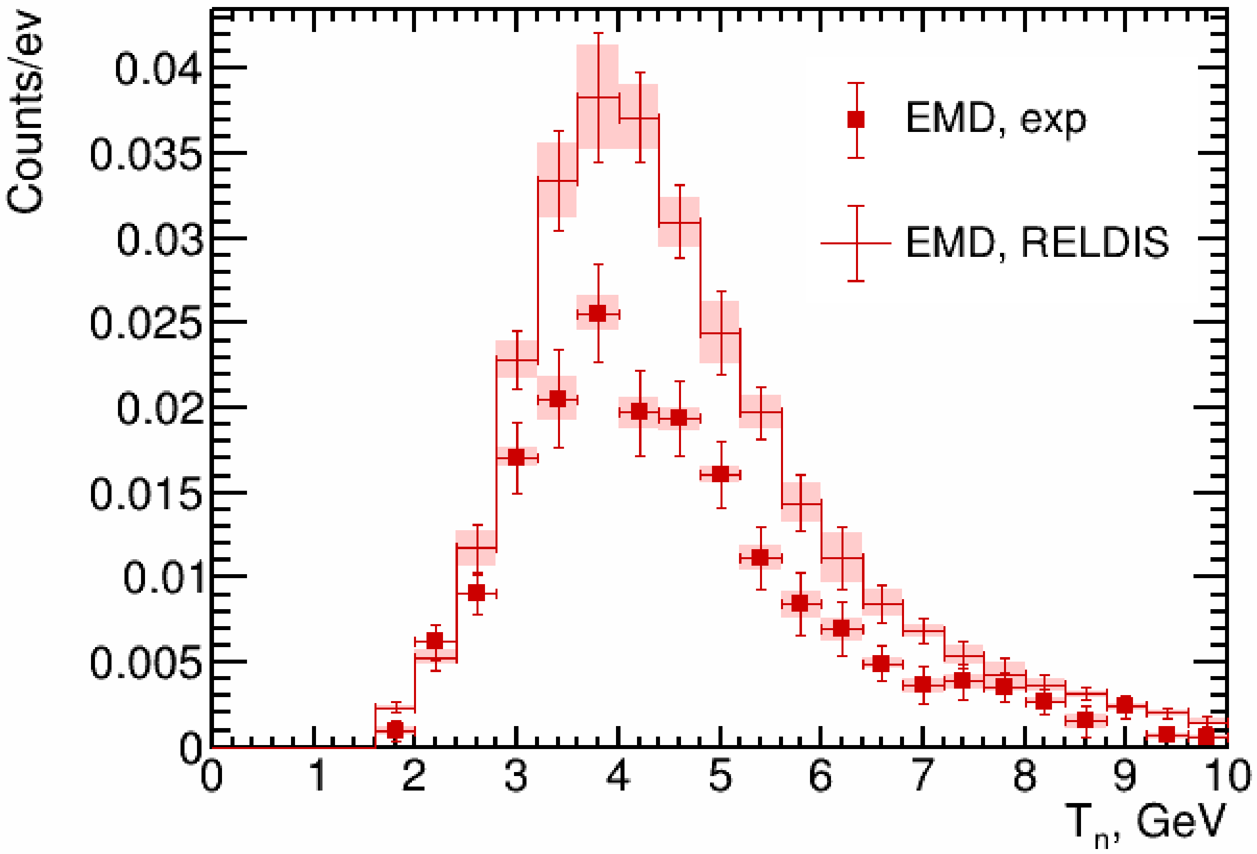
HGND calibration

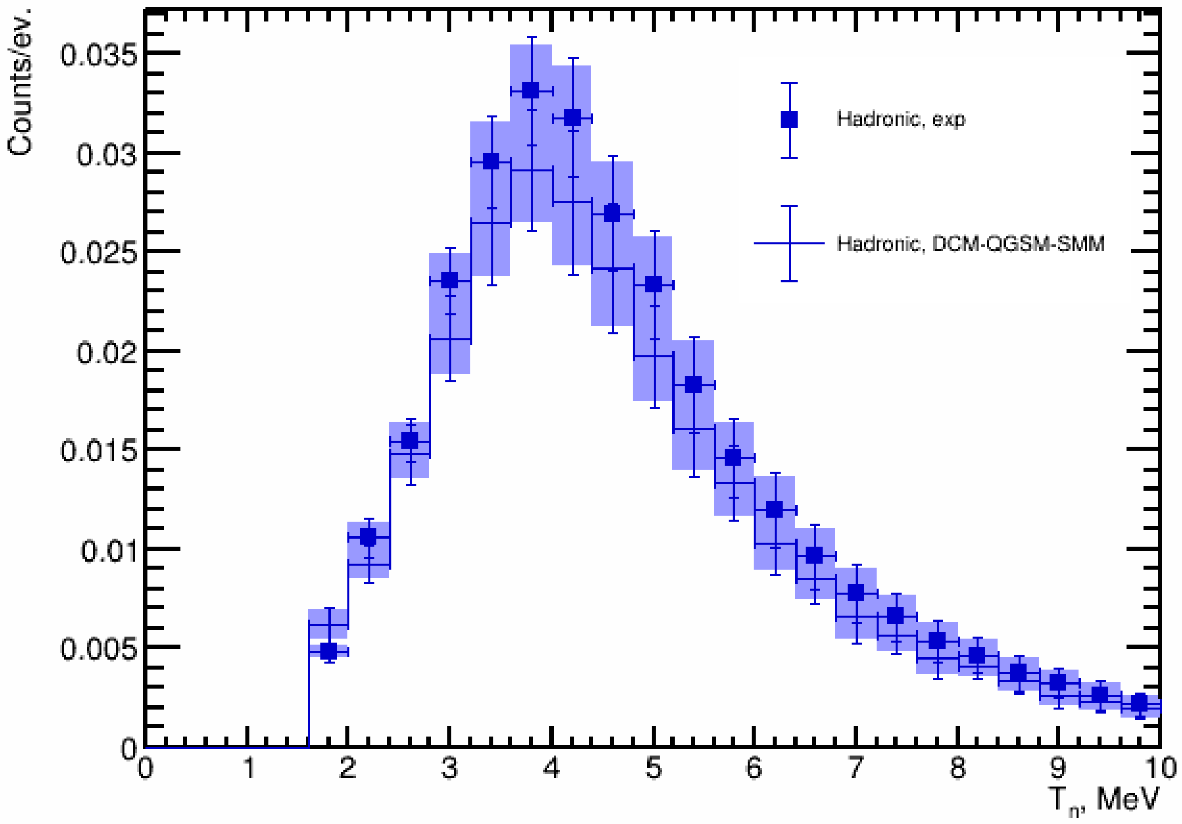
Time-amplitude correction of signals made it possible to get rid of the dependence of time on signal amplitude, which improved the time resolution by ~2.4 times.





EMD vs Nuclear interaction

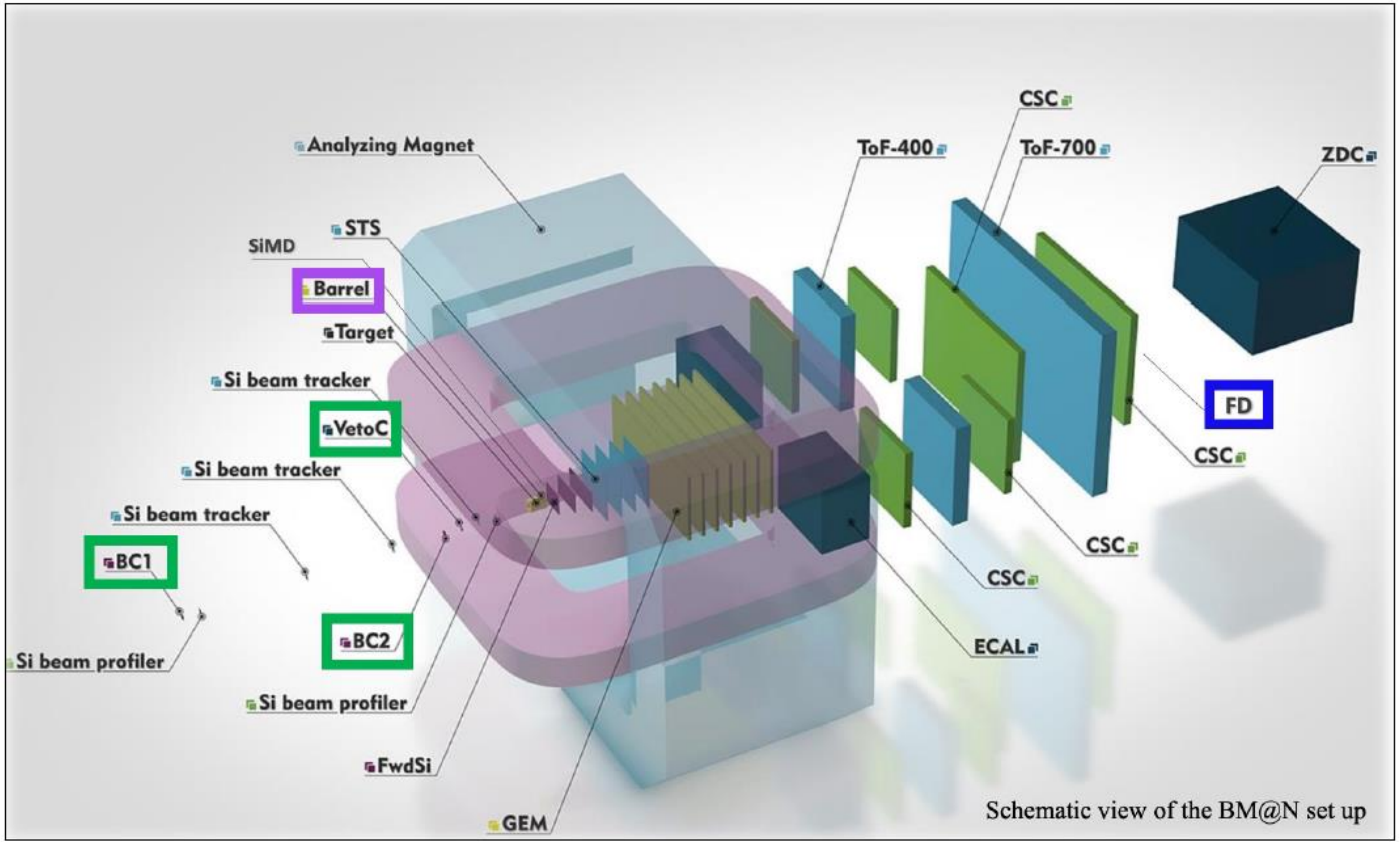




🟢 **BC1, VC, BC2**

🟣 **BD**

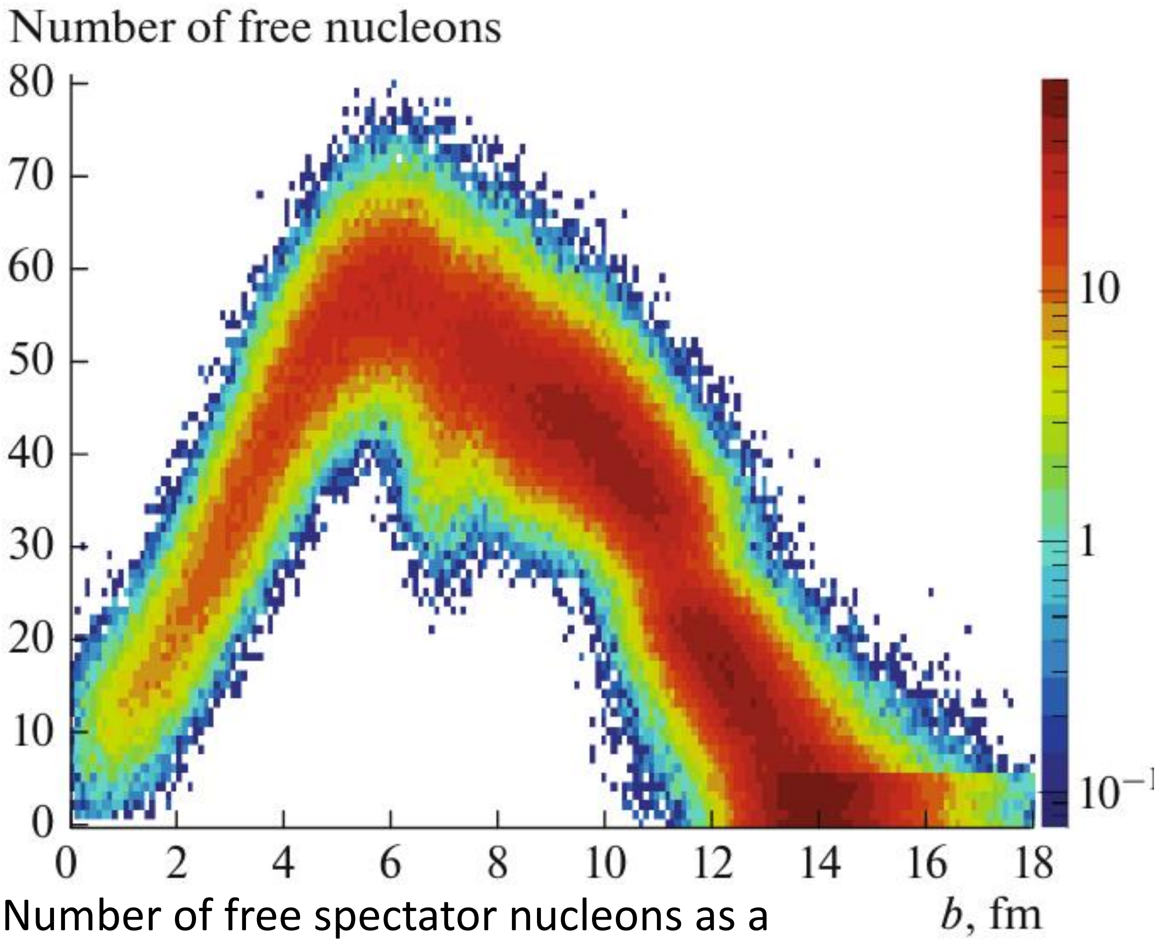
🔵 **FD**



Schematic view of the BM@N set up

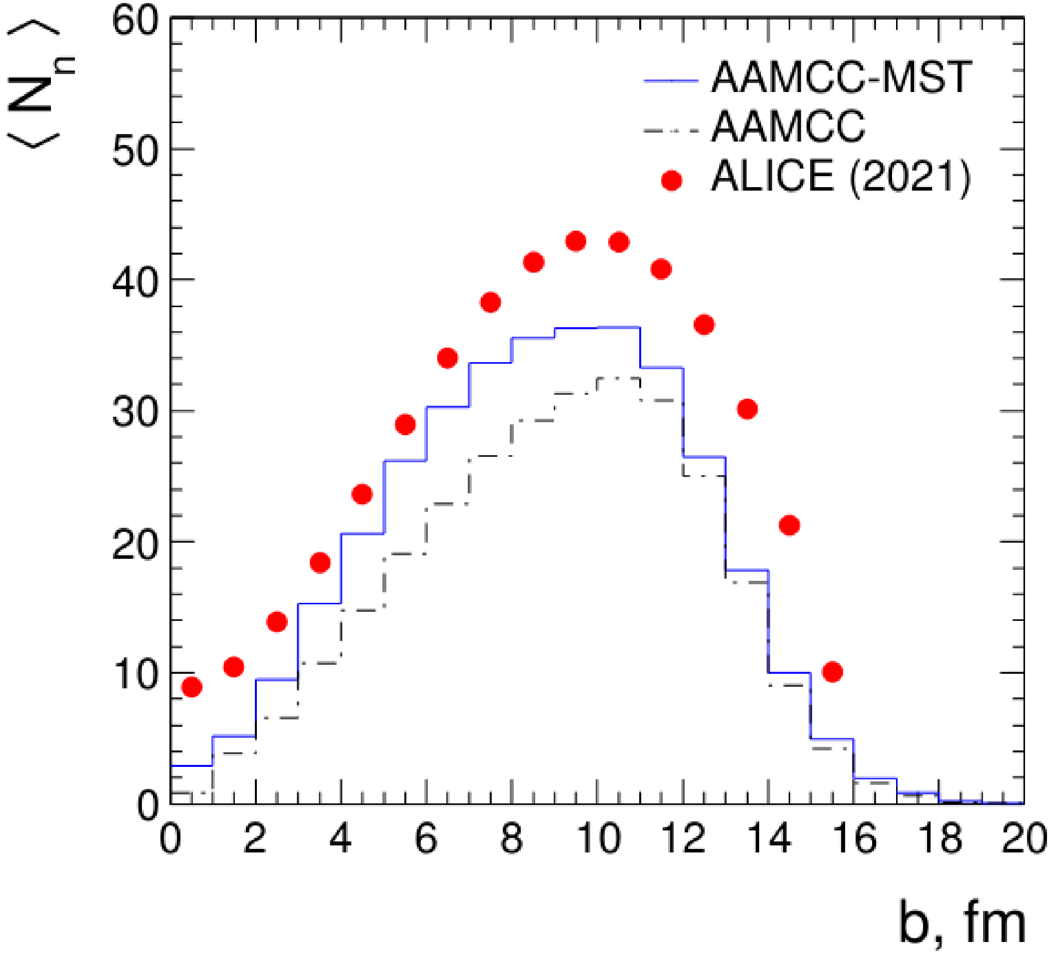
Trigger type	Trigger logic
Beam Trigger (BT)	BT = BC1 * BC2 * !VC
Min. Bias Trigger (MBT)	MBT = BT * !FD
Centrality Trigger 1 (CCT1)	CCT1 = BT * BD
Centrality Trigger 2 (CCT2)	CCT2 = MBT * BD

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

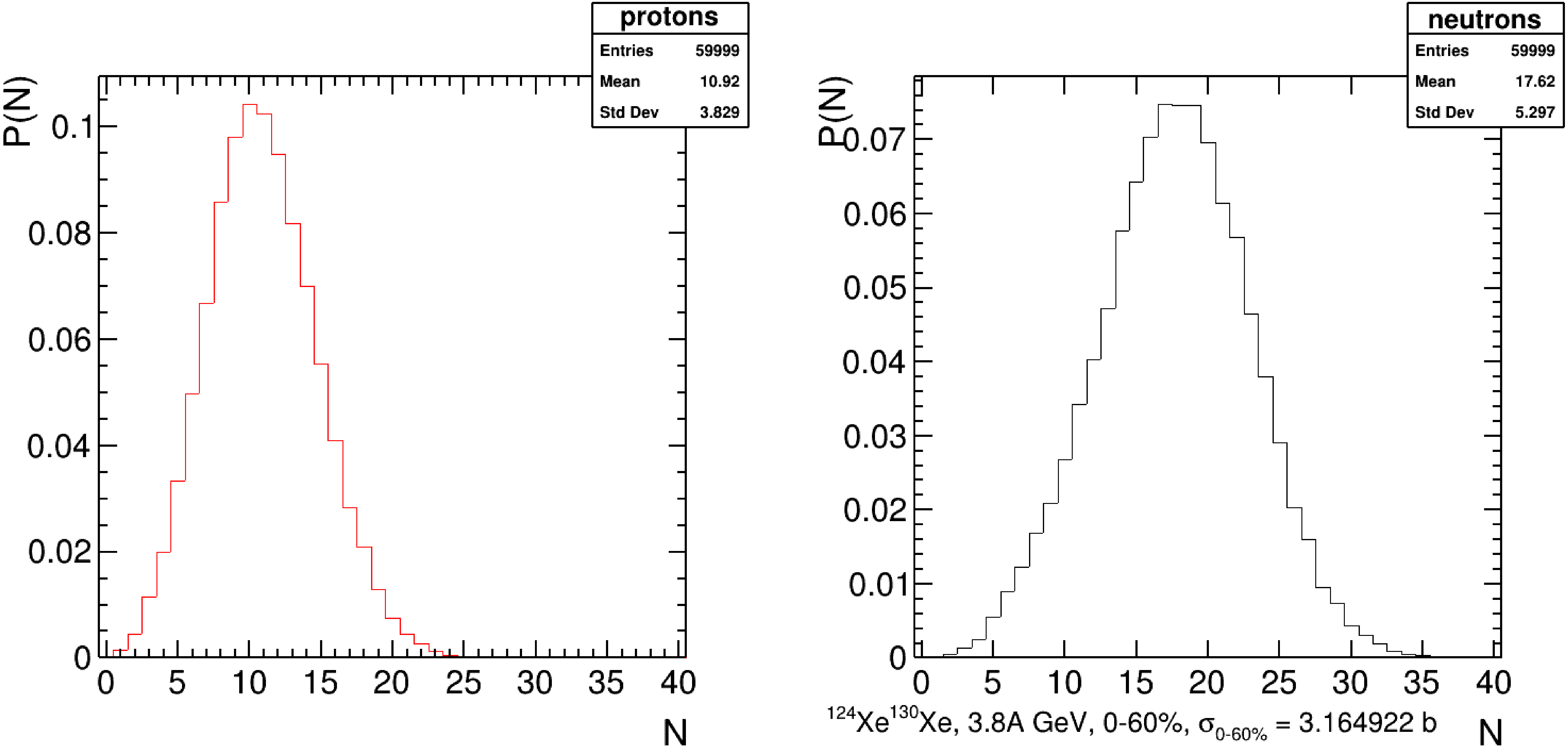
A. Svetlichnyi & I. Pshenichnov, Formation of Free and Bound Spectator Nucleons in Hadronic Interactions between Relativistic Nuclei. *Bulletin of the Russian Academy of Sciences: Physics* **2020**, 84 (8), 911–916.



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

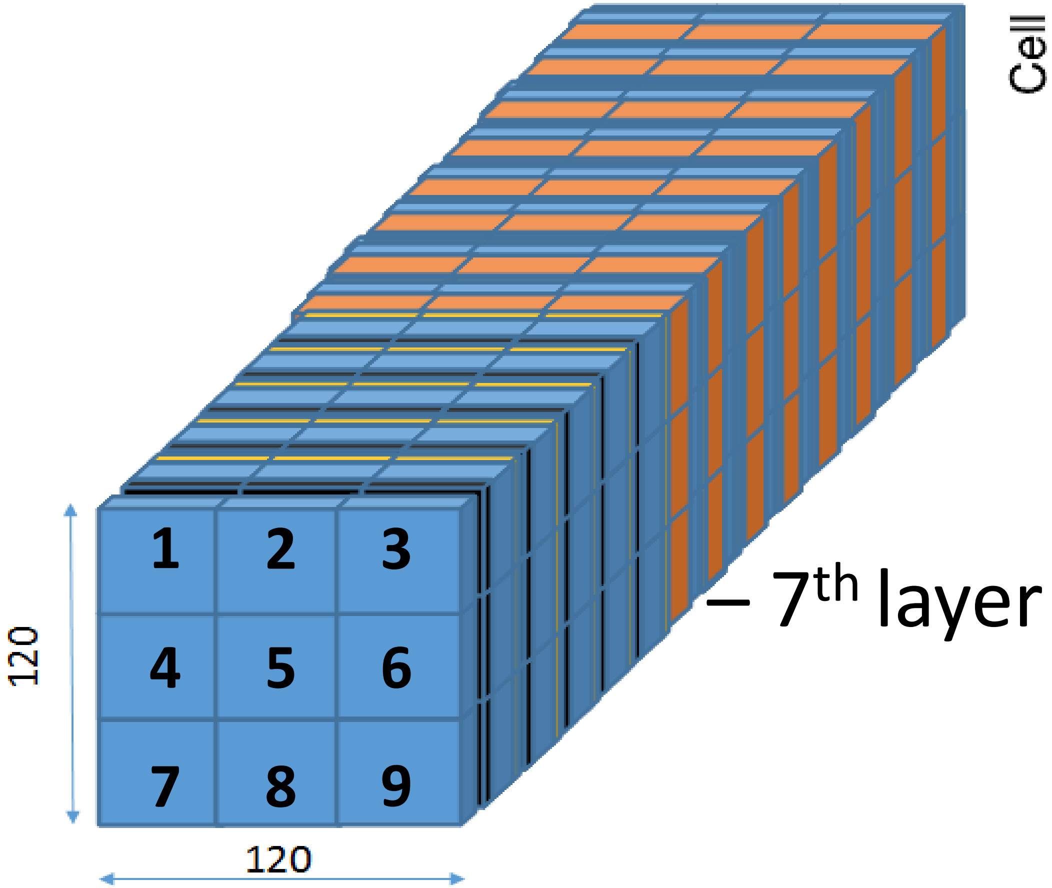
Nepeivoda, R. et al., Pre-Equilibrium Clustering in Production of Spectator Fragments in Collisions of Relativistic Nuclei. *Particles* **2022**, 5, 40–51.

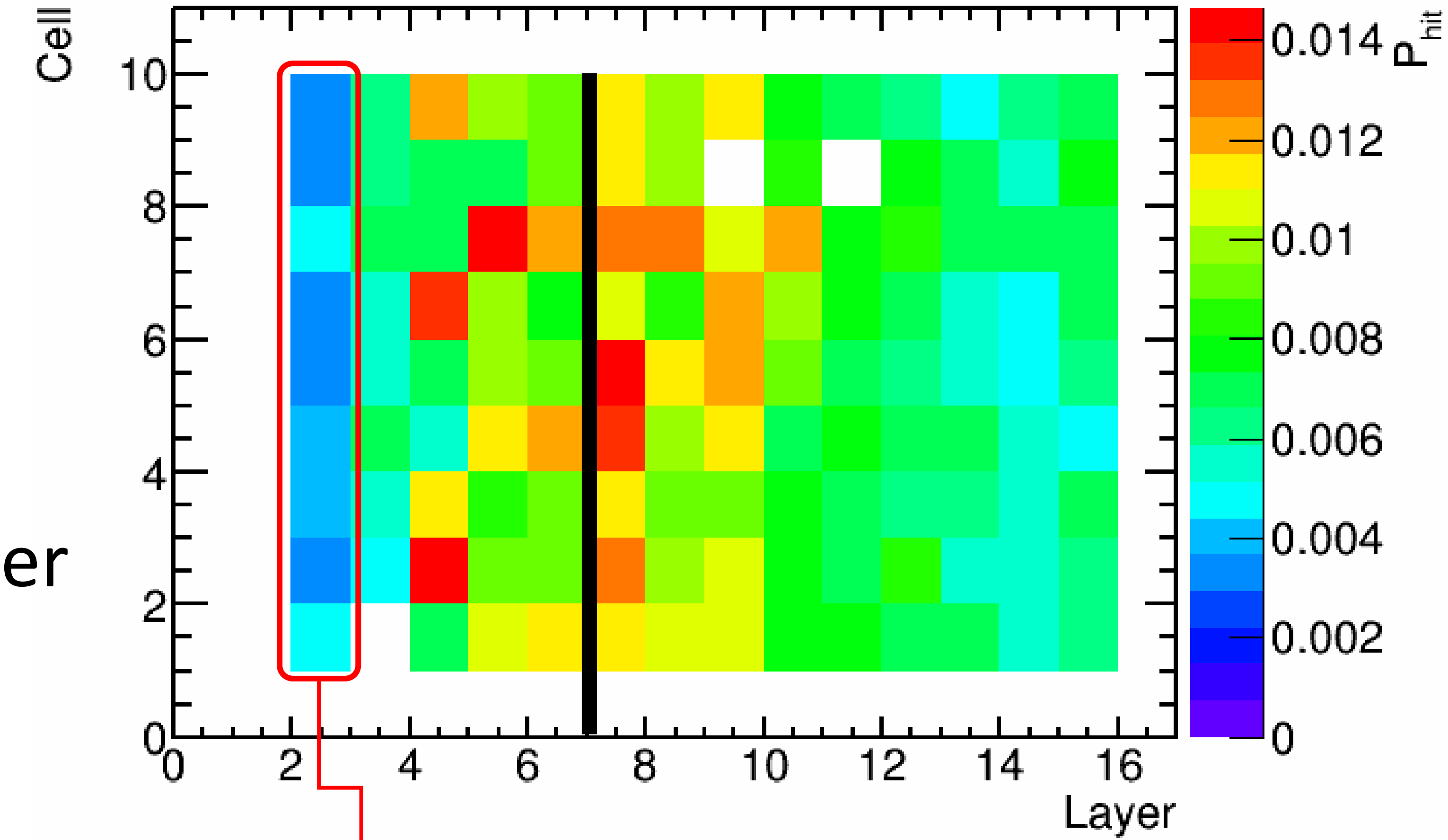
Nuclear interaction



^{124}Xe^{130}Xe, 3.8A GeV, 0-60%, $\sigma_{0\text{-}60\%}$ = 3.164922 b

Reconstruction of energy by maximum velocity

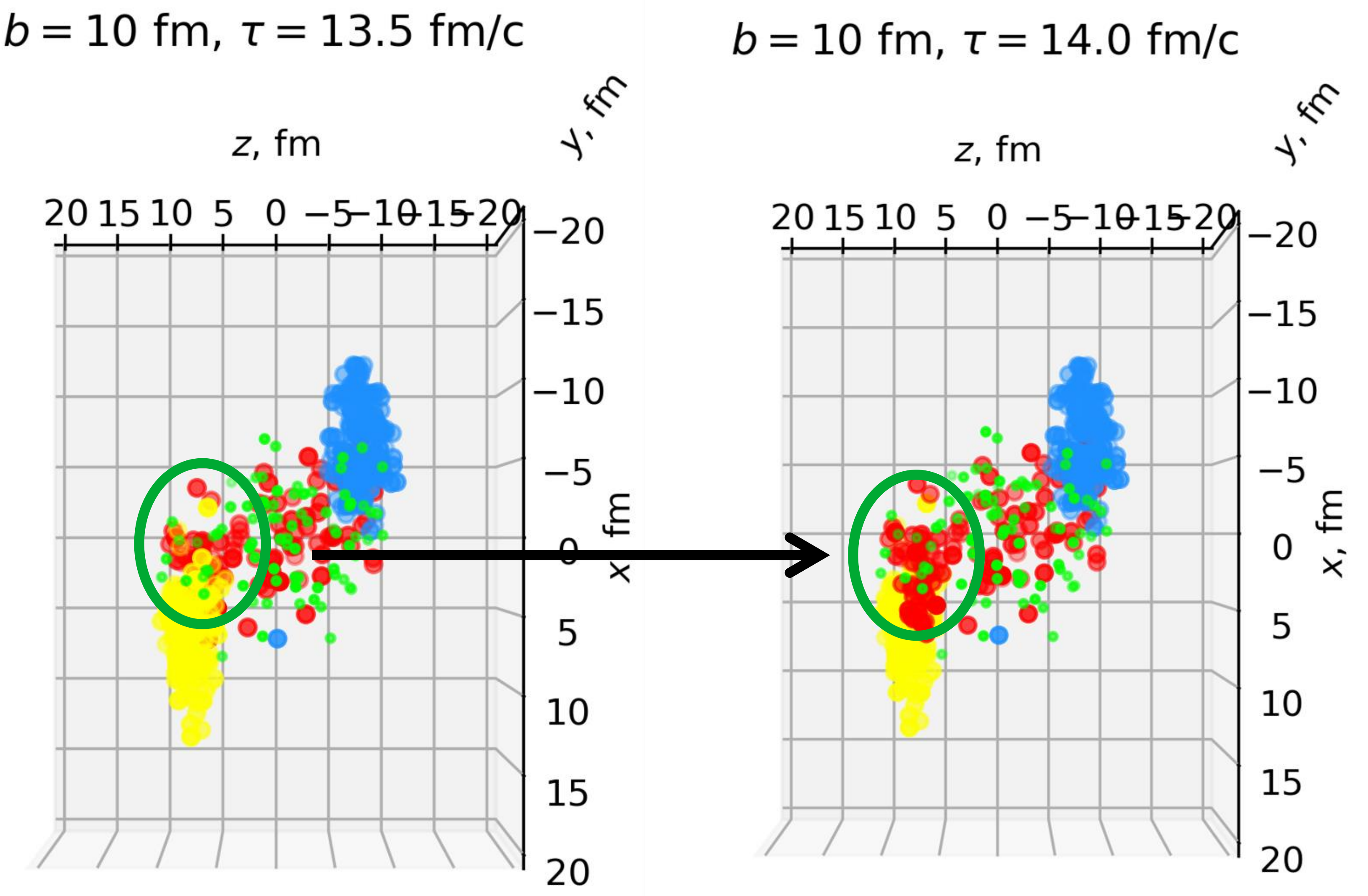




γ-quanta cut – no hits in 1-2 layers in module => 1.55 X_0 or 0.11 λ_{int}

Most of the neutrons are deposited after the 7th layer

Knocking out some spectator nucleons by mesons

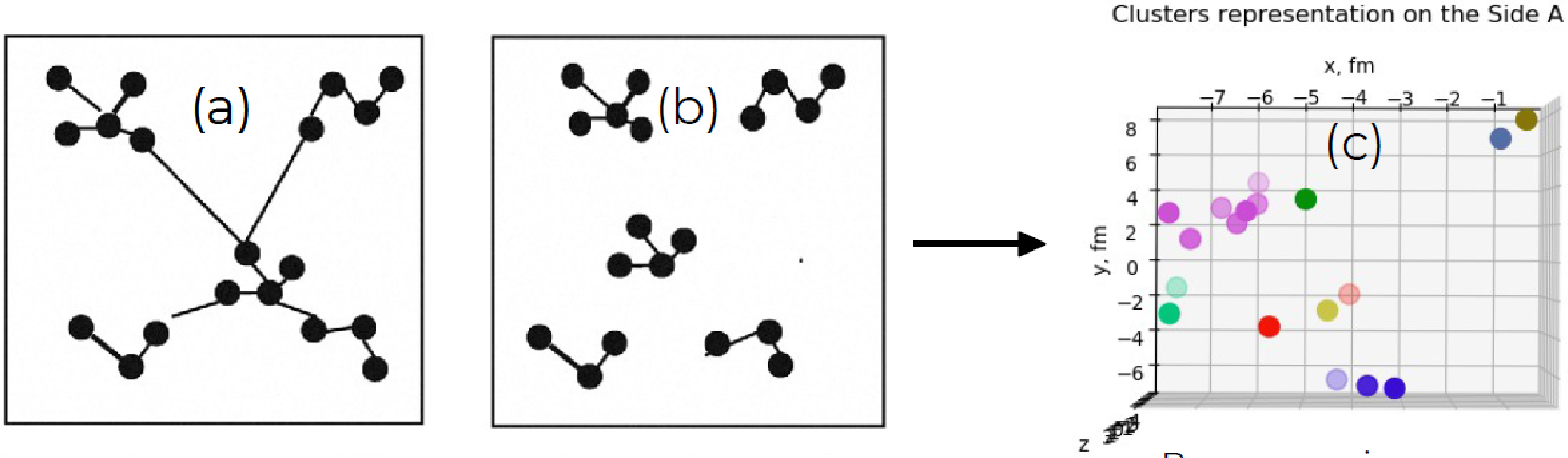


$b = 10$ fm, $\tau = 13.5$ fm/c

$b = 10$ fm, $\tau = 14.0$ fm/c

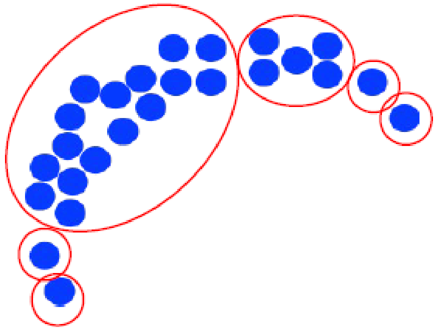
Blue and yellow – spectator nucleons, red – participant nucleons, green – produced mesons

MST-clustering


Clusters representation on the Side A

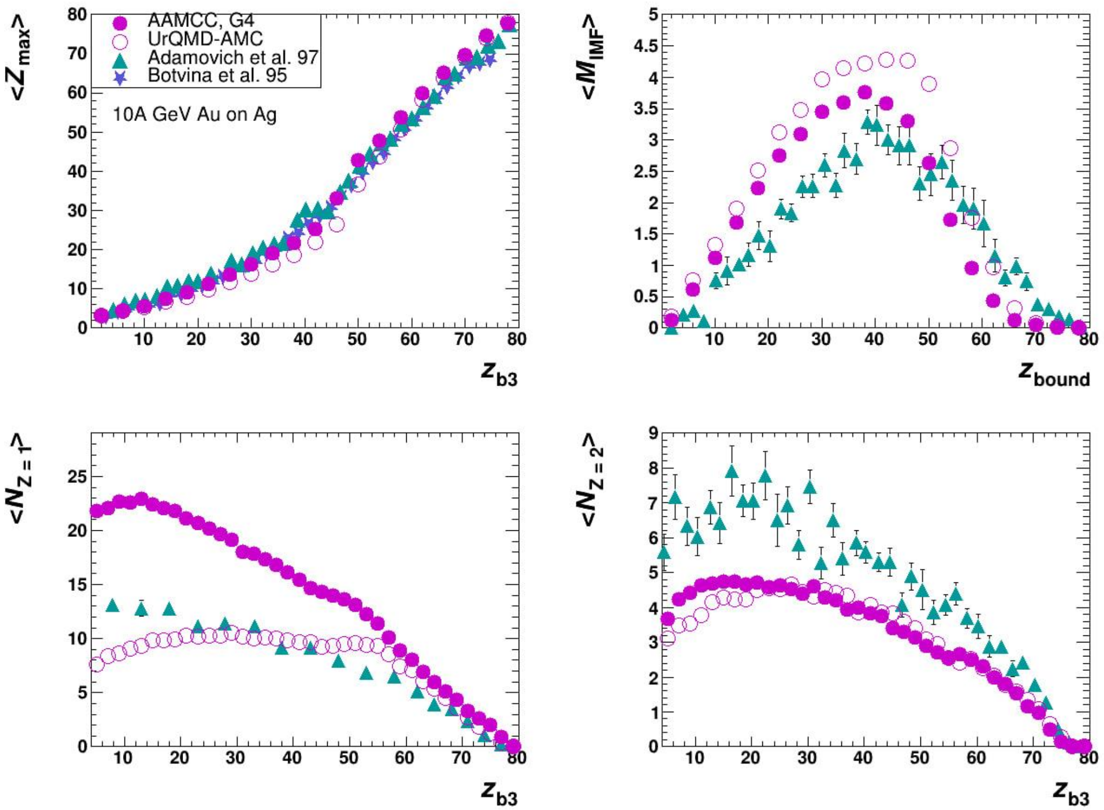
Beam-eye view

- Graph vertexes – nucleons, edges weights – Cartesian distances between them.
- **(a)** The minimum spanning tree is selected from the complete graph
- **(b)** All edges with a weight greater than d are removed. d is the clustering parameter depending on the excitation energy
- **(c)** Connectivity components are separate (pre-)fragments


Prefragments in a central collision

The prefragment is dynamically divided into several prefragments until thermodynamic equilibrium is reached.

^{197}Au fragmentation



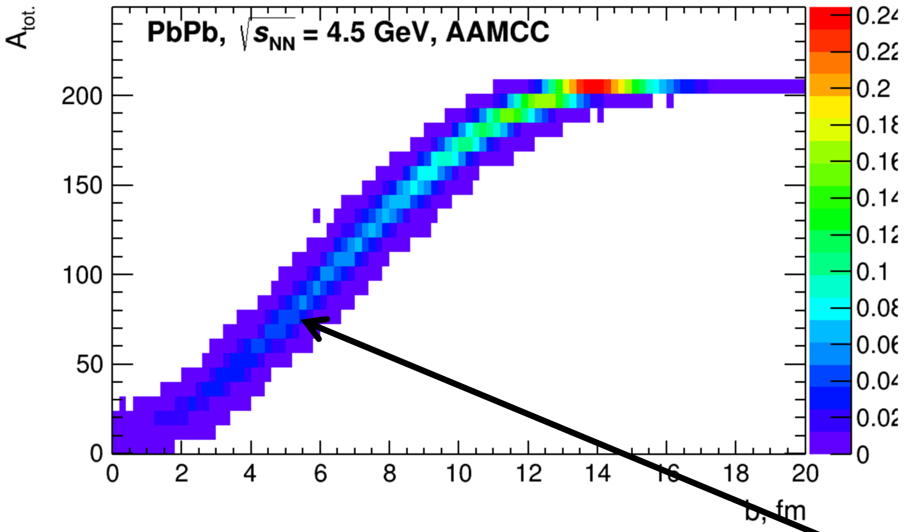
- UrQMD-AMC and AAMCC describe Z_{max}. Models give similar numbers of He

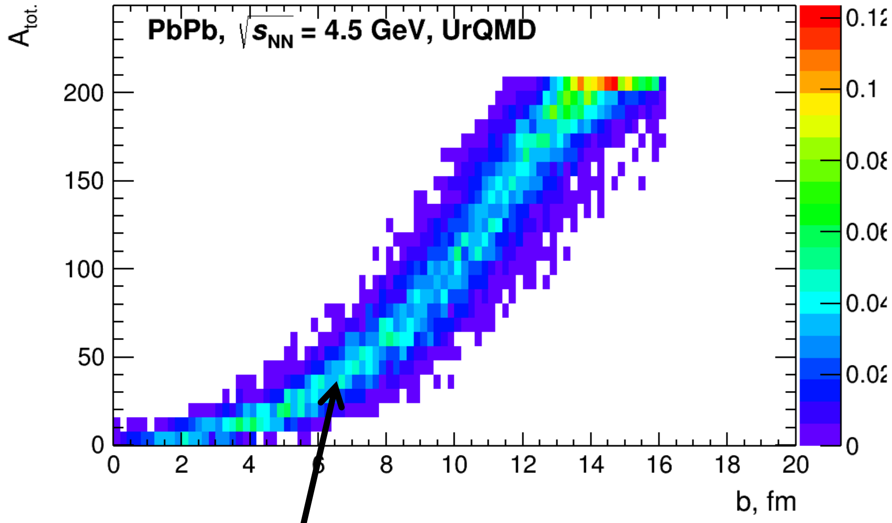
- UrQMD-AMC is systematically lower than AAMCC for $Z_{bound} < 50$. This is due to a smaller spectator volume in UrQMD.

- AAMCC is closer to data on M_{IMF}, while UrQMD-AMC overestimates M_{IMF} in semi-central collisions. This is because of higher excitation energy of prefragments since more nucleons are removed.

- The difference in H fragments can be attributed to the different number of participants, because of a larger contribution of protons from MST-clustering

Spectator matter volume as a function of impact parameter





UrQMD gives less spectators than AAMCC for all b

Abrasion-Ablation Monte Carlo for Colliders

- Abbreviated as AAMCC or A^2MC^2
- Nucleus-nucleus collisions are simulated by means of the Glauber Monte Carlo model 1). Non-participated nucleons form spectator matter (prefragment)
- Excitation energy of prefragment can be calculated via three options:
  - Ericson formula based on the particle-hole model2)
  - parabolic ALADIN approximation3) adjusted to describe the data for light and heavy nuclei
  - Hybrid approximation: a combination of Ericson formula for peripheral collisions and ALADIN approximation otherwise
- Deexcitation is simulated via MST-clusterisation4) accomplished with decay models from Geant45)

1) C. Loizides, J.Kamin, D.d'Enterria Phys. Rev. C **97** (2018) 054910
2) T. Ericson Adv. In Phys. **9** (1960) 737
3) A. Botvina et al. NPA **584**
4) R. Nepeivoda, et al., Particles **5** (2022) 40
5) J. Alison et al. Nucl. Inst. A **835** (2016) 186

github.com/Spectator-matter-group-INR-RAS/AAMCC