Production of spectator neutrons, protons and light fragments on fixed targets at NICA

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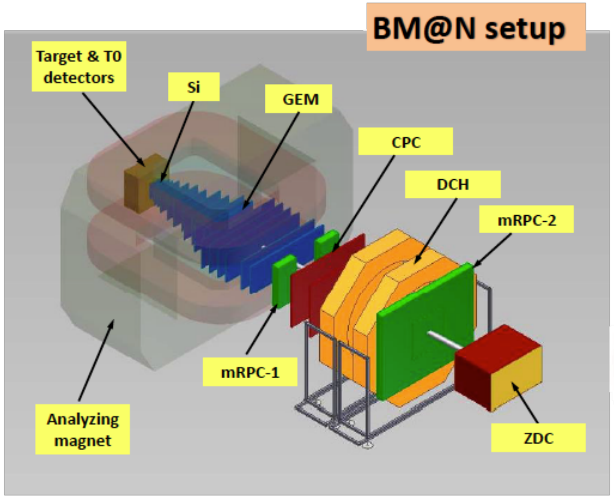
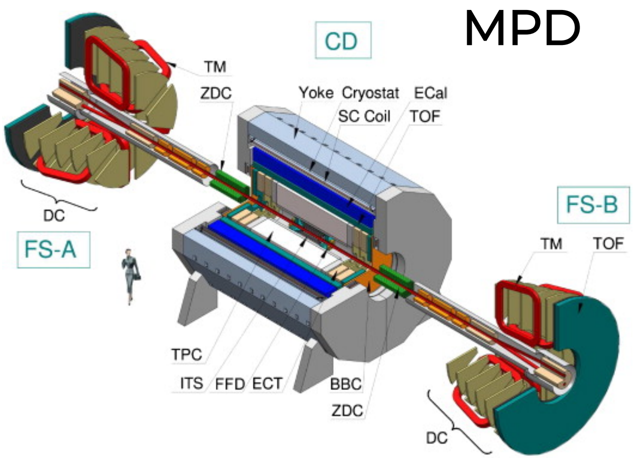
Motivation

- Two experiments at NICA are focused on nucleus-nucleus collision physics: BM@N and MPD. Both experiments can detect forward going particles and fragments.
- Collisions of ^{124}Xe beam with fixed targets are considered as a part of the research program at NICA. The collisions of Xe-CsI has been studied at BM@N and Xe-W are considered at MPD.
- So, reliable models are required to simulate the response of the forward detectors of the both experiments.
  - This requires realistic description of the spectator fragments
  - In this work, the UrQMD*) model has been taken as a baseline





*) S. A. Bass et al, Prog. Part. Nucl. Phys. 41 (1998) 225-370

Outline

- UrQMD-AMC: UrQMD to simulate collisions and AAMCC to build and decay spectator fragments
- Comparison of UrQMD-AMC with data on projectile fragmentation
  - 10.6A GeV Au projectile on heavy nuclei of nuclear emulsion
  - 600A MeV ^{124}Sn on ^{124}Sn
- Production of the forward neutrons and protons at Xe-CsI at BM@N and Xe-W at MPD-FXT
- Production of the light spectator nuclei at Xe-CsI at BM@N and Xe-W at MPD-FXT

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 model[2]
  - parabolic ALADIN approximation[3] 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-clusterisation[4] accomplished with decay models from Geant4[5]
- An option with the pre-simulated collisions is available via reading of MCini file.

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

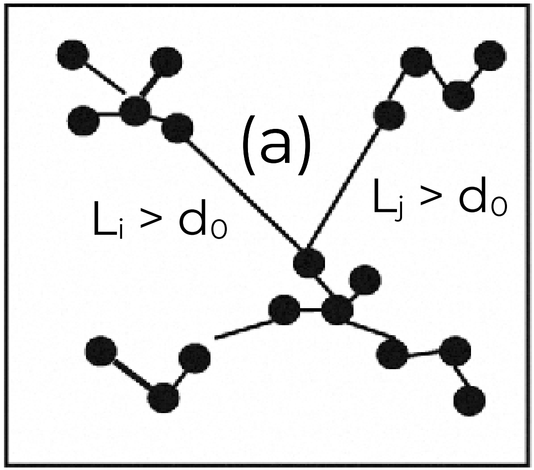
Abrasion-Ablation Monte Carlo for Colliders

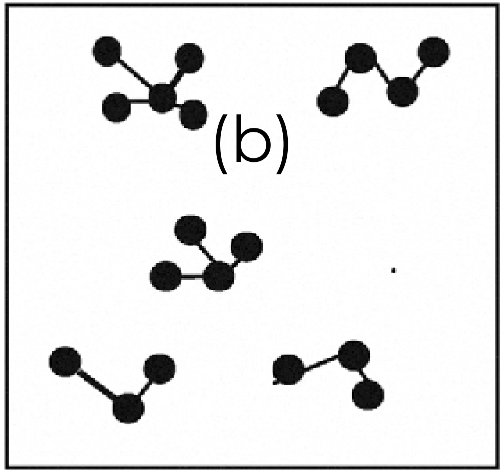
- Decays of prefragments are simulated as follows:
  - pre-equilibrium decays modelled with MST-clustering algorithm [1)]
  - Fermi break-up model from Geant4 v9.2 [2)]
  - Statistical Multifragmentation Model (SMM) from Geant4 v10.4 [2)]
  - Weisskopf-Ewing evaporation model from Geant4 v10.4 [2)]
- They were validated and adjusted to describe the data[3)].
- Deexcitation models can be used independently to simulate secondary decays of prefragments obtained with another model, in particular with UrQMD.
- In this use AAMCC is termed as Ablation Monte Carlo (AMC).

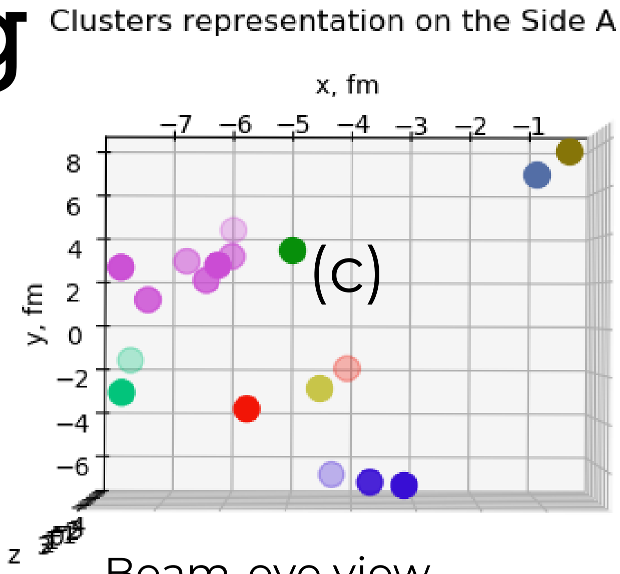
1) R. Nepeivoda, et al., Particles **5** (2022) 40
2) J. Alison et al. Nucl. Inst. A **835** (2016) 186
3) 55th Geant4 Techical Forum
https://indico.cern.ch/event/1106118/contributions/4693132/

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

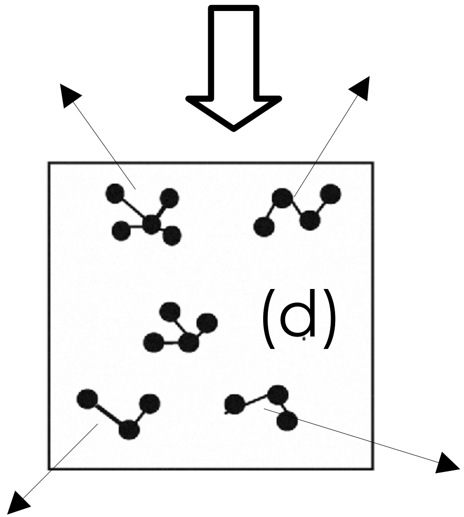
MST-clustering







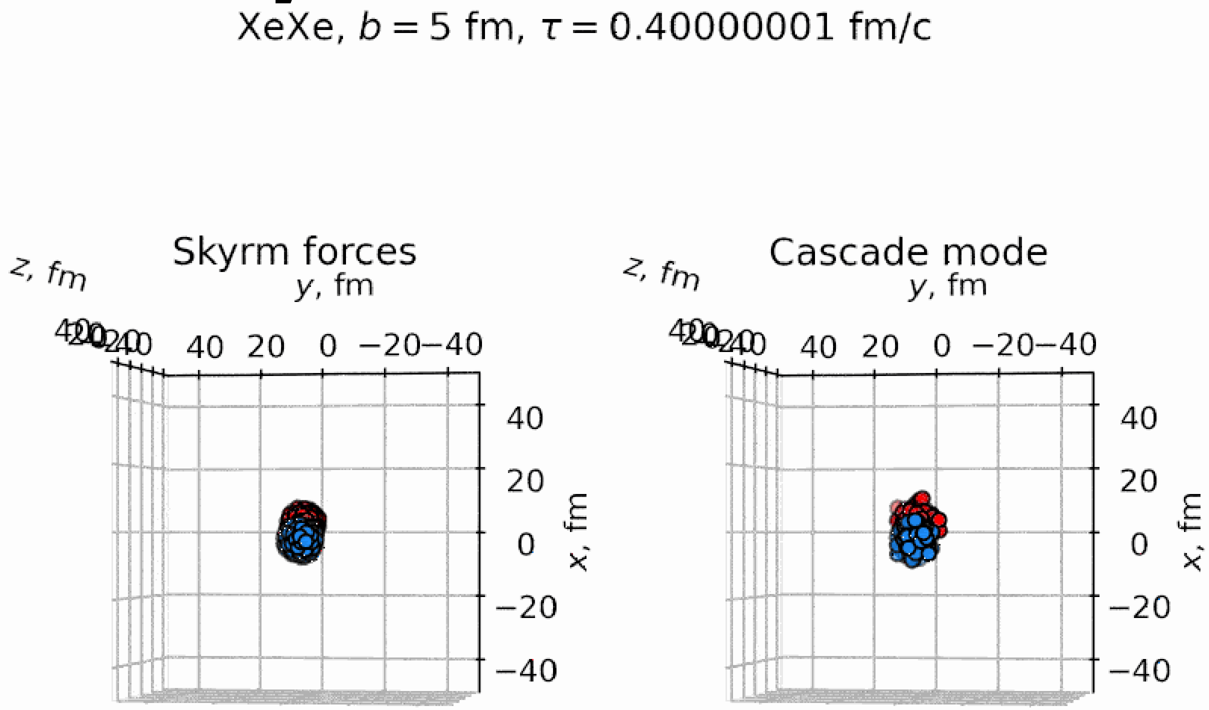
Beam-eye view



- 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 cut-off parameters d_0 are removed.
- **(c)** Connectivity components are separate (pre-)fragments
- **(d)** Separate (pre-)fragments undergo Coulomb repulsion

R. Nepeivoda, et al., Particles **5** (2022) 40
E. Vasyagina, et al., PEPAN Lett., in print

UrQMD: dynamical collision model



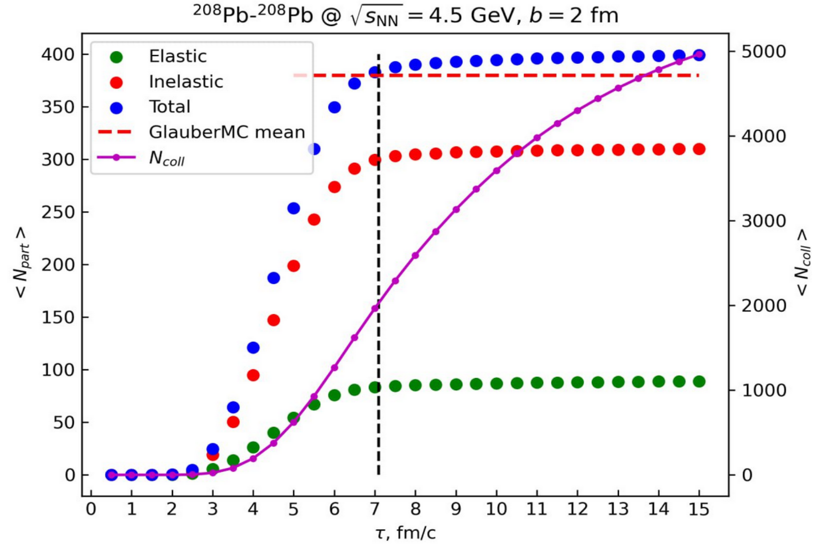
UrQMD provides two options for the calculation: with accounting for the Skyrme forces (Skyrme) and w/o it (Cascade).

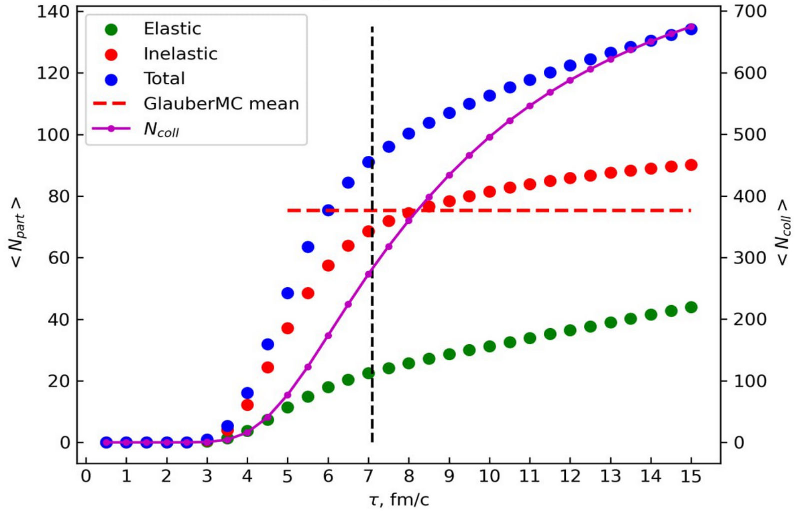
The accounting for the Skyrme forces significantly change the dynamical splitting of the prefragment. Will it change the yields of spectator fragments?

Combining UrQMD and AAMCC

- AMC is developed to simulate secondary decays of spectator fragments from UrQMD.
- MCini output file format adopted in MPD and BM@N is employed.
- It is assumed that spectator matter is formed by the nucleons that do not undergo any collisions.
- As UrQMD simulates the expansion of prefragments we employ MST-clustering with fixed d_0.

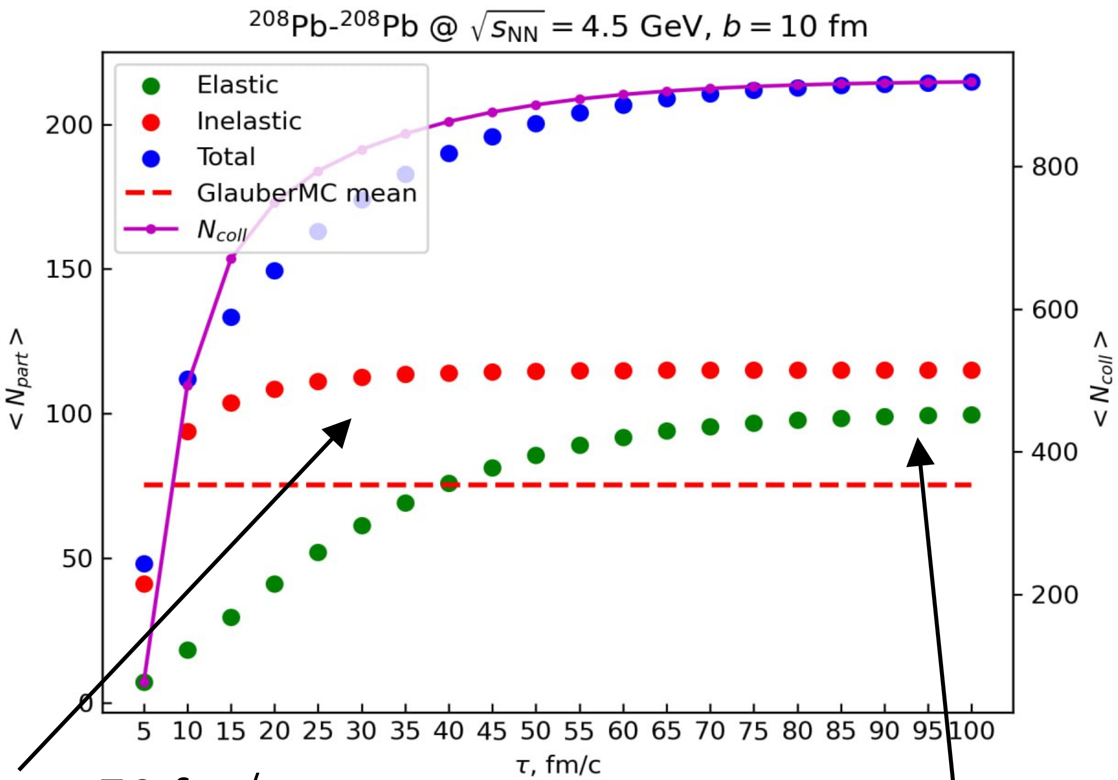
Number of participants in UrQMD as a function of the evolution time





- The average number of collisions continues to rise after the passing time $t_{pass} = 7.1$ fm/c (marked as black vertical line) for both centralities
- For b = 2 fm, this rise is not so significant, and N_{part} reaches saturation at t = 10 fm/c. N_{part} is slightly larger than in GlauberMC just after t_{pass}
- For b = 10 fm, the significant rise of $<N_{part}>$ after t_{pass} is observed. A growing contribution of the elastic collisions is also seen. At t_{pass} inelastic part of $<N_{part}>$ is identical to GlauberMC
- When N_{part} saturates for b = 10 fm?

N_{part} saturates at 80 fm/c



Chemical freeze-out at ~30 fm/c

Kinetic freeze-out occurs much later, at ~80 fm/c

The collision dynamics should be propagated at least until kinetic freeze-out.

Combining UrQMD and AAMCC

UrQMD:

- Version 3.4
- Cascade or Skyrme mode
- Hard sphere nuclear density parametrization
- Evolution time – 100 fm/c
- Other parameters are set to default values

→ MCini file

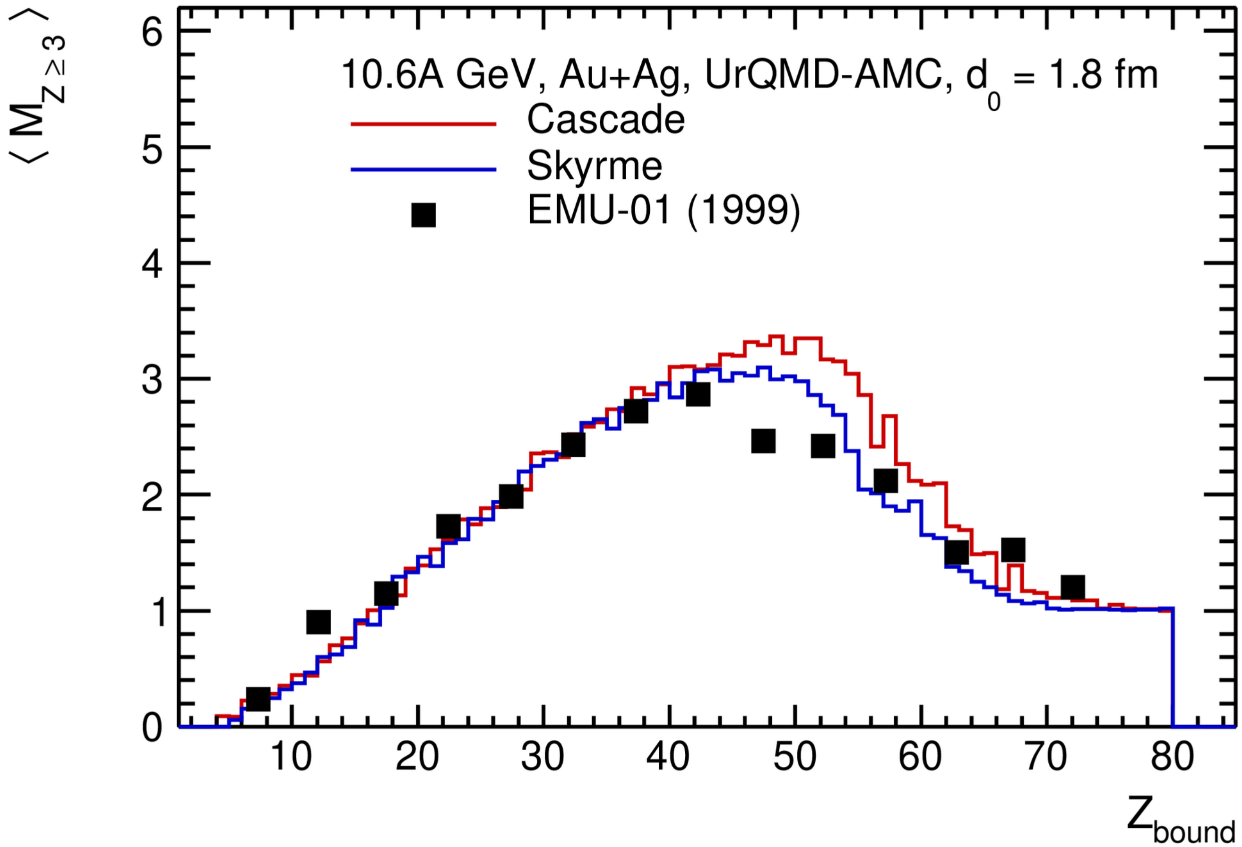
AMC:

- Find spectator nucleons
- Define prefragments via MST-clustering
- Constant $d_0 = 1.8$ fm
- Model prefragments decays
- All the participant data remain intact

→ MCini file

Presently, the pipeline is organized via dedicated bash scripts.
A new pipeline implementation is under development.

^{197}Au fragmentation in nuclear emulsion



Fragmentation events on AgBr were considered

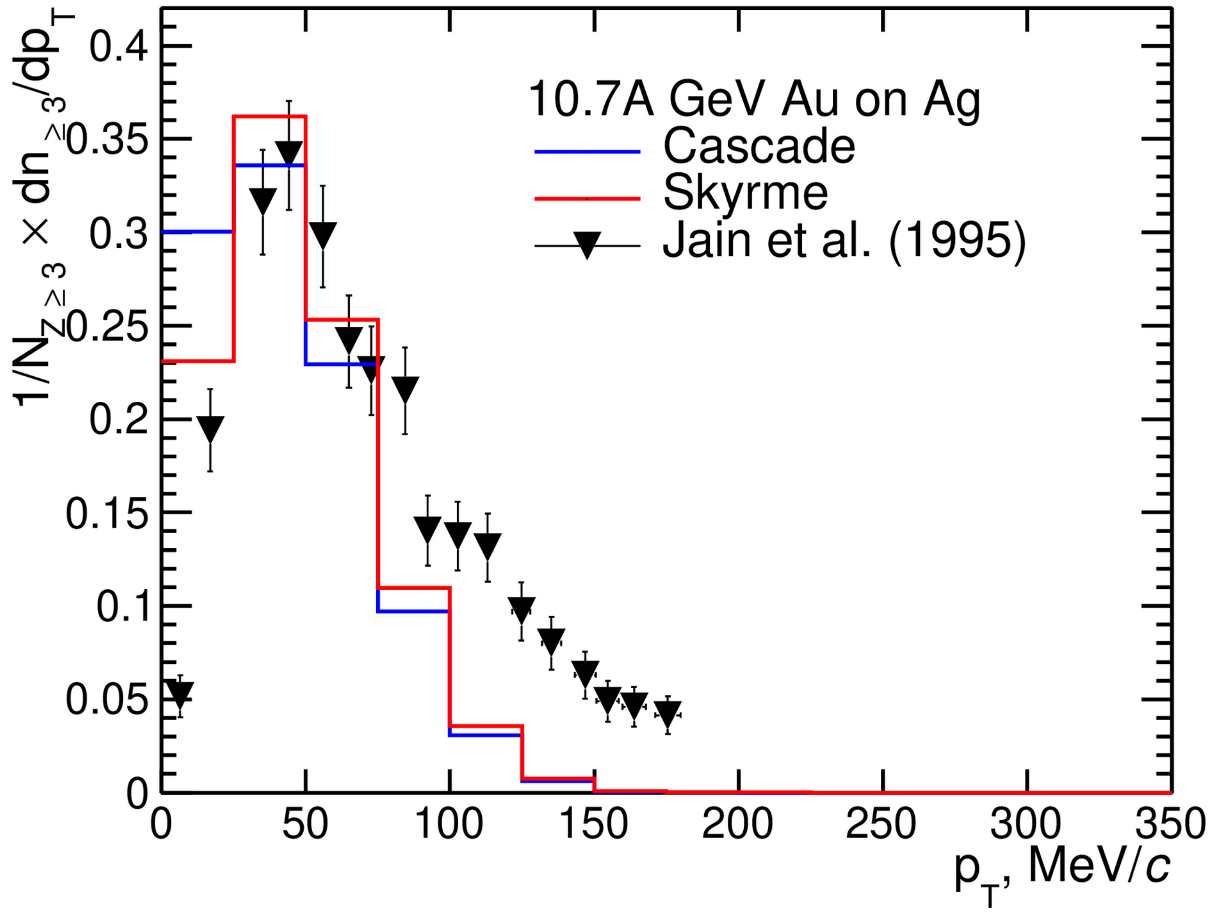
Average multiplicity of fragments with Z ≥ 3 was measured

Z_{bound} – charge bound in fragments with Z ≥ 2

M Adamovich et al (EMU-01 collaboration), Eur. Phys. J. A 5, 429 (1999)

- The UrQMD in cascade mode provides a good description of the data for Z_{bound} < 40, while the date are overestimated otherwise
- Accounting for the Skyrme forces leads to a better description of the data

^{197}Au fragmentation: p_T for fragments

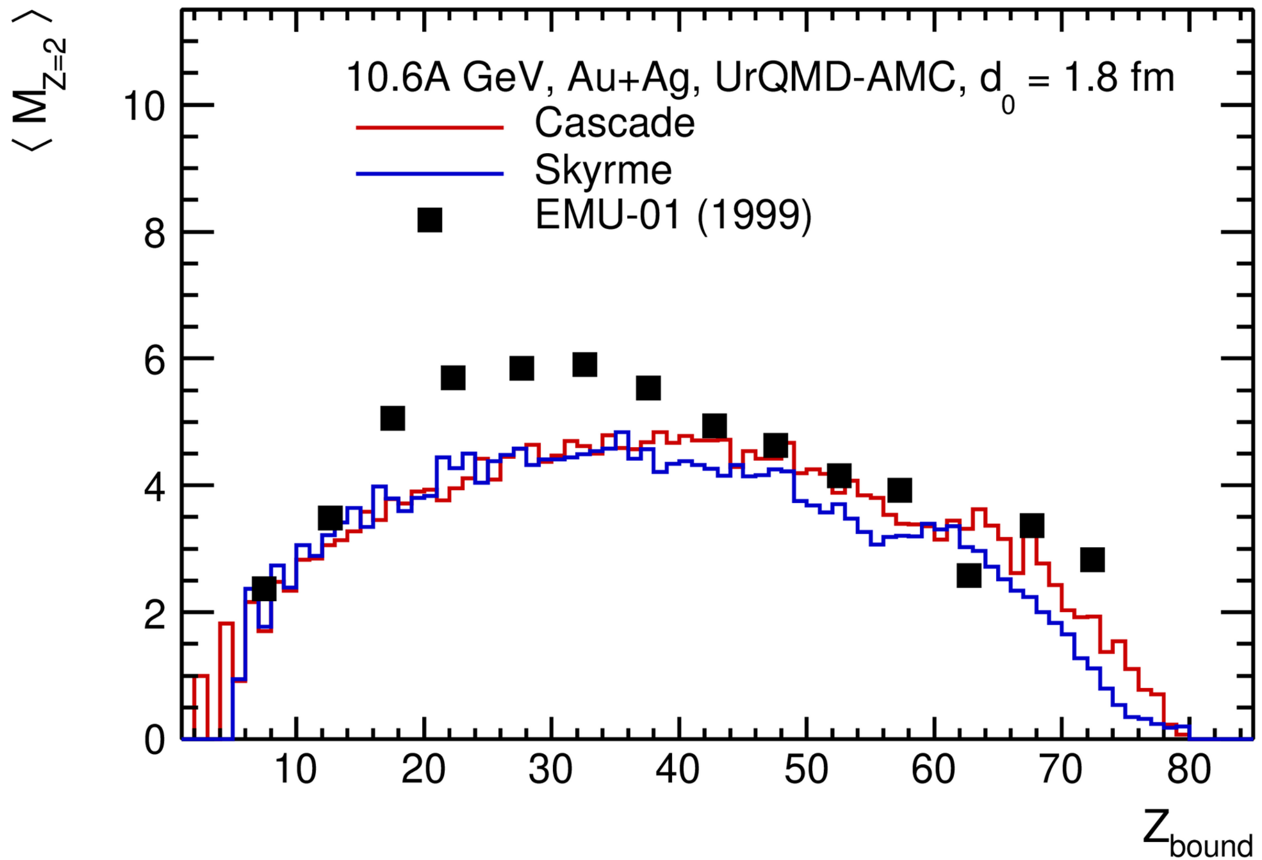


Calculations with Skyrme forces provides a reasonable agreement for intermediate p_T

The bounce-off effect at low p_T is underestimated in the Cascade mode

P. Jain et al Phys. Rev. Lett. 79, 1535 (1995)

^{197}Au fragmentation: He production



Fragmentation events on AgBr were considered

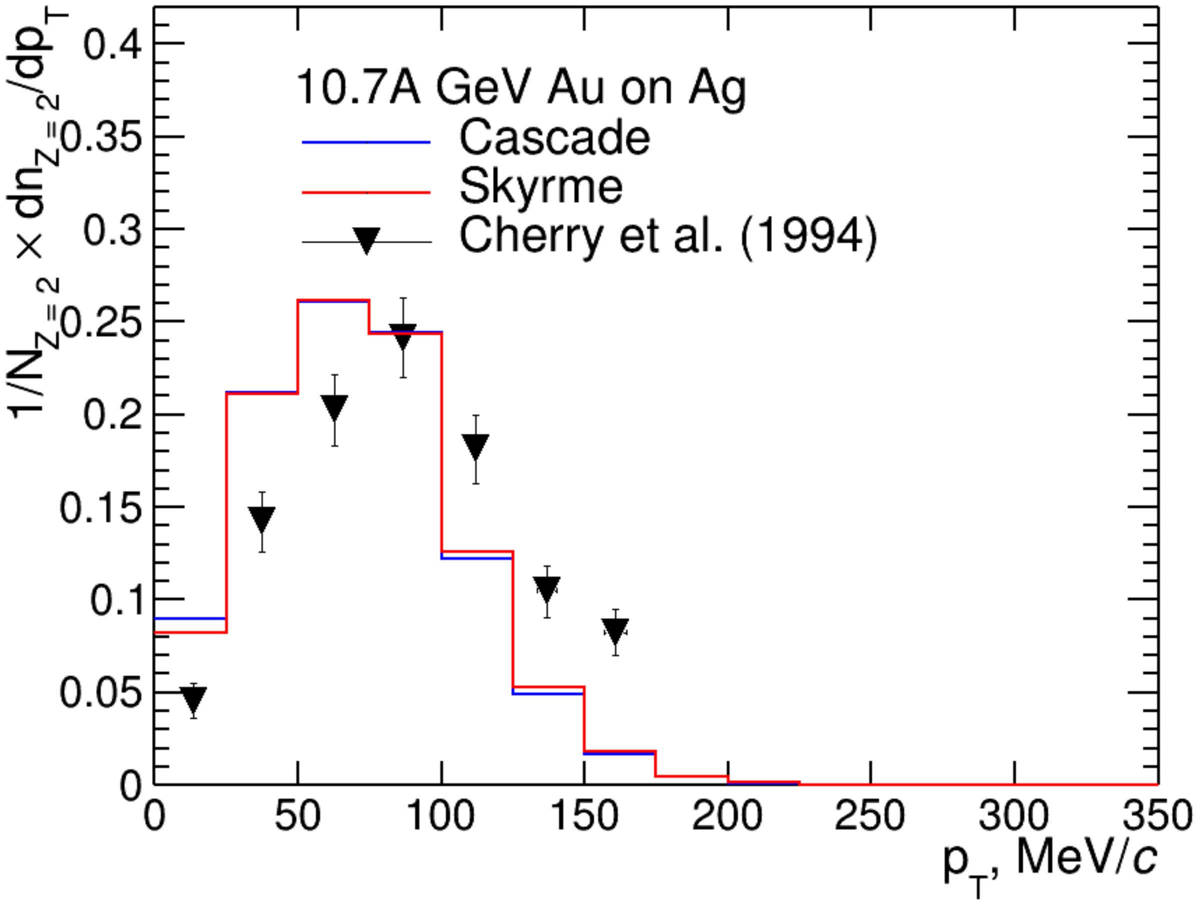
Average multiplicity of helium fragments with Z = 2 was measured

Z_{bound} – charge bound in fragments with Z ≥ 2

M Adamovich et al (EMU-01 collaboration), Eur. Phys. J. A 5, 429 (1999)

- The UrQMD provides a good description of the data for $Z_{bound} < 15$ and $Z_{bound} > 40$, while the data are underestimated otherwise.
- Accounting for the Skyrme forces does not significantly change the $\langle M_{Z=2} \rangle$

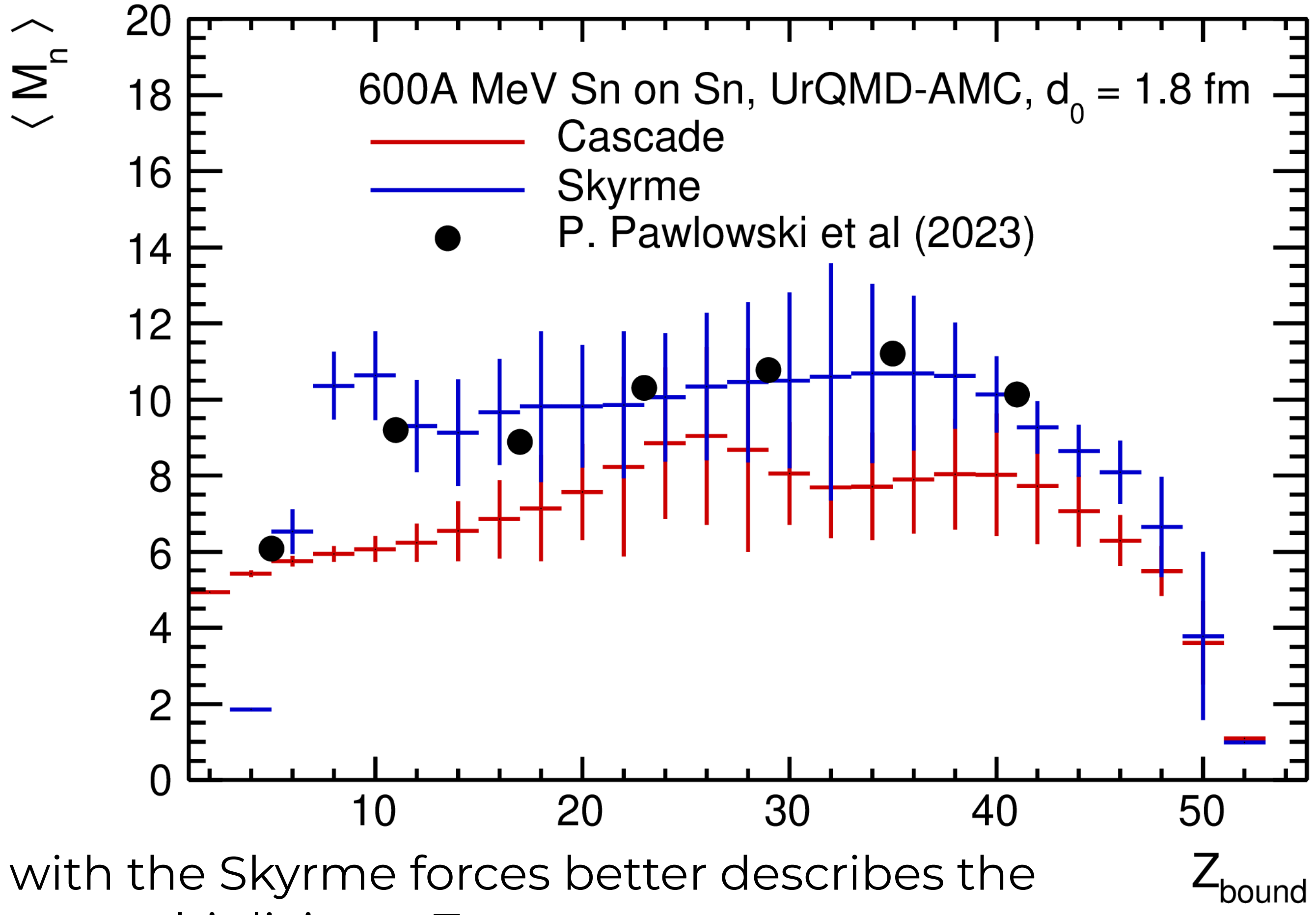
^{197}Au fragmentation: p_T for He



A reasonable agreement for the both Cascade and Skyrme is obtained.

M. Cherry et al Z. Phys. C 62, 25 (1994)

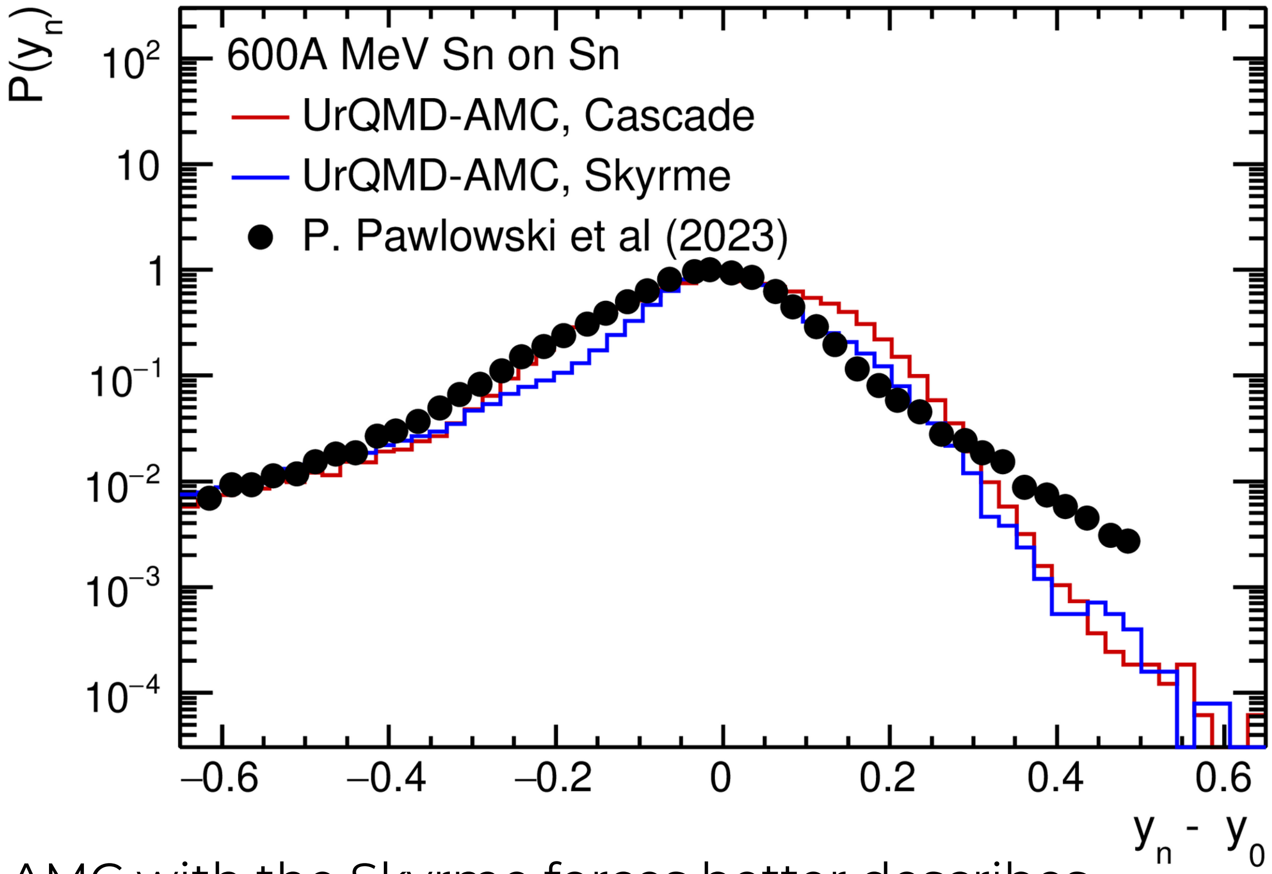
^{124}Sn fragmentation: neutron multiplicity



UrQMD-AMC with the Skyrme forces better describes the average neutron multiplicity vs Z_{bound}

P. Pawlowski et al, Phys. Rev. C, 108, 044610 (2023)

^{124}Sn fragmentation: neutron rapidity distribution

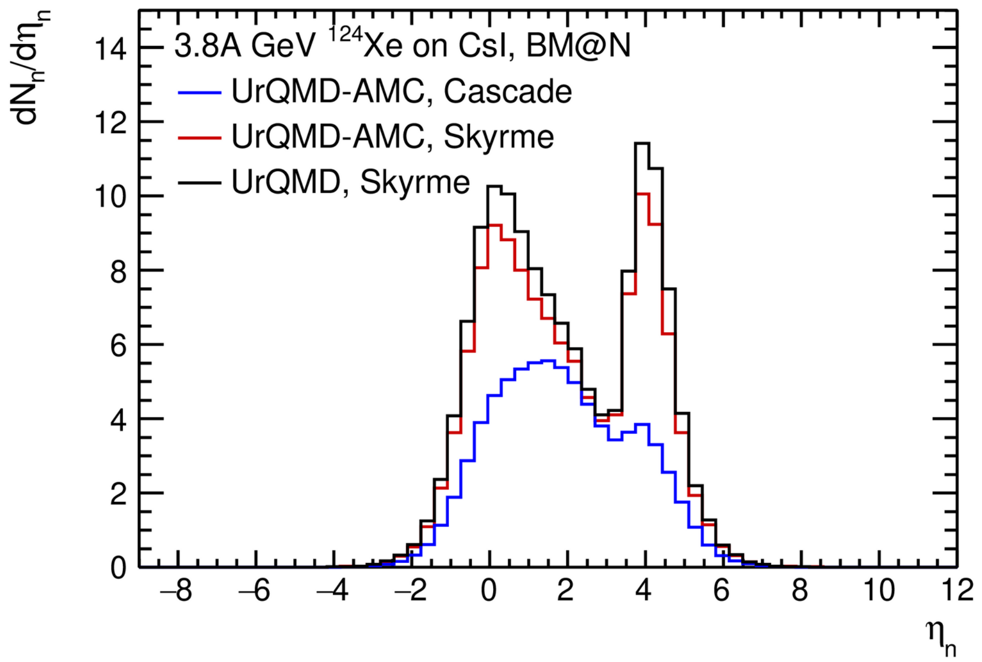


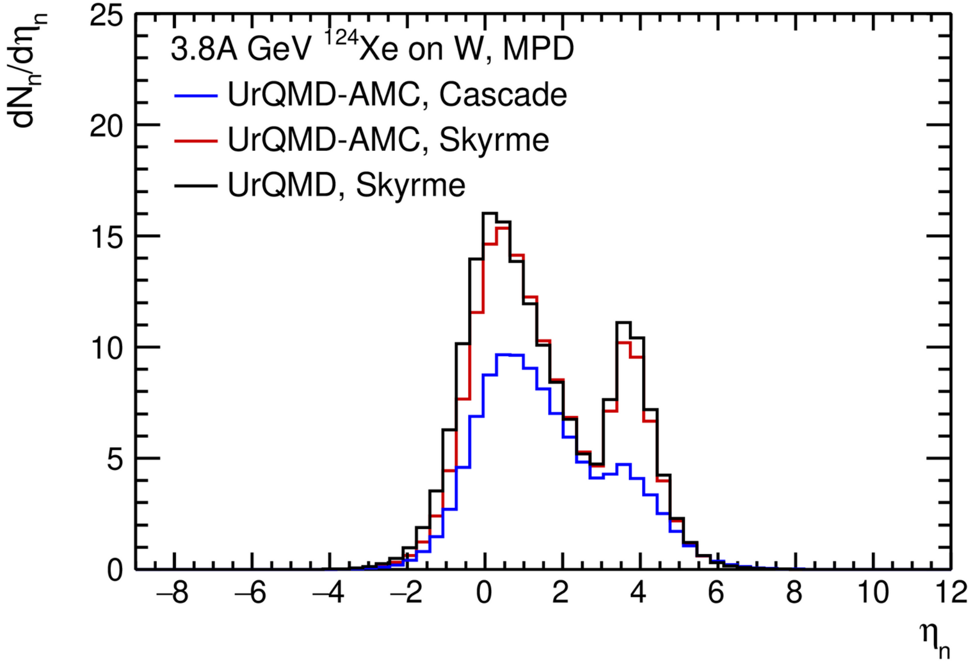
y_0 is the beam rapidity

UrQMD-AMC with the Skyrme forces better describes the rapidity distributions of neutrons.

P. Pawlowski et al, Phys. Rev. C, 108, 044610 (2023)

Forward neutrons from Xe-CsI and Xe-W collisions at NICA

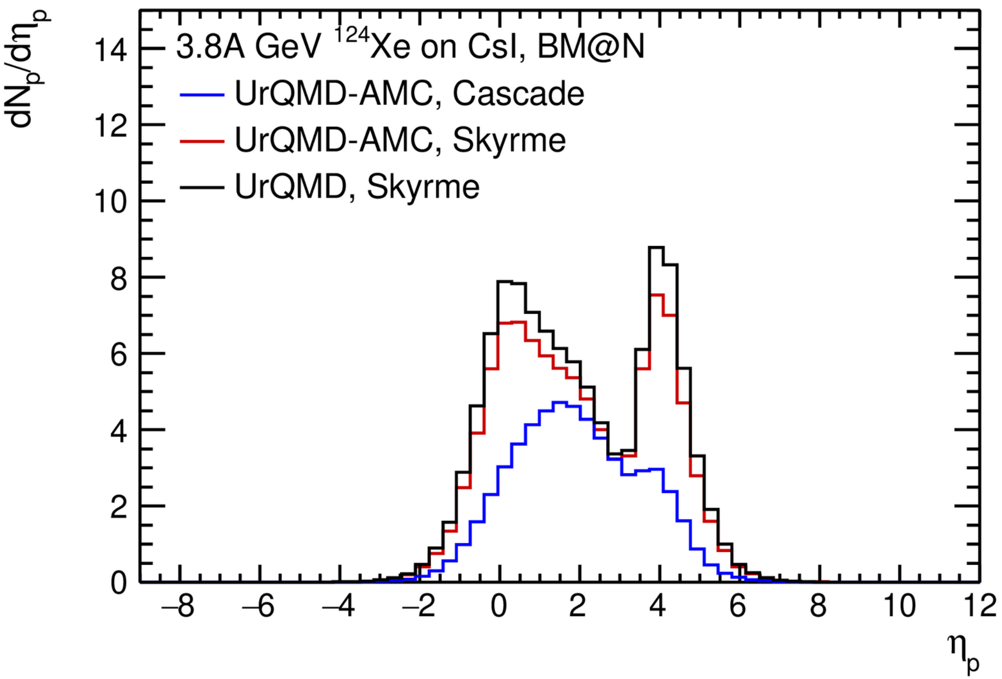


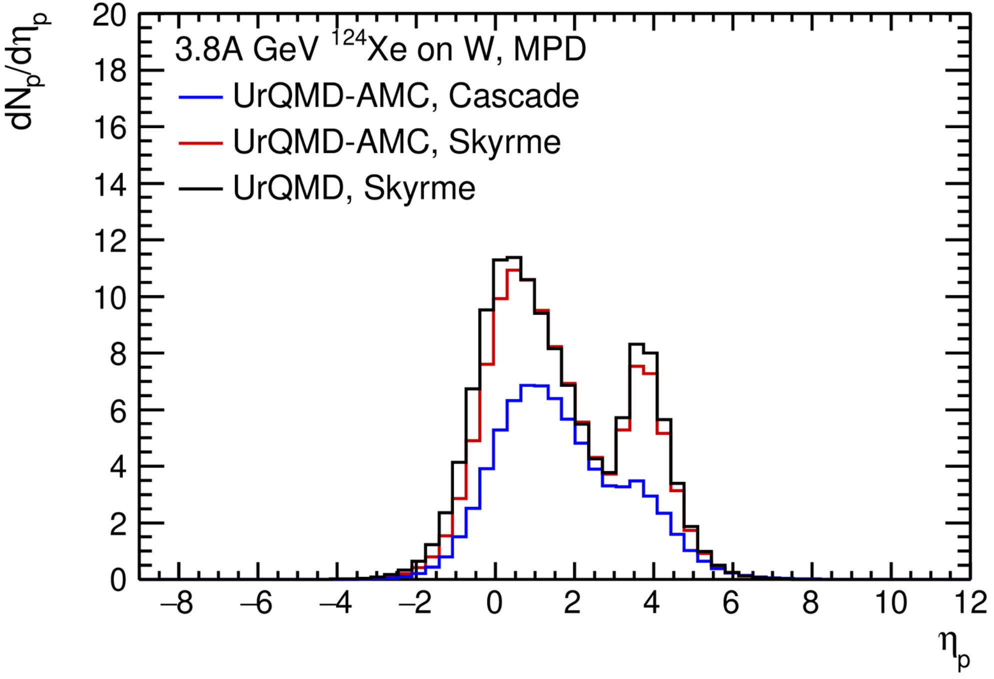


Accounting for the spectator fragments leads to the decrease of the number of the produced neutrons

A large difference between Skyrme and Cascade was obtained

Forward protons at Xe-CsI and Xe-W collisions at NICA

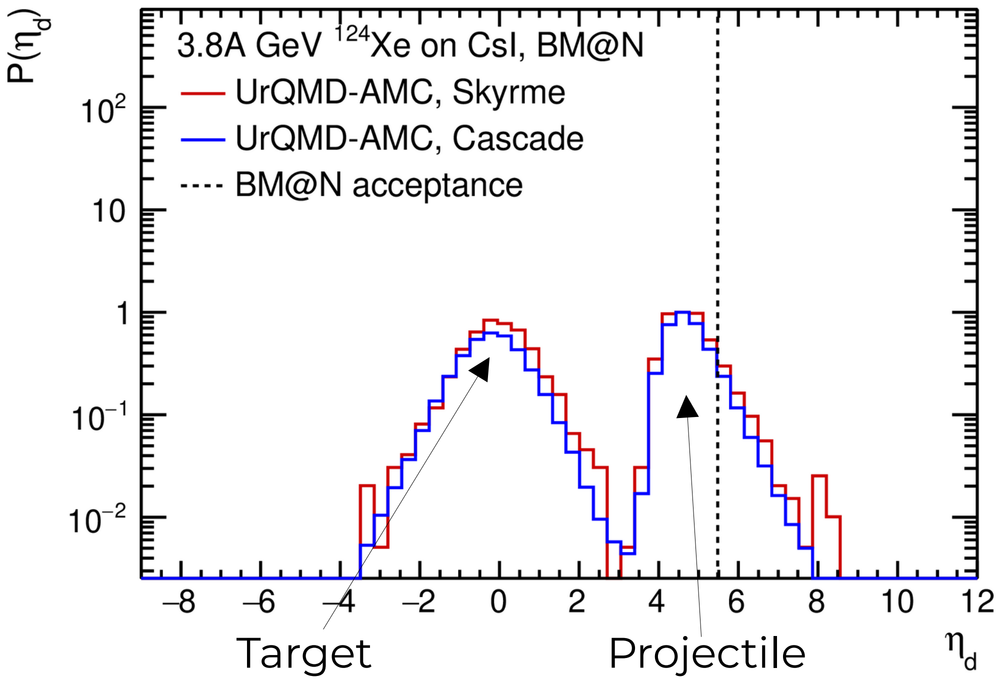


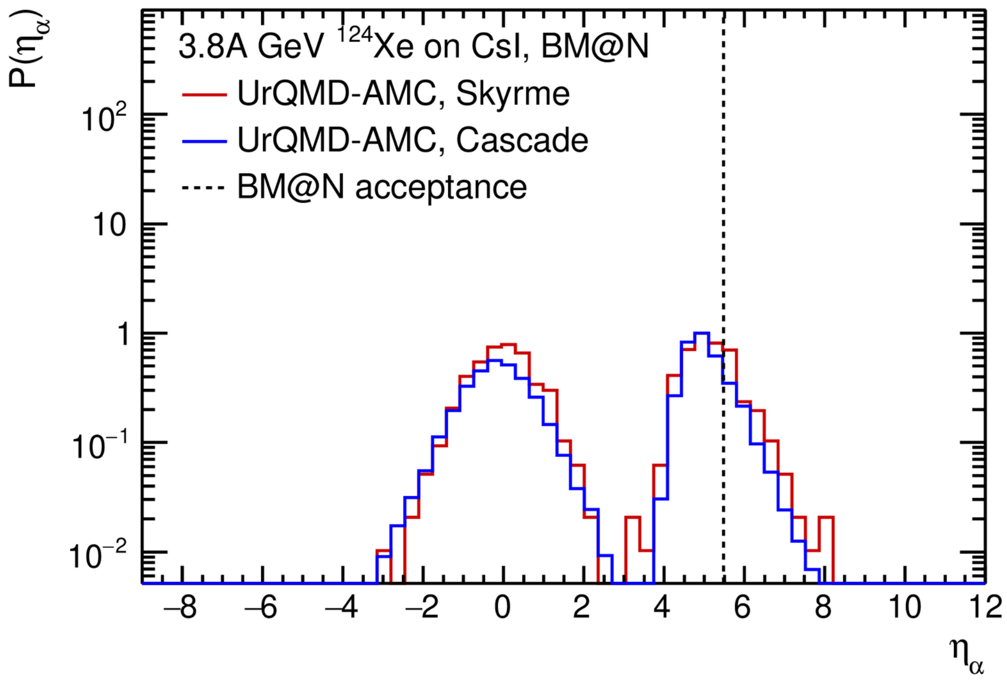


As for neutrons, accounting for the spectator fragments leads to the decrease of the number of the produced neutrons

A large difference between Skyrme and Cascade was obtained

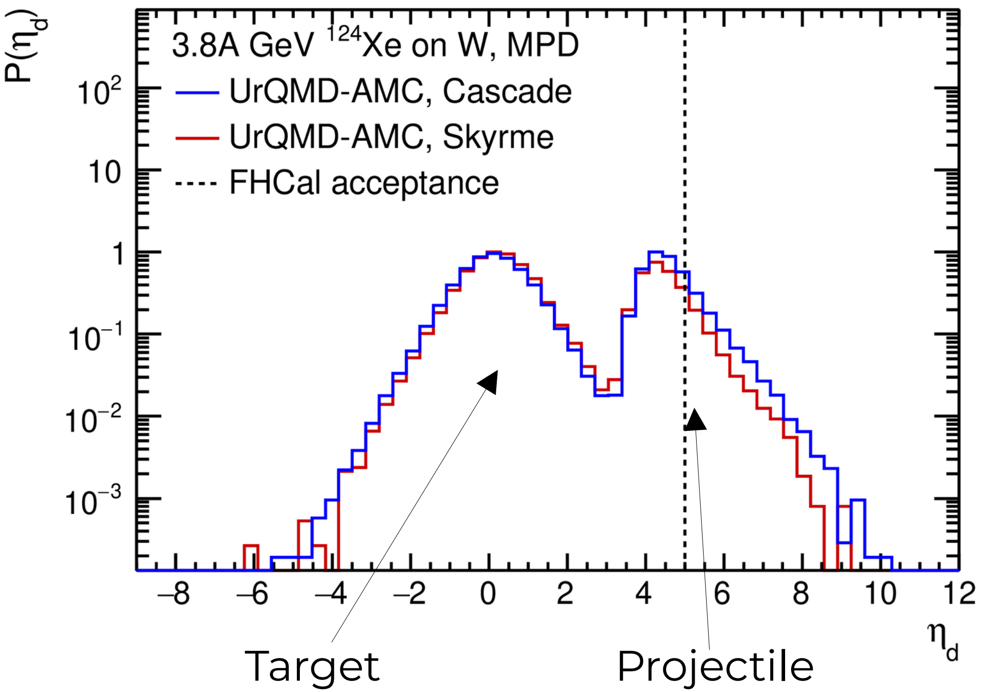
Forward deutrons and alphas from Xe-CsI collisions at BM@N

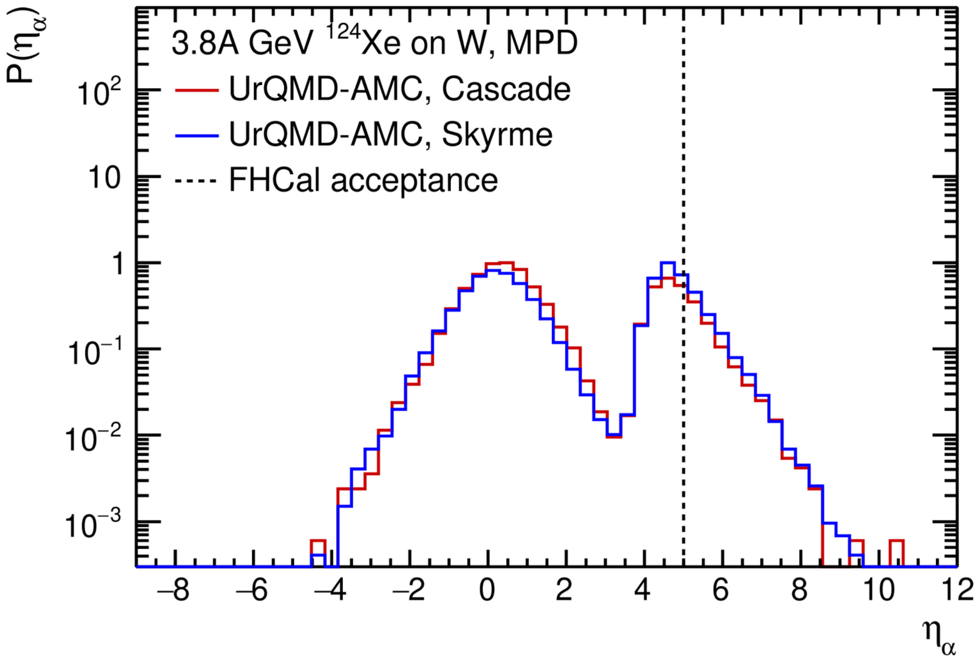




Most of the deutrons and alphas are emitted within the acceptance of the experiment

Forward deutrons and alphas from Xe-W collisions at MPD





Most of the deutrons and alphas are emitted within the acceptance of the experiment

Conclusions

- A hybrid model UrQMD-AMC was developed
- A better description of the data is obtained with UrQMD with accounting of the nucleon-nucleon Skyrme forces
  - The production of nucleons is sensitive to the presence of the Skyrme forces
  - In contrast, the production of fragments in semi-central and central collisions are not is very sensitive
- Accounting for the fragments leads to the reduction of the number of free nucleons
- It is predicted that deutrons and alphas will be emitted mostly within acceptance of the forward detectors at NICA-FXT

Thank you for your attention!

Deepened Impulse, V. Kandinsky 1928