# Participant and spectator nucleons: GlauberMC vs UrQMD

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# Outline

- Abrasion-Ablation Monte Carlo for Colliders model (AAMCC): based on GlauberMC and deexcitation models from Geant4
- Hybrid UrQMD-AMC: UrQMD to simulate collisions and AAMCC to build and decay spectator fragments
- How these models calculate the number of participants at different centralities?
- Time evolution of the number of participanting nucleons and number of collisions in UrQMD
- Comparison of UrQMD-AMC and AAMCC with each other and with data on projectile fragmentation
- Comparison of DCM-SMM vs GlauberMC

# 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)]


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

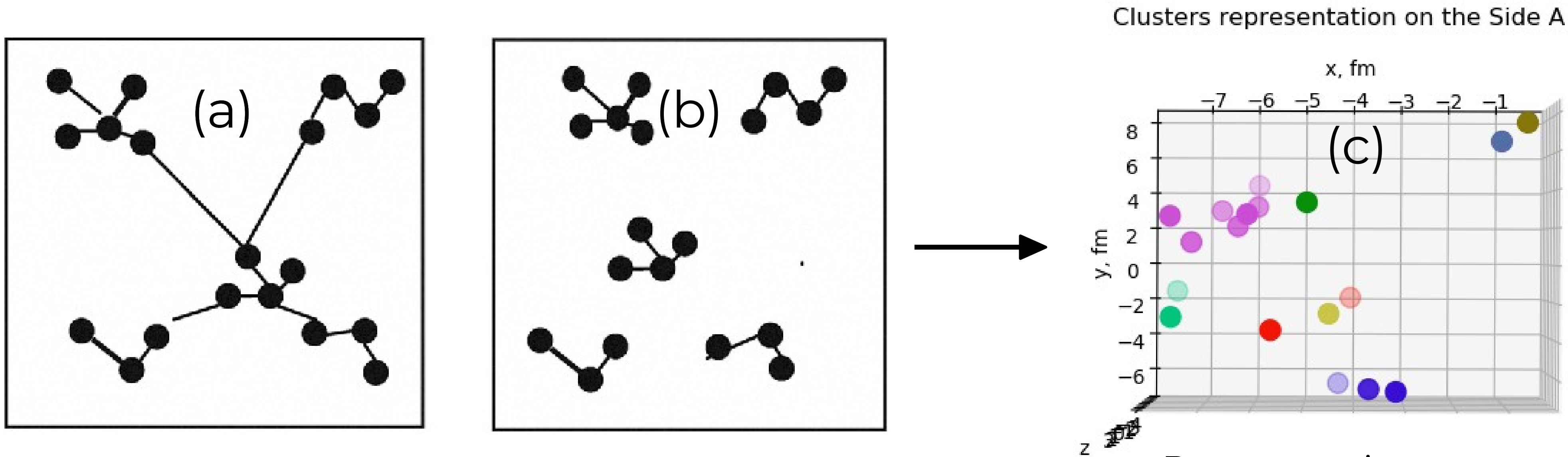

github.com/Spectator-matter-group-INR-RAS/AAMCC

# Abrasion-Ablation Monte Carlo for Colliders

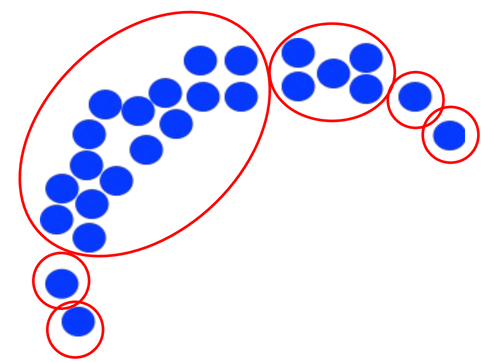
- Decays of prefragments are simulated as follows:
  - pre-equilibrium decays modelled with MST-clustering algorithm [1)]
  - Fermi break-up model from Geant4 v9.2 [2)]
  - Statistical Multifragmentation Model (SMM) from Geant4 v10.4 [2)]
  - Weisskopf-Ewing evaporation model from Geant4 v10.4 [2)]
- 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/

# MST-clustering




Beam-eye view



Prefragments in a central collision

- 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

AAMC²

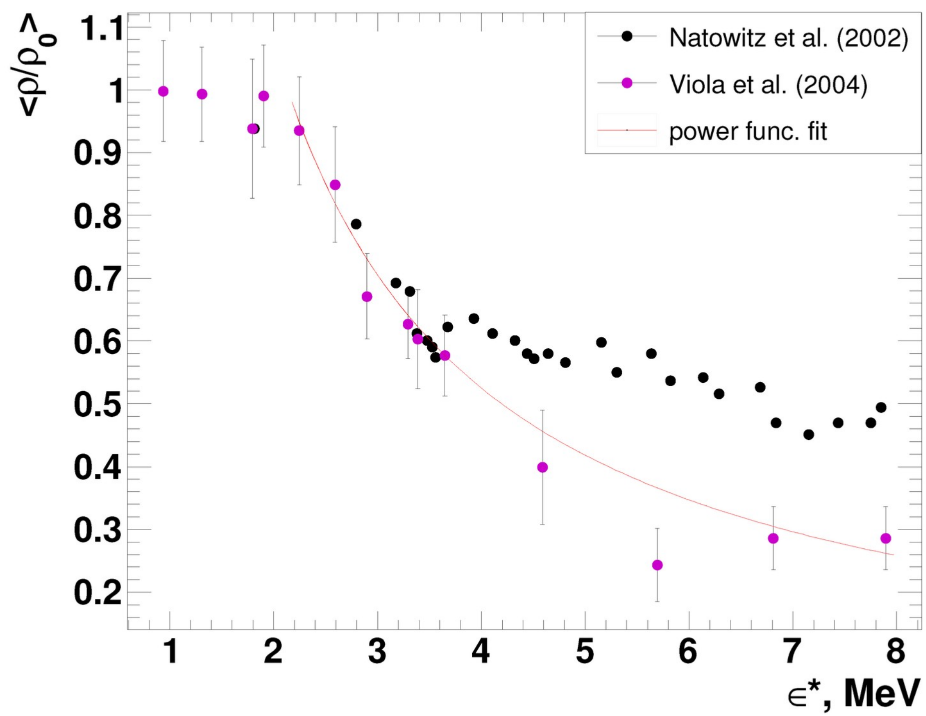
The prefragment is dynamically divided into several prefragments until thermodynamic equilibrium is reached.

R. Nepeivoda, et al., Particles **5** (2022) 40

# Prefragment expansion

- While the size of the prefragment increases, the average distance between nucleons increases as well
- Therefore, if this increase is neglected, $d$ should be decreased to emulate this effect. The characteristic dependence on the density of the prefragment is $d \propto \rho^{1/3}$
- The density parametrization is taken in the form of a piecewise power function, with the parameters taken from experimental data

$$\varepsilon^* > 2\ \mathrm{MeV/nucl}$$
$$\rho/\rho_0 = (\varepsilon^*/\varepsilon_s)^{-\alpha}$$
$$\alpha = -1.02 \pm 0.07$$
$$\varepsilon_s = 0.46 \pm 0.05\ \mathrm{MeV}$$




R. Nepeivoda, et al., Particles **5** (2022) 40

V.Viola et al., Phys. Rev. Lett. **93** (2004) 1
J.Natowitz et al., Phys. Rev. C **66** (2002) 031601

# Combining UrQMD and AAMCC

- AMC is developed to simulate secondary decays of spectator fragments created in other models.
- We employ MCini output file format adopted in MPD.
- It is assumed that spectator matter is formed by non-participated nucleons.
- As UrQMD simulates the expansion of prefragments we employ MST-clustering with fixed $d$.

# Combining UrQMD and AAMCC

**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

→ MCini file

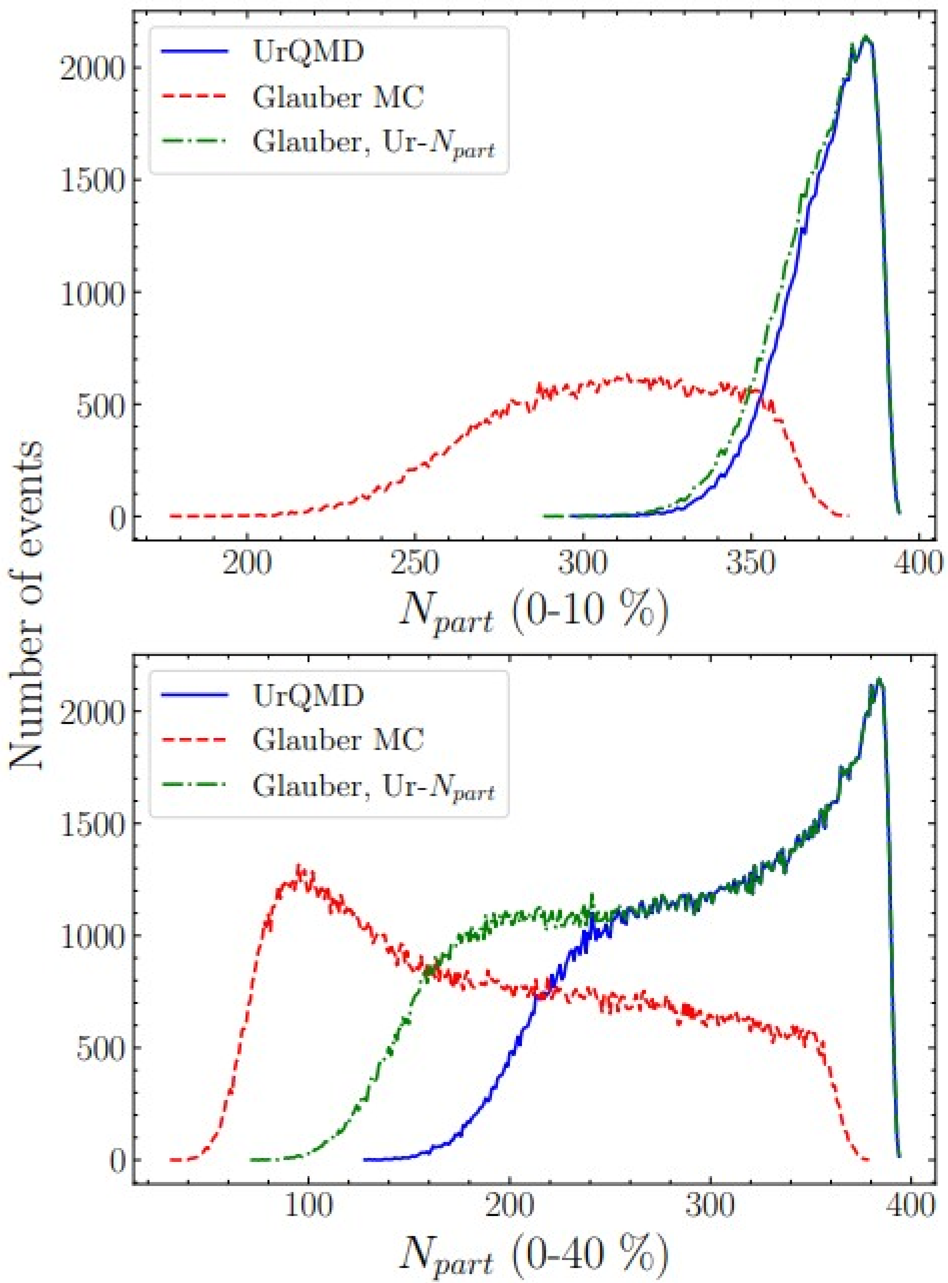
**AMC:**

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

→ MCini file

The pipeline is organized via dedicated bash scripts and works at NCX

# Participants in AuAu at HADES




The nucleons that participated at least once either in inelastic or elastic collision are considered by UrQMD as participants.

The distribution of participants in GlauberMC (red dashed line) and UrQMD (blue solid line) significantly differ.

The dot-dashed green curve (Glauber, Ur-$N_{part}$) depicts the $N_{part}$ from UrQMD for centrality classes defined by Glauber model.

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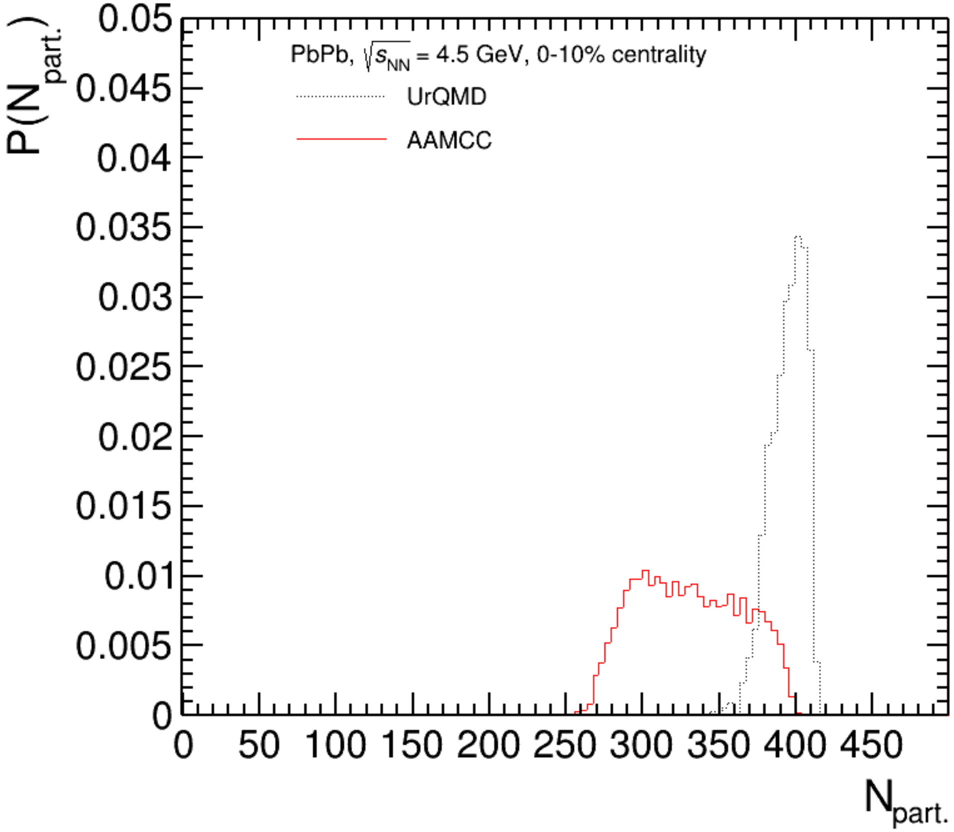
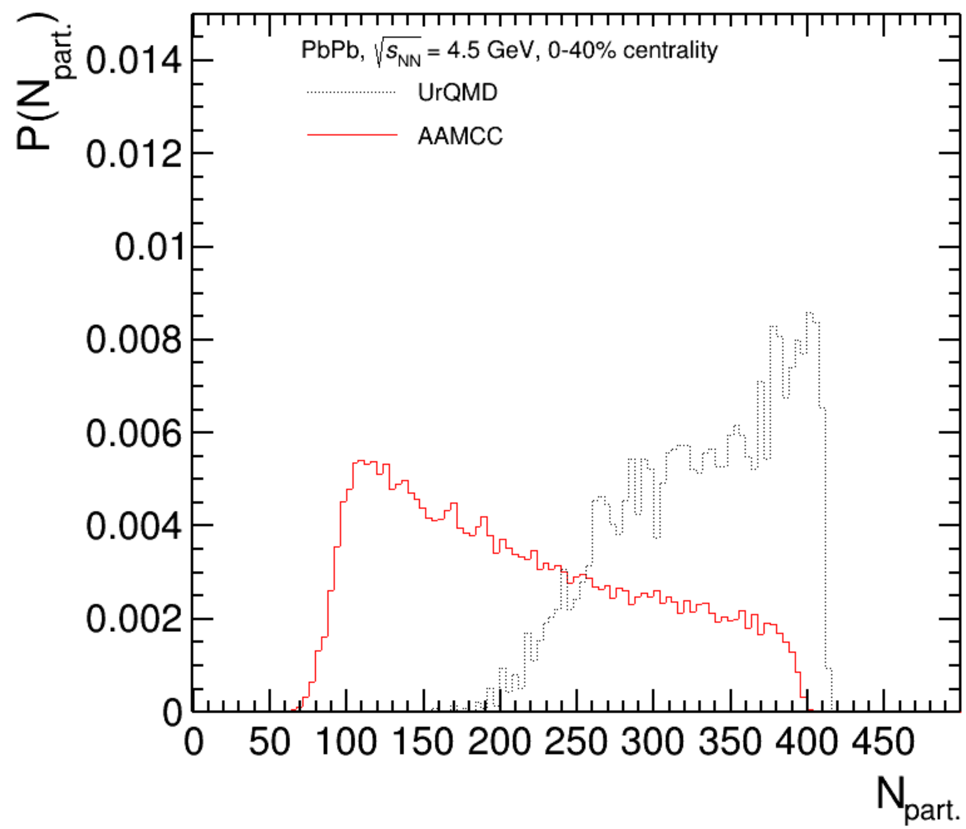
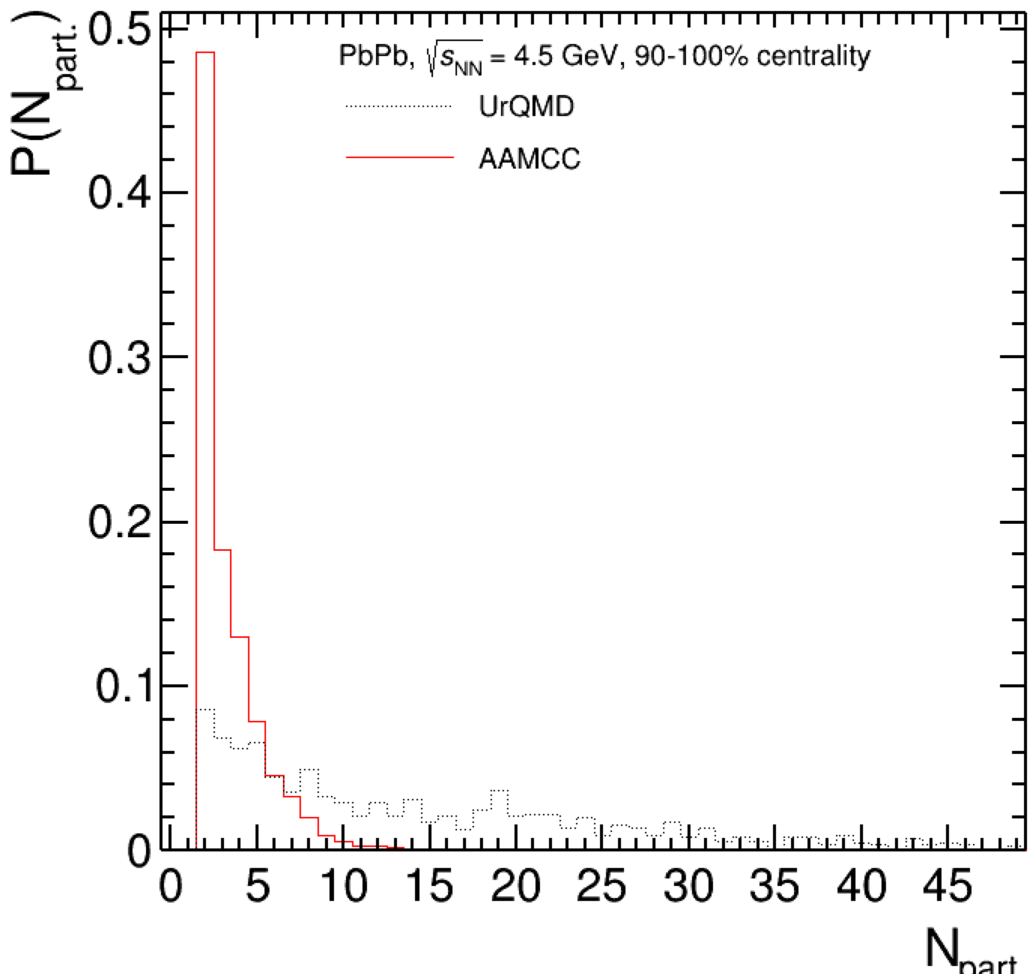
# Distribution of participants in central collisions at MPD



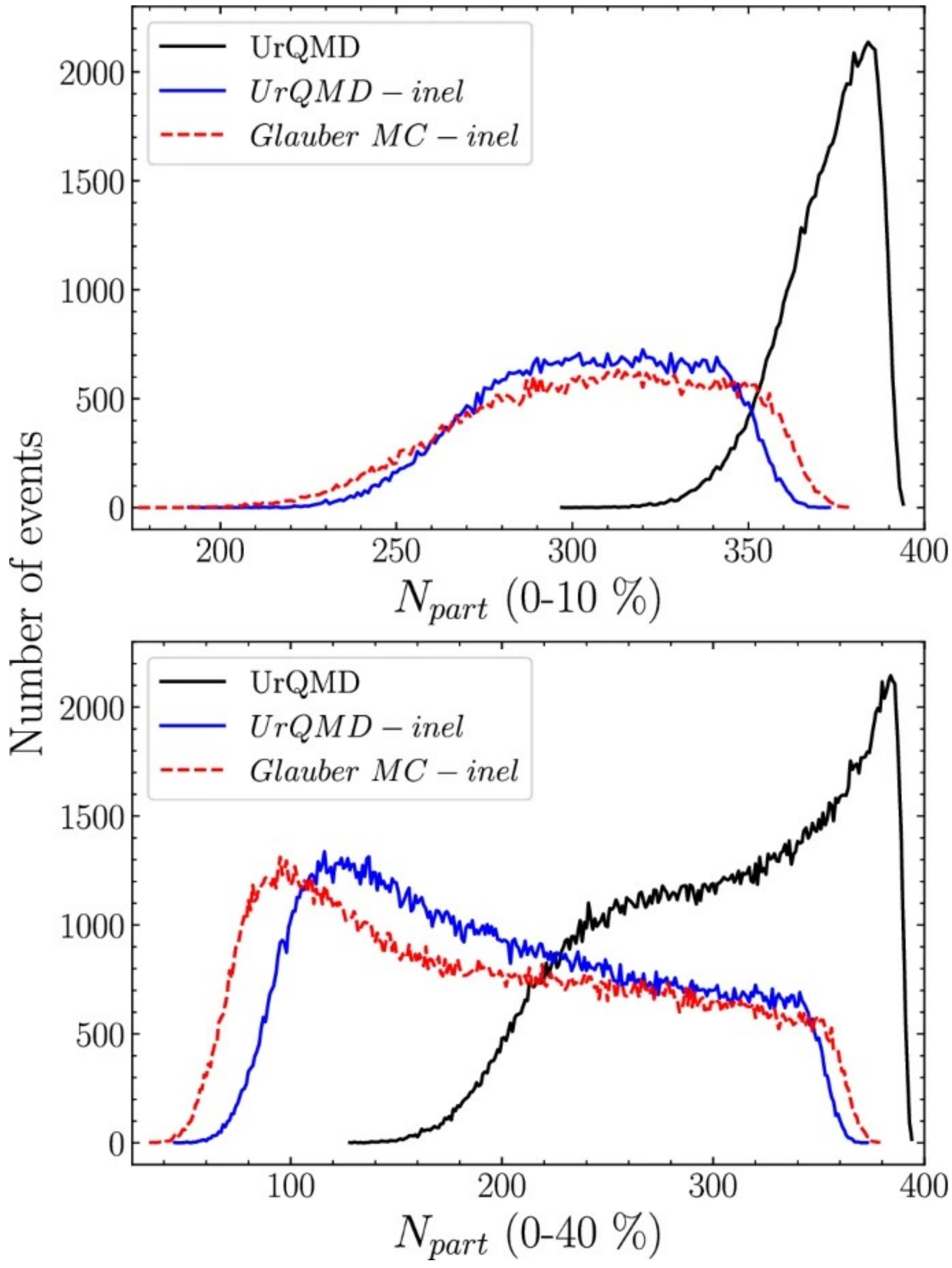

- UrQMD predicts much larger number of participants vs AAMCC
- Note that only inelastic collisions of nucleons from different nuclei are considered in GlauberMC
- In contrast, UrQMD also allows interactions between nucleons of the same prefragment
- In UrQMD the produced particles can also interact with the spectator nucleons in the prefragment after the passing time

# Participant distributions in very peripheral collisions




- As in central collisions, participant distributions are also very different.
- Here UrQMD predicts significantly larger number of participants. On average: AAMCC – 3.35 while UrQMD – 14.17
- However, the difference in prefragment size is small (~5%).

# “Inelastic” participants at HADES




The nucleons that participated at least once either in inelastic or elastic collision are considered as participants by UrQMD

The nucleons that have undergone at least one inelastic collision are considered as participants by UrQMD-inel

UrQMD-inel results are much closer to GlauberMC

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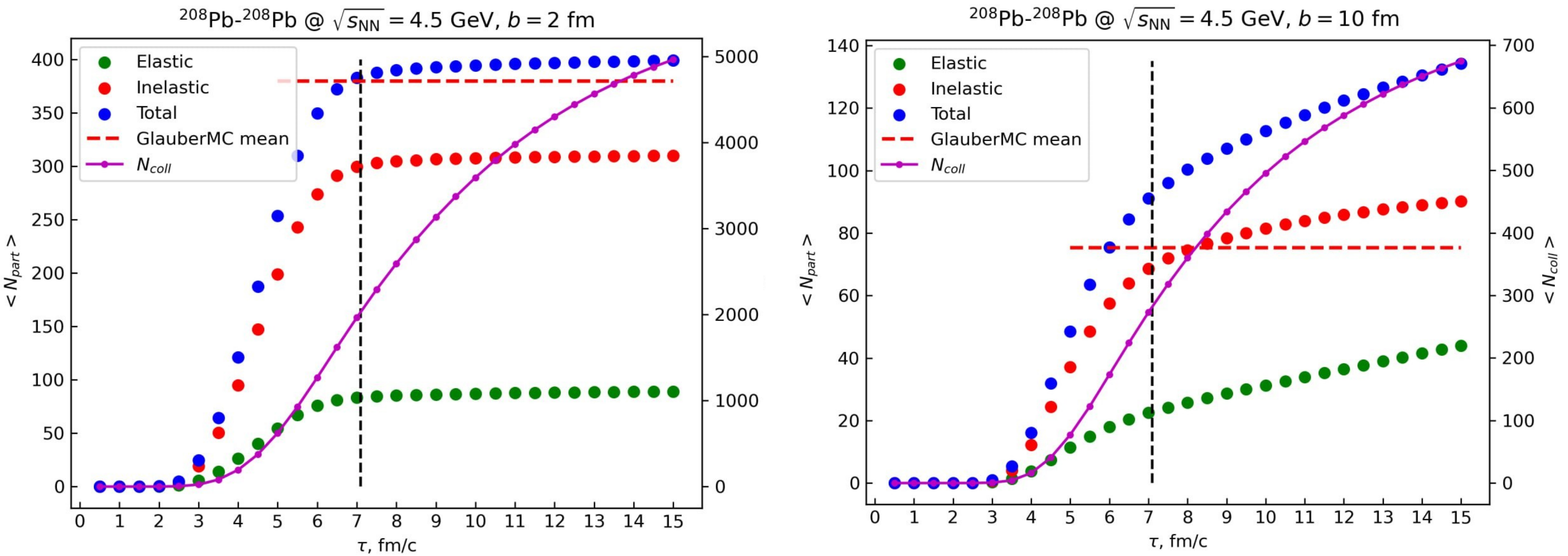
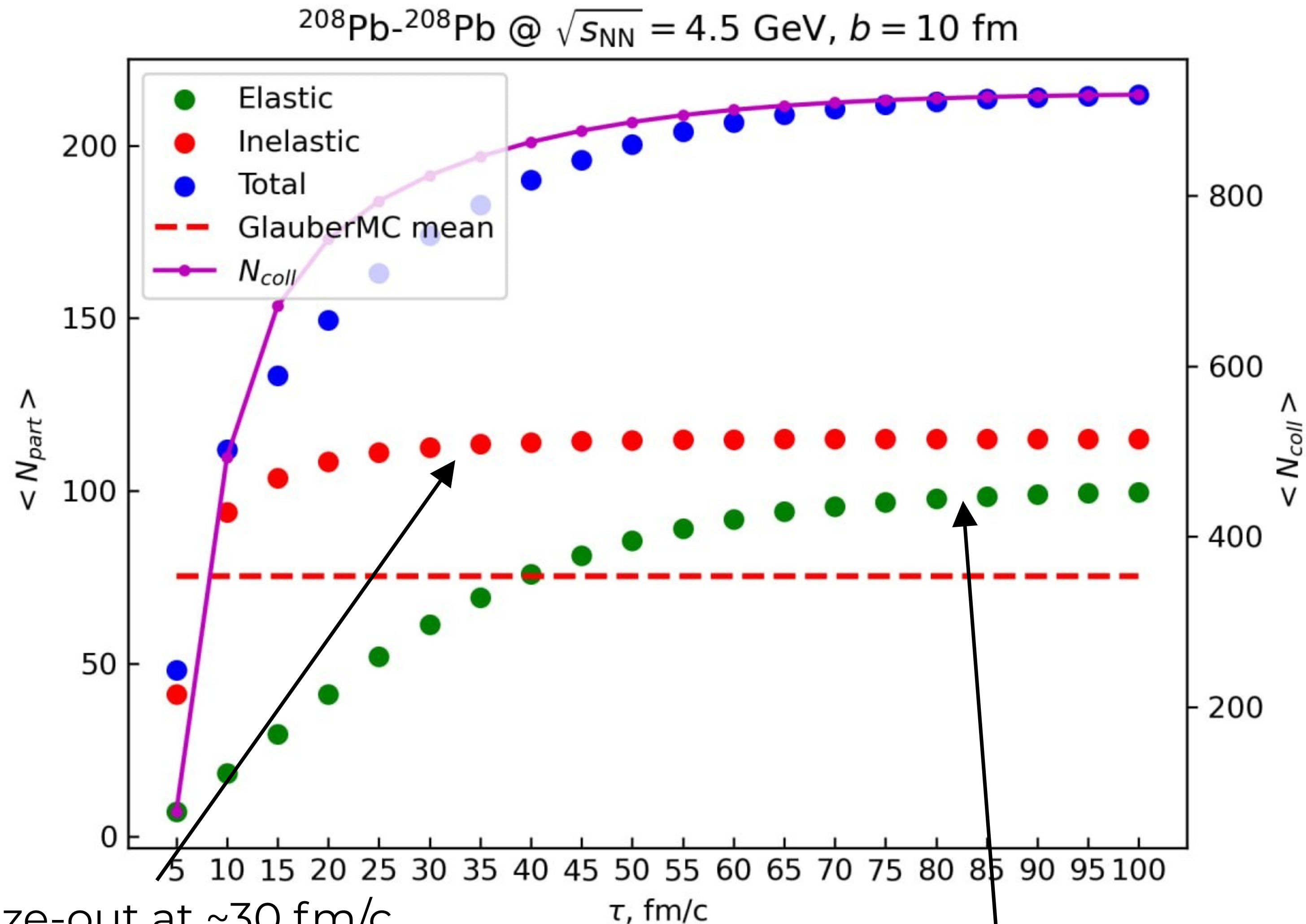
# Number of participants in UrQMD as a function of evolution time




- 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

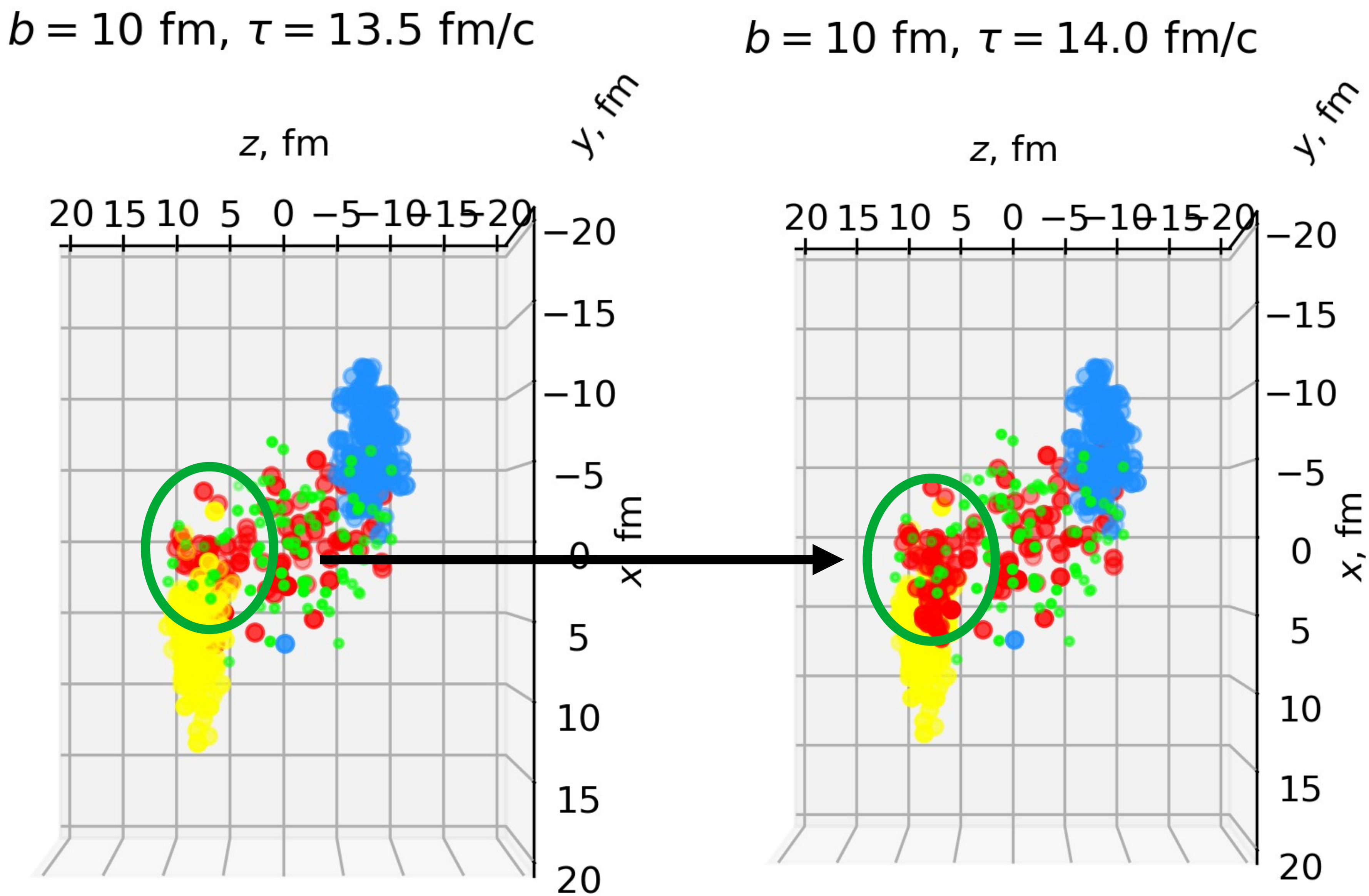



Chemical freeze-out at ~30 fm/c

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

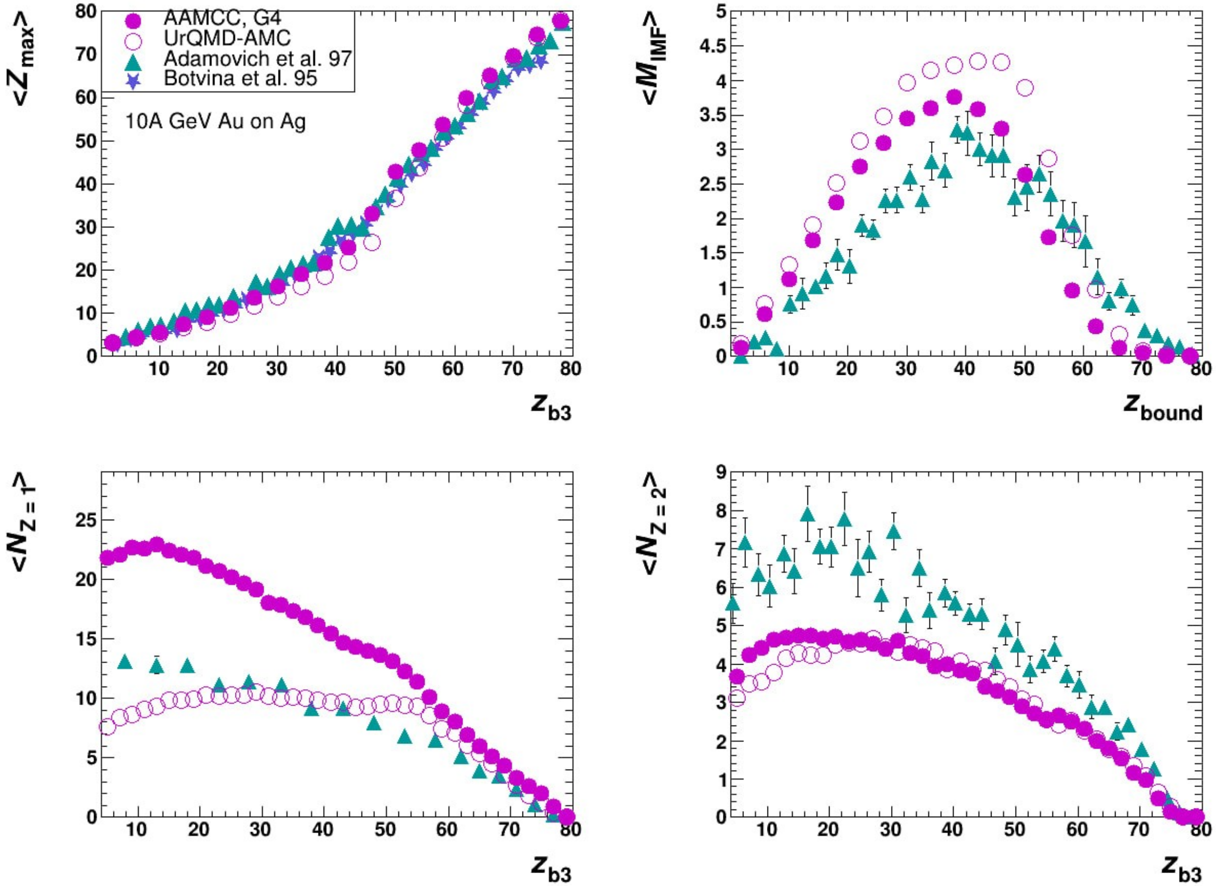
**Elastic interactions mostly add additional excitation to a prefragment**

# Knocking out some spectator nucleons by mesons



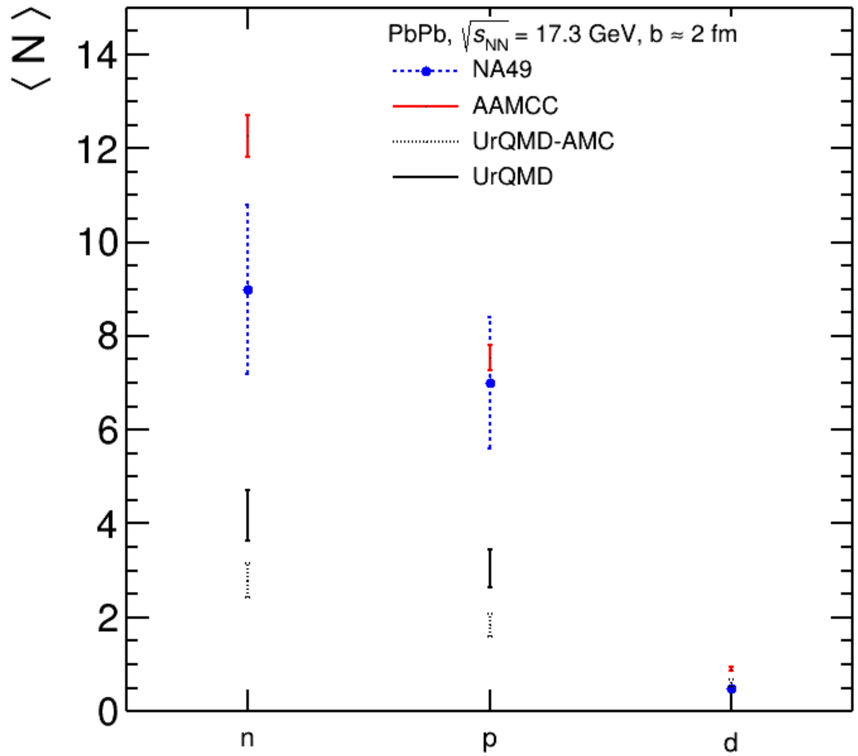

Blue and yellow – spectator nucleons, red – participant nucleons, green – produced mesons

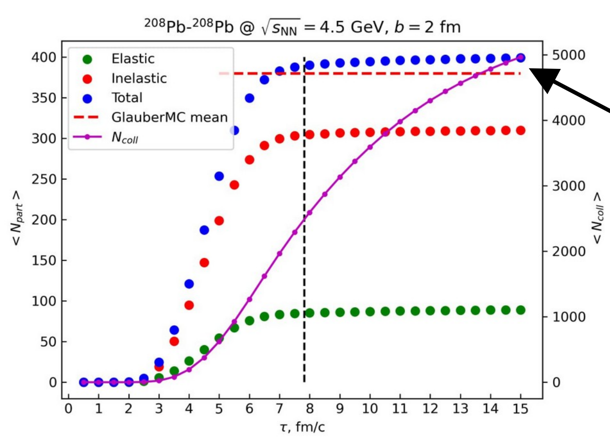
# $^{197}$Au fragmentation




- 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

# Yields of n, p and d in central collisions

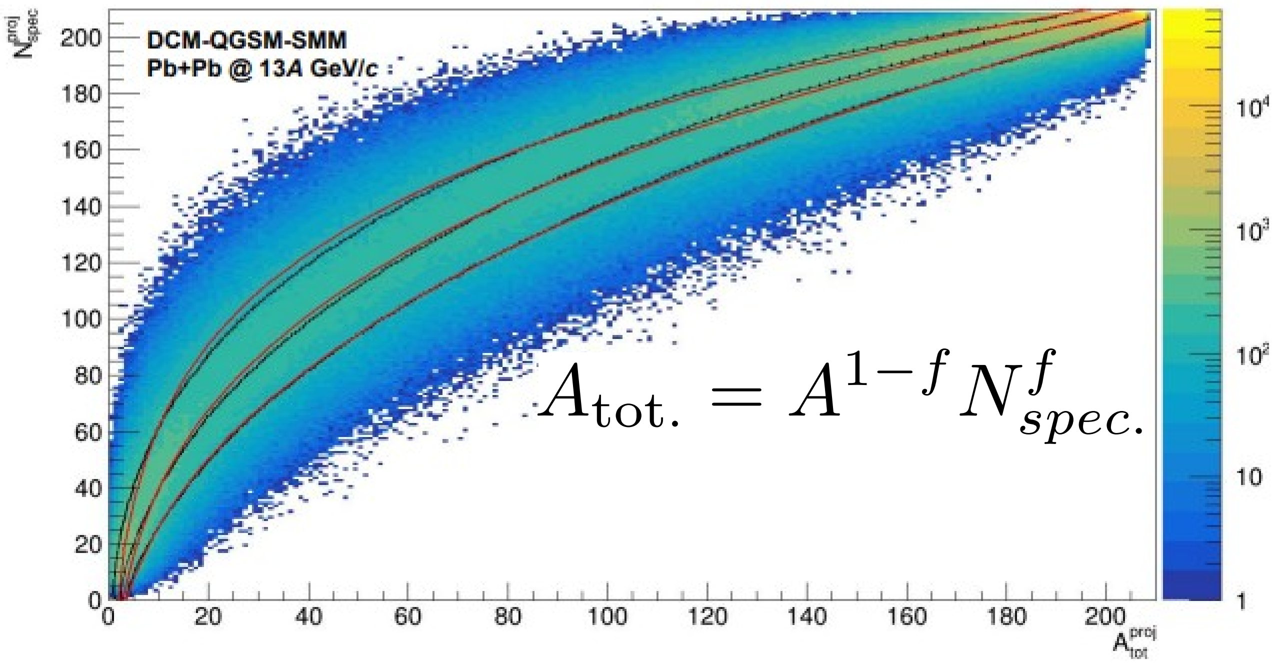



- The collisions were modelled at b = 2 ± 0.1 fm
- Data were obtained by NA49, error bars represent measurement uncertainty[1)]
- AAMCC overestimates the production of neutrons but describes protons and deuterons
- UrQMD-AMC significantly underestimates the data
- UrQMD alone underestimates data as well
- The models describe the data differently because of the difference in $<N_{part}>$ is up to 10 nucleons

1) H. Appelshauser et al. Eur. Phys. J. A **2** (1998) 383

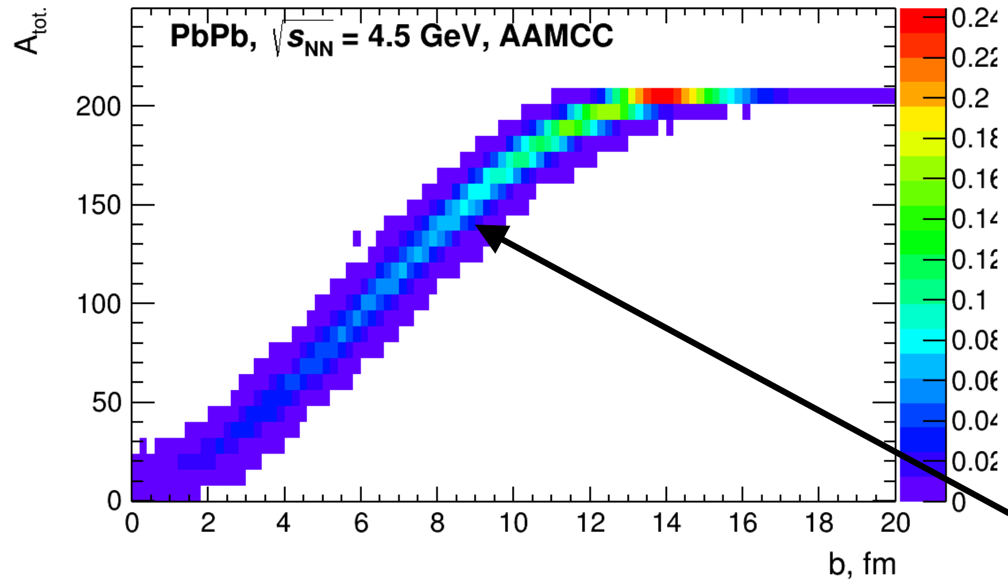
# Parametrisation of $A_{tot}$ to mimic DCM-SMM

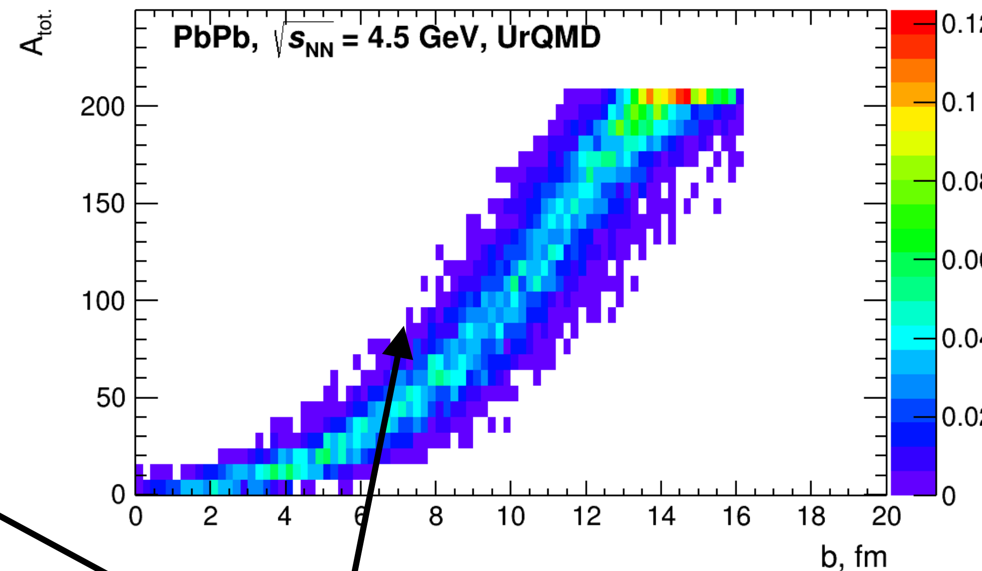



- $A_{tot}$ is the number of bound and unbound spectator nucleons from DCM-SMM, $N_{spec}$ is number of spectator nucleons by GlauberMC[1)].
- Approximation $A_{tot} = A^{1-f} N_{spec}^{f}$ was suggested to relate the total number of spectator nucleons from DCM-SMM and GlauberMC[1)]
- Following Ilya Segal[2)], f = 0.23

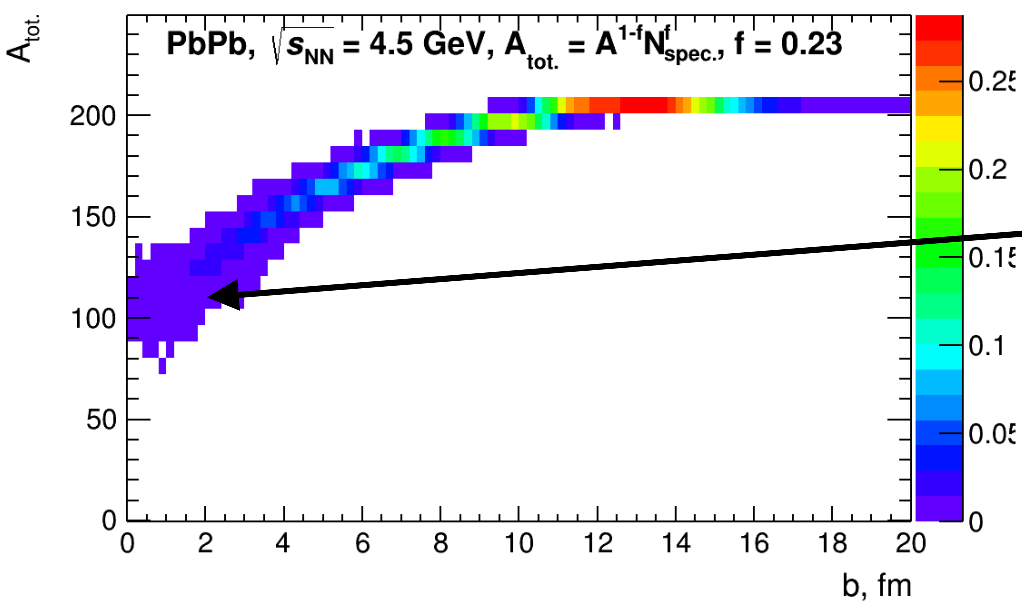
1) Methods for centrality determination in heavy-ion collisions based on Monte-Carlo sampling of spectator fragments, *Ilya Segal, Arkadiy Taranenko, Peter Parfenov*, XXVth International Baldin Seminar, JINR, Dubna, 2023
https://indico.jinr.ru/event/3694/contributions/22392/
2) Private communication with Ilya Segal

# Spectator matter volume as a function of impact parameter



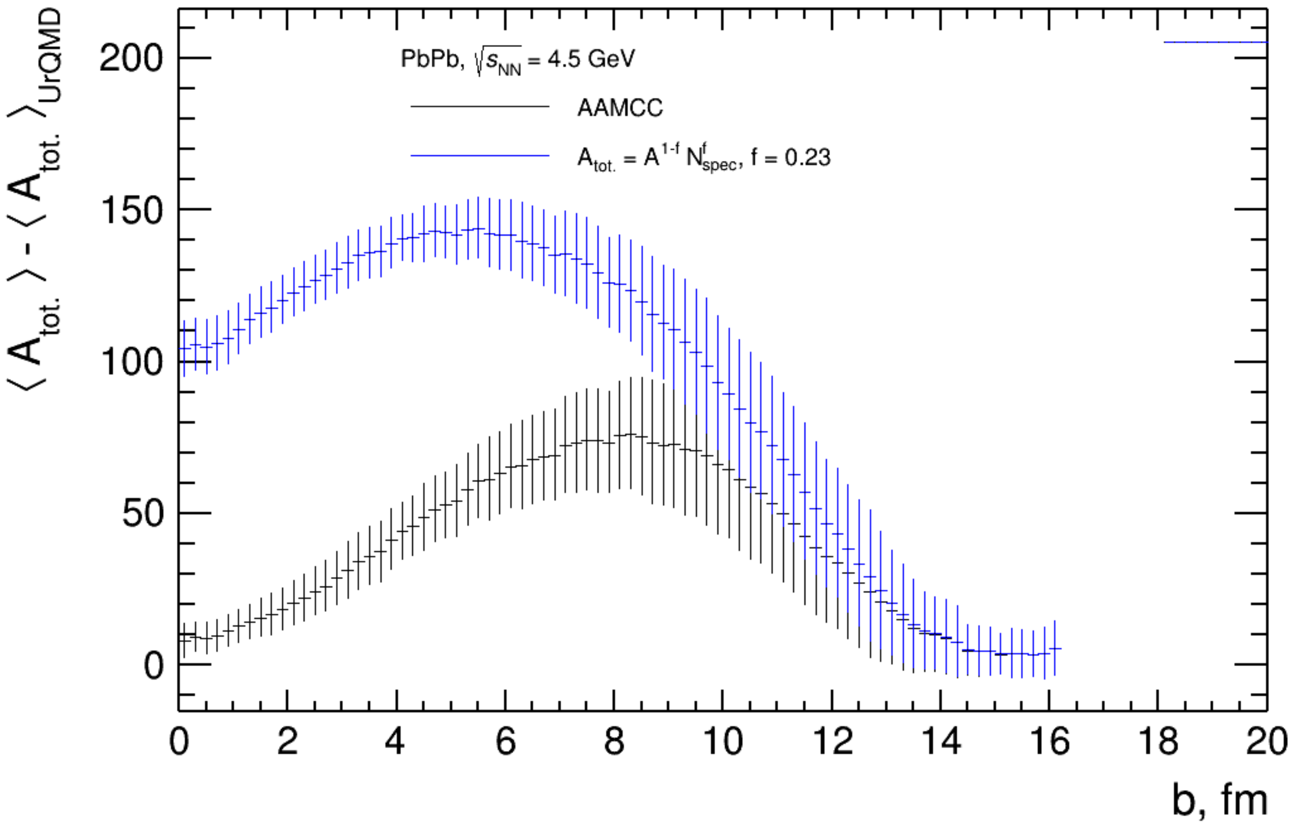

UrQMD gives less spectators than AAMCC for all b




About 100 spectator nucleons in very central events

$A_{tot.}$ is larger than in AAMCC and UrQMD for all b

# Excess of spectator nucleons with respect to UrQMD




Error bars represent std. dev. for given b bin

- The difference in $A_{tot}$ reaches zero in peripheral collisions, b> 14 fm
- The difference between UrQMD and AAMCC has a maximum of 75 nucleons in semi-peripheral events, 6 fm < b < 12 fm. It is small for central events
- For $A^{1-f}N_{spec}^{f}$ parametrisation the difference exceeds 100 for all events with b < 11 fm
- This difference may affects the centrality determination based on the number of spectator nucleons
- Further research is necessary to evaluate the respective difference in FHCal response

# Conclusions

- UrQMD and GlauberMC (AAMCC) define the number of participants differently. Nucleon-nucleon collisions inside the same nucleus, elastic collisions and collisions of produced particles with nucleons are not considered in GlauberMC

- AAMCC is closer to data than other models

- The difference between UrQMD and AAMCC has a maximum of 75 nucleons in semi-peripheral events but it is small for central events

- The difference between parametrisation of $A_{tot}$ by Ilya Segal et al and UrQMD exceeds 100 for all events with $b < 11$ fm

# To do list

- Refinement of participant-spectator separation in UrQMD
  - Adjusting the participants criteria in UrQMD-AMC to bring it closer to one by Glauber MC for NICA energies.
  - Determination of the optimal time to stop the UrQMD evolution.
- Calculation of the FHCal response
  - Comparison of the FHCal response for the different centralities for the different models

# Thank you for your attention!

Deepened Impulse, V. Kandinsky 1928