Fragment and Nuclei Production in Heavy-Ion Collisions

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INTRODUCTION

- Production of initial nucleons

  - The Ultra-relativistic Quantum Molecular Dynamics Model (UrQMD)[1,2,3]

  - The Dubna Cascade Model (DCM) [4]

- Fragments, Clusterization of baryons and deexcitation

  - The Statistical Multifragmentation Model (SMM)[5],

  - New PSG and HYG methods for dynamical stage in SMM.

- Results for nuclei and single/double hypernuclei, comparison with the STAR experimental data

- Conclusions

[1] N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M. Bleicher, Eur. Phys. J. A **61**, 23 (2025).

[2] N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M. Bleicher, Phys. Rev. C **108**, 054904 (2023).

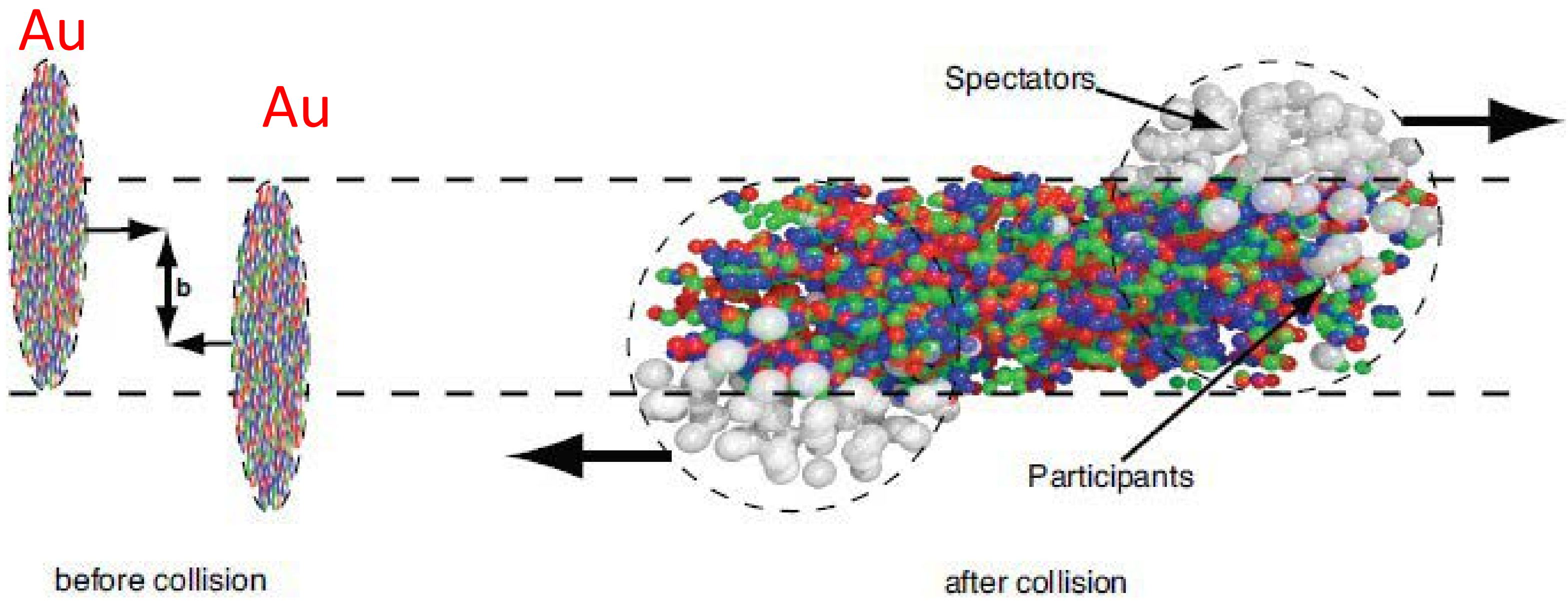
[3] Apiwit Kittiratpattana, Tom Reichert, Nihal Buyukcizmeci, Alexander Botvina, Ayut Limphirat, Christoph Herold, Jan Steinheimer, and Marcus Bleicher, Phys. Rev. C **109**, 044913 (2024)

[4] V. D. Toneev, K. K. Gudima, Nucl. Phys. A 400, 173 (1983).

[5] A. S. Botvina, N. Buyukcizmeci and M. Bleicher, Phys. Rev. C 106, 014607 (2022).

STAR exp.: Central Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV

[5] M. S. Abdallah et al., STAR Collaboration, Phys. Rev. Lett. 128, 202301 (2022)
[6] Hui Liu for STAR Collaboration, Acta Phys. Polon. B, Proc. Suppl. 16, 1–A148 (2023).



Hybrid approaches are successful for the description of dynamics

DCM+CB, URQMD, PSG (primary hot nuclei)

DCM+SMM, URQMD+SMM, PSG+SMM (final cold nuclei)

The Ultra-relativistic Quantum Molecular Dynamics Model (UrQMD)

- The UrQMD includes up to 70 baryonic species (including their antiparticles), as well as up to 40 different mesonic species, which participate in binary interactions. In the present calculations the hard Skyrme type equation of state is used which allows for the attraction between baryons.
- Conservation of the net-baryon number, net-electric-charge, and net-strangeness as well as the total energy and momentum are taken into account.
- The produced particles can be located at all rapidities, however, the considerable part is concentrated in the midrapidity region.
- At the time of t=20–40 fm/c the strong interactions leading to the new particle formation are practically stopped (such as saturation). In that time-moment we consider the relative coordinate positions and velocities of the produced baryons.
- We select the nuclear clusters according to the coordinates and velocities proximity, was suggested in Refs. [1,2,4], and we call it a clusterization of baryons (CB).

[7] M. Bleicher et al., J. Phys. G 25, 1859 (1999),
[8] S.A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998).

CENTRAL COLLISIONS

Nuclear system expands to low densities and passes the density around 0.1-0.3 of normal nuclear density, which corresponds to the freeze-out adopted in the statistical models.

Baryons can still interact and form nuclei at this density.

We divide the nuclear matter into clusters in local chemical equilibrium and apply SMM to describe the nucleation process in these clusters.

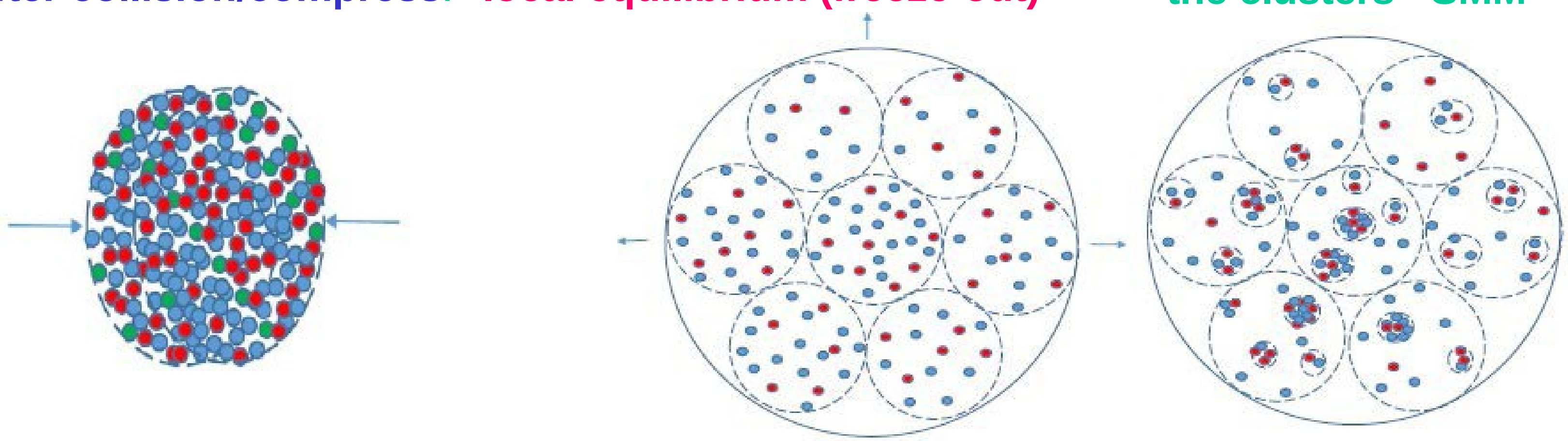
Baryons (both nucleons and hyperons) can produce a cluster with mass number A if their velocities relative to the center-of mass velocity of the cluster is less than vc.

$|\vec{v}_i - \vec{v}_{cm}| < v_c$ for all $i = 1, \ldots, A$, where $\vec{v}_{cm} = \frac{1}{E_A}\sum_{i=1}^{A}\vec{p}_i$

dynamical expansion after collision/compress.

Baryonic clusters in local equilibrium (freeze-out)

nuclei formation inside the clusters - SMM



New methods in SMM:

The dynamical stage can be simulated with the Phase Space Generation (PSG) and HYdrodynamical-like Generation (HYG) methods. They provide very different momenta distributions of baryons which cover the most important limits expected after this stage.

Phys.Rev.C 103 (2021) 064602

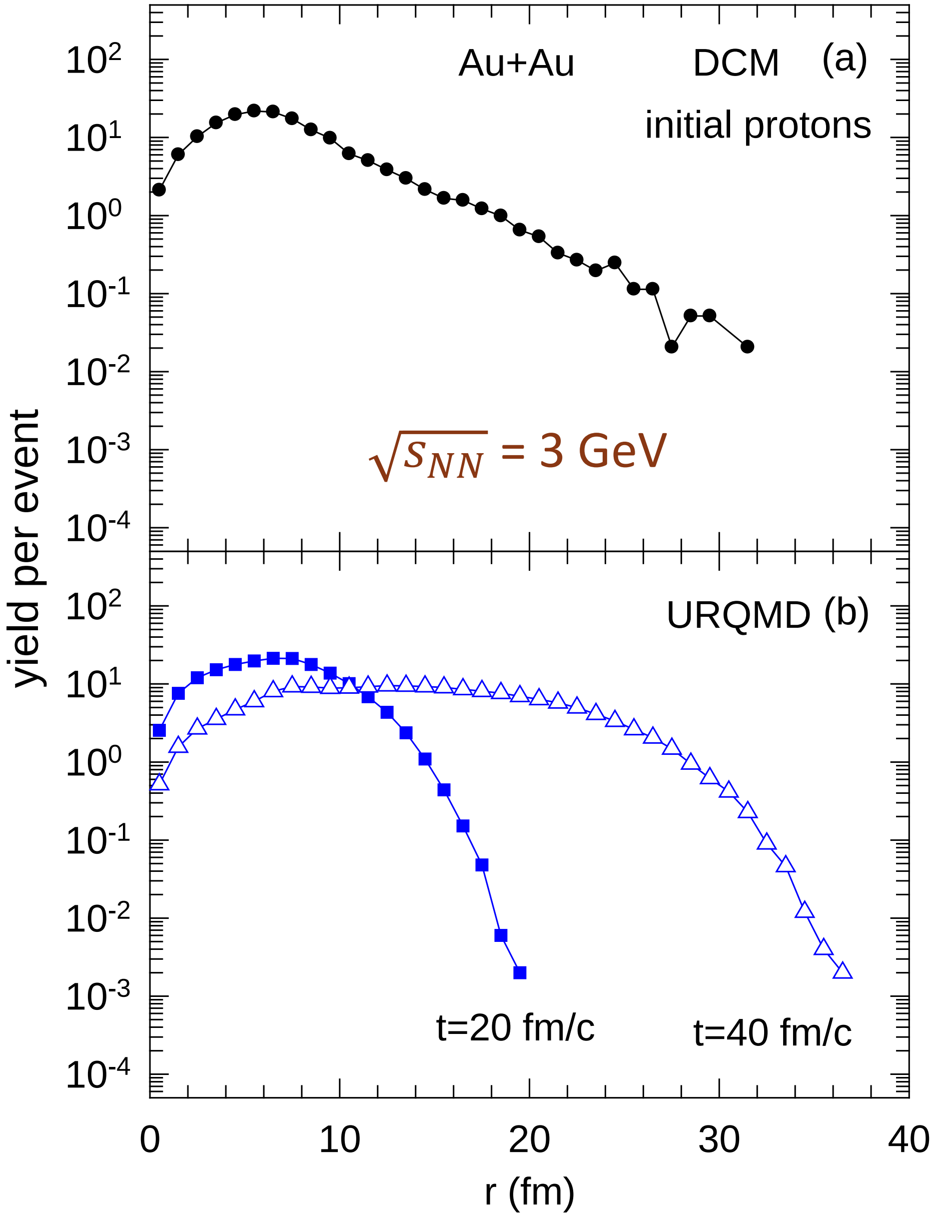
Phys.Rev.C 106 (2022) 014607

Buyukcizmeci, Ergun, Botvina and Bleicher, submitted to PRC (2025)

Methods are well- tested from Fermi energies, intermediate energies up to 3A GeV energies, we continue analyses to improve for higher energies.

Selection of primary clusters (at low freeze-out density) by using the coalescence of baryon (CB) model (Phys. Lett. B742, 7 (2015)): according to their velocities $|V_i - V_0| \leq V_c$ and coordinates $|X_i - X_0| \leq X_c$.

Statistical formation of nuclei inside these clusters with SMM: de-excitation of the excited clusters. The excitation energy (or local temperature) of such clusters is important characteritics for the nuclear matter.

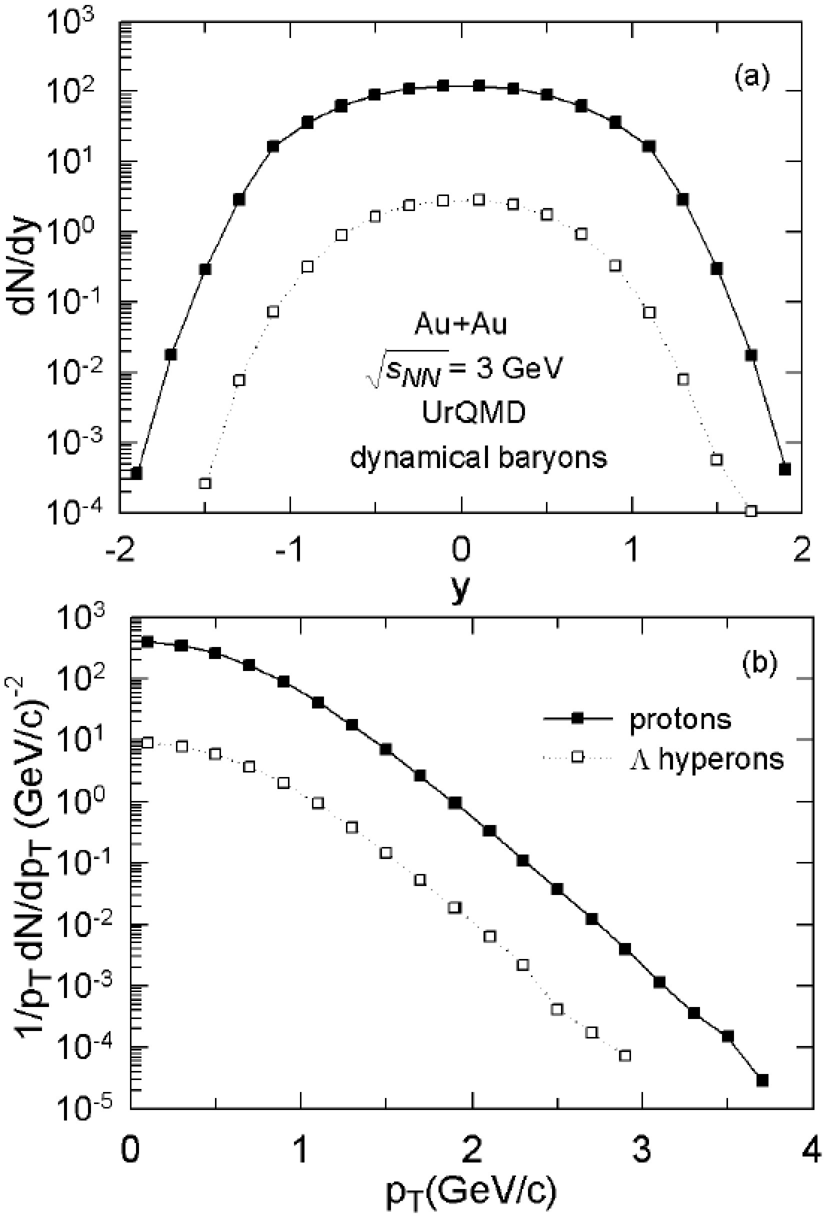


Comparison of coordinate distribution according to the center of collision of initial protons produced with DCM (time independent) and UrQMD (t=20 and 40 fm/c) models :

Initial protons and Λ's

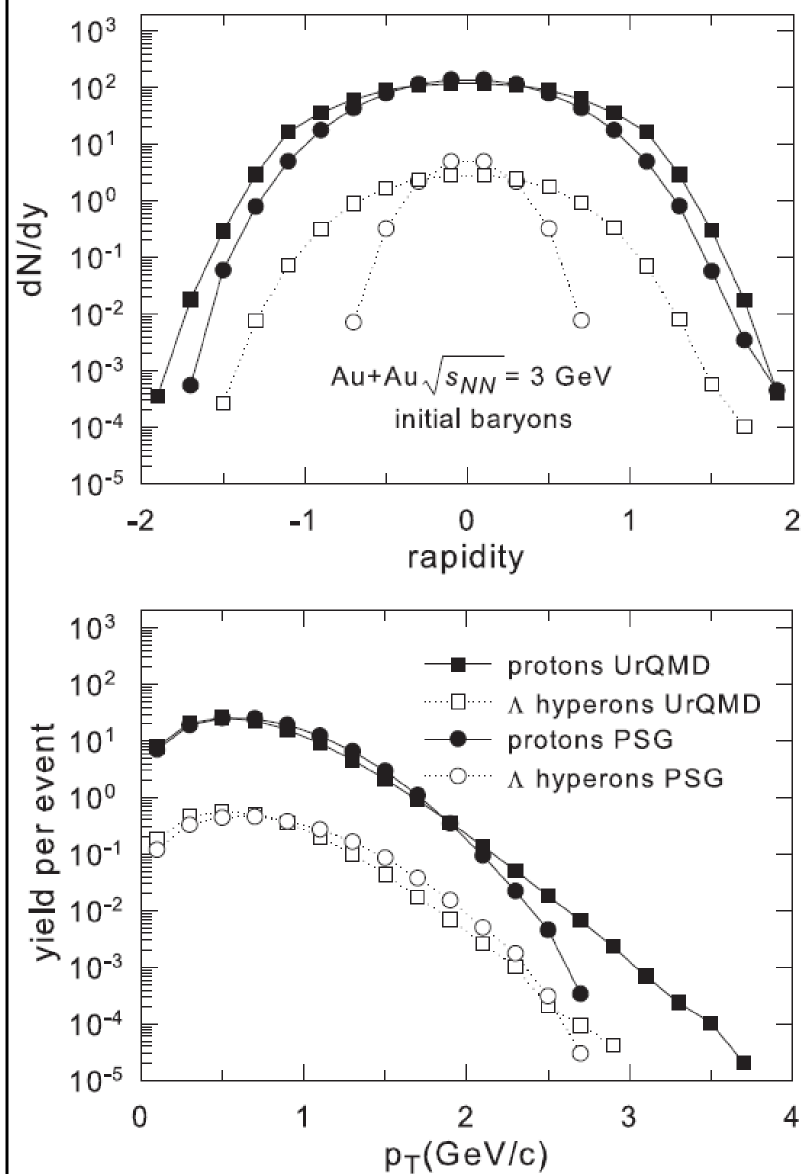
Total proton and Λ distributions after the **UrQMD** calculations of central Au+Au collisions at center-of-mass energy of $\sqrt{s_{NN}} = 3$ GeV. Top panel (a) rapidity distributions. Bottom panel (b) transverse momenta distributions, in the rapidity range |y|<0.5.

[1] N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M.Bleicher, Phys. Rev. C **108**, 054904 (2023).



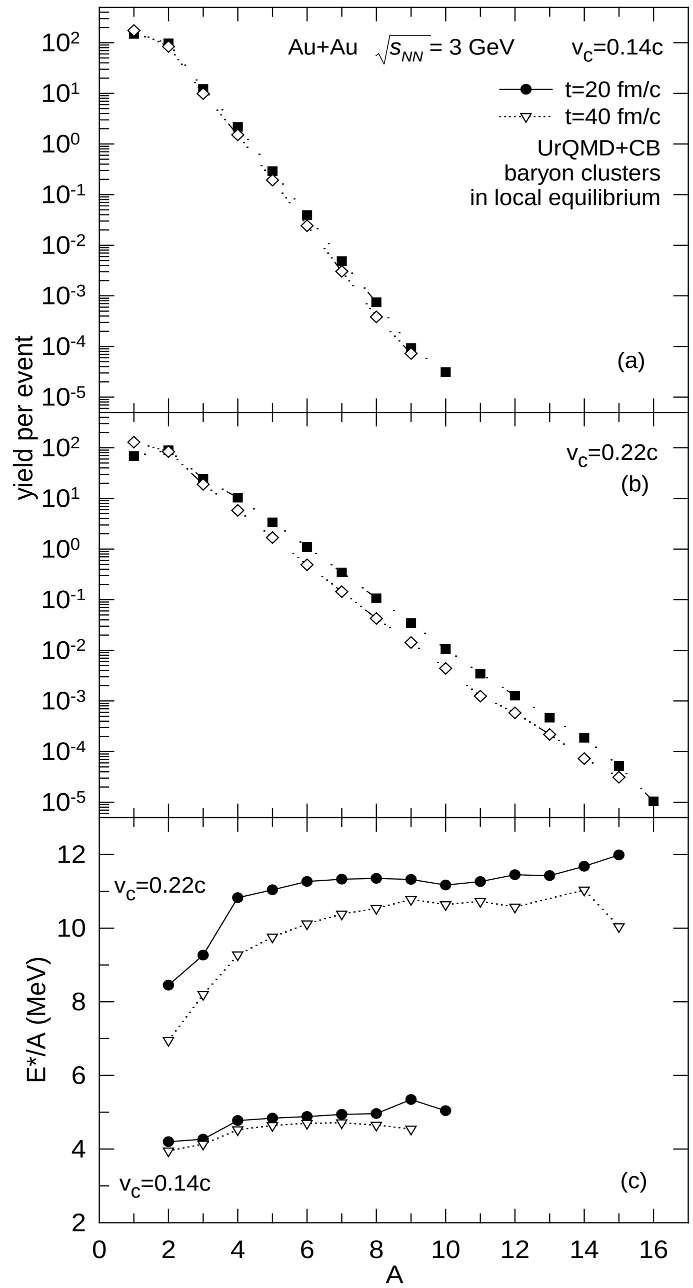
Initial protons and Λ's

Total proton and Λ distributions after the **UrQMD and PSG** calculations of central Au+Au collisions at center-of-mass energy of $\sqrt{s_{NN}} = 3$ GeV. Top panel (a) rapidity distributions. Bottom panel (b) transverse momenta distributions, in the rapidity range |y|<0.5.

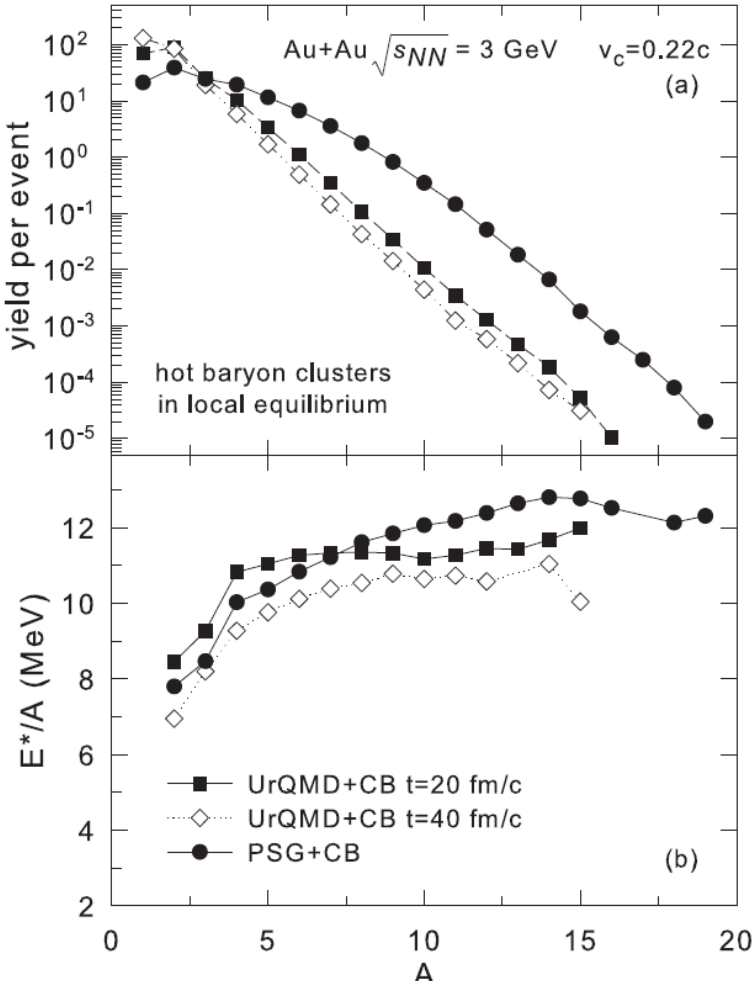


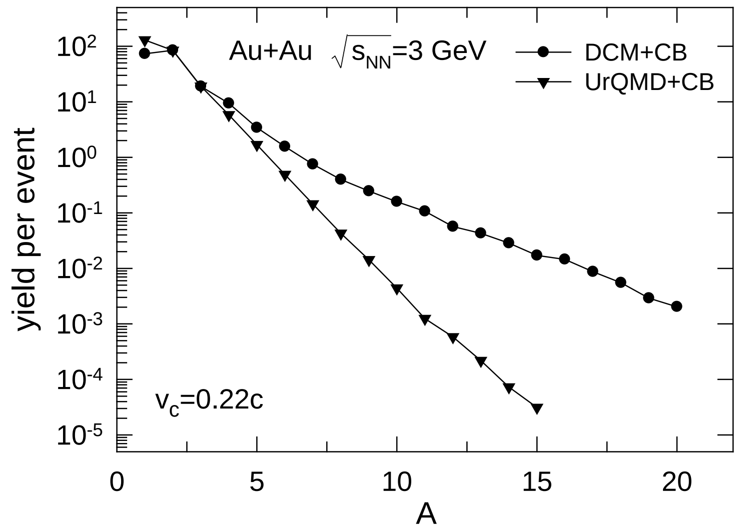
Yields of nuclei and hypernuclei and excitation energies

Figure 2: Calculated distributions of local nuclear clusters (per event) formed from dynamically produced baryons after UrQMD and the clusterization (CB) procedure by using the selection of the baryons with the velocity and coordinate proximity. Top panel (a) mass distributions of the cluster with the velocity parameter vc=0.14c. Middle panel (b) mass distributions of the cluster with the velocity parameter vc=0.22c. Bottom panel (c) average excitation energy of the clusters versus their mass number. The times for stopping the UrQMD calculations and vc parameters are shown in the panels.

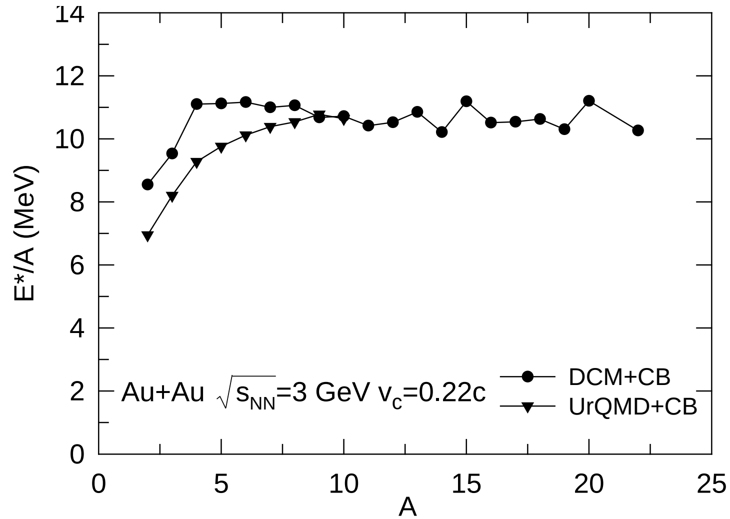


hot baryon clusters





Mass distributions

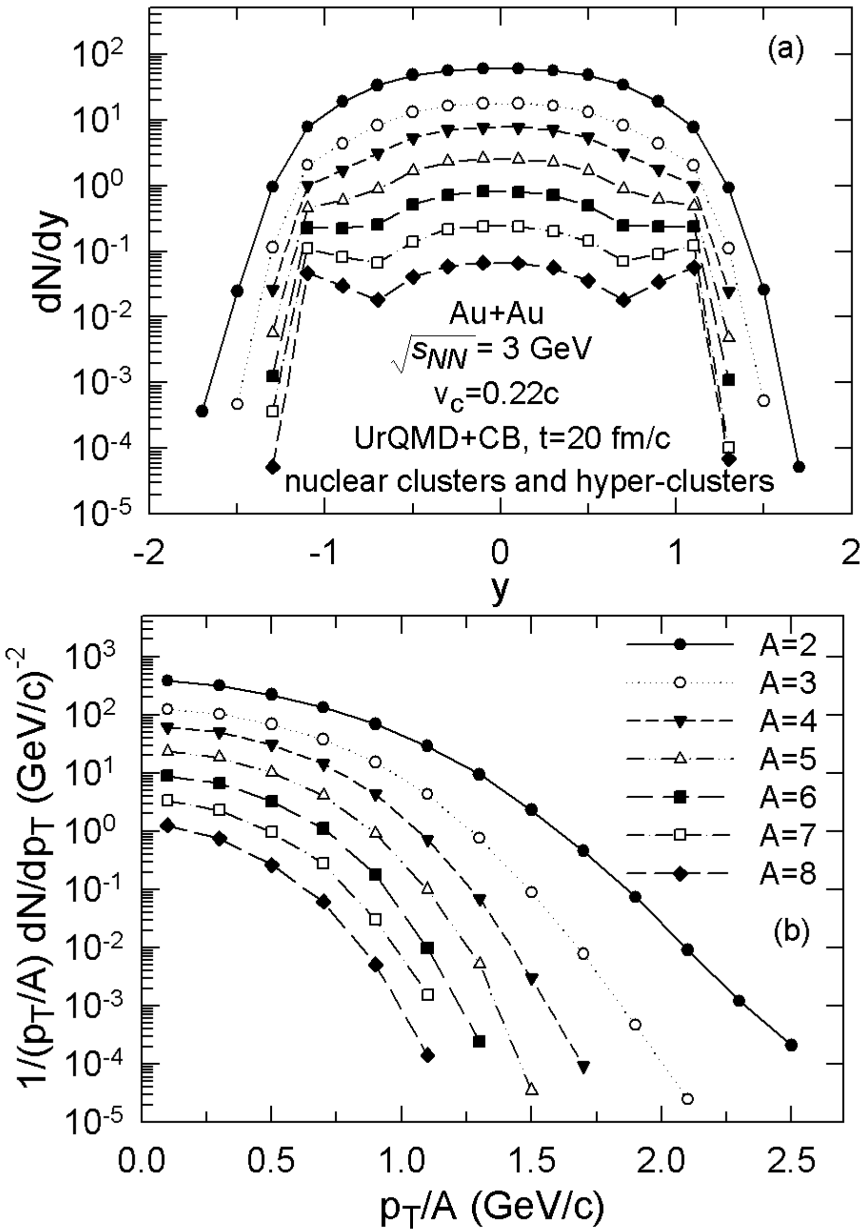


Excitation energies

The calculations are performed with the PSG, UrQMD and DCM to generate baryons in central Au+Au collisions, v_c = 0.22c is applied for the identification of hot clusters.

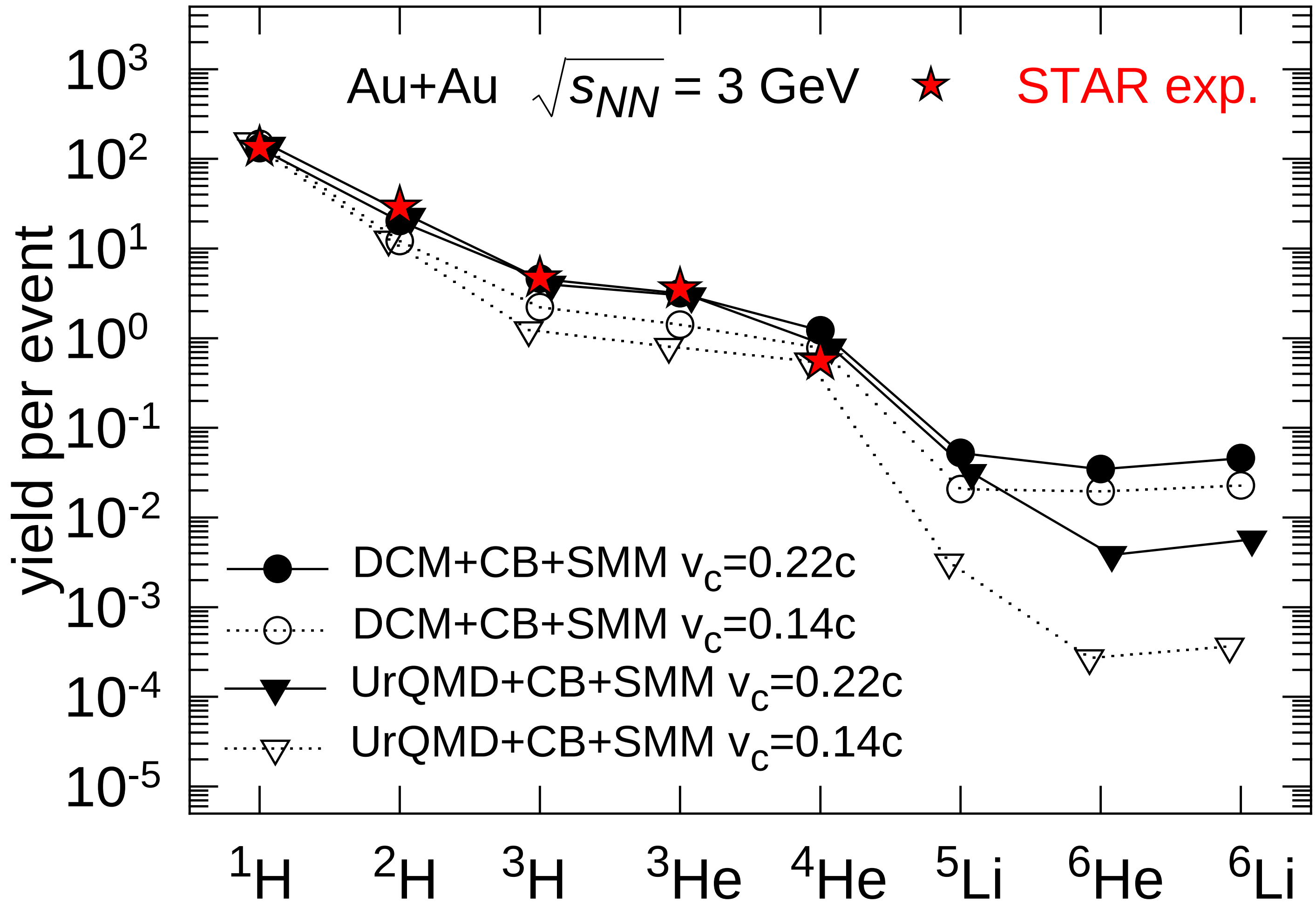
Light nuclei and hypernuclei: A=2-8

Figure 3: Rapidity (a) and transverse momentum per nucleon (b) (integrated over all rapidities) distributions of the excited baryon clusters, which have the mass numbers from A=2 to 8. Yields are per event.



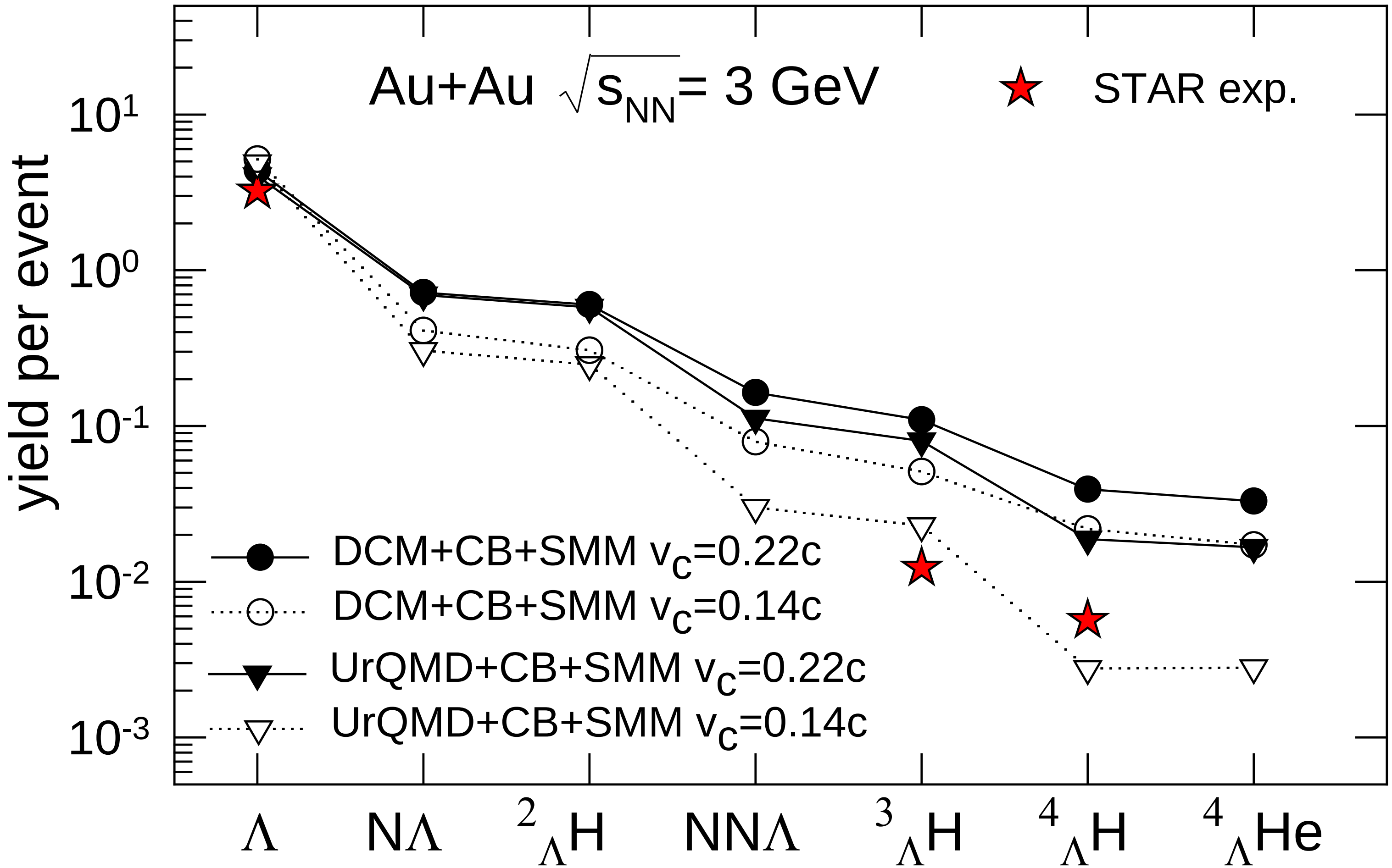
N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M.Bleicher, Phys. Rev. C **108**, 054904 (2023).

Comparison with the STAR data



N. Buyukcizmeci, Yu Lebed, A. S. Botvina, Physics of Particles and Nuclei Letters, 21(5) (2024) 983-986.

Comparison of light hypernuclei with the STAR data



N. Buyukcizmeci, Yu Lebed, A. S. Botvina, Physics of Particles and Nuclei Letters, 21(5) (2024) 983-986.

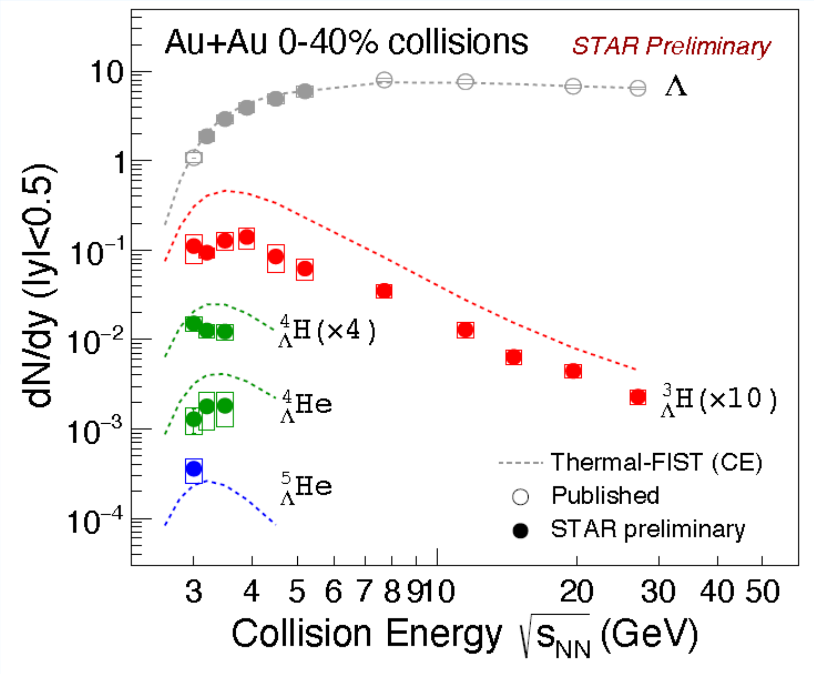
STAR presents new data! Let's see!

Yingjie Zhou for the STAR Collaboration
CCNU, GSI

Apr. 9, 2025

Quark Matter 2025, Frankfurt, Germany

First measurement of A = 5 hypernuclei yield and directed flow in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV



STAR, PRL 128, 202301 (2022)
V. Vovchenko et al., PRC 93, 064906 (2016)

- ${}^3_\Lambda$H plateaus at $\sqrt{s_{NN}}$ = 3-4 GeV

  Interplay between increasing baryon density and stronger strangeness canonical suppression towards low energies

- Across all energies, thermal model describes Λ, overestimates ${}^3_\Lambda$H, ${}^4_\Lambda$H, and ${}^4_\Lambda$He, slightly underestimates ${}^5_\Lambda$He
  - Thermal model includes all unstable nuclei feed down, except ${}^5_{\Sigma^0}$He

10

Prediction power of our models:

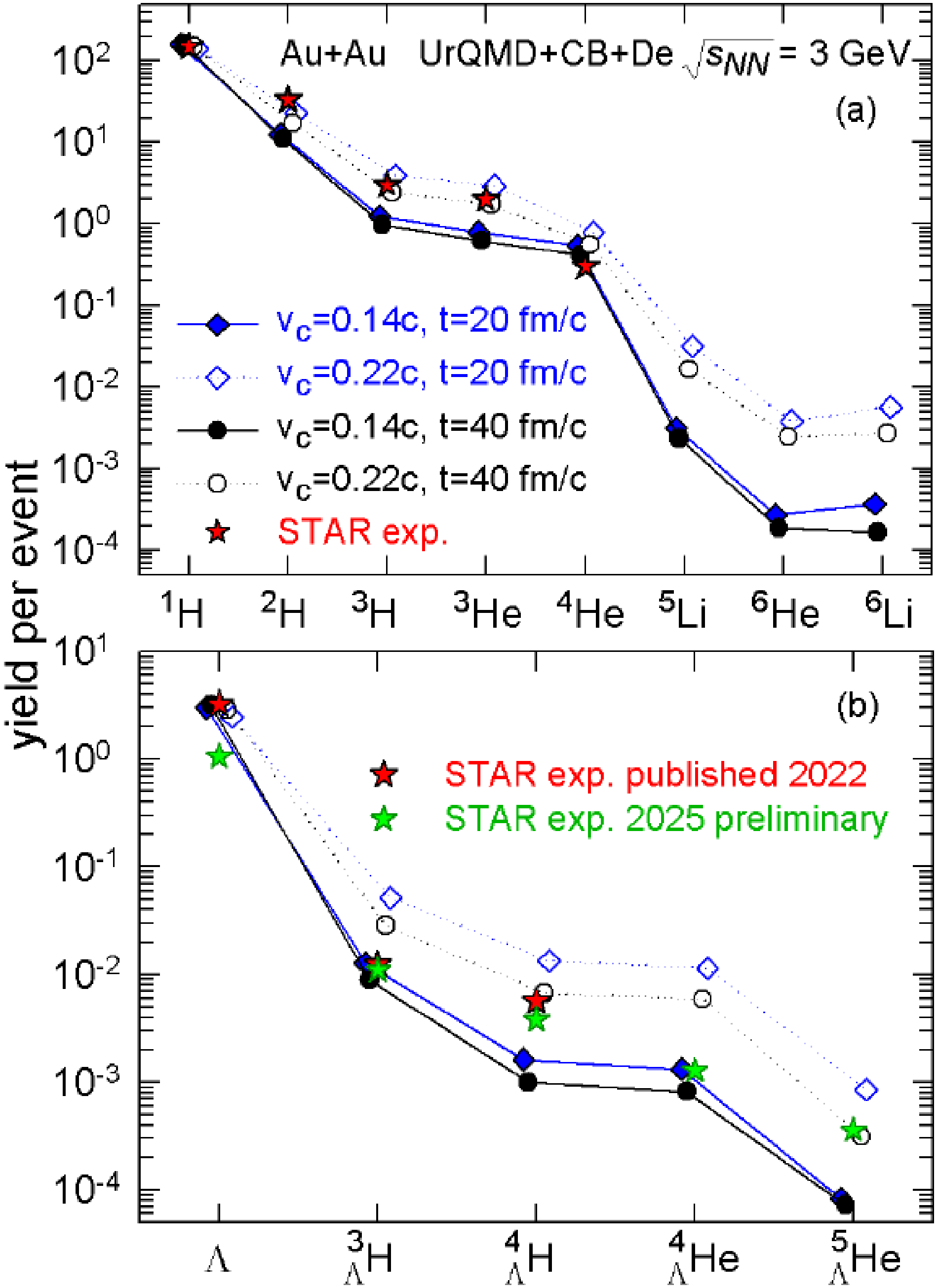
We confirm that our model calculations for ${}^{3}_{\Lambda}$He and ${}^{4}_{\Lambda}$He are also consistent with new presented preliminary data by Yingjie Zhou for the STAR collaboration at Quark Matter 2025, Frankfurt!

$^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi$-

$^{4}_{\Lambda}H \rightarrow {}^{4}He+\pi$-

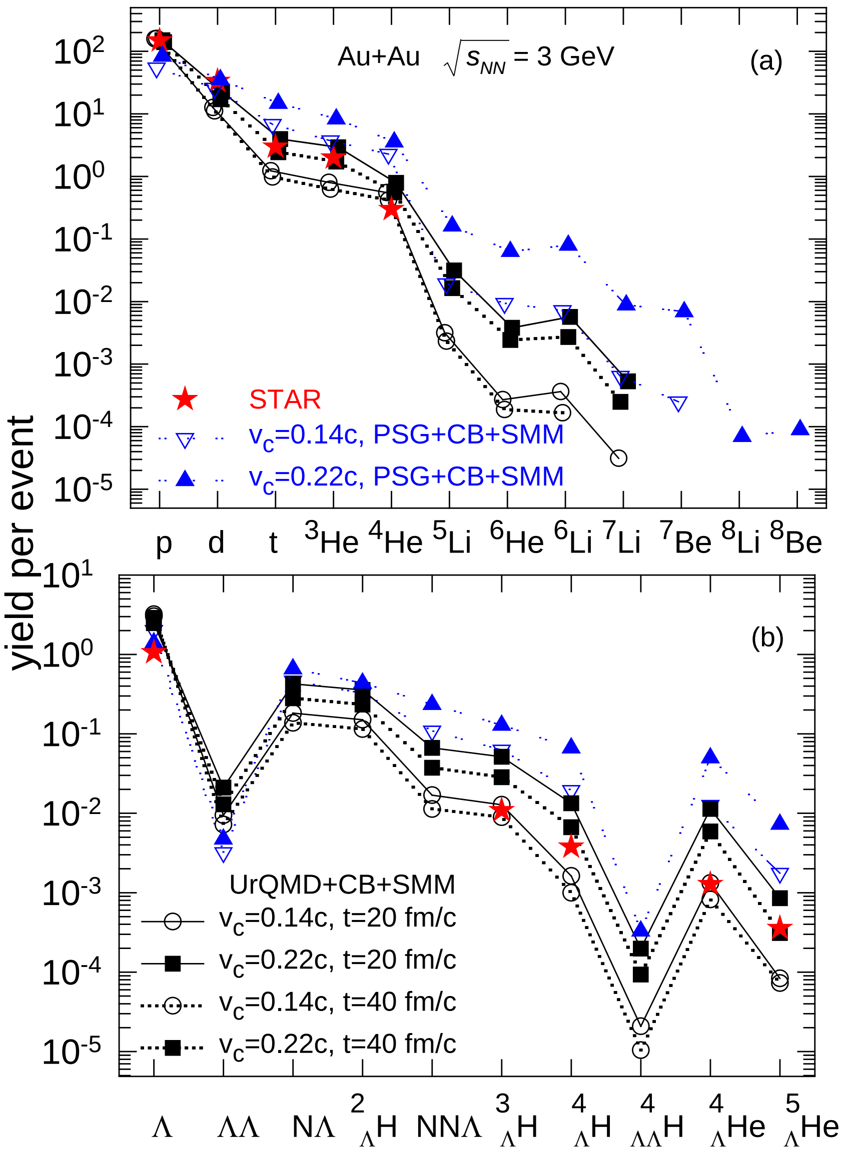
$^{4}_{\Lambda}He \rightarrow {}^{3}He+p+\pi$-

$^{5}_{\Lambda}He \rightarrow {}^{4}He+p+\pi$-



New exotic light nuclei

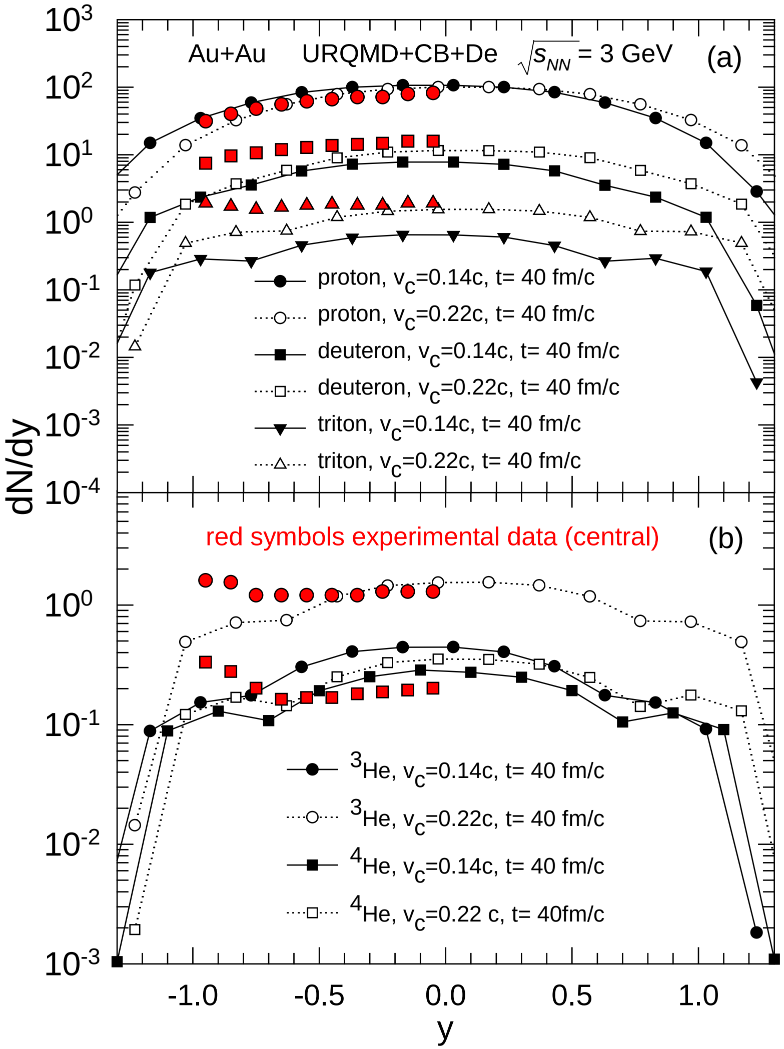
and hypernuclei (exp. data is updated from QM2025), double-hypernuclei.



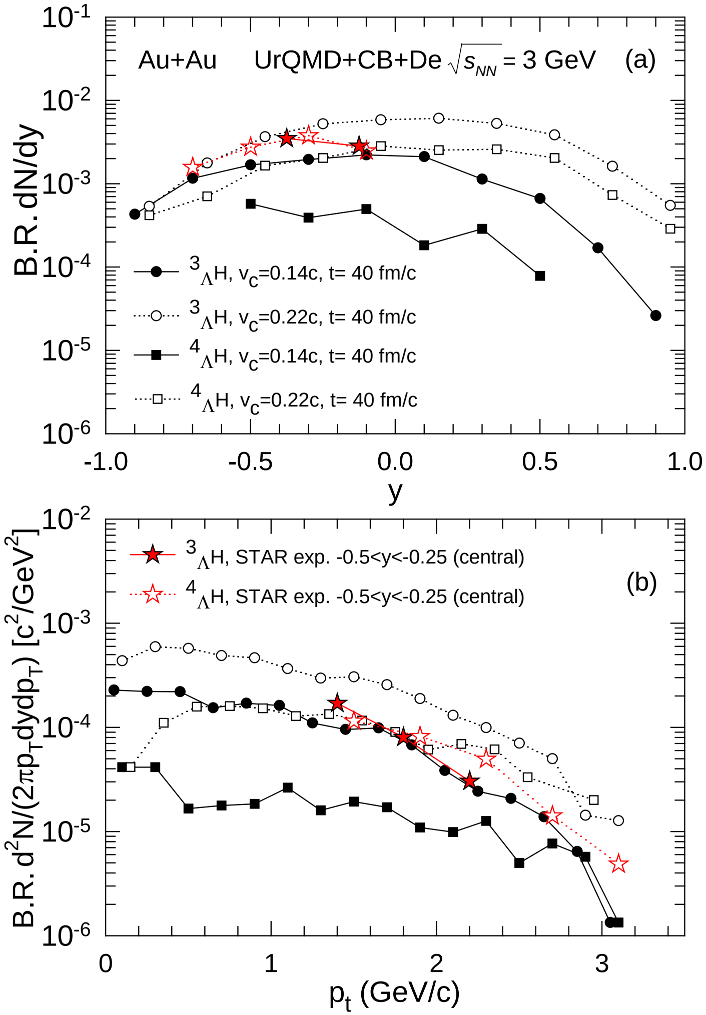
[1] N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M. Bleicher, Eur. Phys. J. A **61**, 23 (2025).

Comparison with the STAR data for light nuclei and hypernuclei

P, d, t, ^{3}He and ^{4}He



$^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H



[2] N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M. Bleicher, Phys. Rev. C **108**, 054904 (2023).

CONCLUSIONS

- It is shown that the (hyper)nuclei yields obtained in the STAR experiments can be successfully described by using the DCM+SMM and UrQMD+SMM hybrid models.
- We use the idea of local chemical equilibrium in the expanding nuclear matter. This agreement can be obtained when the parameters of hot nuclear matter in the clusters coincide with the parameters of finite nuclear systems extracted from multifragmentation studies.
- We predict many heavy (and exotic) nuclei and hypernuclei which detection would be crucial for better determination of the reaction mechanism and properties of hypermatter at subnuclear density.
- We confirm that our model calculations for $^{3}_{\Lambda}$He and $^{4}_{\Lambda}$He are also consistent with new presented preliminary data by Yingjie Zhou for the STAR collaboration at Quark Matter 2025, Frankfurt!
- More experimental data needed (especially, which are related to the correlations of the produced particles and nuclei), and we hope it will be available soon, after the experiments at NICA (Dubna) and FAIR (Darmstadt).
- Thank you for your attention!

INTW2026 will be in Antalya, Türkiye!
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https://intw2024.selcuk.edu.tr/