Recent progress on nuclei and hypernuclei formation theory at high energies

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in collaboration with

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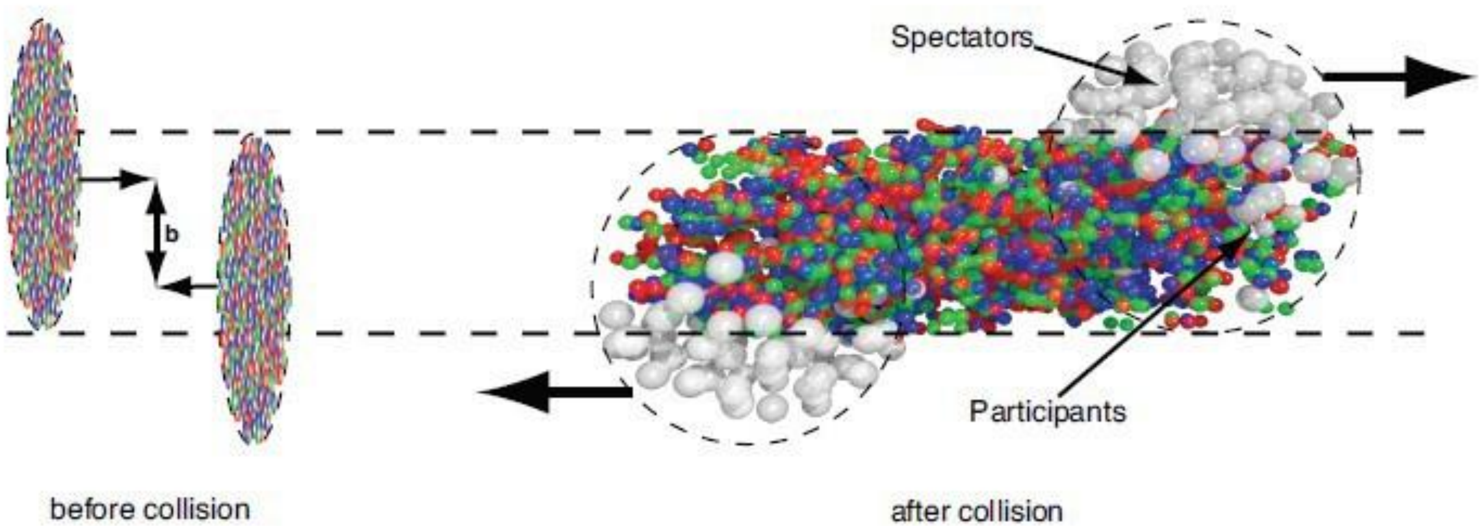
The authors acknowledges the Scientific and Technological Research Council of Turkey (TUBITAK) support under Project No. 121N420 and German Academic Exchange Service (DAAD) support from a PPP exchange grant.

Qualitative picture of dynamical stage of the reaction leading to fragment production (e.g., UrQMD calculations)



- Fragment formation is possible from both participants and spectator residues

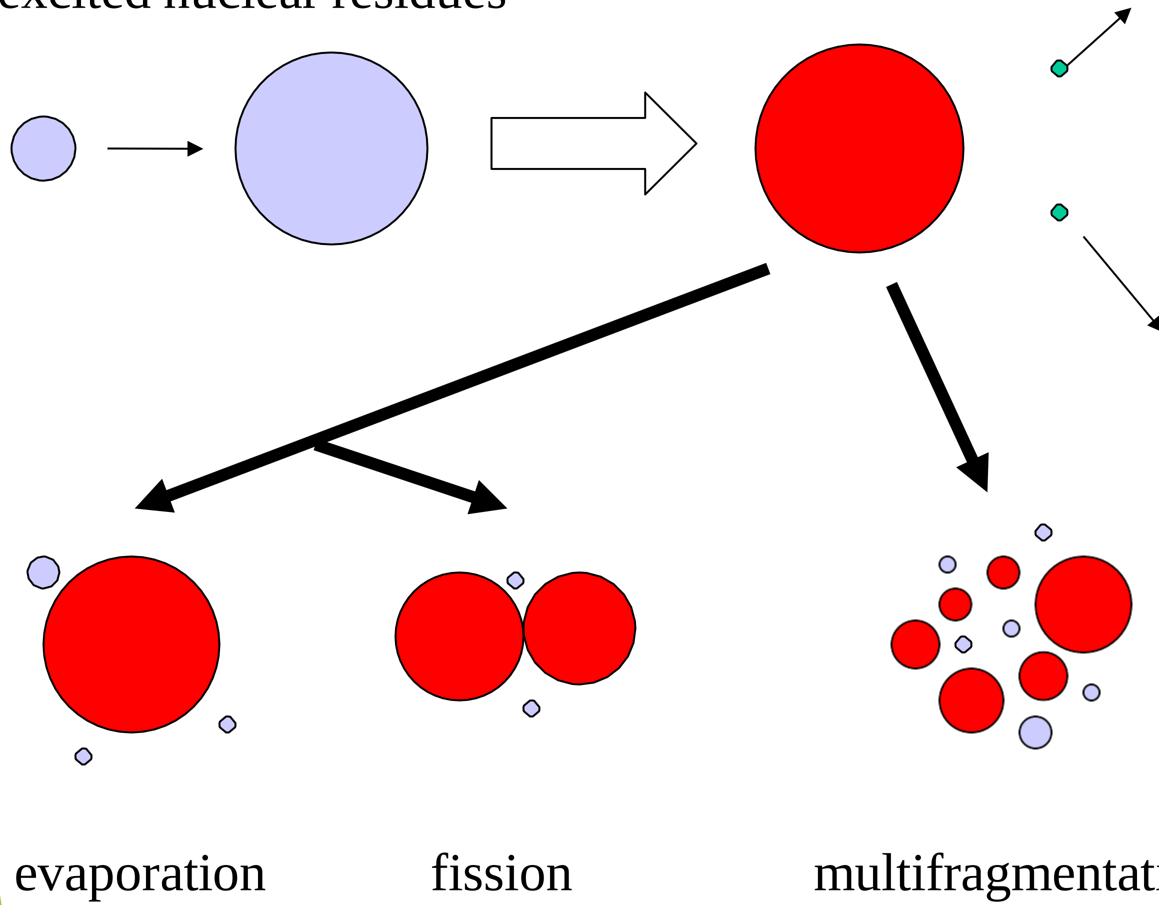
- UrQMD PHSD DCM GiBUU

- All transport modes predict similar picture: Hyperons can be produced at all rapidities, in participant and spectator kinematic regions.

Low/intermediate energies: hadron/lepton collisions with nuclei, the same mechanisms in peripheral ion collisions

Dinamical stage with particle emission and production of excited nuclear residues

Preequlibrium emission + equilibration



Statistical approach

N.Bohr (1936)

Compound-nucleus decay channels (sequential evaporation or fission) dominate at low excitation energy of thermal sources $E^{*}<2$-3 MeV/nucl

N.Bohr, J.Wheeler (1939)
V.Weisskopf (1937)

starting 1980-th :

At high excitation energy $E^{*}>3$-4 MeV/nucl there is a simultaneous break-up into many fragments (e.g. SMM: Phys.Rep.**257**(1995)133)

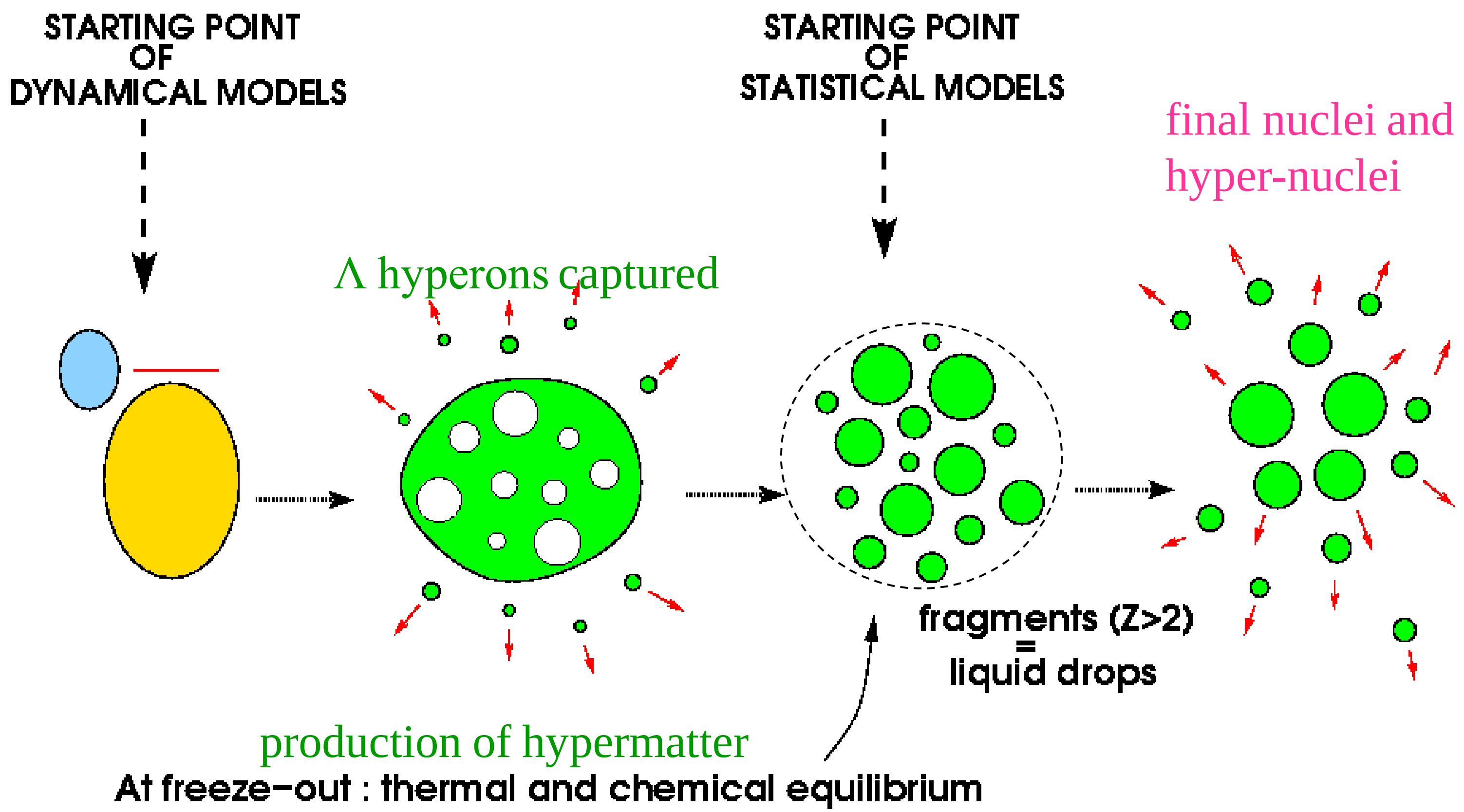
Generalization: statistical de-excitation model for nuclei with Lambda hyperons

In these reactions we expect analogy with

multifragmentation in intermediate and high energy nuclear reactions

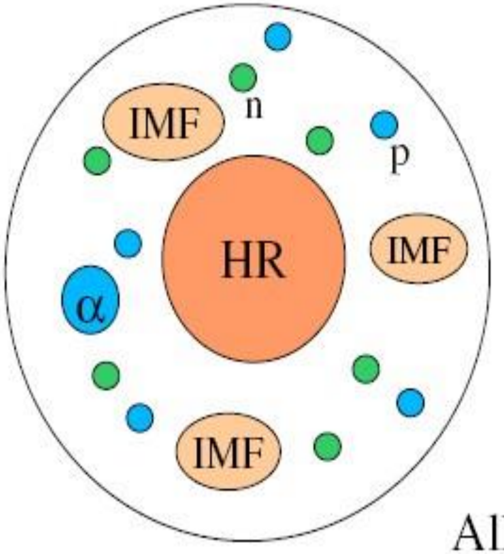
+ nuclear matter with strangeness

A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909



Statistical Multifragmentation Model (SMM)

J.P.Bondorf, A.S.Botvina, A.S.Iljinov, I.N.Mishustin, K.Sneppen, Phys. Rep. **257** (1995) 133



Ensemble of nucleons and fragments
in thermal equilibrium characterized by
neutron number N_0
proton number Z_0, $N_0+Z_0=A_0$
excitation energy $E^*=E_0-E_{CN}$
break-up volume $V=(1+\kappa)V_0$ freeze-out

All break-up channels are enumerated by the sets of fragment multiplicities or partitions, $f=\{N_{AZ}\}$

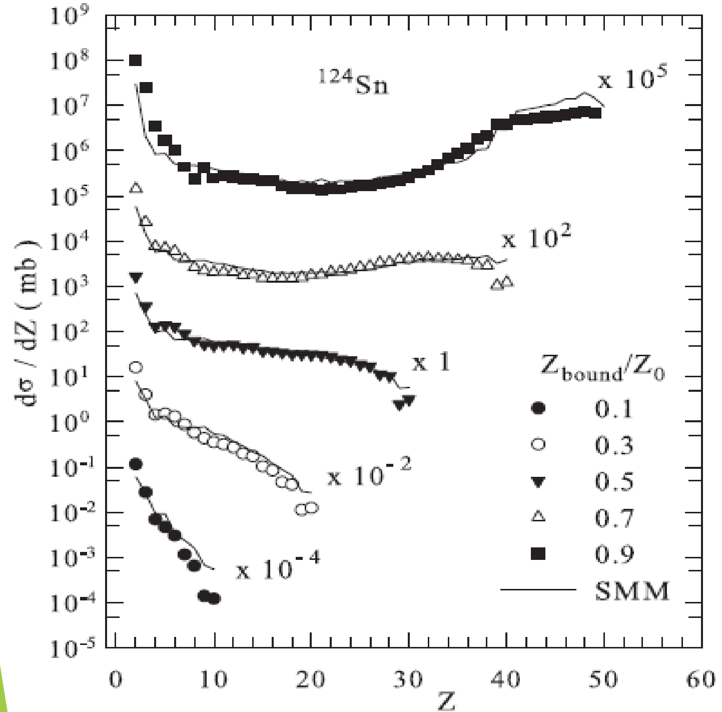
Statistical distribution of probabilities: $W_f \sim \exp\{S_f(A_0, Z_0, E^*, V)\}$
under conditions of baryon number (A), electric charge (Z) and energy (E*) conservation, including compound nucleus.

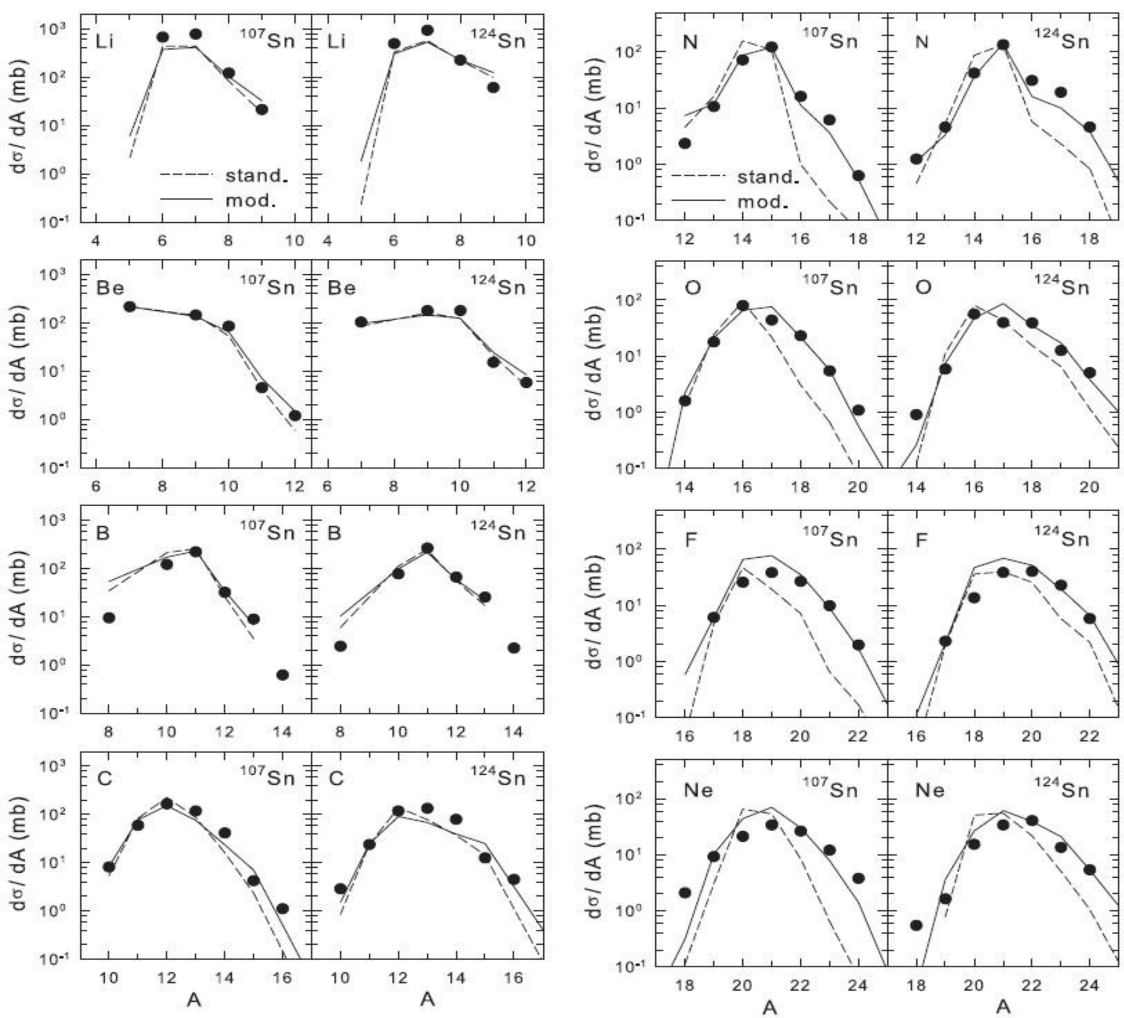
R.Ogul et al. PRC **83,** 024608 (2011) **ALADIN@GSI**

Isospin-dependent multifragmentation of relativistic projectiles

124,107-**Sn**, 124-**La** (600 A MeV) + **Sn** → projectile (multi-)fragmentation

Very good description is obtained within Statistical Multifragmentation Model, including fragment charge yields, isotope yileds, various fragment correlations.

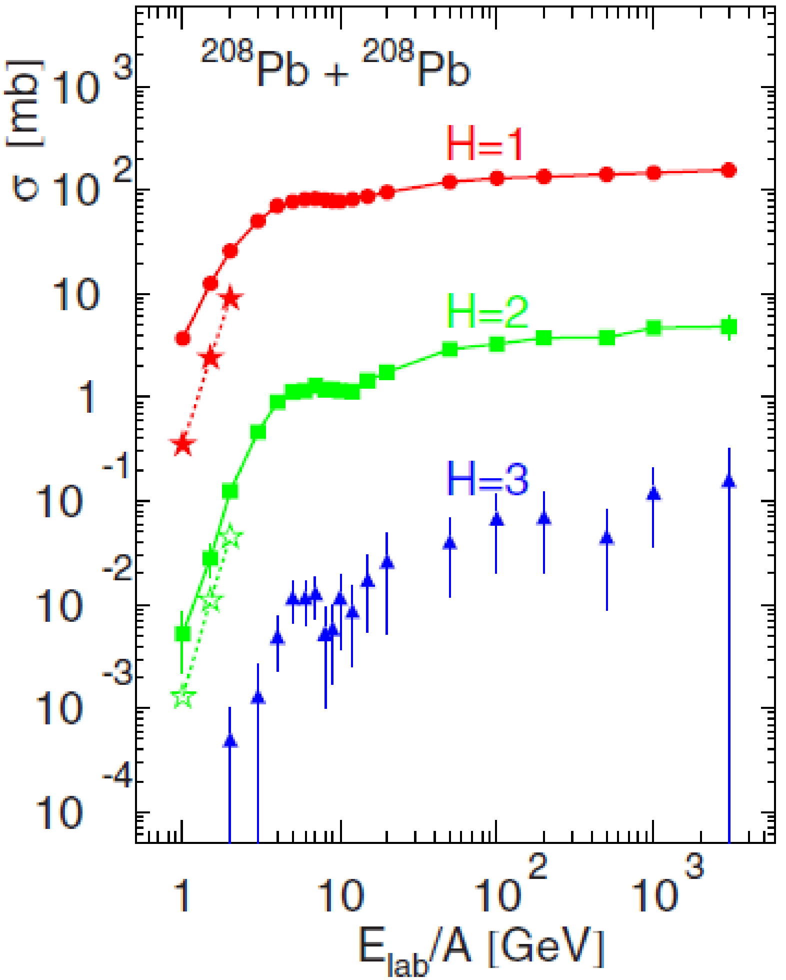


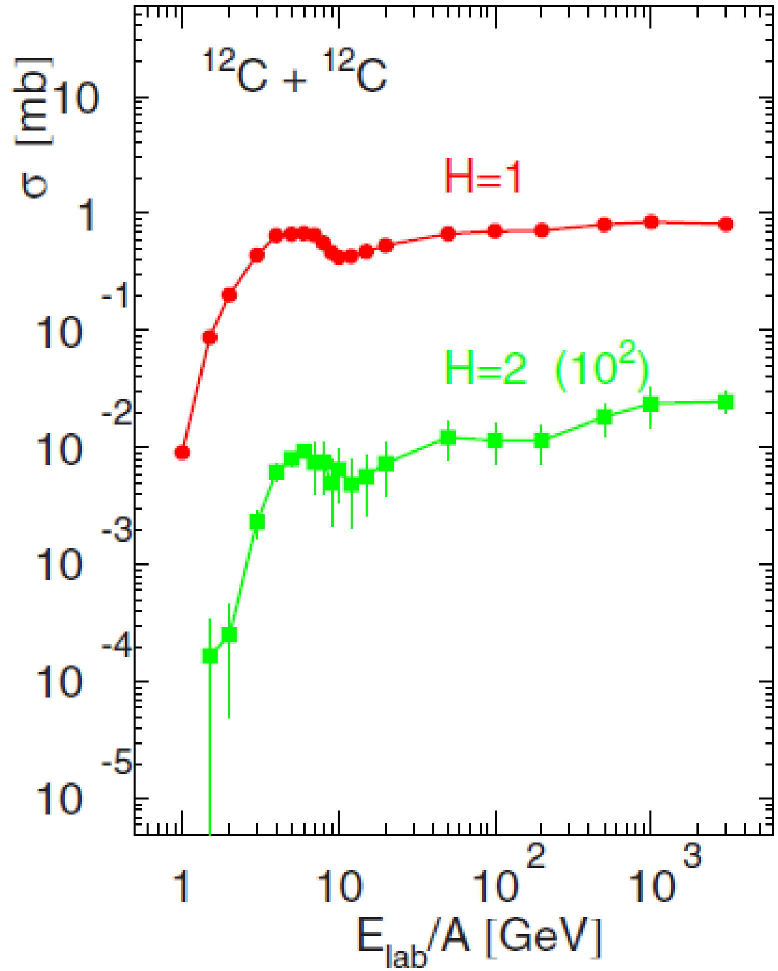


Statistical (chemical) equilibrium is established at break-up of hot projectile residues ! In the case of strangeness admixture we expect it too !

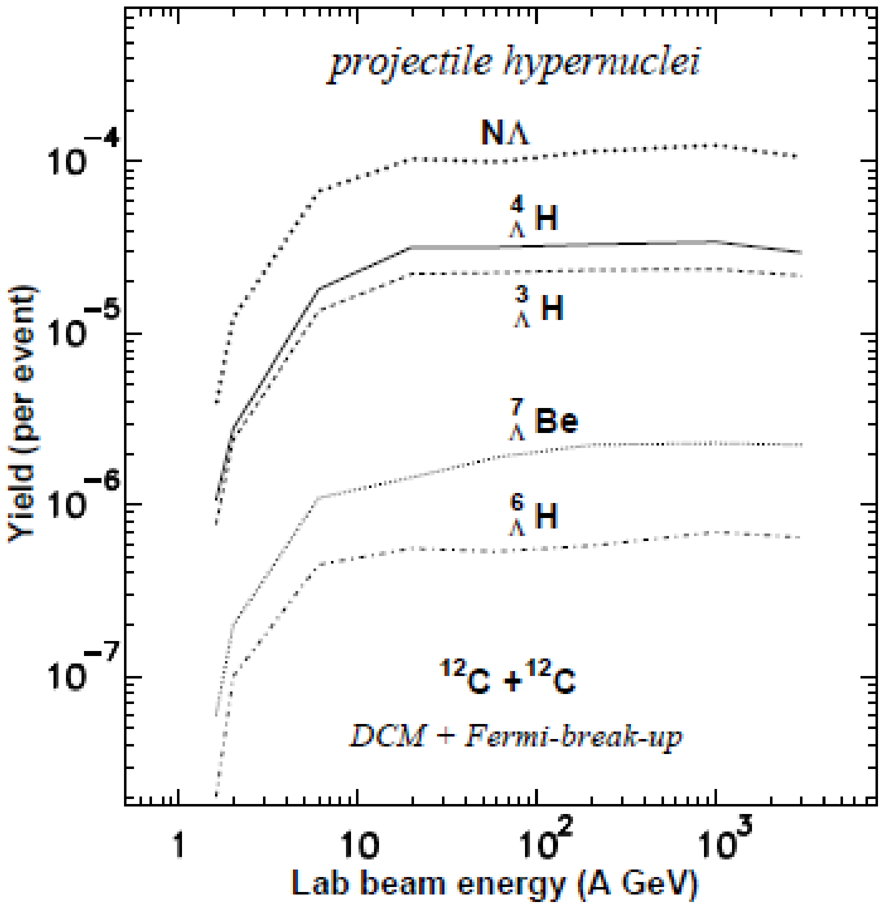
Production of excited hyper-residues in peripheral collisions, decaying into hypernuclei (target/projectile rapidity region).

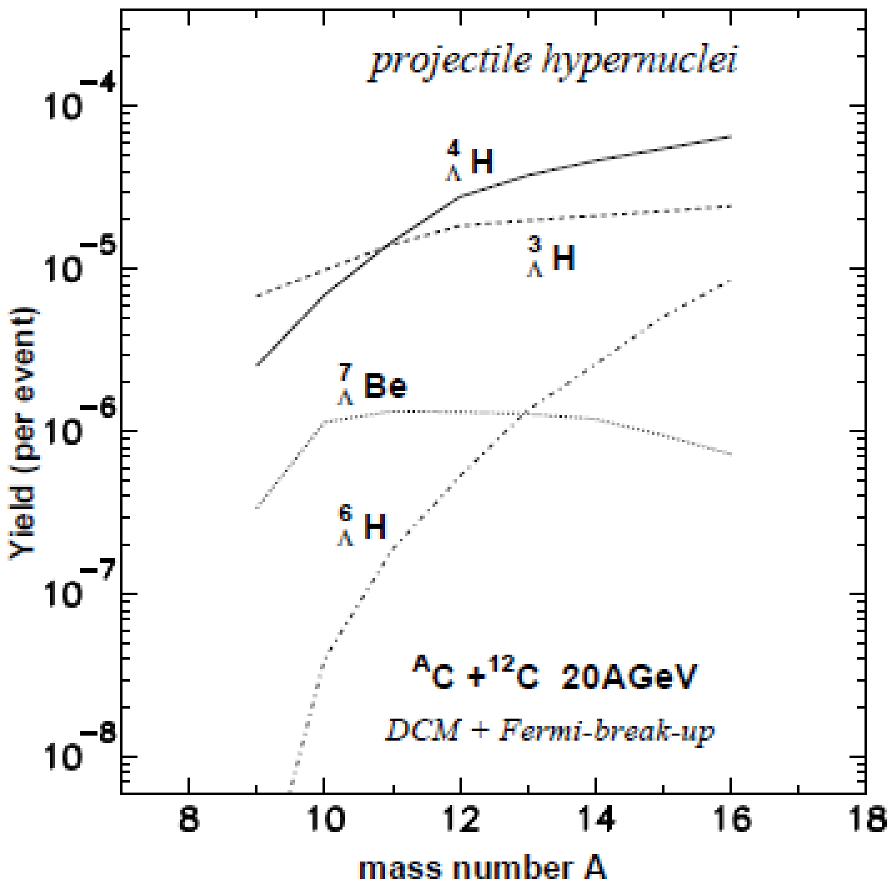
DCM and UrQMD + CB predictions: Phys. Rev. C95, 014902 (2017)





Production of light hypernuclei in relativistic ion collisions

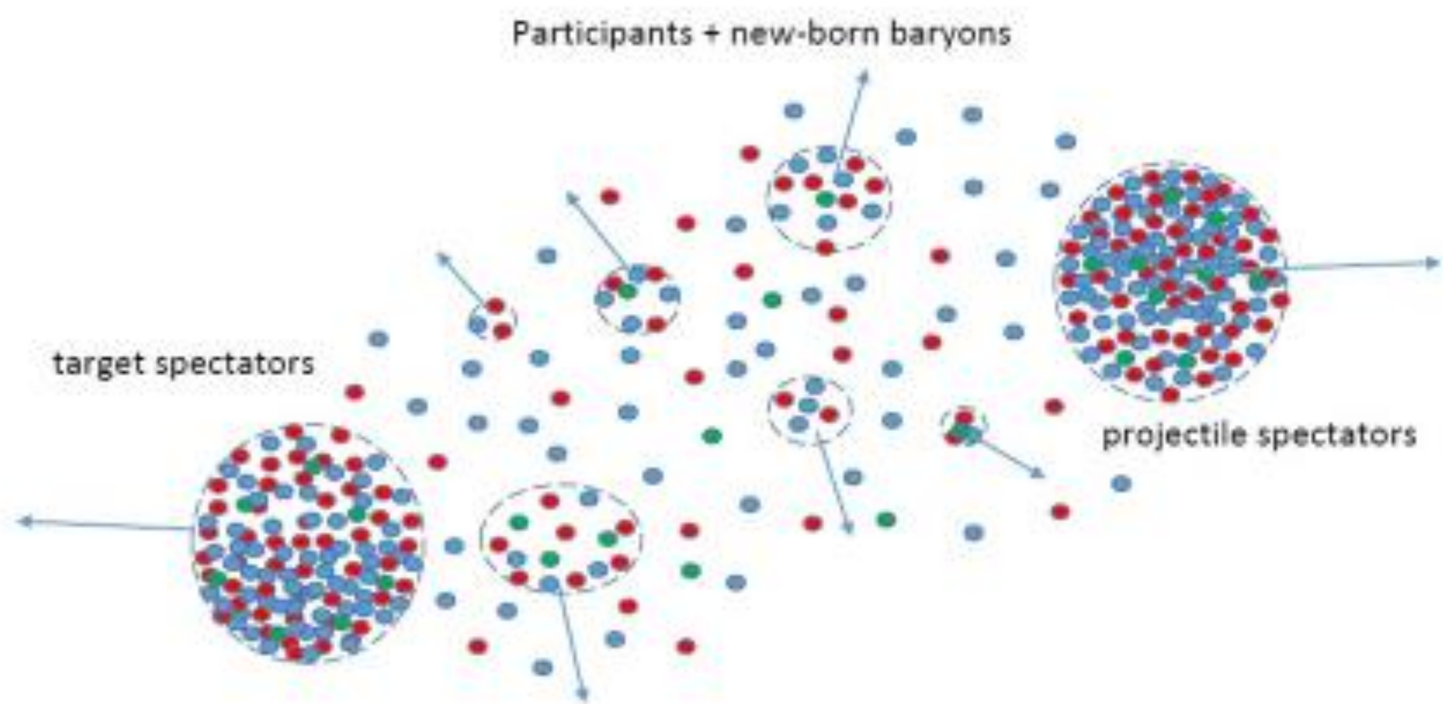




One can use exotic neutron-rich and neutron-poor projectiles, which are not possible to use as targets in traditional hyper-nuclear experiments, because of their short lifetime. Comparing yields of hypernuclei from various sources we can get info about their binding energies and properties of hyper-matter.

A.S.Botvina, K.K.Gudima, J.Pochodzalla, PRC 88, 054605, 2013

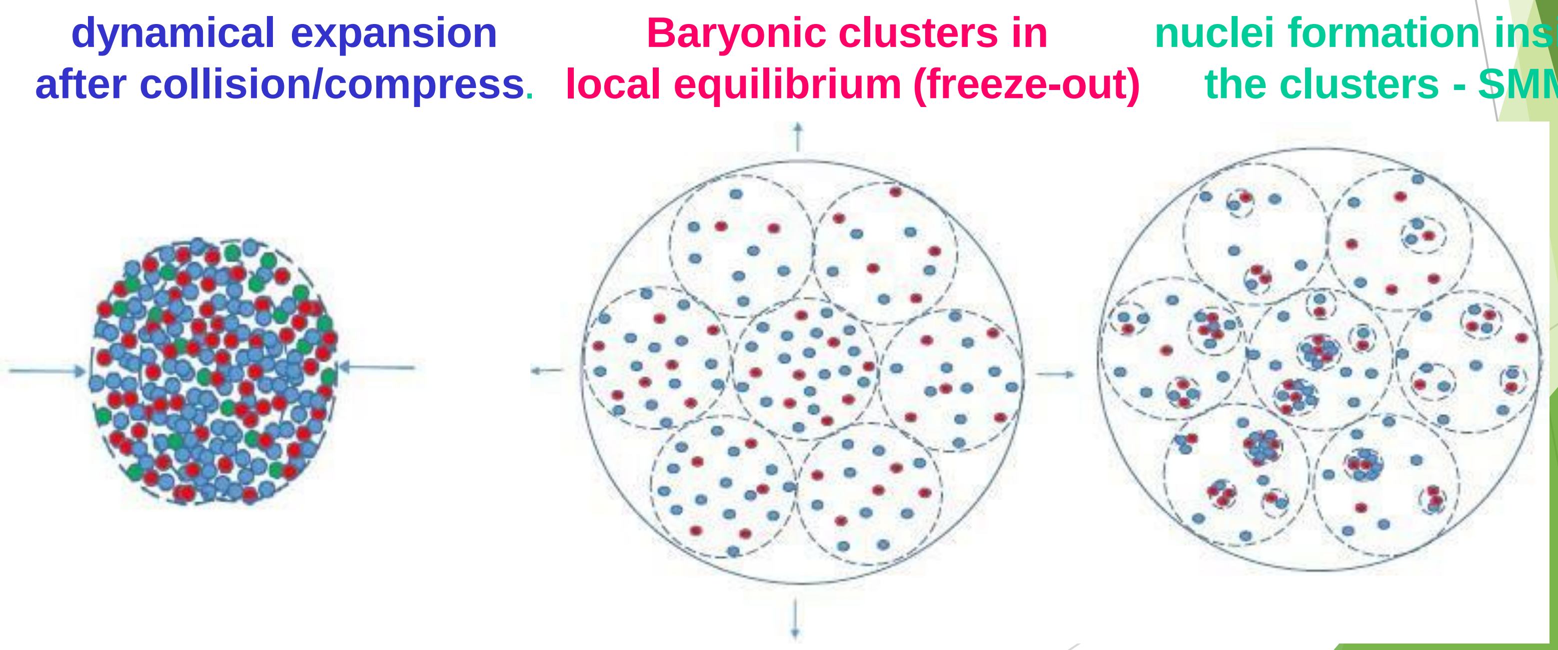
Formation of baryon clusters from the dynamically produced baryons as a results of secondary interaction between them, when they are in the vicinity of each other. Note: baryons in clusters can come to equilibrium and the clusters are excited respective to its ground state. This case is realized in Heavy- Ion collisions of medium/high energies.



Tübitak 118F111, Eur. Phys. J. A **56,** 210 (2020)

CENTRAL COLLISIONS

Nuclear system expands to low densities and passes the density around 0.1 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.



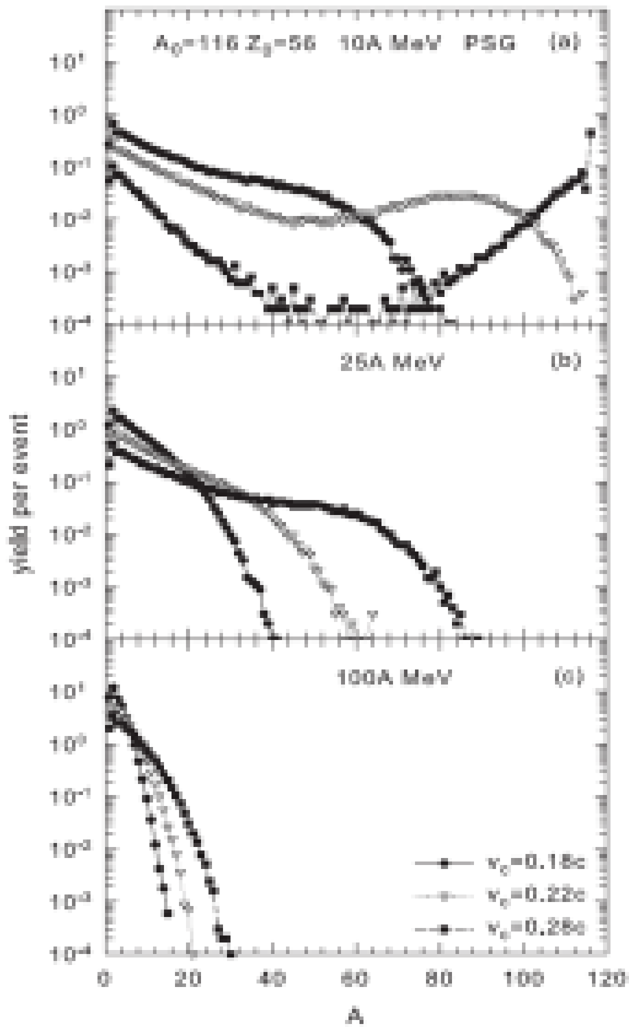
To check this novel mechanism with controlled models:
Phys.Rev.C 103 (2021) 064602 and Phys.Rev.C 106 (2022) 014607

The dynamical stage is 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.

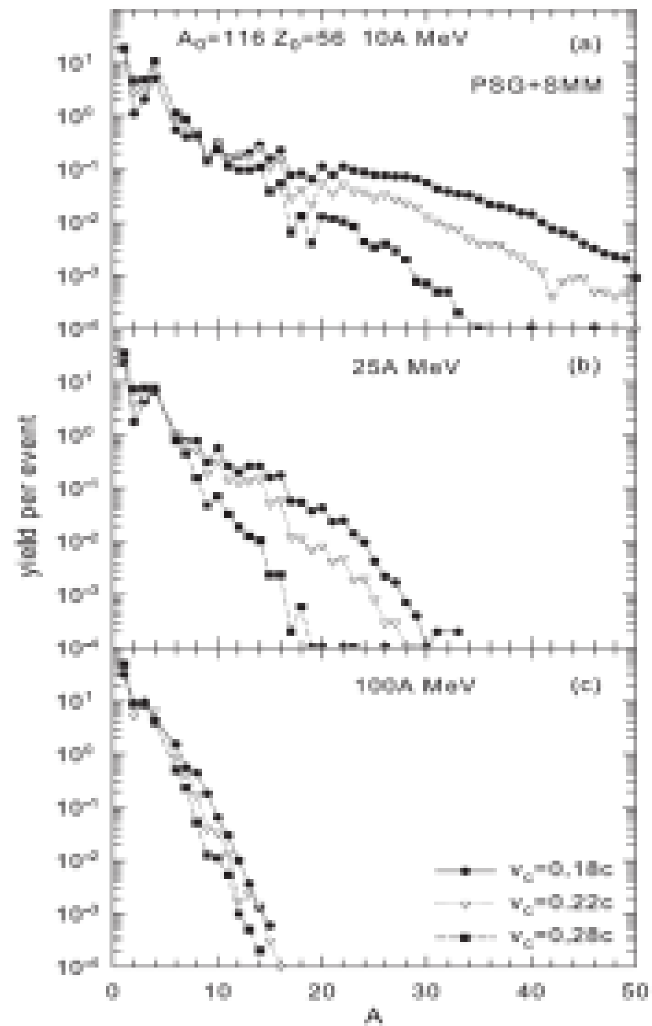
Selection of primary clusters (at low freeze-out density) by using the coalescence of baryon (CB) model (Phys. Lett. B742, 7 (2015)): according to their velocities $|V_i - V_0| \leq V_c$ and coordinates $|X_i - X_0| \leq X_c$.

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.

Nuclear system consists of primary clusters in local equilibrium:



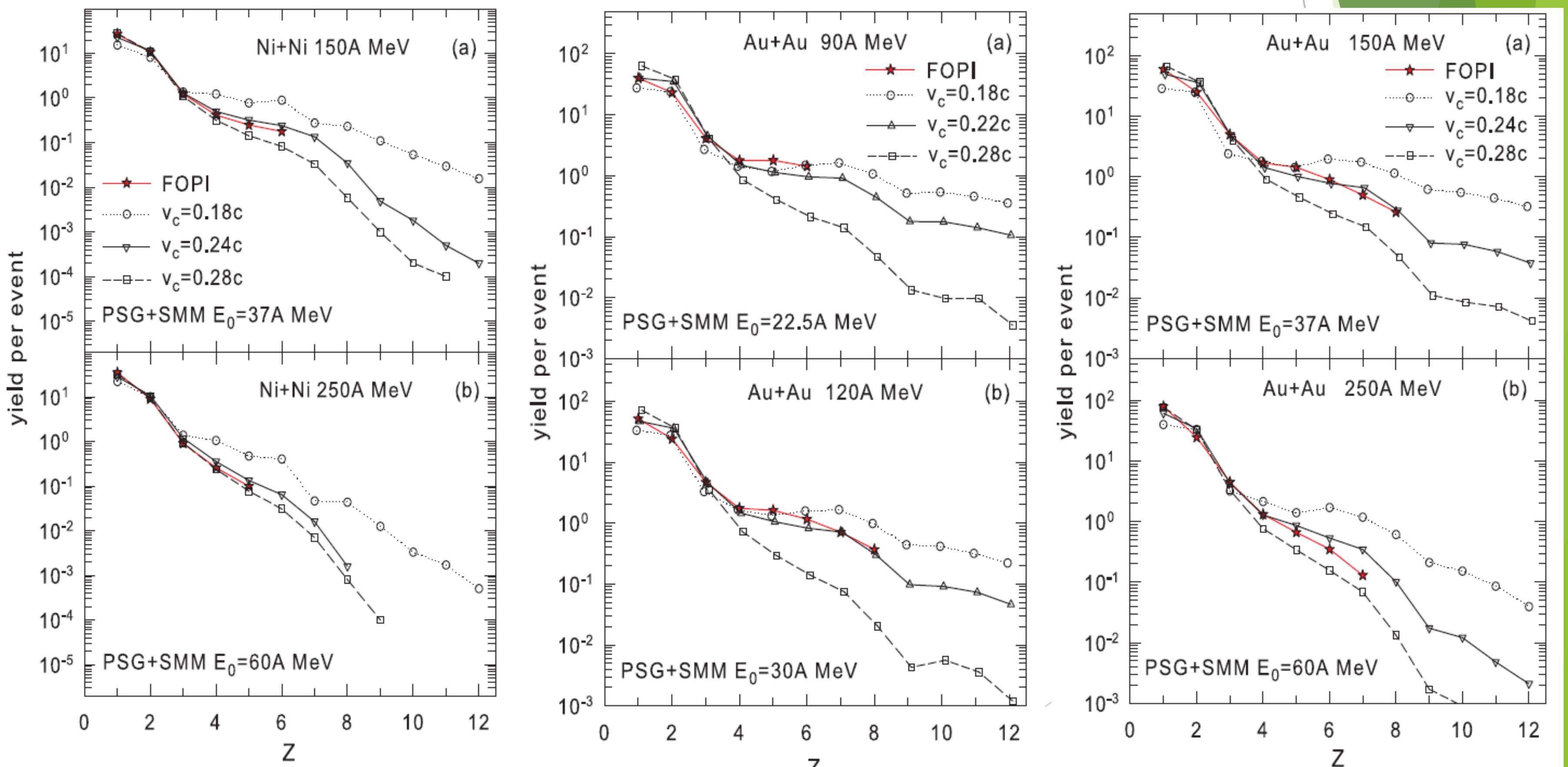
final nuclei after the statistical nucleation (disintegration of the excited clusters via SMM):



For the first, the consistent comparison with FOPI@GSI experimental data - Nucl. Phys. A848(2010)366 - on fragment production in central HI collisions is performed: Both charge yields and flow energies.

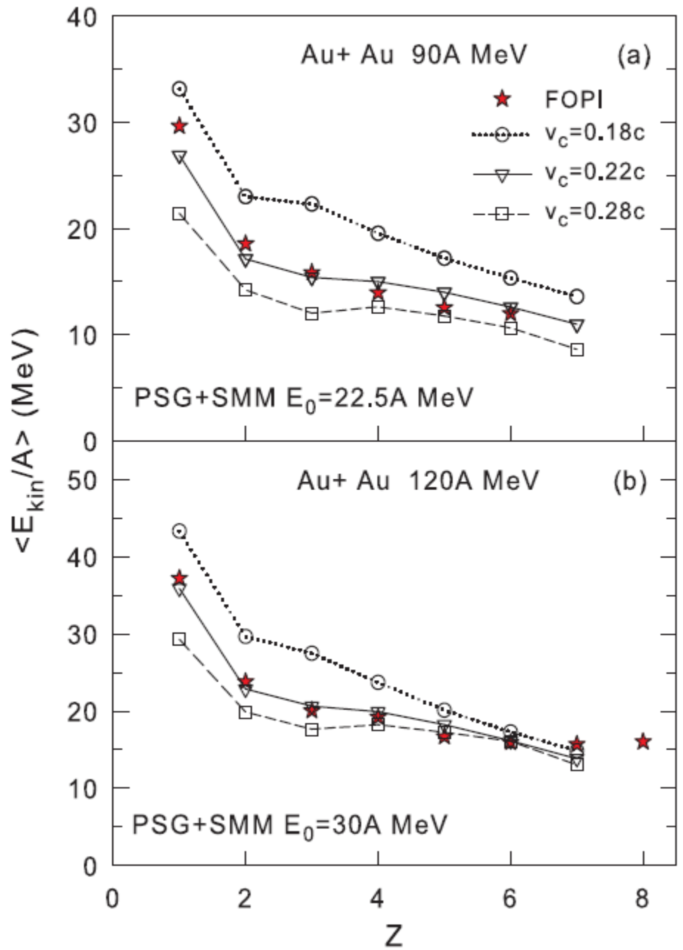
Phys.Rev.C103 (2021) 064602, Phys.Rev.C 106 (2022) 014607

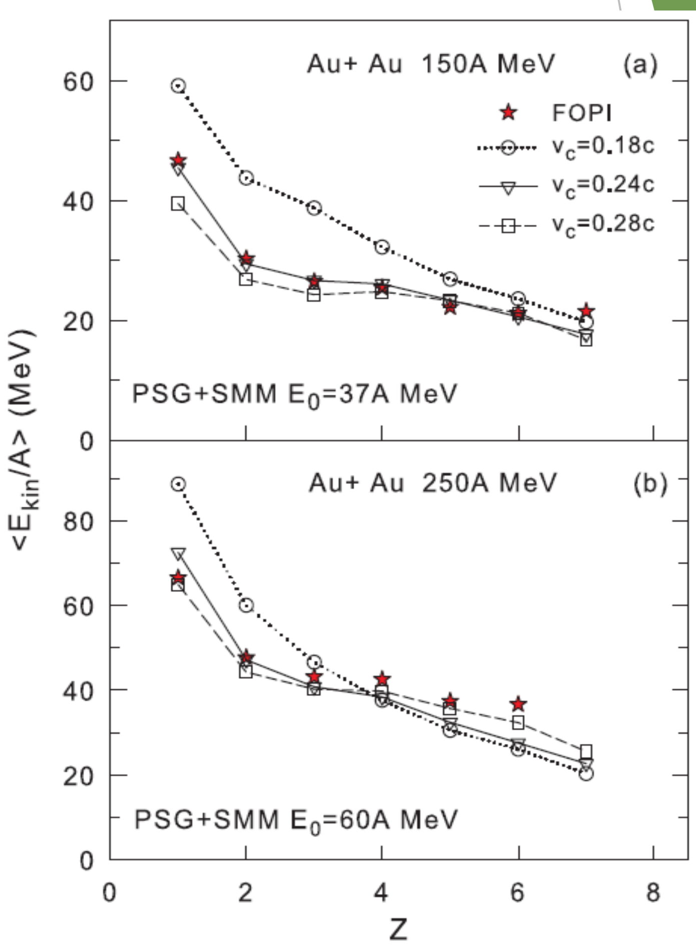
yields of nuclei in different reactions:



(until now the production of nuclei (Z>2) in central collisions was not possible to describe consistently)

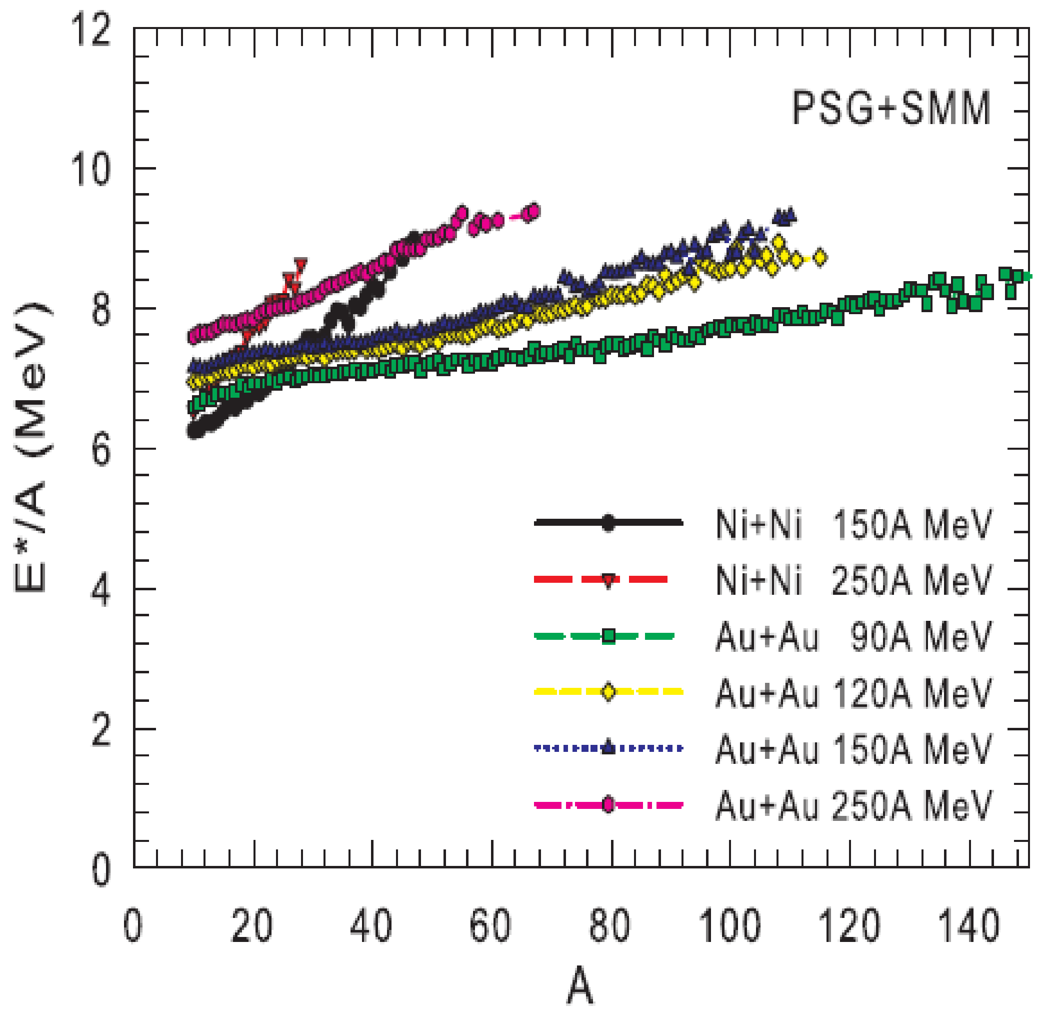
kinetic energies of nuclei in different reactions:





The description is possible if there is a limit for the excitation energy of the clusters: 6–10 MeV/nucleon, close to their binding energies. Temperature T=6--8 MeV (according to the statistical model) which corresponds to the coexistence region of the liquid-gas type phase transition in nuclear matter.

We may speak about an universal mechanism for nuclei formation both in peripheral and central heavy-ion collisions , independently on the way how the low density matter is produced: by thermal-like expansion of the excited residues (peripheral col.) or by dynamical-like expansion (central col.)

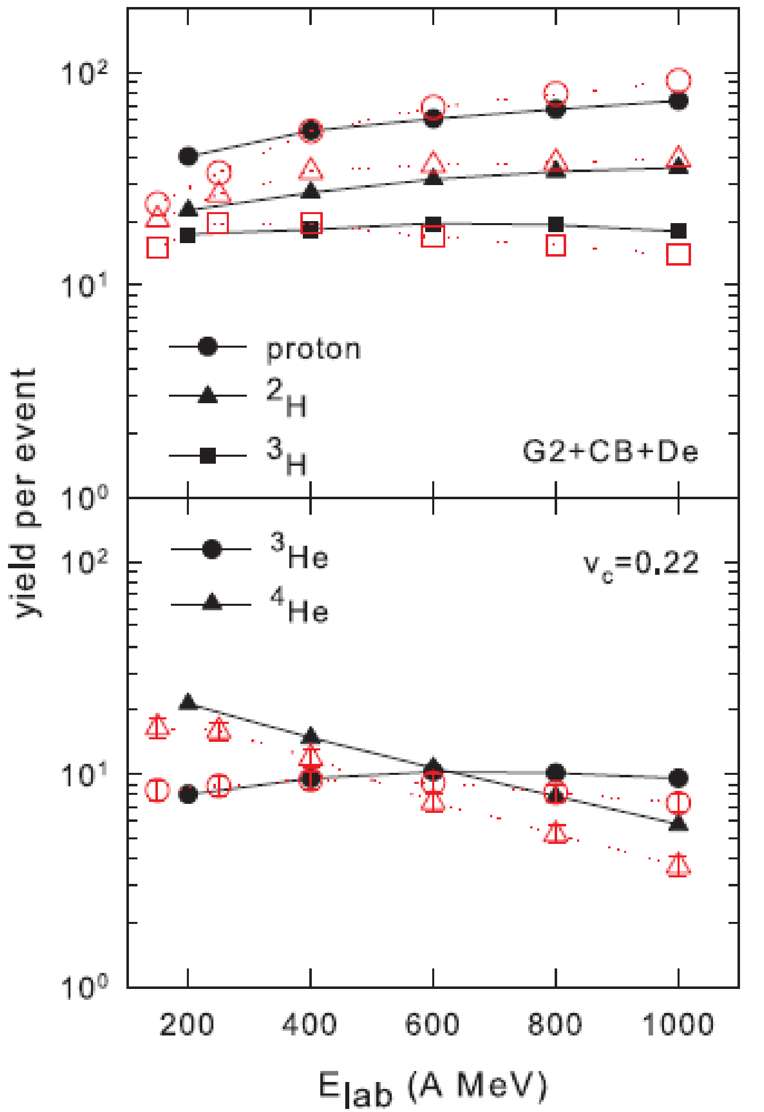


Important beam energy dependence of the light nuclei yields in Au+Au relativistic central collisions can be explained within our approach too.

Note: in simplistic coalescence picture yields of 3He are larger than 4He yields at all energies.
FOPI experimental data (red symbols) show intersection with increasing energy.

Relative behavior of yields of 3He and 4He with energy is important confirmation of the nucleation via the statistical mechanism

Phys.Rev.C103 (2021) 064602

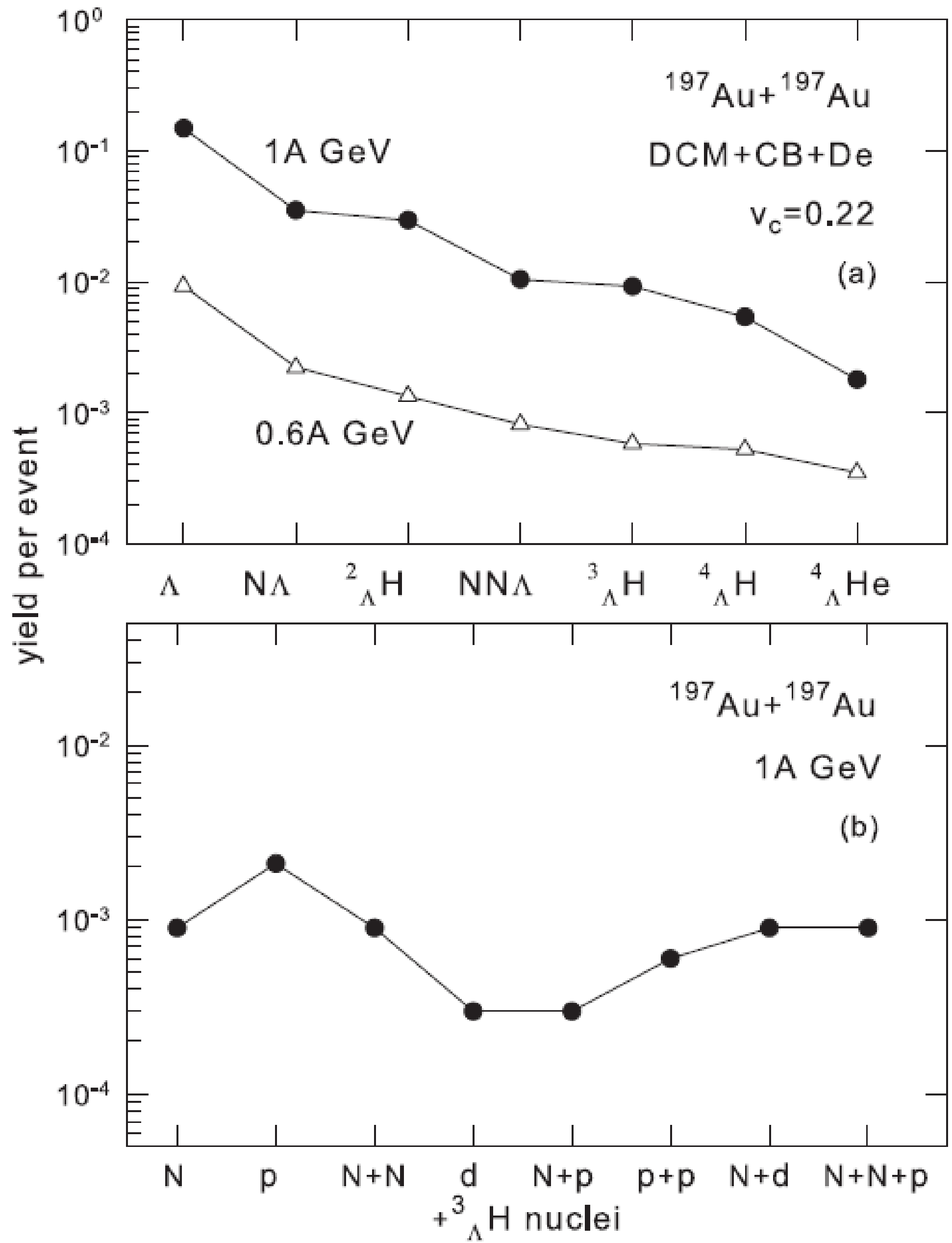


Production of hypernuclei in HI central collisions

Basing on this general mechanism we can predict the hypernuclei yields in relativistic central collisions too. Many different light hypernuclei can be produced. The correlations between nuclear species exist and it can be used for their identification.

Phys.Rev.C103 (2021) 064602

Future study will be to combine UrQMD+CB+De and analyze results of PSG, DCM and UrQMD models.



PRELIMINARY RESULTS: JUNE-NOVEMBER 2022

Formation and correlations of nuclei and hypernuclei in relativistic ion collisions

- We systematically analysed mass yields, transfers momenta, excitations energies of nuclei and hypernuclei produced via different hybrid models and compare STAR experimental data.
- We focused on models to describe nuclei and hypernuclei formation in Au+Au collisions at 1A GeV, 2A GeV and 3A GeV beam energies.
- PSG (Botvina et al. 2021-2022), DCM (Gudima et al.), UrQMD (Bleicher et al)
- primary hot fragments: PSG+CB, DCM+CB and URQMD+CB
- final cold nuclei: PSG+CB+De, DCM+CB+De and URQMD+CB+De

Construction of initial conditions for baryons in dynamical processes

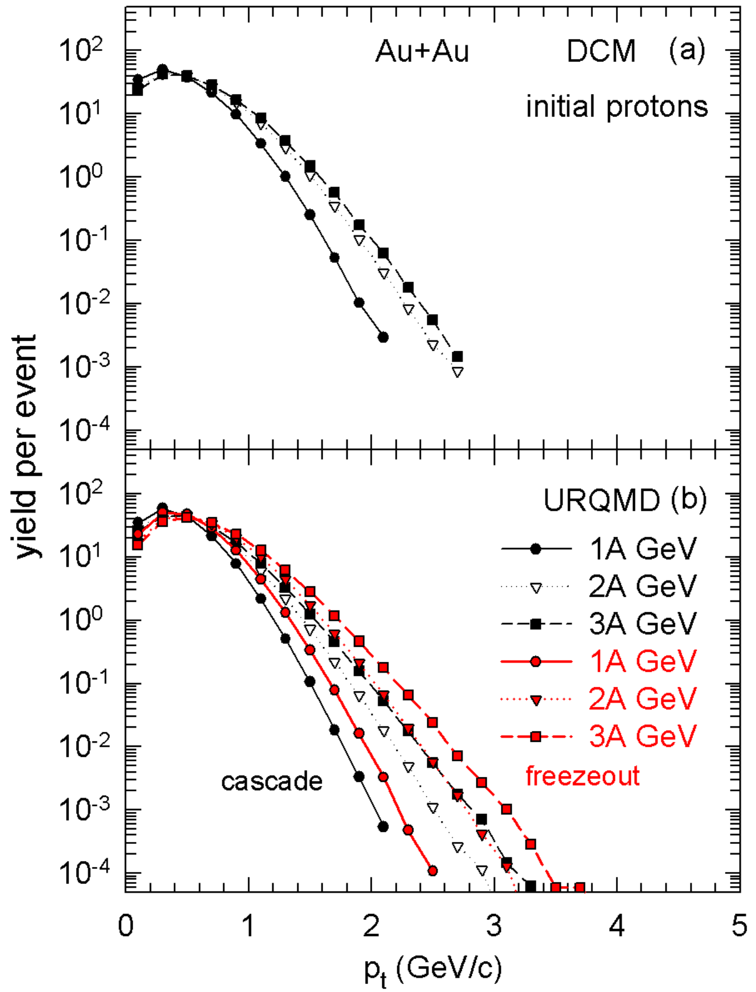


FIG. 1: Transverse momenta distributions

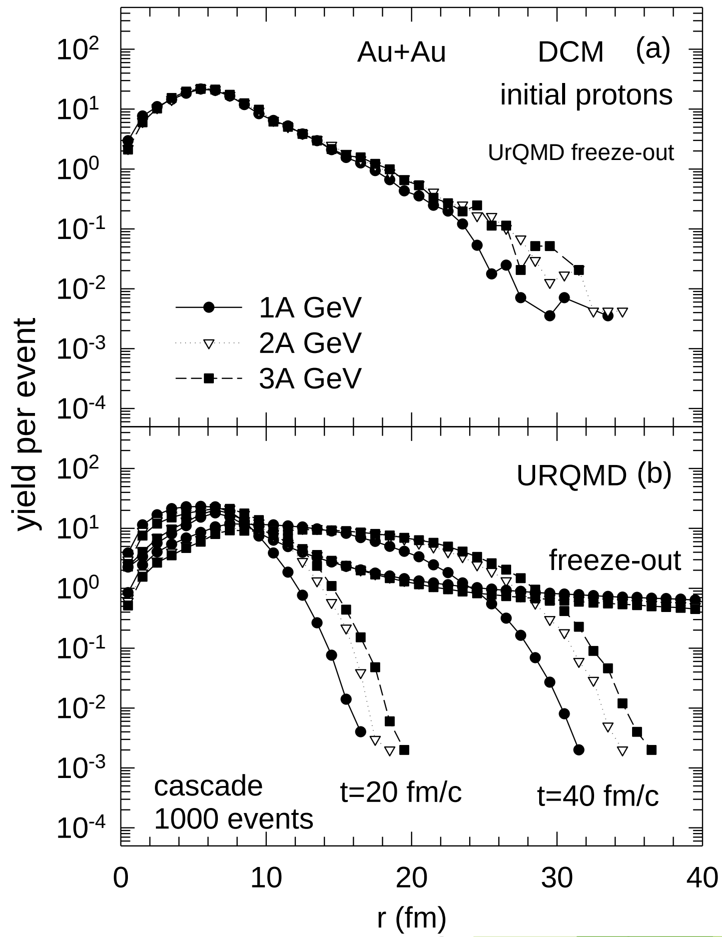


FIG. 2: Coordinate distributions

Au+Au @ 1A GeV, 2A GeV and 3A GeV

comparison of initial protons for DCM and UrQMD

Construction of initial conditions for baryons in dynamical processes

Au+Au@ 1A GeV, 2A GeV and 3A GeV
comparison of initial Lambda yields for DCM and UrQMD

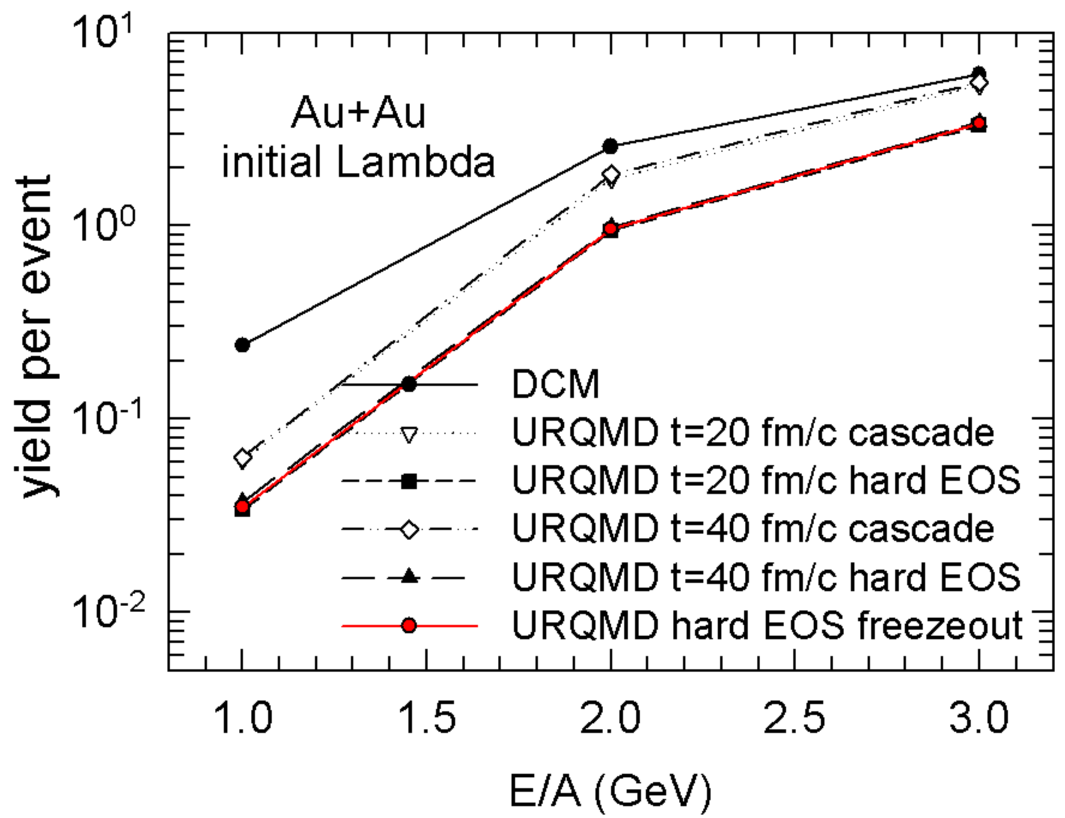
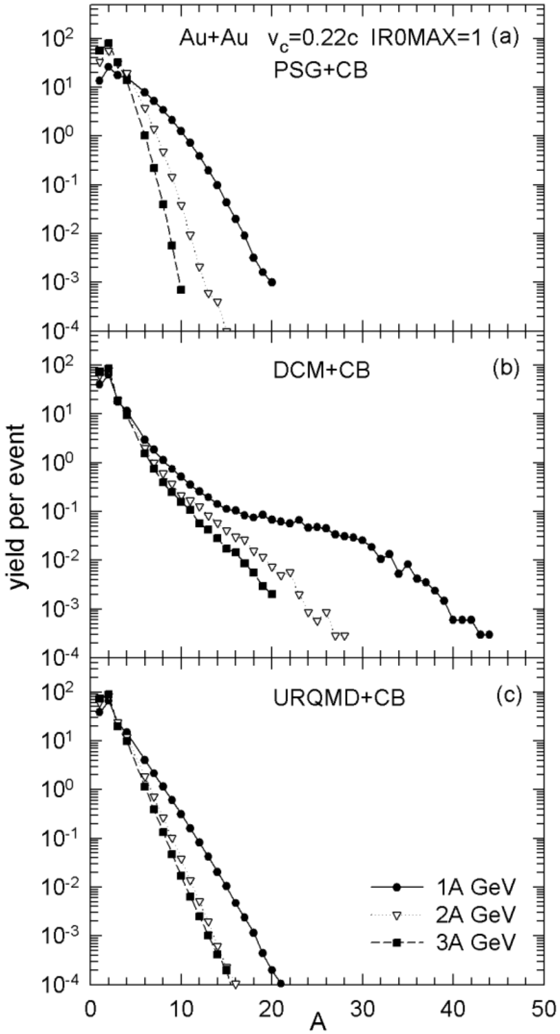


FIG. 3: Yield per event for the initial free lambda produced after the dynamical stage with DCM and with UrQMD for hard EOS and coalescence approaches at t = 20 and 40 fm/c in Au + Au central collisions at different energies.

Mass distributions of fragments

hot

cold



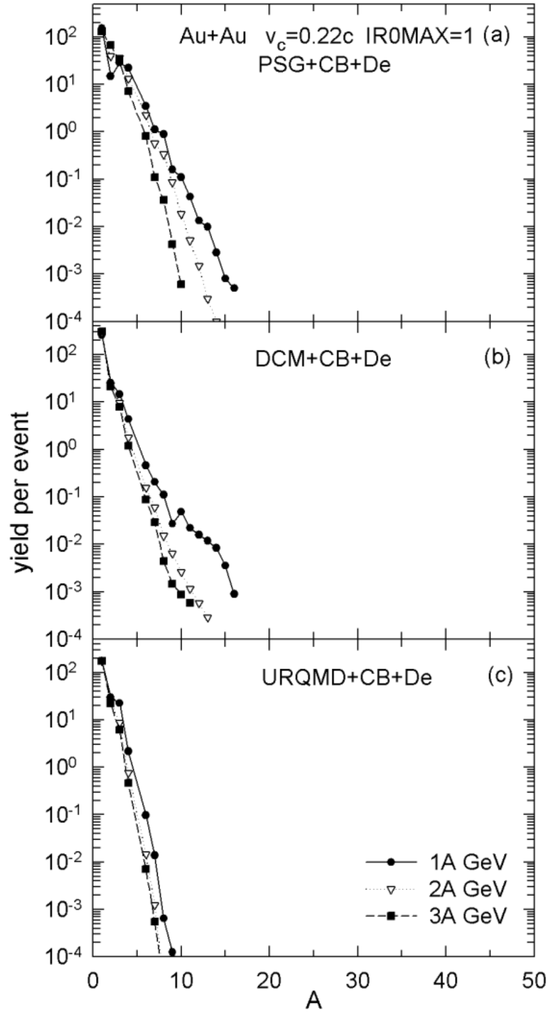


FIG. 4-5: Yield of coalescent clusters versus their mass number A after the CB and CB+De calculations with PSG (a), DCM (b) and UrQMD (c) and de-excitation at the source energy of 1A, 2A, and 3A GeV.

Excitation energies of fragments

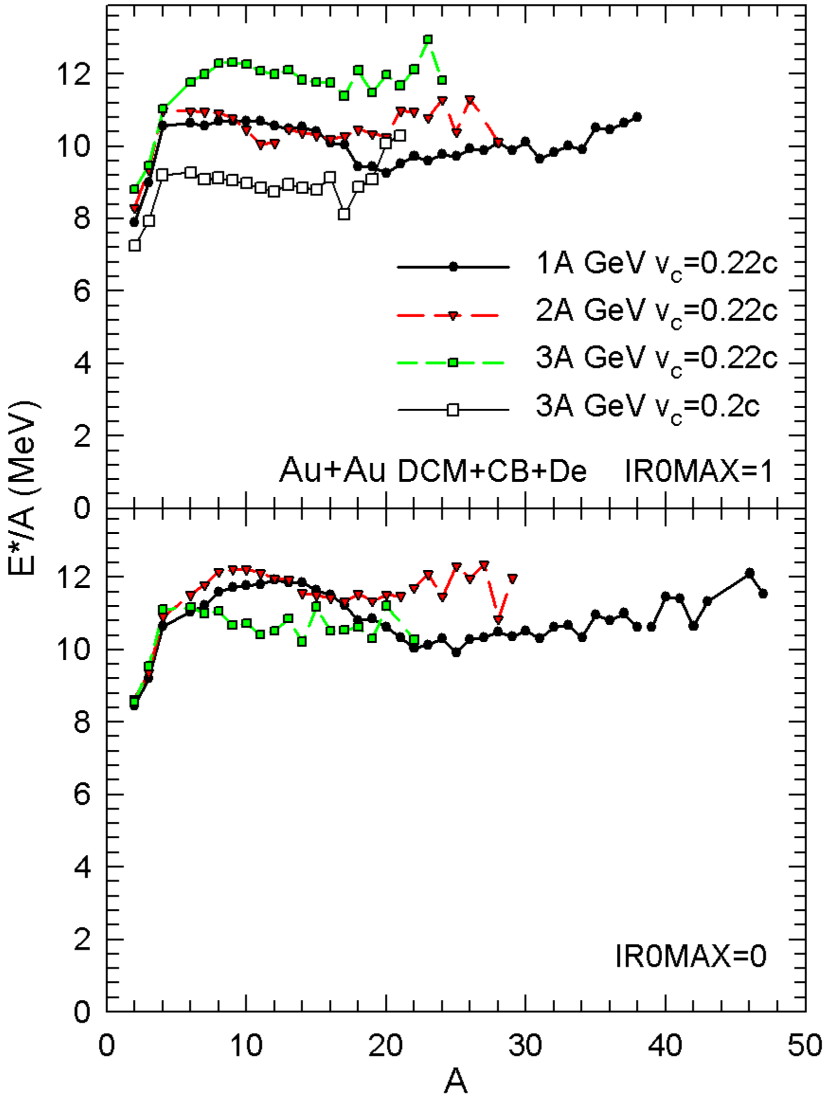


FIG. 8*: Average excitation energy per nucleon (E*/A) of local clusters of nuclear matter versus their mass number A in central Au+Au collisions at 1A GeV, 2A GeV, and 3A GeV, hybrid DCM+CB+De calculations.
The parameters v_c=0.20c, and 0.22c are used in the calculations.

Coordinates of produced fragments are taken into account in the top panel.

Coordinates of produced fragments are NOT taken into account in the bottom panel.

Excitation energies of fragments

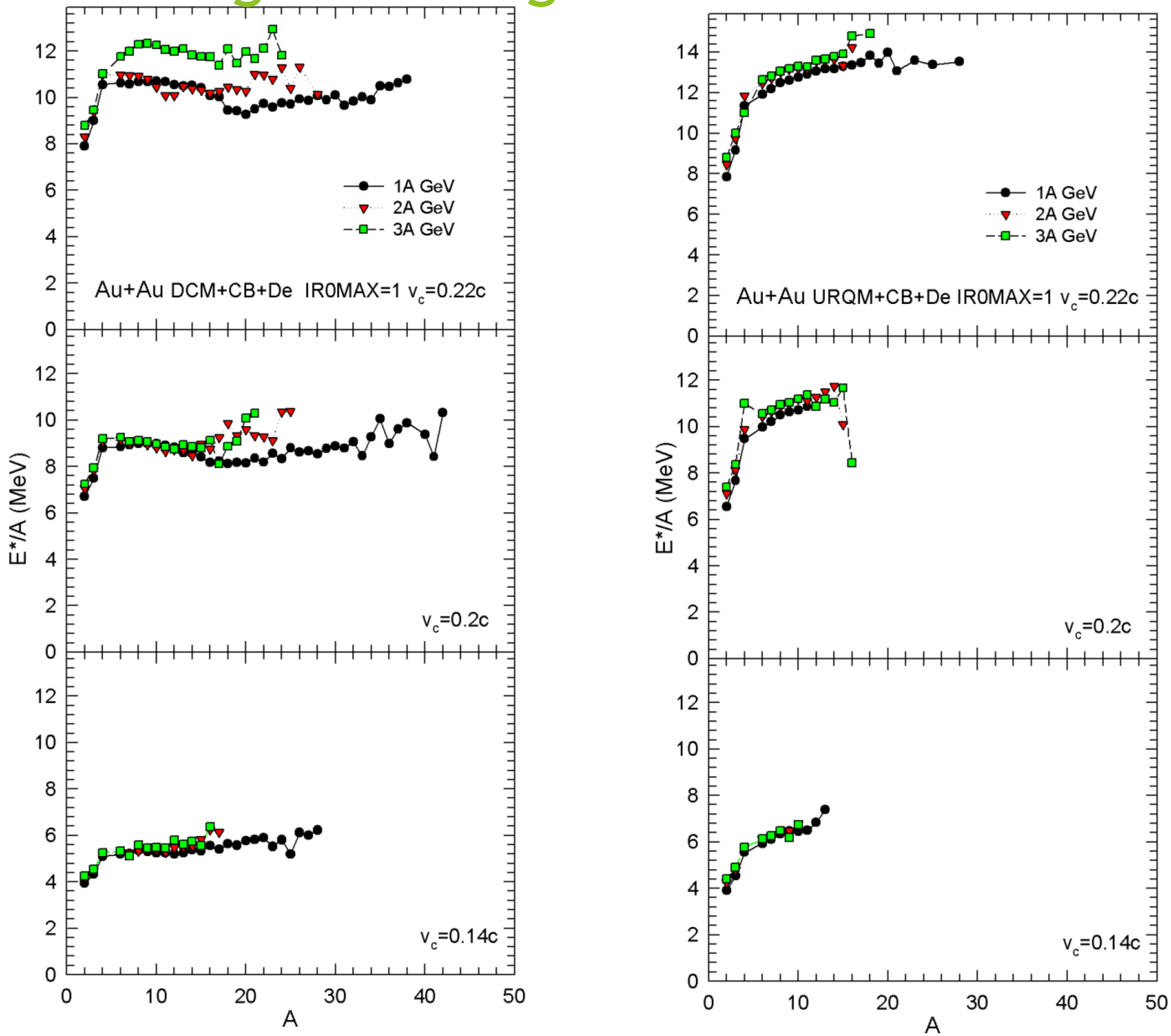
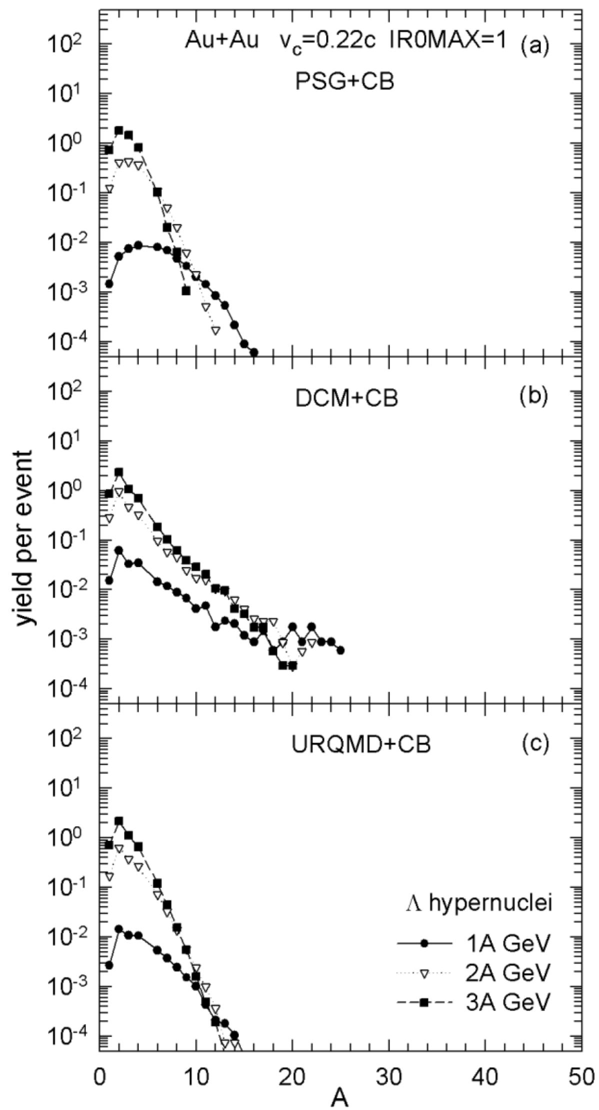


FIG. 8: Average excitation energy per nucleon (E*/A) of local clusters of nuclear matter versus their mass number A in central Au+Au collisions at 1A GeV, 2A GeV, and 3A GeV, hybrid DCM+CB+De calculations.

The parameters vc =0.14c, 0.20c, and 0.22c are used in the calculations. Coordinates of produced fragments are taken into account in the calculations.

Mass distributions of Lambda hypernuclei

hot



cold

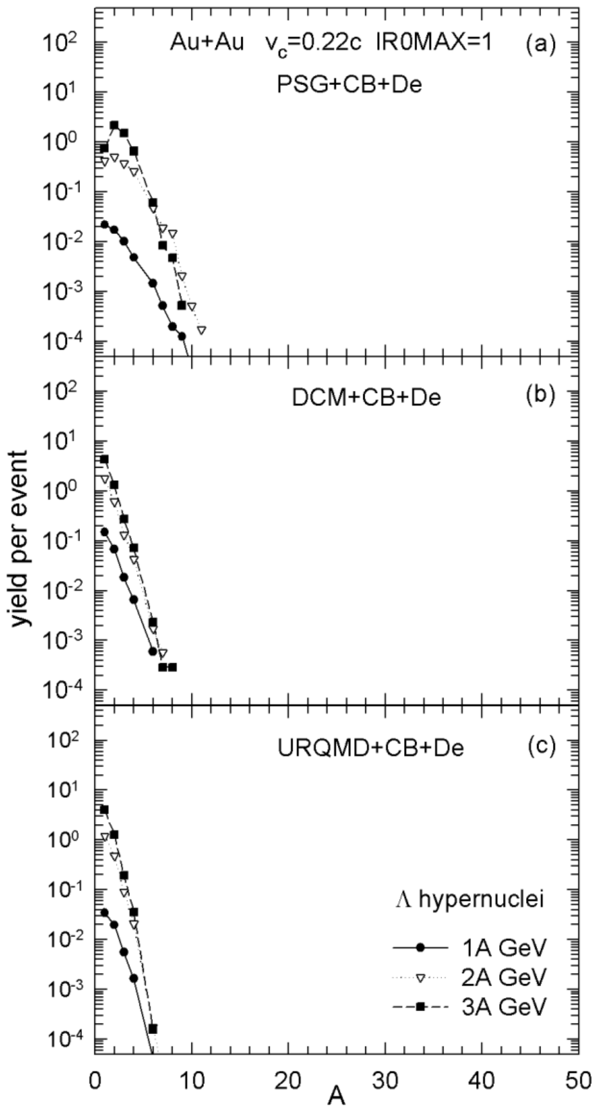


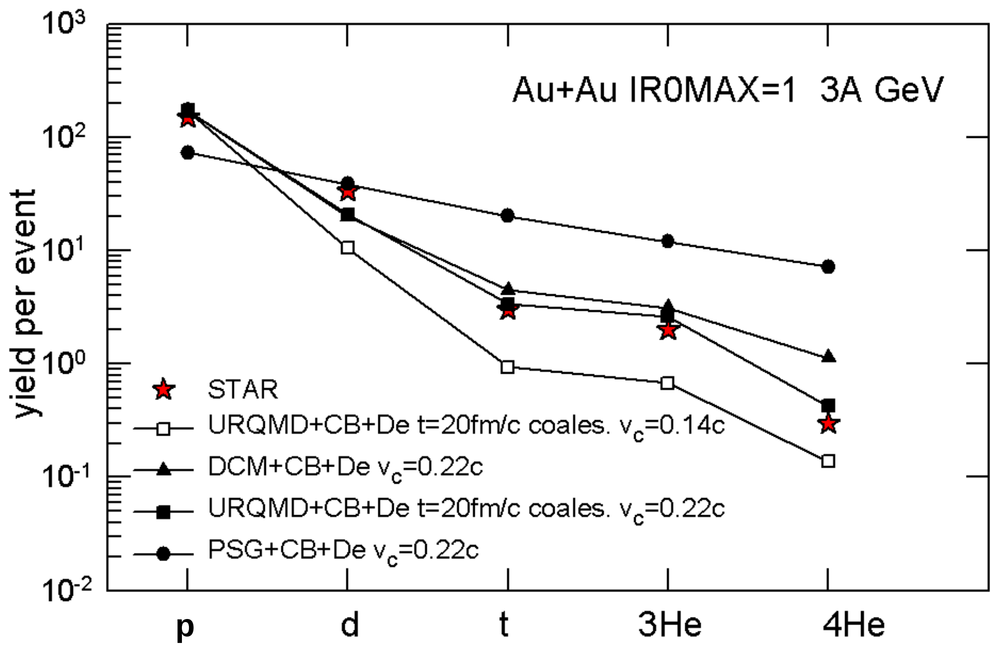
FIG. 6: Yield of Lambda hypernuclei versus their mass number A after the CB and CB+De calculations with PSG (a), DCM (b) and UrQMD (c) at the source energy of 1A, 2A, and 3A GeV.

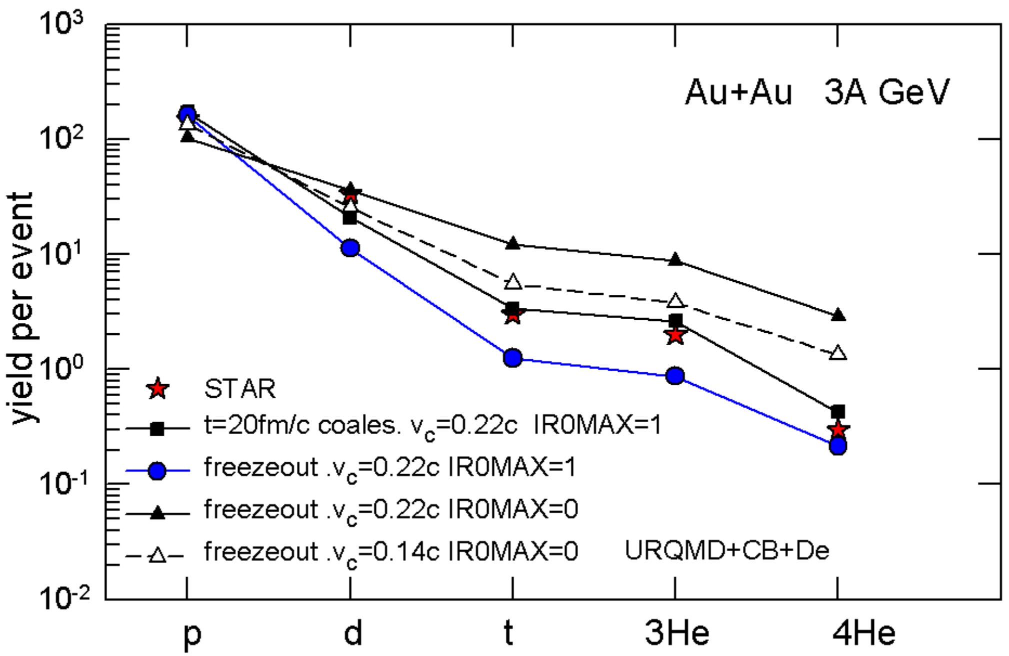
PRELIMINARY RESULTS:

Production of nuclei in HI central collisions

PSG+CB+De
DCM+CB+De
URQMD+CB+De

STAR collaboration,
PRL 128, 202301 (2022).





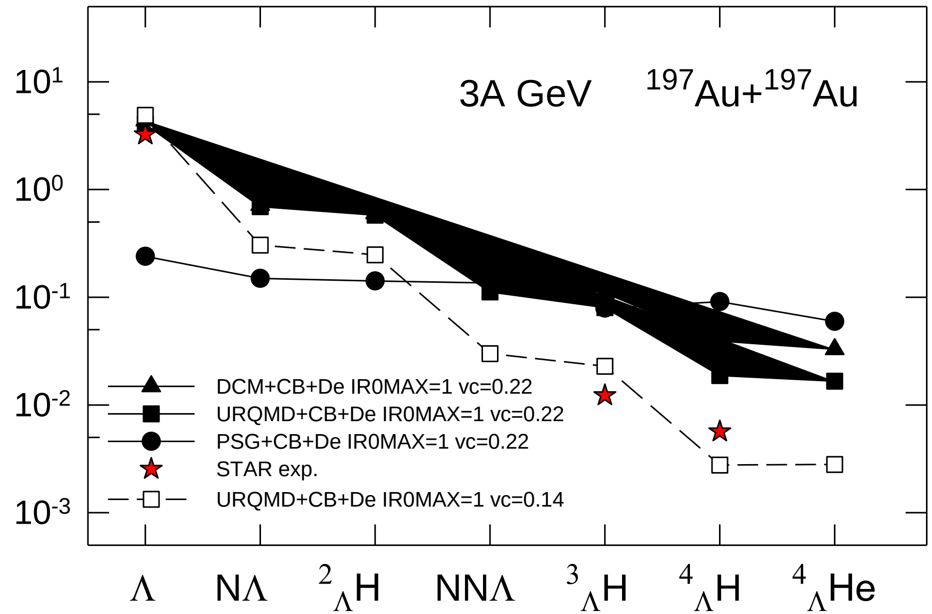
PRELIMINARY RESULTS:

Production of hypernuclei in HI central collisions,

PSG+CB+De

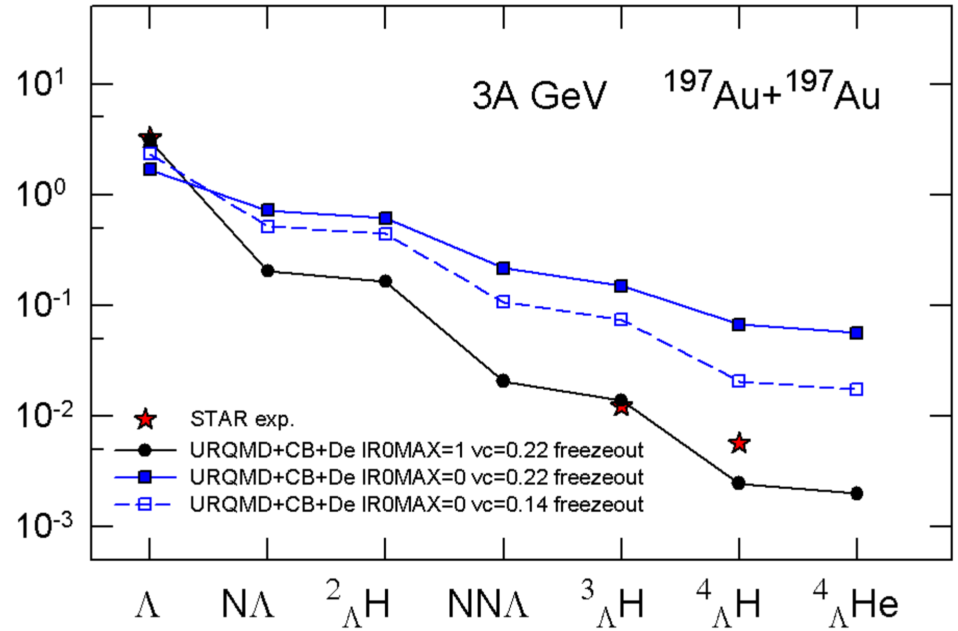
DCM+CB+De

URQMD+CB+De



Λ, 3ΛH, and 4ΛH

Star collaboration,
PRL 128, 202301 (2022).



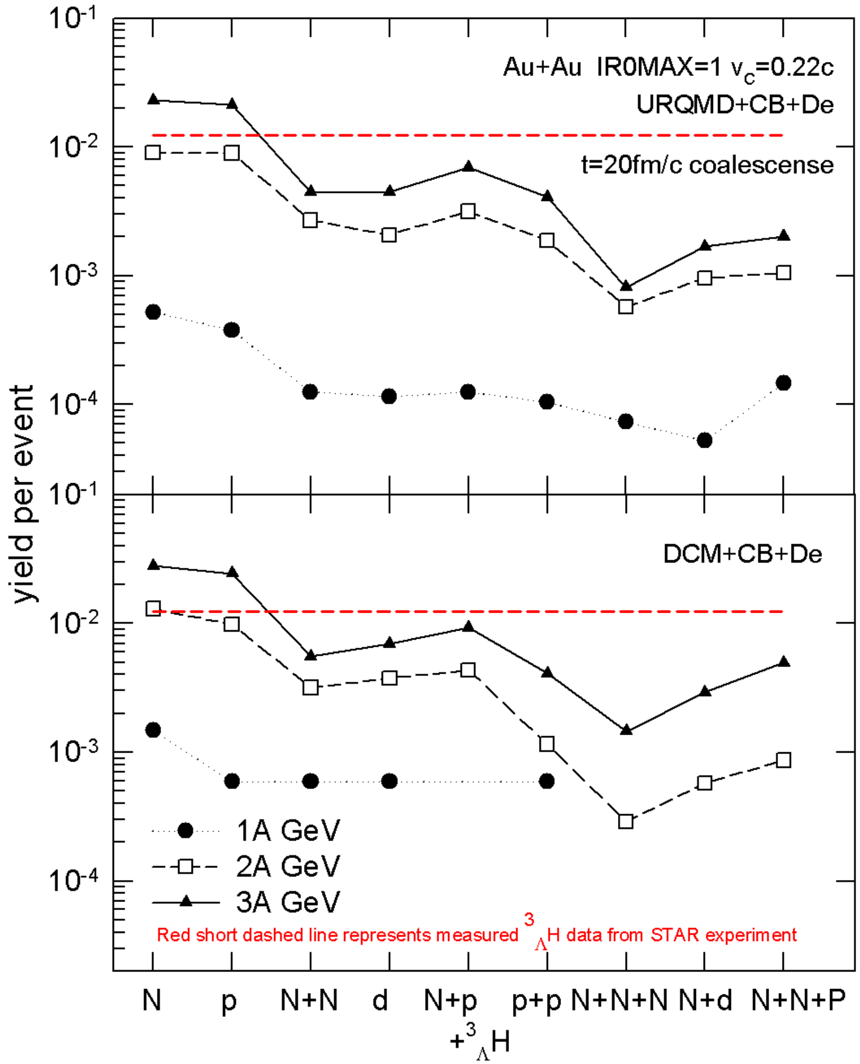


FIG. 13: The yields of correlated particles (neutrons, proton, deutrons) in channels with the 3LHe production are shown in central collisions of two gold nuclei after hybrid DCM+CB+De (a) and UrQMD+CB+De (b) calculations.

Red lines represent STAR experimental data for 3LHe at 3A GeV.

The beam energies and parameters are indicated in panels.

Transverse momenta distributions of protons, deuterons and tiritons

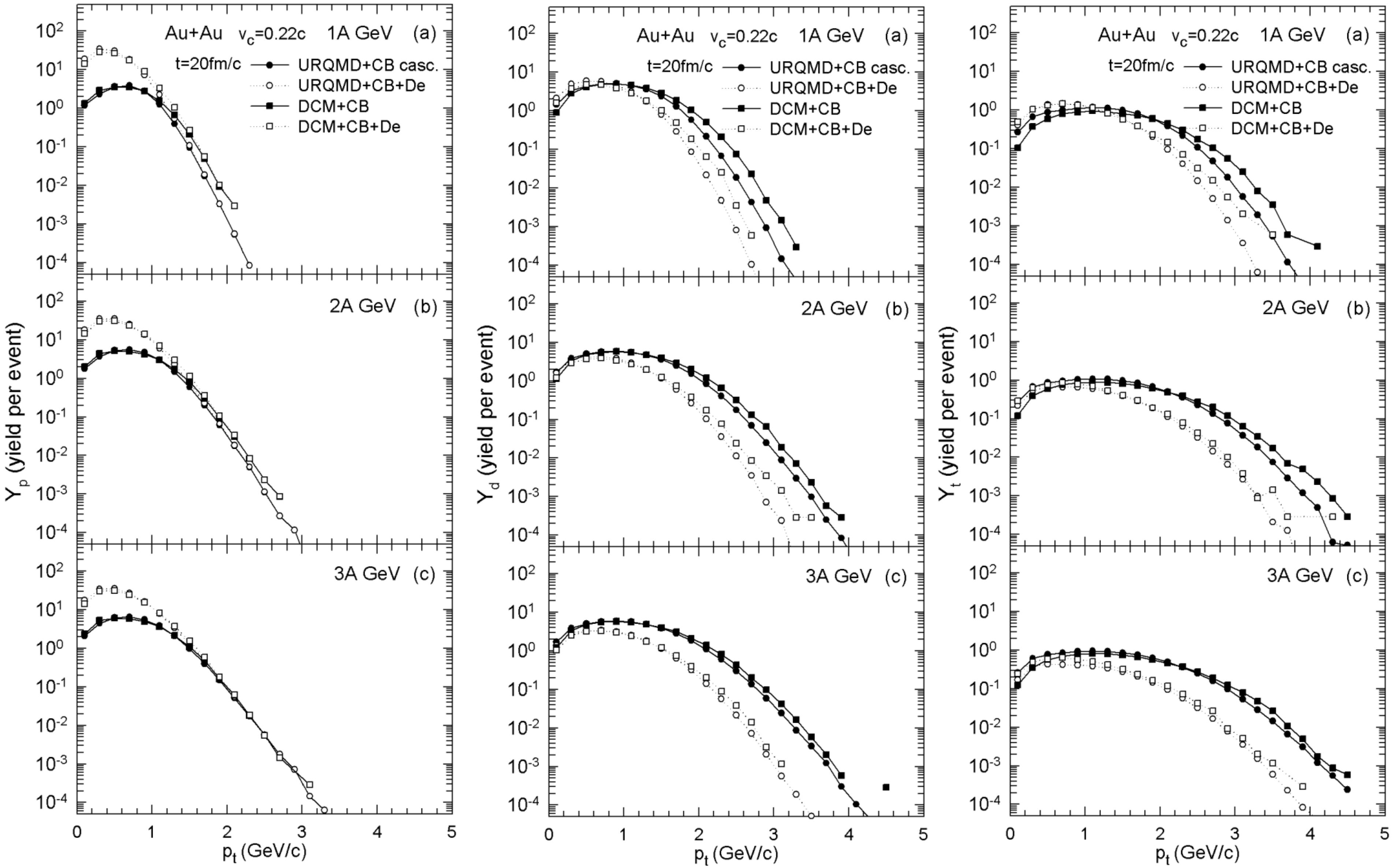


FIG. 15-17: Transverse momenta distributions of protons, deuterons and tiritons produced after the dynamical stage with DCM+CB, DCM+CB+De, UrQMD+CB, and UrQMD+CB+De in Au+ Au central collisions at energies of 1A GeV (a), 2A GeV (b) and 3A GeV (c). The beam energies and parameters are indicated in panels.

Transverse momenta distributions of 3He and 4He

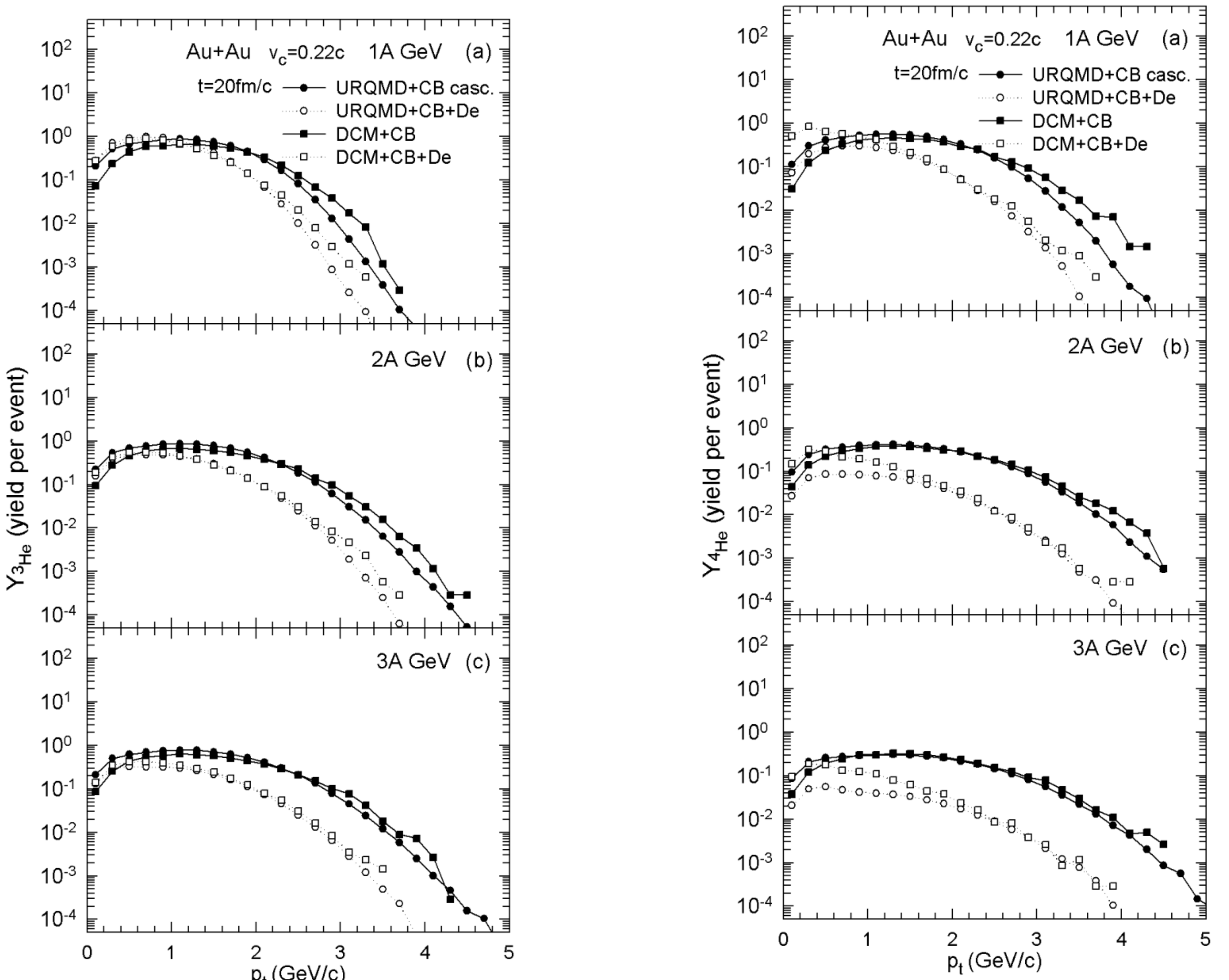


FIG. 18-19: Transverse momenta distributions of 3He and 4He produced after the dynamical stage with DCM+CB, DCM+CB+De, UrQMD+CB, and UrQMD+CB+De in Au+ Au central collisions at energies of 1A GeV (a), 2A GeV (b) and 3A GeV (c). The beam energies and parameters are indicated in panels.

Transverse momenta distributions of Λ, $N\Lambda$ and $NN\Lambda$

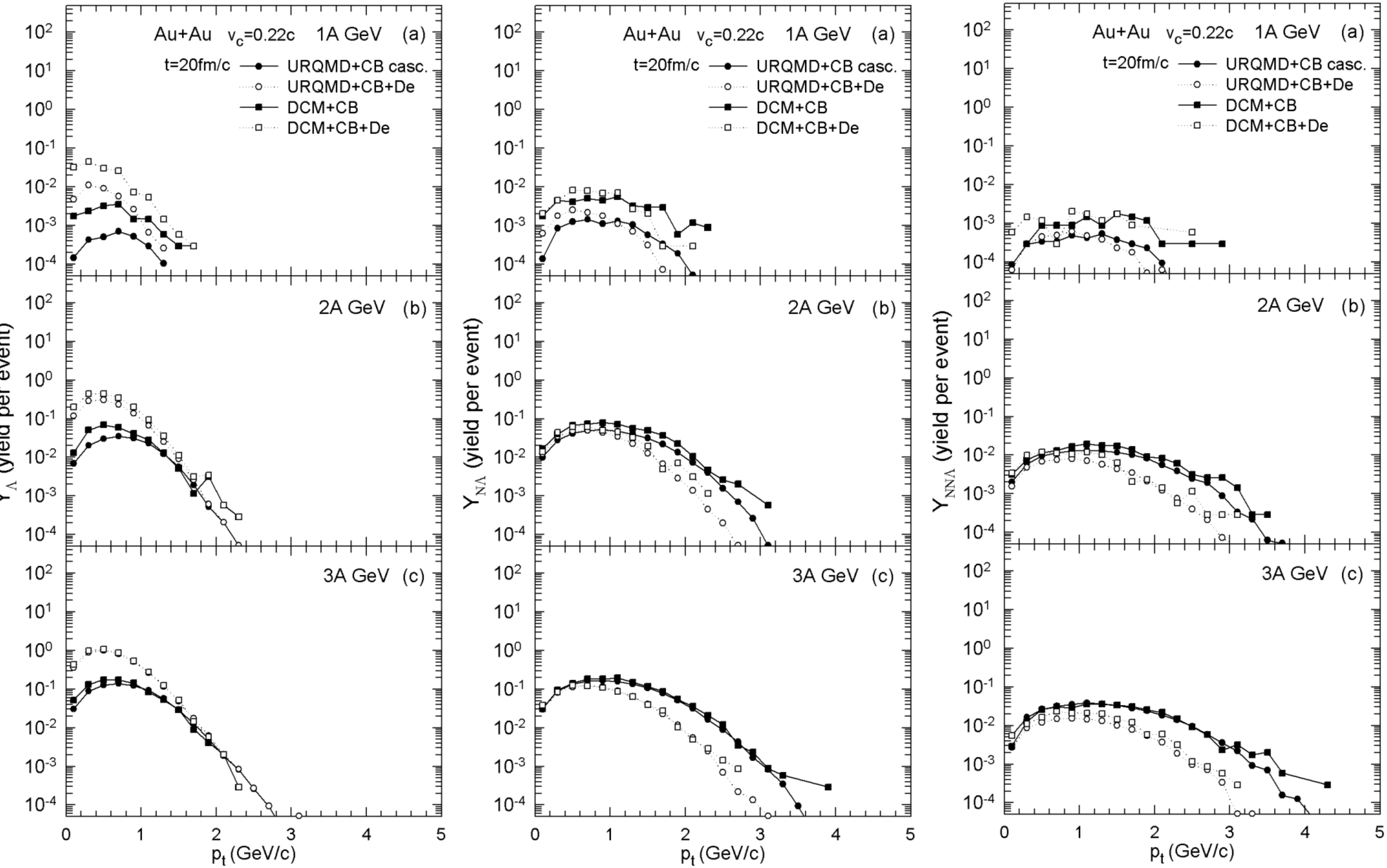


FIG. 20-22: Transverse momenta distributions of Λ, $N\Lambda$ and $NN\Lambda$ produced after the dynamical stage with DCM+CB, DCM+CB+De, UrQMD+CB, and UrQMD+CB+De in Au+ Au central collisions at energies of 1A GeV (a), 2A GeV (b) and 3A GeV (c). The beam energies and parameters are indicated in panels.

Transverse momenta distributions of 3ΛH and 4ΛH

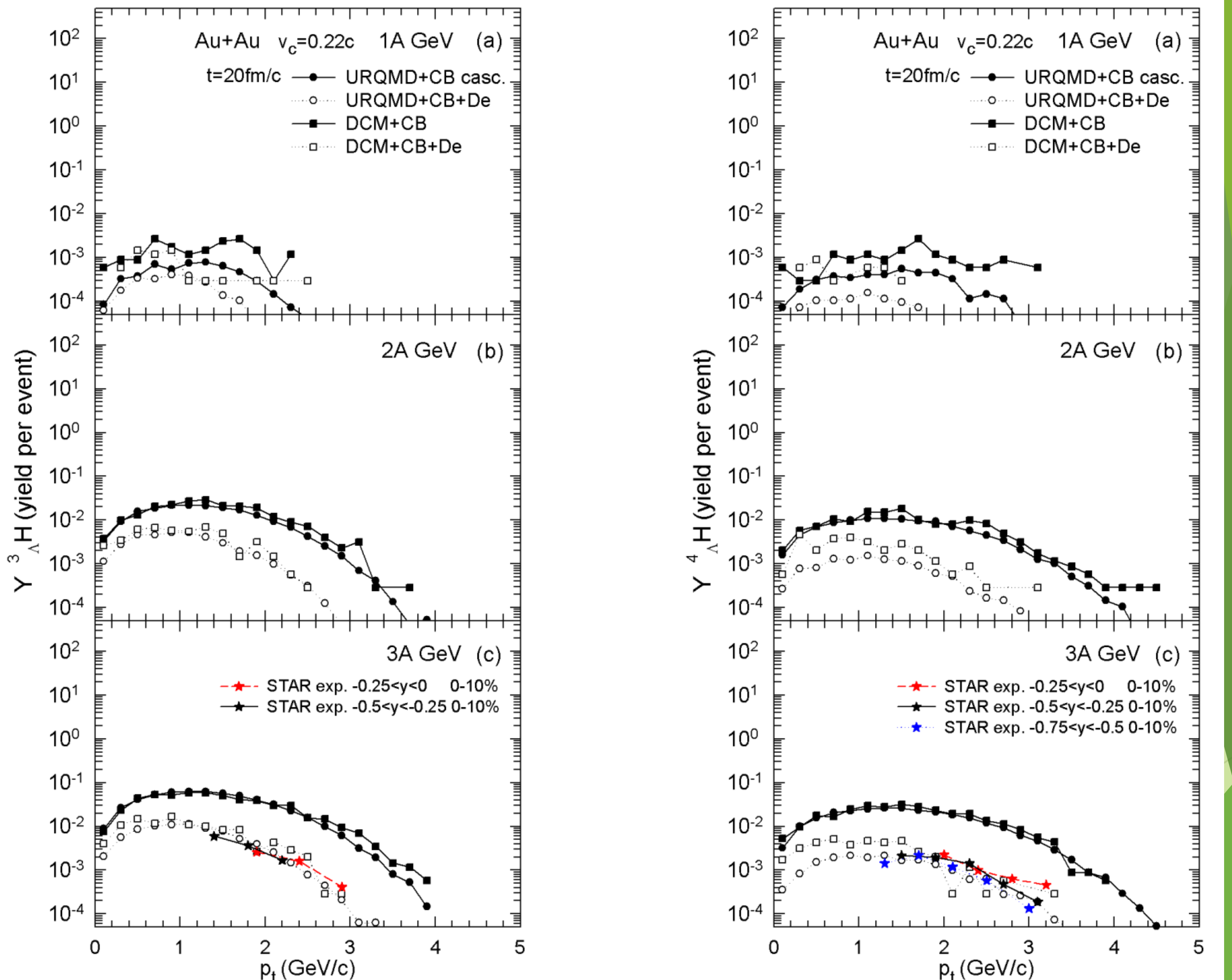
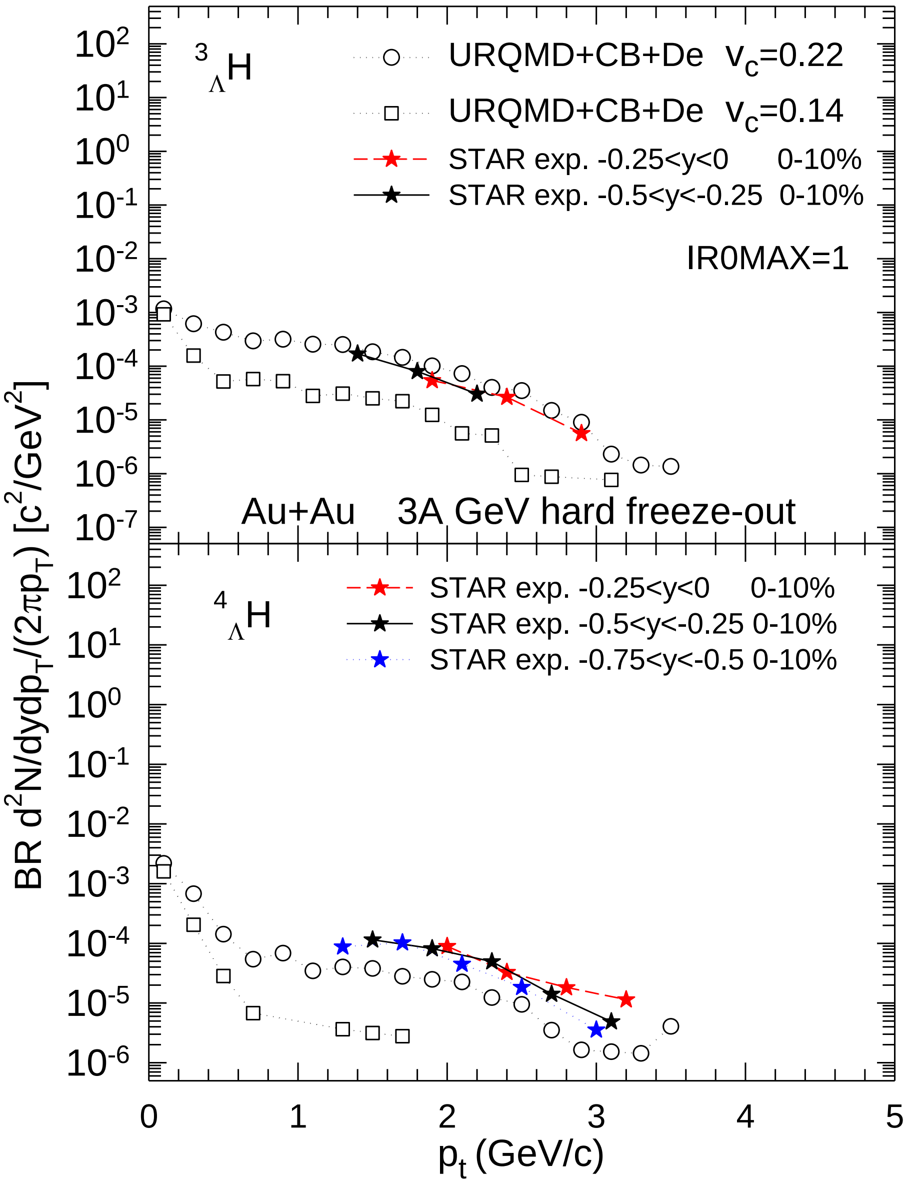
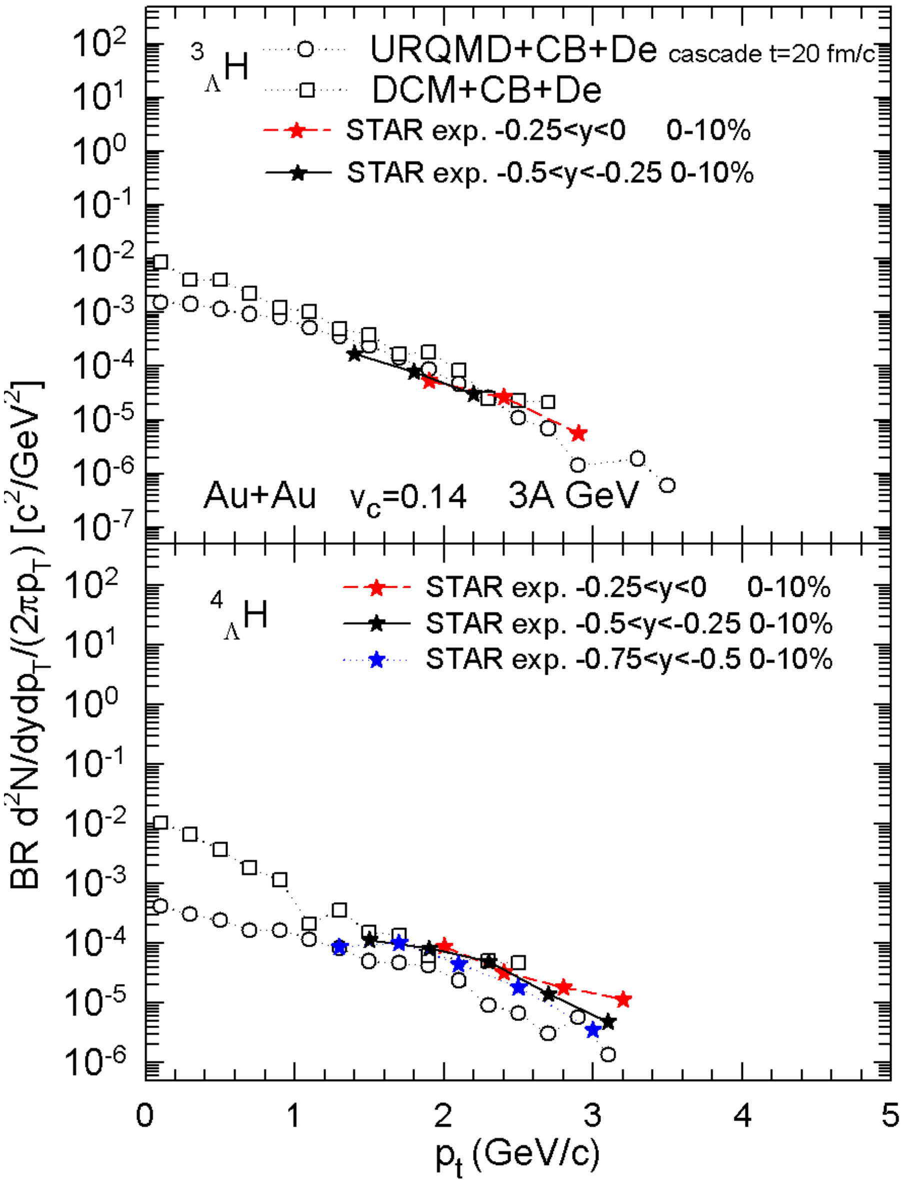


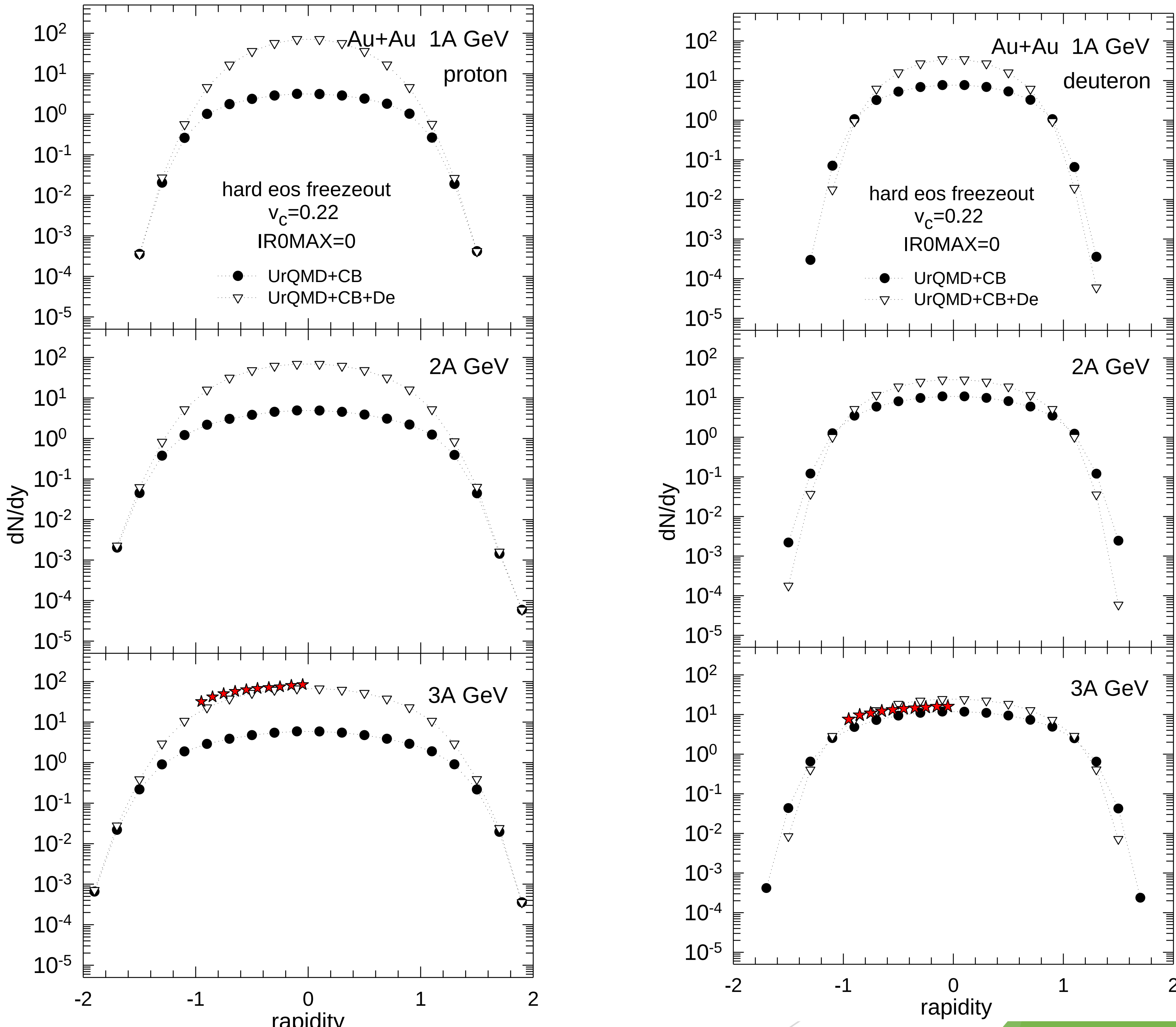
FIG. 23-24: Transverse momenta distributions of 3ΛHe and 4ΛHe produced after the dynamical stage with DCM+CB, DCM+CB+De, UrQMD+CB, and UrQMD+CB+De in Au+ Au central collisions at energies of 1A GeV (a), 2A GeV (b) and 3A GeV (c). Lines with coloured stars are for STAR experimental data. The beam energies and parameters are indicated in panels.



UrQMD hard eos at freezeout



UrQMD cascade t=20 fm/c



Au+Au 1A GeV
proton
hard eos freezeout
v_c=0.22
IR0MAX=0
UrQMD+CB
UrQMD+CB+De
2A GeV
3A GeV
dN/dy
rapidity
Au+Au 1A GeV
deuteron
hard eos freezeout
v_c=0.22
IR0MAX=0
UrQMD+CB
UrQMD+CB+De
2A GeV
3A GeV
dN/dy
rapidity

Conclusions

Collisions of relativistic ions are promising reactions to search for nuclear clusters, exotic clusters with very different isospin, including hypernuclei. These processes can be simulated within dynamical and statistical models.

PSG-novel mechanism: The matter is divided into excited baryon clusters in local equilibrium and after the cluster decay the nuclei and hypernuclei of all sizes (and isospin), including short-lived weakly-bound states, multi-strange nuclei can be produced.

Advantages over other reactions: there is no limit on sizes and isotope content of produced exotic nuclei; probability of their formation may be high; a large strangeness can be deposited in nuclei.

We have very promising results for UrQMD+CB+De and DCM+CB+De models to describe STAR experimental data.

EOS and the symmetry energy of hypermatter at subnuclear density and hyperon interactions in exotic nuclear matter can be investigated.

Thank you for your attention!