CLUSTER PRODUCTION IN HEAVY ION COLLISIONS

Marcus Bleicher
Institut für Theoretische Physik
Goethe Universität Frankfurt
GSI Helmholtzzentrum
Germany

GOETHE UNIVERSITÄT FRANKFURT AM MAIN
HIC for FAIR Helmholtz International Center
GSI
NIC

Outline

- Motivation
- Coalescence vs thermal emission
- Small systems
- Large systems
- Antimatter and Hypermatter
- Conclusions

Motivation

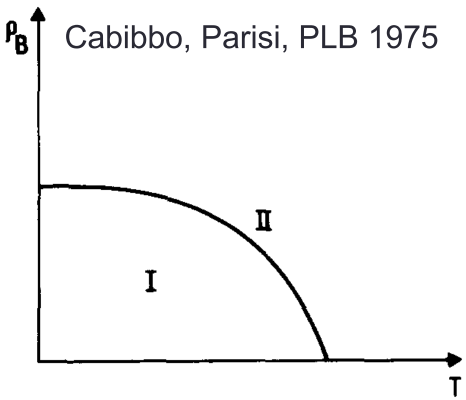
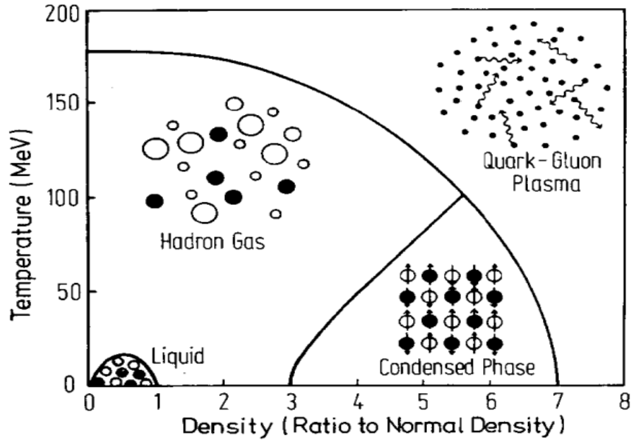
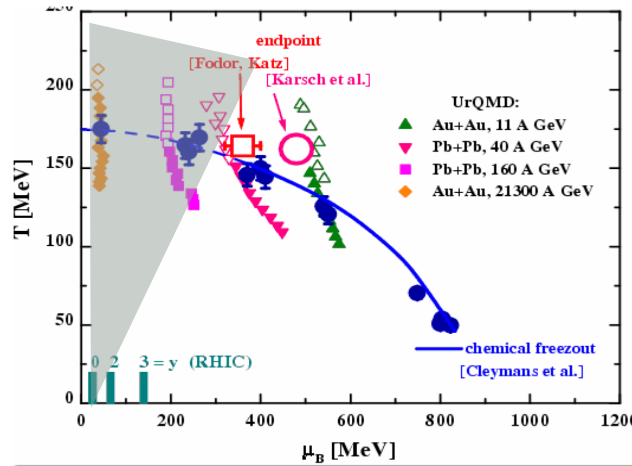


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.



W. Greiner, PR 1986

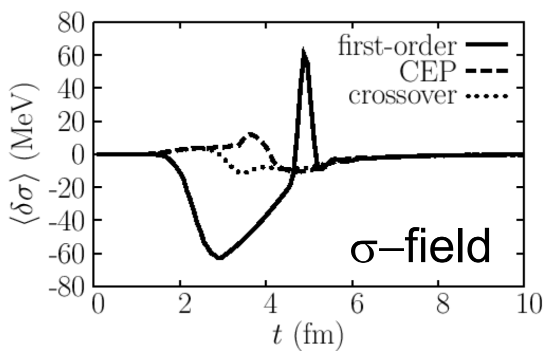


L. Bravina, M.B., et al., JPG 1999

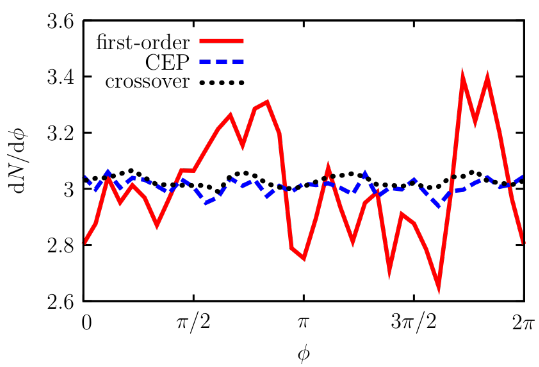
- Learn about phase structure of QCD
- Understand emission structure
- Explore composite particles
- Investigate influence on fluctuation observables

Fluctuations in quark densities → Clusters might **be enhanced**

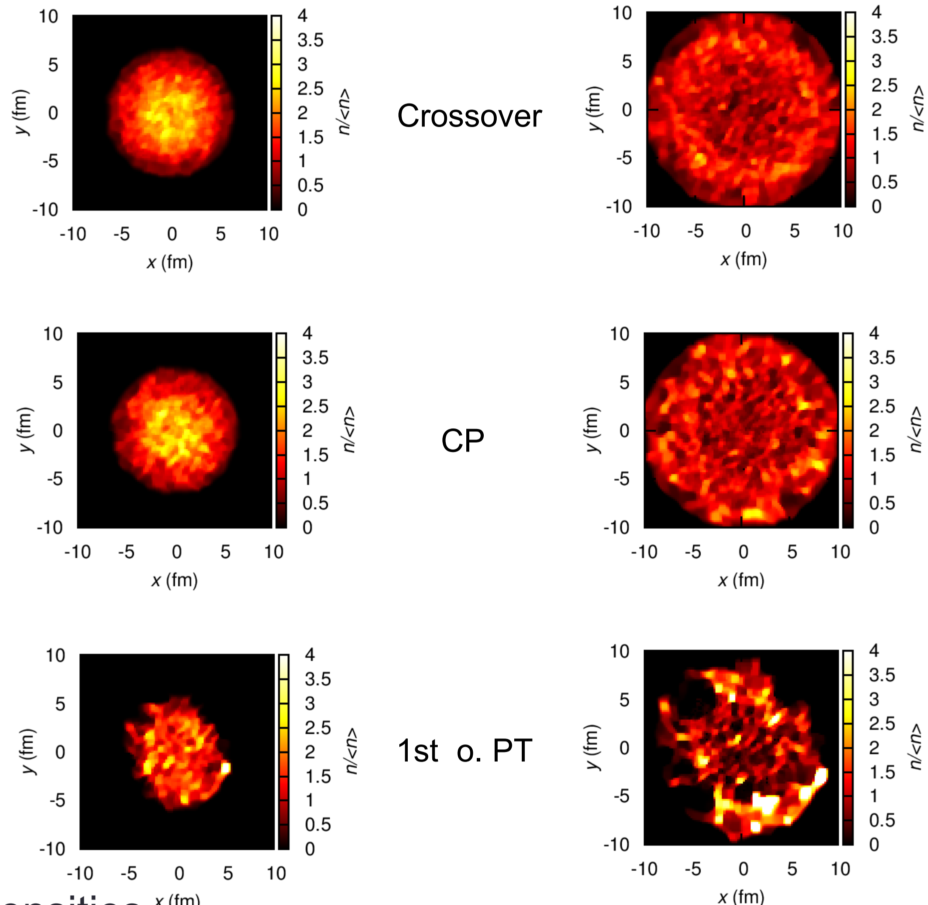
Nonequilibrium fluctuations in PQM



Angular distribution, 12 fm/c



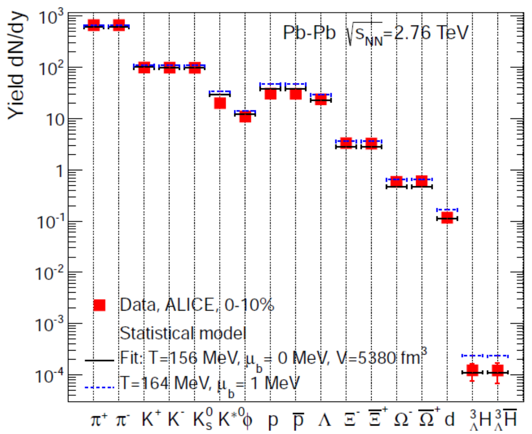
6 fm/c 12 fm/c



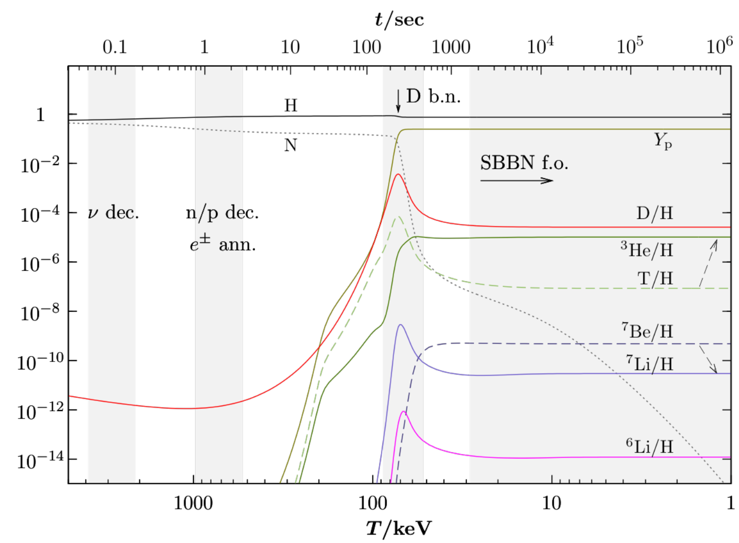
→ Strong fluctuations, inhomogeneous quark densities

C. Herold, M. Nahrgang, M. Bleicher, I. Mishustin, Nucl.Phys. A925 (2014) 14-24

Thermal emission vs. BB nucleosyntesis



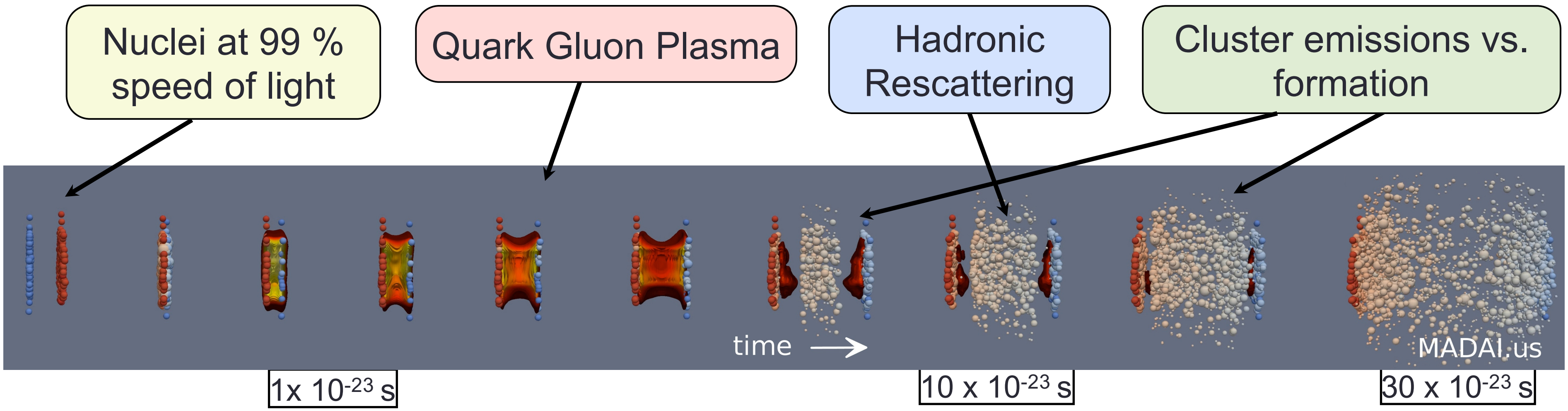
From Braun-Munzinger, Stachel, Andronic



Pospelov, Pradler, Ann.Rev.Nucl.Part.Sci.60:539-568,2010

- Thermal model provides good description of cluster data, e.g. deuteron, even with protons being slightly off
- Surprising result, because the binding energy of the deuteron (2.2 MeV) is much smaller than the emission temperature (150-160 MeV)
- Why is it not immediately destroyed?
  Related to famous deuterium bottleneck in big bang nucleosynthesis:
  If the temperature is too high (mean energy per particle greater than d binding energy) any deuterium that is formed is immediately destroyed
  → delays production of heavier clusters/nuclei.

Time Evolution of Heavy Ion Collisions



Nonequilibrium initial state dynamics → Relativistic Hydrodynamics/ Parton dynamics → Hadron Transport

At high energies hybrid approaches are very successful for the description of the dynamics

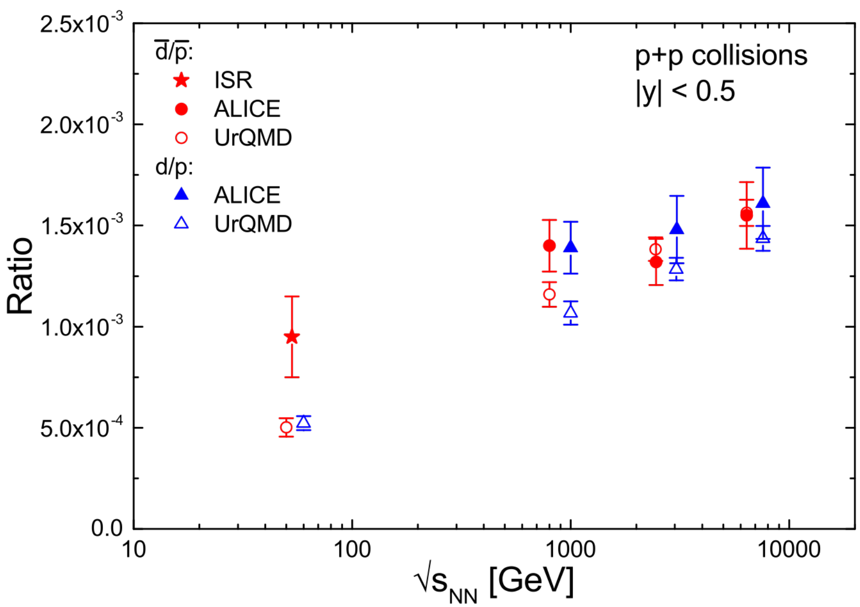
Figure adapted from H. Elfner, arXiv:1404.1763

Coalescence

- Coalescence assumes that that clusters are formed at the end of the kinetic scattering stage (cold/dilute system!)
- Different approaches: Momentum space coalescence and phase space coalescence
- Momentum space coalescence assumes small emission volume (neglecting spatial distribution) → does not work well for large systems
- Phase space (PS) coalescence treats both, the momentum distribution and the space distribution of protons and neutrons
- PS coalescence typically uses a $\Delta p \lesssim 285$ MeV and a $\Delta x \lesssim 3.5$ fm to define the deuteron state

Proton-proton collisions

Deuteron (anti-deuteron): ratios



Good description of pp by coalescence

Absolute yields

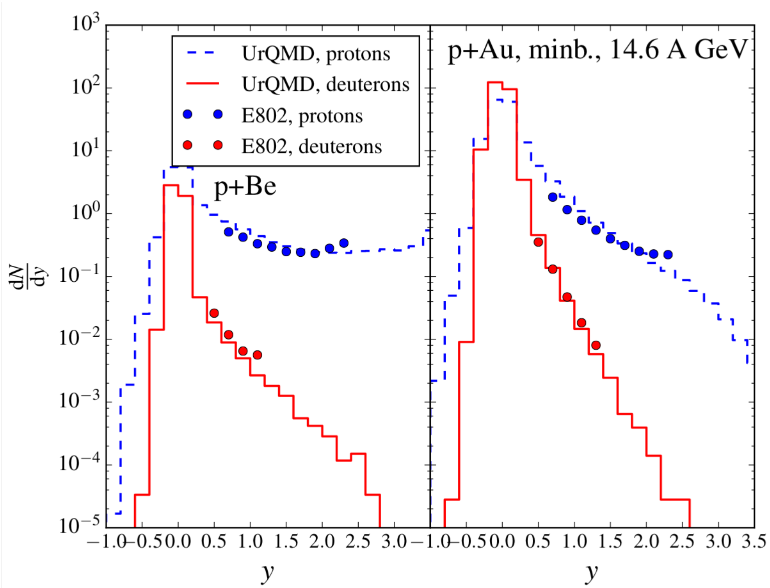
	$\sqrt{s_{NN}}$(TeV)	dN/dy ALICE	dN/dy UrQMD
	0.9	$(1.12\pm0.09\pm0.09)\times10^{-4}$	$(0.96\pm0.05)\times10^{-4}$
d	2.76	$(1.53\pm0.05\pm0.13)\times10^{-4}$	$(1.47\pm0.06)\times10^{-4}$
	7	$(2.02\pm0.02\pm0.17)\times10^{-4}$	$(2.05\pm0.09)\times10^{-4}$
	0.9	$(1.11\pm0.10\pm0.09)\times10^{-4}$	$(1.00\pm0.05)\times10^{-4}$
$\overline{d}$	2.76	$(1.37\pm0.04\pm0.12)\times10^{-4}$	$(1.55\pm0.07)\times10^{-4}$
	7	$(1.92\pm0.02\pm0.15)\times10^{-4}$	$(2.22\pm0.09)\times10^{-4}$

Absolute yields in line with ALICE data

S. Sombun, M. Bleicher et al, Phys.Rev. C99 (2019) no.1, 014901

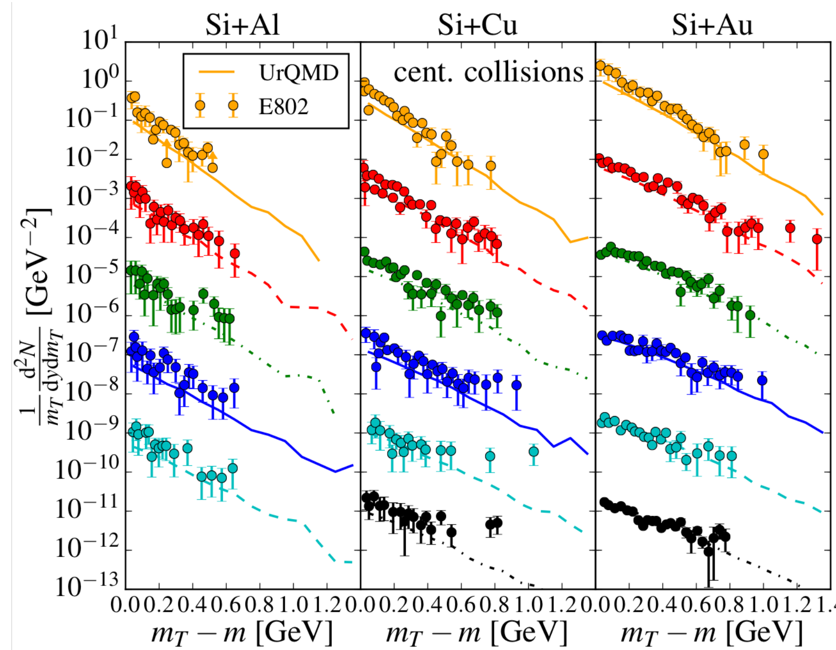
From small to large systems

Proton+nucleus at 14.6 AGeV



Rapidity distributions indicate correct coalescence behavior

Transverse dynamics in Si+(Al/Cu/Au) at 14.6 AGeV

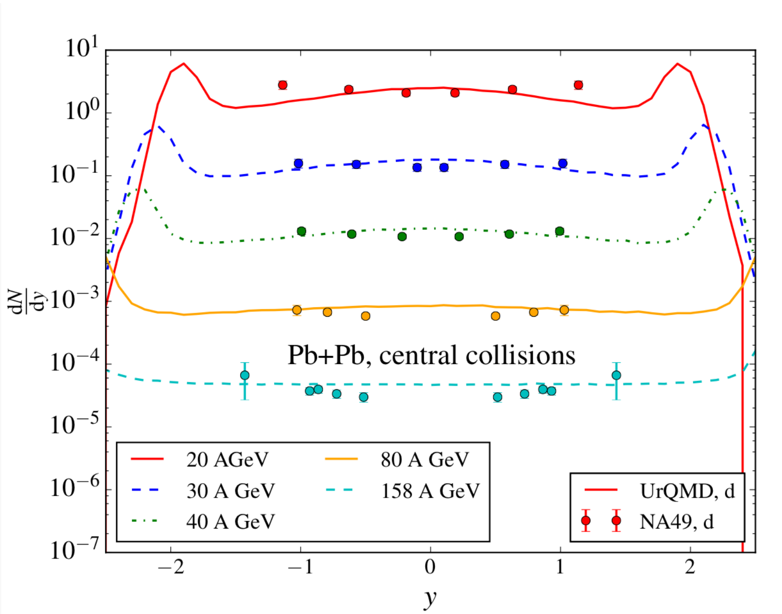


Also transverse expansion is well captured in the coalescence approach

S. Sombun, M. Bleicher et al, Phys.Rev. C99 (2019) no.1, 014901

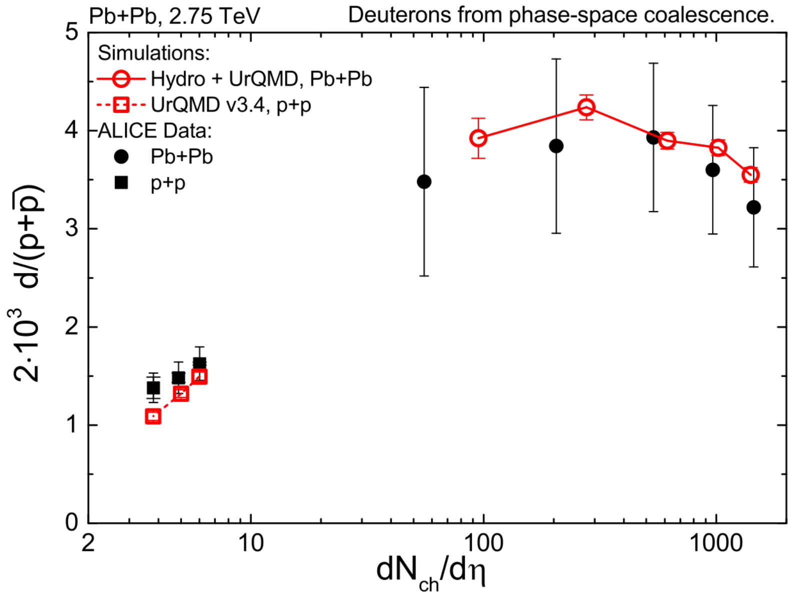
Towards higher energies

Pb+Pb from 20 AGeV to 158 AGeV



Deuteron rapidity distributions well described over a broad range of energies

LHC results: Centrality dependence

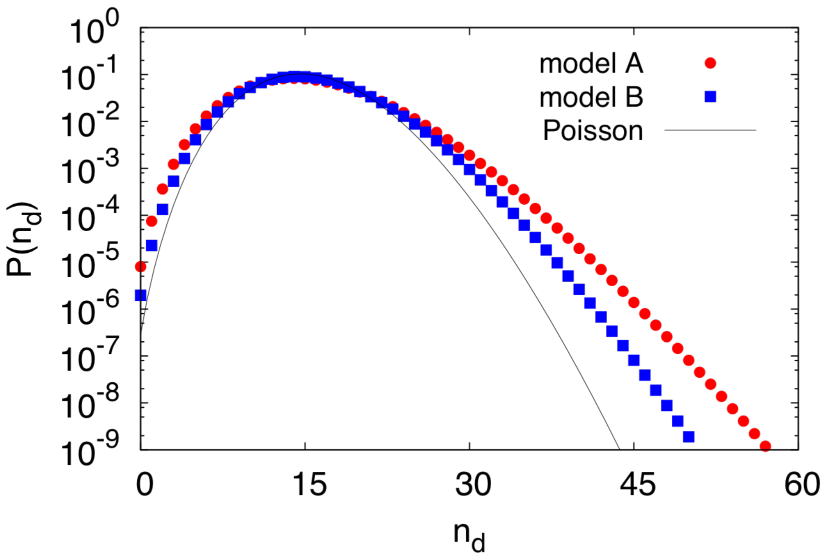


S. Sombun, M. Bleicher et al, Phys.Rev. C99 (2019) no.1, 014901

Decrease of d/p ratio for very central collisions
→ indication for larger freeze-out volume

Can we distinguish thermal emission from coalescence?

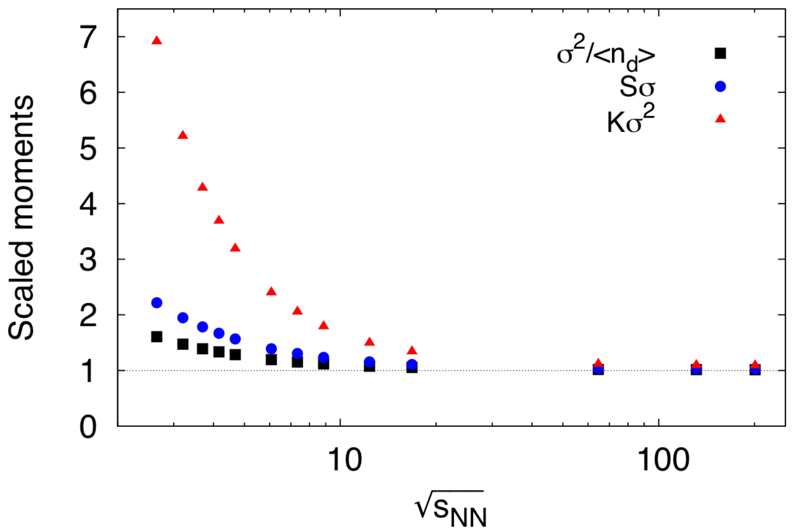
Au+Au at 2 AGeV



Thermal emission would result in Poisson fluctuations

→ Coalescence leads to wider distributions

Moments of distribution

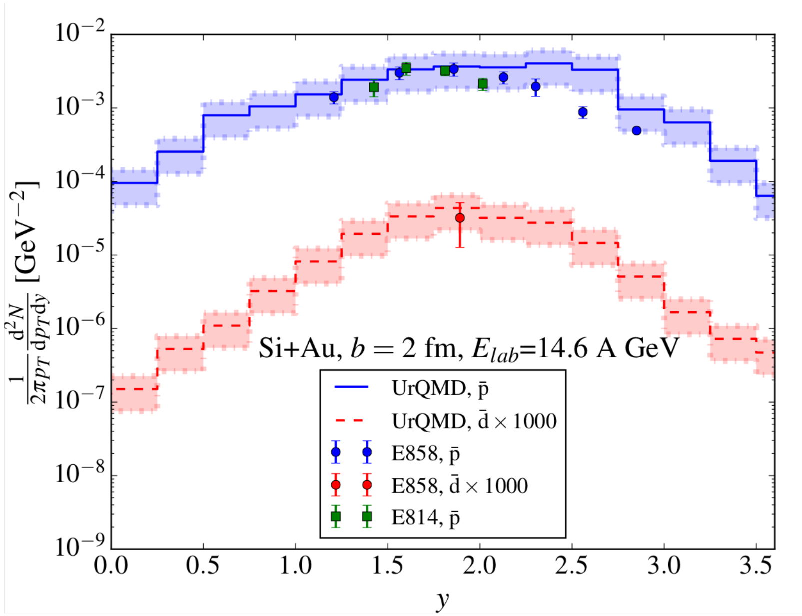


Deviations from Poisson strongest at low energies (largest yield of deuterons)

Z. Feckova, B. Tomasik, M. Bleicher, Phys.Rev. C93 (2016) no.5, 054906

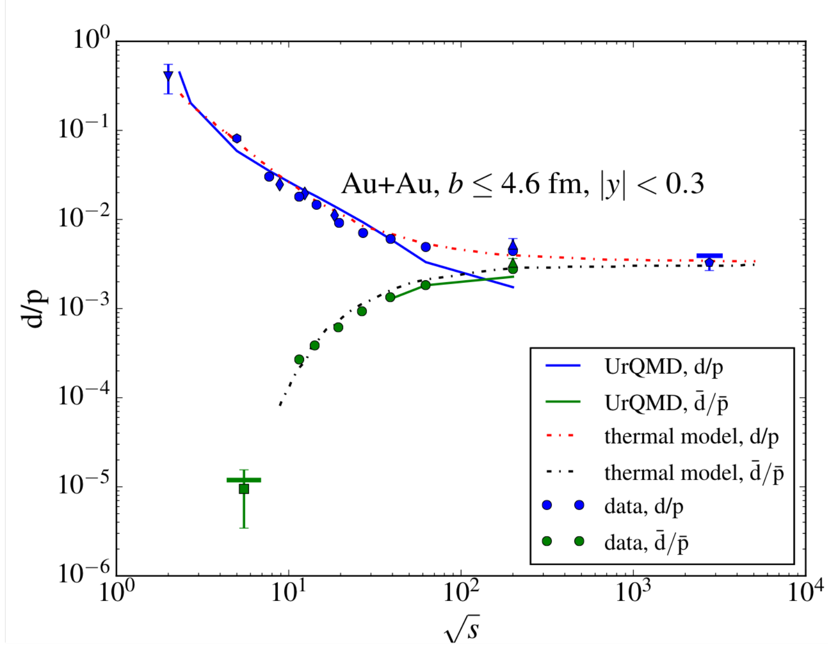
Anti-deuterons

Does coalescence also work for more exotic states?



Surprisingly good description of anti-deuteron yield

Energy dependence of deuterons and anti-deuterons

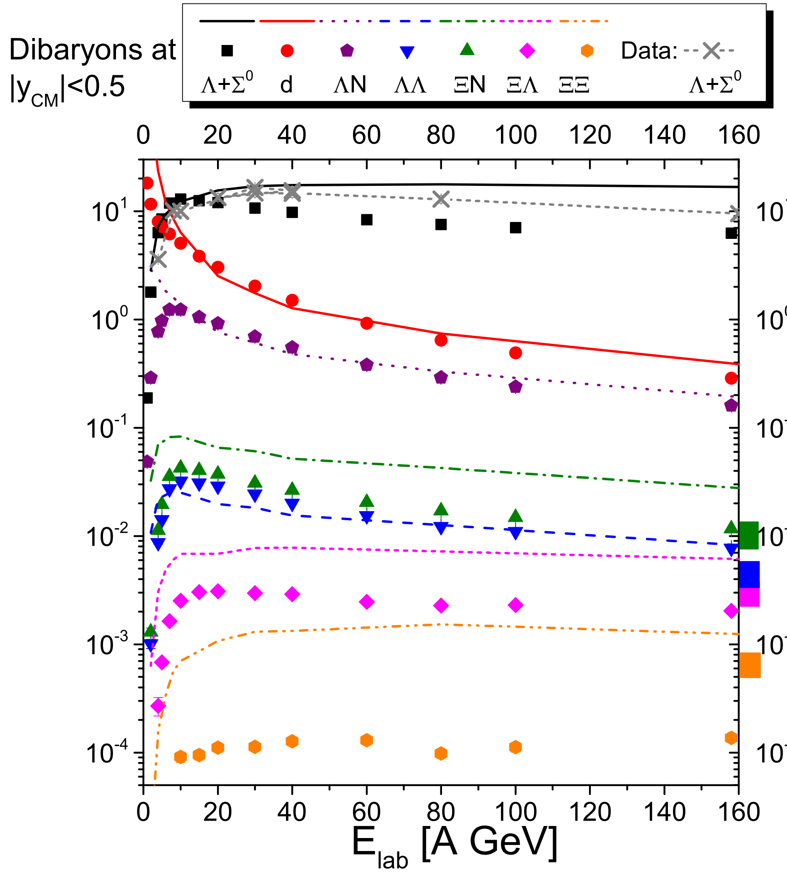


Consistent picture over the whole energy range

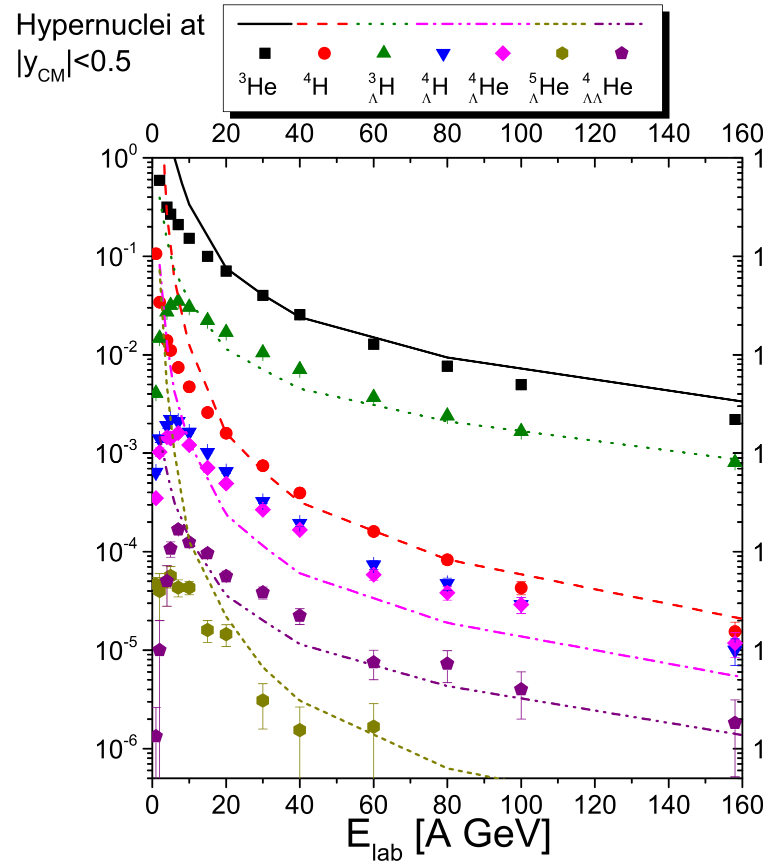
S. Sombun, M. Bleicher et al, Phys.Rev. C99 (2019) no.1, 014901

Hyper and multi-strange matter

DiBaryons



Hypernuclei

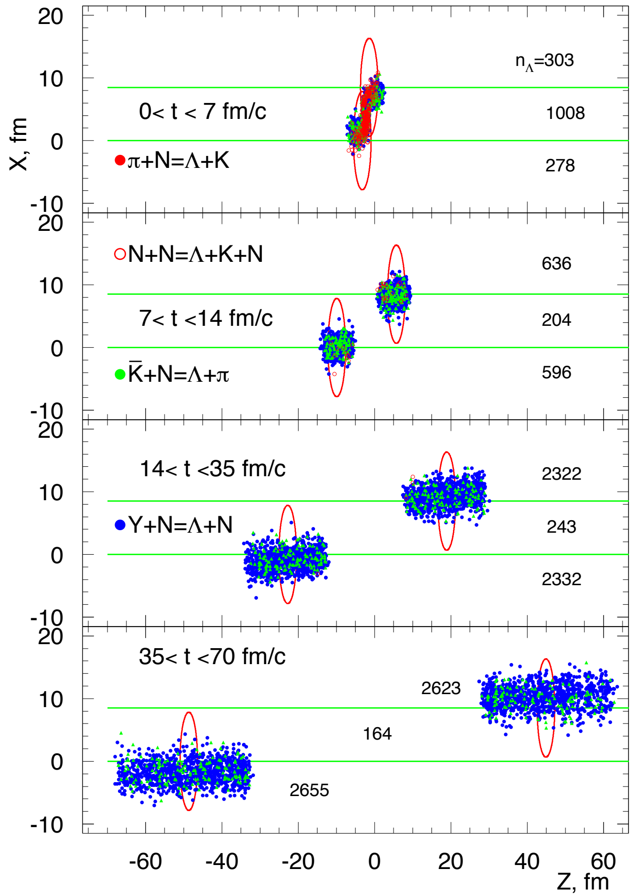


J. Steinheimer, M. Bleicher et al, Phys.Lett. B714 (2012)

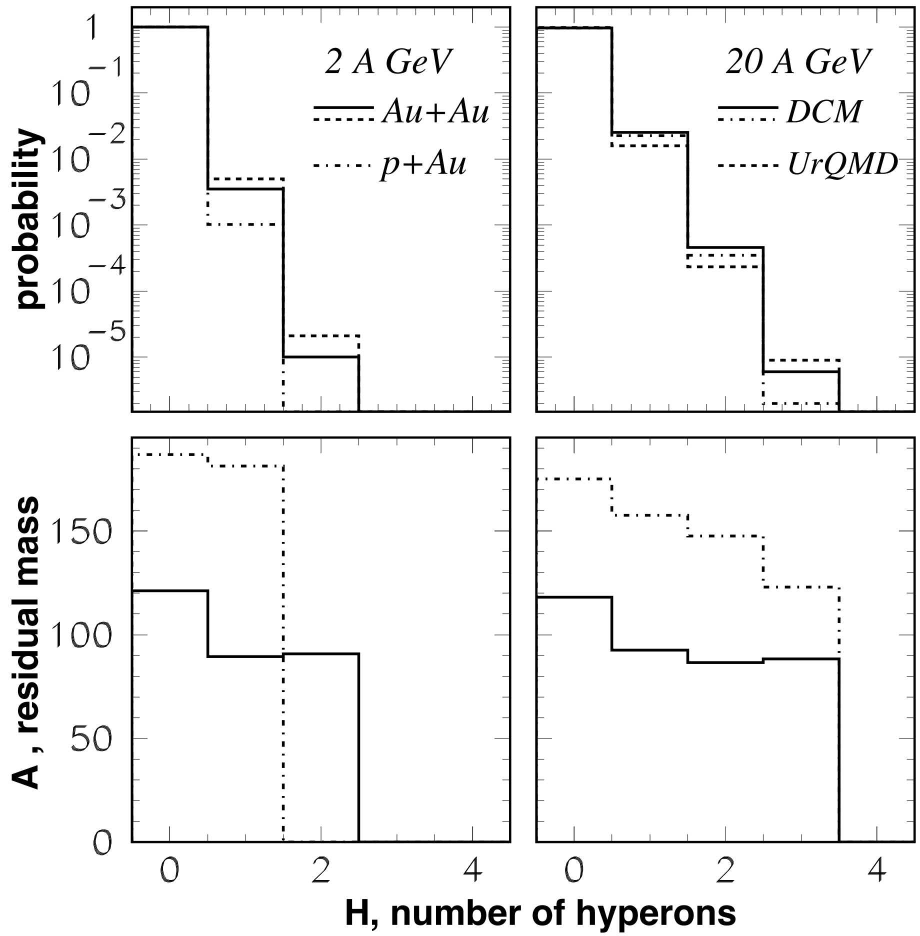
Hybrid model (lines) vs. coalescence (symbols)

Spectator hypermatter: A new road to hypernuclei

Time evolution



Hypernuclei



A. Botvina. M. Bleicher et al., Phys.Rev. C84 (2011) 064904

Significant amount of multi-hyper fragments

Summary

- Coalescence works very well over a broad energy regime
- True process is difficult to distinguish, maybe fluctuations can help
- Results are similar to the obtained from thermal models and hybrid models
- Predictions for hypermatter show that FAIR is ideally positioned to explore this new kind of matter.