

CLUSTER PRODUCTION IN HIGH ENERGY HEAVY ION COLLISIONS

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Outline

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

Motivation

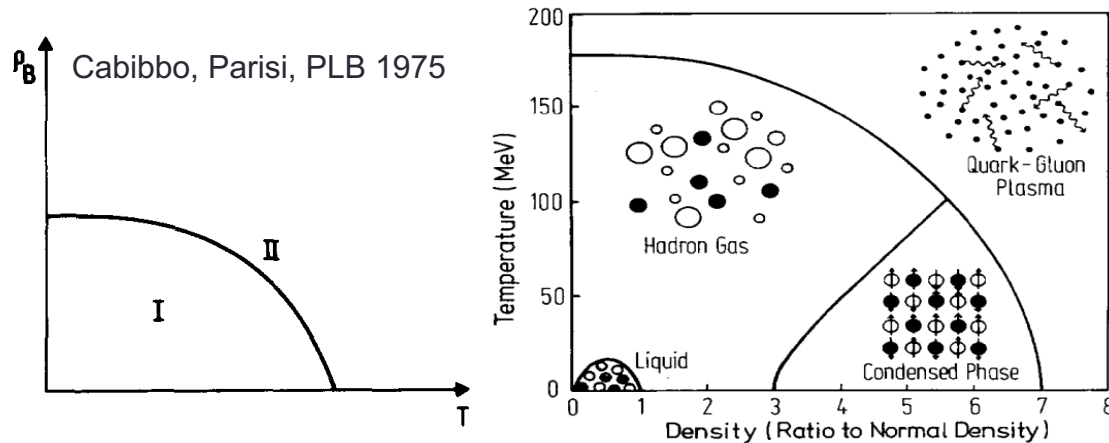
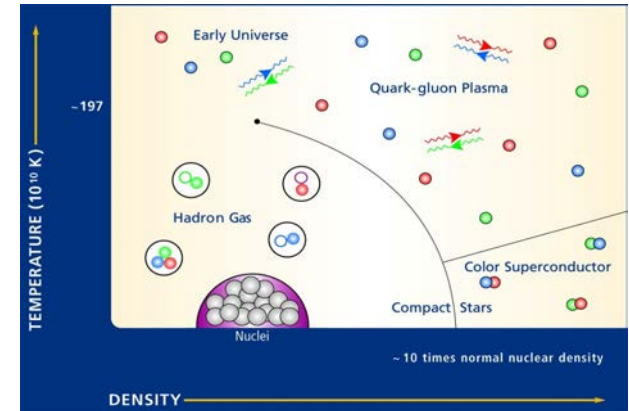


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

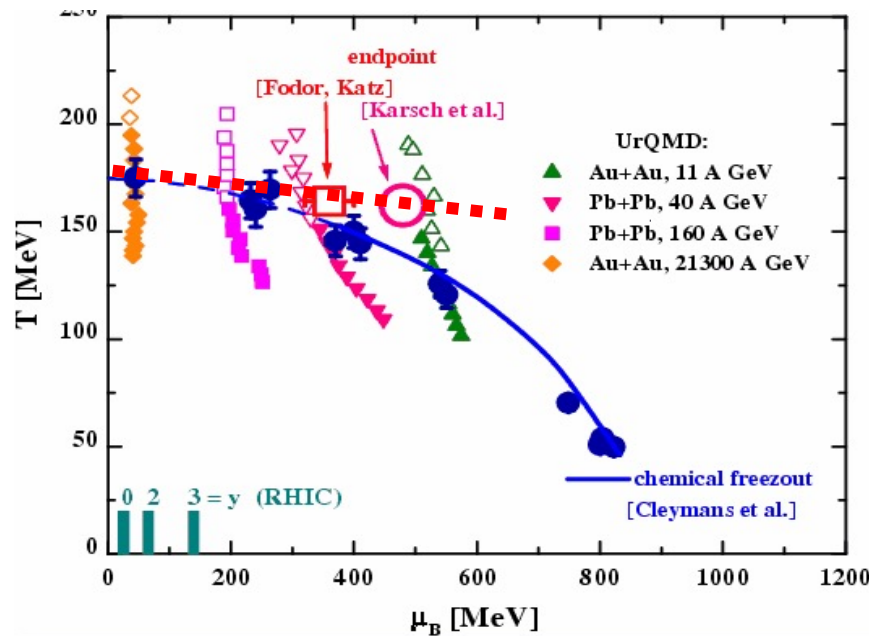
W. Greiner, PR 1986



<http://www.ice.csic.es/en/graphics/phase.jpg>

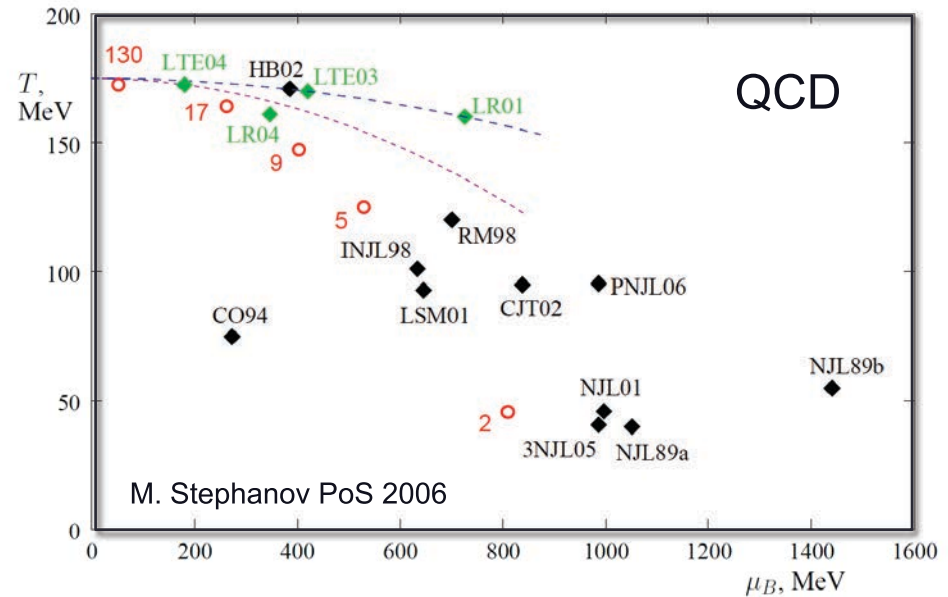
- Learn about phase structure of QCD
- Understand emission structure
- Explore composite particles
- Investigate influence on fluctuation observables

QCD Phase Diagram



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

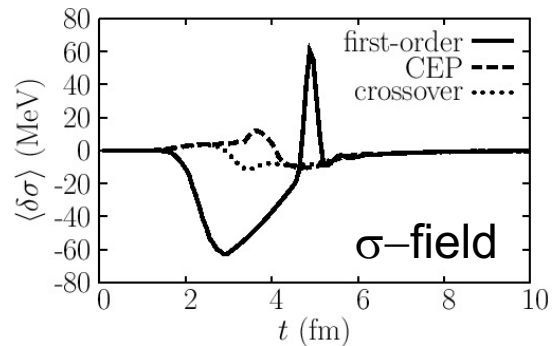
I. Arsene et al., PRC 2007



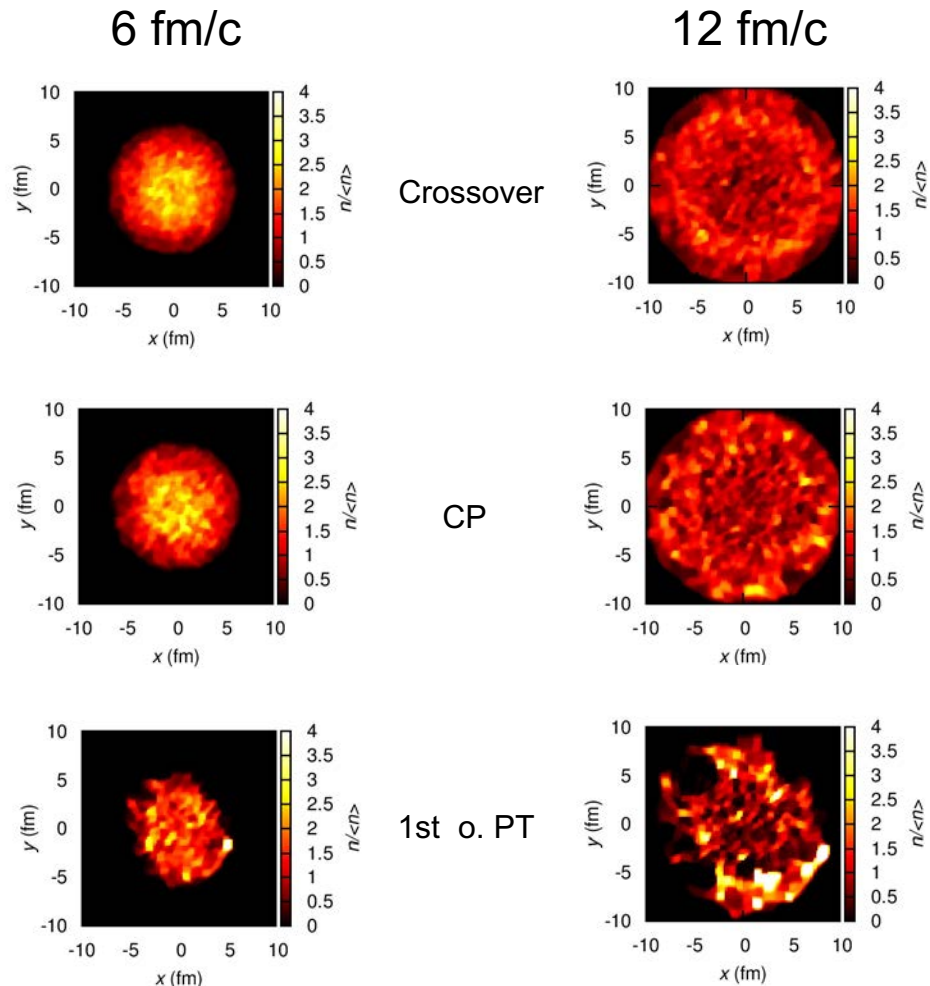
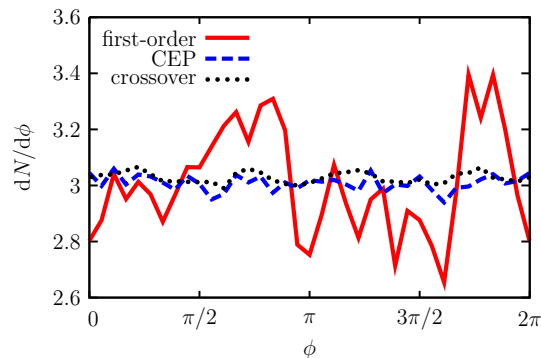
- Except for $\mu_B \rightarrow 0$, many features are unknown
- Order of PT, critical points, dof (Quarkyonic matter?)

Fluctuations in quark densities \rightarrow Clusters might be enhanced

Nonequilibrium fluctuations in PQM

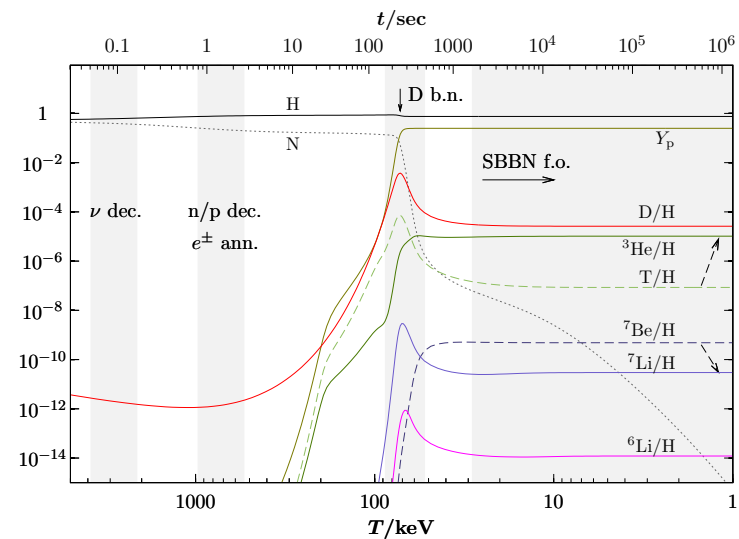
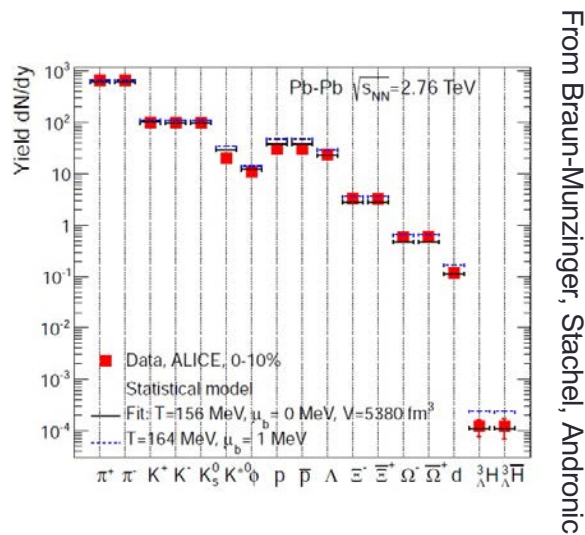


Angular distribution, 12 fm/c



\rightarrow Strong fluctuations, inhomogeneous quark densities \rightarrow Cluster enhancement

Thermal emission vs. BB nucleosynthesis



- 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:

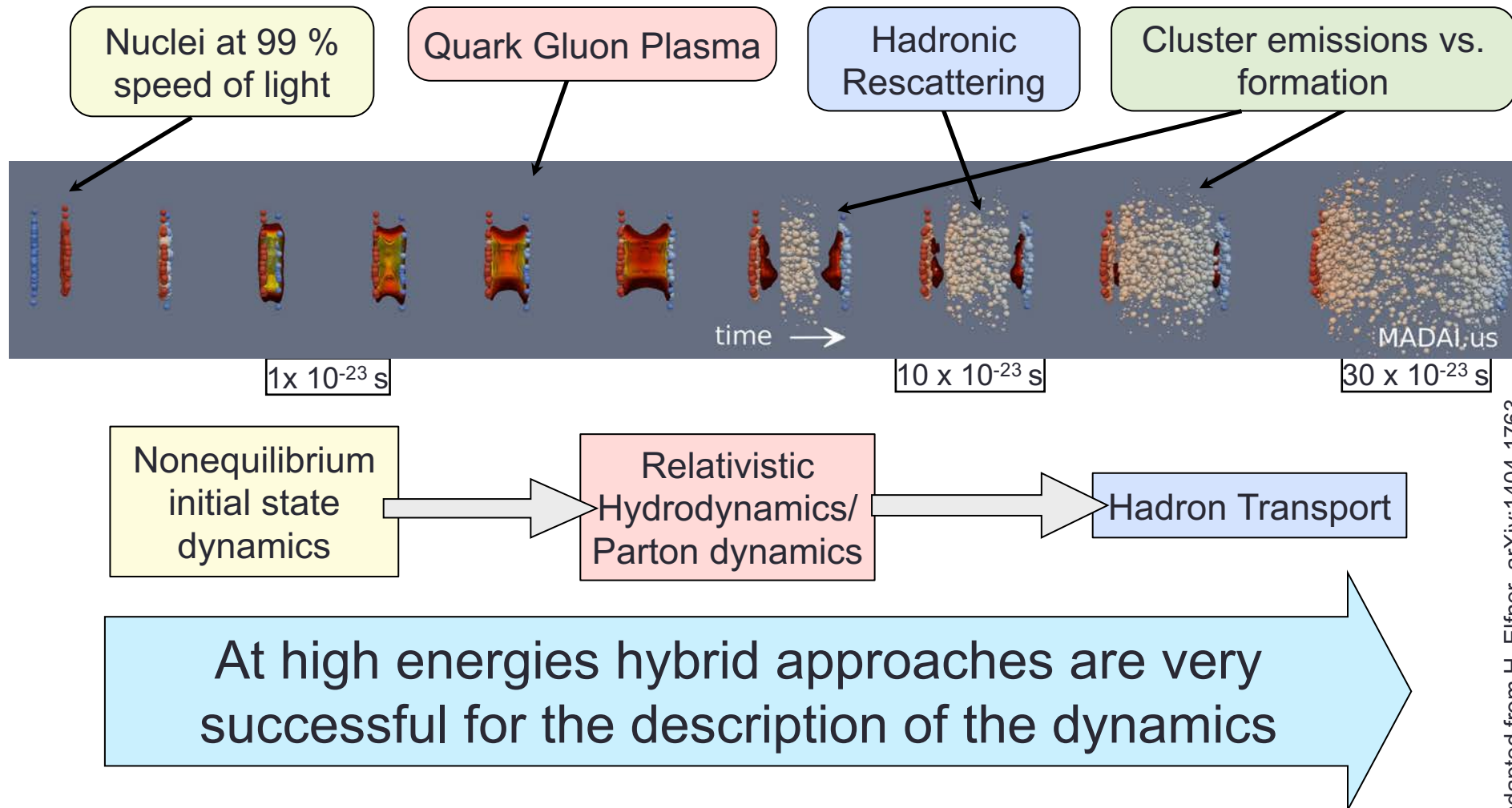
If the temperature is too high (mean energy per particle greater than d binding energy) any deuterium that is formed is immediately destroyed

→ delays production of heavier clusters/nuclei.

Some history...

- Around 1993 the field did not understand anti-deuteron production within the most simple coalescence models
i.e.
$$\frac{1}{\sigma} \frac{Ed^3\sigma_D}{d^3P} = B_2 \left(\frac{1}{\sigma} \frac{Ed^3\sigma_p}{d^3p} \right)^2$$
- Reason:
Freeze-out volume of deuterons and anti-deuterons might be different (S. Mrowczynski, PLB308 (1993))
- Solution: Take space into account (B_2 has to include source)
- See e.g.
M. Bleicher, “Phase space correlations of anti-deuterons in heavy ion collisions” PLB361 (1995)
- Mattiello, Sorge, Nagle, Ko, Aichelin, Heinz, about a dozen papers on clusters from 1995-1999

Time Evolution of Heavy Ion Collisions



Methods to calculate clusters

- **Wigner functions**

- Projection on Hulthen wave function
- No free parameters
- No orthogonality of states

- **Coalescence**

- Employ cut-off parameters
- E-by-E possible
- 2 free parameters

- **Cross sections**

- Introduce explicit processes, e.g. $p+n+\pi \rightarrow d+\pi$
- Dynamical treatment
- 'Fake' 3-body interactions

- **Thermal emission**

- Put deuterons in partition sum
- No free parameter
- Why should a cluster be in?

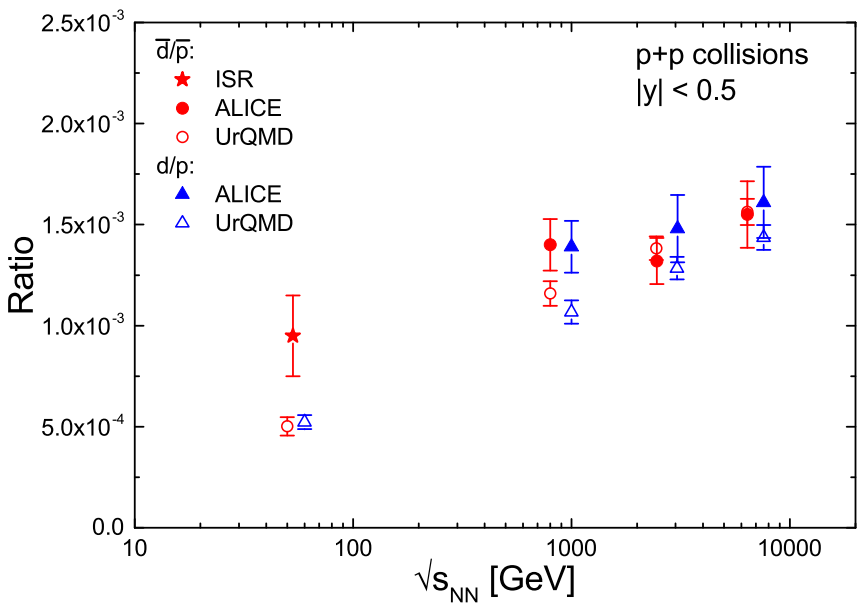
Gyulassy, NPA402 (1983), Oliinychenko, PRC99 (2019),
Butler, PR129 (1963), Mekijan PRL39 (1977)

Coalescence

- Coalescence assumes 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) \rightarrow 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 $\Delta p \lesssim 285 \text{ MeV}$ and a $\Delta x \lesssim 3.5 \text{ fm}$ to define the deuteron state

Proton-proton collisions

Deuteron (anti-deuteron): ratios



Good description of pp by coalescence

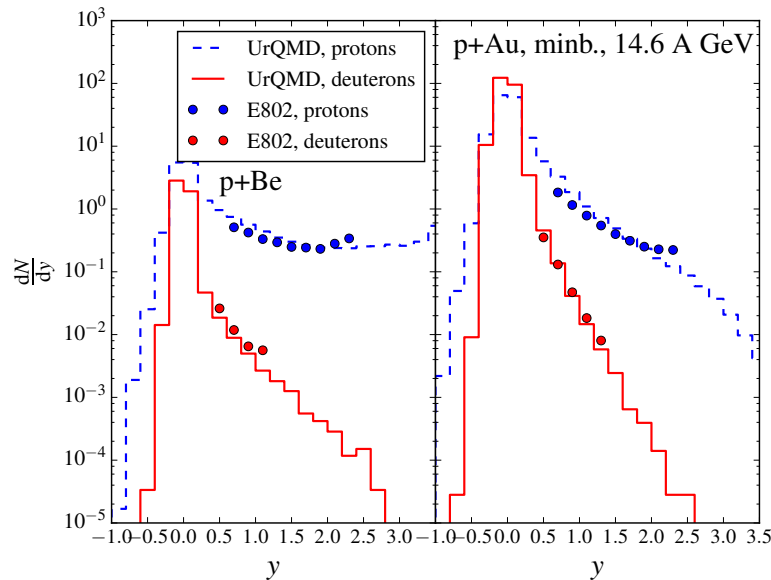
Absolute yields

	$\sqrt{s_{NN}}$ (TeV)	dN/dy	
		ALICE	UrQMD
d	0.9	$(1.12 \pm 0.09 \pm 0.09) \times 10^{-4}$	$(0.96 \pm 0.05) \times 10^{-4}$
	2.76	$(1.53 \pm 0.05 \pm 0.13) \times 10^{-4}$	$(1.47 \pm 0.06) \times 10^{-4}$
	7	$(2.02 \pm 0.02 \pm 0.17) \times 10^{-4}$	$(2.05 \pm 0.09) \times 10^{-4}$
\bar{d}	0.9	$(1.11 \pm 0.10 \pm 0.09) \times 10^{-4}$	$(1.00 \pm 0.05) \times 10^{-4}$
	2.76	$(1.37 \pm 0.04 \pm 0.12) \times 10^{-4}$	$(1.55 \pm 0.07) \times 10^{-4}$
	7	$(1.92 \pm 0.02 \pm 0.15) \times 10^{-4}$	$(2.22 \pm 0.09) \times 10^{-4}$

Absolute yields in line with ALICE data

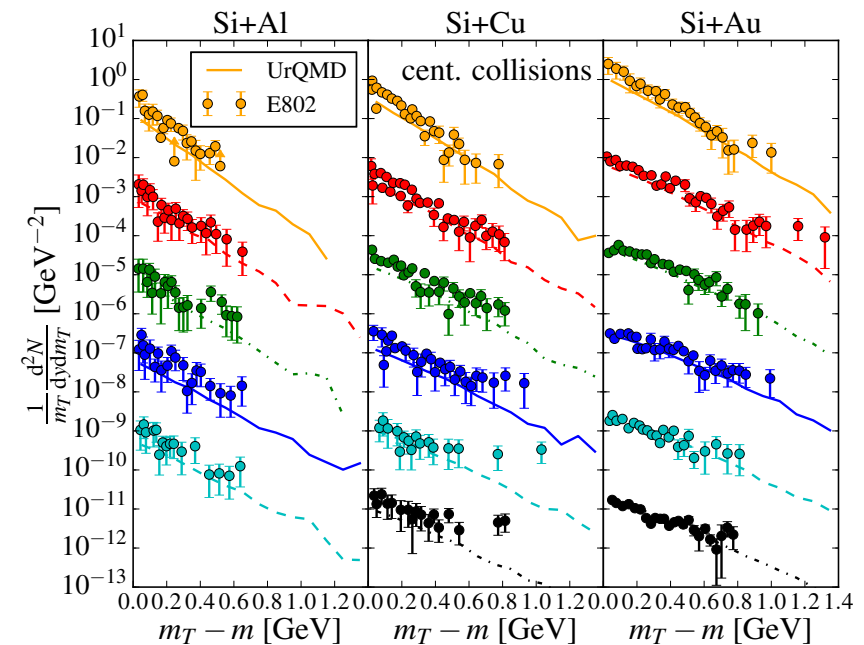
From small to large systems

Proton+nucleus at 14.6 AGeV



Rapidity distributions indicate correct coalescence behavior

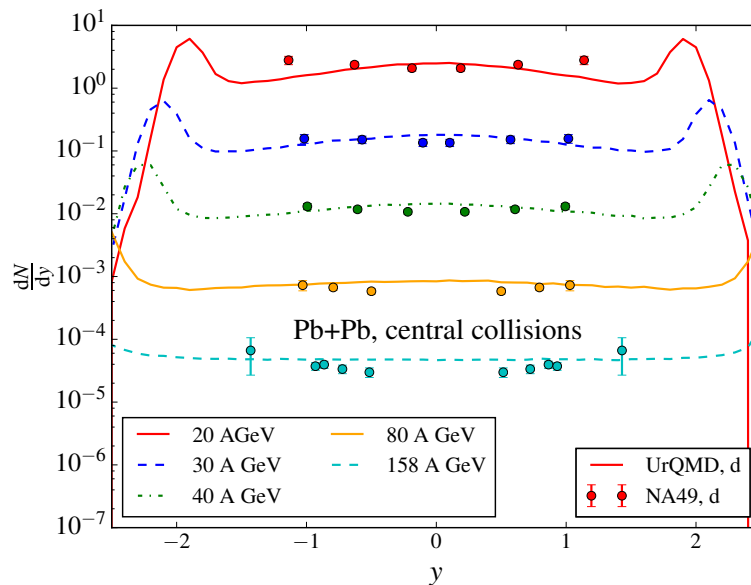
Transverse dynamics in Si+(Al/Cu/Au) at 14.6 AGeV



Also transverse expansion is well captured in the coalescence approach

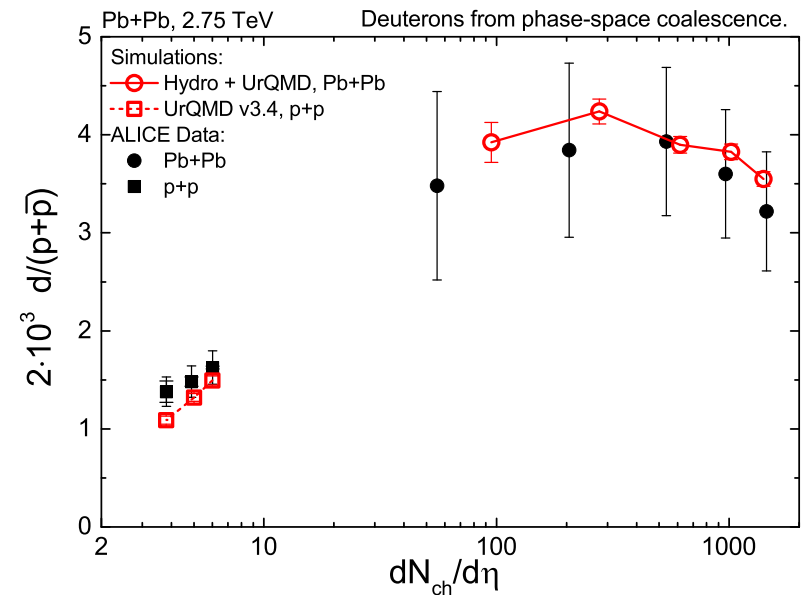
Towards higher energies

Pb+Pb from 20 AGeV
to 158 AGeV



Deuteron rapidity distributions
well described over a broad range
of energies

LHC results:
Centrality dependence

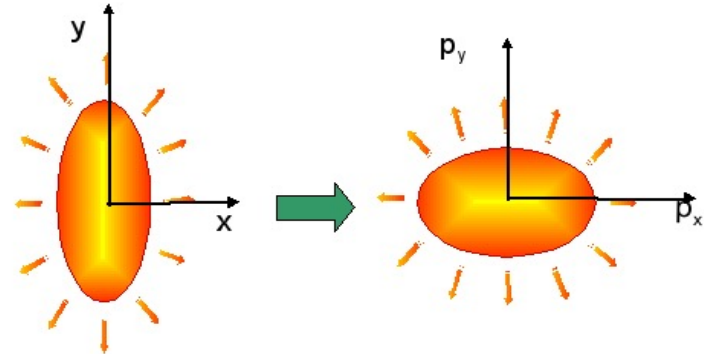


Decrease of d/p ratio for very central
collisions
→ indication for larger freeze-out volume

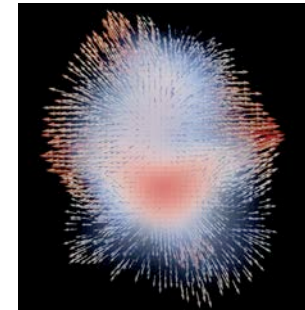
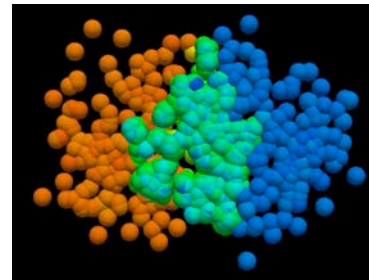
Anisotropic Flow – Higher Order Fourier Coefficients

Simplified picture:

Position-space anisotropy
→ Momentum-space anisotropy

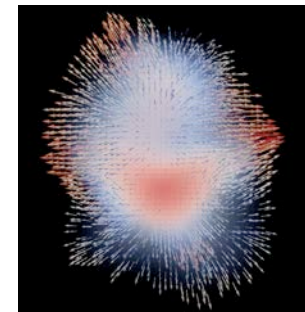
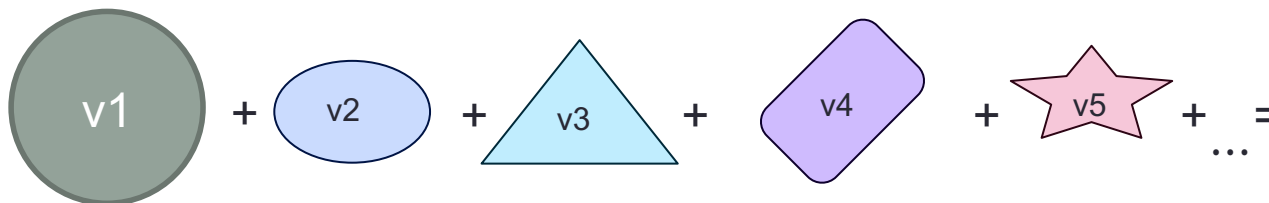


Real picture:
Complicated state,
mean free paths,...



by MADAI.us

Fourier expansion of the radial distribution! → v_n



Can we distinguish thermal emission from coalescence?

→ Scaling

NCQ scaling at high energies

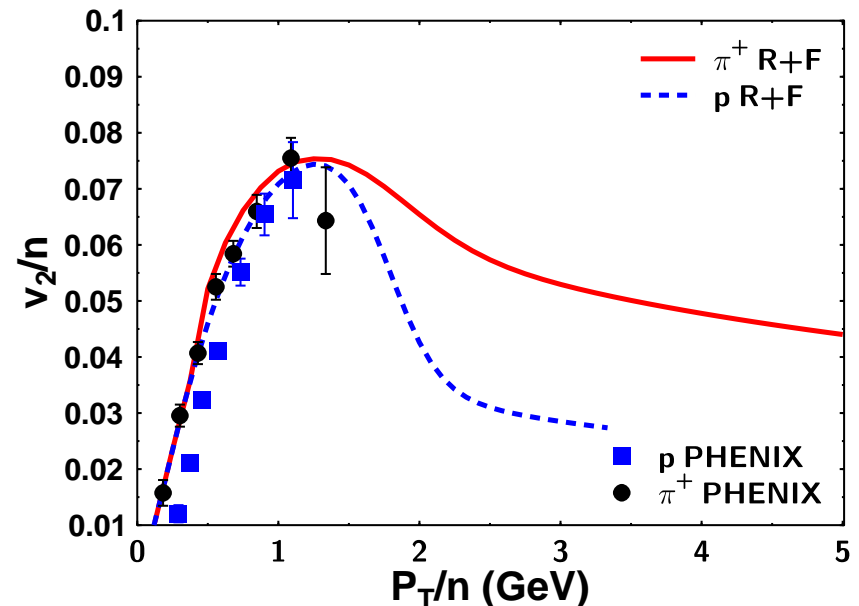
- discovery of “magical factors” of 2 and 3 in measurements of spectra and the elliptic flow of mesons and baryons at RHIC (Fries et al, 2003)
- Predicted v_2 scaling in case of coalescence

$$v_2^h(P_T) = n v_2 \left(\frac{1}{n} P_T \right)$$

→ Check scaling to prove coalescence

Fries et al, Phys.Rev. C68 (2003)

RHIC data

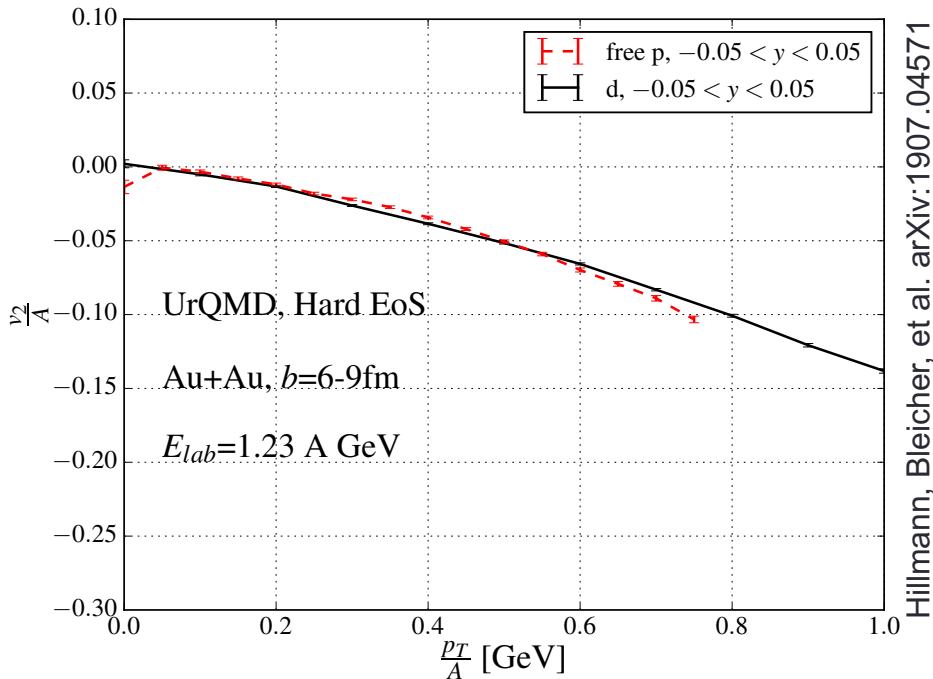


Scaling at LHC is a different story...

Can we distinguish thermal emission from coalescence?

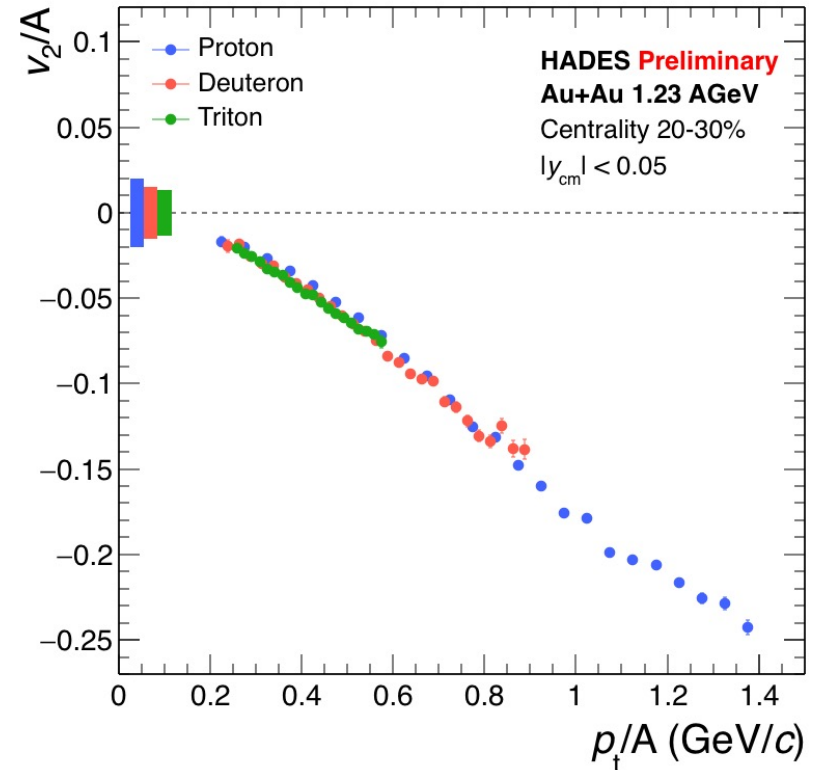
→ Scaling

UrQMD



→ Scaling is observed

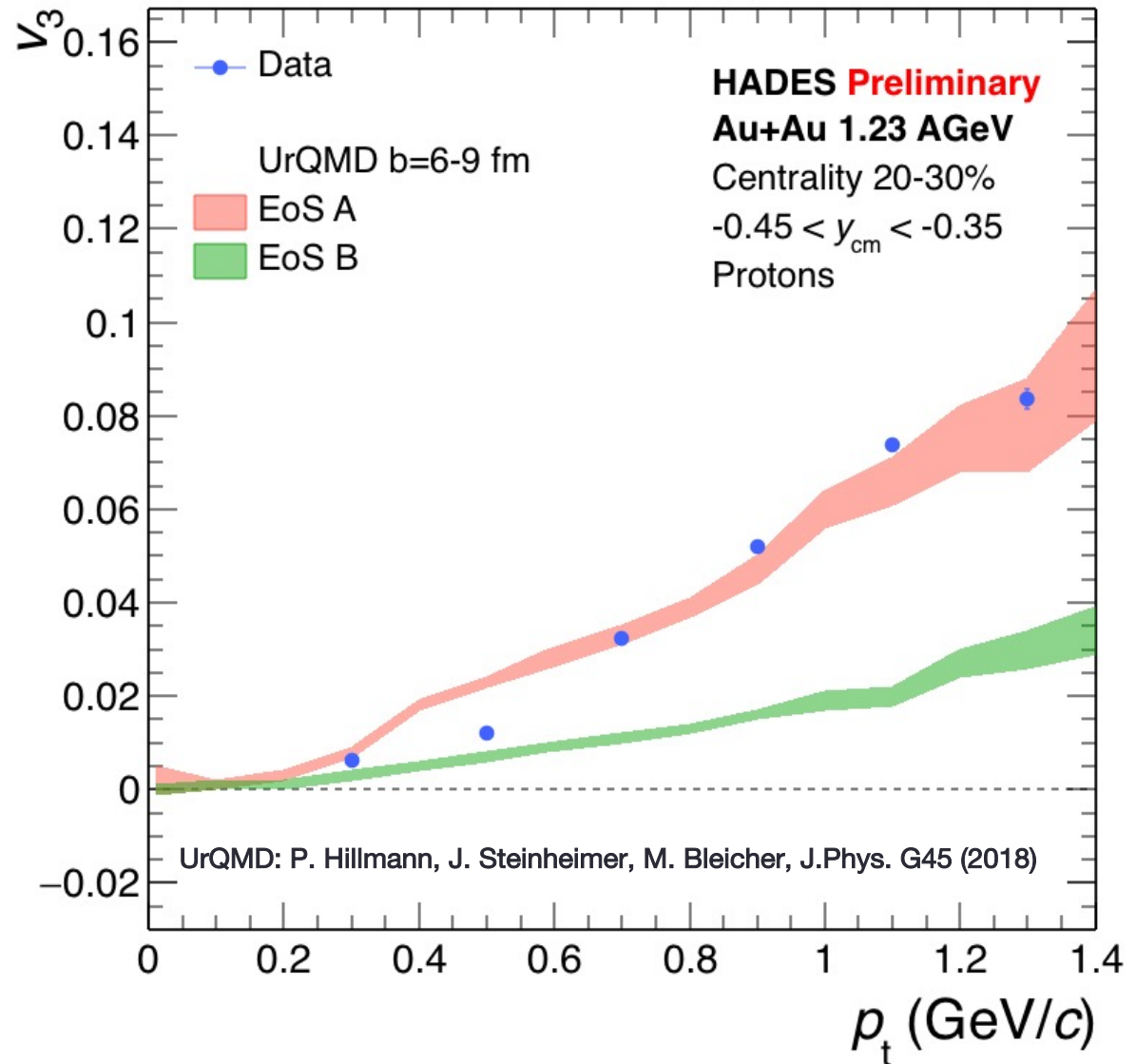
HADES data



Taken from Behruz Kardan, arXiv:1809.07821

Higher order flow

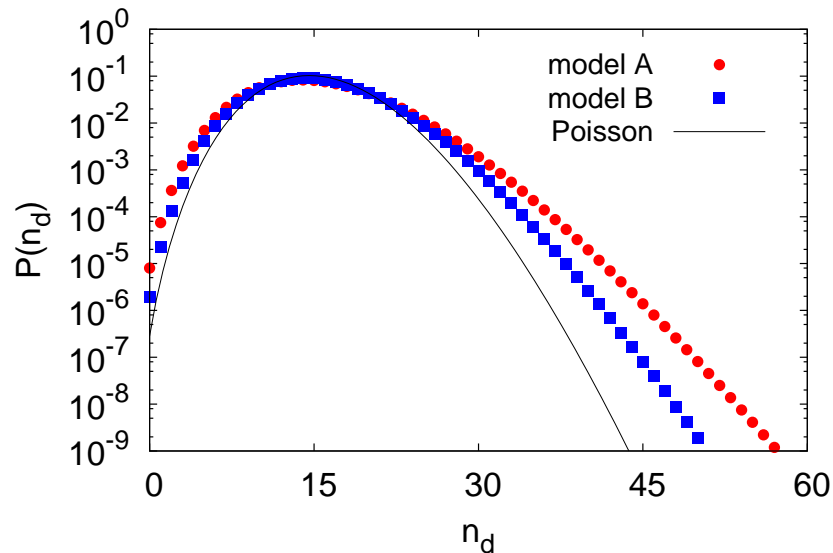
- Also higher order flow works very well.
- Indication that correlations are propagated correctly
- Suggests “hard” (or momentum dependend) equation of state



Can we distinguish thermal emission from coalescence?

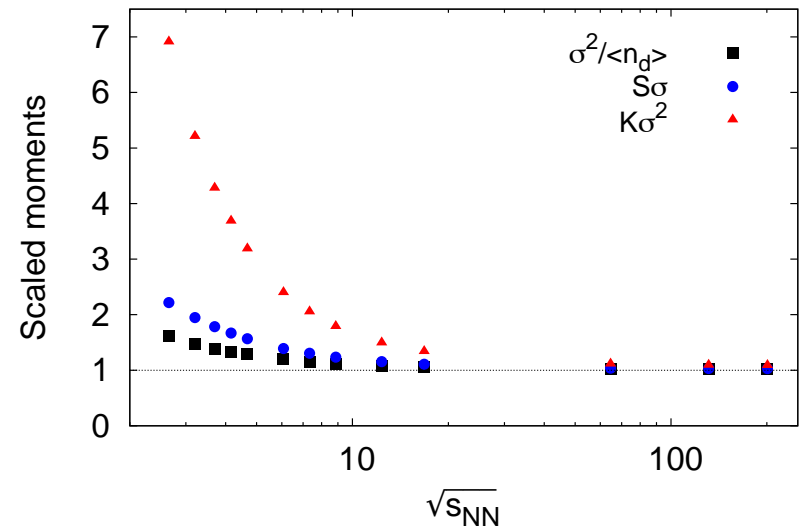
→ Fluctuations

Au+Au at 2 AGeV



Thermal emission would result
in Poisson fluctuations
→ Coalescence leads to
wider (non-poisson) distributions

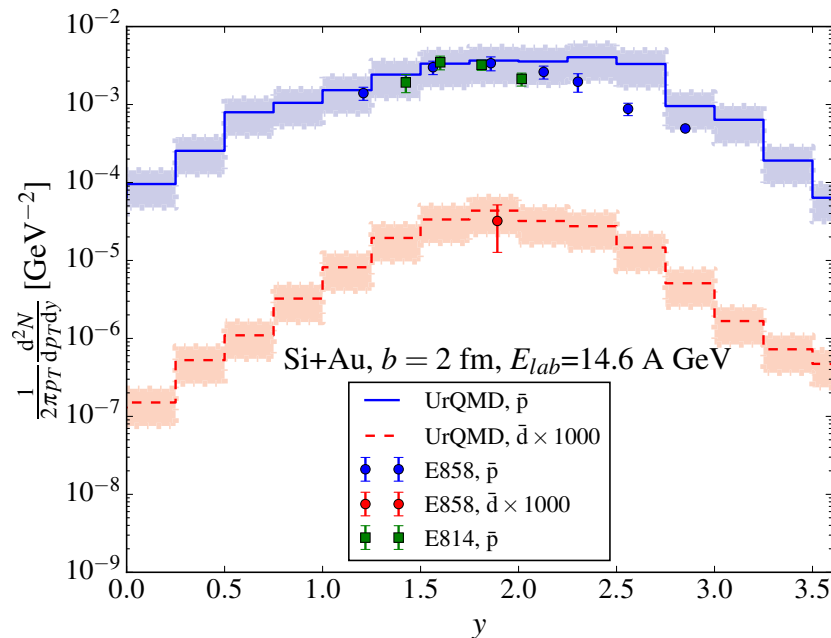
Moments of distribution



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

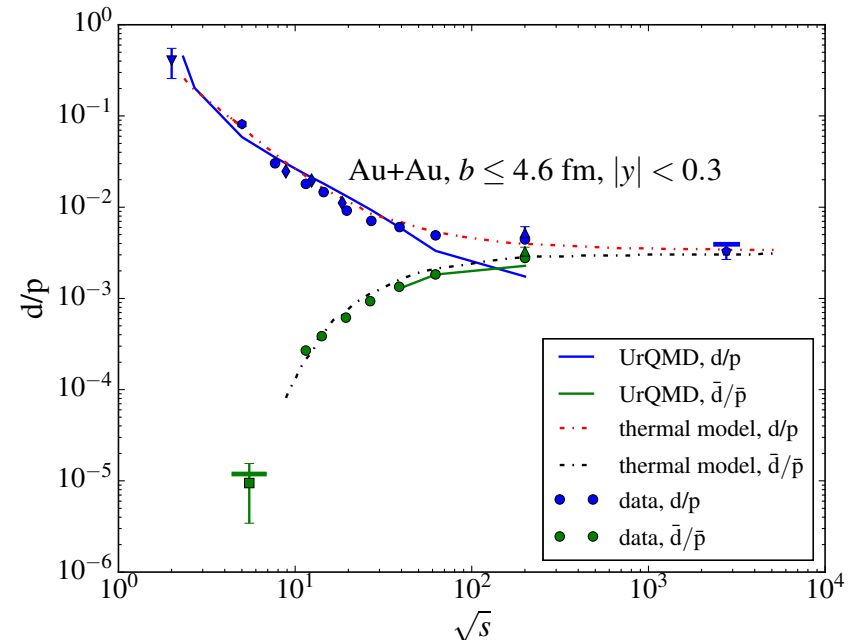
Anti-deuterons

Does coalescence also work for more exotic states?



- Surprisingly good description of anti-deuteron yield
- Same parameters!!

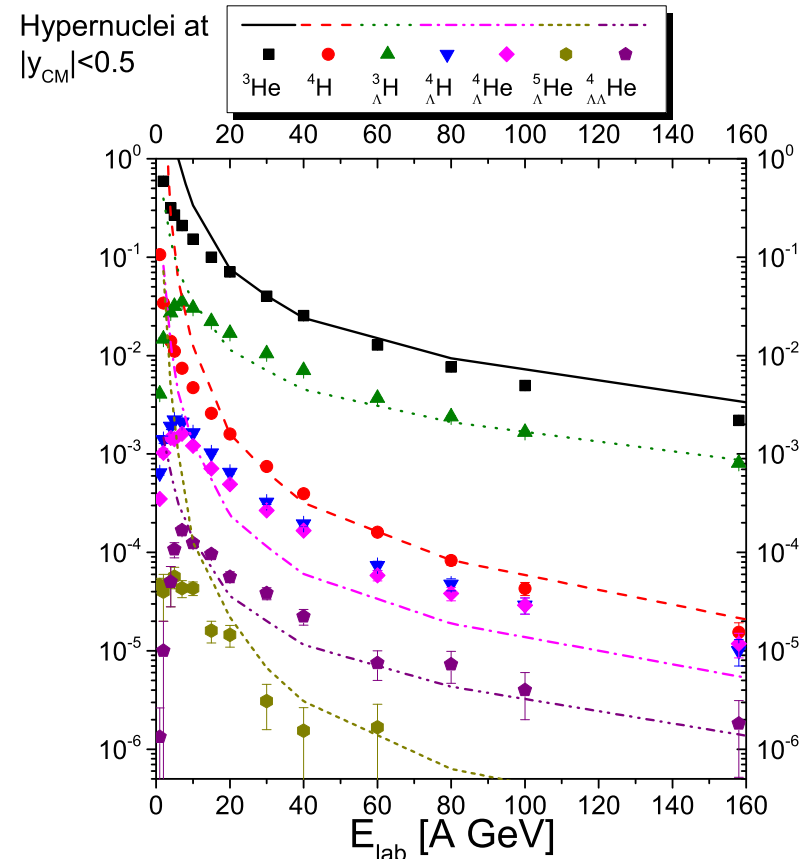
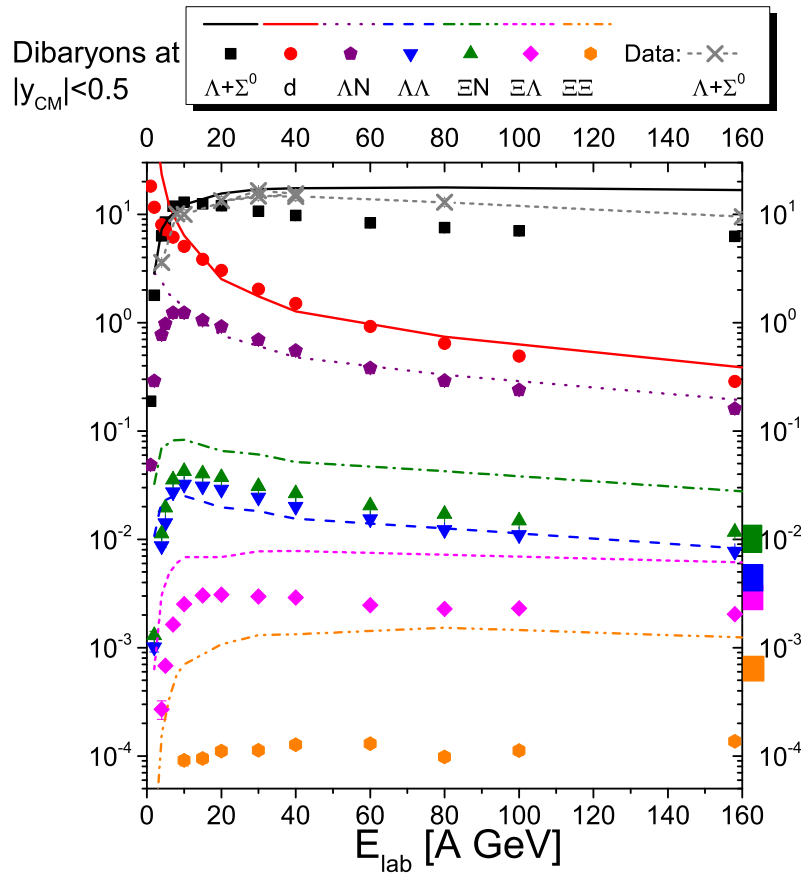
Energy dependence of deuterons and anti-deuterons



Consistent picture over the whole energy range

Hyper and multi-strange matter

DiBaryons

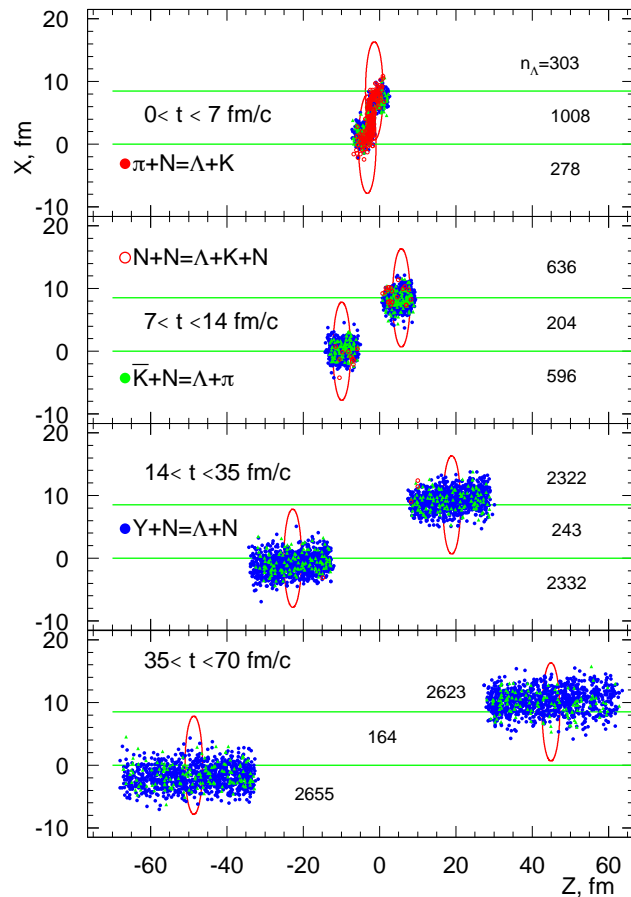


Hybrid model (lines) vs. coalescence (symbols)

See also Bastian, Blaschke, Roepke, et al, Eur.Phys.J. A52 (2016)

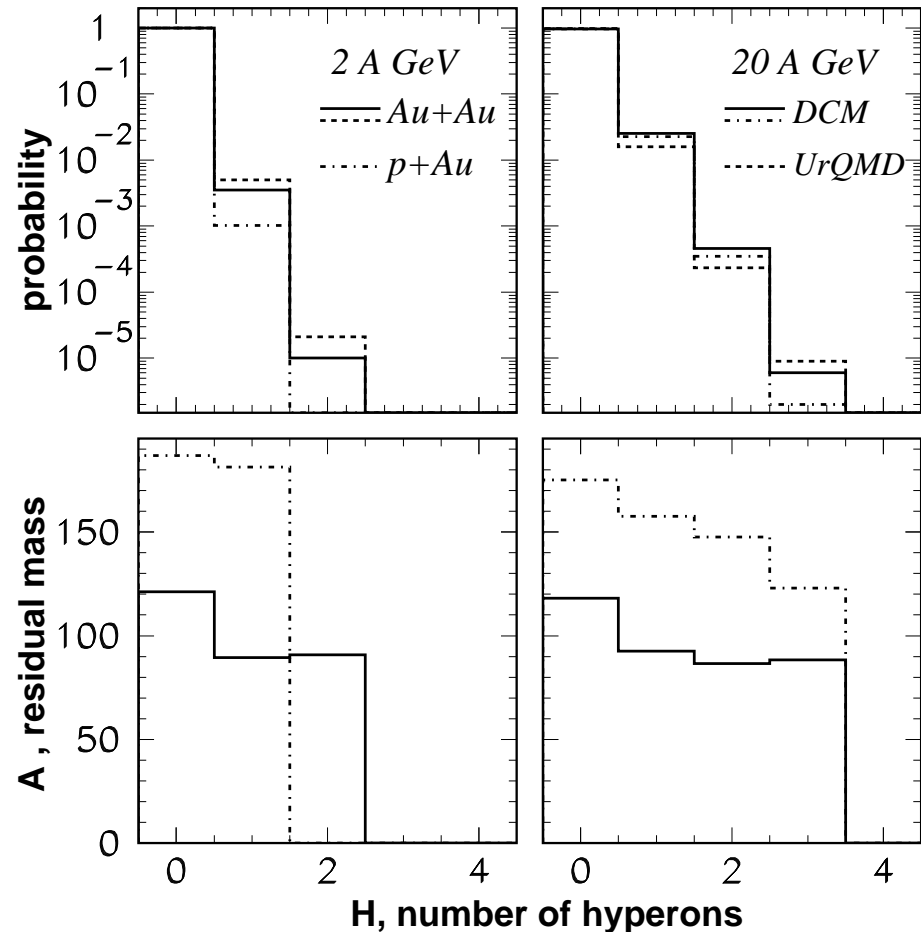
Spectator hypermatter: A new road to hypernuclei

Time evolution



Significant amount of multi-hyper fragments

Hypernuclei



Summary

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