CLUSTER PRODUCTION IN HIGH ENERGY HEAVY ION COLLISIONS

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NIC

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- Ayut Limphirat
- Tom Reichert
- Paula Hillmann

Outline

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

Motivation

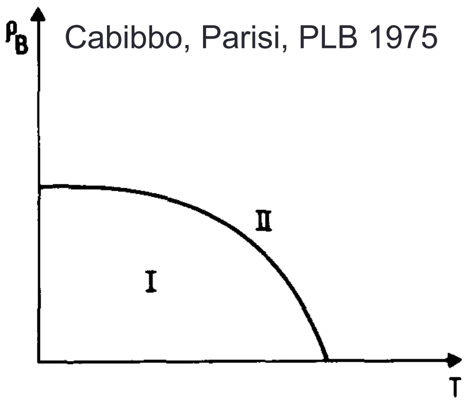
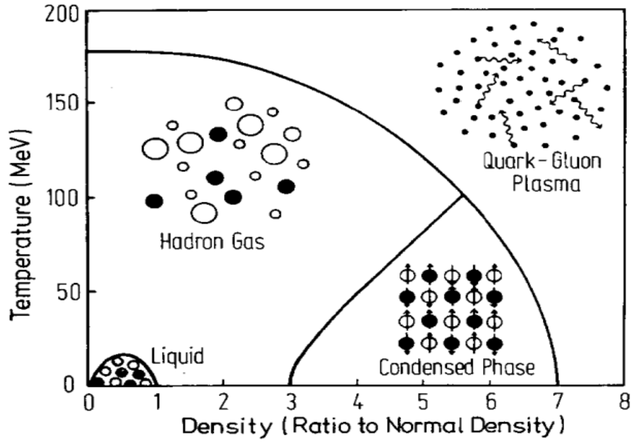
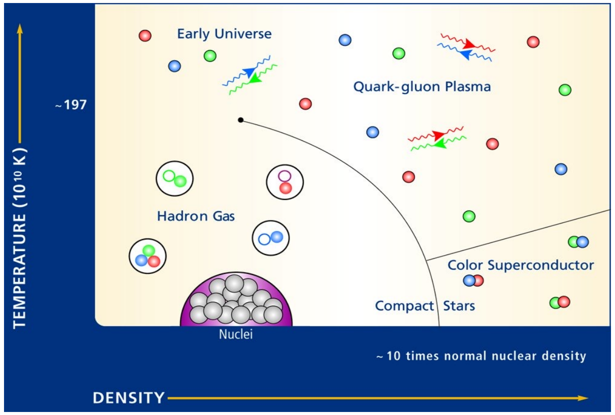


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.



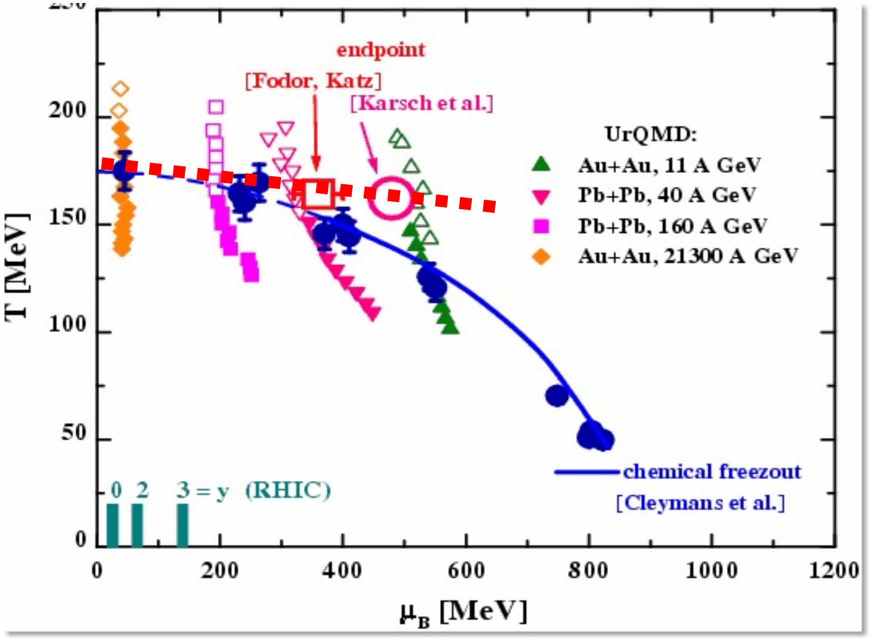
W. Greiner, PR 1986

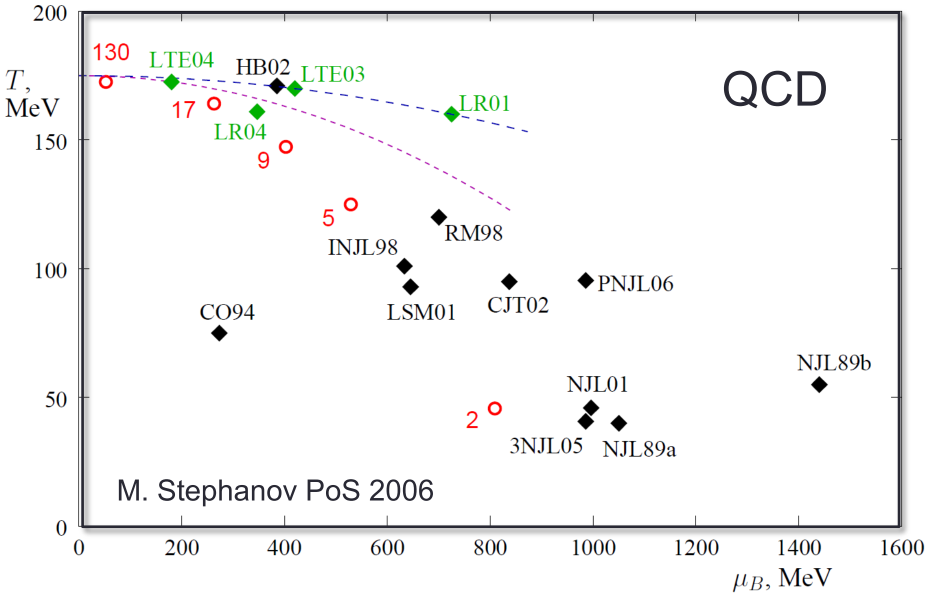


http://www.ice.csic.es/en/graphics/phase.jpg (2010)

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

QCD Phase Diagram



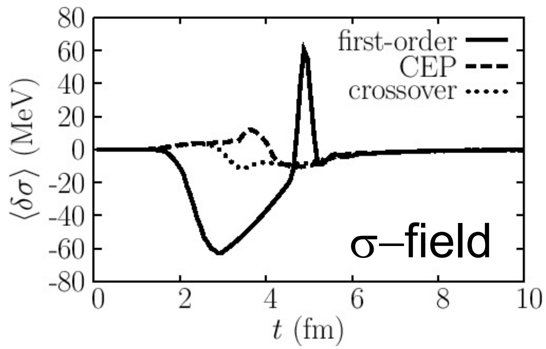


L. Bravina, M.B., et al., JPG 1999
I. Arsene et al., PRC 2007

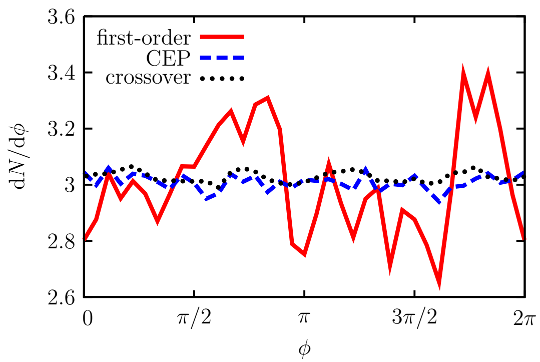
- Except for $\mu_B \rightarrow 0$, many features are unknown
- Order of PT, critical points, dof (Quarkyonic matter?)

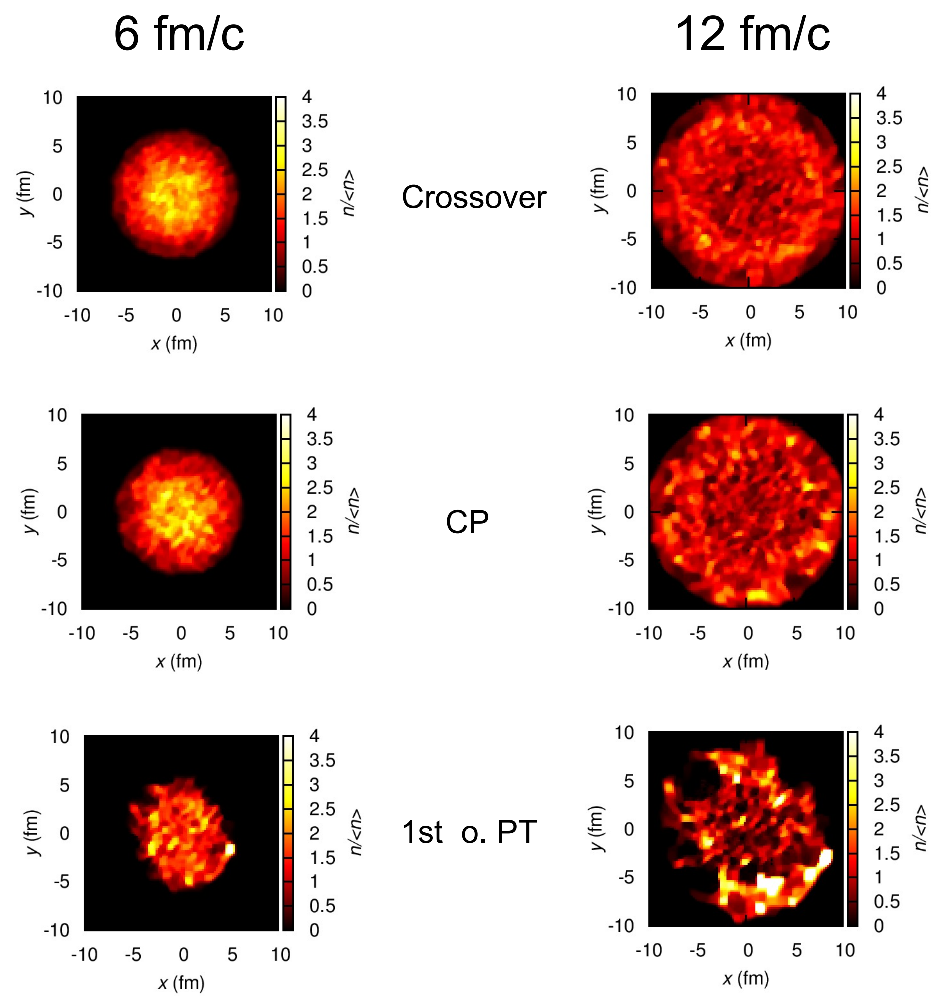
Fluctuations in quark densities → Clusters might **be enhanced**

Nonequilibrium fluctuations in PQM



Angular distribution, 12 fm/c

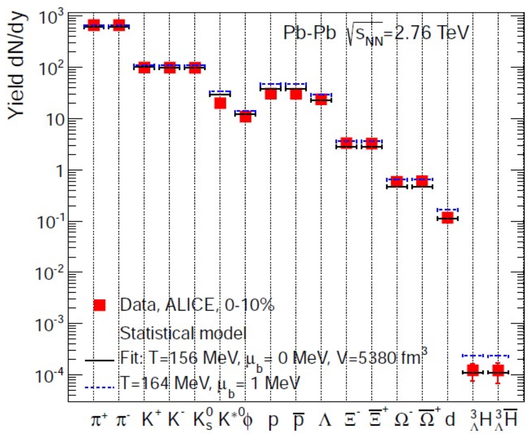




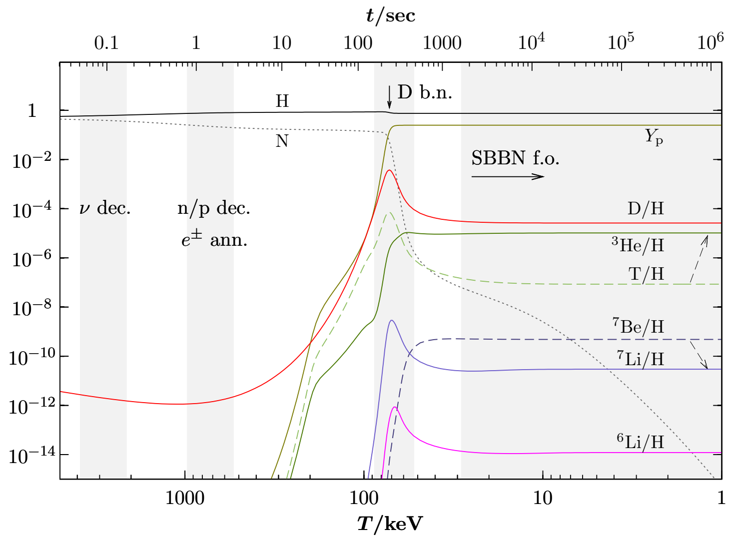
→ Strong fluctuations, inhomogeneous quark densities → Cluster enhancement

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

Thermal emission vs. BB nucleosynthesis



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.

Possible explanation: PCE

- Partial Chemical Equilibrium might solve the problem (see Tim Neidig, Tuesday)
- See also PCE talk by Paula Hillmann (Tuesday) for PCE and fluctuations

- Main idea solve the rate equation with PCE assumption:

$$\frac{\mathrm{d}N_\mathrm{d}}{\mathrm{d}t} = - \sum_{x=\pi,K,\overline{K}} \tilde{\alpha}_{\mathrm{d+x}\rightleftharpoons 2N+x} N_x (N_\mathrm{d} - c_\mathrm{d}^{N^2} N_N^2)$$

Solving the puzzle of high temperature light (anti)-nuclei production in ultra-relativistic heavy ion collisions

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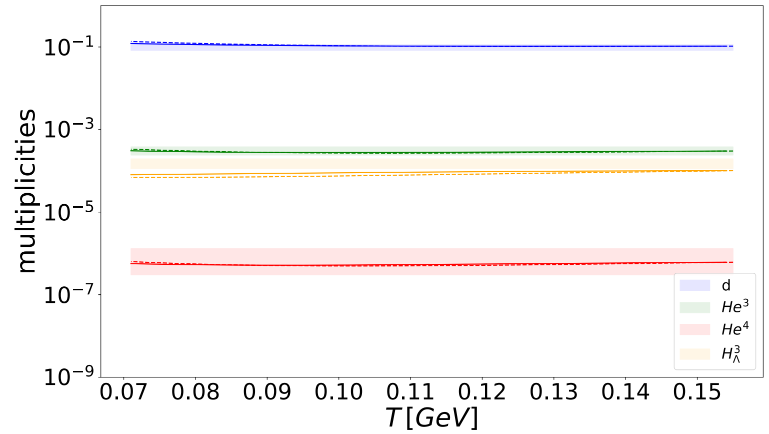
Volodymyr Vovchenko
Nuclear Science Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
(Dated: September 2, 2021)



Some history...

- Around 1993 the field did not understand anti-deuteron production within the most simple coalescence models i.e. $$\frac{1}{\sigma}\frac{E\mathrm{d}^3\sigma_D}{d^3P} = B_2(\frac{1}{\sigma}\frac{E\mathrm{d}^3\sigma_p}{d^3p})^2$$
- **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

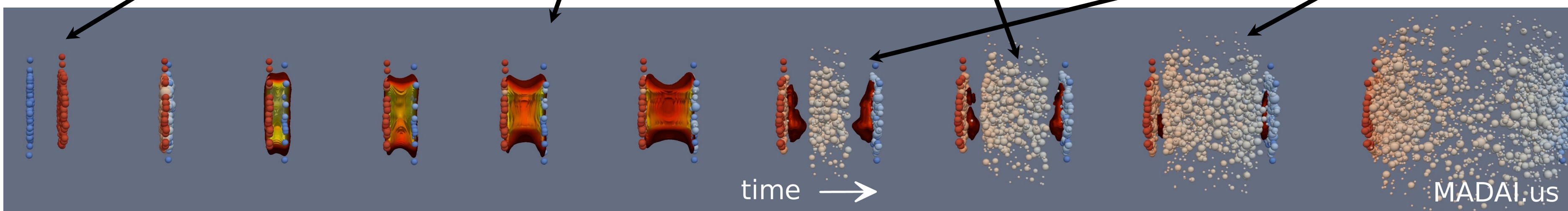
Time Evolution of Heavy Ion Collisions

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Cluster emissions vs. formation



1×10^{-23} s

10×10^{-23} s

30×10^{-23} s

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

Methods to calculate clusters

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

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

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

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

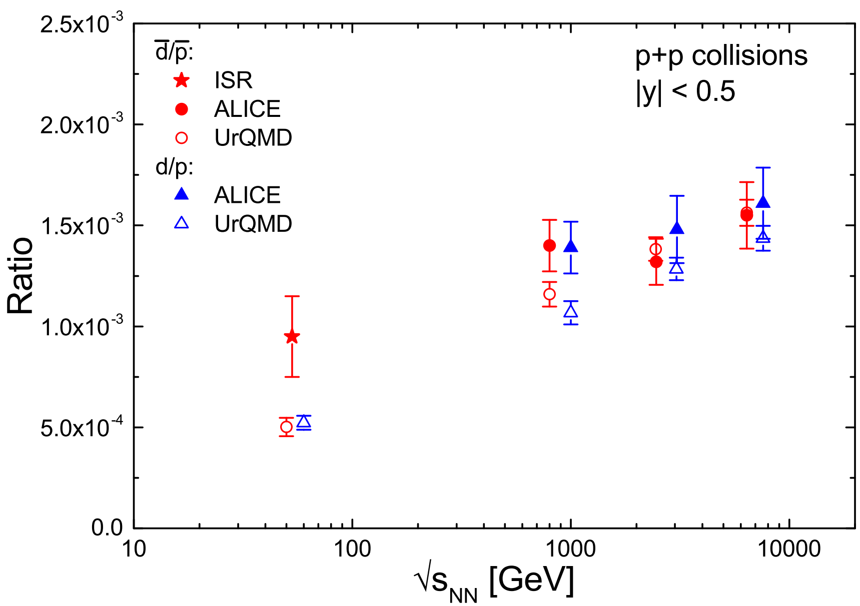
Gyulassy, NPA402 (1983), Oliinychenko, PRC99 (2019), Butler, PR129 (1963), Mekijan PRL39 (1977)

Coalescence

- Coalescence assumes that 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

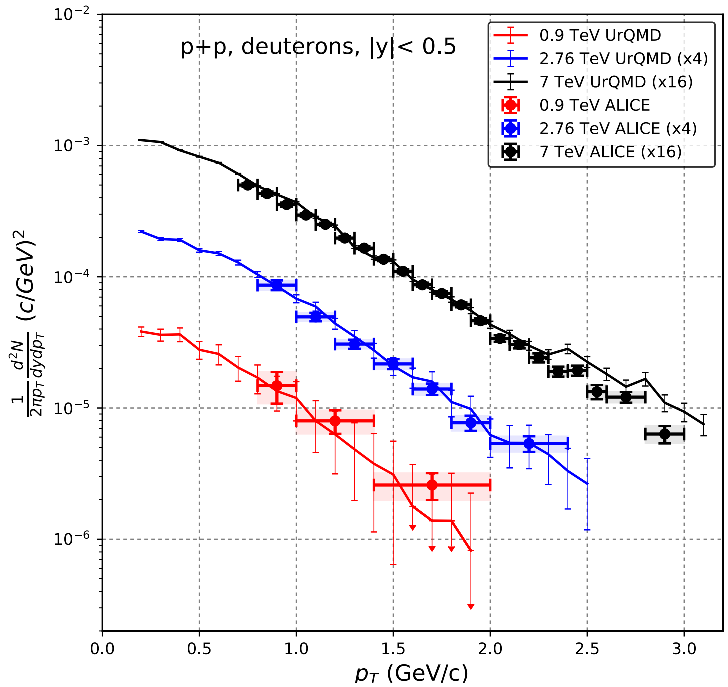
	$\sqrt{s_{NN}}$(TeV)	dN/dy ALICE	dN/dy UrQMD
d	0.9	$(1.12\pm0.09\pm0.09)\times10^{-4}$	$(0.96 \pm 0.05) \times 10^{-4}$
	2.76	$(1.53\pm0.05\pm0.13)\times10^{-4}$	$(1.47 \pm 0.06) \times 10^{-4}$
	7	$(2.02\pm0.02\pm0.17)\times10^{-4}$	$(2.05 \pm 0.09) \times 10^{-4}$
$\overline{d}$	0.9	$(1.11\pm0.10\pm0.09)\times10^{-4}$	$(1.00 \pm 0.05) \times 10^{-4}$
	2.76	$(1.37\pm0.04\pm0.12)\times10^{-4}$	$(1.55 \pm 0.07) \times 10^{-4}$
	7	$(1.92\pm0.02\pm0.15)\times10^{-4}$	$(2.22 \pm 0.09) \times 10^{-4}$

Absolute yields in line with ALICE data

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

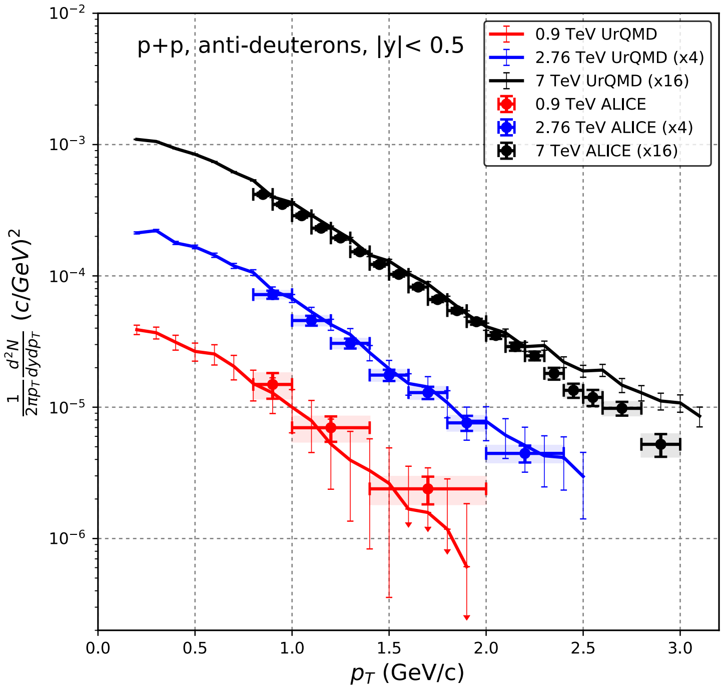
Proton-proton collisions

Transverse momenta (deuterons)



Good description of pp by coalescence

Transverse momenta (anti-deuterons)

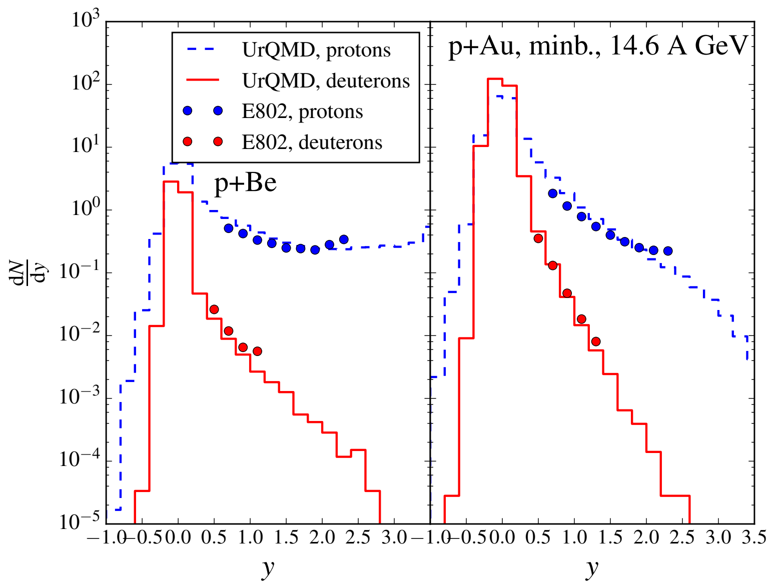


Good description of pp by coalescence

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

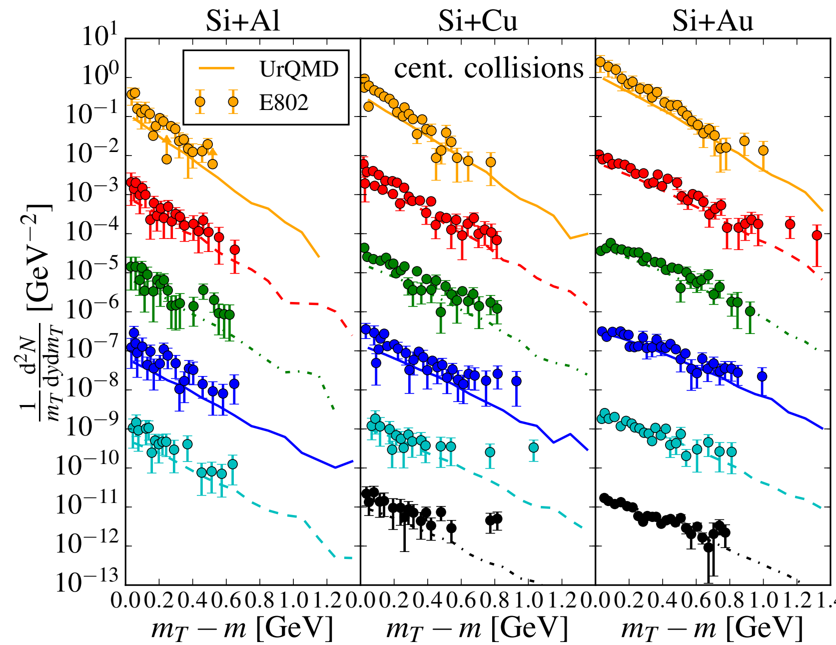
From small to large systems

Proton+nucleus at 14.6 AGeV



Rapidity distributions indicate correct coalescence behavior

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

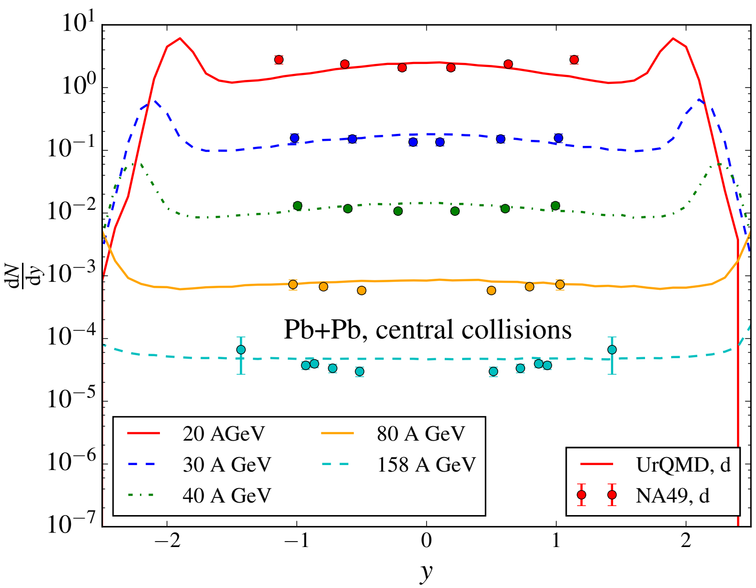


Also transverse expansion is well captured in the coalescence approach

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

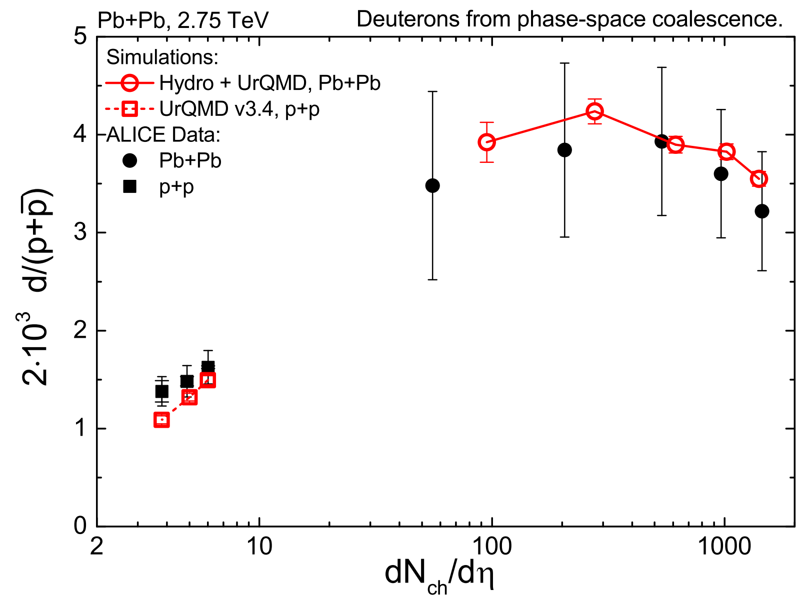
Towards higher energies

Pb+Pb from 20 AGeV to 158 AGeV



Deuteron rapidity distributions well described over a broad range of energies

LHC results: Centrality dependence



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

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

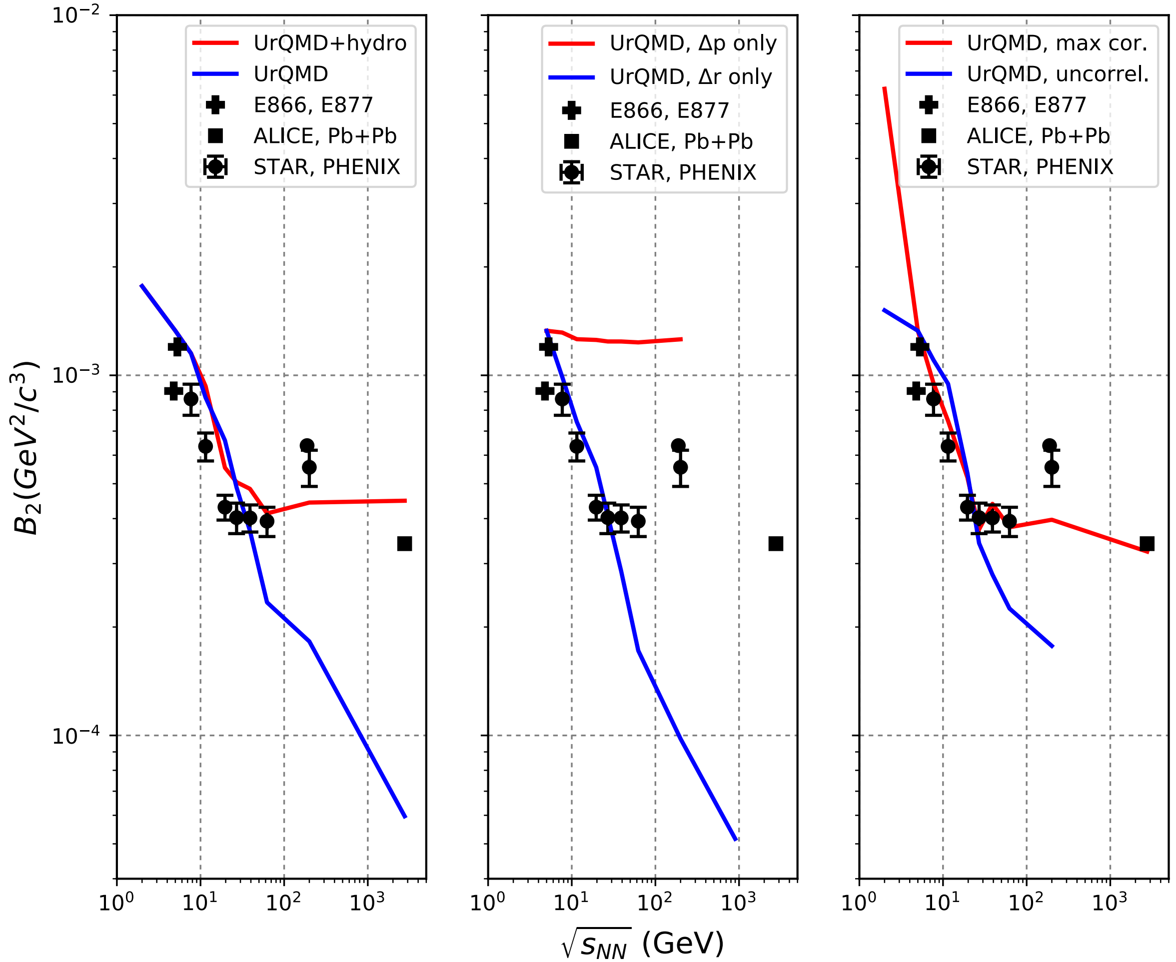
Understanding the energy dependence

$B_2 \sim d/p^2 \sim 1/\mathrm{Volume}$

- Decrease with V is observed
- **Why does it stop?**

- Strong flow aligns the momenta, results in space-mom.space correlation

- Supresses volume effect at high energies



UrQMD vs Hybrid

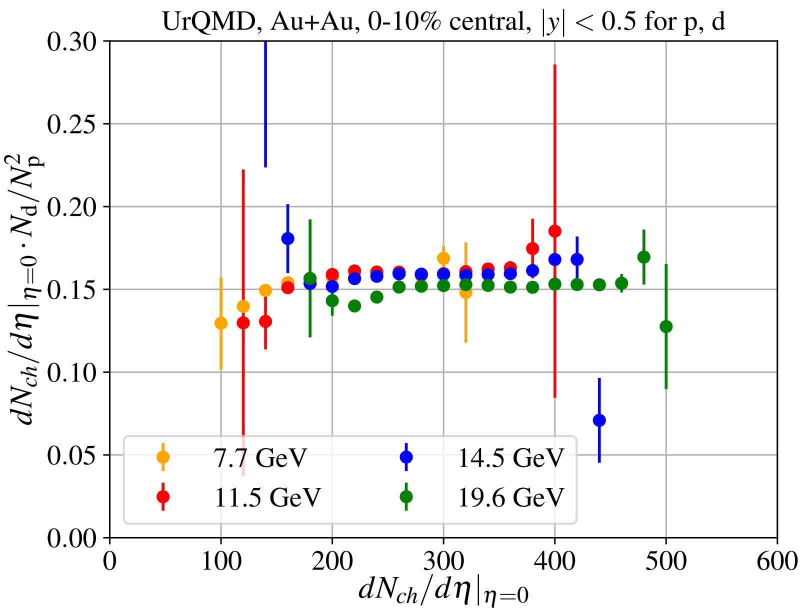
UrQMD: Dp coal. vs Dx coal.

UrQMD: uncorrelated vs. full correlation

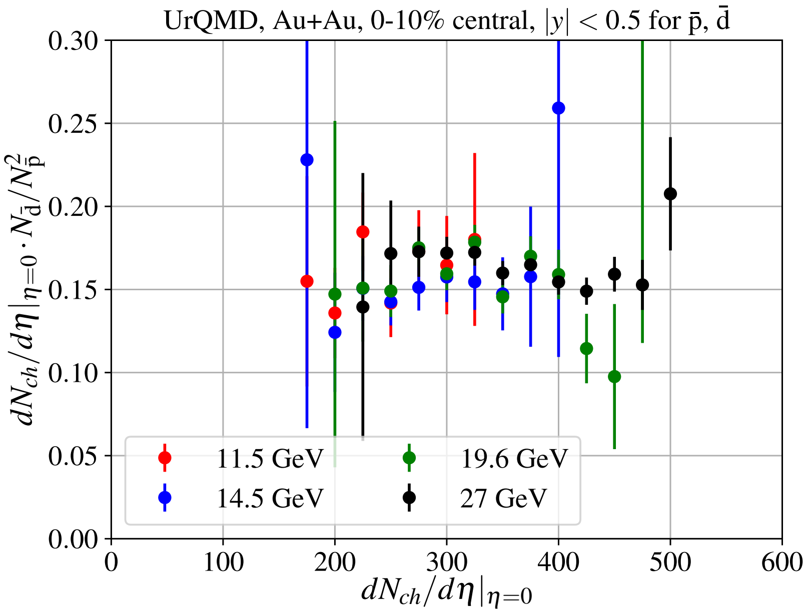
Gaebel et al, Eur.Phys.J.A 57 (2021)

Direct check of volume scaling

deuteron/proton^2 x N_{ch}



Anti-deuteron/anti-proton^2 x N_{ch}

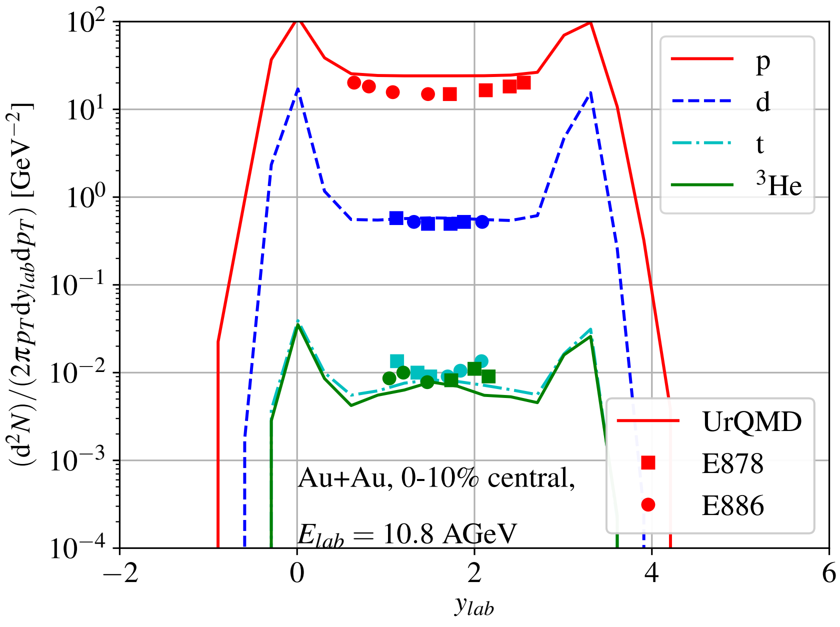


Volume scaling is observed at intermediate energies,
even event-by-event and for deuterons AND anti-deuterons

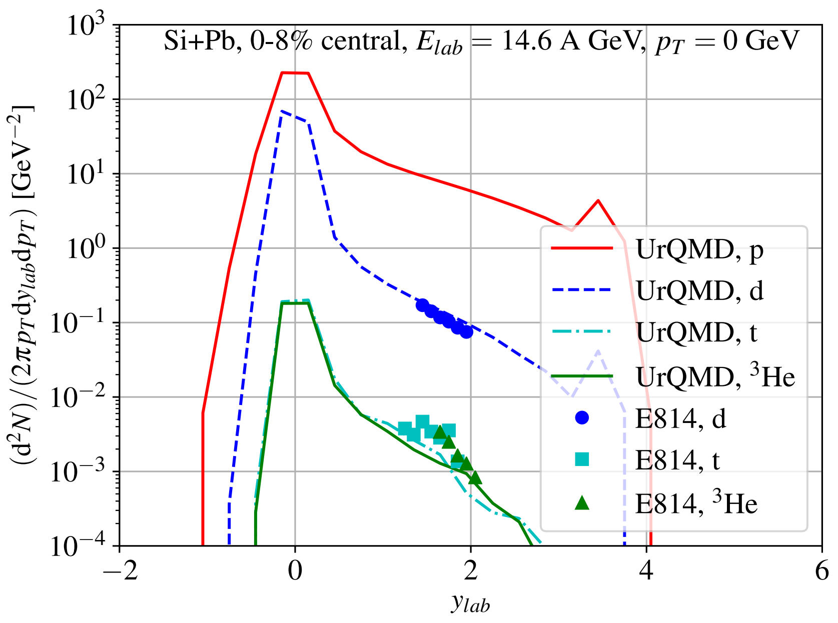
Hillmann et al, e-Print: [2109.05972] [hep-ph]

Extension to tritons is straightforward

Rapidity - OK



Transverse momenta - OK



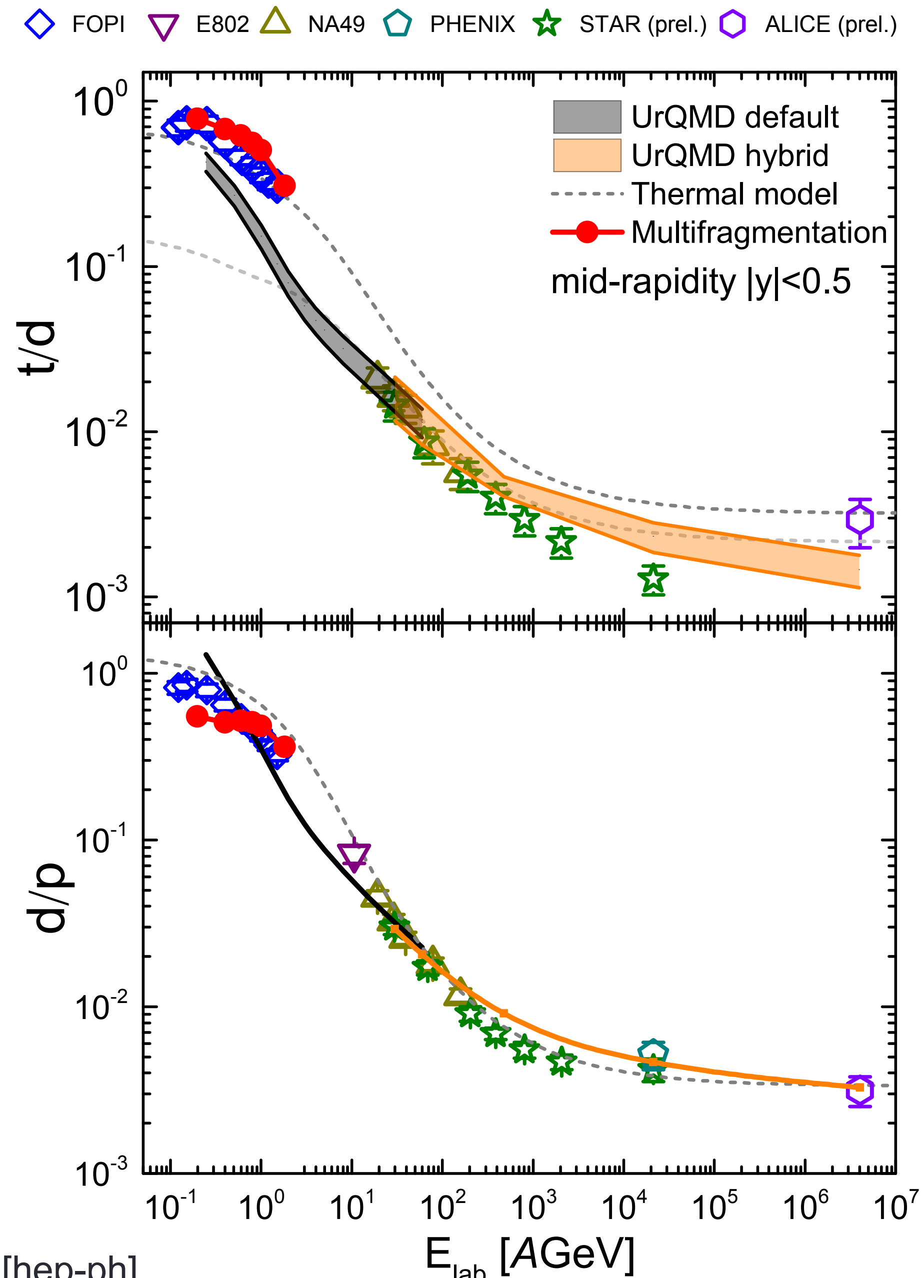
Energy dependence

- Generally good agreement of coalescence with data, except for highest energies (LHC)

- Hybrid and pure transport show similar results in overlap region

- Multifragmentation (hot coalescence is similar)

- Mainly reflects decrease of μ_B with increasing energy

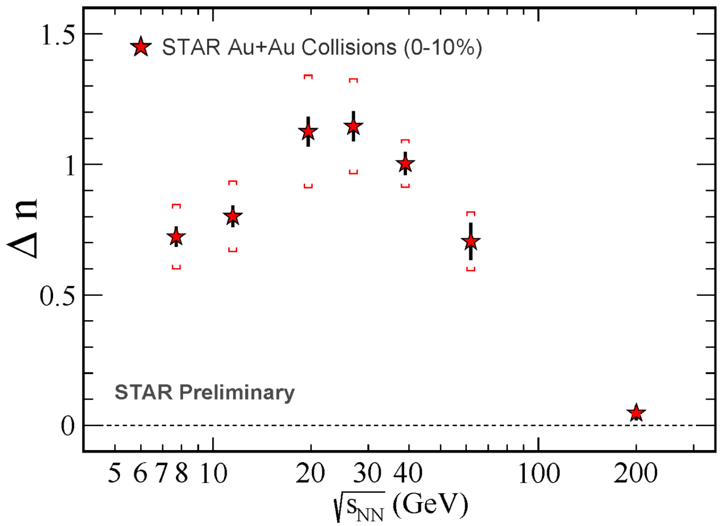


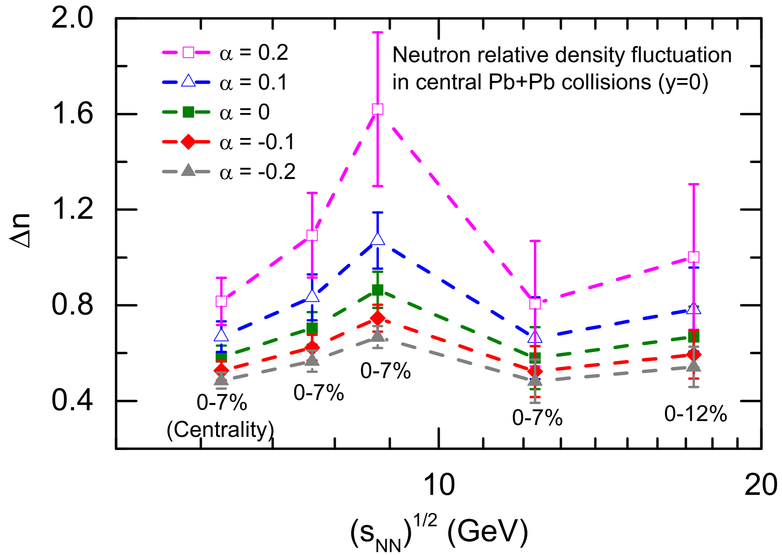
Hillmann et al, e-Print: [2109.05972] [hep-ph]

Neutron density fluctuations?

- Triton to deuteron ratio might yield information on neutron density fluctuations

$$\frac{N_{^3\mathrm{H}} N_p}{N_\mathrm{d}^2} = g\frac{1+(1+2\alpha)\Delta n}{(1+\alpha\Delta n)^2} \approx g(1+\Delta n).$$

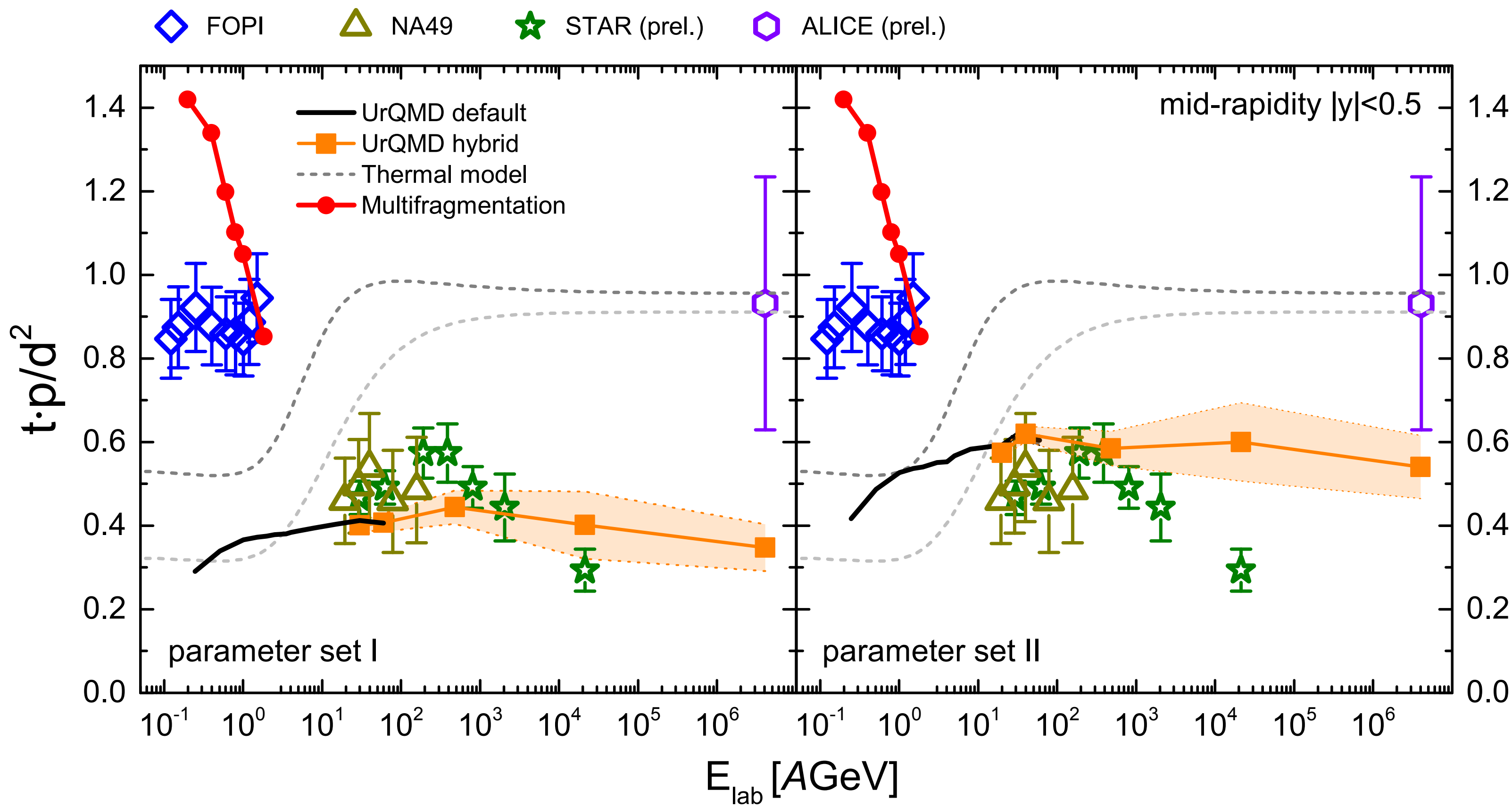




Sun et al, Phys.Lett.B 774 (2017) 103-107

g=0.29, α=p-n correlation

Canceling μ_B: $B_3/(B_2)^2$ ratios



None of the models provide a full description of the data

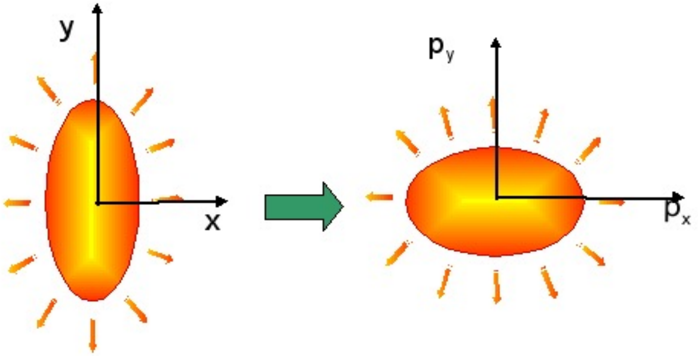
- However coalescence + multi-fragmentation seem to work below LHC energies
- Models dont see suggested density fluctuation peak!

Hillmann et al, e-Print: [2109.05972](2109.05972) [hep-ph]

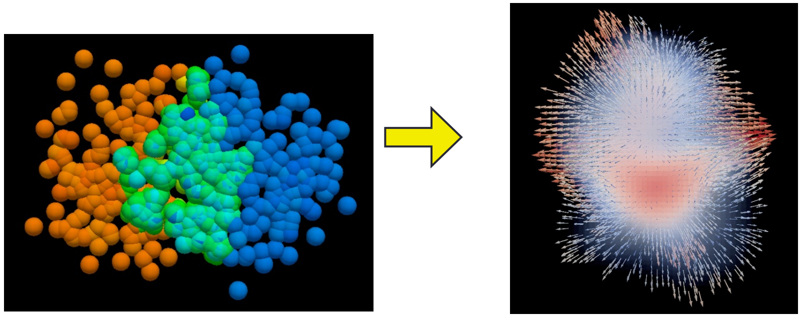
Can we distinguish thermal emission from coalescence? → Anisotropic Flow

Simplified picture:

Position-space anisotropy
→ Momentum-space anisotropy

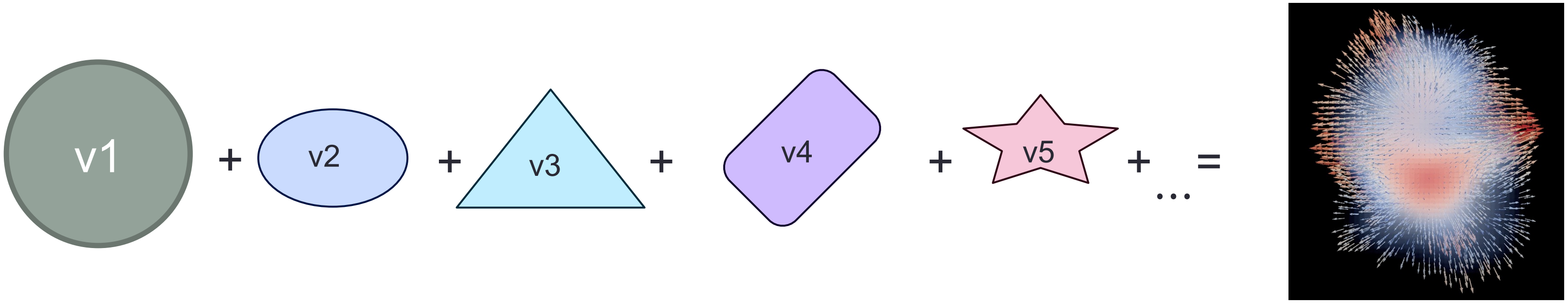


Real picture:
Complicated state,
mean free paths,...



by MADAI.us

Fourier expansion of the radial distribution! → v_n



Adopted from H. Elfner

Can we distinguish thermal emission from coalescence? → Scaling

NCQ scaling at high energies

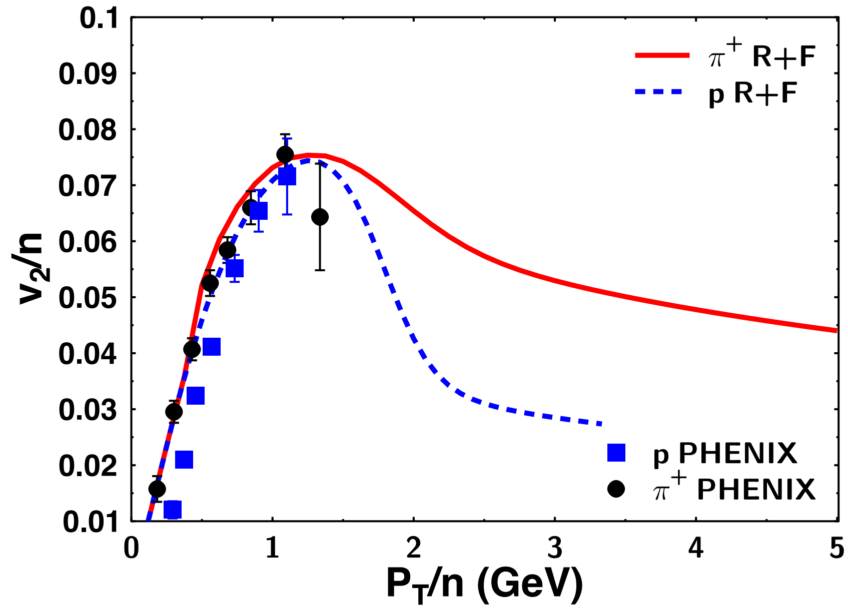
- discovery of “magical factors” of 2 and 3 in measurements of spectra and the elliptic flow of mesons and baryonsat RHIC (Fries et al, 2003)
- Predicted v2 scaling in case of coalescence

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

→ Check scaling to prove coalescence

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

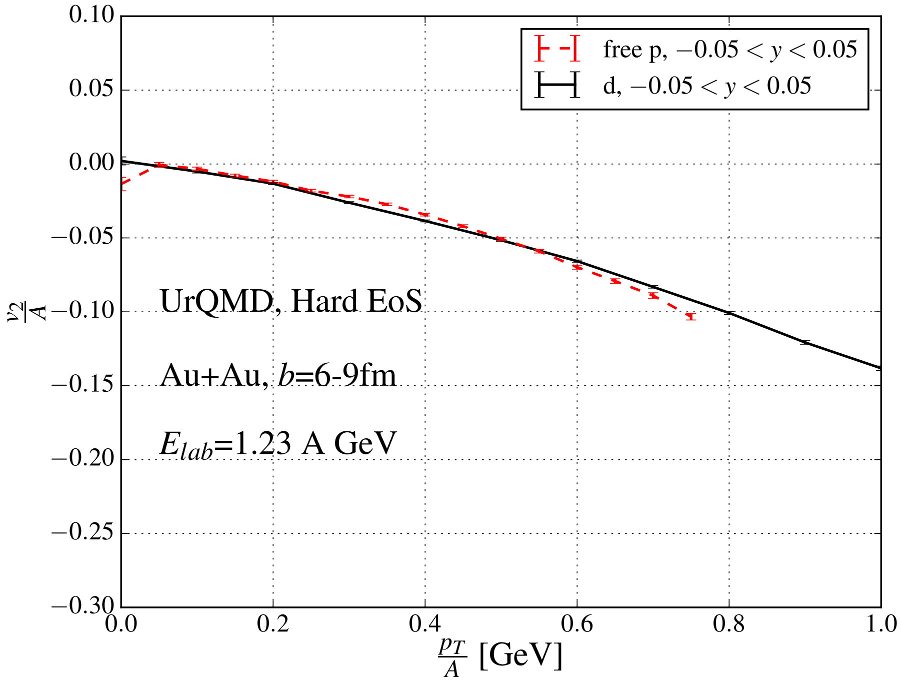
RHIC data



Scaling at LHC is a different story...

Can we distinguish thermal emission from coalescence? → Scaling

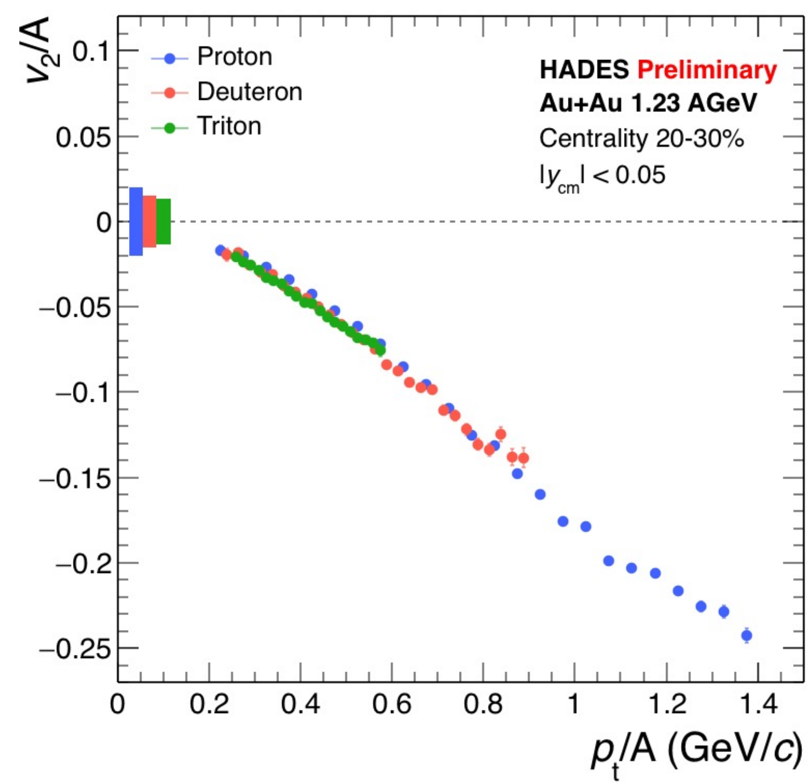
UrQMD



Hillmann, Bleicher, et al. arXiv:1907.04571

→ Scaling is observed

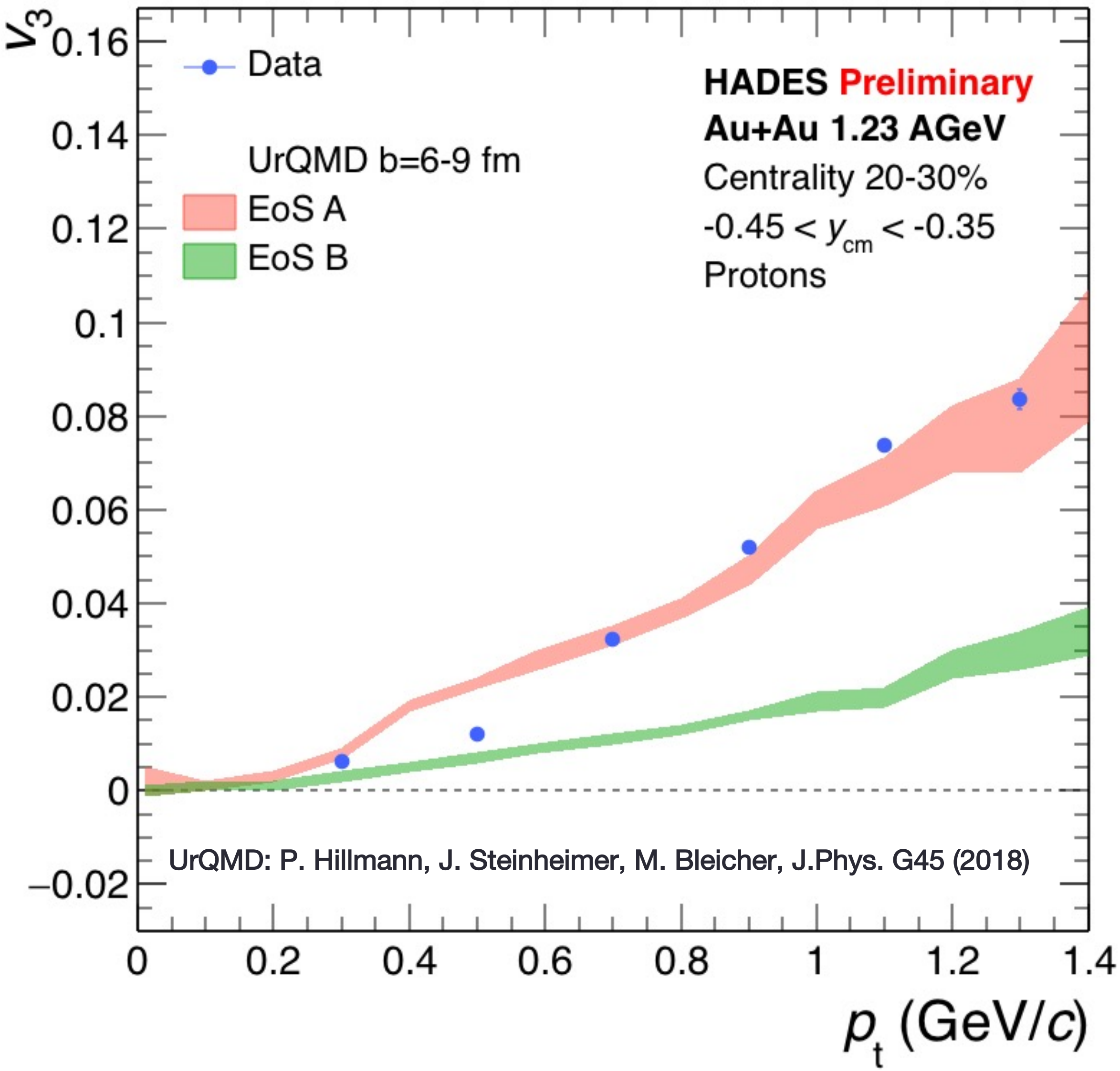
HADES data



Taken from Behruz Kardan, arXiv:1809.07821

Higher order flow

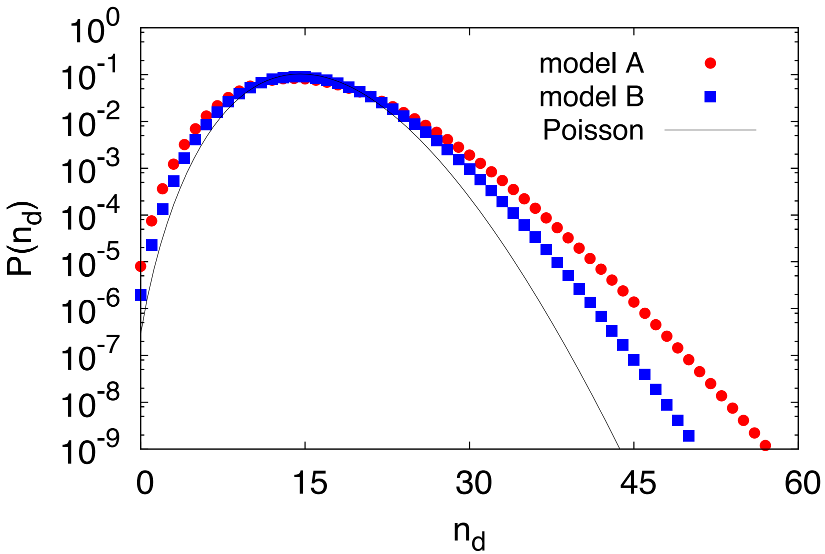
- Also higher order flow works very well.
- Indication that correlations are propagated correctly
- Suggests "hard" (or momentum dependend) equation of state



Can we distinguish thermal emission from coalescence? → Fluctuations

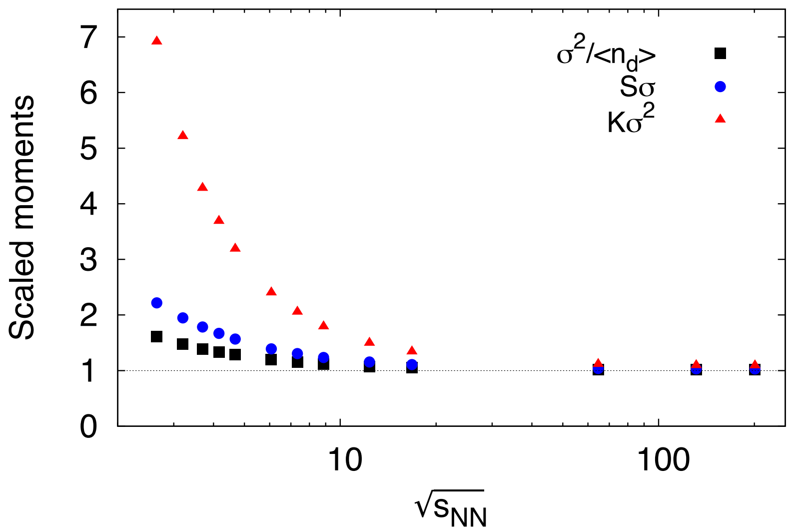
Z. Feckova, B. Tomasik, M. Bleicher, Phys.Rev. C93 (2016) no.5, 054906

Au+Au at 2 AGeV



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

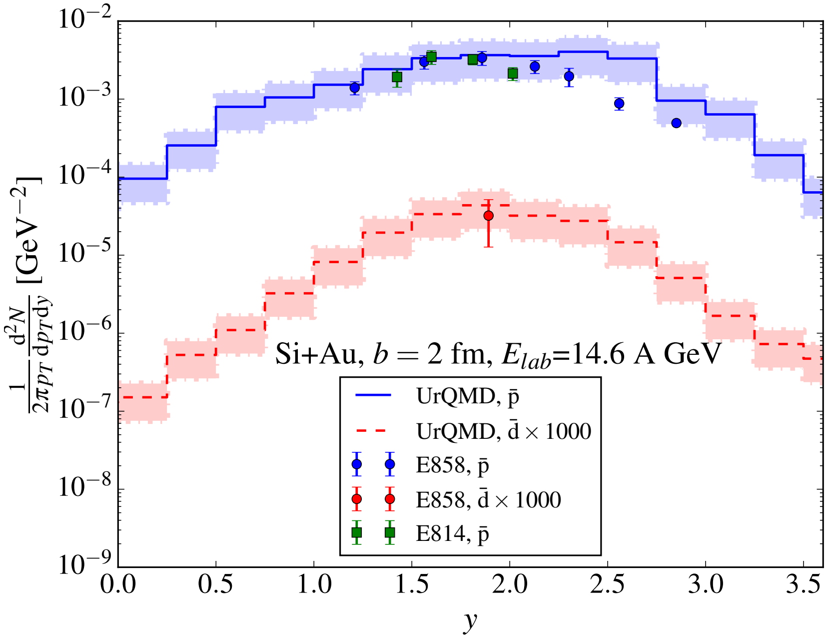
Moments of distribution



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

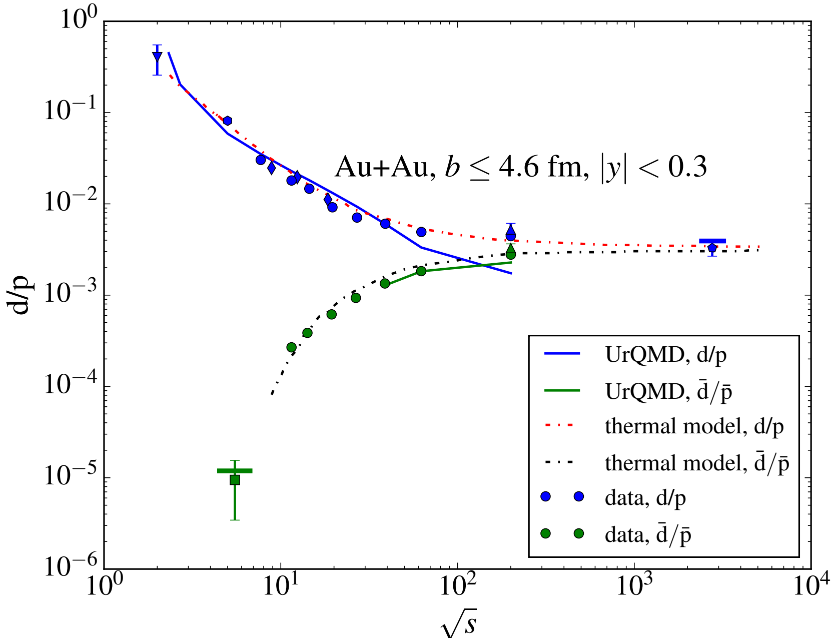
Anti-deuterons

Does coalescence also work for more exotic states?



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

Energy dependence of deuterons and anti-deuterons

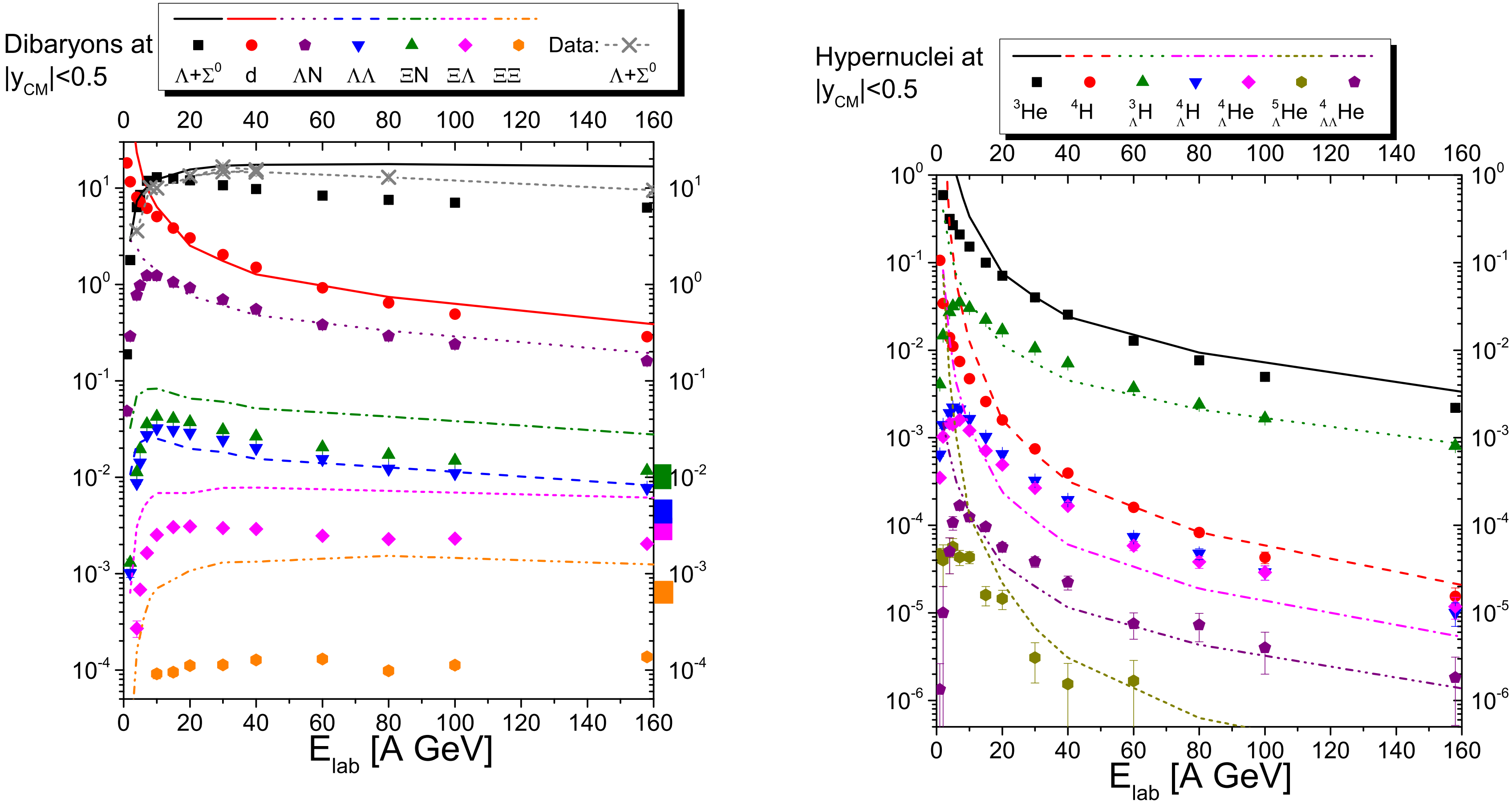


Consistent picture over the whole energy range

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

Hyper and multi-strange matter

DiBaryons Hypernuclei



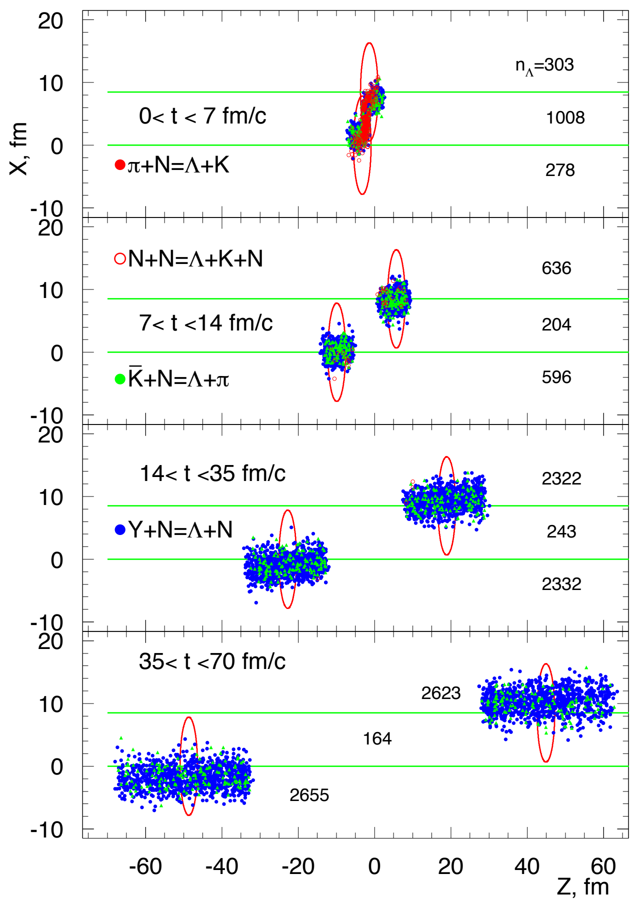
J. Steinheimer, M. Bleicher et al, Phys.Lett. B714 (2012)

Hybrid model (lines) vs. coalescence (symbols)

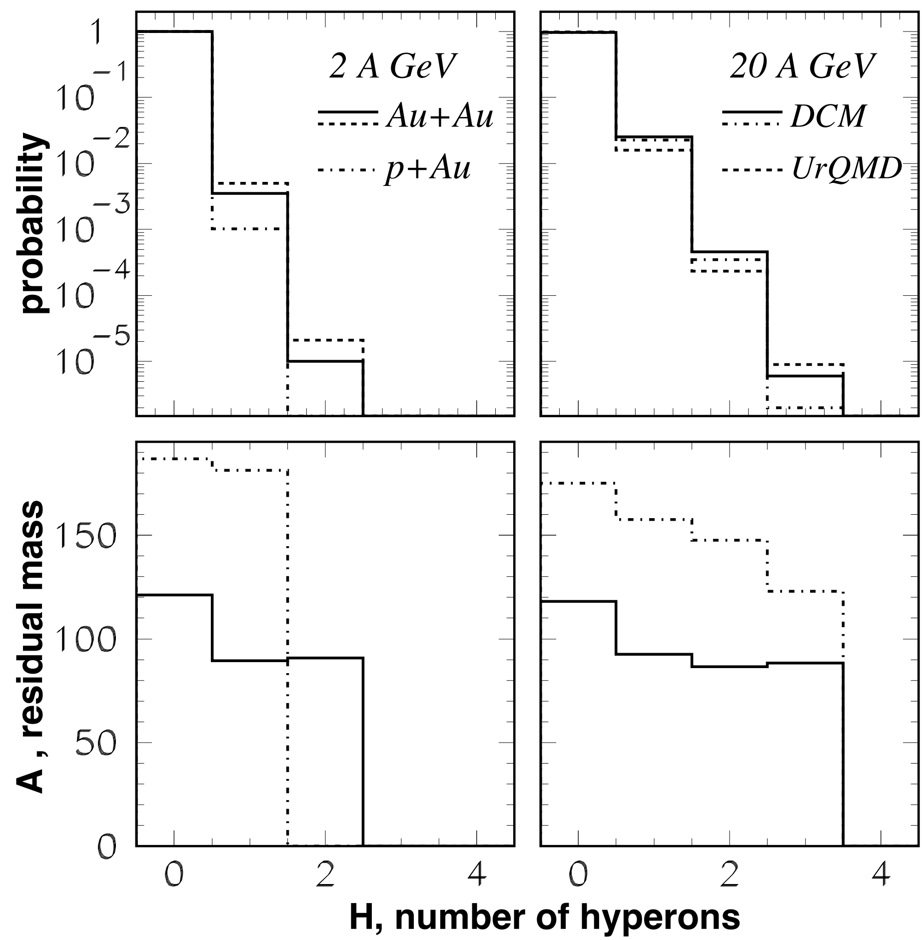
See also Bastian, Blaschke, Roepke, et al, Eur.Phys.J. A52 (2016)

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
- Results are similar to the obtained from thermal models and hybrid models
- True process is difficult to distinguish:

→ fluctuations and flow scaling can help

- Predictions for hypermatter show that FAIR and NICA are ideally positioned to explore this new kind of matter.