CLUSTER PRODUCTION BY COALESCENCE IN HEAVY ION COLLISIONS

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GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN
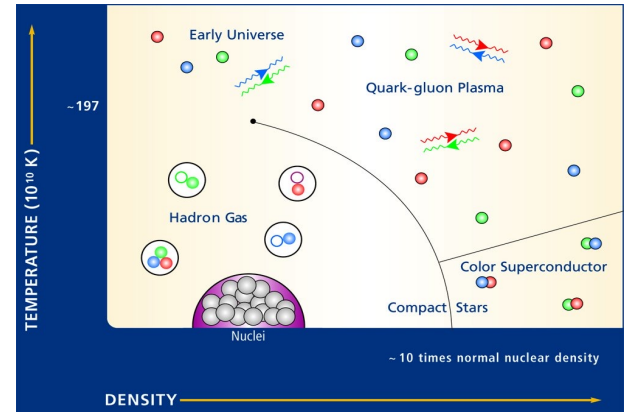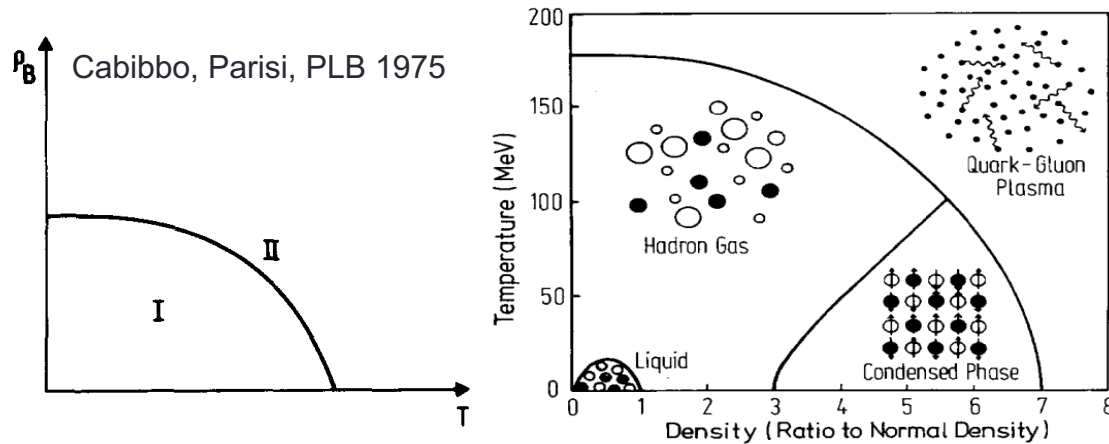
HFHF
Helmholtz Forschungsakademie Hessen für FAIR

This work is done in collaboration with:

- Nihal Buyukcizmeci
- Alexander Botvina
- Christoph Herold
- Ayut Limphirat
- Tom Reichert
- Apiwit Kittiratpattana

Outline

- Motivation

- Coalescence vs thermal emission

- Small systems / large systems

- Antimatter and Hypermatter

- Flow scaling and fluctuations

- Conclusions

Motivation

Cabibbo, Parisi, PLB 1975

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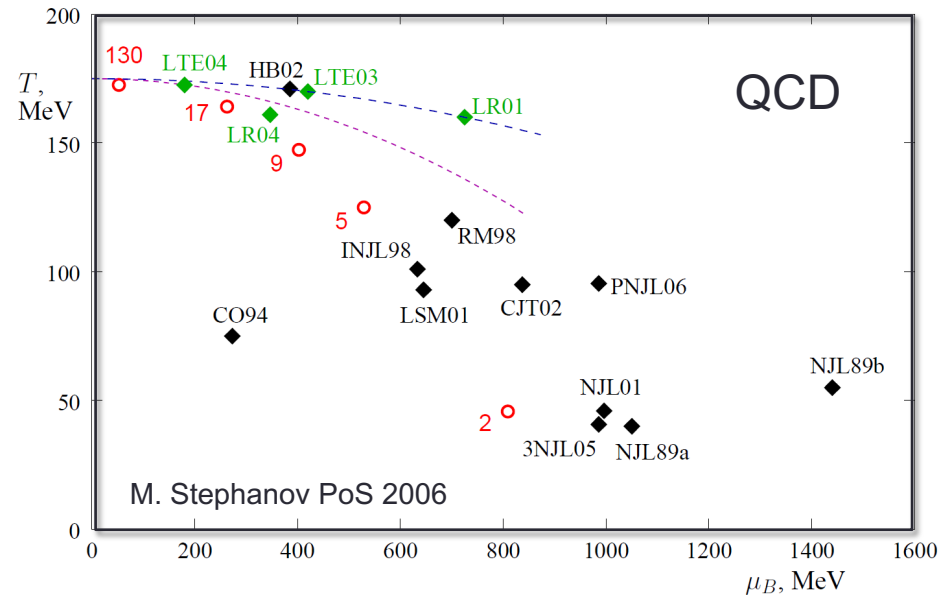
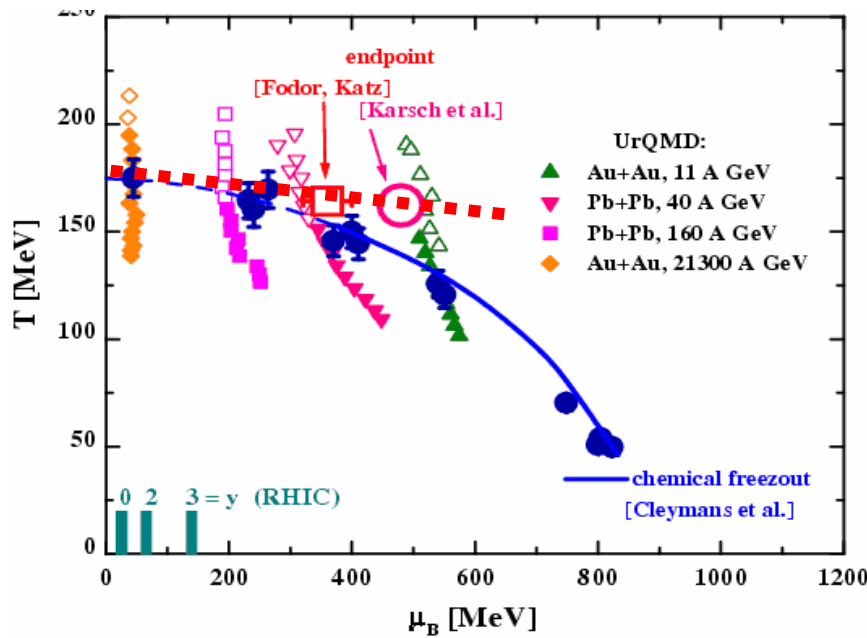http://www.ice.csic.es/en/graphics/phase.jpg (2010)

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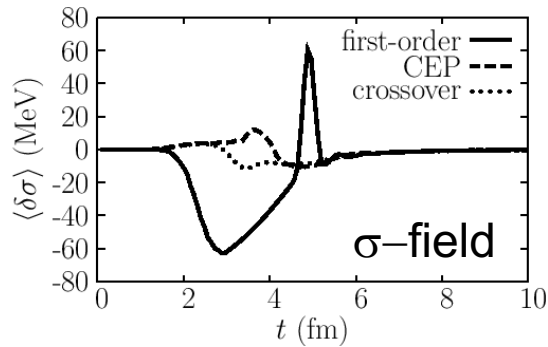
QCD Phase Diagram

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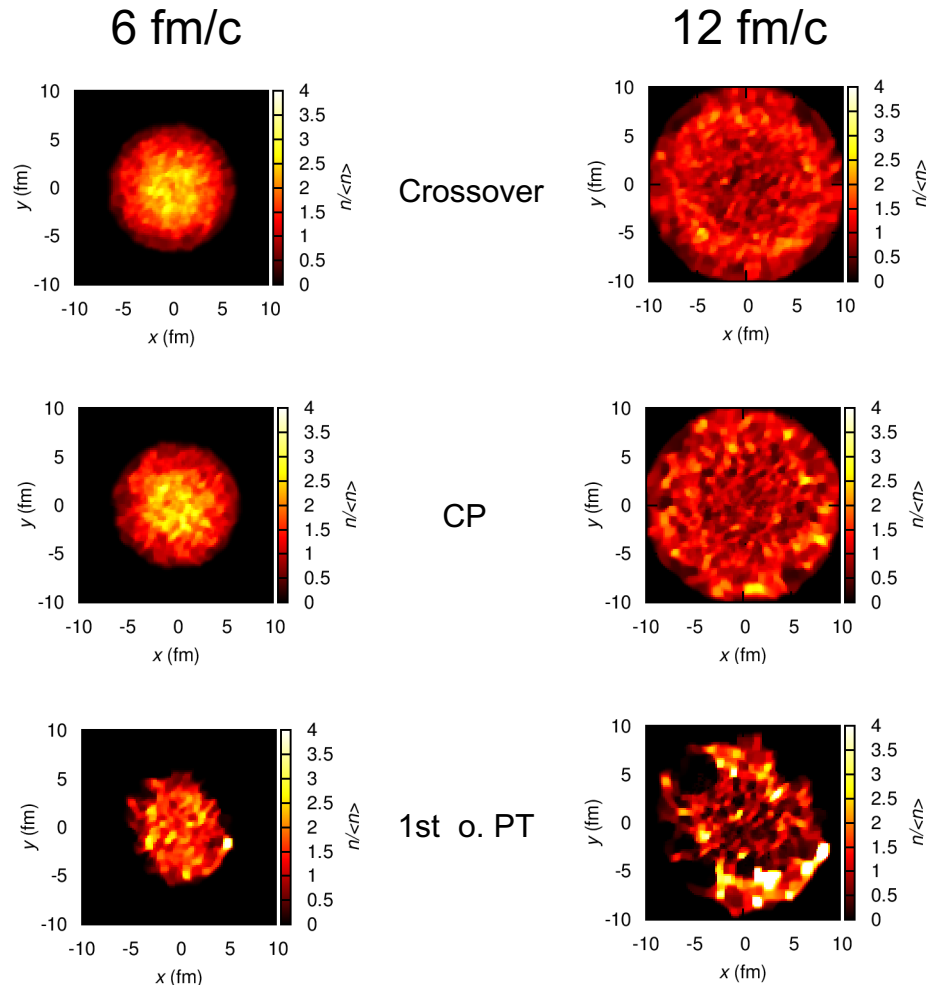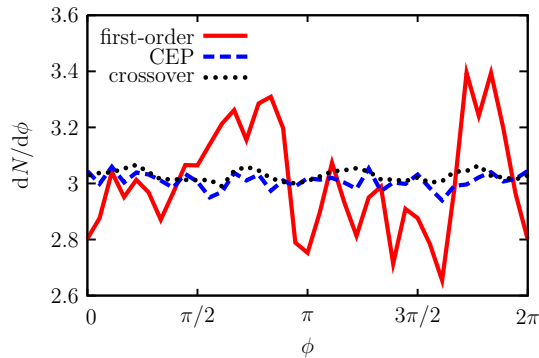I. Arsene et al., PRC 2007

- 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

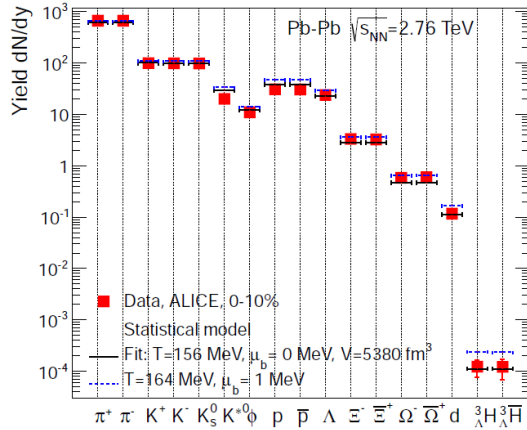
σ−field

Angular distribution, 12 fm/c

6 fm/c

12 fm/c

Crossover

CP

1st o. PT

→ 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
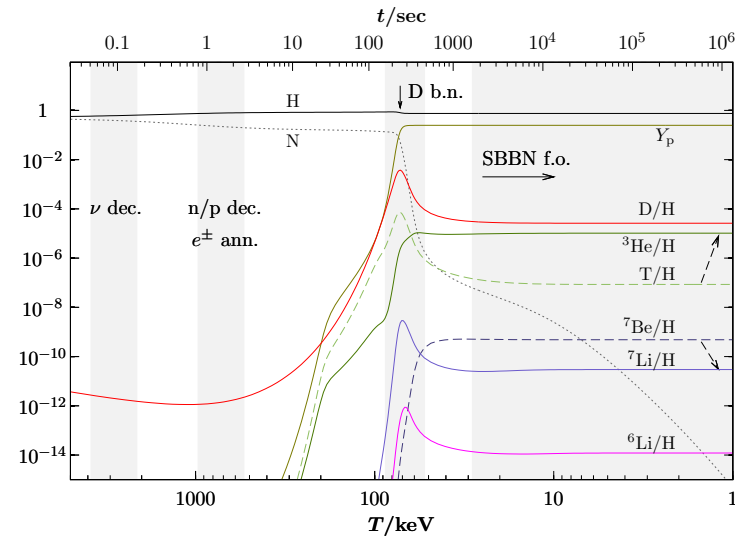
- Thermal model provides good description of cluster data, e.g. deuteron, even with protons being slightly off
- Surprising result, because the binding energy of the deuteron (2.2 MeV) is much smaller than the emission temperature (150-160 MeV)
- Why is it not immediately destroyed?
  Related to famous 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

- Fixing the number of baryons during temperatures decrease

- 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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Max-von-Laue-Strasse 1, 60438 Frankfurt am Main, Germany

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Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtz Center,
Campus Frankfurt, Max-von-Laue-Straße 12, 60438 Frankfurt am Main, Germany

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

T. Neidig et al, *Phys.Lett.B* 827 (2022) 136891
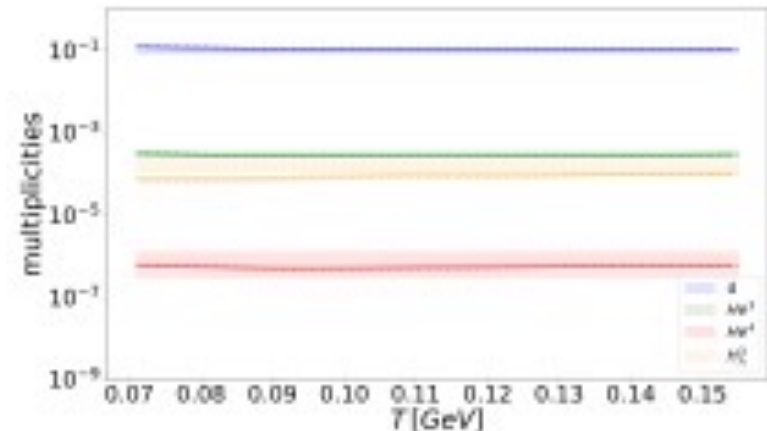
Some history...

- 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))

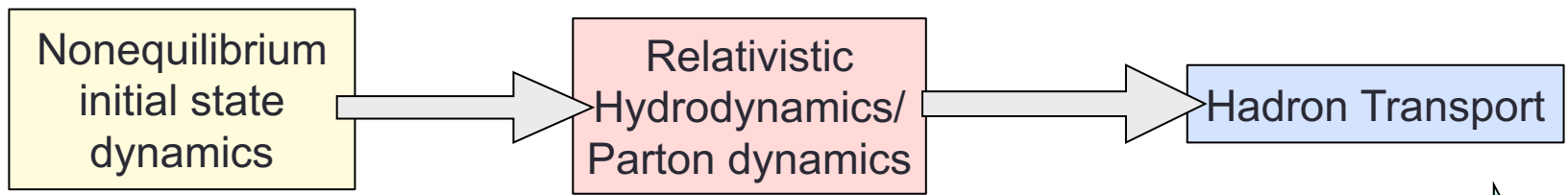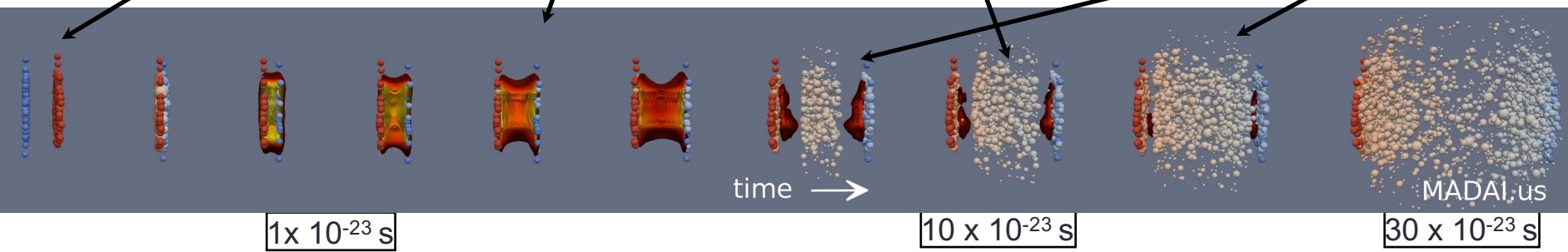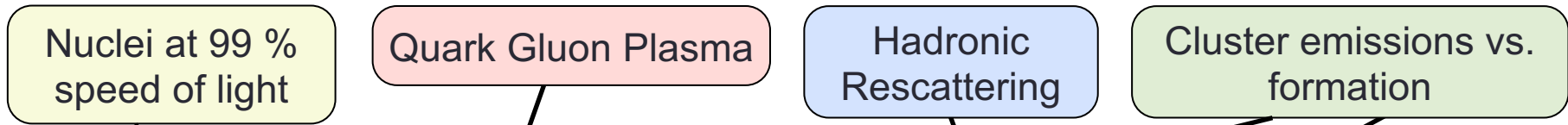- **Solution:** Take space into account (B_2 has to include source)

- 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

time →

MADAI.us

$1x\ 10^{-23}$ s $\qquad$ 10×10^{-23} s $\qquad$ 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)

Methods to calculate clusters

- **Wigner functions**
  - Projection on Hulthen wave function
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- **Coalescenc~~e~~**
  - Employ cut-o~~ff~~
  - E-by-E possi~~ble~~
  - 2 free param~~eters~~

- **Cross sections**
  - Introduce explicit processes, e.g. $p+p+n \rightarrow d+\pi$
  - ~~Thermal~~ treatment
  - ~~Many bo~~dy interactions

- **Correct potentials**
  - Use a Hamiltonian that dynamically binds the nucleons
  - May need complicated forces
  - Difficult for small systems

    $\rightarrow$ Talk by Jörg Aichelin

- **~~E~~mission**
  - ~~Nucleo~~ns in partition
  - ~~One free par~~ameter
  - 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
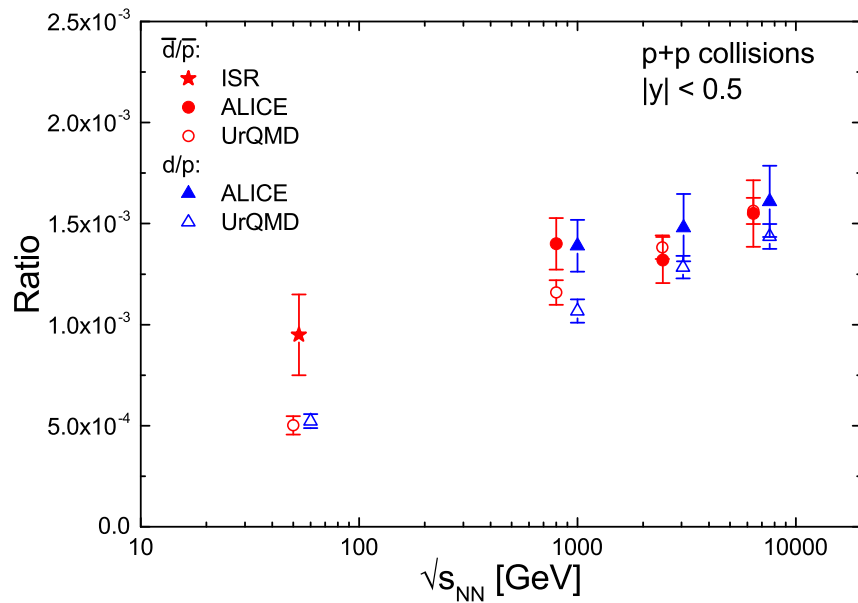
Good description of pp by coalescence

Absolute yields

$\sqrt{s_{NN}}$ (TeV)		ALICE	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	$(1.11\pm0.10\pm0.09)\times10^{-4}$	$(1.00\pm0.05)\times10^{-4}$
$\bar{d}$	2.76	$(1.37\pm0.04\pm0.12)\times10^{-4}$	$(1.55\pm0.07)\times10^{-4}$
	7	$(1.92\pm0.02\pm0.15)\times10^{-4}$	$(2.22\pm0.09)\times10^{-4}$

The header row spans dN/dy over the ALICE and UrQMD columns.

Absolute yields in line with ALICE data

Proton-proton collisions

Transverse momenta (deuterons)
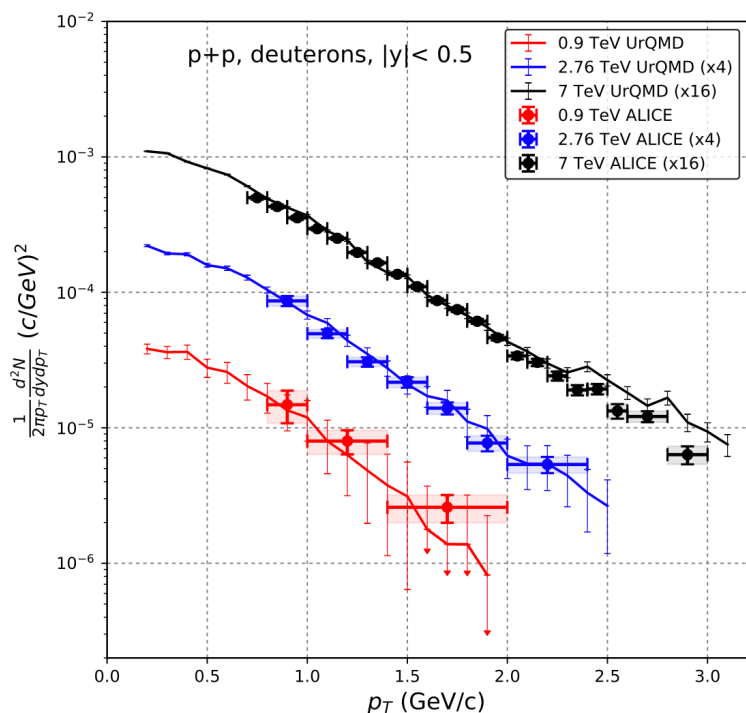
Transverse momenta
(anti-deuterons)

Good description of pp by coalescence
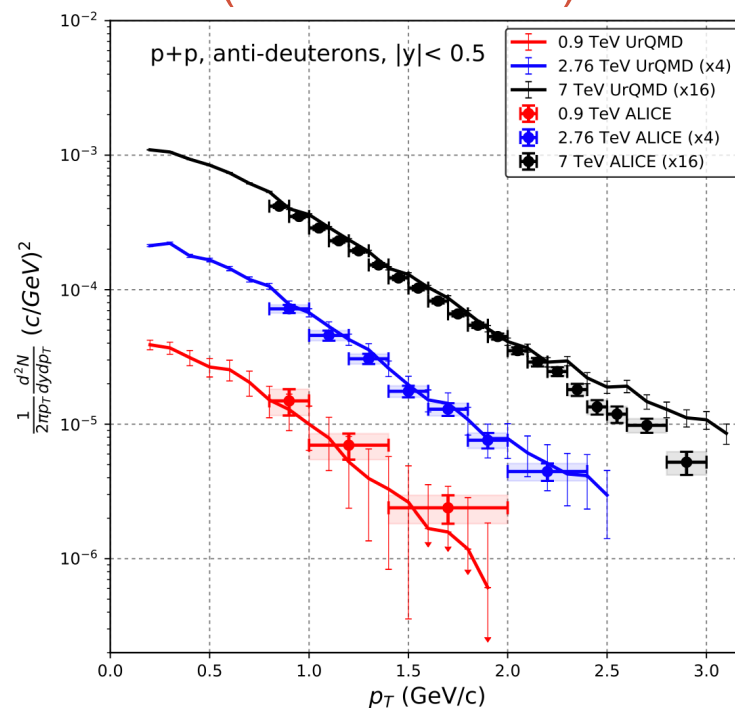
Good description of pp by coalescence

From small to large systems

Proton+nucleus at 14.6 AGeV

Transverse dynamics in
Si+(Al/Cu/Au) at 14.6 AGeV
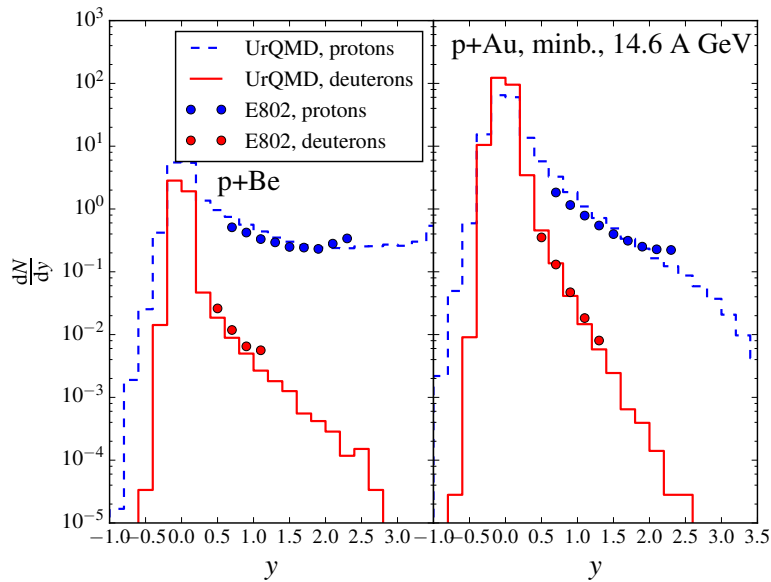
Rapidity distributions indicate
correct coalescence behavior
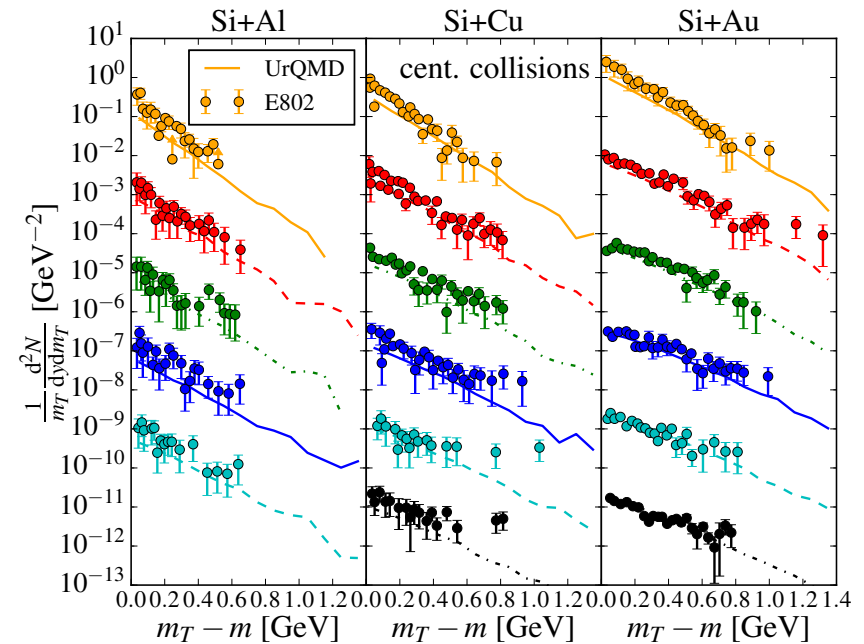
Also transverse expansion is well
captured in the coalescence approach

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

Towards higher energies

Pb+Pb from 20 AGeV to 158 AGeV

Pb+Pb, central collisions

— 20 AGeV	— 80 A GeV
- - 30 A GeV	- - 158 A GeV
⋯ 40 A GeV	

— UrQMD, d
● NA49, d

LHC results: Centrality dependence

Pb+Pb, 2.75 TeV   Deuterons from phase-space coalescence.

Simulations:
—○— Hydro + UrQMD, Pb+Pb
- -□- - UrQMD v3.4, p+p
ALICE Data:
● Pb+Pb
■ p+p
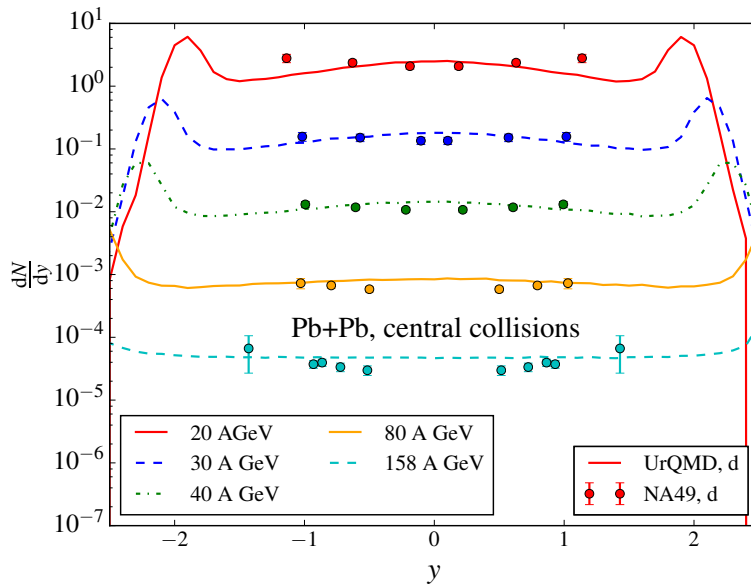
Deuteron rapidity distributions well described over a broad range of energies
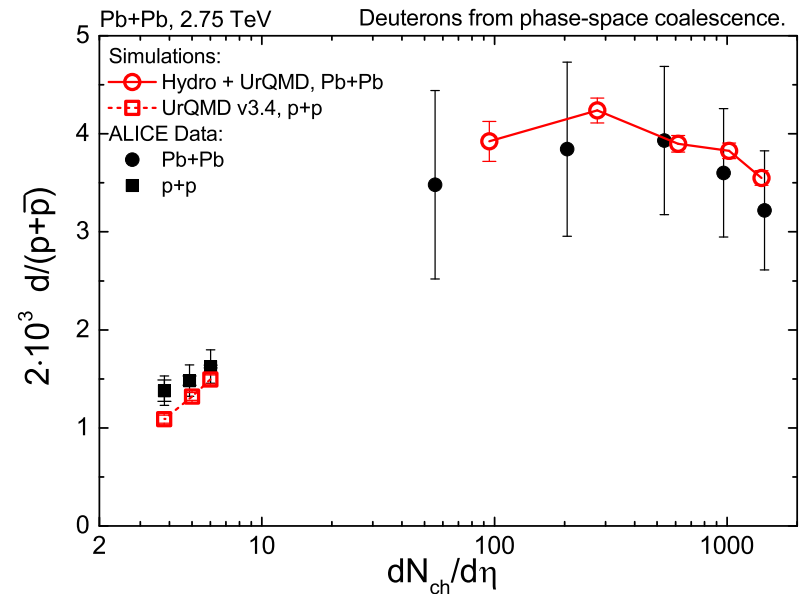
Decrease of d/p ratio for very central collisions
→ indication for larger freeze-out volume

Understanding the energy dependence

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

- 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
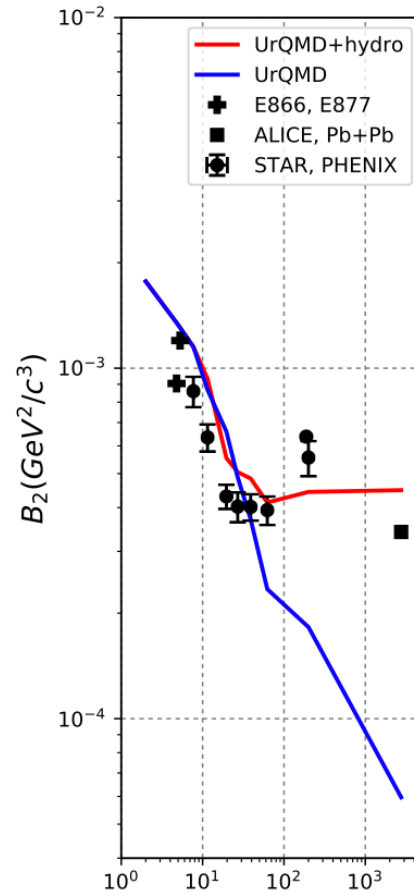
UrQMD vs Hybrid
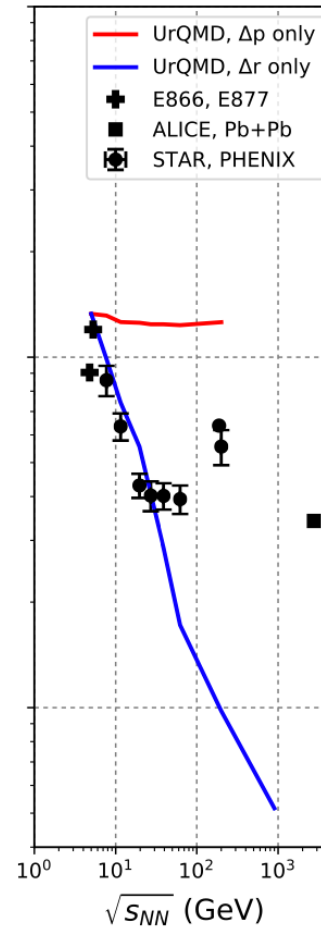
UrQMD:
Dp coal. vs
Dx coal.
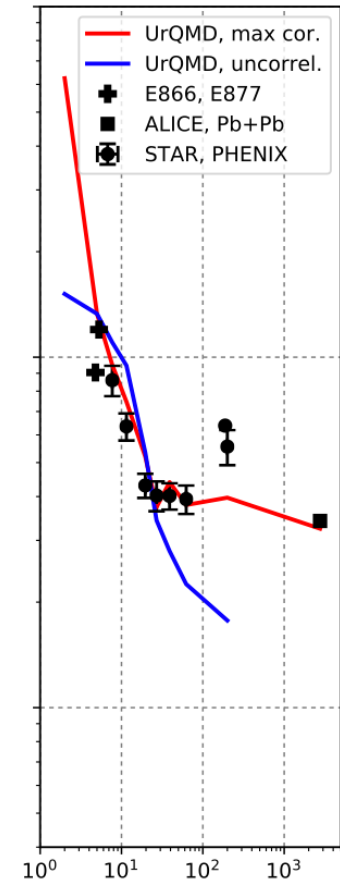
UrQMD:
uncorrelated vs.
full correlation

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

Extension to tritons is straightforward

Hillmann et al, *J.Phys.G* 49 (2022) 5, 055107
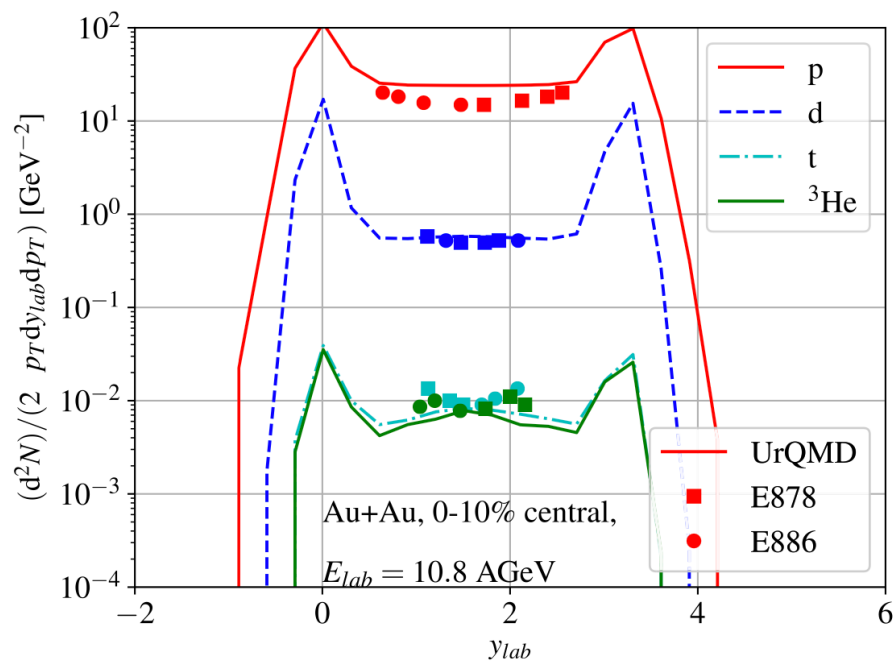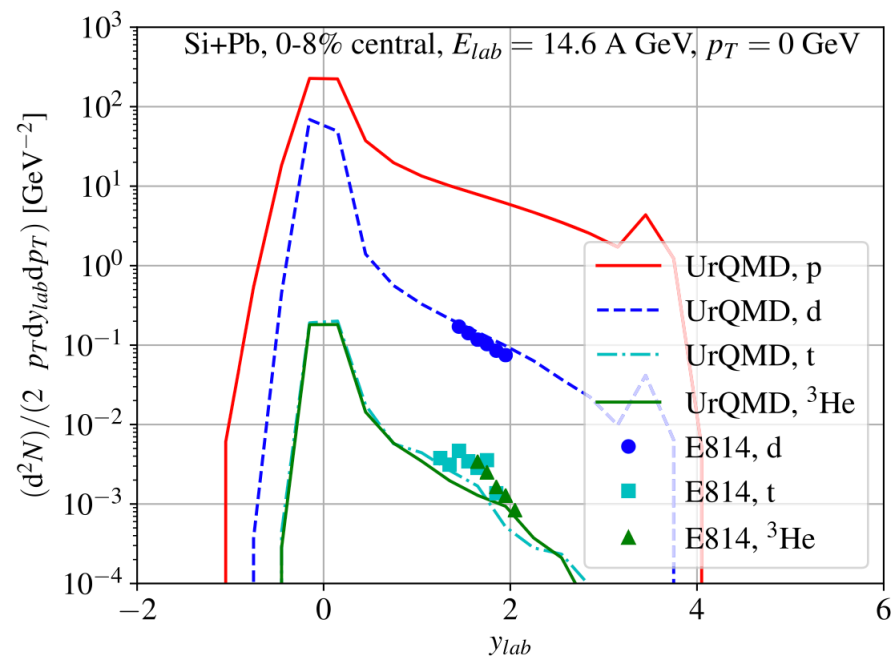
Energy dependence

- 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, *J.Phys.G* 49 (2022) 5, 055107
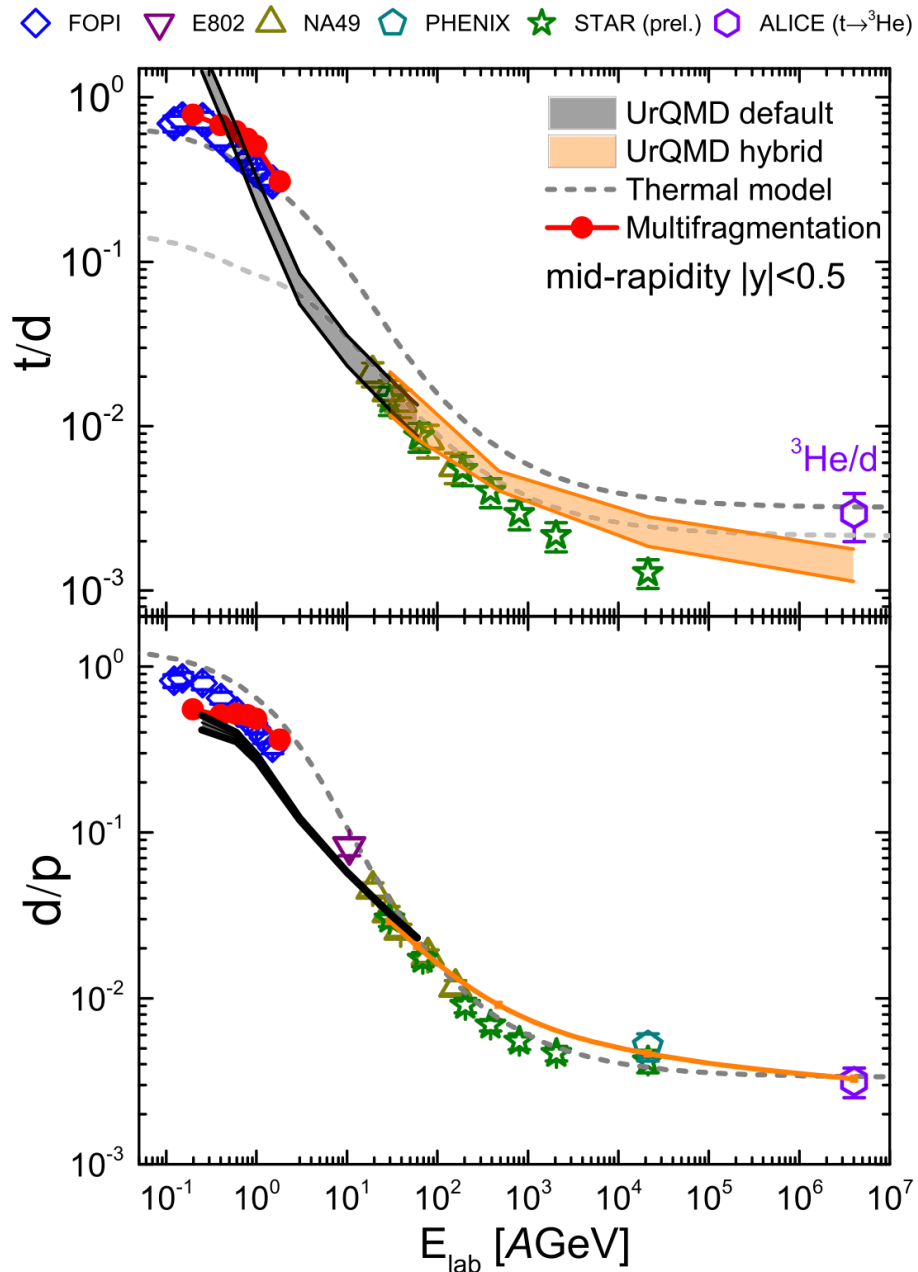
Neutron density fluctuations?

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

$$\frac{N_{^3\text{H}}N_p}{N_d^2} = g\frac{1+(1+2\alpha)\Delta n}{(1+\alpha\Delta n)^2}$$

$$\approx g(1+\Delta n).$$

Sun et al, Phys.Lett.B 774 (2017) 103-107
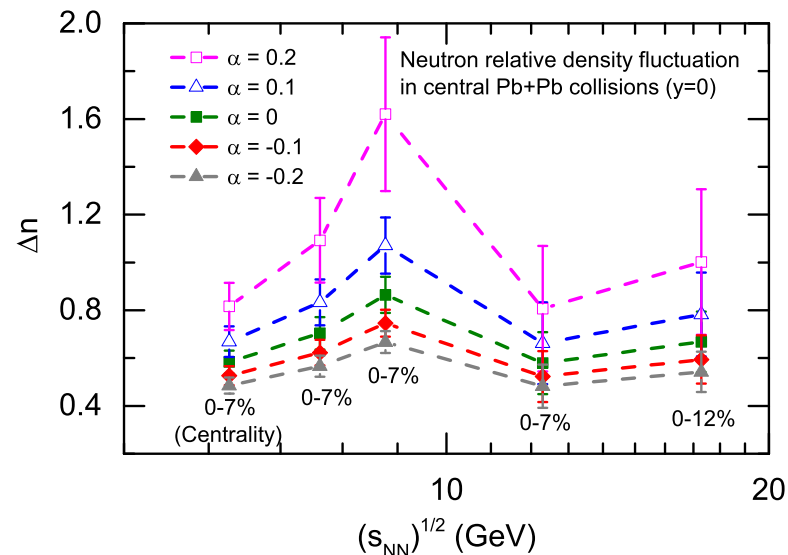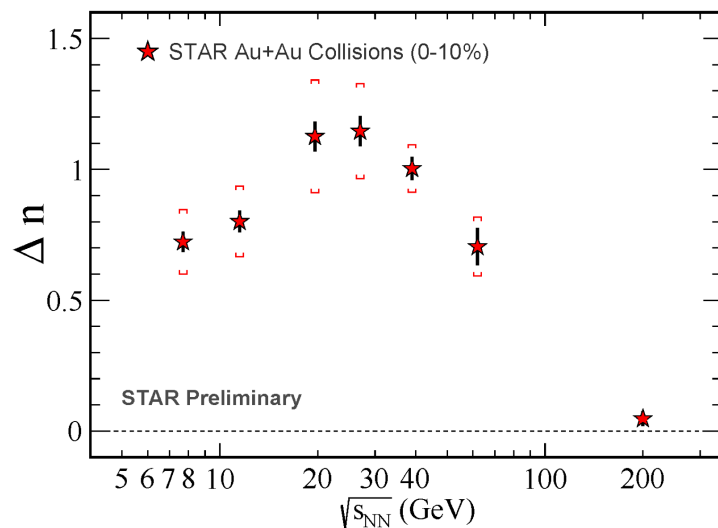
g=0.29, α=p-n correlation

Canceling μ_B: $B_3/(B_2)^2$ ratios
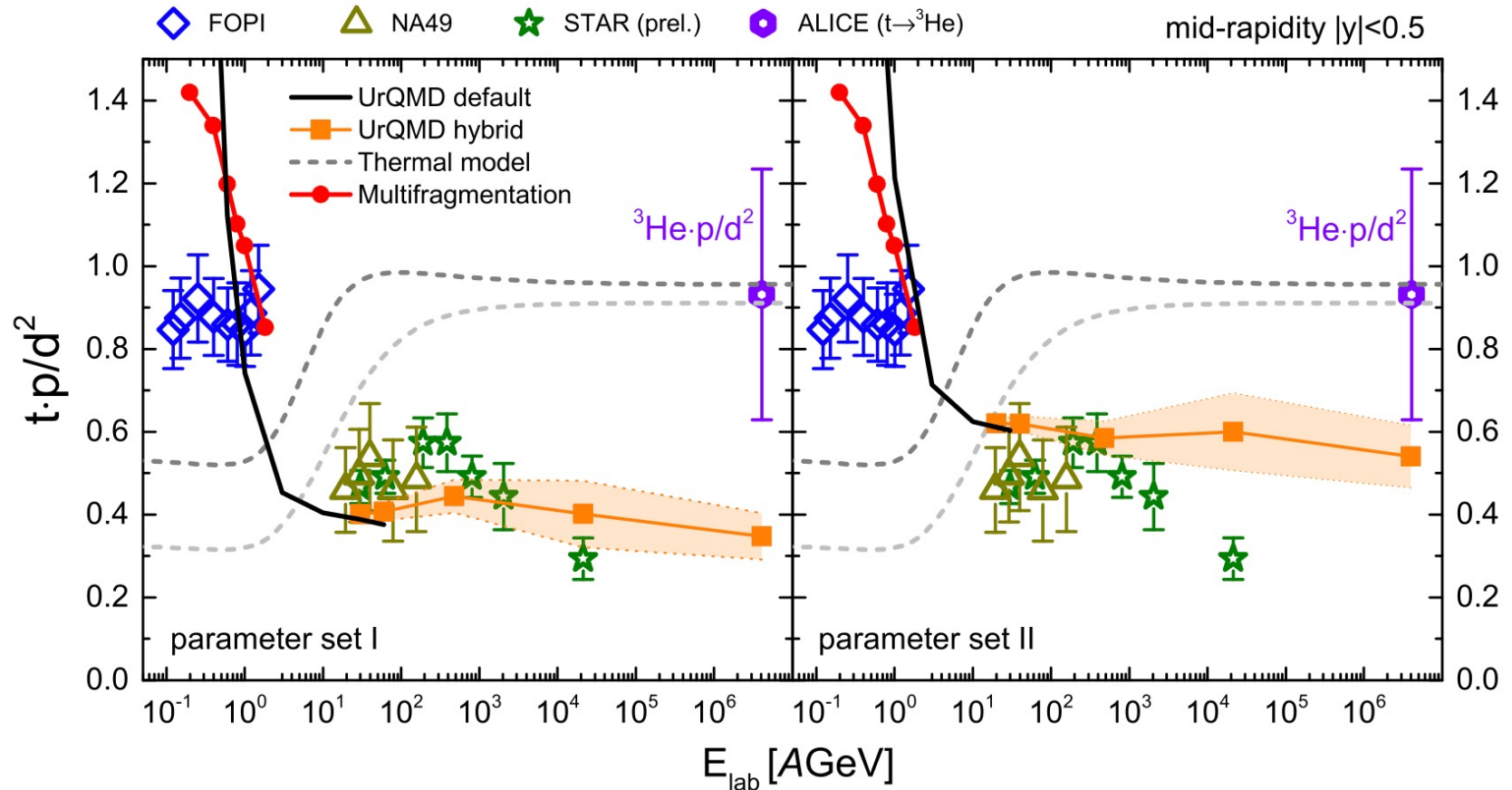
None of the models provide a full description of the data
- However coalescence + multi-fragmentation seem to work below LHC energies
- Models dont see suggested density fluctuation peak!

Hillmann et al, *J.Phys.G* 49 (2022) 5, 055107

Anti-deuterons

Does coalescence also work for more exotic states?

Energy dependence of deuterons and anti-deuterons
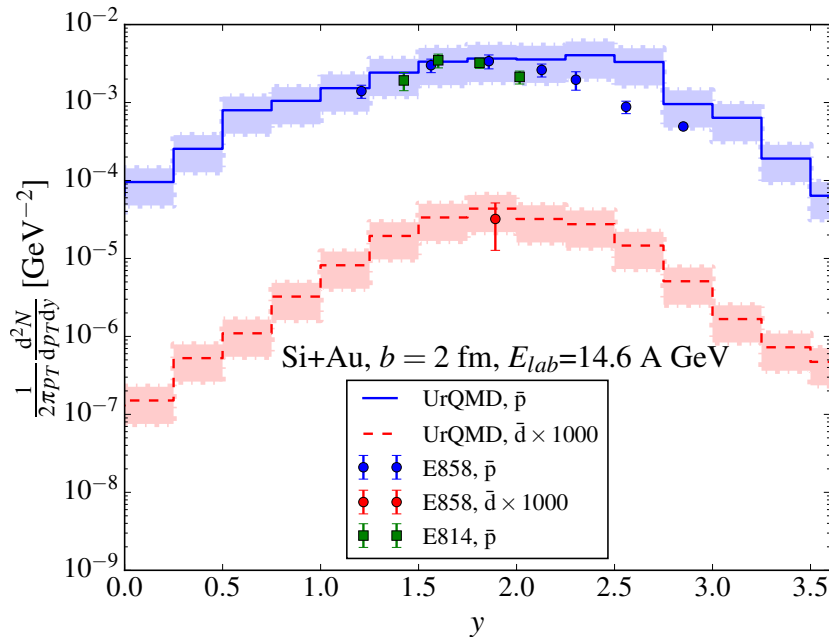
- Surprisingly good description of anti-deuteron yield
- Same parameters!!
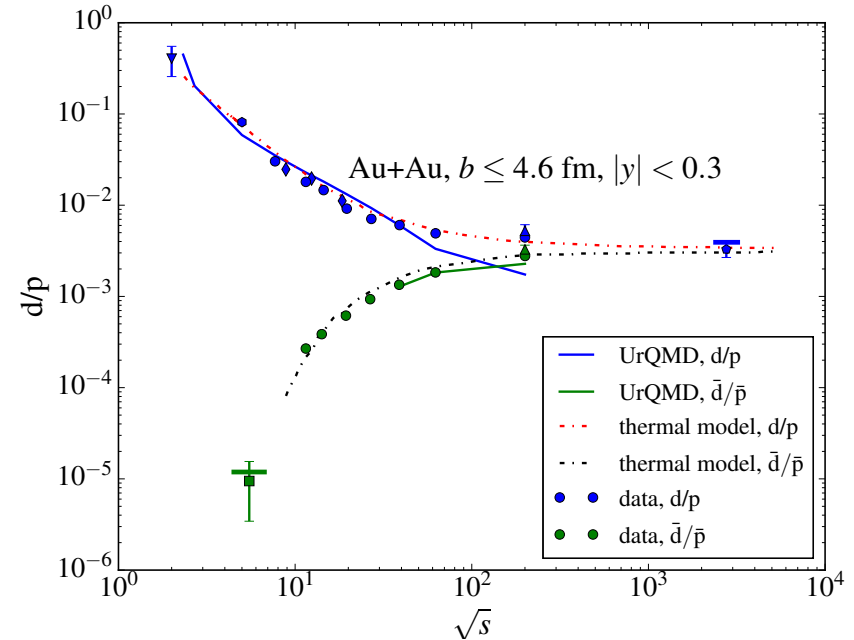
Consistent picture over the whole energy range

Hyper and multi-strange matter

DiBaryons
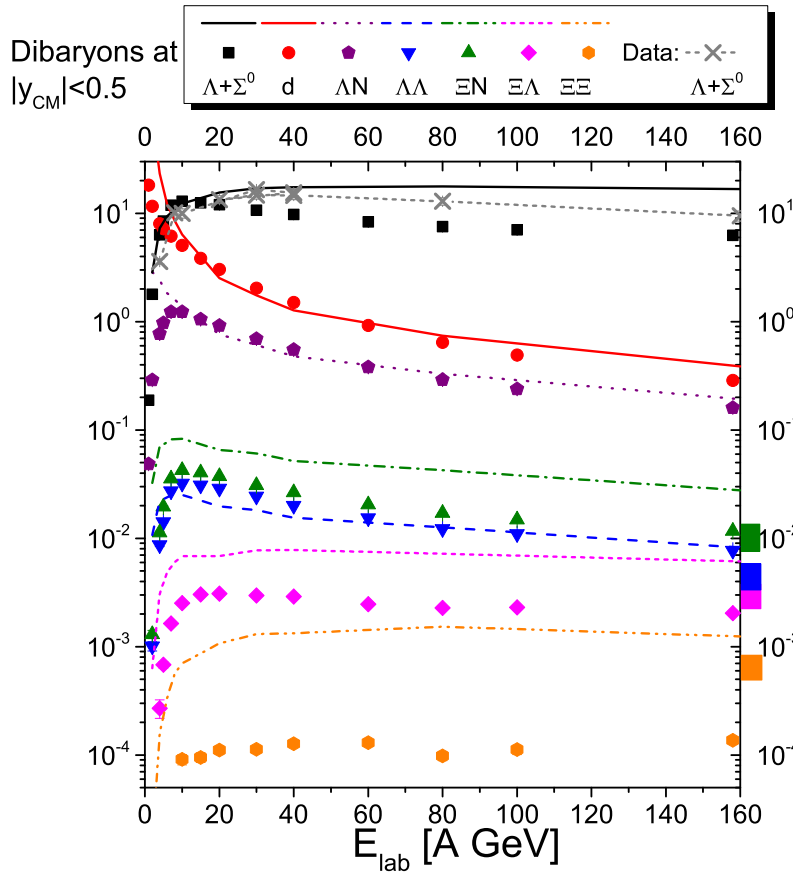
Hypernuclei
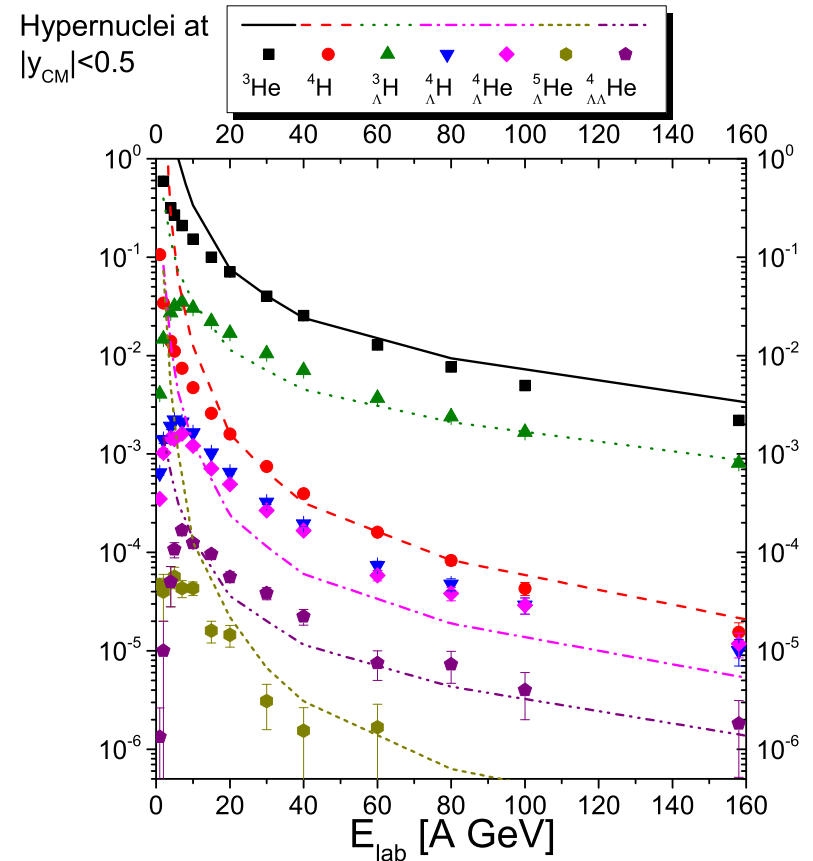
Hybrid model (lines) vs. coalescence (symbols)

See also Bastian, Blaschke, Roepke, et al, Eur.Phys.J. A52 (2016)
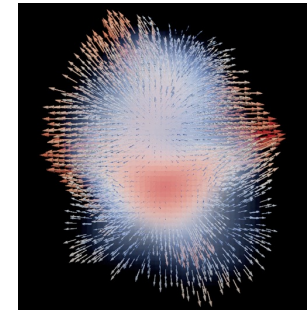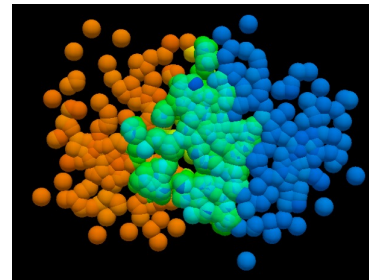
Can we distinguish thermal emission from coalescence?
→ Anisotropic Flow

Simplified picture:
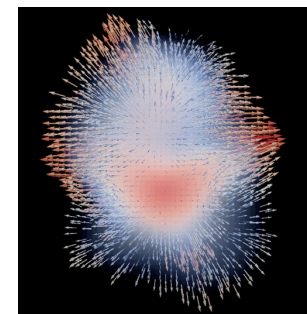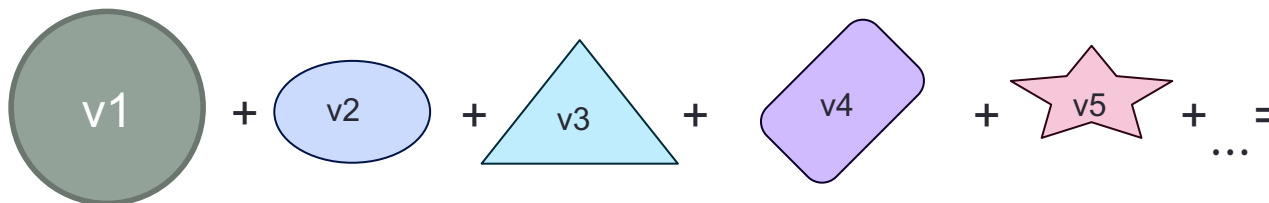
Position-space anisotropy
→ Momentum-space anisotropy
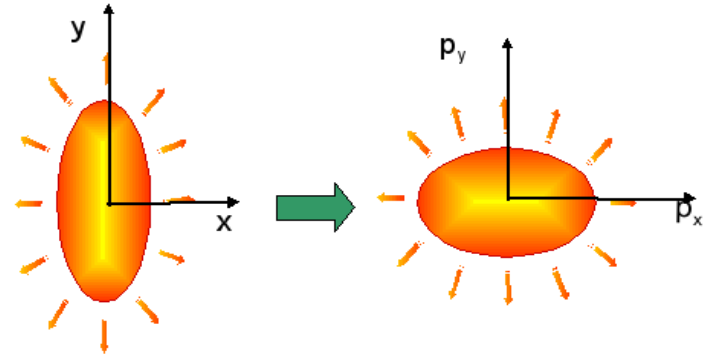
Real picture:
Complicated state,
mean free paths,…

by MADAI.us

Fourier expansion of the radial distribution! → v_n

v1 + v2 + v3 + v4 + v5 + … =
…

Adopted from H. Elfner

Can we distinguish thermal emission from coalescence?
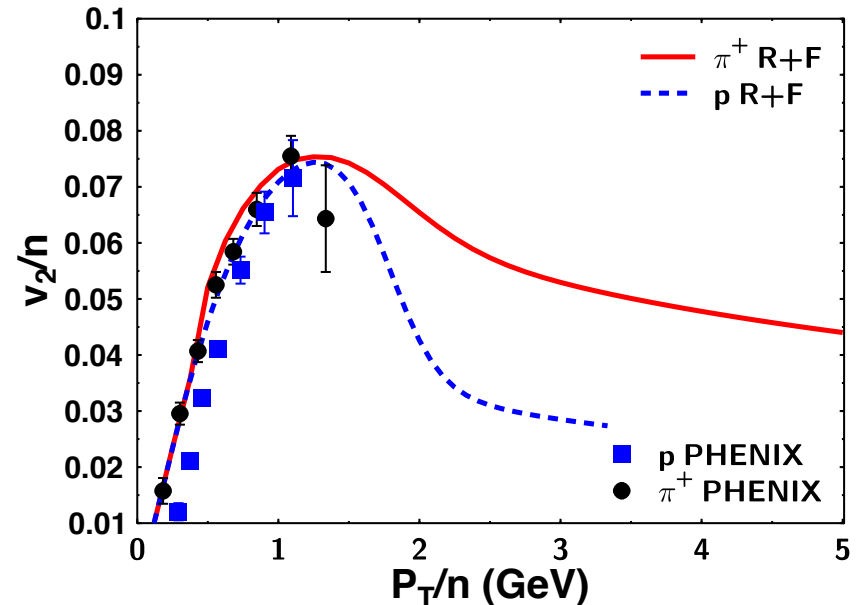# → Scaling

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
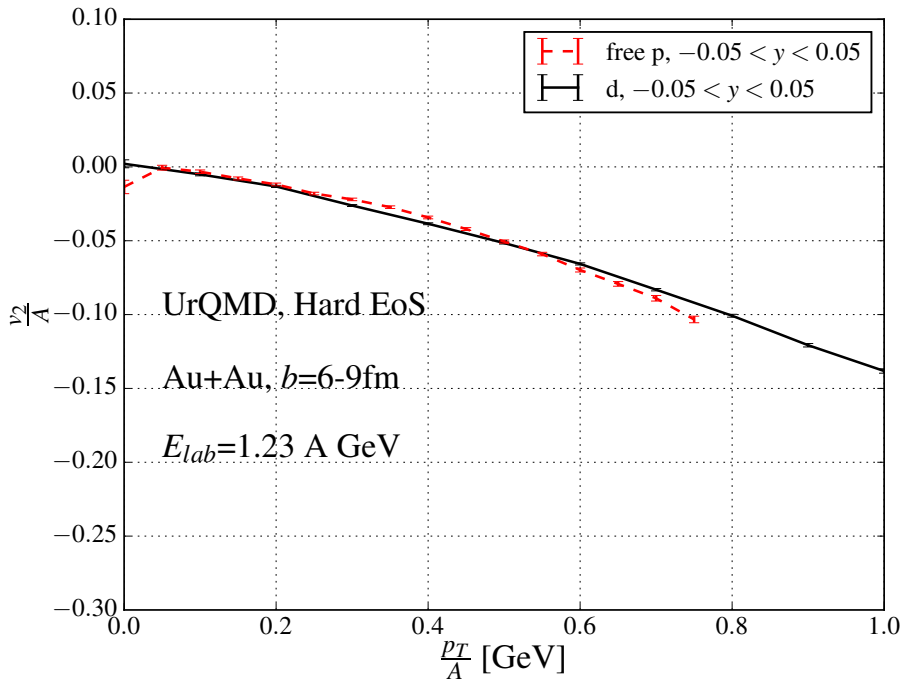

Scaling at LHC is a different story...
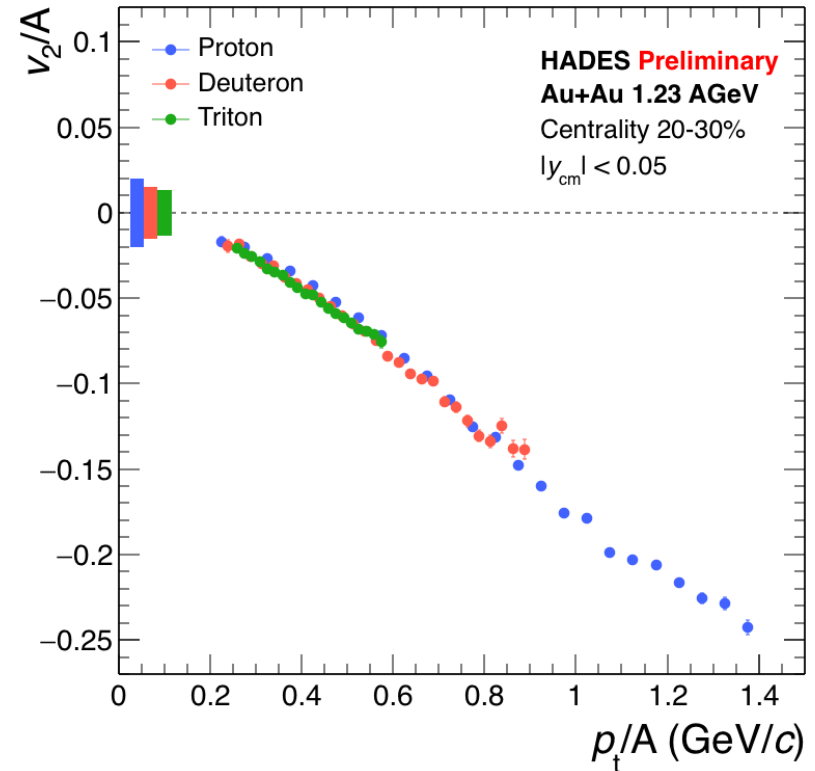
Can we distinguish thermal emission from coalescence? → Scaling
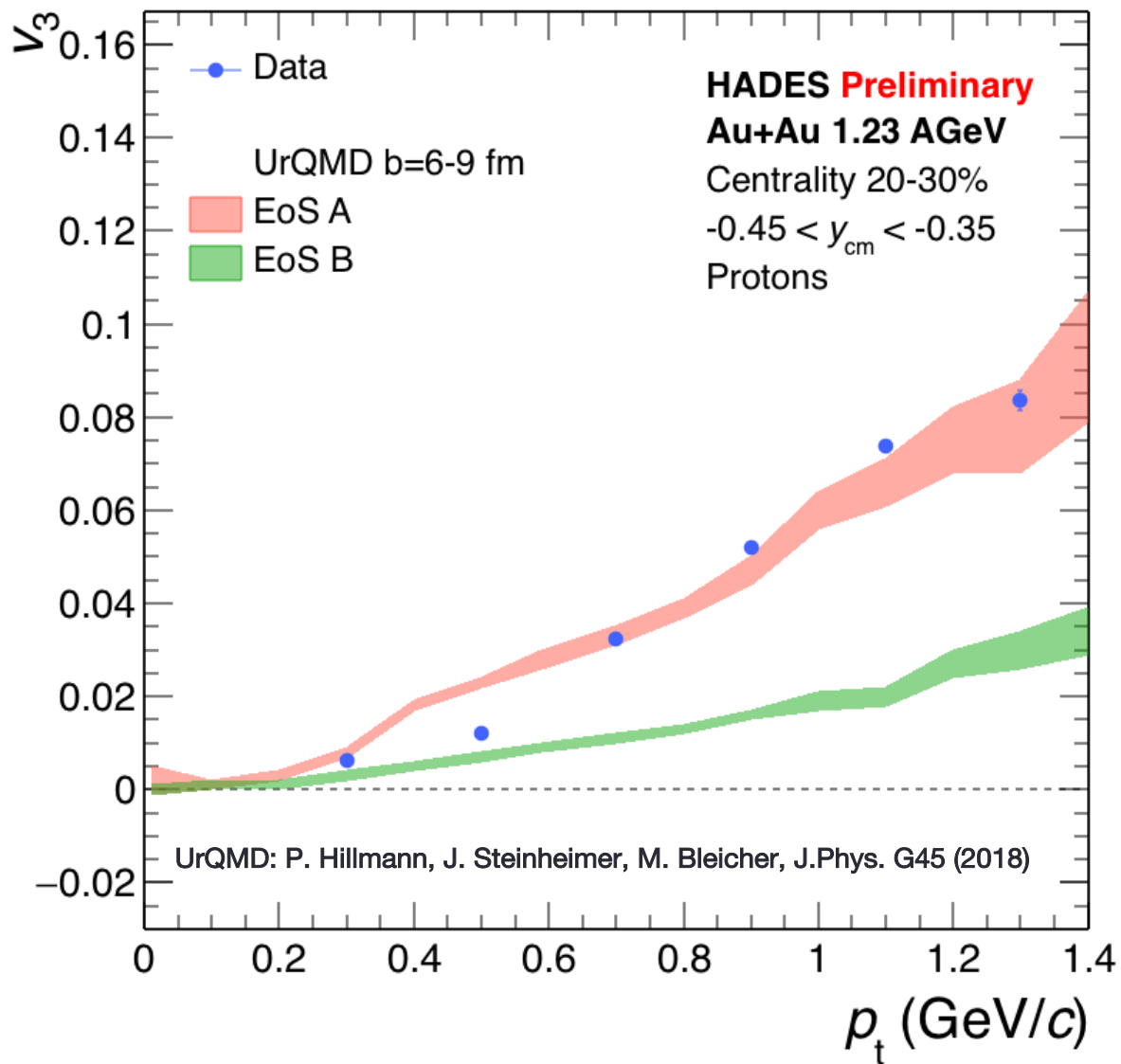
UrQMD

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?
→ Isospin fluctuations

Coalescence formula

$$\Delta\pi = \pi^- - \pi^+$$

$$d = \tilde{B}_2 \cdot (2N_{\text{Au}} - \Delta\pi) \cdot (2Z_{\text{Au}} + \Delta\pi)$$

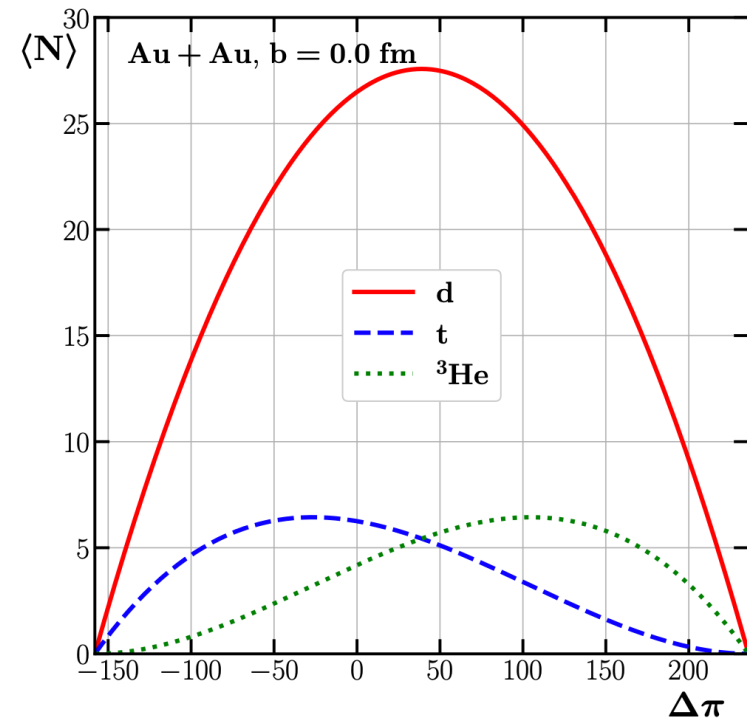$$t = \tilde{B}_3 \cdot (2N_{\text{Au}} - \Delta\pi)^2 \cdot (2Z_{\text{Au}} + \Delta\pi)$$

$$^3\text{He} = \tilde{B}_3 \cdot (2N_{\text{Au}} - \Delta\pi) \cdot (2Z_{\text{Au}} + \Delta\pi)^2$$

→ Coalescence is proportional to proton x neutron number

→ Use $\Delta\pi$ to change p/n ratio

Cluster yield vs $\Delta\pi$

A. Kittiratpattana, eprint: arxiv: 2210.11699

Deuteron production highest for n=p, no protons or neutrons → no deuterons
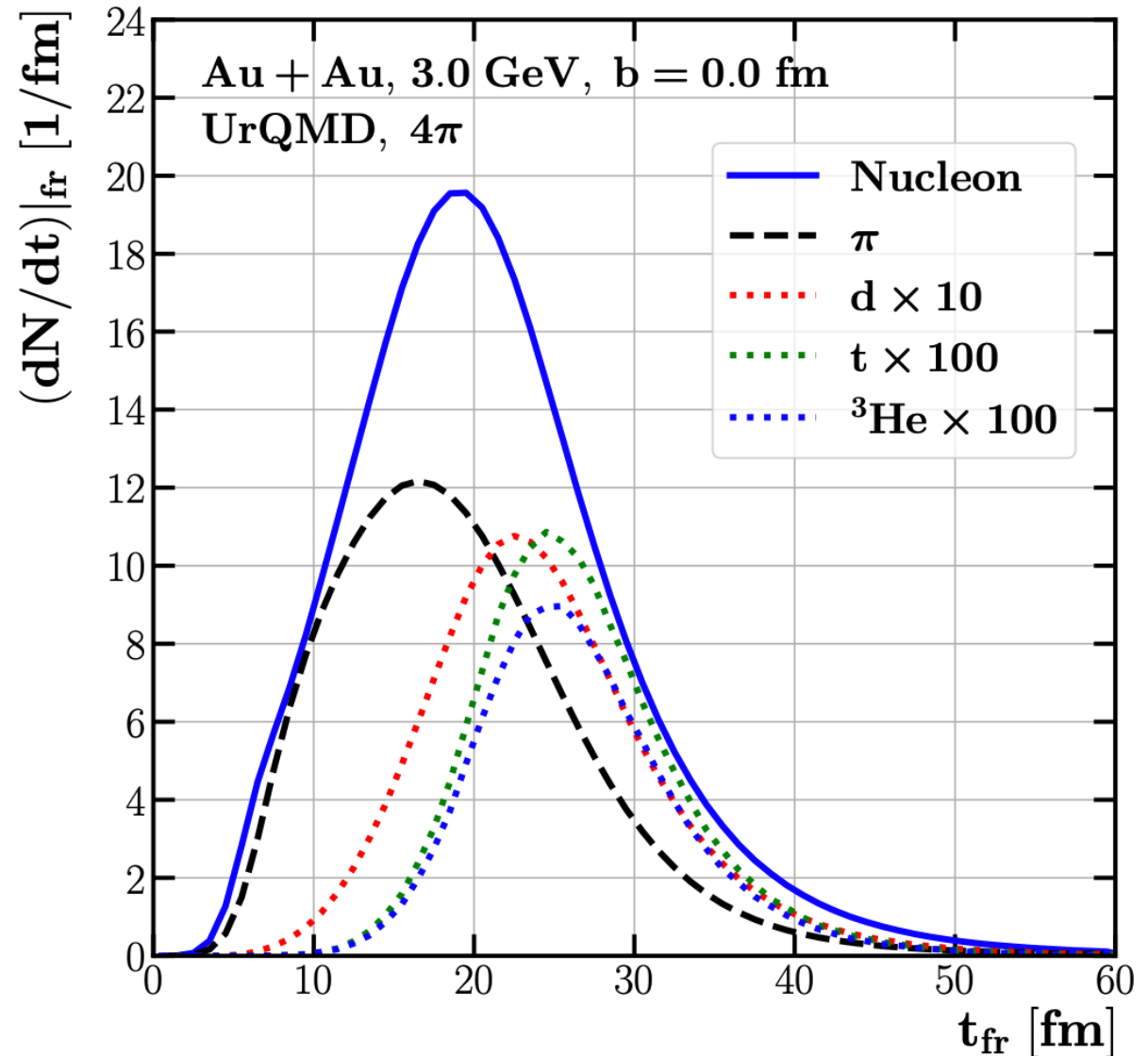
Freeze-out

Clusters are produced after pions are emitted

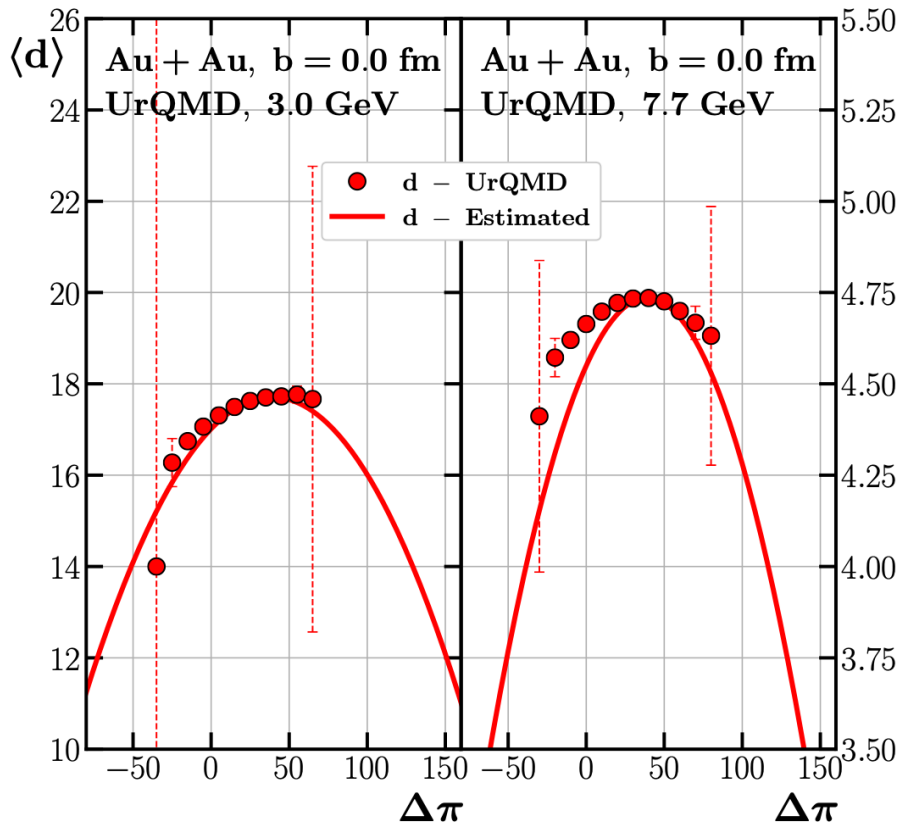Clusters feel emitted isospin

Coalescence depends on proton/neutron number in final state

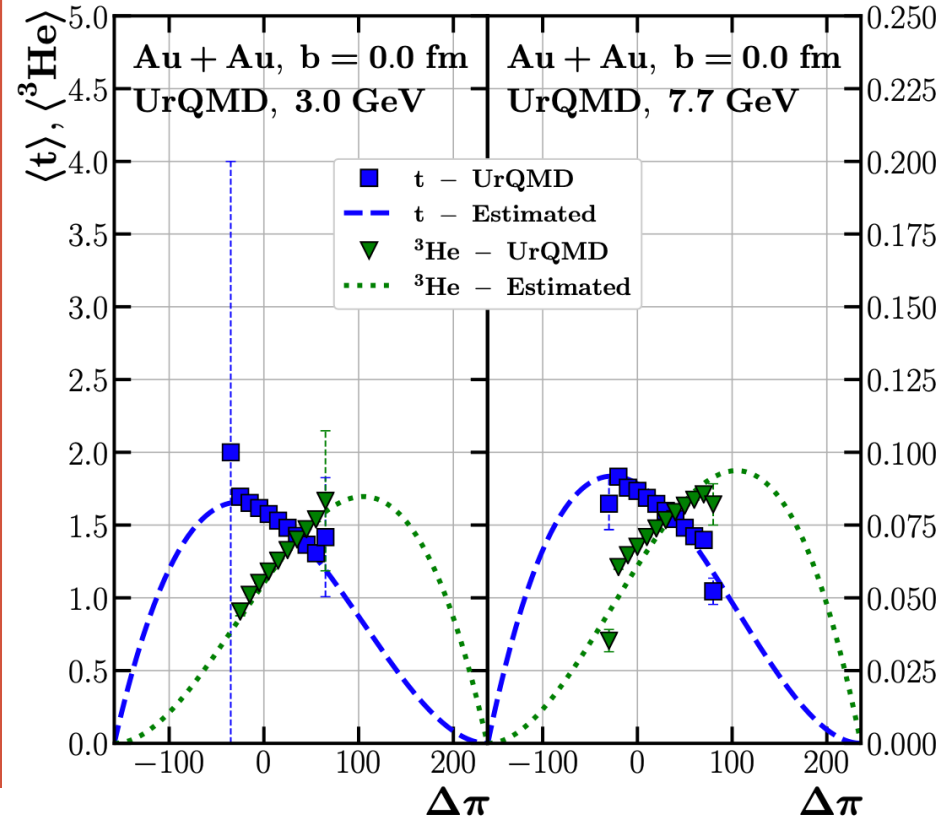→ Pion trigger allows to define nucleon system before coalescence
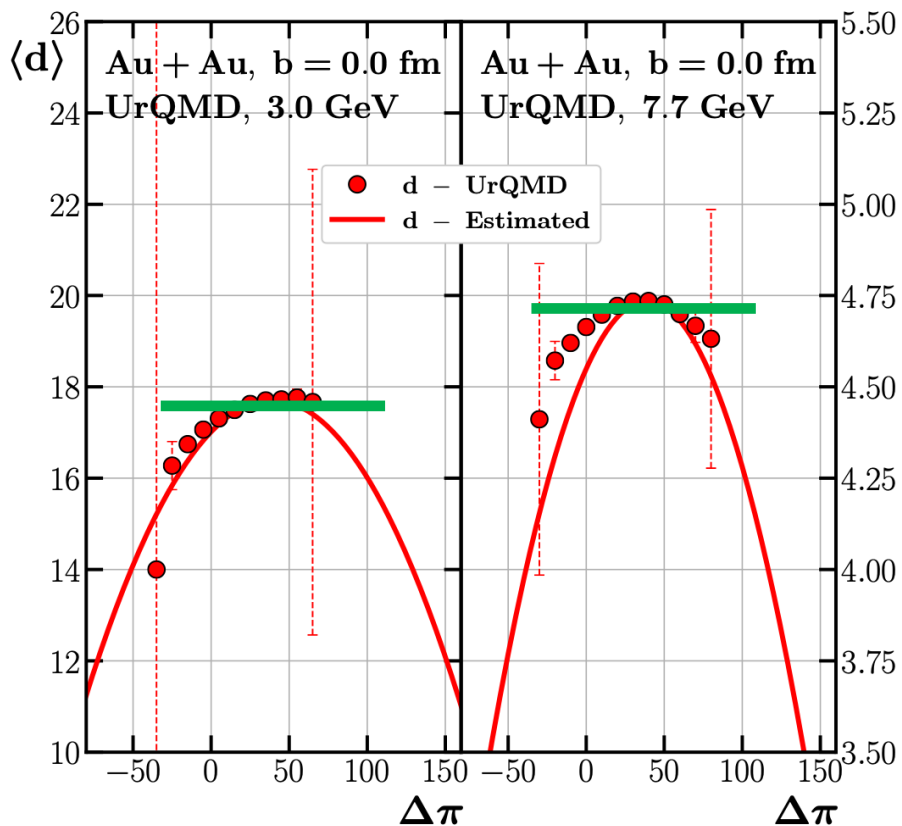
Checking it with UrQMD
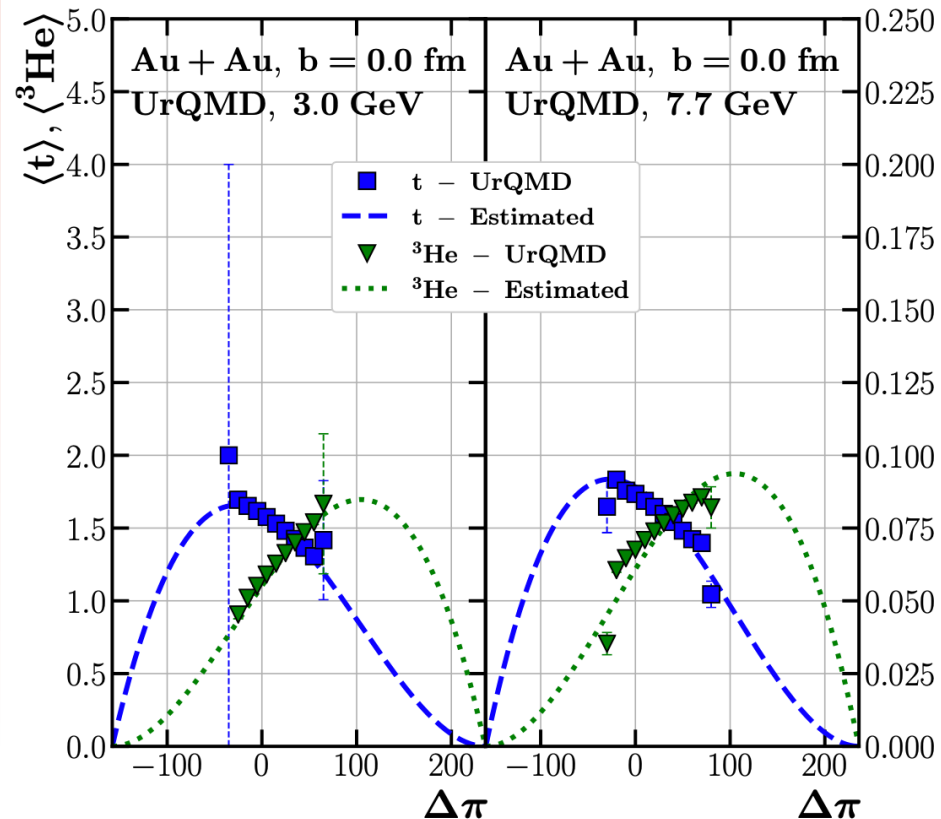

Deuterons

Triton and helium

Thermal model is flat!

Deuterons

Triton and helium

Summary

- Coalescence works very well over a broad energy regime

- True process (thermal or coalescence) can be distinguish:
- → fluctuations and flow

- 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.