PRODUCTION OF LIGHT NUCLEI AND EXOTIC NUCLEI IN RELATIVISTIC NUCLEAR COLLISIONS

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GSI

NIC

Extension of the periodic system

- into the direction of extreme iso-spin asymmetry
- into the direction of anti-matter
- into the direction of strangeness
- into the direction of charm
- → need to produce new quarks
  → need to couple them to new nuclei

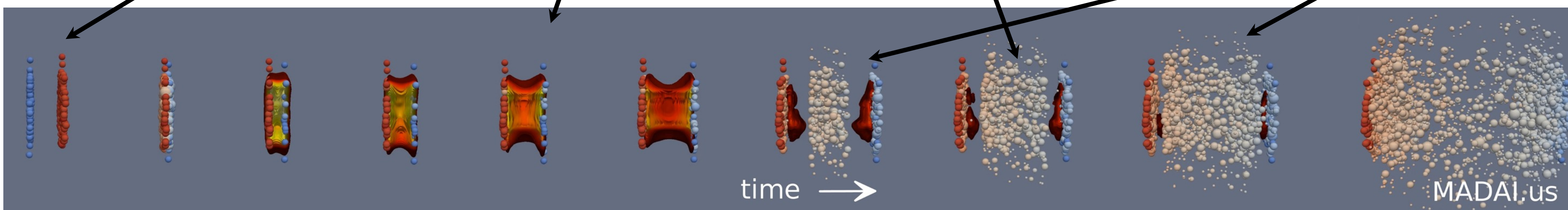
Time Evolution of Heavy Ion Collisions

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

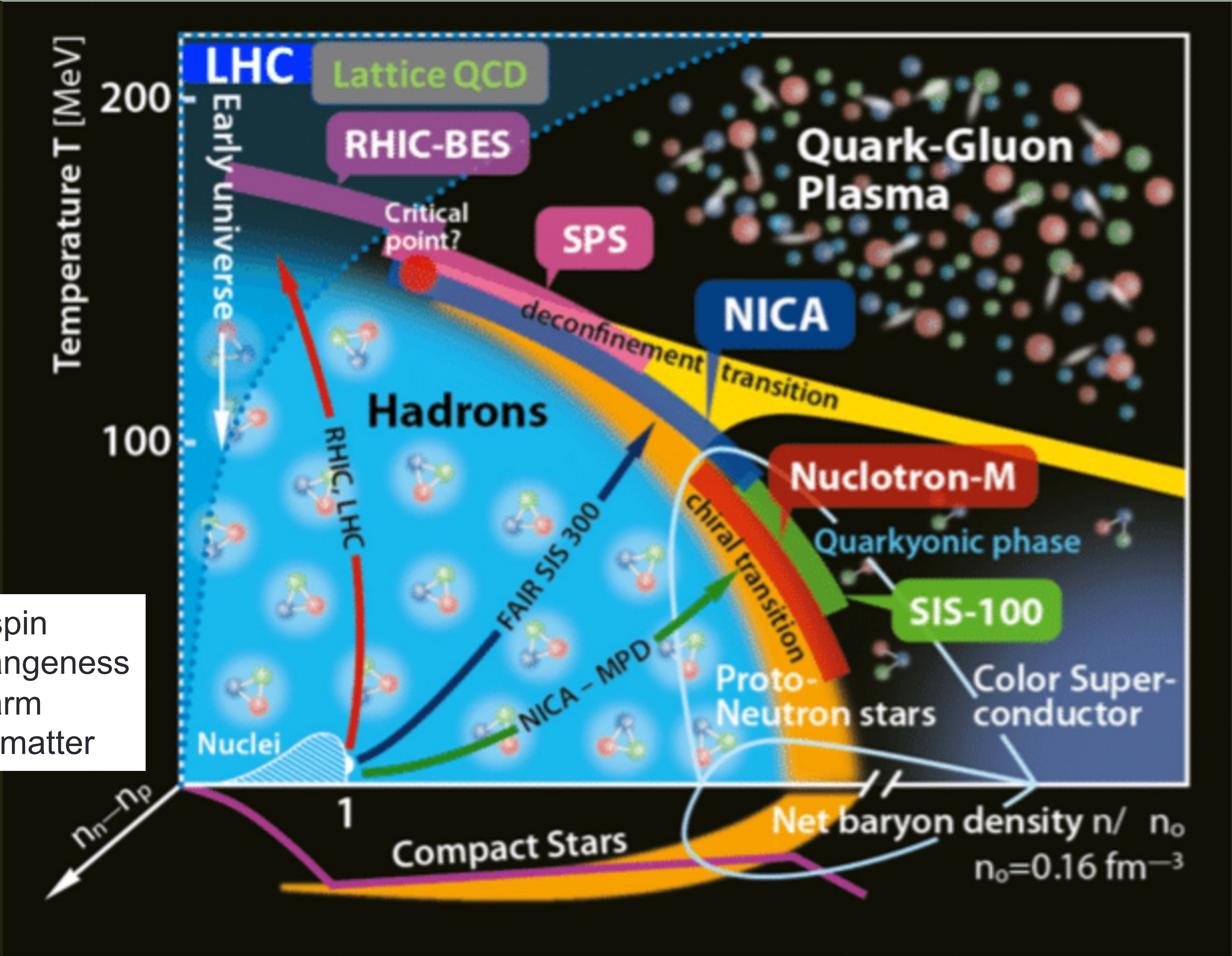
At high energies hybrid approaches are very successful for the description of the dynamics

Figure adapted from H. Elfner, arXiv:1404.1763

QCD (Quantum Chromo Dynamics)

$$\mathcal{L}_{QCD} = \sum_q \left(\bar{\psi}_{qi} i\gamma^\mu \left[\delta_{ij}\partial_\mu + ig\left(G^\alpha_\mu t_\alpha\right)_{ij} \right] \psi_{qj} - m_q \bar{\psi}_{qi}\psi_{qi} \right) - \frac{1}{4} G^\alpha_{\mu\nu} G^{\mu\nu}_\alpha$$

- $G^{\mu\nu}_\alpha = \partial^\mu G^\nu_\alpha - \partial^\nu G^\mu_\alpha - g f^{\alpha\beta\gamma} G^\mu_\beta G^\nu_\gamma$ color fields tensor
- G^μ_α four potential of the gluon fields (α=1,..8)
- t_α 3x3 Gell-Mann matrices; generators of the SU(3) color group
- $f^{\alpha\beta\gamma}$ structure constants of the SU(3) color group
- ψ_i Dirac spinor of the quark field (*i* represents color)
- $g = \sqrt{4\pi\alpha_s}\ (\hbar = c = 1)$ color charge (strong coupling constant)



Isospin
Strangeness
Charm
Antimatter

How do we describe the dynamics?

- QCD has asymptotic freedom
  → Allows perturbative calculations
  at small distances (<<1fm) or
  at very high temperatures (>>1GeV)
- →We are dealing with size ~ 1 - 10 fm, T ~ 50 – 200 MeV

- Lattice QCD only in equilibrium (and $\mu_B/T \ll 1$)
  → no dynamics, no collision, no particle production,...

- Can not use ab-initio QCD
- → Need an effective (dynamical) model

E.g., Nucleon transport in N,π,Δ system : $Df_N = I_{coll}$

(only 1←→2, 2←→2 reactions indicated here)

$$\frac{\partial f_N}{\partial t} + \vec{v}\cdot\frac{\partial f_N}{\partial r} - \nabla_r U_N \cdot \frac{\partial f_N}{\partial p} = I_{NN\to NN} + I_{N\Delta\to N\Delta} + I_{N\pi\to N\pi} + I_{NN\to N\Delta} + I_{NN\to\Delta\Delta} + I_{N\Delta\to\Delta\Delta} + I_{N\Delta\to NN} + I_{N\pi\to\Delta}$$

$$= \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{NN}c^2\cdot\mu_{NN}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$
$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_N(p_2')(1-f_N(p_1))(1-f_N(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}f_N(p_1)f_N(p_2)(1-f_N(p_1'))(1-f_N(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{N\Delta}c^2\cdot\mu_{N\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$
$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_\Delta(p_2')(1-f_N(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_\Delta(p_2)(1-f_N(p_1'))(1-f_\Delta(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{N\pi}c^2\cdot\mu_{N\pi}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$
$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_\pi(p_2')(1-f_N(p_1))(1+f_\pi(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_\pi(p_2)(1-f_N(p_1'))(1+f_\pi(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{NN}c^2\cdot\mu_{N\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$
$$\left[\ldots\right]$$

$$+ \ldots\,(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$
$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_\Delta(p_2')(1-f_N(p_1))(1-f_N(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_N(p_2)(1-f_\Delta(p_1'))(1-f_\Delta(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{N\Delta}c^2\cdot\mu_{\Delta\Delta}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$
$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_\Delta(p_1')f_\Delta(p_2')(1-f_N(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_\Delta(p_2)(1-f_\Delta(p_1'))(1-f_\Delta(p_2'))\right]$$

$$+ \frac{\pi}{\hbar}\frac{g_1 g_2}{4}\frac{(2\pi)^2(\hbar c)^4}{\mu_{N\Delta}c^2\cdot\mu_{NN}c^2}\int\frac{d^3p_2}{(2\pi\hbar)^3}\int\frac{d^3p_1'}{(2\pi\hbar)^3}\int\frac{d^3p_2'}{(2\pi\hbar)^3}\frac{d\sigma}{d\Omega}(p_1'-p_1)\cdot(2\pi\hbar)^3\delta^3(p_1+p_2-p_1'-p_2')\delta(\varepsilon_1+\varepsilon_2-\varepsilon_1'-\varepsilon_2')\cdot$$
$$\left[\frac{p_1'-p_2'}{p_1-p_2}f_N(p_1')f_N(p_2')(1-f_N(p_1))(1-f_\Delta(p_2)) - \frac{p_1-p_2}{p_1'-p_2'}N(p_1)f_\Delta(p_2)(1-f_N(p_1'))(1-f_N(p_2'))\right]$$

$$+ \int\frac{d^3p_\pi}{(2\pi\hbar)^3}\int\frac{d^3p_\Delta}{(2\pi\hbar)^3}|\langle p_\Delta|T|p_N p_\pi\rangle|^2\cdot(2\pi\hbar)^3\delta^3(p_N+p_\pi-p_\Delta)\delta(\varepsilon_N+\varepsilon_\pi-\varepsilon_\Delta)\cdot$$
$$[f_\Delta(p_\Delta)(1+f_\pi(p_\pi))(1-f_N(p_N)) - f_N(p_N)f_\pi(p_\pi)(1-f_\Delta(p_\Delta))]$$

22

Full collision term consists of >10000 different particle combinations

- ➔ **set of transport equations coupled via I_{coll} and mean field**

Taken from Elena Bratkovskaya

Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

Relativistic hadron transport model

- Based on the propagation of hadrons
- Rescattering among hadrons is fully included
- String excitation/decay (LUND picture/PYTHIA) at higher energies
- Provides a solution of the relativistic n-body transport eq.:

$$p^\mu \cdot \partial_\mu f_i(x^\nu, p^\nu) = \mathcal{C}_i$$

The collision term C includes more than 100x100 hadrons

- Includes interaction potentials
- *"Standard Reference"* for low and intermediate energy hadron and nucleus interactions

M. Bleicher et al, J.Phys. G25 (1999) 1859-1896

nucleon	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1192}	Ξ_{1317}	Ω_{1672}
N_{1440}	Δ_{1600}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	
N_{1520}	Δ_{1620}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1700}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1900}	Λ_{1670}	Σ_{1775}	Ξ_{1950}	
N_{1675}	Δ_{1905}	Λ_{1690}	Σ_{1790}	Ξ_{2025}	
N_{1680}	Δ_{1910}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1920}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1930}	Λ_{1820}	Σ_{2030}		
N_{1720}	Δ_{1950}	Λ_{1830}			
N_{1900}		Λ_{1890}			
N_{1990}		Λ_{2100}			
N_{2080}		Λ_{2110}			
N_{2190}					
N_{2200}					
N_{2250}					

0^{-+}	1^{--}	0^{++}	1^{++}
π	ρ	a_0	a_1
K	K^*	K_0^*	K_1^*
η	ω	f_0	f_1
η'	ϕ	f_0^*	f_1'
1^{+-}	**2^{++}**	**$(1^{--})^*$**	**$(1^{--})^{**}$**
b_1	a_2	ρ_{1450}	ρ_{1700}
K_1	K_2^*	K_{1410}^*	K_{1680}^*
h_1	f_2	ω_{1420}	ω_{1662}
h_1'	f_2'	ϕ_{1680}	ϕ_{1900}

List of included particles in the hadron cascade

- Binary interactions between all implemented particles are treated individually
- Cross sections are taken from data when available or models
- Resonances are implemented in Breit-Wigner form
- No a priori in-medium modifications, however collisional broadening and mass dependent decay widths are included

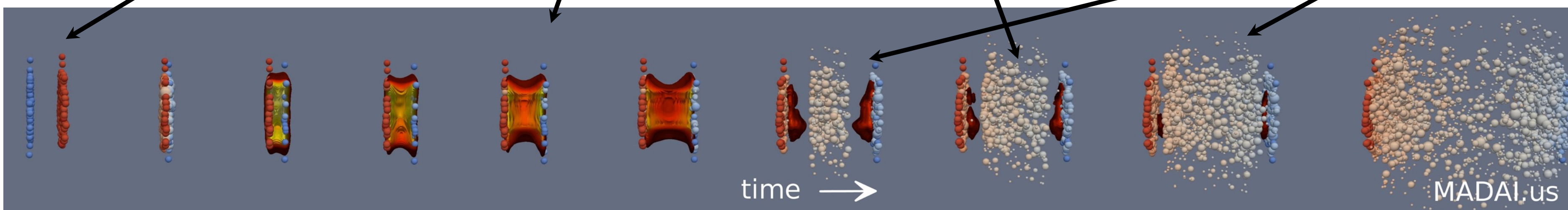
Time Evolution of Heavy Ion Collisions

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Cluster emissions vs. formation



1x 10^{-23} s

10 x 10^{-23} s

30 x 10^{-23} s

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics/ Parton dynamics/ **Hadrons+potentials** → Hadron Transport

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

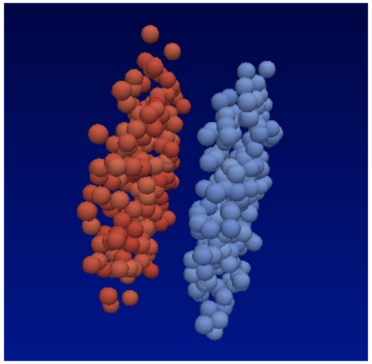
Figure adapted from H. Elfner, arXiv:1404.1763

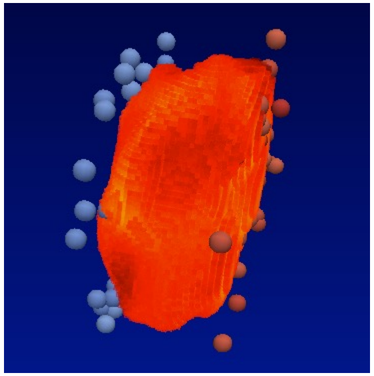
History of Hybrid Approaches

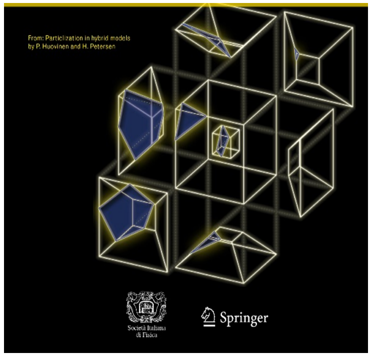
- Started with S. Bass, A. Dumitru, M. Bleicher, Phys.Rev.C60:021902,1999
- Results On Transverse Mass Spectra Obtained With NexSpherio
  F. Grassi, T. Kodama, Y. Hama, J.Phys.G31:S1041-S1044,2005
- 3-D hydro + cascade model at RHIC.
  C. Nonaka, S.A. Bass, Nucl.Phys.A774:873-876,2006
- Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions. (3d hydro + JAM)
  T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara,
  Phys.Lett.B636:299-304,2006
- Integrated (open source) UrQMD 3.4
  H. Petersen, J. Steinheimer, M. Bleicher, Phys. Rev. C 78:044901, 2008
- MUSIC+UrQMD@RHIC and LHC
  B. Schenke, S. Jeon, C. Gale, ... (2008/2010)
- EPOS+Hydro+UrQMD at LHC
  K. Werner, M. Bleicher, T. Pierog, Phys. Rev. C (2010)

UrQMD Hybrid model

H.Petersen, et al, PRC78 (2008) 044901
P. Huovinen, H. P. EPJ A48 (2012) 171







- Initial State:
  - Initialization of two nuclei
  - Non-equilibrium hadron-string dynamics
  - Initial state fluctuations are included naturally

- 3+1d Hydro +EoS:
  - **SHASTA** ideal relativistic fluid dynamics
  - Net baryon density is explicitly propagated
  - Equation of state at finite μ_B

- Final State:
  - Hypersurface at constant energy density
  - Hadronic rescattering and resonance decays within UrQMD

Why are we interested in the production of normal/hyper/anti-clusters?

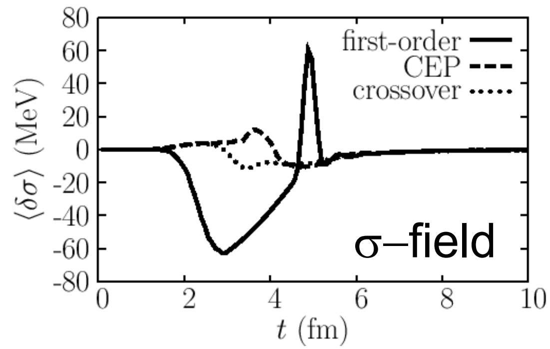
- Light (normal) nuclei (at this energy not created by break-up)
  - Production mechanism under debate (thermal? coalescence?)
  - Can tell us about the source size (alternative to HBT)
  - Can tell us about the QCD phase transition

- Strange hyper-matter nuclei are not very well known
  - Interesting by themselves,
  - Y-N interaction relevant for Neutron Star EoS

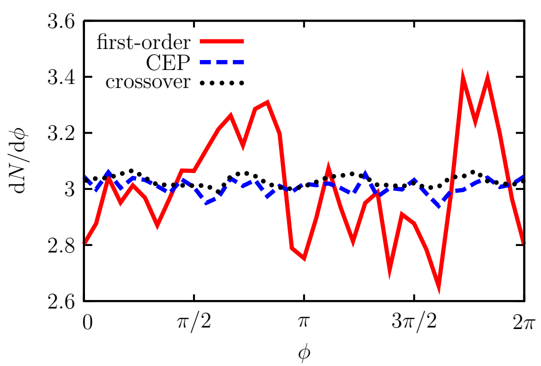
- Anti-matter clusters (anti-nuclei)
  - Allow for test of matter-anti-matter symmetry
  - May tell us about Dark Matter in the Universe (AMS!)

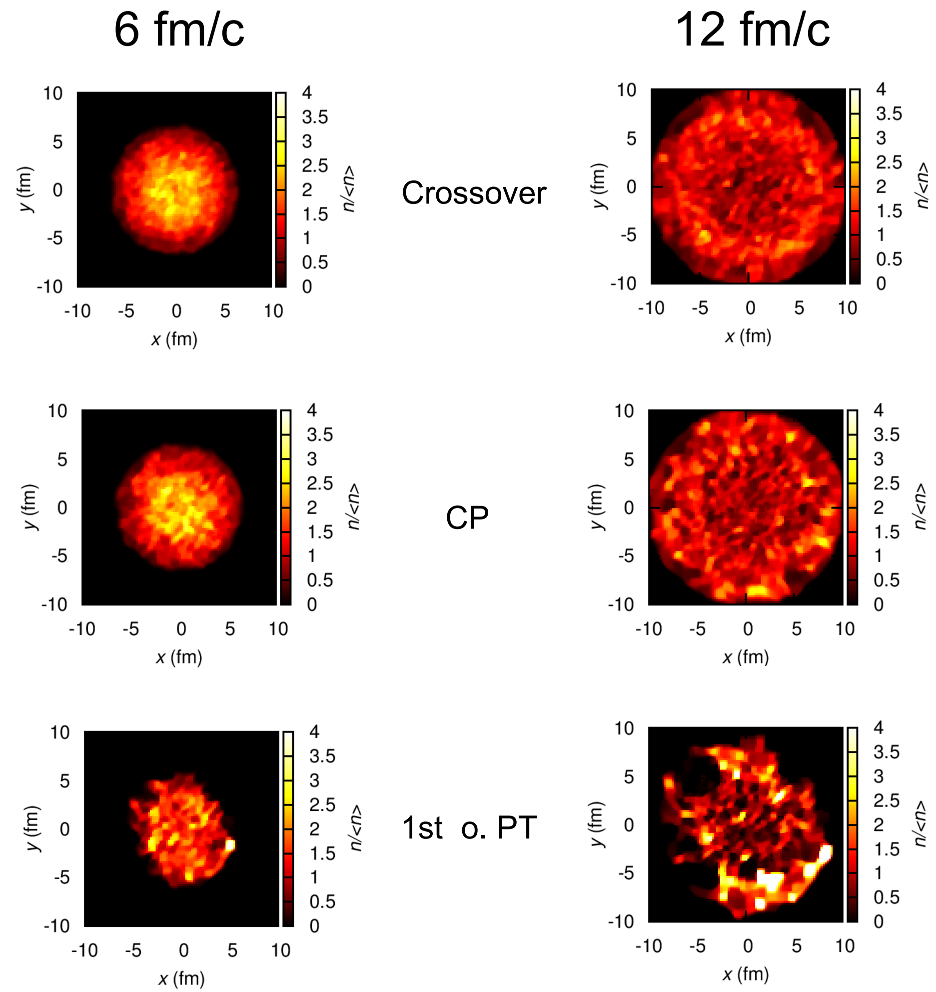
Fluctuations in quark densities → Clusters might **be enhanced**

Nonequilibrium fluctuations in PQM



Angular distribution, 12 fm/c





→ Strong fluctuations, inhomogeneous quark densities → Cluster enhancement

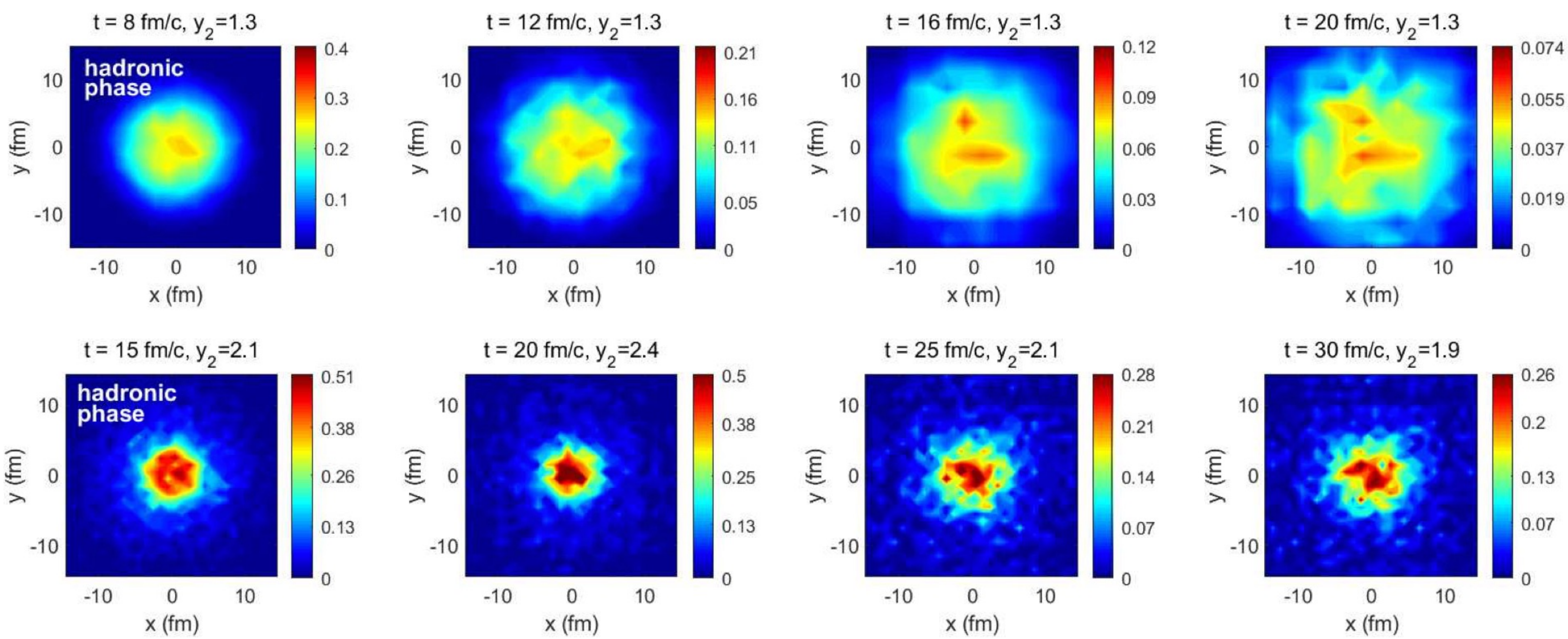
C. Herold, M. Nahrgang, M. Bleicher, I. Mishustin, Nucl.Phys. A925 (2014) 14-24

Similarly...

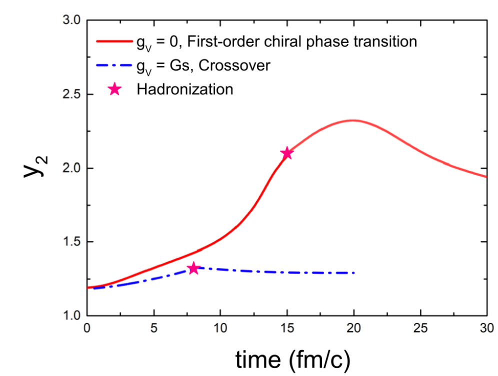
KJ. Sun, CM. Ko, Eur.Phys.J.A 57 (2021) 11

Crossover

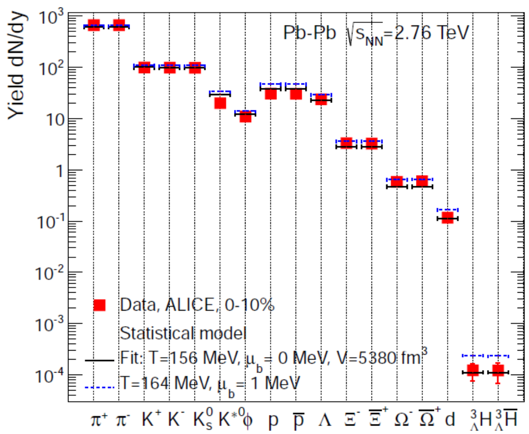
1st o. PT



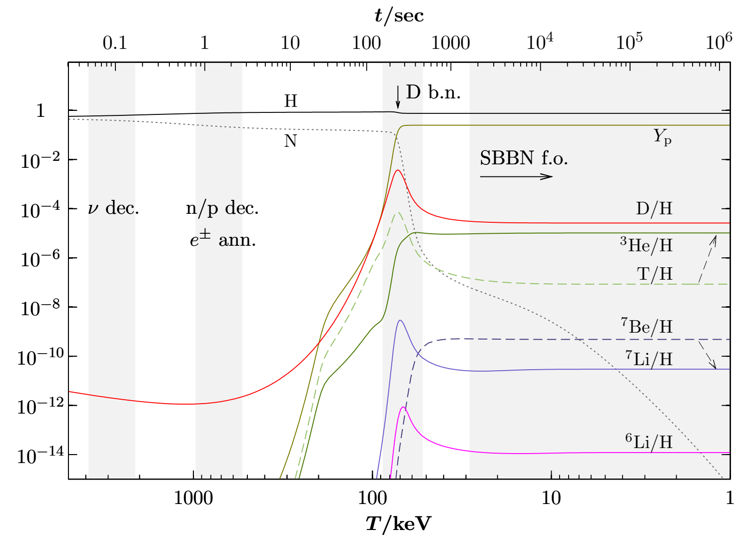
- Visible in the scaled density fluctuations $y_2 = 1 + \Delta n$ is enhanced.



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 ($n_{cluster} = a*\exp(-m_{cluster}/T)$)
- 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.

Methods to calculate clusters in dynamical models

- **Just do it ...**
  - Have proper nuclear potentials
  - Have proper interactions
  - Run your code...
  - Wait until infinity
  - Clusters are stable and will show-up at the end of your simulation

  - Unfortunately its not so easy... cf. J. Aichelin and E. Bratkovskaya

Methods to calculate clusters

- **Wigner coalescence**
  - 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
- **Box 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), Bleicher PLB (1993), Oliinychenko, PRC99 (2019), Butler, PR129 (1963), Mekijan PRL39 (1977)

Coalescence

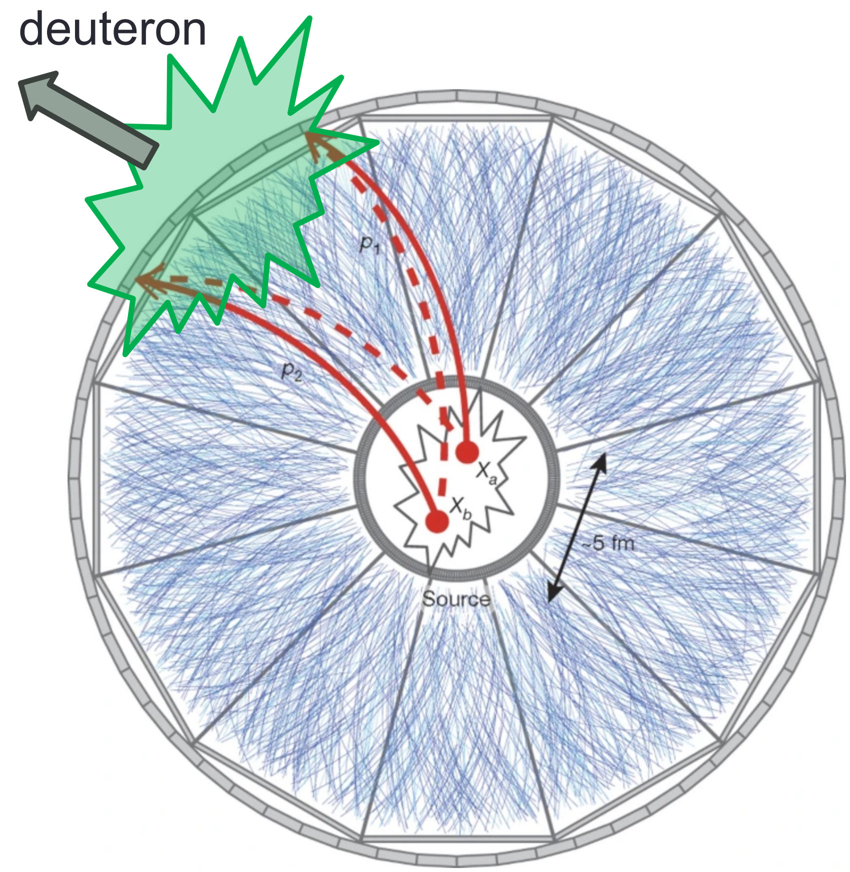
$$dN/d\vec{P} = g \int f_A(\vec{x}_1,\vec{p}_1) f_B(\vec{x}_2,\vec{p}_2) \rho_{AB}(\Delta\vec{x},\Delta\vec{p}) \delta(\vec{P}-\vec{p}_1-\vec{p}_2) d^3x_1\, d^3x_2\, d^3p_1\, d^3p_2$$

- Propagate particle after freeze-out to the same time in 2-particle rest frame

- If $\Delta p = |(p_2 - p_1)| \lesssim 285$ MeV and $\Delta x = |(x_b - x_a)| \lesssim 3.5$ fm

→ deuteron forms

→ $p_d = p_1 + p_2$, $x_d = (x_1 + x_2)/2$



STAR, Nature 527, 345 (2015)

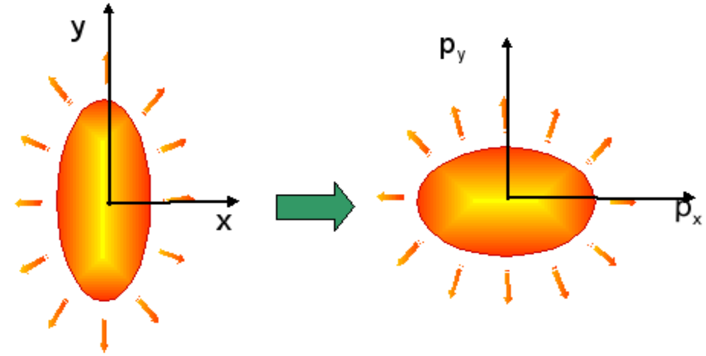
Why do we think coalescence is correct?

- Constituent scaling
- Fluctuations

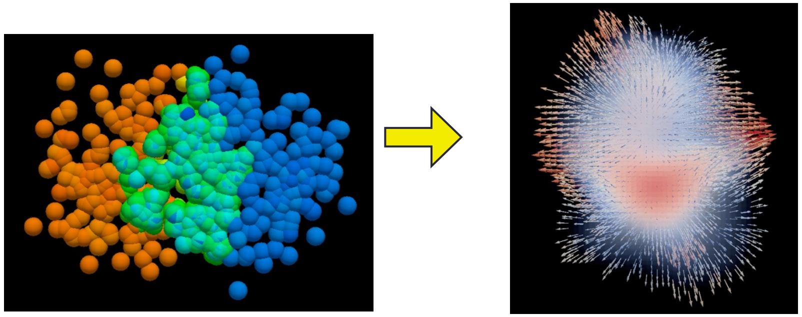
Can we distinguish thermal emission from coalescence? → Anisotropic Flow

Simplified picture:

Position-space anisotropy
→ Momentum-space anisotropy

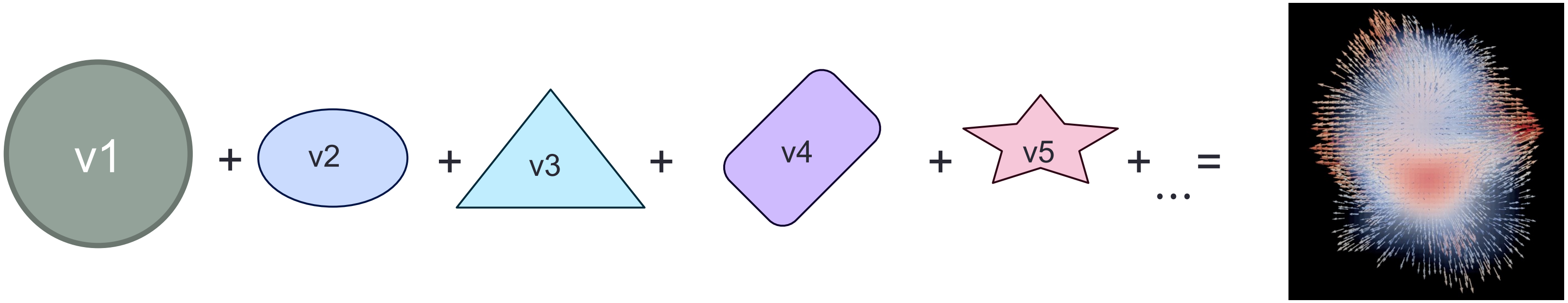


Real picture:
Complicated state,
mean free paths,…



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

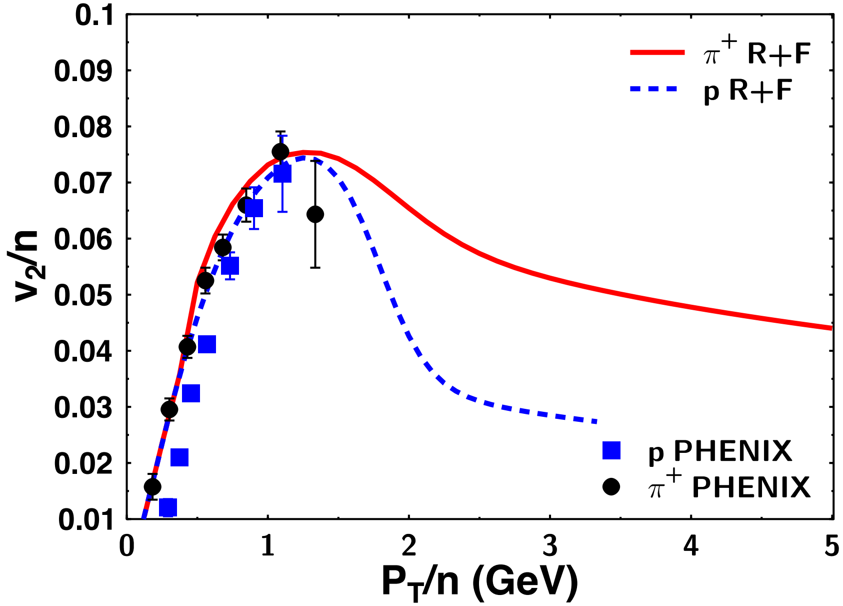
- discovery of “magical factors” of 2 and 3 in measurements of spectra and the elliptic flow of mesons and baryonsat RHIC (Fries et al, 2003)
- Predicted v2 scaling in case of coalescence

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

→ Check scaling to prove coalescence

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

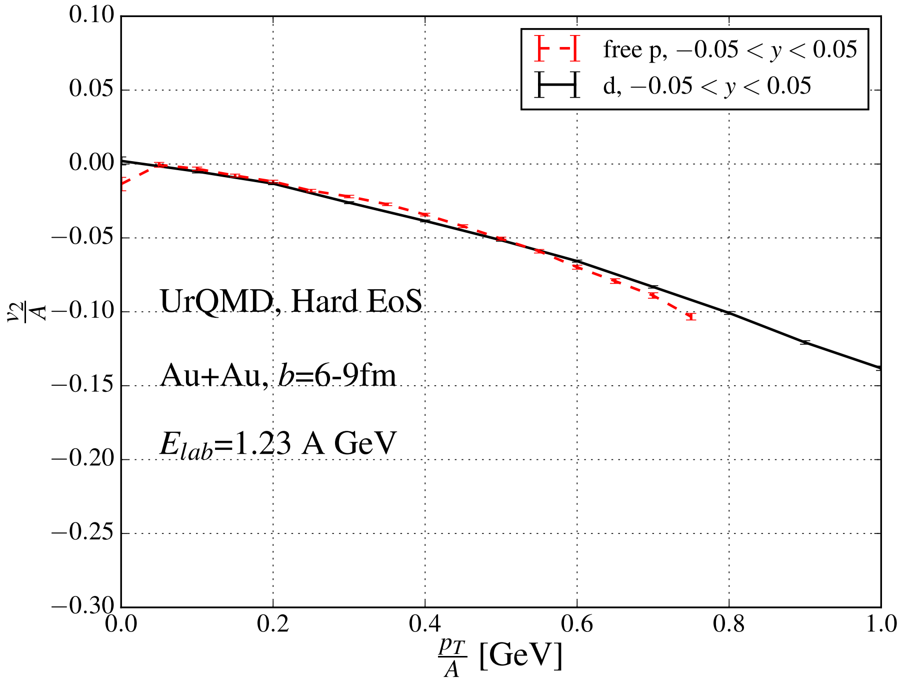
RHIC data



Scaling at LHC is a different story...

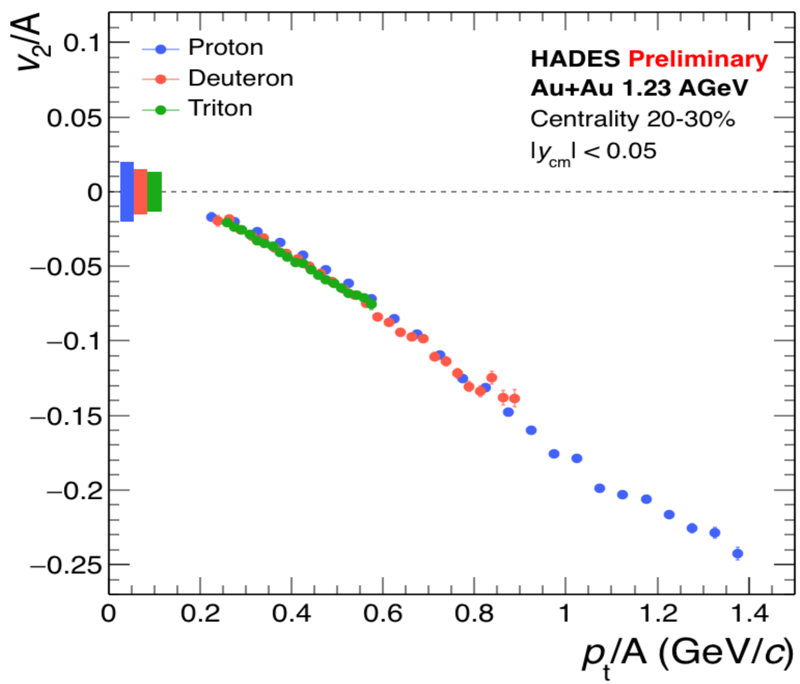
Can we distinguish thermal emission from coalescence?
→ Scaling

UrQMD



Hillmann, Bleicher, et al. arXiv:1907.04571

HADES data

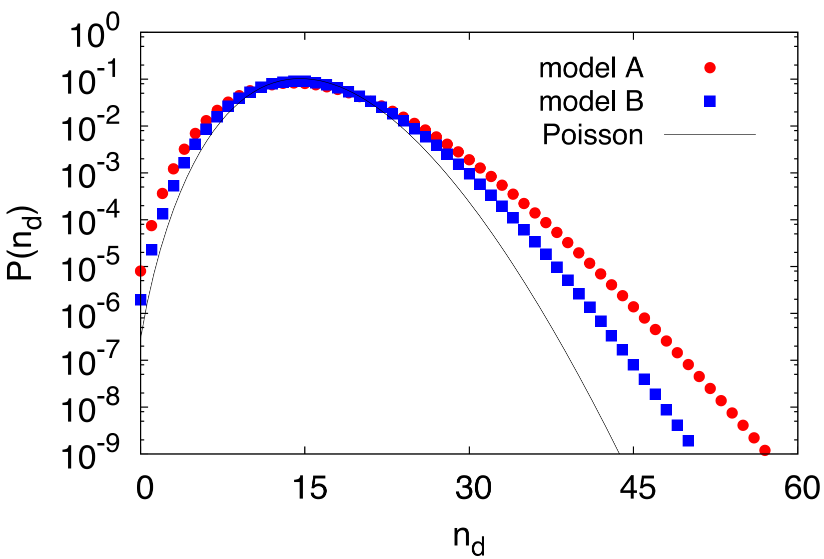


Taken from Behruz Kardan, arXiv:1809.07821

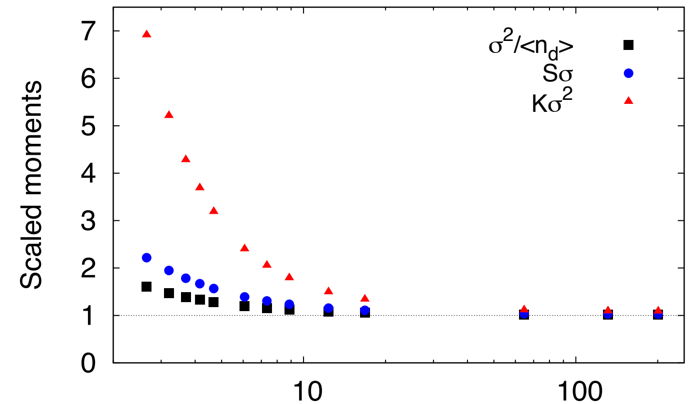
→ Scaling is observed
→ suggests coalescence

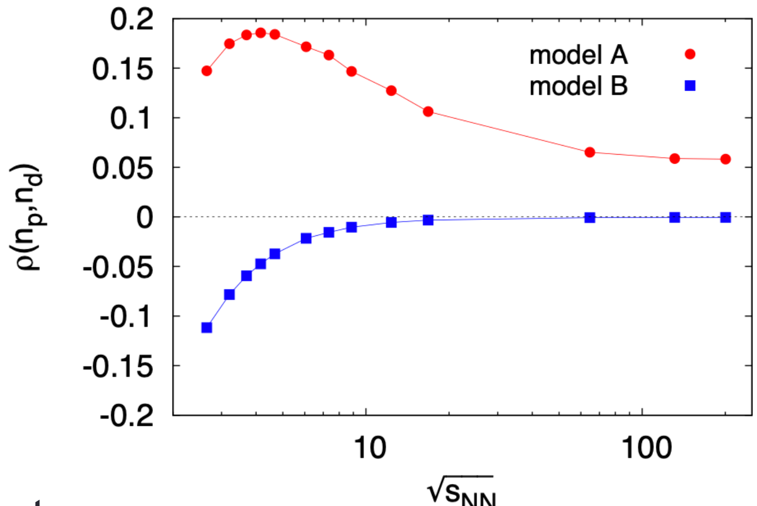
Can we distinguish thermal emission from coalescence? → Fluctuations

Au+Au at 2 AGeV



Moments/Correlations





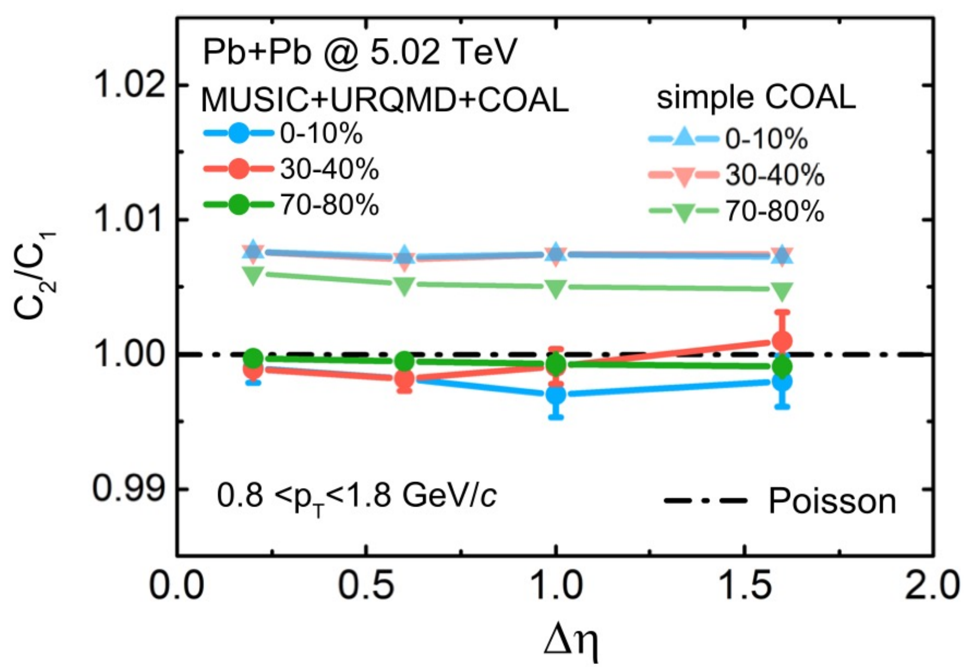
Z. Feckova, B. Tomasik, M. Bleicher, Phys.Rev. C93 (2016) no.5, 054906

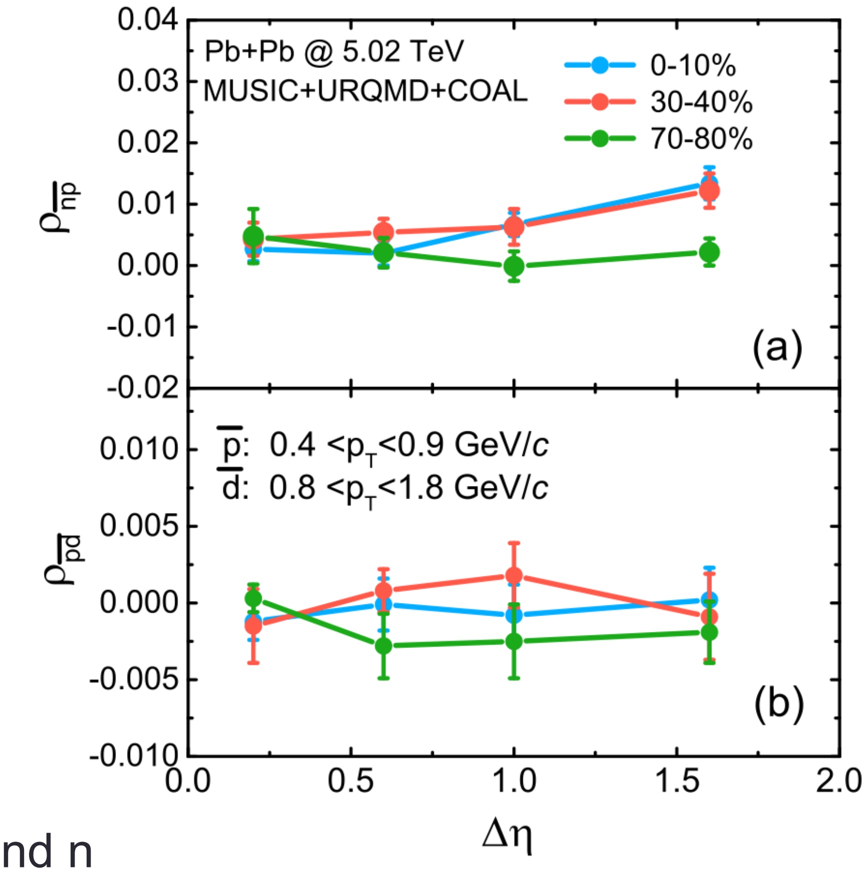
Thermal emission would result in Poisson fluctuations
→ Coalescence leads to wider (non-poisson) distributions

Model A: Correlated p,n, Model B: independent p,n

The full calculation...

KJ. Sun, CM. Ko, Phys.Lett.B 840 (2023) 137864



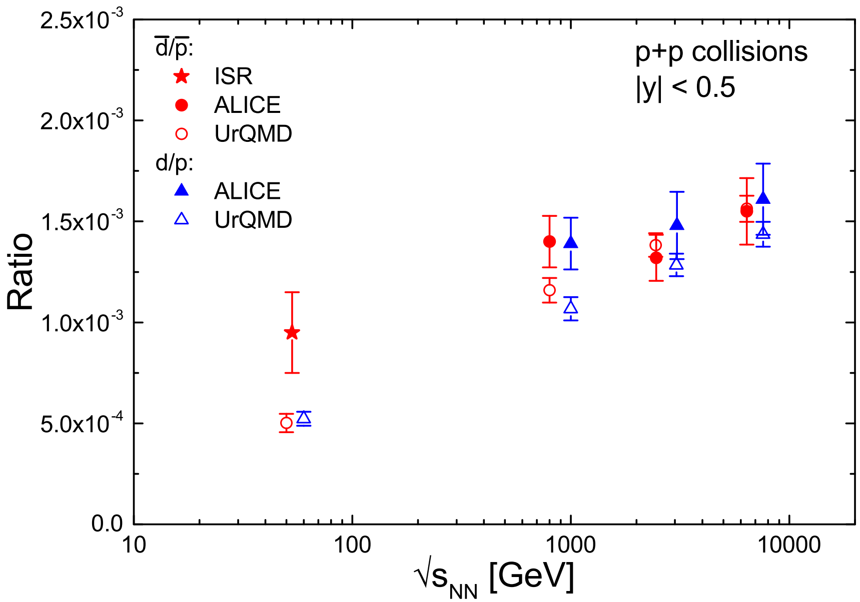


Precision test of this idea:

- Proofs independent fluctuations of p and n
- However: low energies is where it gets interesting !

Proton-proton collisions

Deuteron (anti-deuteron): ratios



Good description of pp by coalescence

Absolute yields

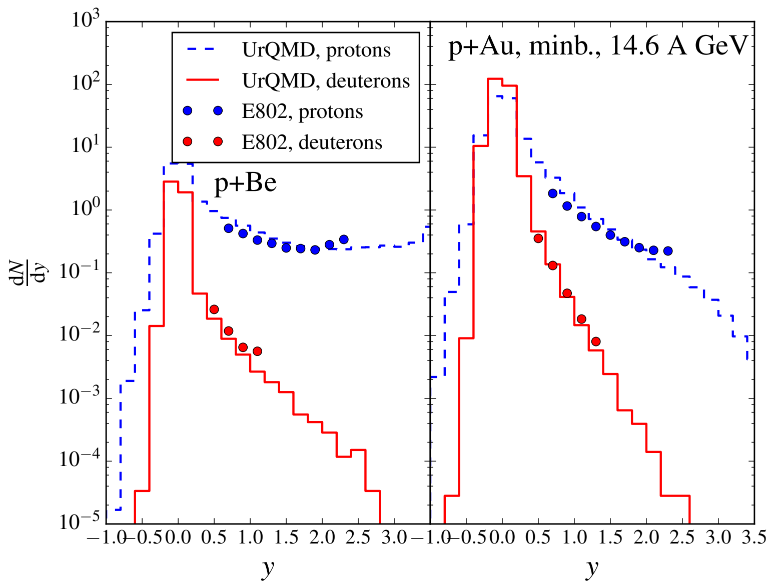
	$\sqrt{s_{NN}}$(TeV)	dN/dy ALICE	dN/dy UrQMD
d	0.9	$(1.12\pm0.09\pm0.09)\times10^{-4}$	$(0.96\pm0.05)\times10^{-4}$
	2.76	$(1.53\pm0.05\pm0.13)\times10^{-4}$	$(1.47\pm0.06)\times10^{-4}$
	7	$(2.02\pm0.02\pm0.17)\times10^{-4}$	$(2.05\pm0.09)\times10^{-4}$
$\overline{d}$	0.9	$(1.11\pm0.10\pm0.09)\times10^{-4}$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

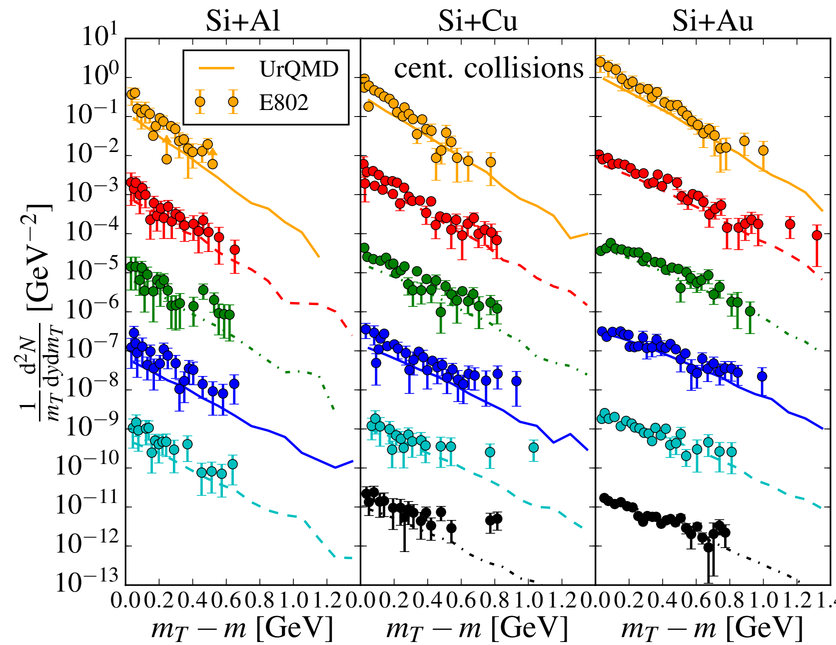
From small to large systems

Proton+nucleus at 14.6 AGeV



Rapidity distributions indicate correct coalescence behavior

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

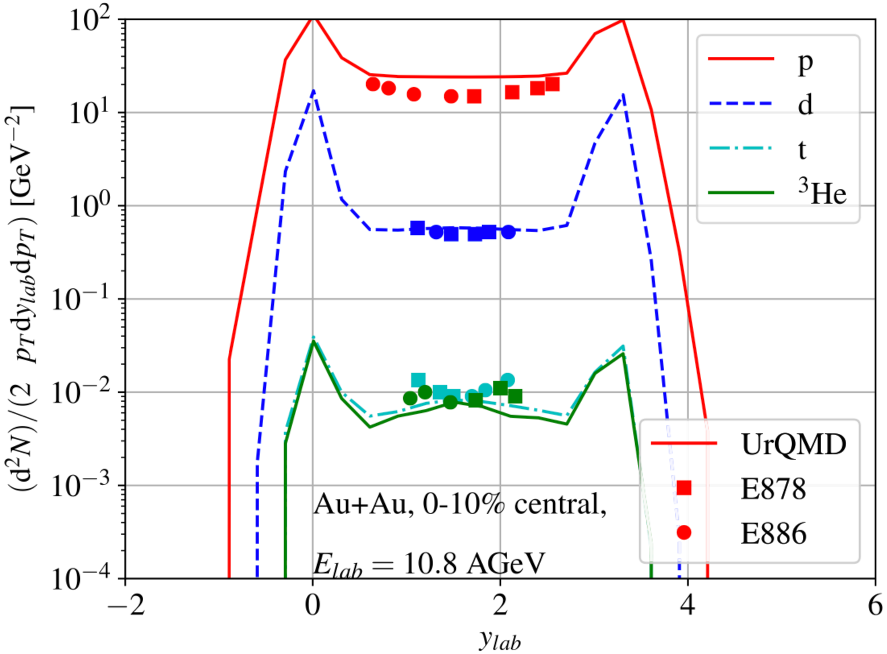


Also transverse expansion is well captured in the coalescence approach

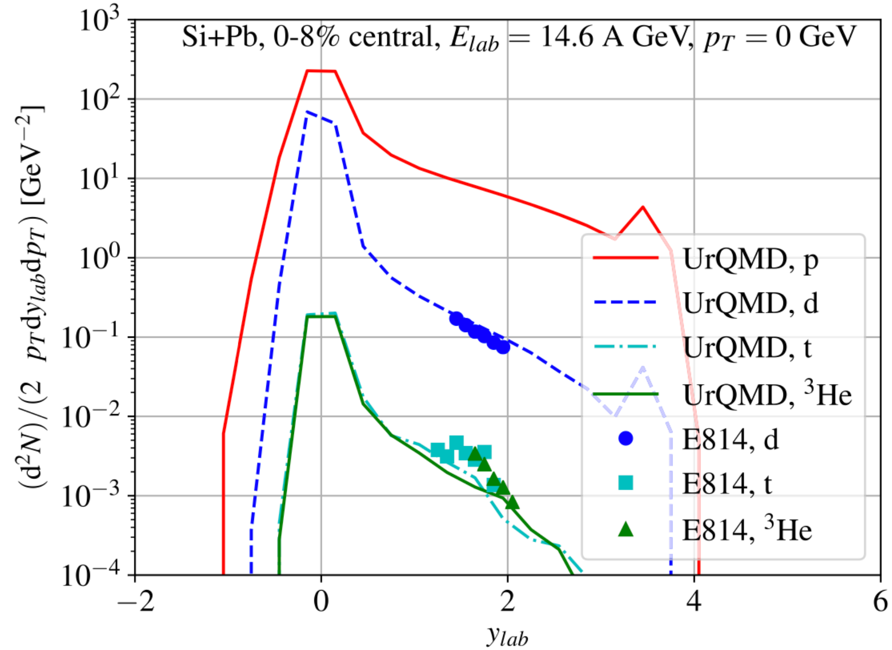
S. Sombun, M. Bleicher et al, Phys.Rev. C99 (2019) no.1, 014901

Extension to tritons is straightforward

Rapidity - OK



Transverse momenta - OK



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

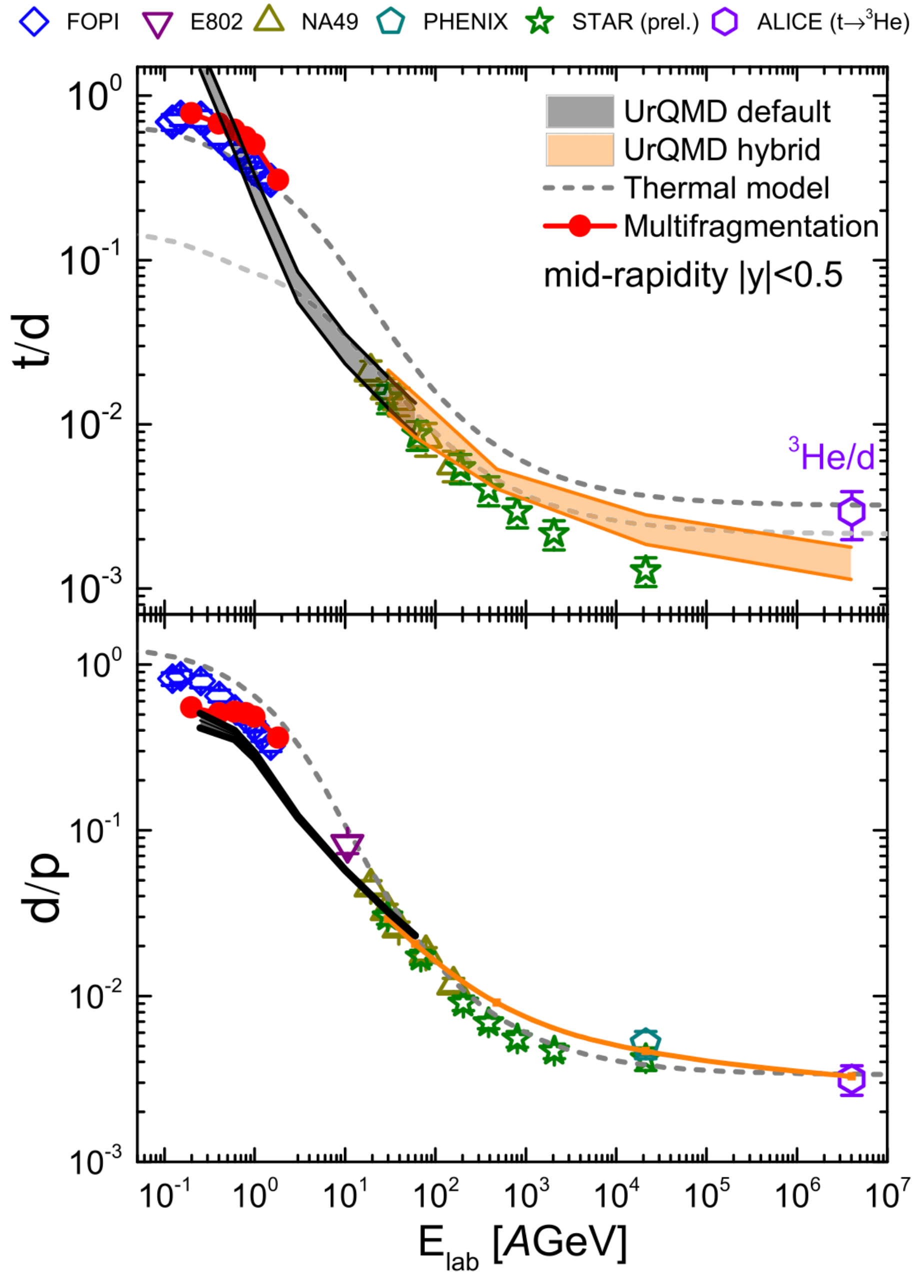
Energy dependence

- 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)

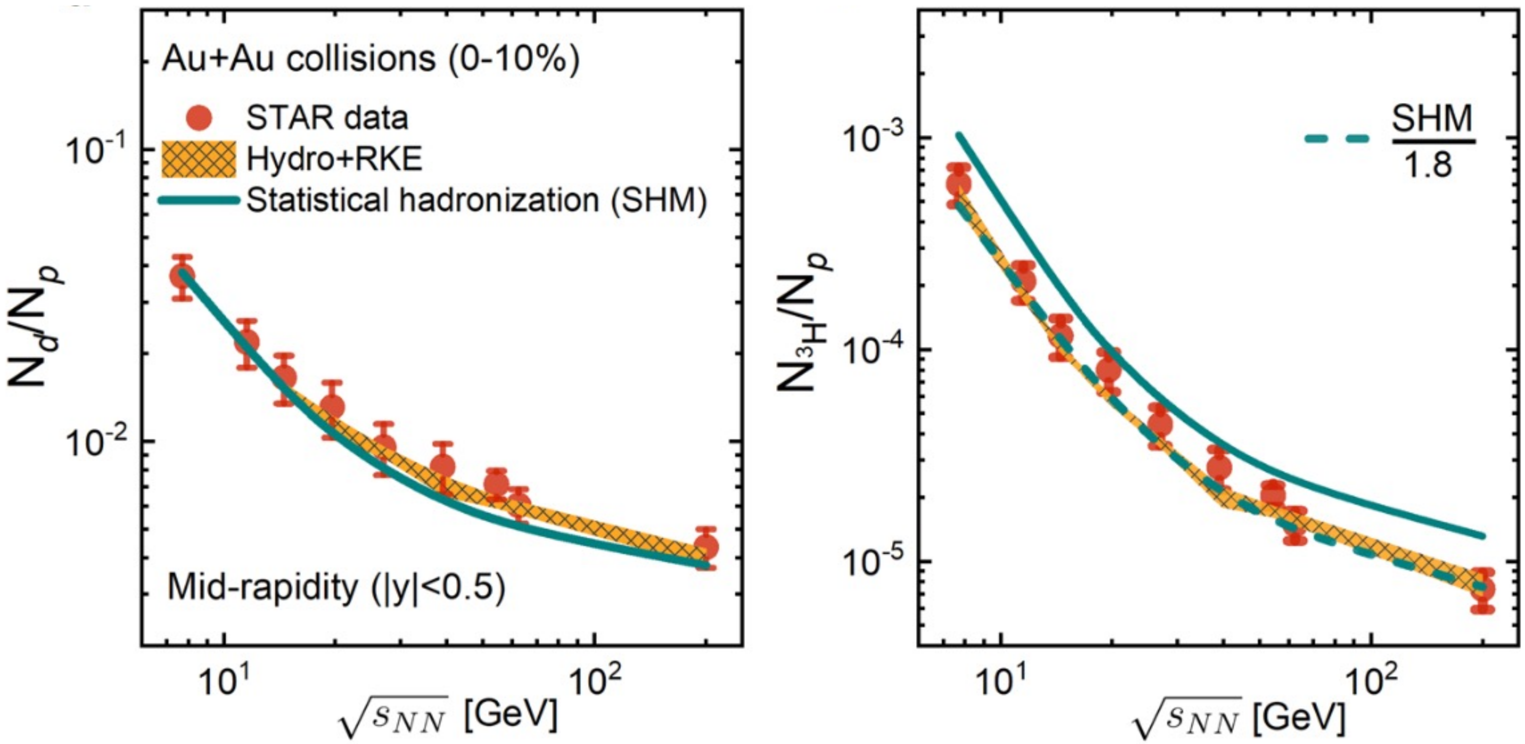
- Mainly reflects decrease of μ_B with increasing energy



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

Beautiful analysis...

Sun, Wang, Ko, Ma, Nature Commun. 15 (2024) 1

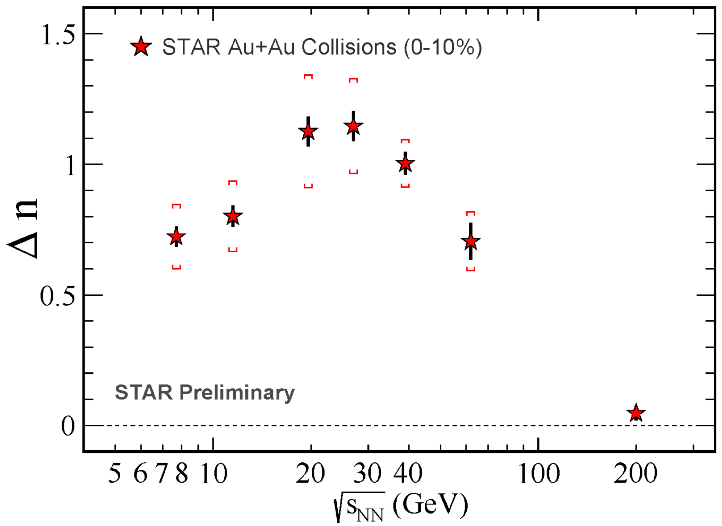


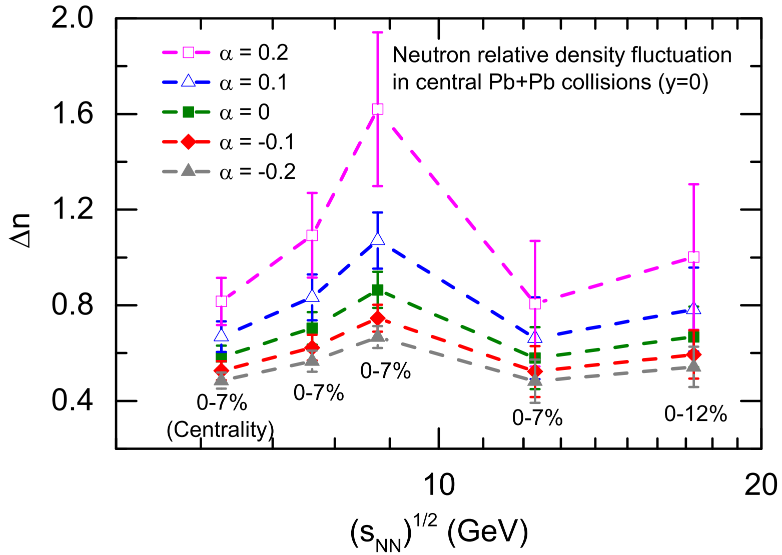
- Consistent analysis confirms that hydro+transport+coalescence is necessary to describe the full breadth of data

Neutron density fluctuations?

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

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

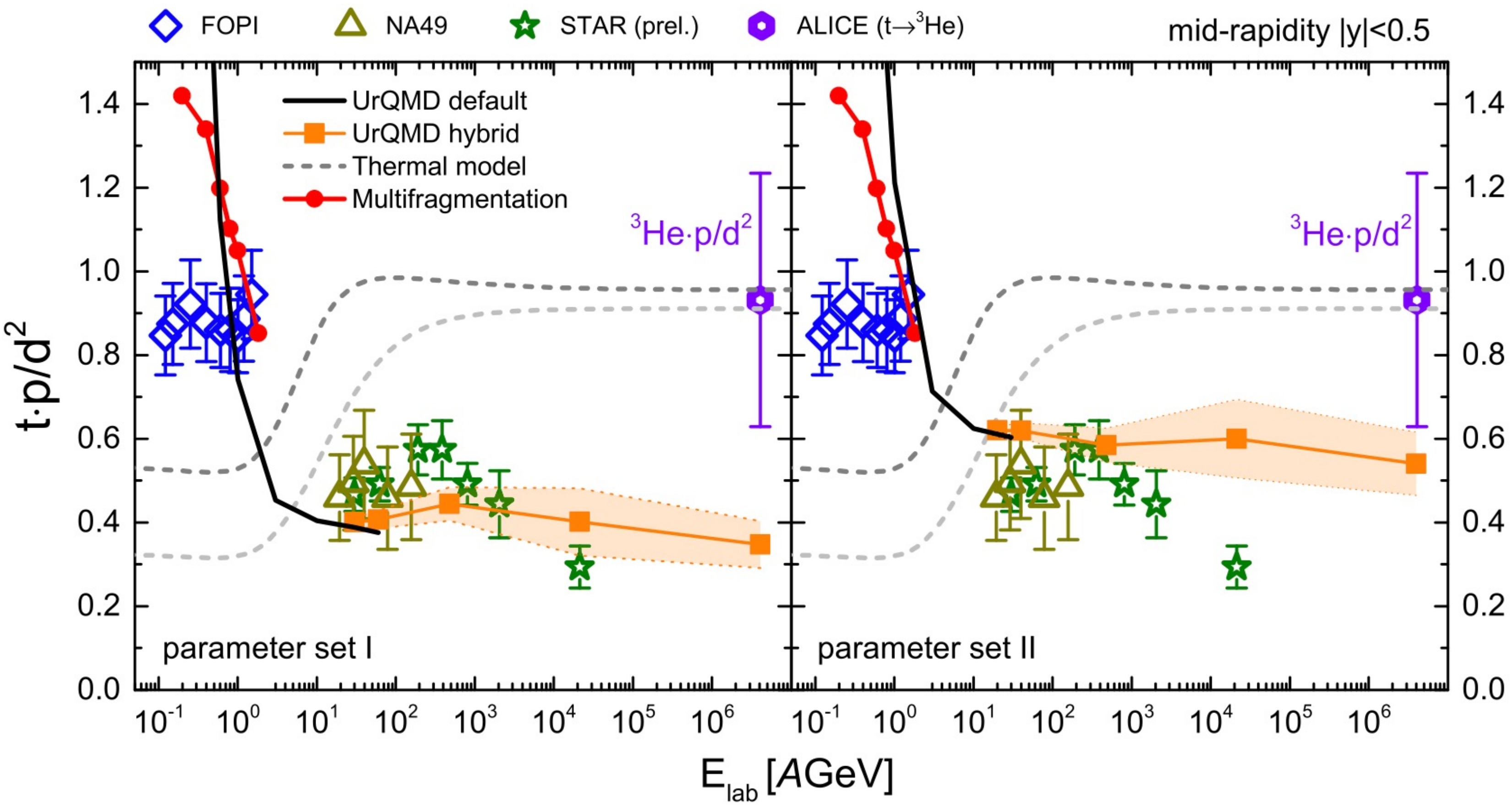




Sun et al, Phys.Lett.B 774 (2017) 103-107

g=0.29, α=p-n correlation

Canceling μ_B: $B_3/(B_2)^2$ ratios



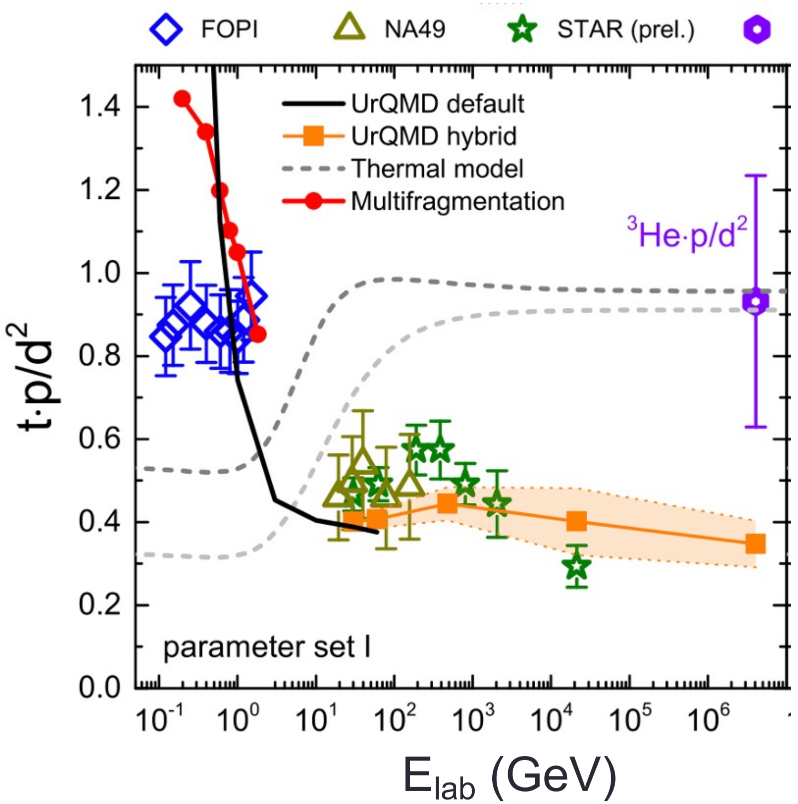
None of the models provide a full description of the data

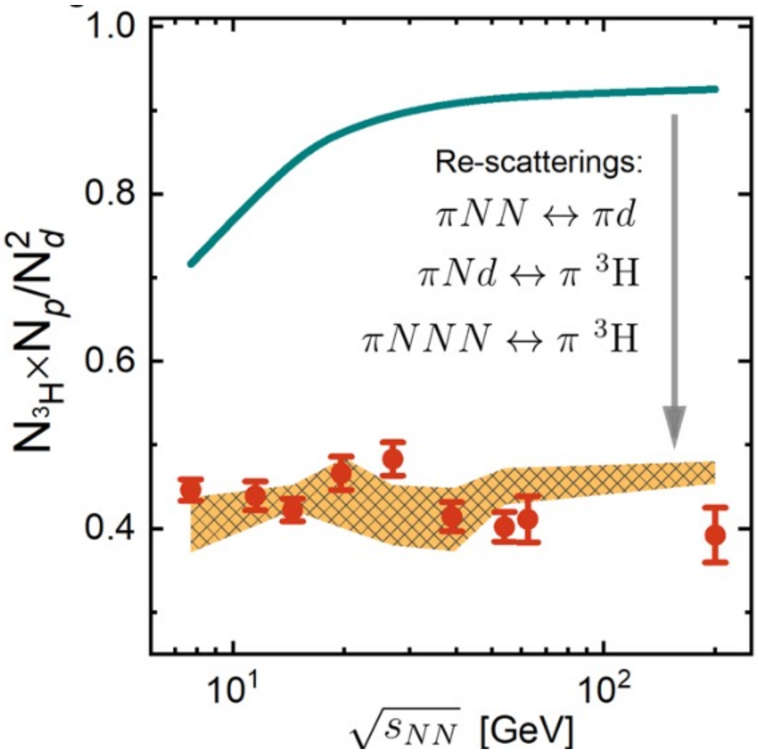
- However coalescence + multi-fragmentation seem to work below LHC energies
- Models dont see suggested density fluctuation peak!

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

Fluctuations or not?

Sun, Wang, Ko, Ma, Nature Commun. 15 (2024) 1

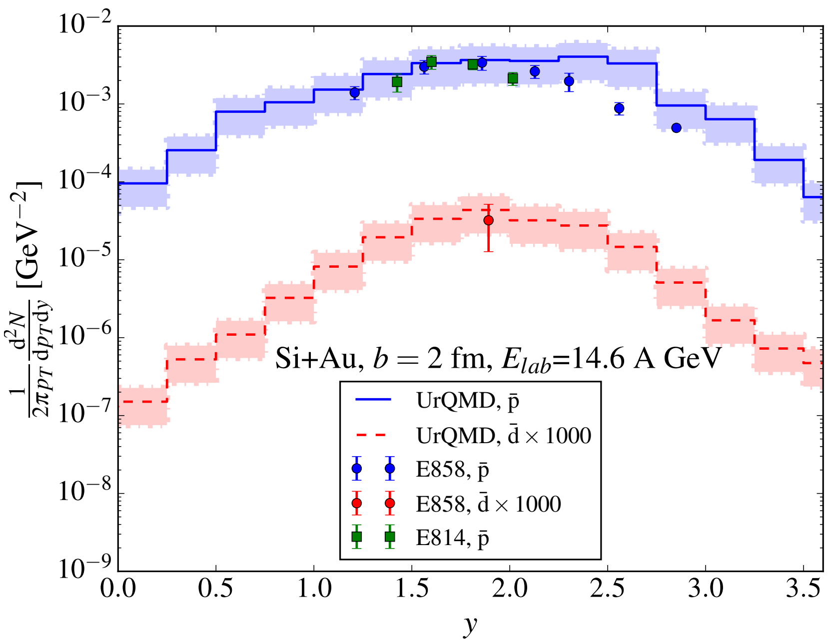




- RHIC data has changed!
- What about the LHC data?

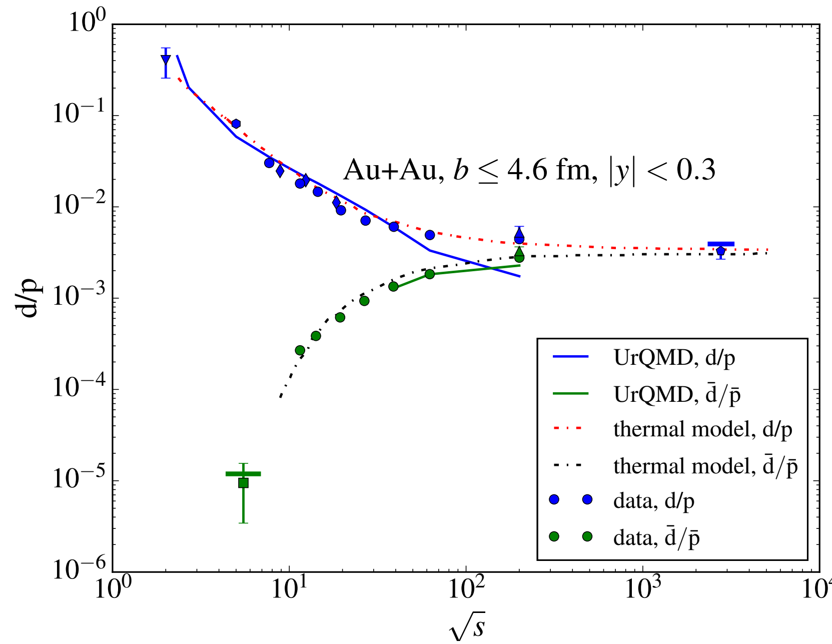
Anti-deuterons

Does coalescence also work for more exotic states at high μ_B?



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

Energy dependence of deuterons and anti-deuterons

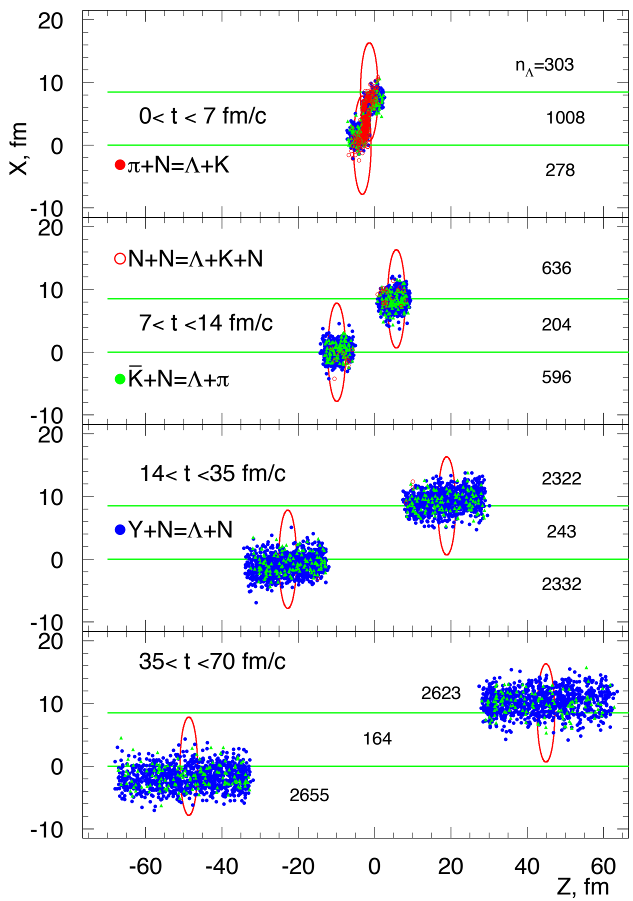


Consistent picture over the whole energy range

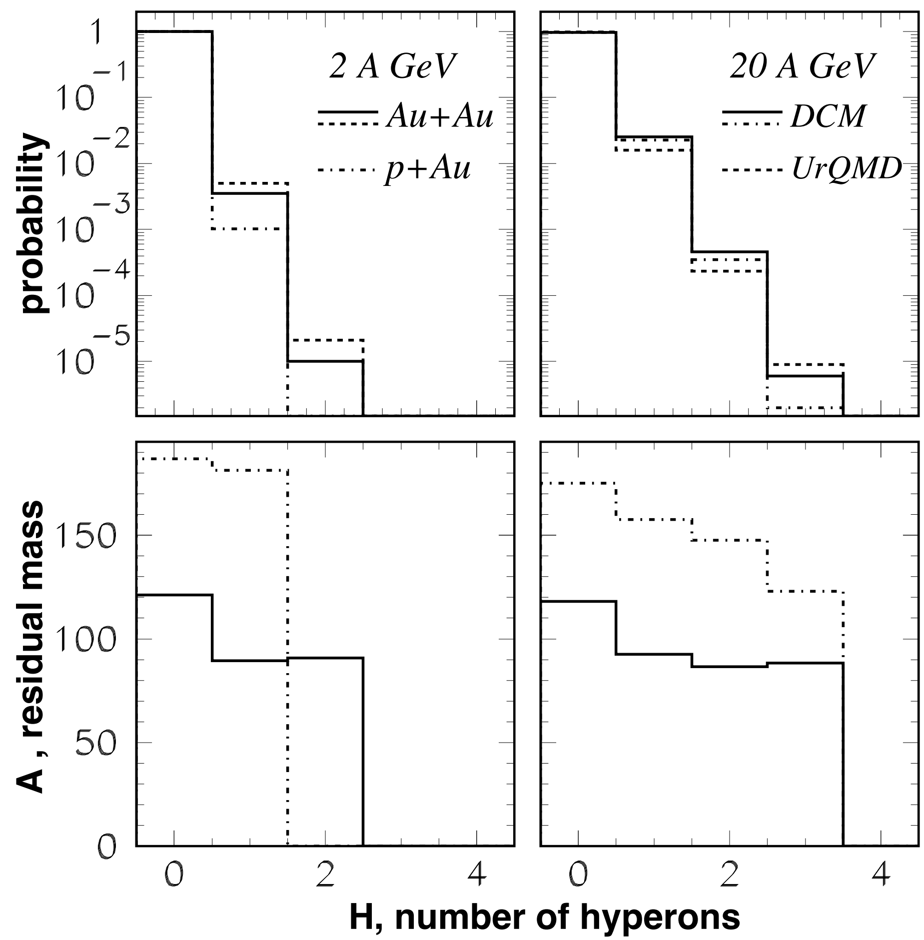
S. Sombun, M. Bleicher et al, Phys.Rev. C99 (2019) no.1, 014901

Spectator hypermatter: A new road to hypernuclei

Time evolution



Hypernuclei

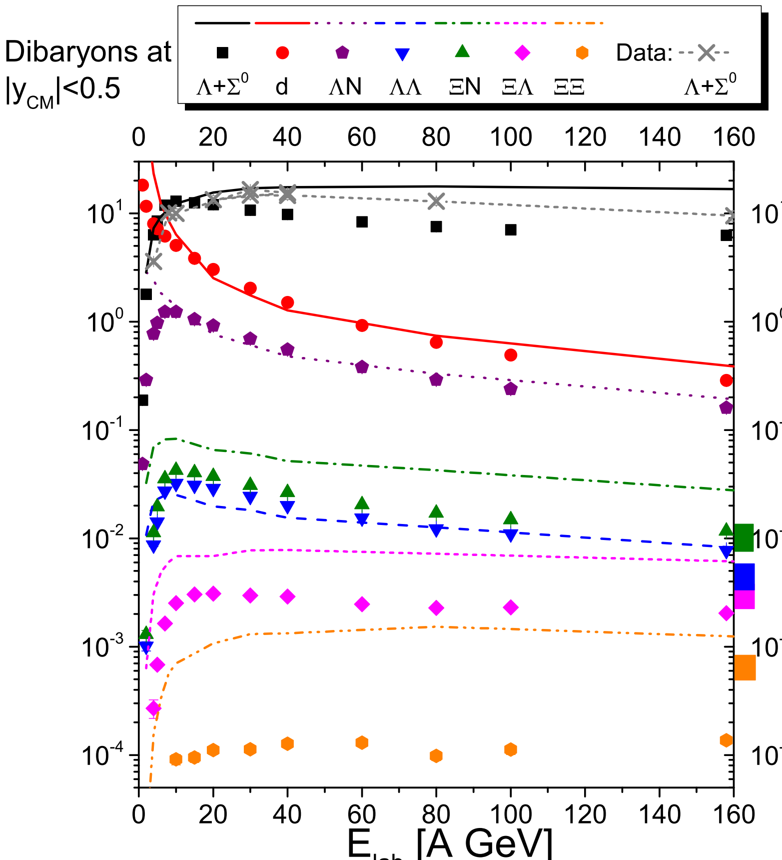


Significant amount of multi-hyper fragments

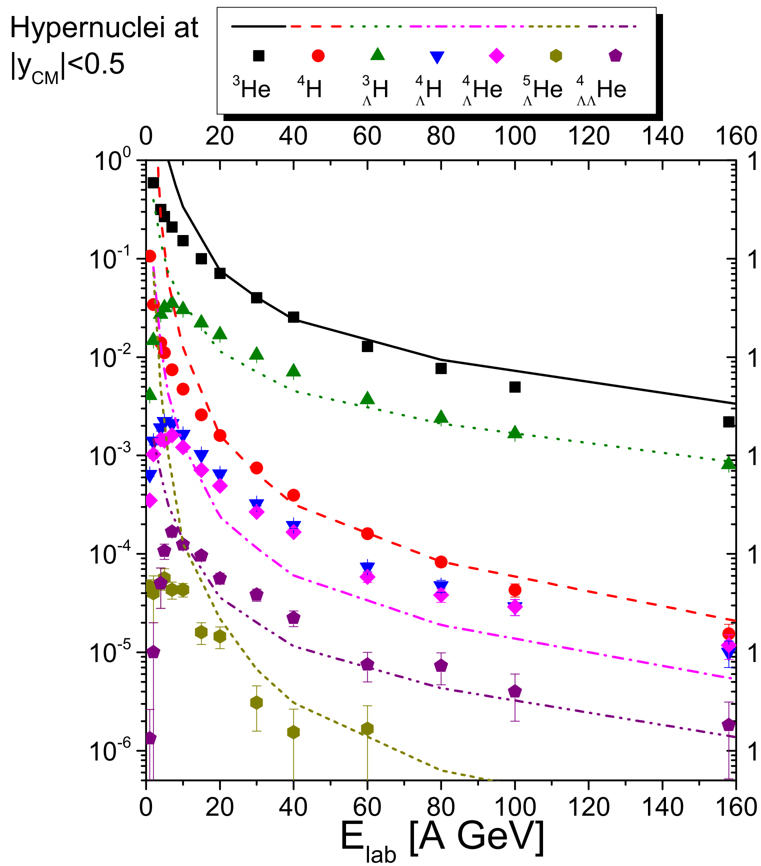
A. Botvina. M. Bleicher et al., Phys.Rev. C84 (2011) 064904

Hyper and multi-strange matter

DiBaryons



Hypernuclei

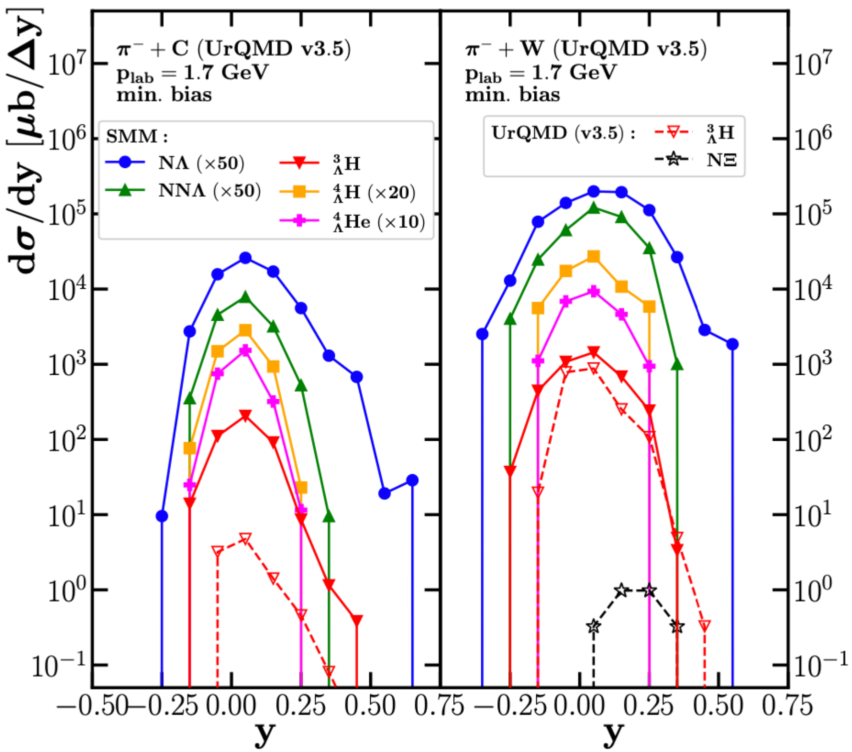


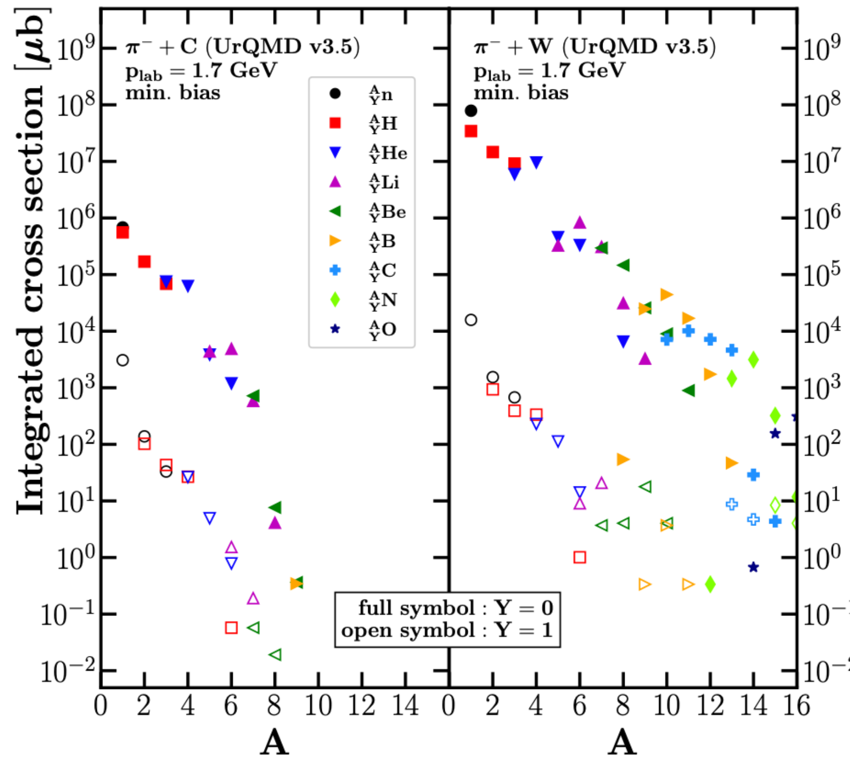
J. Steinheimer, M. Bleicher et al, Phys.Lett. B714 (2012)

Hybrid model (lines) vs. coalescence (symbols)

Interplay of baryon density with strangeness production

Pion beam experiments for hyper nuclei

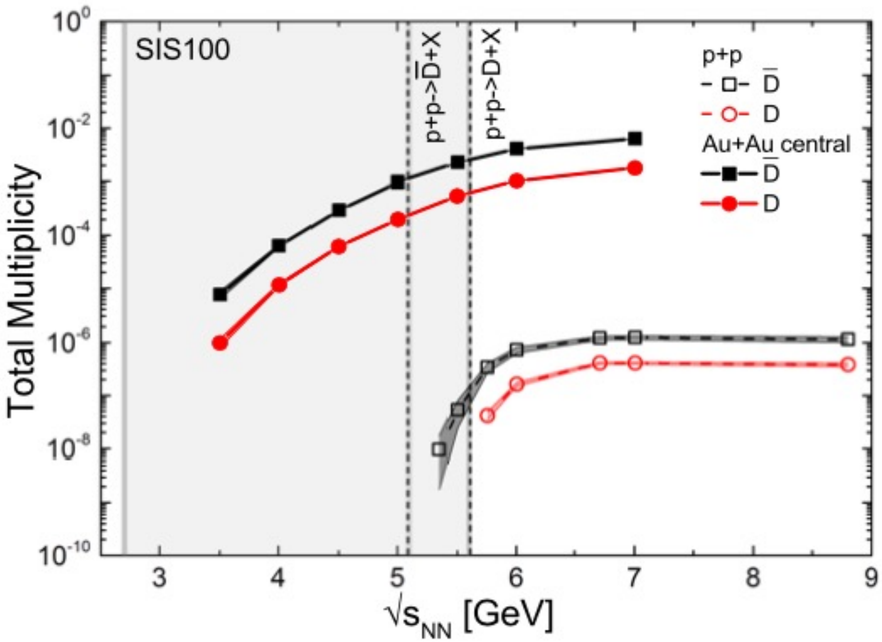




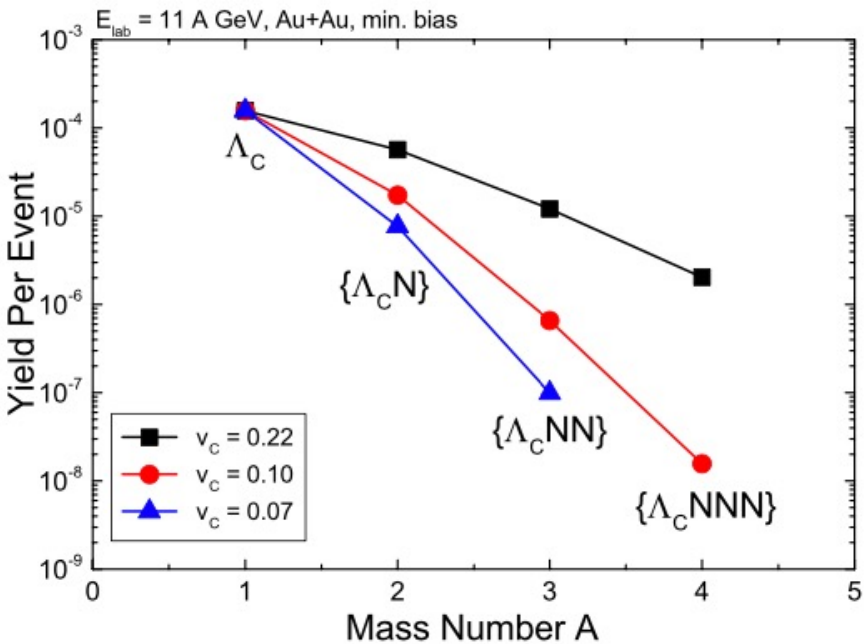
- Pion beam allow for copious poduction of (large!) hypernuclei
- With increased beam energy even multi-strange hypernuclei

Charm nuclei (subtreshold)

Charm production



Charm nuclei



Charm production and charmed nuclei are possible in the FAIR/NICA energy range

J. Steinheimer et al, PRC95 (2017) 1, 014911

Summary

- Coalescence works very well over a broad energy regime (with one fixed parameter set Δx, Δp)
- Flow scaling supports the coalescence picture
- Also anti-nuclei can be described and predicted
- Predictions for various hyper-nuclei have been made
- Even Charmed nuclei seem possible
- Predictions for hypermatter show that GSI/FAIR and NICA are ideally positioned to explore this new kind of matter.