(Hyper-)Nuclei in Heavy Ion Collisions from coalescence

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(Hyper-)Nuclei in HIC

- Different models provide a good description of nuclei production in heavy ion collisions.
- This is true over a wide range of beam energies.
- Despite the fact that nuclei are only weakly bound compared to the excitation energy of the systems created.
- Is there more to learn and use nuclei production than 'it works'?

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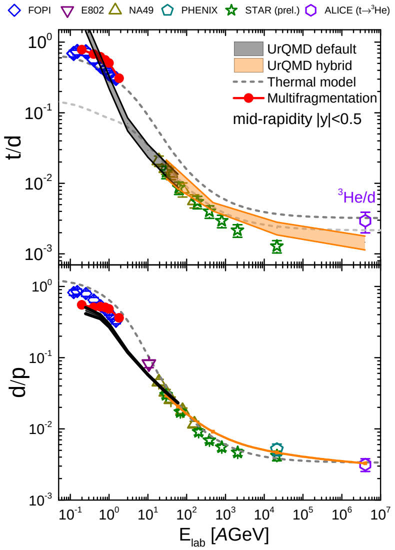
- For arguments and discussions on why it may work see talk by Elena and Susanne.



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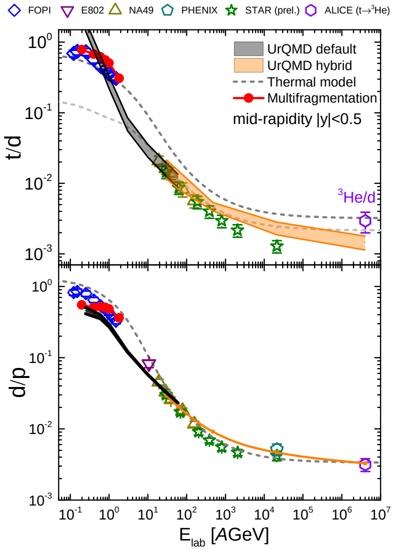
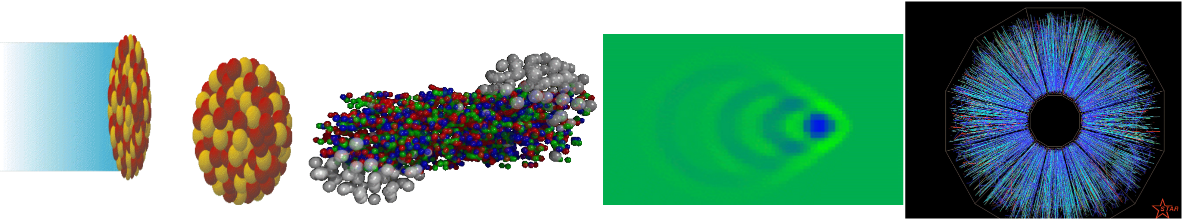
- For more ideas on why nuclei are interesting see e.g. talk by Kai Sun.



(Hyper-)Nuclei in HIC

Need realistic distributions for hadrons as input.
We use UrQMD in cascade, potential and hybrid version to generate event-wise distributions of baryons at last scattering.



Non-equilibrium initial conditions via UrQMD

Hydrodynamic evolution OR transport calculation

Freeze-out via hadronic cascade (UrQMD)

Dynamical formation

- Nuclear interactions are included properly in a microscopic model throughout the whole systems evolution. *"The mother of all Hamiltonians"* [a]
- Then one only needs to extract the expectation value of e.g. the deuteron.

[a] *V. Koch 2022*

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- One attempt in this direction → use QMD as approximation
- PHQMD: J. Aichelin, E. Bratkovskaya, A. Le Fèvre, V. Kireyeu, V. Kolesnikov, Y. Leifels, V. Voronyuk and G. Coci, Phys. Rev. C **101** (2020) no.4, 044905
- Still no full QM approach, i.e. spin- and wave-function anti-symmetrization effects missing. Mainly non-relativistic. Requires fine-tuning.

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- Still no full QM approach, i.e. spin- and wave-function anti-symmetrization effects missing. Mainly non-relativistic. Requires fine-tuning.
- Challenge: How to **estimate** potential future bound states if we cannot solve the QM problem?

[a] *V. Koch 2022*

Phase-Space Coalescence (a practical implementation)

- Take transport model of choice and calculate phase space distributions of baryons.
- A cluster AB is formed whenever the correct combination of baryons occupies a certain phase space volume defined by ρ_{AB}

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

Phase-Space Coalescence

A. Schwarzschild and C. Zupancic, Phys. Rev. **129** (1963), 854-862.

S. T. Butler and C. A. Pearson, Phys. Rev. **129** (1963), 836-842.

J. I. Kapusta, Phys. Rev. C **21** (1980), 1301-1310.

R. Bond, P. J. Johansen, S. E. Koonin and S. Garpman, Phys. Lett. B **71** (1977), 43-47.

J. L. Nagle, B. S. Kumar, D. Kusnezov, H. Sorge and R. Mattiello, Phys. Rev. C **53**, 367-376 (1996).

C. M. Ko, Z. W. Lin and Y. Oh, Nucl. Phys. A **834** (2010), 253C-256C.

A. S. Botvina, J. Steinheimer, E. Bratkovskaya, M. Bleicher and J. Pochodzalla, Phys. Lett. B **742** (2015), 7-14.

A. S. Botvina, K. K. Gudima, J. Steinheimer, M. Bleicher and J. Pochodzalla, Phys. Rev. C **95** (2017) no.1, 014902.

S. Sombun, K. Tomuang, A. Limphirat, P. Hillmann, C. Herold, J. Steinheimer, Y. Yan and M. Bleicher, Phys. Rev. C **99**, no.1, 014901 (2019).

W. Zhao, K. j. Sun, C. M. Ko and X. Luo, Phys. Lett. B **820**, 136571 (2021).

K. J. Sun and C. M. Ko, Phys. Rev. C **103** (2021) no.6, 064909.

R. Scheibl and U. W. Heinz, Phys. Rev. C **59** (1999), 1585-1602.

Phase-Space Coalescence

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Some discussion

- The density ρ_{AB} is often interpreted as wavefunction of the nucleus (only positive probability).
- In practice f_A and f_B are evaluated before nuclei could form and for **free** nucleons, just as scatterings cease.
- So strictly speaking there is no deuteron wave function.
- Problematic especially for large nuclei.
- This leaves some room for the implementation and interpretation of ρ_{AB} as probability density that a set of nucleons may form a cluster.

Phase-Space Coalescence in UrQMD

Numerical procedure: 'Box-coalescence'

1. Look in the two-particle-rest-frame of each possible two-nucleon pair with the correct isospin combination, i.e. *pn* for the deuteron. If their relative distance $\Delta r = |\vec{r}_{n_1} - \vec{r}_{n_2}| < \Delta r_{max,nn}$ and momentum distance $\Delta p = |\vec{p}_{n_1} - \vec{p}_{n_2}| < \Delta p_{max,nn}$, a two nucleon state is potentially formed with the combined momenta $\vec{p}_{nn} = \vec{p}_{n_1} + \vec{p}_{n_2}$ at position $\vec{r}_{nn} = (\vec{r}_{n_1} + \vec{r}_{n_2})/2$.

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2. As second step we boost into the local rest-frame of this two nucleon state and any other possible third nucleon and repeat this procedure.

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2. As second step we boost into the local rest-frame of this two nucleon state and any other possible third nucleon and repeat this procedure.
3. Larger clusters are checked first and a nucleus is formed with the probability given by the spin-isospin-coupling.

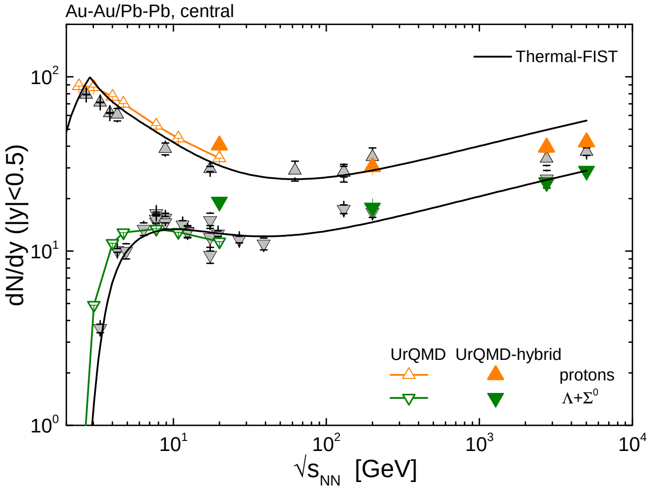
	deuteron	^3H or ^3He	^4He	$^3_\Lambda H$
spin-isospin	3/8	1/12	1/96	1/12
Δr_{max} [fm]	4.0	3.5	3.5	9.5
Δp_{max} [GeV]	0.25	0.32	0.41	0.15

Table: Probabilities and parameters used in the UrQMD phase-space coalescence.

S. Sombun, K. Tomuang, A. Limphirat, P. Hillmann, C. Herold, JS, Y. Yan and M. Bleicher, Phys. Rev. C **99** (2019) no.1, 014901

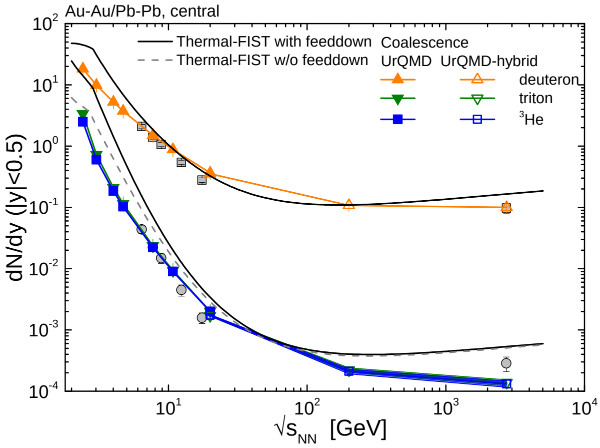
Stable hadron multiplicities

- Overall good description of baryon multiplicities over wide range of energies.
- Too much proton stopping at intermediate energies.
- Cascade model gives too much strangeness at low beam energies and to little at high energies.
- Hybrid models include GC strangeness production.



Light nuclei multiplicities

- Deuteron, triton and ^{3}He are well reproduced.
- Differences between triton and ^{3}He at low beam energies due to isospin asymmetry.
- Slightly too much stopping at intermediate energies.
- ALICE: Deuteron well described, ^{3}He seems underestimated.



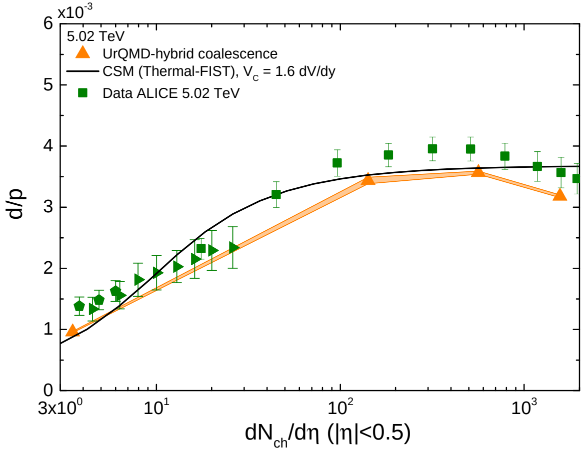
Why is coalescence useful? Two examples.

1. Centrality dependence and annihilation at the LHC

Deuteron to proton ratio

First predicted qualitatively in *S. Sombun, JS, C. Herold, A. Limphirat, Y. Yan and M. Bleicher, J. Phys. G* **45** *(2018) no.2, 025101*

- Both results within uncertainty.
- Centrality dependence well reproduced.
- Small increase due to annihilation then drop-off for smallest systems.



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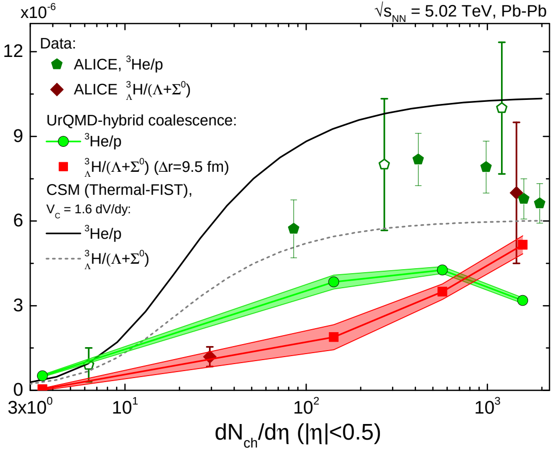

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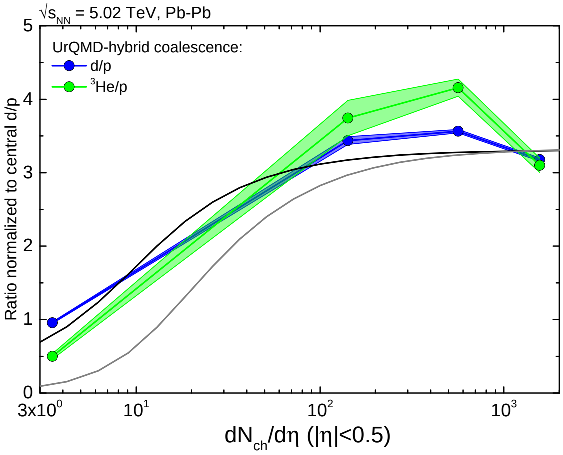
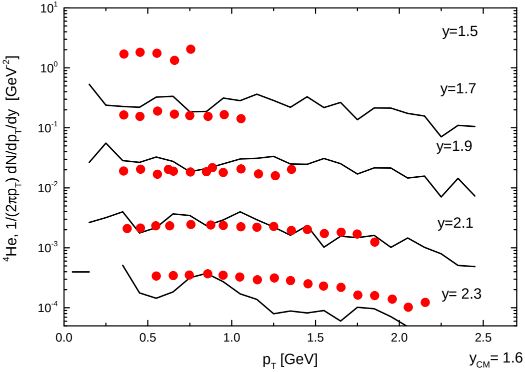
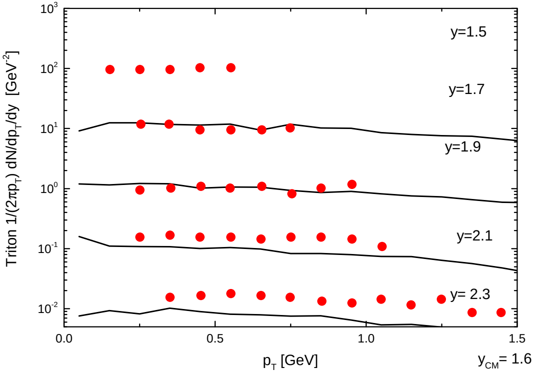


The Helium fit

- ^4He is fitted using AGS data from the E864 Experiment, Phys. Rev. C 61, 090864 (2000).
- Here $A = 3$ also looks a bit on the low side.





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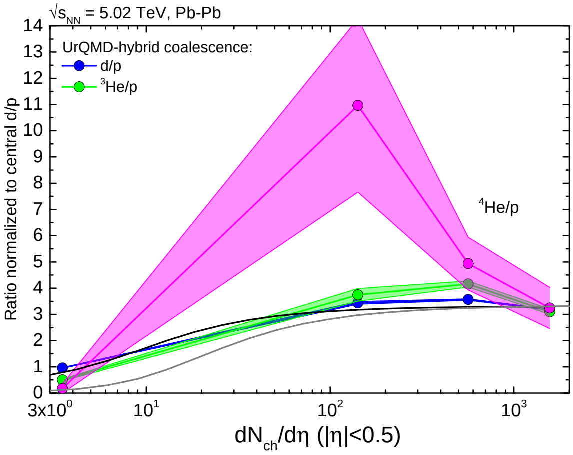
- And the canonical effect is stronger.
- Biggest effect in Helium.



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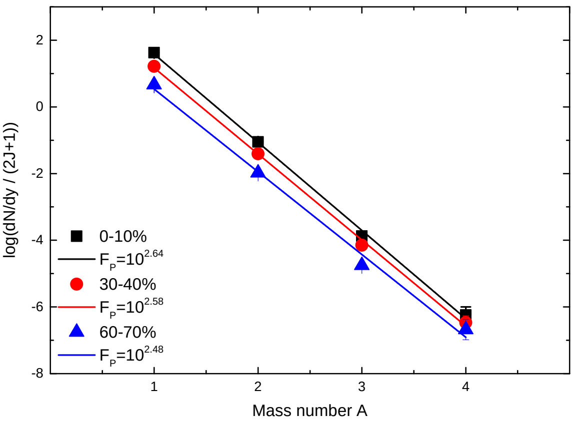
- And the canonical effect is stronger.
- Biggest effect in Helium.
- Penalty factor (or mass dependent suppression) as function of system size may give some insight on the interplay between annihilation and canonical effects.



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2. Baryon number balance at low beam energies

The baryon dN/dy at SIS18/BES energies

- At lower beam energies the light nuclei constitute a significant fraction of the total baryons, even in most central collisions.
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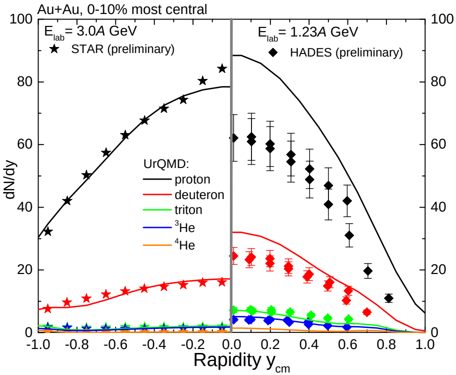
- Both, STAR and HADES experiments have preliminary data on proton and light nuclei.
- Running UrQMD with a realistic EoS (and re-adjusting the coalescence parameters to the STAR date)
- Results for 0-10% most central events differ drastically!



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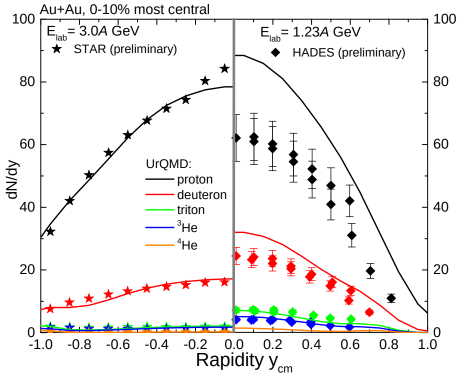
- Running UrQMD with a realistic EoS (and re-adjusting the coalescence parameters to the STAR date)
- Results for 0-10% most central events differ drastically!
- Instead of talking about proton fluctuations or any pion-puzzle, first understand the protons. Is it some problem in the model or Experiment?



Conclusion

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- 1. Nuclei yields can be used to study the effect of annihilation and regeneration as function of centrality at the LHC.
- 2. Nuclei can and should be used to check the baryon balance at SIS/BES energies.

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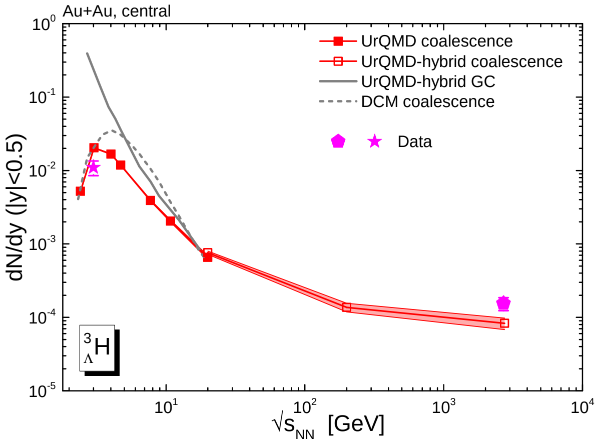
- 2. Nuclei can and should be used to check the baryon balance at SIS/BES energies.
- There are some more and interesting ratios for which there was no time.

Moving on to hypernuclei

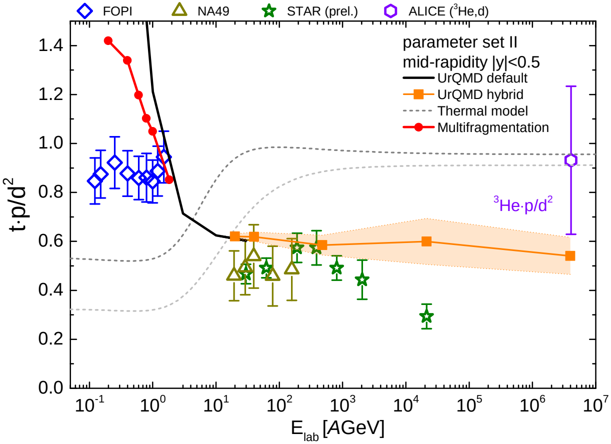
- Data on hypertriton multiplicities is scarce.
- We fixed the parameters mainly from previous calculations.
  J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher and H. Stöcker, Phys. Lett. B **714** (2012), 85-91
- Strangeness at very low energies is overestimated (potential effects)
- Strangeness at intermediate energies is underestimated (the horn)
- Similar to the ^{3}He, $^3_\Lambda$H seems underestimated compared to ALICE data.



T. Reichert, JS, V. Vovchenko, B. Dönigus and M. Bleicher, Phys. Rev. C **107** (2023) no.1, 014912

A special nuclei ratio

- Double ratio shows more sensitivity than log plot.
- Proposed as measure for fluctuations
  K. J. Sun, L. W. Chen, C. M. Ko, J. Pu and Z. Xu, Phys. Lett. B **781** (2018), 499-504
- Double ratio is flat, except increase at low energies.
- This is due to the finite baryon number, i.e. more tritons lead ot less deuterons.
- Fragmentation picture more reasonable here.

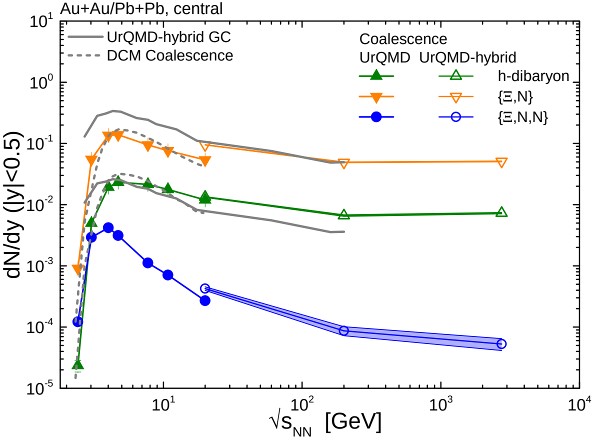


P. Hillmann, K. Käfer, J. Steinheimer, V. Vovchenko and M. Bleicher, arXiv:2109.05972 [hep-ph]. (Accepted in JPG)

Multiplicities for multistrange objects

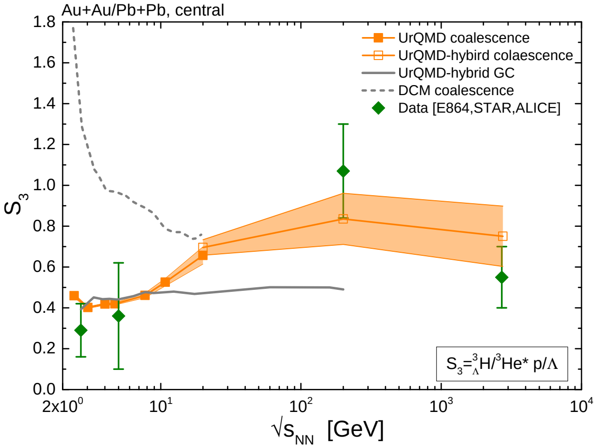
- Using the same parameters as for hypertriton we can predict multihypernuclear objects.
- Most are unlikely to be bound?
- Note: shown is sum over all possible isospin combinations.
- Results consistent with previous estimates.

J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher and H. Stöcker, Phys. Lett. B **714** (2012), 85-91



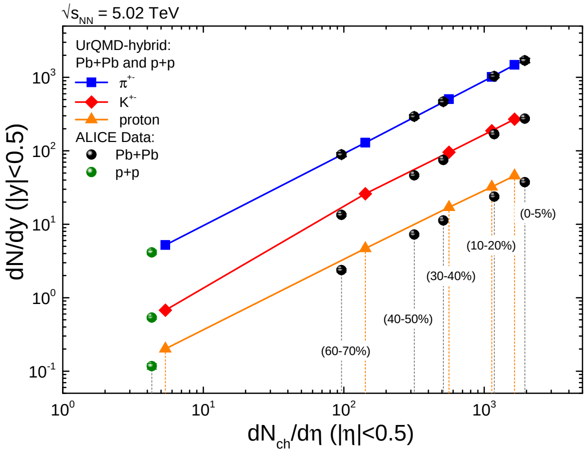
Another special ratio

- Another special ratio which was thought to be sensitive on baryon-strangeness correlations: S_3
- Here, old calculations showed divergent behavior.
- DCM-Coalescence due to drop of ^{3}He number!?
- GC production is constant
- New results shows small increase at higher beam energies.
- Unfortunately error bars are large and only few data are available.



Let's switch to centrality dependence

- With centrality we can study the system size dependence as well as canonical effects with the same detector and similar chemical composition.
- For top LHC energy: UrQMD uses old Pythia for p+p and A+A initial state: too much stopping.
- Slight excess of protons over all centrality's despite annihilation effect.
- Different from 2.7 TeV results where protons essentially match the data.



^{3}He vs. Hypertriton ratios

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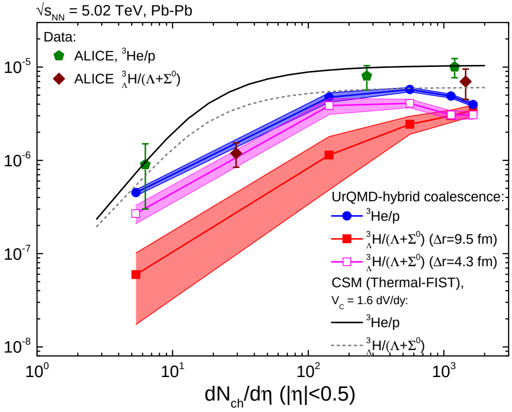

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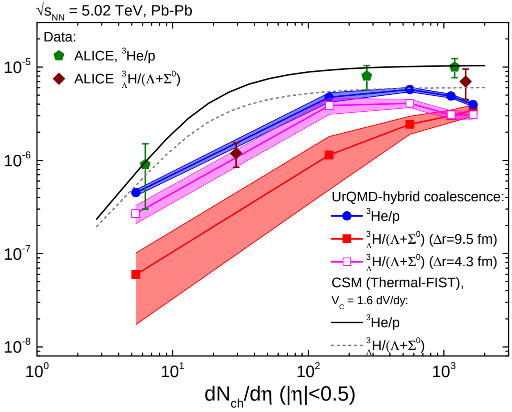

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- The centrality behavior was explained by the relation of source size and system size:
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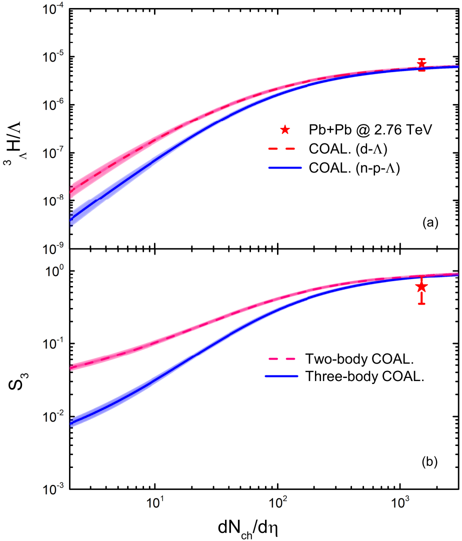

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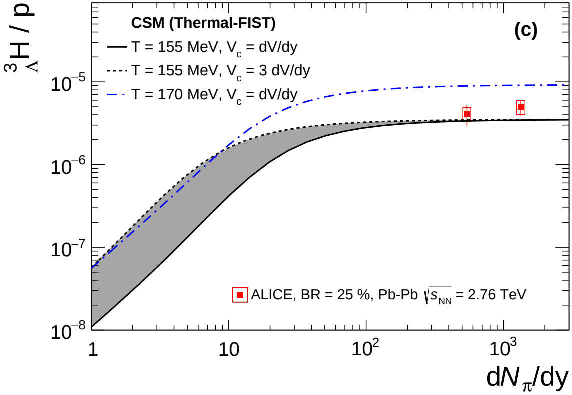
- Also local conservation effects play a role:
  V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B **785** (2018), 171-174



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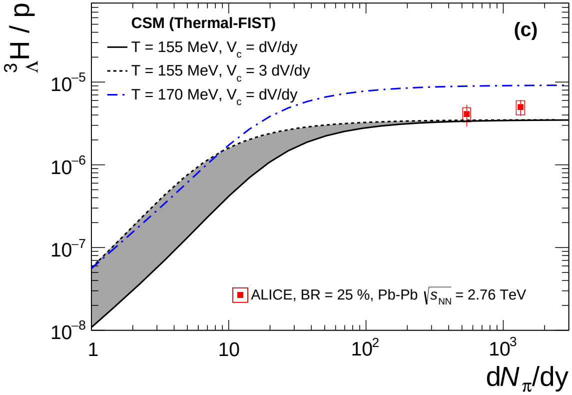
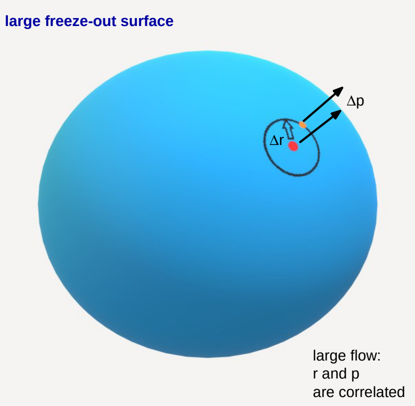
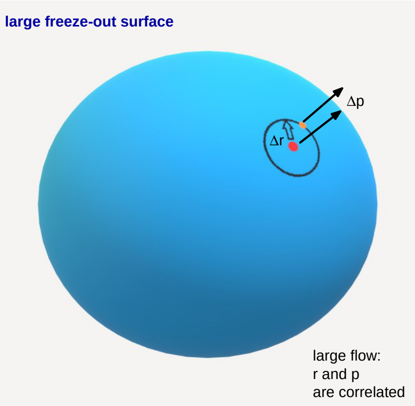
- Our approach: Both are taken into account.

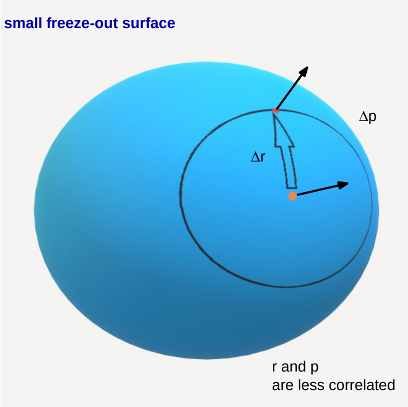


How to understand the source volume



How to understand the source volume

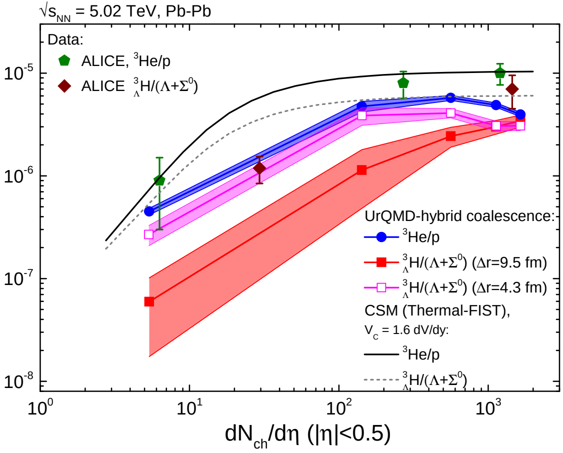




Changing the source size for the hypertriton

- We can change the source size Δr for the ${}^{3}_{\Lambda}$H to be the same as for ^{3}He.
- Adjusting Δp to get a similar value for central collisions.
- Centrality dependence is changed as expected.

Parameters	^{3}He	${}^{3}_{\Lambda}$H	${}^{3}_{\Lambda}$H
Δr_{max} [fm]	4.3	9.5	4.3
Δp_{max} [GeV]	0.35	0.135	0.25



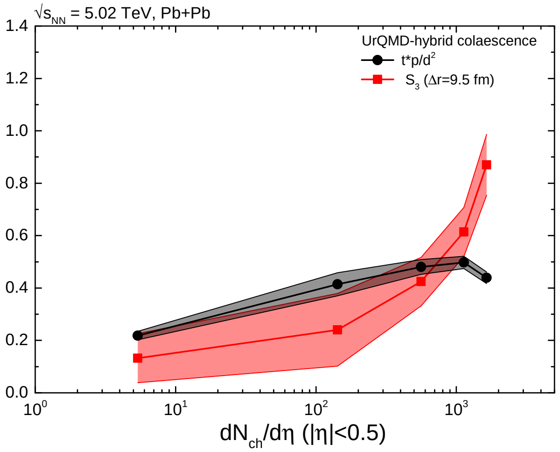
How to understand the source volume

The interpretation as wave function size

- While a large spatial distance at freeze out leads to a de-correlation of momenta for small systems and thus a suppression.
- The interpretation of this as being uniquely connected to the (hyper-)nucleus wave-function is questionable.
- Remember: The large hyernucleus may NOT be considered an isolated quantum state AT the last scattering, only at some time later.
- Weaker interpretation: The coalescence criterion only gives a probability that a set of baryons can form a proper final state nucleus at a later time.
- This the source volume then $\neq$ the size of the wave function.
- Thus, this comparison does not serve to determine the above nor does it help to discern coalescence from the SHM.
- I would argue that it even does not make sense to try and discriminate the two since they are different approaches to describe the same thing. Neither attempts at explaining the production.

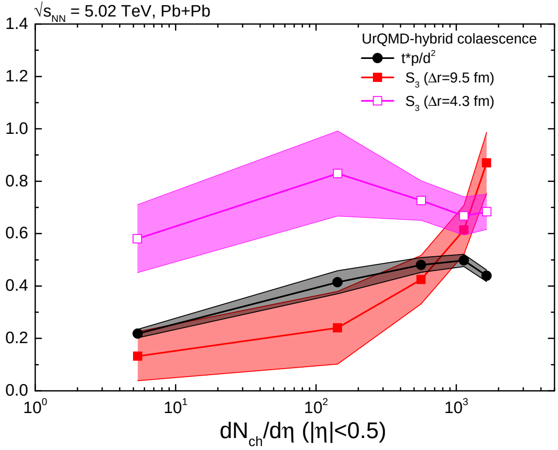
The double ratios for different system sizes

- Similar behavior is observed for the double ratios.



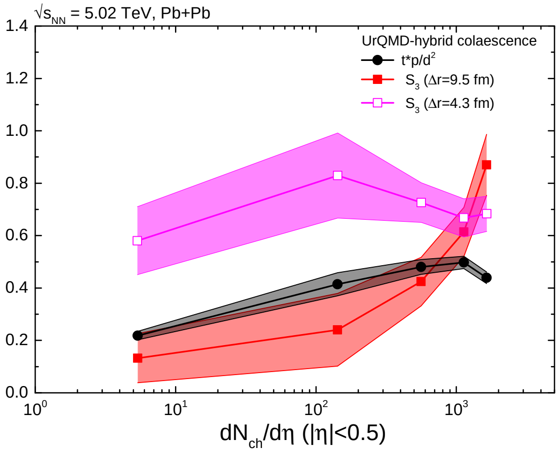
The double ratios for different system sizes

- Similar behavior is observed for the double ratios.
- Different source size gives different behavior.



The double ratios for different system sizes

- Similar behavior is observed for the double ratios.
- Different source size gives different behavior.
- Note that in p+p also canonical effects are naturally included.



- The double ratio $t \cdot p/(d^2)$ is thought to be sensitive to spatial baryon fluctuations at freeze-out.
  K. J. Sun, L. W. Chen, C. M. Ko, J. Pu and Z. Xu, Phys. Lett. B **781** (2018), 499-504
- Can be studies by coalescence in UrQMD.
  P. Hillmann, K. Käfer, JS, V. Vovchenko and M. Bleicher,' J. Phys. G **49**, no.5, 055107 (2022)
- We see a very small enhancement in the scenario with a phase transition.
- Important to use realistic EoS with proper hadronic/nuclear matter.