Light (hyper-)nuclei at the SIS100 using UrQMD

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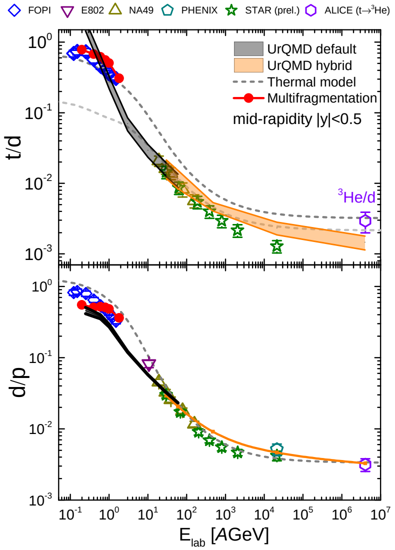
(Hyper-)Nuclei in HIC

- 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'?



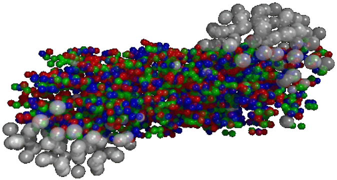
When we want to understand the dynamics of heavy ion collisions in the few GeV energy range we need to take into account the high density equation of state and baryon-baryon interactions.

Important for understanding baryon fluctations and baryon flow.

Leaves an imprint on the formation of nuclei in the final state!

(Hyper-)Nuclei in HIC

- Theoretical predictions need realistic distributions for hadrons as input.
- We use UrQMD in potential version to generate event-wise distributions of baryons at last scattering.
- Note that this means we assume mostly free baryons as input for the coalescence!
- Using UrQMD in potential mode introduces additional correlations at FO which means that the coalescence parameters change w.r.t. the cascade version!



Dynamical formation in PHQMD

- Recent results with dynamic cluster formation in PHQMD show exactly this EoS dependence of production.
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- "Opposite" to our approach where we refit the parameters. Interpretation of the coalescence parameters.
- Disclaimer: Even though QMD potentials provide some degree of bound clusters, solving the full QM problem is much more difficult.

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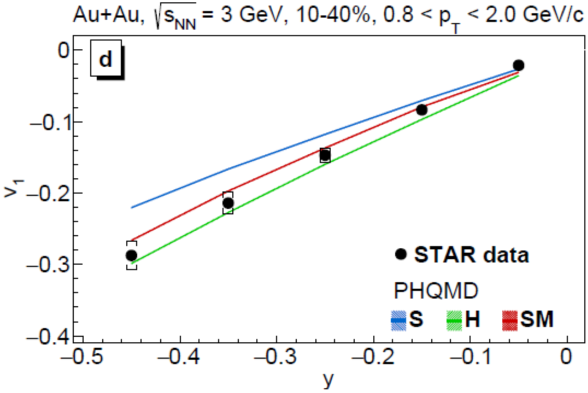
- Disclaimer: Even though QMD potentials provide some degree of bound clusters, solving the full QM problem is much more difficult.
- Besides the yields, also the flow of nuclei is very sensitive on the EoS.
- Extra cross check with data.



Phase-Space Coalescence (a practical implementation)

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

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

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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 $\vec{r}_{nn} = (\vec{r}_{n_1} + \vec{r}_{n_2})/2$.

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

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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	$^3_\Lambda H$	$^4_\Lambda H$
spin-isospin	3/8	1/12	1/96	1/12	1/96
Δr_{max} [fm]	4.0	3.5	3.5	9.5	9.5
Δp_{max} [GeV]	0.33	0.45	0.55	0.15	0.25

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

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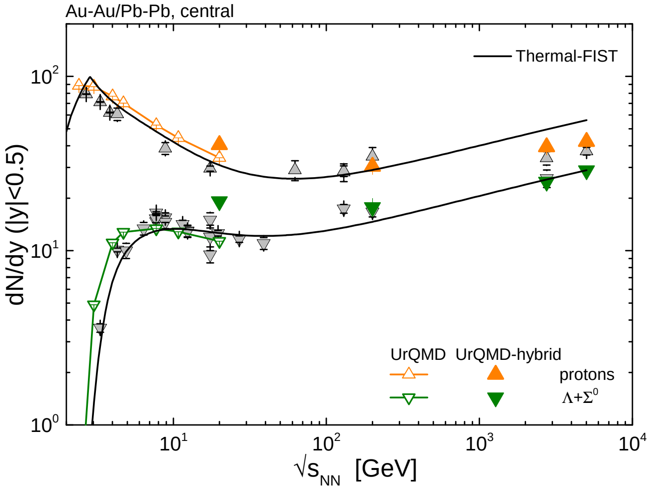
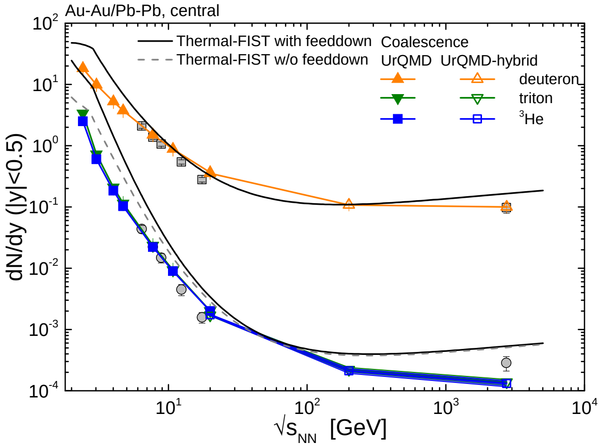
Stable hadron multiplicities

- 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. Fitting the parameters here leads to problems!
- ALICE: Deuteron well described, ^{3}He seems underestimated.



For high densities achieved at the SIS100 we need to take into account the high density EoS via potential interactions.

The EoS in UrQMD

To implement any density dependent EoS in UrQMD:
In UrQMD the real part of the interaction is implemented by a density dependent potential energy $V(n_B)$.
Once the potential energy is known, the change of momentum of each baryon is calculated as:

$$\dot{\mathbf{p}}_i = -\frac{\partial \langle H \rangle}{\partial \mathbf{r}_i} = -\left(\frac{\partial V_i}{\partial n_i} \cdot \frac{\partial n_i}{\partial \mathbf{r}_i}\right) - \left(\sum_{j \neq i} \frac{\partial V_j}{\partial n_j} \cdot \frac{\partial n_j}{\partial \mathbf{r}_i}\right) , \qquad (1)$$

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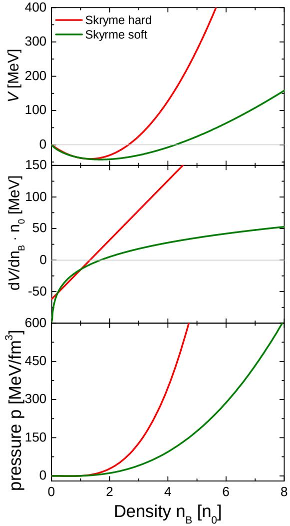
For the potential energy V often a Skyrme model was used that is based on a 2-term expansion in density:

$$U(n_B) = \alpha \cdot n_B + \beta \cdot n_B^{\gamma} \quad \text{with} \quad U(n_B) = \frac{\partial (n_B \cdot V(n_B))}{\partial n_B} \qquad (2)$$

Problem: Once saturation density and binding energy is fixed, only 1 d.o.f. left and EoS likely becomes unphysical. No phase transition possible.



CMF in UrQMD

- Use an effective model for QCD thermodynamics (with parameters) instead.
- CMF (Chiral Mean Field model) developed in Frankfurt. Some call it the Swiss knife (or 'Moving Castle') of effective models.
- Best case: may learn something about interactions and QCD and chiral symmetry
- Worst case: get a smart parametrization of the EoS. Easy to implement.

The strategy

- Fix the CMF parameters (scalar and vector interactions, bare mass,...) using neutron star observables.
- Simulate heavy ion reactions and compare to data. Works very well with HADES flow data.

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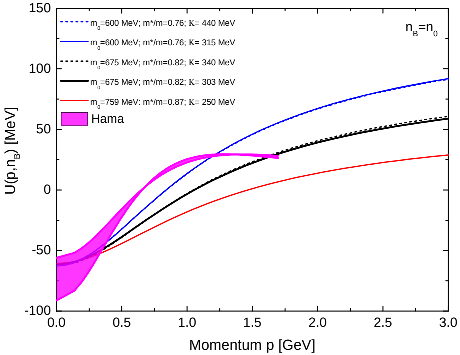

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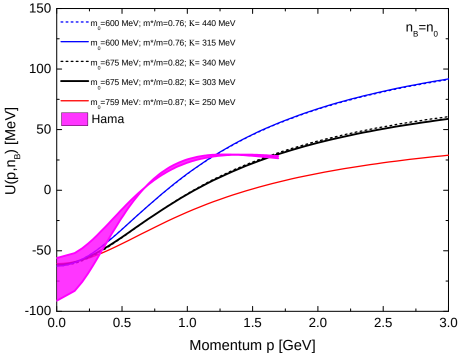

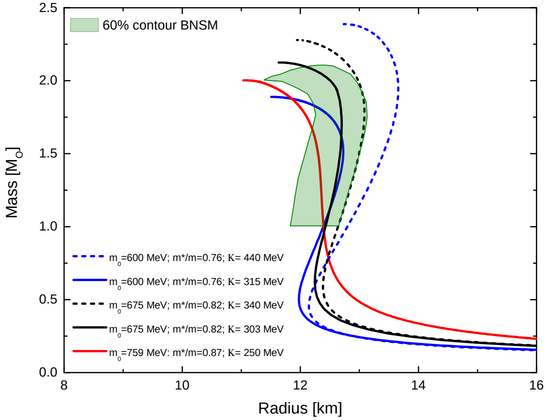

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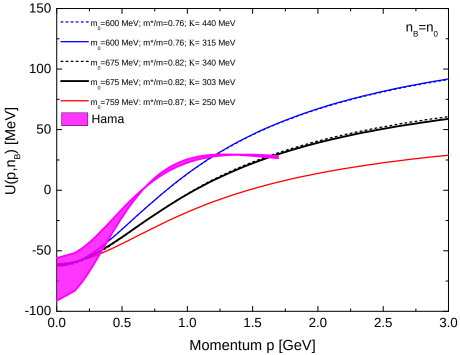

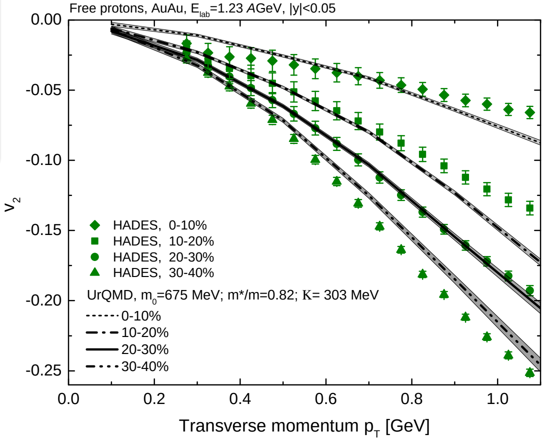

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Comparison with STAR data

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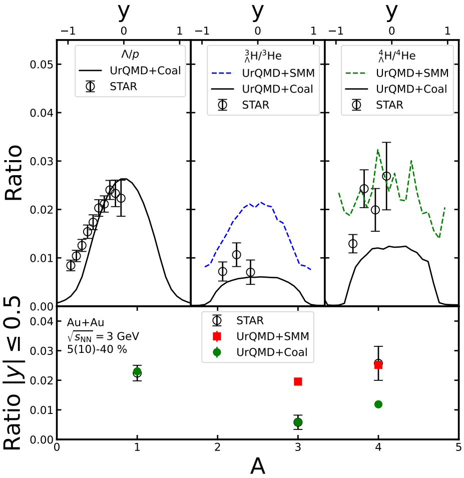

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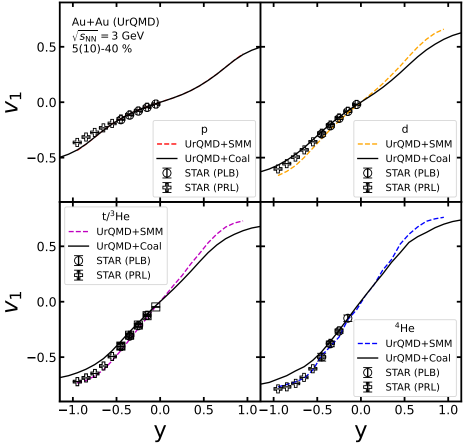

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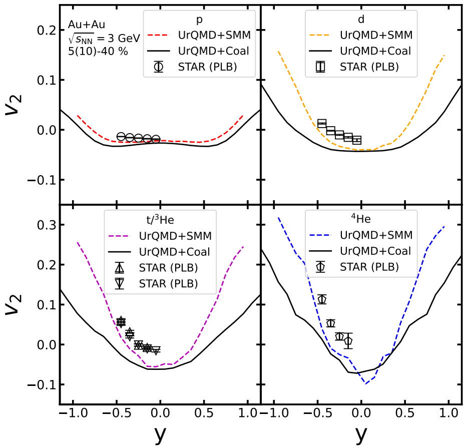

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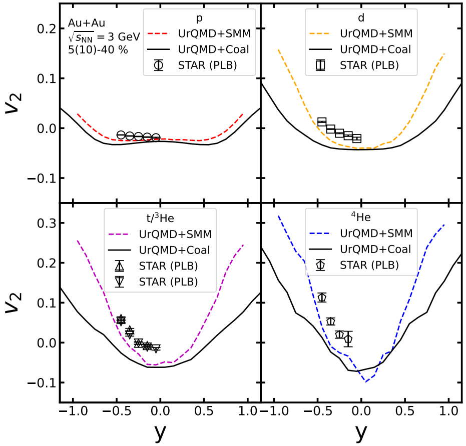

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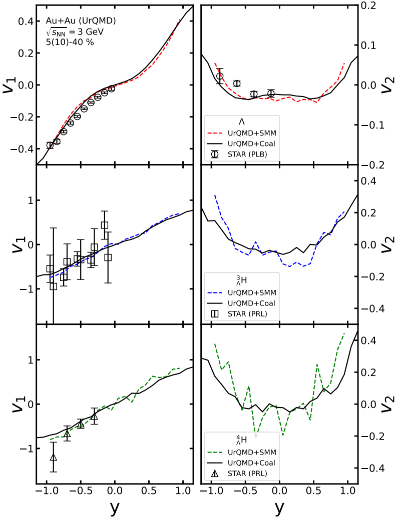
- Less a problem for hypernuclei which are well described.



Flow mass number scaling

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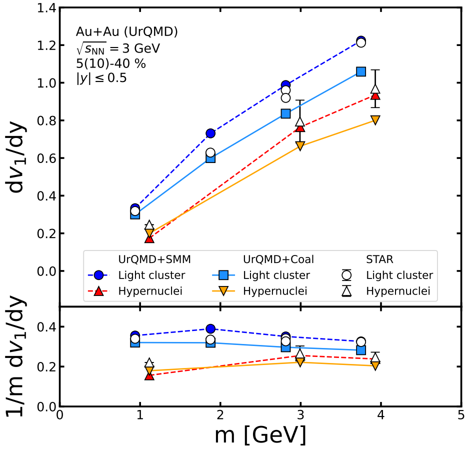

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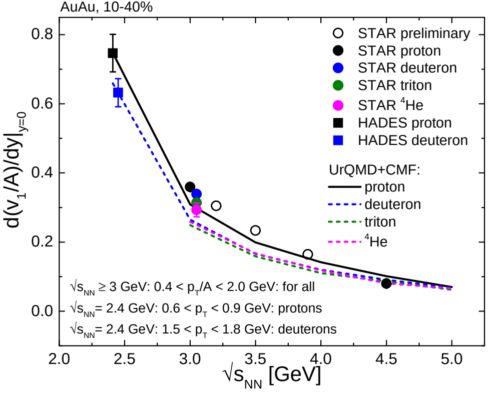

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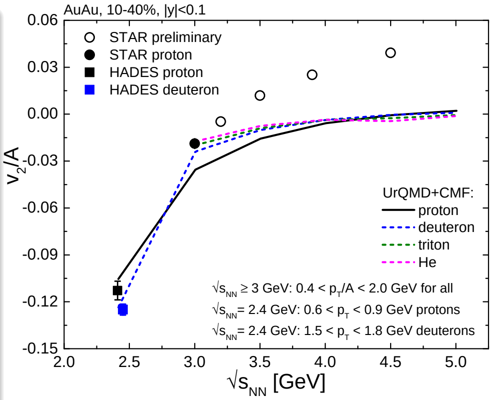

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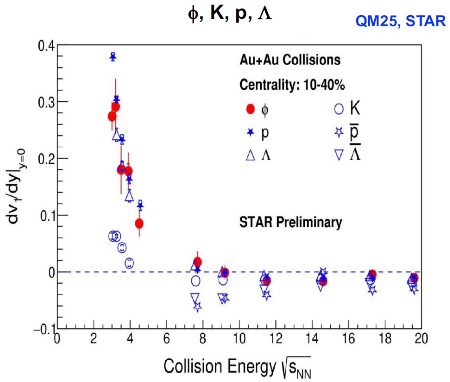

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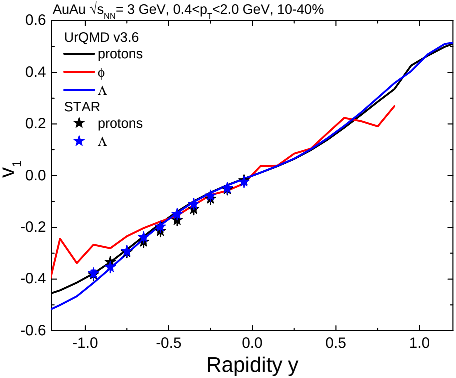

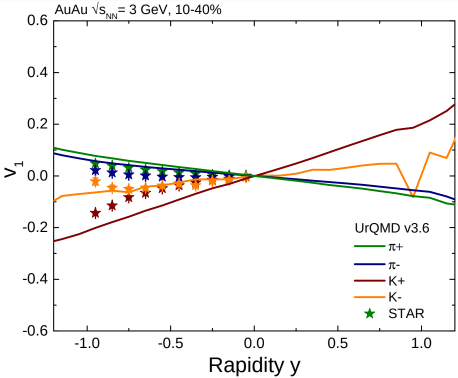

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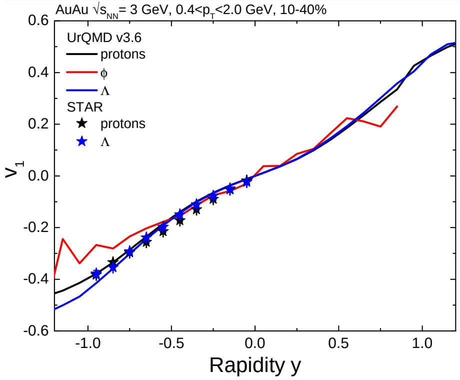

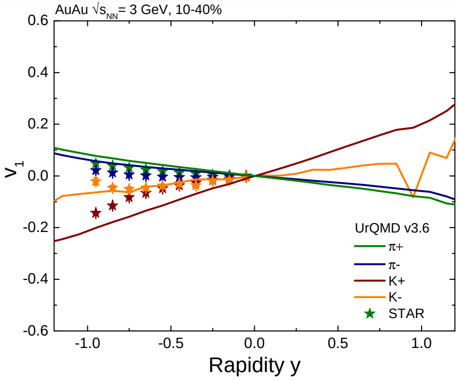

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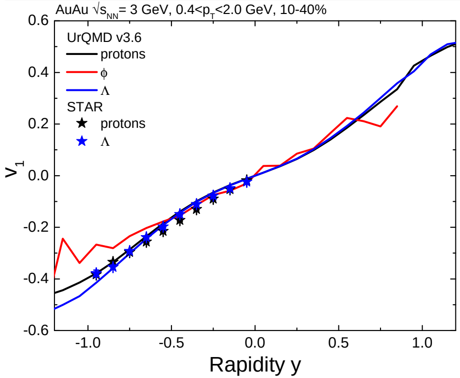
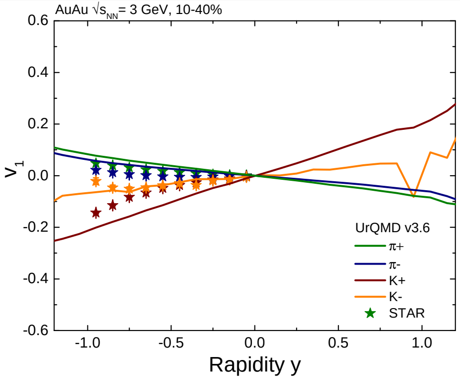
- Cross section for ϕ is small, K$+$ a bit larger, K- even larger and pions largest....!?





Signals of a phase transition

Can nuclei be used as messengers of clumping due to a phase transition?

Light nuclei and fluctuations

- The double ratio $t \cdot p/(d^2)$ is thought to be sensitive to spatial baryon fluctuations at freeze-out.
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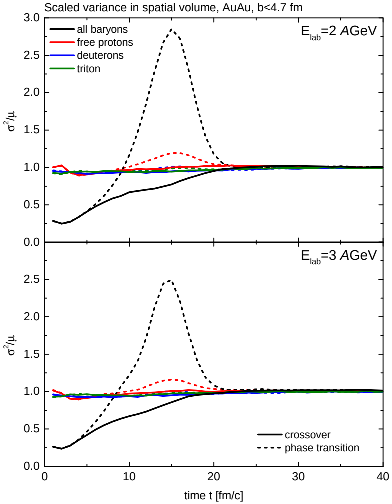

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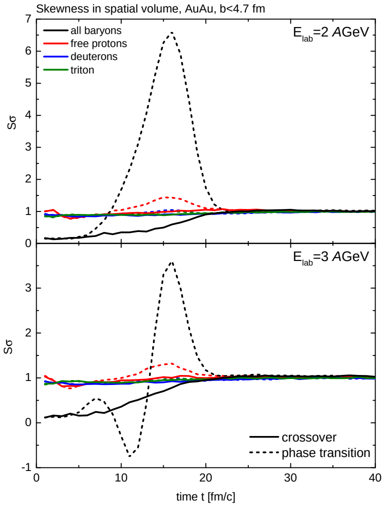

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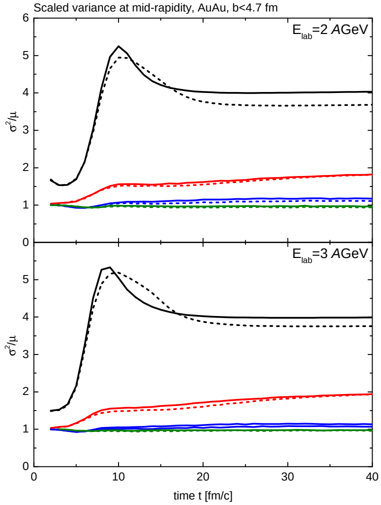

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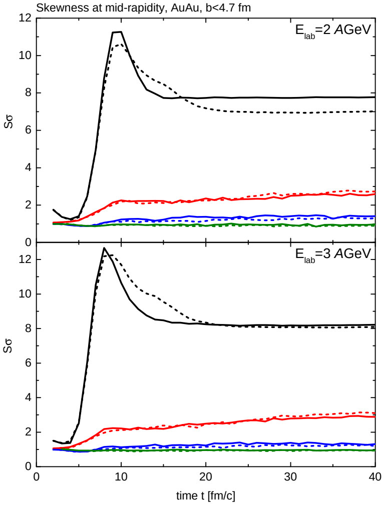
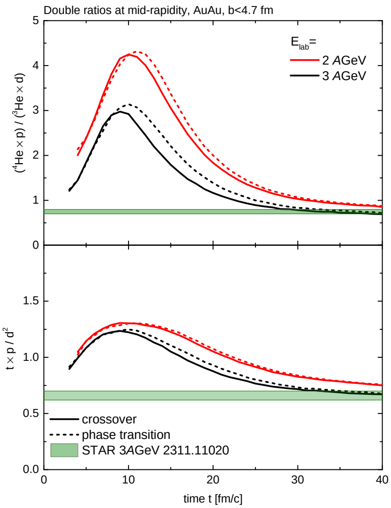


Light nuclei and fluctuations

- 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 studied by coalescence in UrQMD as function of time in a scenario where we have density clumping (or isomers).
- We introduce a strong phase transition in the density dependent potential to mimic the clumping.
- Scaled variance and skewness of baryon number in coordinate space show clear signal.
- Almost no effect in momentum space.
- Small enhancement in time dependence of light nuclei when fluctuations are strong. (finite size effects and finite range properly taken into account)
- We see only a very small final enhancement in the scenario with a phase transition.

T. Bumnedpan, J. Steinheimer, T. Reichert, C. Herold, A. Limphirat and M. Bleicher, Phys. Rev. C **111** (2025) no.3, 034910



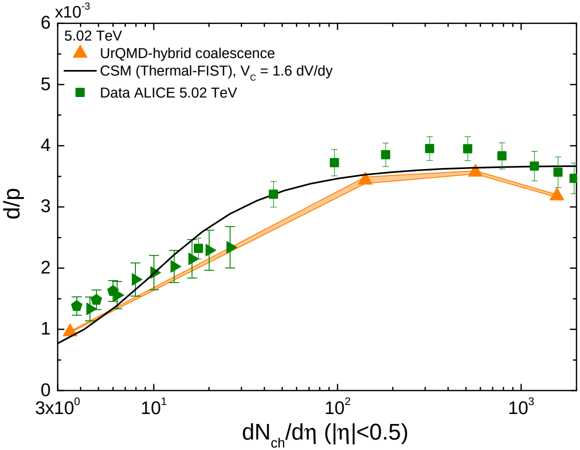
Summary

- Coalescence can be used to successfully describe the production of light nuclei and hypernuclei in various systems.
- The parameters need to be fixed at some reference system.
- Comparing UrQMD simulations with or without potentials changes the correlations at freeze out and thus necessitates a change of parameters $\rightarrow$ an exact relation to the wave function should not be assumed.
- The mass-number scaling of flow breaks down at lower beam energies due to the more complex rapidity dependence. Contributions from spectators are more relevant.
- dv_1/dy - scaling works better than v_2 scaling as it is evaluated at mid-y.
- Flow of different hadrons allows to disentangle their interactions.
- Light nuclei are sensitive to the density fluctuations during a phase transition but final observables are not.
- Things NOT covered: System size dependence of (hyper-) nuclei production and Exotica (charmed nuclei).

Deuteron to proton ratio

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

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



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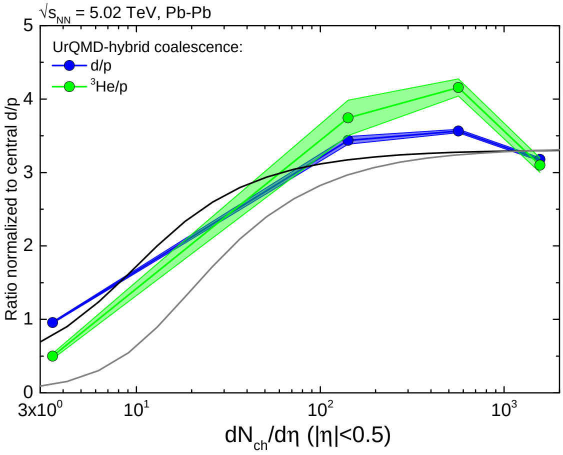

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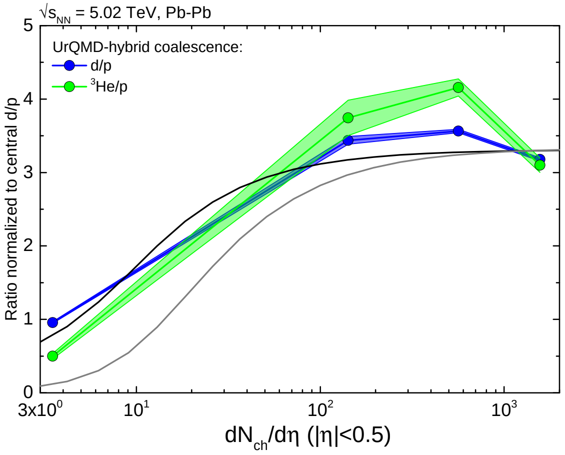
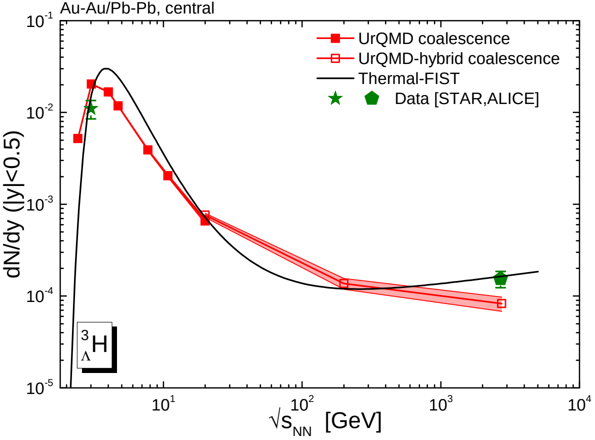


Moving on to hypernuclei

- Data on hypertriton multiplicities is scarce.
- We fixed the parameters, in cascade UrQMD, 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.

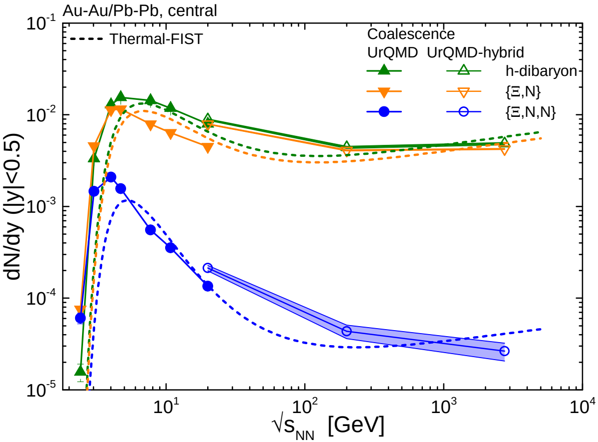


T. Reichert, JS, V. Vovchenko, B. Dönigus and M. Bleicher, Phys. Rev. C **107** (2023) no.1, 014912

Multiplicities for multistrange objects

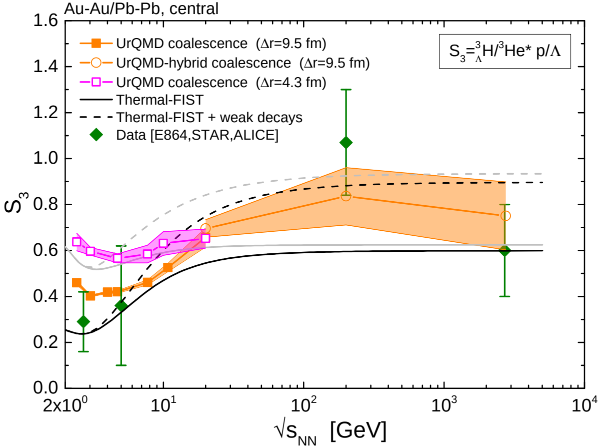
- Using the same parameters as for hypertriton we can predict multihypernuclear objects.
- Most are unlikely to be bound?
- Note: shown is sum over all possible isospin combinations.
- Results consistent with previous estimates.

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



A special ratio

- A special ratio which was thought to be sensitive on baryon-strangeness correlations: S_3
- Here, the thermal model shows similar behavior.
- Small increase at higher beam energies.
- Unfortunately error bars are large and only few data are available.



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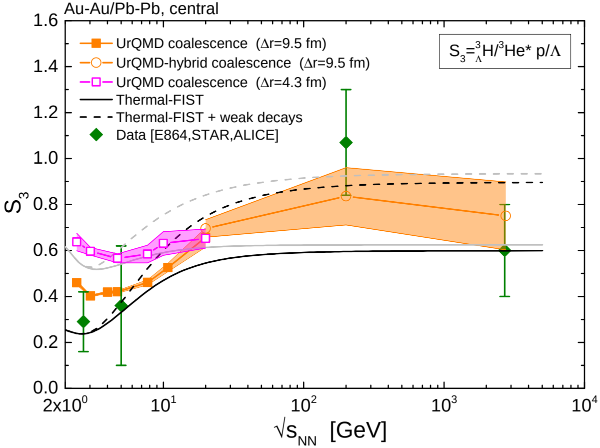
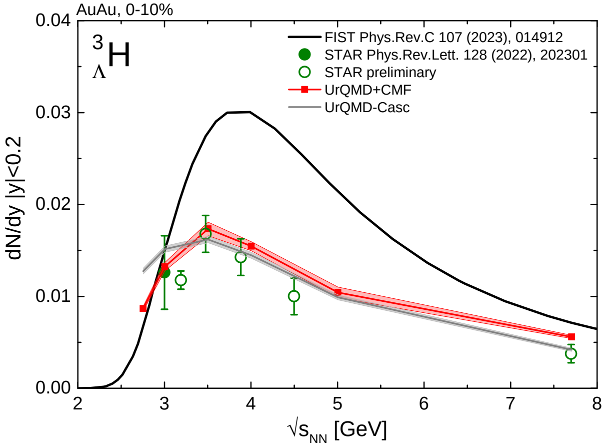
- Unfortunately error bars are large and only few data are available.
- Dependence on 'size' of hypernucleus observed.



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

Refitting the parameters with potentials

- Running with potentials reduces the strangeness yield due to less compression.
- Refitting the parameters to 3AGeV data give very good results.
- Very different from thermal model



Refitting the parameters with potentials

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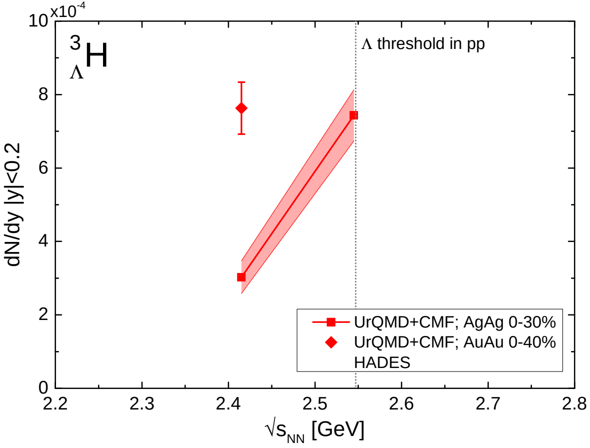
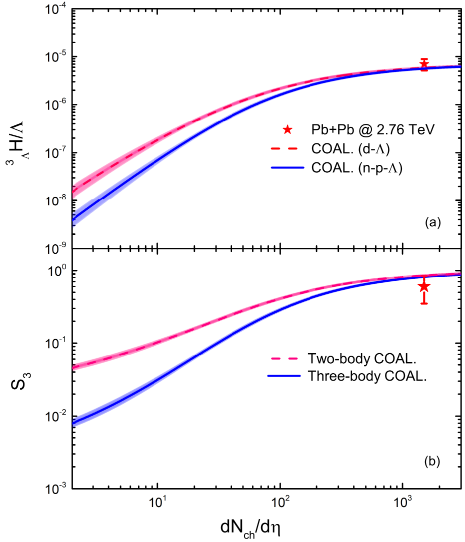
- Refitting the parameters to 3AGeV data give very good results.
- Very different from thermal model
- Predictions for HADES data: Strong system size dependence below threshold.



Let's switch to system size dependence

- Can the system size dependence be used to measure a difference in Δr:
  9.5 fm vs. 4.3 fm
- The centrality behavior was explained by the relation of source size and system size:
  K. J. Sun, C. M. Ko and B. Dönigus, Phys. Lett. B **792** (2019), 132-137



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- Also local conservation effects play a role:
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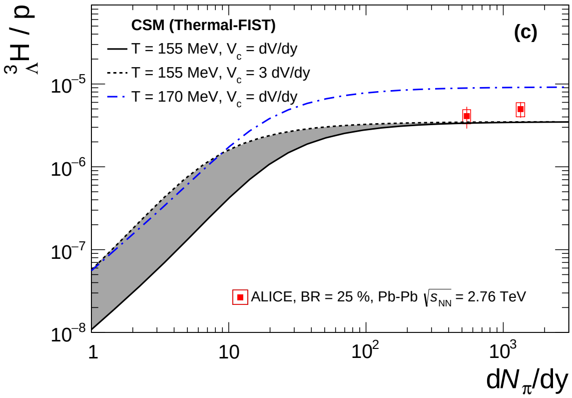

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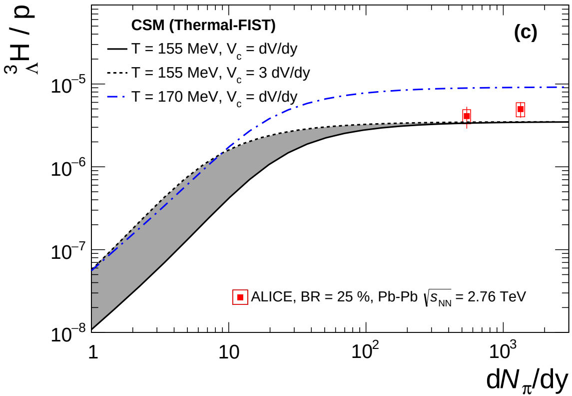
- Our approach: Both are taken into account.

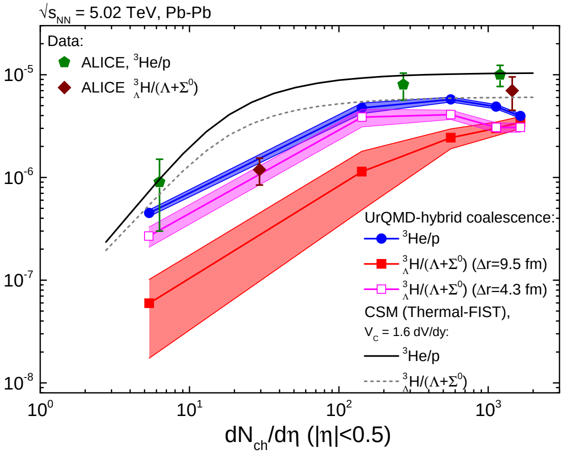


Changing the source size for the hypertriton

- 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.

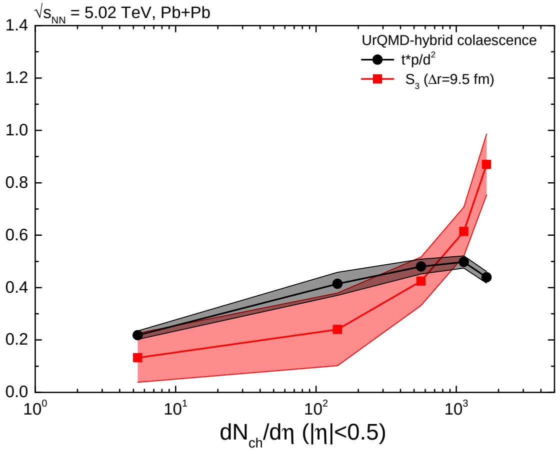
Parameters	^{3}He	${}^3_\Lambda$H	${}^3_\Lambda$H
Δr_{max} [fm]	4.3	9.5	4.3
Δp_{max} [GeV]	0.35	0.135	0.25

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



The double ratios for different system sizes

- Similar behavior is observed for the double ratios.



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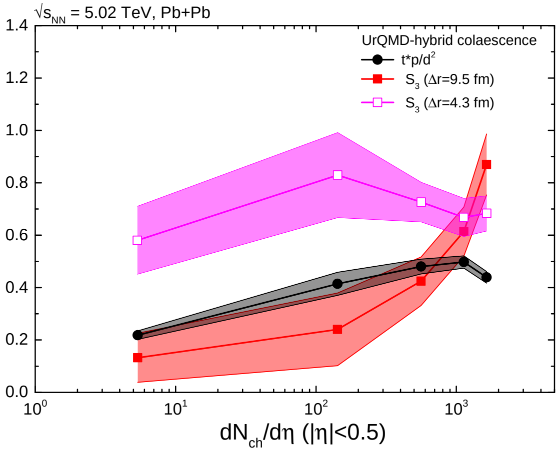
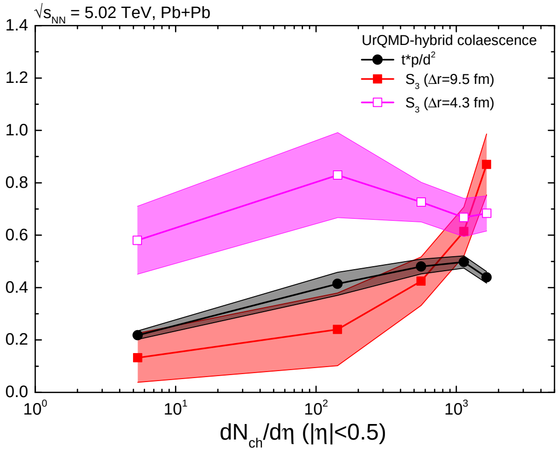


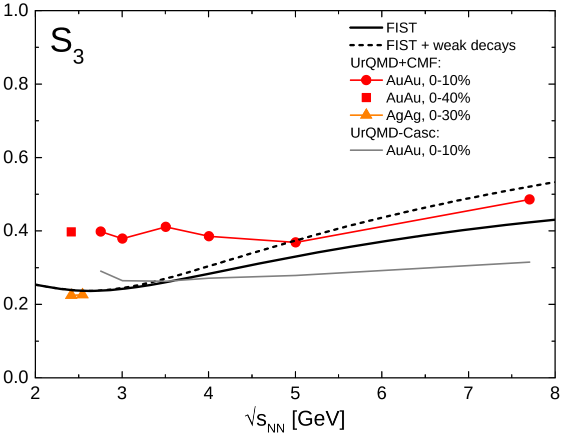
The double ratios for different system sizes

- 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.

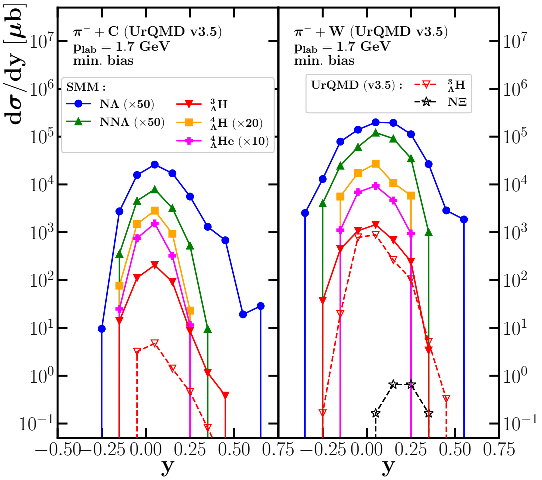


System sizes in other experiments - future HADES data

- Different sized systems have been studied at the same beam energy with the HADES detector
- A comparison of AuAu vs. AgAg may also reveal a system size dependence of S_3
- Changing the parameters from cascade to potential mode does change the absolute value of S_3 but not the qualitative behavior.



- Using a pion beam it is straight forward to create a hyperon inside the target nucleus.



A. Kittiratpattana, T. Reichert, N. Buyukcizmeci, A. Botvina, A. Limphirat, C. Herold, J. Steinheimer and M. Bleicher, [arXiv:2305.09208 [nucl-th]].

System sizes in other experiments - Pion Beam

- Using a pion beam it is straight forward to create a hyperon inside the target nucleus.
- The absorption or fragmentation of the nucleus then leads to the formation of hyperclusters of various sizes.

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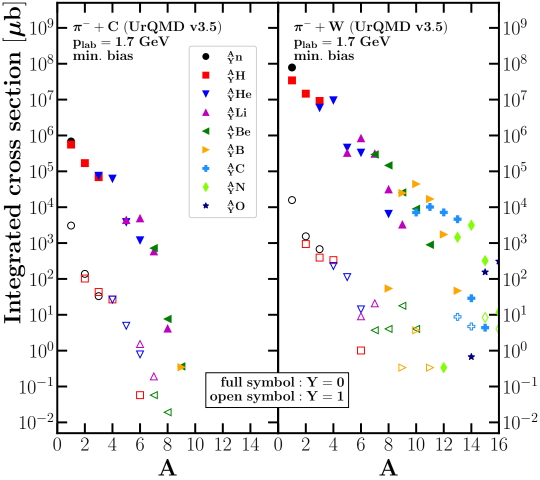
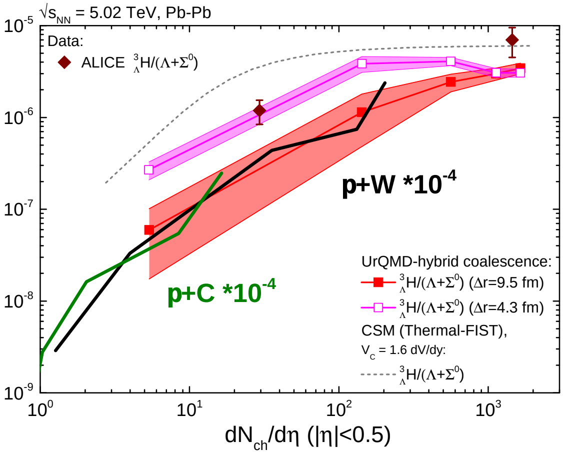


System sizes in other experiments - Pion Beam

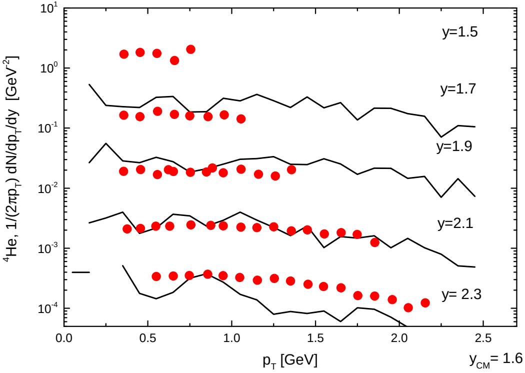
- Using a pion beam it is straight forward to create a hyperon inside the target nucleus.
- The absorption or fragmentation of the nucleus then leads to the formation of hyperclusters of various sizes.
- Scaling S_3, due to the significantly different penalty factor, shows the same system size dependence as ALICE data!

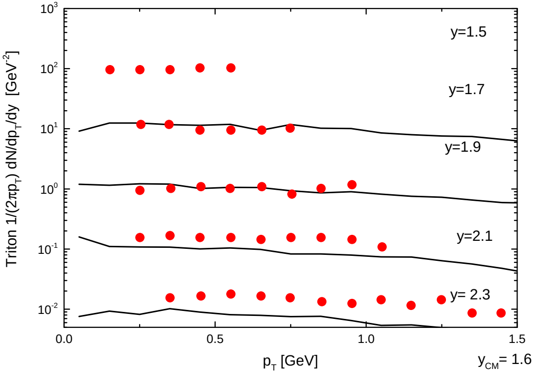
A. Kittiratpattana, T. Reichert, N. Buyukcizmeci, A. Botvina, A. Limphirat, C. Herold, J. Steinheimer and M. Bleicher, [arXiv:2305.09208 [nucl-th]].



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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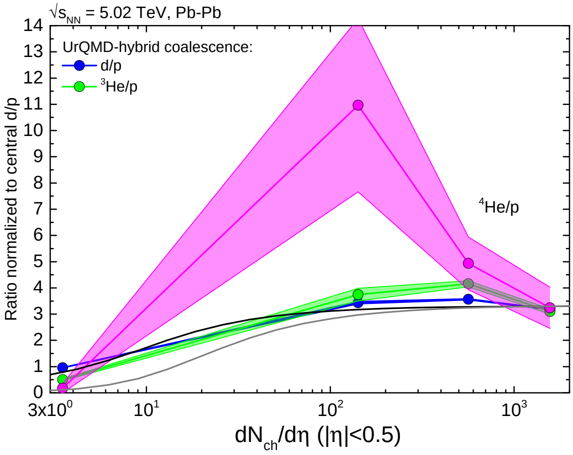
- Biggest effect in Helium.



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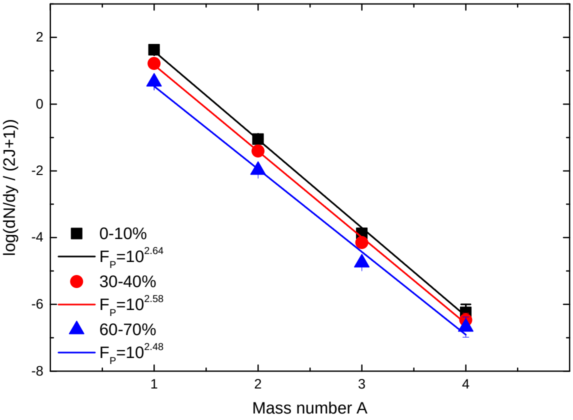
- Biggest effect in Helium.
- Penalty factor (or mass dependent suppression) as function of system size may give some insight on the interplay between annihilation and canonical effects.



Light nuclei multiplicities - refit with EoS

- Refitting the parameters at 3 AGeV, including a realistic EoS leads to more ^{3}He!