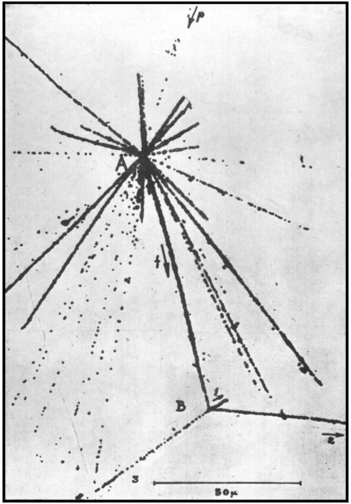
Hypernuclei in Heavy Ion Collisions

Tom Reichert
thanks to: Jan Steinheimer-Froschauer, V. Vovchenko, B. Dönigus and M. Bleicher

Institut für Theoretische Physik, Goethe-Universität Frankfurt

14.06.2022

First hypernuclear event



- Hypernuclei are nuclei with at least one bound hyperon.
- The first hypernuclear measurement by Danysz and Pniewski from a cosmic ray emulsion event (1952).

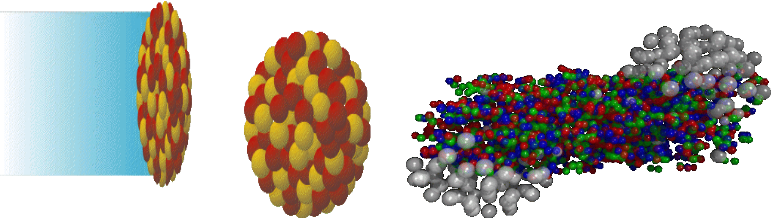
KARTKA POCZTOWA cena 2000 zł

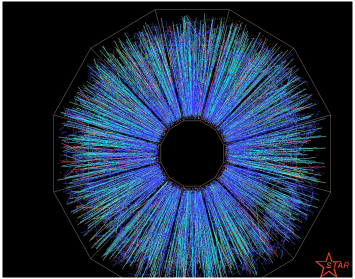
40 ROCZNICA ODKRYCIA
MATERII HIPERJĄDROWEJ

Profesor Marian Danysz (1909-1983)
Profesor Jerzy Pniewski (1913-1989)

POCZTA POLSKA - V 1993 r. Nakład 200.000 Proj. Maciej Jędrysik

Hypernuclear production mechanisms in HIC





- Fireball in a HI-collision is an abundant source of strangeness
- Clusters are formed at or after the hadronic freezeout
- Big discovery potential but short lifetime, fast expansion and finite size emission make things complicated.

Hypernuclear production mechanisms in HIC

- Nuclei are weakly bound, compared to the momentum transfer of last scatterings before freeze out.
- True for all models: The observed final state must be formed after the last scattering of their constituents.

Cluster formation after freeze out from the fireball

- (Hyper-)Nuclei can be formed after kinetic freeze out and after all other interactions have ceased.
- Calculation of clusters is usually done by coalescence mechanism.
- Different versions of implementation but mostly similar results.

Phase-Space Coalescence (a practical implementation)

- Take transport model of choice and calculate phase space distributions of baryons.
- A cluster 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).

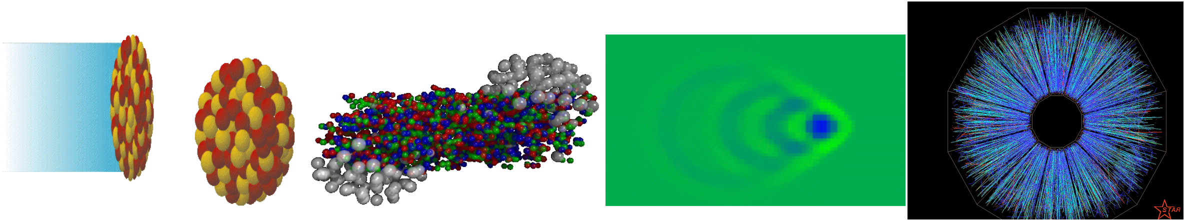
W. Zhao, K. j. Sun, C. M. Ko and X. Luo, Phys. Lett. B **820**, 136571 (2021).

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 in UrQMD

- Coalescence needs realistic distributions for hadrons as input.
- We use UrQMD in cascade 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)

Phase-Space Coalescence in UrQMD

Numerical procedure: 'Box-coalescence'

1. We look in the two-particle-rest-frame of each possible two-nucleon pair with the correct isospin combination. If their relative distance $\Delta r = |\vec{r}_{n_1} - \vec{r}_{n_2}| < \Delta r_{max,nn} = 3.575$ fm and momentum distance $\Delta p = |\vec{p}_{n_1} - \vec{p}_{n_2}| < \Delta p_{max,nn} = 0.285$ GeV, a two nucleon state is potentially formed with the combined momenta at position $\vec{r}_{nn} = (\vec{r}_{n_1} + \vec{r}_{n_2})/2$.

Phase-Space Coalescence in UrQMD

Numerical procedure: 'Box-coalescence'

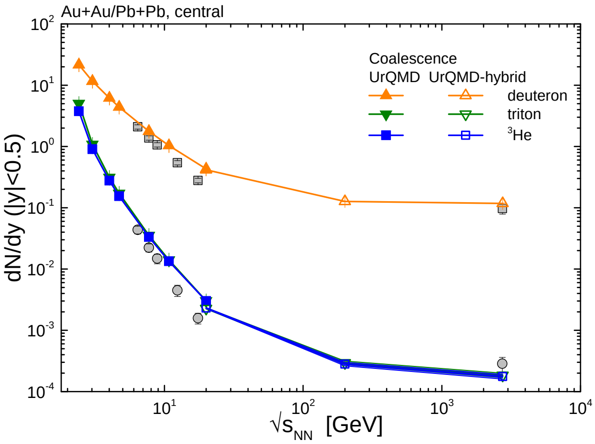
1. We look in the two-particle-rest-frame of each possible two-nucleon pair with the correct isospin combination. If their relative distance $\Delta r = |\vec{r}_{n_1} - \vec{r}_{n_2}| < \Delta r_{max,nn} = 3.575$ fm and momentum distance $\Delta p = |\vec{p}_{n_1} - \vec{p}_{n_2}| < \Delta p_{max,nn} = 0.285$ GeV, a two nucleon state is potentially formed with the combined momenta at position $\vec{r}_{nn} = (\vec{r}_{n_1} + \vec{r}_{n_2})/2$.
2. As second step we boost into the local rest-frame of this two nucleon state and any other possible third nucleon. If the conditions of their relative distance $\Delta r = |\vec{r}_{nn} - \vec{r}_{n_3}| < \Delta r_{max,nnn}$ and momentum distance $\Delta p = |\vec{p}_{nn} - \vec{p}_{n_3}| < \Delta p_{max,nnn}$ are fulfilled, a triton $(Z = 1)$ or helium-3 $(Z = 2)$ is formed with the probability of $(1/12)$.

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.

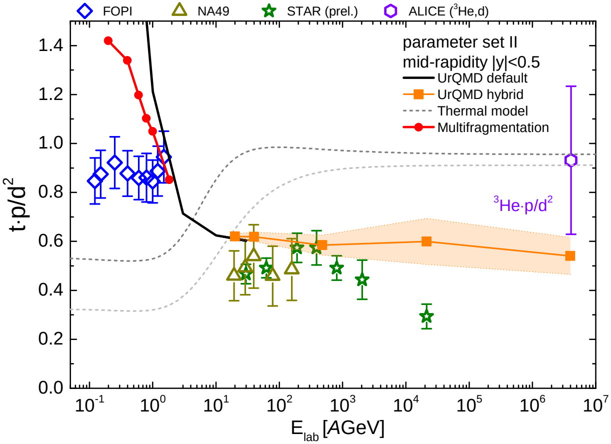
Probabilities	d	t, ^{3}He
spin-isospin factor	3/8	1/12

Parameters	NN	NNN
Δr_{max} [fm]	3.575	4.3
Δp_{max} [GeV]	0.285	0.35



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 too many free protons (larger clusters are missing).
- Multifragmentation of fireball picture more reasonable here?

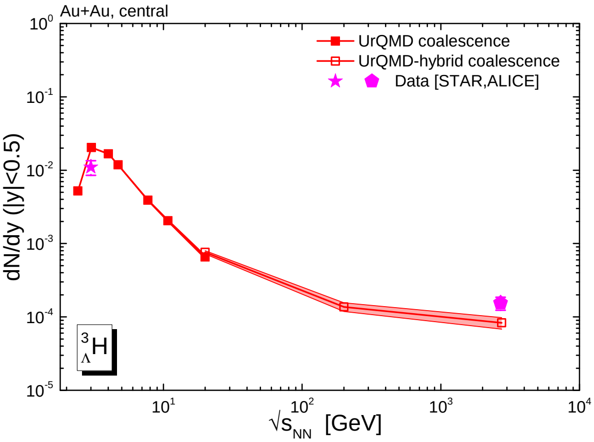


P. Hillmann, K. Käfer, J. Steinheimer, V. Vovchenko and M. Bleicher, J. Phys. G **49**, no.5, 055107 (2022)

Moving on to hypernuclei

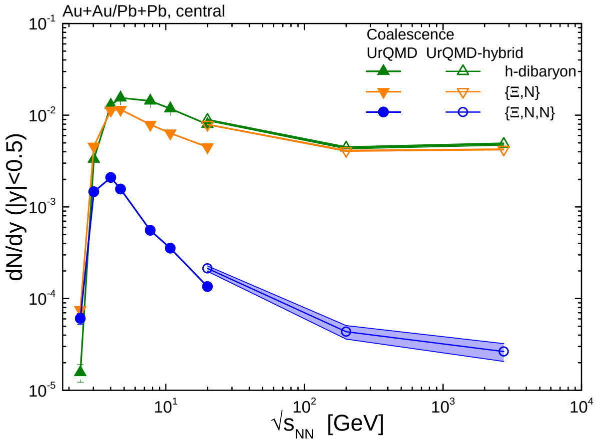
- Data on hypertriton multiplicities is scarce.
- We fixed the parameters mainly from previous calculations.
  J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher and H. Stöcker, Phys. Lett. B **714** (2012), 85-91
- Strangeness at very low energies is overestimated (potential effects)
-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

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



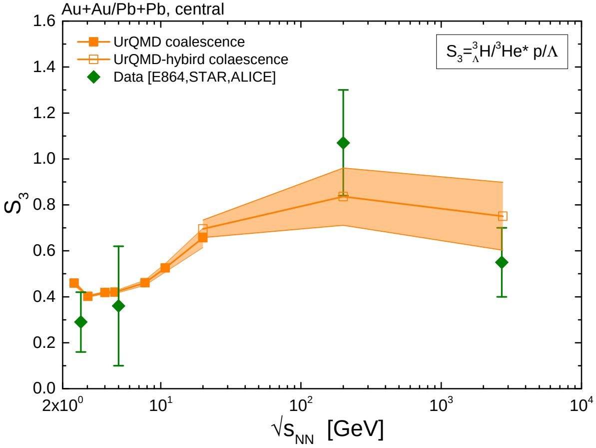
Multiplicities for multistrange objects

- 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.
- Multistrange particle production slightly increased in hybrid model due to thermalization.
- Huge discovery potential.



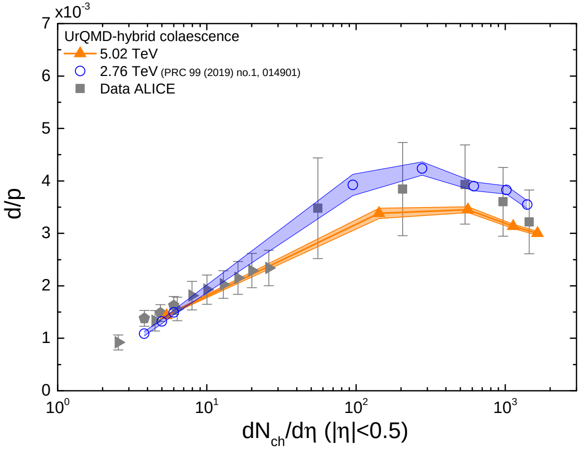
Another special ratio

- Another special ratio which was thought to be sensitive on baryon-strangeness correlations: S_3
- New results shows small increase at higher beam energies.
- Unfortunately error bars are large and only few data are available.



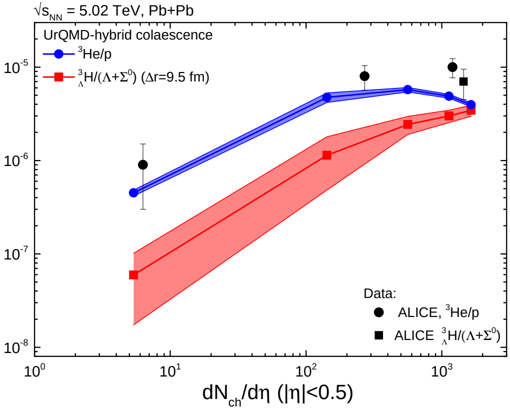
Deuteron to proton ratio

- New results at 5 TeV (orange) compared to old results at 2.7 TeV (blue).
- Slight increase in protons, still both results within uncertainty.
- Centrality dependence well reproduced.
- Small increase due to annihilation then drop-off for smallest systems.



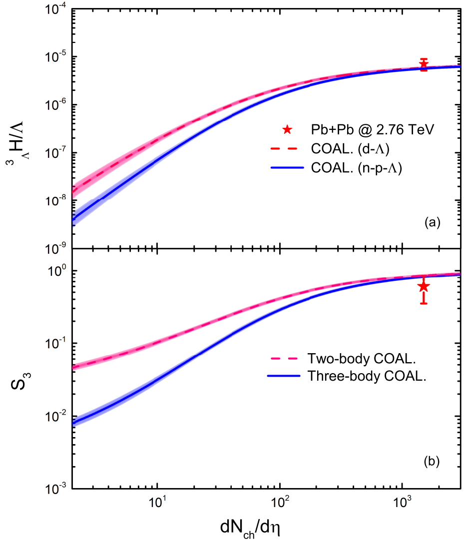
^{3}He vs. Hypertriton ratios

- ^{3}He shows behavior similar to deuteron.
- Hypertriton comes as a surprise: much faster drop-off.



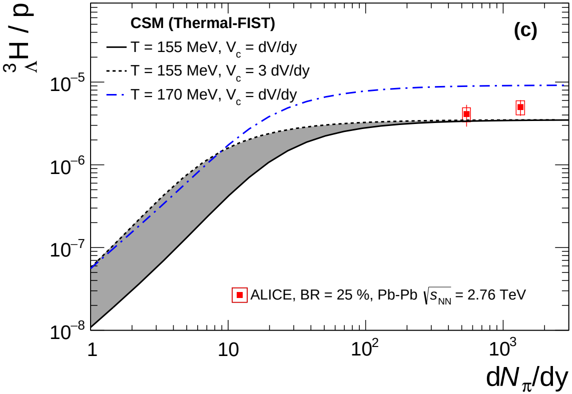
^{3}He vs. Hypertriton ratios

- ^{3}He shows behavior similar to deuteron.
- Hypertriton comes as a surprise: much faster drop-off.
- Can this be explained by the 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

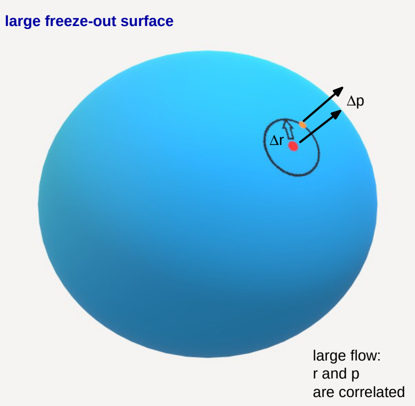


^{3}He vs. Hypertriton ratios

- ^{3}He shows behavior similar to deuteron.
- Hypertriton comes as a surprise: much faster drop-off.
- Can this be explained by the 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
- Also local conservation effects play a role:
  V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B **785** (2018), 171-174
- Our approach: Both are taken into account.

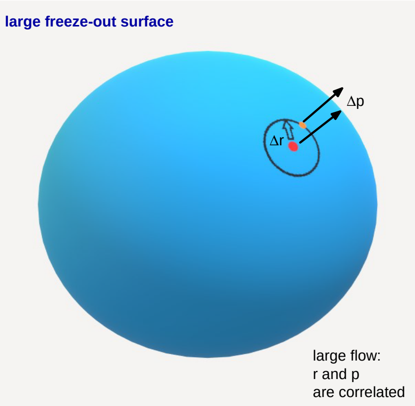


How to understand the source volume

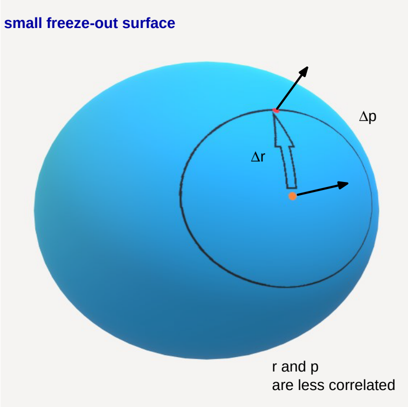

large freeze-out surface

large flow:
r and p
are correlated

How to understand the source volume



large flow:
r and p
are correlated

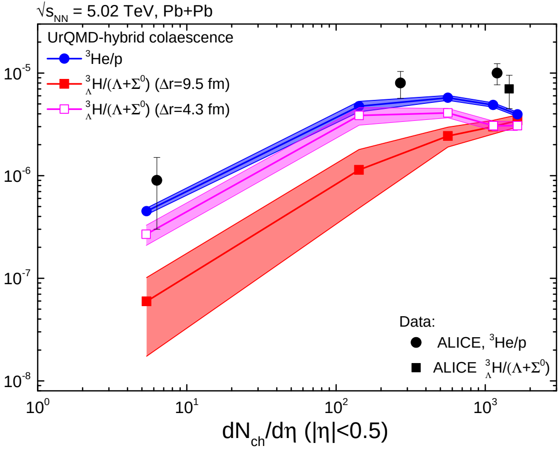


r and p
are less correlated

Changing the source size for the hypertriton

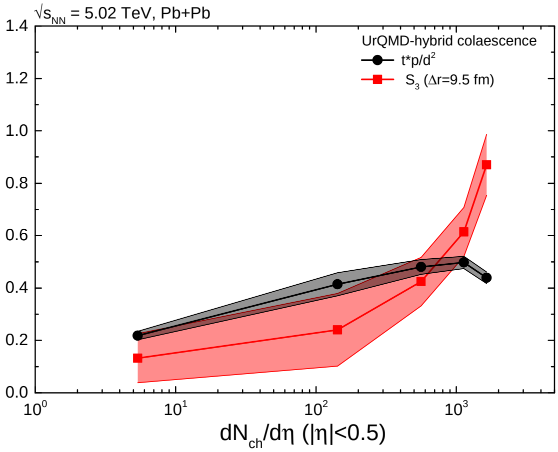
- We can change the coalescence size Δr for the ${}^{3}_{\Lambda}$H to be the same as for ^{3}He.
- Adjusting Δp to get a similar value for central collisions.
- Centrality dependence is changed as expected.

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



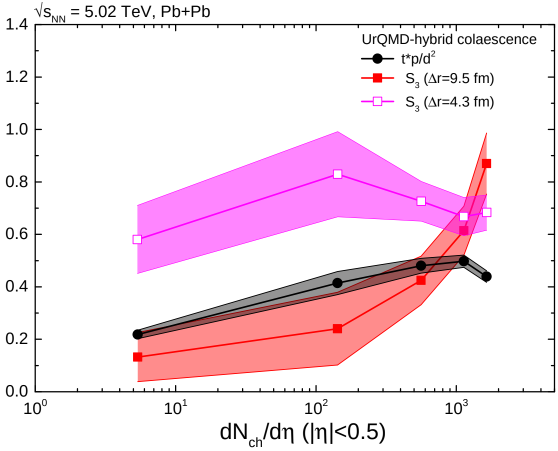
The double ratios for different system sizes

- Similar behavior is observed for the double ratios.



The double ratios for different system sizes

- Similar behavior is observed for the double ratios.
- Different coalescence size gives different behavior.
- Note that in p+p also canonical effects are naturally included.
- ALICE data (SQM22) in pp at 13 TeV suggests $S_3 = 0.2$ at $\mathrm{d}N_{ch}/\mathrm{d}\eta = 30$.
- However: ALICE data (SQM22) in pPb at 5.02 TeV suggests $S_3 = 0.45 \pm 0.1$ at $\mathrm{d}N_{ch}/\mathrm{d}\eta = 30$.



Conclusion

- Light (hyper-)nuclei can be described within the coalescence formalism reasonably well with only 2 parameters.
- Heavy ion collisions can be an abundant source of small as well as large multi-strange hypernuclei.
- The production rate of (hyper)nuclei is influenced by the coalescence volume vs. system size which depends on centrality.