Hypernuclei in Heavy Ion Collisions

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

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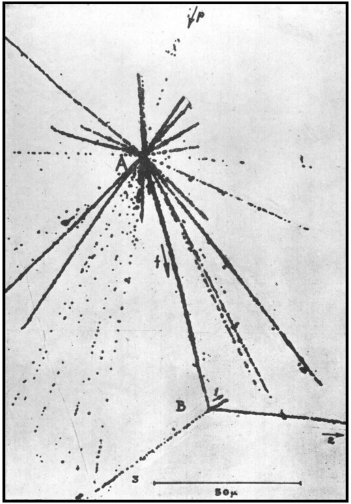
First hypernuclear event



- 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

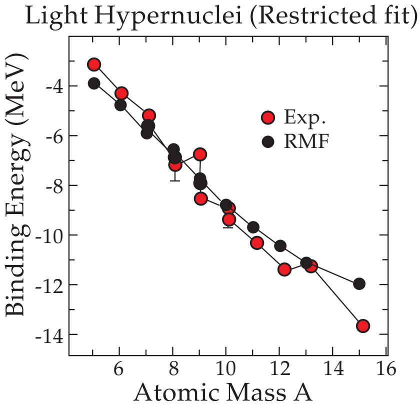
40 ROCZNICA ODKRYCIA
MATERII HIPERJĄDROWEJ

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

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

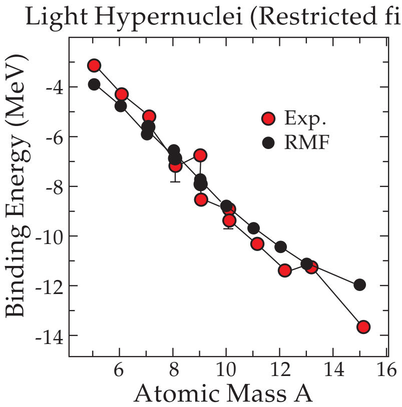
POLSKA
1500 ZŁOTYCH

(Multi-)Lambda binding energies



- Emulsion data exists up to mass number $A = 15$
- Λ binding energies increase linearly with mass number

(Multi-)Lambda binding energies



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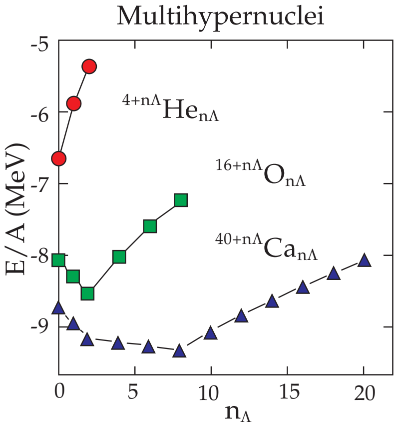
J. Schaffner-Bielich, February 18, 2010, Nantes



- Binding energy increases for heavy systems, some magic numbers.

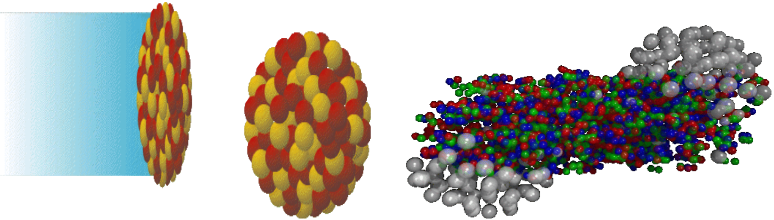
J. Schaffner-Bielich, February 18, 2010, Nantes

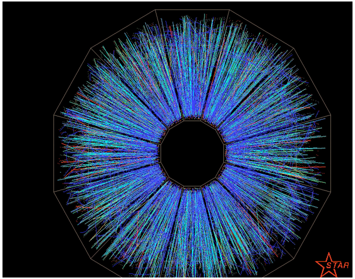
Ξ hypernuclei

- First bound Ξ hypernucleus seen in 1959 (Wilkinson, Lorant, Robinson, Lokanathan, PRL 3 (1959) 397)
- Two hypernuclei emitted: $\Xi + N \to \Lambda + \Lambda$
- ${}^{8}_{\Xi}$B with $B_\Xi = 8.1 \pm 1.2$

Hypernucleus	B_{Ξ^-} [MeV]	B_{Ξ^0} [MeV]
${}^{8}_{\Xi}$He	8.1 ± 1.2	14.2 ± 1.8
${}^{11}_{\Xi}$B	9.2 ± 2.2	0.4 ± 2.8
${}^{13}_{\Xi}$C	18.1 ± 3.2	-4.3 ± 3.8
${}^{15}_{\Xi}$C	16.0 ± 4.7	11.1 ± 5.3
${}^{17}_{\Xi}$O	16.0 ± 5.5	-4.5 ± 6.1
${}^{28}_{\Xi}$Al	23.2 ± 6.8	13.3 ± 7.4

Hypernuclear production mechanisms in HIC





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

High energies: Phase-Space Coalescence

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

Numerical procedure: 'Box-coalescence'

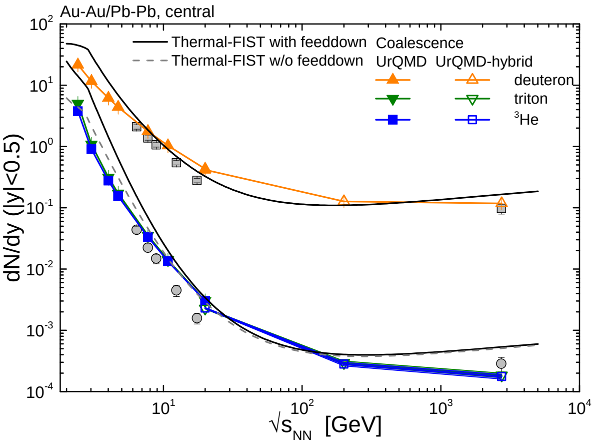
1. We look in the two-particle-rest-frame of each possible two-nucleon pair with the correct isospin combination. If their relative distance $\Delta r = |\vec{r}_1 - \vec{r}_2| < \Delta r_{max,nn} = 3.575$ fm and momentum distance $\Delta p = |\vec{p}_1 - \vec{p}_2| < \Delta p_{max,nn} = 0.285$ GeV, a two nucleon state is potentially formed with the combined momenta at position $\vec{r}_{nn} = (\vec{r}_1 + \vec{r}_2)/2$.
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 $\Delta r = |\vec{r}_{nn} - \vec{r}_3| < \Delta r_{max,nnn}$ and momentum distance $\Delta p = |\vec{p}_{nn} - \vec{p}_3| < \Delta p_{max,nnn}$ 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.

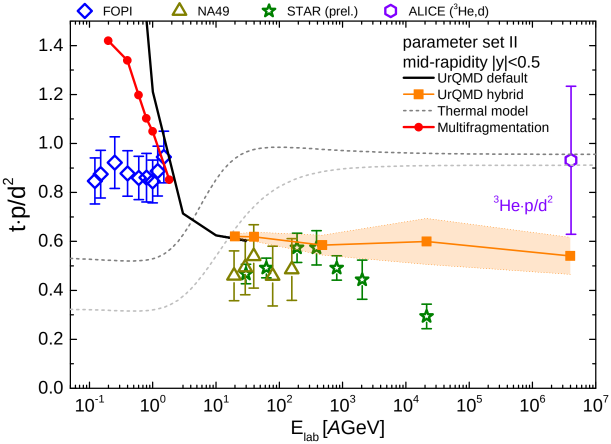
Probabilities	d	t, ^{3}He
spin-isospin factor	3/8	1/12

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?

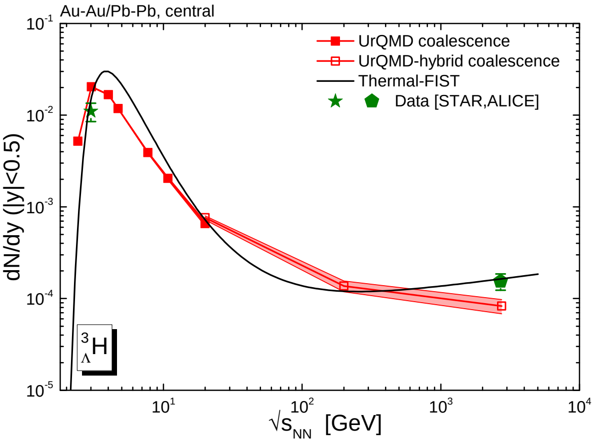


P. Hillmann, K. Käfer, J. Steinheimer, V. Vovchenko and M. Bleicher, J. Phys. G **49**, no.5, 055107 (2022)

Moving on to hypernuclei

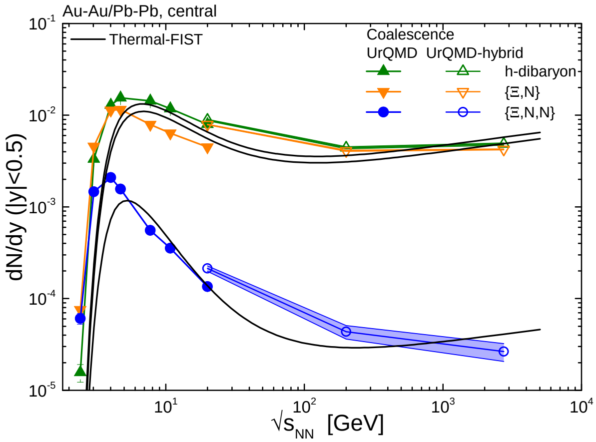
- Data on hypertriton multiplicities is scarce.
- We fixed the parameters mainly from previous calculations.
  J. Steinheimer, K. Gudima, A. Botvina, I. Mishustin, M. Bleicher and H. Stöcker, Phys. Lett. B **714** (2012), 85-91
- Strangeness at very low energies is overestimated (potential effects)
- 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



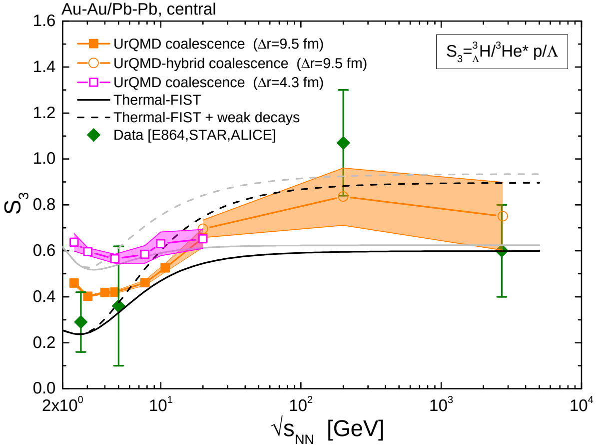
Multiplicities for multistrange objects

- 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.



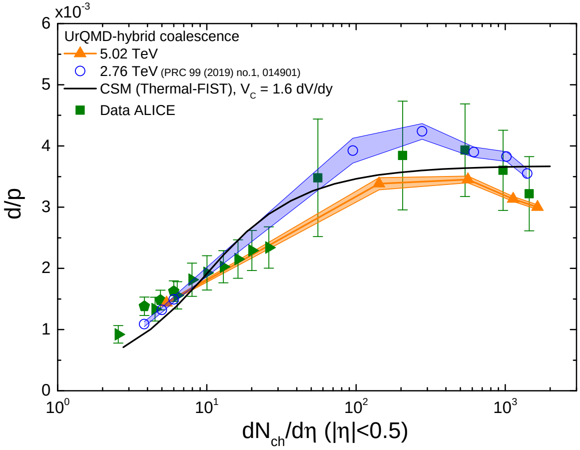
Another special ratio

- Another special ratio which was thought to be sensitive on baryon-strangeness correlations: $S_3 = {}^3_\Lambda\mathrm{H}/{}^3\mathrm{He}\cdot p/\Lambda$
- New results shows small increase at higher beam energies.
- Unfortunately error bars are large and only few data are available.
- UrQMD with $\Delta r = 9.5$ fm describes data best



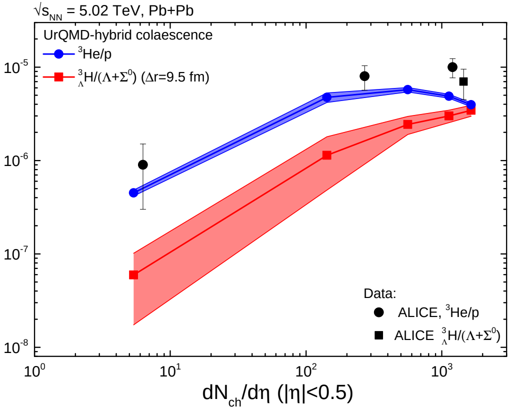
Deuteron to proton ratio

- 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.



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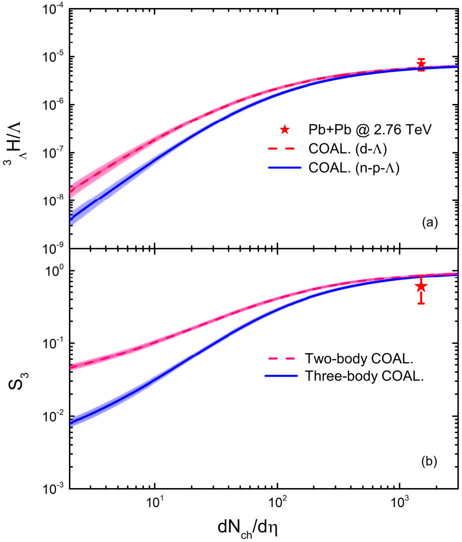
- Can this be explained by the difference in Δr: 9.5 fm vs. 4.3 fm
- The centrality behavior was explained by the relation of source size and system size:
  K. J. Sun, C. M. Ko and B. Dönigus, Phys. Lett. B **792** (2019), 132-137



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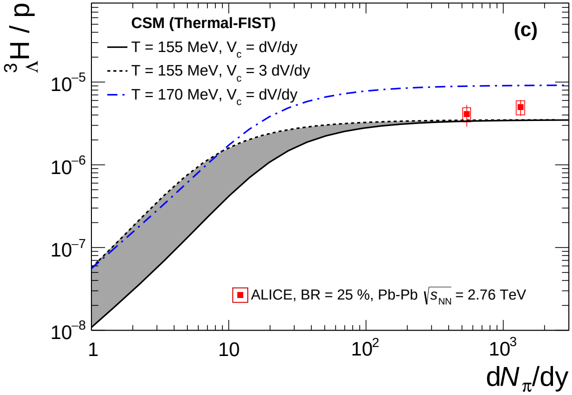
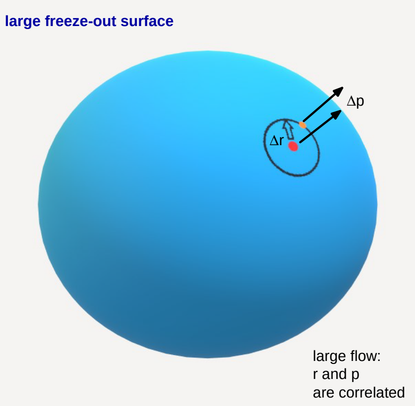
- Also local conservation effects play a role:
  V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B **785** (2018), 171-174
- Our approach: Both are taken into account.



How to understand the source volume



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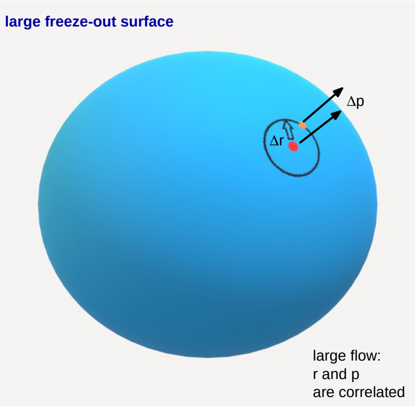
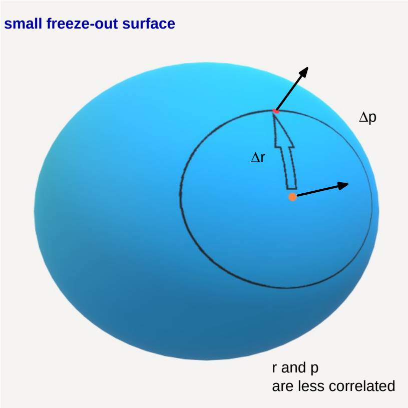
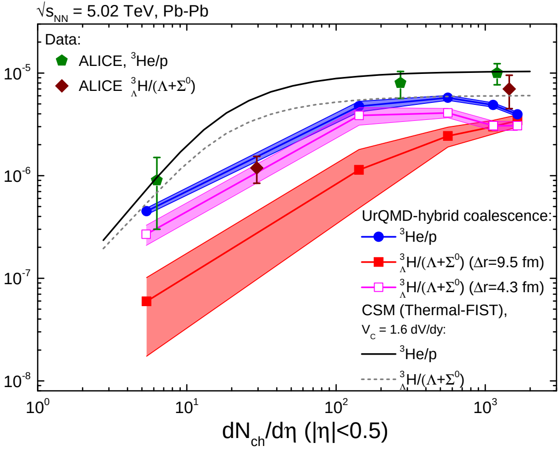




Changing the source size for the hypertriton

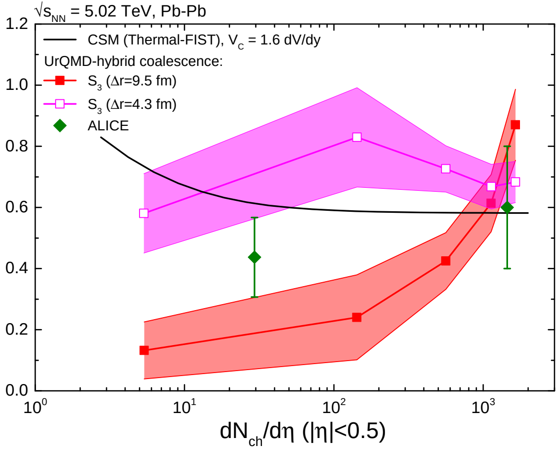
- We can change the coalescence size Δr for the ${}^{3}_{\Lambda}$H to be the same as for ^{3}He.
- Adjusting Δp to get a similar value for central collisions.
- Centrality dependence is changed as expected.

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.
- 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.

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