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15th Workshop on Critical Point and Onset of Deconfinement
LBL, Berkeley, California, USA
Tom Reichert

Production of light- & hypernuclei in UrQMD

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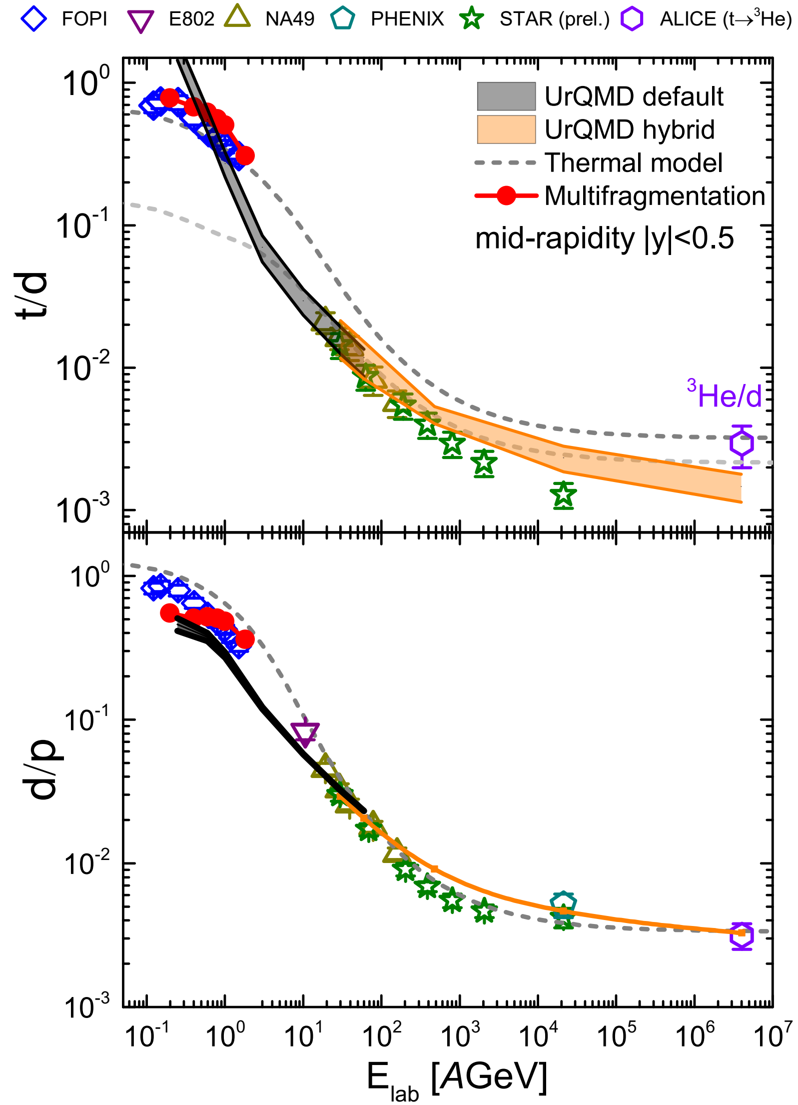
(Hyper-)Nuclei motivation

- Different models provide a good description of nuclei production in heavy ion collisions
- This is true over wide range of energies
- Despite the fact that nuclei are only weakly bound compared to the temperature of the system
- B = 2 MeV, T = 100-150 MeV ?



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

Methods of cluster production

Wigner functions

- Projection on Hulthen wave function
- No free parameters
- No orthogonality of states

M. Kachelriess et al. Eur.Phys.J.A 57 (2021)
M. Gyulassi et al. Nucl.Phys.A 402 (1983)

Kinetic production

- Introduce explicit processes, e.g. $np\pi \rightarrow d\pi$
- Dynamical treatment
- Mimic 3-body interactions

J. Staudenmaier et al. Phys.Rev.C 104 (2021) 3, 034908
D. Oliinychenko et al. Phys.Rev.C 99 (2019) 4, 044907

Potential

- Hamiltonian which binds cluster
- Might involve complicated forces
- Difficult for small systems

J. Aichelin, et al. Phys.Rev.C 101 (2020) 4, 044905
S. Gläßel, et al. Phys.Rev.C 105 (2022) 1, 014908

Coalescence

- Employ cut-off parameters
- Event-by-event possible
- 2 free, energy-independent parameters

S. Butler, C. Pearson. Phys.Rev. 129 (1963) 836-842
S. Sombun et al. Phys.Rev.C 99 (2019) 1, 014901

Thermal emission

- Clusters in partition sum
- No free parameter

P. Braun-Munzinger, et al. Phys.Lett.B 344 (1995) 43-48
A. Andronic, et al. Nature 561 (2018) 7723, 321-330
V. Vovchenko, et al. Phys.Lett. B (2020) 135746

Multifragmentation

- Break up of thermal nuclear system
- Microcanonical ensembles
- Deexcitation via Fermi break up

Bondorf et al. Phys.Rept. 257 (1995) 133-221
Steinheimer et al. Phys.Lett.B 714 (2012) 85-91

Coalescence

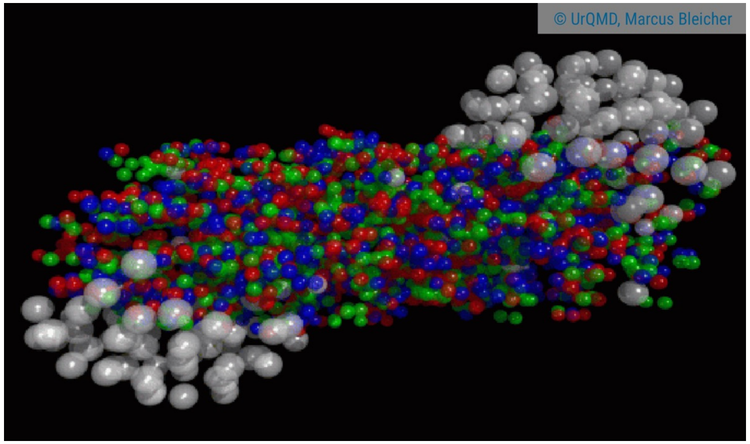
- Clusters are weakly bound compared to momentum transfer (temperature)
- Clusters are formed after kinetic freeze-out
- Coalescence: Cluster is formed if correct constituents occupy certain phase space volume

$$\frac{\mathrm{d}N}{\mathrm{d}^3k} = g\int \mathrm{d}p_1^3\mathrm{d}p_2^3\mathrm{d}x_1^3\mathrm{d}x_2^3 f_A(p_1,x_1)f_B(p_2,x_2)\rho_{AB}(\Delta x,\Delta p)\delta(k-(p_1+p_2))$$

- Need realistic phase space distribution functions of nucleons

→ Use microscopic transport model keeping all n-body correlations

Ultra-relativistic Quantum Molecular Dynamics



- Hadron/String transport approach
- Based on propagation of hadrons
- Rescattering among hadrons fully included
- String excitation and decay (LUND model, PYTHIA)
- Solution for the time dependent n-body distribution of hadrons
- Collision term includes more than 100 hadrons up to 4 GeV in mass
- Soft/Hard Skyrme or CMF EoS can be switched on

M. Bleicher, et al. J.Phys. G25 (1999), 1859-1896
S. Bass, et al. Prog.Part.Nucl.Phys. 41 (1998) 255-369
M. Omana Kuttan, et al. Eur.Phys.J.C 82 (2022) 5, 427

Box-Coalescence

1. Boost into local rest frame of each possible nucleon+nucleon pair with the correct isospin combination at kinetic freeze-out. If relative distance $\Delta x < \Delta x_{max}$ and relative momentum $\Delta p < \Delta p_{max}$ the two-nucleon system is marked a deuteron candidate.
2. Boost into local rest frame of deuteron+nucleon and check again if $\Delta x < \Delta x_{max}$ and $\Delta p < \Delta p_{max}$. A triton or ^{3}He is then formed with a probability of 1/12 at the position $r_{NNN} = (r_1 + r_2 + r_3)/3$ and with momentum $p_{NNN} = p_1 + p_2 + p_3$

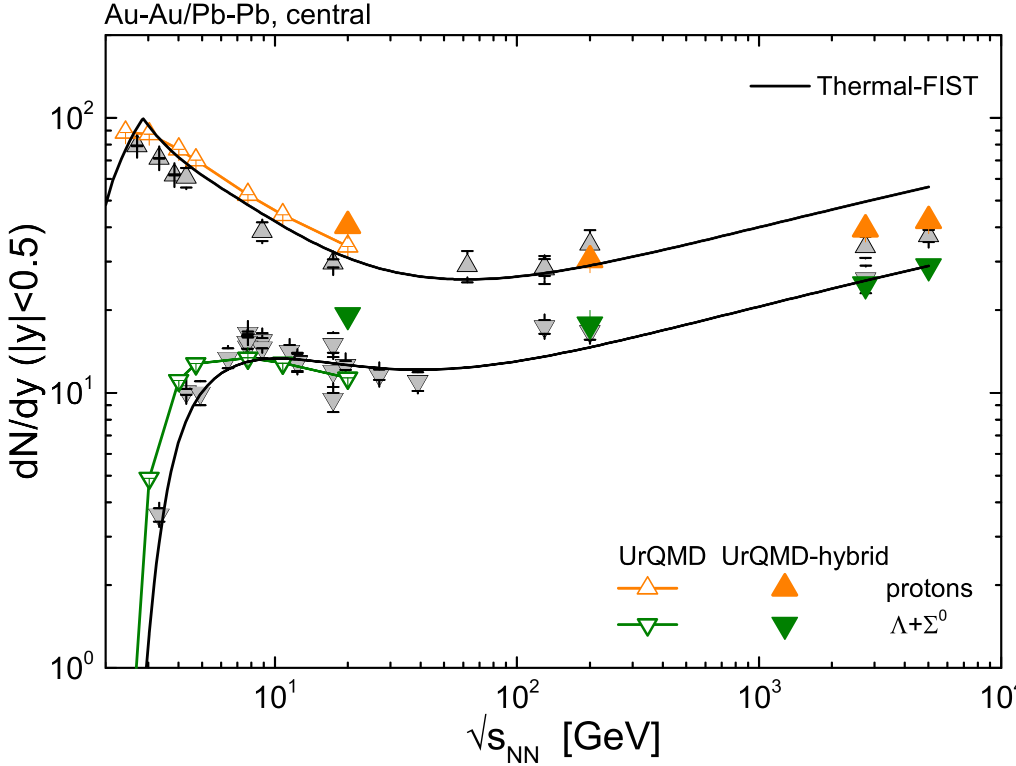
→ Straight forward extension to hypernuclei

	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

S. Sombun et al. Phys.Rev.C 99 (2019) 1, 014901
P. Hillmann et al. J.Phys.G 49 (2022) 5, 055107
T. Reichert et al. Phys.Rev.C 107 (2023) 1, 014912

Stable hadron multiplicities

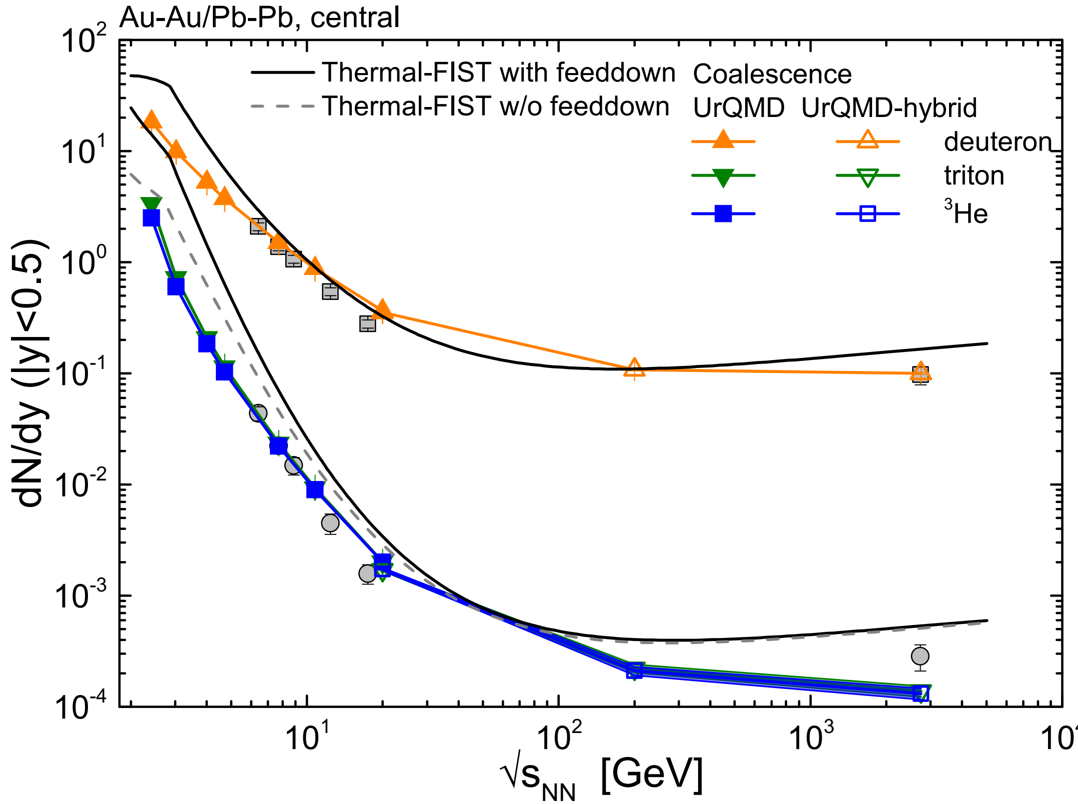
- Good description of baryon multiplicities over wide range of energies
- Too much proton stopping at intermediate energies
- Cascade model gives too much strangeness at low beam energies and too little at high energies
- Hybrid models include GC strangeness production



Reichert et al. Phys.Rev.C 107 (2023) 1, 014912

Light nuclei multiplicities

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



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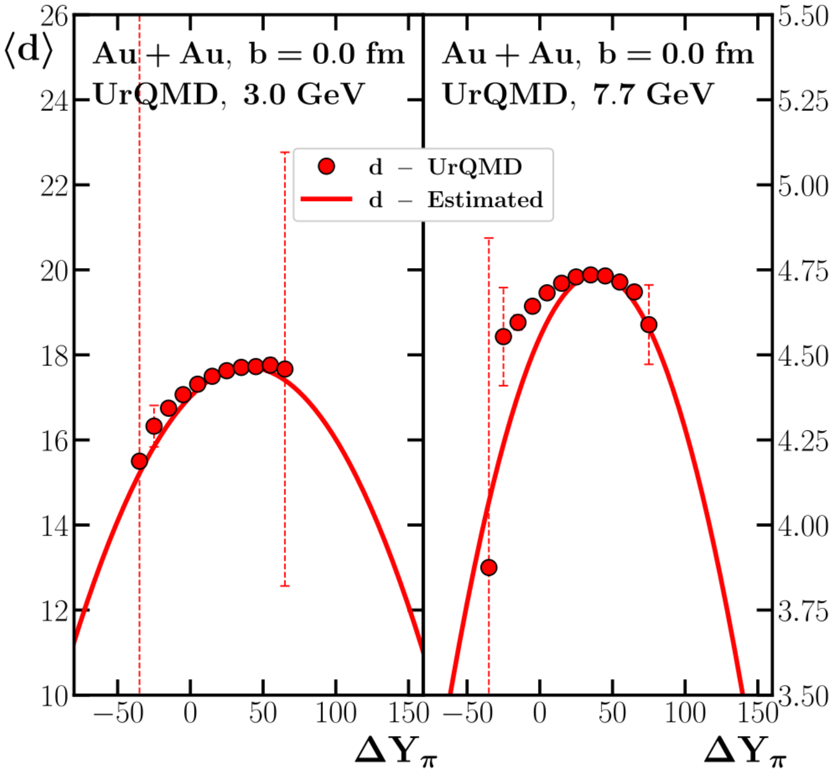
→ Clusters probe interesting physics across all energies

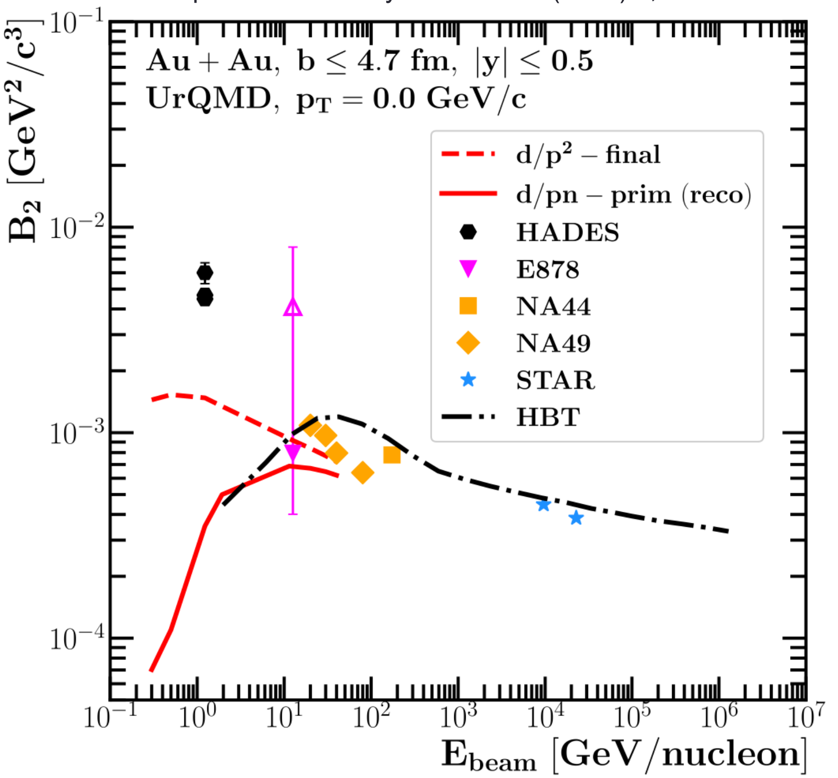
Light nuclei multiplicities vs. net-isospin

- Nuclei yields are sensitive to net-isospin (here: $\Delta\pi = \pi^- - \pi^+$)
- Allows to distinguish from (grand-canonical) thermal emission
- Has to be taken into account to correct B_2 at low energies

Kittiratpattana et al. Phys.Rev.C 107 (2023) 4, 044911

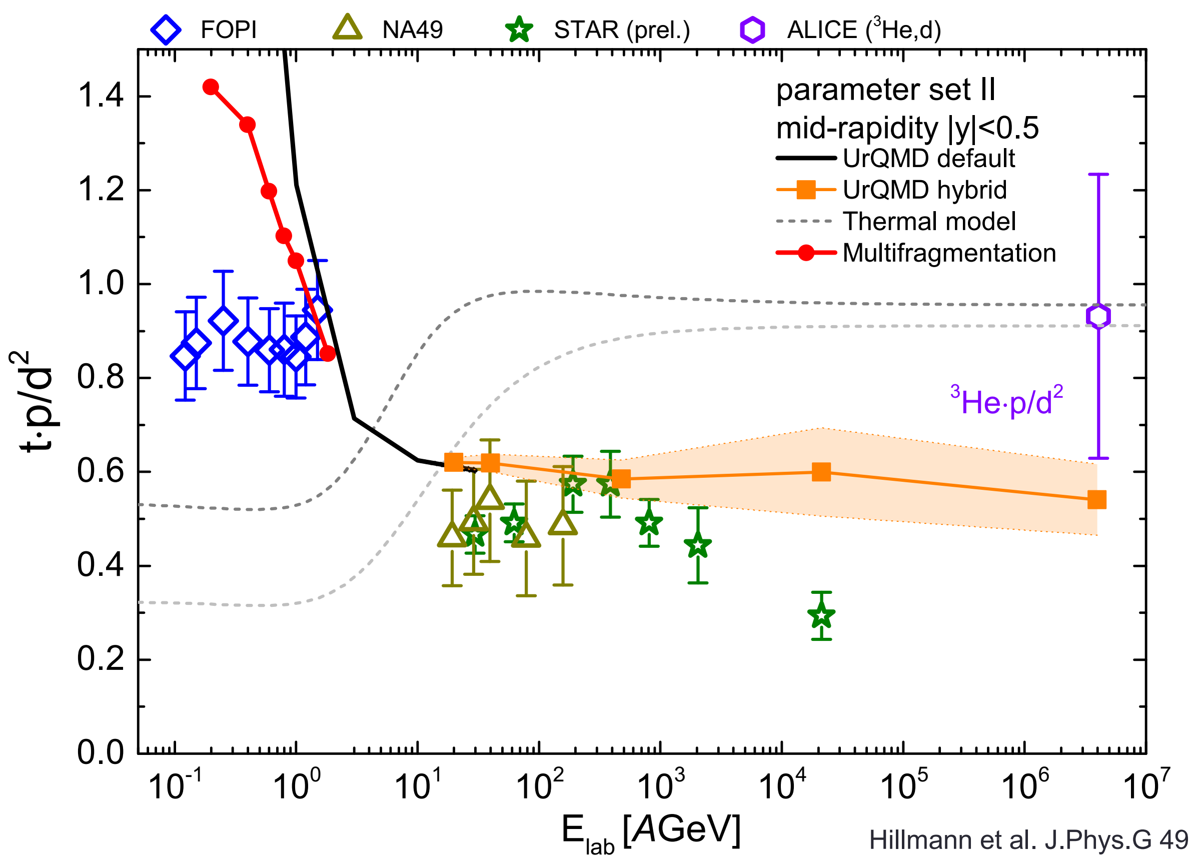


Kittiratpattana et al. Phys.Rev.C 106 (2022) 4, 044905



The tp/d^2 ratio

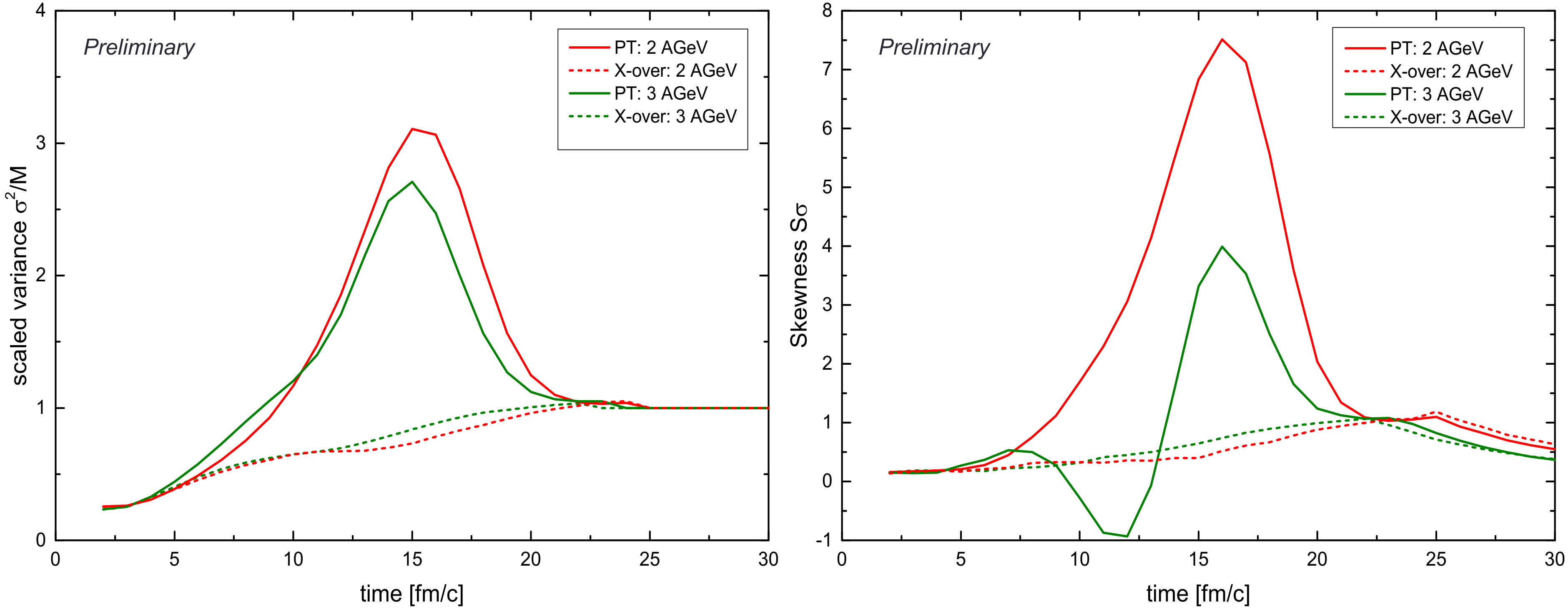
- The double ratio $t \cdot p/d^2$ is proposed to be sensitive to spatial baryon fluctuations at freeze-out Sun et al. Phys.Lett.B 781 (2018) 499-504



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

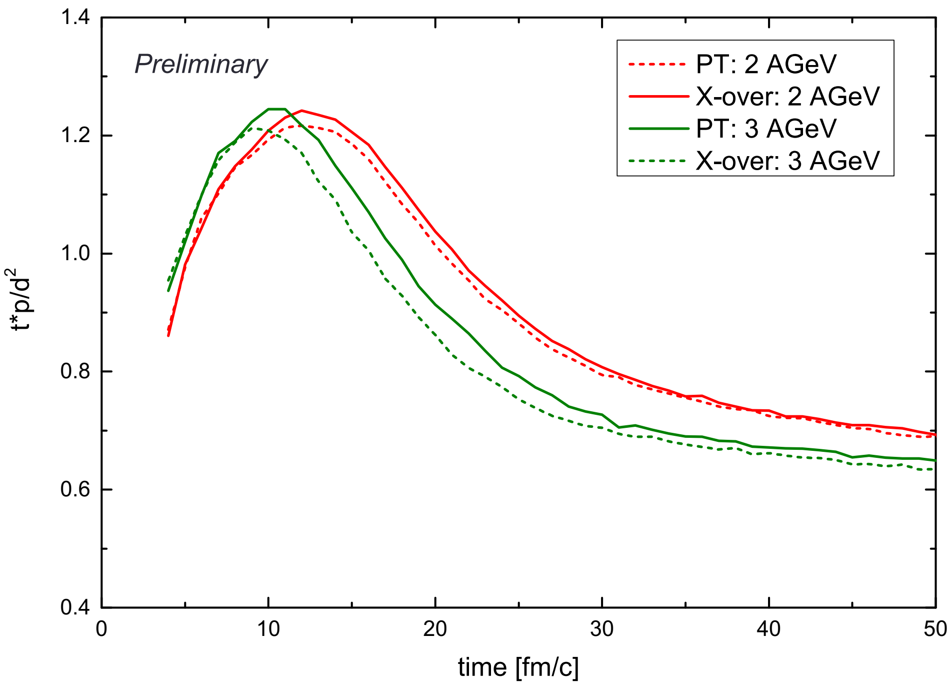
Light nuclei fluctuations

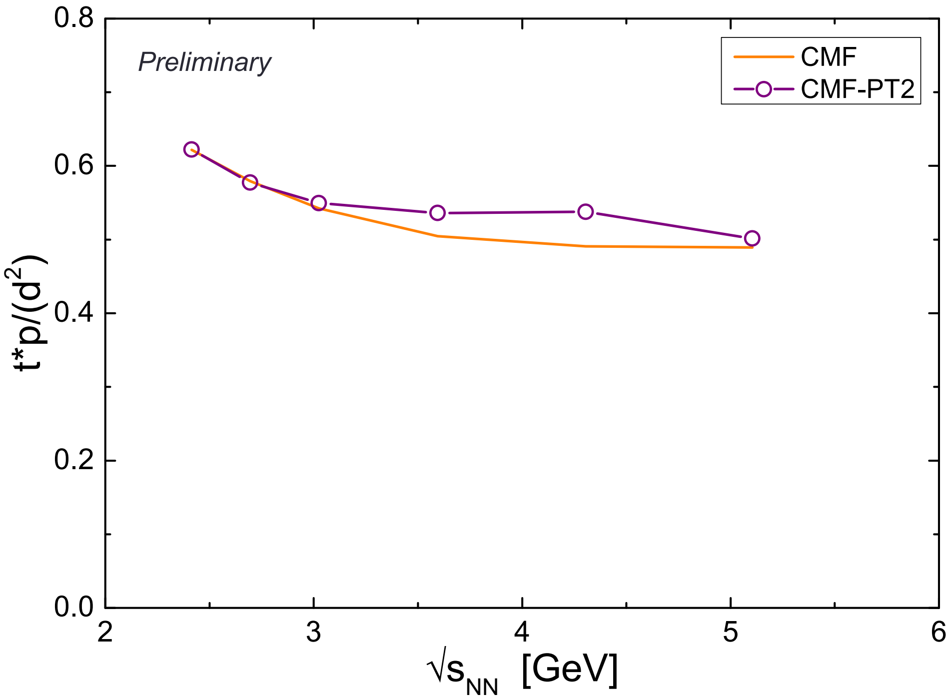
- The double ratio $t \cdot p/d^2$ is proposed to be sensitive to spatial baryon fluctuations at freeze-out
- Can be checked in UrQMD as a function of time
- Both σ^2/M and $S\sigma$ show clear signal in coordinate space



Light nuclei fluctuations

- Only small enhancement in time dependence of $t \cdot p/d^2$ even with strong fluctuations
- Only small enhancement at freeze-out in the scenario with phase transition





Hypernuclei multiplicities

- Data on ${}^3_\Lambda H$ multiplicities is scarce
- Strangeness at very low energies is overestimated (potential effects)
- Strangeness at intermediate energies is underestimated (the horn)
- Similar to the ${}^3He$, ${}^3_\Lambda H$ seems underestimated compared to ALICE data

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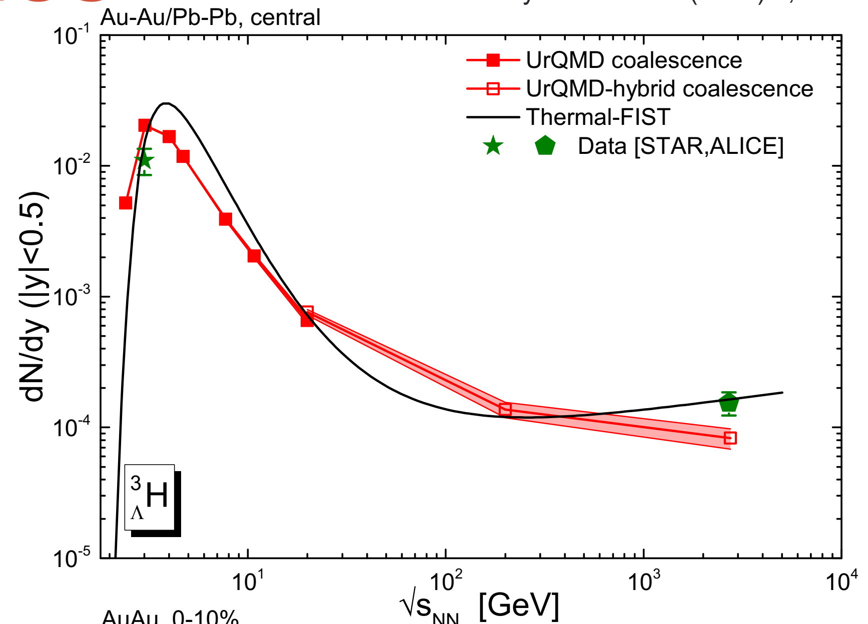
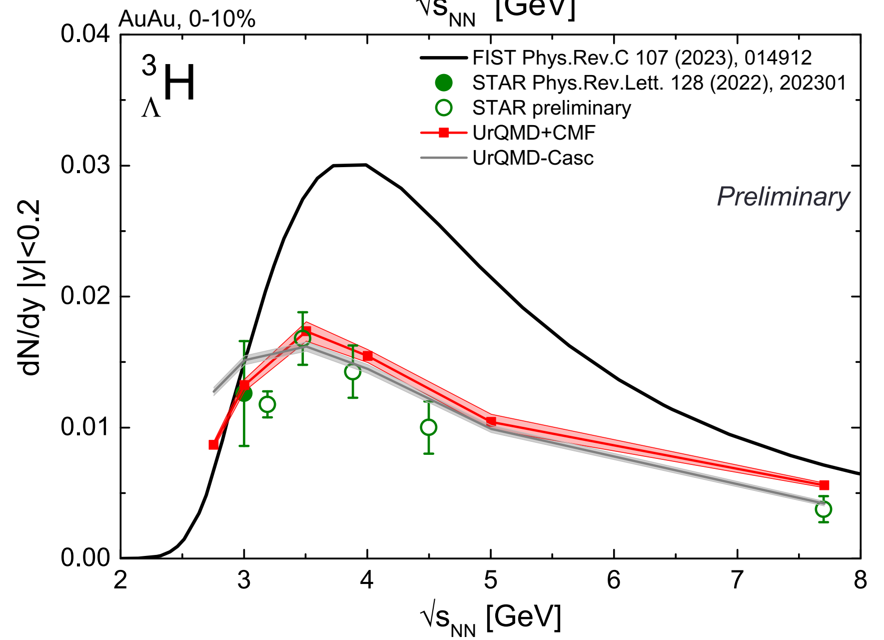




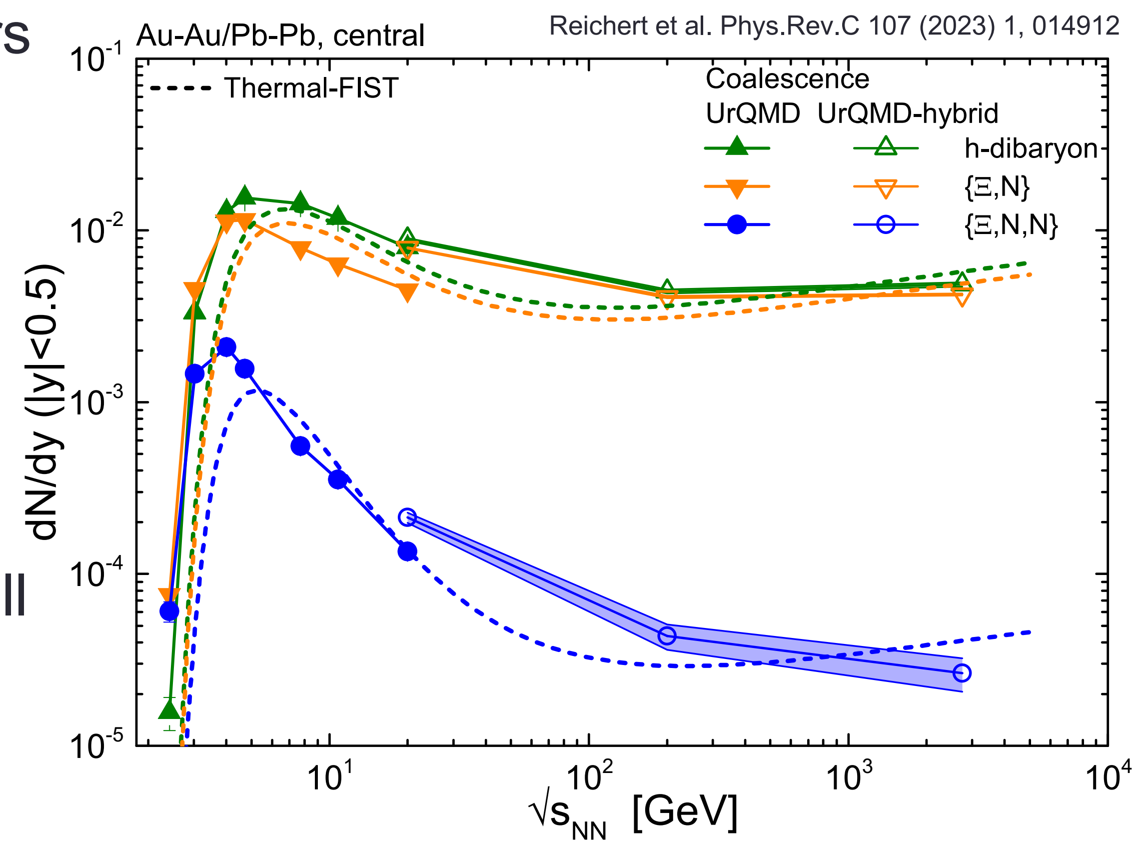
Hypernuclei multiplicities

- Using the same parameters as for hypertriton we can predict
multi-hypernuclear objects

- Most are unlikely to be bound?

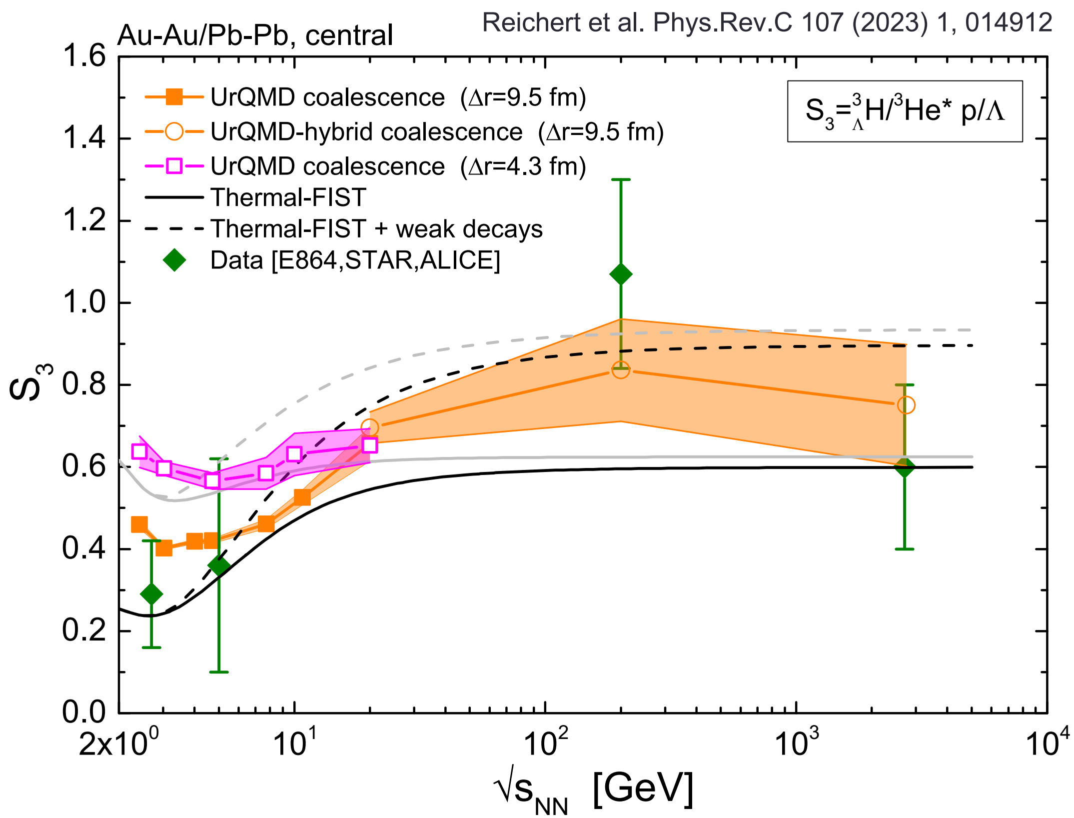
- Note: shown is sum over all possible isospin combinations

- Results consistent with previous estimates



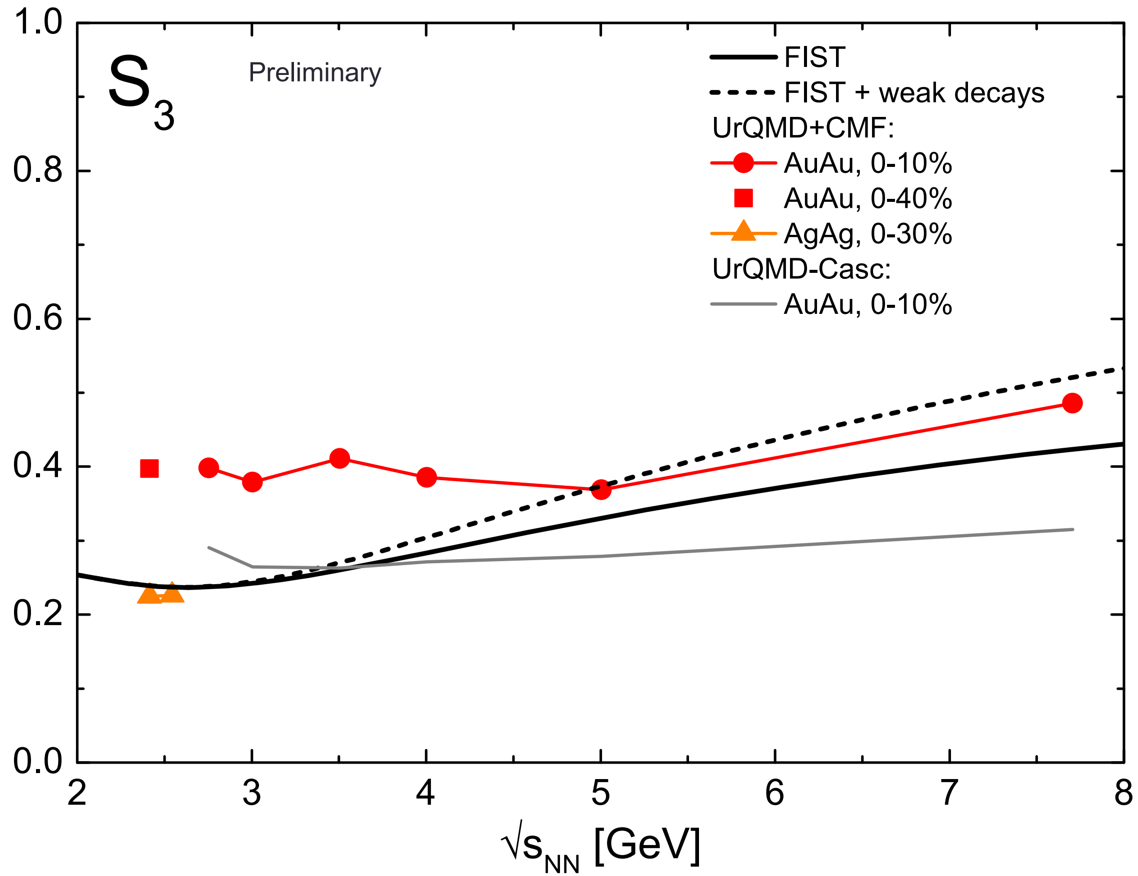
Another special ratio S_3

- S_3 is thought to be sensitive to baryon-strangeness correlation
- Thermal model and coalescence show similar behavior
- Unfortunately, error bars are large and there is few data available
- Dependence on coalescence source size observed



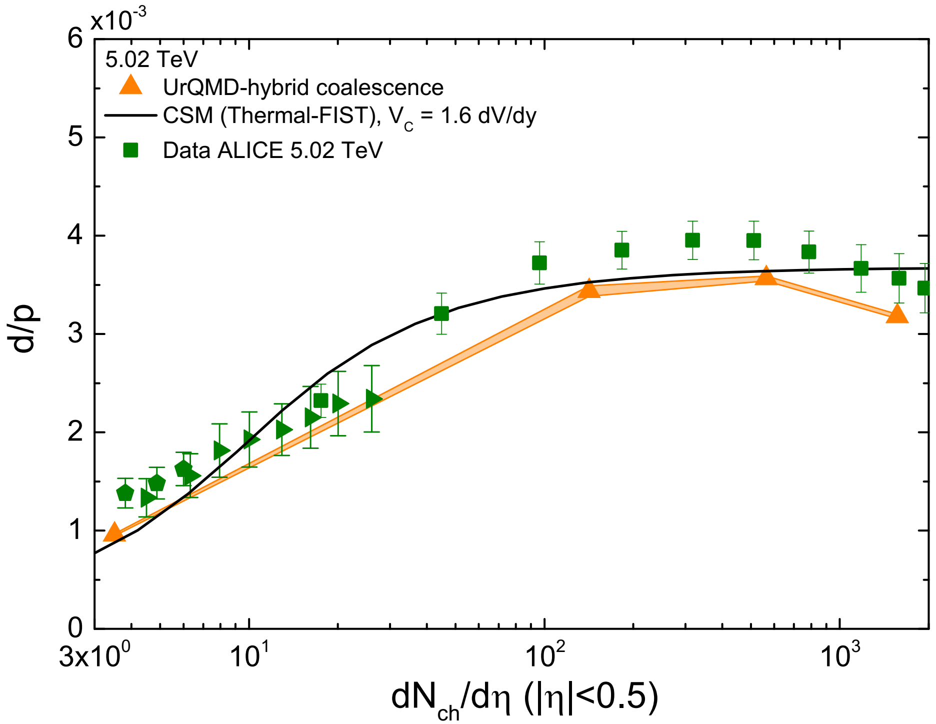
System size dependence at low energies

- HADES studied different systems at the same energy
- A comparative study of Ag+Ag versus Au+Au might reveal a system size dependence
- Suppression of S_3 in smaller Ag+Ag system



Light nuclei to proton ratio d/p

- d/p of UrQMD+coalescene and Thermal-FIST within exp. Uncertainties
- Centrality dependence well reproduced
- Small increase due to annihilation, then drop-off for small systems



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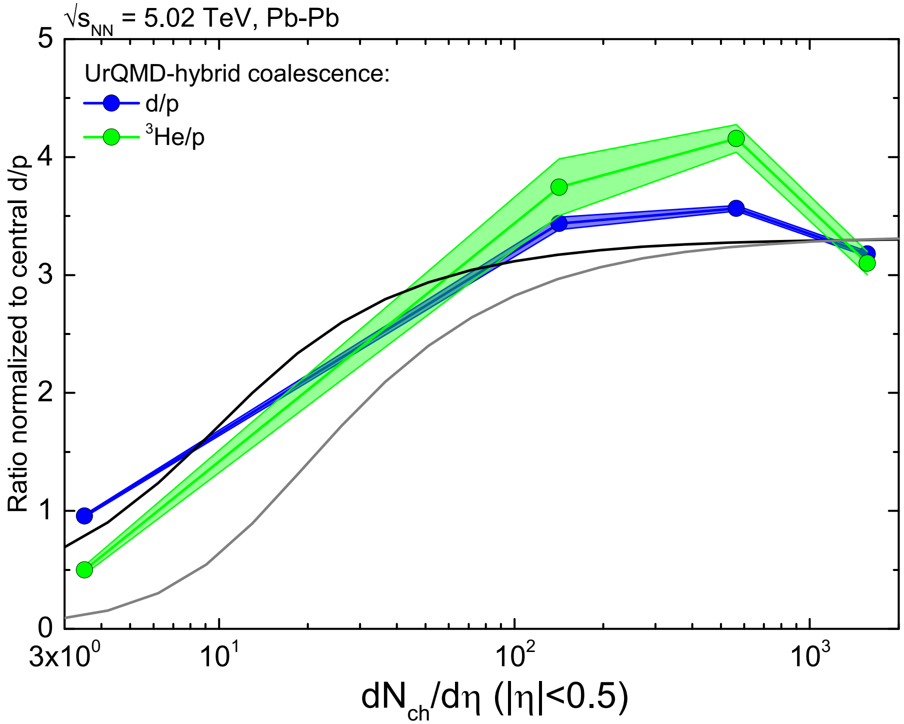
Light nuclei to proton ratio $^3He/p$

- d/p of UrQMD+coalescene and Thermal-FIST within exp. Uncertainties
- Centrality dependence well reproduced
- Small increase due to annihilation, then drop-off for small systems
- Same systematic observed for ^{3}He/p



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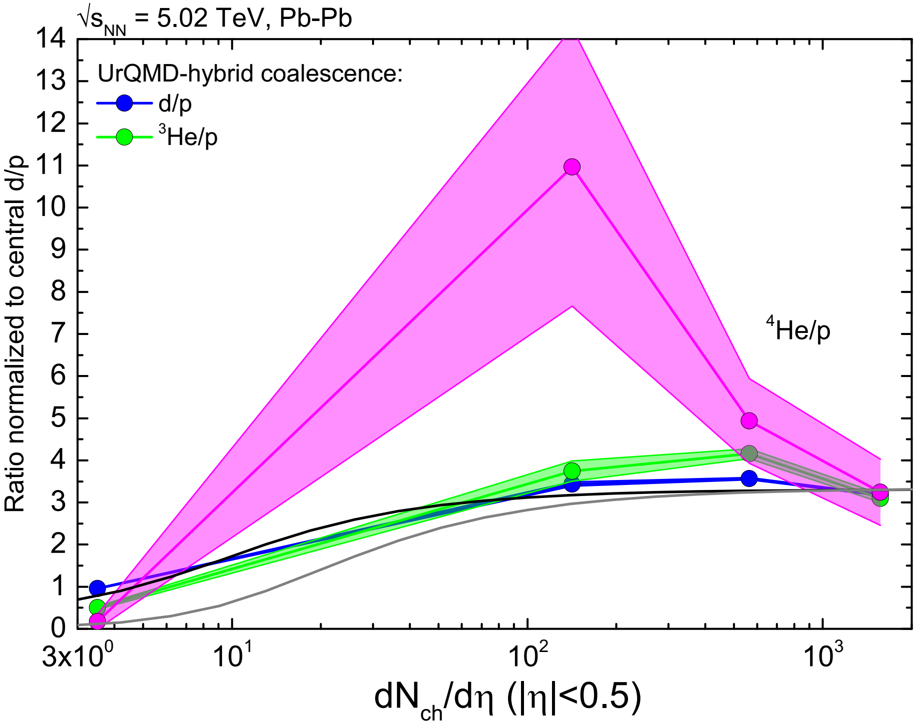
Light nuclei to proton ratio $^4He/p$

- d/p of UrQMD+coalescene and Thermal-FIST within exp. Uncertainties
- Centrality dependence well reproduced
- Small increase due to annihilation, then drop-off for small systems
- Same systematic observed for ^{3}He/p
- Huge effect seen in ^{4}He/p



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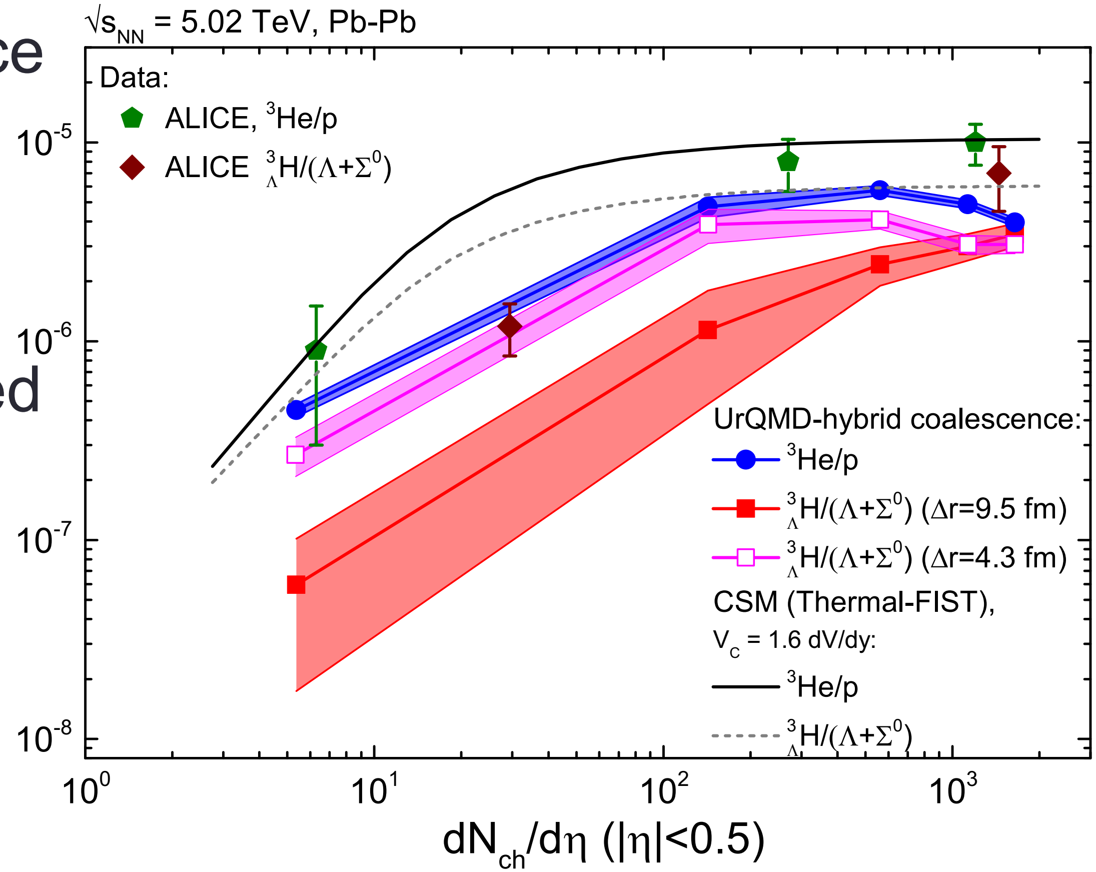
Centrality dependence of hypernuclei

- We can change the source size Δr for the $^3_\Lambda H$ to be the same as for ^3He
- Δp thus has to be adjusted to give a similar value in central collisions
- Centrality dependence is changed as expected



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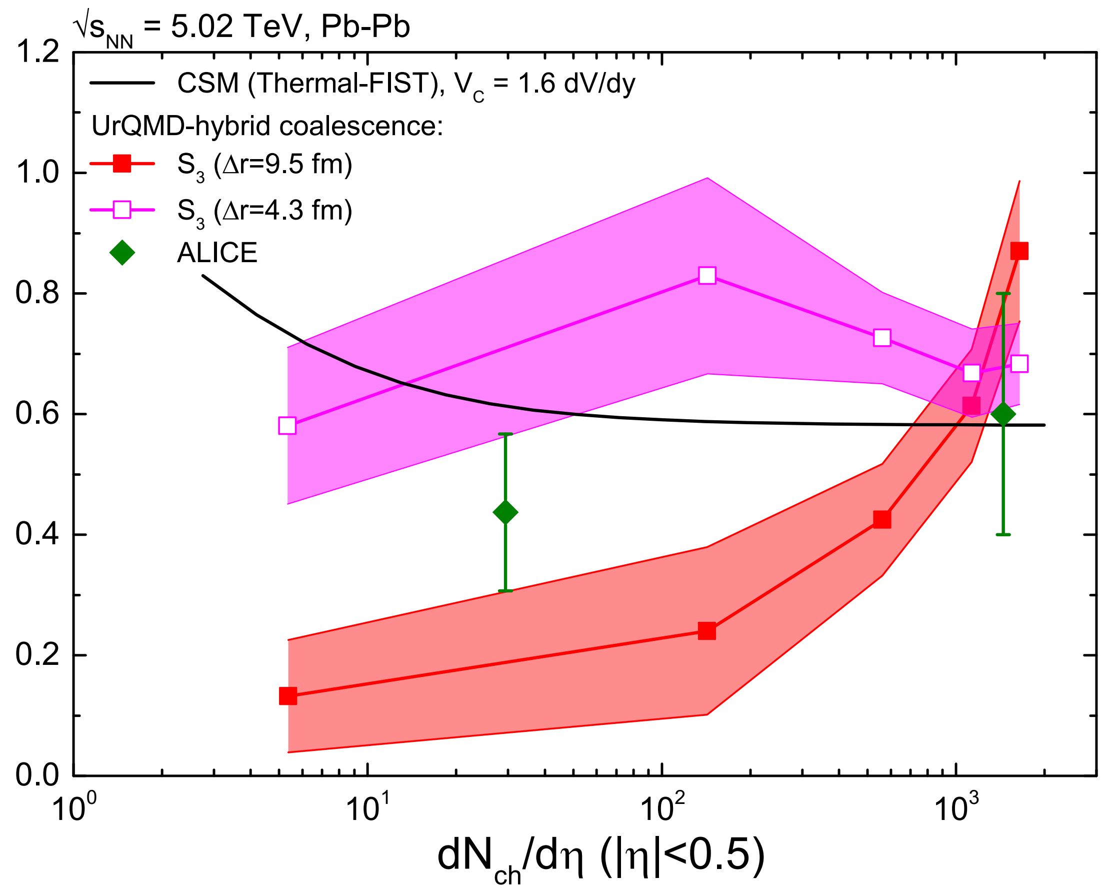
Centrality dependence of S_3

- Similar behavior is observed for the double ratios
- Different source sizes give different behavior
- Note that in pp also canonical effects are naturally included
- Experimental situation is not yet conclusive



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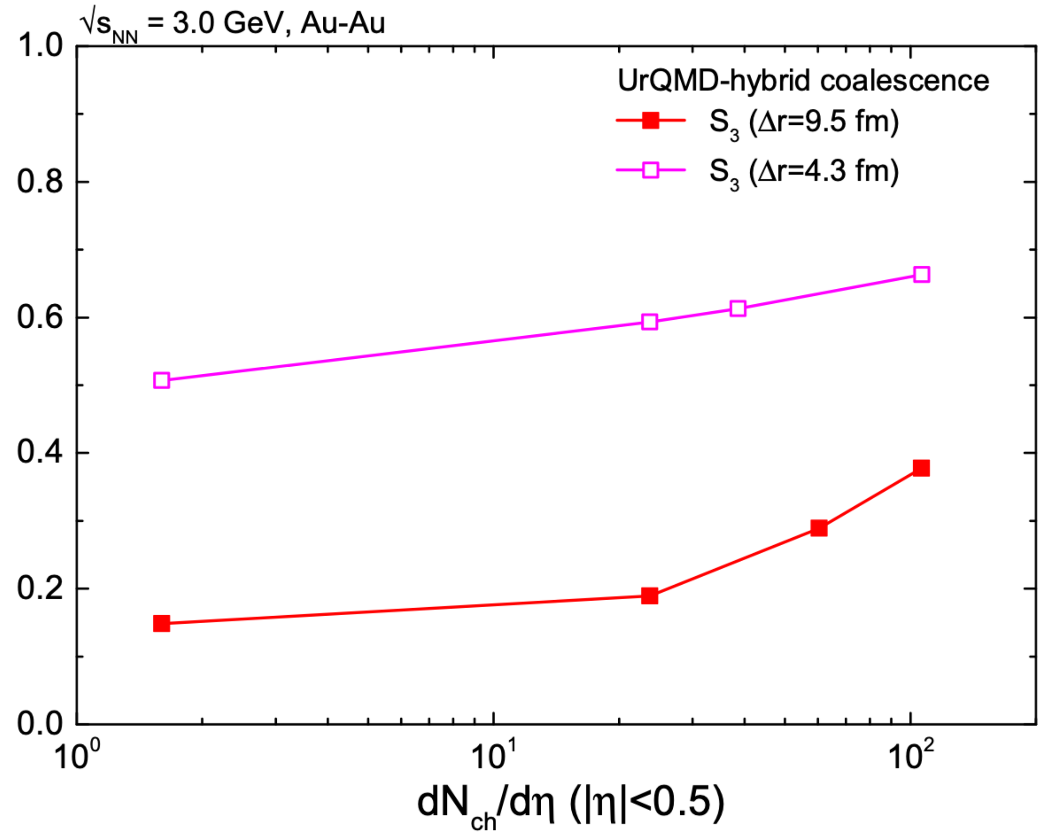
Centrality dependence of S_3

- Dependence on source size also observed at 3 GeV
- Here Δr also affects S_3 in central collisions
- Preliminary STAR data at 3 GeV:

S_3 = 0.2 - 0.5 at $dN_{ch}/d\eta$ = 20 – 50

- Not conclusive either



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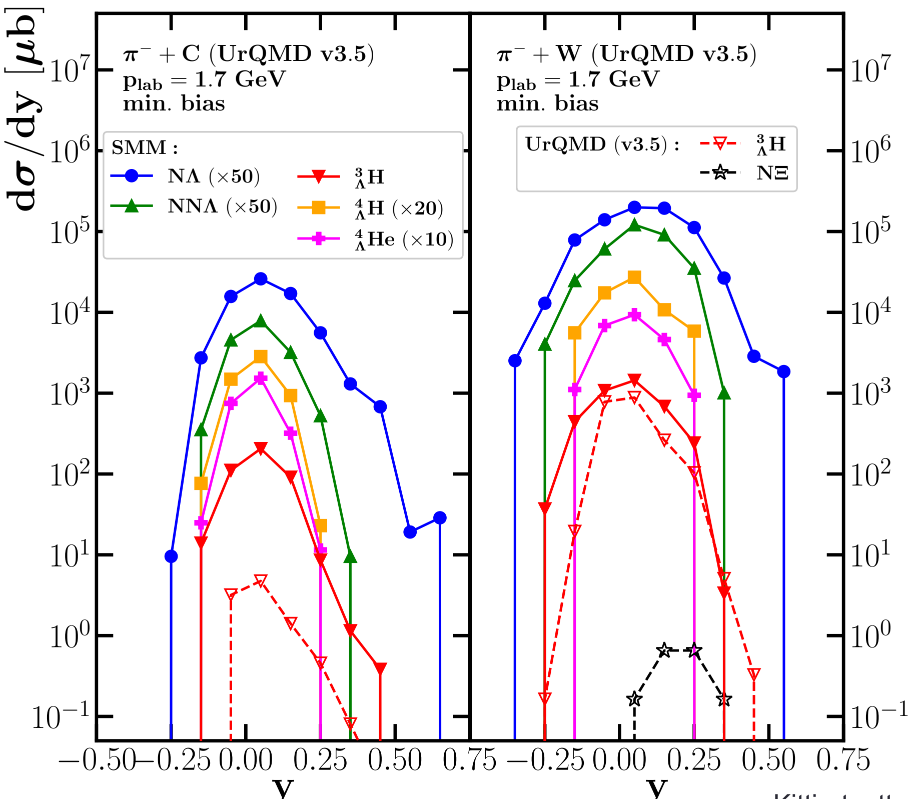
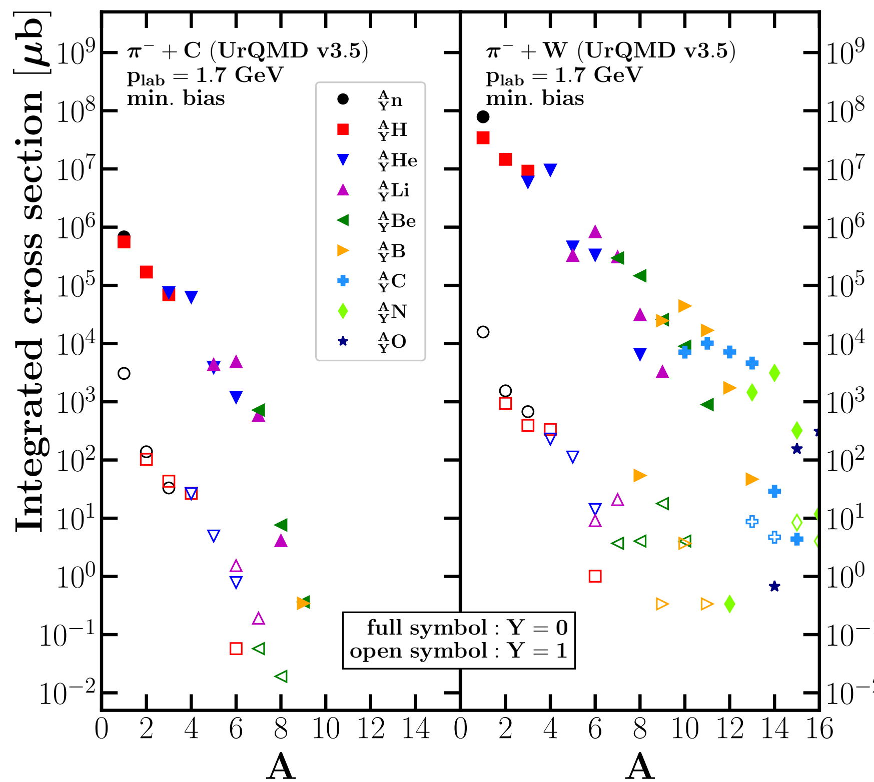
Cluster production in pion induced reactions

- Using a pion beam allows to create hyperon within the target
- (Hyper-)nuclei formation through fragmentation





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System size dependence in pion induced reactions

- Using a pion beam allows to create hyperon within the target
- (Hyper-)nuclei formation through fragmentation

- Abundant (hyper-)nuclei yields even more large mass numbers
- One might event observe Ξ-hypernuclei
- Same system size dependence as ALICE data (scaled S_3)

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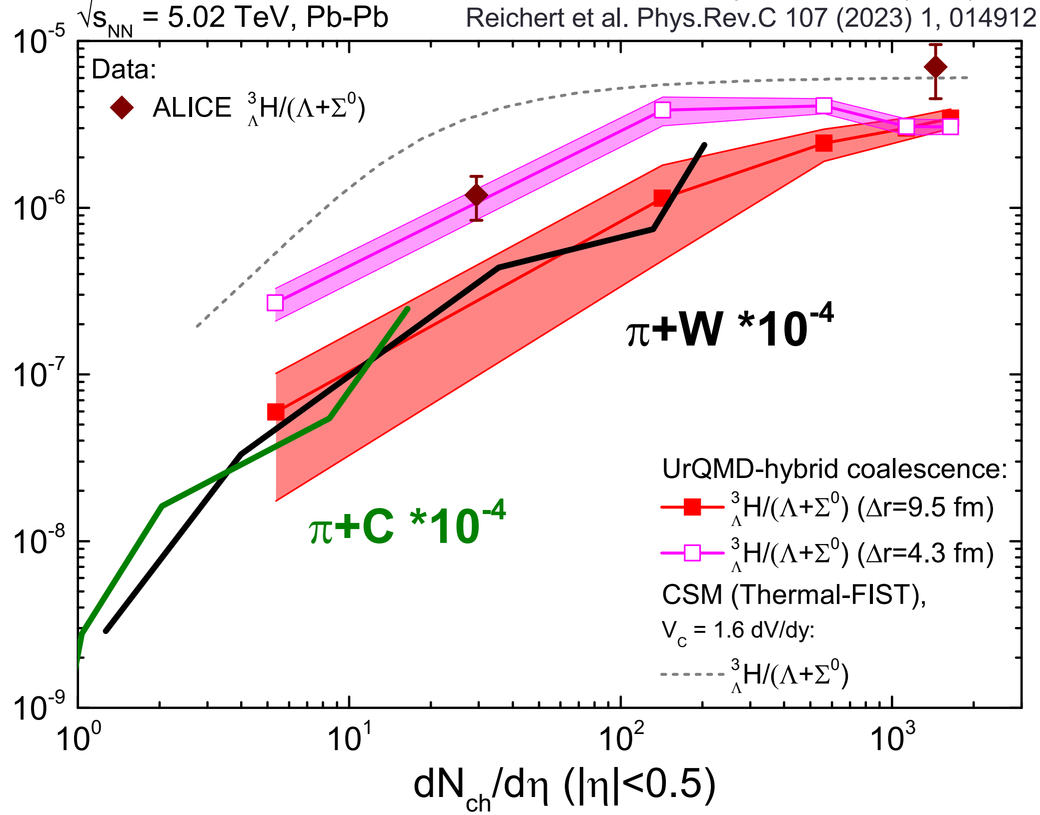

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Take-home messages

- Coalescence successfully describes the production of light- and hypernuclei in various systems and energies
- Isospin effects at high baryon densities are relevant
- Strong annihilation signal seen in ^{4}He/p ratio at the LHC
- Strong fluctuations in coordinate space seen, signal in momentum space is rather weak
- System size dependence of hypertriton production can tell us about its source size, can be studied in various systems
- Pion beams pose a unique tool to study multi-hypernuclear objects

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HFHF Helmholtz Forschungsakademie Hessen für FAIR
ITP Institute for Theoretical Physics