THERMAL MODEL OR COALESCENCE?

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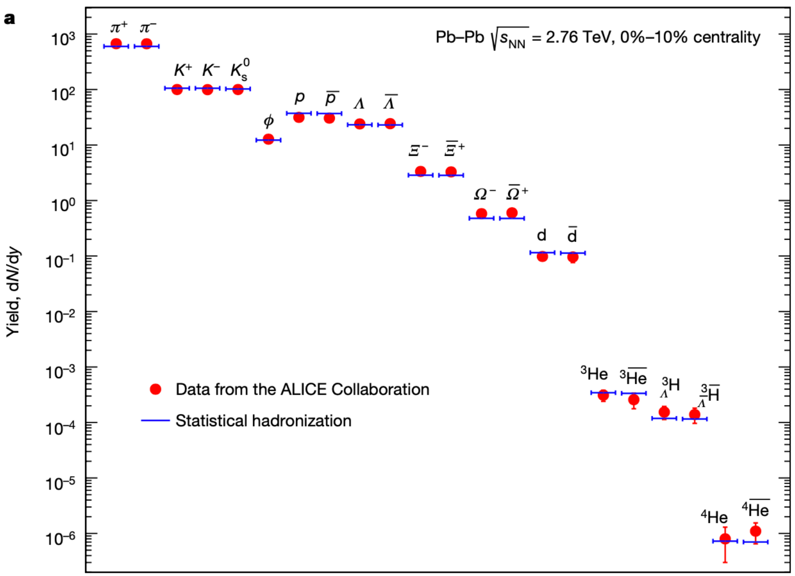
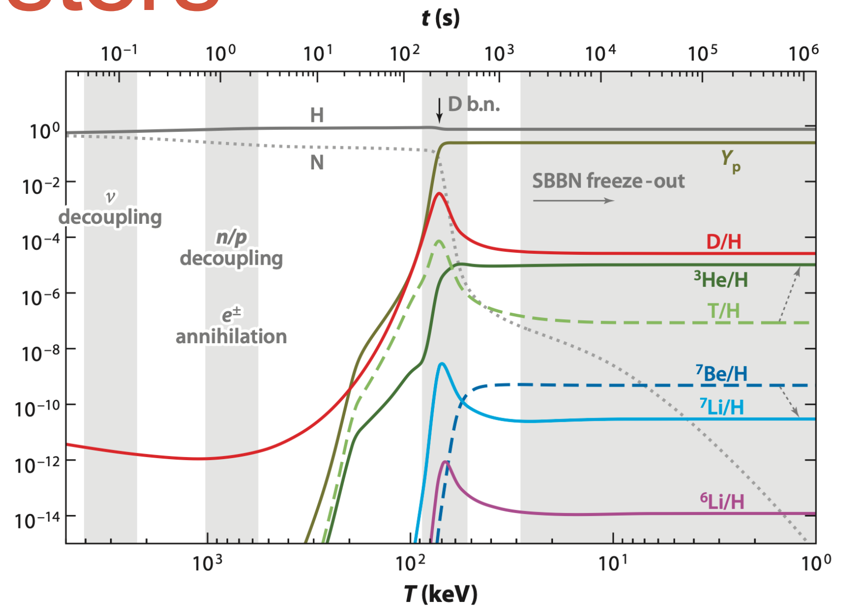
Motivation – Light clusters



A. Andronic et al. Nature 561 (2018) 7723, 321-330



M. Pospelov, J. Pradler. Ann.Rev.Nucl.Part.Sci. 60 (2010) 539-568

- Thermal model provides good description of cluster yields
- Surprising because deuteron binding energy (B_d=2.2 MeV) is much smaller than emission temperature (T=150-160 MeV)
- Similar problem in BB nucleosynthesis, known as deuteron Bottleneck

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)
→ Talk by Maximilian Horst on Mon

Kinetic production

- Introduce explicit processes, e.g. $np\pi \to d\pi$
- Dynamical treatment
- ‘Fake’ 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
→ Talks by Elena Bratkovskaya on Tue, Kai Sun on Mon

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
→ Talk by Susanne Gläßel on Mon

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
→ Talk by Jan Steinheimer on Wed

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
→ Talk by Johanna Stachel on Tue

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

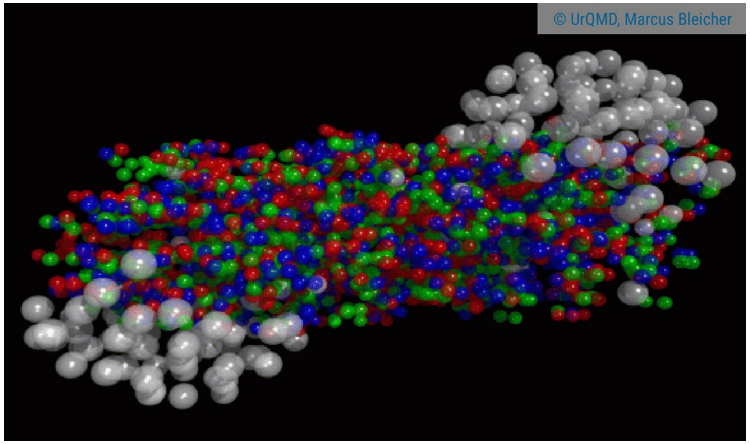
- Clusters are weakly bound compared to momentum transfer (temperature)
- Clusters are formed after kinetic freeze-out
- Coalescence: Cluster is formed if correct constituents occupy certain phase space volume

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

- 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
→ Talk by Jan Steinheimer on Wed

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

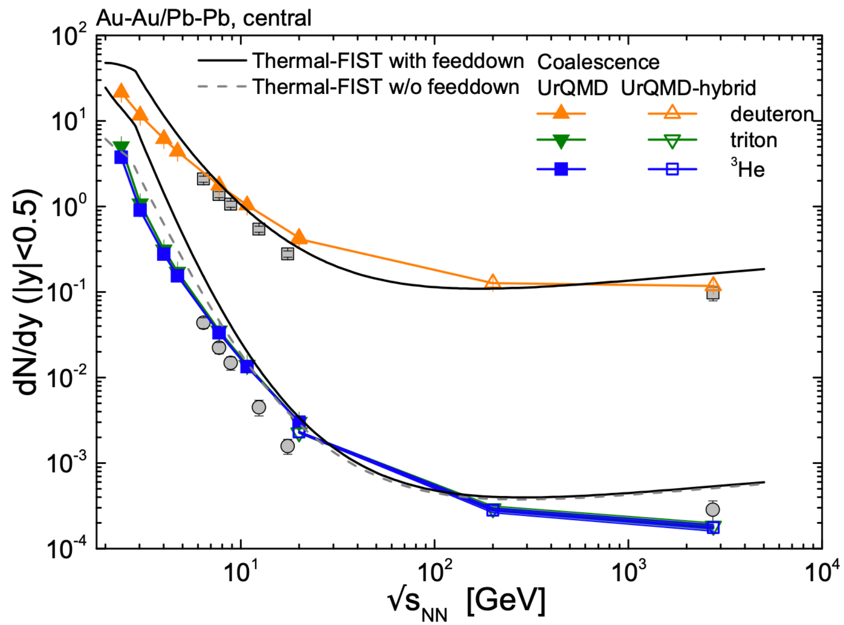
Thermal model vs. Coalescence

- Light cluster multiplicities in coalescence and thermal models is similar although model assumptions differ

S. Das Gupta, A. Mekjian. Phys. Rept. 72, 131 (1981)
S. Mrowczynski. Eur. Phys. J. ST (229), no.22-23, 3559-3583 (2020)

- Is there a way to distinguish cluster production at the chemical freeze-out (thermal model) from cluster production at the kinetic freeze-out (coalescence)?

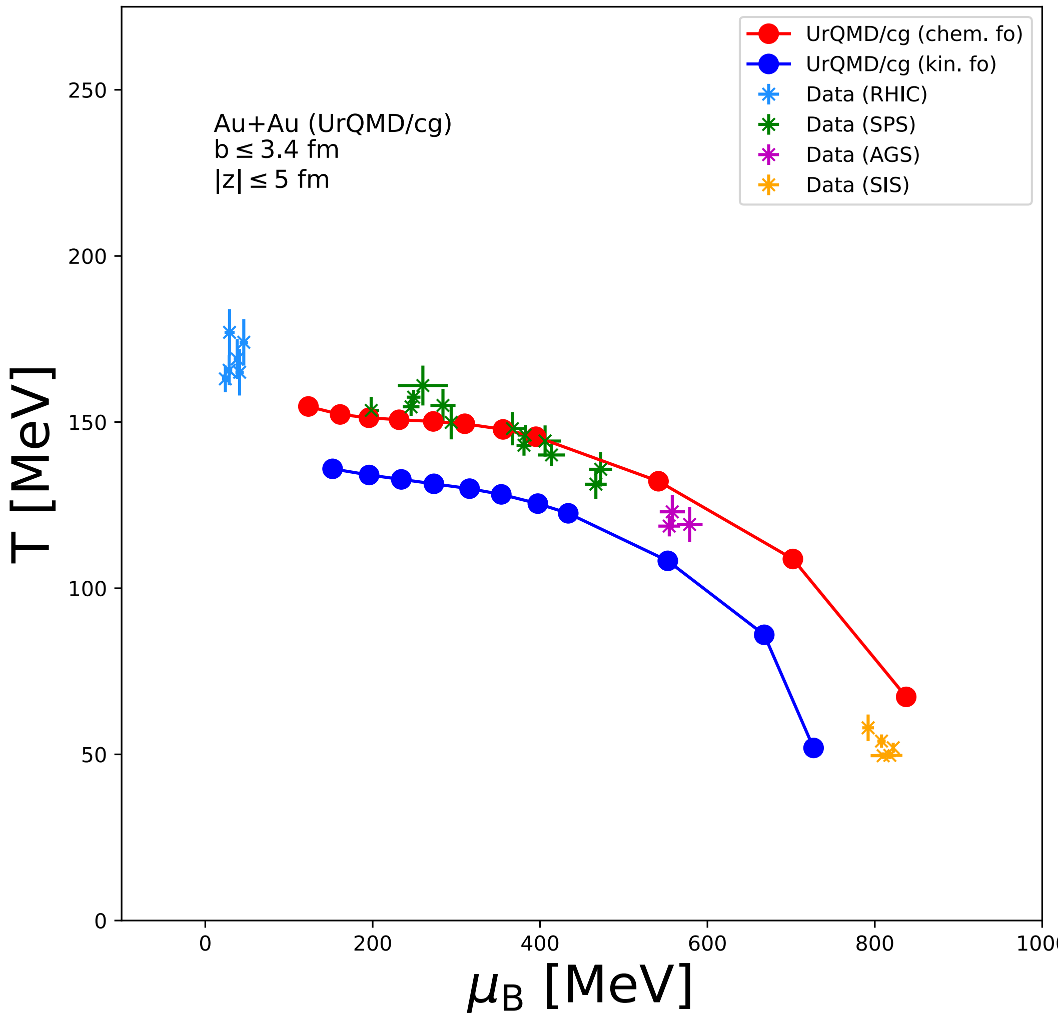
- Transport: Freeze-out distributions have finite width



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

Chemical and kinetic freeze-out

- Chemical freeze-out from UrQMD matches measured data
- Sequential chemical and kinetic freeze-out in the model
- Clusters are produced at kinetic freeze-out



T. Reichert, et al. Eur.Phys.J.A 56 (2020) 10, 267
B. Müller. MDPI Physics 4 (2022) 2, 597-608

Kinetic freeze-out hierarchy

- Pions decouple earlier than nucleons

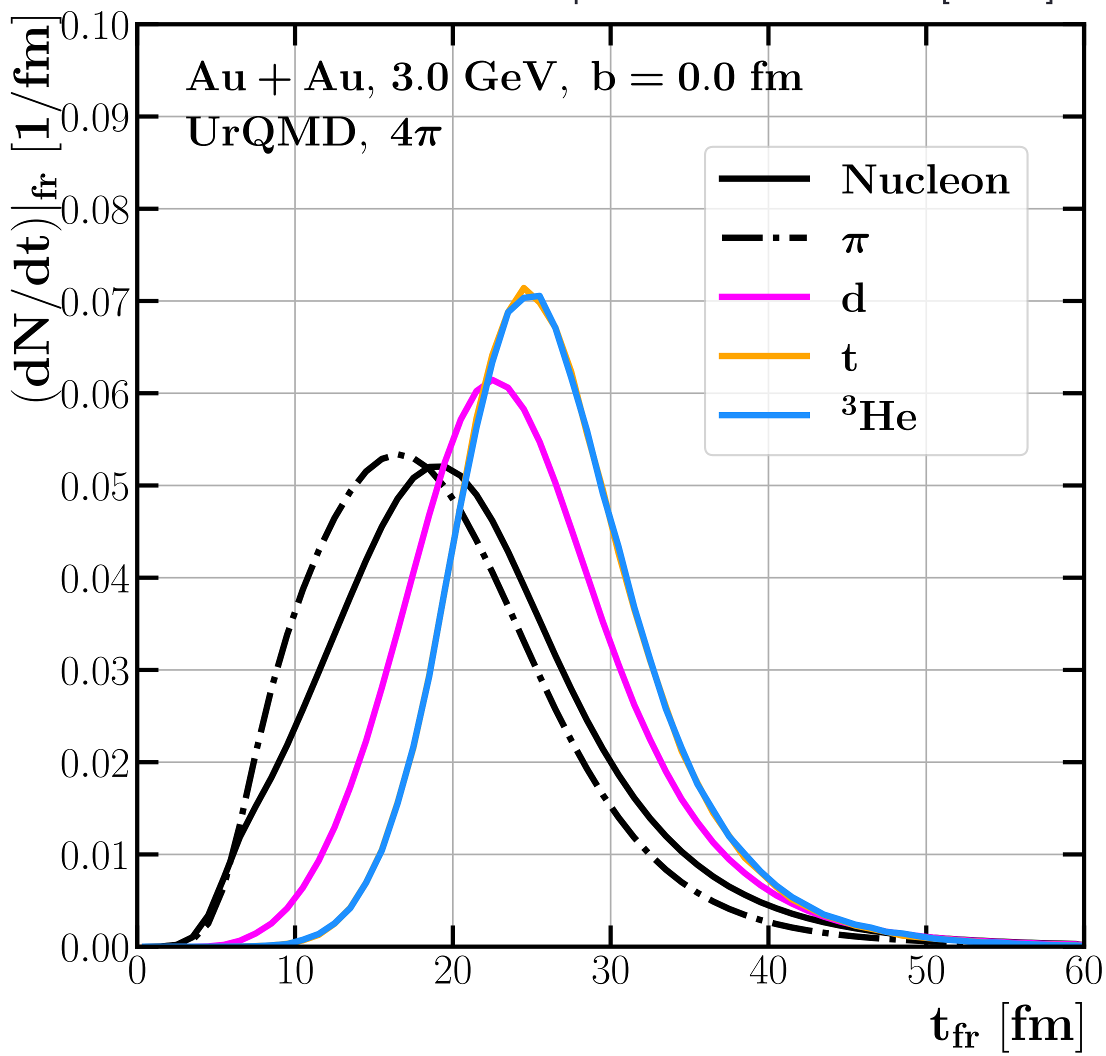
→ Affects isospin balance in nucleons

- Clusters are formed after pion decoupling

→ Cluster production is sensitive to isospin content of baryons

→ Pion trigger allows to select nucleon system before coalescence

A. Kittiratpattana et al. 2210.11699 [nucl-th]



How far can we shift the isospin content?

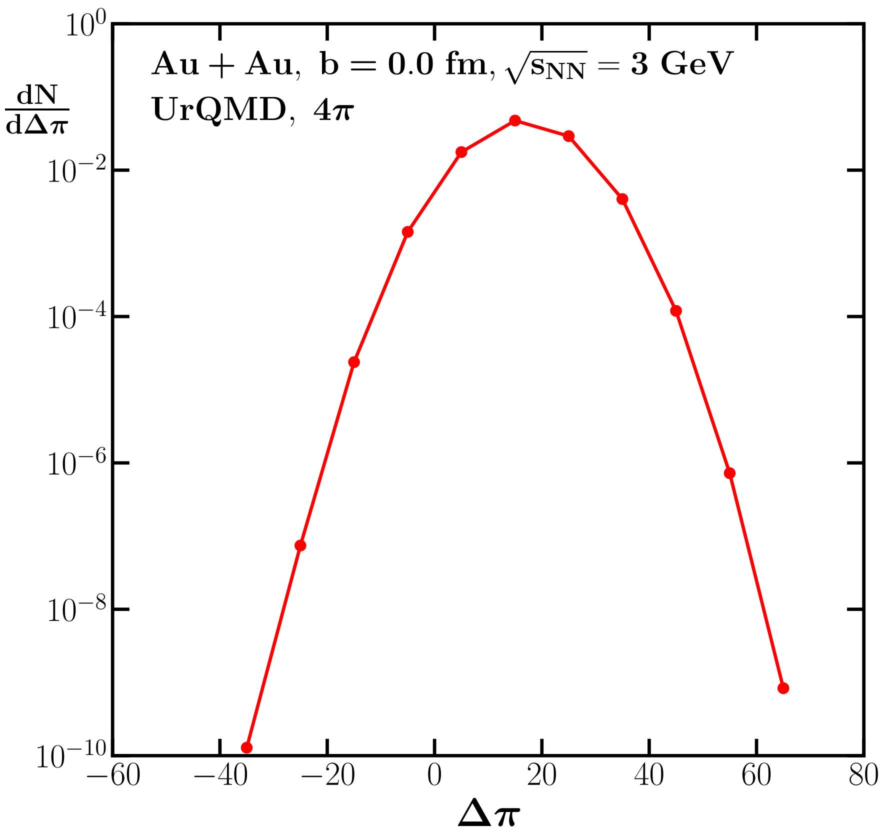
→ Isospin fluctuation strongest if pion number on the order of 2A

→ Calculation at $\sqrt{s_{NN}} = 3$ GeV and $\sqrt{s_{NN}} = 7.7$ GeV

→ Full phase space acceptance

→ Suppress volume effects

→ Ultra-central collisions, b = 0 fm, $A_{part} > 380$



$\Delta\pi \equiv \pi^- - \pi^+$

Estimating the isospin effect on clusters

- Difference in $\Delta\pi \equiv \pi^- - \pi^+$ defines the proton/neutron ratio before coalescence
- Cluster yield is proportional to proton times neutron number

→ No deuterons if there are no protons (no neutrons)

$$d \propto (2N - \Delta\pi) \cdot (2Z + \Delta\pi)$$
$$t \propto (2N - \Delta\pi)^2 \cdot (2Z + \Delta\pi)$$
$$^3He \propto (2N - \Delta\pi) \cdot (2Z + \Delta\pi)^2$$

A. Kittiratpattana et al. 2210.11699 [nucl-th]
A. Kittiratpattana et al. Phys.Rev.C 106 (2022) 4, 044905

Estimating the isospin effect on clusters

A. Kittiratpattana et al. 2210.11699 [nucl-th]

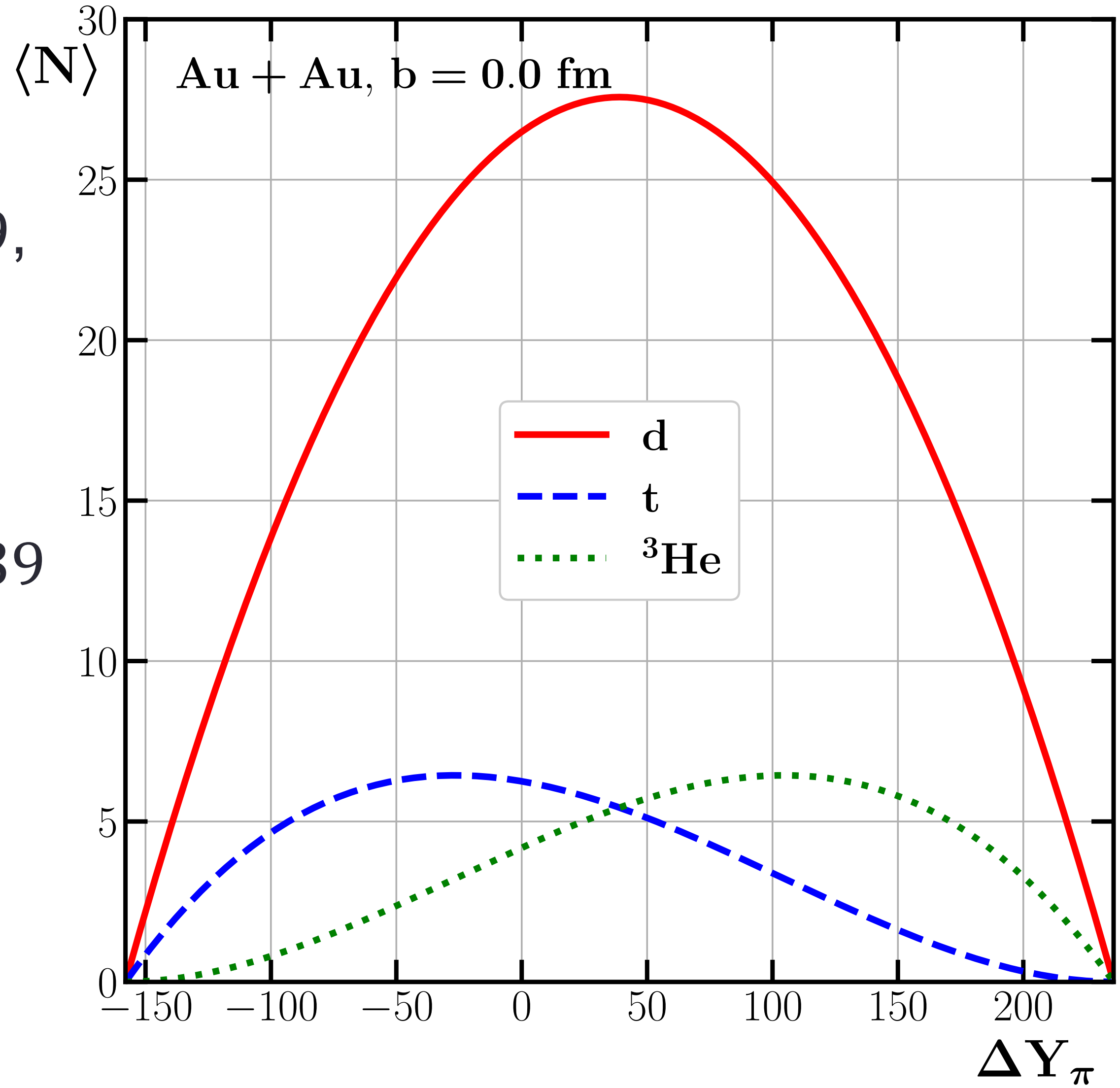
- Deuteron follows parabolic shape

→ Maximum at $\Delta\pi = 39$, i.e. p = n

- Triton, ^{3}He follow 3rd order polynomial

→ Equal yield at $\Delta\pi = 39$

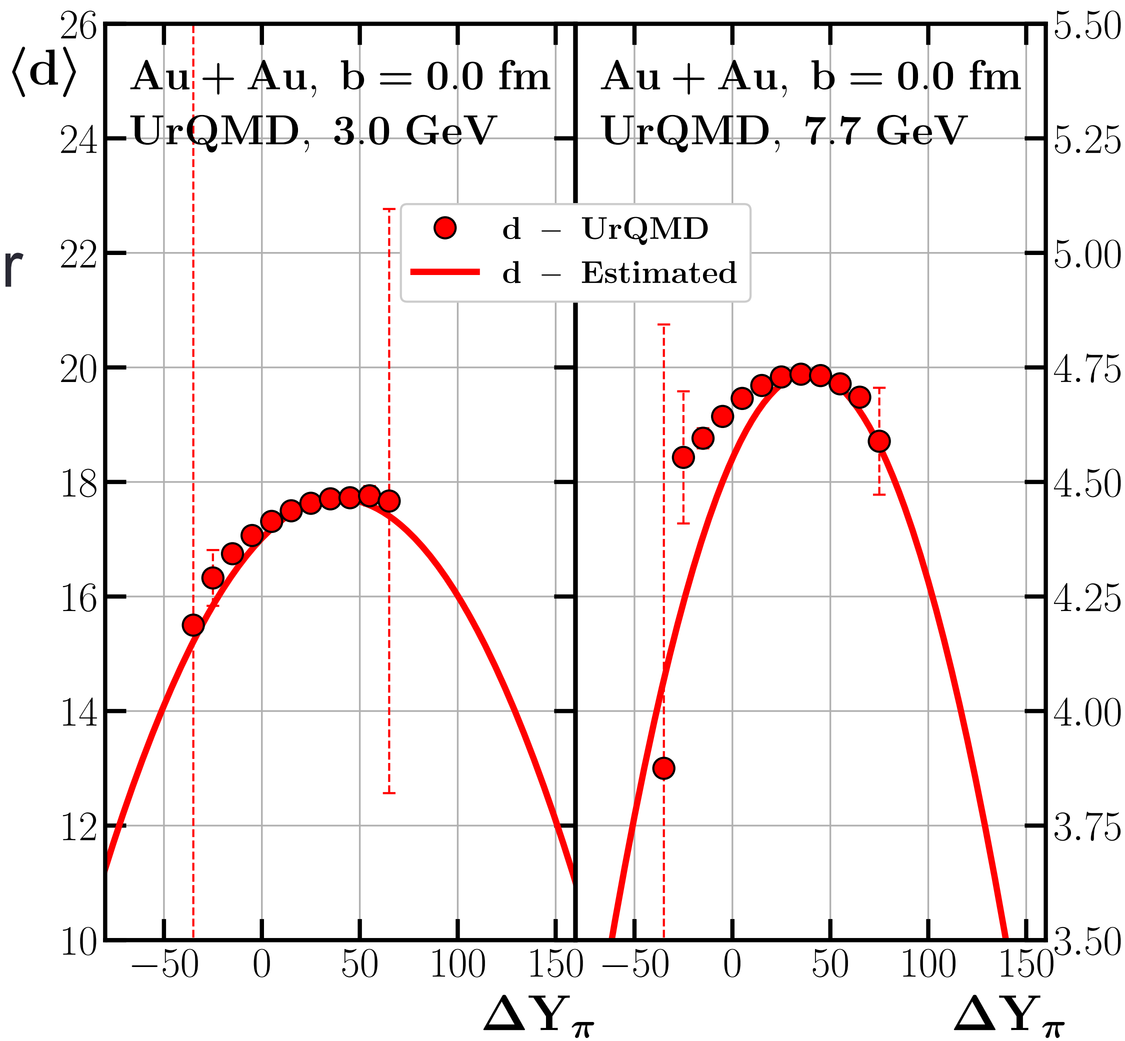
- Zero clusters at the extremes, i.e. no protons (neutrons)



UrQMD calculation

- Maximum of deuteron number at $\Delta\pi = 39$ confirmed
- Decrease towards larger and smaller isospin differences
- Pion decoupling before cluster production
- Thermal model gives a flat dependence

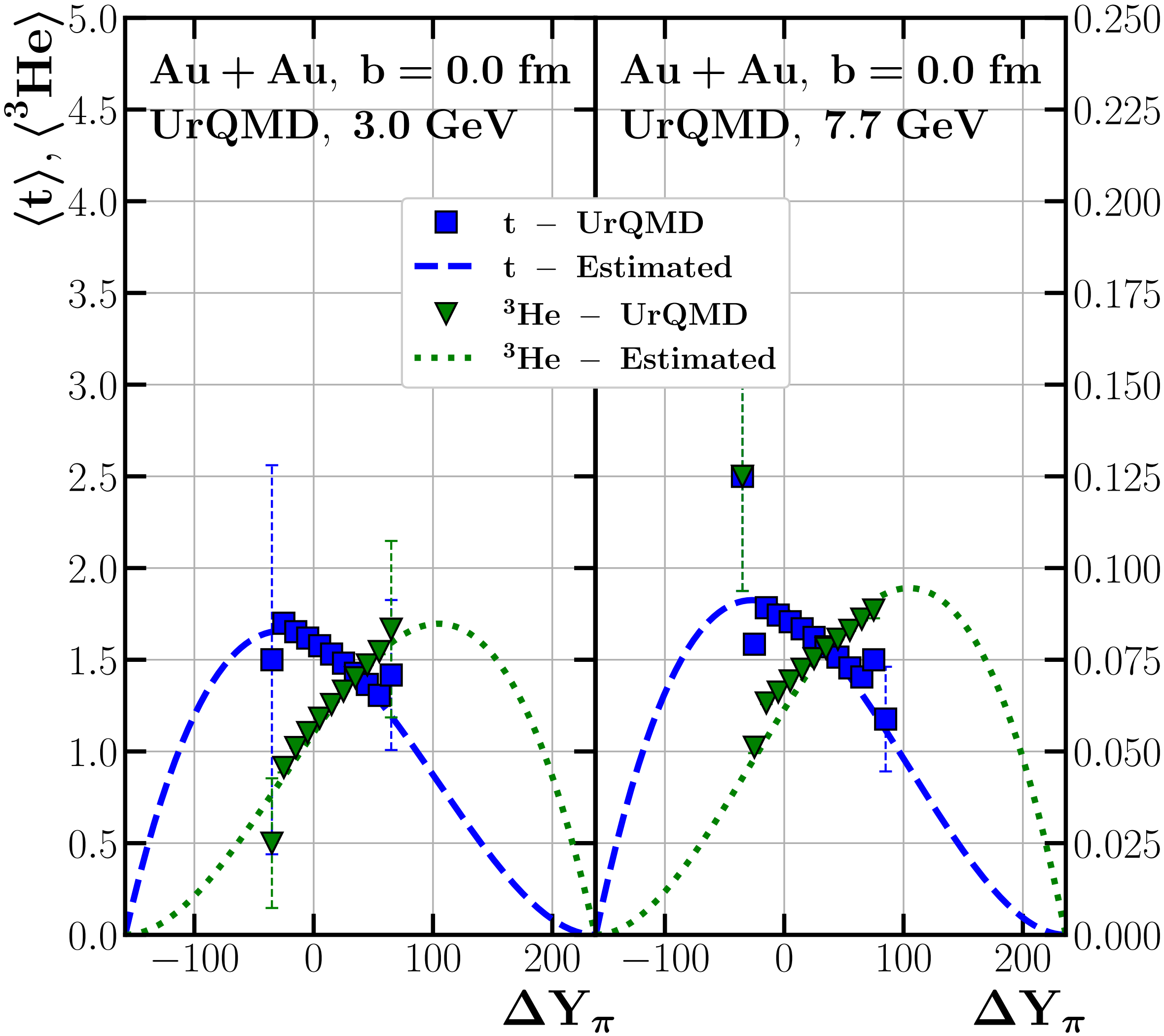
A. Kittiratpattana et al. 2210.11699 [nucl-th]



UrQMD calculation

A. Kittiratpattana et al. 2210.11699 [nucl-th]

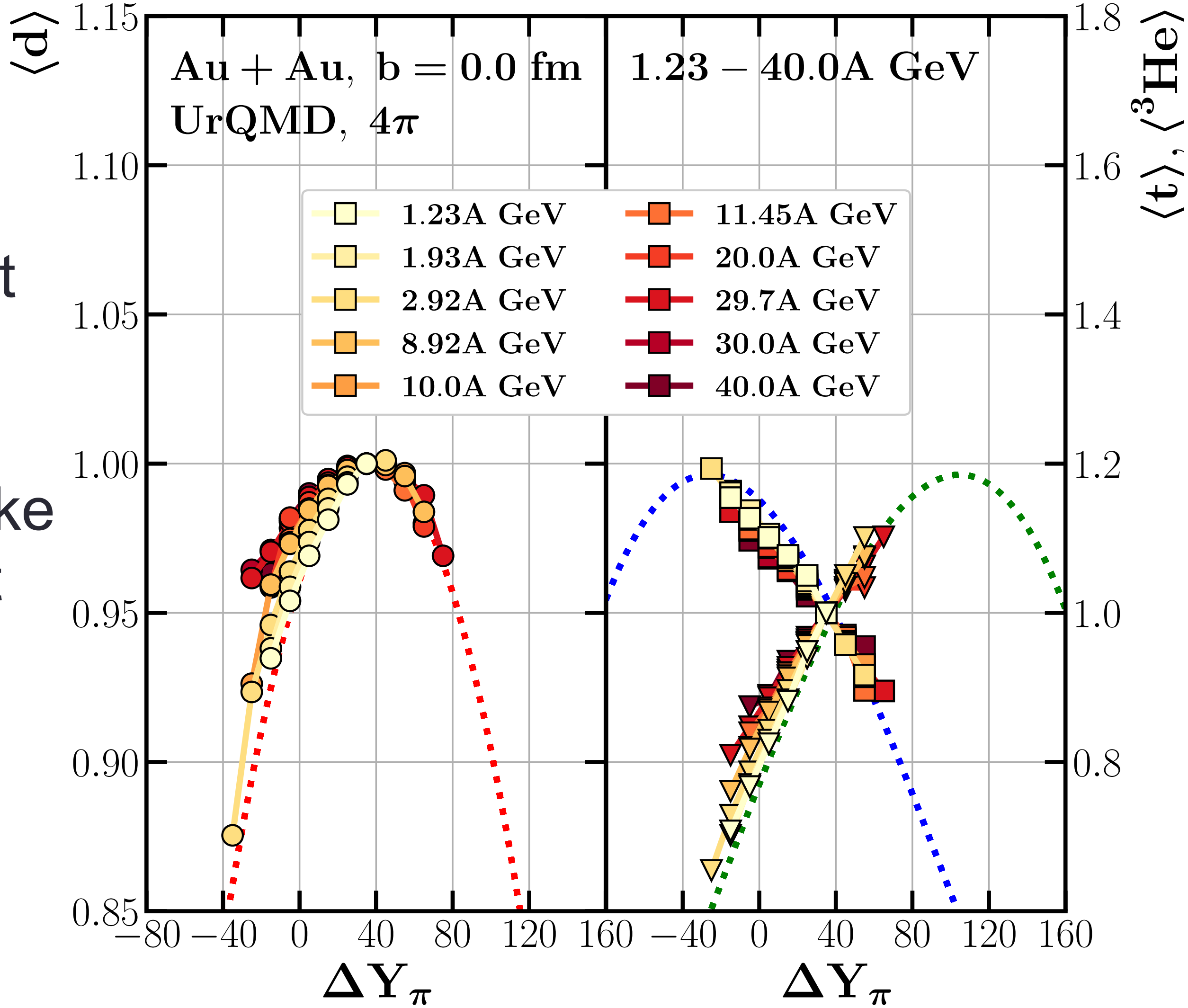
- Equal yield of triton and ^{3}He at $\Delta\pi = 39$ confirmed
- Triton > ^{3}He at smaller $\Delta\pi$
- ^{3}He > Triton at larger $\Delta\pi$
- Pion decoupling before cluster production



UrQMD calculation

- Behavior is present over large range of energies
- Can be measured at HADES, STAR and NA61
- Higher energies: Take total isospin content into account, i.e. Kaons, …

A. Kittiratpattana et al. 2210.11699 [nucl-th]



Summary

- Isospin triggering allows to distinguish between thermal cluster production and coalescence
- Evidence for sequential kinetic decoupling of pions and nucleons and cluster formation via coalescence
- Effect is present in the GSI/HADES, low RHIC-BES, CERN/SPS and upcoming FAIR energy range

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