Light nuclei production in ultrarelativistic heavy-ion collisions via catalysis reactions

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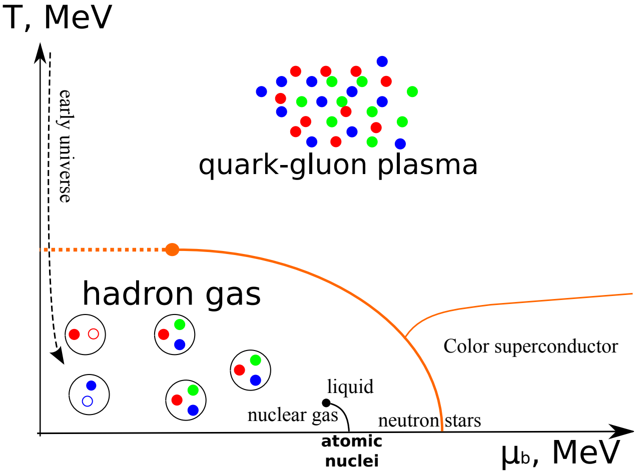
May 19, 2020

Light nuclei and critical fluctuations



Generic critical point feature: **spatial** fluctuations increase

Nucleon density fluctuations in coordinate space

Kaijia Sun et al., Phys. Lett. B 774, 103 (2017)
Kaijia Sun et al., Phys. Lett. B 781 (2018) 499-504

Proton and neutron density:

$$\rho_n(x) = \langle \rho_n \rangle + \delta\rho_n(x)$$

$$\rho_p(x) = \langle \rho_p \rangle + \delta\rho_p(x)$$

Correlations and fluctuations:

$$C_{np} \equiv \langle \delta\rho_n(x)\delta\rho_p(x) \rangle \,/\, (\langle \rho_n \rangle \langle \rho_p \rangle)$$

$$\Delta\rho_n \equiv \left\langle \delta\rho_n(x)^2 \right\rangle / \langle \rho_n \rangle^2$$

From a simple coalescence model

$$N_d \approx \frac{3}{2^{1/2}} \left(\frac{2\pi}{mT}\right)^{3/2} \int d^3x \, \rho_p(x)\rho_n(x) \sim \langle \rho_n \rangle N_p (1 + C_{np})$$

$$N_t \approx \frac{3^{1/2}}{4} \left(\frac{2\pi}{mT}\right)^{3} \int d^3x \, \rho_p(x)\rho_n^2(x) \sim \langle \rho_n \rangle^2 N_p (1 + 2C_{np} + \Delta\rho_n)$$

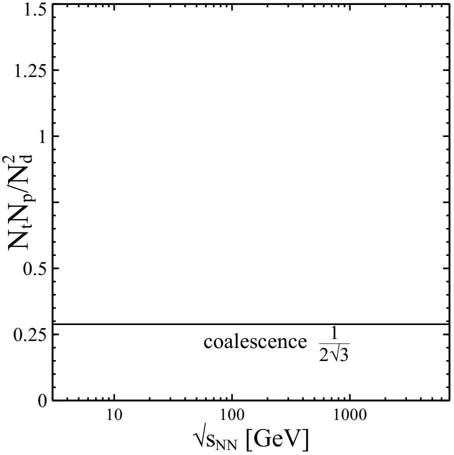
$$\frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}} \frac{1 + 2C_{np} + \Delta\rho_n}{(1 + C_{np})^2}$$

Thermal ratio $\frac{g_t g_p}{g_d^2} \left(\frac{3m \cdot m}{(2m)^2}\right)^{3/2} = \frac{1}{2\sqrt{3}}$ Fluctuations and correlations

Light nuclei are sensitive to spatial density fluctuations

Comparing the *p*-*d*-*t* ratio to NA49, STAR, and ALICE data

Data: NA49 [Anticic:2010mp,Blume:2007kw,Anticic:2016ckv], STAR [Adam:2019wnb,Zhang:2019wun], ALICE [Adam:2015vda]; model JAM + coalescence [Liu:2019nii]; see DO Quark Matter 2019 proceedings



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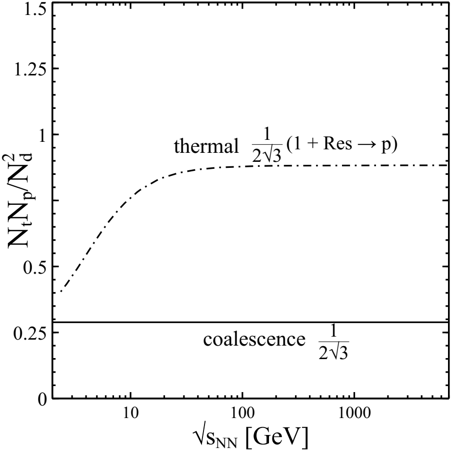

Thermal: first nuclei form, then resonance decays.

Coalescence: first resonances decay, then nuclei form.

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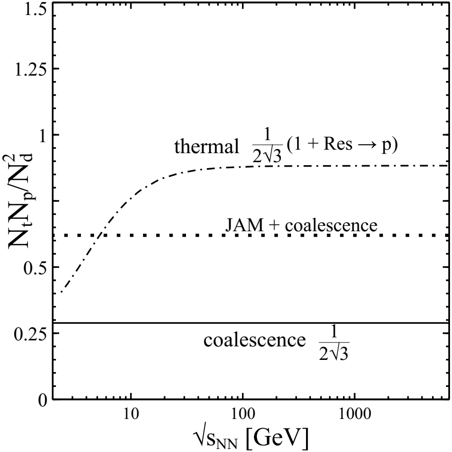

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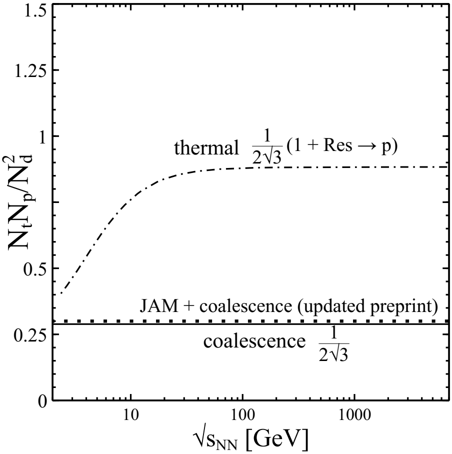

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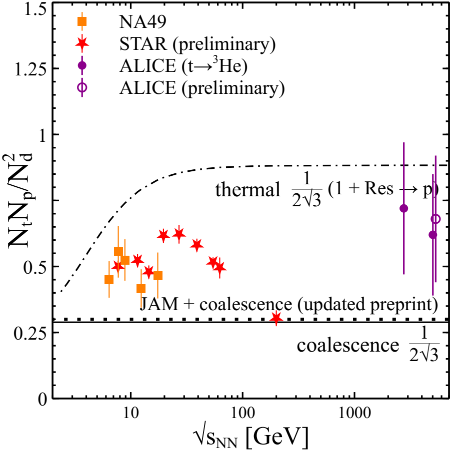


Are the bumps related to fluctuations? Can one generate them without critical point?

Light nuclei production mechanism

- QM perturbation theory

  N + N + *pert* → d, d + *pert* → N + N

  Fast large $V(t) \gg E_{bind}$, $t_{pert} \ll h/E_{bind} \sim 100$ fm/c

  Kapusta:1980zz

- Slower $V(t)$: melting, Mott transition in a hot medium

  Light nuclei in a field, Π and Σ depend on medium

  Ropke:2017own; Blaschke, Kozhevnikova, et al

- $V(t) \sim \delta(t)$ aka "collisions"

  Danielewicz:1991dh,Oh:2009gx,Longacre:2013apa,Oliinychenko:2018ugs

  - pion catalysis

    $\pi NN \leftrightarrow \pi d$ – important because of high pion abundance
  - other catalysis

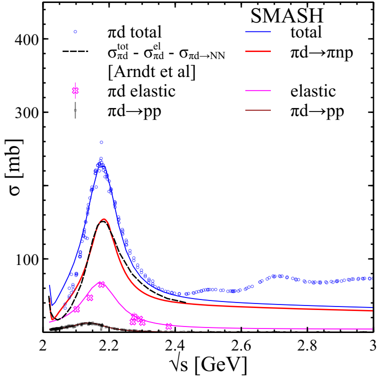
    $\rho NN \leftrightarrow \pi d$, $\pi\pi d$; $NNN \leftrightarrow Nd$, etc
  - other reactions, $N\Delta \leftrightarrow d\pi$

In this talk I focus on pion catalysis. Other mechanisms are certainly possible. Several mechanisms may work together.

Light nuclei production by pion catalysis

- $\pi d \leftrightarrow \pi np$, $\pi t \leftrightarrow \pi nnp$, $\pi^3\mathrm{He} \leftrightarrow \pi npp$
- Disintegration cross section fit to data
- Reverse rates fixed by detailed balance relations

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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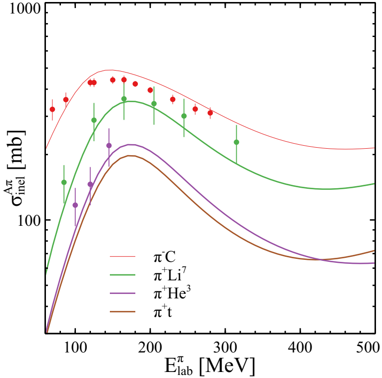
Data: Mihul:1992br,Angelescu:1996ev,Ashery:1981tq,Binon:1970ye



Technical details of reactions implementation

Treating $\pi d \leftrightarrow \pi np$, $\pi t \leftrightarrow \pi nnp$, $\pi\,^3\mathrm{He} \leftrightarrow \pi npp$
directly would be ideal

- Impossible within geometric approach to collision finding
- Recently stochastic collisions implemented in SMASH
- Now it is possible
- But all results here obtained with

$$pn \leftrightarrow d'$$

$$d'\pi \leftrightarrow d\pi$$

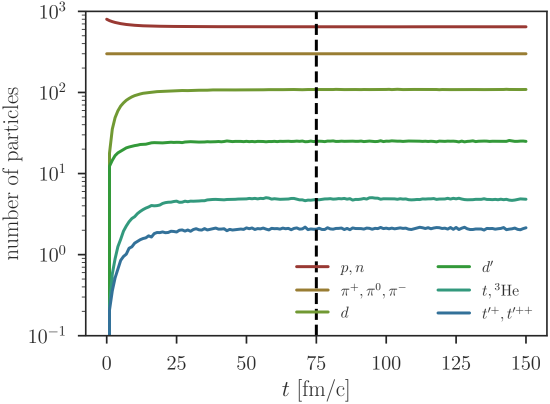
$$d'N \leftrightarrow t'$$

$$t'\pi \leftrightarrow t\pi$$

It does NOT mean that d' and t' states are essential for this approach. They are not!

Testing detailed balance in the box

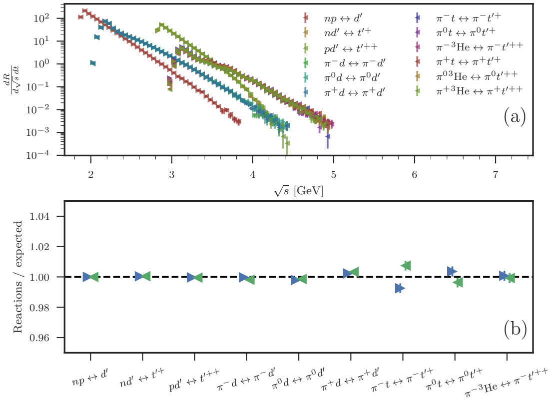
Put some nucleons and pions in the box, allow only reactions forming nuclei and wait



Detailed balance is fulfilled

Testing detailed balance in the box

Count reactions when yields are equilibrated, forward rates should be equal to reverse. Far less trivial test, than yield equilibration. Great bug detector!



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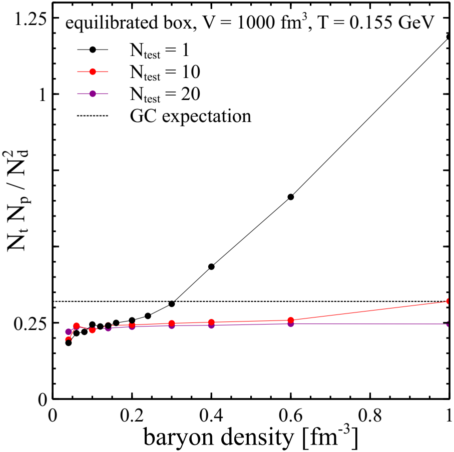
Testing detailed balance in the box

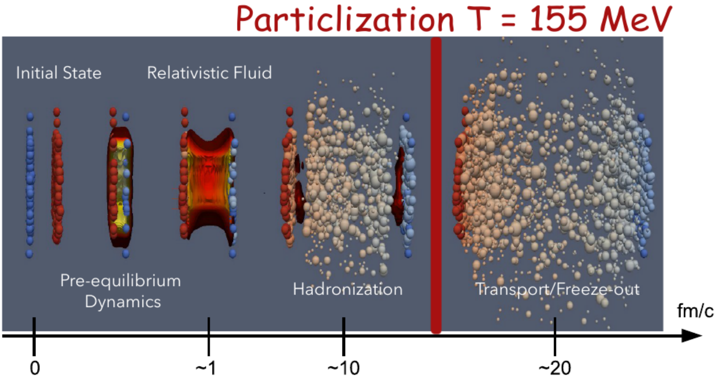


- Needs care at high density: testparticles, $N_{test} = 10$
- Small, but persistent deviation of tp/d^2 from analytical
- Likely related to geometrical collision criterion, I hope stochastic rates fix it

Deuterons at LHC with pion catalysis

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907

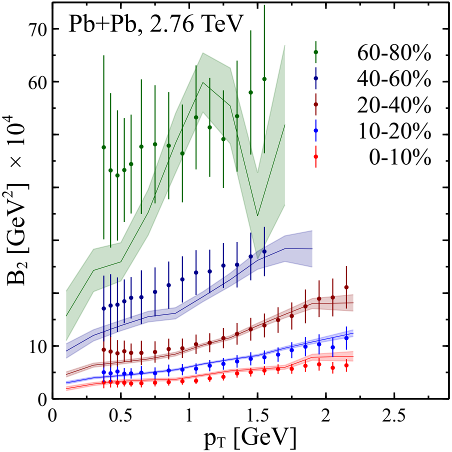
DO, Pang, Elfner, Koch, MDPI Proc. 10 (2019) no.1, 6



- CLVisc hydro L. G. Pang, H. Petersen and X. N. Wang, arXiv:1802.04449 [nucl-th]
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)

LHC, deuteron: $B_2(p_T)$ for different centralities

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907

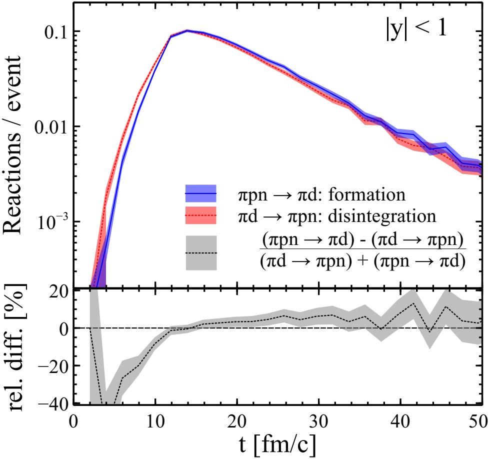


$$B_2(p_T) = \frac{\frac{1}{2\pi}\frac{d^3N_d}{p_T dp_T dy}\Big|_{p_T^d = 2p_T^p}}{\left(\frac{1}{2\pi}\frac{d^3N_p}{p_T dp_T dy}\right)^2}$$

No free parameters. Works well for all centralities.

Is $\pi d \leftrightarrow \pi np$ reaction equilibrated

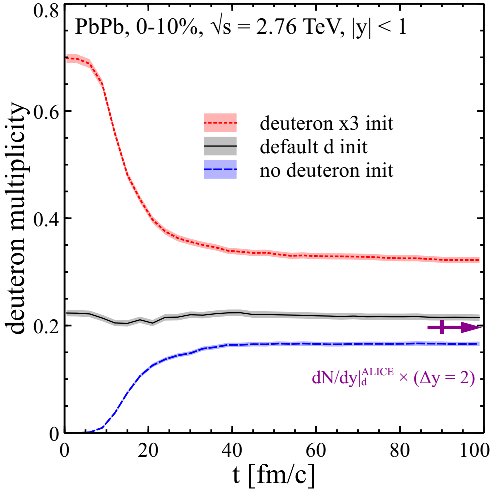
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



After about 12-15 fm/c within 5% $\pi d \leftrightarrow \pi np$ is equilibrated

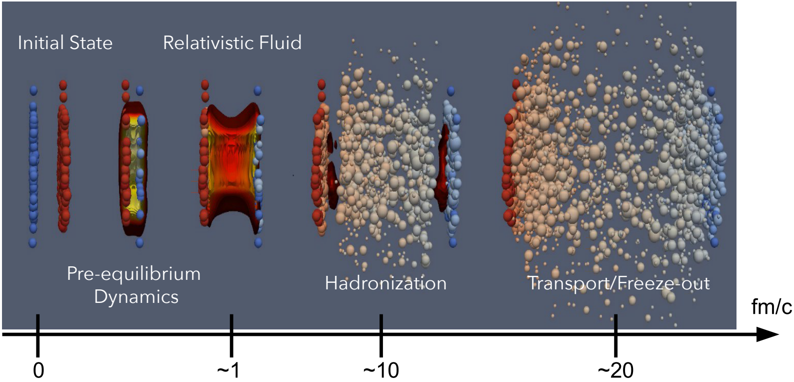
Deuteron yield

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



The yield is almost constant. No deuterons at particlization: yield is lower by ∼ 20%.

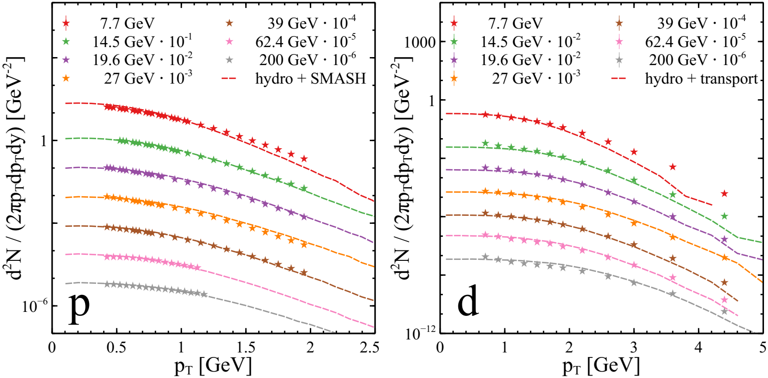
Hybrid approach for STAR energies



- MUSIC hydro B. Schenke, S. Jeon, C. Gale, PRC 82, 014903 (2010)
  viscous 3+1D hydrodynamics with j_B, EoS with μ_B, μ_S, μ_Q
  particlization at constant energy density
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)
  Same light nuclei reactions as used for LHC

d,t @ STAR by MUSIC + SMASH with catalysis reactions

Data: Alt:2006dk, Anticic:2010mp, Adams:2003xp, Adamczyk:2017iwn, Abelev:2009bw, Adcox:2003nr, Klay:2001tf, Ahle:1999in,Adam:2019wnb, Zhang:2019wun



MUSIC + SMASH with explicit catalysis reactions describes deuterons rather well (as good as protons)

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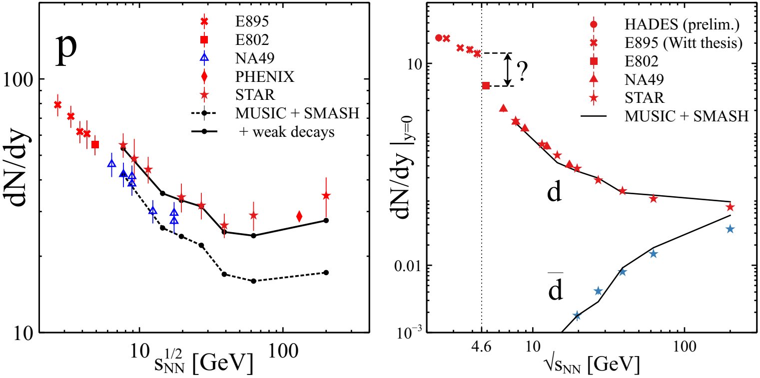

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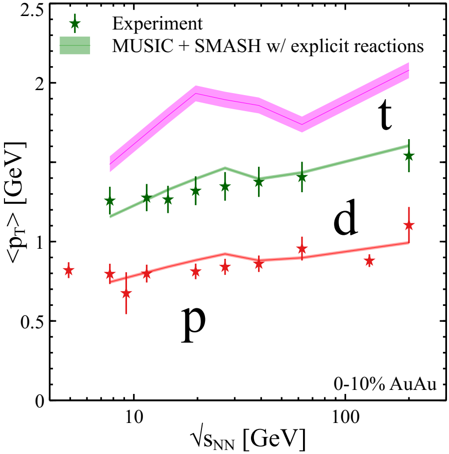

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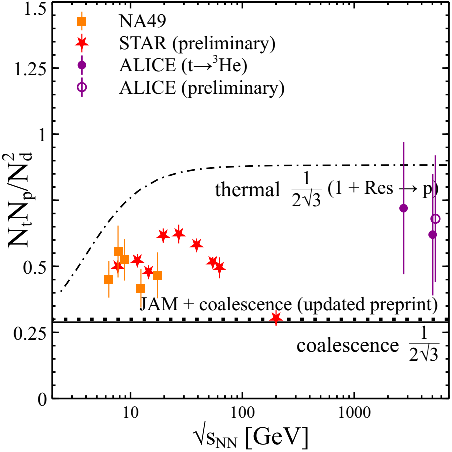

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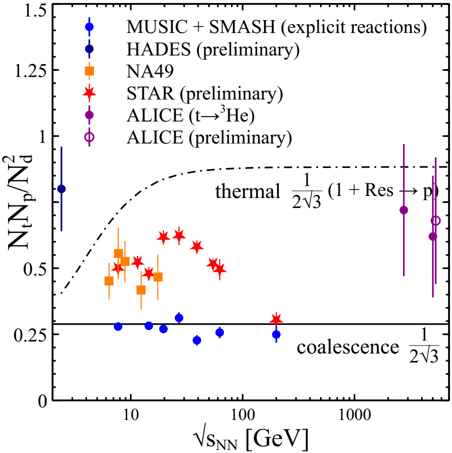

Do catalysis reactions act as coalescence?

d,t @ STAR by MUSIC + SMASH with catalysis reactions

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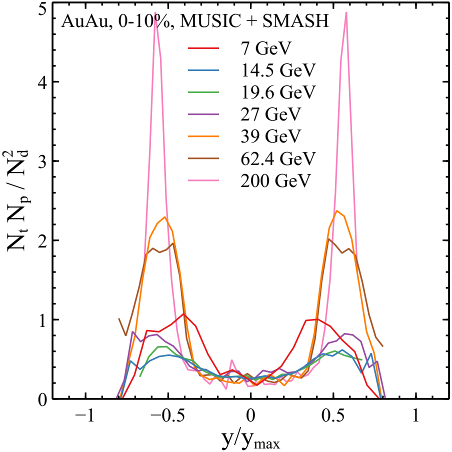
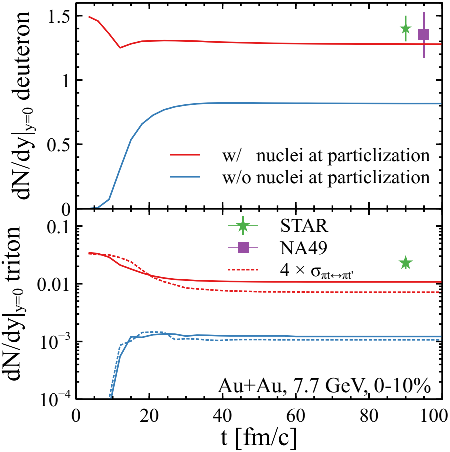


Do catalysis reactions act as coalescence? Not necessarily!

(Caveat, this was obtained with $N_{test} = 1$.)

Is deuteron/triton in partial equilibrium at STAR energies?



Yes for deuteron. At 7.7 GeV it still behaves similarly to LHC.

Triton seems to be off any equilibrium dramatically! Something fishy in the calculation? But it's tested in the box...

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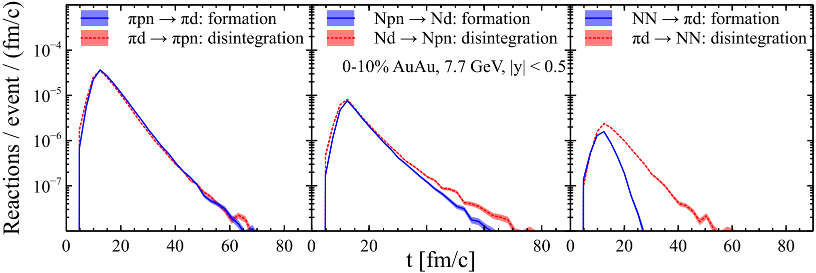

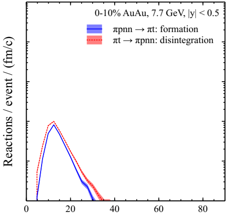

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MUSIC + SMASH: intermediate conclusions

- hydro + SMASH describes deuteron well both at STAR and LHC energies with the same pion catalysis reactions
- Deuteron is close to partial equilibrium both at STAR and LHC
- Triton is way off equilibrium (maybe a side effect of d' and t'?)
- $N_t N_p / N_d^2$ ratio comes out flat and coalescence-like at mid-rapidity

Now let's try

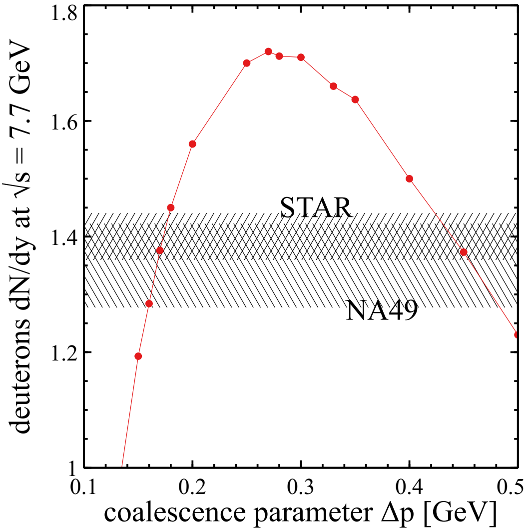
1) MUSIC + SMASH + coalescence

2) SMASH + coalescence

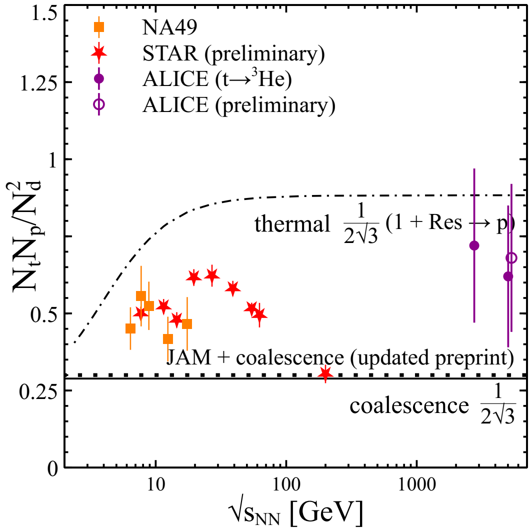
My rather simple coalescence

- Partially inspired by Sombun et al (UrQMD + coalescence)
- Coalescence at the latest of the last interaction times
- $pn \to d$, $dn \to t$
- $\Delta p_d = \Delta p_t = 0.42$ GeV, $\Delta R_{d,t} = h/\Delta p_d$
- Rejection with isospin factors 3/8 (d) and 1/4 (t)
- Tune to 7.7 GeV: STAR and NA49 agree here

Tuning the coalescence (there is only one parameter!)



Coalescence and p-t-d double ratio



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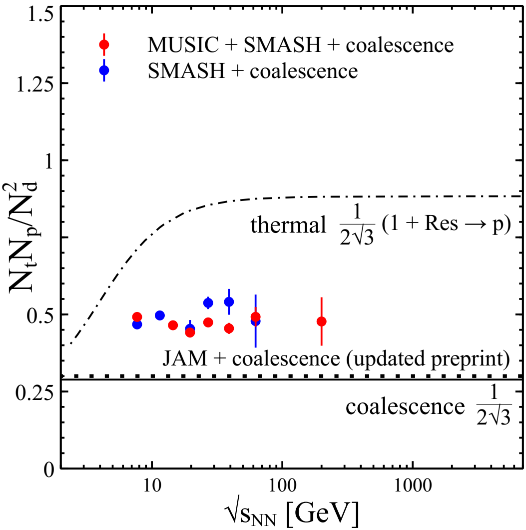
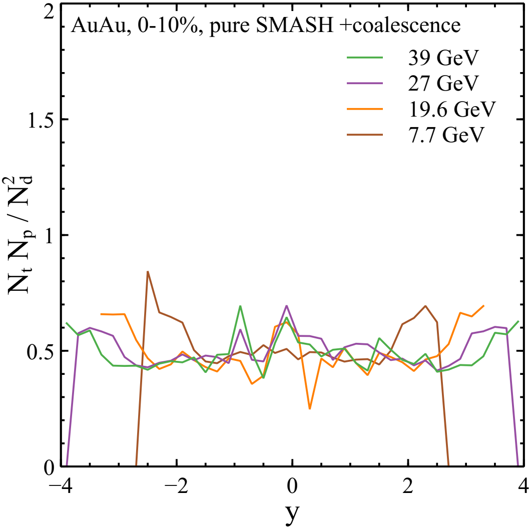


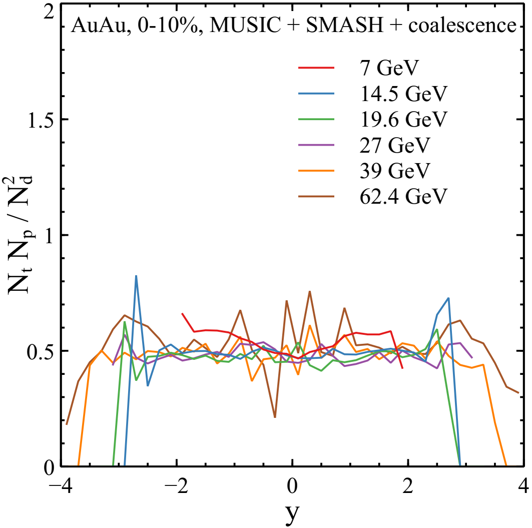
The ratio is flat as a function of energy

Coalescence and p-t-d double ratio



The ratio is flat as a function of rapidity

Coalescence and p-t-d double ratio



The ratio is flat as a function of rapidity

Summary and outlook

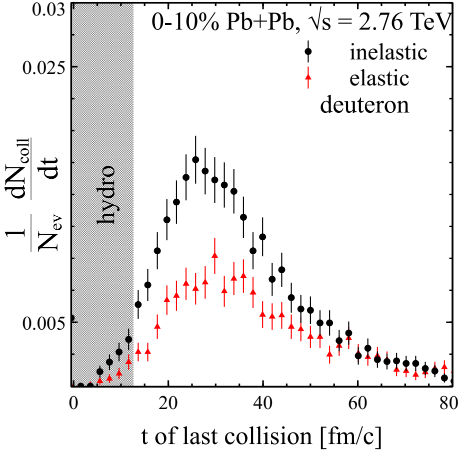
- The ratio $N_t N_p / N_d^2$ may be related to the critical point
- In coalescence models $N_t N_p / N_d^2(\sqrt{s}, y)$ is always flat regardless of
    - The underlying model: JAM, SMASH, MUSIC + SMASH
    - How well the underlying model describes protons
    - What the specific details of coalescence procedure are
- Alternative to coalescence: explicit catalysis reactions
    - Describe deuterons as good as protons in the underlying model
    - Suggest that deuteron is close to partial chemical equilibrium (PCE) both at STAR and LHC energies
    - Triton seems to be out of PCE, still under investigation
    - $N_t N_p / N_d^2$ may be flat (MUSIC + SMASH), but not necessarily (SMASH)

Outlook: investigate the effect of nuclear potentials with, try hydro with a critical point in the EoS

Backup

Does deuteron freeze out at 155 MeV?

Only less than 1% of final deuterons originate from hydrodynamics



Deuteron freezes out at late time

Its chemical and kinetic freeze-outs roughly coincide

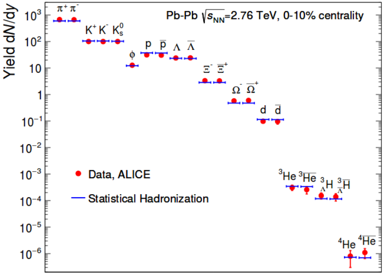
Thermal model and “snowballs in hell” puzzle

- Nuclei formed early — at hadronic freeze-out

$$N_A \approx g_A V \, (\pi T m_A/2)^{3/2} \, e^{(A\mu_B - m_A)/T}$$

- ALICE fit of yields, Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV: $T = 155$ MeV
- Nuclei momentum spectra: $T_{kin} \simeq 110$ MeV
- How can they survive from chemical to kinetic freeze-out?
- Binding energies: d, $^3\mathrm{He}$, $^3_\Lambda\mathrm{H}$, $^4\mathrm{He}$ – few MeV

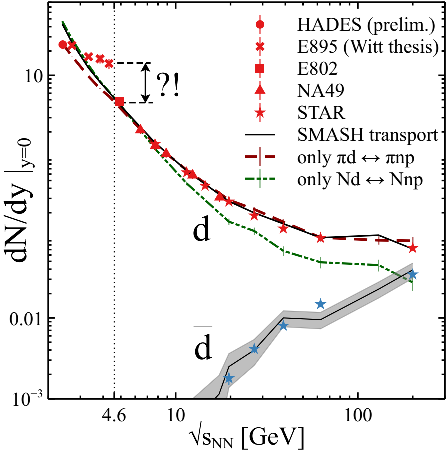
Snowballs in hell.



Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561 (2018) no.7723, 321-3305

Light nuclei: rapid chemical freeze-out at 155 MeV, like hadrons?

Deuterons @ STAR by pure SMASH with catalysis reactions

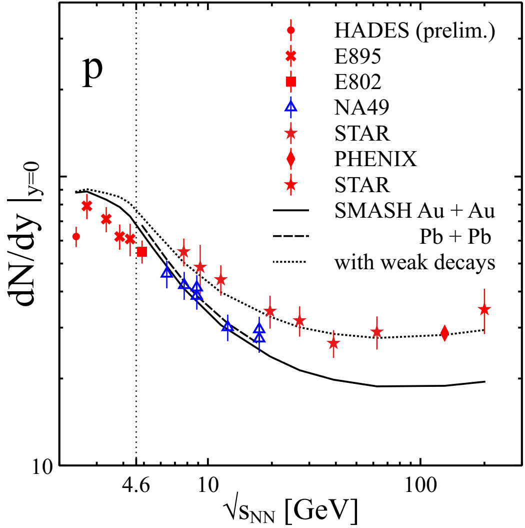


Pion catalysis dominates at STAR energies

Note the (unpublished) jump around 4.6 GeV,

no jump there for protons

SMASH and proton spectra



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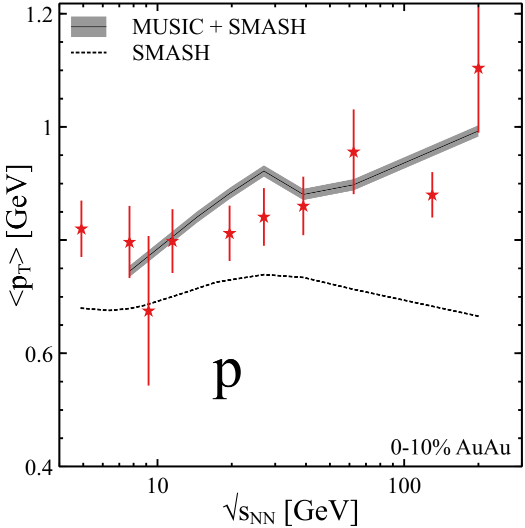


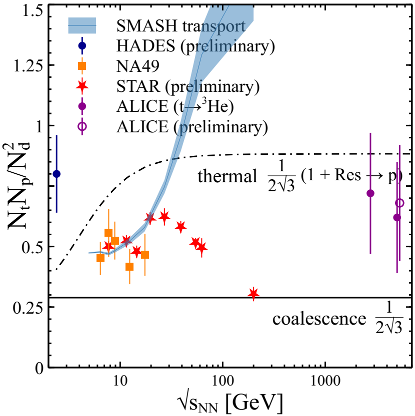
SMASH: underestimates proton mean p_T

MUSIC + SMASH: reasonable description of proton spectra

Deuterons @ STAR by pure SMASH with catalysis reactions

- Pion catalysis still dominates at STAR energies
- Deuteron and antideuteron dN/dy is described very well, because proton dN/dy is decribed well too by pure SMASH
- However, deuteron $< p_T >$ is underestimated by pure SMASH, as it is underestimated for protons
- What about $N_p N_t / N_d^2$?

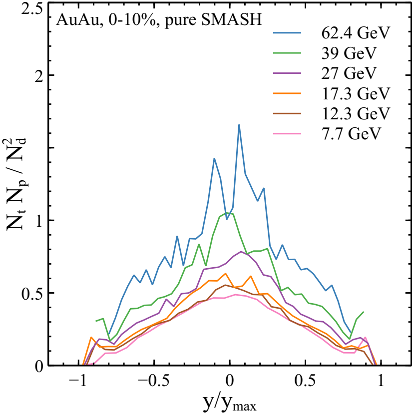
$N_p N_t / N_d^2$ @ STAR by pure SMASH with catalysis reactions



- Not flat as function of $\sqrt{s}$ and y
- Triton way above the data at $\sqrt{s} \geq 20$ GeV
- Same reactions as before! $\Longrightarrow$ underlying model matters

Same results with testparticles, $N_{test} = 10$.

$N_p N_t / N_d^2$ @ STAR by pure SMASH with catalysis reactions



- Not flat as function of $\sqrt{s}$ and y
- Triton way above the data at $\sqrt{s} \geq 20$ GeV
- Same reactions as before! $\Longrightarrow$ underlying model matters

Same results with testparticles, $N_{test} = 10$.