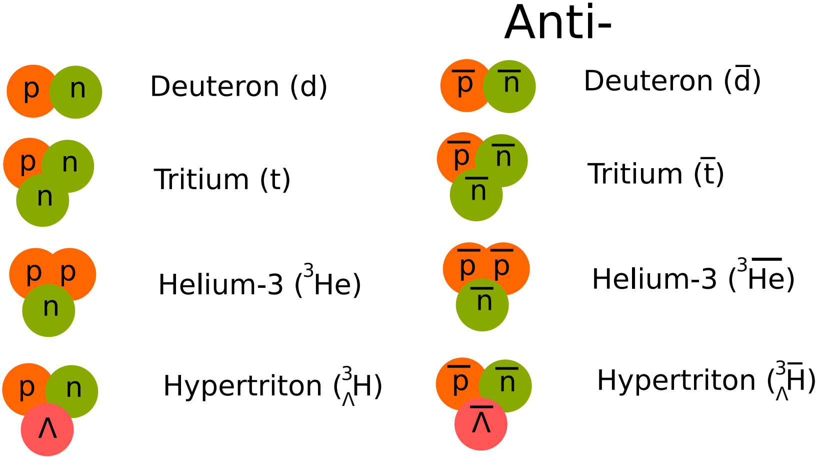
Light nuclei production in ultrarelativistic heavy-ion collisions

Dmytro (Dima) Oliinychenko
Lawrence Berkeley National Laboratory

April 8, 2020

Light nuclei in heavy ion collisions



Deuteron (d)

Tritium (t)

Helium-3 ($^{3}\mathrm{He}$)

Hypertriton ($^{3}_{\Lambda}\mathrm{H}$)

Deuteron ($\bar{\mathrm{d}}$)

Tritium ($\bar{\mathrm{t}}$)

Helium-3 ($^{3}\overline{\mathrm{He}}$)

Hypertriton ($^{3}_{\Lambda}\overline{\mathrm{H}}$)

These and other nuclei are created in heavy ion collisions

Anti-helium by Alpha-Magnetic Spectrometer

The First Five Years of the Alpha Magnetic Spectrometer
on the International Space Station:

Unlocking the Secrets of the Cosmos

December 8, 2016

S. Ting

- Few events (compatible with) $^3\overline{\mathrm{He}}$, $^4\overline{\mathrm{He}}$

  Caveats: hard measurement, 1 event/year, not published

- Where do they come from?

  Antimatter clouds? Dark matter annihilations? pp collisions?

Understanding anti-helium measurement by AMS

- K. Blum, K. C. Y. Ng, R. Sato and M. Takimoto,
  "Cosmic rays, antihelium, and an old navy spotlight,", PRD 96, no. 10, 103021 (2017)

  Conclusion: $\overline{\mathrm{He}}$ production compatible with pp

  Use coalescence model for $pp \to \overline{\mathrm{He}} + X$

- V. Poulin, P. Salati, I. Cholis, M. Kamionkowski and J. Silk,
  "Where do the AMS-02 antihelium events come from?", PRD 99, no. 2, 023016 (2019)

  Conclusion: pp cannot produce that much $\overline{\mathrm{He}}$

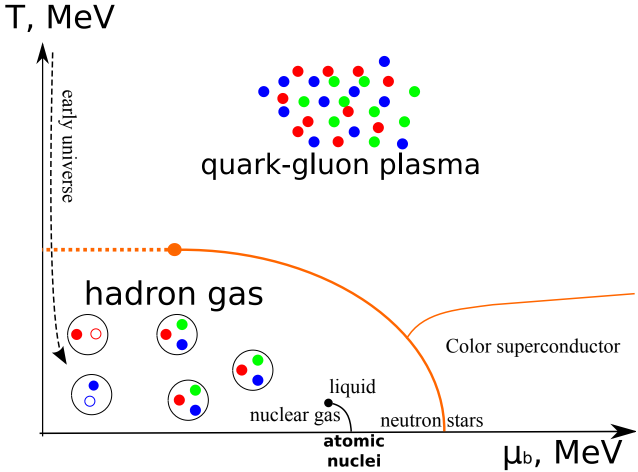
  advocate presence of anti-clouds in our Galaxy

  Use coalescence model for $pp \to \overline{\mathrm{He}} + X$

Both use pp collisions data from ALICE to calibrate models

Extrapolation from $pp \to \bar{d}$ to $pp \to \overline{\mathrm{He}} + X$, $pA \to \overline{\mathrm{He}} + X$, $AA \to \overline{\mathrm{He}} + X$, from high to low energies, from midrapidity to forward rapidity involved

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:

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

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

From a simple coalescence model

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

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

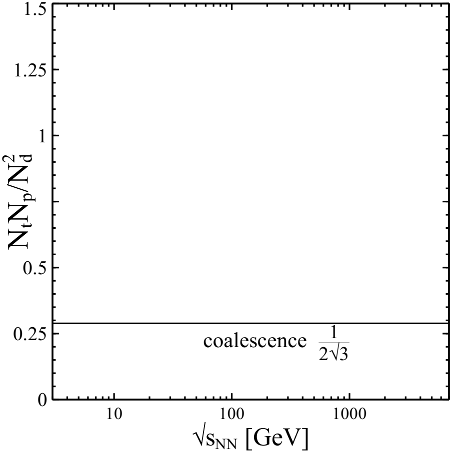
$$\frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}} \frac{1 + 2C_{np} + \Delta\rho_n}{(1 + C_{np})^2}$$

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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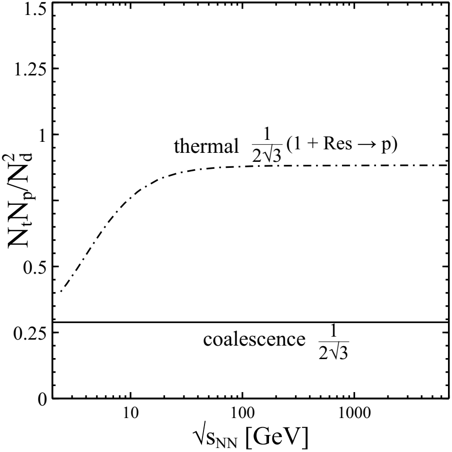

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Coalescence: first resonances decay, then nuclei form.

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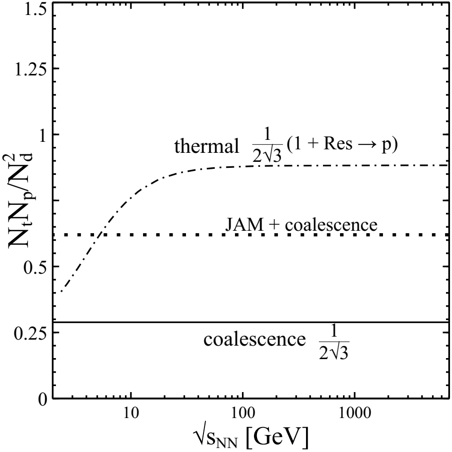

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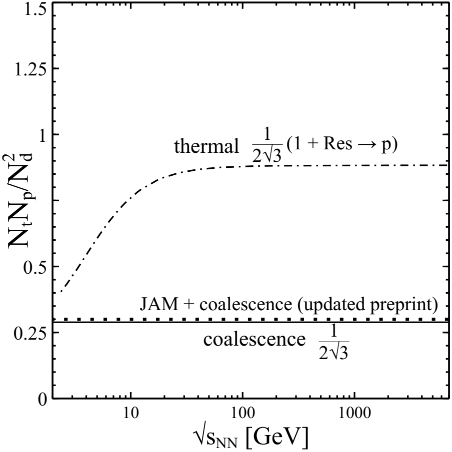

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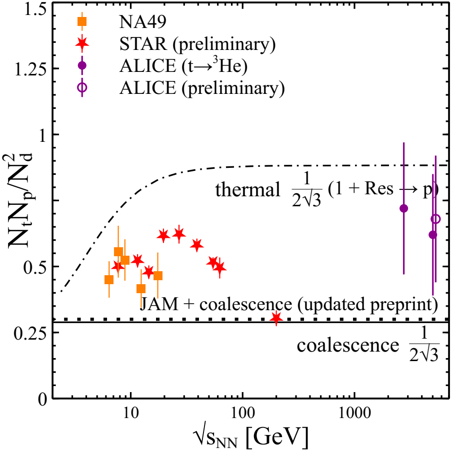
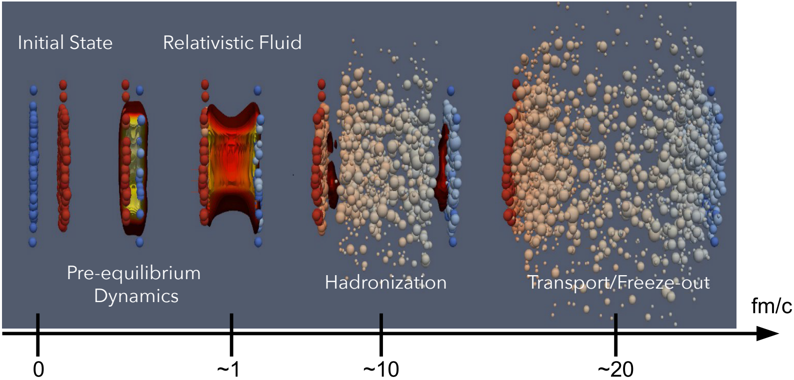


Are the bumps related to fluctuations? Can one generate them without critical point?

Trying different model, different coalescence

- JAM + coalescence
  - Fixed time coalescence, $t_{coal} = 50$ fm/c
  - $\Delta R_d = 4$ fm, $\Delta R_t = 3.4$ fm, $\Delta p_d = \Delta p_t = 0.3$ GeV
  - Tuned to reproduce d, t dN/dy at 200 GeV
  - How well does JAM reproduce proton spectra?
- SMASH + coalescence / MUSIC hydro + SMASH + 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
  - Control, how well proton spectra are reproduced (still not perfect)

Hybrid approach

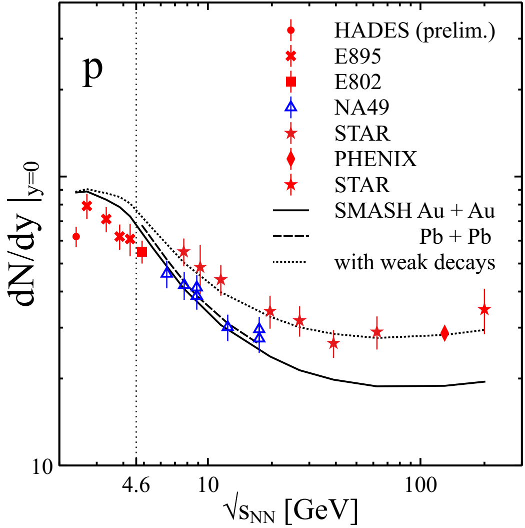


- MUSIC hydro B. Schenke, S. Jeon, C. Gale, PRC 82, 014903 (2010)

  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)

SMASH or MUSIC + SMASH and proton spectra



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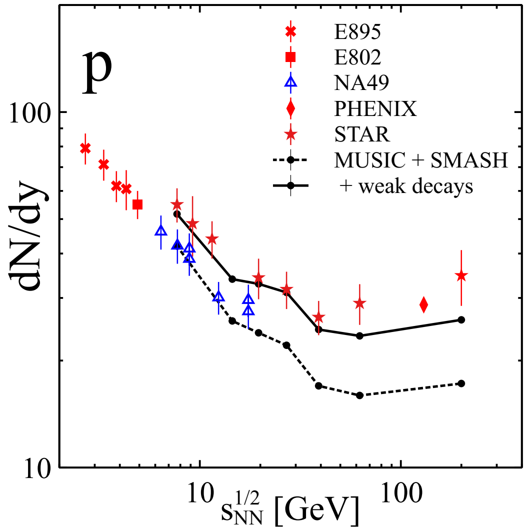

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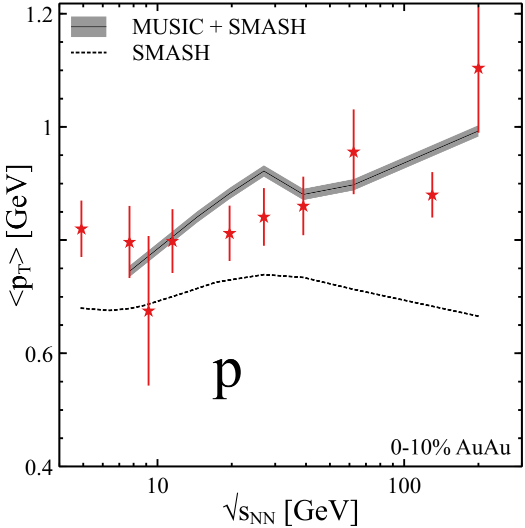
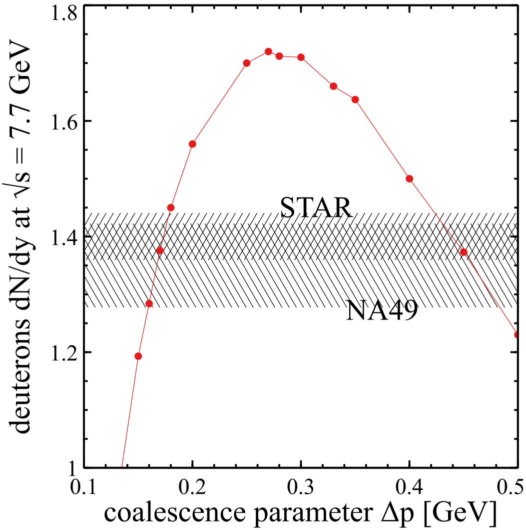


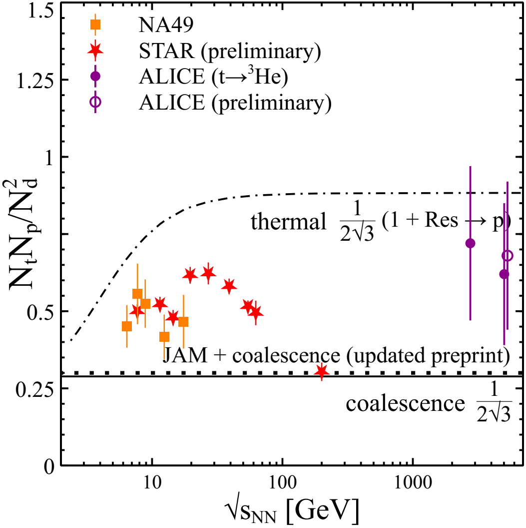
SMASH: underestimates proton mean p_T

MUSIC + SMASH: reasonable description of proton spectra

Tuning the coalescence (there is only one parameter!)



Coalescence and p-t-d double ratio



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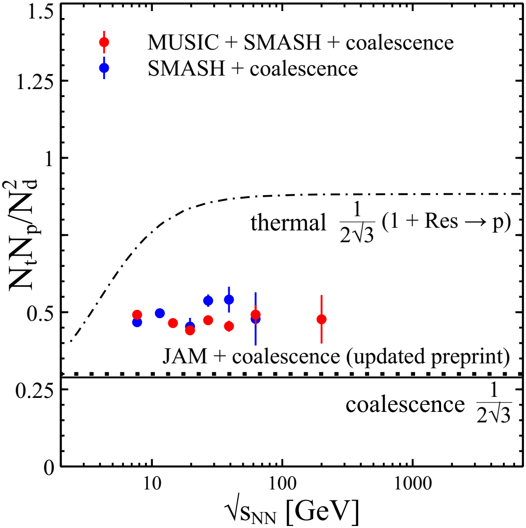
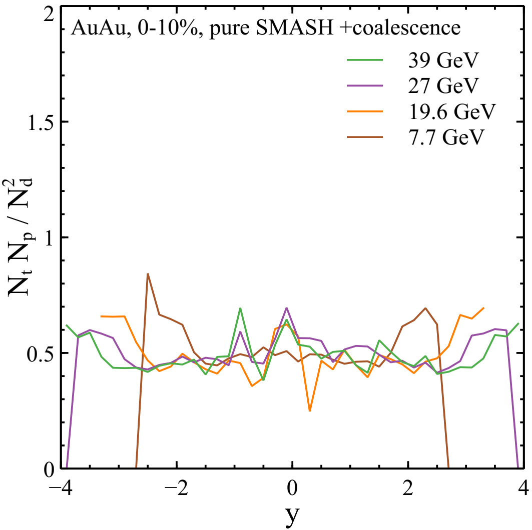


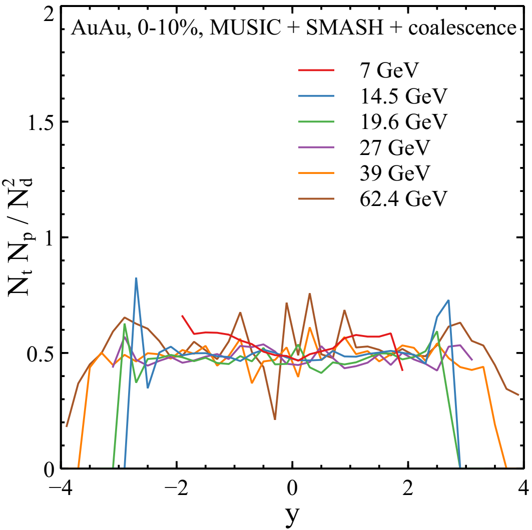
The ratio is flat as a function of energy

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

Coalescence: conclusions and outlook

- The ratio $N_t N_p / N_d^2(\sqrt{s}, y)$ is 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
- $N_t N_p / N_d^2$ depends solely on coalescence parameters
- Can we get a non-flat ratio as in experiment?
  - A) Introduce additional fluctuations of nucleon spatial density
    - Nuclear mean-field potentials
    - Critical fluctuations
  - B) Try alternative model of nuclei production

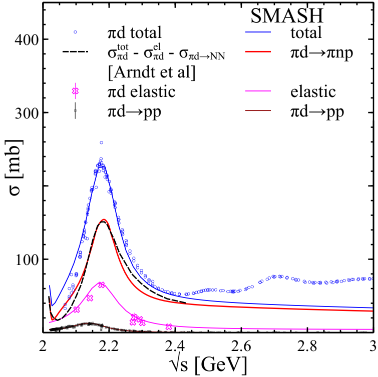
Light nuclei production via explicit catalysis reactions

$Xpn \leftrightarrow Xd$, $Xpnn \leftrightarrow Xt$

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
- Put protons and pions in the box, wait until it thermalizes, $N_t N_p / N_d^2 \approx 0.27$

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



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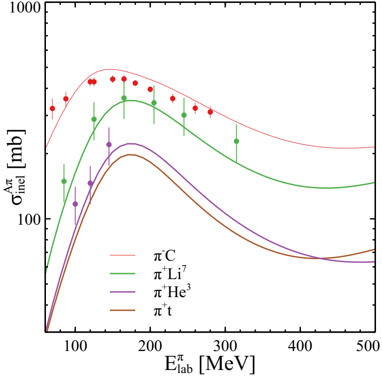
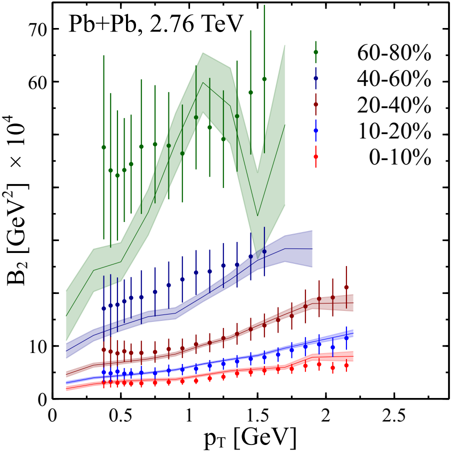
Data: Mihul:1992br,Angelescu:1996ev,Ashery:1981tq,Binon:1970ye



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

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

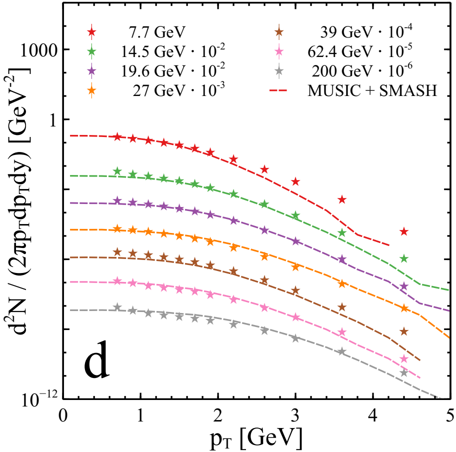


$$B_2(p_T) = \frac{\frac{1}{2\pi}\frac{d^3N_d}{p_T dp_T dy}\Big|_{p_T^d = 2p_T^p}}{\left(\frac{1}{2\pi}\frac{d^3N_p}{p_T dp_T dy}\right)^2}$$

No free parameters. Works well for all centralities.

Deuterons @ 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 well as protons)

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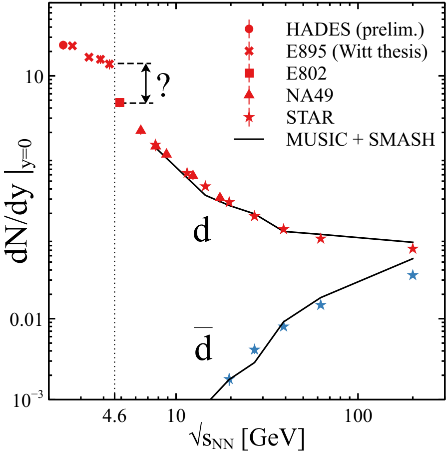

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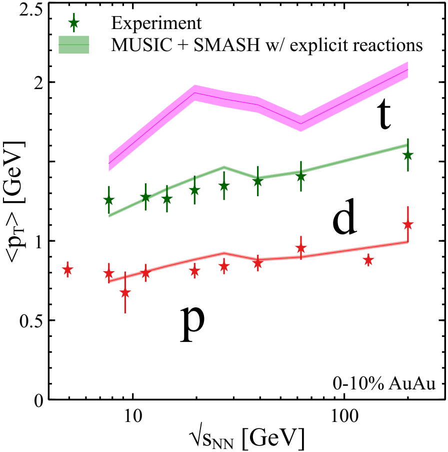

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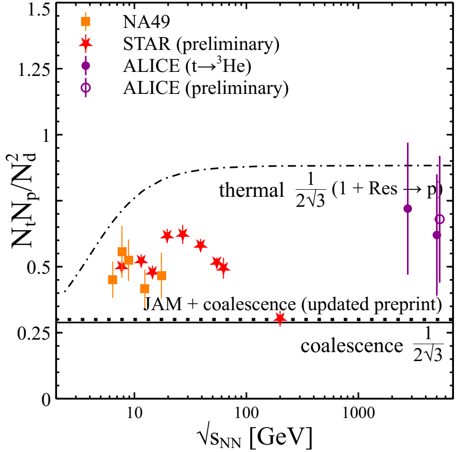

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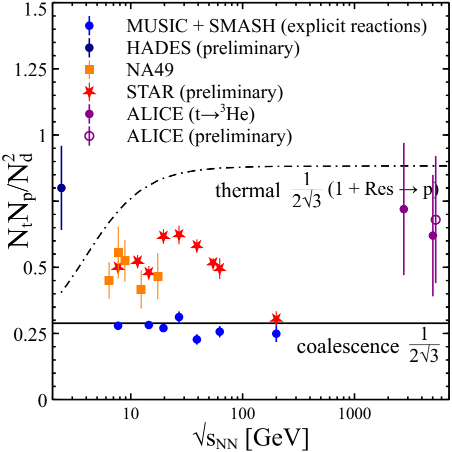

Do catalysis reactions act as coalescence?

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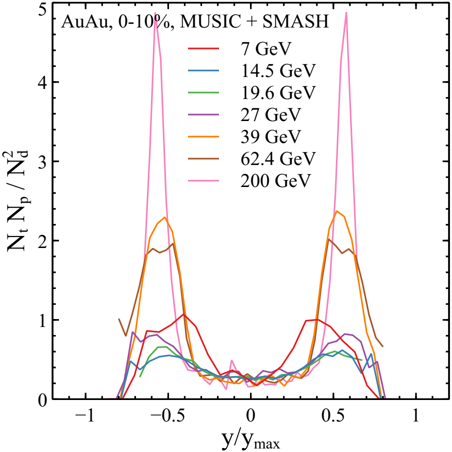
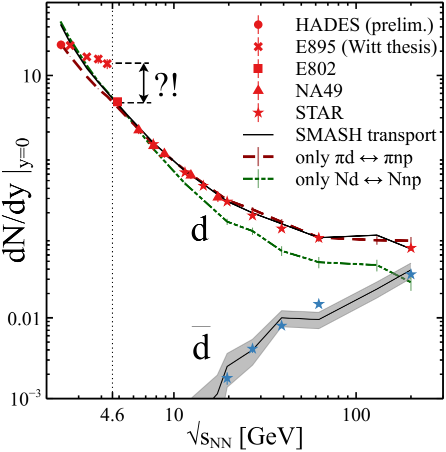


Do catalysis reactions act as coalescence? Not necessarily!

Deuterons @ STAR by pure SMASH with catalysis reactions



Pion catalysis dominates at STAR energies

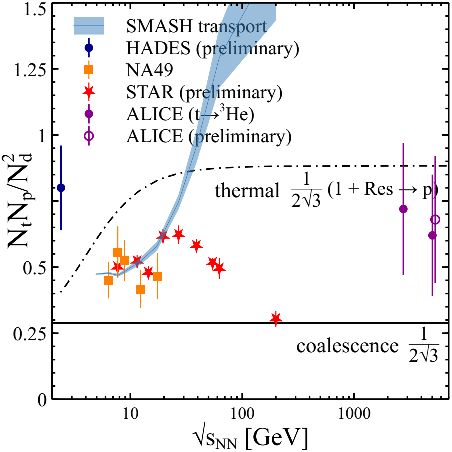
Note the (unpublished) jump around 4.6 GeV,

no jump there for protons

Deuterons @ STAR by pure SMASH with catalysis reactions

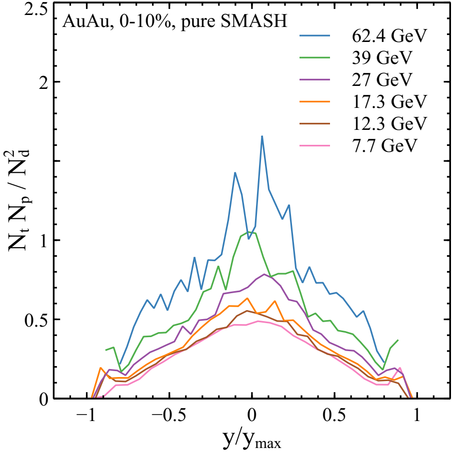
- Pion catalysis dominates at STAR energies
- Deuteron and antideuteron dN/dy is described very well, because proton dN/dy is decribed well too
- However, deuteron $< p_T >$ is underestimated, as for protons $\implies$ need MUSIC + SMASH
- What about $N_p N_t / N_d^2$?

$N_p N_t / N_d^2$ @ 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

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



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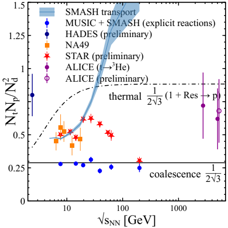
Summary and outlook

- The ratio $N_t N_p / N_d^2$ may be related to the critical point
- In coalescence models $N_t N_p / N_d^2$ is always flat
- Alternative to coalescence: explicit catalysis reactions
  - Describe deuterons as good as protons in the underlying model
  - $N_t N_p / N_d^2$ may be flat (MUSIC + SMASH), but not necessarily (SMASH)
  - Can we use this knowledge to construct a model, which reproduces experimental $N_t N_p / N_d^2$ without critical point?

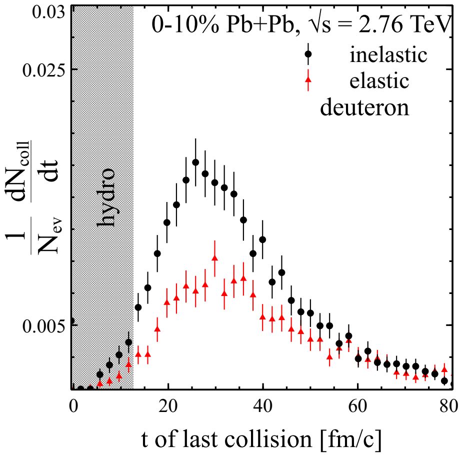


Outlook: understand the difference MUSIC + SMASH vs SMASH, try model with a critical point

Backup

Does deuteron freeze out at 155 MeV?

Only less than 1% of final deuterons originate from hydrodynamics

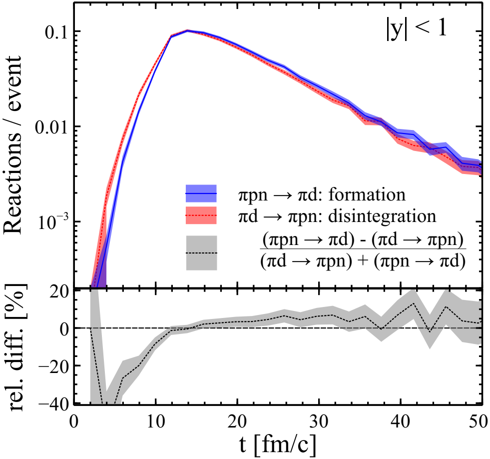


Deuteron freezes out at late time

Its chemical and kinetic freeze-outs roughly coincide

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

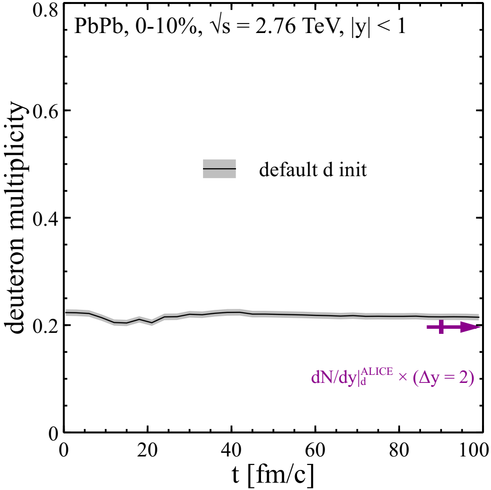
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

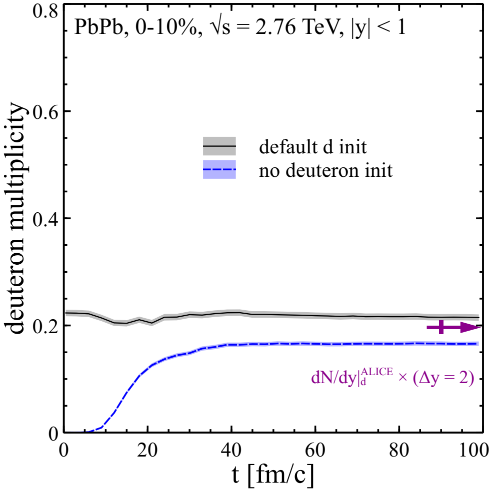
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



The yield is almost constant. Why? Does afterburner really play any role?

Deuteron yield

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



No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

Deuteron yield

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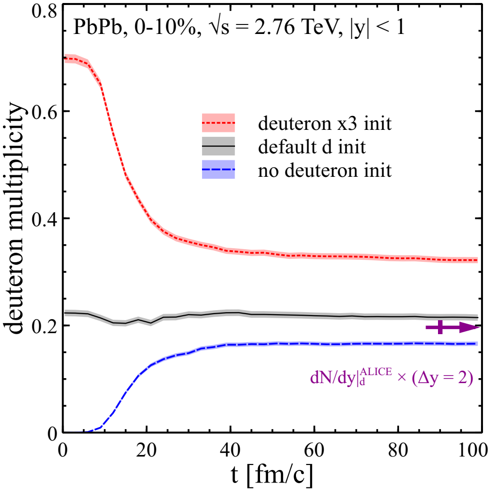

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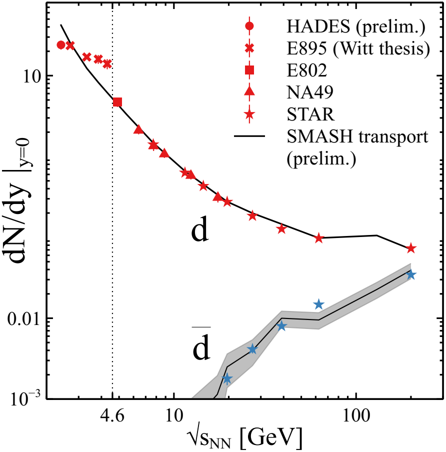
Why thermal model describes light nuclei yields at LHC

- Stable hadron yields (π, K, N, Λ, ...) comprising resonances are fixed at chemical freeze-out
- Nuclei are kept in partial (relative) equilibrium by huge cross-sections of $A + h \leftrightarrow A \times N + h$ until kinetic freeze-out
  - Therefore nuclei yields stay constant from hadron chemical freeze-out to kinetic
  - This picture works for all measured nuclei at LHC
    Xu, Rapp, Eur. Phys. J. A55 (2019) no.5, 68
    Vovchenko et al, arXiv:1903.10024
  - It works even if no nuclei are produced at chemical freeze-out
    DO, Pang, Elfner, Koch, Phys.Rev. C99 (2019) no.4, 044907
    DO, Pang, Elfner, Koch, MDPI Proc. 10 (2019) no.1, 6

Exactly the same mechanism, lower energies

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



Still works for deuteron!

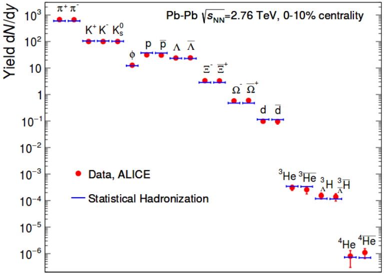
Thermal model and “snowballs in hell” puzzle

- 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?