Light nuclei production in AA, pA, pp: what can one study with JETSCAPE?

Dmytro (Dima) Oliinychenko
Lawrence Berkeley National Laboratory
March 18, 2020

BEST COLLABORATION

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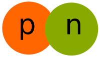
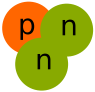
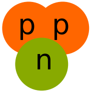
Light nuclei in heavy ion collisions



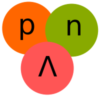
Deuteron (d)



Tritium (t)

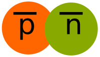


Helium-3 (^{3}He)

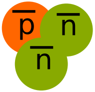


Hypertriton ($^{3}_{\Lambda}$H)

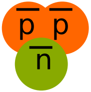
Anti-



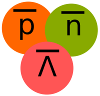
Deuteron ($\overline{d}$)



Tritium ($\overline{t}$)



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 $\overline{\mathrm{He}}$

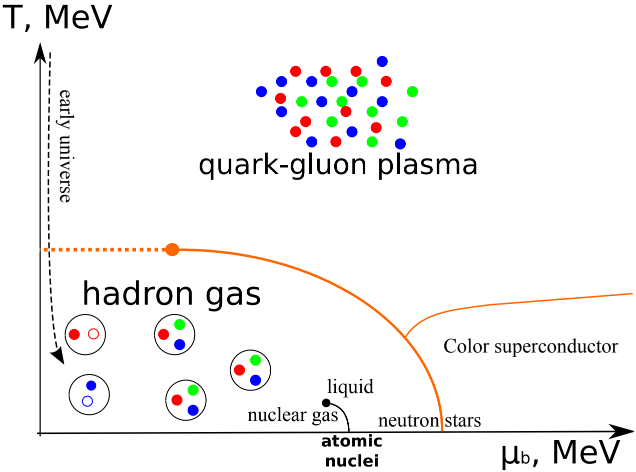
  advocate presence of anti-clouds in our Galaxy

  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

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

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

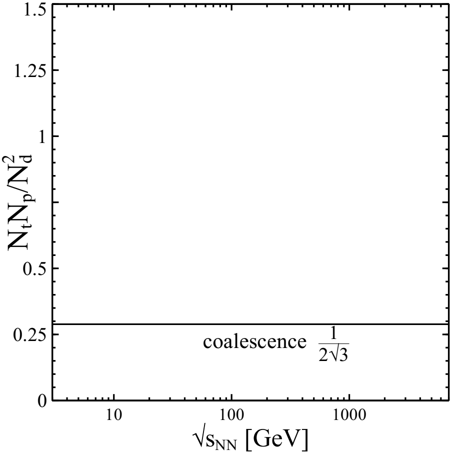
$$\frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}} \frac{1 + 2C_{np} + \Delta\rho_n}{(1 + C_{np})^2}$$

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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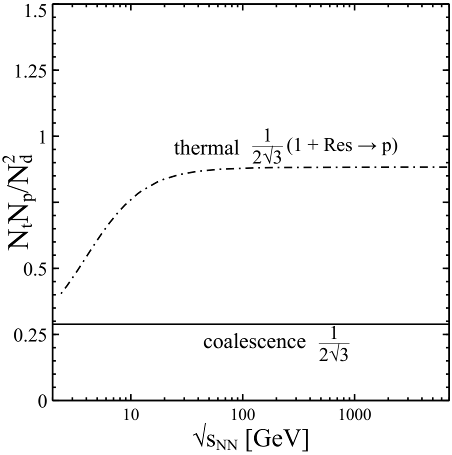

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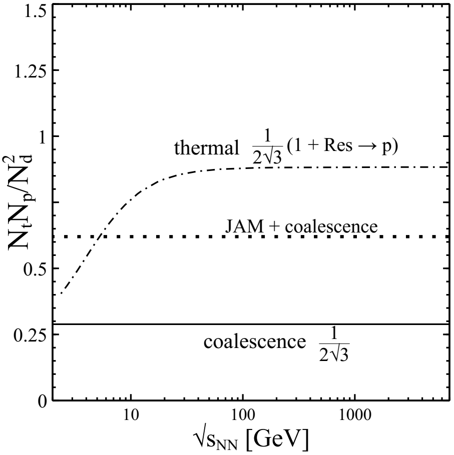

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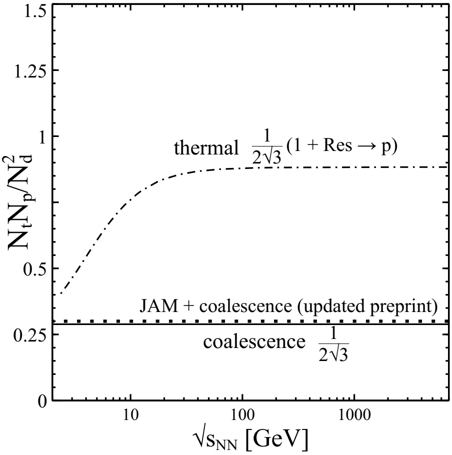

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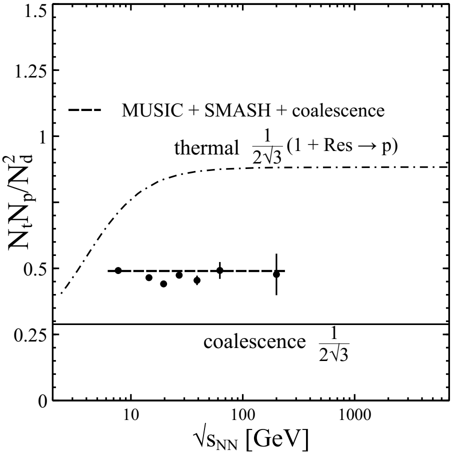

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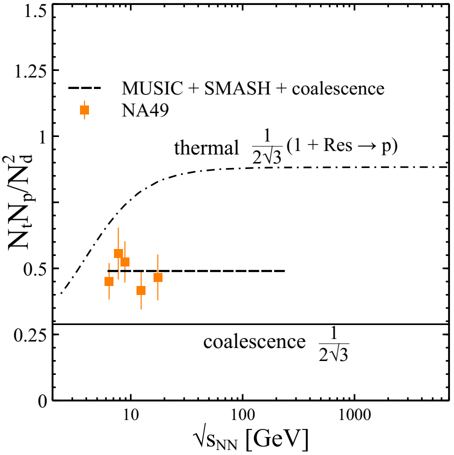

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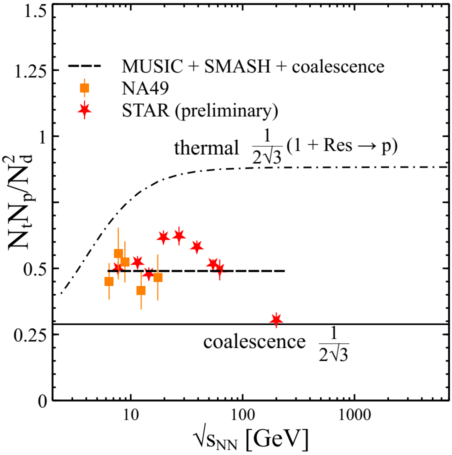

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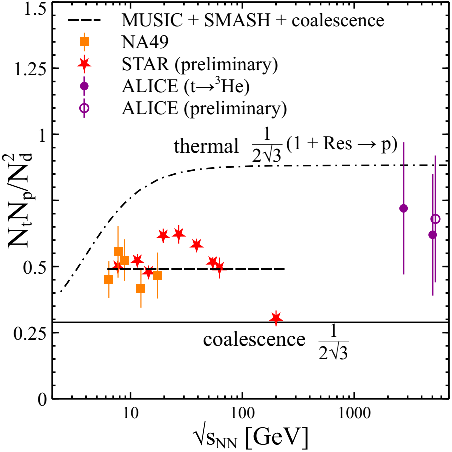

Models do not agree with each other and with the data.

Are the bumps related to fluctuations?

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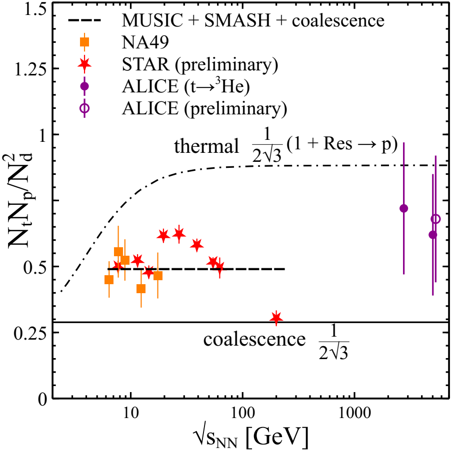

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Are the bumps related to fluctuations?

Models: differences and similarities

Model	Thermal + blast wave	Coalescence
Core idea	Nuclei in thermal equilibrium with hadrons	Nucleons bind if close enough
Kinetic equilibration	Essential assumption	May be imposed or not
Nuclei form	Before resonances decay into nucleons	After resonances decay into nucleons
Nuclei wavefunctions	Do not matter	Matter
Fluctuations	Do not matter	Matter

Assuming

- kinetic equilibrium
- no nucleon density fluctuations
- spatially compact wavefunctions
- no resonance decays

coalescence turns into blast wave + thermal model

DO, QM'19 proceedings; Scheibl, Heinz, PRC 59 (1999) 1585-1602

We can test model assumptions using light nuclei from jets

Light nuclei from jets

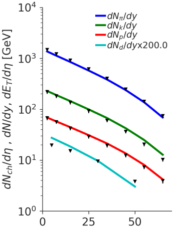
- No kinetic equilibrium
- No critical point effects
- Are nuclei formed before or after all resonances decay into nucleons?
- Does nucleus wavefunction matter?
  Can be tested with ${}^{3}_{\Lambda}\mathrm{H}$ from jets
- Does jet spatial structure differ in pp, pA, AA?
  Compare nuclei production in jets
- ALICE is already measuring deuterons in jets

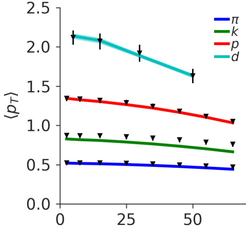
Light nuclei with JetScape

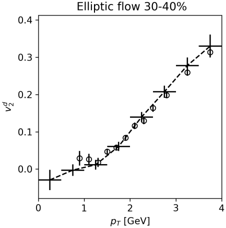
- Light nuclei from JetScape bulk via SMASH built-in $\pi d \leftrightarrow \pi np$ reactions

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

  - Done by D. Everett and J.-F. Paquet







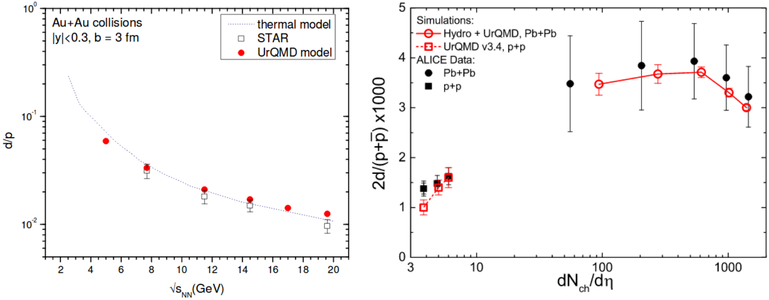
- JetScape + coalescence afterburner:
  predict light nuclei production in pp, pA, AA jets
  - Need coordinates of last interaction for jet particles
- Currently only particles from hydro,
  but not from jets get into SMASH
  Put all particles into SMASH, let evolve, look at light nuclei

Example of [hydro +] transport + coalescence

Recipe to make a deuteron:

1. Take nucleon pair at $t =$ maximum of last interaction times
2. Boost to their rest frame
3. Bind $|\Delta p| < 0.28$ GeV and $|\Delta x| < 3.5$ fm
4. Take isospin factor into account

UrQMD — Sombun et al, Phys.Rev. C99 (2019) no.1, 014901



I made a similar open-source coalescence afterburner for d, t, $^{3}\mathrm{He}$.

Let's use it

Backup

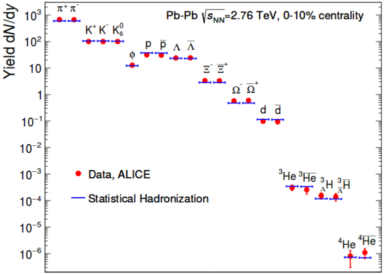
Thermal model and “snowballs in hell” puzzle

- Nuclei formed early — at hadronic freeze-out

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

- 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.

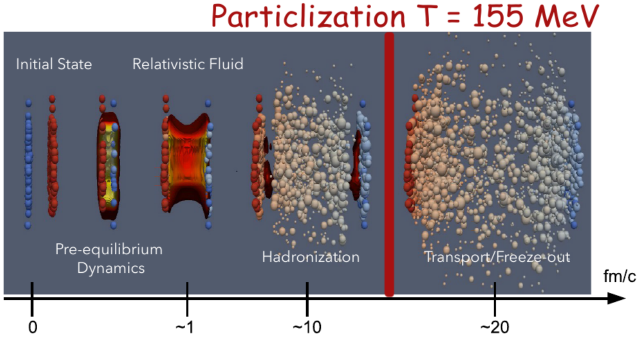


Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561 (2018) no.7723, 321-3305

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

Hybrid approach

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907
DO, Pang, Elfner, Koch, MDPI Proc. 10 (2019) no.1, 6

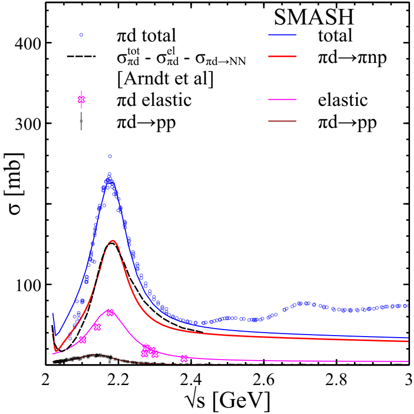


- CLVisc hydro L. G. Pang, H. Petersen and X. N. Wang, arXiv:1802.04449 [nucl-th]
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)
- Treat deuteron as a single particle
  - implement deuteron + X cross-sections explicitly

Light nuclei production by pion catalysis

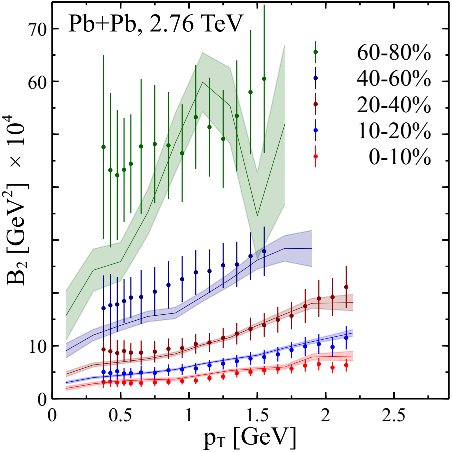
- $\pi d \leftrightarrow \pi np$, $\pi t \leftrightarrow \pi nnp$, $\pi^3\mathrm{He} \leftrightarrow \pi npp$
- all are tested to obey detailed balance within 1% precision
- large disintegration cross sections → large reverse rates

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



$B_2(p_T)$ for different centralities

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

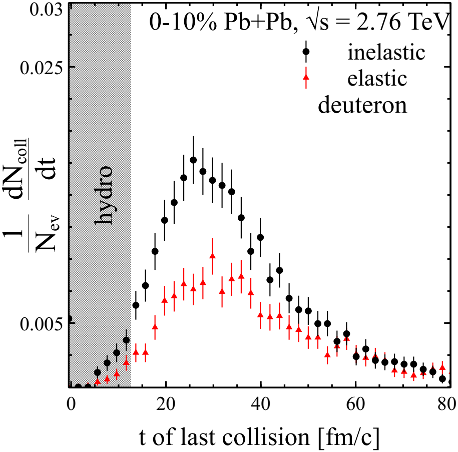


$$B_2(p_T) = \frac{\frac{1}{2\pi}\frac{d^3N_d}{p_T dp_T dy}\Big|_{p_T^d=2p_T^p}}{\left(\frac{1}{2\pi}\frac{d^3N_p}{p_T dp_T dy}\right)^2}$$

No free parameters. Works well for all centralities.

Does deuteron freeze out at 155 MeV?

Only less than 1% of final deuterons originate from hydrodynamics

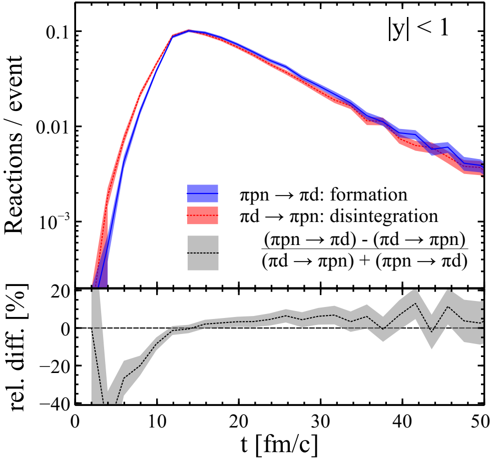


Deuteron freezes out at late time

Its chemical and kinetic freeze-outs roughly coincide

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

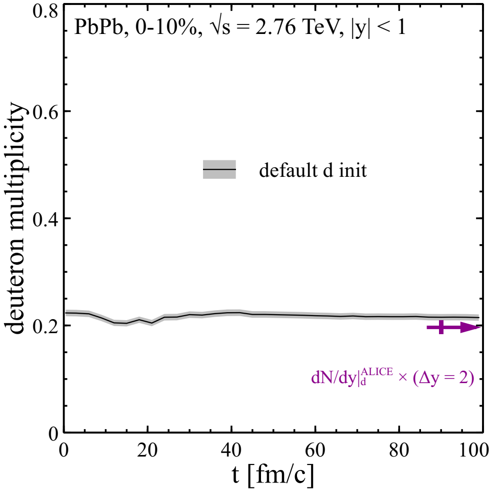
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

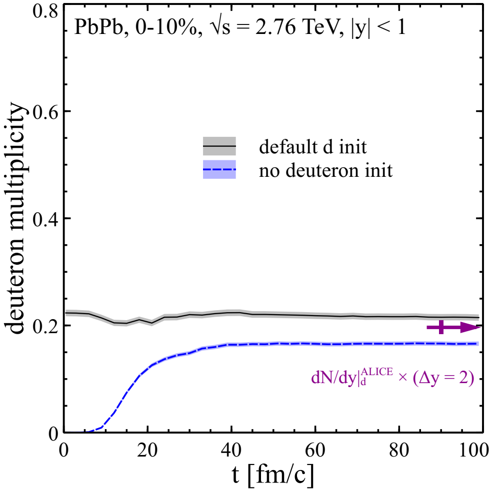
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

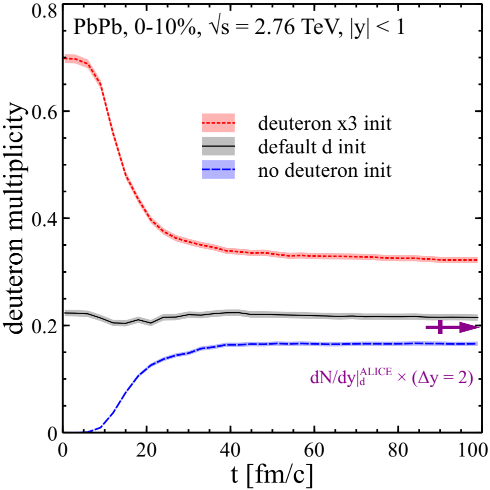
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

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



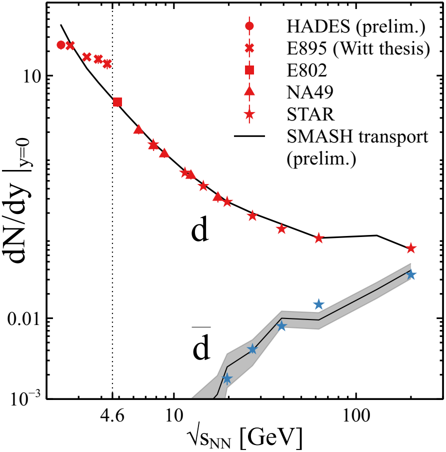
No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

Why thermal model describes light nuclei yields at LHC

- Stable hadron yields (π, K, N, Λ, $\dots$) 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!