Light nuclei production in heavy ion collisions

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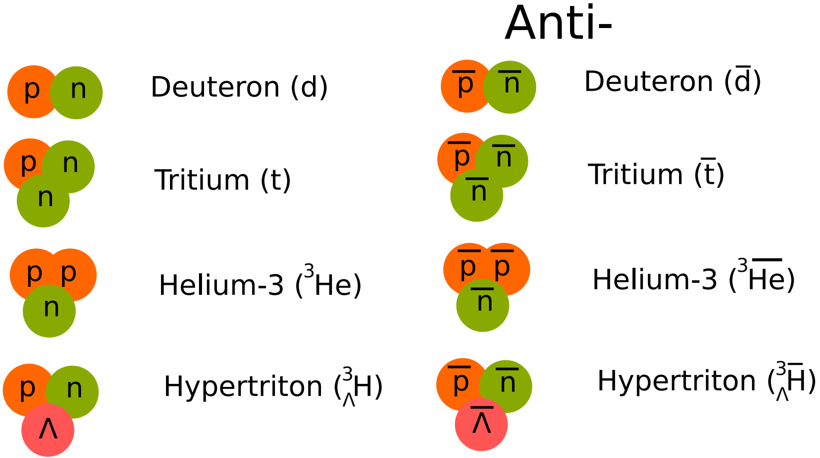
November 7, 2019

Quark Matter 2019, Wuhan, 4-9 November 2019

Light nuclei and anti-nuclei



Anti-

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

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

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

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

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 $\overline{\mathrm{He}}$

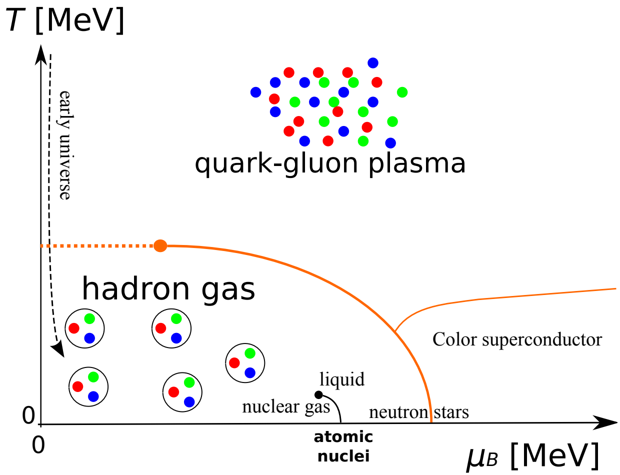
  advocate presence of anti-clouds in our Galaxy

  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

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

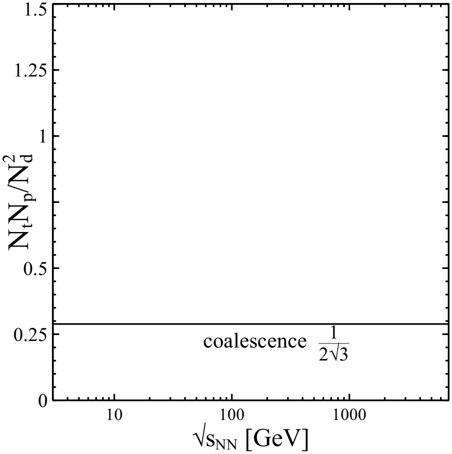
$$\frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}} \frac{1 + 2C_{np} + \Delta\rho_n}{(1 + C_{np})^2}$$

Thermal ratio $\frac{g_t g_p}{g_d^2} \left(\frac{3m \cdot m}{(2m)^2}\right)^{3/2} = \frac{1}{2\sqrt{3}} \approx 0.29$ 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, talk by Dingwei Zhang], ALICE [Adam:2015vda]; model JAM + coalescence [Liu:2019nii]



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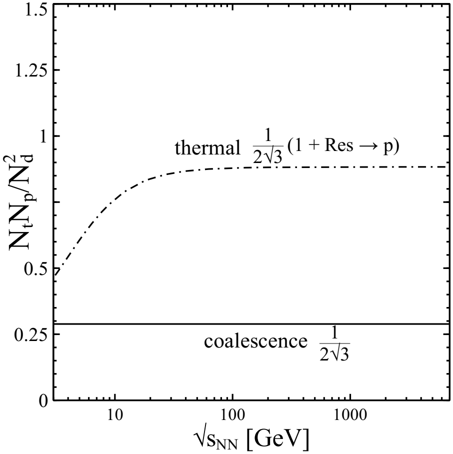

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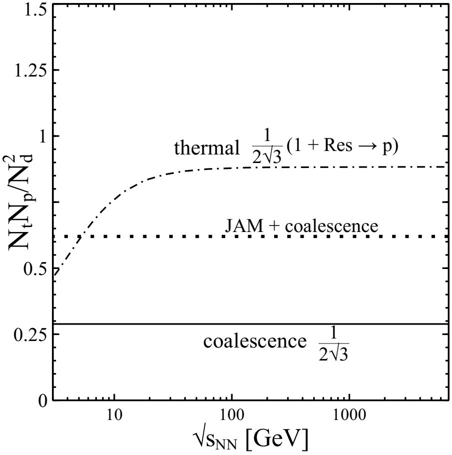

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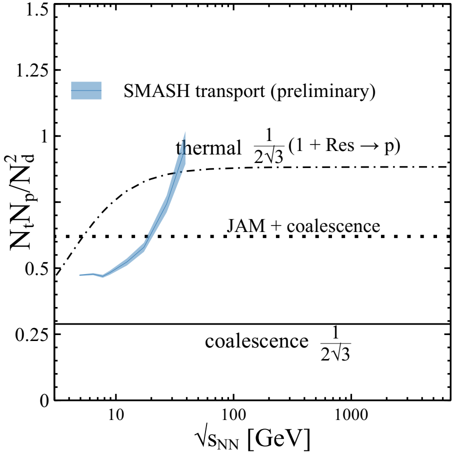

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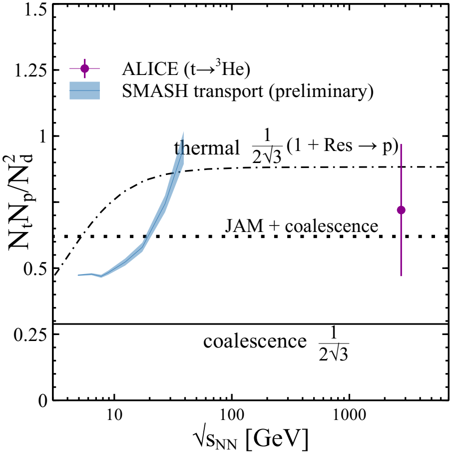

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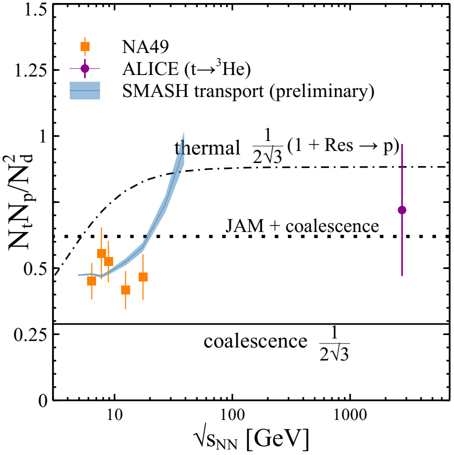

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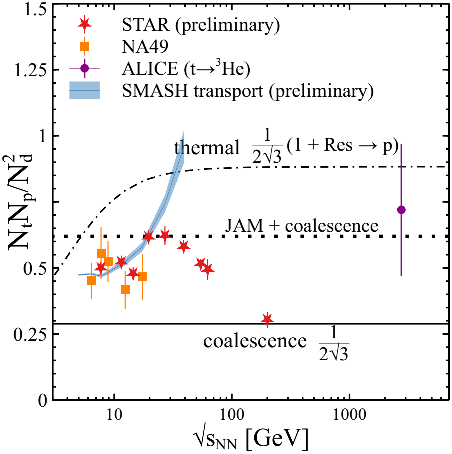

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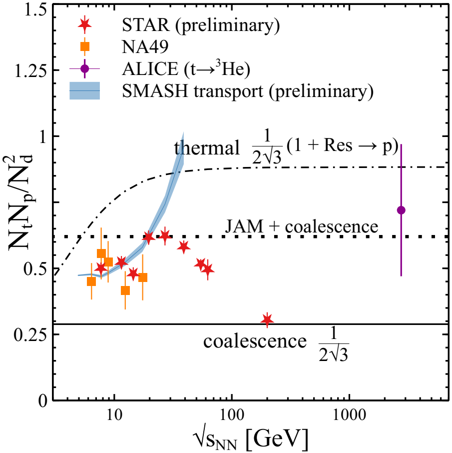


Models do not agree with each other and with the data.

Are the bumps related to fluctuations? E. Shuryak: do $^4\mathrm{He}$ excited states play role?

Why do models disagree?

This disagreement is conceptual: different ideas about when, where, and how light nuclei are produced

Let us overview, test and understand:

*Coalescence model***s**
Thermal model
Purely dynamical models

Types of coalescence

Main principles:

- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

Analytical coalescence

- Without nuclei wavefunction
  Gutbrod et al, PRL 37 (1976) 667-670
  Csernai, Kapusta, Phys. Rept. 131 (1986) 223-318
- With nuclei wavefunction
  Sato, Yazaki, Phys. Lett. 98B (1981) 153-157
  Scheibl, Heinz, Phys.Rev. C59 (1999) 1585-1602
  Mrowczynski, Acta Phys. Polon. B48 (2017) 707
  Sun, Chen, Phys.Rev. C95 (2017) no.4, 044905

Disclaimer: References list is not comprehensive. Sorry.

Dynamical model + coalescence

- Transport + coalescence
  Zhu, Ko, Yin, PRC 92 (2015) no.6, 064911
  Dong et al., EPJ A 54 (2018) no.9, 144
  Liu et al., arXiv:1909.09304
- Hydro + coalescence
  Ivanov, Soldatov, EPJ A 53 (2017) no.11, 218
- Hybrid + coalescence
  Sombun et al, Phys.Rev. C99 (2019) no.1, 014901

Simple analytical coalescence framework

- Nucleons bind into nuclei if they are close in phase space
  $$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_\mathrm{p} \frac{dN_\mathrm{p}}{d^3P_\mathrm{p}}\right)^Z \left(E_\mathrm{n} \frac{dN_\mathrm{n}}{d^3P_\mathrm{n}}\right)^N \Bigg|_{P_\mathrm{p}=P_\mathrm{n}=P_A/A}$$
  Naive $B_A = const$ model is excluded by data: ALICE, STAR, NA49
- Expectations from a "simple analytical coalescence":
  - $B_A \sim V_{HBT}^{-(A-1)}, \quad B_{A=2} \sim 1/V_{HBT}, \quad B_{A=3} \sim 1/V_{HBT}^2$
  - $B_A(p_T)$ grows with p_T in AA, $B_A(p_T) \approx const$ in pp
  - B_A decreases with larger multiplicity
  - $v_2^d(2p_T) = 2v_2^p(p_T)$

Qualitatively these expectations are fulfilled.

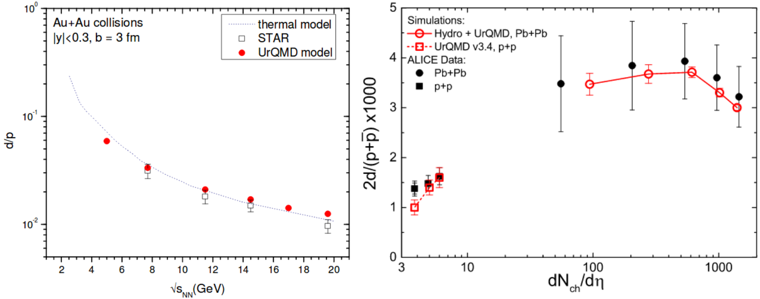
- Attempts to get more precision:
  - More realistic proton phase space distribution from dynamical models
  - Advanced coalescence: account for nuclei wavefunction

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

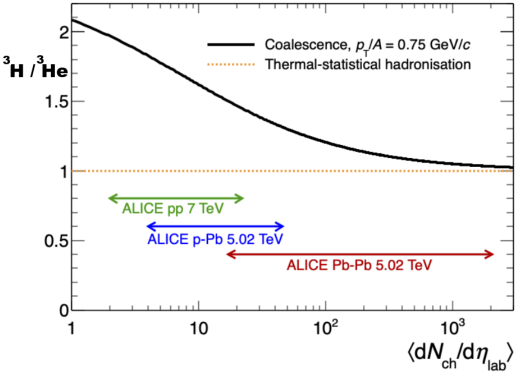


Good description from low to high energies with 2 parameters

Advanced analytical coalescence

Scheibl, Heinz, Phys.Rev. C59 (1999) 1585-1602; Bellini, Kalweit, Phys.Rev. C99 (2019) no.5, 054905

Prediction: large wavefunctions are suppressed



$$N_A \sim (R^2 + r_A^2/4)^{-3/2}$$

R – size of the system

r_A – size of nucleus

Does wavefunction size matter? To be tested in small systems.

Advanced analytical coalescence

Scheibl, Heinz, Phys.Rev. C59 (1999) 1585-1602; Bellini, Kalweit, Phys.Rev. C99 (2019) no.5, 054905

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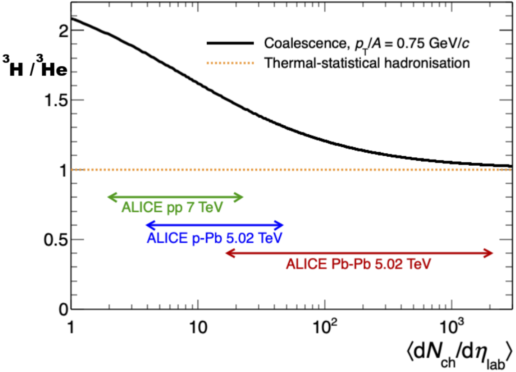


$N_A \sim (R^2 + r_A^2/4)^{-3/2}$

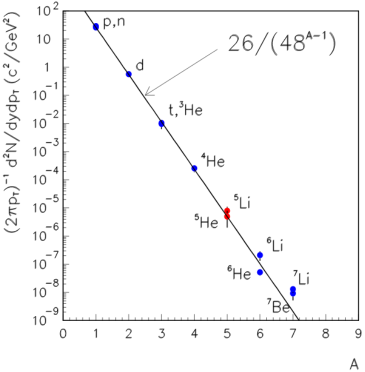
R – size of the system

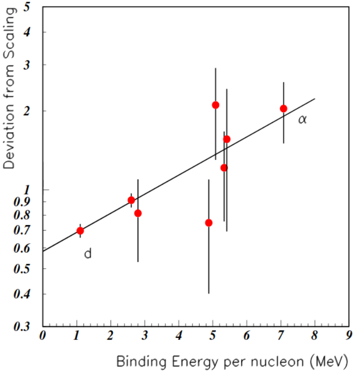
r_A – size of nucleus

Does wavefunction size matter? Yes (see ALICE data, L. Barioglio and A. Bartsch talks). But: same effect from thermal model + canonical suppression.

Wavefunction size: recalling AGS results

AGS, E864 experiment, central Au-Pb/Pt, 11.6 A GeV





$y = 1.9$, $p_T/A = 200$ MeV

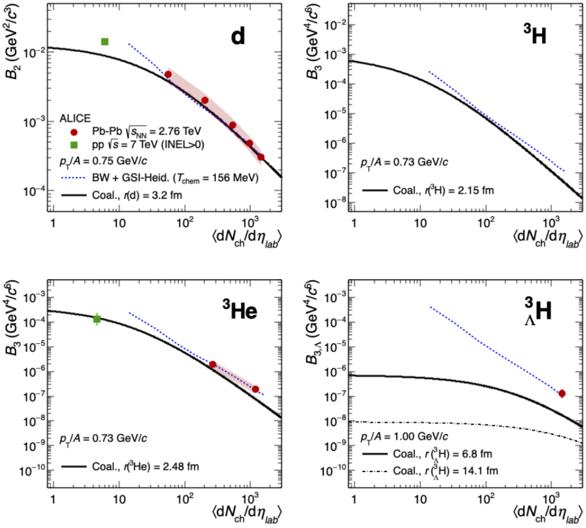
after correction for A, I_z and spin

Larger wavefunctions are suppressed, as advanced coalescence expects

Prediction: ${}^{3}_{\Lambda}\mathrm{H}$ is big, it must be suppressed

Thermal + blast wave model vs. coalescence

Bellini, Kalweit, Phys. Rev. C99 (2019) no.5, 054905



Does wavefunction size matter?

Coalescence: yes, Thermal: no

Thermal: yields at $T = 156$ MeV, spectra — blast wave, $T \approx 115$ MeV

Advanced analytical coalescence: ${}^3_\Lambda\mathrm{H}$ is big, it must be suppressed

Data: ${}^3_\Lambda\mathrm{H}$ disfavors coalescence

- Thermal production in AA at higher energies and coalescence at lower?
- Maybe ${}^3_\Lambda\mathrm{H}$ is born small?

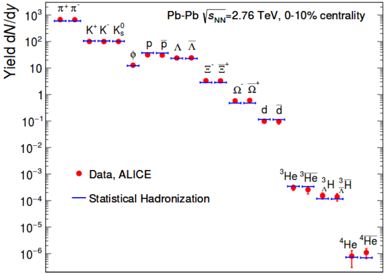
Thermal model and “snowballs in hell” puzzle

- 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, $^3\mathrm{He}$, $^3_\Lambda\mathrm{H}$, $^4\mathrm{He}$ – 2.2, 7.7, 0.13, 8.5 MeV

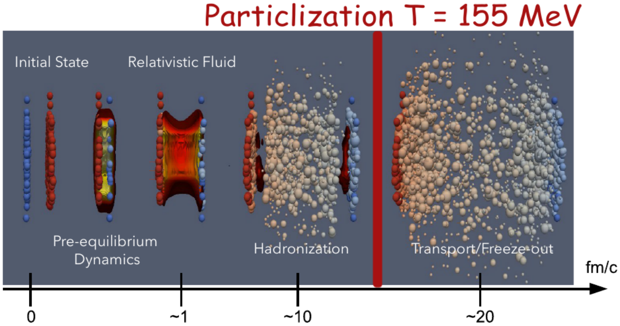
Snowballs in hell.



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

Purely dynamical model

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

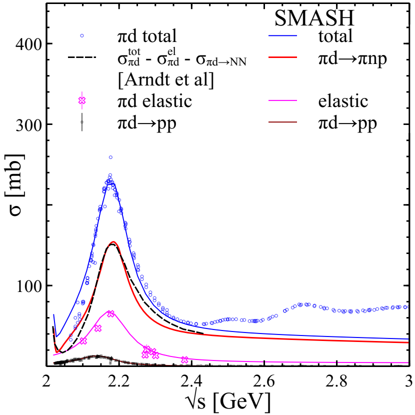


- CLVisc hydro L. G. Pang, H. Petersen and X. N. Wang, arXiv:1802.04449 [nucl-th]
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)
- Treat deuteron as a single particle
  - implement deuteron + X cross-sections explicitly

Light nuclei production by pion catalysis

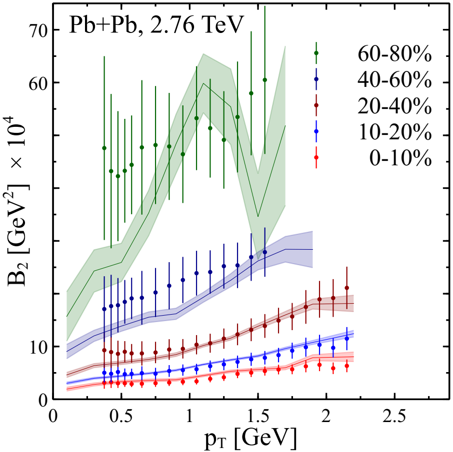
- $\pi d \leftrightarrow \pi np$, $\pi t \leftrightarrow \pi nnp$, $\pi^3\mathrm{He} \leftrightarrow \pi npp$
- all are tested to obey detailed balance within 1% precision
- large disintegration cross sections → large reverse rates

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



$B_2(p_T)$ and v_2 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.

$B_2(p_T)$ and v_2 for different centralities

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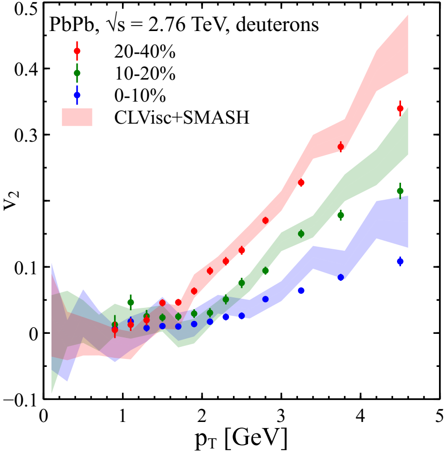

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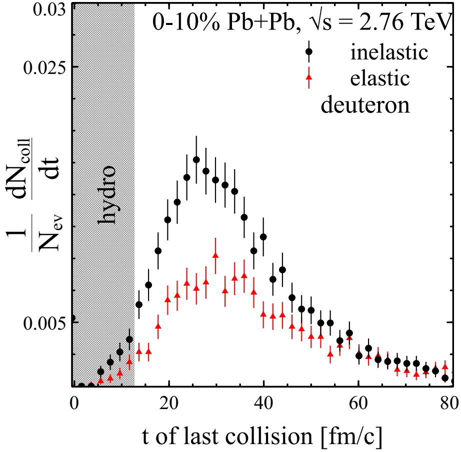
No free parameters. Works well for all centralities.

Does deuteron freeze out at 155 MeV?

Only less than 1% of final deuterons originate from hydrodynamics

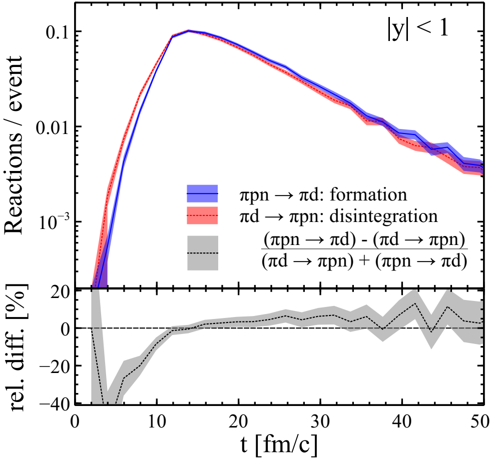


Deuteron freezes out at late time

Its chemical and kinetic freeze-outs roughly coincide

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

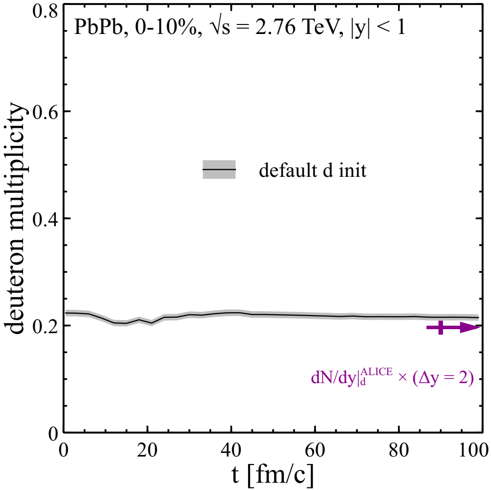
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

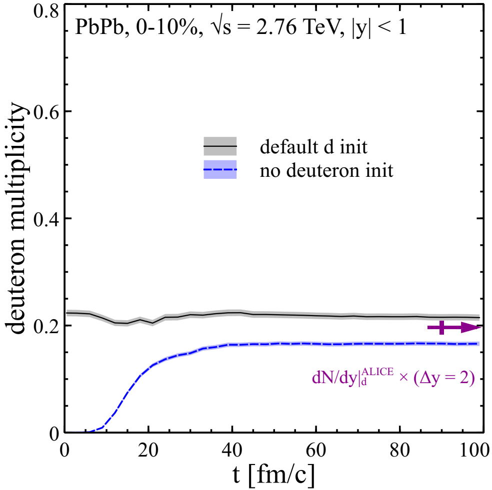
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

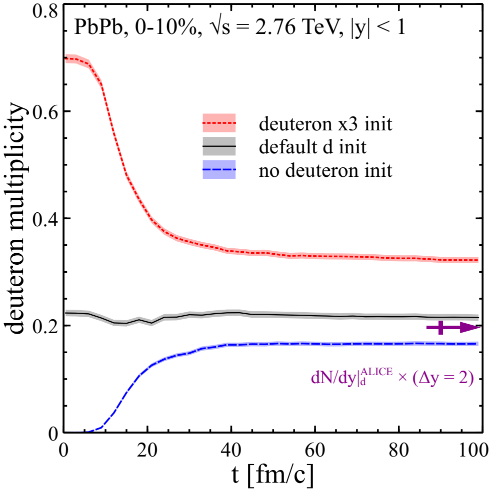
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

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



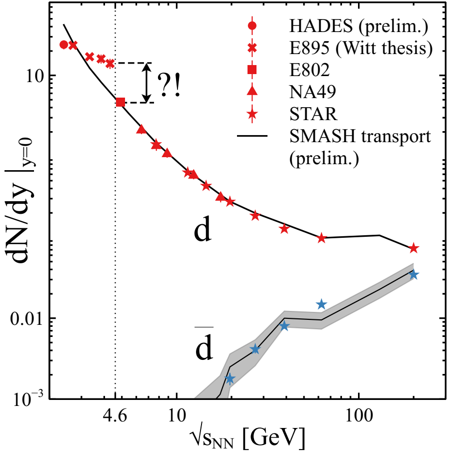
No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

Why thermal model describes light nuclei yields at LHC

- Stable hadron yields (π, K, N, Λ, ...) 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
- If wavefunction is large or very large – does not matter as long as the cross-sections are large enough to keep relative equilibrium
  - This might explain thermal $^{3}\mathrm{He}$ and $^{3}_{\Lambda}\mathrm{H}$ at LHC

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!

Note (unpublished) jump from 14 to 5 in deuteron yield at ≈ 4.6 GeV.

Conclusions

We need better understanding of light nuclei production

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We need better understanding of light nuclei production

- Potential benefits
  - Estimation of background for antimatter in space from pp, pA, AA.
    May lead to discovery of antimatter clouds in the Universe
  - Possible detection of critical point from density fluctuations $\Longrightarrow \frac{N_t N_p}{N_d^2}$

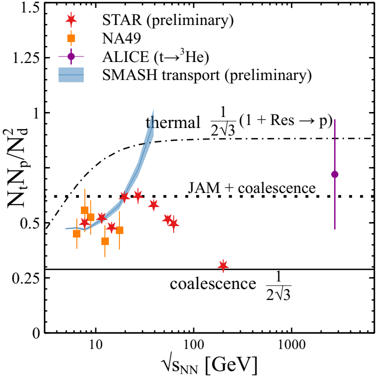
Conclusions

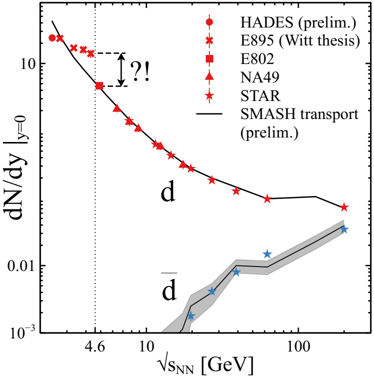
We need better understanding of light nuclei production

- Potential benefits
  - Estimation of background for antimatter in space from pp, pA, AA. May lead to discovery of antimatter clouds in the Universe
  - Possible detection of critical point from density fluctuations $\Longrightarrow \frac{N_t N_p}{N_d^2}$
- Challenges
  - No present model can explain measured $\frac{N_t N_p}{N_d^2}\left(\sqrt{s_{NN}}\right)$
  - Need to improve models, both dynamical and analytical
  - Need models including critical point
  - Does wavefunction size matter? Sometimes yes, sometimes no... To be further tested in small systems
  - Need hadronic exclusive cross-sections: $d+\pi$, $d+p$, $t+\pi$, $t+p$, $\ldots$ to be measured or analytically computed

Thank you!

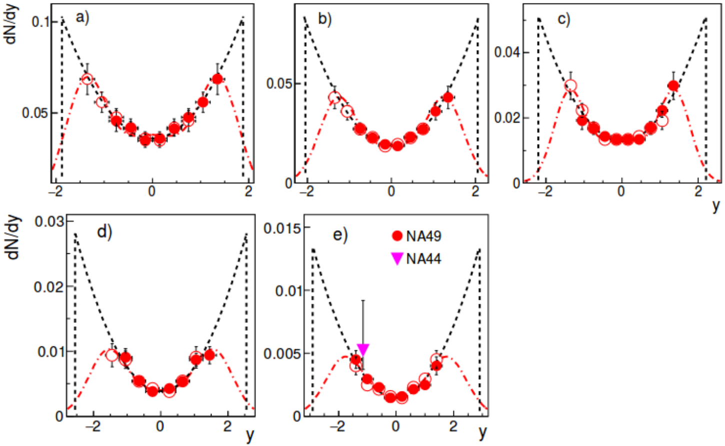
Thank you!


STAR (preliminary)
NA49
ALICE (t→^{3}He)
SMASH transport (preliminary)
thermal $\frac{1}{2\sqrt{3}}(1 + \text{Res} \to p)$
JAM + coalescence
coalescence $\frac{1}{2\sqrt{3}}$
$N_t N_p / N_d^2$
1.5
1.25
1
0.5
0.25
0
10
100
1000
$\sqrt{s_{NN}}$ [GeV]


HADES (prelim.)
E895 (Witt thesis)
E802
NA49
STAR
SMASH transport (prelim.)
?!
d
$\bar{d}$
$dN/dy\,|_{y=0}$
10
0.01
10^{-3}
4.6
10
100
$\sqrt{s_{NN}}$ [GeV]

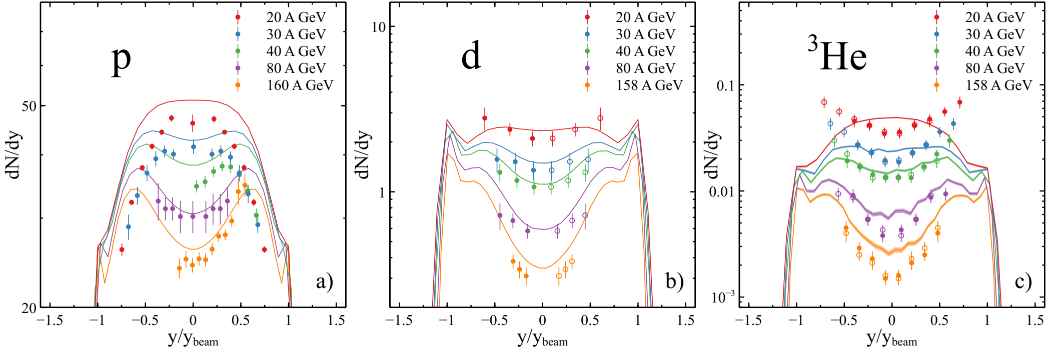
Rapidity dependence from NA49

Central PbPb, $\sqrt{s_{NN}} = 6.3 - 17.3$ GeV, deuteron



Uncertainty at high rapidity: AMS needs 4π yields of $\overline{\mathrm{He}}$

Helium-3: lines by SMASH (preliminary), circles by NA49



Rule of thumb: light nuclei are described as good/bad as protons

Naive coalescence framework

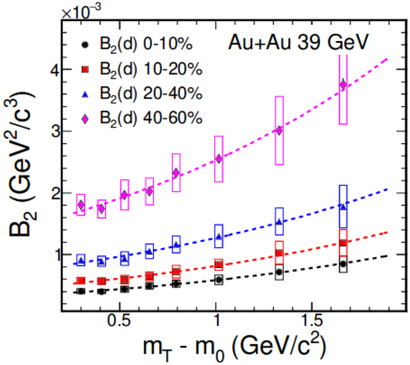
- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

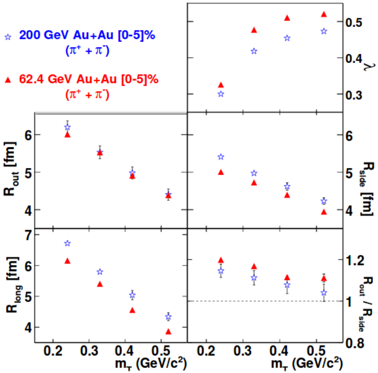
  $$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_{\mathrm{p}} \frac{dN_{\mathrm{p}}}{d^3P_{\mathrm{p}}}\right)^Z \left(E_{\mathrm{n}} \frac{dN_{\mathrm{n}}}{d^3P_{\mathrm{n}}}\right)^N \Bigg|_{P_{\mathrm{p}}=P_{\mathrm{n}}=P_A/A}$$

- Expectations:
  - $B_A \sim \left(\frac{4}{3}\pi p_0^3\right)^{A-1}$ or $B_A \sim V_{HBT}^{-(A-1)}$
  - $B_2 \sim 1/V_{HBT}$, $B_3 \sim 1/V_{HBT}^2$
  - $B_A(p_T) \approx const$ in pp
  - larger charged multiplicity, smaller B_A
  - $v_2^d(2p_T) = 2v_2^p(p_T)$

Are these naive expectations fulfilled?

Dependencies of B_2: transverse momentum



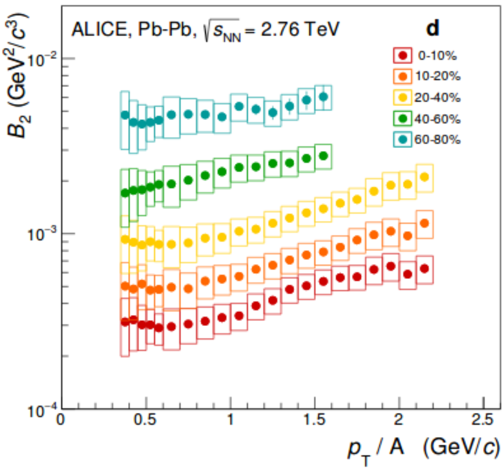


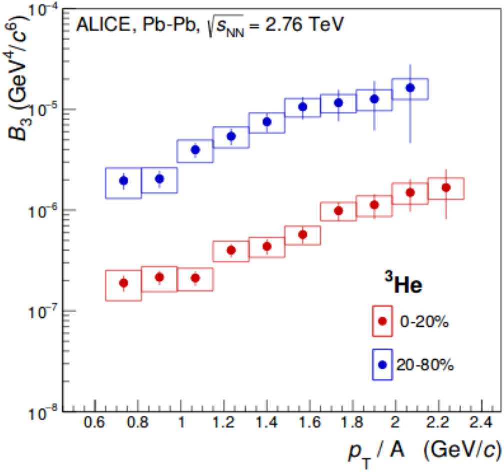
compatible with coalescence expectation

$$V_{HBT}(m_T)\downarrow,\ B_2(m_T)\uparrow$$

Dependencies of B_2: transverse momentum

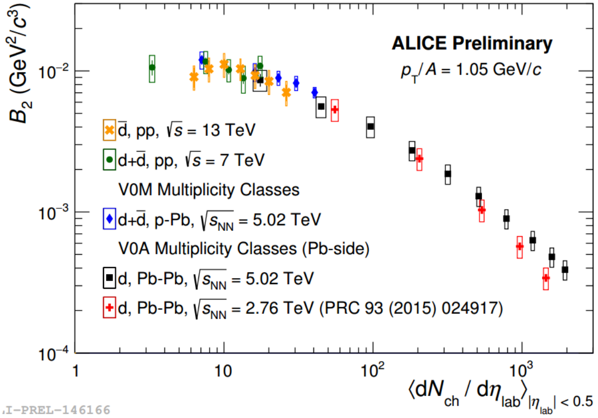
ALICE, Phys. Rev. C93 (2016) no.2, 024917





compatible with coalescence expectation

Dependencies of B_2: system size



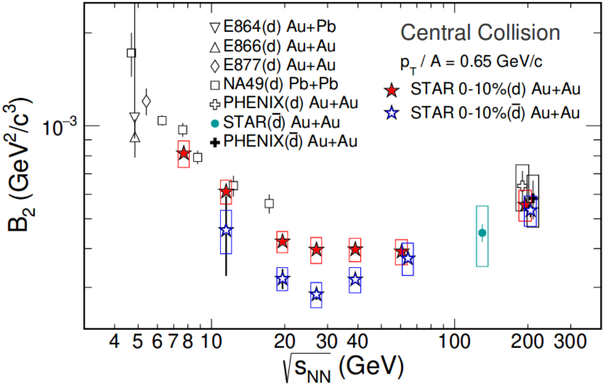
M. Puccio, Quark Matter 2018 proceedings, NPA 982 (2019) 447-450

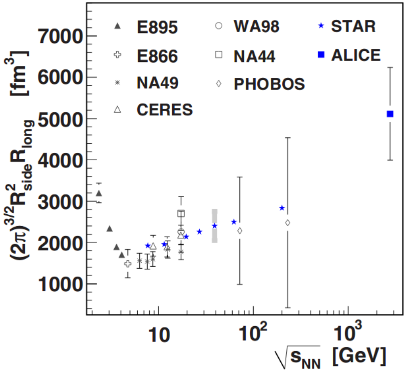
compatible with coalescence expectation

$$V \uparrow, \ B_2 \downarrow$$

Dependencies of B_2: collision energy

STAR, Phys. Rev. C 92 (2015) no.1, 014904
STAR, arXiv:1903.11778

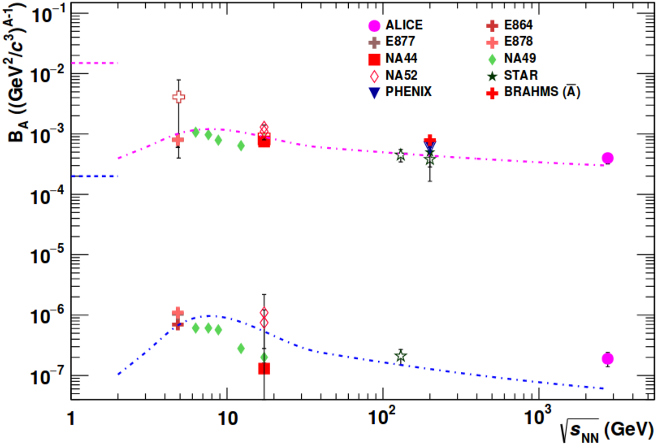




Not really compatible with $B_A \sim V_{HBT}^{-(A-1)}$ qualitatively!

Dependencies of B_2: collision energy

Braun-Munzinger, Dönigus Nucl. Phys. A 987 (2019) 144-201



But the order of magnitude is still right

Most important deuteron production/disintegration reactions

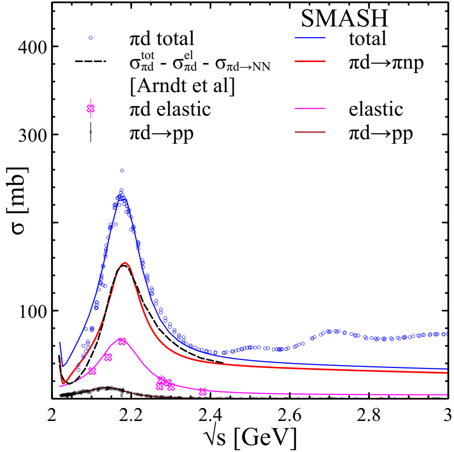
Largest d + X disintegration rate → largest reverse production rate

Most important = largest $\sigma^{\rm inel}_{d+X} n_X$

X	$\sigma^{\rm inel}_{d+X}$ [mb] ($\sqrt{s} - \sqrt{s_{thr}} = [0.05, 0.25]$ GeV)	$\frac{dN^X}{dy}\|_{y=0}$
$\pi^{\pm}$	80 - 160	732
K^{+}	< 40	109
K^{-}	< 80	109
p	50 - 100	33
$\bar{p}$	80 - 200	33
γ	< 0.1	comparable to π?

$\pi + d$ are the most important because of pion abundance

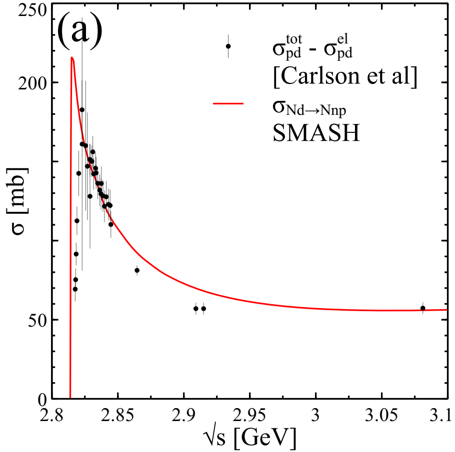
Reactions of deuteron with pions



$\pi d \leftrightarrow \pi np$ is the most important at LHC energies

$\sigma_{\pi d}^{inel} > \sigma_{\pi d}^{el}$, not like for hadrons

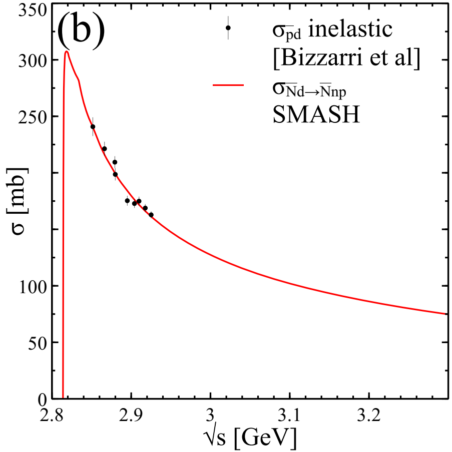
Reactions of deuteron with (anti-)nucleons



$Nd \leftrightarrow Nnp$, $\bar{N}d \leftrightarrow \bar{N}np$: large cross-sections

but not important at LHC energies, because N and $\bar{N}$ are sparse

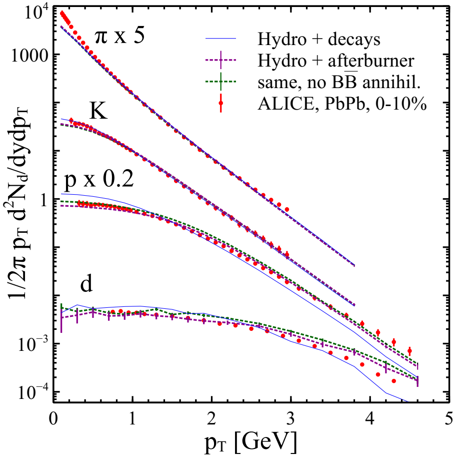
Reactions of deuteron with (anti-)nucleons



$Nd \leftrightarrow Nnp$, $\bar{N}d \leftrightarrow \bar{N}np$: large cross-sections

but not important at LHC energies, because N and $\bar{N}$ are sparse

Transverse momentum spectra

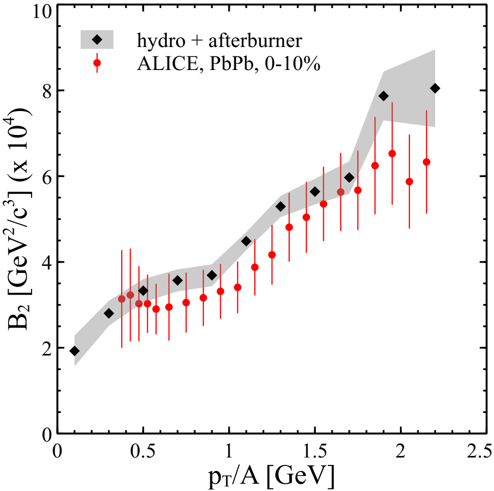


Pion and kaon spectra not affected by afterburner

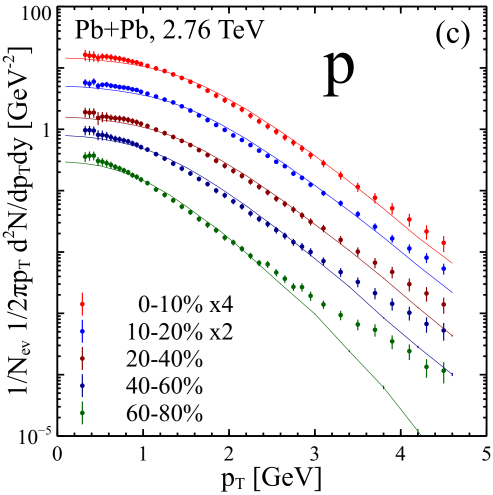
Proton spectra: pion wind effect and $B\bar{B}$ annihilations ($\sim 10\%$)

Obtaining $B_2(p_T)$ coalescence parameter

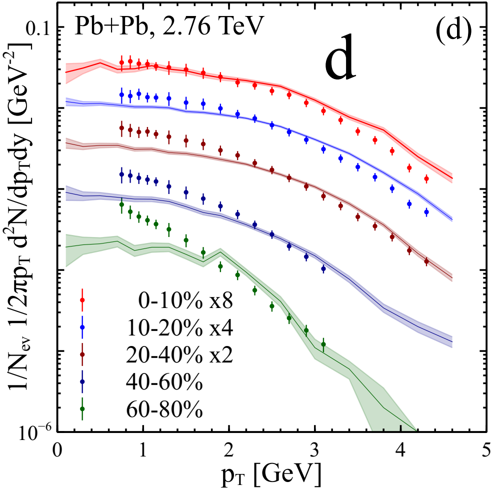
$$B_2(p_T) = \frac{\frac{1}{2\pi}\frac{d^2N_d}{p_T dp_T dy}\Big|_{p_T^d=2p_T^p}}{\left(\frac{1}{2\pi}\frac{d^2N_p}{p_T dp_T dy}\right)^2}$$



p_T-spectra for different centralities



p_T-spectra for different centralities

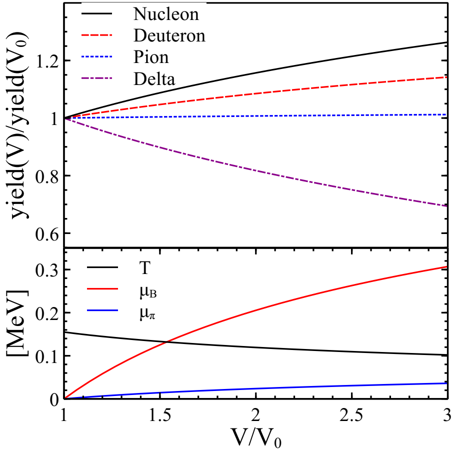


Toy model of deuteron production: no annihilations

- only π, N, Δ, and d
- isoentropic expansion
- pion number conservation
- baryon (not net!) number conservation

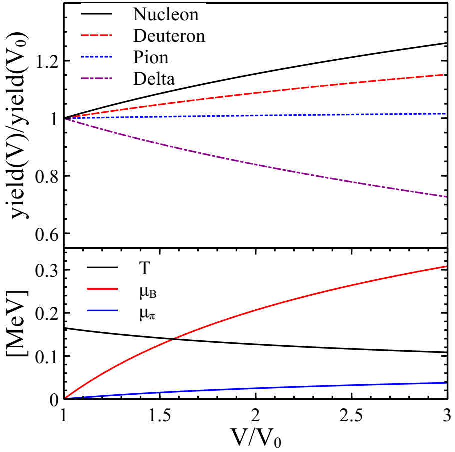
$$\begin{aligned}
(s_\pi(T,\mu_\pi) + s_N(T,\mu_B) + +s_\Delta(T,\mu_B+\mu_\pi) + s_d(T,2\mu_B))V &= const \\
(\rho_\Delta(T,\mu_B+\mu_\pi) + \rho_\pi(T,\mu_\pi))V &= const \\
(\rho_N(T,\mu_B) + \rho_\Delta(T,\mu_B+\mu_\pi) + 2\rho_d(T,2\mu_B))V &= const
\end{aligned}$$

Toy model of deuteron production: results



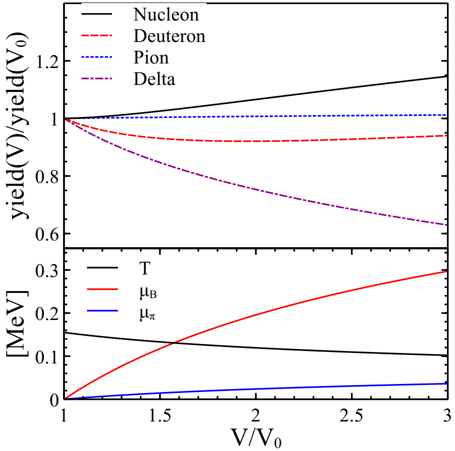
No annihilation: deuteron yield grows, like in simulation.

Toy model of deuteron production: results



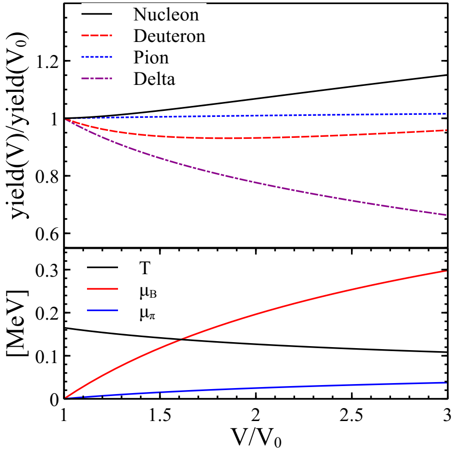
$T_{\text{particlization}} = 165$ MeV. Relative yields are similar, like in simulation.

Toy model of deuteron production: results



Annihilation out of equilibrium: $\mu_B = \mu_B \frac{V/V_0}{a + V/V_0}$, $a = 0.1$ $T_{\text{particlization}} = 155$ MeV.

Toy model of deuteron production: results



Annihilation out of equilibrium: $\mu_B = \mu_B \frac{V/V_0}{a+V/V_0}$, $a = 0.1$ $T_{\mathrm{particlization}} = 165$ MeV.

Qualitatively similar to our simulation.