“Snowballs from hell”:
light nuclei production in heavy ion collisions

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June 12, 2019

Strangeness in Quark Matter 2019

BEST
COLLABORATION

Outline

- Light (anti-)nuclei: challenges
    - *Snowballs from hell*
    - *Light nuclei and critical fluctuations*
    - *Antihelium from space*

Outline

- Light (anti-)nuclei: challenges

    Snowballs from hell
    Light nuclei and critical fluctuations
    Antihelium from space

- Which models could address these challenges?
  How well do they work?

    Naive coalescence (no account of wavefunction)
    Advanced coalescence (account of wavefunction)
    Dynamical models + coalescence
    Dynamical models (no coalescence)

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  Snowballs from hell
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- Possible solution of *Snowballs from hell* challenge

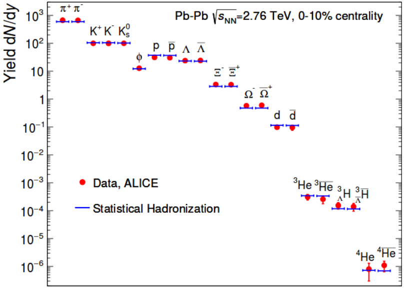
Challenge I: Snowballs from hell

- Nuclei yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV:

$$N_A = \frac{g_A V}{2\pi^2} T m_A^2 K_2(m_A/T), \quad T = 155 \text{ MeV}$$

- Nuclei 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

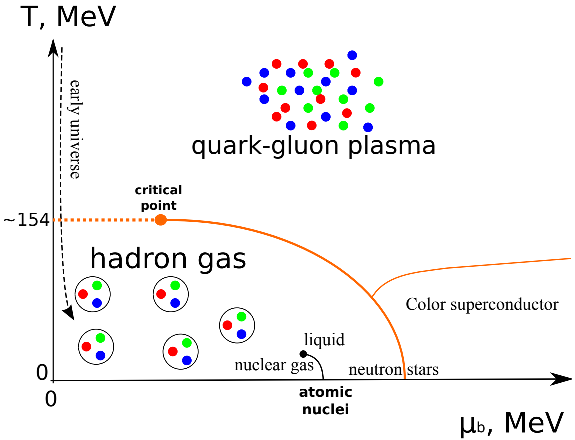
Snowballs in hell.



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

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

Challenge II: 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

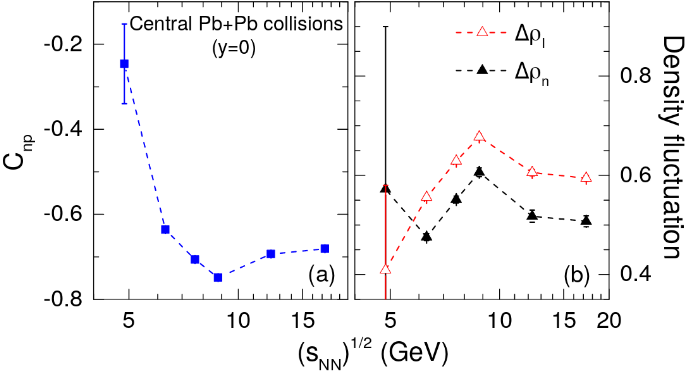
$$N_d \approx \frac{3}{2^{1/2}} \left(\frac{2\pi}{mT}\right)^{3/2} \int d^3x \, \rho_p(x)\rho_n(x) \quad \sim \langle \rho_n \rangle N_p(1 + C_{np})$$
$$N_t \approx \frac{3^{1/2}}{4} \left(\frac{2\pi}{mT}\right)^{3} \int d^3x \, \rho_p(x)\rho_n^2(x) \quad \sim \langle \rho_n \rangle^2 N_p(1 + 2C_{np}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

Thermal model expectation (with N_p – thermal protons)

Light nuclei are sensitive to spatial density fluctuations

Extracting fluctuations from NA49 data

$$C_{np} \equiv \langle \delta\rho_n(x)\delta\rho_p(x)\rangle / (\langle\rho_n\rangle \langle\rho_p\rangle), \; \Delta\rho_n \equiv \frac{\langle(\delta\rho_n)^2\rangle}{\langle\rho_n\rangle^2}$$



Kaijia Sun et al., Phys. Lett. B 781 (2018) 499-504
data: NA49, Phys. Rev. C94 (2016) no.4, 044906

Are the bumps related to fluctuations?

Can one reproduce them without assuming critical point?

Challenge III: 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)

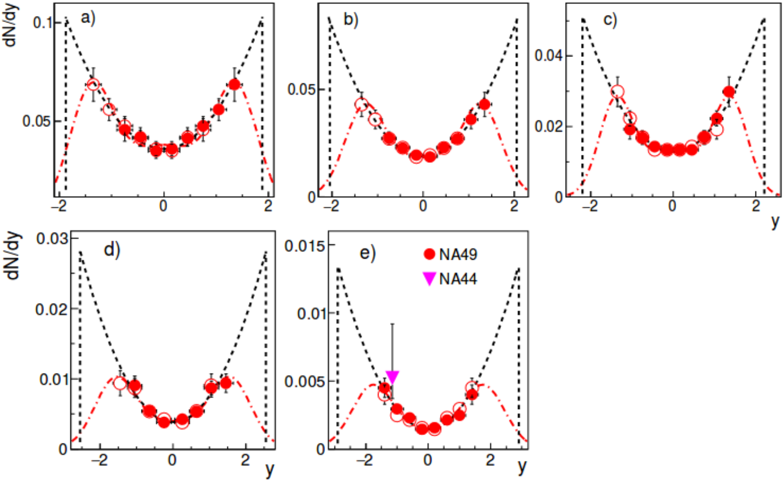
  Conclusion: pp cannot produce that much $\overline{\mathrm{He}}$

  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

Rapidity dependence from NA49

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



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

Theoretical approaches to light nuclei production

- Thermal model
- Analytical coalescence
  - Without nuclei wavefunction
    Gutbrod et al, Phys. Rev. Lett. 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
- Dynamical model + coalescence
  - Transport + coalescence
    Zhu, Ko, Yin, Phys.Rev. C92 (2015) no.6, 064911
    Dong et al., Eur.Phys.J. A54 (2018) no.9, 144
  - Hydro + coalescence
    Ivanov, Soldatov, Eur.Phys.J. A53 (2017) no.11, 218
  - Hydro + transport + coalescence
    Sombun et al, Phys.Rev. C99 (2019) no.1, 014901
- Dynamical model, no coalescence
  - Light nuclei as a single degree of freedom
    Danielewicz, Bertsch, Nucl.Phys. A533 (1991) 712-748
    Oh, Ko, Phys. Rev. C80 (2009) 064902
    Oliinychenko, Pang, Elfner, Koch, Phys.Rev. C99 (2019) no.4, 044907
  - Light nuclei bound by potentials
    Kireyeu et al, KnE Energ.Phys. 3 (2018) 406-409

Disclaimer: References list is not comprehensive. Sorry.

Naive coalescence framework

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

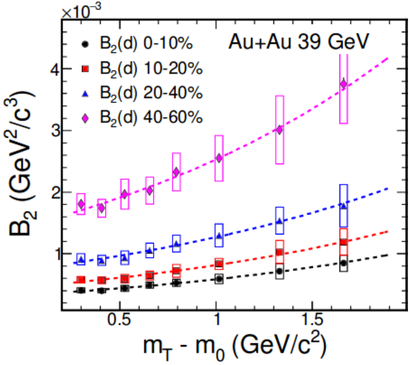
$$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_\mathrm{p} \frac{dN_\mathrm{p}}{d^3P_\mathrm{p}} \right)^Z \left(E_\mathrm{n} \frac{dN_\mathrm{n}}{d^3P_\mathrm{n}} \right)^N \Bigg|_{P_\mathrm{p}=P_\mathrm{n}=P_A/A}$$

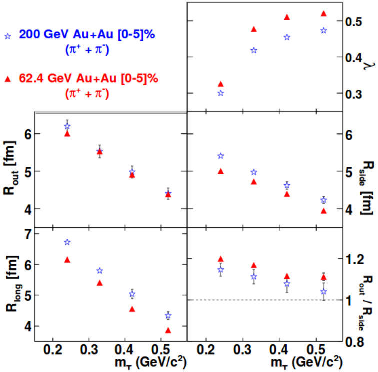
- Expectations:
  - $B_A \sim \left(\frac{4}{3}\pi p_0^3\right)^{A-1}$ or $B_A \sim V_{HBT}^{-(A-1)}$
  - $B_2 \sim 1/V_{HBT}$, $B_3 \sim 1/V_{HBT}^2$
  - $B_A(p_T) \approx$ *const* in pp
  - larger charged multiplicity, smaller B_A
  - $v_2^d(2p_T) = 2v_2^p(p_T)$

Are these naive expectations fulfilled?

Dependencies of B_2: transverse momentum

STAR, arXiv:1903.11778
STAR, Phys.Rev. C 80 (2009) 024905



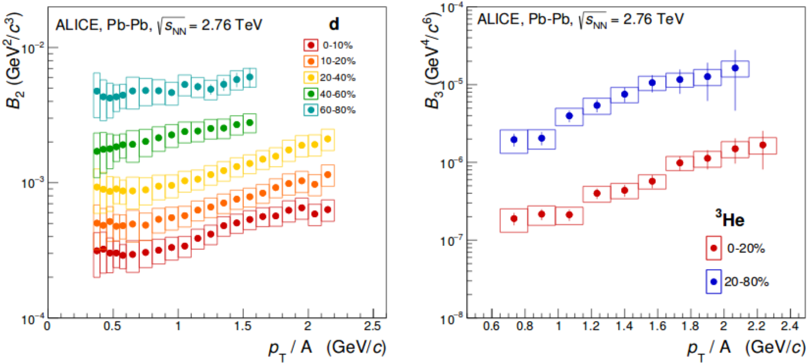


compatible with coalescence expectation

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

Dependencies of B_2: transverse momentum

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

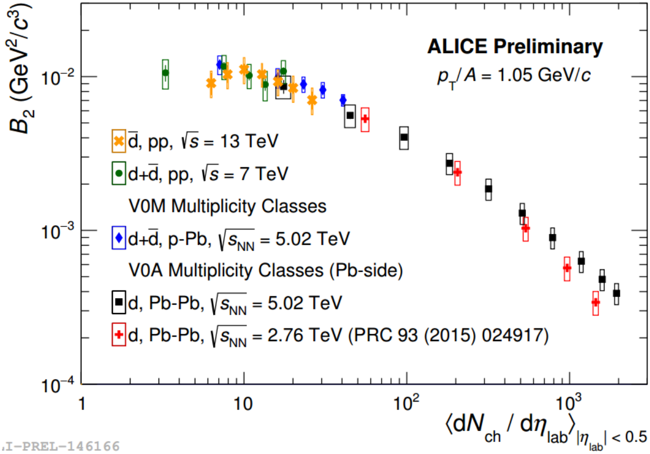


compatible with coalescence expectation

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

Dependencies of B_2: system size

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

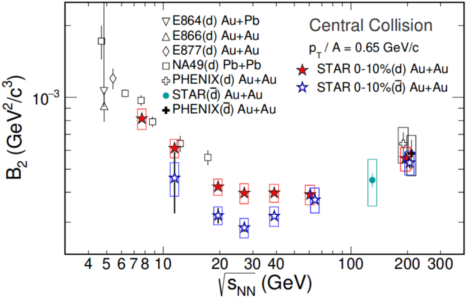


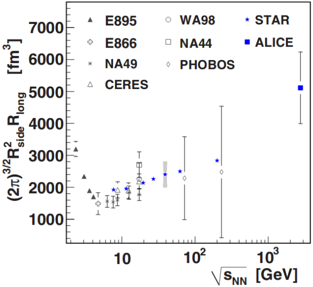
compatible with coalescence expectation

$V \uparrow$, $B_2 \downarrow$

Dependencies of B_2: collision energy

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



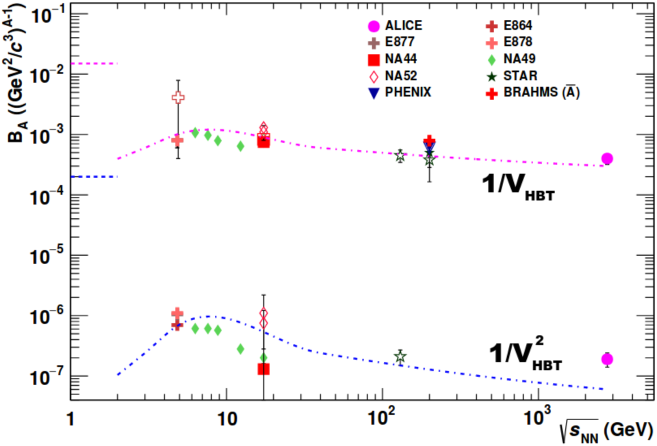


Not really compatible with $B_A \sim V_{HBT}^{-(A-1)}$ qualitatively!

$V_{HBT} \searrow\nearrow \implies$ naive coalescence: $B_A \nearrow\searrow$

Dependencies of B_2: collision energy

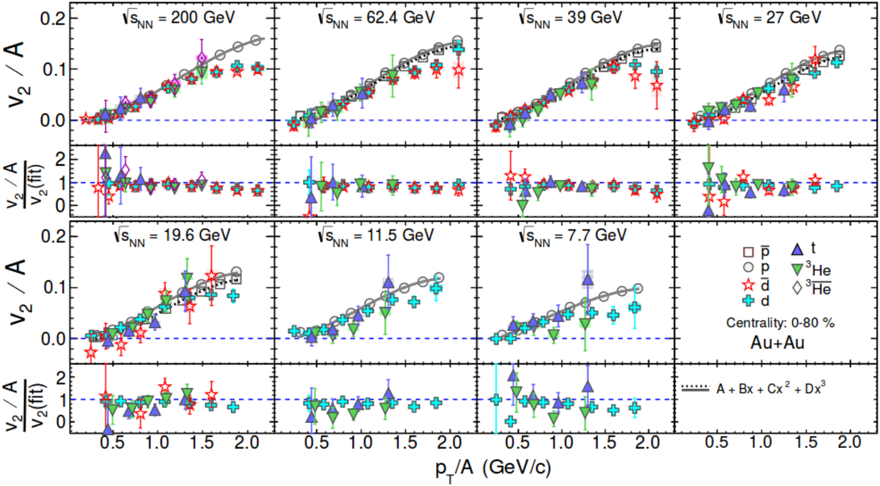
Braun-Munzinger, Dönigus Nucl. Phys. A 987 (2019) 144-201



But the order of magnitude is still right

Elliptic flow of light nuclei

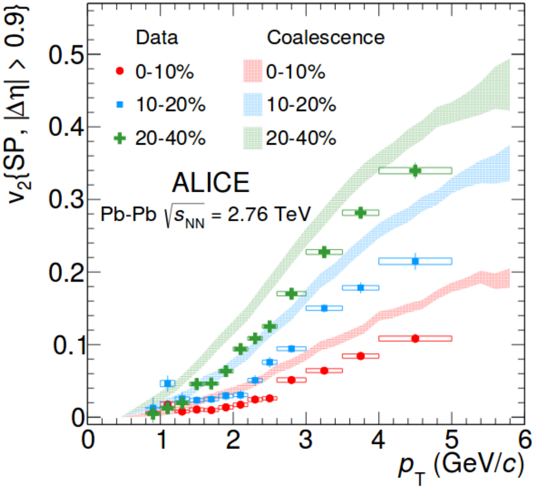
STAR, Phys. Rev. C 94 (2016) no.3, 034908



Good agreement with $v_2^A(Ap_T) = Av_2^p(p_T)$

Elliptic flow of light nuclei

ALICE, Eur.Phys. J. C 77 (2017) no.10, 658



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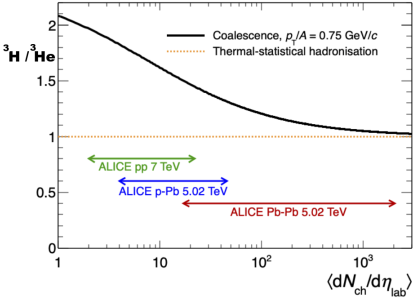
Advanced coalescence

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

Prediction: large wavefunctions are suppressed

$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{m_T R_\perp^2(m_T) R_{||}(m_T)} \qquad \langle C_d \rangle = \frac{1}{\left[1 + \frac{r^2}{4R_\perp^2}\right]\left[1 + \frac{r^2}{4R_{||}^2}\right]^{1/2}}$$

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

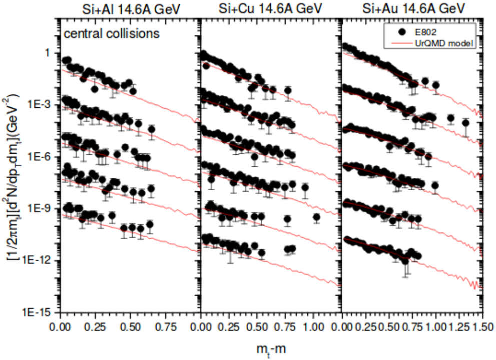


Does wavefunction size matter? To be tested.

[Hydro +] transport + coalescence

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

- Take nucleon pair at $t =$ max. of latest interaction times
- Boost to their rest frame
- Bind $|\Delta p| < 0.28$ GeV and $|\Delta x| < 3.5$ fm
- Take isospin factor into account



Good description from low to high energies with 2 parameters

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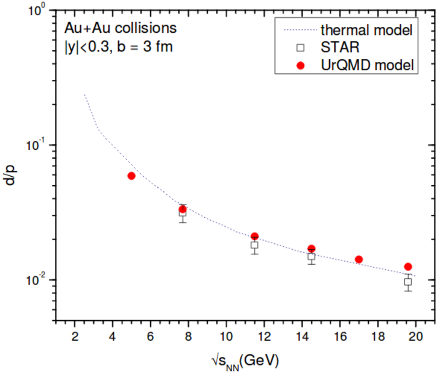

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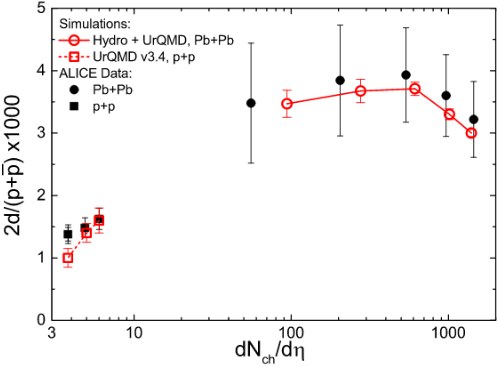


Good description from low to high energies with 2 parameters

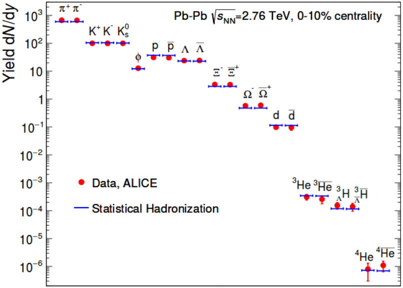
Challenge I: Snowballs from hell

- Assuming rapid freeze-out of nuclei together with hadrons
- Nuclei yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV:

$$N_A = \frac{g_A V}{2\pi^2} T m_A^2 K_2(m_A/T), \; T = 155 \text{ MeV}$$

- 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.

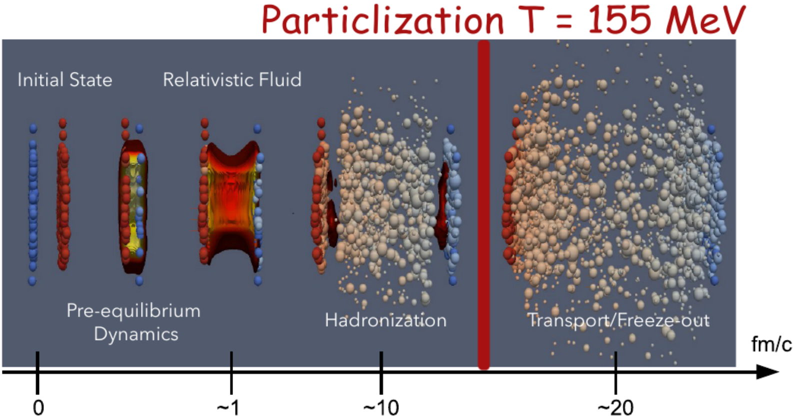


Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561 (2018) no.7723, 321-3305

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

Purely dynamical model

Oliinychenko, Pang, Elfner, Koch, Phys.Rev. C99 (2019) no.4, 044907
Oliinychenko, Pang, Elfner, Koch, MDPI



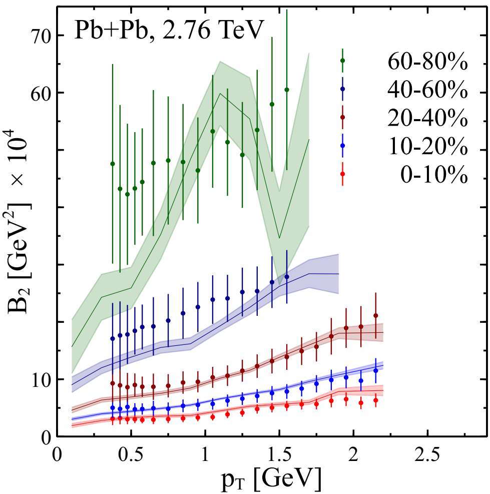
- CLVisc hydro L. G. Pang, H. Petersen and X. N. Wang, arXiv:1802.04449 [nucl-th]
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)
- Treat deuteron as a single particle
  - implement deuteron + X cross-sections explicitly

Reactions with deuteron implemented in SMASH

- $\pi d \leftrightarrow \pi np$, $\pi d \leftrightarrow np$, elastic $\pi d \leftrightarrow \pi d$
- $Nd \leftrightarrow Nnp$, elastic $Nd \leftrightarrow Nd$
- $\bar{N}d \leftrightarrow \bar{N}np$, elastic $\bar{N}d \leftrightarrow \bar{N}d$
- CPT conjugates of all above – reactions for anti-deuteron
- all are tested to obey detailed balance within 1% precision

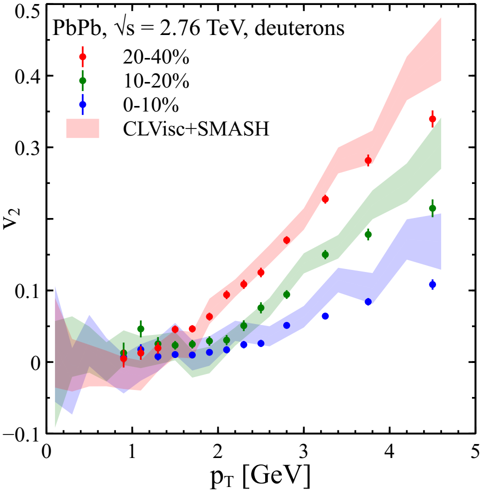
$\pi d \leftrightarrow \pi np$ is the most important at high (LHC) energies
$Nd \leftrightarrow Nnp$ is the most important at low (AGS) energies

$B_2(p_T)$ and v_2 for different centralities



No free parameters. Works well for all centralities.

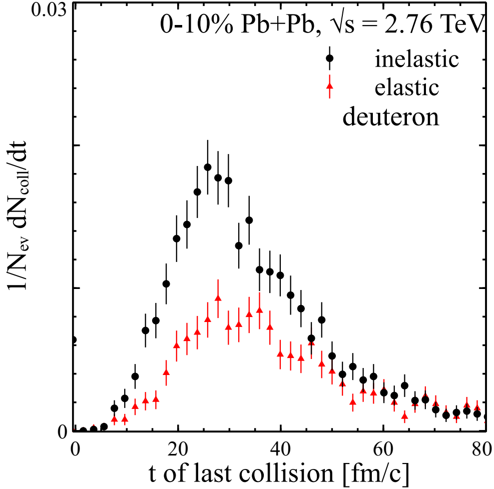
$B_2(p_T)$ and v_2 for different centralities



No free parameters. Works well for all centralities.

Does deuteron freeze out at 155 MeV?

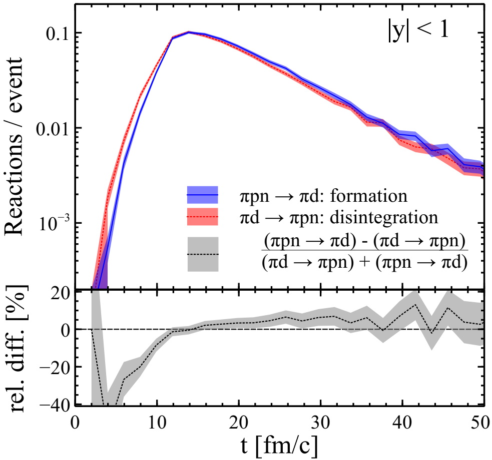
Only less than 1% of final deuterons original from hydrodynamics



Deuteron freezes out at late time

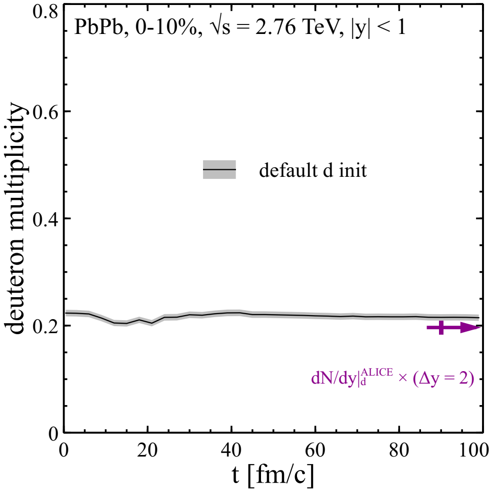
Its chemical and kinetic freeze-outs roughly coincide

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



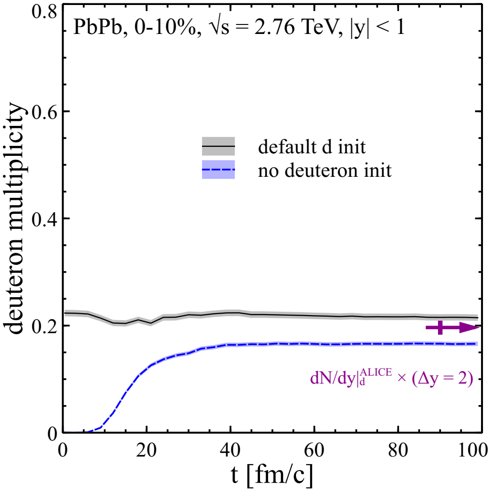
After about 12-15 fm/c within 5% $\pi d \leftrightarrow \pi np$ is equilibrated

Deuteron yield



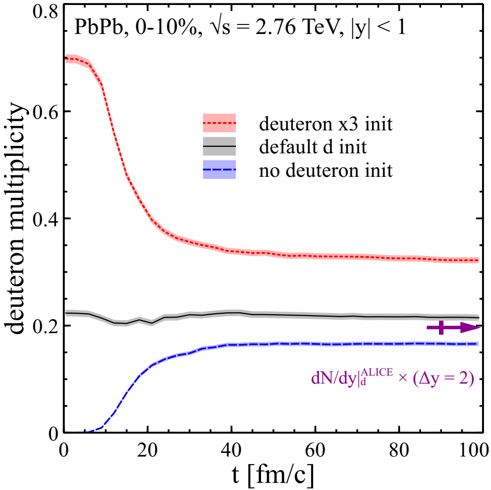
The yield is almost constant. Why? Does afterburner really play any role?

Deuteron yield



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

Deuteron yield



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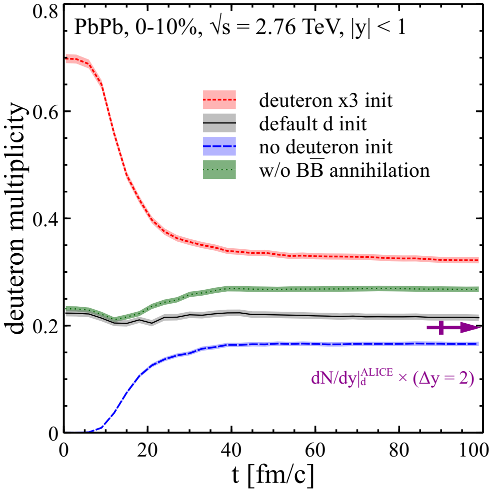
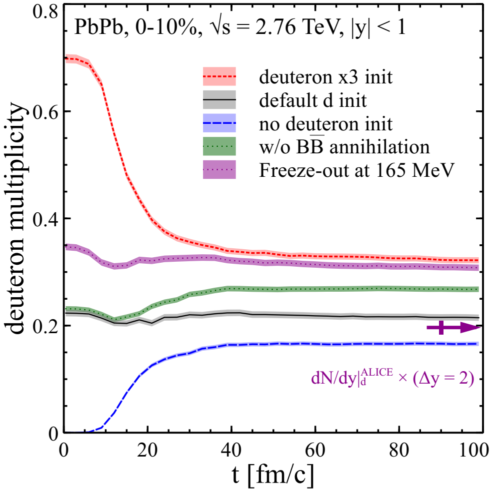


Without $B\bar{B}$ annihilations yield coincidence is less impressive

Deuteron yield



But it persists if T of particlization is changed to 165 MeV

Why thermal model works for light nuclei

- Stable hadron yields (π, K, N, Λ, dots) including resonances are fixed at chemical freeze-out
- Each conserved hadron gets chemical potential
- 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
  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
  Oliinychenko, Pang, Elfner, Koch, Phys.Rev. C99 (2019) no.4, 044907
  Oliinychenko, Pang, Elfner, Koch, MDPI
- If wavefunction is large or or very large – does not matter as long as the cross-sections are large enough to keep relative equilibrium

Conclusions

- Nuclei do not freeze out chemically with hadrons.
  But their yields are determined at chemical freeze-out.
  Because nuclei are bound to nucleons by partial equilibrium.

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Conclusions

- Nuclei do not freeze out chemically with hadrons. But their yields are determined at chemical freeze-out. Because nuclei are bound to nucleons by partial equilibrium.
- Advanced coalescence: does wavefunction size matter? To be tested.
- Dynamical models + coalescence: need them to understand the role of fluctuations on light nuclei. Thermal / blast wave does not help here. Correct underlying phase-space distribution of nucleons is important.
- Need more purely dynamical models studies. Need hadronic exclusive cross-sections: $d + \pi$, $d + p$, $t + \pi$, $t + p$, . . . to be measured or analytically computed.

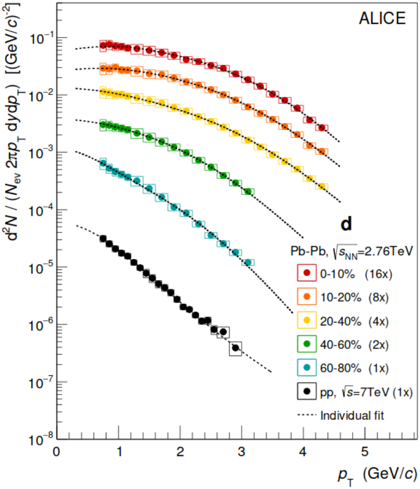
Thank you!

Selected experimental results: spectra

- NA49 Phys.Rev. C94 (2016) no.4, 044906
  - $\sqrt{s_{NN}} = 6.3 - 17.3$ GeV
  - central Pb+Pb collisions
  - d, t, ^{3}He
  - p_T and y differential
- STAR arXiv:1903.11778
  - $\sqrt{s_{NN}} = 7.7 - 200$ GeV
  - 5 centrality classes Au+Au
  - d, $\bar{d}$
  - midrapidity, p_T differential
- ALICE Phys.Rev. C93 (2016) no.2, 024917
  - $\sqrt{s_{NN}} = 2.76$ TeV
  - 5 centrality classes Pb+Pb, pp
  - d, $^3\mathrm{He}$, $^3_\Lambda\mathrm{H}$, $^4\mathrm{He}$ and anti-particles
  - midrapidity, p_T differential

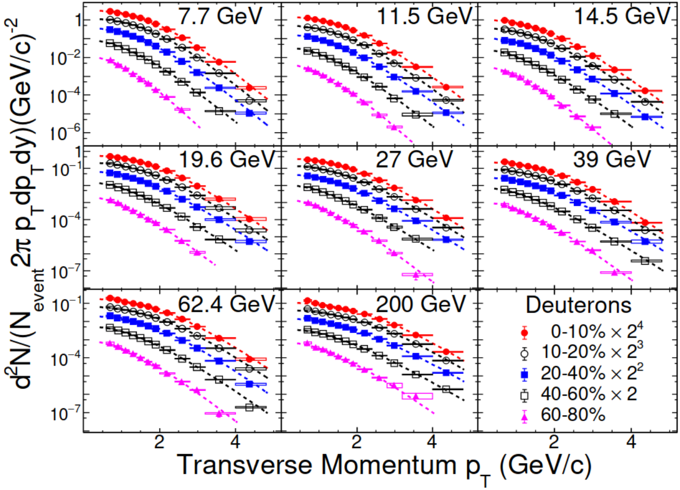
Flashing deuteron spectra

ALICE, PbPb @ $\sqrt{s_{NN}} = 2.76$ TeV and pp @ 7 TeV, deuteron



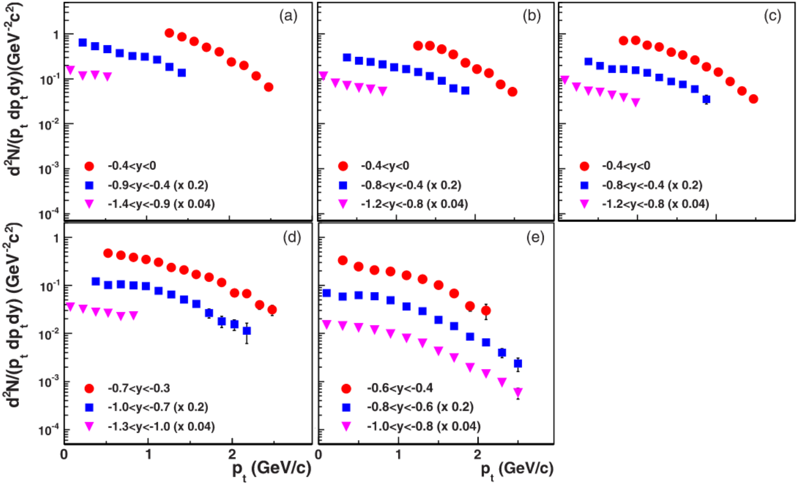
Flashing deuteron spectra

STAR, AuAu @ $\sqrt{s_{NN}} = 7.7 - 200$ GeV, deuteron



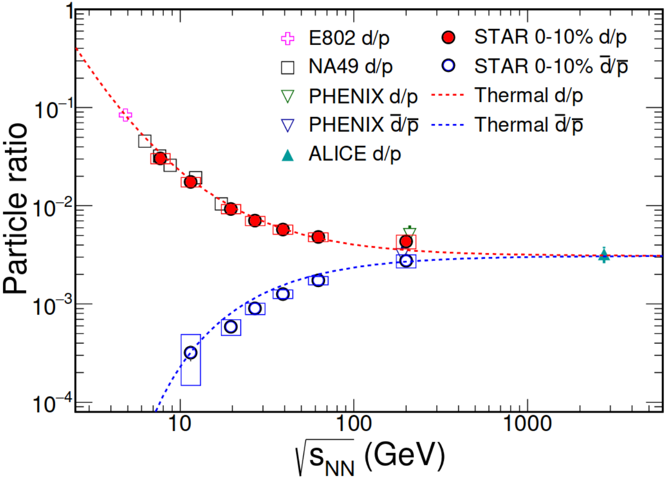
Flashing deuteron spectra

NA49, central PbPb, $\sqrt{s_{NN}} = 6.3 - 17.3$ GeV, deuteron



Can one obtain a physical picture out of these spectra? Yes!

Integrated spectra: midrapidity d/p ratio

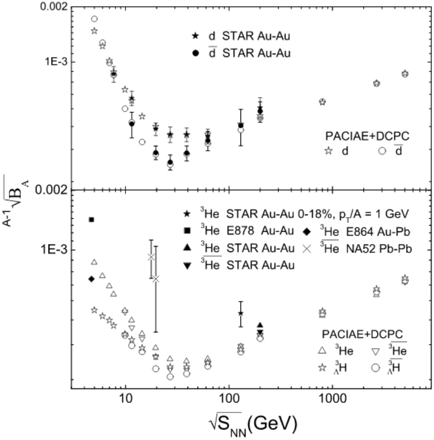


Light nuclei are rare in relativistic HIC

“Penalty factor” at $\sqrt{s_{NN}} > 5$ GeV: $10^{-1} \rightarrow 3 \cdot 10^{-3}$

Transport + coalescence

Dong et al., Eur.Phys.J. A54 (2018) no.9, 144



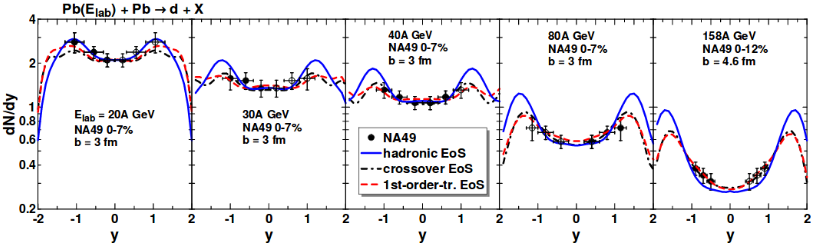
- Form cluster if $m \le |m_{inv}| \le m + \Delta m$ and $|x_i - x_j| < D$
- Δm and D depend on nucleus

  the values are not specified in the publication

Hydro+coalescence

Ivanov, Soldatov, Eur.Phys.J. A53 (2017) no.11, 218

$$E_A \frac{d^3\tilde{N}_{N,Z}}{d^3P_A} = \frac{N_{tot}^N Z_{tot}^Z}{A_{tot}^A} \left(\frac{P_{NZ}^3}{M_N \bar{A}_{cell}} \right)^{A-1} \left(E \frac{d^3\tilde{N}^{(N)}}{d^3p} \right)^A$$



- 3-fluid hydrodynamics
- Computing coalescence spectra in every hydro cell
- Parameter P_{NZ} fit to match yield

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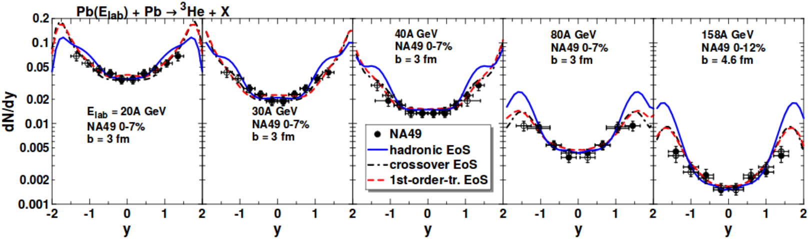

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Most important deuteron production/disintegration reactions

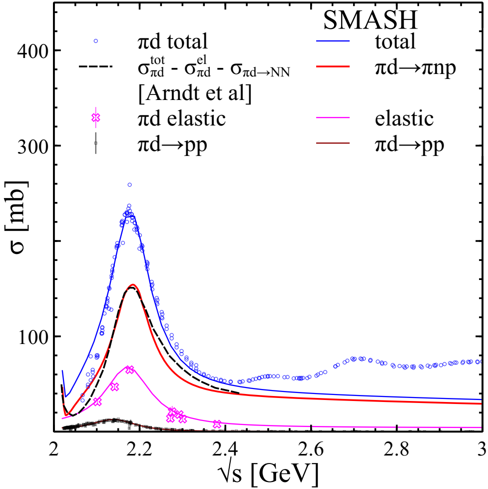
Largest d + X disintegration rate → largest reverse production rate

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

X	$\sigma^{\text{inel}}_{d+X}$ [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

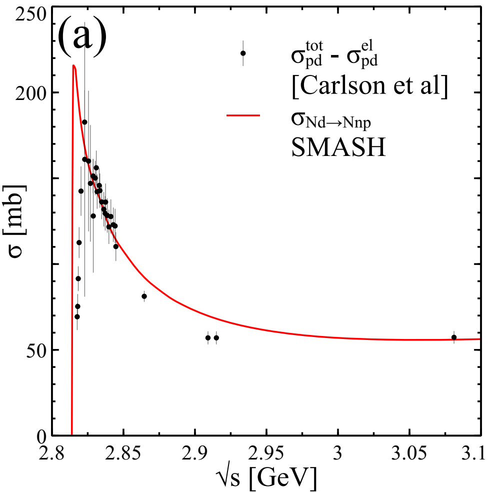
Reactions of deuteron with pions



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

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

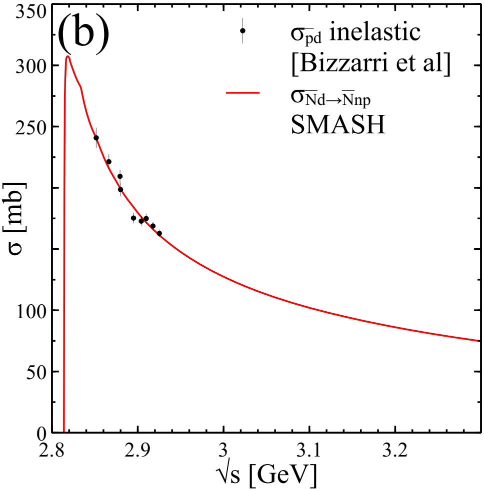
Reactions of deuteron with (anti-)nucleons



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

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

Reactions of deuteron with (anti-)nucleons



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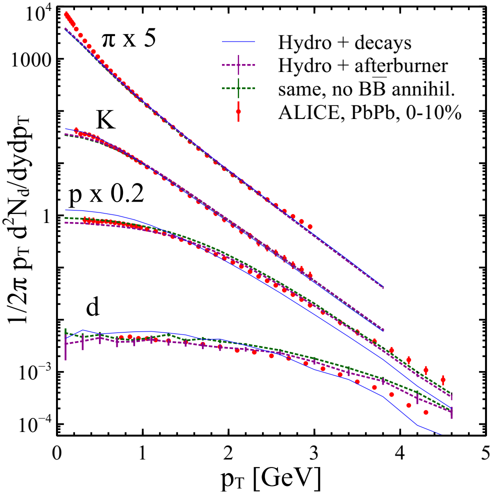
Transverse momentum spectra

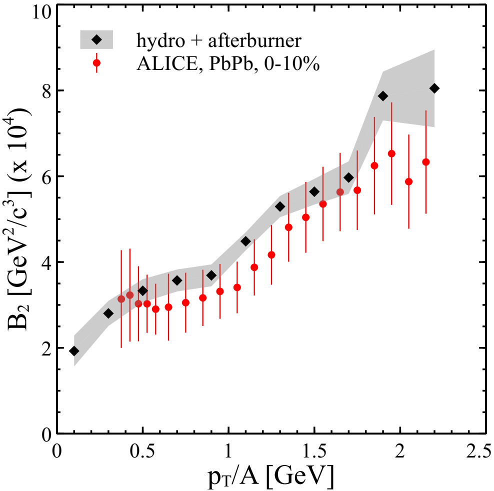


Pion and kaon spectra not affected by afterburner

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

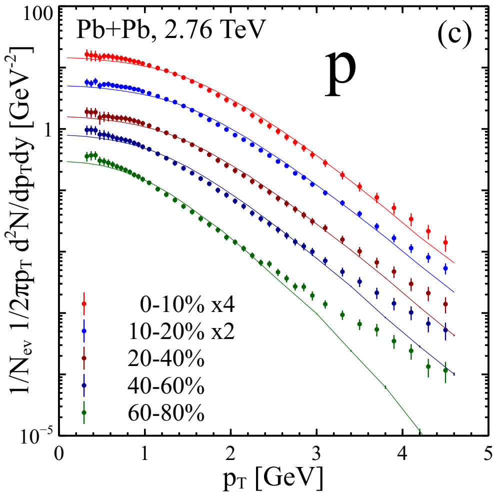
Obtaining $B_2(p_T)$ coalescence parameter

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



Reproducing B_2 without any free parameters

p_T-spectra for different centralities



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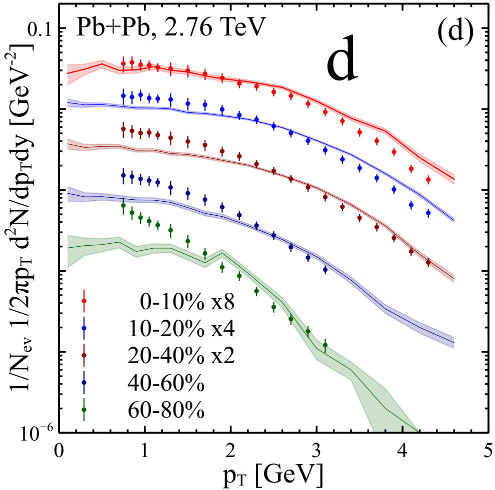
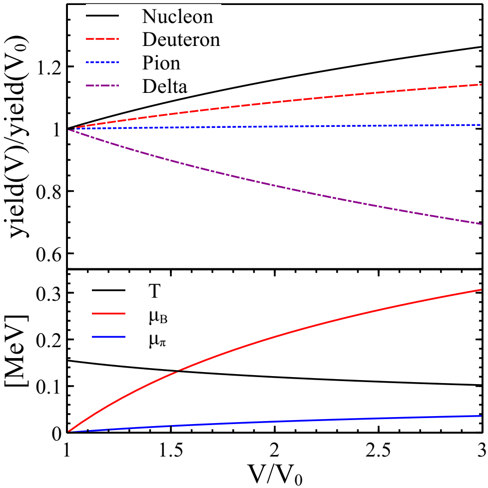


Toy model of deuteron production: no annihilations

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

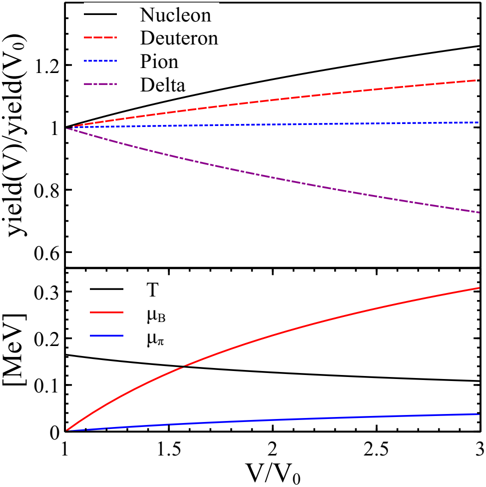
$$\begin{aligned}
(s_\pi(T,\mu_\pi) + s_N(T,\mu_B) + +s_\Delta(T,\mu_B+\mu_\pi) + s_d(T,2\mu_B))V &= const \\
(\rho_\Delta(T,\mu_B+\mu_\pi) + \rho_\pi(T,\mu_\pi))V &= const \\
(\rho_N(T,\mu_B) + \rho_\Delta(T,\mu_B+\mu_\pi) + 2\rho_d(T,2\mu_B))V &= const
\end{aligned}$$

Toy model of deuteron production: results



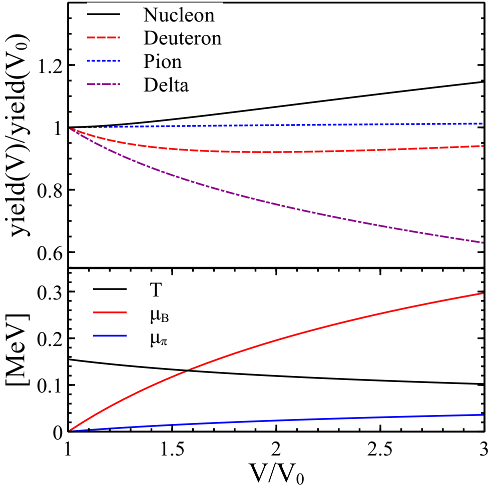
No annihilation: deuteron yield grows, like in simulation.

Toy model of deuteron production: results



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

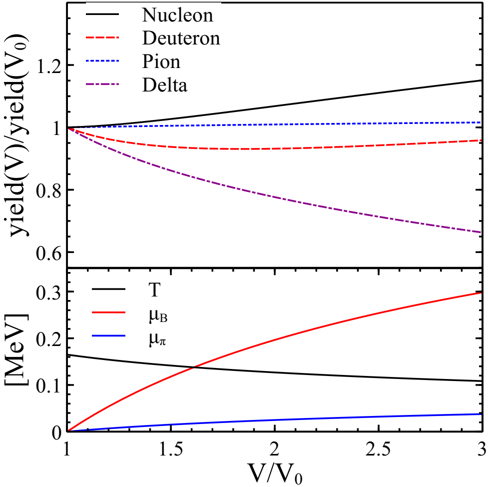
Toy model of deuteron production: results



Annihilation out of equilibrium: $\mu_B = \mu_B \frac{V/V_0}{a+V/V_0}$, $a = 0.1$

$T_{\mathrm{particlization}} = 155$ 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.