Review of the light nuclei production in both theoretical and experimental side

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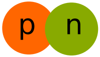
Lawrence Berkeley National Laboratory

September 1, 2020

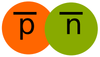
RHIC BES seminar

Subject of this talk: Light nuclei and anti-nuclei

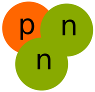
Anti-



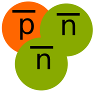
Deuteron (d)



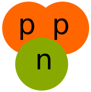
Deuteron ($\bar{d}$)



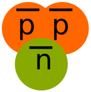
Tritium (t)



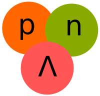
Tritium ($\bar{t}$)



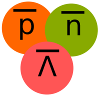
Helium-3 (^{3}He)



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



Hypertriton ($^3_\Lambda$H)



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

Main question: Nuclei (or pp, or $p\bar{p}$, or e^+e^-) collide at high energy. How many light (anti-)nuclei of each sort will be born in collision and where do they fly?

Anti-helium by Alpha-Magnetic Spectrometer

- 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?

Is anti-helium at AMS compatible with $pp \to \overline{\mathrm{He}}$?

- 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

- 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

- M. Kachelriess, S. Ostapchenko and J. Tjemsland
  "Revisiting cosmic ray antinuclei fluxes with a new coalescence model", arXiv:2002.10481 [hep-ph]

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

Different coalescence models, tuned to (subsets of) data from

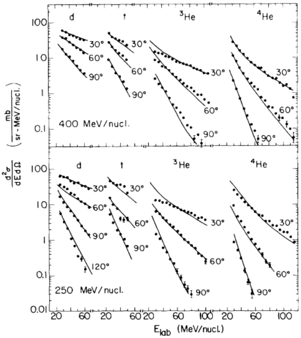
- $e^+e^- \to \overline{\mathrm{He}}$ at Z resonance [ALEPH, OPAL]
- $pp \to \overline{\mathrm{He}}$ at 53 GeV [CERN ISR], at 0.9, 2.76, 7 TeV [ALICE]

Naive coalescence framework

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

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

B_A: B_2 for deuteron, B_3 for tritium, $^3\mathrm{He}$, B_4 for $^4\mathrm{He}$



p_0 "coalescence momentum"

$$B_A = \frac{1}{Z!(A-Z)!}\left(\frac{4}{3}\pi p_0^3\right)^{A-1}$$

Gutbrod et al, PRL 37 (1976) 667-670

Described A = 2, 3, 4 spectra in

$Ne + U$ at 250, 400 A MeV

But: different p_0 for each A

Note large sensitivity to p_0

Not state-of-the art approach for B_A

The role of wavefunction and source size

Overlap of nucleus wavefunction and source size matters
Sato, Yazaki, Phys. Lett. 98B (1981) 153-157

For deuteron:

$$\frac{4}{3}\pi p_0^3 \Rightarrow 2^3 \frac{3}{4}(2\pi)^3 \int d^3\vec{r}|\Psi_d(\vec{r})|^2 S_2(\vec{r})$$
$$S_2(\vec{r}) = \int d\vec{r'} S_p(\vec{r}-\vec{r}')S_n(\vec{r}')$$

$S_{p,n}$ – normalized spatial distributions of p,n; "source functions"
$\Psi_d(\vec{r})$ – deuteron wavefunction

Relation to femtoscopic (HBT) correlations
Scheibl, Heinz, Phys.Rev. C59 (1999) 1585-1602
Blum, Takimoto, PRC 99, no.4, 044913 (2019)

$$C_2(p,q) = \int d^3\vec{r}\Psi_{pp}(q,\vec{r}r)S_2(\vec{r})$$
$$\Psi_{pp}(q,\vec{r}) \sim (e^{iqr} \pm e^{-iqr})$$

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Analytical coalescence

- Source is homogeneous on the scale of wavefunction size
- Gaussian source
- $q^2 \ll m^2$
- A-particle correlation function $= \prod$ (2-particle correlations)
  Scheibl, Heinz, Phys.Rev. C59 (1999) 1585-1602
  Blum, Takimoto, PRC 99, no.4, 044913 (2019), m vs m_T discrepancy

$$\frac{B_A}{m^{2(A-1)}} \approx \frac{2J_A+1}{2^{A-1}\sqrt{A}} \left(\frac{\pi^{3/2}}{m^3 (R_\perp^2(p_T)+d_A^2/4)^2 (R_{||}^2(p_T)+d_A^2/4)} \right)^{A-1}$$

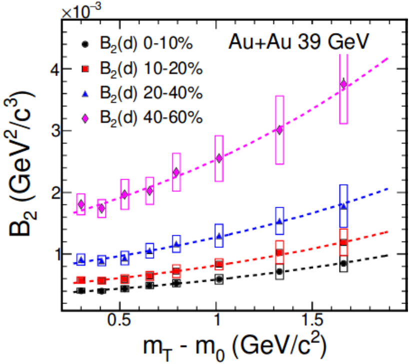
Simplified qualitative expectations:

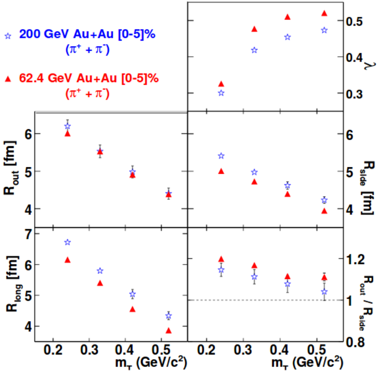
- $B_A \sim V_{HBT}^{-(A-1)}$
- $B_2 \sim 1/V_{HBT}$, $B_3 \sim 1/V_{HBT}^2$
- $B_A(p_T) \approx const$ in pp
- larger charged multiplicity, smaller B_A

Are these expectations fulfilled?

Dependencies of B_2: transverse momentum

STAR, PRC 99 (2019) 6, 064905
PRC 80 (2009) 024905



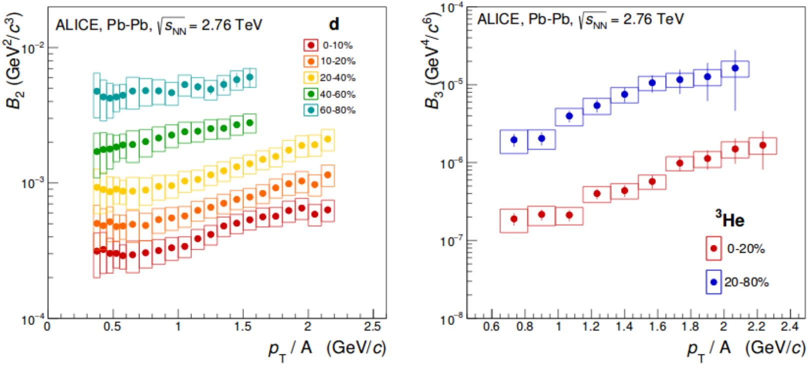


compatible with coalescence expectation

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

Dependencies of B_2: transverse momentum

ALICE, PRC93 (2016) no.2, 024917

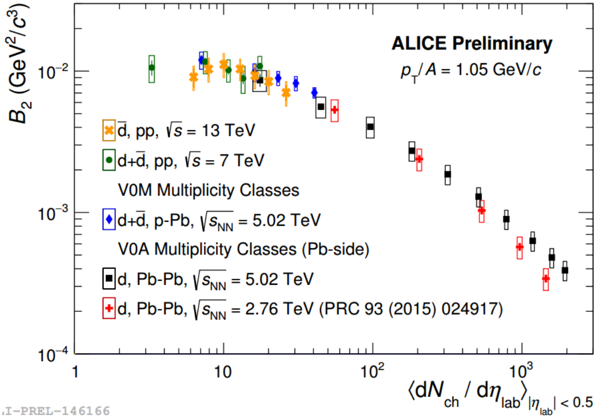


compatible with coalescence expectation

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

Dependencies of B_2: system size

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

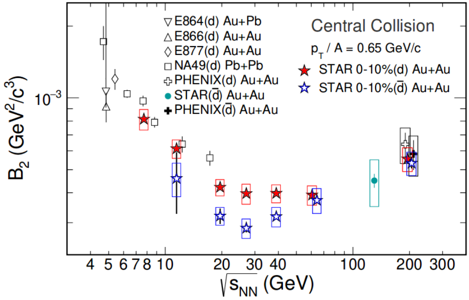


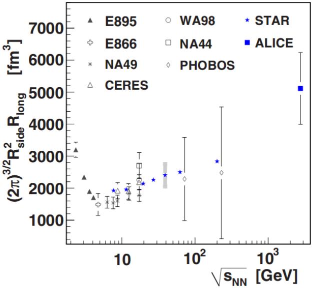
compatible with coalescence expectation

$V\uparrow,\ B_2\downarrow$

Dependencies of B_2: collision energy

STAR, PRC 92 (2015) no.1, 014904
STAR, PRC 99 (2019) 6, 064905

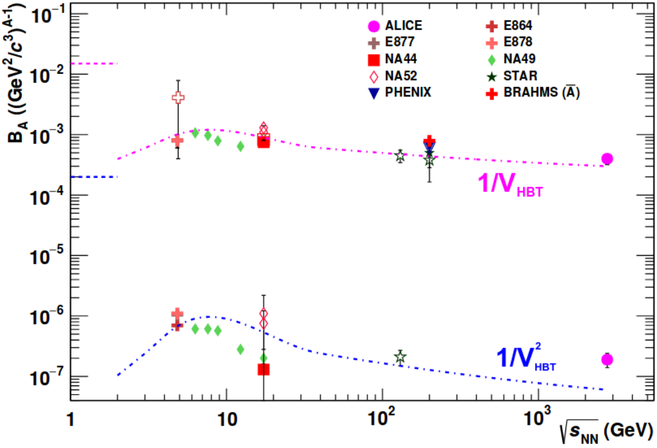




Not really compatible with $B_A \sim V_{HBT}^{-(A-1)}$ qualitatively!

Dependencies of B_2: collision energy

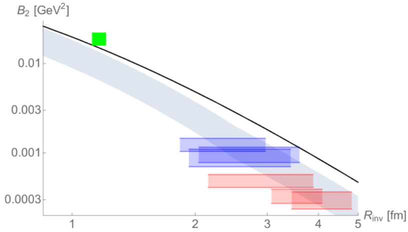
Braun-Munzinger, Dönigus Nucl. Phys. A 987 (2019) 144-201

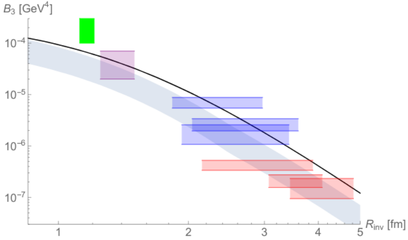


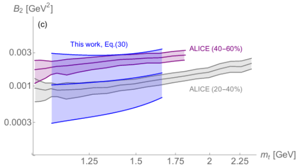
But the order of magnitude is still right

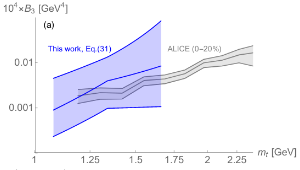
More quantitative comparison

Blum, Takimoto, PRC 99, no.4, 044913 (2019)
Bellini, Blum, Kalweit, Puccio, 2007.01750 [nucl-th]









Need HBT-measurement, further comparison for NA49, STAR data

Challenge: simple phenomenological formula to fit

$$B_A(\sqrt{s}, dN_{ch}/d\eta, p_T, y)$$

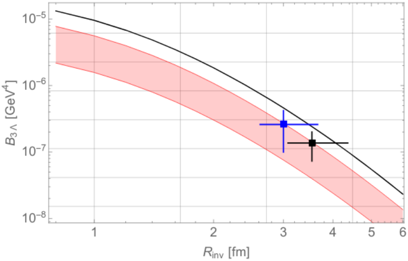
Testing coalescence with hypertriton

${}^{3}_{\Lambda}\mathrm{H}$ is d bound to Λ by 130 keV, size $\sim$ 10 fm

Large wavefunction compared to system size $\Rightarrow$ suppression

- Coalescence model is far below the data
  Bellini, Kalweit, Phys. Rev. C99 (2019) no.5, 054905
- Coalescence model is compatible with the data
  Zhang, Ko, PLB 780, 191-195 (2018); Bellini, Blum, Kalweit, Puccio, 2007.01750 [nucl-th]

  More careful consideration of ${}^{3}_{\Lambda}\mathrm{H}$ wavefunction



Research in progress, waiting for more ALICE, and for STAR measurements

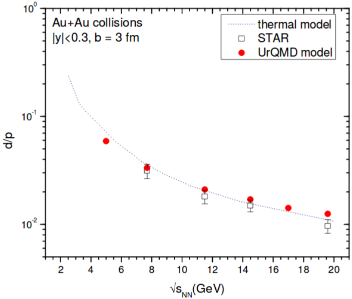
Need ${}^{3}_{\Lambda}\mathrm{H}$ and HBT measurements

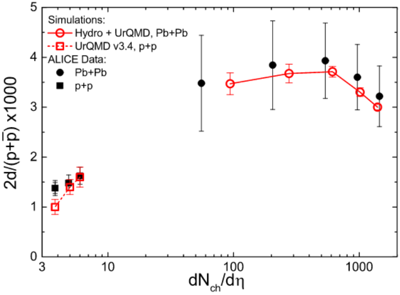
Realistic source function: [hydro +] transport + coalescence

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

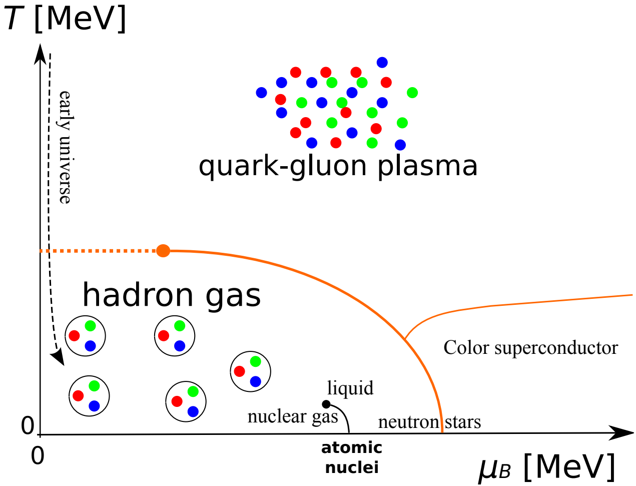
UrQMD — Sombun et al, PRC 99 (2019) no. 1, 014901





Good description from low to high energies with 2 parameters

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

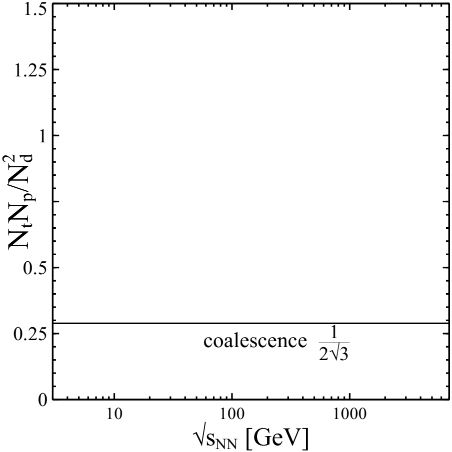
$$\frac{g_t g_p}{g_d^2} \left(\frac{3m \cdot m}{(2m)^2}\right)^{3/2} = \frac{1}{2\sqrt{3}} \approx 0.29$$

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], ALICE [Adam:2015vda]; model JAM + coalescence [Liu:2019nii]



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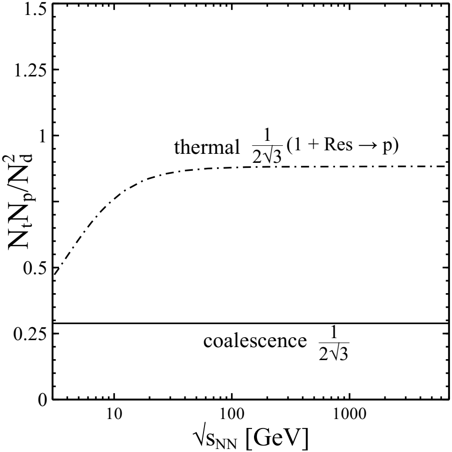

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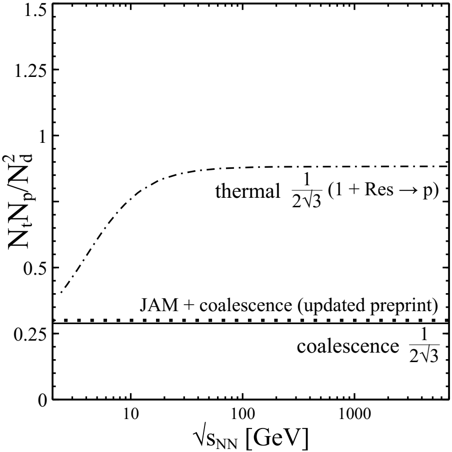

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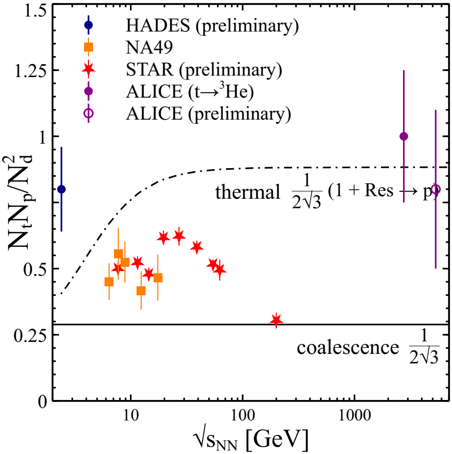
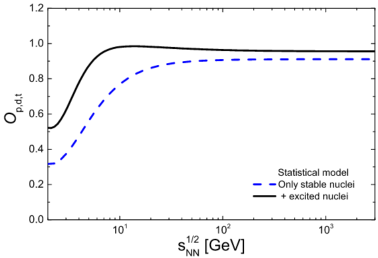


Are the bumps related to fluctuations?

Critical point and $^4\mathrm{He}$ excited states

- Deeply attractive nucleon-nucleon potential V around the critical point
  $N_t N_p / N_d^2 \approx 0.29 \langle e^{-V/T} \rangle$
  $N_\alpha N_t N_p^2 / N_{^3He} N_d^3 \approx 0.42 \langle e^{-3V/T} \rangle$: more sensitive
  Shuryak, Torres-Rincon, PRC 101, no.3, 034914 (2020)
- Decay of many $^4\mathrm{He}$ excited states, thermal model, no V
  Vovchenko, Dönigus, Kardan, Lorenz, Stoecker, arXiv:2004.04411 [nucl-th]



$$\mathcal{O}_{p,d,t} \equiv N_p N_t / N_d^2$$

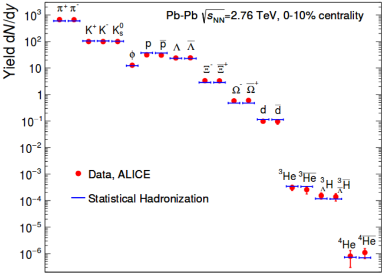
Thermal model and “snowballs in hell”

- 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 per particle: d, $^3\mathrm{He}$, $^3_\Lambda\mathrm{H}$, $^4\mathrm{He}$ – $\simeq$ 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?

Relation of thermal + blast wave to coalescence model

Blast-wave model:

- Cooper-Frye formula on hypersurface Σ, $B \ll m$
- If boost-invariant hypersurface $\Rightarrow$ Siemens-Rasmussen formula
- $\mu_{p,n}$ before resonance decays
  normalization to thermal model yields
  light nuclei formed at chemical freeze-out

$$E_d \frac{dN_d}{d^3 p_d} = \int_\Sigma p_d^\mu d\sigma_\mu \, e^{(\mu_p - \frac{p_d^\nu}{2} u_\nu)/T} e^{(\mu_n - \frac{p_d^\nu}{2} u_\nu)/T}$$

Coalescence model:

$$E_d \frac{dN_d}{d^3 p_d} = \int_\Sigma p_d^\mu d\sigma_\mu \, e^{(\mu_p - \frac{p_d^\nu}{2} u_\nu)/T} e^{(\mu_n - \frac{p_d^\nu}{2} u_\nu)/T} C_d(r_d, p_d)$$

$$C_d(r_d, p_d) = \int \frac{d^3q \, d^3r}{(2\pi^3)} \mathcal{D}(q, r) \frac{f(r_d + r/2, p_d/2 + q/2) f(r_d - r/2, p_d/2 - q/2)}{f^2(r_d, p_d/2)}$$

- $\mathcal{D}(q, r)$ – Wigner transform of deuteron wavefunction
- $C_d(r_d, p_d)$ – measures fireball inhomogeneity over wavefunction size
  $C_d(r_d, p_d) = 1$ for large homogeneous fireball
- $\mu_{p,n}$ after resonance decays
  light nuclei formed at kinetic freeze-out

Thermal model and "snowballs in hell" puzzle

- Nuclei formed early — at hadronic freeze-out

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

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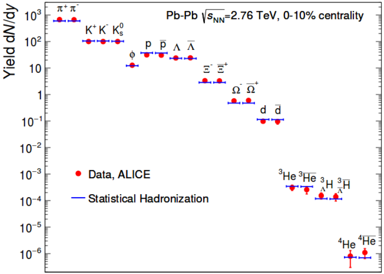
Snowballs in hell.



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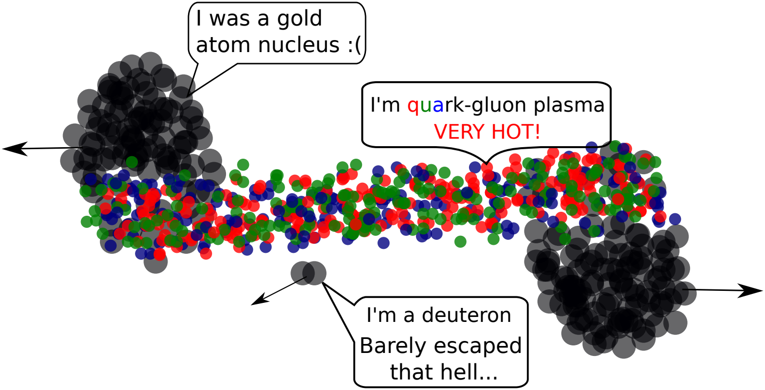
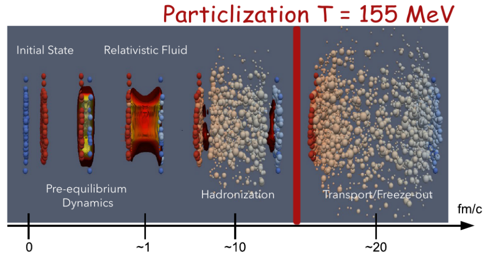
"Snowballs in hell"



How deuteron survived: Oliinychenko et. al, Phys.Rev.C 99 (2019) 4, 044907

Purely dynamical model

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

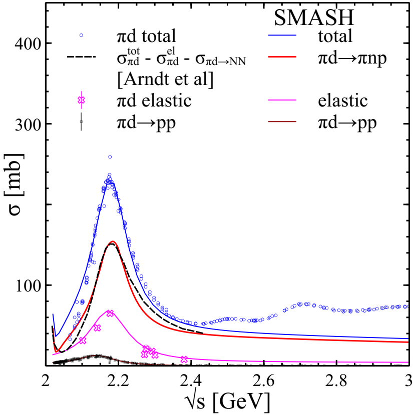


- CLVisc hydro L. G. Pang, H. Petersen and X. N. Wang, arXiv:1802.04449 [nucl-th]
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)
- Treat deuteron as a single particle
    - implement deuteron + X cross-sections explicitly

Light nuclei production by pion catalysis

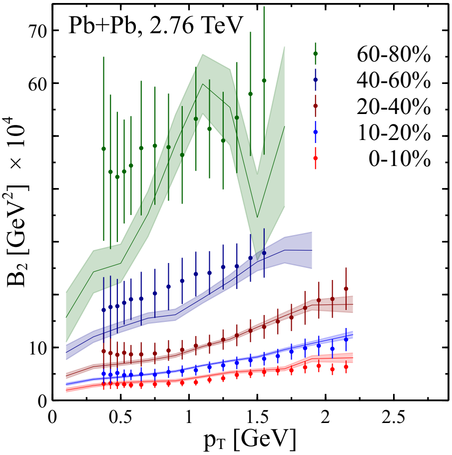
- $\pi d \leftrightarrow \pi np$, $Nd \leftrightarrow Nnp$
- all are tested to obey detailed balance within 1% precision
- large disintegration cross sections $\rightarrow$ large reverse rates

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.

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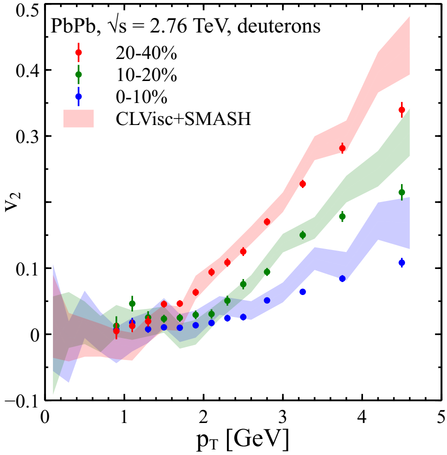

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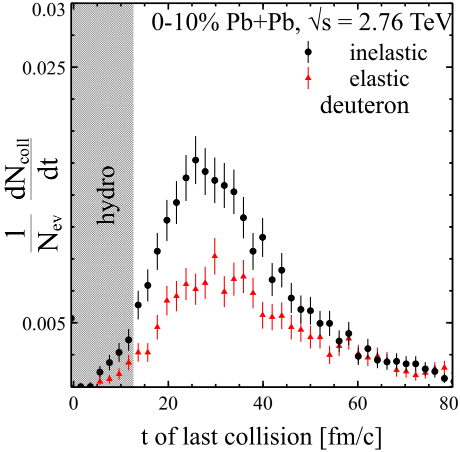
No free parameters. Works well for all centralities.

Does deuteron freeze out at 155 MeV?

Only less than 1% of final deuterons originate from hydrodynamics

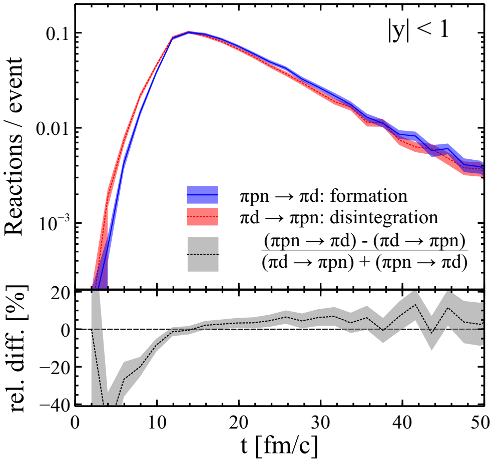


Deuteron freezes out at late time

Its chemical and kinetic freeze-outs roughly coincide

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

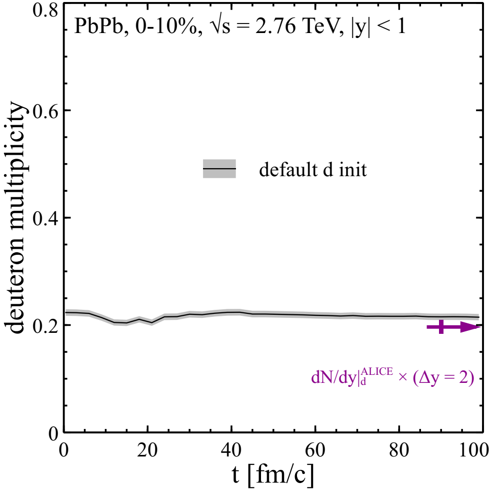
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

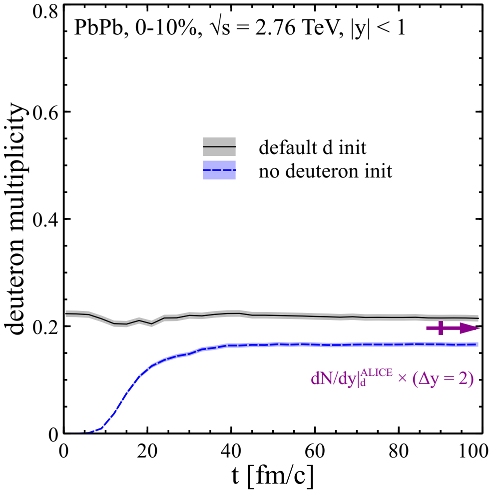
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

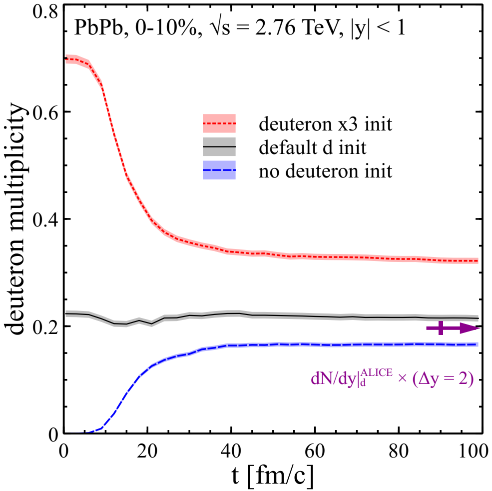
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



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

Deuteron yield

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



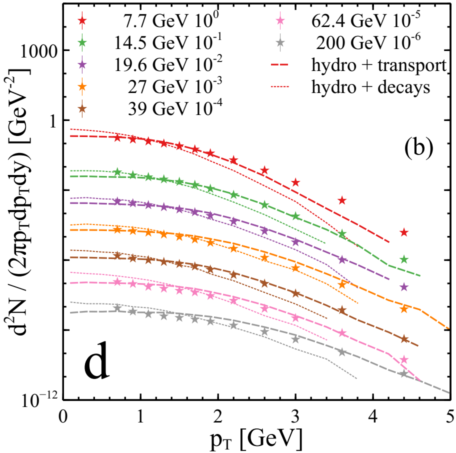
No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

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

Exactly the same mechanism, lower energies

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



Same mechanism still works for deuteron down to 7.7 GeV!

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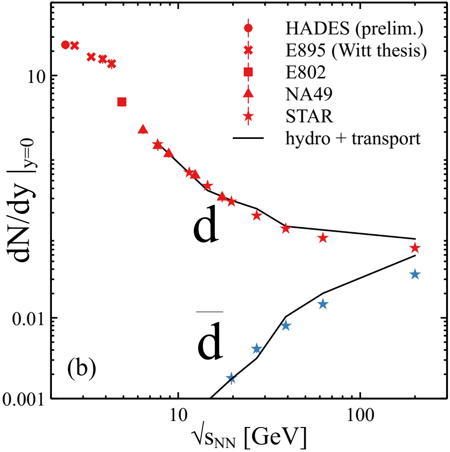

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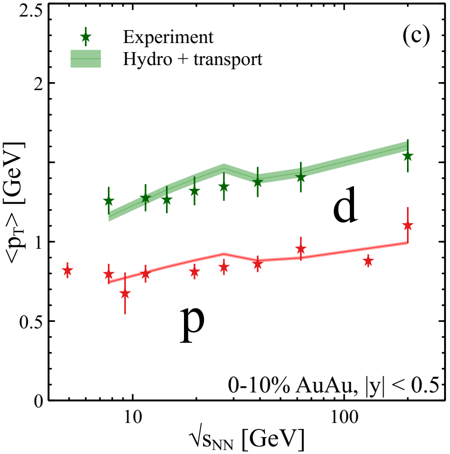

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Conclusions

Need better understanding of light nuclei production

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- Potential benefits
  - 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
    $\Longrightarrow \frac{N_t N_p}{N_d^2}$, other ratios

Conclusions

Need better understanding of light nuclei production

- Potential benefits
  - 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
    $\Longrightarrow \frac{N_t N_p}{N_d^2}$, other ratios
- Challenges
  - Need model for light nuclei yields in e^+e^-, pp, $p\bar{p}$, AA
    as a function of $\sqrt{s}$, $dN_{ch}/d\eta$, p_T, y
  - Need to improve models, both dynamical and analytical
  - Need models including critical point
  - Does wavefunction size matter?
    Still an open question: small systems, ${}^3_\Lambda\mathrm{H}$
  - Need hadronic exclusive cross-sections:
    $d+\pi$, $d+p$, $t+\pi$, $t+p$, etc, to be measured or analytically computed

Thank you!

Most important deuteron production/disintegration reactions

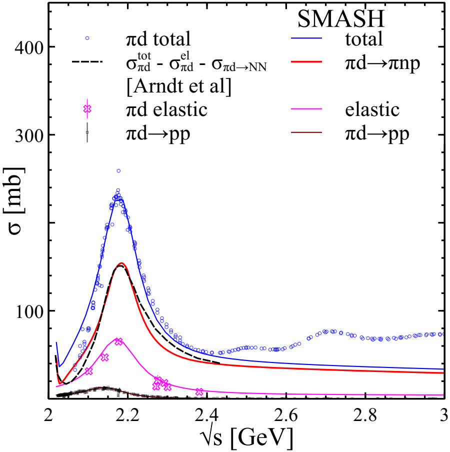
Largest d + X disintegration rate $\rightarrow$ largest reverse production rate

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

X	$\sigma^{\mathrm{inel}}_{d+X}$ [mb] ($\sqrt{s} - \sqrt{s_{thr}} = [0.05, 0.25]$ GeV)	$\frac{dN^X}{dy}\vert_{y=0}$
$\pi^\pm$	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

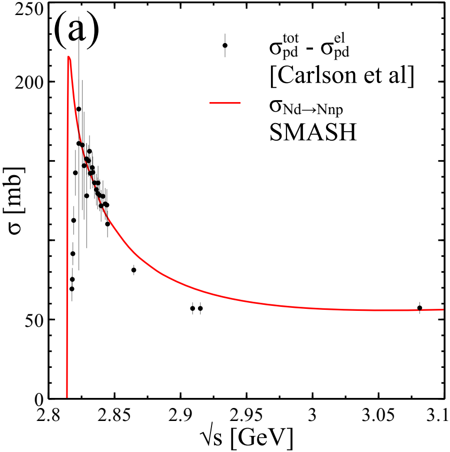
Reactions of deuteron with pions



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

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

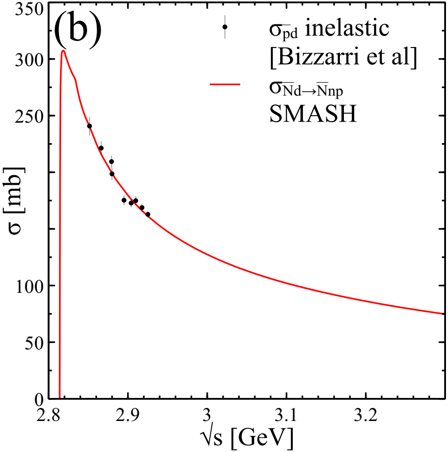
Reactions of deuteron with (anti-)nucleons



$Nd \leftrightarrow Nnp$, $\bar{N}d \leftrightarrow \bar{N}np$: 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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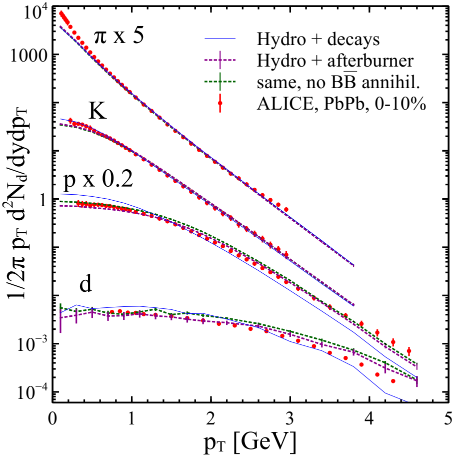
Transverse momentum spectra

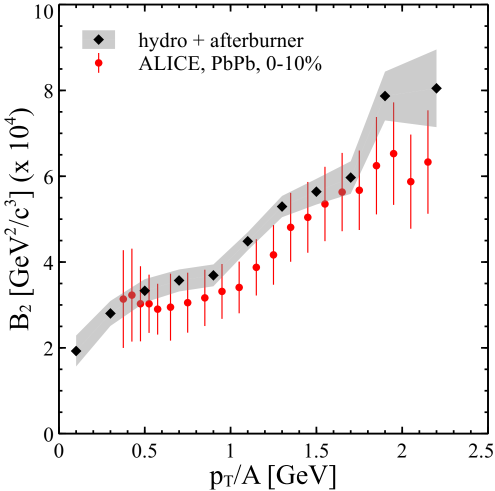


Pion and kaon spectra not affected by afterburner

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

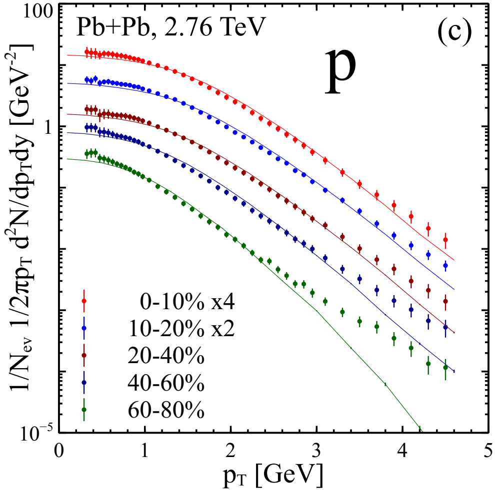
Obtaining $B_2(p_T)$ coalescence parameter

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

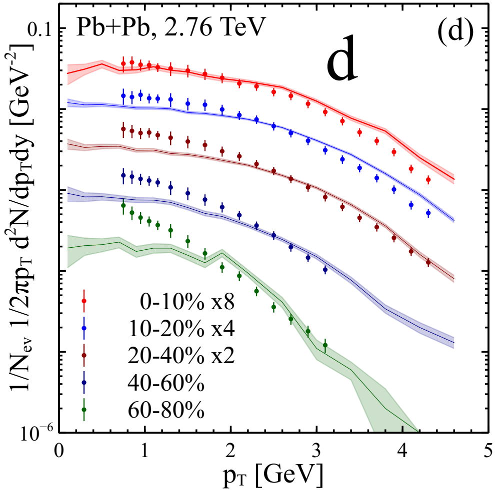


Reproducing B_2 without any free parameters

p_T-spectra for different centralities



p_T-spectra for different centralities

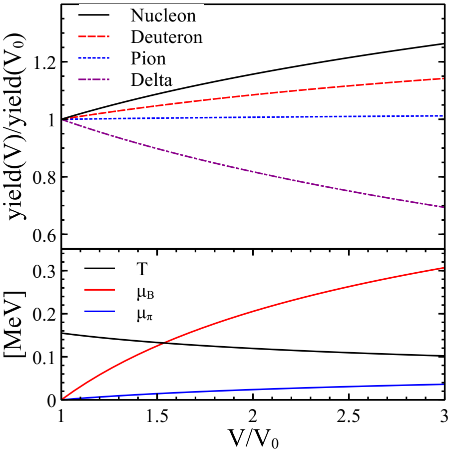


Toy model of deuteron production: no annihilations

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

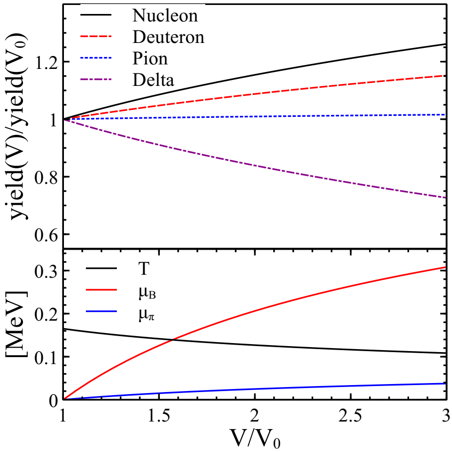
$$
\begin{aligned}
(s_\pi(T,\mu_\pi) + s_N(T,\mu_B) + +s_\Delta(T,\mu_B+\mu_\pi) + s_d(T,2\mu_B))V &= const \\
(\rho_\Delta(T,\mu_B+\mu_\pi) + \rho_\pi(T,\mu_\pi))V &= const \\
(\rho_N(T,\mu_B) + \rho_\Delta(T,\mu_B+\mu_\pi) + 2\rho_d(T,2\mu_B))V &= const
\end{aligned}
$$

Toy model of deuteron production: results



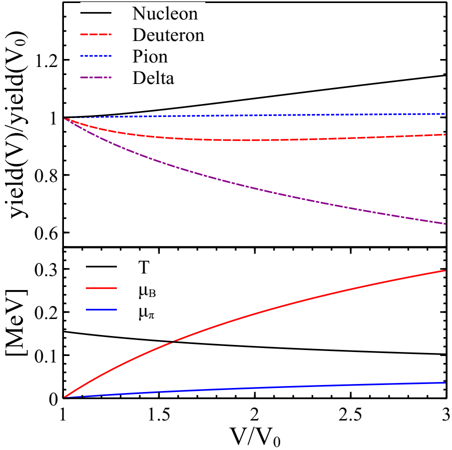
No annihilation: deuteron yield grows, like in simulation.

Toy model of deuteron production: results



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

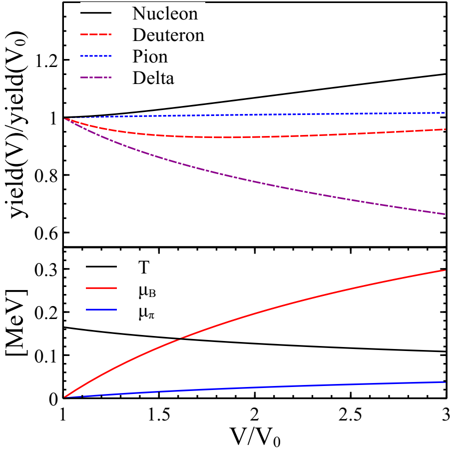
Toy model of deuteron production: results



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.