Multiplicity scaling of light nuclei productions in heavy-ion collisions

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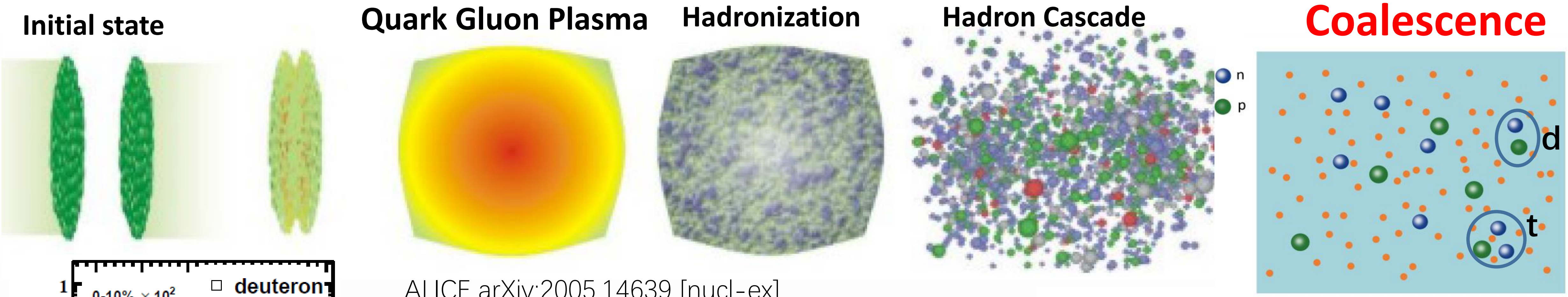
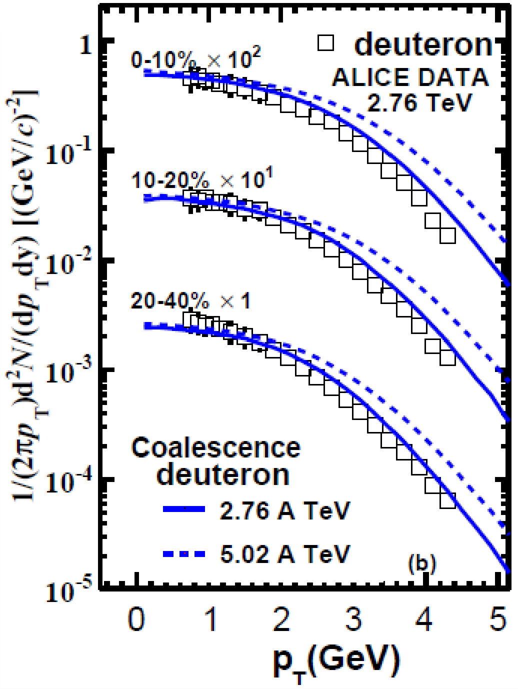
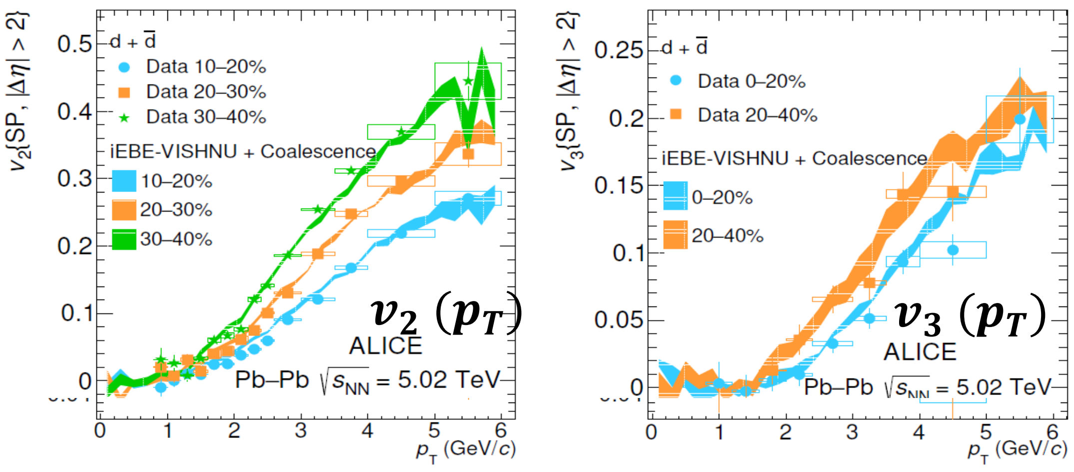
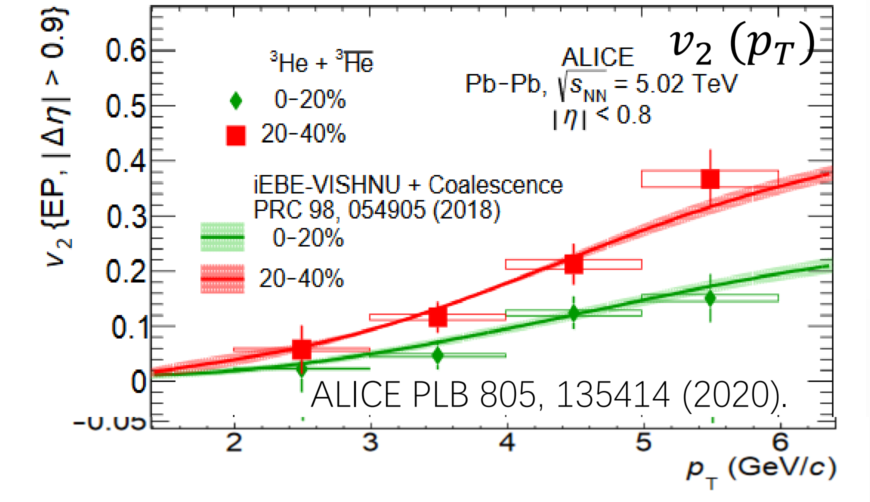
Predictions for spectra and $v_n\ (p_T)$ of light nuclei





ALICE arXiv:2005.14639 [nucl-ex].

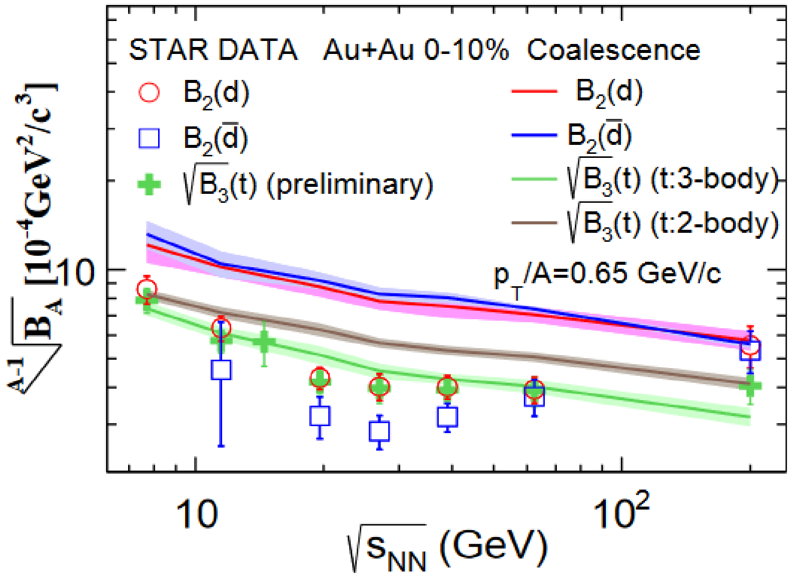


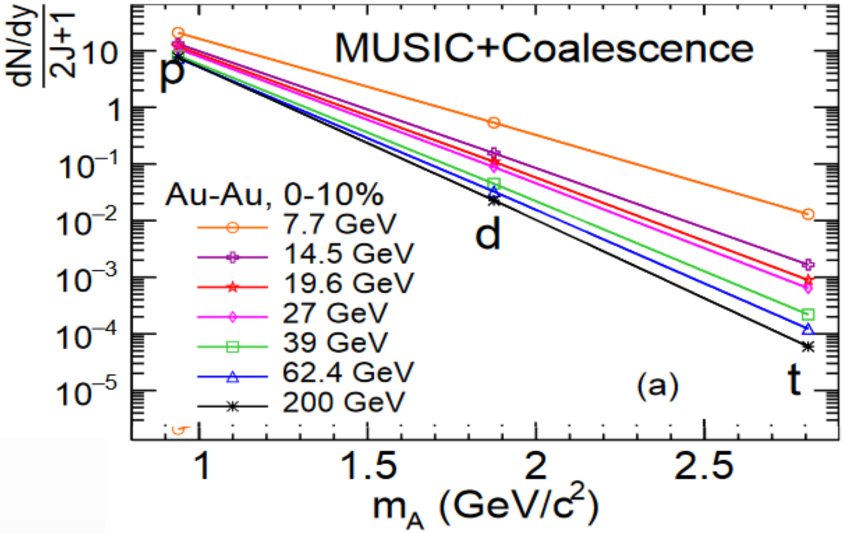


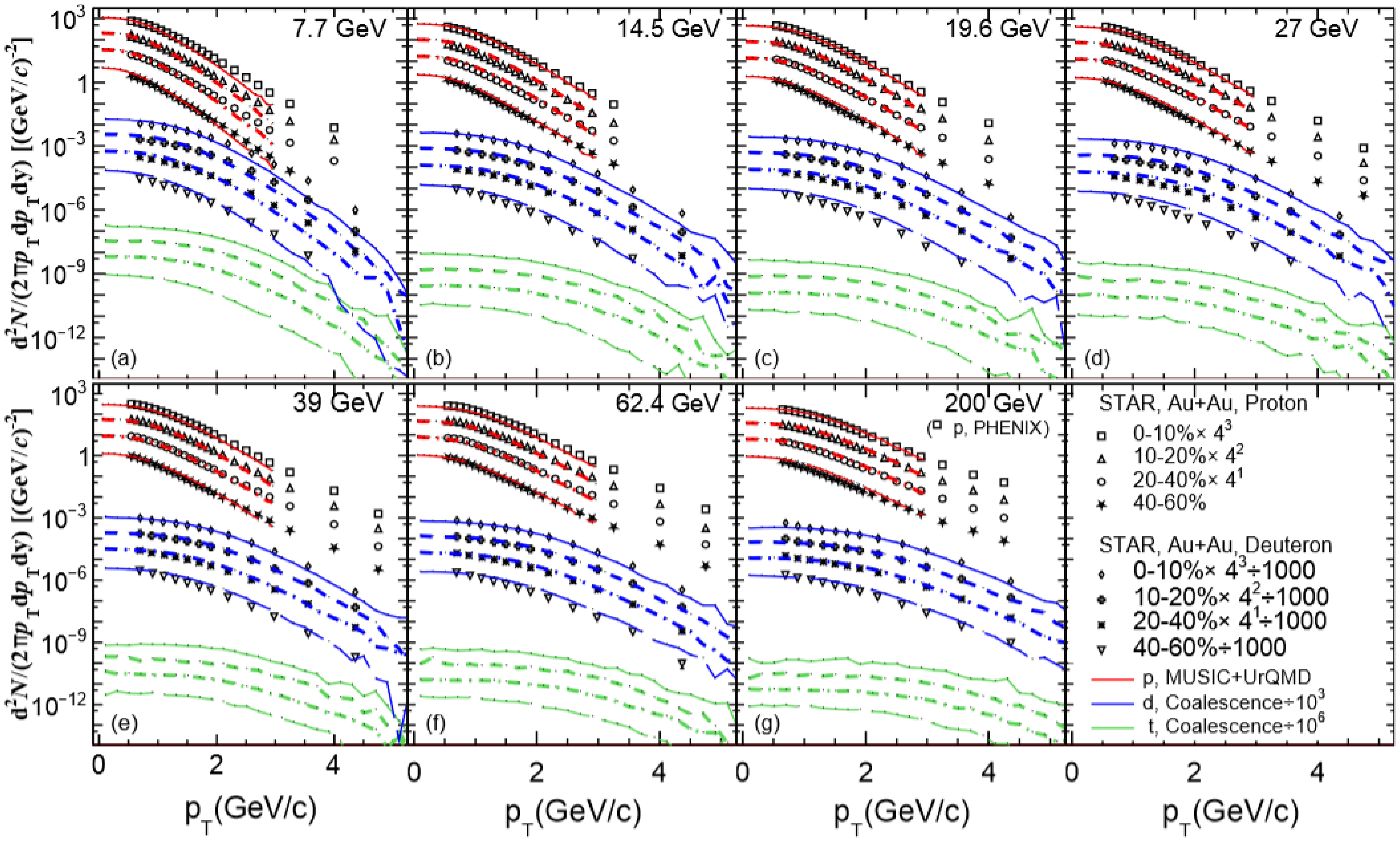
W. Zhao, L. Zhu, H. Zheng, C.M. Ko and H. Song, Phys. Rev.C 98, no. 5, 054905 (2018).

- iEBE-VISHNU + Coalescence nicely predict spectra, $v_2\ (p_T)$ and $v_3\ (p_T)$ of light nuclei at different centrality bins for the ALICE measurements.

Light nuclei production at RHIC BES region







W. Zhao, K. j. Sun, C. M. Ko and X. Luo, [arXiv:2105.14204 [nucl-th]].
W. Zhao, L. Zhu, H. Zheng, C.M. Ko and H. Song, Phys. Rev.C 98, no. 5, 054905 (2018).
W. Zhao, C. Shen, C. M. Ko, Q. Liu and H. Song, PRC 102, 044912 (2020).

- iEBE-MUSIC +Coalescence well describe the spectra of light nuclei from 7.7 to 200 GeV.
- $B_2(\mathrm{d}/\bar{d})$ and $\sqrt{B_3(t)}$ decrease monotonically with multiplicity. dN/dy/(2J+1) decreases exponentially vs m_A

Multiplicity scaling of $N_p \cdot N_t/N_d^2$

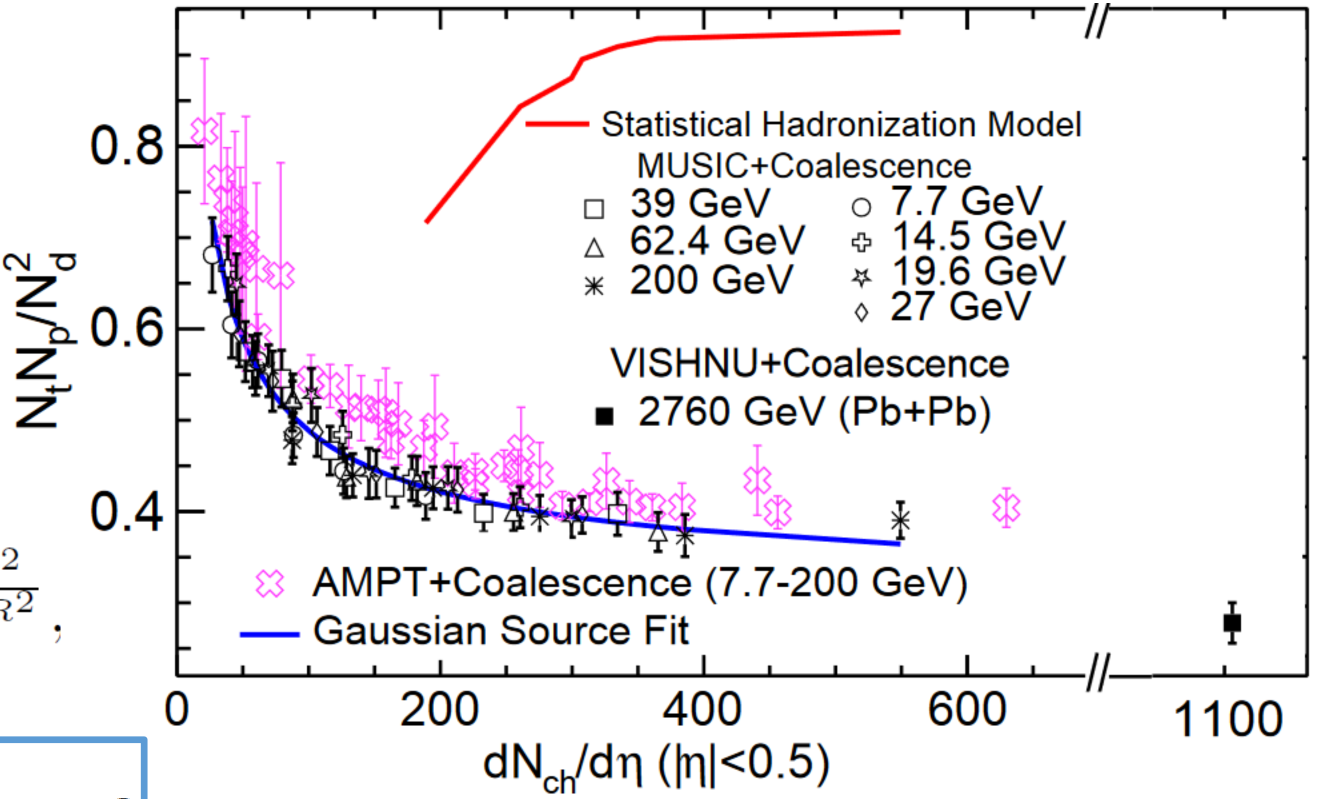
$$N_\mathrm{d} = g_\mathrm{d}\int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_n(\mathbf{x}_1,\mathbf{p}_1) \times f_p(\mathbf{x}_2,\mathbf{p}_2) W_\mathrm{d}(\mathbf{x},\mathbf{p}),$$

$$N_\mathrm{t} = g_\mathrm{t}\int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_n(\mathbf{x}_1,\mathbf{p}_1) f_n(\mathbf{x}_2,\mathbf{p}_2) f_p(\mathbf{x}_3,\mathbf{p}_3) W_\mathrm{t}(\mathbf{x},\boldsymbol{\lambda},\mathbf{p},\mathbf{p}_\lambda),$$

For Gaussian source:

$$f_{p,n}(\mathbf{x},\mathbf{k}) = \frac{N_{p,n}}{(2\pi)^3(mT_K R^2)^{\frac{3}{2}}} e^{-\frac{k^2}{2mT_K}-\frac{x^2}{2R^2}},$$

$$\frac{N_t N_p}{N_d^2} = \frac{4}{9}\left(\frac{1+\frac{2r_d^2}{3R^2}}{1+\frac{r_t^2}{2R^2}}\right)^3 = \frac{4}{9}\left(1+\frac{\frac{4}{3}r_d^2 - r_t^2}{2R^2+r_t^2}\right)^3$$



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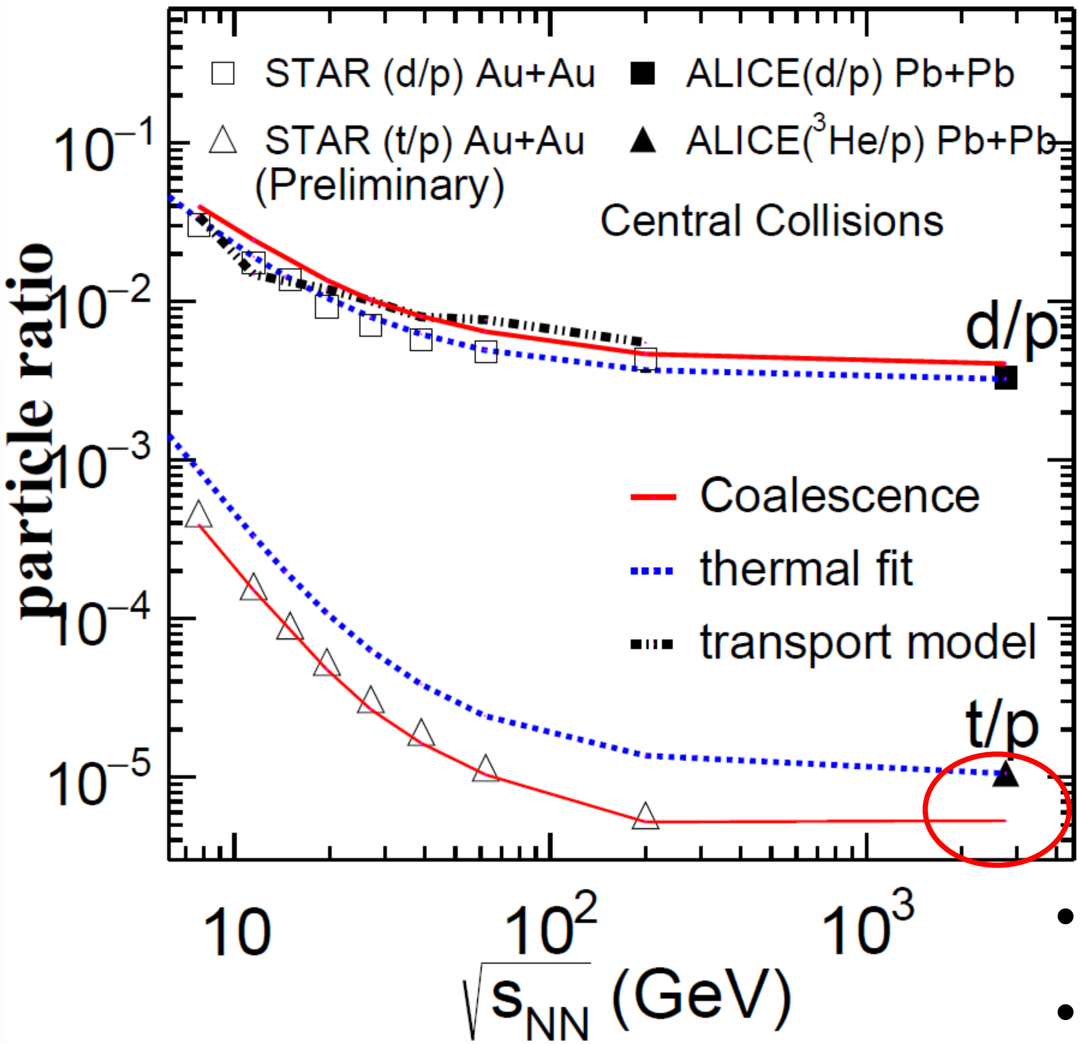
W. Zhao, L. Zhu, H. Zheng, C.M. Ko and H. Song, PRC 98, 054905 (2018).
W. Zhao, C. Shen, C. M. Ko, Q. Liu and H. Song, PRC 102, 044912 (2020).
K.-J. Sun, C. M. Ko, and B. Donigus, Phys. Lett.B792,132 (2019).

- Multiplicity scaling of $N_p \cdot N_t/N_d^2$ from MUSIC or AMPT+Coalescence is observed.
- Statistical model gives the opposite trend of $N_p \cdot N_t/N_d^2$.

Comparisons between different models



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

1. It nicely describe the d/p from RHIC to LHC energies.
2. It overestimate the t/p at RHIC, but fit that at LHC.

- Transport model: $\pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd, NN \leftrightarrow \pi d,$

1. It nicely describe the d/p at RHIC.
2. No t/p calculations.

- Coalesence model:

1.It reasonably describes the d/p from RHIC to LHC energies.
2.It well describe the t/p at RHIC, but underestimate that at LHC.

- The t/p at LHC is much larger than that at top RHIC.
- **Discrepancy of triton (helium-3) productions between top RHIC energy and LHC energy needs to be understood.**

W. Zhao, etc,al,PRC 98,054905 (2018); W. Zhao, etc,al,PRC 102, 044912 (2020). W. Zhao, etc,al, [arXiv:2105.14204 [nucl-th]]. D.Oliinychenko, etc,al. arXiv:2009.01915. Andronic, etc,al, Nature 561, 321 (2018). D. Zhang (STAR), arXiv:2002.10677(2020)

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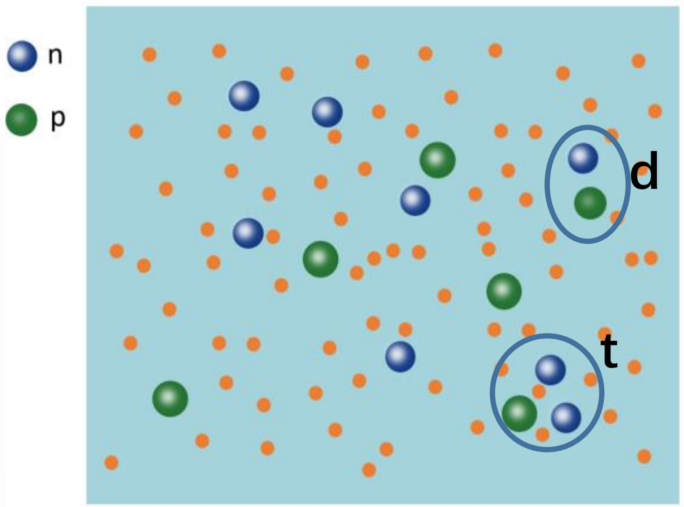
Coalescence model

$$\frac{d^3N_A}{d\mathbf{P}_A^3} = \frac{g_A}{Z!\cdot N!}\int \Pi_{i=1}^{A} p_i^{\mu} d^3\sigma_{i\mu}\frac{d^3\mathbf{p}_i}{E_i} f(\mathbf{x}_i,\mathbf{p}_i,t)\times f_A(\mathbf{x}_1',...,\mathbf{x}_A';\mathbf{p}_1',...,\mathbf{p}_A';t')\delta^{(3)}\left(\mathbf{P}_A-\sum_{i=1}^{A}\mathbf{p}_i\right),$$

H. Sato and K. Yazaki, PLB98, 153 (1981); E. Remler, Ann. Phys. 136, 293 (1981); M. Gyulassy, K. Frankel, and E. Remler, NPA402,596 (1983); S. Mrowczynski, J. Phys. G 13, 1089 (1987); S. Leupold and U. Heinz, PRC50, 1110 (1994); R. Scheibl and U. W. Heinz, PRC59. 1585(1999);



$$f_2(\rho,\mathbf{p}_\rho) = 8g_2\exp\left[-\frac{\rho^2}{\sigma_\rho^2}-\mathbf{p}_\rho^2\sigma_\rho^2\right],\quad \rho=\frac{1}{\sqrt{2}}(\mathbf{x}_1'-\mathbf{x}_2'),\quad \mathbf{p}_\rho=\sqrt{2}\,\frac{m_2\mathbf{p}_1'-m_1\mathbf{p}_2'}{m_1+m_2},$$

$$f_3(\rho,\boldsymbol{\lambda},\mathbf{p}_\rho,\mathbf{p}_\lambda) = 8^2g_3\exp\left[-\frac{\rho^2}{\sigma_\rho^2}-\frac{\boldsymbol{\lambda}^2}{\sigma_\lambda^2}-\mathbf{p}_\rho^2\sigma_\rho^2-\mathbf{p}_\lambda^2\sigma_\lambda^2\right],$$

$$\boldsymbol{\lambda} = \sqrt{\frac{2}{3}}\left(\frac{m_1\mathbf{x}_1'+m_2\mathbf{x}_2'}{m_1+m_2}-\mathbf{x}_3'\right),$$

$$\mathbf{p}_\lambda = \sqrt{\frac{3}{2}}\,\frac{m_3(\mathbf{p}_1'+\mathbf{p}_2')-(m_1+m_2)\mathbf{p}_3'}{m_1+m_2+m_3},$$

No free parameters. Here, σ_ρ and σ_λ are taken from [Atom. Data Nucl. DataTabl.99, 69 (2013)].

1.The light nuclei productions encode the phase-space information of nucleons.

Coalescence Parameters ($\sqrt[A-1]{B_A}$)

B_A (A=2,3) describe the coalescence probability

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^Z \left(E_n \frac{d^3 N_n}{dp_n^3} \right)^{A-Z}$$

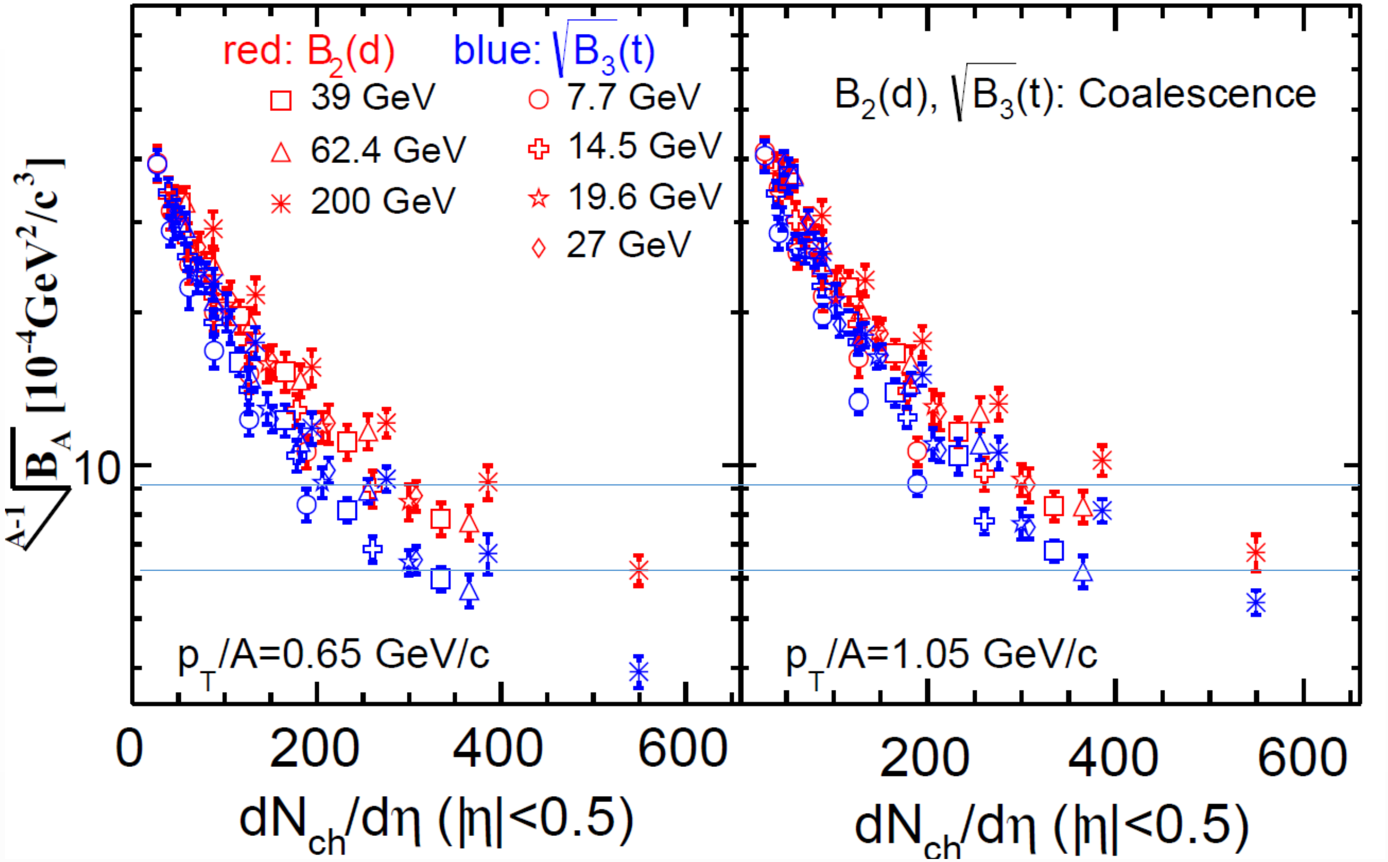
$$\approx B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A \Big|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$

$B_A \propto V_{\mathrm{eff}}^{1-A}$. V_{eff}: effective volume.

S. Leupold and U. Heinz, PRC50, 1110 (1994);
R. Scheibl and U. W. Heinz, PRC59. 1585(1999);

Triton productions:

Three body: $p + n + n \rightarrow t$

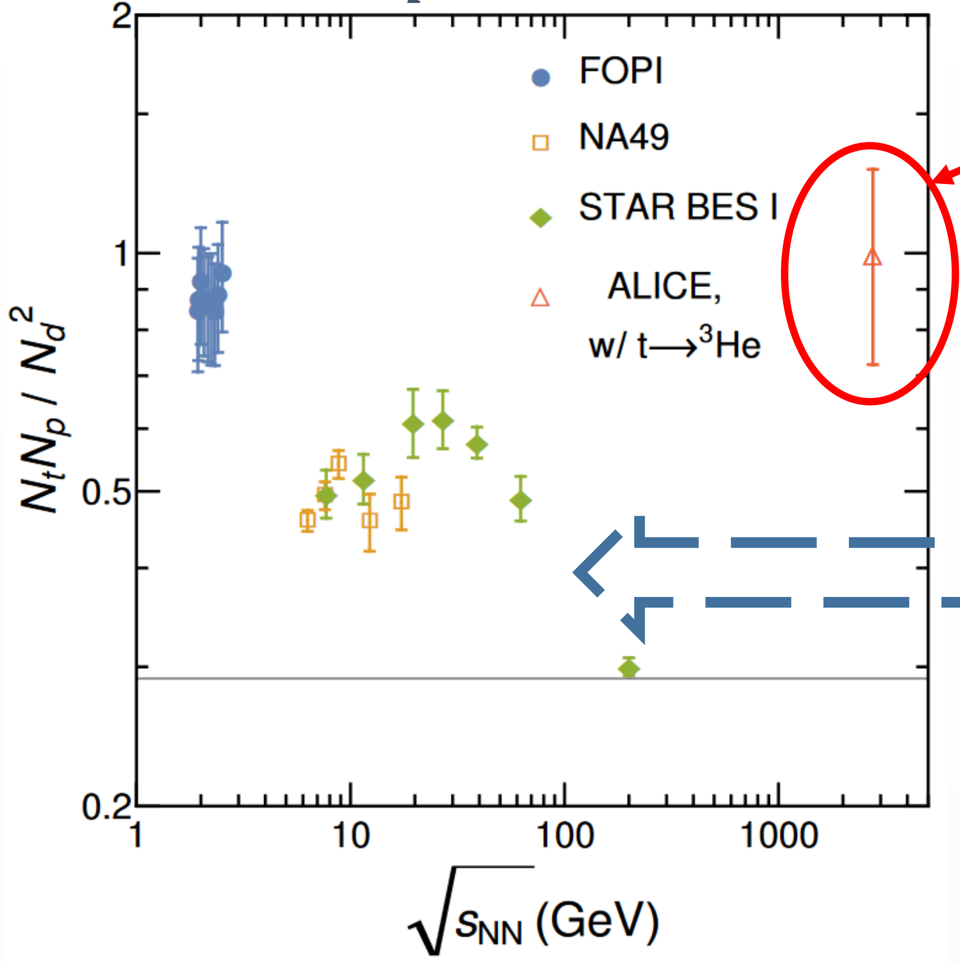


W. Zhao, C. Shen, C. M. Ko, Q. Liu and H. Song, PRC 102, 044912 (2020).
W. Zhao, K. j. Sun, C. M. Ko and X. Luo, [arXiv:2105.14204 [nucl-th]].

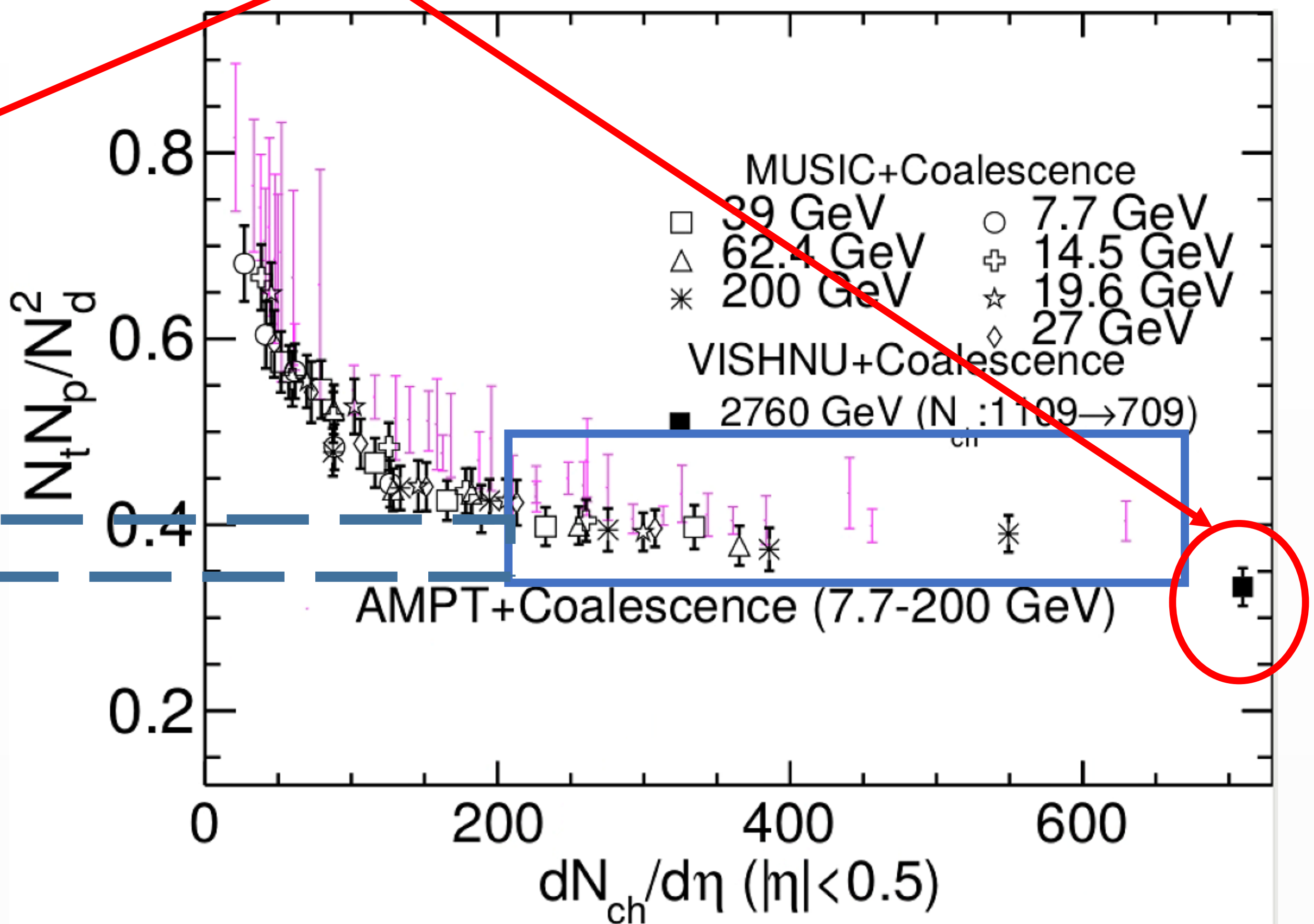
- $B_2(\mathrm{d}/\bar{d})$ and $\sqrt{B_3(t)}$ decrease monotonically with multiplicity.
- The slopes of $B_2(\mathrm{d}/\bar{d})$ and $\sqrt{B_3(t)}$ are different, attribute to the different sizes of deuteron and triton.
- $\sqrt[A-1]{B_A}$ at p_T/A=1.05 GeV is slightly larger than p_T/A=0.65 GeV, caused by the smaller V_{eff} at higher p_T.

p-d-t ratio $N_p \cdot N_t/N_d^2$

LHC



D. Zhang (STAR), arXiv:2002.10677(2020).



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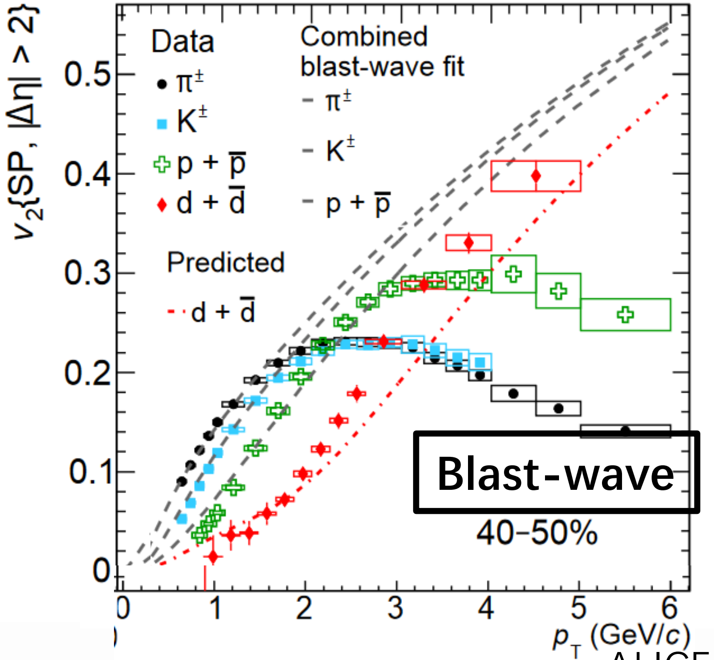
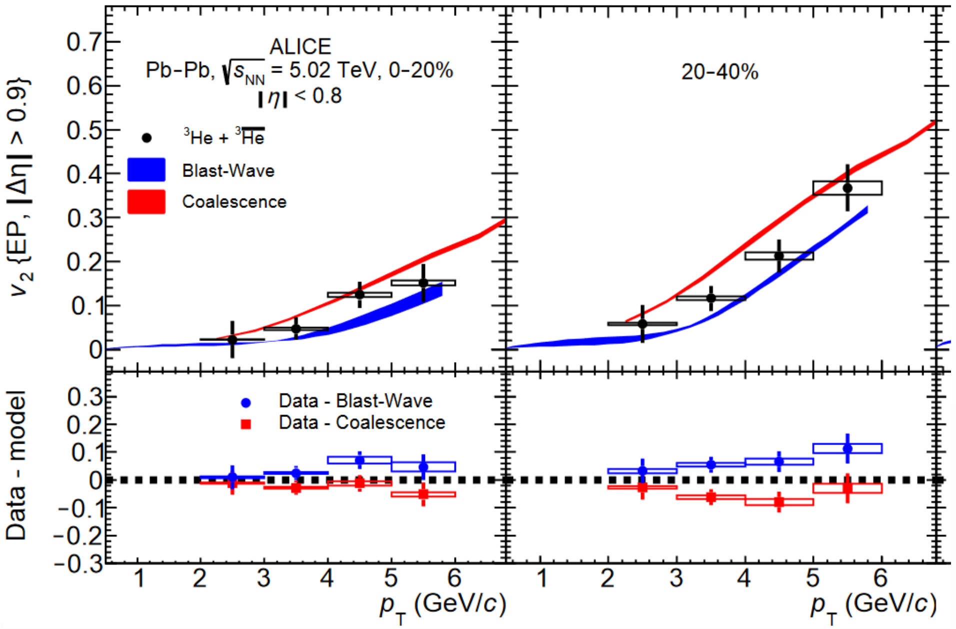
W. Zhao, K. j. Sun, C. M. Ko and X. Luo, [arXiv:2105.14204 [nucl-th]].

- The STAR data observes the non-monotonic dependence of $N_p \cdot N_t/N_d^2$ on collision energy in central collisions at RHIC.
- In central collisions at RHIC, $N_p \cdot N_t/N_d^2$ calculated by iEBE-MUSIC +Coalescence is flat.
- $N_p \cdot N_t/N_d^2$ at Pb-Pb at LHC from coalescence much smaller than the ALICE data.

Collective flow of light nuclei



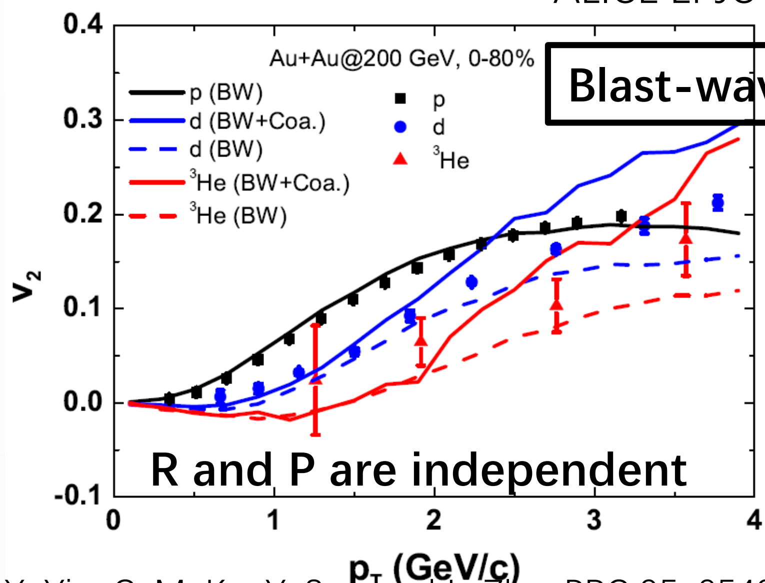


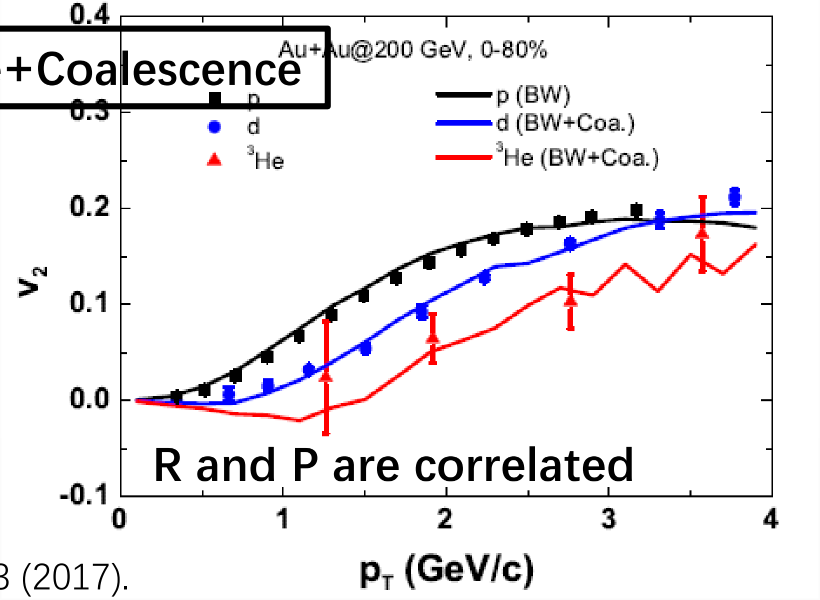
ALICE EPJC 77,10, 658 (2017).

- Blast wave underpredicts $v_2(p_T)$ of d and 3He.
- Simple Coalescence overestimates $v_2(p_T)$ of d and 3He.

$$v_{2,^3\mathrm{He}}(p_\mathrm{T}) = \frac{3v_{2,\mathrm{p}}(p_\mathrm{T}/3) + 3v_{2,\mathrm{p}}^3(p_\mathrm{T}/3)}{1 + 6v_{2,\mathrm{p}}^2(p_\mathrm{T}/3)}.$$

- In the framework of coalescence model, **the collective flow of light nuclei is sensitive to the correlations between spatial and momentum distributions of nucleon.**

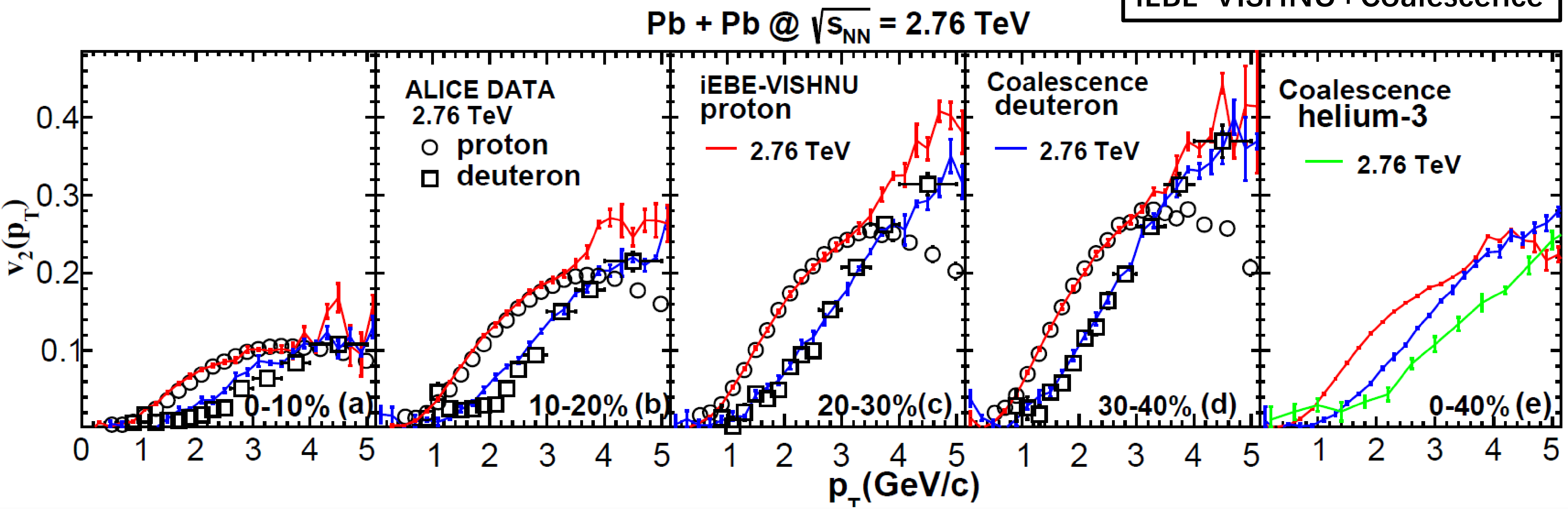




X. Yin, C. M. Ko, Y. Sun and L. Zhu, PRC 95, 054913 (2017).

$v_2(p_T)$ of light nuclei in Pb + Pb 2.76 TeV

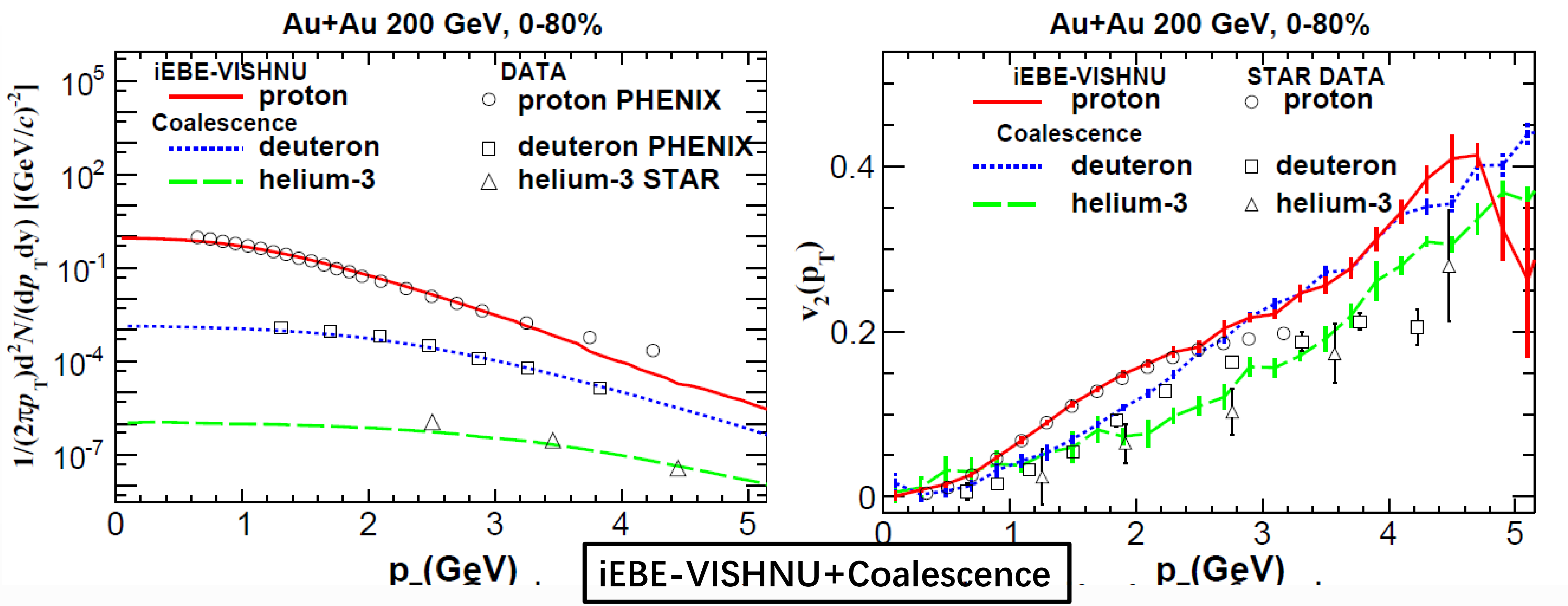
iEBE-VISHNU+Coalescence



- iEBE-VISHNU + Coalescence well reproduce the $v_2(p_T)$ of deuteron in all centrality bins in Pb+Pb at 2.76 TeV.
- iEBE-VISHNU naturally gives a good description of spatial-momentum correlations of nucleon at kinetic freeze-out.
- No free parameters in the model simulations.

W. Zhao, L. Zhu, H. Zheng, C.M. Ko and H. Song, Phys. Rev.C 98, no. 5, 054905 (2018).

Light nuclei production in Au + Au at 200 GeV



- iEBE-VISHNU + Coalescence gives a good predictions for the spectra and $v_2(p_T)$ of d and 3He in Au+Au 200 GeV.

W. Zhao, L. Zhu, H. Zheng, C.M. Ko and H. Song, Phys. Rev.C 98, no. 5, 054905 (2018).