The spectra and flow of light nuclei in relativistic heavy ion collisions at RHIC and the LHC

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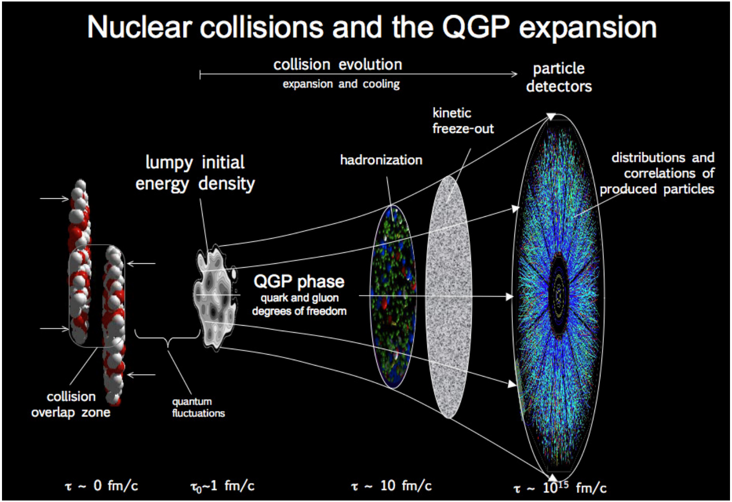
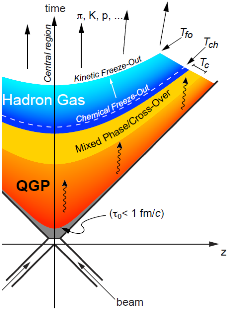
The process of heavy-ion collisions



U. W. Heinz, hep-ph/0407360.

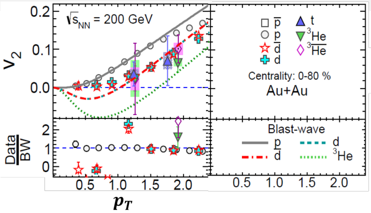
When light nuclei formed in heavy-ion collisions

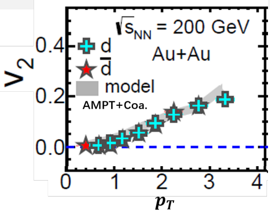


- Hadrons emitted from the region that reaches limiting temperature and abundances fixed at chemical freeze-out.
- Light nuclei can be formed by baryons after kinetic freeze-out, which is sensitive to nucleon emission source.
- Light nuclei produced at chemical freeze-out might break up and re-form during the chemical freeze-out and the kinetic freeze-out.

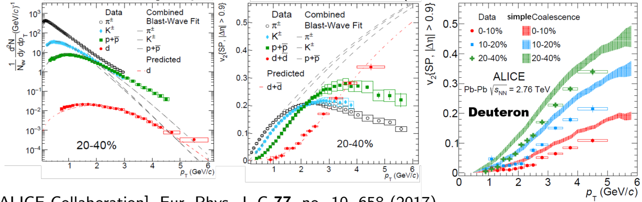
- Studying the light nuclei production will help to understand the nucleon emission source and the nucleosynthesis mechanism in heavy-ion collisions.

light nuclei generations in RHIC and LHC





L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C **94**, no. 3, 034908 (2016).

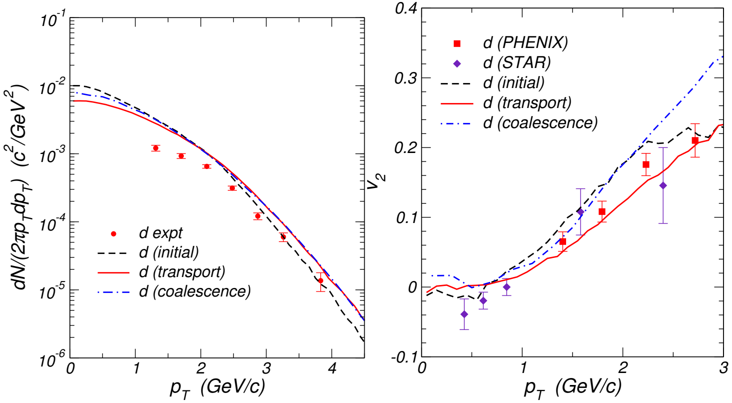


S. Acharya *et al.* [ALICE Collaboration], Eur. Phys. J. C **77**, no. 10, 658 (2017).

- Blast wave underpredicts $v_2(p_T)$ of d and ^{3}He at RHIC, but well describes spectra and $v_2(p_T)$ of d in LHC.
- AMPT + coalescence reproduces the $v_2(p_T)$ of d at Au + Au 200 GeV. Simple coalescence overestimates $v_2(p_T)$ of d at LHC Pb + Pb.

Transport and Coalescence model

- Transport model: with production and annihilation of *d* in AMPT.
- Coalescence model: AMPT+Coalescence.



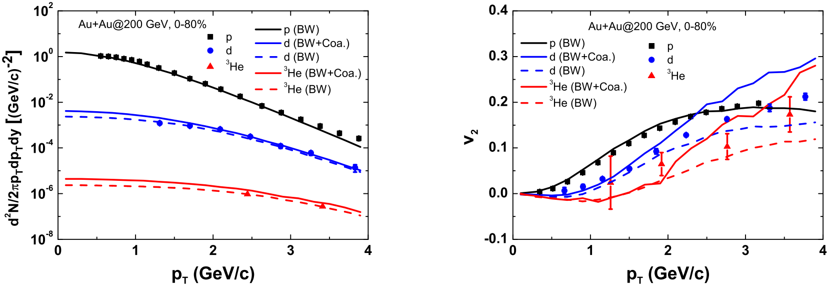
- Transport and Coalescence models give similar *d* spectra.

Y. Oh, Z. W. Lin and C. M. Ko, Phys. Rev. C **80**, 064902 (2009).

Blast Wave + Coalescence

Blast Wave + Coalescence

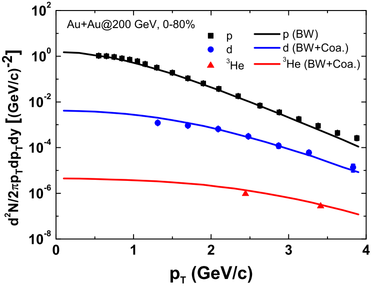
- Transverse size R_0 is constant (independent on p_T), nucleons are uniform inside a cylinder.

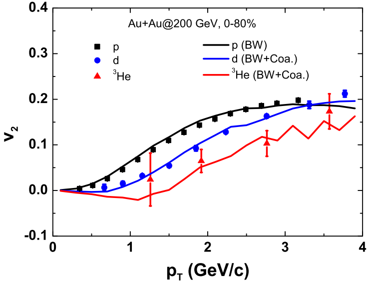


- The Blast Wave + Coalescence can't describe spectra and $v_2(p_T)$ of light nuclei. The constant R_0 is unrealistic.

X. Yin, C. M. Ko, Y. Sun and L. Zhu, Phys. Rev. C **95**, no. 5, 054913 (2017).

- With additional $R_0 = 10e^{0.23(p_T - 0.9)}$ correlations of hadrons:





- The Blast Wave + R_0 - p_T correlations + Coalescence reproduces spectra and $v_2(p_T)$ of light nuclei. The R_0 - p_T correlations are better .

X. Yin, C. M. Ko, Y. Sun and L. Zhu, Phys. Rev. C **95**, no. 5, 054913 (2017).

iEBE-VISHNU + Coalescence

Coalescence Model

The production probability of nucleus of atomic number A is:

$$\frac{d^3N_A}{d\mathbf{P}_A^3} = g_A \int \Pi_{i=1}^{A} p_i^{\mu} d^3\sigma_{i\mu} \frac{d^3\mathbf{p}_i}{E_i} f(\mathbf{x}_i, \mathbf{p}_i, t)$$

$$\times f_A(\mathbf{x}_1', ..., \mathbf{x}_A'; \mathbf{p}_1', ..., \mathbf{p}_A'; t')\delta^{(3)}\left(\mathbf{P}_A - \sum_{i=1}^{A} \mathbf{p}_i\right),$$

where g_A is statistical factor, $\mathbf{x}_i$ and $\mathbf{p}_i$ are in fireball frame. $\mathbf{x}_i'$ and $\mathbf{p}_i'$ are Lorentz transformed to the rest frame of produced nucleus. And $\int p^{\mu} d^3\sigma_{\mu} \frac{d^3\mathbf{p}}{E} f_p(\mathbf{x}, \mathbf{p}, t) = N_p$, $\int p^{\mu} d^3\sigma_{\mu} \frac{d^3\mathbf{p}}{E} f_n(\mathbf{x}, \mathbf{p}, t) = N_n$, f_A is Winger function.

Wigner function

Wigner function for two-body Coalescence:

$$f_2(\boldsymbol{\rho}, \mathbf{p}_\rho) = 8g_2 \exp\left[-\frac{\boldsymbol{\rho}^2}{\sigma_\rho^2} - \mathbf{p}_\rho^2\sigma_\rho^2\right],$$

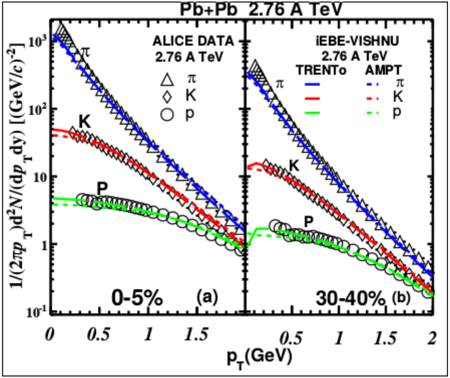
$$\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{x}_1' - \mathbf{x}_2'), \quad \mathbf{p}_\rho = \sqrt{2}\ \frac{m_2\mathbf{p}_1' - m_1\mathbf{p}_2'}{m_1 + m_2}, \tag{1}$$

Wigner function for three-body Coalescence:

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

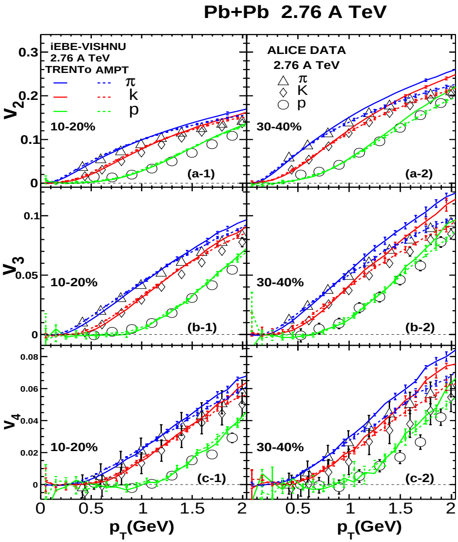
$$\begin{aligned} \boldsymbol{\lambda} &= \sqrt{\frac{2}{3}}\left(\frac{m_1\mathbf{x}_1' + m_2\mathbf{x}_2'}{m_1 + m_2} - \mathbf{x}_3'\right), \\ \mathbf{p}_\lambda &= \sqrt{\frac{3}{2}}\ \frac{m_3(\mathbf{p}_1' + \mathbf{p}_2') - (m_1 + m_2)\mathbf{p}_3'}{m_1 + m_2 + m_3}, \end{aligned} \tag{3}$$

- spectra of π, K and p.

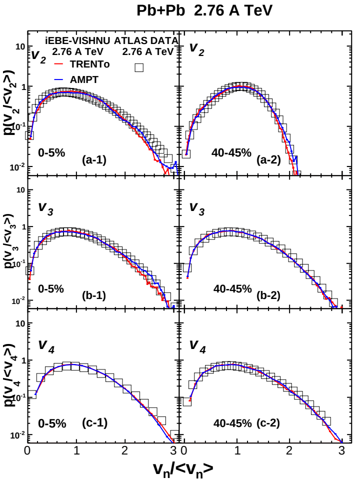


- Hydrodynamics can well describe dynamics evolutions of heavy-ion collisions.

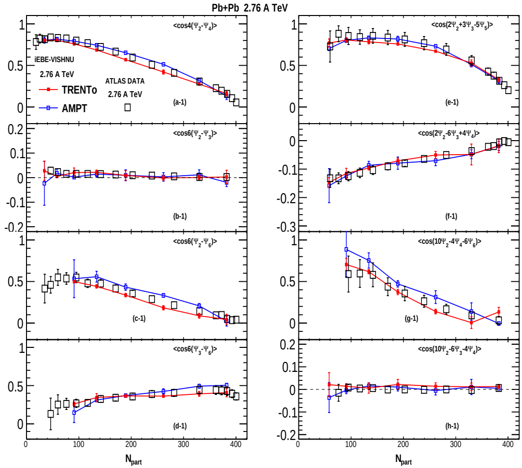
- $v_n\{p_T\}$ for π, K and p



- Event-by-event v_n distributions.



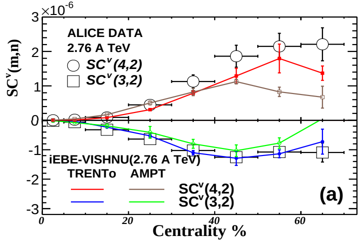
- Event-plane correlations

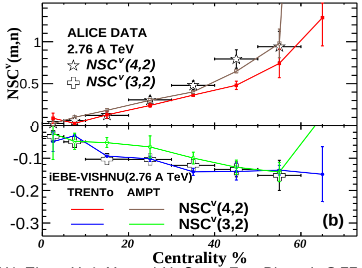


W. Zhao, H. j. Xu and H. Song, Eur. Phys. J. C **77**, no. 9, 645 (2017).

- Symmetry Cumulant

Pb+Pb 2.76 A TeV

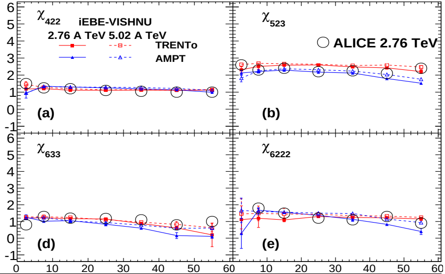


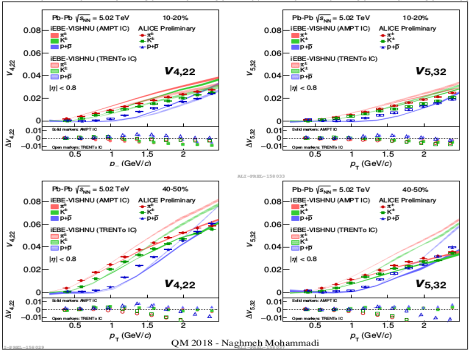


W. Zhao, H. j. Xu and H. Song, Eur. Phys. J. C **77**, no. 9, 645 (2017). Naghmeh Mohammadi, Quark Matter 2018, (unpublished).

- Non-linear response cofficients

Pb+Pb 2.76 A TeV v.s. 5.02 A TeV





Hydrodynamic model is the standard model to describe the dynamics evolutions of heavy-ion collisions.

Set-up

iEBE-VISHNU + Coalescence

- The coalescence processes for d: $p + n \rightarrow d$.
- Two coalescence processes are included for production of ^{3}He: $p + p + n \rightarrow ^3$He and $d + p \rightarrow ^3$He.

Table 1: Statistical factor (g), radius (R), oscillator frequency (ω), and width parameter (σ_ρ, σ_λ) for deuteron and helium-3. .

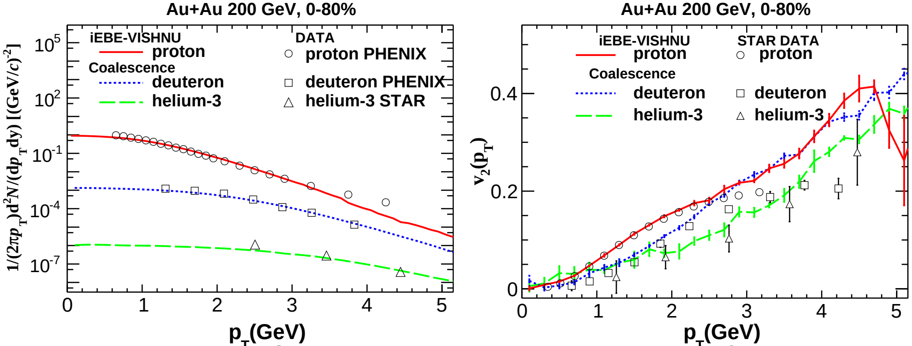
Nucleus	g	R (fm)	ω (sec^{-1})	$\sigma_\rho, \sigma_\lambda$ (fm)
deuteron	3/4	2.1421	0.1739	2.473
$p + p + n \rightarrow ^3$He	1/4	1.9661	0.5504	1.390
$d + p \rightarrow ^3$He	1/3	1.9661	0.3389	1.536

W. Zhao, L.L. Zhu, H. Zheng, C. M. Ko and H. Song in preparation.

RESULTS

Light nuclei production in Au + Au 200 GeV

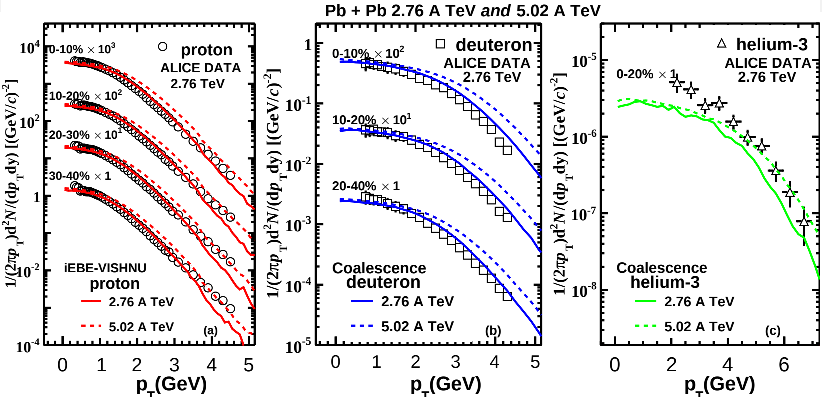
- iEBE-VISHNU + Coalescence



- iEBE-VISHNU + Coalescence gives a good predictions for the spectra and $v_2(p_T)$ of d and ^{3}He in Au+Au 200 GeV.
- iEBE-VISHNU gives a good description of space momentum correlations of hadrons naturally.

W. Zhao, L.L. Zhu, H. Zheng, C. M. Ko and H. Song in preparation.

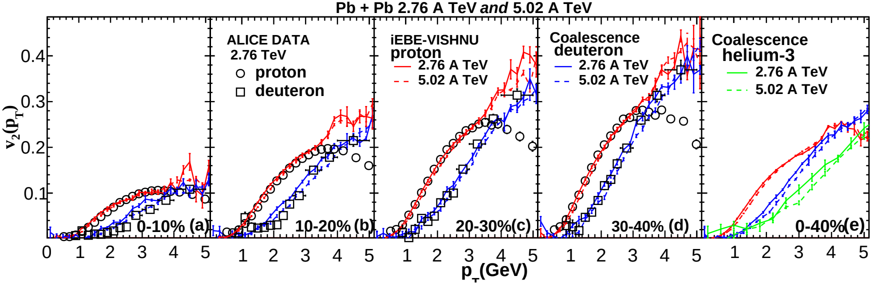
Spectra of light nuclei in Pb + Pb 2.76 and 5.02 TeV



- iEBE-VISHNU + Coalescence gives a good description for the spectra of d and underestimeta spectra of ^{3}He in Pb + Pb 2.76 TeV.
- The spectra of d and ^{3}He in Pb + Pb 5.02 TeV is higher and flatter.

W. Zhao, L.L. Zhu, H. Zheng, C. M. Ko and H. Song in preparation.

$v_2(p_T)$ of light nuclei in Pb + Pb 2.76 and 5.02 TeV



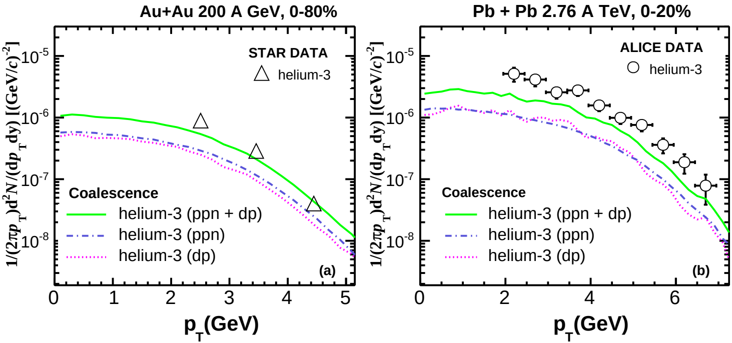
- iEBE-VISHNU + Coalescence well reproduce the $v_2(p_T)$ of d in Pb + Pb 2.76 TeV.
- iEBE-VISHNU + Coalescence predicts the $v_2(p_T)$ of d and ^{3}He in Pb + Pb 5.02TeV. And the $v_2(p_T)$ of d is slightly lower.

W. Zhao, L.L. Zhu, H. Zheng, C. M. Ko and H. Song in preparation.

- iEBE-VISHNU + Coalescence do a great job in describing the spectra and elliptic flow of light nuclei at Au + Au 200 GeV and Pb + Pb 2.76 TeV.

- iEBE-VISHNU generates the proper space-momeutum correlations of hadrons at kinetic freezeout.
- Coalescence together with proper space-momeutum correlations of hadrons might the mechnism of light nuclei productions in heavy-ion collisions.
- ^{3}He is largely underestimated in Pb + Pb 2.76 TeV.

The productions of ^{3}He



- Including the $d + p \to {}^3$He enhances the spectra of ^{3}He by two.
- Together $p + p + n \to {}^3$He with $d + p \to {}^3$He can describe spectra in Au + Au 200 GeV, but underestimate that in Pb + Pb 2.76 TeV.
- Production of ^{3}He need be further studied, such as including 3-body interactions in transport model and the Pauli principle effects in Winger function of ^{3}He.

W. Zhao, L.L. Zhu, H. Zheng, C. M. Ko and H. Song in preparation.

Summary

- Studying light nuclei helps to understand the nucleon emission source and nucleosynthesis mechnaism in heavy-ion collisions.
- `iEBE-VISHNU` + Coalescence can well describe the spectra and elliptic flow of light nuclei at Au + Au 200 GeV and Pb + Pb 2.76 TeV. `iEBE-VISHNU` generates the proper space-momeutum correlations of hadrons at kinetic freezeout.
- Coalescence might the mechnism of light nuclei productions in heavy-ion collisions.
- The productions of ^{3}He require further studying.

Thanks