Light nuclei production at LHC from AMPT

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Outline

- Motivation
- A microscopic coalescence approach
- Results for Pb-Pb collisions
- Summary and outlook

Motivation

Light nuclei production has been studied at RHIC and LHC,

- ✧ Search for nuclei that do not exist in nature in order to study if nuclei and antinuclei have same properties and to discover the stability of hypernuclei and its antinuclei, such as ${}^{3}_{\Lambda}H$, which was discovered by STAR Collaboration.
- ✧ Use light nuclei to study the space-time structure of the emission source in heavy-ion collisions, complementing the method using the (HBT) interferometry of particles emitted at freeze-out.

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- ✧ Use light nuclei to study the space-time structure of the emission source in heavy-ion collisions, complementing the method using the (HBT) interferometry of particles emitted at freeze-out.

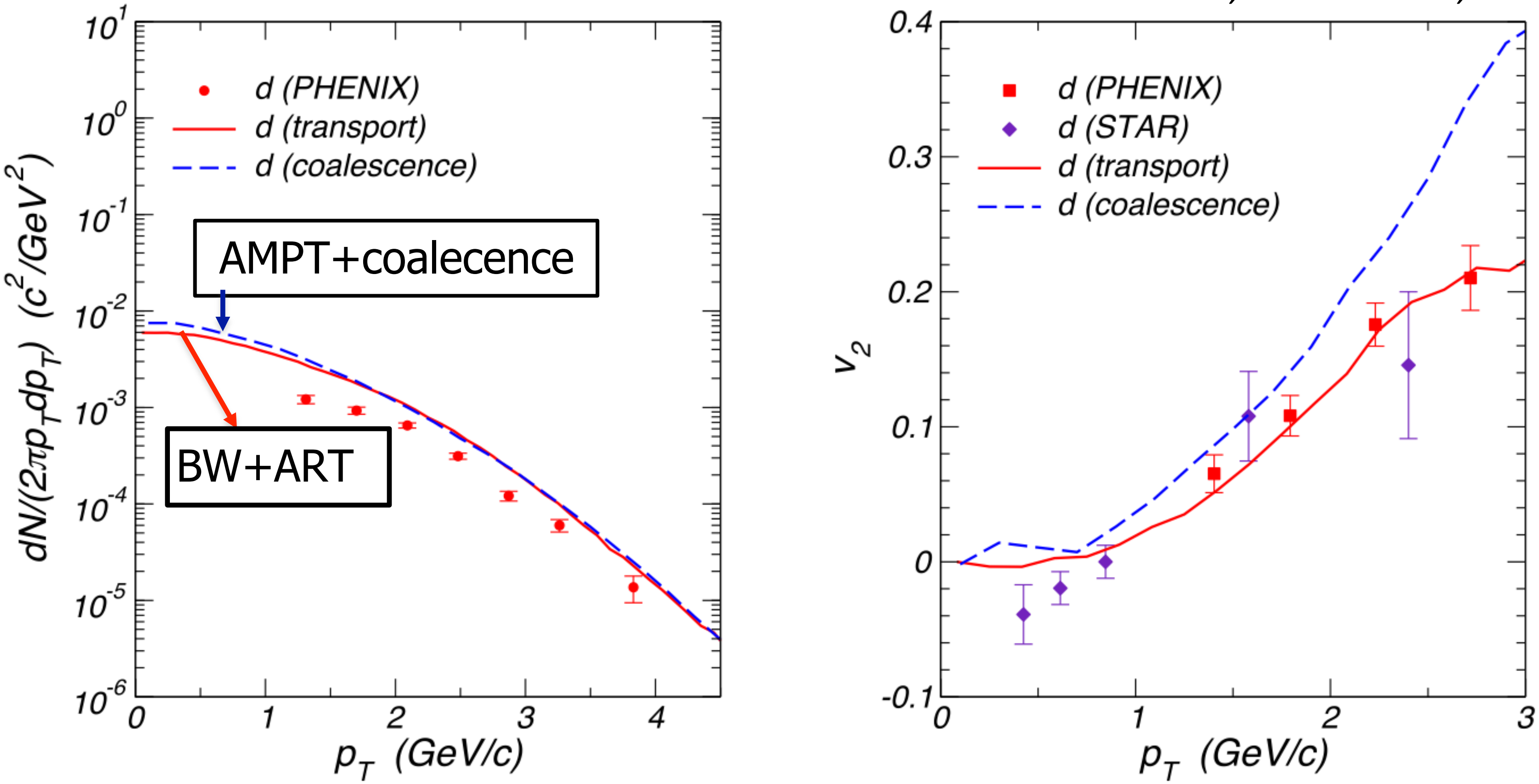
Production of light nuclei is typically discussed within two approaches:

① Thermal-statistical model

② Coalescence model

Deuteron p_T spectrum and elliptic flow@RHIC

Oh, Lin & Ko et al, PRC80, (2009)



- ✧ Similar p_T spectra are obtained from transport and coalescence models
- ✧ Transport model can descirbe the experimental elliptic flow well

Experimental results at LHC

At **LHC**, the simple coalescence model can not describe deuteron v_2, while the blast-Wave model gives a good description.

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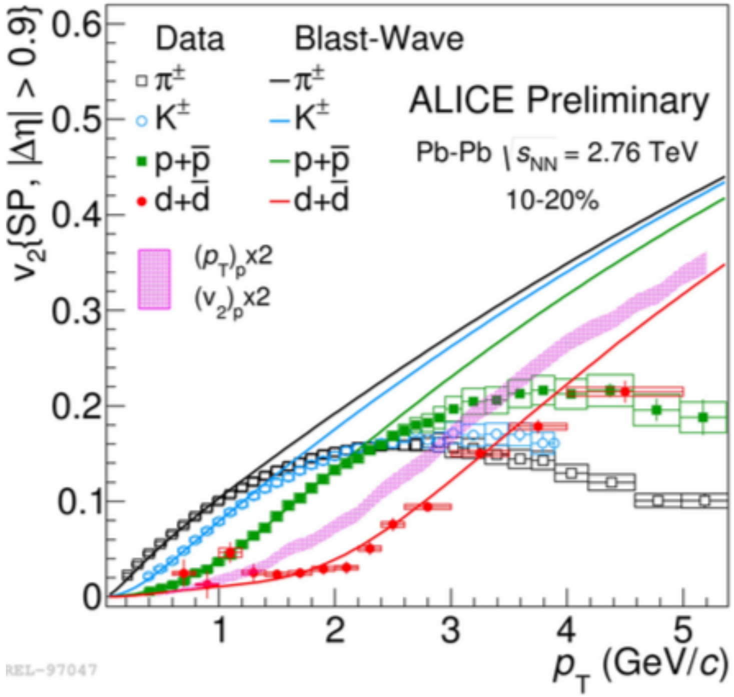

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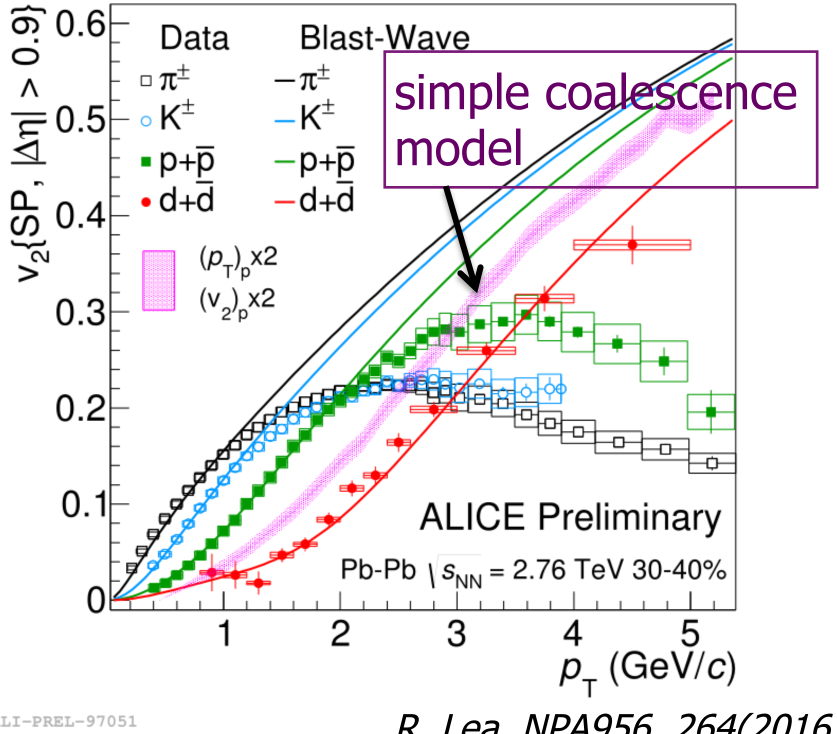

simple coalescence model

R. Lea, NPA956, 264(2016)

We try to understand if a more realistic coalescence model could also describe the experimental data at LHC.

Coalescence model

Nuclei are produced by recombination of nucleons at freeze-out using the sudden approximation in the coalescence model.

The momentum distribution

the phase-space distribution functions for protons and neutrons at freeze-out

$$\frac{d^3N_A}{dp_A^3} = g_A \int \prod_{i=1}^{Z} p_i^\mu d^3\sigma_{i\mu} \frac{d^3\vec{p}_i}{E_i} f_p(\vec{x}_i,\vec{p}_i,t_i) \times \int \prod_{j=1}^{N} p_j^\mu d^3\sigma_{j\mu} \frac{d^3\vec{p}_j}{E_j} f_n(\vec{x}_j,\vec{p}_j,t_j)$$

$$\times f_A(x_1',\cdots,x_Z';x_1',\cdots,x_N';p_1',\cdots,p_Z';p_1',\cdots,p_N';t')$$

$$\times\delta^{(3)}\left(\vec{P}_A-\sum_{i=1}^{Z}\vec{p}_i-\sum_{j=1}^{N}\vec{p}_j\right)$$

Wigner function of nuclei

$g_A = \frac{2J_A+1}{2^A}$: statistical factor

$\vec{x}_i,\vec{p}_i(\vec{x}_i',\vec{p}_i')$: the coordinate and momentum of the i-th nucleon in the center of mass frame (rest frame of nuclei) of all emitted particles

Wigner functions of d and ^{3}He

In this study, we approximate the wave functions of deuteron and Helium-3 by those of the ground state of a harmonic oscillator.

Deuteron

$$f_2(\vec{\rho},\vec{p}_\rho)=\int d^3\vec{y}\,\phi^*(\vec{\rho}-\frac{\vec{y}}{2})\phi(\vec{\rho}+\frac{\vec{y}}{2})e^{-i\vec{\rho}\bullet\vec{p}_\rho}$$

$$f_2(\vec{\rho},\vec{p}_\rho)=8g_2\exp(-\frac{\vec{\rho}^2}{\sigma_\rho^2}-\vec{p}_\rho^2\sigma_\rho^2)$$ with $$\vec{\rho}=\frac{\vec{x}_1'-\vec{x}_2'}{\sqrt{2}},\vec{p}_\rho=\frac{\vec{p}_1'-\vec{p}_2'}{\sqrt{2}}$$

the width parameter $\sigma_\rho=1/\sqrt{\mu_1\omega}$

ω is the oscillator frequency in the harmonic wave function

$$\mu_1=2/(1/m_1+1/m_2)^{-1}$$

Helium-3

$$f_3(\vec{\rho},\vec{\lambda},\vec{p}_\rho,\vec{p}_\lambda)=8^2g_3\exp(-\frac{\vec{\rho}^2}{\sigma_\rho^2}-\frac{\vec{\lambda}^2}{\sigma_\lambda^2}-\vec{p}_\rho^2\sigma_\rho^2)$$ with

$$\vec{\lambda}=\frac{\vec{x}_1'+\vec{x}_2'-2\vec{x}_3'}{\sqrt{6}}$$

$$\vec{p}_\lambda=\frac{\vec{p}_1'+\vec{p}_2'-2\vec{p}_3'}{\sqrt{6}}$$

Since the nucleon phase-space distribution could be from different models, we have adopted two approaches to investigate the light nuclei production:

- ✧ **Blast wave model + Coalescence model**
- ✧ **AMPT model + Coalescence model**

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Blast-wave model

In the blast wave model, all produced particles are assumed in thermal equilibrium and undergo collective expansion.

The invariant momentum distribution

$$E\frac{d^3N}{d^3\vec{p}}=\frac{d^3N}{p_T dp_T dy d\phi_p}=\int_{\Sigma^\mu} d^3\sigma_\mu p^\mu f(x,p)$$

f(x, p): the Lorentz-invariant thermal distribution of nucleons

Neglect the effect of quantum statistics at high temperature

$$f(x,p)=\frac{2\xi}{(2\pi)^3}\exp(-p^\mu u_\mu / T_K)$$

four momentum $p^\mu=(p^0,\vec{p})=(m_T\cosh y, p_T\cos\phi_p, p_T\sin\phi_p, m_T\sinh y)$

the azimuthal angle of the nucleon momentum with respect to x axis

flow four-velocity $u^\mu=\cosh\rho(\cosh\eta, \tanh\rho\cos\phi_b, \tanh\rho\sin\phi_b, \sinh\eta)$

the azimuthal angle of the transverse flow velocity with respect to x axis

ρ: transverse flow rapidity $\rho=\frac{1}{2}\ln\frac{1+|\vec{\beta}|}{1-|\vec{\beta}|}$

$$E\frac{d^3N}{d^3\vec{p}}=\frac{2\xi\tau_0}{(2\pi)^3}\int_{\Sigma^\mu} d\eta\, r\, dr\, d\phi\, m_T\cosh(\eta-y)\exp\left[-\frac{\cosh\rho(m_T\cosh y\cosh\eta-\vec{p}_T\bullet\vec{\beta}-m_T\sinh y\sinh\eta)}{T_K}\right]$$

Parametrization

The invariant momentum distribution

$$E\frac{d^3N}{d^3\vec{p}}=\frac{2\xi\tau_0}{(2\pi)^3}\int_{\Sigma^\mu} d\eta\, r\, dr\, d\phi\, m_T\cosh(\eta-y)\exp\left[-\frac{\cosh\rho(m_T\cosh y\cosh\eta-\vec{p}_T\bullet\vec{\beta}-m_T\sinh y\sinh\eta)}{T_K}\right]$$

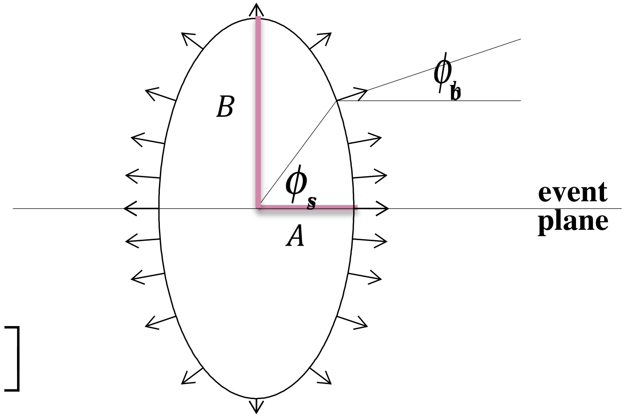
Parametrization:

$\varepsilon(p_T)=c_1\exp(-p_T/c_2)$

The transverse flow velocity: $\beta=\beta(r)\left[1+\varepsilon(p_T)\cos(2\phi_b)\right]$

The radial flow velocity: $\beta(r)=\beta_0[\sqrt{(\frac{x}{A})^2+(\frac{y}{B})^2}]$

The spatial distribution of nucleon: $r\leq R_0\left[1+s_2\cos(2\phi_s)\right]$

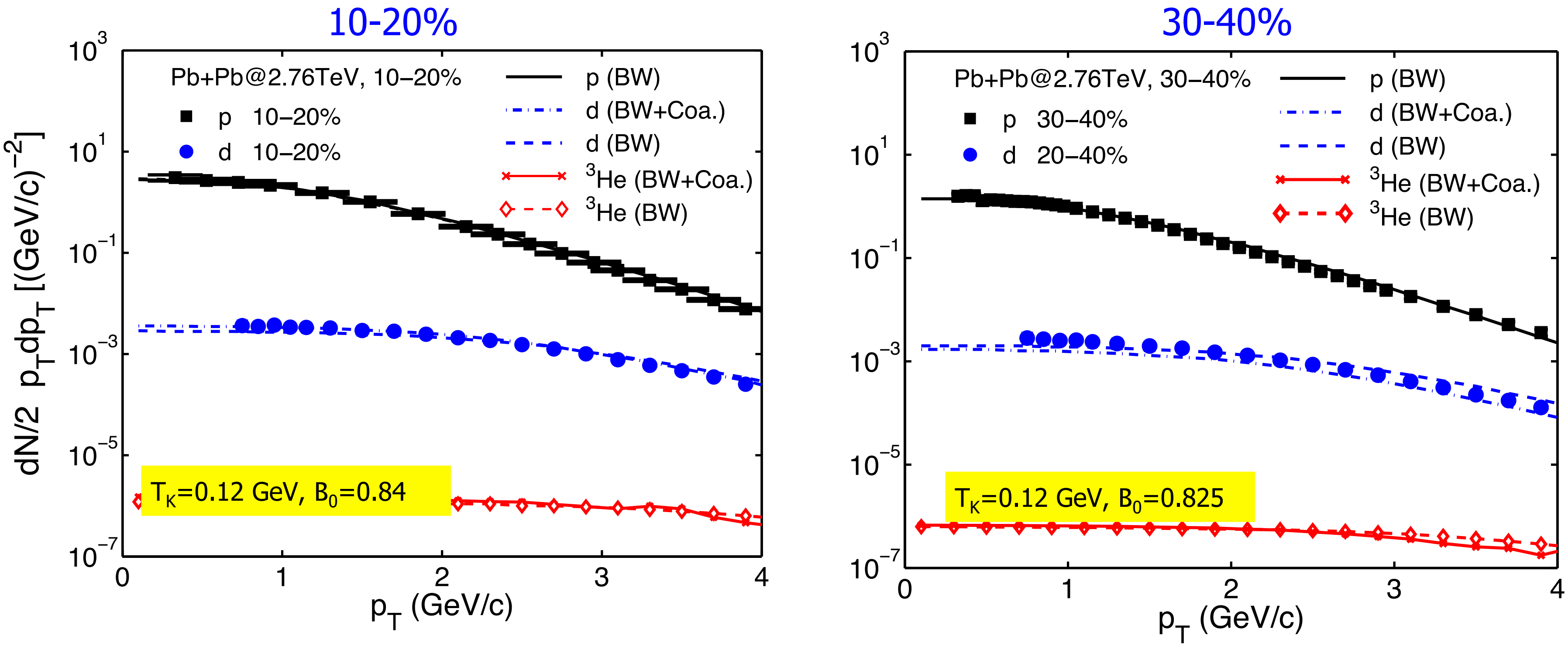


All parameters are determined by fitting the proton transverse spectrum and elliptic flow. Results for light nuclei are then obtained by replacing the mass and introducing the fugacity.

Preliminary results for Pb+Pb@ 2.76 TeV

Transverse momentum spectra

Zhu, Zheng, Ko et al, in preparation



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- ✧ Both the blast-wave and coalescence models can describe measured transverse momentum spectra very well at LHC.
- ✧ We have also predicted the spectrum and elliptic flow of Helium-3. It is of interest to compare it with future experimental data.

Elliptic flow (preliminary)

Introduce **a space-momentum correlation** to reduce the coalescence probability of nucleons moving along the reaction plane.

For in-plane ($|p_{Tx}|>|p_{Ty}|$) nucleons, the spatial distribution of high momentum nucleons (p_T>0.9 GeV) has a larger radius parameter $R_0 = 10e^{r_b(p_T-0.9)}$.

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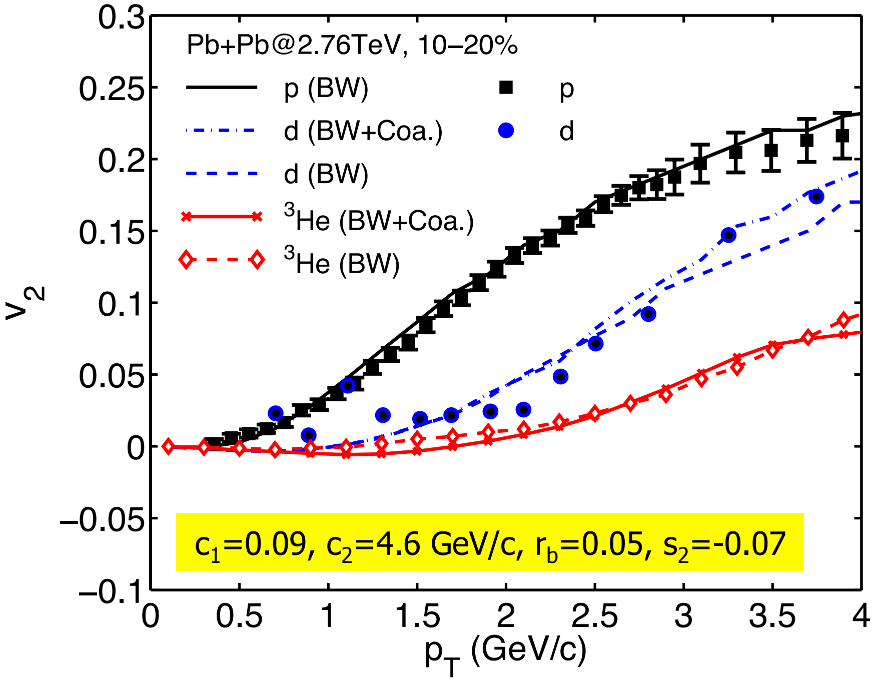

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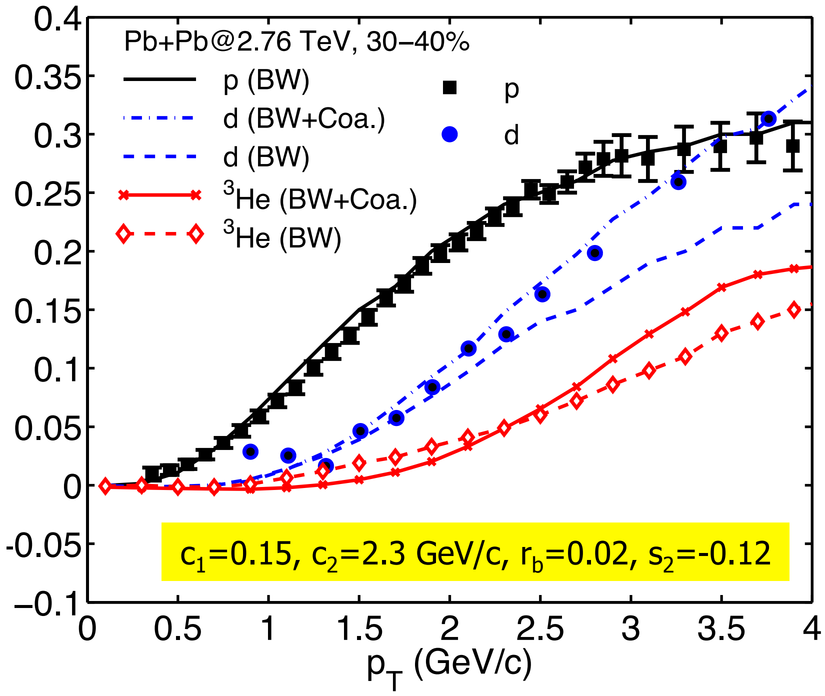

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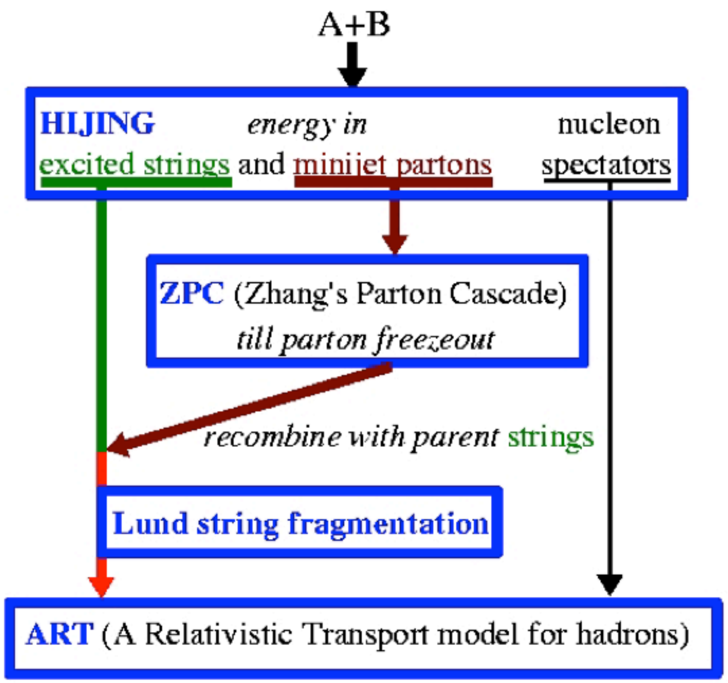
The AMPT model

Structure of the default AMPT model



A+B

HIJING *energy in* excited strings and minijet partons — nucleon spectators

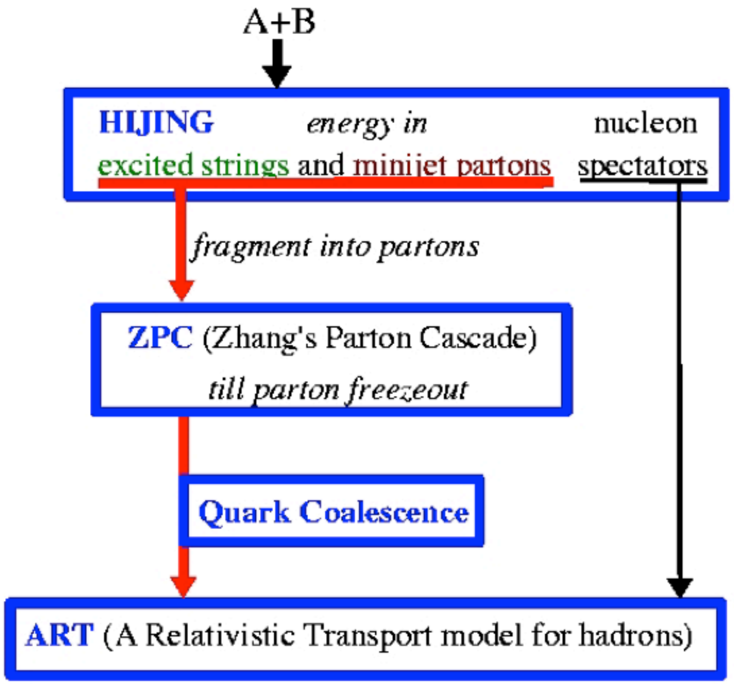
ZPC (Zhang's Parton Cascade) *till parton freezeout*

recombine with parent strings

Lund string fragmentation

ART (A Relativistic Transport model for hadrons)

Structure of AMPT model with string melting



A+B

HIJING *energy in* excited strings and minijet partons — nucleon spectators

fragment into partons

ZPC (Zhang's Parton Cascade) *till parton freezeout*

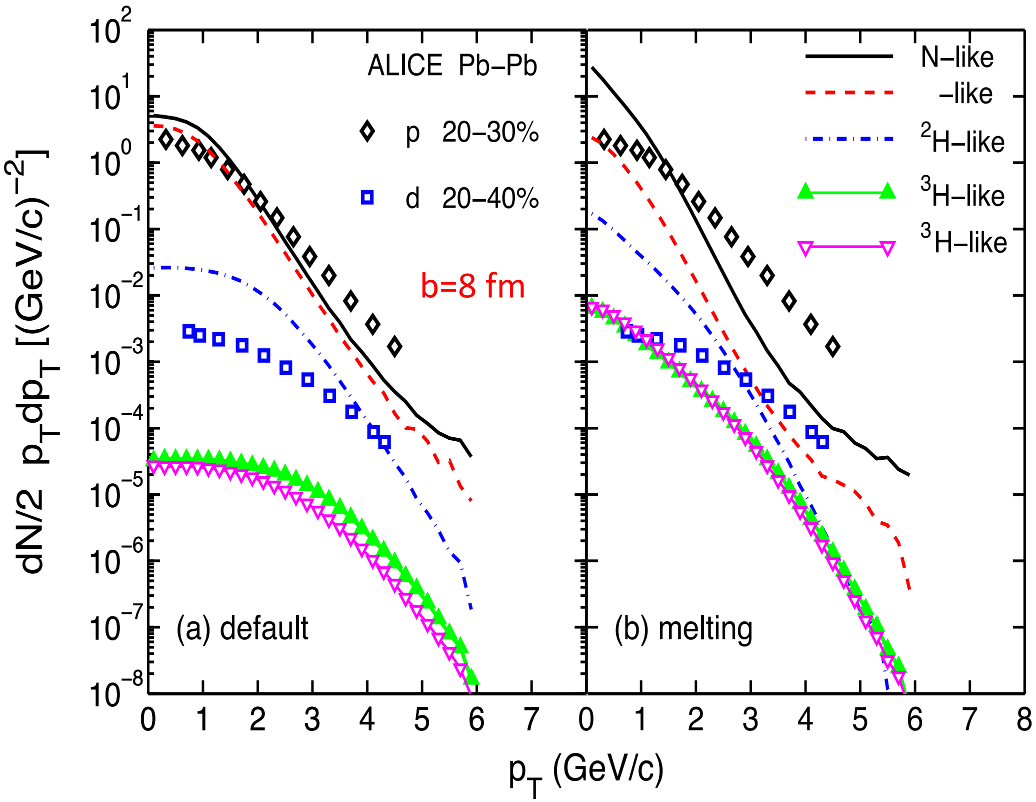
Quark Coalescence

ART (A Relativistic Transport model for hadrons)

Lin, Ko, et al, PRC72 (2005)

- Initial particle distribution is generated by HIJING.
- In default AMPT model, the jet quenching is replaced by taking into account the scattering of minijet partons via ZPC model.
- In SM AMPT model, all minijets are converted to the valence quarks and antiquarks, which are converted to hadrons via a **spatial coalescence model**

Transverse momentum spectra

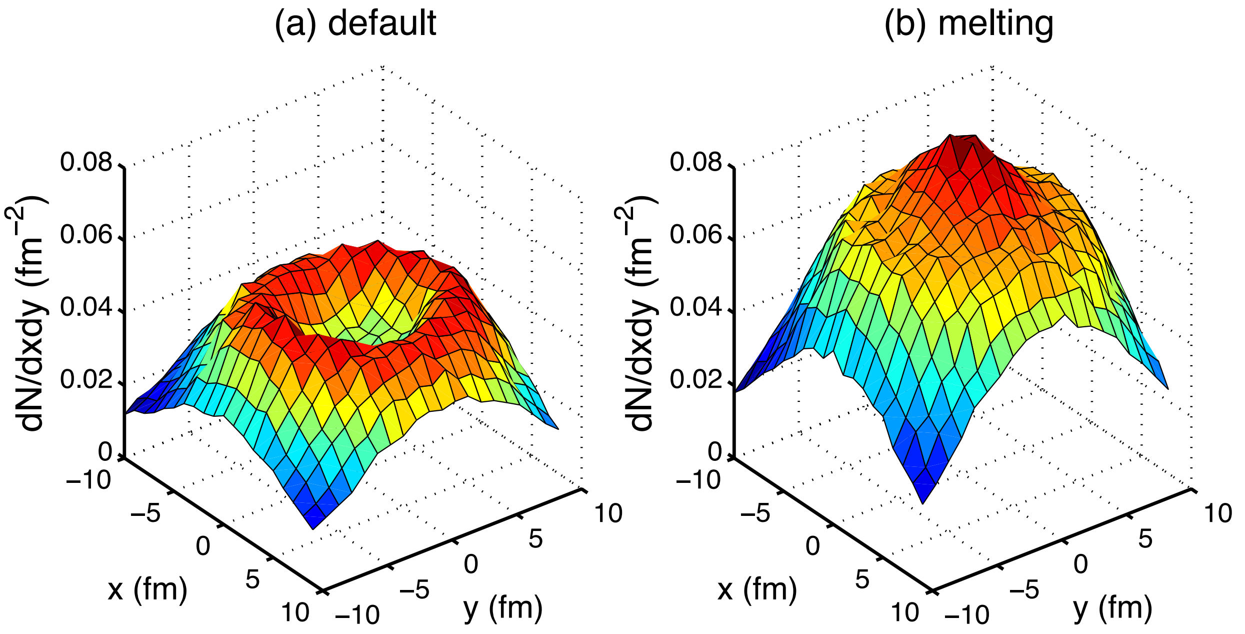


Zhu, Ko & Yin PRC(2015)

- Both default and string-melting AMPT model cannot describe the experimental data.
- Baryons are not properly described by AMPT with string melting, which gives a larger deuteron number and a soft p_T spectrum at midrapidity.

space-time structure of nucleons at kinetic freeze-out

The nucleon number density distribution in the transverse plane

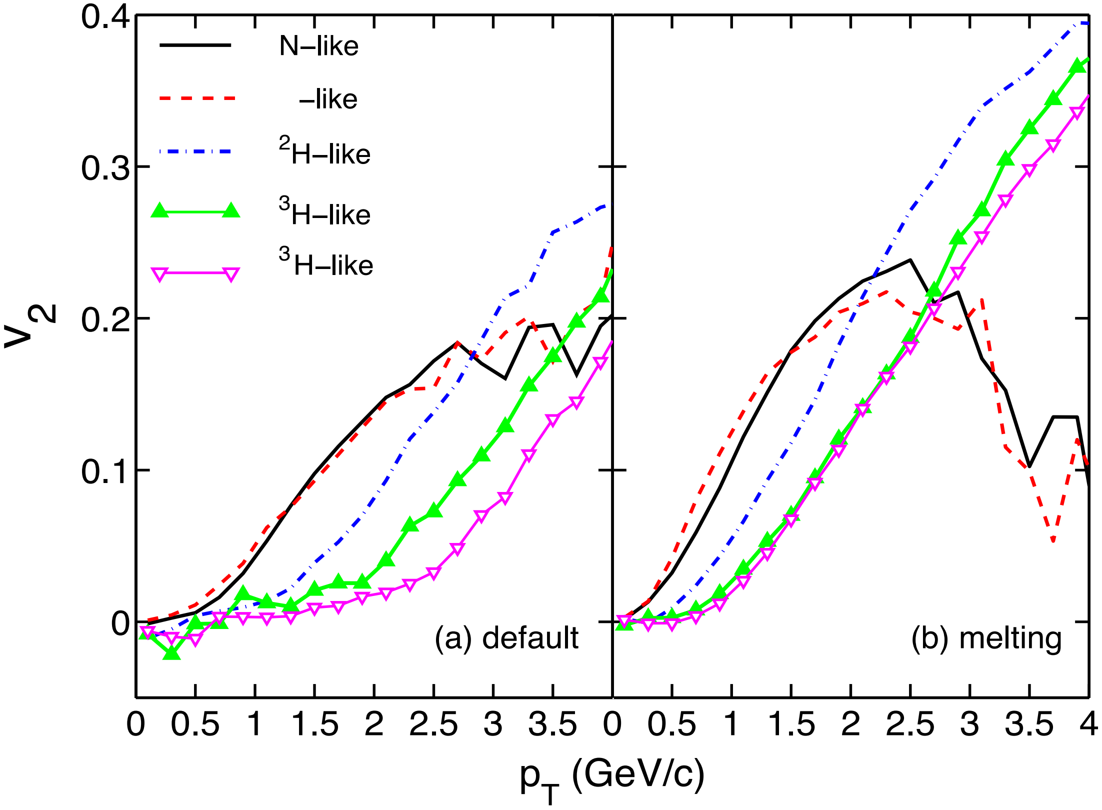


- ✧ In default AMPT, the nucleon number density at freeze-out peaks approximately at a circle with a radius of about 6 fm in the transverse plane.
- ✧ In string melting AMPT, freeze-out nucleons has a sharp peak at origin, which seems unreasonable.

Elliptic flow at Pb+Pb collisions@2.76 TeV

The momentum distribution of nucleus A produced in a heavy-ion collision event can be written as

$$f_A(p_T,\phi,y)=\frac{N_A(p_T,y)}{2\pi}\left\{1+2\sum_n v_n(p_T,y)\cos\left[n(\phi-\Psi_n)\right]\right\}$$



Neglecting the fluctuation of event plane angle, the elliptic flow can be calculated by:

$$v_2(p_T)=\left\langle\frac{p_x^2-p_y^2}{p_x^2+p_y^2}\right\rangle$$

- As the nuclei get heavier, their elliptic flows become smaller, similar to the mass ordering of elliptic flow seen in hydrodynamic description of collective flow.
- Due to the strong partonic scattering, the elliptic flow of nuclei are larger in the SM AMPT model.

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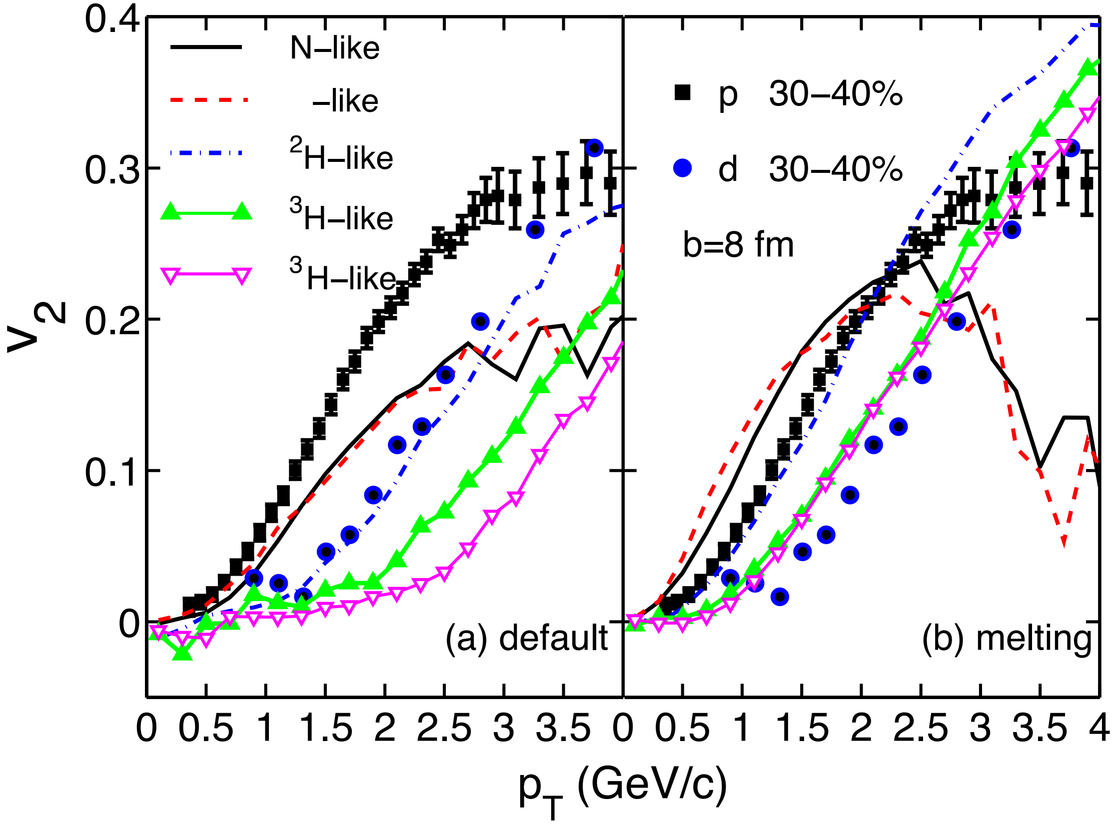

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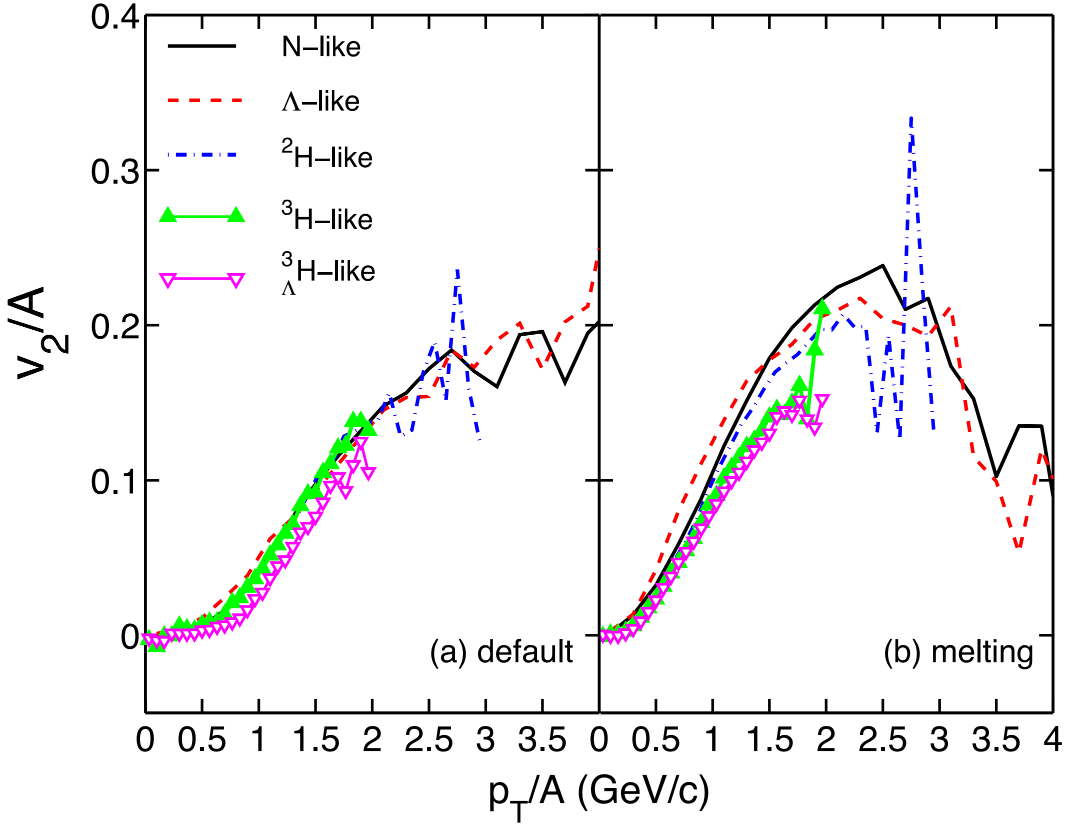
Scaled Elliptic flows



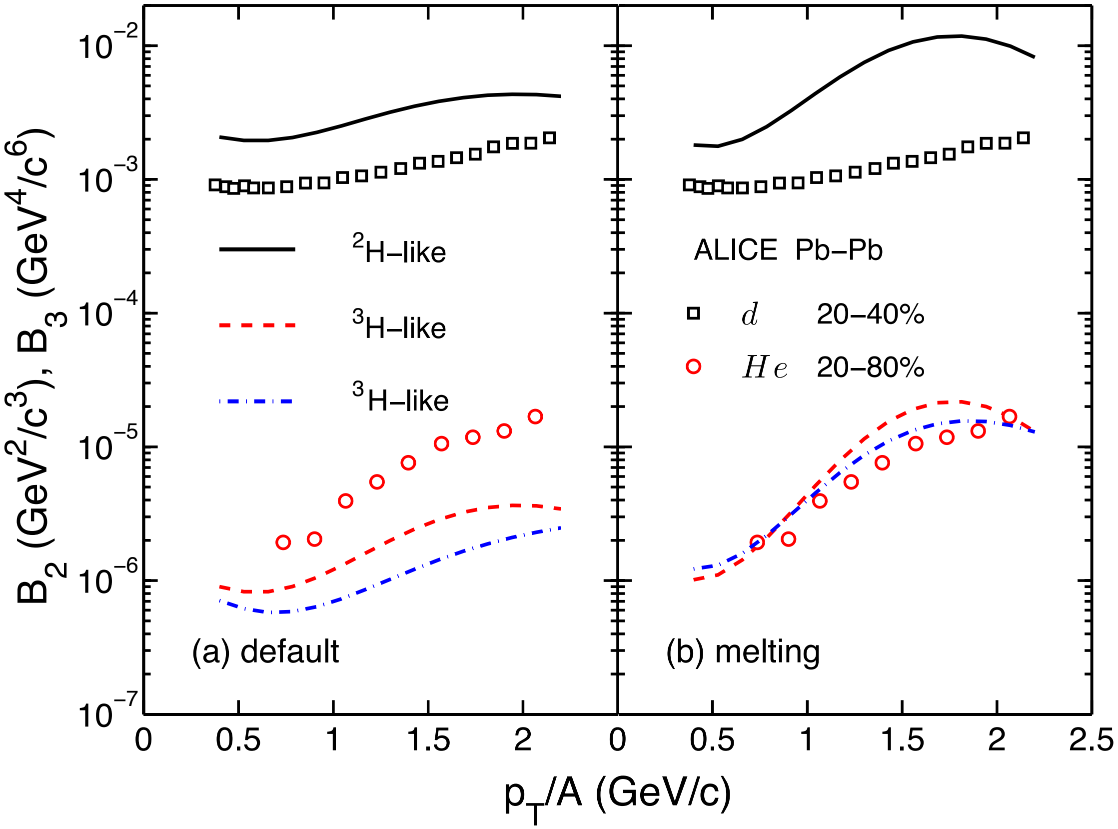
- ✧ A unique feature of the coalescence model is its prediction of an approximate constituent nucleon number scaling of the elliptic flows of nuclei.
- ✧ The scaled v2 of all light nuclei are similar in the default AMPT, while there are some deviations in the string melting AMPT, which may again be related to its baryon problem.

Coalescence parameter

In coalescence model, the spectral distribution of the composite nuclei is related to the one of the primordial nucleons by,

$$E_A \frac{d^3N_A}{d\vec{p}_A^3} = B_A \left(E_p \frac{d^3N_p}{d\vec{p}_p^3} \right)^A$$

B_A: coalescence parameter for nuclei A with mass number A and momentum of p_i=Ap_p.



- ✧ Both B_2 and B_3 increase with increasing transverse momentum in both the default and the SM AMPT models.
- ✧ Except B_3 from SM AMPT model, others from both AMPT models can not give a quantitative description of data.

Summary and outlook

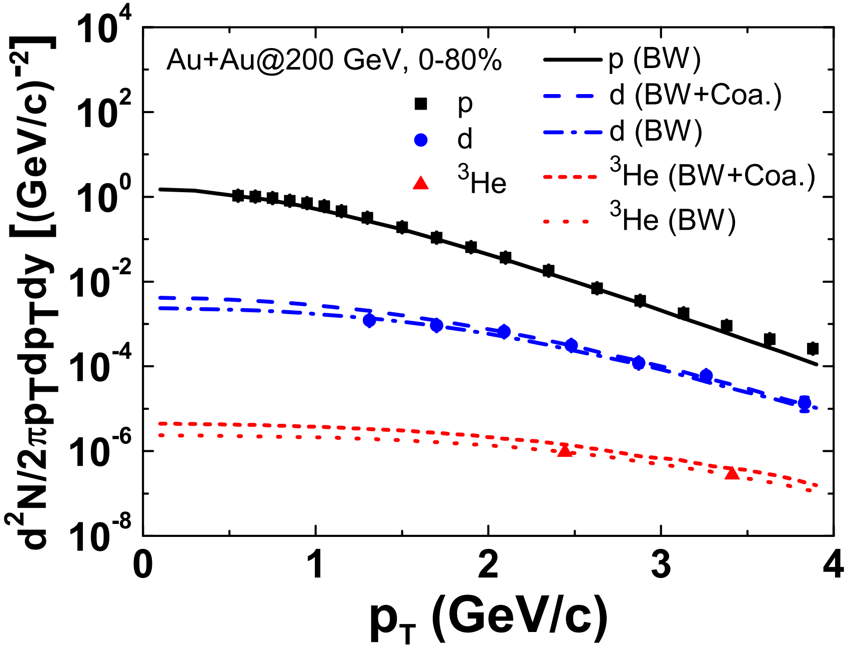
- ✓ The coalescence model based on the nucleon phase-space distribution from the blast-wave model can describe both the transverse momentum spectra and elliptic flows of light nuclei in heavy ion collisions at LHC.
- ✓ The coalescene model based on nucleons from AMPT model can't give a quantitative description of the experimental data.
- ✓ We have also predicted the spectrum and elliptic flow of Helium-3 (triton).

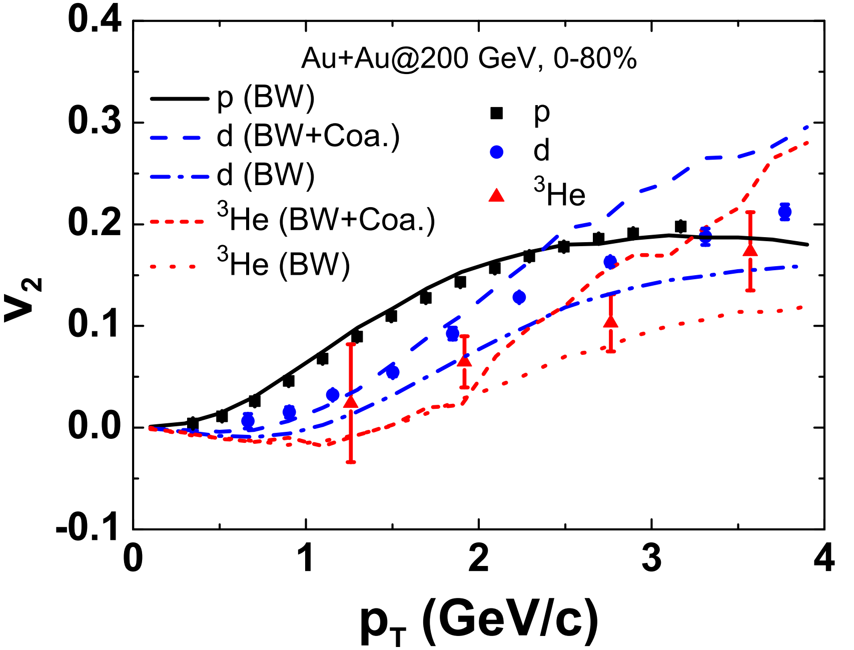
- ◆ Since the baryon problem has recently been solved by Lin and He, it is very interesting to reinvestigate light nuclei production from the colaescence model using nucleons from the updated AMPT model.
- ◆ It's also of interest to use the nucleons from hydro+URQMD model. In this case, we don't need to include the space-momentum correlation by hand.

Thanks

Spectrum and elliptic flow@ RHIC

Yin, et al, PRC95, 054913(2017)





- ✓ Phase-space distributions of protons and neutrons at freeze-out are obtained from the blast-wave model, which are treated as the input for the coalescence model.
- ✓ The coalescence model with the spatial distribution of nucleons independent of their momenta fails to describe experimentally measured elliptic flows of light nuclei.

Extended blast-wave model

Introduce **a space-momentum correlation** to reduce the coalescence probability of nucleons moving along the reaction plane.

For in-plane ($|p_{Tx}|>|p_{Ty}|$) nucleons, the spatial distribution of high momentum nucleons (p_T>0.9 GeV) has a larger radius parameter $R_0 = 10e^{r_b(p_T-0.9)}$.