Collective flow in 2.76 and 5.02 A TeV Pb+Pb collisions

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arXiv:1703.10792

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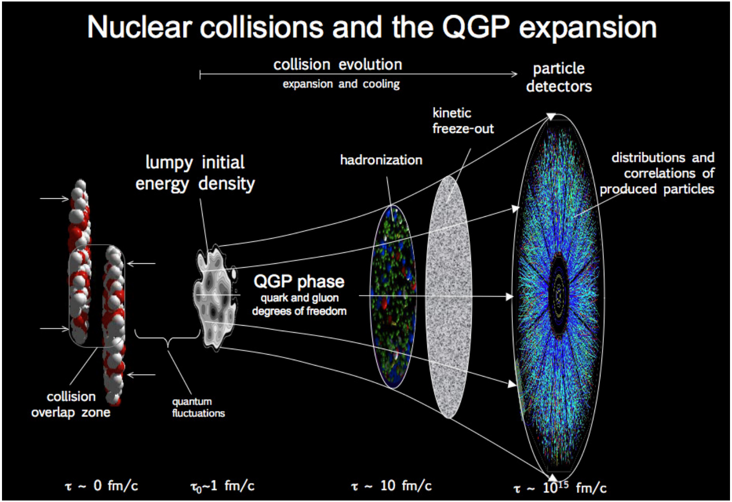
Outline

Introduction

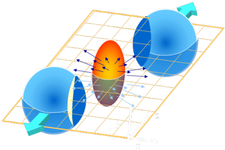
The process of heavy-ion collisions

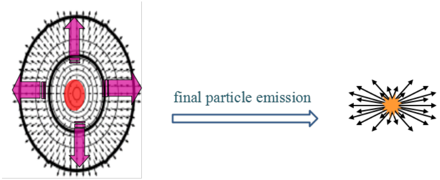


U. W. Heinz, hep-ph/0407360.

Collective flow

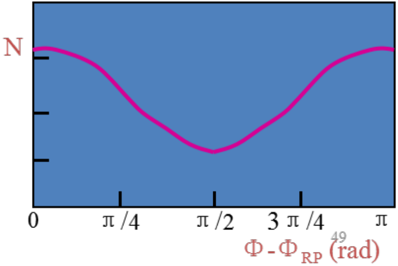
- Pressure gradients (larger in -plane) push bulk “out” − >”flow”:





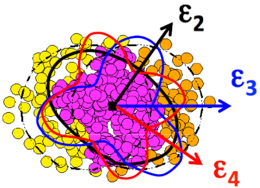
leading to the “double peaks” structure:

- The internal pressure gradients lead to strong anisotropic flow.



Higher order flow harmonics

- In experimental, the initial states fluctuate event-by-event.



- One can get higher order flow harmonics by Fourier unfolding of the final observed momentum distribution $dN/(p_T dp_T dy d\phi)$:

$$\frac{dN_i}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN_i}{p_T dp_T dy}[1 + 2v_2^i(p_T)cos(2\phi_p) + 2v_3^i(p_T)cos(3\phi_p) + 2v_4^i(p_T)cos(4\phi_p) + ...]. \quad (1)$$

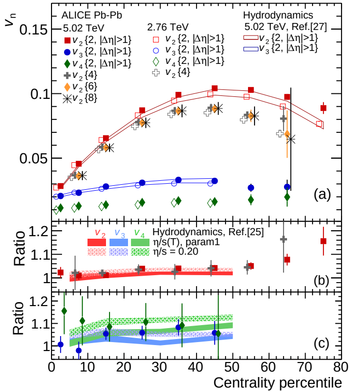
Other flow observables

- Many other detailed flow observables can reflect the fluctuations of initial states, non-linear response, flow angle correlations, mode-coupling effects and factorizations breaking effects of the system:
  - event-by-event v_n distributions
  - event-plane correlations
  - *Symmetric Cumulant*
  - non-linear response coefficients
  - flow factorizations ratio
- A systematic study of these flow observables can help to test the model calculations and the extracted QGP viscosity as well as to further evaluate and constrain the initial condition models.

Collective flow in 2.76 and 5.02 A TeV Pb+Pb collisions

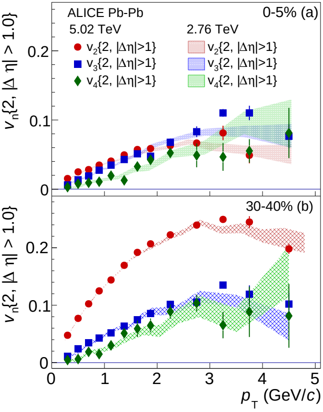
Motivation

- integrated-v_n



ALICE PRL 13, 132302 (2016)

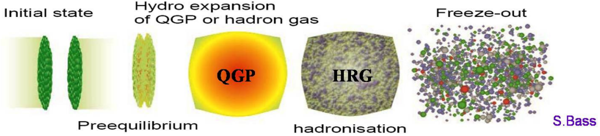
- $v_n(p_T)$ for all charged



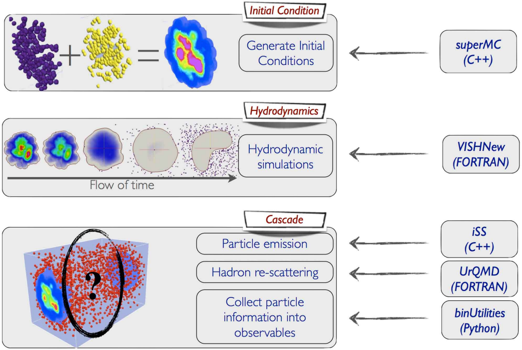
- These can fix parameters in hydro model then to calculate other observables.

Model and Set up

- Heavy-ion collisions process:



- Hydrodynamics simualtions:



C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz. Comput. Phys. Commun. **199**, 61 (2016)

VISHNU hybrid model

- For hydrodynamics part, VISHNU solves $T^{\mu\nu}$, $\pi^{\mu\nu}$ and Π:

$$\partial_\mu T^{\mu\nu}(x) = 0, \qquad T^{\mu\nu} = eu^\mu u^\nu - (p+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu},$$
$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta + \Pi\zeta T\partial_\mu\left(\frac{\tau_\Pi u^\mu}{2\zeta T}\right)\right], \tag{2}$$
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}\dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle} + \pi^{\mu\nu}\eta T\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{2\eta T}\right)\right],$$

- Switch from hydrodynamics to hadron cascade (Cooper-Frye formula):

$$E\frac{d^3N_i}{d^3p}(x) = \frac{g_i}{(2\pi)^3}p\cdot d^3\sigma(x)\, f_i(x,p) \tag{3}$$

- Hadron cascade simulated by UrQMD by:

$$\frac{df_i(x,p)}{dt} = C_i(x,p) \tag{4}$$

H. Song, S. A. Bass and U. Heinz, PRC **83**, 024912 (2011).
C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz, Comput. Phys. Commun. **199**, 61 (2016)

Initial conditions

- TRENTo parameterizes initial entropy density by:

$$s = s_0 \left(\frac{\tilde{T}_A^p + \tilde{T}_B^p}{2} \right)^{1/p} . \quad (5)$$

where $\tilde{T}(x, y) = \sum_{i=1}^{N_{\text{part}}} \gamma_i \, T_p(x - x_i, y - y_i)$,
$T_p(x, y) = \frac{1}{2\pi w^2} \exp(-\frac{x^2+y^2}{2w^2})$ and turing p makes TRENTo match KLN, EKRT, WN, etc.

- AMPT construct energy density by energy decompositions of individual partons via a Gaussian smearing:

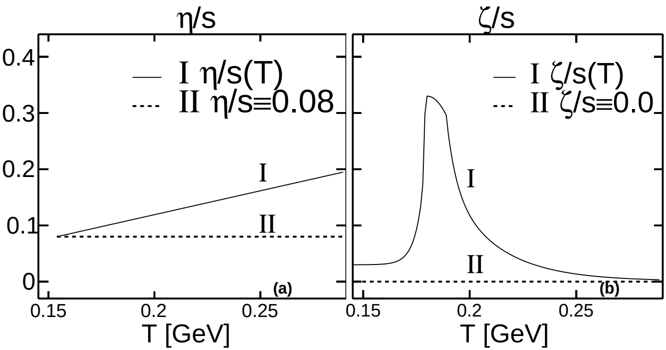
$$\epsilon = K \sum_i \frac{E_i^*}{2\pi\sigma^2\tau_0\Delta\eta_s} \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma^2}\right), \quad (6)$$

J. S. Moreland, J. E. Bernhard and S. A. Bass, PRC **92** (2015) no.1, 011901.
H. j. Xu, Z. Li and H. Song, PRC **93**, no. 6, 064905 (2016)

Set up

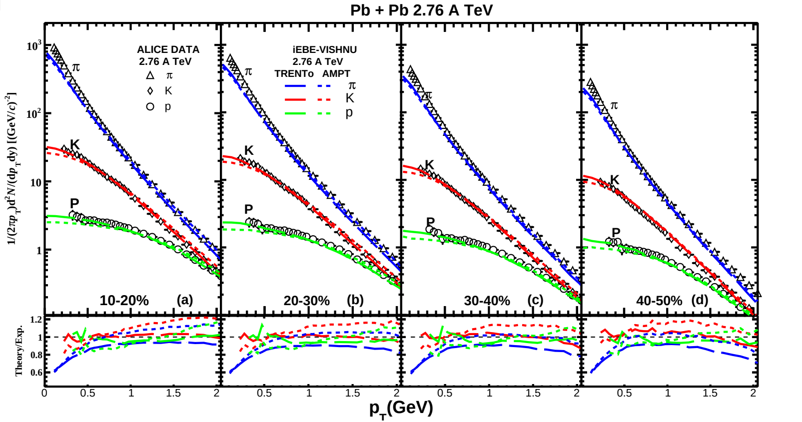
iEBE-VISHNU + TRENTo / AMPT

- TRENTo : $\eta/s(T)$ and $\zeta/s(T)$ (para-I) .
- AMPT: $\eta/s \equiv 0.08$ and $\zeta/s \equiv 0$ (para-II).



Results and Discussion

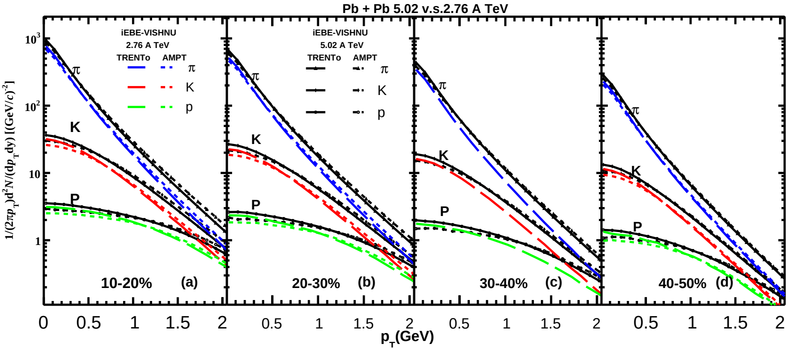
p_T-spectra for 2.76 A TeV



- iEBE-VISHNU + TRENTo / AMPT describes π , K and proton data well.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

p_T-spectra for 5.02 A TeV



- Stronger radial flow is developed in systems of 5.02 A TeV collisions energy.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

Q-cumulant

- 2-particle azimuthal correlations:

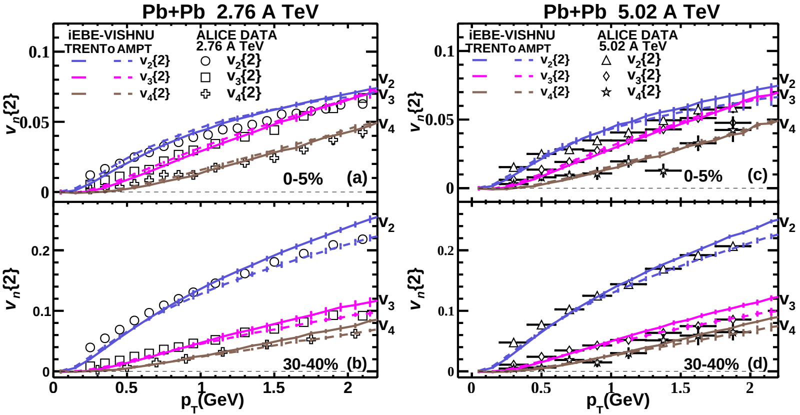
$$\langle 2 \rangle_{n,-n}^{|\Delta\eta|} = \frac{Q_n^A \cdot Q_n^{B*}}{M_A \cdot M_B}, \quad (7)$$

flow harmonics:

$$c_n\{2, |\Delta\eta|\} = \langle\langle 2 \rangle\rangle_{n,-n}^{|\Delta\eta|}, \quad v_n\{2, |\Delta\eta|\} = \sqrt{c_n\{2, |\Delta\eta|\}} \quad (8)$$

where $Q_n = \sum_{i=1}^{M} e^{in\varphi_i}$, and Q_n can be Particles Of Interests (POIs) to calculate $v_n(p_T)$.

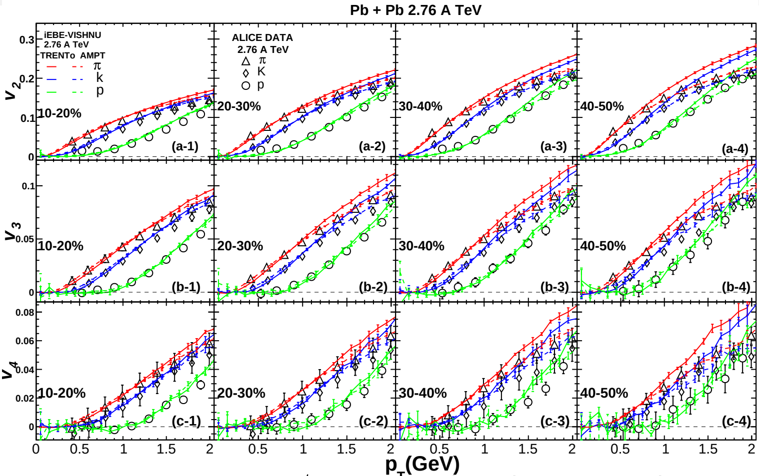
$v_n(p_T)$ for all charged hadrons



- iEBE-VISHNU + TRENTo / AMPT can describe $v_n(p_T)$ of Pb+Pb at 2.76 and 5.02 A TeV well.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

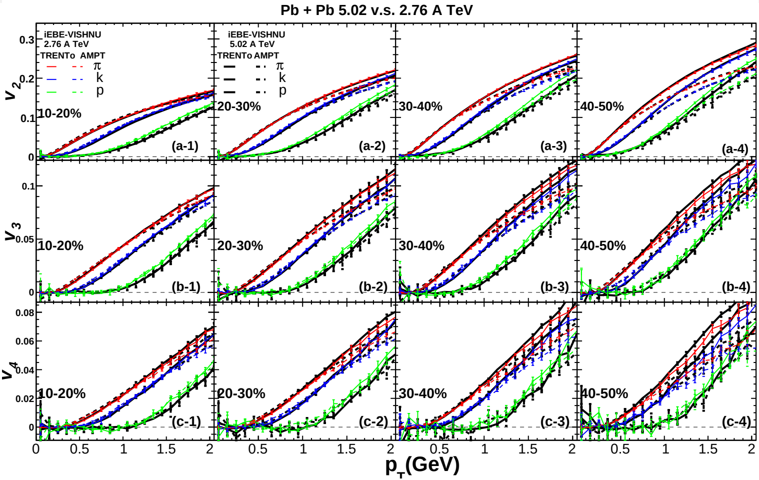
$v_n(p_T)$ for π,K and proton at 2.76 A TeV



- iEBE-VISHNU + TRENTo / AMPT can describe π , K and proton data well.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

$v_n(p_T)$ for π,K and proton at 5.02 A TeV



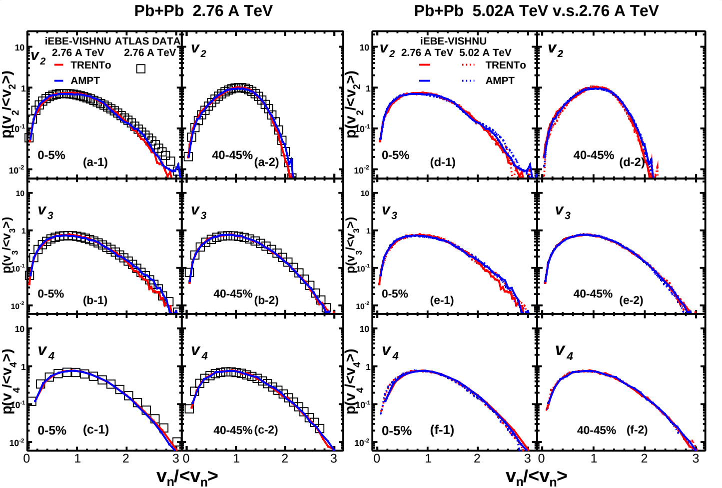
- Mass-splitting between π and proton increased slightly at 5.02 A TeV collisions energy.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

Event-by-event v_n distributions

- The event-by-event v_n distributions reflect the initial states fluctuations, providing strong constraints for the initial condition models
- One need do standard Bayesian unfolding to suppress the non-flow and finite multiplicities effects.

Event-by-event v_n distribution

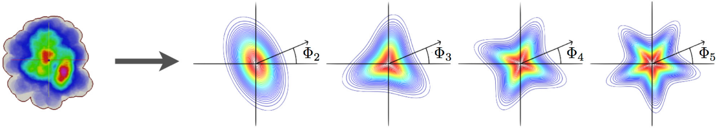


- iEBE-VISHNU + TRENTo / AMPT can fit scaled-v_n distributions well.
- The scaled v_n distributions are insensitive to collision energy.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

Event-plane correlations

- Event-plane correlations reveal the patterns of initial state fluctuations, and evaluate correlations of flow angles.



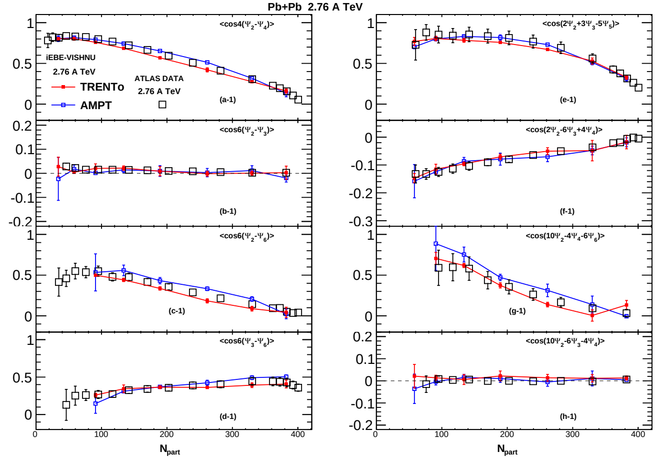
we use Scalar-Product:

$$\cos\left[c_1 n_1 \Psi_{n_1} - c_2 n_2 \Psi_{n_2}\right] = \frac{\langle \tilde{Q}^{c_1}_{n_1 A} \tilde{Q}^{c_2 *}_{n_2 B} \rangle}{\sqrt{\langle \tilde{Q}^{c_1}_{n_1 A} \tilde{Q}^{c_1 *}_{n_1 B} \rangle} \sqrt{\langle \tilde{Q}^{c_2}_{n_2 A} \tilde{Q}^{c_2 *}_{n_2 B} \rangle}}$$

$$\begin{aligned} &\cos\left[c_1 n_1 \Psi_{n_1} + c_2 n_2 \Psi_{n_2} - c_3 n_3 \Psi_{n_3}\right] \\ &= \frac{\langle \tilde{Q}^{c_1}_{n_1 A} \tilde{Q}^{c_2}_{n_2 A} \tilde{Q}^{c_3 *}_{n_3 B} \rangle}{\sqrt{\langle \tilde{Q}^{c_1}_{n_1 A} \tilde{Q}^{c_1 *}_{n_1 B} \rangle \langle \tilde{Q}^{c_2}_{n_2 A} \tilde{Q}^{c_2 *}_{n_2 B} \rangle \langle \tilde{Q}^{c_3}_{n_3 A} \tilde{Q}^{c_3 *}_{n_3 B} \rangle}}, \end{aligned} \tag{9}$$

where $\tilde{Q}_n \equiv \frac{1}{N} \sum_j e^{i n \varphi_j}$.

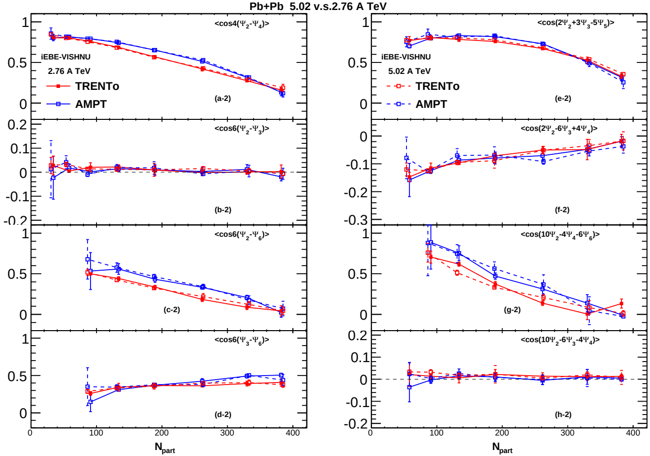
Event-plane correlations at 2.76 A TeV



- iEBE-VISHNU + TRENTo / AMPT generately reproduce date.
- Some correlations are sensitive to initial conditions.

W. Zhao, H. j. Xu and H. Song,. arXiv:1703.10792 [nucl-th].

Event-plane correlations at 5.02 A TeV



- No significant difference between these two collision energies.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

Symmetric Cumulants ($SC(m, n)$)

- $SC(m, n)$ values correlations of flow harmonics:

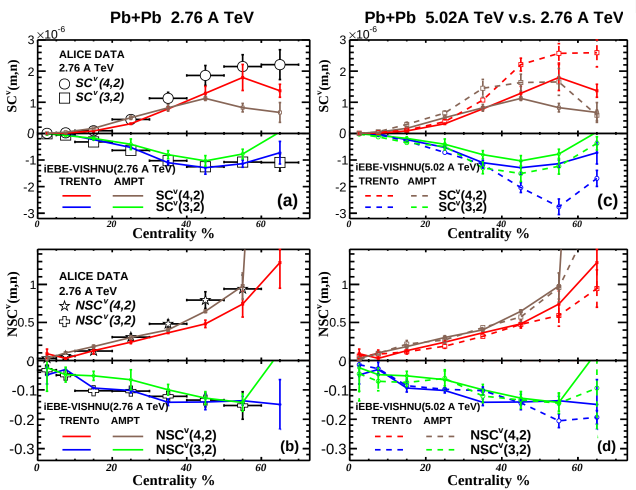
$$
\begin{aligned}
SC^{v}(m,n) &= \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle_c \\
&= \langle\langle 4\rangle\rangle_{n,m,-n,-m} - \langle\langle 2\rangle\rangle_{n,-n} \cdot \langle\langle 2\rangle\rangle_{m,-m} \\
&= \left\langle v_m^2 v_n^2 \right\rangle - \left\langle v_m^2 \right\rangle \left\langle v_n^2 \right\rangle . \qquad (10)
\end{aligned}
$$

- the Normalized Symmetric Cumulants:

$$
NSC^{v}(m,n) = \frac{SC^{v}(m,n)}{\langle v_m^2\rangle\langle v_n^2\rangle} \qquad (11)
$$

where $\langle v_m^2\rangle$ and $\langle v_n^2\rangle$ can be calculated by the 2-particle cumulants

Symmetric Cumulants



- iEBE-VISHNU + TRENTo / AMPT describe the $(N)SC^{v}(m,n)$ well.
- $NSC^{v}(m,n)$ has no significant dependence on collision energies.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

Non-linear response coefficients

For low harmonics, v_n(n=2,3), magnitudes are linear in initial ε_n(n=2,3).

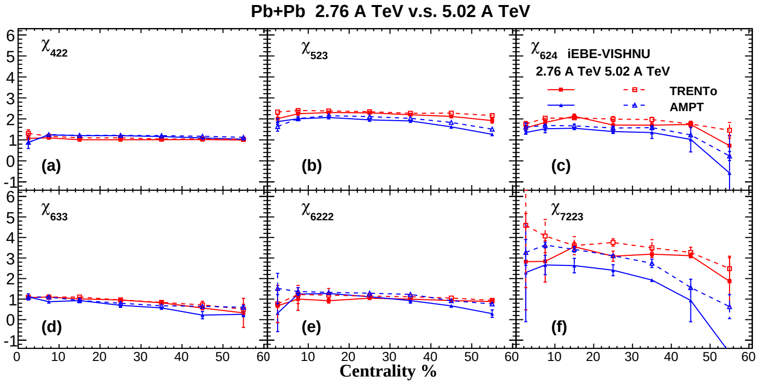
Higher harmonics, $v_n(n \geq 4)$, receive contributions from mode-coupling.

- Non-linear response coefficients evalue the mode-coupling effects:

$$\begin{aligned} V_4 &= V_{4L} + \chi_{422} V_2^2, \quad V_5 = V_{5L} + \chi_{523} V_2 V_3, \\ V_6 &= V_{6L} + \chi_{624} V_2 V_{4L} + \chi_{633} V_3^2 + \chi_{6222} V_2^3, \\ V_7 &= V_{7L} + \chi_{725} V_2 V_{5L} + \chi_{734} V_3 V_{4L} + \chi_{7223} V_2^2 V_3 . \end{aligned} \tag{12}$$

We implement Scalar-Product method to calculate these coefficients.

Non-linear response coefficients



- No obvious centrality or energy dependence;
- It does depend on the initial conditions.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

p_T-dependent factorization ratio ($r_{2,3}(p_T)$)

- Due to the initial state fluctuation, hadrons at different p_T do not share a common flow angle.
- $r_n(p_T)$ evaluates the break-up of factorizations of flow harmonics:

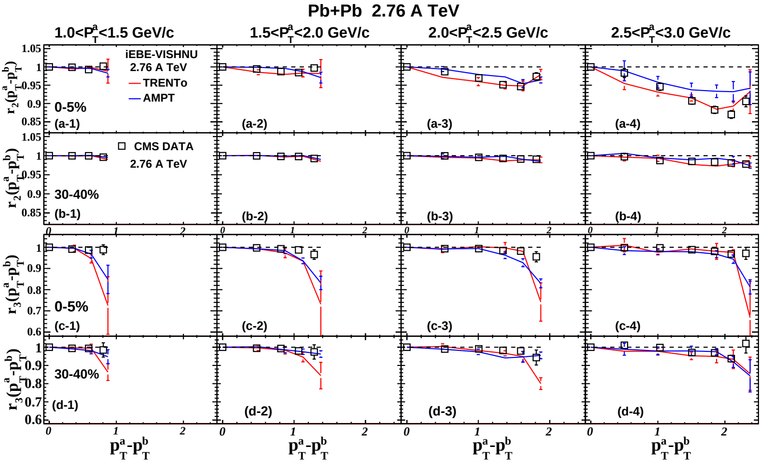
$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^b, p_T^b)}}, \quad (13)$$

where:

$$V_{n\Delta} \equiv \langle\langle \cos(n\Delta\phi)\rangle\rangle = \langle \tilde{Q}_n^{a(b)} \tilde{Q}_n^{a(b)*} \rangle, \quad (14)$$

and $\tilde{Q}_n^{a(b)} \equiv \frac{1}{N}\sum_j e^{in\varphi_j}$ calculated within a specific $p_T^{a(b)}$ bin .

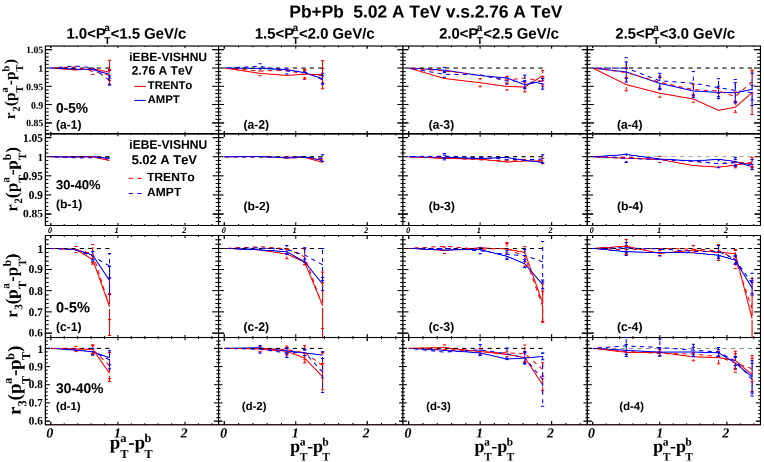
Factorization ratio for 2.76 A TeV



- iEBE-VISHNU + TRENTo / AMPT describe r_2 and r_3 well;
- r_3 drop sharply at large $p_T^a - p_T^b$, due to hadronic rescattering.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

Factorization ratio for 5.02 A TeV



- r_2 and r_3 are close for two collision energies.

W. Zhao, H. j. Xu and H. Song, arXiv:1703.10792 [nucl-th].

Summary

Summary

iEBE-VISHNU + TRENTo / AMPT with two forms of QGP transport coefficients, we calculate:

- integrated and differential v_n, the event-by-event v_n distributions, the event-plane correlations, Symmetric Cumulant, the nonlinear response coefficients, p_T-dependtdent factorization ratio.

- Raising from 2.76 to 5.02 A TeV, multiplicities increased by $\sim 30\%$, transport properties of the QGP do not change significantly.

Some observables are sensitive to initial conditions, such as:

- Symmetric Cumulant $SC^v(4,2)$,
- Event plane correlations $\langle cos6(\Psi_2 - \Psi_6)\rangle$ and $\langle cos(10\Psi_2 - 4\Psi_4 - 6\Psi_6)\rangle$,
- The non-linear response coefficients χ_{624} and χ_{7223}.

- Thank You.