

VISHNU hybrid model for viscous QCD matter

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Outlook

- Introduction
- Higher order flow harmonics of identified hadrons in 2.76A TeV Pb+Pb collisions
- Baryon diffusion in relativistic heavy ion collisions
- Summary

Reference:

HJX, Zuopeng Li, Huichao Song, PRC93, 064905(2016)

HJX, Hengfeng Huang, Huichao Song, in preparation

Relativistic heavy ion collisions

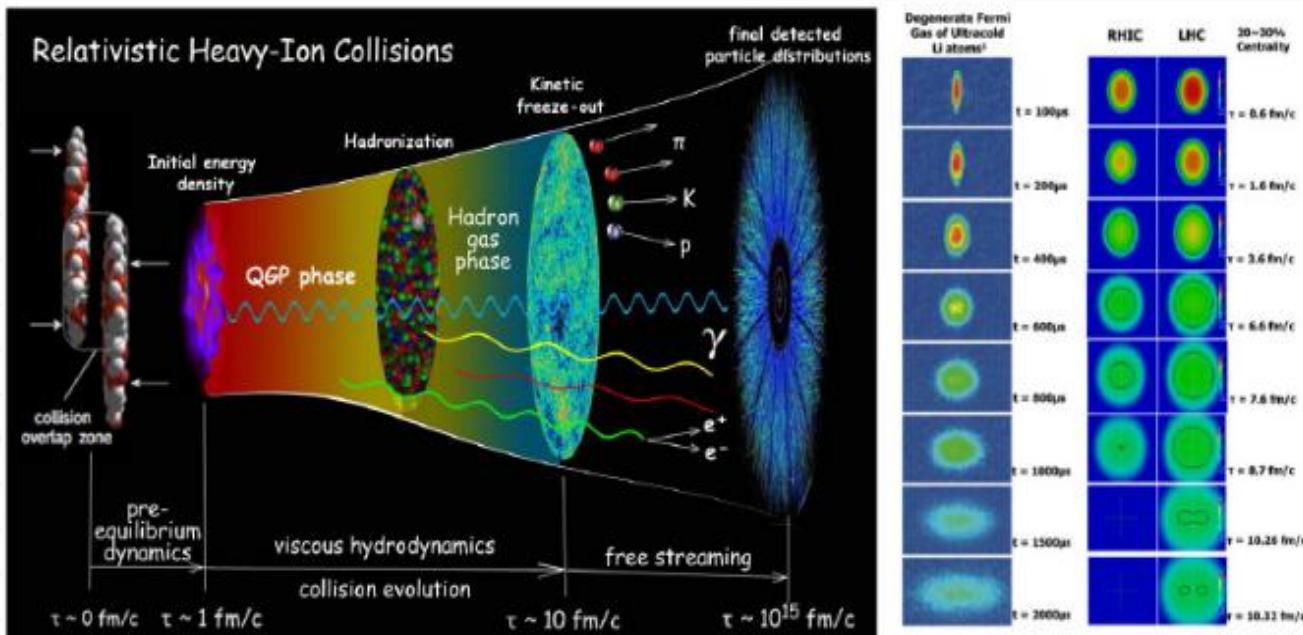
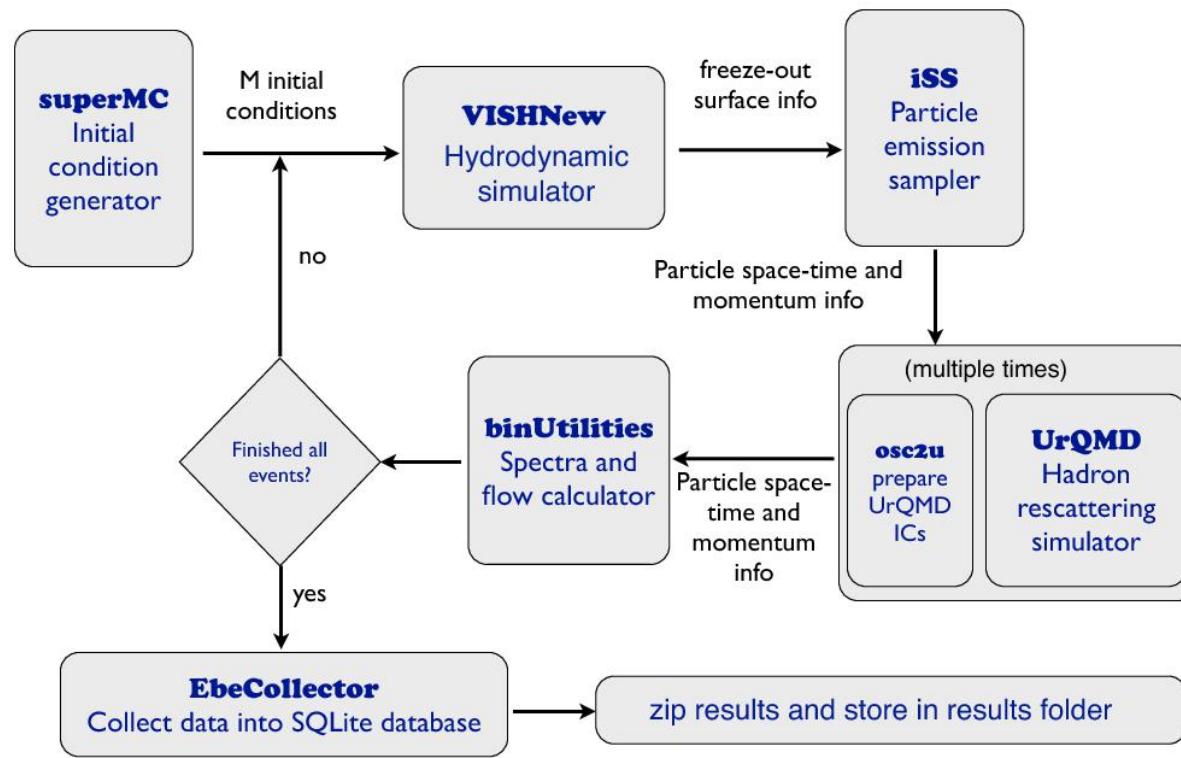


Illustration of the dynamical evolution of relativistic heavy-ion collisions

iEBE-VISHNU hybrid model



The work flow for a single iEBE-VISHNU job with M events [Chun Shen, Comput.Phys.Commun. 199 (2016) 61-85]

Hydrodynamics

The local conservation of Energy and momentum

$$\partial_\tau \tilde{T}^{\tau\tau} + \partial_x(v_x \tilde{T}^{\tau\tau}) + \partial_y(v_y \tilde{T}^{\tau\tau}) = \mathcal{S}^{\tau\tau},$$

$$\partial_\tau \tilde{T}^{\tau x} + \partial_x(v_x \tilde{T}^{\tau x}) + \partial_y(v_y \tilde{T}^{\tau x}) = \mathcal{S}^{\tau x},$$

$$\partial_\tau \tilde{T}^{\tau y} + \partial_x(v_x \tilde{T}^{\tau y}) + \partial_y(v_y \tilde{T}^{\tau y}) = \mathcal{S}^{\tau y}.$$

$$\mathcal{S}^{\tau\tau} = -p - \tau^2 \pi^{\eta\eta} - \tau \partial_x(p v_x + \pi^{x\tau} - v_x \pi^{\tau\tau})$$

$$- \tau \partial_y(p v_y + \pi^{y\tau} - v_y \pi^{\tau\tau})$$

$$\approx -p - \tau^2 \pi^{\eta\eta} - \tau \partial_x(p v_x) - \tau \partial_y(p v_y),$$

$$\mathcal{S}^{\tau x} = -\tau \partial_x(p + \pi^{xx} - v_x \pi^{\tau x}) - \tau \partial_y(\pi^{xy} - v_y \pi^{\tau x})$$

$$\approx -\tau \partial_x(p + \pi^{xx}),$$

$$\mathcal{S}^{\tau y} = -\tau \partial_x(\pi^{xy} - v_x \pi^{\tau y}) - \tau \partial_y(p + \pi^{yy} - v_y \pi^{\tau y})$$

$$\approx -\tau \partial_y(p + \pi^{yy}).$$

The transport equation for the shear viscous pressure tensor

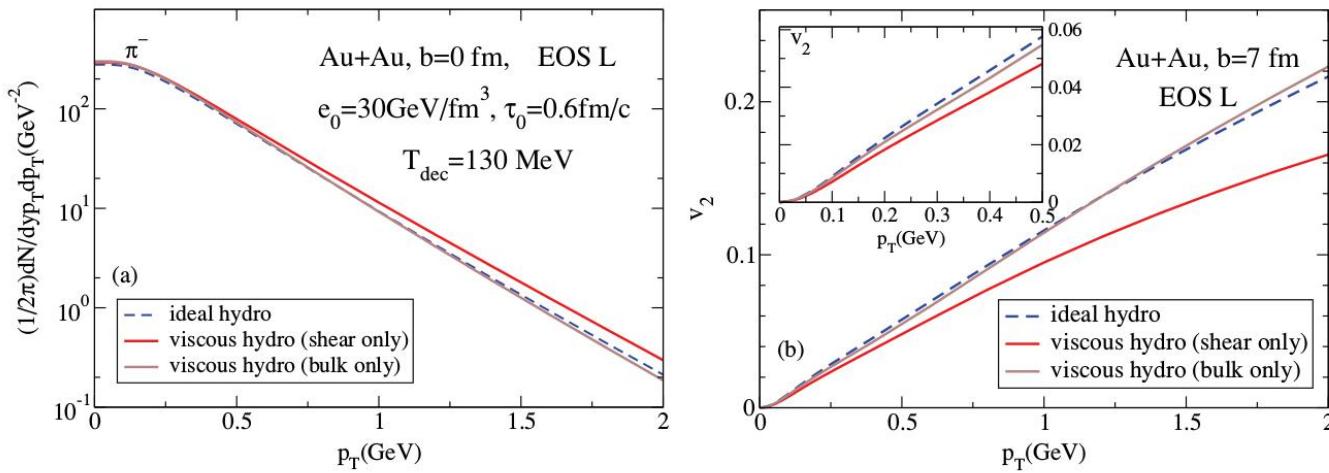
$$\begin{aligned} & (\partial_\tau + v_x \partial_x + v_y \partial_y) \tilde{\pi}^{mn} \\ &= -\frac{1}{\gamma_\perp \tau_\pi} (\tilde{\pi}^{mn} - 2\eta \tilde{\sigma}^{mn}) - (u^m \tilde{\pi}_j^n + u^n \tilde{\pi}_j^m) \\ & \quad \times (\partial_\tau + v_x \partial_x + v_y \partial_y) u^j. \end{aligned}$$

[H. Song, U. Heinz, PRC77, 064901(2008)]

Hydrodynamics

Interplay of shear and bulk viscous

$$\begin{aligned}\Delta^{\mu\alpha} \Delta^{\nu\beta} D\pi_{\alpha\beta} &= -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) \\ &\quad - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi} d_\lambda \left(\frac{\tau_\pi}{\eta T} u^\lambda \right), \\ D\Pi &= -\frac{1}{\tau_\Pi}(\Pi + \zeta\theta) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi} d_\lambda \left(\frac{\tau_\Pi}{\zeta T} u^\lambda \right)\end{aligned}$$



[H. Song, U. Heinz, PRC81, 024905(2010)]

shear viscosity

Anisotropic flow

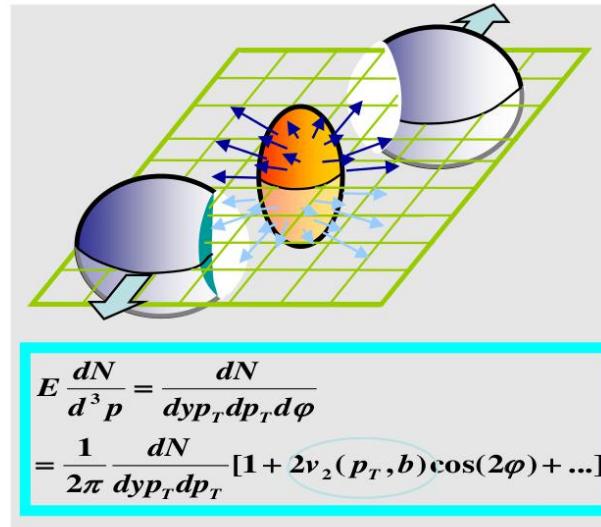
Even: non-zero

Odd: zero

2: elliptic flow

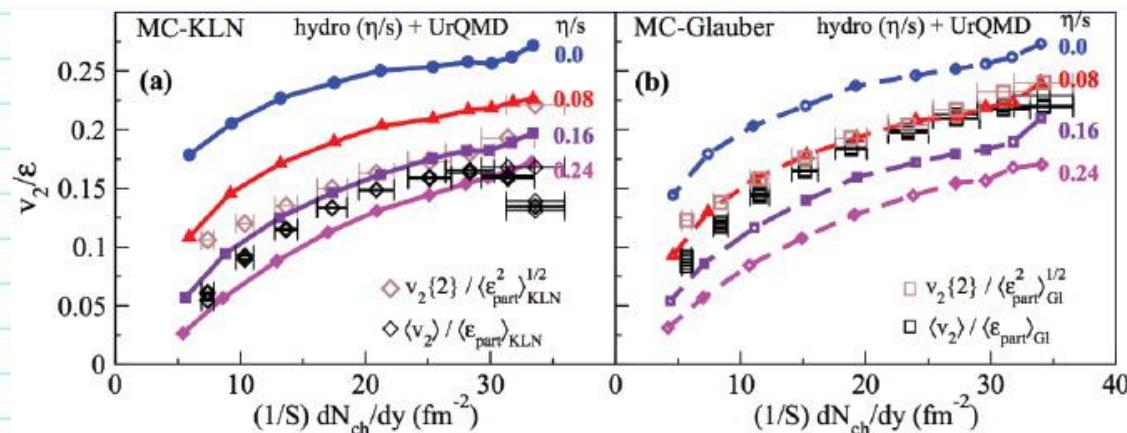
3: triangular flow

4: quadrangular flow



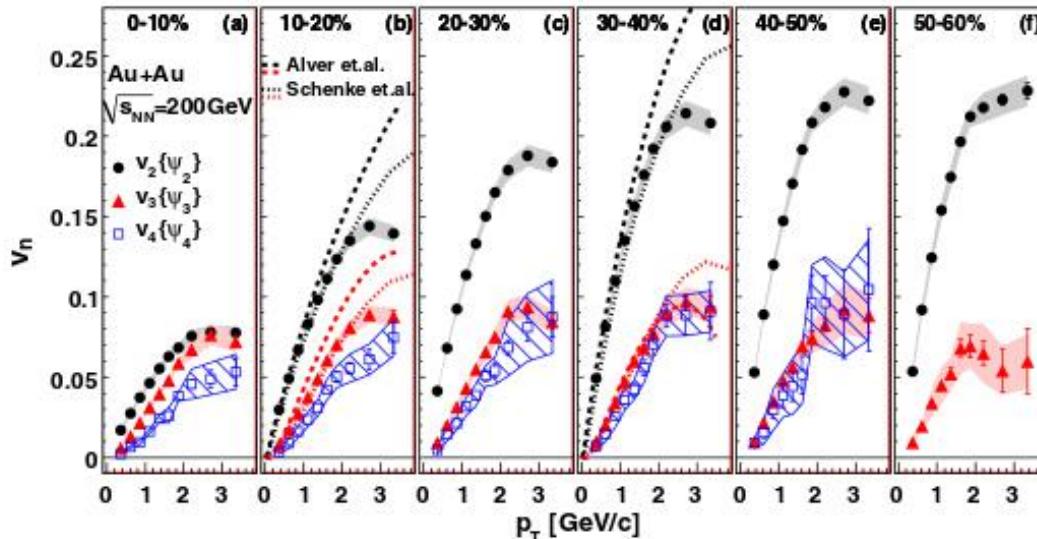
Extract the η/s of QCD matter [Song, Phys. Rev. Lett. 106, 192301 (2011)]

An ultra-hot perfect fluid

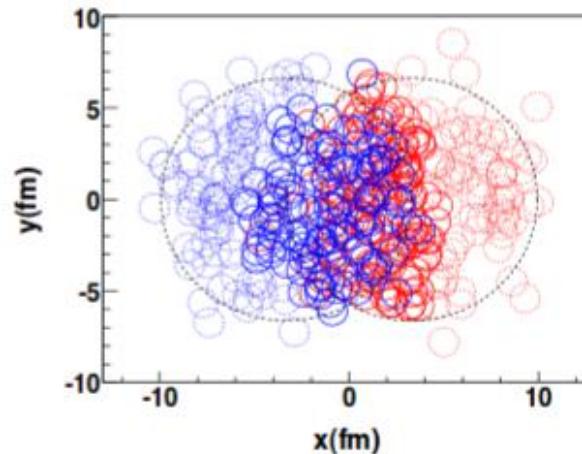


Trangular flow

Non-vanished triangular flow [PHENIX, PRL107, 252301(2011)]

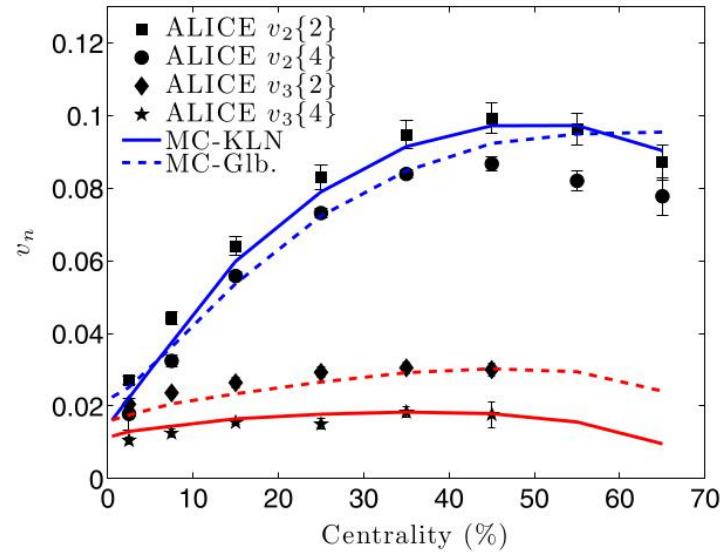


Initial fluctuation
[MC Glauber
PHOBOS,
arXiv:0805.4411]



MC-Glb and MC-KLN

Initial conditons: MC-Glauber or MC-KLN model



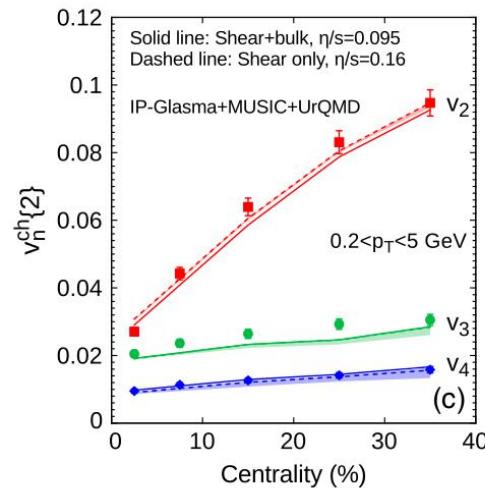
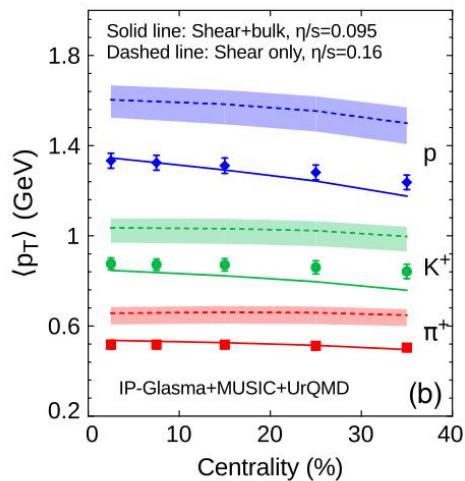
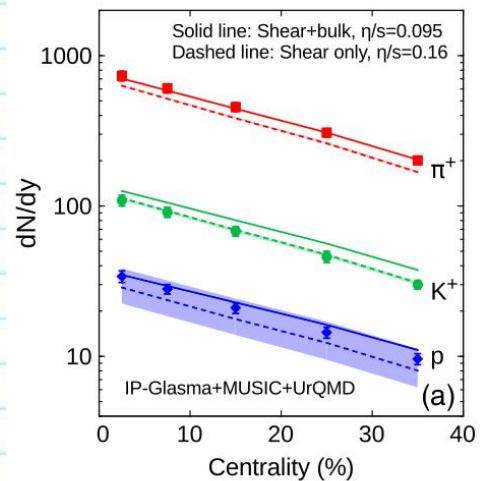
Fail to reproduce the data [Z. Qiu, PLB707,151(2012)]

State-of-the-art initial models:

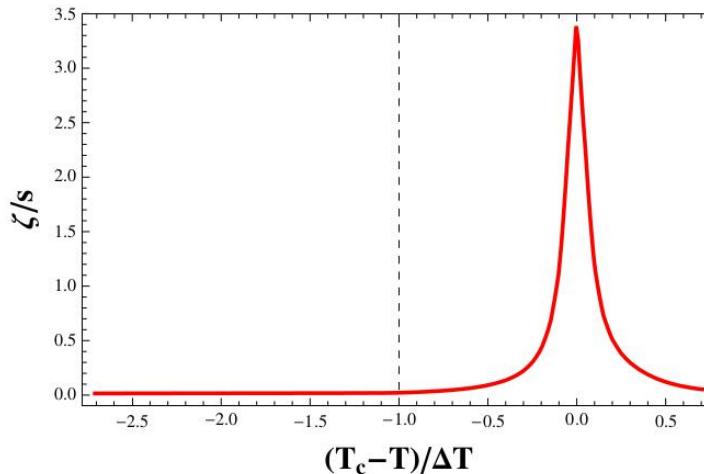
- IP-glasma [C. Gale, PRL110, 012302(2013)]
- TRENTo [J. Moreland, PRC92, 011901(2015)]

Bulk viscosity

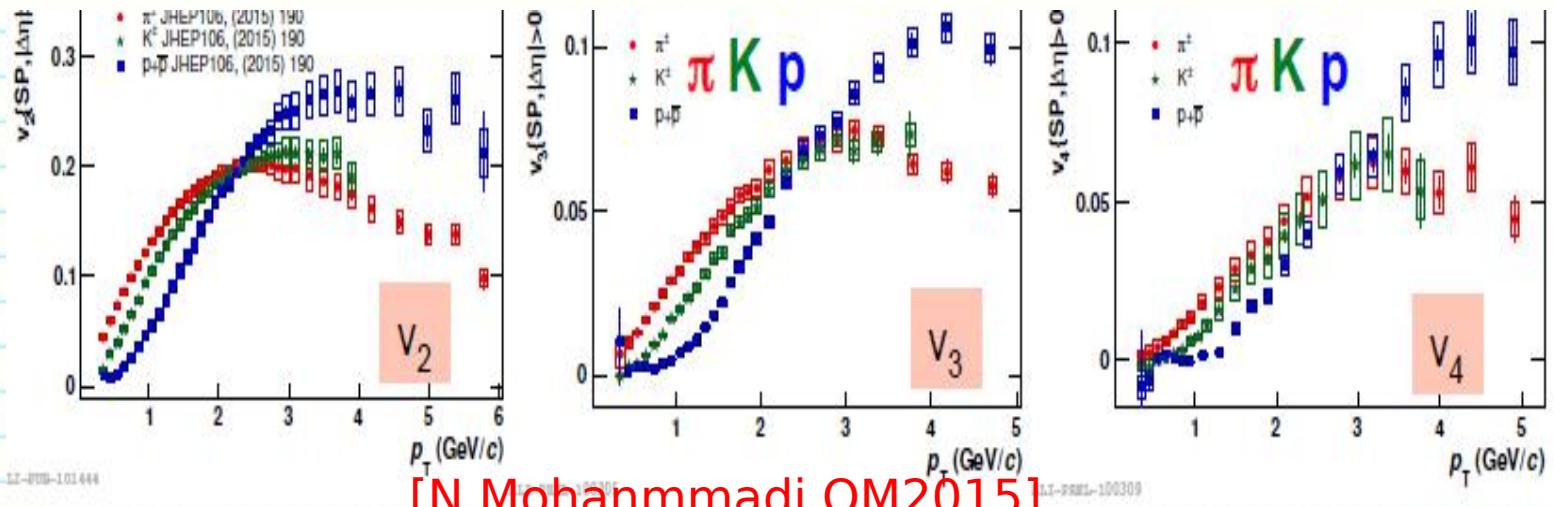
Importance of the bulk viscosity [S. Ryu,et.al, PRL115,132301(2015)]



Bulk viscosity near QCD critical point [A. Monnai, arXiv:1606.00771]



High-order flow harmonics of identified hadrons in 2.76A TeV Pb+Pb collisions



Reference:

HJX, Zuopeng Li, **Huichao Song**, PRC93, 064905(2016)
8/24/2016

Improvement

1. AMPT Initial conditions

-fluctuations of partons in momentum & position space

$$\epsilon(x, y) = K \sum_i \frac{p_i \cdot U_0}{2\pi\sigma^2\tau_0\Delta\eta_s} \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma^2}\right),$$

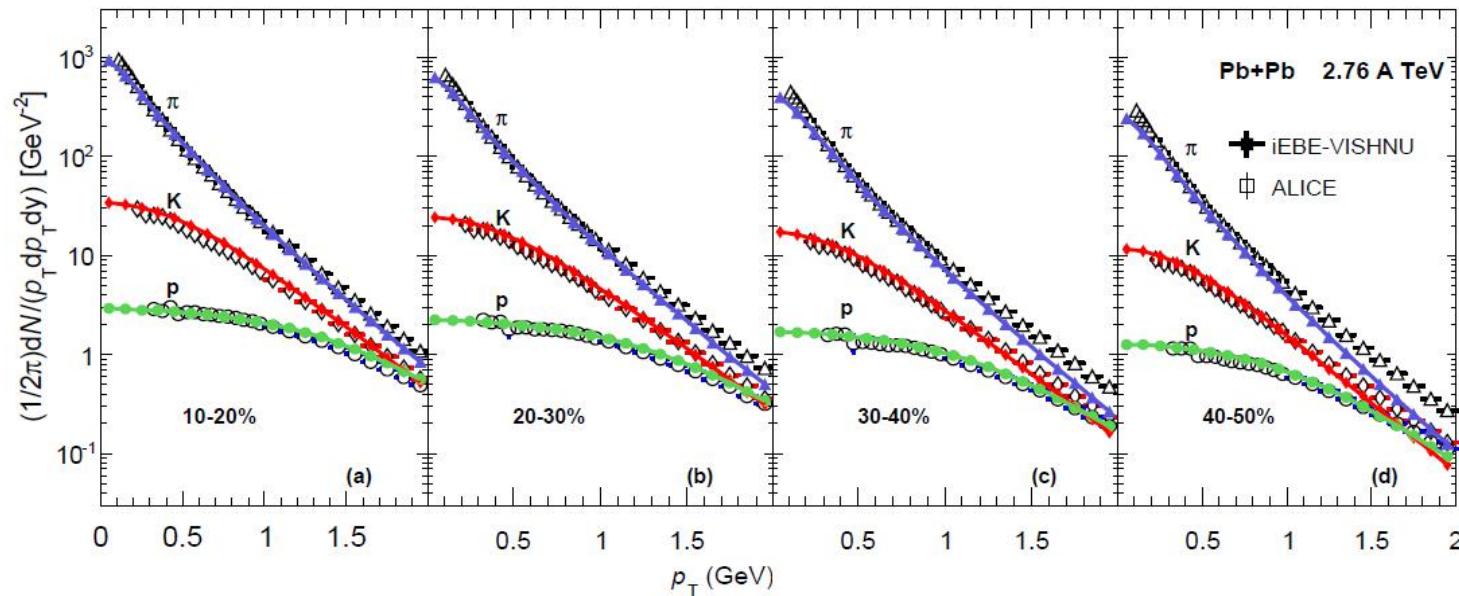
2. Flow calculations

Q-cumulants method [A. Bilandzic, et.al., PRC83, 044913]

$$Q_n \equiv \sum_{i=1}^M e^{in\phi_i}, \quad \langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}.$$

Comparison

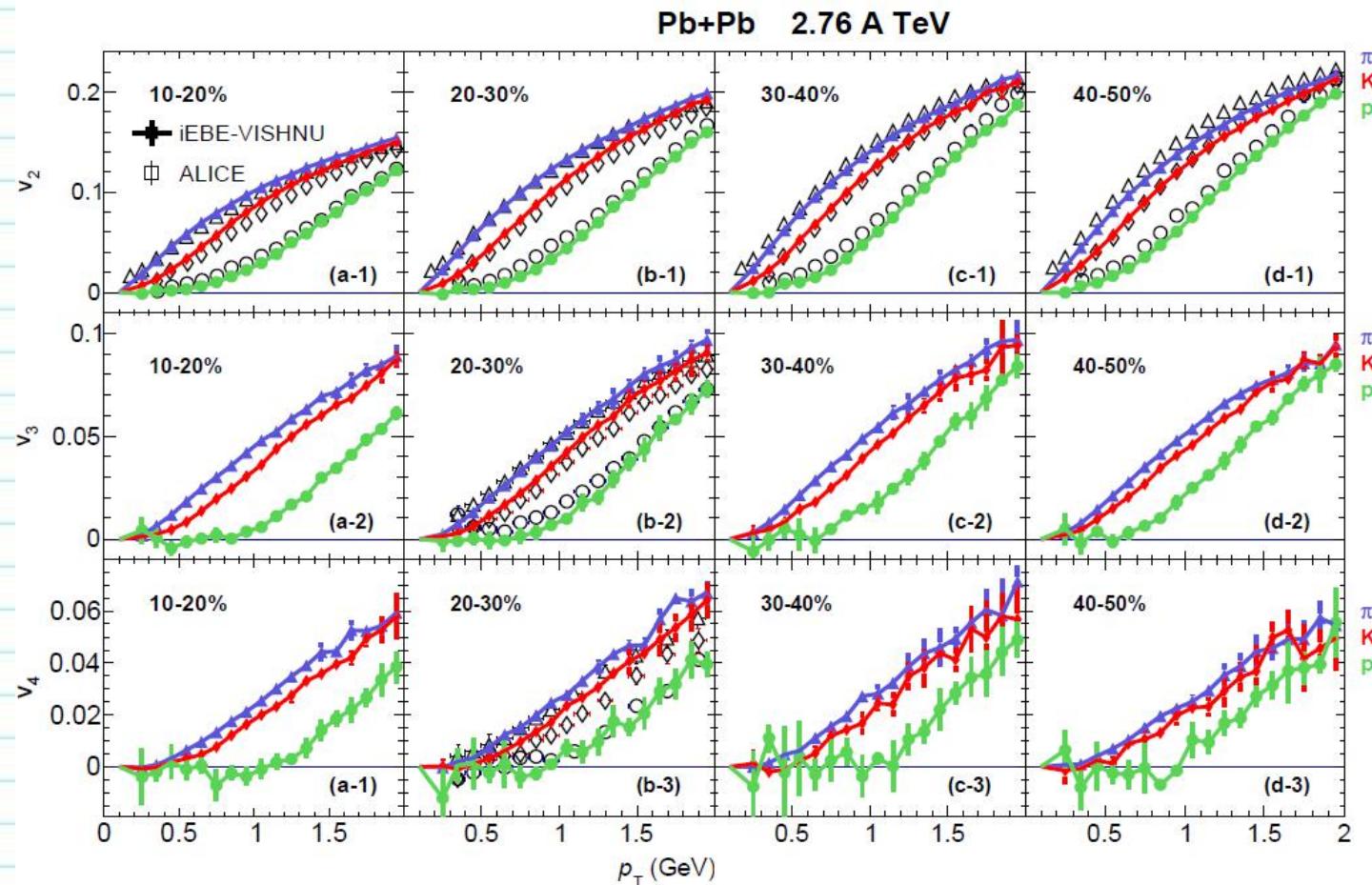
pT spectra



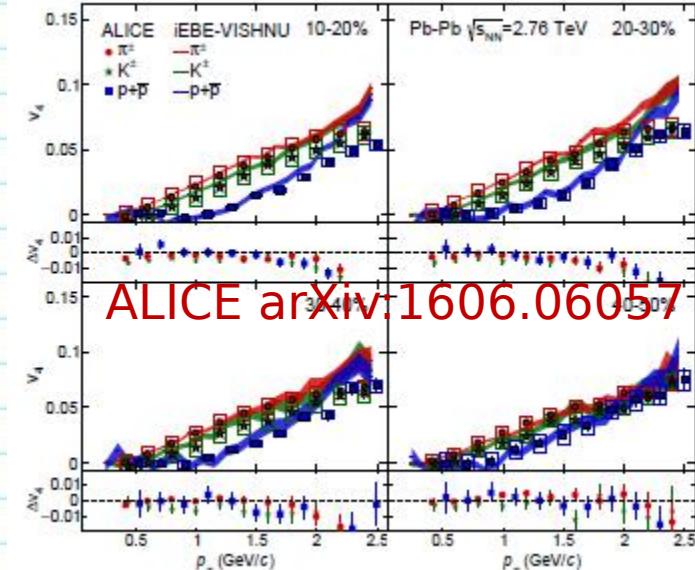
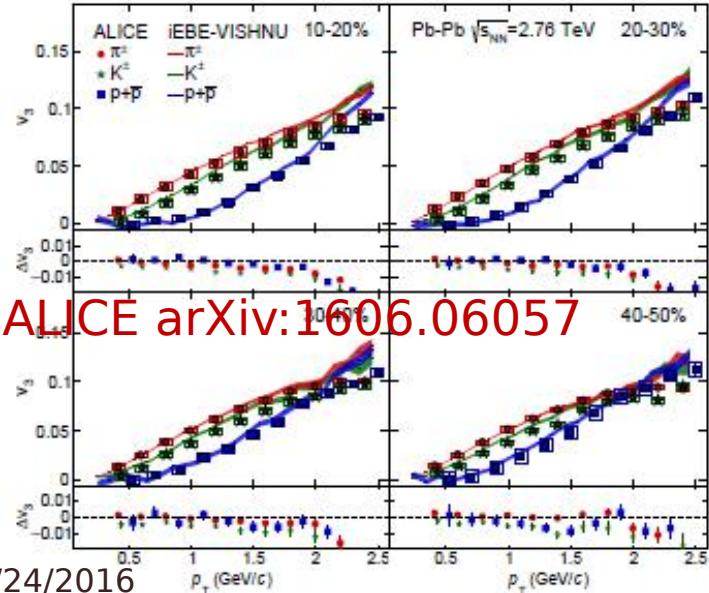
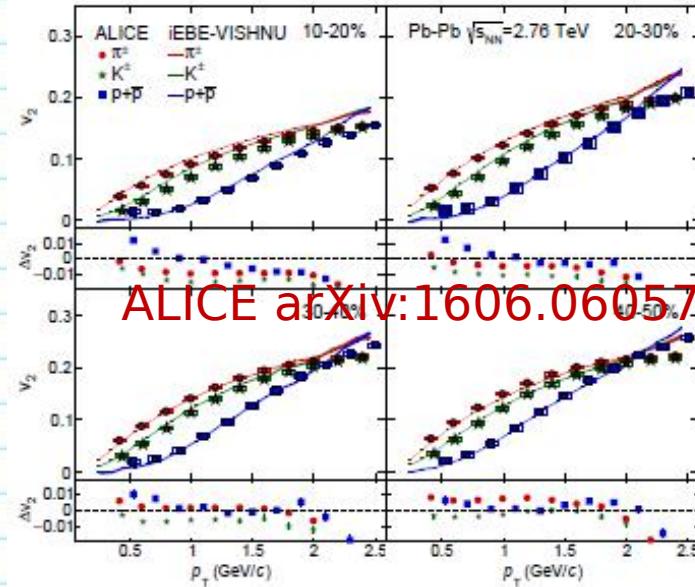
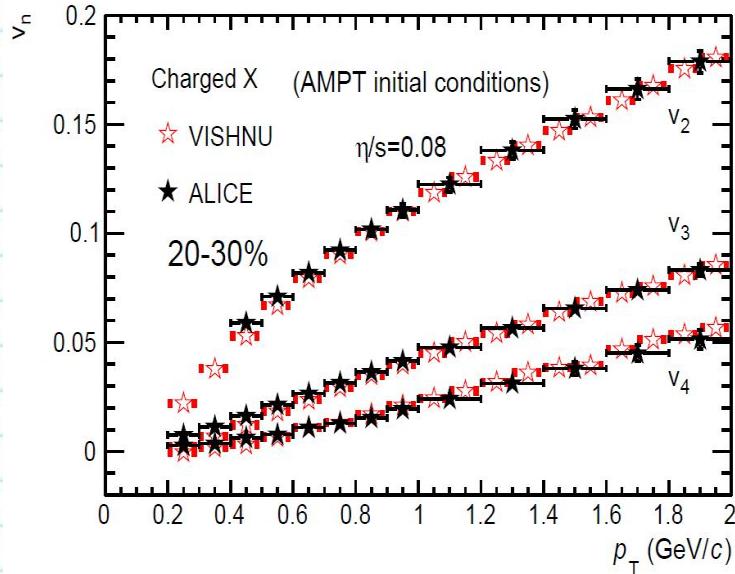
Parameters: $\tau_0 = 0.4 \text{ fm}/c$, $\eta/s = 0.08$,
 $T_{\text{sw}} = 165 \text{ MeV}$,
S95P-PCE EOS

Comparison

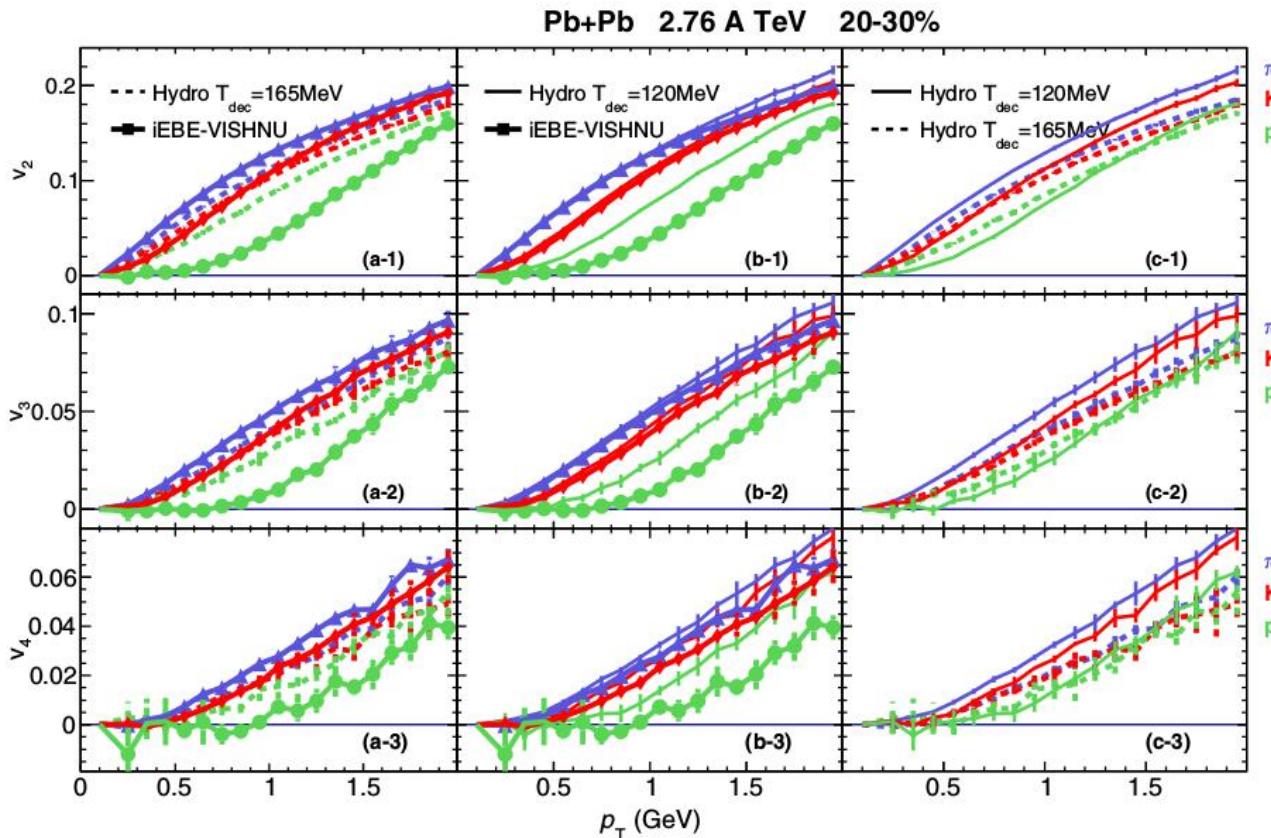
Flow harmonic of identified hadrons



Comparison



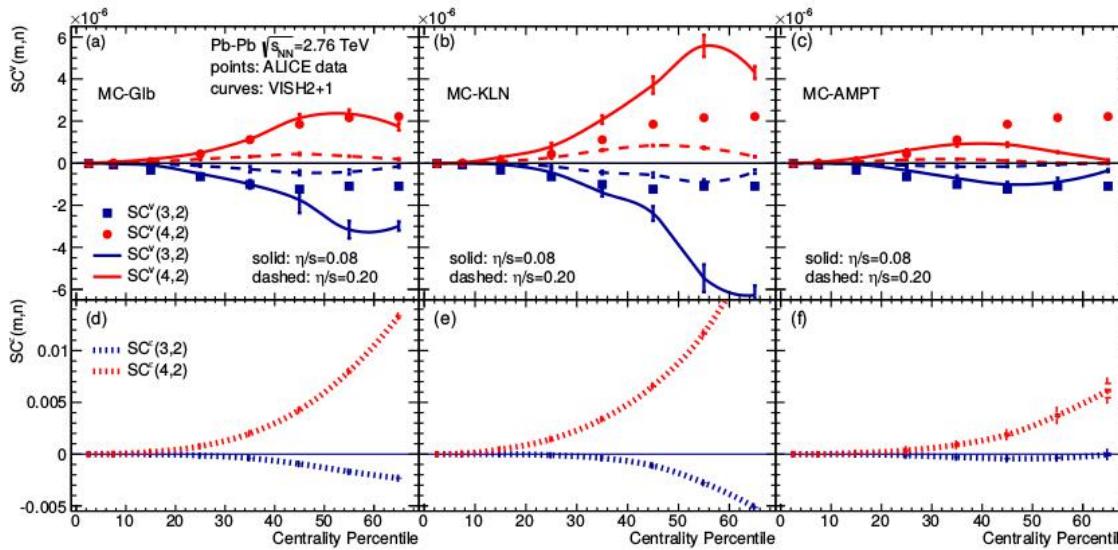
Mass splitting



Three comparison runs:

1. $T_{sw} = 165\text{MeV}$ with full UrQMD afterburner
2. $T_{sw} = 165\text{ MeV}$ with UrQMD decay only mode
3. $T_{sw} = 120\text{MeV}$ with UrQMD decay only mode

V_m-V_n correlations



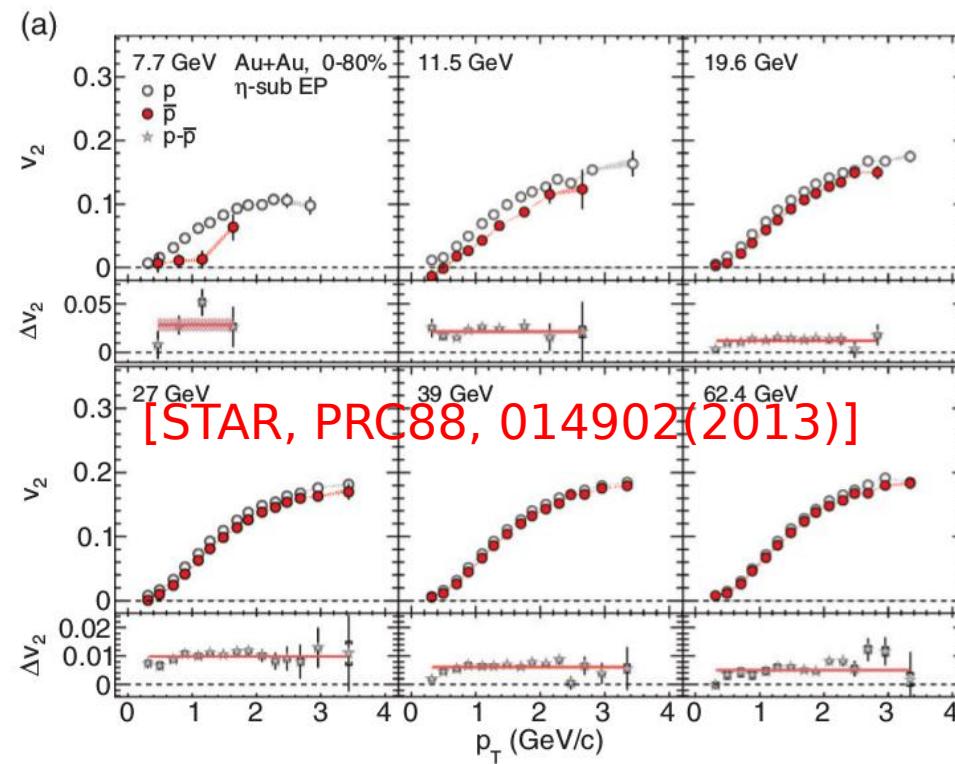
[Zhu, Zhou, Xu, Song arXiv:1608.05305]

Symmetric 2-harmonic-4-particle Cumulants (or Standard candles)

$$\begin{aligned}
 & \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle_c \\
 &= \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle\rangle \\
 &\quad - \langle\langle \cos[m(\varphi_1 - \varphi_2)] \rangle\rangle \langle\langle \cos[n(\varphi_1 - \varphi_2)] \rangle\rangle \\
 &= \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle
 \end{aligned}$$

[X. Zhu's talk 25/08 分会3 9:00am]
8/24/2016

Baryon diffusion in relativistic heavy ion collisions



Reference:

8/24/2016 HJX, Hengfeng Huang, **Huichao Song**, in preparation

Baryon diffusion

We consider the hydrodynamic equation

$$\partial_{;\mu} T^{\mu\nu} = 0, \quad (6)$$

$$\partial_{;\mu} j^\mu = 0, \quad (7)$$

where

$$T^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi) \Delta^{\mu\nu} + \pi^{\mu\nu}, \quad (8)$$

$$j^\mu = n u^\mu + q^\mu, \quad (9)$$

with ϵ , P , n and u^μ are energy density, pressure, particle density and flow velocities of fluid cells. For the approximation of first order in Knudsen and inverse Reynolds numbers, the equation of motion for bluk pressure Π , particle-diffusion current q^μ and shear-stress tensor $\pi^{\mu\nu}$ reads,

$$\tau_\Pi \dot{\Pi} + \Pi = -\xi \theta + \mathcal{J}, \quad (10)$$

$$\tau_q \dot{q}^{\langle\mu\rangle} + q^\mu = \kappa \nabla^{;\mu} \alpha + \mathcal{J}^\mu, \quad (11)$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\langle\mu\nu\rangle} = 2\eta \sigma^{\mu\nu} + \mathcal{J}^{\mu\nu}, \quad (12)$$

with $\tau_\Pi, \tau_q, \tau_\pi$ are the relaxation time and ξ, κ, η are the transport coefficients. Here $\alpha = \mu/T$ and $\beta = 1/T$ with μ and T are chemical potential and temperature. We foucs on ultrarelativistic limit and the bluk pressure is zero. Then in the Grad's 14-moment approximation, we have

$$\mathcal{J}^\mu / \tau_q = -q^\mu \theta - \frac{3}{5} q_\nu \sigma^{\mu\nu} + \frac{\beta}{20} \Delta^{\mu\nu} \nabla_{;\lambda} \pi_\nu^\lambda - \frac{\beta}{20} \pi^{\mu\nu} \nabla_{;\nu} \alpha - \frac{1}{\tau_q} q_\nu \omega^{\nu\mu}, \quad (13)$$

$$\mathcal{J}^{\mu\nu} / \tau_\pi = -\frac{4}{3} \pi^{\mu\nu} \theta - \frac{10}{7} \pi^{\lambda\langle\mu} \sigma_{\lambda}^{\nu\rangle} + \frac{2}{\tau_\pi} \pi_\lambda^{\langle\mu} \omega^{\nu\rangle\lambda}. \quad (14)$$

Baryon diffusion in VISHNU

Partice-diffusion

$$\partial_\tau q^\tau + \partial_x(v_x q^\tau) + \partial_y(v_y q^\tau) = Q^\tau, \quad (148)$$

$$\partial_\tau q^x + \partial_x(v_x q^x) + \partial_y(v_y q^x) = Q^x, \quad (149)$$

$$\partial_\tau q^y + \partial_x(v_x q^y) + \partial_y(v_y q^y) = Q^y, \quad (150)$$

with

$$\begin{aligned} Q^\tau &= -\frac{1}{\tau_q u^\tau} (q^\tau - \partial^\tau \alpha + u^\tau D\alpha) - q_\nu D u^\nu - \frac{q^\tau \theta}{u^\tau} - \frac{3}{5} \frac{q_\nu \sigma^{\tau\nu}}{u^\tau} + q^\tau (\partial_x v_x + \partial_y v_y) \\ &= -\frac{1}{\tau_q u^\tau} (q^\tau - \partial_\tau \alpha + u^\tau D\alpha) - (q^\tau D u^\tau - q^x D u^x - q^y D u^y) - \frac{q^\tau \theta}{u^\tau} \\ &\quad - \frac{3}{5} \frac{q^\tau \sigma^{\tau\tau} - q^x \sigma^{\tau x} - q^y \sigma^{\tau y}}{u^\tau} + q^\tau (\partial_x v_x + \partial_y v_y), \end{aligned} \quad (151)$$

$$\begin{aligned} Q^x &= -\frac{1}{\tau_q u^\tau} (q^x - \partial^x \alpha + u^x D\alpha) - v_x q_\nu D u^\nu - \frac{q^x \theta}{u^\tau} - \frac{3}{5} \frac{q_\nu \sigma^{x\nu}}{u^\tau} + q^x (\partial_x v_x + \partial_y v_y) \\ &= -\frac{1}{\tau_q u^\tau} (q^x + \partial_x \alpha + u^x D\alpha) - v_x (q^\tau D u^\tau - q^x D u^x - q^y D u^y) - \frac{q^x \theta}{u^\tau} \\ &\quad - \frac{3}{5} \frac{q^\tau \sigma^{\tau x} - q^x \sigma^{xx} - q^y \sigma^{xy}}{u^\tau} + q^x (\partial_x v_x + \partial_y v_y), \end{aligned} \quad (152)$$

$$\begin{aligned} Q^y &= -\frac{1}{\tau_q u^\tau} (q^y - \partial^y \alpha + u^y D\alpha) - v_y q_\nu D u^\nu - \frac{q^y \theta}{u^\tau} - \frac{3}{5} \frac{q_\nu \sigma^{y\nu}}{u^\tau} + q^y (\partial_x v_x + \partial_y v_y) \\ &= -\frac{1}{\tau_q u^\tau} (q^y + \partial_y \alpha + u^y D\alpha) - v_y (q^\tau D u^\tau - q^x D u^x - q^y D u^y) - \frac{q^y \theta}{u^\tau} \\ &\quad - \frac{3}{5} \frac{q^\tau \sigma^{\tau y} - q^x \sigma^{xy} - q^y \sigma^{yy}}{u^\tau} + q^y (\partial_x v_x + \partial_y v_y). \end{aligned} \quad (153)$$

Setup

Transport coefficients

$$\tau_q = \ln 2 / 2\pi \quad [\text{M. Natsuume, PRD77(2008)}]$$
$$\kappa T/s = 0.001 \quad [\text{A. Monnai, PRC86(2012)}]$$

Initial Baryon density distribution

$$n(x,y) = \text{norm} * s(x,y)$$

Equation of state

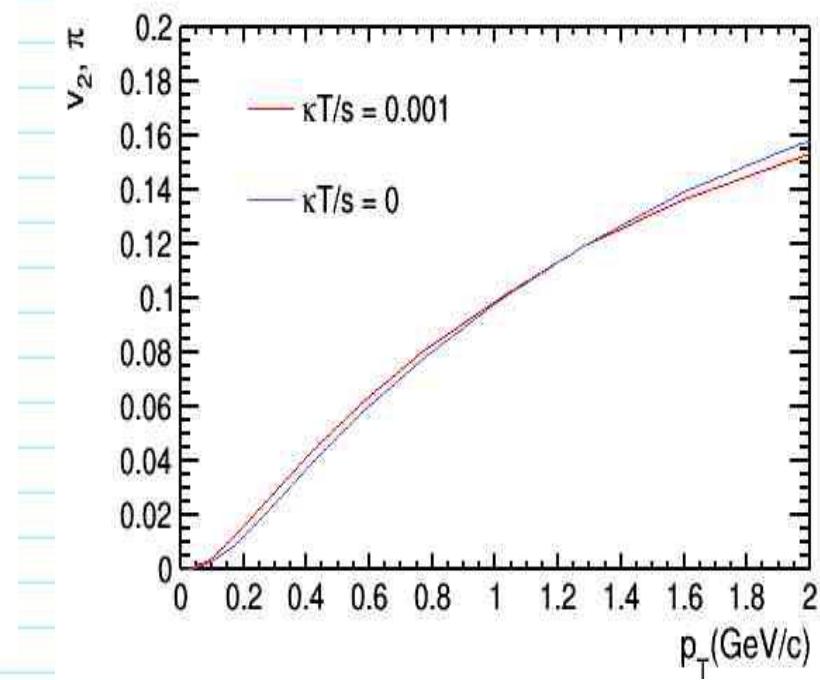
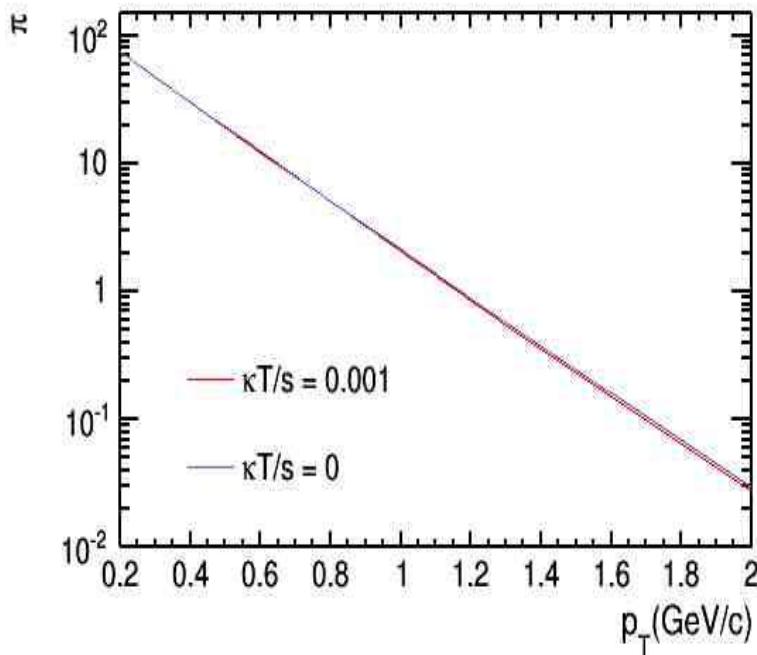
$$E = E(n,T); P = P(n;T); s = s(n;T) \quad [\text{P. Huovinen}]$$

Freeze-out hypersurface

$$T = T_{\text{dec}} = 135 \text{ MeV}; E_{\text{dec}} \text{ isn't a constant}$$

Points

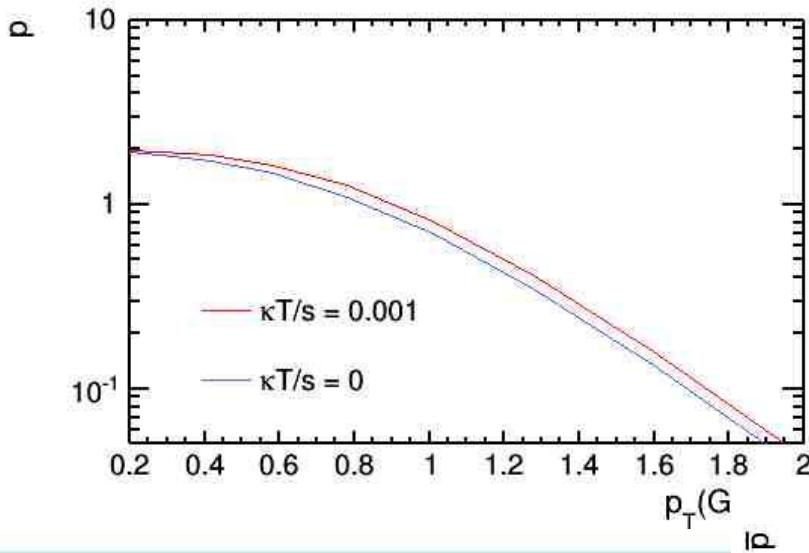
Preliminary



Effect of Baryon diffusion on pions are very small

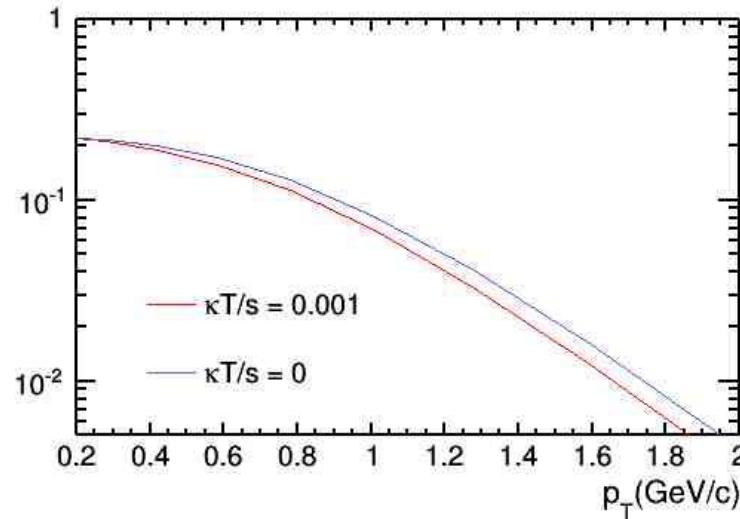
Proton spectra

Preliminary



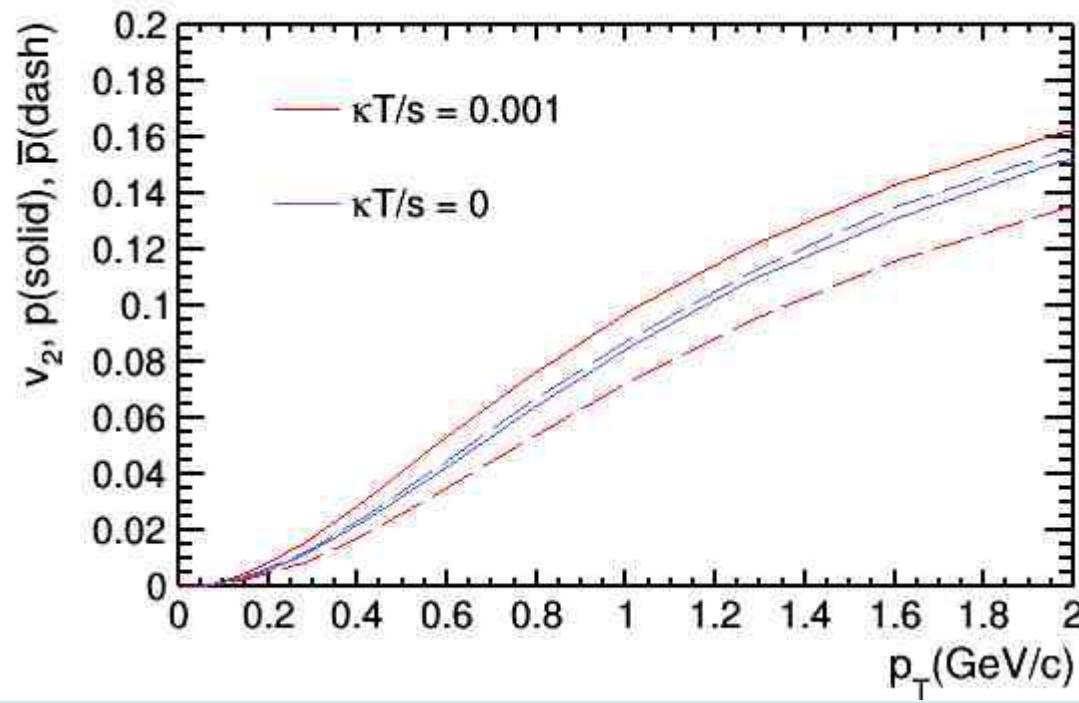
Extract the baryon chemical potential from the multiplicity ratio between proton and anti-proton

Baryon diffusion increase the proton multiplicity, but decrease the anti-proton multiplicity



Proton v2

Preliminary



Baryon diffusion increase the v2 difference between proton and anti-proton

Summary

1. Using **iEBE-VISHNU** hybrid model with the AMPT initial conditions, we investigate the **higher order flow harmonics** of identified hadrons in 2.76A TeV Pb+Pb collisions:
 - $v_3(p_T)$ and $v_4(p_T)$ present similar mass orderings among pion, kaon and proton as the v_2 mass ordering.
 - iEBE-VISHNU calculations generally describe the data below 2 GeV.
2. We study the **baryon diffusion** in viscous QCD matter with high baryon density:
 - Effect of Baryon diffusion on light mesons is very small
 - Baryon diffusion increase the v_2 difference between proton and anti-proton