The effect of longitudinal fluctuation in event-by-event (3+1)D hydrodynamics

LongGang Pang

With XinNian Wang and Qun Wang
LBNL & USTC
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- Why fluctuating initial condition and E-By-E hydrodynamics?
- AMPT initial condition for 3+1D hydrodynamic simulation.
- Spectra and elliptic flow at RHIC and LHC
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- SUMMARY
Collision geometry and harmonic flow in relativistic heavy ion collisions.

**Smooth and fluctuating initial condition**

\[
\frac{dN}{dYp_Tdp_Td\phi} = \frac{g_s}{(2\pi)^3} \int \sum p^\mu d\Sigma_\mu \frac{1}{\exp((p \cdot u - \mu)/T_{FO})} \pm 1
\]

\[
= N_0 (1 + 2 \sum_{i=1}^{\infty} v_n \cos(n(\phi - \Psi_n)))
\]
The transverse distribution in fluc ini can be decomposed in different shapes.

- $v_2$ and $v_3$ have strong linear response to $\varepsilon_2$ and $\varepsilon_3$.
- High order harmonic flows do not.
- For non central collisions, $v_4$, $v_5$ may also depend on $\varepsilon_2^2$, $\varepsilon_2\varepsilon_3$. 

Zhi Qiu, U. Heinz, Phys.Rev. C84 (2011) 024911
M. Luzum, Phys.Rev. C85 (2012) 024908
The recent experimental data for $v_n$ and di-hadron correlation

Higher order harmonic flows and di-hadron correlation can only be studied with fluctuating initial condition in E-By-E simulation. (Hydro, URQMD, AMPT, BAMPS . . .)

Fluctuating initial condition has important effect on $p_T$ spectra and $v_2$. (shown latter)
AMPT initial condition

**Hijing**

- energy in
- excited strings and minijet partons
- fragment into partons
- nucleon spectators
- Do Nothing

**ZPC** (Zhang's Parton Cascade)

- till tau0 (thermalization time)

- Generate initial energy density and flow velocity from cascaded partons

**3+1D HYDRO evolution till freezeout**

**Resonance Decay**

(Extended from Kolb's azhydro)
Get $T^{\mu \nu}$ from cascaded partons

$$T^{\mu \nu} = K \sum_i \frac{p_i^\mu p_i^\nu}{p_i^\tau} f$$

$$f = \frac{1}{\tau_0 \sqrt{2\pi \sigma_s^2 \eta_s^2 2\pi \sigma_r^2}} \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma_r^2} - \frac{(\eta_s - \eta_{si})^2}{2\sigma_{\eta_s}^2}\right)$$

We assumed local thermalization and solve $e$ and $u^\mu$ from $T^{\mu \nu}$.

$K$ and $\tau_0$ are got from fitting the multiplicity of charged hadrons for central collisions.

$K = 1.45$ and $\tau_0 = 0.4$ fm for RHIC

$K = 1.6$ and $\tau_0 = 0.2$ fm for LHC

Longitudinal fluctuation and initial flow velocity are introduced by cascaded partons.
Initial state fluctuation

AMPT: Energy density and flow velocity fluctuation
- Mini-jet partons from binary collisions.
- Fragmentation and melting of strings.
- Parton cascade.

Other fluctuating initial conditions
- MC Glauber and MC KLN: T.Hirano, Y.Nara
- URQMD: H.Petersen, M.Bleicher, GuangYou Qin
- EPOS/NEXUS/NeXSPheRIO: K.Werner, H.J.Drescher, et al
- IP-Glasma: B.Schenke
Other fluctuations

Fluctuations that we did not consider

- **Hydrodynamic fluctuation.**
  J.I. Kapusta, B. Müller, M. Stephanov, Phys.Rev. C85 (2012) 054906

- **Turbulents by jet medium interaction.**
  poster by Koichi and Hirano.

- **Thermal fluctuation.**
  P. Kovtun, G.D. Moore, P. Romatschke, Phys.Rev. D84 (2011) 025006
Transverse distribution

MC Glauber initial condition

$$e(x, y, \eta_s) = H(\eta_s) * K * (\alpha n_{bc} + (1 - \alpha) n_{wn}).$$

AMPT initial condition

Get $T^{\mu\nu}$ from cascaded partons 4 momentum and spacial distribution.
Longitudinal distribution

Tube like longitudinal distribution

\[ H(\eta_s) = \exp\left(\frac{(|\eta_s| - w/2)^2}{\sigma_w^2}\right) \]

- \( w = 5.9 \)
- \( \sigma_w = 0.4 \)

AMPT partons \( \eta_s \) distribution

AuAu 200 GeV/n, 30-40\%, \( t_{\text{large}} = 50.2 \text{fm} \)
Hydrodynamic evolution for AMPT initial condition
Hydrodynamic evolution for AMPT initial condition

Transverse plane

The multiarmons squeezed out by hot spots may play an important role in understanding $v_n$. 
Hydrodynamic evolution for AMPT initial condition

Reaction plane
(RHIC) Centrality dependence of multiplicity and $p_T$ spectra

- 3+1D viscous hydro will give a wider shoulder at central rapidity. Bjorn, Phys. Rev. C 85, 024901 (2012)  Piotr, Phys. Rev. C 85, 034901 (2012)
- We did not consider net baryon density at large rapidity yet.
The Chemical Equilibrated EOS (s95p-v1) underestimated proton production.
Partial Chemical Equilibrated EOS will fix this at RHIC energy.
PCE EOS fails to describe LHC results.
(RHIC) Calculate $v_2$ from Participant Plane (PP) and Event Plane (EP)

\[ v_2 = \frac{\int \cos(2(\phi - \Psi_n)) \frac{dN}{dY d\phi d_pT} dN}{\int \frac{dN}{dY d\phi d_pT} dN} \]  

\[ \Psi_n = \frac{1}{n} \arctan \frac{\langle r \sin(n \phi_r) \rangle}{\langle r \cos(n \phi_r) \rangle} + \pi \]  

\[ \Psi_n = \frac{1}{n} \arctan \frac{\langle pT \sin(n \phi_p) \rangle}{\langle pT \cos(n \phi_p) \rangle} \]  

These two definitions should give out similar results.

We use the continues particle spectra to calculate EP, no resolution problem.
Elliptic flow for EP, PP method compared with Exp.

The effect of longitudinal fluctuation in event-by-event (3+1)D hydrodynamics.
(LHC) The elliptic flow for identified particles.
The elliptic flow for identified particles.

Figure from AIP Conf.Proc. 1441 (2012) 766-770 by Ulrich W. Heinz, Chun Shen and Huichao Song.

- Pure hydro has the proton $v_2$ puzzle for central collisions.
- Viscous hydro + URQMD may give a better fit for proton $v_2$ at central collisions.
Fluctuation effect

\[ \frac{1}{2\pi} \frac{d^2N}{dYdp_T} \left( \frac{\text{GeV/c}}{\text{c}} \right)^2 \]

\( \pi^+ \) for AuAu 200 GeV/nucleon, 30-40%

- E-By-E
- One Shot Tube
- E-By-E Tube

Longitudinal fluctuation

Transverse fluctuation
Effect of transverse energy density fluctuation

Fast isotropic expansion of each hot spot at early stage in transverse plane

- R. Chatterjee, H. Holopainen, T. Renk, and K. J. Eskola, Phys. Rev. C 83 (2011) 054908
- B. Schenke, S. Jeon, C. Gale, Phys. Rev. Lett. 106, 042301
- Z. Qiu and U. W. Heinz, Phys. Rev. C 84, 024911
- Also seen in our AMPT initial condition

Harder $p_T$ spectra and smaller $v_2$ at large $p_T$!
Effect of longitudinal fluctuation

Observed: Elliptic flow is suppressed due to longitudinal fluctuation.

Understanding:

- Non zero pressure gradient along $\eta_s$ at central rapidity.
- Faster expansion along $\eta_s$ direction for each hot spot.
The effect of longitudinal fluctuation on di-hadron correlation

\[ C'12 = \frac{\langle N_t N_a \rangle_s}{\langle N_t N_a \rangle_m} \]  

(AuAu 200 GeV/n Centrality 30 – 40%, 2 GeV/c \( \leq p_{trig}^{trig}, p_{assoc}^{assoc} \leq 3 \) GeV/c.

Without LF, di-hadron correlation is constant along rapidity direction
We studied the E-by-E hydrodynamic simulation with AMPT initial condition. The E-by-E simulation gives good agreement with experiment data for spectra and elliptic flow.

Fluctuation has important effect on $p_T$ spectra and $v_2$.

- **TF**: Fast isotropic expansion of each hotspot in transverse plane at early stage.
- **LF**: Bigger longitudinal pressure gradient and expansion rate.

LF introduced by AMPT have important effect on two particle correlation.
Thanks!