Longitudinal Expansion of Hot QCD Matter in Relativistic Viscous Hydrodynamic Models

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AM and T. Hirano, arXiv:1102.5053 [nucl-th]
Introduction

- Quark-gluon plasma (QGP): the color-deconfined matter

Relativistic heavy ion collisions to realize the extreme state

\[ \sqrt{s_{NN}} = 200 \text{(GeV)} \quad \text{at RHIC} \]
\[ \sqrt{s_{NN}} = 2.76, 5.5 \text{(TeV)} \quad \text{at LHC} \]

Quantification of the space-time evolution of the QGP consistent for both RHIC and LHC

Determination of its properties from experimental data (e.g. transport coefficients)

In this work we focus on viscous hydro and color glass condensate
Introduction

- Modeling a high-energy heavy ion collision

Color glass condensate (CGC)
Description of saturated gluons in the nuclei before a collision ($\tau < 0$ fm/c)

Relativistic hydrodynamics
Description of collective motion of the QGP ($\tau \sim 1$-10 fm/c)
First Results from LHC

- Mid-rapidity multiplicity

**ALICE data (most central 0-5%)**

\[
\frac{dN_{\text{ch}}}{d\eta} = 1584 \pm 4(\text{stat}) \pm 76(\text{phys})
\]

CGC; fit to RHIC data but no longer valid at LHC?

K. Aamodt *et al.* PRL105 252301
CGC in Heavy Ion Collisions

- Saturation scale in MC-KLN model
  \[ Q_{s,A}^2(x; x_\perp) = 2 \text{ GeV}^2 \frac{T_A(x_\perp)}{1.53 \text{ fm}^{-2}} \left( \frac{0.01}{x} \right) \]

  Fixed via **direct** comparison with data

  \[ \frac{dN_{ch}}{d\eta} \text{ gets steeper with increasing } \lambda; \text{ RHIC data suggest } \lambda \sim 0.28 \]

- CGC + Hydrodynamic Model

  Initial condition
  From the CGC \[ \rightarrow \]

  Hydrodynamic evolution \[ \rightarrow \]

  Observed particle distribution \[ \rightarrow \]

  a missing piece!

  Need to estimate the hydrodynamic effects with

  (i) **non-boost invariant** expansion

  (ii) **viscous** corrections

  \[ \text{There are few numerical codes which can deal with both} \]
Hydrodynamic Model

- Full 2\textsuperscript{nd} order viscous hydrodynamic equations

\[ \partial_{\mu} T^{\mu\nu} = 0 \]

Energy-momentum conservation

**EoM for bulk pressure**

\[ D\Pi = \frac{1}{\tau_{\Pi}} \left( -\Pi - \zeta_{\Pi\Pi} \frac{1}{T} \nabla_{\mu} u^\mu - \zeta_{\Pi\delta} \delta D \frac{1}{T} + \chi_{\Pi\Pi}^{b} \Pi D \frac{1}{T} + \chi_{\Pi\Pi}^{c} \Pi \nabla_{\mu} u^\mu + \chi_{\Pi\pi}^{c} \nabla_{\mu} u^\mu \right) \]

**EoM for shear tensor**

\[ D\pi^{\mu\nu} = \frac{1}{\tau_{\pi}} \left( -\pi^{\mu\nu} + 2\eta \nabla^{\langle \mu} u^{\nu \rangle} + \chi_{\pi\pi}^{b} \pi^{\mu\nu} D \frac{1}{T} + \chi_{\pi\pi}^{c} \pi^{\mu\nu} \nabla_{\rho} u^{\rho} + \chi_{\pi\pi}^{d} \pi^{\rho} \nabla^{\langle \mu} u_{\rho}^{\nu \rangle} + \chi_{\Pi\Pi}^{c} \Pi \nabla^{\langle \mu} u_{\nu \rangle} \right) \]

FIRST time the full equations are estimated

\[ D = u^{\mu} \partial_{\mu} \]

\[ \nabla^{\mu} = \Delta^{\mu\nu} \partial_{\nu} \]

Solution in (1+1)-D relativistic coordinates (= no transverse flow) with piecewise parabolic iterative method

Numerically novel approach
Model Input for Hydro

- **Equation of state and transport coefficients**

<table>
<thead>
<tr>
<th>Equation of State:</th>
<th>Lattice QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear viscosity:</td>
<td>$\eta = s/4\pi$</td>
</tr>
<tr>
<td>Bulk viscosity:</td>
<td>$\zeta_{\text{eff}} = (5/2)[(1/3) - c_s^2]\eta$</td>
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</tbody>
</table>

- **Initial conditions**

  | Initial flow:     | Bjorken flow (i.e. flow rapidity $Y_f = \eta_s$) |
  | Energy distribution: | CGC with $p_T$ cut $0.1 < p_T < 3.0$ GeV |
  | Dissipative currents: | $\delta T^{\mu\nu} = 0$ |
  | Initial time:     | $\tau = 1$ fm/c |
Results

- CGC initial distributions + (1+1)D viscous hydro

![Graphs showing results for RHIC and LHC](image)

- Outward entropy flux: Flattening
- Entropy production: Enhancement

\[ \frac{dN_{\text{ch}}^{\text{hydro}}}{dy} \approx \frac{2}{3} \times \frac{1}{3.6} \times \frac{dS}{dY_f} \]

If the true \( \lambda \) is larger at RHIC, it enhances \( dN/dy \) at LHC;
A candidate factor for explaining the “gap” at LHC?
Results

- Deviation from boost-invariant flow

The systems are far from boost invariant at RHIC and LHC

Ideal flow $\approx$ viscous flow due to competition between
deceleration by suppression of overall pressure at early stage and
acceleration by entropy production at late stage
Summary and Outlook

- We solved full 2\textsuperscript{nd} order viscous hydro in (1+1)-dimensions for the “shattered” color glass condensate

Non-trivial deformation of CGC rapidity distribution due to

(i) outward entropy flux \textit{(non-boost invariant effect)}
(ii) entropy production \textit{(viscous effect)}

Viscous hydrodynamic effect may play an important role in understanding the seemingly large multiplicity at LHC

- Future prospect includes:
  - Detailed analyses on parameter dependences
  - A (3+1)-dimensional viscous hydrodynamic model, etc...

\textit{AM & T. Hirano, in preparation}
The End

- Thank you for listening!
- Website: http://tkynt2.phys.s.u-tokyo.ac.jp/~monnai/index.html