Current Status of QGP hydro + hadron cascade approach

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Outline

- Introduction
  - Motivation
  - A short history of hybrid approaches
  - Importance of hadronic dissipation
- Hybrid approach
  - Initial condition
  - Hydrodynamic evolution
  - Hadronic afterburner
- Results
  - Default setting compared with data
  - Systematic studies on modeling
- Summary
Introduction

- Main purpose: Understanding of QCD matter in equilibrium under extreme condition (QGP)
  - Equation of state
  - Transport coefficients
- Heavy ion collisions at relativistic energies
  - Unique opportunity, but complicated dynamics
- Analysis codes play important roles in various fields
  - Cosmic microwave background: CAMB, CMBFAST, etc.
  - Elementary particle reactions: PYTHIA, HERWIG, etc.
- Development of analysis code in relativistic heavy ion collision toward understanding of the QGP
Introduction (contd.)

- Hydrodynamics describes dynamics of matter under \textit{local} thermal equilibrium
  - Hydrodynamics can be applicable in the intermediate stage.
  - Need modeling before and after hydro regime
    - Initial conditions
    - Freezeout

- Detailed and systematic analysis based on ideal hydro towards quantifying viscous effects
Hybrid Approach

Conventional hydro model

Hybrid model

hadron fluid

QGP fluid

collision axis

QGP fluid

hadron gas

collision axis

time

hadron gas

QGP fluid

time

collision axis
Short History of Hybrid Approach

- (1+1)D ideal hydro + UrQMD: Dumitru et al. (’99)
  - mean $p_T$, HBT, ...
- (2+1)D ideal hydro + RQMD: Teaney et al. (’01)
  - $v_2(p_T)$, $v_2$(cent), $v_2$(sqrt{s}), ...
- Importance of hadronic viscosity: TH and Gyulassy (’05)
- (3+1)D ideal hydro + JAM: TH et al. (’06)
- (3+1)D ideal hydro + UrQMD: Nonaka et al. (’06)
- (3+1)D ideal hydro + UrQMD: Werner et al. (’09)
  - $v_2$(eta), ...
- (2+1)D viscous hydro + UrQMD: Heinz-Song (’10)
- (2+1)D viscous hydro + UrQMD: Soltz et al. (’10)
Typical Results So Far

Large suppression in small multiplicity events

Teaney et al. (’01)  TH et al. (’07)
Typical Results So Far (contd.)

Suppression in forward and backward rapidity

Importance of hadronic viscosity

TH et al. (’05)
Typical Results So Far (contd. 2)

Mass dependence is o.k. from hydro+cascade. When mass splitting appears?

Mass ordering comes from hadronic rescattering effect. Interplay btw. radial and elliptic flows.

TH et al. (’08)
A Hybrid Approach: Initial Condition

Model*
- MC-Glauber
- MC-KLN (CGC)
- $\varepsilon_{part}$, $\varepsilon_{R.P.}$
- Centrality cut

*H.J. Drescher and Y. Nara (2007)
A Hybrid Approach: Hydrodynamics

Ideal Hydrodynamics*
- Initial time 0.6 fm/c
- Model EoS
  - lattice-based#
  - 1st order

#Lattice part: M. Cheng et al. (2008) + resonance gas (Monnai)
A Hybrid Approach: Hadronic Cascade

**Interface**
- Cooper-Frye formula at switching temperature $T_{sw} = 160$ MeV
- Resonance gas model at $T=160$ MeV

**Hadronic afterburner**
- Hadronic transport model based on kinetic theory $\rightarrow$ JAM*

*Y. Nara et al., (2000)*
Eccentricity Fluctuation

Interaction points of participants vary event by event.

→ Apparent reaction plane also varies.
→ The effect is significant for smaller system such as Cu+Cu collisions.

Adopted from D.Hofman (PHOBOS), talk at QM2006

A sample event from Monte Carlo Glauber model

See also talks by Poskanzer
Event-by-Event Eccentricity

\[
\begin{align*}
\sigma_x^2 &= \langle x^2 \rangle - \langle x \rangle^2, \\
\sigma_y^2 &= \langle y^2 \rangle - \langle y \rangle^2, \\
\sigma_{xy} &= \langle xy \rangle - \langle x \rangle \langle y \rangle. \\
\end{align*}
\]

\[
\langle \cdots \rangle = \frac{\int d^2x_\perp \cdots s_0(x_\perp)}{\int d^2x_\perp s_0(x_\perp)},
\]

\[
\varepsilon_{\text{RP}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}
\]

\[
\varepsilon_{\text{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}
\]

\[
\tan 2\Psi = \frac{\sigma_y^2 - \sigma_x^2}{2\sigma_{xy}}.
\]
Initial Condition with an Effect of Eccentricity Fluctuation

- Throw a dice to choose $b$
- Shift: ($<x>, <y>$)
- Rotation: $\Psi$

E.g.)

$N_{\text{part}}^{\text{min}} = 279$
$N_{\text{part}}^{\text{max}} = 394$

in Au+Au collisions at 0-10% centrality

Average over events

Reaction plane

Participant plane

Average over events
Eccentricity w.r.t. Participant Plane

Large fluctuation in small system such as Cu+Cu and peripheral Au+Au
Need these effects for apple-to-apple comparison
Caveat in Monte Carlo Approach

How do we consider this?

Naïve Glauber calculation:

$$\rho_{WS}(\vec{x}) = \int \delta^{(3)}(\vec{x} - \vec{x}_0) \rho_{WS}(\vec{x}_0) d^3 \vec{x}_0$$

MC-Glauber calculation:

$$\rho_{WS}(\vec{x}) \neq \rho(\vec{x}) = \int \Delta(\vec{x} - \vec{x}_0) \rho_{WS}(\vec{x}_0) d^3 x_0$$

$$\Delta(\vec{x} - \vec{x}_0) = \frac{\theta(r - |\vec{x} - \vec{x}_0|)}{V}$$

$$V = \frac{4\pi r^3}{3}, \quad r = \sqrt{\frac{\sigma_{in}^{pp}}{\pi}}$$

Finite nucleon profile
More diffused!

→ Reduction of eccentricity by ~5-10%
→ Necessity of re-tuning parameters in Woods-Saxon density
→ We have retuned parameters.

\[ R = 6.38 \text{ fm} \rightarrow 6.42 \text{ fm (Au)} \]
\[ \delta r = 0.535 \text{ fm} \rightarrow 0.44 \text{ fm (Au)} \]

Caveat in Monte Carlo Approach 2

2-component model:

\[ \frac{dS}{d^2 x_\perp} = C \left[ \frac{1 - \delta}{2} \frac{dN_{\text{part}}}{d^2 x_\perp} + \delta \frac{dN_{\text{coll}}}{d^2 x_\perp} \right] \]

Given from Monte Carlo

Interaction point (part./coll.)

Coarse grained

Interaction region

\[ r = \sqrt{\frac{\sigma_{\text{in}}}{\pi}} \sim 1.15 \text{ fm} \]

See also, Appendix in
H.-J. Drescher and Y. Nara, PRC75, 034905 (2007)
Matter Profile after Coarse-Graining

One typical central event

0.5 $\times \sigma_{\text{in}}$  \hspace{2cm} $\sigma_{\text{in}}$  \hspace{2cm} 2 $\times \sigma_{\text{in}}$

See also talks by Petersen and Holopainen
Eccentricity with Smeared Profile

~10% reduction around $N_{\text{part}} \sim 50-100$ in the default model (smearing area = $\sigma_{\text{in}}$)

How to quantify smearing area?

- Modeling of entropy production and thermalization process: CGC + Glasma?
- Open problem: Importance of understanding hydrodynamic initial conditions
Gold and Copper, Deformed?

Radius in Woods-Saxon

\[ R_0 \rightarrow R_0 (1 + \beta_2 Y_{20} + \beta_4 Y_{40}) \]

\[ \beta_2 = -0.13, \beta_4 = -0.03^* \]

Oblate Au+Au Collision

P. Filip et al., PRC 80, 054903 (2009).

Important in very central collision(?)

*P. Möller et al, At. Data Nucl. Data Table 59, 185 (1995)
Deformed Gold and Copper

Effect of deformation is seen only in very central events
Initial Condition Dependence

\[ \varepsilon_{\text{MC-KLN}} \geq \varepsilon_{\text{MC-Glauber}} \]
Steeper Transverse Profile in CGC

Closer to hard sphere than Glauber

Note: Original KLN model (not MC-KLN)
Inputs in Model Calculations

Parameters are fixed in Au+Au collisions

Glauber: \[ \frac{dS}{d^2 x_{\perp}} = C \left[ \frac{1 - \delta}{2} \frac{dN_{\text{part}}}{d^2 x_{\perp}} + \delta \frac{dN_{\text{coll}}}{d^2 x_{\perp}} \right] \]

KLN: standard parameters
Systematic Studies on Elliptic Flow

Default setting as a reference result (Red Line)

- MC-Glauber, $\varepsilon_{\text{part}}$, spherical nuclei
- Lattice-based crossover EoS
- Hadronic rescattering

1. With rescattering vs. without rescattering
2. Lattice-based crossover vs. 1st order phase transition
3. $\varepsilon_{\text{part}}$ vs. $\varepsilon_{\text{R.P.}}$
4. Glauber vs. CGC (factorized KLN)
5. Spherical vs. deformed nuclei
Comparison with Data

Note: \( v_2^2 > v_2^{\text{true}} > v_2^4 \)


Slight overshoot in peripheral region

Comparison with Data (contd.)

System size dependence

→ Overshoot also in peripheral collisions
→ Room for (tiny) QGP viscosity

PHOBOS: PRC72, 051901(R) (2005); PRL98, 242302 (2007).
**Effect of Hadronic Rescattering**

$v_2$ is slightly enhanced in peripheral collisions.

$\rightarrow$ Not yet “quenched” at hadronization

$v_2$ in central collisions is generated during the QGP
EoS Dependence

1st order phase transition mimics viscous correction? No room for QGP viscosity in the 1st order p.t. model
Effect of Eccentricity Fluctuation

Effect of fluctuation $\rightarrow$ Large in small system
Importance of eccentricity w.r.t. participant plane
Initial Condition Dependence

- Sensitive to initial models.
- Perfect fluid and CGC, compatible?
  → Need more studies on initial condition and viscosity
Effect of Deformation

Almost no effects in semi-central collisions
Small effect in central and peripheral event
Comparison with Data: $p_T$ dist.

$p_T$ distribution is output in hybrid models.

→ At work up to 2-3 GeV/c

$p_T$ Dist. in Cu+Cu Collisions

\[ \frac{1}{2\pi p_T^2} \frac{dN}{dp_T \ dy} \ (c^2/\text{GeV}^2) \]

- $\pi^+$
- $p$

Cu+Cu

0-5%
10-15% ($\times 10^{-1}$)
20-30% ($\times 10^{-2}$)
40-50% ($\times 10^{-3}$)

Cu+Cu

0-5%
10-15% ($\times 10^{-1}$)
20-30% ($\times 10^{-2}$)
40-50% ($\times 10^{-3}$)
Comparison with Data: $v_2(p_T)$

Need (tiny?) viscosity in small system (such as Cu+Cu and peripheral Au+Au collision) Not enough statistics → Stay tuned!

STAR: PRC72, 014904(2005)
Comparison with Data: PID $v_2(p_T)$

![Graphs showing comparison with data for PID $v_2(p_T)$ for Au+Au and Cu+Cu collisions.](image)
$v_2$ vs. Transverse Density

$v_2/\epsilon$ monotonically increases with transverse density even within ideal hydro QGP.

$\rightarrow$ Finite lifetime effect

$\rightarrow$ Mimics viscosity

$\rightarrow$ This should be subtracted(?)
Summary

- Importance of hadronic dissipation
- Development of a hybrid model (Ideal hydro + hadronic afterburner) toward understanding of the QGP
- Systematic analyses of elliptic flow data using the hybrid model
  - Glauber vs. CGC, $\varepsilon_{\text{part}}$ vs. $\varepsilon_{R,P}$, spherical vs. deformed, 1st order vs. crossover, ...
- Comment on $v_2/\varepsilon$
- Toward quantifying viscous corrections
Example from UrQMD

Initial State

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid using for each particle

$$\epsilon_{ct}(x, y, z) = N \exp \frac{(x - x_p)^2 + (y - y_p)^2 + (z - z_p)^2}{2\sigma^2}$$

- Event-by-event fluctuations are taken into account
- Spectators are propagated separately in the cascade

Hannah Petersen  
BNL Workshop, 28.04.10  
11
What is Elliptic Flow?
How does the system respond to spatial anisotropy?

No secondary interaction

Hydro behavior

INPUT
Spatial Anisotropy

Interaction among produced particles

OUTPUT
Momentum Anisotropy

Ollitrault ('92)
Mass Splitting $\neq$ Mass Effect

$m_p < m_\phi$ but $v_{2,p} < v_{2,\phi}$ in low $p_T$ region

$\rightarrow$ Importance of hadronic species dependent cross sections

TH et al., (’08)
Arrival at Hydrodynamic Limit

\[ \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle} \]

\[ \frac{v_2}{\varepsilon} = \frac{\text{momentum anisotropy}}{\text{spatial anisotropy}} = \frac{\text{output}}{\text{input}} = \text{response} \]

Experimental data reach hydrodynamic limit curve for the first time at RHIC.