Evolution of elliptic and triangular flow as a function of beam energy in a hybrid model

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FAIRNESS 2013
September 19, 2013
Outline

Introduction

Hybrid model

Results

Summary
First order phase transition with critical point?

QGP volume and lifetime decreases with decreasing $\sqrt{s_{NN}} \Rightarrow$ completely vanishes at some point? Any QGP at FAIR?

Beam energy scan

Flow observables $v_n$ imply collective behavior in the system $\Rightarrow$ considered as evidence of QGP

Charged hadron $v_2$, however, shows only weak collision energy dependence (no turn-off seen on this signal!).


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Hybrid model energy scan
Differential $v_2$ almost identical for all $\sqrt{s_{NN}}$.

$v_3$ more sensitive to beam energy? Generated solely by event-by-event fluctuations of the initial state, while $v_2$ is strongly affected also by collision geometry.

Can these dependencies be reproduced using a hybrid model?
Transport + hydrodynamics hybrid model

Image source: Duke University

Transport
- **Microscopic** description of the whole phase-space distribution
- **Non-equilibrium** evolution based on the Boltzmann equation
  \[ p^\mu \partial_\mu f_i(x, p) = C_i \]
- **Partonic** or **hadronic** degrees of freedom
- Phase transition?

Hydrodynamics
- **Macroscopic** description
- **Local equilibrium** is assumed
- System evolves according to conservation laws
  \[ \partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu N^\mu = 0 \]
- **Equation of state** provides the phase transition
- Before and after: **Initial conditions? Freeze-out?**
Transport + hydrodynamics hybrid model


Initial State from UrQMD\(^1\) string/hadronic cascade

- Start the hydrodynamical evolution when nuclei have passed through each other: \( t_{\text{start}} = \max\{\frac{2R_{\text{nucleus}}}{\sqrt{\gamma_{CM}^2 - 1}}, 0.5 \text{ fm}\} \).
- Energy-, momentum- and baryon number densities (3D Gaussians) are mapped onto the hydro grid
- Event-by-event fluctuations are taken into account (width of Gaussians \( \sigma = 1.0 \text{ fm} \))
- Spectators are propagated separately in the cascade

Transport + hydrodynamics hybrid model


Hydrodynamical evolution

- (3+1)D ideal hydrodynamics using SHASTA$^2$
- Equation of state$^3$:
  - Chiral model coupled to Polyakov loop to include the deconfinement phase transition
  - Qualitative agreement with lattice QCD data at $\mu_B = 0$
  - Applicable also at finite baryon densities
  - Has the same degrees of freedom as UrQMD in hadronic phase

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Transport + hydrodynamics hybrid model


Freeze-out Procedure

- Transition from hydro to transport ("particlization") when energy density $\epsilon$ is smaller than critical value $x\epsilon_0$, where $\epsilon_0 = 146$ MeV/fm$^3$ represents the nuclear ground state and $x \geq 1$.

- Cornelius hypersurface finding algorithm
  

- Particle distributions are generated according to the Cooper-Frye formula

- Rescatterings and final decays calculated via hadronic cascade (UrQMD)

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$^4$In this study $x = 2$, corresponding to temperature $T \approx 154$ MeV.
Particle $m_T$ spectra

(0-7)% centrality.

$E_{lab} = 40\text{A GeV} \, m_T$ distribution at $|y|<0.5$

\begin{align*}
\text{Left: } & \pi^-, K^+, K^- \text{ at } \sqrt{s_{NN}} \approx 9 \text{ GeV.} \\
\text{Right: } & \pi^-, K^+, p \text{ at } \sqrt{s_{NN}} = 200 \text{ GeV.}
\end{align*}


(0-5)% centrality.
Elliptic flow

Generated by pressure gradients due to spatial anisotropy of initial state.

Initial spatial anisotropy: eccentricity $\epsilon_2 = \sqrt{\langle r^2 \cos(2\phi) \rangle^2 + \langle r^2 \sin(2\phi) \rangle^2} / \langle r^2 \rangle$.

Final momentum anisotropy: $v_2\{\text{EP}\} = \frac{v_2\{\text{observed}\}}{R_2} = \frac{\langle \cos[2(\phi_i - \psi_2)] \rangle}{\langle \cos[2(\psi_2 - \psi_2^\text{true})] \rangle}$.  

Rising slope in 0-5% centrality not reproduced; qualitative agreement at midcentrality.


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No contribution from hadronic rescattering in most central collisions. In midcentral collisions $\approx 10\%$ effect.

Pre-equilibrium dynamics more important at lower energies.

Hydro contribution vanishes at $\sqrt{s_{NN}} = 5$ GeV.
Elliptic flow

\[ v_2(p_T) \] overestimated at higher \( p_T \). Add viscosity? Particlization condition?


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Effect of particlization condition on elliptic flow

\[ \sqrt{s_{NN}} = 11.5 \text{ GeV, } b = 8.2 - 9.4 \text{ fm} \]

The earlier end of the hydrodynamical evolution flattens the \( p_T \)-slope.
Triangular flow

Originates from the event-by-event fluctuations in the spatial nucleon configuration of the initial state.

FIG. 3: Distribution of nucleons on the transverse plane for a \( \sqrt{s_{NN}} = 200 \) GeV Au+Au collision event with \( \epsilon_3 = 0.53 \) from Glauber Monte Carlo. The nucleons in the two nuclei are shown in gray and black. Wounded nucleons (participants) are indicated as solid circles, while spectators are dotted circles.


\[ \epsilon_3 = \sqrt{\frac{\langle r^3 \cos(3\phi) \rangle^2 + \langle r^3 \sin(3\phi) \rangle^2}{\langle r^3 \rangle}} \]

\[ \nu_3^{\{EP\}} = \frac{\langle \cos[3(\phi_i - \psi_3)] \rangle}{\langle \cos[3(\psi_3 - \psi_3^{\text{true}})] \rangle} \]
Triangular flow

Clear energy dependence from $\sqrt{s_{NN}}$ = 5 to 27 GeV!

Total $v_3$ vanishes at $\sqrt{s_{NN}}$ = 5 GeV (no compensation from transport)
Preliminary data shows a somewhat different energy evolution.
Agreement on the magnitude in central collisions.

Y. Pandit [STAR Collaboration], QM2012 talk.
Collision geometry

$\epsilon_2$ more sensitive than $\epsilon_3$ to changes on $b$ and $\sqrt{s_{NN}}$.

$\sqrt{s_{NN}}$-dependence mainly due to the longer initial transport evolution.
Scaled flow coefficients

\( v_2 \) response to \( \epsilon_2 \) remains roughly the same in both centrality classes and all energies.

Energy dependence of \( v_3 \) persists through scaling.
Scaled flow coefficients

\[ \langle t_{\text{hydro}} \rangle = \text{average total duration of hydrodynamical phase in the simulation} \]

\( v_3 \) generated purely by hydro \( \Rightarrow \) points form an uniform function of \( \langle t_{\text{hydro}} \rangle \)

\( v_2 \) generated by hydro + transport \( \Rightarrow \) non-uniform behavior as a function of \( \langle t_{\text{hydro}} \rangle \)
Summary

- **Elliptic flow** $v_2$ changes little as a function of beam energy; transport compensates for diminishing hydrodynamics.
- $v_2(p_T)$ overshoots the data; particlization condition might require adjustment (viscosity?)
- **Triangular flow** $v_3$ has much more notable energy dependence, growing from $\approx 0$ at $\sqrt{s_{NN}} = 5$ GeV to 0.02 at $\sqrt{s_{NN}} = 27$ GeV in midcentral collisions.
- Preliminary STAR data shows a different energy evolution, agreement on the magnitude of the central collision $v_3$ at $\sqrt{s_{NN}} = 7.7$ GeV.
- $v_3$ is the better indicator of the presence of low-viscous fluid – challenging to measure at low energies though...
- Hydrodynamically behaving matter might still be produced in the most central heavy ion collisions at highest FAIR energies!
Extra slides
Some interesting findings:

- Non-monotonic $\sqrt{s_{NN}}$ dependence of net-proton $v_1$
- Difference in particle and antiparticle $v_2$ at lower energies
- $R_{CP}$ suppression turns to enhancement between $\sqrt{s_{NN}} = 39$ and 27 GeV

$v_1$ and $v_2$ figures from L. Kumar [STAR Collaboration], arXiv:1211.1350 [nucl-ex].

$R_{CP}$ from Hot Quarks 2012 talk by S. Horvat.
Reaction plane analysis suggests increased flow contribution from hydrodynamics at lower energies!
- Applicability of ideal hydro at $E_{lab} = 2$ GeV?
Triangular flow

Contribution of initial state fluctuations to event plane $v_2$:

$$
\sigma_{v2} = \sqrt{\frac{1}{2}(v_2\{EP\}^2 - v_2\{RP\}^2)}
$$

$v_3 \approx \sigma_{v2}$ at high energies.
Triangular flow

Differential $v_3$ challenging to interpret due to small magnitudes.

Eccentricity probability distributions

Eccentricity $b=0.5-3.4$ fm

Eccentricity $b=8.2-9.4$ fm

Eccentricity $b=11.5-13.3$ fm
Triangularity probability distributions

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**Triangularity b=0-3.4 fm**

**Triangularity b=8.2-9.4 fm**

**Triangularity b=11.5-13.3 fm**
Particle multiplicity

Charged pion multiplicity as a function of $\sqrt{s_{NN}}$. 

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Particle multiplicity

Kaons, total multiplicity

Midrapidity multiplicity

Charged kaon multiplicity as a function of $\sqrt{s_{NN}}$. 

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32 / 23