Beam energy scan in a UrQMD+hydro hybrid model

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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?

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.
Charged hadron $v_2$ shows weak collision energy dependence.

Beam energy scan

Differential $v_2$ almost identical for all $\sqrt{s_{NN}}$.

$v_3$ more sensitive to beam energy?

Hybrid model
Transport + hydrodynamics hybrid model


Initial State from UrQMD\textsuperscript{1} string/hadronic cascade

- Start the hydrodynamical evolution when nuclei have passed through each other: \( t_{\text{start}} = \max\left\{ \frac{2R_{\text{nuclei}}}{\sqrt{\gamma_{\text{CM}}^2 - 1}}, 0.5 \text{ fm} \right\} \).
- 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.

Hydro starting times

![](http://example.com/graph.png)
Hydrodynamical evolution

- **(3+1)D ideal** hydrodynamics using SHASTA\textsuperscript{2}
- **Equation of state**\textsuperscript{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


Hydro duration in computational frame

Duration of hydrodynamical phase

Average hydro duration [fm/c]

0 5 10 15 20 25

\( \sqrt{s_{NN}} \) [GeV]

10 100

b_0_3.4

b_8.2_9.4

b_11.5_13.3
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 $x \geq 1$.

- 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.
Transport + hydrodynamics hybrid model

Cornelius hypersurface finding algorithm


A method for finding the elements of 3D particlization hypersurface in 4D space for the Cooper-Frye procedure, without holes or double counting.

Fig. 9. Reduction of a four dimensional problem into a series of three dimensional problems.
Results
Particle multiplicity

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

Kaons, total multiplicity

Midrapidity multiplicity

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

J. Auvinen (FIAS, Frankfurt) Hybrid model energy scan April 25, 2013 17 / 34
(0-7)% centrality.

Left: $\pi^-, K^+, K^-$ at $\sqrt{s_{NN}} \approx 9$ GeV.
Right: $\pi^-, K^+, K^-$ at $\sqrt{s_{NN}} \approx 12$ GeV.

Particle $m_T$ spectra

(0-7)% centrality.

Left: $\pi^-, K^+, K^-$ at $\sqrt{s_{NN}} \approx 17$ GeV.
Right: $\pi^-, K^+, p$ at $\sqrt{s_{NN}} = 200$ GeV.

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

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

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

No contribution from hadronic rescattering in most central collisions. Pre-equilibrium dynamics become more important at lower energies.
Hydro contribution on $v_2$

Hydro contribution to $v_2$ negligible at $\sqrt{s_{NN}} = 5$ GeV; roughly 60% at highest energies.
$v_2(p_T)$ overestimated at higher $p_T$.


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Effect of hydro ending condition on elliptic flow

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

Revision of hydro-to-cascade transition condition could fix \( v_2(p_T) \).
Elliptic flow

No clear energy dependence on differential flow.

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Triangular flow

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

\[ v_3\{\text{EP} \} = \frac{\langle \cos[3(\phi_i - \psi_3)] \rangle}{\langle \cos[3(\psi_3 - \psi_3^{\text{true}})] \rangle} \]

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.

Midcentral $v_3$ rises from $\approx 0$ to $\approx 0.015 - 0.02$. 
Preliminary data displays quite different behavior, however.

Y. Pandit [STAR Collaboration], QM2012 talk.
Increase at lower values of $\sqrt{s_{NN}}$; no change after 19.6 GeV.
\[ v_3(p_T) \]

Charged hadron \( v_3(p_T) \)

\begin{align*}
|y| < 1.0 & \\
b = 6.7 - 8.2 \text{ fm}
\end{align*}

Comparison with preliminary STAR data.

Collision geometry

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

- **Multiplicities**: Pion production in reasonable agreement with data, kaons overproduced.

- **Elliptic flow**: Integrated $v_2$ similar to the STAR data, $v_2(p_T)$ overshoots the data (particlization at higher energy density?).

- **Triangular flow**: $v_3 \approx 0$ at $\sqrt{s_{NN}} = 5$ GeV, then rises until reaches value 0.015 - 0.02 at $\sqrt{s_{NN}} = 19.6$ GeV. Qualitative disagreement with preliminary STAR data, which has flat $v_3$ at low $\sqrt{s_{NN}}$ and begins increasing at 27 GeV.
Extra slides
\( \delta v_2 \) visibly energy-dependent on midcentral collisions; equal to \( v_3 \) in magnitude in central collisions.
Eccentricity probability distributions

- Eccentricity $b=0-3.4$ fm
- Eccentricity $b=8.2-9.4$ fm
- Eccentricity $b=11.5-13.3$ fm

$E_{\text{cm}} = 5$ GeV
$E_{\text{cm}} = 7.7$ GeV
$E_{\text{cm}} = 11.5$ GeV
$E_{\text{cm}} = 15$ GeV
$E_{\text{cm}} = 19.6$ GeV
$E_{\text{cm}} = 27$ GeV
$E_{\text{cm}} = 39$ GeV
$E_{\text{cm}} = 62.4$ GeV
$E_{\text{cm}} = 200$ GeV
Triangularity probability distributions

![Triangularity b=0-3.4 fm](image1)

![Triangularity b=8.2-9.4 fm](image2)

![Triangularity b=11.5-13.3 fm](image3)
(Square root of) variances of $\langle \epsilon_2 \rangle$ and $\langle \epsilon_3 \rangle$

Both eccentricity and triangularity have variances of same size.
Relative variances of $\langle \epsilon_2 \rangle$ and $\langle \epsilon_3 \rangle$

Triangularity has larger relative variance than eccentricity; remains practically same from most central to midcentral collisions.
Relative variance of $\langle \epsilon_2 \rangle$ and $v_2$ fluctuations

$$\frac{\delta v_2}{v_2} \approx \frac{\delta \epsilon_2}{\epsilon_2} \text{ in midcentrality.}$$
Energy-momentum tensor anisotropy

\[ \epsilon_p = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle} \]

\[ \sqrt{s_{NN}} = 19.6 \text{ GeV}, b = 2 \text{ fm} \]

\[ \sqrt{s_{NN}} = 19.6 \text{ GeV}, b = 7 \text{ fm} \]