Evolution of anisotropic flow of produced particles from Au+Au collisions at $\sqrt{s} = 7.7 - 200$ GeV in a hybrid models

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1. Why measure anisotropic flow?
2. Anisotropic flow ($V_n$) and sQGP at RHIC/LHC
3. Elliptic flow results from Beam Energy Scan (RHIC) and comparison with hybrid models
4. Outlook for flow measurements at NICA
Phase Diagram of the Strongly-Interacting Matter

Top RHIC/LHC: validation of the cross over transition leading to the sQGP

Top RHIC energy/LHC - access to high $T$ and small $\mu_B$
RHIC-BES/SPS/NICA/FAIR - access to different systems and a broad domain of the ($\mu_B$, $T$)-plane

\[ \frac{\eta}{s}(T, \mu), \frac{\zeta}{s}(T, \mu), c_5(T), q(T), \alpha_s(T), \text{etc} \]
Anisotropic Collective Flow at RHIC/LHC

Initial eccentricity (and its attendant fluctuations), $\varepsilon_n$, drives momentum anisotropy, $v_n$, with specific viscous modulation.

\[
\varepsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}
\]

\[
\frac{dN}{d\phi} \propto \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos \left[ n(\phi - \Psi_n) \right] \right)
\]
Anisotropic Collective Flow at top RHIC / LHC

\( \langle p_T, \text{centrality} \rangle \) - sensitive to the early stages of collision. Important constraint for transport properties: EOS, \( \eta/s \), \( \zeta/s \), etc.

\( v_n \) of identified hadrons:

- **Mass ordering at** \( p_T < 2 \text{ GeV/c} \)
  - (hydrodynamic flow, hadron rescattering)

- **Baryon/meson grouping at** \( p_T > 2 \text{ GeV/c} \)
  - (recombination/coalescence), Number of constituent quark (NCQ) scaling

**No difference** between particles and antiparticles
Beam-Energy Dependence of Elliptic Flow ($v_2$)

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- Small change in $v_2$ ($p_T$) for inclusive and identified charged hadrons (pions, kaons and (anti)protons) as the $\sqrt{s_{NN}}$ changes by a factor $\sim 25$ (from 7.7 GeV to 200 GeV).

- Substantial particle-antiparticle split at lower energies

**Goal of this work:**

1) Perform simulations with hybrid models ($v$HLLE+UrQMD and AMPT), analyse them as in the real experiment and make comparison with RHIC BES published measurements of $v_2$.

2) Make projections for measurements at NICA energies ($\sqrt{s_{NN}} = 4 \text{–} 11$ GeV)?

Hybrid models for anisotropic flow at RHIC/LHC

1) UrQMD + 3D viscous hydro model vHLLE + UrQMD

https://github.com/yukarpenko/vhlle_


**Initial conditions:** model UrQMD

QGP phase: 3D viscous hydro (vHLLE) with crossover EOS (XPT)

Hadronic phase: model UrQMD

2) A Multi-Phase Transport model (AMPT) for high-energy nuclear collisions. _The main source codes: Zi-Wei Lin (http://myweb.ecu.edu/linz/ampt/v1.26t9b/v2.26t9b)_

**Initial conditions:** model HIJING

QGP phase: Zhang’s parton cascade for modeling partonic scatterings

Hadronic phase: model ART

TPC(E) half $\eta < 0 \rightarrow \eta_-$  
TPC (W) half $\eta > 0 \rightarrow \eta_+$

$$v_n = \frac{\langle \cos[n(\varphi_{\eta_{\pm}} - \Psi_{n,\eta_{\pm}})] \rangle}{\sqrt{\langle \cos[n(\Psi_{n,\eta_+} - \Psi_{n,\eta_-})] \rangle}}$$

The resulting values for event plane resolution for simulated events from hybrid models: vHLLÉ+UrQMD and AMPT are close to STAR experimental data.
vHLLE+UrQMD: Elliptic flow at top RHIC energy: $\sqrt{s_{NN}} = 200$ GeV

Reasonable agreement between results of vHLLE+UrQMD model and published PHENIX data for 200 GeV including KET/nq scaling
$v_2$ of charged mesons at RHIC BES ($\sqrt{s_{NN}} = 27$ GeV)


reasonable agreement between vHLLE+UrQMD and data for charged pions and kaons
$v_2$ of (anti)protons at RHIC BES ($\sqrt{s_{NN}} = 27$ GeV)


Difference between results from vHLLE+UrQMD model and data for protons and antiprotons. Model predicts that $v_2$ (protons) < $v_2$ (antiprotons), data show $v_2$ (protons) > $v_2$ (antiprotons) and the difference is growing with decreasing of collision energy.
AMPT: $v_2$ of identified hadrons at RHIC BES ($\sqrt{s_{NN}} = 27$ GeV)


Difference between results from AMPT model SM and data for all particles – tuning of parameters?
Model also predicts that $v_2$ (protons) < $v_2$ (antiprotons), data show $v_2$ (protons) > $v_2$ (antiprotons)
$v_2$ of protons and antiprotons at RHIC BES ($\sqrt{s_{NN}} = 11.5$ GeV)

Models AMPT and vHLLE+UrQMD predicts also predicts that $v_2$ (protons) < $v_2$ (antiprotons), data show $v_2$ (protons) > $v_2$ (antiprotons)
Pure String/Hadronic Cascade models (no QGP phase) give smaller $v_2$ signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=7.7-11.5 GeV and models give similar $v_2$ signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=4.5 GeV.
Summary

We performed a high statistics simulations with hybrid models (vHLLE+UrQMD and AMPT) for several points in collision energy from RHIC BES program.

The events were analysed in a similar way as the real experimental data and results were compared with STAR published results of $v_2$ for charged pions, kaons and (anti)protons.

The results from vHLLE+UrQMD model are in a better agreement with experimental data than for AMPT. Both models in the present configuration fail to reproduce the difference between elliptic flow signal of particles and antiparticles: models predict that $v_2$ (protons) < $v_2$ (antiprotons), data show $v_2$ (protons) > $v_2$ (antiprotons)

Model/Data comparison for NICA energy range (4-11 GeV):
Pure String/Hadronic Cascade models (no QGP phase) give smaller $v_2$ signal compared to STAR data for Au+Au $\sqrt{s_{NN}}=7.7-11.5$ GeV and models give similar $v_2$ signal compared to STAR data for Au+Au $\sqrt{s_{NN}}=4.5$ GeV.

Thank you for your attention!
Anisotropic Flow in Heavy-Ion Collisions: 1988

Provides reliable estimates of pressure & pressure gradients

Can address questions related to thermalization

Gives insights on the transverse dynamics of the Medium

Provides access to the transport properties of the medium: EOS, sound speed ($c_s$), viscosity, etc


Excitation function of differential elliptic flow

High precision differential measurements of anisotropic flow?