Anisotropic Flow Measurements of Identified Particles in the STAR Experiment

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Outline

➢ Motivation

➢ Results

• $v_2/v_3$ measurements at 200, 54.4, 39 and 27 GeV
• $v_1/v_2$ measurements at 3 GeV

➢ Summary
Conjectured phase diagram of strong interactions

- Study the properties of QCD medium
- Search for Critical End Point
- Locate the first-order phase boundary

The collective behavior would be different between QGP phase and hadron phase
They are dominated by different interactions
**Motivation**

Directed flow:

\[
\frac{dN}{d\phi} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi))
\]

- Directed flow: \( v_1 = \langle \cos(\phi - \Psi) \rangle \)
- Elliptic flow: \( v_2 = \langle \cos(2(\phi - \Psi)) \rangle \)
- Triangular flow: \( v_3 = \langle \cos(3(\phi - \Psi)) \rangle \)

- Azimuthal anisotropy parameters \((v_1, v_2, v_3)\) are sensitive to the early stage of the system evolution and Equation-of-State (EoS) of medium

- Elliptic flow \((v_2)\)
  - Positive \(v_2\), preference of in-plane emission
  - Negative \(v_2\), preference of out-of-plane emission \((\sqrt{s_{NN}} \sim < 4 \text{ GeV})\)

Motivation: $v_1/v_2$ Measurements at Low Energy

- Proton $\langle p_x \rangle$ slope ($F$) ($\langle p_x \rangle$ is similar to $v_1$) and $v_2$ results from E895 and E877 ($\sqrt{s_{NN}} \sim 2.7$ GeV - 5 GeV) show:
  - Positive slope of $\langle p_x \rangle$ at mid-rapidity
  - In-plane $v_2$ to out-of-plane $v_2$

- $v_1$ and $v_2$ are very sensitive to the stiffness of nuclear EoS in the high baryon density region
- $K$ is directly connected to mean-field potential in UrQMD model

Nuclear incompressibility: $K = 9(\frac{\partial P}{\partial \rho})|_{\rho=\rho_0}$

Results-I
$v_2/v_3$ Measurements in High Energy Collisions at STAR

Both hydro simulations qualitatively reproduce identified particle $v_2$ and $v_3$ in 200 GeV $Au+Au$ collisions

- At these three energies (27, 39, and 54.4 GeV), $v_2$ behaves similarly

1), P. Alba, et al. PRC 98 (2018) 034909
Number of constituent quark (NCQ) scaling of $v_n$ has been well achieved at 200 GeV

Difference of $v_n$ between particle and anti-particle increases with decreasing collision energy

The difference of baryons is larger than mesons

Results-II
STAR Fixed Target Setup

<table>
<thead>
<tr>
<th>Beam Energy (GeV/nucleon)</th>
<th>(\sqrt{s_{NN}}) (GeV)</th>
<th>Events (M)</th>
<th>Year</th>
<th>(\mu_B) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.85</td>
<td>3.0</td>
<td>250</td>
<td>2018</td>
<td>721</td>
</tr>
</tbody>
</table>

**Conventions:** beam-going direction is the positive direction (Yellow beam)

Particle Identification

- Good capability of particle identification by using Time Projection Chamber (TPC) and Time of Flight (TOF) at STAR
K$_S^0$ and Λ are reconstructed in π$^+\pi^-$ and pπ$^-$ channel respectively using KF particle package, good purity is achieved

- Background is obtained by rotating daughter π$^-$ tracks
- ϕ mesons are reconstructed in K$^+K^-$ channel
- Background is obtained by using mixed event
The acceptance plot $p_T$ versus rapidity measured by using STAR detector (TPC and TOF) for $\pi^+$, $K^+$, $K^0_S$, $p$, $\phi$ and $\Lambda$

The acceptance of all particles covers from mid-rapidity to target rapidity region.
Rapidity Dependence

- Rapidity dependence of $v_1$ and $v_2$ for identified particles ($\pi^\pm, K^\pm, K_S^0, p, \Lambda$)
- The negative elliptic flow observed at mid-rapidity region for all hadrons
- The results from UrQMD with baryonic mean-field potential qualitatively describe the data
Strong $p_T$ dependence of the slope of directed flow ($dv_1/dy$) for identified particles ($\pi^\pm, K^\pm, K_S^0, p, \Lambda$)

Small charge dependence for pions and kaons

The UrQMD calculations with baryonic mean-field (MF) potential qualitatively describe the data
Centrality Dependence of $dv_1/dy$ and $v_2$

- Clear centrality dependence of $dv_1/dy$ and $v_2$ for identified particles
- Shadowing effect of spectators in the peripheral collisions
  - More negative $v_2$
- The UrQMD calculations with baryonic mean-field (MF) potential qualitatively describe the data except kaons

The number of constituent quark (NCQ) scaling for $v_2$ holds down to 4.5 GeV, consistent with the nature of partonic collectivity.

Different color dash lines represent the fit to data from 200 GeV – 4.5 GeV.

At 3 GeV, the measured $v_2$ for all particles are negative and NCQ scaling is absent, especially for positive charged particles.

The $v_1$ slopes ($dv_1/dy|_{y=0}$) of baryons at 3 GeV are positive and larger than those of mesons.

For the first time, kaon and $\phi$ $v_1$ slopes are found to be positive at 3 GeV, consistent with a change of EoS.

Negative elliptic flow at mid-rapidity for all hadrons at 3 GeV.
The $v_1$ slopes ($dv_1/dy|_{y=0}$) of baryons at 3 GeV are positive and larger than those of mesons.

For the first time, kaon and $\phi$ $v_1$ slopes are found to be positive at 3 GeV, consistent with a change of EoS.

Negative elliptic flow at mid-rapidity for all hadrons at 3 GeV.

The results from UrQMD with baryonic mean-field potential qualitatively describe data at 3 GeV.

EoS dominated by the baryonic interactions at 3 GeV.
Summary

- Flow measurements in high energy collisions at 200, 54.4, 39 and 27 GeV → Partonic collectivity

- At 3 GeV, negative elliptic flow and positive slope of directed flow at mid-rapidity for all hadrons are observed

- Hadronic transport model (UrQMD) with baryonic mean-field potential qualitatively describe the data at 3 GeV → New medium properties and an EoS dominated by baryonic interactions, produced in 3 GeV Au+Au collisions

Thank you for your attention!
Backup
Flow Method

- **2-particle Correlation Method (2PC)**
  \[ c_n \{2\} = \langle \langle 2 \rangle \rangle_{a|b} = \langle \langle e^{i n (\phi_1^a - \phi_2^b)} \rangle \rangle = \frac{\langle \langle Q_n^a Q_n^b \rangle \rangle}{\langle \langle M_a M_b \rangle \rangle} \]
  - The non-flow contribution is reduced with \( \Delta \eta \) gap

- **Event Plane Method (EP)**
  \[ \Psi_n = \left( \tan^{-1} \frac{\sum_i w_i \sin(n \phi_i)}{\sum_i w_i \cos(n \phi_i)} \right) / n \]
  \[ v_n = \frac{\langle \cos(n (\phi - \Psi_n)) \rangle}{\langle \cos(n (\Psi_n - \Psi_{RP})) \rangle} = \frac{v_n^{obs}}{R_n} \]
  - The detector acceptance effect has been corrected by applying re-centering and shift calibration
  \[ \langle \cos(k m (\Psi_m - \Psi_r)) \rangle = \frac{\sqrt{\pi}}{2\sqrt{2}} \chi m \exp(-\chi_m^2/4) \left[ I_{(k-1)}(\chi_m^2/4) + I_{(k+1)/2}(\chi_m^2/4) \right] \]
  - Modified Bessel function is used for resolution calculation
NCQ scaling for $v_2$

![Graphs showing NCQ scaling for $v_2$ in Au+Au collisions at different energies and particle types.](image-url)