Azimuthal anisotropic flow of identified hadrons in Au + Au collisions at BES-II energies at STAR

Prabhupada Dixit
(For the STAR Collaboration)
Indian Institute of Science Education and Research (IISER) Berhampur

Critical Point and Onset of Deconfinement (CPOD), 2022

Supported in part by the

[Logos for U.S. Department of Energy, Office of Science, IISER Berhampur, STAR]
Outline

❖ Introduction & motivation
❖ STAR detectors
❖ Analysis details
❖ Results
   ★ $p_T$ dependence of $v_n$
   ★ Centrality dependence
   ★ NCQ Scaling
   ★ $v_3/v_2^{3/2}$ ratio
❖ Summary
Elliptic flow coefficient ($v_2$): Initial spatial anisotropy (dominant source) + Event-by-event fluctuations
Triangular flow coefficient ($v_3$): Event-by-event fluctuations in the overlap region

\[
\frac{dN}{d(\phi - \Psi_n)} = N_0 \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos(\phi - \Psi_n) \right]
\]

\[v_n = \langle \langle \cos n(\phi - \Psi_n) \rangle \rangle\]

**Importance of $v_2$ and $v_3$**

- Sensitive to the initial state and transport properties of the medium.
- Measurements of $v_2$ and $v_3$ are important to constrain the models.

C. Shen et al/ JPG 38 (2011) 124045
Results from RHIC BES-I

\[ \phi \] mesons seem to deviate from the NCQ scaling at \( \sqrt{s_{NN}} < 19.6 \) GeV.

\( \Phi \) But statistics is not significant to draw any conclusion.

\( \text{★ High Statistics data from BES-II enable us to measure } v_2 \text{ and } v_3 \text{ of multi-strange hadrons and } \phi \text{ mesons with high precession specifically at low energy regime.} \)

Prabhupada Dixit, CPOD-2022
STAR detectors and particle identification

- Full azimuthal coverage
- Excellent particle identification capability

**BES-II upgrades**

- iTPC upgrade: Larger pseudorapidity coverage (-1.5 < \(\eta\) < 1.5)
- Better dE/dx and momentum resolution.
- Better track quality.

**Time Projection Chamber (TPC)**

**Time of Flight (ToF)**

Reconstruction of (multi-)strange hadrons and \(\phi\) mesons

---

Data set information for this analysis:

- System: Au+Au
- Year: 2019 (BES-II data)
- Collision energy: 19.6 and 14.6 GeV
- #Events: ~380M (19.6 GeV) & ~400M (14.6 GeV)
- Source of systematic uncertainty: Variation of analysis cuts e.g. collision vertex selection cuts, particle identification cuts, quality track selection cuts etc.

---

Prabhupada Dixit, CPOD-2022
Analysis details

The $n^{th}$ order flow coefficient is given by

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

- The reaction plane of the collision can not be determined directly from the experiment.
- The event plane is used as a proxy for the reaction plane.

Event plane determination

$$\Psi_n = \frac{1}{n} \tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$

$$Q_x = \sum_i w_i \cos(n\phi_i)$$

$$Q_y = \sum_i w_i \sin(n\phi_i)$$

The weight factor $w_i = p_T \times \phi$-weight.

$\phi$-weight: accounts for the azimuthal acceptance correction of the detectors.

Event plane resolution

$$R_n = \langle \cos n(\Psi_n - \Psi_R) \rangle$$

Experimentally, $R_n(sub) = \sqrt{\langle \cos n(\Psi_A - \Psi_B) \rangle}$

★ Sub-event plane method is used to calculate $v_n$.
★ $\eta$ gap of 0.1 is taken between two sub-event planes $\Psi_A$ (-1.5 < $\eta$ < -0.05) and $\Psi_B$ (0.05 < $\eta$ < 1.5).
★ To calculate $v_n$ of a particle in a negative $\eta$ region, event plane from positive $\eta$ side is used and vice versa.

To minimize non-flow correlation

TPC + iTPC $|\eta| < 1.5$

Prabhupada Dixit, CPOD-2022
\[ v_n^{S+B}(M_{inv}) = \langle \cos [n(\phi - \psi_n)] \rangle = v_n^S \frac{S}{S+B}(M_{inv}) + v_n^B \frac{B}{S+B}(M_{inv}) \]

\[ v_n^B(M_{inv}) = p_0 + p_1 M_{inv} \]

Prabhupada Dixit, CPOD-2022
Results: $p_T$ dependence of $v_2 \oplus 19.6$ GeV

\
\begin{align*}
\text{Mass ordering observed in the low } p_T \text{ region } (p_T < 1.5 \text{ GeV/c}) & : \text{Radial flow} \\
\text{Baryon to meson separation observed in the high } p_T \text{ region} & : \text{Quark coalescence}
\end{align*}

\*$\text{The statistical errors are reduced by a factor of } \sim 3 \text{ compared to BES-I.}\*$

Prabhupada Dixit, CPOD-2022
Results: Centrality dependence of $v_2$ @ 19.6 GeV

Strong centrality dependence of $v_2$ → Spatial anisotropy is a dominant cause for $v_2$
Results: Centrality dependence of $v_2$ @14.6 GeV

Strong centrality dependence of $v_2$ → Spatial anisotropy is a dominant cause for $v_2$
Results: Centrality dependence of $v_3$ @19.6 GeV

Weak centrality dependence of $v_3$ → Event-by-event fluctuation is a dominant cause for $v_3$
Results: NCQ scaling in $v_2$ @ 19.6 GeV

The scaling for $v_2$ holds within 20% for particles and within 10% for anti-particles (except at low $p_T$ for $\Lambda$ and $\bar{p}$)

Partonic collectivity in the initial stage of the system and hadronization via coalescence.

Prabhupada Dixit, CPOD-2022
Results: NCQ scaling in $v_3$ @19.6 GeV

The modified scaling for $v_3$ holds within 30% for particles and within 15% for anti-particles.
Results: NCQ scaling in $v_2 @ 14.6$ GeV

- The scaling for $v_2$ holds within 15% for the (multi-)strange hadrons except low $p_T$ $\Lambda$.
- $\phi$ mesons are following the NCQ scaling at 14.6 GeV.
- The rising trend in the $K_S^0$ $v_2$ at $(m_T - m_0)/n_q > 1$ GeV/$c^2$ may arise due to the non-flow contribution. Non-flow estimation is underway.

$\star$ See S. Zhou’s talk for light hadrons $v_2$ at 14.6 GeV

Prabhupada Dixit, CPOD-2022
Results: \( v_3/v_2^{3/2} \) ratio @ 19.6 GeV

The ratio \( v_3/v_2^{3/2} \) shows non-trivial \( p_T \) dependence.

\( v_3/v_2^{3/2} \) ratios are sensitive to the initial state fluctuations and transport properties of the medium.

Prabhupada Dixit, CPOD-2022
Summary

Using high statistics BES-II data, precise measurements of $v_2$ of identified hadrons in 19.6 and 14.6 GeV Au+Au collisions have been presented, with improved statistical significance by a factor of 3 compared to BES-I.

New results of $v_2$ and $v_3$ of (multi-)strange hadrons and $\phi$ mesons are presented.

$p_T$ dependence of $v_2$

Confirmation of usual trend of mass ordering in $v_2$ at low $p_T$ and baryon-meson separation at high $p_T$ in low energies at 19.6 GeV using strange and multi-strange hadrons.

Centrality dependence of $v_n$

Strong centrality dependence of $v_2$ : initial spatial anisotropy is a dominant cause for $v_2$.

Weak centrality dependence of $v_3$: event-by-event fluctuation is a dominant cause for $v_3$.

NCQ scaling

The NCQ scaling holds for both particles and anti-particles.

The scaling holds for $\phi$ mesons at 14.6 GeV.

The scaling suggests the collectivity in the partonic phase of the system and hadronization via quark coalescence.

$v_3/v_2^{3/2}$ ratio

The ratio shows weak dependence of $p_T$ above $p_T > 1.0$ GeV/c.

Can be used to constrain the initial state fluctuations and $\eta/s$ of the medium.

Prabhupada Dixit, CPOD-2022
Thank you ...