First-order event plane correlated directed and triangular flow from fixed-target energies at RHIC-STAR

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Outline

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Anisotropic Flow

- Flow is the measure of azimuthal anisotropy
- Azimuthal distribution of particles

\[ \frac{E}{d^3N} \frac{d^2N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n)) \right) \]

- Sensitive to the equation of state
- Sensitive to early times in the evolution of the system

**Directed flow**

\[ v_1 = \langle \cos(\phi - \Psi_1) \rangle \]

\( v_1 \rightarrow \) sideward motion of emitted hadrons with respect to collision reaction plane

**Triangular flow**

\[ v_3 = \langle \cos 3(\phi - \Psi_1) \rangle \]

\( v_3 \rightarrow \) driven by the shape of the initial collision geometry
The primary aim of relativistic heavy-ion collisions → Understand the properties and the evolution of strongly interacting matter, 
**Quark–Gluon Plasma (QGP)**

- Minimum in baryon’s $d\langle v_1\rangle/dy$ predicted to be sensitive to softening of EoS → **Signature of a 1st-order phase transition** between hadronic matter and QGP
- At high energies, $v_3$ → uncorrelated with the 1st order event plane, contrary to observation at lower energy


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STAR Experiment

- **Fixed-Target (FXT) program at Solenoidal Tracker At RHIC (STAR)** → low center-of-mass energies and high baryon density region
- **BES-II FXT mode**: Au+Au collisions at $\sqrt{s_{NN}} = 3, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, \text{ and } 7.7 \text{ GeV}$. 

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Nuclear Phy A 808-811 (2017)

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ISMD 2023, Sharang Ray Sharma
Particle Identification

- Two main detectors are used for particle identification in **STAR**
  - Time Projection Chamber (TPC)
    \[
    z_x = \ln \left( \frac{\langle dE/dx \rangle}{\langle dE/dx \rangle_B} \right)
    \]
  - Time of Flight (ToF)
    \[
    m^2 = p^2 \left( \frac{c^2 T^2}{L^2} - 1 \right)
    \]

https://www.star.bnl.gov/
Event Plane Reconstruction

Event Plane Detector (EPD) → Measures charged particles emitted in the forward and backward directions

TPC and EPD are divided into 2 and 4 regions, respectively, based on their pseudorapidity (\( \eta \)) coverage

\[
\vec{Q} = \begin{pmatrix}
Q_y \\
Q_x
\end{pmatrix} = \begin{pmatrix}
\sum_i w_i \sin(\phi) \\
\sum_i w_i \cos(\phi)
\end{pmatrix}
\]

\[
\Psi_1 = \tan^{-1}\left( \frac{\sum_i w_i \sin(\phi)}{\sum_i w_i \cos(\phi)} \right)
\]

where \( \phi \) is azimuthal angle and \( w_i \) is the weight for the \( i^{th} \) hits, \( \Psi_1 \) is the first-order event plane angle
In FXT mode collision, 3-sub event method was used to determine the EPD first order event plane resolution.

\[
\langle \cos(\Psi_{T} - \Psi_{T}) \rangle = \sqrt{\frac{\langle \cos(\Psi_{T} - \Psi_{T}^{a}) \rangle \langle \cos(\Psi_{T} - \Psi_{T}^{c}) \rangle}{\langle \cos(\Psi_{T} - \Psi_{T}) \rangle}}
\]

- \( a \) → EPD-AB \((-5.3 < \eta < 3.3)\)
- \( b \) → EPD-C \((-3.3 < \eta < 2.9)\)
- \( c \) → TPC B \((-1.0 < \eta < 0)\)
Phase Space Distribution

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Au+Au 3.2 GeV

- Rapidity: $y_{\text{cms}} = y + |y_{\text{mid}}|$, for FXT 3.2 GeV, $y_{\text{mid}} = -1.127$

- $p_T$ region:
  - $\pi$: $0.2 < p_T < 1.6$, $K$: $0.4 < p_T < 1.6$, $p$: $0.4 < p_T < 2$ (GeV/c)
  - $d$: $0.8 < p_T < 3.5$, $t$: $1.2 < p_T < 4$ (GeV/c)
Directed Flow ($v_1$) Results
Rapidity dependence of $v_1$ ($\pi^+$, $K^+$, $p$)

- Magnitude of $v_1$ increases with increasing rapidity.
- Magnitude of $v_1$ increases with increasing mass of the particle ($p > K^+ > \pi^+$).
Centrality dependence of $v_1 (\pi^+)$

- $v_1$ changes sign moving from central to peripheral collision
- $v_1$ slope is maximum for peripheral collision
Centrality dependence of $v_1$ ($K^+$)

- $v_1$ has weak centrality dependence for kaon
- $v_1$ slope is maximum for mid-central collision
Centrality dependence of $v_1$ (p)

- $v_1$ has weak centrality dependence compared to pions
- $v_1$ slope is maximum for mid-central collision
Collision energy dependence of $v_1$ slope ($\pi$, $K$, $p$)

- $v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

$$v_1(y) = by + cy^3$$

- Fitting range $\rightarrow [y: -1, 0]$
- Increasing collision energy $\rightarrow$ decreasing $v_1$ slope
- Mass ordering in slope: $dv_1/dy|_p > dv_1/dy|_K > dv_1/dy|_\pi$

The slope for published collider data was extracted using 1st order polynomial.
Rapidity dependence of $v_1$ (net $p$ and net $K$)

- Net particle $v_1$ is defined as

$$v_{1,\text{net}} = \frac{v_{1,p} - r v_{1,p}^\text{\bar{}}}{1 - r}$$

where $v_{1,p}, v_{1,p}^\text{\bar{}}$ → particle and antiparticle $v_1$ and $r$ is the ratio of anti-particles to particles

- Magnitude of net particle $v_1$ increases with increasing rapidity
Collision energy dependence of $v_1$ slope (net p and net K)

$v_1(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_1/dy$)

$v_1(y) = by + cy^3$

- Fitting range $\rightarrow [y: -1, 0]$
- Increasing collision energy $\rightarrow$ decreasing $v_1$ slope

The slope for published data was extracted using 1st order polynomial

Rapidity dependence of $v_1$ (p, d, t)

- Magnitude of $v_1$ increases with increasing rapidity
- Magnitude of $v_1$ increases with increasing mass of the particle
Collision energy dependence of $v_1$ slope (p, d, t)

- $v_1(y)$ fitted with a 3$^{rd}$ order polynomial to extract the slope parameter ($b = dv_1/dy$)
  $$v_1(y) = by + cy^3$$
- Fitting range $\rightarrow [y: -1, 0]$
- Increasing collision energy $\rightarrow$ decreasing $v_1$ slope

The slope for published data was extracted using 1$^{st}$ order polynomial

Triangular Flow ($v_3$) Results
Rapidity dependence of $v_3$

- Weak rapidity dependence of $v_3$ observed for pions
- Magnitude of proton $v_3$ increases with increasing rapidity
Collision energy dependence of $v_3$ slope

- $v_3(y)$ fitted with a 3rd order polynomial to extract the slope parameter ($b = dv_3/dy$)

\[ v_3(y) = by + cy^3 \]

- Fitting range $\rightarrow$ [y: -1, 0]
- Increasing collision energy $\rightarrow$ decreasing magnitude of $v_3$ slope

**Graph:**

- Au+Au, Collisions at RHIC, 10-40 %
- STAR Preliminary

**Data Points:**

- This analysis
  - $\pi^+$
  - $p$
- $p$: HADES (20-30 %)
- $p$: STAR Preliminary

**Legend:**

- HADES $\rightarrow$ p (20-30 %): 0.6 < $p_T$ < 0.9 GeV/c

Rapidity dependence of $v_3$

- Weak rapidity dependence of $v_3$ observed for deuteron compared to proton
Collision energy dependence of $v_3$ slope

- $v_3(y)$ fitted with a 3$^{rd}$ order polynomial to extract the slope parameter ($b = dv_3/dy$)

  $$v_3(y) = by + cy^3$$

- Fitting range $\rightarrow [y: -1, 0]$

- Increasing collision energy $\rightarrow$ decreasing magnitude of $v_3$ slope

HADES $\rightarrow$ p (20-30 %): $0.6 < p_T < 0.9$ GeV/c

Summary

- The rapidity, centrality, and collision energy dependence of directed flow ($v_1$) and triangular flow ($v_3$) of identified hadrons, net particle, and light nuclei for Au+Au collisions at 3.2, 3.5, and 3.9 GeV are presented.
- Magnitude of $v_1$ and $v_3$ increases with increasing rapidity.
- Slope of $v_1$ ($dv_1/dy$) decreases with increasing collision energy for all particles and light nuclei.
- $dv_1/dy$ for both net-kaon and net-proton shows a non monotonic behaviour at lower collision energies.
- Magnitude of $v_3$ slope ($dv_3/dy$) decreases with increasing collision energy for all particles and light nuclei.
Thank you for your attention!