Beam-energy dependence of the azimuthal anisotropic flow from RHIC

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Introduction

Ø Lattice QCD finds a smooth crossover at large T and $\mu_B \sim 0$ MeV

Ø Various models find a strong 1st-order phase transition at large $\mu_B$
Introduction

QCD Phase Diagram

- Lattice QCD finds a smooth crossover at large $T$ and $\mu_B \sim 0$ MeV

- Various models find a strong 1st-order phase transition at large $\mu_B$

- Strong interest in the theoretical calculations which span a broad $(T, \mu_B)$ domain.
  
  ✓ Search for QCD critical point
  ✓ Search for signals of the 1-st order phase transition
  ✓ Search for turn-off of the QGP signatures
Introduction

QCD Phase Diagram
Step-by-step on the QCD Phase Diagram

Beam-Energy Scan (BES-I) at RHIC

<table>
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<tr>
<th>√s_{NN} (GeV)</th>
<th>Events (10^6)</th>
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Beam-Energy Scan (BES-II) at RHIC

<table>
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<tr>
<th>Collision Energy (GeV)</th>
<th>$\mu_B$ (MeV) in 0-5% central collisions</th>
<th>Fixed Target Energy (GeV)</th>
<th>Fixed Target $\mu_B$ (MeV)</th>
<th>Proposed Event Goals in BES-II</th>
<th>BES-I Events</th>
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$\mu_B$ (MeV) in 0-5% central collisions

Fixed Target Energy (GeV)

Fixed Target $\mu_B$ (MeV)

Proposed Event Goals in BES-II

BES-I Events
Anisotropic flow

Asymmetry in initial geometry → Final-state momentum anisotropy (flow)
Anisotropic flow

Asymmetry in initial geometry → Final-state momentum anisotropy (flow)

\[ \varepsilon^+ \varepsilon^- \]

Introduction

\[ \frac{dN}{d\varphi} = 1 + 2 \sum_{n}^{\infty} \nu_n \cos(\varphi - \Psi_n) \]

- The flow harmonic coefficients \( (\nu_n) \) are influenced by eccentricities \( (\varepsilon_n) \), fluctuations, speed of sound \( (c_s(\mu_B, T)) \), and specific shear viscosity \( \eta_s(\mu_B, T) \)
Anisotropic flow

Asymmetry in initial geometry → Final-state momentum anisotropy (flow)

\[ \varepsilon_+ - \varepsilon_- \]

Introduction


\[ \frac{dN}{d\varphi} = 1 + 2 \sum_{n} v_n \cos(\varphi - \Psi_n) \]

- The flow harmonic coefficients \((v_n)\) are influenced by eccentricities \((\varepsilon_n)\), fluctuations, speed of sound \((c_s(\mu_B, T))\), and specific shear viscosity \(\frac{\eta}{\mathcal{S}}(\mu_B, T)\)

- Comprehensive set of flow measurements are important for:
  - Differentiate between initial-state models
  - Aid the extraction of \(\frac{\eta}{\mathcal{S}}(T, \mu_B)\)
Introduction

The Solenoidal Tracker At RHIC

Time Projection Chamber

- Tracking and identification of charged particles
- Full azimuthal coverage
- $|\eta|<1$ coverage
Azimuthal anisotropy measurements

Correlation function

Two-particle correlation function $C_r(\Delta \varphi = \varphi_a - \varphi_b)$,

$$C_r(\Delta \varphi) = \frac{dN}{d\Delta \varphi} \quad \text{and} \quad v_n^{ab} = \frac{\sum_{\Delta \varphi} C_r(\Delta \varphi) \cos(n \Delta \varphi)}{\sum_{\Delta \varphi} C_r(\Delta \varphi)}$$

Flow

Non-flow
Azimuthal anisotropy measurements

Correlation function

Two-particle correlation function $C_\varphi(\Delta \varphi = \varphi_a - \varphi_b)$,

$$C_\varphi(\Delta \varphi) = \frac{dN}{d\Delta \varphi} \text{ and } v_n^{ab} = \frac{\sum_{\Delta \varphi} C_\varphi(\Delta \varphi) \cos(n \Delta \varphi)}{\sum_{\Delta \varphi} C_\varphi(\Delta \varphi)}$$

$n > 1$

$\nu_n^{ab} = \nu_n^a \nu_n^b + \delta_{\text{short}}$

$n = 1$

$\nu_1^{ab} = \nu_1^a \nu_1^b + \delta_{\text{long}}$

Flow

Non-flow
Azimuthal anisotropy measurements

Correlation function

Two-particle correlation function $C_r(\Delta \phi = \phi_a - \phi_b)$,

$$C_r(\Delta \phi) = \frac{dN}{d\Delta \phi} \quad \text{and} \quad \nu_{n}^{ab} = \frac{\sum_{\Delta \phi} C_r(\Delta \phi) \cos(n \Delta \phi)}{\sum_{\Delta \phi} C_r(\Delta \phi)}$$

$n > 1$

$$\nu_{n}^{ab} = \nu_{n}^{a} \nu_{n}^{b} + \delta_{\text{short}}$$

$n = 1$

$$\nu_{1}^{ab} = \nu_{1}^{a} \nu_{1}^{b} + \delta_{\text{long}}$$

Flow

Non-flow

Non-flow

Short – range

HBT

Decay

Azimuthal anisotropy measurements

Correlation function

Two-particle correlation function \( Cr(\Delta \varphi = \varphi_a - \varphi_b) \),

\[
Cr(\Delta \varphi) = \frac{dN}{d\Delta \varphi} \quad \text{and} \quad v_n^{ab} = \frac{\sum_{\Delta \varphi} Cr(\Delta \varphi) \cos(n \Delta \varphi)}{\sum_{\Delta \varphi} Cr(\Delta \varphi)}
\]

\( n > 1 \)

\( v_n^{ab} = \nu_n^a \nu_n^b + \delta_{\text{short}} \)

\( n = 1 \)

\( v_1^{ab} = \nu_1^a \nu_1^b + \delta_{\text{long}} \)

Flow

Non-flow

Non-flow suppression is needed

Long – range

Short – range

Momentum Conservation

Di–jets

HBT

Decay

Short-range non-flow suppression

The $v_2$ vs. centrality at $\sqrt{s_{NN}} = 200$ GeV different using $\Delta \eta$ cuts

✓ Short-range non-flow effect reduced using $\Delta \eta > 0.7$ cut
Long-range non-flow suppression

\[ v_{11}^{ab} = v_1^{even}(p_T^a) v_1^{even}(p_T^b) + \delta_{long} \]

\[ v_{11}(p_T^a, p_T^b) = v_1^{even}(p_T^a) v_1^{even}(p_T^b) - K p_T^a p_T^b \]
Long-range non-flow suppression

\[ \nu_{11}^{ab} = \nu_1^{even}(p_T^a) \nu_1^{even}(p_T^b) + \delta_{\text{long}} \]

\[ \nu_{11}(p_T^a, p_T^b) = \nu_1^{even}(p_T^a)\nu_1^{even}(p_T^b) - K \ p_T^a \ p_T^b \]

\( \nu_{11} \) in Eq(1) represents NxM matrix which we fit with N+1 parameters

- \( \nu_{11} \) characteristic behavior gives a good constraint for \( \nu_1^{even}(p_T) \) extraction
Long-range non-flow suppression

\[ \nu_{11}(p_T^a, p_T^b) = \nu_{1}^{even}(p_T^a)\nu_{1}^{even}(p_T^b) - K p_T^a p_T^b \]

The extracted \( \nu_{1}^{even}(p_T) \) and the momentum conservation parameter, \( K \), at \( \sqrt{s_{NN}} = 200 \)

➢ The characteristic behavior of \( \nu_{1}^{even}(p_T) \) shows a weak centrality dependence
Long-range non-flow suppression

\[ \nu_{11}(p_T^a, p_T^b) = \nu_{1}^{\text{even}}(p_T^a)\nu_{1}^{\text{even}}(p_T^b) - K \ p_T^a \ p_T^b \]

The extracted \( \nu_{1}^{\text{even}}(p_T) \) and the momentum conservation parameter, \( K \), at \( \sqrt{s_{NN}} = 200 \) GeV.

- The characteristic behavior of \( \nu_{1}^{\text{even}}(p_T) \) shows a weak centrality dependence
- The momentum conservation parameter, \( K \), scales as \( \langle N_{ch} \rangle^{-1} \)

\[ (a) \text{ Au+Au 200 GeV} \]

\[ (b) \text{ STAR Preliminary} \]

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Flow harmonics
Beam-Energy Dependence of $v_1^{\text{even}}$

$$v_{11}(p_T^a, p_T^t) = v_1^{\text{even}}(p_T^a) v_1^{\text{even}}(p_T^t) - K p_T^a p_T^t$$

The extracted $v_1^{\text{even}}(p_T)$ at all BES energies

- Similar characteristic behavior of $v_1^{\text{even}}(p_T)$ at all energies
- $v_1^{\text{even}}(p_T)$ agrees with hydrodynamic calculations at 200 GeV

[Graph showing the behavior of $v_1^{\text{even}}(p_T)$ at various energies (200 GeV, 62.4 GeV, 39 GeV, 27 GeV, 19.6 GeV, 14.5 GeV, 11.5 GeV, 7.7 GeV)]

Beam-Energy Dependence of $\nu_1^{even}$

$$\nu_{11}(p_T^a, p_T^t) = \nu_1^{even}(p_T^a)\nu_1^{even}(p_T^t) - K p_T^a p_T^t$$

The extracted $\nu_1^{even}$ (Centrality) and the momentum conservation parameter at different beam energies

For different beam energies:

$\nu_1^{even}$ increases weakly as collisions become more peripheral
Beam-Energy Dependence of $v_1^{\text{even}}$

$$v_{11}(p_T^a, p_T^b) = v_1^{\text{even}}(p_T^a)v_1^{\text{even}}(p_T^b) - K p_T^a p_T^b$$

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For different beam energies;

- $v_1^{\text{even}}$ increases weakly as collisions become more peripheral
- Momentum conservation parameter, $K$, scales as $\langle N_{ch} \rangle^{-1}$
Beam-Energy Dependence of $v_1^{even}$

$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a)v_1^{even}(p_T^t) - K p_T^a p_T^t$

The extracted $v_1^{even}$ vs. $\sqrt{s_{NN}}$ at 0%-10% centrality
Beam-Energy Dependence of $v_1^{even}$

$$v_{11}(p_T^a, p_T^t) = v_1^{even}(p_T^a)v_1^{even}(p_T^t) - K p_T^a p_T^t$$

The extracted $v_1^{even}$ vs. $\sqrt{s_{NN}}$ at 0%-10% centrality

- $|v_1^{even}|$ shows similar values to $v_3$ at $0.4 < p_T < 0.7\text{ (GeV/c)}$

- $\varepsilon_3 > \varepsilon_1$

- $v_3$ has larger viscous damping effect than $v_1^{even}$
Beam-Energy Dependence of $v_n$

The extracted $v_{n>1}$ (Centrality) at all BES energies

- $v_n$ (Centrality) has similar trends for different beam energies.
- $v_n$ (Centrality) decreases with harmonic order, n.
The extracted $v_{n>1}$ vs. $\sqrt{s_{NN}}$ at 0-40% centrality

- $v_{n}(\sqrt{s_{NN}})$ shows a monotonic increase with beam energy.
- $v_{n}(\sqrt{s_{NN}})$ decreases with harmonic order, $n$, (viscous effects).
Viscous Attenuation

- Acoustic ansatz
  - Sound attenuation in the viscous matter reduces the magnitude of $\nu_{n=2,3}$.
    $$ \nu_{n} \propto k \varepsilon_{n}, \quad k = e^{-\beta n^2} $$

- Anisotropic flow attenuation:
  $$ \frac{\nu_{n}}{\varepsilon_{n}} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s} \frac{1}{RT} $$
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- From macroscopic entropy considerations:
  \[ S \sim (RT)^3 \sim \langle N_{Ch} \rangle \text{ then } RT \sim \langle N_{Ch} \rangle^{1/3} \]
  \[ \ln \left( \frac{v_n}{\varepsilon_n} \right) \propto - \left( \frac{\eta}{s} \right) \langle N_{Ch} \rangle^{-1/3} \]
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\[
\ln \left( \frac{\nu_n}{\varepsilon_n} \right) \propto -\left( \frac{\eta}{s} \right) \langle N_{Ch} \rangle^{-1/3}
\]

Using two different harmonics:

\[
\ln \left( \frac{\nu_n^{1/n}}{\nu_2^{1/2}} \right) + \ln \left( \frac{\varepsilon_2^{1/2}}{\varepsilon_n^{1/n}} \right) \langle N_{Ch} \rangle^{1/3} \propto -A \left( \frac{\eta}{s} \right)
\]

\[
\beta'' = \ln \left( \frac{\nu_n^{1/n}}{\nu_2^{1/2}} \right) \langle N_{Ch} \rangle^{1/3} \propto -A \left( \frac{\eta}{s} \right)
\]
The viscous coefficient shows a non-monotonic behavior with beam energy.

\[ \beta'' = \ln \left( \frac{v_n^{1/n}}{v_2^{1/2}} \right) \langle N_{\text{ch}} \rangle^{1/3} \propto -A \left( \frac{\eta}{s} \right) \]

Figure 3. \( \sqrt{s_{\text{NN}}} \) dependence of the \( p_T \)-integrated \( v_n \) (left panel) and the viscous coefficient \( \beta'' \) (right panel). Results are shown for 0-40% central Au+Au collisions; the shaded lines are the systematic uncertainty.
Summary

Comprehensive set of flow measurements were presented for Au+Au collision system at all BES energies with one set of cuts.

- For $\nu_n$:
  - $\nu_n$ vs centrality indicates a similar trend for different beam energies.
  - Momentum conservation parameter, $K$, scales as $\langle N_{\text{ch}} \rangle^{-1}$
  - $\nu_n(\sqrt{s_{NN}})$ shows a monotonic increase with beam-energy.

- The viscous coefficient shows a non-monotonic behavior with beam-energy

For different beam energies, these comprehensive measurements provide additional constraints for theoretical models, as well as $\frac{\eta}{s}$ extraction.
THANK YOU