Beam Energy Dependence of Azimuthal Correlations in Au-Au Collisions at Mid and Forward Rapidity

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The BES at RHIC allows the study of a broad domain of \((\mu_B, T)\) – plane.

\(\mu_B\) & T variations via beam energy or rapidity selections.

F. Becattini, PoSCPOD07:012,2007
QCD Phase Diagram

- Strong interest in measurements which span a broad \((\mu_B, T)\) domain.

- Investigate signatures for the first-order phase transition

- Investigate transport coefficients as a function of \((\mu_B, T)\)

- Possible non-monotonic patterns

- Search for critical fluctuations

PRL 112, 162301 (2014)

PRL 112, 032302 (2014)

PRL 116, 112302 (2016)
STAR Detector at RHIC

- TPC detector covers $|\eta| < 1$
- FTPC detector covers $2.5 < |\eta| < 4$

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Correlation function technique

- All current techniques used to study $\nu_n$ are related to the correlation function.
- Two particle correlation function $C(\Delta \varphi = \varphi_1 - \varphi_2)$ used in this analysis,

$$C(\Delta \varphi) = \frac{dN/d\varphi_{\text{same}}}{dN/d\Delta \varphi_{\text{mix}}} \quad \text{and} \quad \nu_n^2 = \frac{\sum_{\Delta \varphi} C(\Delta \varphi) \cos(n \Delta \varphi)}{\sum_{\Delta \varphi} C(\Delta \varphi)}$$

$$\nu_n(p_T) = \frac{\nu_n^2(p_{Tref}, p_T)}{\sqrt{\nu_n^2(p_{Tref})}} \quad \text{and} \quad \nu_n(\eta) = \frac{\nu_n^2(\eta, \eta_{ref})}{\sqrt{\nu_n^2(\eta_{ref})}}$$

- Factorization ansatz for $\nu_n$ verified.
- Non-flow signals, as well as some residual detector effects (track merging/splitting) minimized with $|\Delta \eta = \eta_1 - \eta_2| > 0.7$ cut.
Results

\[ \nu_n(pT) = \frac{\nu_n^2(p_{T\text{ref}},p_T)}{\sqrt{\nu_n^2(p_{T\text{ref}})}} \]

- |\eta| < 1

\[ \nu_n(\eta) = \frac{\nu_n^2(\eta,\eta_{\text{ref}})}{\sqrt{\nu_n^2(\eta_{\text{ref}})}} \]

- |\eta_{\text{ref}}| < 1 and |\eta| < 4
- 0.2 < p_T < 4\text{GeV}/c

\[ \nu_n(\sqrt{s_{NN}}) \]

- Viscous coefficient

Data presented with only statistical uncertainties
\( \nu_n(p_T) \) indicate a similar trend for different beam energies.

\( \nu_n(p_T) \) decreases with harmonic order \( n \).
\( \nu_n(p_T) \)

\( |\eta| < 1 \) and \( |\Delta\eta| > 0.7 \)

- \( \nu_n(p_T) \) indicate similar trends for different beam energies.
- \( \nu_n(p_T) \) decreases with harmonic order \( n \).
\( \nu_n(\eta) \) shows a weak dependence at different energies.

\( \nu_n(\eta) \) decreases with harmonic order \( n \).

\( |\eta| < 1 \) and \( |\Delta\eta| > 0.7 \)

\( 0.2 < p_T < 4\text{GeV}/c \)
\( v_n(\eta) \)

|\( |\eta| < 1 \) and |\( \Delta \eta \)| > 0.7

0.2 < \( p_T < 4 \text{GeV}/c \)

- Mid rapidity \( v_n(\eta) \) shows a weak dependence for different energies.
- \( v_n(\eta) \) decreases with harmonic order \( n \).
\( v_n(\eta) \)
\[ \text{for } |\eta_{ref}| < 1 \text{ and } |\eta| < 4 \]
\[ 0.2 < p_T < 4\text{GeV/c} \]

\( v_2(\eta) \) show similar trends for the respective beam energies.

\( v_2(\eta) \) increases with beam energy over the measured \( \eta \) range.

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\( \nu_n(\eta) \)

\[ |\eta_{ref}| < 1 \text{ and } |\eta| < 4 \]

\[ 0.2 < p_T < 4\text{GeV/c} \]

- Mid and forward rapidity \( \nu_n(\eta) \) decreases with harmonic order \( n \).
Reasonable agreement between the STAR and PHOBOS measurements.
\[ v_n(\sqrt{S_{NN}}) \]

- Mid rapidity \( v_n(\sqrt{S_{NN}}) \) shows a monotonic increase with beam energy.
- \( v_n(\sqrt{S_{NN}}) \) decreases with harmonic order \( n \).
Mid and forward rapidity $v_2(\sqrt{s_{NN}})$ shows a monotonic increase with beam energy.

Forward rapidity $v_2(\sqrt{s_{NN}})$ shows a stronger dependence.
Viscous coefficient

- Use $v_n(p_T, \text{cent})$ to extract the viscous coefficient as a function of $\sqrt{s_{NN}}$, based on the acoustic ansatz
  - the viscous coefficient encodes the transport coefficient $\frac{\eta}{s}$
Viscous coefficient

- The $v_n$ measurements are sensitive to $\varepsilon_n$, transport coefficient $\eta/s$ and the expanding parameter $RT$.

- Acoustic ansatz
  - Sound attenuation in the viscous matter reduces the magnitude of $v_n$.

- Anisotropic flow attenuation,
  $$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}$$

- For two different harmonics $n$ and $n'$ ($n' = 2$),
  $$\frac{(v_n)^{\frac{1}{n}}}{(v_{n'})^{\frac{1}{n'}}} \propto c \ e^{-\beta (n-n')} \quad \text{and} \quad \beta \propto \frac{\eta}{s} \frac{1}{RT} \quad c = \frac{(\varepsilon_n)^{\frac{1}{n}}}{(\varepsilon_{n'})^{\frac{1}{n'}}}$$

- From macroscopic entropy considerations
  $$\left( \frac{dN}{d\eta} \right) \propto \left( \frac{dN}{d\eta} \right)^{1/3} \ln \left( \frac{(v_n)^{\frac{1}{n}}}{(v_2)^{\frac{1}{2}}} \right) \propto -(n-2) \frac{\eta}{s} + \left( \frac{dN}{d\eta} \right)^{1/3} \ln(c)$$

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The viscous coefficient $\xi$ shows a non-monotonic behavior with beam energy in both cases, $n = 3$ and $n = 4$. 

$|\eta| < 1$ and $|\Delta\eta| > 0.7$  
$0.2 < p_T < 4 \text{ GeV/c}$
III. Conclusion

Comprehensive set of STAR measurements for $\nu_n(p_T, \eta, \text{cent}, \sqrt{s_{NN}})$ presented.

- Mid and forward rapidity $\nu_2$ shows a monotonic increase with beam energy,
  - Stronger $\sqrt{s_{NN}}$ dependence for forward $\nu_2$.

- For a given $\sqrt{s_{NN}}$, $\nu_n$ decrease with the harmonic order.
  - Similar patterns but different magnitude for different $\sqrt{s_{NN}}$

- The viscous coefficient $\xi$, which encodes the transport coefficient $\frac{\eta}{s}$, indicates a non-monotonic pattern for the beam energy range studied.
THANK YOU