Azimuthal Anisotropy Measurement by STAR

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Outline

• Physics motivation

• Beam energy dependence
  – $v_2\{4\}(p_T)$
  – $v_2\{2\}$ and $v_2\{4\}$ difference

• $v_3$ measurement
  – Centrality, $\Delta \eta$, $p_T$ dependence

• Flow fluctuation and nonflow
  – Isolation of nonflow and flow for $v_2$ from $\eta-\eta$ cumulant
  – $v_2$ fluctuation upper limit from $v_2\{2\}$, $v_2\{4\}$

• Summary

[Red box: Concentrate on AuAu; dAu separate talk F. Wang]
Particle collectivity to probe QGP early stage
Event-by-event initial state geometry fluctuation
- Final state momentum anisotropy, odd harmonics
Unknown reaction plane, fluctuation of participant plane
- Flow + flow fluctuation + nonflow
Few-particle correlation, unrelated to participant plane
The Solenoidal Tracker At RHIC (STAR)

- Time Projection Chamber: $dE/dx$, PID, momentum
- Forward Time Projection Chambers ($2.8 < |\eta| < 3.8$)
- Time Of Flight detector: $PID$, $1/\beta$
- Barrel ElectroMagnetic Calorimeter: $E/p$, trigger
- Endcap ElectroMagnetic Calorimeter ($1.0 \leq |\eta| < 2.0$)
- Forward Meson Spectrometer ($2.5 < |\eta| < 4.0$)
\( v_2 \) Beam Energy Dependence

\begin{itemize}
\item \( v_2 \) increases as beam energy.
  \begin{itemize}
  \item \( v_2(p_T) \)
  \item \( \langle p_T \rangle \)
  \item particle composition
  \end{itemize}
\end{itemize}

STAR preliminary

\[ v_2^* = 4 + v_2^* \cdot E_P + v_2^* \cdot E_P + v_2^* \cdot E_P + v_2^* \cdot E_P \]

STAR Preliminary

STAR BES energy QM2012
$v_2\{4\} (p_T)$ Beam Energy Dependence

- $v_2(p_T)$ indeed same w/ ± 30% < 10% below 1 GeV/c
- $\langle v_2 \rangle$ increase mainly due to $\langle p_T \rangle$

$v_2$ syst. err. ~ 7%

\( v_2 \{4 \} \) Comparison with Viscous Hydro

- Viscous hydro with constant \( \eta/s \) and zero net baryon density can not reproduce the trend of experimental data.

\[ \text{Hydro: C. Shen and U. Heinz, Phys. Rev. C 85, 054902(2012)} \]

Methods may be different
**v_2\{2\}, v_2\{4\} Beam Energies Dependence**

\[ \frac{v_2\{4\}}{v_2\{2\}} = \frac{\sqrt{v^2 - \sigma^2}}{\sqrt{v^2 + \sigma^2 + \delta}} \]

- \(v_2\{4\}/v_2\{2\}\) is closer to 1 at the lower collision energies, indicating smaller nonflow and/or fluctuation.

Li YI, IS2013, Spain
AuAu@200GeV $v_3$ Centrality Dependence

- $v_3$ centrality dependence.
- $v_3$ depends on methods. Need to look at $\Delta \eta$ window for methods.


$p_T$: 0.15-2GeV/c
$v_3$ Measurement $\Delta\eta$ Dependence

- Strong $\Delta\eta$-dependence

Nonflow, and/or fluctuation from event plane decorrelation?

- Model comparisons have to use same $|\Delta\eta|$
$v_3$ Comparison with other Experiment

\begin{align*}
v_3 &\approx \cos^3 \phi - \Psi_{EP}^2 \\
\Psi_{EP}^A &\approx \Delta \eta_{EP}^A \\
\Psi_{EP}^B &\approx \Delta \eta_{EP}^B
\end{align*}

\begin{table}
\begin{tabular}{|c|c|c|}
\hline
 & $|\eta|$ & $\langle \Delta \eta \rangle$ \\
\hline
STAR TPC & < 1.0 & 0.63 \\
STAR FTPC & < 1.0 & 3.21 \\
PHENIX & < 0.35 & 1.9 \\
ALICE & < 0.8 & > 1.0 \\
ATLAS & < 2.5 & > 0.8 \\
\hline
\end{tabular}
\end{table}

**EP decorrelation:**

\begin{align*}
\nu_3 &\approx \frac{\langle \cos 3(\phi - \Psi_{EP}) \rangle}{\sqrt{2\langle \cos 3(\Psi_{EP}^A - \Psi_{EP}^B) \rangle}} \\
\Psi_{EP}^A, \Psi_{EP}^B &\approx \Delta \eta_{EP}
\end{align*}

- STAR TPC: $\phi$, EP are both in TPC
- STAR FTPC: $\phi$ TPC, EP FTPC
- PHENIX: $\phi$ central arms, EP RXN

$\nu_3(\rho_T)$ same between RHIC and LHC.

\textit{Hannah Petersen, QM12}

\textit{Xiao, Liu, Wang, 1208.1195}

\textit{HP, Batthacharya, Bass, Greiner PRC 84 (2011)}
$v_3(p_T)$ Comparison with Models

Qualitative agreement with data:
- $\eta/s = 0.08$ hydro w/ Glauber initial condition
- NeXSPheRIO at low $p_T$
- PHSD mid central collision

Model $|\Delta\eta|$?

\( \nu_2 \) Flow Fluctuation Upper Limit

Upper limit for \( \frac{\sigma_2}{\nu_2} \):

\[
R_{\nu(2-4)} = \sqrt{\frac{\nu_2\{2\}^2 - \nu_2\{4\}^2}{\nu_2\{2\}^2 + \nu_2\{4\}^2}}
\]

- Compare models to data fluctuation upper limit
- Models have eccentricity fluctuations only. Data may have other fluctuation sources.
- Premature to conclude which \( \nu \) model is favored.
Isolation of Flow and Nonflow using 2- and 4-Particle \( \eta \)–\( \eta \) Cumulants

\[
V_2(\eta_\alpha, \eta_\beta) = v(\eta_\alpha)v(\eta_\beta) + \sigma(\eta_\alpha)\sigma(\eta_\beta) + \sigma'(\Delta \eta) + \delta(\Delta \eta)
\]

\[
v(\eta_\beta) = v(-\eta_\beta), \sigma(\eta_\beta) = \sigma(-\eta_\beta)
\]

\[
V_4(\eta_\alpha, \eta_\alpha, \eta_\beta, \eta_\beta)^{1/2} = v(\eta_\alpha)v(\eta_\beta) - \sigma(\eta_\alpha)\sigma(\eta_\beta) - \sigma'(\Delta \eta)
\]

\[
\Delta V\{2\} = V\{\eta_\alpha, \eta_\beta\} - V\{\eta_\alpha, -\eta_\beta\} = \Delta \sigma' + \Delta \delta
\]

\[
\Delta V\{4\}^{1/2} = -\Delta \sigma'
\]
\[ \Delta V \{4\}^{1/2} = -\Delta \sigma' \]

- Flow fluctuation appears independent of \( \Delta \eta \).
$\Delta \eta$-Dependence $\delta(\Delta \eta)$

\[ \Delta V\{2\} = V\{\eta_\alpha, \eta_\beta\} - V\{\eta_\alpha, -\eta_\beta\} = \Delta \sigma' + \Delta \delta \]
‘Flow’ vs $\eta$

$\nu_2$ flow seems independent of $\eta$.

$\left(\frac{\text{Fluctuation}}{\text{flow}}\right)^2$ for $\nu_2 \sim 13\%$
Nonflow $\delta_n$

$\delta_n$ drops as $\eta$ gap increases.

AuAu@200GeV 20-30%
Summary

• $<v_2\{4\}>$ values rise with increasing beam energy
  Possibly related to weaker radial flow at the lower energy, $<p_T>$.

• $v_3$ shows strong $\Delta\eta$ dependence
  – Event plane decorrelation
  – Nonflow

• $v_2$ in AuAu@200GeV 20-30%:
  Nonflow $\delta_2/v_2^2 \sim 4\%$
  Flow fluctuation $\sigma_2^2/v_2^2 \sim 13\%$