Beam Energy Dependence of First and Higher-Order Flow Harmonics from the STAR Experiment at RHIC

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Outline:

- Introduction and motivation
- The Beam Energy Scan at RHIC
- The STAR experiment
- $\nu_1$ in 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV Au+Au Collisions
- $\nu_3$ results in 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV Au+Au and 62.4 and 200 GeV Cu+Cu Collisions.
- $\nu_n$ (n=1-5) as a function of $p_T$ in 200 GeV Au+Au Collisions
- Summary
Introduction: Anisotropic Flow in Heavy ion Collisions

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

\[
\nu_n = \left\langle \cos n(\varphi - \psi_n) \right\rangle, \quad n = 1, 2, 3, \ldots
\]

- n=1 \quad \text{Directed Flow}
  - conventional(rapidity odd)
  - dipole asymmetry(rapidity even)

- n=2 \quad \text{Elliptic flow}
- n=3 \quad \text{Triangular flow}
- n=4, 5

Anisotropy in position space (initial) \(\rightarrow\) Anisotropy in momentum space (final)
Motivation: $v_1(y)$ Structure

J. Brachmann et al., PRC 61, 24909 (2000).

L.P. Csernai, D. Rohrich PLB 458, 454 (1999)

Anti-flow/3rd flow component: $v_1(y)$ of nucleons crosses zero 3 times (so-called “wiggle”) or flat $v_1$ at midrapidity due to 1$^\text{st}$ order phase transition.
Motivation: $v_3/v_n$

$\varepsilon_2^2 = \frac{\langle r^2 \cos(2\varphi) \rangle^2 + \langle r^2 \sin(2\varphi) \rangle^2}{\langle r^2 \rangle^2}$

$\varepsilon_3^2 = \frac{\langle r^2 \cos(3\varphi) \rangle^2 + \langle r^2 \sin(3\varphi) \rangle^2}{\langle r^2 \rangle^2}$

Triangular anisotropy in initial geometry can be quantified by “participant triangularity” analogous to participant eccentricity.

$v_3$ and higher harmonics ($v_n$) are sensitive to initial-state fluctuations and hydrodynamic evolution and they probe smaller length scale than $v_2$. 
RHIC Beam Energy Scan (BES) Program

**Motivation:**
Search for signals of phase boundary
Search for signals for critical point

**Established observables:**

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- RHIC successfully completed first phase of BES program in 2011.
- Directed flow results at $v_{NN} = 7.7, 11.5, 19.6, 27$ and 39 GeV are presented here.
- $v_3$ results in $7.7, 11.5, 19.6, 27, 39, 62.4$ and 200 GeV Au+Au and 62.4 and 200 GeV Cu+Cu collisions are presented.
- Transverse momentum dependence of higher harmonics ($n = 1-5$) at 200 GeV Au+Au collisions are presented.
STAR Experiment

- Time of Flight (TOF) provides excellent particle identification $p_T < 1.6$ GeV/c for pions ($0 < m^2 < 0.10$ (GeV $c^2$)$^2$), kaons ($0.20 < m^2 < 0.35$ (GeV $c^2$)$^2$) and $p_T < 2.8$ GeV/c for protons ($0.8 < m^2 < 1.0$ (GeV $c^2$)$^2$)

- Beam Beam Counters (BBC) ($3.3 < |\eta| < 5.0$) are used to reconstruct the first-order event plane at 39 GeV and lower beam energies. BBC provides adequate event plane resolution.

- Greatly reduced non-flow effects in $v_1$ study because of $\eta$ gap between TPC and BBC.

- Time Projection Chamber (TPC) is main tracking detector at STAR.

- Forward TPC (FTPC) ($2.5 < |\eta| < 4.0$) also provides tracking at forward rapidity
Proton and pion $v_1$

Directed flow of protons and pions at five different energies in central (0-10%), mid-central (10-40%) and peripheral (40-80%) collisions near midrapidity.

Baryon stopping + positive space-momentum correlation cannot explain both proton and pion flow simultaneously.

Beam energy dependence of $v_1$ slope ($F = dv_1/dy'$)

$$F = r F_{\text{anti-p}} + (1 - r) F_{\text{trans}},$$
where $r$ is the observed ratio of antiprotons to protons.

- Possible signature of EOS softening.
- $F_{\text{trans}}$ (labeled $p - \bar{p}$ in Fig.) is also called “net-proton” $v_1$ slope.
- We observe non-monotonic behavior of net-proton $v_1$ slope.
- UrQMD and AMPT cannot explain even the sign of the net proton data.
- Need more input from theory and more statistics to accurately measure centrality dependence to fully understand underlying physics.
Triangular flow: Method of Measurement

\[ \left\langle v_3^2 \{2\} \right\rangle = \frac{\int_{\Delta \eta = a}^{\Delta \eta = b} v_3^2 \{2, \Delta \eta\} \frac{dn}{d(\Delta \eta)} d(\Delta \eta)}{\int_{\Delta \eta = a}^{\Delta \eta = b} \frac{dn}{d(\Delta \eta)} d(\Delta \eta)} \]

The differences among methods are due to different \( \Delta \eta \) windows used to measure \( v_3 \).

We use TPC \( \eta \) sub-event plane method, with \( \eta \) gap of 0.05 between the two sub-events.
Beam Energy Dependence: 7.7-200 GeV Au+Au Collisions

- Triangular flow as a function of $p_T$: measurements at 7.7, 11.5, 19.6, 27 & 39 GeV lie below 200 GeV points at low $p_T$ but difference is less at higher $p_T$. 

STAR Preliminary
Beam Energy and System Size Dependence

- Triangular flow as a function of centrality within 0-20%, integrated in $p_T$ ($0.2 < p_T < 2.0$ GeV/c) and $\eta$ ($|\eta| < 1.0$): $v_3$ appears almost flat up to 27 GeV, with a large increase thereafter.
- $v_3$ persists all the way down to 7.7 GeV where jets are negligible.
- Triangular flow vs. $N_{\text{part}}$ depends on beam energy, but $v_3(N_{\text{part}})$ is about the same for Au+Au and Cu+Cu at each energy.
Flow harmonics ($n=1-5$) at 200 GeV: $p_T$ dependence

- $n=1$ is signal associated with dipole asymmetry, corrected for momentum conservation.
- Model curves for $n=1$ are from Retinskaya, Luzum & Ollitrault, PRL 108, 252302 (2012) ($\eta/s=0.16$); higher $n$ curves are from Gardim et al., arXiv:1203.2882 (ideal hydro) and for $n=2$ and $n=3$ with $\eta/s=0.16$ are from B. Schenke et al., PRL 106, 042301 (2011).
- The models do a good job describing the general features of the data. These comparisons suggest that low or zero viscosity is favored.
• For mid-central Au+Au collisions, proton directed flow slope \((dv_1/dy)\) changes sign from positive to negative between 7.7 and 11.5 GeV and remains small but negative up to 200 GeV; slope for pions, kaons and antiprotons remains always negative.

• The \(v_1\) slope for net protons shows non-monotonic behavior at low beam energies (is negative at 11.5 and 19.6 GeV & positive at all other energies). UrQMD & AMPT do not qualitatively account for the algebraic signs. More input from theory is necessary to fully understand this behavior.

• Triangular flow as a function of \(p_T\) measured for Au+Au at BES energies and compared with 62.4 and 200 GeV Au+Au and Cu+Cu. We also report centrality and \(N_{\text{part}}\) dependence of \(v_3\).

• All flow harmonics \((n=1-5)\) measured as a function of \(p_T\). These measurements provide significant inputs for understanding both initial fluctuation and transport properties.