PHENIX results on charged-hadron azimuthal anisotropies in Au+Au collisions at center-of-mass energies from 39 to 200 GeV

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Contents

• Energy dependence of $v_n$ in Au+Au
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• $v_2$ at high $p_T$ at 200 GeV in Au+Au
Azimuthal anisotropic observables

Anisotropic particle production is characterized by Fourier Coefficient $v_n$. 

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

\[
v_n = \langle \cos[n(\phi - \Psi_n)] \rangle, \quad n = 1, 2, 3, \ldots
\]

Initial geometrical anisotropy: $\varepsilon_n$

\[\downarrow\]

Momentum anisotropy: $v_n$

$v_n$ is sensitive to
- Initial condition
- QGP properties ($\eta/s$, partonic level flow)

2017/2/8

vn_PHENIX/QM2017  M.Shimomura
Energy dependence of $v_n$
$v_2$ at energy scan

*Aim: to map out the QCD phase diagram.*

\[ v_2 \text{ is not changing from 39 -200 GeV within uncertainty.} \]

**How about higher order harmonic $v_3$ ?**

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$v_3$ at 200, 62.4 and 39GeV
Ratio of $v_3$ (39,62 GeV)/$v_3$(200 GeV)

$v_3$ is also saturated for 39 – 200 GeV.
Forward/Backward $v_n$ in Cu+Au

Details are described in Hiroshi Nakagomi’s Poster[K03]
\( v_n \) in Cu+Au (mid-rapidity)

Cu+Au collisions provide additional insight of initial geometry(\( \varepsilon_n \)) effect.

- \( v_2/\text{eccentricity}(dN/d\eta) \) does not depend on the collision systems at mid-rapidity.
How about forward and backward?

Possibilities
1. Asymmetric initial geometry due to initial-state fluctuations along $\eta$: $\varepsilon_n(\eta) \neq \varepsilon_n(-\eta)$
2. Twisted plane azimuth: $\Psi_n(\eta) \neq \Psi_n(-\eta)$
3. Asymmetric energy density: $dN/dn(\eta) \neq dN/dn(-\eta)$

$v_n$ in Cu+Au provides insight of longitudinal eccentricity effect.
→ Measure $dN/d\eta$ and $v_n$ at forward/backward.

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Charged particle $dN/d\eta$ ($\eta$) and $v_n(\eta)$

200 GeV

20~30%

Au+Au

Cu+Au

Cu+Cu

PHENIX preliminary

$v_n$ PHENIX/QM2017 M.Shimomura
Charged particle $dN/d\eta$ ($\eta$) and $v_n(\eta)$

In Cu+Au

- $dN/d\eta$(Au-going) > $dN/d\eta$(Cu-going)
Charged particle $dN/d\eta$ ($\eta$) and $v_n(\eta)$

In Cu+Au

- $dN/d\eta$(Au-going) > $dN/d\eta$(Cu-going)
Charged particle $dN/d\eta (\eta)$ and $v_n(\eta)$

In Cu+Au

- $dN/d\eta$(Au-going) $> dN/d\eta$(Cu-going)
- $v_n$(Au-going) $> v_n$(Cu-going)
Charged particle $dN/d\eta (\eta)$ and $v_n(\eta)$

In Cu+Au
- $dN/d\eta$(Au-going) $> dN/d\eta$(Cu-going)
- $v_n$(Au-going) $> v_n$(Cu-going)
Possible definitions of eccentricity

\[
\epsilon_{n,\text{Au}(\text{Cu})} = \frac{\langle r^n \cos[n(\phi_{\text{Au}(\text{Cu})} - \Phi_{n,\text{Cu}+\text{Au}})] \rangle}{\langle r^n \rangle}
\]

\(\epsilon\) calculated by participant geometry with MC-Glauber model.

Three types of \(\epsilon\) are examined for eccentricity scaling.

\(\epsilon_{n,\text{Au}}\): Use only participants which belong to Au nuclei

\(\epsilon_{n,\text{Cu}}\): Use all participants (common participant \(\epsilon\))

\(\epsilon_{n,\text{Cu}+\text{Au}}\): Use only participants which belong to Cu nuclei
Forward/backward $v_n$ vs. $dN_{ch}/d\eta$

$v_{n,\text{Au-going}} \neq v_{n,\text{Cu-going}}$

$v_n (dN/d\eta)$ at Au-going $\neq v_n (dN/d\eta)$ at Cu-going
\( \frac{v_n}{\varepsilon_n} \) do not agree.

\( \frac{v_{n,Au-going}}{\varepsilon_{n,Au}} \) and \( \frac{v_{n,Cu-going}}{\varepsilon_{n,Cu}} \) do not agree.
\( \frac{v_n}{\varepsilon_n} (2) \)

\[
\begin{align*}
\text{Cu+Au Au-going } & \varepsilon_{2,\text{Au-going}} = \varepsilon_{2,\text{Cu}} \\
\text{Cu+Au Cu-going } & \varepsilon_{2,\text{Cu-going}} = \varepsilon_{2,\text{Au}}
\end{align*}
\]

\[
\begin{align*}
\text{Cu+Au Au-going } & \varepsilon_{3,\text{Au-going}} = \varepsilon_{3,\text{Cu}} \\
\text{Cu+Au Cu-going } & \varepsilon_{3,\text{Cu-going}} = \varepsilon_{3,\text{Au}}
\end{align*}
\]

Charged hadron \( 3<|\eta|<3.9 \)

\( \sqrt{s_{\text{NN}}}=200 \text{ GeV} \)

\( dN_{\text{local}}^{\text{ch}} / d\eta \)

(\( v_n,\text{Au-going} / \varepsilon_n,\text{Cu} \)) and (\( v_n,\text{Cu-going} / \varepsilon_n,\text{Au} \)) do not agree.
\[ \frac{v_n}{\varepsilon_n} (3) \]

(\(v_{n,Au\text{-going}} \big/ \varepsilon_{n,CuAu}\)) and (\(v_{n,Cu\text{-going}} \big/ \varepsilon_{n,CuAu}\)) agree!
- F/B asymmetry is caused by \( dN/d\eta \) (initial energy density).
$v_2$ for charged hadrons at high $p_T$
Azimuthal anisotropy at high $p_T$

- $v_2$ measurement is same as low $p_T$, but reasons are different.
- $v_2$ at high $p_T$ is due to initial anisotropy and parton energy loss.

[PHENIX: PRC.92.034913 (2015)]

2004 data: 800 M events

(a) Au+Au, 200 GeV $\Theta$ 0-10%  20-30%  10-20%  30-40%

(b) 40-50%  60-70%  50-60%  Minimum Bias

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\( v_2 \) at high \( p_T \) in Au+Au at 200GeV

- Difference between charged hadron and \( \pi^0 \) \( v_2 \) diminishes with \( p_T \).
- Proton contribution is seen at more central collisions.
High $p_T v_2$ at different centralities

- At $p_T > 6\text{GeV/c}$, $v_2$'s of different centralities converge.
- This is not consistent with path-length dependent energy loss, large uncertainties notwithstanding.
Upcoming improvement to high $p_T v_2$

Improvements are expected with:

- 8 times larger statistics with all 2014+2016 data. (3B $\rightarrow$ 12+12 B)

- 2 times better RP resolution with FVTX

- Tuning EMCAL energy cut depending on $p_T$ to increase signal tracks at high $p_T$. 
Summary

- Energy scan
  - $v_n$ is saturated from $\sqrt{s_{NN}}=39$ GeV up to 5 TeV.

- Forward/Backward $v_n$ in Cu+Au
  - $dN/d\eta$(Au-going) > $dN/d\eta$(Cu-going)
  - $v_n$(Au-going) > $v_n$(Cu-going)
  - Initial geometry could be boost invariant at same $dN/d\eta$ between $-4<\eta<+4$

- $v_2$ for charged hadrons at high $p_T$
  - At higher $p_T$, no significant difference in $v_2$ between charged hadrons and $\pi^0$.
  - At $p_T$ above 6 GeV/c, $v_2$ looks constant around 0.1 from centralities around 0-30% within uncertainties that will be reduced in the future.
Related PHENIX Posters

[Poster]

• **K03:NAKAGOMI Hiroshi**
  Forward/Backward asymmetry of $v_n$ in Cu+Au at RHIC-PHENIX
Back Up
\[ \varepsilon_{n,\text{Au(Cu)}} = \frac{\langle r^n \cos[n(\phi_{\text{Au(Cu)}} - \Phi_{n,\text{Cu+Au}})] \rangle}{\langle r^n \rangle} \]
- Common $\varepsilon_{n,Cu+Au}$ scales $v_n$ at both Au-going and Cu-going.
- F/B asymmetry is caused by $dN/d\eta$ (initial energy density).
$v_2$ at 200, 62.4 and 39 GeV

$v_2(p_T)$ is already saturated at 39 GeV!
$v_n$ saturation up to LHC energy

$v_2$, $v_3$ and $v_4$ are saturated from 39GeV up to LHC energy.
$\eta/d_{ch} \text{ local}$

$0 \leq d_{ch} \leq 200$ GeV

$0.01 \leq v_3 \leq 0.04$

Charged hadron

$|\eta|<0.35$, $0<p_T<3$ GeV/c

$\sqrt{s_{NN}}=200$ GeV

Au+Au PHENIX PRL 107 252301

Cu+Au PHENIX PRC 94 054910

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v3 vs. $p_T$ for AuAu/CuAu

- Weak centrality dependence in AuCu
- CuAu is always bigger than AuAu.
Mid-rapidity $v_2/\varepsilon_2$

- Au+Au 200GeV
- Cu+Au 200GeV
- Cu+Cu 200GeV

Charged hadron $v_2$ $|\eta|<0.35$

MC-Glauber

Mid-rapidity $v_3/\varepsilon_3$

- Au+Au 200GeV
- Cu+Au 200GeV

Charged hadron $v_3$ $|\eta|<0.35$

MC-Glauber

PHENIX preliminary
Weighted $N_{\text{part}}$ scaling: $N_{\text{part}} = w N_{\text{part,Au}} + (2-w) N_{\text{part,Cu}} \quad (2 N_{\text{part,Cu}} < N_{\text{part}} < 2 N_{\text{part,Au}})$

Cu-going side $dN/d\eta$

Au-going side $dN/d\eta$
\( v_n / (\varepsilon_n^* N_{\text{part}}^{1/3}) \) in Cu+Au (mid-rapidity)

[PRC.92.034913]
[PRC94,054910]
$\varepsilon_3^* N_{\text{part}}^{(1/3)}$ scaling for $v_3$

$\varepsilon_3^* N_{\text{part}}^{(1/3)}$ scaling works well in $v_3$. 

arxiv:1509.07784
Scaling

- Different Energy and System (AuAu200, CuCu200, AuAu62)
- Different Centrality (0-50%)
- Different particles ($\pi$ / $K$ / $p$)

$$v_2(K_{ET}/n_q)/n_q/\varepsilon/N_{part}^{1/3}$$

Almost scale to one curve.