Systematic Study of Elliptic Flow
at RHIC-PHENIX

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University of Tsukuba

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14 Countries; 69 Institutions
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- RHIC-PHENIX
- Elliptic Flow (v_2)
- Motivation

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- System size dependence
- Universal v_2

Conclusion
Quark Gluon Plasma (QGP)

Prediction from Lattice QCD

\[ T \sim 170 \text{ MeV} \]
\[ \rho \sim 1.0 \text{ GeV/fm}^3 \]

Quarks become de-confined

Phase transition to QGP

* Normal Nucleus: \[ \rho \sim 0.2 \text{ GeV/fm}^3 \]

High energy nuclear collision

Au+Au \[ \sqrt{s} = 200 \text{GeV} \]

\[ \text{RHIC} : 5 \sim 15 \text{ GeV/fm}^3 \]
Relativistic Heavy Ion Collider (RHIC)

- Brookhaven National Laboratory
- First relativistic heavy ion collider in the world
- Circumference 3.83 km, 2 rings
- Collision species (Au+Au, Cu+Cu, d+Au, p+p)
- Energy (A+A); up to 100 GeV/nucleon
- PHENIX is one of the main experiment groups

Time-evolution after collision:
- Thermal freezeout
- Chemical freezeout
- Hadronization
- QGP thermal equilibrium
- Collision

PHENIX Experiment
Elliptic Flow ($v_2$)

$v_2$ is the strength of the elliptic anisotropy of produced particles.

A sensitive probe for studying properties of the hot dense matter made by heavy ion collisions.

non central collision

beam axis $z$

$\frac{dN}{d\phi} = n\left\{1 + 2v_2 \cos\left[2(\phi - \Phi_{RP})\right]\right\}$

The initial geometrical anisotropy is transferred by the pressure gradients into a momentum space anisotropy $\rightarrow$ the measured $v_2$ reflects the dense matter produced in the collisions.

If yield is (x direction)$\succ$(y direction), $v_2 >0$. 

Fourier expansion of the distribution of produced particle angle, $\Phi$, to RP $\rightarrow$ indicates ellipticity.
Motivation

From the results at 200 GeV

$v_2$ at low $p_T (< \sim 2 \, \text{GeV/c})$ can be explained by a hydro-dynamical model.

$v_2$ at mid $p_T (< 4\sim 6 \, \text{GeV/c})$ is consistent with recombination model.

The results are consistent with Quark number +KE$_T$ scaling.

How about other systems and energies !?

KE$_T = m_T - m_0$
Results

- Energy dependence
- System size dependence
  - Eccentricity scaling
- Universal $v_2$
  - Quark number + $K_{ET}$ scaling
  - Universal scaling
$N_{\text{part}}$ --- Number of nucleons participating the collision
$N_{\text{coll}}$ --- Number of binary collisions
eccentricity($\varepsilon$) --- geometrical eccentricity of participant nucleons

- Nucleus formed by wood-Saxon shape
- Monte-Carlo simulation with Glauber model
- Participant eccentricity which is calculated with long and short
  axis determined by distribution of participants at each collision.

$$
\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}
$$
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- **Is going to check next**: Pink circle

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Energy dependence

Comparison of $\sqrt{s} = 62.4$ and 200 GeV

- dependence of centrality (Npart)
- compare the results in Cu + Cu which is smaller collision size than Au+Au
- comparison of PID hadrons. pi/K/p

$v_2$ of 200GeV and 62GeV are consistent
Energy dependence

- identified hadrons (π/K/p)
- p_T dependence

\( v_2 = 17 \text{GeV} \) (SPS) decreases to about 50% of RHIC energies.
Higher collision energy has larger \( v_2 \) up to RHIC energy.
Above 62.4 GeV, \( v_2 \) is saturated.

\[ \downarrow \] indicate the matter reached thermal equilibrium state at RHIC

<\( p_T \>) \text{ of 62.4 GeV and 200 GeV are consistent within errors on } \pi/K/p \text{. Therefore } v_2 \text{ agree at any } p_T \text{ region in figures.}

\( v_2 \) of \( \sqrt{s} = 17 \text{GeV} \) (SPS) decreases to about 50% of RHIC energies.
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System Size Dependence

Eccentricity Scaling

What can change the size of collision system.

• Species of collision nucleus (Au+Au, Cu+Cu)
• Centrality
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System size dependence

Compare $v_2$ normalized by eccentricity ($\varepsilon$) in the collisions of different size.

$0.2<p_T<1.0$ [GeV/c]
System size dependence

Compare $v_2$ normalized by eccentricity ($\varepsilon$) in the collisions of different size.

$0.2 < p_T < 1.0 \text{ [GeV/c]}$

$v_2$ vs. $N_{\text{part}}$

$v_2/\varepsilon$ vs. $N_{\text{part}}$

$v_2/\varepsilon$ (Au+Au) = $v_2/\varepsilon$ (Cu+Cu) !

Systematic errors from eccentricity is not included here.
System size dependence

Compare $v_2$ normalized by eccentricity ($\varepsilon$) in the collisions of different size.

$v_2/\varepsilon$ vs. $N_{\text{part}}$

$0.2<p_t<1.0$ [GeV/c]

$v_2/\varepsilon$ is not constant and it shades depending on $N_{\text{part}}$.

$v_2/\varepsilon$ (Au+Au) = $v_2/\varepsilon$ (Cu+Cu)!

but $v_2/\varepsilon$ is not constant and it shades depending on $N_{\text{part}}$.

$v_2$ can be normalized by $\varepsilon$ at same $N_{\text{part}}$, but $\varepsilon$ is not enough to determine $v_2$.

Systematic errors from eccentricity is not included here.
System size dependence

0.2<p_T<1.0 [GeV/c]

$\frac{v_2}{N_{part}^{1/3}}$ vs. $N_{part}$

$\frac{v_2}{\varepsilon}$ vs. $N_{part}$

$\frac{v_2}{\varepsilon}$ (Au+Au) = $\frac{v_2}{\varepsilon}$ (Cu+Cu)

$v_2$/eccentricity is scaled by $N_{part}^{1/3}$ and not dependent on the collision system.

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Systematic errors from eccentricity is not included here.
System size dependence

1.0 < p_T < 2.0 [GeV/c]

$v_2$ vs. $N_{\text{part}}$

$\frac{v_2}{\varepsilon}$ vs. $N_{\text{part}}$

$V_2/\varepsilon/N_{\text{part}}^{1/3}$ vs. $N_{\text{part}}$

Systematic errors from eccentricity is not included here.

$v_2$/eccentricity is scaled by $N_{\text{part}}^{1/3}$ and not dependent on the collision system.
System size dependence

2.0 < p_T < 4.0 [GeV/c]

\( v_2 \) vs. \( N_{\text{part}} \)

\( v_2/\epsilon \) vs. \( N_{\text{part}} \)

Dividing by \( N_{\text{part}}^{1/3} \)

\( V_2/\epsilon/N_{\text{part}}^{1/3} \) vs. \( N_{\text{part}} \)

Systematic errors from eccentricity is not included here.

\( v_2/\text{eccentricity} \) is scaled by \( N_{\text{part}}^{1/3} \) and not dependent on the collision system.

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Universal $v_2$

- Quark number + $K_{ET}$ scaling
- Universal Scaling
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Quark number + $K_{ET}$ scaling (AuAu 62.4 GeV)

PHENIX: Error bars include both statistical and systematic errors.

STAR: Error bars include statistical errors. Yellow band indicates systematic errors.

Centrality 10-40 %

Star results: Phys. Rev. C 75

quark number + $K_{ET}$ scaling is OK at 62.4 GeV, too!

$v_2(p_T)/n_{\text{quark}}$ vs. $K_{ET}/n_{\text{quark}}$ is the universal curve independent on particle species.
Centrality dependence of PID $v_2$ vs. $p_T$ for Cu+Cu 200GeV is measured.
Quark number + $K_{ET}$ scaling seems to work out at Cu+Cu 200GeV.

At all centrality, (between 0 - 50 %) $v_2$ of $\pi/K/p$ is consistent to quark number + $K_{ET}$ scaling.

- $\pi$
- $K$
- $p$

Quark number + $K_{ET}$ scaling seems to works out at Cu+Cu 200GeV.
Summary of Scaling

- Collision energy: no change
- Eccentricity of participants: eccentricity scaling
- Particle species: $n_q + K_{ET}$ scaling
- Number of participants: $N_{part}^{1/3}$ scaling
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Universal Scaling

quark number + $K_{ET}$ scaling.

$\frac{v_2}{n_q}$ vs. $m_t - m_t/n_q \pi$

- 0-10 %
- 10-20 %
- 20-30 %
- 30-40 %
- 40-50 %
Universal Scaling

ex. Au+Au 200GeV π

quark number + $K_{ET}$ scaling.

+ eccentricity scaling
Universal Scaling

quark number + $K_{ET}$ scaling.

+ eccentricity scaling

+ Npart$^{1/3}$ scaling

$v_2(K_{ET}/n_q)/n_q/\epsilon_{par}/N_{part}^{1/3}$ is consistent at 0-50% centralities.

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Universal Scaling

Different System (Au+Au, Cu+Cu)
Different Energy (200GeV - 62.4GeV)
Different Centrality (0-50%)
Different particles ($\pi$, K, p)

$\frac{v_2}{(\varepsilon_{\text{part}}N_{\text{part}}^{1/3}n_q)}$

$2/ndf = 8.1$

Universal Curve!!
Conclusion

- \( v_2 \) were measured at 4 systems.
  - (Au+Au, Cu+Cu) x (62.4GeV, 200GeV)
- Same \( v_2(p_T) \) are obtained in different collision energies (\( \sqrt{s} = 62.4 - 200\text{GeV} \))
- \( v_2(p_T) \) of various hadron species are scaled by quark number + \( K_{ET} \) scaling at these three systems. (no results for Cu+Cu 62.4GeV )
- \( v_2(N_{\text{part}}) \) scaled by participant Eccentricity are consistent between Au+Au and Cu+Cu collisions
- \( v_2(p_T)/\epsilon_{\text{par}} \) are scaled by \( N_{\text{part}}^{1/3} \).
- \( v_2(K_{ET}/n_q)/n_q/\epsilon_{\text{par}}/N_{\text{part}}^{1/3} \) has Universal Curve.
  - This indicates \( v_2 \) are determined by the initial geometrical anisotropy and its time evolution effect depending on the initial volume.
Calculation by simple expansion model

Assumption

Calculation is done by Dr. Konno

Time until chemical freeze-out is proportional to $N_{\text{part}}^{1/3}$.

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Summary of $v_2$ production and development

**Low to mid $p_T$**

- **Time $t$**
  - **collision**
    - Determine initial geometrical eccentricity, $\varepsilon$, with the participant.
  - **thermal equilibrium**
    - Determine pressure gradient from $\varepsilon$.
  - **expanding**
    - $v_2$ is expanding during finite time.
    - Not depending on the kind of quarks.
      - This finite time becomes longer with larger collision system, and the $v_2$ increases proportionally.
    - radial flow depending on each mass expands.
  - **hadronization**
    - No change
  - **freeze out**
    - Measurement

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Summary (1)

When the systems have same $N_{\text{part}}$, $v_2$ is scaled by $\varepsilon$ of participant geometry.

If $v_2$ only depends on eccentricity of initial participant geometry, $v_2/\varepsilon$ should be constant at any $N_{\text{part}}$, but it is not.

Therefore, to explain $v_2$, in addition to the initial geometrical eccentricity, there are something related to $N_{\text{part}}$.
Summary (2)

With same eccentricity, $v_2$ is scaled by (number of participants)$^{1/3}$.

$v_2$ becomes consistent after scaled by not only $\varepsilon$ but also $N_{\text{part}}^{1/3}$.

Is it because of thickness increasing along beam axis then energy per unit area increasing?

$v_2(200\text{GeV}) = v_2(62.4\text{GeV})$

This concludes that increasing $dN/dy$ doesn’t change $v_2$ at RHIC energy.

It might be because that number of participant to $1/3$ (like length) is proportional to the time period taken to freeze out $v_2$, and $v_2$ expands proportional to that period.
Back Up
Various scalings.
Eccentricity of $N_{\text{part}}$ and $N_{\text{part}}^{1/3}$ looks best.
Comparison of AuAu to CuCu

Cu+Cu and Au+Au, 200GeV, PID by EMC

Apply quark number + KET scaling, eccentricity scaling and Npart$^{1/3}$ scaling.
Energy dependence

\[ \sqrt{s_{NN}} \text{ (GeV)} \]

\begin{itemize}
\item PHENIX : Preliminary.
\item PHOBOS : nucl-ex/0610037 (2006).
\end{itemize}
Quark number + $K_{ET}$ scaling (AuAu 200GeV)

Quark number + $K_{ET}$ scaling exists.
Additional quark number + $K_{ET}$ scaling (PbPb 17.2GeV)

$v_2$ of $p$, $\bar{p}$, $\Xi$ - C. Alt et al (NA49 collaboration) nucl-ex/0606026 submitted to PRL
$v_2$ of $K^0$ (preliminary) - G. Stefanek for NA49 collaboration (nucl-ex/0611003)

- Quark number + $K_{ET}$ scaling doesn’t seem to work out at SPS.
- No flow at partonic level due to nonexistence of QGP?
- Errors are too big to conclude it.
$t_{f0}$ vs. $N_{\text{part}}$

\[
T(t) = T_0 \left( \frac{t_0 (R_0 + \beta t_0)^2}{t (R_0 + \beta t)^2} \right)^{1/3}
\]

\[
t_{f0} = \frac{\sqrt{R_0^2 + 4 \beta T K N_p} - R_0}{2 \beta T}
\]

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Comparison between Au+Au and Cu+Cu

Both behave same at mid central.
Additional $N_{\text{part}}$ scaling

Au+Au 200GeV

At high $p_T (> 6 \text{GeV/c})$, scaling might work out but errors are too large to conclude.

→ need to analyze the data with higher statistics. (ex. Run7)

By spectra analysis, the strength of the suppression seems to be consistent at same $N_{\text{part}}$. It doesn’t depend on the nucleus species of collision system (Au+Au, Cu+Cu).

→ $R_{AA}$ can be scaled by $N_{\text{part}}$. 
Analysis

- EMCAL for Particle Identification resolution = 380 ps
- TOF for Particle Identification resolution = 120 ps
- DC + PC1 for good track selection and to determine p
- BBC to determine reaction plane and vertex

**<PID by TOF measurement>**

Using TOF or EMC with BBC, the flight time of the particles is obtained. Mass of the particle is calculated by the flight time and the momentum measured by DC.

**<Reaction Plane determination>**

The reaction plane is obtained by measurement of the anisotropic distribution for the produced particles with north and south BBCs located at $|\eta| \sim 3 - 4$. 
Resolution Calculation of Reaction Plane

\[ \text{resolution} = \langle \cos(2(\Psi_{\text{measured}} - \Psi_{\text{true}})) \rangle \approx \sqrt{\langle \cos(2(\Psi_A - \Psi_B)) \rangle} \]

\(\Psi_{A,B}\) : reaction plane determined for each sub sample.

\[
\nu_2^{\text{real}} = \frac{\nu_2^{\text{measured}}}{\text{resolution}}
\]

\(\text{BBC North + South combined}\)