What have we learned from Anisotropic Flow at RHIC?

Hiroshi Masui
for the PHENIX Collaboration

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Workshop 8: How perfect is this matter?
RHIC Scientists Serve Up “Perfect” Liquid

New state of matter more remarkable than predicted -- raising many new ques

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TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion -- a giant atom "smasher" located at the U.S. Department of Energy’s Brookhaven National Laboratory -- have created a new state of hot, dense matter out of the quarks and gluons that make up protons and neutrons, but it is not a state quite different and even more remarkable than predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists found that the collisions of gold ions nearly perfect liquid, nearly perfect liquid, nearly perfect liquid, nearly perfect liquid.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal sponsor of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of RHIC's heavy ion collisions appears to be more like a liquid.
**Definitions**

- **Anisotropic Flow**
  - Azimuthal correlation to reaction plane
  - Elliptic flow ($v_2$)

\[
\epsilon = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle
\]

\[
v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle
\]

\[
E \frac{d^3N}{dp^3} = \frac{1}{2\pi p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi)] \right)
\]

\[
v_n = \left\langle \cos[n(\phi - \Psi)] \right\rangle
\]
Outline

• Elliptic Flow and Hydrodynamics
• PHENIX experiment
  – Particle identification, event plane
• Eccentricity scaling and speed of sound
• Kinetic energy (Hydro) scaling and Partonic collectivity
• Summary
**$v_2$ and hydrodynamics**

Large elliptic flow at RHIC

Elliptic flow is well described by hydrodynamics
- Magnitude, particle type up to $p_T \sim 1.5$ GeV/c
- Indicate early thermalization $\tau < 1$ fm/c, extremely low viscosity $< 0.1$

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PHENIX experiment

- **Hadron identification**
  - Time-of-Flight
    - $|\eta| < 0.35$, $|\phi| < \pi/4$
  - EM Calorimeter
    - $|\eta| < 0.35$, $|\phi| < \pi/2$
- **Event plane**
  - Beam Beam Counter, $3 < |\eta| < 3.9$, full azimuth
Hadron identification

- **Time-of-flight**
  - $|\phi| < \pi/4$, $|\eta| < 0.35$
  - Timing resolution ~ 120 ps
    - $\pi/K$ separation ~ 2 GeV/c
    - K/p separation ~ 4 GeV/c
- **Good timing resolution**

- **EM Calorimeter**
  - $|\phi| < \pi/2$, $|\eta| < 0.35$
  - Timing resolution ~ 400 ps
    - $\pi/K$ separation ~ 1 GeV/c
    - K/p separation ~ 2 GeV/c
- **Large acceptance**
**Event plane @ 3<|\eta|<4**

- Large rapidity gap
  - Central arm $|\eta| < 0.35$ \[\Longleftrightarrow\] BBC 3 < $|\eta|$ < 4
  - Smaller non-flow contribution

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**v₂ from ideal fluid dynamics**

\[
\frac{v_2}{\varepsilon} = \frac{1}{\sqrt{3}}
\]
\[t_0 = 0.6 \text{ fm/c}\]

\[
1/R = \sqrt{1/\langle x^2 \rangle + 1/\langle y^2 \rangle}
\]
transverse size of system

- \(v_2\) scales initial eccentricity (\(\varepsilon\))
- \(v_2/\varepsilon\) is independent on system size \(R\)
- \(v_2\) grows with \(c_s\)
- Can we test these relations from the data?

Can we test eccentricity scaling of $v_2$?

- Does $v_2$ scale eccentricity?
  - Centrality dependence of $v_2/\varepsilon$
- Is $v_2/\varepsilon$ independent of system size?
  - $Au+Au$ vs $Cu+Cu$
- Estimate of speed of sound can be made from the measurement of $v_2/\varepsilon$
Eccentricity and integrated $v_2$

- Eccentricity is usually estimated by Glauber Model
- Integrated $v_2$ is proportional to eccentricity
- Advantage of integrated $v_2$:
  - Reduce large systematic error from Glauber MC, typically 20 – 30 %
  - Cancel systematic error from event plane determination
Eccentricity scaling

Scaling holds for a broad range of centrality

- Centrality 30-40%, b ~ 8.7 fm

Independent of system size

\[ k \sim 3.1 \text{ obtained from data} \]

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Estimate of $c_s$

$\frac{v_2}{\epsilon} @ <p_T> \sim 0.45$ GeV/c

$\epsilon$ = 0.35 ± 0.05
- Indicate softer EOS compared to $c_s=1/\sqrt{3}$
- $v_2/\epsilon \sim 0.1$ (peripheral) – 0.2 (central) at STAR and PHOBOS
- Integrated $v_2$ does not develop so much in the late hadronic stage

$\text{NOTE} \quad v_2$ value is typically factor 2 larger than

\[ v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle} \]
Kinetic energy scaling works up to $K_{E_T} \sim 1 \text{ GeV}$

- Indicate hydrodynamic behavior

Possible hint of quark degrees of freedom at higher $K_{E_T}$

*Kinetic energy of a particle in a relativistic fluid

$K_{E_T} \sim m_T - m_0$ at $y \sim 0$
What can we learn from identified hadrons?

- **NCQ (Number of Constituent Quark) scaling of $v_2$ indicate partonic collectivity at RHIC**
  - No re-scattering in hadronic stage
  - Longer life time ~ 40 fm/c
  - Thermal s-quark coalesce/recombine to form $\phi$ meson

### QM2005, M. Oldenburg, STAR
- $\phi \rightarrow K^+K^-$
  - Typical S/N ~ 0.3
- Centrality 20 – 60%
  - S/N is good
  - Event plane resolution is good
  - Separation of $v_2$ between meson and baryon is good
  - Magnitude of $v_2$ does not vary very much

**Before subtraction**

- Signal + Background
- Background

**After subtraction**

$\text{Au+Au} \sqrt{s_{\text{NN}}}=200 \text{ GeV, 20-60\%}$

$P_T^{\text{pairs}}=1.5-2.8 \text{ GeV/c}$
**Meson v₂**

- Obtained from invariant mass fit method
  - Consistent with standard subtraction method
  - Smaller systematic error
- **p_T < 2 GeV/c**
  - Consistent with mass ordering from hydrodynamics

\[ v_2^{\text{measured}} = \frac{N_S v_2^S + N_B v_2^B}{N_S + N_B} \]


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**Partonic Collectivity (i)**

- **Hydro + NCQ scaling works for $\phi$ meson**
  - STAR result favors NCQ=2 for $\phi$
  - Consistent with other multi-strange hadrons ($\Omega$, $\Xi$) from STAR
  → Collective flow of s-quark
Partonic Collectivity (ii)

Hydro + NCQ scaling describes $v_2$ for a variety of particles measured at RHIC
– Scaling breaks for higher $p_T$

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Summary

- **What have we learned from anisotropic flow + hydrodynamics at RHIC?**
  - Large $v_2$ → Early thermalization, $\tau < 1$ fm/c
  - $v_2$ scales eccentricity, independent of system size (Au, Cu)
    - Estimated speed of sound = $0.35 \pm 0.05$
  - Partonic Collectivity
    - Kinetic energy + NCQ scaling works for a broad set of particles

- **Strongly interacting partonic matter**
  - Centrality, energy dependence of $v_2$
  - $v_4/(v_2)^2$ as a probe for degree of thermalization

- **What more can be learned?**
  - PHENIX talks in this session
    - 2:25 PM: S. Sakai, heavy flavor electron $v_2$
    - 4:20 PM: J. Newby, HBT
Thank you
Back up
$v_2/\varepsilon$, STAR, PHOBOS

\[ v_2/\varepsilon \]

\[ v_2/\varepsilon \text{ part} \]

**HYDRO (EoS H)**

**HYDRO (EoS Q)**

\[ 1/S \text{ d}N_{\text{ch}}/\text{dy} \]

\[ v_2/\varepsilon \text{ part} \]

**HYDRO (EoS H)**

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\[ 1/S \text{ d}N_{\text{ch}}/\text{dy} \]

CIPANP 2006, S. Voloshin, STAR

QM2005, S. Manly, PHOBOS

- $v_2/\varepsilon \sim 0.1 - 0.2$

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