Soft physics at RHIC

Hiroshi Masui,
University of Tsukuba

Fall KPS meeting, Nov. 2013
### RHIC heavy ion collisions

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- **Au+Au**
- **Cu+Cu**
- **d+Au**
- **U+U & Cu+Au**

- **STAR only**
- **Test run**
RHIC heavy ion collisions

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- Variety of collision systems (d to U), wide range (5-200 GeV) of collision energies
## RHIC heavy ion collisions

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- Variety of collision systems (d to U), wide range (5-200 GeV) of collision energies
- **QGP properties** at top RHIC energy

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- Variety of collision systems (d to U), wide range (5-200 GeV) of collision energies
- **QGP properties** at top RHIC energy
- Search for **QCD critical point & phase boundary** by Beam Energy Scan (BES) program phase-I
### RHIC heavy ion collisions

#### PHENOMENOLOGY

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- Variety of collision systems (d to U), wide range (5-200 GeV) of collision energies
- **QGP properties** at top RHIC energy
- Search for **QCD critical point & phase boundary** by Beam Energy Scan (BES) program phase-I
- Study **structure of QCD phase diagram**

Test run
Multi-particle correlations

- Powerful tools to study the bulk properties of the system
  - Azimuthal anisotropy
    \[ \langle e^{i n \phi} e^{-i n \psi} \rangle \rightarrow \langle v_n^2 \rangle \]
    \[ \langle e^{i \phi_1} e^{i \phi_2} e^{-i 2 \psi} \rangle \rightarrow \langle a_1^2 \rangle \]
    Initial geometry (+fluctuations), shear viscosity
    Local parity violation, chiral magnetic effect
  - Femtoscopy (identical bosons)
    \[ \langle \rho_1(x) \rho_2(x) \rangle \rightarrow 1 + e^{-R^2 q^2} \]
    Source size, geometrical anisotropy at freeze-out
  - Conserved charge fluctuations
    \[ \langle (N - \bar{N})^2 \rangle \rightarrow \chi_2 \]
    Susceptibility, QCD critical point

- I’m going to review the recent correlation measurements from RHIC
• Fast triggers
  ‣ Hard probes by electrons & photons
• TOF + EMC + Aerogel
  ‣ hadrons
• Forward beam counters (BBC, MPC, RXN)
  ‣ support measurements of azimuthal anisotropy
  ‣ large pseudorapidity gap reduces ‘non-flow’ effects
• VTX, FVTX
  ‣ heavy flavors
• Large acceptance - Time Projection Chamber (TPC)
• PID capabilities have been (will be) significantly improved
  ‣ TOF (2009-) - charged hadrons
  ‣ MTD (2013-) - muons
  ‣ HFT (from 2014) - heavy flavors
Azimuthal anisotropy

\[ \frac{dN}{d\phi} \propto 1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + 2v_3 \cos(3\phi) + \ldots \]
**Flow in d+Au?**

- Large $v_2$ in 0-5% d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
- Near side correlation in 0-5% on Au-going side
  - No near side peak on d-going side
  - Need to understand away side jet contributions to extract $v_n$
- Interesting to see the centrality dependence
  - (Two-particle) non-flow scales like $1/N$

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PHENIX, arXiv:1303.1794v1 [nucl-ex]

$|\Delta\eta|=0.48-0.7$

![Graph showing $v_2$ vs. $p_T$ for d+Au and p+Pb collisions.](image)

- PHENIX, 200 GeV, d+Au, 0-5%, $|\Delta\eta|=0.48-0.7$
- ATLAS, 5.02 TeV, p+Pb, 0-2%, $|\Delta\eta|=2.5$

P. Bozek:
- $d+Au$ 200 GeV
- $p+Pb$ 4.4 TeV

---

$\Delta\eta>3$

![Graph showing $C(\Delta\phi)$ for d+Au 0-5% collisions.](image)

- a) $d+Au$ 0-5% (BBC_Au)
- $1.0<P_{T,\text{trig}}<3.0$ GeV/c
- $|\eta_{\text{trig}}|<0.35$

![Graph showing $C(\Delta\phi)$ for Au-going and d-going side.](image)

- Asso: d-going, $3.1<\eta<3.9$
- Asso: Au-going, $-3.7<\eta<-3.1$

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H. Masui, KPS, Nov/1/2013
Geometry control

- Test the relation between initial geometry and final momentum anisotropy
  - Achieve higher density in deformed collisions with the same energy
  - Path length dependence
  - Finite odd harmonics from geometry overlap
  - Control magnetic field (test chiral magnetic effect)

Collisions with deformed nuclei; U + U
- body-body collision
- tip-tip collision

Asymmetric collisions; Cu + Au

* Average deformation of Uranium ~ 28%
  Cu ~ 16%, Au ~ -13%
Results

Slope of $v_2$ for multiplicity dependence

STAR Preliminary

$\sqrt{s_{NN}} = 193$ GeV

STAR, APS2013

Centrality percentile by ZDC

0.1% most central

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

Cu+Au

$\Delta v_1 (\Psi_{1,SMC})$

$\nu_{1} \times 10$

$30-40\%$

$40-50\%$

$50-60\%$

$30-60\%$

$0.0$

$0.5$

$1.0$

$1.5$

$2.0$

$2.5$

$3.0$

$p_T$ (GeV/c)

$p_T$ (GeV/c)

PHENIX, RHIC&AGS users meeting

- $v_2$ slope shows clear difference between Au+Au and U+U
  - super central U+U could enhance tip-tip collisions
- Large $v_1$ @ mid-rapidity in Cu+Au (not observed in Au+Au)
  - also for pions. Need more statistics for protons
Break down of NCQ scaling

- Number of Constituent Quark scaling of $v_2$
  - Indication of deconfinement at early stage of heavy ion collisions
- Meson-baryon splitting at 62.4 GeV - NCQ scaling of $v_2$
  - No difference between particles and anti-particles
- Meson-baryon splitting is gone at 11.5 GeV
- NCQ scaling is broken between particles and anti-particles
At the beginning of the RHIC

Now

Femtoscopy
**Triangular oscillation**

- $R_{out}$ shows clear oscillation with respect to $\Psi_3$
- Finite $R_{out}$, zero $R_{side}$
  - could suggest triangular flow is dominated at freeze-out
    - whereas triangular source shape is very small at freeze-out
  - Important to study $k_T$ dependence of asHBT

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**Freeze-out eccentricity @ BES**

- Spatial anisotropy is sensitive to equation of state
  - might be signal for 1st order phase transition
- Pion freeze-out eccentricity smoothly decreases as a function of beam energy
  - STAR data don’t show non-monotonic energy dependence
Fluctuations
Higher \((n>2)\) order moments

- At critical point (with infinite system)
  - susceptibilities and correlation length diverge
    - both quantities cannot be directly measured

- Experimental observables
  - Moment (or cumulant) of conserved quantities: net-baryons, net-charge, net-strangeness, ...
  - Moment product (cumulant ratio) ↔ ratio of susceptibility
    \[ \kappa_2 = \langle (\delta N)^2 \rangle \sim \xi^2, \kappa_3 = \langle (\delta N)^3 \rangle \sim \xi^{4.5}, \kappa_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N) \rangle^2 \sim \xi^7 \]
    \[ S \sigma = \frac{\kappa_3}{\kappa_2} \sim \frac{\chi_3}{\chi_2}, \quad K \sigma^2 = \frac{\kappa_4}{\kappa_2} \sim \frac{\chi_4}{\chi_2} \]
    - directly related to the susceptibility ratios (Lattice QCD)
    - higher moments (cumulants) have higher sensitivity to correlation length

- Signal = Non-monotonic behavior of moment products (cumulant ratios) vs beam energy

\[ M. A. \text{~Stephanov, } \textit{PRL} \textbf{102}, 032301 (2009) \]
Non-gaussian fluctuations

- 3rd moment = Skewness $S$
  - Asymmetry
- 4th moment = Kurtosis $K$
  - Peakedness
- Both moments = 0 for gaussian distribution
- Critical point induces non-gaussian fluctuations

From Wikipedia
Net-proton fluctuations

- Data
  - efficiency uncorrected*
- Data compared to various expectations
  - Poisson
  - (Negative-) binomial*
- No significant excess compared to Poisson & UrQMD
  - Need precision measurements at low energies

* under investigation (not shown here)
Net-charge fluctuations

- No significant excess compared to Poisson, models
  - STAR ≠ PHENIX → acceptance ? efficiency correction ?
Summary

- Multi-particle correlations are powerful tool to understand the underlying collision dynamics in heavy ion collisions

- **Azimuthal anisotropy**
  - Flow in d+Au? Need centrality dependence
  - Possibility to enhance tip-tip collisions by using $v_2$
  - Hint of turn-off signal by breakdown of NCQ scaling between particles and anti-particles

- **Femtoscopy**
  - Triangular flow is dominated at freeze-out?
  - Smooth energy dependence of final freeze-out eccentricity

- **Fluctuations**
  - Need precision measurements for QCD critical point search
Back up
Large $v_2$ difference for baryons

- Difference of $v_2$ between particles and anti-particles increase in low energies
- Baryons show larger difference than mesons
**Disappearance of charge separation**

- **Charge separation** ($\gamma_{os} - \gamma_{ss}$) at 200 GeV
  - chiral magnetic effect?

- Separation decreases with decreasing beam energies, disappears at $\sqrt{s_{\text{NN}}} = 11.5$ GeV or less

*ALICE, arXiv:1207.0900*