Collective flow measurements at RHIC energies

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Contents
- Radial and anisotropic flows
- Correlations with reaction planes
- Fluctuations
Chemical and Thermal kinetic freeze-out with radial flow

Hadron yields are fitted with chemical thermal model in order to extract \((T_{ch}, \mu_B)\) parameters.

Hadron pT spectra are fitted with Blast-wave model in order to extract \((T_{kin}, \beta_T)\) parameters.
Directed flow ($v_1$)

negative slope of $dv_1/dy$ for net-proton softening of Equation of State


arXiv: 1601.07692
Directed flow ($v_1$) in Cu+Au at RHIC

- Non-zero $v_1$ at $\eta \sim 0$
- Possible E-field effect: Charge dependent $v_1$
  \[ \Delta v_1 = v_1\{h^+\} - v_1\{h^-\} \]

STAR, QM15
arXiv: 1608.04100
Chiral magnetic effect
charge separation w.r.t. reaction plane
“Same-sign --- Opposite-sign” charged pair somewhat reduced by mixed event subtraction…
Chiral magnetic wave

Charge dependent $v_2 : \Delta v_2 = v_2^{\{\pi^\prime\}} - v_2^{\{\pi^+\}}$

vs charge asymmetry of event : $A_{ch}$

\[ r = \frac{\Delta v_2}{\Delta A_{ch}} \]

\[ v_2^{(+)} , v_2^{(-)} \]


\[ r = 3.1985 \pm 0.2903 \]

\[ A_{ch} = \frac{N^+ - N^-}{N^+ + N^-} \]
Small vs Large system
--- indication of elliptic flow evolution ---

p+p (high mult.)  

\[ p + p \text{ (high mult.)} \]

p+A  

\[ p + A \]

A+A  

\[ A + A \]

CMS, QM15

(a) \( pp \sqrt{s} = 7 \text{ TeV}, N_{\text{trk}}^{\text{offline}} \approx 110 \)

(b) \( p\text{Pb} \sqrt{s_{NN}} = 5.02 \text{ TeV}, 220 < N_{\text{trk}}^{\text{offline}} \leq 260 \)

(c) \( p\text{Pb} \sqrt{s_{NN}} = 2.76 \text{ TeV}, 220 < N_{\text{trk}}^{\text{offline}} \leq 260 \)

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pAu, dAu, $^3$HeAu at RHIC

--- interpretation works with hydro-dynamics ---


Elliptic flow
- mass dependence from hydro-dynamics
- number of quark scaling based on quark coalescence

Higher order event anisotropy

Collective expansion originated from fluctuating initial density distribution

Mass dependence and meson/baryon separation

3rd order event anisotropy ($v_3$)

--- Triangular expansion ---

normalized by system energy density:

$$n_{ch, PP} = \frac{(dN_{ch}/d\eta)}{(N_{part}/2)}$$
Anisotropic shape after the expansion

Elliptic and Triangular shape at freeze-out remained (2\textsuperscript{nd}) or reversed (3\textsuperscript{rd})


\begin{itemize}
  \item $\text{Au+Au 200GeV}$
  \item $n=2$
  \item $n=3$
  \item $R^2_{\phi}$ [m$^2$]
  \item $\phi - \Psi_n$ [rad]
  \item $\mu=\pm$
  \item $0-10\%$
  \item $20-30\%$
  \item sys. error
\end{itemize}
Shape and/or flow relation to the jet modification

\[ \Delta \phi = \phi_{\text{Asso.}} - \phi_{\text{Trig.}} \]
$N_{CQ}$ and hydro scaling of $v_2$

--- partonic & hadronic effects ---

Extraction of quark $p_T$ distribution

--- based on quark coalescence ---

$$k_s = \frac{N(\Omega)}{N(\phi)} = \frac{N(sss)}{N(ss)}$$

Suppression and flow of heavy quark

Strong suppression and sizable flow of heavy quarks via single inclusive electron measurements.
Identification/separation of heavy quarks

Improvement with Silicon Vertex Detector (VTX) upgrade at PHENIX

Improvement with Heavy-Flavor Tracker (HFT) upgrade at STAR

\[ \frac{v_2}{n_q} \text{ vs. } \frac{(m_T - m_0)}{n_q} \text{ (GeV/c}^2\text{)} \]

\[ R_{AA} \text{ vs. } p_T^e \text{ [GeV/c]} \]
Thermal photon yield and flow

- Large photon yield from early stage
- Large photon flow from later stage
- New data from STAR at arXiv:1607.01447 with somewhat smaller yield
- Bremsstrahlung with B-field...

arXiv:1509.07758
Net-proton distribution


Change of correlation length at phase boundary close to the critical point

Fluctuation of conserved quantity (net-Baryon number)

Net-proton distribution

Net proton distribution in Au+Au collisions at RHIC.

Fluctuation of conserved quantity (net-Baryon number)

Change of correlation length at phase boundary close to the critical point.
Net-Proton
\[0.4 < p_T < 2 \text{ (GeV/c)}, \mid y \mid < 0.5\]
- **0-5%**
- **5-10%**
- **70-80%**
- **UrQMD, 0-5%**

**STAR Preliminary**

**STAR, QM15**
Summary

- Radial and anisotropic flows
- Correlations with reaction planes
- Fluctuations

M. Kitazawa, H. Sako, et. al. (J-PARC-HI LOI)