Beam-energy scan in relativistic heavy-ion collisions

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Contents

• Critical fluctuation
• Collective expansion
• Vortical, Chiral magnetic fluid
• Future plan
QCD phase diagram and Critical Point

- Cross over phase transition at high T and small $\mu_B$
- $1^{st}$ order phase transition at high $\mu_B$
- Critical end point search via RHIC beam energy scan program
- New direction towards high-density matter in future facilities
Baryon density and chemical freeze-out

Baryon density increases with reducing beam energy.

Baryon density peaks at about 8 GeV based on model.
Net-proton as a proxy for conserved net-Baryon fluctuation

possible signal from critical point which could be taken as a change of correlation length with 4\textsuperscript{th} order cumulant.
from Net-Baryon towards net-Strangeness

Net Lambda cumulant ratio

Net Kaon cumulant ratio

Trying to get signal from net-strangeness to be compared with net-proton and net-charge results
Off-diagonal cumulants among net-proton, net-kaon and net-charge

\[ \sigma_{Q}^{2}, \sigma_{Q,p}^{1,1}, \sigma_{Q,k}^{1,1}, \sigma_{p,Q}^{1,1}, \sigma_{p,k}^{2}, \sigma_{k,Q}^{1,1}, \sigma_{k,p}^{1,1}, \sigma_{k}^{2} \]

\[ \sigma_{x,y}^{2} = \langle xy \rangle - \langle x \rangle \langle y \rangle \]

\[ C_{x,y} = \frac{\sigma_{x,y}^{1,1}}{\sigma_{y}^{2}} \]

- \( \sigma \) : net-proton
- k : net-kaon
- Q : net-charge
6th order cumulants of net-proton and net-charge

Higher order cumulants are expected to be more sensitive to the critical fluctuation than lower orders.
Unfolding of “unkown and critical” net-distribution

\[ Df = U_{\text{out}} - S_{\text{out}} \]

volume fluctuation can be included as a part of response matrix
Unfolding of net-proton distribution based on GEANT detector response matrix

\[ \mathcal{R}(N_p, N_{p\bar{p}}; n_p, n_{p\bar{p}}) \]

Reversed response matrix

Eff.corr
Unfolding

Au+Au, \( \sqrt{s_{NN}} = 19.6 \) GeV

STAR, QM18

C_2

STAR Preliminary

C_3

STAR Preliminary

C_4

STAR Preliminary

C_3/C_2

STAR Preliminary

C_4/C_2

STAR Preliminary

NFQCD2018, 6/Jun/2018, Kyoto

ShinIchi Esumi, Univ. of Tsukuba, TChou
Directed flow $v_1$ and its slope with respect to rapidity

STAR: 1708.07132

J. Brachmann et al., PRC 61, 24909 (2000).
$v_1$ slope ($dv_1/dy$) of quark based on the quark coalescence

\[
v_1^{\text{trans. } u(d)} = \frac{v_1^{\text{net } p} - v_1^{\overline{p} \text{bar}} (3 - N_{\text{trans. } u+d})/3}{N_{\text{trans. } u+d}}
\]

transported quark assumption works at lower energy

produced quark assumption works at high energy
$v_2$ evolution with beam energy and quark coalescence

- Squeeze out and sign change
- Mass splitting
- Number of quark scaling

mass dependence of $v_2$ and evolution with beam energy

Increasing radial and elliptic flow with beam energy
beam energy dependence of $v_2$ in small system at d+Au collisions

beam energy and multiplicity dependence of $v_2$ in small system
--- 3 different methods (no-subtr., near-side scaled subtr., templ. fit) ---

non-flow dominated

over-subtracted?

over-estimated?

reference fitting to be in the middle

NFQCD2018, 6/Jun/2018, Kyoto

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Longitudinal de-correlation of event plane of $\Phi_2$ (top) and $\Phi_3$ (bot.)

- stronger in $r_3$ than in $r_2$
- larger energy dep. for $r_2$ in central collisions
- different centrality dep. between $r_2$ and $r_3$
- opposite effect on $\eta/S$ between $r_2$ and $r_3
Global polarization via Lambda decay

The Fastest Fluid
by Sylvia Morrow

Superhot material spins at an incredible rate.

B
y
L

STAR Au+Au 20%-50%

UrQMD+vHLLE, Λ
primary - primary+feed-down
AMPT, Λ
primary - primary+feed-down

STAR, arXiv:1805.04400

Nature548.62 (2017)
• Λ ○ Λ

PRC76.024915 (2007)
• Λ ○ Λ

this analysis
• Λ ○ Λ

\sqrt{s_{NN}} [GeV]
Lambda polarization

- Strong centrality dependence
- No significant $p_T$ and $\eta$ dependences
Lambda polarization

Azimuthal angle dependence

Charge asymmetry dependence

$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-}$
Lambda longitudinal-local polarization

\[ \langle \cos(\theta^* \rho) \rangle \]

\[ \text{Au+Au } \sqrt{s_{NN}} = 200 \text{ GeV} \]
10\%-60\%

STAR, QM18

Preliminary
Chiral Magnetic Effect via $\gamma_{os,ss}$ correlator

$\gamma = \langle \cos (\phi_A + \phi_B - 2\Phi_{RP}) \rangle$

Chiral Magnetic Effect via R.P. projected event-by-event charge asymmetry distribution

\[ \langle \sin \phi_+ \rangle - \langle \sin \phi_- \rangle \]

with “charge shuffling + cos term” normalization

--- Ajit correlator ---

STAR, QM18, Chirality workshop 2018
Chiral Magnetic Wave via charge asymmetry of $v_2$

charge dependent $v_2 (\Delta v_2)$ vs charge asymmetry of event ($A_{ch}$)

\[
A_{ch} = (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-)
\]

\[
\Delta v_2 = v_2^- - v_2^+ \approx r A_{ch}
\]

\[
\text{STAR Preliminary}
\]

\[
\text{STAR, QM18}
\]

\[
\text{STAR, QM18}
\]
STAR experimental detector upgrade for BES2

- New forward trigger + Event Plane Detector
- Very important for flow and fluctuation analyses → independent from main detector
  → reduces systematics (non-flow, centrality)!
- iTPC upgrade
  → increases TPC acceptance to ~1.5 in η
  → improves dE/dx resolution

Critical Point

from high-T to high-$\mu_B$ Beam Energy Scan 2 at STAR
STAR Experiment at RHIC
Beam Energy Scan
--- Program Phase 2 ---

inner TPC readout-chamber upgrade (iTPC)

Event Plane Detector (EPD)

End-cap Time-of Flight (eTOF)

Fixed-target mode
Summary

- Critical fluctuation
- Collective expansion
- Vortical, Chiral magnetic fluid
- Future plan (including FAIR, NICA, HIAF, J-PARC)

J-PARC at JAEA/KEK for heavy-ion collisions (Tokai, Japan)

FAIR at GSI (Darmstadt, Germany)