Rapidity Correlations in the RHIC Beam Energy Scan

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Introduction

- Effect of the initial density fluctuations on particle azimuthal distributions in heavy-ion collisions
  - Characterized by Fourier expansion
    \[ \frac{dN}{d(\varphi - \Psi_{RP})} \propto 1 + \sum n 2v_n \cos[n(\varphi - \Psi_{RP})] \]
  - Azimuthal correlations provide a wealth of insights, e.g. the “perfect fluid” discovery

- Effect of initial density fluctuations in the longitudinal direction in (pseudo)rapidity space
  \[ \frac{N(\eta)}{\langle N(\eta) \rangle} \propto 1 + \sum_{n} \sqrt{n + \frac{1}{2}} a_n P_n(\eta / Y) \]
  - Long-range correlations from the asymmetry in forward-backward going participants
  - Short-range correlations from resonance decays, jet fragmentation, and Bose-Einstein correlation

Motivation: Explore rapidity correlations in the STAR Beam Energy Scan data

Increasing viscosity decreases the observed \( v_n \)}

S. Jowzaee, Quark Matter 2017
• Rapidity correlation observable: \( R_2(y_1, y_2) = -1 + \frac{\langle \rho_2(y_1, y_2) \rangle}{\langle \rho_1(y_1) \rangle \langle \rho_1(y_2) \rangle} \)

• Legendre Polynomials decomposition of \( R_2(y_1, y_2) \)

• A specific normalization is used to minimize the residual centrality dependence

\[
C_N(y_1, y_2) = \frac{R_2(y_1, y_2) + 1}{C_p(y_1) C_p(y_2)} = 1 + \sum_{n,m=1}^{\infty} \langle a_n a_m \rangle \frac{T_n(y_1) T_m(y_2) + T_n(y_2) T_m(y_1)}{2} \\
C_p(y_1) = \int_{-Y}^{Y} \frac{(R_2(y_1, y_2) + 1) dy_2}{2Y}, C_p(y_2) = \int_{-Y}^{Y} \frac{(R_2(y_1, y_2) + 1) dy_1}{2Y}
\]

\( \langle a_1 a_1 \rangle \) – forward-backward fluctuations
\( \langle a_2 a_2 \rangle \) – fluctuations of the width of dN/dy
\( \langle a_n a_m \rangle \) – shorter range correlations (for m=n+2 and larger)


• In a wounded nucleon model


\( \rho(y; w_L, w_R) = w_R (a + by) + w_L (a - by) \),

\( C(y_1, y_2) = \rho_2(y_1, y_2) - \rho(y_1) \rho(y_2) = \rho(y_1) \rho(y_2) \sum_{i,k=0}^{\infty} \langle a_i a_k \rangle T_i(y_1 / Y) T_k(y_2 / Y) \approx y_1 y_2 b^2 \langle w_-^2 \rangle \)

\( w_- = (w_L - w_R) \)  \( \langle a_1 a_1 \rangle = Y^2 b^2 \langle w_-^2 \rangle \)  \( \text{positive } \langle a_1 a_1 \rangle \)
• Recent results from viscous hydrodynamics model study

Including shear and bulk viscosity: lower \((m,n)\) \(a_n a_m\) increase higher \((m,n)\) \(a_n a_m\) decrease

More sources: \(a_n a_m\) decrease

• ATLAS analysis results

\[ C_N(\eta_1, \eta_2) = \frac{1}{N} \sum_{i=1}^{N} \delta(\eta_i - \eta_1) \delta(\eta_i - \eta_2) \]

\[ \sqrt{s_{NN}} = 2.76\text{ TeV}, \text{Pb+Pb}, 7\mu b^{-1} \]

\[ 100 \leq N_{ch} < 120 \]

\[ p_T > 0.2\text{ GeV} \]

with SRC

w/o SRC
Dataset and Analysis Details

• BES-I dataset: Au+Au at \( \sqrt{s_{NN}} \) : 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, & 200 GeV

• Particles of interest: \( h^\pm, \pi^\pm, K^\pm, \) & \( p^\pm \) (2\( \sigma \) cuts on dE/dx, & require correct TOF)
  • \( 0.2<p_T<2.0 \) GeV/c, \( p_{tot}<1.6 \) GeV/c for \( h^\pm, \pi^\pm, K^\pm \)
  • \( 0.4<p_T<2.0 \) GeV/c, \( p_{tot}<3.0 \) GeV/c for \( p^\pm \)

• Centrality
  • \( N_{\text{tracks}} \) with \( 0.5<|\eta|<1 \) for \( h^\pm, \pi^\pm, K^\pm \)
  • \( N_{\pi,K} \) with \( 0<|\eta|<1 \) for \( p^\pm \)
  • Only 0-5% central events shown here

• Correction of pseudocorrelations
  • Z-vertex binning and Track merging

• Systematic uncertainties from track and event cuts

• Same analysis code used for UrQMD events

S. Jowzaee, Quark Matter 2017
Measurement of the correlation function in this analysis

\[ R_2(y_1, y_2, \Delta \varphi) = \frac{\langle \rho_2(y_1, y_2, \Delta \varphi) \rangle}{\langle \rho_1(y_1, \varphi_1) \rangle \langle \rho_1(y_2, \varphi_2) \rangle} \]

\[ R_2(y_1, y_2), \ R_2(\Delta y, \Delta \varphi) \]

\[ \Delta y = y_1 - y_2, \quad \Delta \varphi = \varphi_1 - \varphi_2 \]

\[ C_N(y_1, y_2) \rightarrow \langle a_n a_m \rangle \]

Note:

- fewer pairs/event in STAR BES-I data than at the LHC
- Narrower rapidity acceptance in STAR compared to LHC
- SRC was not subtracted as done by ATLAS

\[ \rho(y_1, y_2) \rightarrow \langle a_n a_m \rangle \]

\[ \langle a_n a_m \rangle \text{ by } (n,m) \]

\[ \Delta y = 0, \ 0.1 \]

\[ \Delta \varphi = 0, \ 0.1 \]

\[ R_2(y_1, y_2) \]

\[ \Delta y = 0, \ 0.1 \]

\[ \Delta \varphi = 0, \ 0.1 \]

\[ <R_2(\Delta y)> \]

\[ R_2(\Delta \eta) \]

\[ h^+ h^+, 27.0 \text{ GeV, 0-5\%} \]

\[ h_R^2(\eta, \Delta \eta) \]

\[ h_R^2(dy, \Delta y) \]

\[ h_R^2(dy, \Delta \varphi) \]
Like sign $h^+h^+$, 0-5% centrality for Data and UrQMD.

Energy-dependent $\Delta \eta \sim 0$ correlations with rise and fall around 19.6 GeV.

UrQMD generally does not reproduce the observed correlations.

SRC was not subtracted.

STAR Preliminary.
Like sign $h^+h^+$, 0-5% centrality for **Data** and **UrQMD**

The diagonal $a_n a_m$ ($m=n$) coefficients are generally positive for charged hadrons (correlations)
\[ \pi^+\pi^+, \text{K}^+\text{K}^+, \text{and pp, 0-5\% centrality} \]

Minima in \( <R_2> \) of protons around \( \Delta y=0 \) at all beam energies

Point at \( \Delta y=0 \) reflects combination of SRC and the removal of track merging effects

SRC was not subtracted
$\pi^+\pi^+$, $K^+K^+$ and $pp$ for data and UrQMD, 0-5% centrality

Unlike kaons and pions, the $<a_1a_1>$ coefficient of protons is negative (anti-correlations)
Baryon correlations

• ALICE analysis results
  
  ALICE Collaboration, arXiv:1612.08975v1
  p+p at $\sqrt{s_{NN}}=7$ TeV

• TPC/Two-Gamma Collaboration (PEP, SLAC) results
  $e^+e^-$ annihilation at 29 GeV

In BES-I data, simplest explanation is limited energy available to create 2\textsuperscript{nd} nearby like-sign proton (requires 2 $p\bar{p}$ pairs produced)
$\Delta \phi$ “Ridge”

- A strong correlation structure is observed in $R_2$ of LS and US $h$ & $\pi$ at 19.6-27.0 GeV
- The observed structure is similar in shape to “cluster” emission observed in $p+p$ at RHIC and the LHC

CMS Collaboration, JHEP 1009, 091 (2010)
• The magnitude of the $|<a_n a_m>|$ coefficients of $h^+ h^+$ and $\pi^+ \pi^+$ increases near 19.6 GeV
• In protons and kaons, $|<a_n a_m>|$ coefficients does not change significantly near 19.6 GeV

$<a_1 a_1>$ coefficient is negative for protons in all eight beam energies
SRC is dominant in near-side projection, and it is stronger for US pairs than for LS pairs.
The observed structure is strong in transverse direction of $\Delta\phi$ and it is charge independent.
Summary

- Two-particle rapidity correlations studied for LS and US h, p, K and π in Au+Au in the STAR Beam Energy Scan data

- The shape of the rapidity correlations quantified by decomposing the correlation functions onto a basis set of Legendre polynomials
  - The sign of the $<a_1a_1>$ coefficient indicates correlations vs. anti-correlations

- There are minima in the $<R_2(\Delta y)>$ of protons around $\Delta y=0$
  - This was also observed at higher beam energies
  - $<a_1a_1>$ is negative for protons (anti-correlations), and is positive for π and K (correlations)
  - It is an approximately 1σ effect, but is observed at all eight beam energies
  - Upcoming BES-II will provide larger and better datasets (broader rapidity acceptance) for these analyses

- A charge-independent and beam-energy localized (19.6 & 27 GeV) structure is observed in $R_2$ for pions
Thank you!

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Back-up