The role of longitudinal correlations and fluctuations

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Outline

1. 1D multiplicity correlation along the longitudinal direction
2. 2D di-hadron correlation and near side ridge
3. Decorrelation of event plane/anisotropic flow along $\eta$
4. Longitudinal fluctuations in CGC model
5. Conclusion
1D multiplicity correlation along the longitudinal direction

**Definition**

**Longitudinal:**
- Space-time rapidity $\eta_s = \frac{1}{2} \ln \frac{t+z}{t-z}$ at initial state
- Rapidity $Y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ and pseudo-rapidity $\eta = \frac{1}{2} \ln \frac{p+p_z}{p-p_z}$ of final charged hadrons

**Fluctuation:** deviation of one variable from its event average.

$$\delta f = f - \langle f \rangle \quad (1)$$

**Correlation:** the extent to which two or more variables fluctuate together.

$$C_{12} = \langle \delta f_1 \delta f_2 \rangle = \langle (f_1 - \langle f_1 \rangle)(f_2 - \langle f_2 \rangle) \rangle = \langle f_1 f_2 \rangle - \langle f_1 \rangle \langle f_2 \rangle \quad (2)$$

Normalized correlation function:

$$C_{12} = \frac{\langle f_1 f_2 \rangle}{\langle f_1 \rangle \langle f_2 \rangle} \quad (3)$$
1D multiplicity correlation along the longitudinal direction

Longitudinal fluctuations and multiplicity correlation

Figure: The longitudinal fluctuations of charged multiplicity in 3 typical events from ATLAS-CONF-2015-020

Two particle correlation function in pseudo-rapidity is,

\[ C(\eta_1, \eta_2) = \frac{\langle N(\eta_1)N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle} \equiv < R(\eta_1)R(\eta_2) >, \quad R(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle} \]

(4)

where \( N(\eta) \equiv dN/d\eta \).
Study the longitudinal structure by two particle rapidity correlation

In practice, \( \langle dN/d\eta \rangle \) are different for different centrality classes. The corrected two particle correlation function can be decomposed into orthogonal polynomials,

\[
C_N(\eta_1, \eta_2) = 1 + \sum_{n,m=1}^{\infty} a_{n,m} \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2}
\]

where \( T_n(\eta) \equiv \sqrt{n + \frac{1}{2}} P_n(\eta/Y) \).

\[
P_0(x) = 1 \quad (6)
\]
\[
P_1(x) = x \quad (7)
\]
\[
P_2(x) = (3x^2 - 1)/2 \quad (8)
\]
\[
P_3(x) = (5x^3 - 3x)/2 \quad (9)
\]

The physical meaning of $a_{n,m}$

A. Bzdak and D. Teaney, PRC 87 (2013) 024906

- $a_{1,1}$ describes the forward-backward asymmetry.
- $a_{2,2}$ describes the enhancement of forward-backward multiplicity correlation STAR PRL.103,172301(2009).
- The meanings of high order $a_{n,m}$ are still unclear.
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Recent EBE hydrodynamics by Akihiko Monnai and Bjorn Schenke, PLB752 (2016) 317-321 and Piotr Bozek et.el, PRC92 (2015) no.5, 054913 show that pure hydro underestimated $a_{n,m}$. While Piotr Bozek et.el show that $60-70\%$ of the $a_{n,m}$ come from non-flow effect. So $n$-particle rapidity correlation is suggested recently to eliminate $(n-1)$-particle non-flow correlations.

$$\langle a_ia_ka_m \rangle_3 = \int dy_1dy_2dy_3 \frac{C_3(y_1,y_2,y_3)T_i(y_1)T_k(y_2)T_m(y_3)}{\rho(y_1)\rho(y_2)\rho(y_3)}$$ (10)

Adam Bzdak and Piotr Bozek, PRC93 (2016) no.2, 024903
2D di-hadron correlation and near side ridge

2D fluctuations from EBE hydro with AMPT initial conditions

L.G. Pang, Q. Wang, X.N. Wang, PRC.89.064910.

- Calculate the di-hadron correlation as functions of $\Delta \eta$ and $\Delta \phi$.
- Expect that the event plane/anisotropic flow are different at different rapidities.
Di-hadron correlation in P+P and P+A collisions

CMS Collaboration, 1009.4122.

ATLAS Collaboration, 1212.5198v3

Measurements of dihadron correlations have been giving insight into the properties of the dense Quantum Chromodynamic (QCD) medium formed in high energy heavy ion collisions for almost a decade. Particularly interesting was a more recent observation of pronounced dihadron correlations between particles with small relative azimuthal angles (|Δφ|) extending over a large relative pseudorapidity interval (|Δη|), where

|Δη| = \ln\left(\tan\left(\frac{q}{2}\right)\right)

and q is the polar angle relative to the counterclockwise beam axis), as first measured in AuAu collisions at the Relativistic Heavy Ion Collider [1, 2]. At the Large Hadron Collider (LHC) those early measurements were extended into much higher beam energies as compared to those at RHIC [3, 4, 5, 6, 7]. Strikingly, such results in the new era started with high multiplicity events produced in pp collisions at \( p_{\text{s}} = 7 \text{ TeV} \) at the Compact Muon Solenoid (CMS) experiment, revealing also in this case a long (ridge-like) dihadron correlation in |Δη| for pairs close in azimuthal angle [3]. The confirmation of the ridge-like structure in heavy ion experiments came afterwards, with its observation in the 0% most central PbPb collisions at \( p_{\text{s}} = 2.76 \text{ TeV} \) [4, 5]. More recently, those results were expanded in CMS for all collision centralities and over a broader range of hadron traverse momentum \( p_T \), as can be seen in Ref. [6, 7].

The CMS detector has nearly 4\( \pi \) solid angle acceptance and is particularly suited for the study of dihadron correlations. Such measurement is based primarily on data from the inner tracker, consisting of silicon pixel and strip detectors, contained within the 3.8 T axial magnetic field of the large superconducting solenoid. For PbPb collisions, the primary minimum-bias trigger uses signals from either the beam scintillator counters (BSC, \( |η| < 4.65 \)) or the steel/quartz-fibre Cherenkov forward hadron calorimeters (HF, \( 2.9 < |η| < 5.2 \)). Coincident signals from detectors located at both ends (i.e., a pair of BSC or a pair of HF modules) are required. A complete description of the CMS detector can be found in Ref. [8].
Di-hadron correlation from pQCD

2D di-hadron correlation and near side ridge

Away side ridge from back-to-back jets

Near side peak from same side jet
Di-hadron correlation from color flux tube/glasma

Away side ridge from back-to-back jets + flow (or boosted flux tube)

Near side ridge is associated with color flux tube
Color flux tube + isotropic fragmentation does not generate near side ridge

- Near side peak from minijets and short strings.
- Away side ridge from back-to-back jet pairs.
- Isotropic fragmentation of string + free streaming does not generate near side ridge.
Color flux tube + collective motion (flow) leads to near side ridge


EBE-hydro from HIJING/AMPT initial condition, L.G. Pang, Q. Wang, X.N. Wang, PRC89 (2014) no.6, 064910

- Particles from the same color flux tube need to be boosted to the same direction such that particles with large pseudo-rapidity gap ($\Delta \eta$) fluctuate together.
Other explanations for near side ridge structure

Partons scattering off (boost invariant) color electric domains.

T. Lappi, B. Schenke, S. Schlichting, and R. Venugopalan
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String-string interactions + subsequent string fragmentation

Feofilov’s poster

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Feofilov’s poster

Medium(Color flux tube) kicked by (back-to-back) jets.

Cheuk-Yin Wong, PRC76. 054908
Cheuk-Yin Wong, PRC78. 064905
Cheuk-Yin Wong, PRC84. 024981
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Partons scattering off (boost invariant) color electric domains.

String-string interactions + subsequent string fragmentation

Medium(Color flux tube) kicked by (back-to-back) jets.

IP-Glasma + Lund string fragmentation

Feofilov’s poster

see Prithwish Tribedy’s talk on May 25th
Maxime Guilbaud’s talk and Brian Cole’s talk on May 23rd.

- None-vanishing $v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$ in p+p collisions.
- The mass ordering of the $v_2$ in p+p collisions.
- Ridge in low multiplicity p+p event.

Remarks:

- Strong evidence for collective flow.
- Question: can mass ordering and $v_2\{m\}$ pin down some explanations?
- Another constraint: the momentum distribution of the ridge particles
  - Lund string fragmentation .vs. Cooper-Frye particlization.
The longitudinal structure that is responsible for 'ridge'

Figure: Fig from: Annu. Rev. Nucl. Part. Sci. 2010. 60:46389, by Francois Gelis, Edmond Iancu, Jamal Jalilian-Marian, and Raju Venugopalan

- Color flux tube (glasma): color electric field, color magnetic field
The longitudinal entropy deposition

\[ \rho(\eta, x, y) = f_+(\eta)N_+(x, y) + f_-(\eta)N_-(x, y) \]

Adil and Gyulassy PRC 72.034907 (2005)

Gluon density is twisted because of the asymmetric distribution of forward and backward going participants.
Model the longitudinal fluctuations and entropy deposition

Usual CGC: (a).
Torqued fireball model: (b), (c)
EPOS: (c)
HIJING, AMPT, UrQMD: (c), (d)
Effect of longitudinal fluctuations

H. Petersen, et al.
PRC84 (2011) 054908
Effect of longitudinal fluctuations

L.G. Pang et al. PRC86 (2012) 024911

H. Petersen, et al. PRC84 (2011) 054908
Effect of longitudinal fluctuations

L.G. Pang et al. PRC86 (2012) 024911

K. Xiao et al. PRC87 (2013) 1, 011901

H. Petersen, et al. PRC84 (2011) 054908

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The role of longitudinal correlations and fluctuations
Decorrelation of event plane/anisotropic flow along $\eta$

**Decorrelations with big $\Delta \eta$ gap**

Piotr Bozek’s method

$$\cos(k\Delta_{FB}) = \frac{\langle \exp(ik(\phi_F - \phi_B)) \rangle}{\sqrt{\langle \exp(ik(\phi_{F1} - \phi_{F2})) \rangle \langle \exp(ik(\phi_{B1} - \phi_{B2})) \rangle}}$$  \hspace{1cm} (11)

Kai Xiao’s method

$$r_n(\Delta \eta = 2\eta_a) = \frac{\langle \cos(\Psi_n(-\eta_a) - \Psi_n(\eta_a)) \rangle}{(R_n(\eta_a)R_n(-\eta_a))}$$  \hspace{1cm} (12)

- $R_n$ is the resolution factor to remove the effect of finite multiplicity.

Our method based on $Q_n$ vector (LongGang, Pang et.al PRC91 (2015)4, 044904)

$$Q_n = \frac{1}{N} \sum_{j=1}^{N} \exp(in\phi_j) = V_n \exp(in\Psi_n)$$  \hspace{1cm} (13)

where $\phi_j = \arctan(p_y/p_x)$.

$$r_n(\Delta \eta = 2\eta_a) = \frac{\langle Q_n(\eta_a)Q_n^*(-\eta_a) \rangle}{\sqrt{\langle Q_n^2(\eta_a) \rangle \langle Q_n^2(-\eta_a) \rangle}}$$  \hspace{1cm} (14)

- This method captures both anisotropic fluctuations and event plane angle fluctuations.
Decorrelation of event plane/anisotropic flow along $\eta$

CMS methods, PRC 92 (2015) 034911

\begin{equation}
    r_n(\eta^a, \eta^b) = \frac{V_{n\Delta}(\eta^a, \eta^b)}{V_{n\Delta}(\eta^a, \eta^b)}
\end{equation}

\begin{equation}
    r_n(\Delta \eta = 2\eta_a) = \frac{<Q_n(-\eta_a)Q_n^*(\eta_b)>}{<Q_n(\eta_a)Q_n^*(\eta_b)>}
\end{equation}

- If $\eta_b$ is far away from $\eta_a$, no short range correlation.

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The role of longitudinal correlations and fluctuations
String length fluctuations

The initial condition for (3+1)D hydrodynamics is given by HIJING/AMPT model. Where the length of soft strings is sensitive to beam energy and centrality.
Decorrelation of **$n$**th order anisotropic flows

- EBE hydro match CMS measurements for $r_2$ except 0 − 5% most central collisions.
- $r_3$ match experimental data for all centralities.
- Much stronger decorrelation at RHIC energy.

Decorrelation of event plane/anisotropic flow along $\eta$ in Pb+Pb collisions from torqued fireball model

fluctuations improve description of $r_2$ in Pb-Pb except for $r_2$ in central collisions


- String length fluctuations improved $r_2$ in A+A collisions.
- $r_2$ and $r_3$ are underestimated too in most central collisions.
String length fluctuations are crucially important for p+Pb collisions.
The role of longitudinal correlations and fluctuations

Longitudinal fluctuations in 3D-Glasma

Gluon fields in one nucleus from JIMWLK

The global geometry clearly remains correlated over the entire rapidity range. The typical transverse length scale changes with rapidity. The eccentricities and corresponding angles from the energy momentum tensor $\tau$ separately (see e.g. [7]). From the resulting fields at equations are solved forward in time, for each rapidity given these initial conditions, the source free Yang-Mills [33] we determine the discretized analogue of Eqs. (6)-(7). In rapidity structure of the nucleus is only mildly modified even after on smaller scales, one also observes that the large scale increase of the saturation obviously demonstrated in [56, 60] the increase of the characteristic transverse length scale $x_s\approx2$.

For a left moving nucleus at LHC energies of $76$ TeV at the largest value using the IPSat/IP-Glasma model.

Bjorn Schenke and Soren Schlichting, arXiv:1605.07158

- The typical transverse length scale changes with rapidity.
- The global geometry clearly remains correlated over the entire rapidity range.
Longitudinal decorrelation in 3D-Glasma

Bjorn Schenke and Soren Schlichting, arXiv:1605.07158

- With smaller $\alpha_s$, 3D-Glasma may solve the most central puzzle.
Conclusion

Two particle multiplicity correlation

- Is used to study the forward-backward asymmetry.
- Understanding high order $a_{n,m}$

Di-hadron correlation

- Near side ridge in p+p favors color flux tube/glasma + collective flow.
- Initial stage interaction: tube scatters with (1) partons, (2) tubes, (3) high momentum jets
- Mass ordering and $v_2\{m\}$ are important to find out the right physics for near side ridge in p+p.

Event-plane/anisotropic flow decorrelation along the longitudinal direction

- Asks for string length fluctuations in color flux tube models.
- Has strong centrality and beam energy dependence.
- Color flux tube vs. Glasma and the importance of valence quarks.