





Azimuthal correlations of longitudinal structure at mid-rapidity in Pb-Pb collisions at 2.76 TeV with ALICE

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What about in the longitudinal direction?



Event plane method

Scalar product method

Two-particle correlation method

Multi-particle correlation method (Cumulant method)

Lee-Yang zeros method

> QCD medium expansion investigated via particle correlations

	Bin-by-bin correlation	General quantification	Method
φ		Fourier decomposition (v _n)	EP, SP, 2PC, Cumulant,
η	Forward-backward corr.	Legendre decomposition (a _n)	2PC, Multi-particle (Bzdak 1210.1965, 1509.02967)
(φ, η)	Corr. between (φ, η) windows (ALICE in pp, JHEP 05 (2015) 097)	Spherical harmonics?	

ALICE

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QCD medium expansion investigated via particle correlations

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- Forward-backward multiplicity correlation
 - Correlations between two $\eta\text{-windows}$
- \blacktriangleright Legendre decomposition of the η -distribution
 - Initially proposed by A.Bzdak, D.Teaney, arXiv:1210.1965
 - Decomposition of $dN/d\eta$ structure with Legendre/Chebychev polynomials

$$ho(y; a_0, a_1, ...) =
ho(y) \left[1 + \sum_{i=0}^{} a_i T_i \left(y/Y \right)
ight]$$

• "Measurement of forward-backward multiplicity correlations in lead-lead, protonlead and proton-proton collisions with the ATLAS detector", PRC 95, 064914 (2017)

ALICE

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Based on the decomposition in the transverse direction



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Based on the decomposition in the transverse direction



- Longitudinal flow decorrelations
- ATLAS, EPJ C 76 (2018) 142



Based on the decomposition in the longitudinal direction



 Correlations among longitudinal structures in different φ regions

Corr. between to windows

- ✓ Further characterization of the medium expansion in the longitudinal direction
- ✓ Approach in (ϕ , η) space

New constraints to the 3+1D heavy-ion models



- > The longitudinal structures in different ϕ regions have correlations originating from
 - ✓ Initial longitudinal + transverse geometry
 - ✓ Collective expansion in both longitudinal and transverse directions
 - ✓ Other physics mechanisms (SRC, CGC ...)

- > The second order event plane (Ψ_2) from V0 detectors
- \blacktriangleright Division of the azimuthal angle into four regions w.r.t. Ψ_2
 - Two ϕ_{in} and two ϕ_{out} bins





- > The second order event plane (Ψ_2) from V0 detectors
- $\blacktriangleright\,$ Division of the azimuthal angle into four regions w.r.t. Ψ_2
 - Two ϕ_{in} and two ϕ_{out} bins
- \blacktriangleright Legendre decomposition of the longitudinal structure in each ϕ bin
 - E.g. ϕ_{in} bin

$$\frac{1}{\int_{\Psi_2-\pi/4}^{\Psi_2+\pi/4} d\varphi} \int_{\Psi_2-\pi/4}^{\Psi_2+\pi/4} \frac{N(\varphi,\eta)}{\langle N_{in}(\varphi,\eta) \rangle} d\varphi \propto 1 + \sum_{q} q_{q}(\varphi_{in}) T_n(\eta)$$

with $N(\varphi,\eta) = \frac{d^2 N}{d\varphi d\eta}$ in each event

• Equivalent to $\frac{N(\eta)}{\langle N(\eta) \rangle} \propto 1 + \sum a_n(\varphi_i) T_n(\eta)$ when tracking efficiency in φ is uniform

• First few terms of Legendre polynomials

$$P_0(x) = 1$$
 $P_3(x) = \frac{1}{2}(5x^3 - 3x)$
 $P_1(x) = x$ $P_4(x) = \frac{1}{8}(35x^4 - 30x^2 + 3)$
 $P_2(x) = \frac{1}{2}(3x^2 - 1)$ $P_4(x) = \frac{1}{8}(35x^4 - 30x^2 + 3)$





- > Correlations among the longitudinal structures in different φ bins \rightarrow Correlations among coefficients from different φ bins
- > Conditional $a_n \rightarrow a_n(\phi_i | a_m(\phi_j))$
 - n,m = 1,2,3,... i,j=in, out
 - Mean a_n in ϕ_i region for given events with a_m in ϕ_j region
 - E.g. $a_1(\phi_{out}|a_1(\phi_{in})=0.1)$ corresponds to the mean $a_1(\phi_{out})$ with events that have $a_1(\phi_{in})=0.1$
 - n=m and cases up to n=3 are investigated



Applied corrections

- Event-plane resolution effects (difference between Ψ_2 and Φ_2)
- Multiplicity effects (difference between the true multiplicity and the measured multiplicity)



➤ a_n(φ_i | a_m(φ_j))

• $a_n(\phi_i | a_m(\phi_j)) = average a_n$ in ϕ_i region for given events with a_m in ϕ_j region



Analysis Details



3D ALICE Detector Schematics



- Pb-Pb collisions at $Vs_{NN} = 2.76$ TeV (MB, Central, Semi-central triggers)
- TPC-ITS track $|\eta| < 0.8$
- Centrality is estimated with multiplicity in V0 detectors (2.8 < η < 5.1 and -3.7 < η < -1.7)
- Event plane angle is estimated with V0 detectors





• a₁ is a parameter quantifying forward-backward asymmetry





- a₁ is a parameter quantifying forward-backward asymmetry
- Transverse distribution of the number of participating nucleons from two incoming nuclei fluctuates event-to-event, and may lead to the opposite sign of a_1 in opposite ϕ bins
- Momentum conservation of the medium through the expansion may generate negative slopes in conditional a_1 between opposite ϕ bins
- Short Range Correlations (SRC) may lead similar longitudinal shapes in two adjacent ϕ bins





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 HIJING results show features of shortrange correlations (SRC) (e.g. particles from jet fragmentation in two adjacent φ regions → positive slope)





 HIJING results show features of shortrange correlations (SRC) (e.g. jet and its fragmented particles in two adjacent φ regions → positive slope)

Slopes can be extracted by fitting conditional a₁ in each centrality class





- Negative slopes in conditional a_1 with opposite φ regions are observed in data and AMPT Opposite-sign a_1 values in opposite φ regions
- Centrality dependence in data and AMPT indicates the different level of contributions to the longitudinal structures from long-range correlations (LRC) and SRC (→ more negative slopes in central classes)





• a₃ and higher order coefficients are considered to originate from SRC









- Conditional a_3 mostly remains 0, which indicates the independence between a_3 values from different ϕ bins (SRC)
- Similar trends are observed in HIJING and AMPT







- a₂ is a parameter quantifying mid-peripheral asymmetry ← Fluctuations in the nuclear stopping power, CGC flux tube and its subsequent influence on the QCD medium, ...
- Positive a_2 corresponds to events with more particles at larger $|\eta|$ than at mid-rapidity









Significant increase in conditional a₂ with increasing positive a₂ in central classes, for all φ combinations







- A distinctive feature of conditional a₂ is observed in data → Significant increase in conditional a₂ in the positive x-axis in central classes, for all φ combinations
- One possible physics scenario CGC flux tube extended in the longitudinal direction during the preequilibrium stage eventually influences the QCD medium in the radial direction, and the expansion rate is isotropic in central classes



Fig. from Int. J. Mod. Phys. A28 (2013) 1330001

Summary



- Collective flow analyses in the transverse direction have provided information on bulk properties of Quark-Gluon Plasma
- New technique to study 3D response of the medium to the initial conditions is developed
- Azimuthal correlations of longitudinal structure show
 - ✓ Contributions from long- and short-range correlations in the longitudinal structure, and different level of contributions depending on the centrality
 - ✓ Distinct features of azimuthal collectivity of a_2 in central collisions
- AMPT and HIJING cannot successfully describe longitudinal measurement results, and new 3+1D model is needed





Thank you!

Backup

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Why Legendre Polynomials?

- In principle, any orthogonal basis can be chosen for longitudinal decomposition
- Relation to the physical quantity is important
- η-acceptance is limited in detectors → Orthogonal functions should be defined within limited range
- Compared to other orthogonal polynomials, weighting function of Legendre polynomials is simple, 1
 - Easier to evaluate coefficients
 - More open for new methods (Multi-particle correlation ...)
- First few terms of Legendre polynomials within [-1, 1]



Why Legendre Polynomials?

ATLAS [2, 3] used single particle density ratio, $R(\eta)$, defined by

$$R(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle},\tag{1}$$

where $N(\eta) \equiv dN/d\eta$ is the multiplicity distribution in a single event and $\langle N(\eta) \rangle$ is the average multiplicity distribution for a given centrality bin. To investigate the azimuthal dependence of longitudinal fluctuations with uneven efficiencies of ALICE detectors, $R(\eta)$ is re-defined by

$$R(\eta) \equiv \frac{1}{\int \mathrm{d}\varphi} \int \frac{N(\varphi, \eta)}{\langle N(\varphi, \eta) \rangle} \mathrm{d}\varphi , \qquad (2)$$

where the integral range of φ is equivalent to the range of each of the φ bins. With flat detector efficiency φ , eq. (2) is the same as eq. (1).

Within the considered η range [-Y, Y], $R(\eta)$ is decomposed with

$$R(\eta) = 1 + \sum_{n} a_n T_n(\eta) , \qquad (3)$$

$$T_n(\eta) = \sqrt{n + \frac{1}{2}} P_n(\eta/Y) , \qquad (4)$$

while $\sqrt{n+\frac{1}{2}}$ is for normalization, such that

$$\int_{-Y}^{Y} T_n(\eta) T_m(\eta) \,\mathrm{d}\eta = \delta_{nm} \,. \tag{5}$$

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B-2

Color Glass Condensate (CGC)

- A hadron or nucleus probed via gluon exchange
 - At low energy, only valence quarks are present in the hadron wave function
 - When energy increases, new partons are emitted, and the emission probability is proportional to ln(1/x) → if density of contituents remains small, the evolution is linear
 - At higher energy, partons start overlapping in phase-space and the evolution is nonlinear



Int. J. Mod. Phys. A28 (2013) 1330001

Flow Decorrelations

• ATLAS, Eur. Phys. J. C 76 (2018) 142

$$r_{n|n;k}(\eta) = \frac{\left\langle \boldsymbol{q}_{n}^{k}(-\eta)\boldsymbol{q}_{n}^{*k}(\eta_{\text{ref}})\right\rangle}{\left\langle \boldsymbol{q}_{n}^{k}(\eta)\boldsymbol{q}_{n}^{*k}(\eta_{\text{ref}})\right\rangle} = \frac{\left\langle \left[v_{n}(-\eta)v_{n}(\eta_{\text{ref}})\right]^{k}\cos kn(\Phi_{n}(-\eta)-\Phi_{n}(\eta_{\text{ref}}))\right\rangle}{\left\langle \left[v_{n}(\eta)v_{n}(\eta_{\text{ref}})\right]^{k}\cos kn(\Phi_{n}(\eta)-\Phi_{n}(\eta_{\text{ref}}))\right\rangle}$$

