Tracing the emergence of collective phenomenon in small systems

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Based on Björn Schenke, Sören Schlichting, PS arXiv:2201.08864
Two (multi) particle correlations

$\Delta \eta$ difference in pseudorapidity
$\Delta \phi$ difference in azimuthal angle

**Ridge:** Collimate structure ($\Delta \phi$) that is long range in $\Delta \eta$

Ridge in pp and pA collisions similar to AA collisions

Long-range correlations have only been observed in high multiplicity events at LHC energies in the small system


Similar results at:
Interpretation of n-particle correlations in small systems

Different mechanisms have been proposed:

1. Initial state correlations

2. Response to initial geometry

Other possible explanations:

Explore rapidity dependence of both the mechanisms in p+Pb collisions at $\sqrt{s} = 5.02$ TeV

**Critical Details:**

1. 3D Glasma initial state
   - Relax the assumption of boost-invariance by using CGC with JIMWLK\(^1\) evolution

2. Sub-nucleonic fluctuations
   - Needed to describe the momentum anisotropy in pA collisions

3. Solve classical Yang-Mills equations up to $\tau = 0.2$ fm/c and compute unequal rapidity correlations

\(^1\)Jalilian-Marian, Iancu, McLerran, Weigert, Leonidov and Kovner
3D IP-Glasma

- Size of the proton (quantified by trace of Wilson line) grows with decreasing x.
- Series of independent 2+1D CYM simulations using initial gauge fields

\[ A_{x \perp}^i (\tau = 0^+) = A_{p}^i (+y_{obs}) + A_{Pb}^i (-y_{obs}); \quad E_{x \perp}^n (\tau = 0^+) = \frac{i}{g} \left[ A_{p}^i (+y_{obs}), A_{Pb}^i (-y_{obs}) \right] \]

Gluon multiplicity

Standard JIMWLK parameters: \( \alpha_s = 0.15 \quad m = 0.2 \text{ GeV} \)

Total number of events

\[
N_{\text{events}} = N_{b_\perp} \times N_p \times N_{Pb} = 4096
\]

- \( N_p \equiv \text{Number of protons} = 32 \)
- \( N_{Pb} \equiv \text{Number of Pb nuclei} = 8 \)
- \( N_{b_\perp} \equiv \text{Number of different impact parameters used} = 16 \)

Gluon rapidity distribution

\( \frac{dN/ dy}{dN/ dy(y=0)} \)
Further insights into low and high multiplicity events

Saturation scale $Q_s^{p/Pb}$ obtained from dipole scattering amplitude


System size

$$S_\perp = \frac{\int d^2x_\perp x_\perp^2 T^{\tau\tau}(x_\perp)}{\int d^2x_\perp T^{\tau\tau}(x_\perp)}$$

Highest multiplicities result from exotic protons with large $Q_s^p$.

Except for most peripheral events, multiplicity driven by change in $Q_s$ values.
Event geometry & Initial State (IS) momentum anisotropy

Event geometry

Eccentricities \( \varepsilon_n \)

IS momentum anisotropy

Anisotropic energy flow \( \varepsilon_p \) ≡ Azimuthal anisotropy gluon \( v_2 \)

- Opposite trends in centrality in \( \varepsilon_2 \) and initial state \( v_2 \)
- Initial state \( v_2 \) largely independent of rapidity in all centrality bins.
Event geometry & initial state momentum anisotropy

Normalized rapidity correlation function $C^N_\phi$

$$C^N_\phi(\eta_1, \eta_2) = \frac{\langle \text{Re}\phi(\eta_1)\phi^*(\eta_2) \rangle}{\sqrt{\langle |\phi(\eta_1)|^2 \rangle \langle |\phi(\eta_2)|^2 \rangle}};$$

Event geometry is correlated across large rapidity intervals whereas initial momentum correlations are relatively short ranged in rapidity.
How to distinguish the source of anisotropy?


Use the correlation of mean transverse momentum $[p_T]$ and $\nu_2^2$ at fixed multiplicity.

$$\hat{\rho}(\nu_2^2, [p_T]) = \frac{\langle \delta \nu_2^2 \delta [p_T] \rangle}{\sqrt{\langle (\delta \nu_2^2)^2 \rangle \langle (\delta [p_T])^2 \rangle}}$$

where

$$\delta O \equiv \delta O - \frac{\langle \delta O \delta N \rangle}{\sigma_N^2} \delta N$$

$$\delta O = O - \langle O \rangle$$


The two origins of $\nu_2$ have very distinct predictions for this correlator.
Correlation from geometry


Wounded nucleon picture

\[
\begin{align*}
R(A) &> R(B) \\
\langle p_T \rangle(A) &< \langle p_T \rangle(B) \\
\varepsilon_2(A) &> \varepsilon_2(B)
\end{align*}
\]

\{ v_2 \text{ and } \langle p_T \rangle \text{ are anti-correlated} \}
Correlation from initial momentum anisotropy


Color domain cartoon (particle produced from same domain are correlated)

\[ R(A) > R(B) \]
\[ \langle p_T \rangle(A) < \langle p_T \rangle(B) \]
\[ \varepsilon_p(A) < \varepsilon_p(B) \]

\{ \text{ } v_2 \text{ and } \langle p_T \rangle \text{ are correlated} \}
Estimators for correlation between $[p_T]$ and $\nu_2$

For small systems, we employ the following estimators

$$\nu_2 \rightarrow \varepsilon_2 \text{ or } \varepsilon_p$$

$$[p_T] \rightarrow [s]$$

where $[s] = [e^{3/4}]$ is the average initial entropy density in a given event

ABC: region A with $-2.4 < y < -0.8$, central region B with $|y| < 0.8$ and region C with $0.8 < y < 2.4$


Infrared regulators (size) have a strong effect on geometric $\hat{\rho}$ estimator

Origin of collectivity in small systems

Experimental observation

Long-range rapidity correlation in high-multiplicity events

Theoretical explanations

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$

1 < $p_T$ < 3 GeV/c

Experimental observation

Theoretical explanations
Conclusion & Outlook

- Event geometry and initial state anisotropy are the possible explanations of long range azimuthal correlations observed in small systems.

- Investigated the rapidity dependence of the two possible explanations in pPb at $\sqrt{s} = 5.02$ TeV within the 3+1D IP-Glasma model.

- Geometry decorrelates with rapidity (faster for low multiplicity); initial state anisotropy decorrelates more quickly (faster for high multiplicity)

- In the future, couple 3D IP-Glasma with viscous hydrodynamics (e.g. MUSIC)

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Thank you
BACK-UP
JIMWLK evolution

Employ JIMWLK small-x evolution to the proton and nucleus

\[ V_{x\perp}(Y + dY) = \exp \left\{ -i \frac{\alpha_s dY}{\pi} \int_{z\perp} K_{x\perp - z\perp} \cdot \left( V_{z\perp} \xi_{z\perp} V_{z\perp}^\dagger \right) \right\} \]

\[ \times V_{x\perp}(Y) \exp \left\{ i \frac{\alpha_s dY}{\pi} \int_{z\perp} K_{x\perp - z\perp} \cdot \xi_{z\perp} \right\} \]

Functional Langevin equation


IR regularised JIMWLK kernel


\[ K_{x\perp - z\perp} = m|x\perp - z\perp| K_1(m|x\perp - z\perp|) \frac{x\perp - z\perp}{(x\perp - z\perp)^2} \]

Circles represent where proton hits in a given event, whose centrality is color coded

- red (0 – 5)%,
- blue (40 – 50)%,
- green (60 – 70)%
- orange (80 – 90)%.
Longitudinal structure of high-energy collisions

Incorporate longitudinal structure using 3D IP-Glasma model

Based on the high-energy factorisation of inclusive observables

\[ \langle \mathcal{O} \rangle = \int [D\rho_p][D\rho_{Pb}]W_{y_{obs}-y}^{p} [\rho_p]W_{y_{obs}+y}^{Pb} [\rho_{Pb}] \mathcal{O}[\rho_p, \rho_{Pb}] \]

Evolution of weight-functional \( W_{\Delta y} \) with rapidity separation \( \Delta y \) provided by JIMWLK evolution equation

High energy factorisation proven only for inclusive quantities which encompass measurements at a single rapidity

Using same prescription to calculate un-equal rapidity correlation
Correlations and $e_p$ and $v_2$

- **(0-5)%**
  - $n = 2$, $\alpha_s = 0.3$, $m = 0.2$ GeV
  - $n = 3$, $\alpha_s = 0.3$, $m = 0.2$ GeV
  - $n = 2$, $\alpha_s = 0.15$, $m = 0.2$ GeV
  - $n = 3$, $\alpha_s = 0.15$, $m = 0.2$ GeV
  - $n = 2$, $\alpha_s = 0.15$, $m = 0.4$ GeV
  - $n = 3$, $\alpha_s = 0.15$, $m = 0.4$ GeV

- **(40-50)%**
  - $n = 2$, $\alpha_s = 0.15$, $m = 0.2$ GeV
  - $n = 3$, $\alpha_s = 0.15$, $m = 0.2$ GeV
  - $n = 2$, $\alpha_s = 0.15$, $m = 0.4$ GeV
  - $n = 3$, $\alpha_s = 0.15$, $m = 0.4$ GeV

- **(80-90)%**
  - $n = 2$, $\alpha_s = 0.15$, $m = 0.2$ GeV
  - $n = 3$, $\alpha_s = 0.15$, $m = 0.2$ GeV
  - $n = 2$, $\alpha_s = 0.15$, $m = 0.4$ GeV
  - $n = 3$, $\alpha_s = 0.15$, $m = 0.4$ GeV
Event geometry & IS momentum anisotropy
FIG. 11. Rapidity dependence of the real and imaginary parts of the 2\textsuperscript{nd} and 3\textsuperscript{rd} order spatial eccentricities (top-panel) for three different events in the (0 – 5)\% centrality class (top-panel). Similar result are given for the azimuthal anisotropy of initial state gluon $v_2^g$ and initial state momentum anisotropy $\epsilon_p$ in the bottom panel. Simulation parameters: $\alpha_s = 0.15$ and $m = \bar{m} = 0.2$ GeV.
Dipole scattering amplitude

FIG. 13. Dipole scattering amplitudes $1 - D(r_\perp, |d_\perp| < 0.2R_p)$ of the lead nucleus (top) and proton (bottom) at three different rapidities $Y = -2.4, 0, +2.4$ as a function of dipole size $|r_\perp|$ in units of the proton radius $R_p$.

$$D(|r_\perp|, |d_\perp| < 0.2R_p) = c.$$ 

The parameterisation $D(r_\perp) = \exp(-Q_s^2 r_\perp^2/4)$ gives $Q_s = 2/|r_\perp| c \log^{1/2}(1/c)$.