Initial state geometry and fluctuations in deformed and asymmetric nuclear collisions in the IP-Glasma framework

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Introduction

In this work we address:

▶ the role of initial geometry and fluctuations on global observables.
▶ how to constrain mechanism of multi-particle production in A+A collisions.

We study:

▶ Systems with varying initial geometry (deformed nuclei)
▶ Event-by-event fluctuation of multiplicity, eccentricity & their correlation.
Modelling multi-particle production

Approach-I:
Monte Carlo Glauber (MC-Glauber) model combining,
  ▶ Geometry of collisions,
  ▶ Two-component model with negative-binomial fluctuation.
→ MC-Glauber+NBD initial condition.

Approach-II:
Ab initio Color Glass Condensate (CGC) framework combining,
  Saturation model of HERA DIS to construct hadron/nuclear wave-functions (IP-Sat model).
  Classical Yang-Mills description to calculate gluon field after collisions (Glasma description).
→ IP-Glasma initial condition.
MC-Glauber model

Multiplicity is computed from the expression:

$$\frac{dN}{d\eta} = n_{pp} \left( xN_{\text{coll}} + (1-x)\frac{N_{\text{part}}}{2} \right),$$

$$n_{pp} = 2.5 - 0.25 \ln(s_{\text{NN}}) + 0.023 \ln^2(s_{\text{NN}}) \rightarrow \text{avg no. of ch. particles.}$$

$$x \rightarrow \text{“hardness” scale, } N_{\text{coll}} \rightarrow \text{binary collisions, } N_{\text{part}} \rightarrow \text{participants.}$$

Intrinsic correlation between the multiplicity and the initial shape.

Multiplicity fluctuation is introduced as:

$$P_n^{NB}(\bar{n}, k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}.$$

Each n-n collision as identical sources with mean $\bar{n}$ & width $\sim 1/k$

$\rightarrow$ no unique implementation ($x$, $k$ are free parameters)
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Approach-II:
*Ab initio* Color Glass Condensate (CGC) framework combining,

- Saturation model of HERA DIS to construct hadron/nuclear wave-functions (*IP-Sat* model).
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→ IP-Glasma initial condition.
IP-Sat : Color charge distribution inside Nuclei

IP-Sat (Impact Parameter dependent saturation) parametrization HERA DIS → proton-dipole scattering matrix $S^p_{\text{dip}}(r_\perp, x, b_\perp) \sim \exp(-r^2 Q^2_{sp}/2)$

The nuclear scattering matrix is obtained as

$$S^A_{\text{dip}}(r_\perp, x, b_\perp) = \prod_{i=0}^{A} S^p_{\text{dip}}(r_\perp, x, b_\perp)$$

$i \rightarrow$ nucleons are distributed according to Fermi distribution.

$S^A_{\text{dip}} \rightarrow$ distribution of nuclear saturation scale $Q_s(b_\perp, x)$ solving:

$$S^A_{\text{dip}}(r_\perp = r_S, x, b_\perp) = \exp(-1/2) \implies Q^2_s = \frac{2}{r^2_S}$$

Iteratively solving $x = \frac{Q_s(b_\perp, x)}{\sqrt{s}} \rightarrow Q_s(b_\perp, \sqrt{s})$

Lumpy color charge density distribution $g^2\mu(x_\perp) \sim Q_s(x_\perp)$

Kowalski, Lappi, Venugopalan 0705.3047
Lappi, arXiv:0711.3039, 1104.3725

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One solves

\[ [D_\mu, F^{\mu\nu}] = J^\nu \]

In the presence of color current

\[ J_{A,B}^\nu \approx \delta(x^\perp)\rho(x^\perp)\delta^\nu\pm \]

\( \rho(x^\perp) \) sampled from local Gaussian distribution \( W[\rho] \)

\[ \langle \rho^a(x^\perp)\rho^b(y^\perp) \rangle = \delta^{ab}\delta^2(x^\perp-y^\perp)g^2\mu^2(x^\perp) \]

The field after collision at \( \tau = 0 \)

\[ A^i = A^i(A) + A^i(B), \quad A^\eta = \frac{ig}{2} [A^i(A), A^i(B)] \]

Evolution at \( \tau > 0 \) according to

\[ [D_\mu, F^{\mu\nu}] = 0 \]
IP-Glasma : Multiplicity and Energy density

E-by-E soln. of CYM equation on 2+1D lattice $\rightarrow F^{\mu\nu}(\tau, x_\perp, \eta)$.

- **Multiplicity ($n$):** In the transverse Coulomb Gauge at $\tau = 0.4$ fm:

$$
\frac{dN_g}{dy} = \frac{2}{N^2} \int \frac{d^2k_T}{\tilde{k}_T} \left[ \frac{g^2}{\tau} \text{tr} (E_i(k_\perp)E_i(-k_\perp)) + \tau \text{tr} (\pi(k_\perp)\pi(-k_\perp)) \right]
$$

- **Energy density ($\epsilon$):** $F^{\mu\nu} \rightarrow T^{\mu\nu}$ (stress energy tensor).

$$
T^{\mu\nu} = -g^{\gamma\delta} F^{\mu}_\gamma F^{\nu}_\delta + \frac{1}{4} g^{\mu\nu} F^{\gamma}_\delta F^{\delta}_\gamma
$$

solving eigen value eq. $u_\mu T^{\mu\nu} = \epsilon u^\nu$ gives $\epsilon$ and flow $u^\nu$

Gale, Jeon, Schenke, Tribedy, Venugopalan 1209.6330
Correlated multi particle production from disconnected diagrams connected by color averaging.

2-particle correlation $\rightarrow$ ridge.

n-particle correlation $\rightarrow$ negative-binomial fluctuation.

Yang-Mills introduces non-local gauge-field correlation over length scale $1/Q_s \rightarrow$ Glasma flux tube picture.

$\rightarrow$ IP-Glasma generates negative-binomial fluctuation non-perturbatively. (no need to put by hand)
Initial geometry and fluctuations in A+A

IP-Glasma provides good description of initial geometry and fluctuations in p+p, p+A, A+A.

In the same framework we study (asymmetric) Cu+Au and (deformed) U+U nuclear collisions.
Sampling deformed collisions at RHIC

The Woods-Saxon distribution

\[ \rho(r) = \frac{\rho_0}{1 + \exp \left( \frac{[r - R']}{a} \right)} \]

\[ R' = R \left[ 1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta) \right] \]

4 more d.o.f in addition to impact parameter → additional fluctuations.
Tip–Tip (\(\Theta_1 = \Theta_2 = 0\)), Side-Side (\(\Theta_1 = \Theta_2 = \Phi_1 = \Phi_2 = \pi/2\))
Energy density ($\epsilon$) from IP-Glasma model (at $\tau = 0$)

Schenke, Tribedy, Venugopalan 1403.2232

Au+Au (no-deformation)  
Au+Au (side-side deformed)  
Cu+Au (asymmetric)

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Energy density ($\epsilon$) from IP-Glasma model (at $\tau = 0$)

Schenke, Tribedy, Venugopalan 1403.2232
Correlation between geometry and multiplicity

Glauber

\[ \frac{dN}{d\eta} \sim x N_{\text{coll}} + (1-x) N_{\text{part}} / 2 \]

\[ N_{\text{coll}} = \begin{cases} 16 & \text{small} \\ 4 & \text{large} \end{cases} \]

\[ N_{\text{part}} = \begin{cases} 8 & \text{small} \\ 8 & \text{large} \end{cases} \]

\[ \frac{dN}{d\eta} \uparrow \varepsilon_2(v_2) \downarrow \]

\[ \frac{dN}{d\eta} \downarrow \varepsilon_2(v_2) \uparrow \]

strong correlation
Correlation between geometry and multiplicity

**Glauber**

\[ \frac{dN}{d\eta} \sim x N_{\text{coll}} + (1-x) \frac{N_{\text{part}}}{2} \]

- \( N_{\text{coll}} = 16 \)
- \( N_{\text{part}} = 8 \)

\( N_{\text{coll}} = 4 \)

- \( N_{\text{coll}} = 4 \)
- \( N_{\text{part}} = 8 \)

**CGC**

\[ \frac{dN}{d\eta} \sim Q_{S,\text{min}}^2 S_\perp / \alpha_s(Q_{S,\text{min}}^2) \]

\[ \frac{dN}{d\eta} \sim (4Q_{SP}^2 \times S_\perp) / \alpha_s(4Q_{SP}^2) \]

\[ \frac{dN}{d\eta} \sim 4 \times (Q_{SP}^2 \times S_\perp) / \alpha_s(Q_{SP}^2) \]

- \( x(4 S) \)
- \( S P^2 Q \)
- \( x S P^2 (Q S) \)
- \( S,\text{min} \)

\[ dN/d\eta \uparrow \varepsilon_2(v_2) \downarrow \]

- strong correlation (linear)

\[ dN/d\eta \downarrow \varepsilon_2(v_2) \uparrow \]

\[ \sim dN/d\eta \varepsilon_2(v_2) \downarrow \]

\[ \sim dN/d\eta \varepsilon_2(v_2) \uparrow \]

- weak correlation (logarithmic)
Multiplicity : centrality dependence

- Local Running coupling on each point on lattice $\alpha_s(k_\perp)$

Larger systems $\rightarrow$ smaller multiplicity per participants.
U+U min-bias & tip-tip are very close unlike 2-component model.
A plateau for Cu+Au at central events.
Eccentricity for different systems

The spatial eccentricities that characterize the geometry

\[ \varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle^2 + \langle r^n \sin(n\phi) \rangle^2}}{\langle r^n \rangle}, \langle \cdots \rangle \rightarrow \text{weight } \varepsilon(x_\perp, \tau) \]

- \( \varepsilon_2 \) very sensitive to initial geometry of colliding system.
- Tip-tip for U+U \( \leftrightarrow \) Au+Au
- MC-KLN given largest \( \varepsilon_2 \) but consistent at large \( N_{\text{part}} \).
Higher order moments of $\epsilon_n$

Fluctuation driven moments are very similar for different systems. Universal $\sim 1/N$ like trend for odd moments.
Even-by-event fluctuation of eccentricities

Event-by-event fluctuation of $\varepsilon_n$ provided decisive test for models of initial condition at LHC.

→ The same can be true at RHIC (cumulants are measured so far).

Universal distribution towards most central events (mean $\propto$ width).
Smaller system $\rightarrow$ larger fluctuations.
IP-Glasma $\rightarrow$ smaller width compared to MC-Glauber results.
Correlation of multiplicity and eccentricities

Full overlap events → very low spectators and very high multiplicity. The STAR results → ultra-central $U + U$ and $Au + Au$ collisions. → selected using a combined cuts on multiplicity and ZDC (spectators)

Heinz and Kuhlman nucl-th/0506088

see H.Wang’s talk

H.Wang, P.Sorensen, Hard Probes 2013
Correlation between multiplicity and ellipticity

Select ultra-central (full overlap) events using cuts on neutron numbers. → combination of tip-tip or side-side events

▶ Stronger anti-correlation in MC-Glauber compared to IP-Glasma
Correlation between multiplicity and ellipticity

Select ultra-central (full overlap) events using cuts on neutron numbers. → combination of tip-tip or side-side events

Stronger correlation in MC-Glauber compared to IP-Glasma

Opposite slope for ultra-central Au+Au events.

→ comparison data can constrain the dependence of geometry on multiplicity
Summary

- Asymmetric (Cu+Au) and deformed (U+U) nuclear collisions are studied in IP-Glasma and two-component MC-Glauber framework.
- Eccentricity found to be sensitive to different A+A collision geometries.
- Fluctuation driven moments of $\varepsilon_n$ are similar for different A+A systems.
- Probability distribution of $\varepsilon_n(\nu_n)$ can constrain models of initial condition at RHIC.
- Correlation between multiplicity and eccentricity can further constrain models of initial conditions.