3D Glasma Initial state from small-x evolution

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Based on: B. Schenke, S. Schlichting
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Motivation

Experiment:
Exciting new insights into 3-D dynamics
long. multiplicity & geometry fluctuations, p+p, p+A, A+A, …

Theory:
Variety of models developed involving different degrees of freedom
hadrons, strings, const. quarks,…

Bozek, Broniowski, PLB 752, 206 (2016), Pang, Petersen, Qin, Roy, Wang, EPJ A52, 97 (2016), Monnai, Schenke, PLB 752, 317 (2016), …
Initial state in high-energy collisions

Energy deposition in high-energy collisions dominated by small-x gluons

$\rightarrow$ **Color-Glass Condensate effective field theory**

Based on input from DIS fits IP-Glasma model provides successful microscopic description of transverse properties of initial state

event-by-event eccentricities, multiplicity distributions, …
Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 110 (2013) no.1, 012302

$\rightarrow$ Extend to 3-D to explore long. dynamics at high-energies
**Color-Glass Condensate description**

Nucleon structure at small $x$ characterized by correlation functions of light like Wilson lines

$$V_x = \mathcal{P} e^{-ig \int dx^- A^+}$$

Based on high-energy factorization single inclusive observables e.g. can be calculated to leading log. (LL) accuracy as an average over color charge distributions inside projectile and target

$$\frac{dN}{dy}\bigg|_{y_{\text{obs}}} = \int [DU][DV] \mathcal{W}^p_{y_{\text{obs}}-y_p}[U] \mathcal{W}^t_{y_{\text{obs}}-y_t}[U] \frac{dN}{dy}[U,V]$$

Evolution of weight-functionals $\mathcal{W}_{\Delta y}$ with the rapidity separation $\Delta y$ is described by JIMWLK evolution equation

High-energy factorization above proven for single inclusive observables, and un-equal rapidity correlations with rapidity separation $y^1_{\text{obs}} - y^2_{\text{obs}} \ll 1/\alpha_s$ but breaks down when $y^1_{\text{obs}} - y^2_{\text{obs}} \sim 1/\alpha_s$
3D-Glasma Initial state

Practical description:

1) Generate configuration of Wilson lines $U, V$ at initial rapidity separation $y_{\text{Init}}$ based on IP-Sat

2) Evolve Wilson lines $U, V$ from initial rapidity $y_{\text{Init}}$ to all rapidities $y_{\text{obs}}$ of interest ($y_{\text{obs}} > y_{\text{Init}}$)

3) Compute observables at all rapidities of interest by solving class. Yang-Mills equations
Small-x evolution — formalism

Stochastic formulation of (LL) JIMWLK evolution
Blaizot, Iancu, Weigert NPA 713, 441 (2003), Lappi, Mäntysaari EPJ C 73, 2307 (2013)

\[ V_x(Y + dY) = \exp \left\{ -i \frac{\sqrt{\alpha_s} dY}{\pi} \int_{z} K_{x-z} \cdot (V_z \xi_z V_z^\dagger) \right\} V_x(Y) \exp \left\{ i \frac{\sqrt{\alpha_s} dY}{\pi} \int_{z} K_{x-z} \cdot \xi_z \right\} \]

provides an efficient way to study on an event-by-event basis

Even though NLL effects are known to be important to e.g. slow down evolution of DIS structure functions, we stay at LL accuracy and use \( \alpha_s \) as a free parameter to adjust evolution speed

Since we are interested in impact parameter dependence, need to introduce infrared regulator to suppress gluon radiation at large distance scales

\[ K_r^{(\text{mod})} = m |r| K_1(m |r|) \ K_r \]

-> Need to check sensitivity of results to infrared regulator \( m \sim \Lambda_{\text{QCD}} \)
Small-x evolution — results

Small scale fluctuations develop and become finer and finer as characterized by the growth of $Q_s(Y)$

Smoothening of geometric profile and growth in impact parameter space (‘Gribov diffusion’)  
(c.f. SS, Schenke PLB 739 (2014) 313-319)
3-D Glasma Initial state

Contour plots of initial state energy density (T^{\tau \tau}) in a single 2.76 TeV Pb+Pb event (b=0)

Energy deposition dominated by approx. boost-invariant flux tubes with characteristic transverse size of nucleon

Short & long range fluctuations (\eta & x), center of mass shifts (\eta)
Comparison to 2.76 TeV Pb+Pb data

So far all comparison based on initial state only (no hydro), for central 2.76 TeV Pb+Pb (b=0)

Multiplicity:

Event averaged multiplicity distribution $dN/dy$ shows good agreement with ALICE data for small value of $\alpha_s = 0.15$

Evolution speed of dipole gluon distribution for same value of $\alpha_s = 0.15$

$$\frac{d\ln Q_s^2}{dY} = 0.28 - 0.3$$

consistent with extractions from DIS structure functions.
Long. multiplicity fluctuations

Characterized by correlation function

\[ C(Y_1, Y_2) = \left( \frac{dN}{dY_1} \right) \left( \frac{dN}{dY_2} \right) / \left( \frac{dN}{dY_1} \right) \left( \frac{dN}{dY_2} \right) \]

subject to norm. condition

Similar structure to ATLAS measurement

ATLAS-CONF-2015-020

Decomposition in Legendre polynomials

Bzdak, Teaney, PRC 87, 024906 (2013)

\[ \frac{dN}{dY} \propto 1 + \sum_n a_n T_n(Y) \]

shows dominance of \( a_1 a_1 \) forward/backward asymmetry

Dominant effect from \( Q_s \) fluctuations at initial rapidity scale

De-correlation of transverse geometry

Charaterize in terms of initial state eccentricity $|\varepsilon_n|$ and eccentricity plane $\Psi_n$

### Event 1
- Relative change in eccentricity
  - $n=2$, $n=3$

### Event 2
- Change in event-plane orientation
  - $n=2$, $n=3$

### Event 3
- Relative change in eccentricity
  - $n=2$, $n=3$

$\alpha_s=0.3 \quad m=0.4 \text{ GeV}$
De-correlation of transverse geometry

Characterize overall de-correlation by forward/backward ratio using initial state $\varepsilon_n$ instead of $Q_n$

$$r_n(\eta_a, \eta_b) = \frac{\langle \text{Re}[\varepsilon_n(-\eta_a) \cdot \varepsilon_n^*(\eta_b)] \rangle}{\langle \text{Re}[\varepsilon_n(\eta_a) \cdot \varepsilon_n^*(\eta_b)] \rangle}$$

Simultaneous description of $r_2, r_3$ in central events (0-5%) provides a challenge in various models

Conclusions & Outlook

Developed event-by-event description of 3-D initial state based on high-energy factorization

longitudinal structure is determined by JIMWLK evolution

First applications to initial state in central Pb+Pb collisions shows promising results

avg. multiplicity, multiplicity & geometric fluctuations

Can be extended towards comprehensive study of different collisions systems (p+p,p+p/A)

include running coupling, event selection, ...

Develop parametric models based on microscopic insights

Backup
De-correlation of transverse geometry

Dependence on coupling constant

Dependence on IR regulator
De-correlation of transverse geometry

Eccentricity change

Event plane de-correlation