The glasma initial state at LHC

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Outline

• Saturation scale from HERA, $b$–dependent fits

• MV model
  – Value of $Q_s$
  – Classical Yang-Mills calculation

• Beyond MV: using directly bCGC, IPsat dipole cross sections

Talk based on

• T. L., S. Srednyak, R. Venugopalan, in progress
Multiplicities at RHIC: assumptions

RHIC @ 130 GeV: \( \frac{dN_{\text{tot}}}{d\eta} \approx 1000 \)

RHIC @ 200 GeV: \( \frac{dN_{\text{tot}}}{d\eta} \approx 1150 \)

Assume either

- Fast thermalization, ideal hydro, entropy conservation
  or
- parton-hadron duality

\[ N_{\text{init}}(\text{gluons}) \approx N_{\text{final}}(\text{hadrons}) \]

Note: For \( E_T,\text{init}/E_T,\text{final} \) these scenarios are widely different.

For LHC I’ll use same identification \( N_{\text{init}} \approx N_{\text{final}} \).
Glass and Glasma

**Gluon saturation:** At large energies (small $x$) the hadron/nucleus wavefunction is characterized by saturation scale $Q_s \gg \Lambda_{QCD}$.

At $p_T \sim Q_s$: strong gluon fields $A_\mu \sim 1/g \quad \blacktriangleright \quad$ large occupation numbers $\sim 1/\alpha_s \quad \blacktriangleright \quad$ classical field approximation.

**CGC:** The saturated wavefunction of one nucleus

**Glasma:**[1]

- The coherent, classical field configuration of two colliding sheets of CGC.
- Initial condition for heavy ion collision at $0 < \tau \lesssim 1/Q_s$.

Value of $Q_S$ from DIS, from proton to nucleus

Kowalski, Teaney [2], Kowalski, T.L., Venugopalan [3]: DGLAP-improved parametrization of dipole cross section, fit to HERA data.

Result $Q_S(b_{\text{med}}) \approx 1.2 \text{GeV}$ at RHIC, $Q_S(b_{\text{med}}) \approx 1.6 \ldots 1.9 \text{GeV}$ at LHC.

Also get detailed geometrical “lumpy” picture of nucleus; ▶ noncentral collisions etc.

Relating DIS to AA in the MV model, $Q_s$ vs. $g^2 \mu$

MV model, CYM has $g^2 \mu$, DIS has $Q_s$, what is the relation?\[4\]

Compute the Wilson line correlator $\Rightarrow$ correlation length $\sim 1/Q_s$ vs. $g^2 \mu$.

Result, consistently with numerical CYM calculations, is $Q_s \approx 0.6 g^2 \mu$.

$[N_y = 1; \text{no longitudinal structure. Analytical results } N_y \to \infty.]$

See also discussion by K. Fukushima\[5\]

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MV numerical results: energy, gluon multiplicity

\[
\frac{dE}{d\eta} = f_E \frac{(g^2 \mu)^3 \pi R_A^2}{g^2}
\]

\[
\frac{dN}{d\eta} = f_N \frac{(g^2 \mu)^2 \pi R_A^2}{g^2}
\]

For strong fields \( f_E, N \) are \( \sim \) cst.

\[
dN/ d^2k_T \text{ has tail } \sim \frac{1}{k_T^4}, \text{ IR-finite.}
\]

Result: \[
\frac{dN}{d\eta} \approx 0.9 \frac{Q_s^2 \pi R_A^2}{g^2}
\]

\[ \approx 1100 \text{ for } Q_s = 1.2 \text{GeV}. \]

Beyond MV: constructing Wilson lines

For given \( \frac{d\sigma_{\text{dip.}}}{d^2b_T}(x, r_T, b_T) \) (use here IPsat and bCGC from Kowalski, Motyka, Watt \[8\]) construct corresponding

\[
U(x_T) = P e^{ig \int dx^- A^+(x^-, x_T)}
= \prod_{x^-} \left( 1 + igA^+(x^-, x_T) \, dx^- \right),
\]

\( A^+ \) at different \( x^- \) independent. ("Nonlocal Gaussian")

Problem with these HERA-tested and \( b \)-dependent parametrizations: Not positive definite at large \( k_T \).

Multiplicity at RHIC and LHC

One final parameter: what is $x$ in $Q_s(x)$? Denote $x = c_x Q_s(x) / \sqrt{s}$

**Version 1** Take $c_x = 1$, i.e. solve $x$ from $x = Q_s(x) / \sqrt{s}$

<table>
<thead>
<tr>
<th>$c_x$</th>
<th>$x$</th>
<th>$Q_s$ [GeV]</th>
<th>$dN_g / d\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>$5.56 \times 10^{-3}$</td>
<td>1.1</td>
<td>1000</td>
</tr>
<tr>
<td>1.00</td>
<td>$5.05 \times 10^{-3}$</td>
<td>1.0</td>
<td>850</td>
</tr>
</tbody>
</table>

**Version 2** Choose $c_x$ so that $x = c_x Q_s(x) / \sqrt{s}$ gives $dN_g / d\eta = 1150$ at RHIC 200 GeV.

<table>
<thead>
<tr>
<th>$c_x$</th>
<th>$x$</th>
<th>$Q_s$ [GeV]</th>
<th>$dN_g / d\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.58</td>
<td>$1.98 \times 10^{-4}$</td>
<td>1.9</td>
<td>2900</td>
</tr>
<tr>
<td>0.24</td>
<td>$0.67 \times 10^{-4}$</td>
<td>1.6</td>
<td>2200</td>
</tr>
</tbody>
</table>
Gluon spectrum

Used dipole model parametrizations don't give $1/k_T^4$ tail in momentum space (unlike MV) ➤ softer spectrum.

- Underestimate energy, does not match perturbative expectation

+ Numerics converges very well in continuum limit

MV model result was $\langle p_T \rangle \approx Q_s$, now

$$\langle p_T \rangle \approx 0.6Q_s \text{ (RHIC)} \ldots 0.7Q_s \text{ (LHC)}$$
$\sqrt{s}$ dependence

IPsat: both $Q_s$ and multiplicity close to $\lambda = 0.3$–behavior purely from DGLAP

bCGC: The $b$-dependent fit leads to a smaller $\lambda$ than GBW $\Rightarrow$ slower increase with energy.
Conclusions

• Towards a consistent quantitative calculation of the glasma initial state

• Predictions for LHC from on HERA-tested dipole cross sections

• Extend to noncentral collisions, more realistic “lumpy” nuclear geometry: work in progress.
Backups
Relation to DIS

DIS at high energy/small $x$: dipole cross section, which can be calculated from the classical field:

$$\hat{\sigma}(\mathbf{r}_T) = \int d^2 b_T \frac{1}{N_c} \text{Tr} \left( 1 - U^\dagger \left( \mathbf{b}_T + \frac{\mathbf{r}_T}{2} \right) U \left( \mathbf{b}_T - \frac{\mathbf{r}_T}{2} \right) \right)$$

$$U(\mathbf{x}_T) = P \exp \left\{ ig \int dx^- A^+_{\text{cov}}(\mathbf{x}_T, x^-) \right\}$$

This same Wilson line gives the (LC gauge) pure gauge field in the $\tau = 0$ initial condition for the two nucleus problem.

$$A^i_{(\text{one nucleus})} = \frac{i}{g} U(\mathbf{x}_T) \partial^i U^\dagger(\mathbf{x}_T)$$