Small-$x$ Physics in Coherent $pA/AA$ interactions at LHC

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Outline

- Small-$x$ physics (high energies);
- Parton saturation phenomenon;
- Photonuclear reactions at Ultraperipheral Heavy Ion Collisions (UPC);
- Heavy quark and vector meson production in UPC’s;
- Summary.
Gluon Distribution

From HERA data:

\[ xG(x,Q^2) \]

\[ Q^2 = 20 \text{ GeV}^2 \]

\[ Q^2 = 200 \text{ GeV}^2 \]

\[ Q^2 = 5 \text{ GeV}^2 \]

Transverse Distribution:

Information from deep inelastic lepton-proton scattering (DIS) at DESY-HERA.

Bjorken variable \( x \approx Q^2/W_{\gamma p}^2 \), with \( Q^2 \) photon virtuality.
Theoretical Expectations

- For high energies (small-$x$) the hadrons are characterized by a high density of gluons.
- In this regime, the recombination process $gg \rightarrow g$ cannot be disregarded.

$\Rightarrow$ Modification of the evolution equations by including non-linear terms (leads to saturation of growth of gluon density!)

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High energy evolution equations

- Recently, a promising evolution equation (it allows asymptotic analytical solutions) is the Balitsky-Kovchegov (BK 1996/1999) and its corresponding extensions.

- Projectile can be described as a quark-antiquark dipole and target as a collection of dipoles (onia).

- BK obtains QCD evolution equation on rapidity variable $Y = \ln(1/x)$ for the dipole-target amplitude, $N(r, b, Y)$, with single and multiple dipole-dipole scattering.

- In the toy model for $(0 + 1)$ dimensions, where $N = N(Y)$:

  $$\frac{dN}{dY} = k(N - N^2), \quad N(Y) = \frac{e^{kY}}{e^{kY} + c}, \quad (k > 0)$$

- Solution is logistic curve. Important property: amplitude saturates at high energies $N(Y \to \infty) = 1$. 
Solution has 3 behaviors: (1) regions where amplitude is small non-linear corrections are small; (2) transition region and (3) asymptotic region where $N \simeq 1$.

Limit of transition region is characterized by saturation scale $Q_s(Y)$. BK solution, $Q_s \propto \exp(\bar{\alpha}_s^2 \lambda Y) \sim x^{-\lambda}$.

For $r < 1/Q_s \rightarrow N \ll 1$ and for $r > 1/Q_s \rightarrow N \simeq 1$. 
Today - any signal of saturation?

- **HERA:** $\sqrt{s_{ep}} = 300$ GeV, $Q_s \simeq 1$ GeV (hard to disentangle!).

- **FUTURE:** THERA: $\sqrt{s_{ep}} = 1$ TeV and LHC: $\sqrt{s_{pp}} = 14$ TeV.
Future: $eA$ collisions

- eRHIC: $\sqrt{s_{eA}} = 100$ GeV and THERA: $\sqrt{s_{eA}} = 1$ TeV.

⇒ Main motivation:

- Nuclear saturation scale:

\[
Q_s^2(x; A) = \frac{3\pi^2}{2} \frac{\alpha_s}{x} \frac{G_A(x, Q_s^2(x; A))}{\pi R_A^2}
\]

- The nucleus amplifies the dynamical effects associated to the high parton density.

- Relation between proton saturation scale and nuclear saturation scale, $Q_{s,A} \propto A^\alpha Q_{s,p}$ ($\alpha = 1/3$?).

- Intense theoretical investigations on saturation effects in nucleus collisions (Color Glass Condensate, etc...)

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An alternative:

Ultraperipheral Heavy Ion Collisions (UPC's):

\[ \gamma p \text{ Processes: } \sigma(pA \rightarrow pAX) = n_A(\omega) \otimes \sigma^{\gamma p}(W_{\gamma p}) \]
\[ \gamma A \text{ Processes: } \sigma(AA \rightarrow AAX) = n_A(\omega) \otimes \sigma^{\gamma A}(W_{\gamma A}) \]
\[ \gamma\gamma \text{ Processes: } \sigma(AA \rightarrow AAX) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma}(W_{\gamma\gamma}) \]

The number of equivalent photons: \[ n_A(\omega) = \int d^2b \, N(\omega, b) \]
Photoproduction reactions at UPC’s

- The photoproduction cross section is given by,

\[
\sigma_{AA\rightarrow fAA}(\sqrt{s}) = \int \frac{d\omega}{\omega} n_A(\omega) \sigma_{\gamma A\rightarrow fX}(\omega)
\]

\[
\sigma_{pA\rightarrow fpA}(\sqrt{s}) = \int \frac{d\omega}{\omega} n_A(\omega) \sigma_{\gamma p\rightarrow fX}(\omega)
\]

\[
n_A(\omega) = \frac{2Z^2\alpha}{\pi\omega} \left[ \frac{\bar{\eta}}{K_0(\bar{\eta})} K_1(\bar{\eta}) + \frac{\bar{\eta}^2}{2} (K_1^2(\bar{\eta}) - K_0^2(\bar{\eta})) \right], \quad \bar{\eta} = \frac{2\omega R}{\gamma}
\]

- For PbPb at LHC, \(\gamma = 2930\) and \(\sqrt{S_{NN}} = 5500\) GeV, giving the maximum energy \(W_{\gamma A} \lesssim 950\) GeV.

- For pPb at LHC, \(\gamma = 4690\), giving the maximum c.m.s. \(\gamma p\) energy \(W_{\gamma p} \approx 1500\) GeV (5 × DESY-HERA energy).
Heavy Quark Photoproduction

Phenomenological model using parton saturation at small-$x$:

Dipole frame for $\gamma p$ scattering: probing projectile fluctuates into a quark-antiquark pair (a dipole) with transverse separation $r$ long after the interaction.

$$\sigma (\gamma p \rightarrow Q\bar{Q}X) = \sum_{h,\bar{h}} \int \int dz \; d^2r \; \Psi_{h,\bar{h}}^{\gamma} \sigma_{dip}(x, r) \Psi_{h,\bar{h}}^{\gamma^*}$$

Basic blocks: photon wavefunction, $\Psi^\gamma$ and dipole-target cross section, $\sigma_{dip}$.
Vector Meson Photoproduction

- Photoproduction of vector mesons \((V = \rho, J/\Psi)\):

\[\text{Im} \, \mathcal{A} (\gamma p \rightarrow V p) = \sum_{h, \bar{h}} \int dz \, d^2 \mathbf{r} \, \Psi_{h, \bar{h}}^\gamma \sigma_{\text{dip}}(\tilde{x}, \mathbf{r}) \, \Psi_{h, \bar{h}}^V,\]

where \(\Psi_{h, \bar{h}}^\gamma(z, \mathbf{r})\) and \(\Psi_{h, \bar{h}}^V(z, \mathbf{r})\) are the light-cone wavefunctions of the photon and vector meson, respectively.

- Total cross section:

\[
\sigma (\gamma p \rightarrow V p) = \frac{\left[\text{Im} \, \mathcal{A}(s, t = 0)\right]^2}{16\pi \, B_V} (1 + \beta^2)
\]

where \(\beta\) is the ratio of real to imaginary part of the amplitude and \(B_V\) labels the slope parameter.
**Dipole cross section**

In the Color Glass Condensate (CGC) formalism, $\sigma_{dip}$ can be computed in the eikonal approximation,

$$\sigma_{dip}(x, r) = 2 \int d^2 b \left[ 1 - S(x, r, b) \right], \quad N(x, r, b) = 1 - S(x, r, b)$$

- CGC phenomenological model [Iancu-Itakura-Munier, PLB590(2004)199]:

$$\sigma_{dip}^{\text{CGC}}(x, r) = \sigma_0 \left\{ \begin{array}{ll} N_0 \left( \frac{\tau^2}{4} \right) \gamma_{\text{eff}}(x, r), & \text{for } \tau \leq 2, \\ 1 - \exp \left[ -a \ln^2 (b \tau) \right], & \text{for } \tau > 2, \end{array} \right.$$  

where $\tau = rQ_{\text{sat}}(x)$ and $\gamma_{\text{eff}}(x, r) = \gamma_{\text{sat}} + \frac{\ln(2/\tau)}{\kappa x y}$, where $\gamma_{\text{sat}} = 0.63$ is the LO BFKL anomalous dimension at saturation limit.

- Saturation scale $Q_{\text{sat}}^2(x) = \left( \frac{x_0^2}{x} \right)^\lambda \sim \left( \frac{10^{-4}}{x} \right)^{0.3} \text{GeV}^2$

- Extension for nuclei using the Glauber-Gribov formalism.

$$\sigma_{dip}^A(\vec{x}, r^2, A) = 2 \int d^2 b \left\{ 1 - \exp \left[ -\frac{1}{2} A T_A(b) \sigma_{dip}^{\text{proton}}(\vec{x}, r^2) \right] \right\}$$
Heavy Quark Photoproduction in $pA$ collisions

- Gonçalves-Machado [Phys.Rev.C73:044902,2006]

- Rapidity distribution:

- Integrated cross section for the photoproduction of heavy quarks in $pA$ collisions at LHC:

|       | $X$ | COLLINEAR | CGC |
|-------|-----|-----------|-----|
| LHC   | $c\bar{c}$ | 17 mb     | 5 mb|
|       | $b\bar{b}$ | 155 $\mu$b | 81 $\mu$b |
Results (II)

Vector Meson Photoproduction in $pA$ collisions

- Gonçalves-Machado [Phys.Rev.C73:044902,2006]

- Rapidity distribution:

  Integrated cross section for the photoproduction of vector mesons in $pA$ collisions at LHC:

|       | $X$  | CGC |
|-------|------|-----|
| LHC   | $\rho$ | 14 mb |
|       | $J/\Psi$ | 95 $\mu$b |
Heavy Quark Photoproduction in $AA$ collisions

Gonçalves-Machado, [EPJC 31, 371-378 (2003)]

| $Q\bar{Q}$ | Collinear | SAT-MOD | SEMIHARD | CGC |
|------------|-----------|---------|----------|-----|
| $c\bar{c}$ | 2056 mb   | 862 mb  | 2079 mb  | 633 mb |
| $b\bar{b}$ | 20.1 mb   | 10.75 mb | 18 mb    | 8.9 mb |
Results (IV)

Comparison with RHIC and predictions to LHC:

| HEAVY ION | J/Ψ (3097) | φ (1019) | ω (782) | ρ (770) |
|-----------|------------|---------|--------|--------|
| LHC       | CaCa       | 436 µb  | 12 mb  | 14 mb  | 128 mb |
|           | PbPb       | 41.5 mb | 998 mb | 1131 mb| 10069 mb |
Summary

- The QCD dynamics at high energies is of utmost importance for building a realistic description of $pp/pA/AA$ collisions at LHC.

- We propose two specific final states (heavy quarks and mesons) where the experimental identification could be feasible in UPC’s as an alternative to $eA$ colliders.

- Photoproduction of heavy quarks should provide a feasible and clear measurement of the underlying QCD dynamics at high energies.

- The photoproduction of $\rho$ mesons is dominated by physics below saturation scale and good place to see saturation effects.