Total Gluon Shadowing due to Gluon Number Fluctuation Effects

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Outline

1. **Motivations**
   - QCD evolution with Pomeron Loops
   - Statistical Physics - hdQCD correspondence
2. **The ratio R_{pA} in the geometric and diffusive scaling regime**
   - Unintegrated Gluon Distributions (single event)
   - Unintegrated Gluon Distributions (averaged)
   - R_{pA} in the geometric and diffusive scaling regime
3. **Summary**

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QCD evolution with Pomeron Loops

Modification of QCD evolution equation due to Gluon Number Fluctuations (GNF) effects:

The most significant progress was achieved in following concurrent approaches:

- GNF can be interpreted as evolution equation with Pomeron Loops;
- GNF has deep connection with reaction-diffusion processes in statistical physics;
- GNF can be incorporated in effective Hamiltonian approach;

At the present, each one of these approaches has its own difficulties and we still haven't close and self consistent evolution equation, which reflects appropriately effects of Gluon Number Fluctuations.

QCD evolution with Pomeron Loops

Phenomenological applications:

- **Small Corrections** in DIS;
- **Remarkable Effects** in hadron-hadron and nuclei-nuclei collisions; since in such symmetric configuration original gluon number fluctuations may provide significant contribution to evolution of the interacting system.

The main (known) consequences of Pomeron Loops effect:

- Geometrical Scaling $\longrightarrow$ Diffusive Scaling;
- $Q_S \longrightarrow < Q_S >$;
- Evolution slow down **[at asymptotic energies]**;

- How GNF affects on physical quantities ?

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Statistical Physics - hdQCD correspondence

Correspondence between Reaction-Diffusion (RD) processes and hdQCD evolution

Conjecture **[Iancu, Mueller, Munier (2005)]**

Saturation momentum changes its shape due to Pomeron loops / Fluctuation effects

- **Single event:**

$$Q_s^2(A,Y) = c_A\, Q_s^2(A)\, \frac{\exp[\frac{\chi(\gamma_c)}{\gamma_c}\overline{\alpha}_s Y]}{[2\overline{\alpha}_s Y \chi''(\gamma_c)]^{\frac{3}{2\gamma_c}}} \qquad Q_s^2(A) \propto Q_0^2\, \alpha_s^2 A^{1/3}\, \ln(\alpha_s^2 A^{1/3})$$

convenient notation: $\rho = \ln k_\perp^2/k_0^2$

$$\rho_s(A,Y) = \ln \frac{c_A Q_s^2(A)}{k_0^2} + \frac{\chi(\gamma_c)}{\gamma_c}\,\overline{\alpha}_s\, Y - \frac{3}{2\gamma_c}\, \ln[2\overline{\alpha}_s Y \chi''(\gamma_c)]$$

- **Multiple events:**

$$\langle \rho_s(A,Y) \rangle = \ln \frac{c_A^h\, Q_s^2(A)}{k_0^2} + \left(\frac{\chi(\gamma_c)}{\gamma_c} - \frac{\pi^2 \gamma_c \chi''(\gamma_c)}{2\ln^2(1/\alpha_s^2)} \right) \bar{\alpha}_s Y$$

Statistical Physics - hdQCD correspondence

Modification of Unintegrated Gluon Distribution

$$\langle \{h_A, \varphi_A\}(\rho - \rho_s(A,Y)) \rangle = \int d\rho_s \; \{h_A, \varphi_A\}(\rho - \rho_s(A,Y)) \, P(\rho_s - \langle \rho_s \rangle)$$

where

$$P(\rho_s) \simeq \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\rho_s - \langle\rho_s\rangle)^2}{2\sigma^2}\right] \quad \text{and} \quad \sigma^2 = \langle \rho_s(A,Y)^2 \rangle - \langle \rho_s(A,Y) \rangle^2 = D_{\mathrm{dc}} \bar{\alpha}_s Y$$

Important Limit: $\sigma^2 \ll 1$

For example, in the case when rapidity is much smaller then $Y_{DS} \simeq 1/(D_{\mathrm{dc}}\, \bar{\alpha}_s)$,

$$\sigma^2 \ll 1$$

$\Longrightarrow$ Gaussian distribution is strongly peaked near $\langle \rho_s \rangle$:

$$P(\rho_s, \langle \rho_s \rangle) \longrightarrow \delta(\rho_s - \langle \rho_s \rangle)$$

$\Longrightarrow$ Averaged gluon distribution nearly preserves the form of an individual distribution:

$$\langle h_A(\rho - \rho_s(A,Y)) \rangle \approx h_A(\rho - \langle \rho_s(A,Y) \rangle)$$

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Unintegrated Gluon Distributions (single event)

Two definitions of Unintegrated Gluon Distributions

For the forward scattering amplitude $N(x_\perp, b_\perp, Y)$ in QCD:

- Braun's definition:

  [typically appears in cross sections for gluon production in proton-nucleus collisions];

$$h_A(k_\perp, b_\perp, Y) = \frac{N_c}{(2\pi)^3 \alpha_s} k_\perp^2 \nabla_{k_\perp}^2 \int \frac{d^2 x_\perp}{x_\perp^2} e^{ik_\perp \cdot x_\perp} N(x_\perp, b_\perp, Y)$$

- Kovchegov's definition:

  [derived from the non-Abelian Weizsacker-Williams field of a nucleus and counts the number of gluons in the wave function of the hadron];

$$\varphi_A(k_\perp, b_\perp, Y) = \frac{N_c}{(2\pi)^3 \alpha_s} \int \frac{d^2 x_\perp}{x_\perp^2} e^{ik_\perp \cdot x_\perp} N(x_\perp, b_\perp, Y)$$

- Relation:

$$h_A(k_\perp, Y) = k_\perp^2 \nabla_{k_\perp}^2 \varphi_A(k_\perp, Y)$$

Unintegrated Gluon Distributions (averaged)

Explicit form of Unintegrated Gluon Distributions in saturation and linear domains (single event)

$$h_A(\rho - \rho_s(A,Y)) = \begin{cases} h_A^{max} \; \exp\left[-\left(\rho_s(A,Y) - \rho\right)\right] & \text{for} \quad \rho < \rho_s(A,Y), \\ h_A^{max} \; \exp\left[-\gamma_c(\rho - \rho_s(A,Y))\right] & \text{for} \quad \rho > \rho_s(A,Y) \end{cases}$$

$$\varphi_A(\rho - \rho_s(A,Y)) = \begin{cases} \varphi_A^{max} \; \left[\frac{1}{2}\left(\rho_s(A,Y) - \rho\right) + 1\right] & \text{for} \quad \rho < \rho_s(A,Y), \\ \varphi_A^{max} \; \exp\left[-\gamma_c(\rho - \rho_s(A,Y))\right] & \text{for} \quad \rho > \rho_s(A,Y) \end{cases}$$

Unintegrated Gluon Distributions (averaged over many events)

$$\langle \{h_A, \varphi_A\}(\rho - \rho_s(A,Y)) \rangle = \int d\rho_s \; \{h_A, \varphi_A\}(\rho - \rho_s(A,Y)) \, P(\rho_s - \langle \rho_s \rangle)$$

$$\langle h_A(\rho - \rho_s(A,Y)) \rangle \simeq \frac{h_A^{max}}{\sqrt{2\pi\sigma^2}} \left(\frac{1+\gamma_c}{\gamma_c}\right) \exp\left[-\frac{(\rho - \langle \rho_s(A,Y) \rangle)^2}{2\sigma^2}\right]$$

$$\langle \varphi_A(\rho - \rho_s(A,Y)) \rangle \simeq \frac{\varphi_A^{max} \, \sigma^3}{2\sqrt{2\pi}[\rho - \langle \rho_s(A,Y) \rangle]^2} \exp\left[-\frac{[\rho - \langle \rho_s(A,Y) \rangle]^2}{2\sigma^2}\right]$$

R_{pA} in the geometric and diffusive scaling regime

The ratio R_{pA} for single and multiple events

R_{pA} for single event

R_{pA} for multiple events

$$R^{h}_{pA} = \frac{h_A(k_\perp, Y)}{A^{1/3}\, h_p(k_\perp, Y)} \quad - - - - - - - > \quad R^{<h>}_{pA} = \frac{<h_A(k_\perp, Y)>_{Q_S}}{A^{1/3}\, <h_p(k_\perp, Y)>_{Q_S}}$$

$$R^{\varphi}_{pA} = \frac{\varphi_A(k_\perp, Y)}{A^{1/3}\, \varphi_p(k_\perp, Y)} \quad - - - - - - - > \quad R^{<\varphi>}_{pA} = \frac{<\varphi_A(k_\perp, Y)>_{Q_S}}{A^{1/3}\, <\varphi_p(k_\perp, Y)>_{Q_S}}$$

R_{pA} in the geometric and diffusive scaling regime

R_{pA} in the geometric scaling regime

$$R_{pA}^{h,\varphi}(k_\perp, Y, A) \simeq \frac{1}{A^{\frac{1}{3}}} \left[\frac{\langle Q_s(A,Y)\rangle^2}{\langle Q_s(p,Y)\rangle^2}\right]^{\gamma_c} \frac{\ln\left(\frac{k_\perp^2}{\langle Q_s(A,Y)\rangle^2}\right) + \frac{1}{\gamma_c}}{\ln\left(\frac{k_\perp^2}{\langle Q_s(p,Y)\rangle^2}\right) + \frac{1}{\gamma_c}}$$

R_{pA} in the diffusive scaling regime

$$R_{pA}^{<h>}(k_\perp, Y, A) = \frac{1}{A^{\frac{1}{3}}} \left[\frac{\langle Q_s(A,Y)\rangle^2}{\langle Q_s(p,Y)\rangle^2}\right]^{\frac{\Delta\rho_S}{2\sigma^2}} \left[\frac{k_\perp^2}{\langle Q_s(A,Y)\rangle^2}\right]^{\frac{\Delta\rho_S}{\sigma^2}}$$

$$R_{pA}^{<\varphi>} = \frac{1}{A^{\frac{1}{3}}} \left[\frac{\langle Q_s(A,Y)\rangle^2}{\langle Q_s(p,Y)\rangle^2}\right]^{\frac{\Delta\rho_S}{2\sigma^2}} \left[\frac{k_\perp^2}{\langle Q_s(A,Y)\rangle^2}\right]^{\frac{\Delta\rho_S}{\sigma^2}} \frac{\left[\ln\left(\frac{k_\perp^2}{\langle Q_s(A,Y)\rangle^2}\right) + \Delta\rho_s\right]^2}{\left[\ln\left(\frac{k_\perp^2}{\langle Q_s(A,Y)\rangle^2}\right)\right]^2}$$

where

$$\Delta\rho_s \equiv \langle\rho_s(A, Y)\rangle - \langle\rho_s(p, Y)\rangle = \ln\frac{\langle Q_s(A,Y)\rangle^2}{\langle Q_s(p,Y)\rangle^2} = \ln\frac{c\, c_A^{h,\varphi}\, Q_0^2\, x_\perp'^2\, \alpha_s^2 A^{1/3}\, \ln(\alpha_s^2 A^{1/3})}{c_p^{h,\varphi}\, [\alpha_s \sqrt{\ln(1/\alpha_s)}]^{2/\gamma_c}}$$

R_{pA} in the geometric and diffusive scaling regime

R_{pA} in the geometric scaling regime (fixed α_s)

[Mueller (2003)], [Iancu,Itakura,Triantafyllopoulos (2004)]

$$R_{pA}^{h,\varphi}(k_\perp, Y, A) \simeq \frac{1}{A^{1/3\,(1-\gamma_c)}}$$

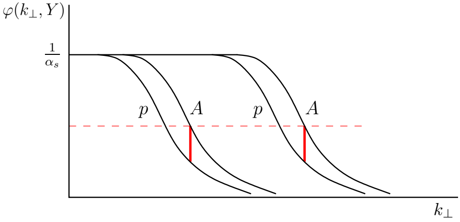
- Only partial gluon shadowing ;
- R_{pA} practically does not depends on $k_\perp$ and Y ;

R_{pA} in the diffusive scaling regime (fixed α_s)

$$R_{pA}^{<h>,<\varphi>} \simeq \frac{1}{A^{1/3\left(1-\frac{\Delta\rho_s}{2\sigma^2}\right)}} \left[\frac{k_\perp^2}{\langle Q_s(A,y)\rangle^2}\right]^{\frac{\Delta\rho_s}{\sigma^2}}$$

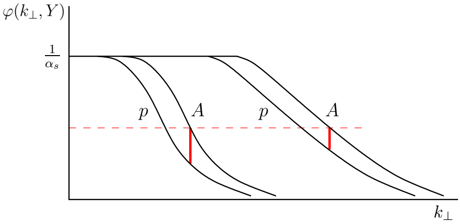
- Gluon shadowing increase with Y ;
- Total gluon shadowing at asymptotic rapidities $(Y \to \infty)$;
- R_{pA} has characteristic dependence on $k_\perp$ and Y ;

R_{pA} in the geometric and diffusive scaling regime



Geometric Scaling Regime

Shapes of the gluon distributions of nucleus and of proton remain same.



Diffusive Scaling Regime

With increasing rapidity, shapes of gluon distributions of nucleus and of proton become identical !

[total gluon shadowing]

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Concluding remarks:

- The total gluon shadowing is not possible in the geometric scaling regime in the fixed coupling case.
- The total gluon shadowing appear in the two cases:
  - Geometric scaling regime with running coupling (at asymptotic energies); **[Iancu,Itakura,Triantafyllopoulos (2004)]**
  - Diffusive scaling regime with fixed coupling (at asymptotic energies); **[Kozlov, Shoshi,Xiao (2006)]**
- Does running coupling + fluctuations effects give total gluon shadowing at moderate rapidities ?

For the technical details (e.g. precise form of R_{pA} for different initial conditions):

Kozlov, Shoshi, Xiao arXiv:hep-ph/0612053