

Gluon saturation beyond (naïve) leading logs

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Outline

- Introduction
- Kinematical constraint for BFKL
- Leading Logs from DIS at NLO
- Kinematical constraint for the BK equation
- Applications and conclusion

G.B., [arXiv:1311.xxxx](#) *to appear*

See also the summarized version: [G.B., arXiv:1301.0773](#)

Gluon saturation/CGC in dense-dilute collisions

DIS observables and forward particle production in pp/pA:

- theoretically best understood observables sensitive to gluon saturation at high energy
- abundant available or incoming data from HERA, LHC, RHIC
- successful phenomenology within the Color Glass Condensate

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→ 2 directions for improvement:

- 1 Study to less inclusive observables, like multi-particle correlations
- 2 Go to higher orders or other refinements for more precision

Gluon saturation/CGC at higher orders

The calculation of higher order corrections within the CGC has started:

- NLO corrections to DIS structure functions
Balitsky, Chirilli (2011)
G.B. (2012)
- NLO corrections to forward single inclusive particle production in pA (or pp)
Chirilli, Xiao, Yuan (2012)
- NLL corrections to the BK equation
Balitsky, Chirilli (2008)
- **NEW:** NLL corrections to the full B-JIMWLK evolution being obtained
Balitsky, Chirilli, arXiv:1309.7644
Kovner, Lublinsky, Mulian, arXiv:1310.0378

Need for further resummations

However, besides running coupling effects, pathologically large corrections of two types plague higher order results and have to be resummed to obtain reliable results from BK and JIMWLK at NLL.

- Kinematical corrections: due to a too naive treatment of the high-energy limit.
→ Main topic of the rest of this talk.
- Dynamical corrections: induced from DGLAP evolutions of the projectile and of the target, due to the duality between low x_{Bj} and high Q^2 evolutions.
→ Left for further studies.

The same problems appear in the linear regime for the BFKL equation, and the corresponding resummations have been fully performed.

Ciafaloni, Colferai, Salam, Staśto (1998-2007)

Altarelli, Ball, Forte (1999-2008)

Kinematical issues for BFKL in momentum space

Conventional derivations of the BFKL evolution require kinematical approximations for the t-channel gluons propagators, or for the energy denominators in the dipole model derivation.

Usual justification for those approximations: multi-Regge kinematics

- Strong ordering in rapidity y (or in k^+ , or in k^-) of the emitted gluons
- and all \mathbf{k}_\perp 's of the same order

Sufficient but not necessary condition for the kinematical approximations to be valid.

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Problem: unrestricted integral over \mathbf{k}_\perp in the BFKL equation

⇒ *A posteriori* not consistent to assume all \mathbf{k}_\perp 's of the same order!

Kinematical issues for BFKL in momentum space

Necessary and sufficient condition for the required kinematical approximations:

Strong ordering of the emitted gluons *both* in k^+ and in k^- simultaneously

Strong ordering is guaranteed only for the evolution variable chosen for the BFKL equation: y , k^+ or k^- , depending on the factorization scheme.

⇒ Need to impose by hand the missing k^- and/or k^+ ordering in the equation via a kinematical constraint in the BFKL kernel.

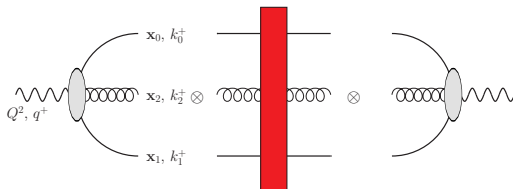
In momentum space: Ciafaloni (1988)

Kwieciński, Martin, Sutton (1996)

Andersson, Gustafson, Kharraziha, Samuelsson (1996)

Analog in Mellin space: Salam (1998)

DIS at high energy at NLO



$$\begin{aligned} \sigma_{T,L}^{\gamma}(Q^2, x_{Bj}) &= 2 \frac{2N_c \alpha_{em}}{(2\pi)^2} \sum_f e_f^2 \int d^2\mathbf{x}_0 \int d^2\mathbf{x}_1 \int_0^1 dz_1 \\ &\times \left\{ \mathcal{I}_{T,L}^{LO}(\mathbf{x}_{01}, z_1, Q^2) \left[1 + \mathcal{O}(\bar{\alpha}) \right] \left[1 - \langle S_{01} \rangle_0 \right] \right. \\ &\left. + \bar{\alpha} \int_{z_{\min}}^{1-z_1} \frac{dz_2}{z_2} \int \frac{d^2\mathbf{x}_2}{2\pi} \mathcal{I}_{T,L}^{NLO}(\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2, z_1, z_2, Q^2) \langle S_{01} - S_{02} S_{21} \rangle_0 \right\} \end{aligned}$$

with $z_n = k_n^+ / q^+$

G.B. (2012); see also Balitsky, Chirilli (2011).

Extraction of LL from NLO

The LL contained in the NLO term seems consistent with BK

$$\bar{\alpha} \int_{z_{\min}}^{z_f} \frac{dz_2}{z_2} \int \frac{d^2 \mathbf{x}_2}{2\pi} \mathcal{I}_{T,L}^{NLO}(\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2, z_1, z_2, Q^2) \langle \mathcal{S}_{01} - \mathcal{S}_{02} \mathcal{S}_{21} \rangle_0$$

$$\sim \mathcal{I}_{T,L}^{LO}(x_{01}, z_1) \bar{\alpha} \log\left(\frac{z_f}{z_{\min}}\right) \int \frac{d^2 \mathbf{x}_2}{2\pi} \frac{x_{01}^2}{x_{02}^2 x_{21}^2} \langle \mathcal{S}_{01} - \mathcal{S}_{02} \mathcal{S}_{21} \rangle_0$$

locally

$$\mathcal{I}_{T,L}^{NLO}(\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2, z_1, z_2=0) = \frac{x_{01}^2}{x_{02}^2 x_{21}^2} \mathcal{I}_{T,L}^{LO}(x_{01}, z_1)$$

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However: for any small but **finite** $z_2 = k_2^+ / q^+$

$$\mathcal{I}_{T,L}^{NLO}(\mathbf{x}_0, \mathbf{x}_1, \mathbf{x}_2, z_1, z_2) \ll \frac{x_{01}^2}{x_{02}^2 x_{21}^2} \mathcal{I}_{T,L}^{LO}(x_{01}, z_1)$$

when $z_1(1-z_1)x_{01}^2 \ll z_2 x_{02}^2 \simeq z_2 x_{21}^2$.

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when $z_1(1-z_1)x_{01}^2 \ll z_2 x_{02}^2 \simeq z_2 x_{21}^2$.

\Rightarrow Splitting of a dipole into **much larger** dipoles do not contribute to LL's !

Corrected real gluon emission kernel

Real emission contribution to the usual LL:

$$\bar{\alpha} \frac{dk_2^+}{k_2^+} \frac{d^2 \mathbf{x}_2}{2\pi} \frac{x_{01}^2}{x_{02}^2 x_{21}^2} \left\langle \mathcal{S}_{02} \mathcal{S}_{21} - \frac{1}{N_c^2} \mathcal{S}_{01} \right\rangle_{Y_2^+ = \log(k_2^+/k_{\min}^+)}$$

Ordering in k^+ guaranteed by the choice of factorization scheme/evolution in k^+ , at k_f^+ .

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Modification: forbid gluon emission at large distance, multiplying the real contribution by $\theta(k_f^+ x_{01}^2 - k_2^+ \min(x_{02}^2, x_{21}^2))$

→ Mixed-space analog of the k^- ordering (kinematical constraint).

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→ Mixed-space analog of the k^- ordering (kinematical constraint).

Same general idea as in the previous study in mixed space:

Motyka, Staśto (2009)

However: inappropriate treatment of virtual corrections and other problems there.

Calculating virtual corrections from unitarity

Assume the kinematical constraint to preserve the probabilistic interpretation of the parton cascade.

Evolution of $\langle S_{01} \rangle$ over a finite range $Y_f^+ = \log(k_f^+/k_{\min}^+)$:

$$\begin{aligned} \langle S_{01} \rangle_{Y_f^+} &= \langle S_{01} \rangle_0 D_{01}(Y_f^+) + \bar{\alpha} \int_0^{Y_f^+} dY_2^+ D_{01}(Y_f^+ - Y_2^+) \\ &\quad \times \int \frac{d^2 \mathbf{x}_2}{2\pi} \frac{x_{01}^2}{x_{02}^2 x_{21}^2} \theta \left(Y_f^+ - Y_2^+ - \log \left(\frac{\min(x_{02}^2, x_{21}^2)}{x_{01}^2} \right) \right) \\ &\quad \times \left\langle S_{02} S_{21} - \frac{1}{N_c^2} S_{01} \right\rangle_{Y_2^+} \end{aligned}$$

with the probability $D_{01}(Y^+)$ of no splitting for the dipole 01 in the range Y^+ .

Calculating virtual corrections from unitarity

In the vacuum (absence of target), $S_{01} = S_{02} = S_{21} = 1$.

→ equation determining $D_{01}(Y^+)$.

Solution:

$$D_{01}(Y^+) = \exp \left[-\bar{\alpha} \frac{2C_F}{N_c} \int \frac{d^2 \mathbf{x}_2}{2\pi} \frac{x_{01}^2}{x_{02}^2 x_{21}^2} (Y^+ - \Delta_{012}) \theta(Y^+ - \Delta_{012}) \right]$$

with the notation

$$\Delta_{012} = \max \left\{ 0, \log \left(\frac{\min(x_{02}^2, x_{21}^2)}{x_{01}^2} \right) \right\}$$

Typical behavior:

$$\Delta_{012} = 0 \quad \text{for } x_{02}^2 \lesssim x_{01}^2 \quad \text{and} \quad x_{21}^2 \lesssim x_{01}^2$$

$$\Delta_{012} \sim \log \left(\frac{x_{02}^2}{x_{01}^2} \right) \sim \log \left(\frac{x_{21}^2}{x_{01}^2} \right) \quad \text{for } x_{01}^2 \ll x_{02}^2 \sim x_{21}^2$$

Kinematically constrained BK equation (kcBK)

Rewriting the new evolution equation as a differential equation and discarding irrelevant terms explicitly of order NLL:

$$\partial_{Y^+} \langle \mathcal{S}_{01} \rangle_{Y^+} = \bar{\alpha} \int \frac{d^2 \mathbf{x}_2}{2\pi} \frac{x_{01}^2}{x_{02}^2 x_{21}^2} \theta(Y^+ - \Delta_{012}) \\ \times \left\{ \left\langle \mathcal{S}_{02} \mathcal{S}_{21} - \frac{1}{N_c^2} \mathcal{S}_{01} \right\rangle_{Y^+ - \Delta_{012}} - \left(1 - \frac{1}{N_c^2} \right) \langle \mathcal{S}_{01} \rangle_{Y^+} \right\}$$

G.B., arXiv:1311.xxxx *to appear*

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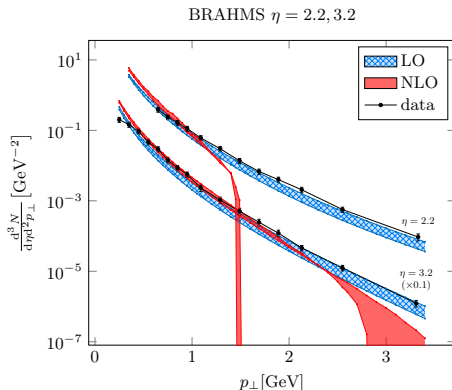
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Slows down the BK evolution:

- Restriction of phase space by the theta function
- Shift of the Y^+ argument of the dipole amplitude in the real term but not in the virtual term.

Large effect especially at small Y^+ .

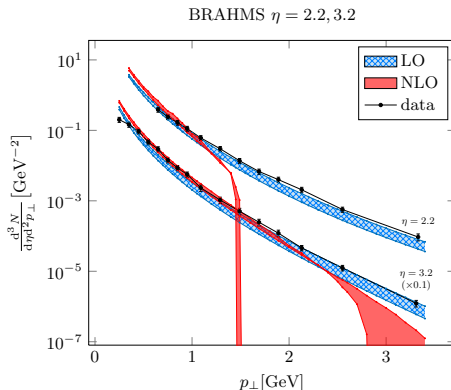
pA: single inclusive hadron production at NLO+LL



Staśto, Xiao, Zaslavsky, arXiv:1307.4057

→ Large negative NLO corrections at large p_{\perp} !

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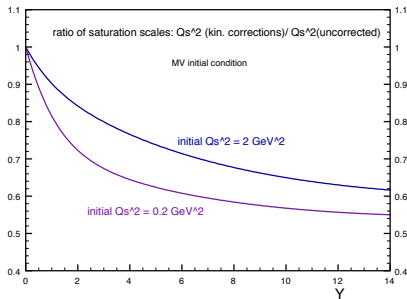
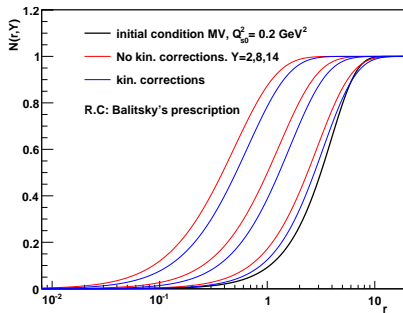


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Most likely origin: use of the standard BK instead of kcBK to subtracted LL's from NLO terms.

Numerics for kcBK

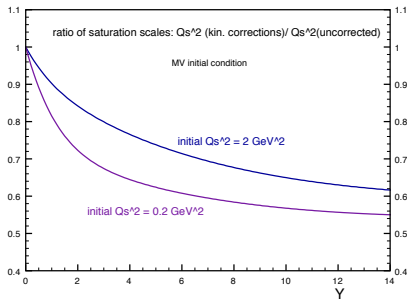
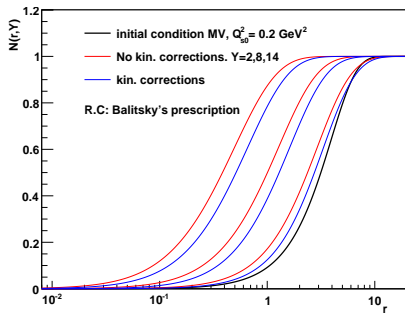


Main effects of the kinematical constraint (running coupling case):

- slows down the beginning of the Y^+ evolution, especially for softer initial Q_s
- at large Y^+ : \sim constant rescaling of the saturation scale

Work in progress; Albacete, Armesto, G.B., Milhano

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Impact on the DIS fits of AAMQS?

Work in progress; Albacete, Armesto, G.B., Milhano

Conclusion

Kinematical constraint in BK/BFKL/... :

- Makes the derivation of the equation more consistent:
→ from naïve LL to consistent LL
- Allows to subtract exactly the LL's actually present in observables at NLO
- Resum the largest corrections in the (anti-)collinear limit appearing in the evolution kernel at N^n LL

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⇒ New standard for CGC phenomenology: BK with running coupling and kinematical constraint (krcBK).

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) New standard for CGC phenomenology: BK with running coupling and kinematical constraint (krcBK).

Future developments:

Kinematical constraint for JIMWLK?

Resummation of large *dynamical* higher order corrections for BK, to get a full collinear-resummed BK ? at NLL ?