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IMPACT-PARAMETER DEPENDENCE OF COLINEARLY IMPROVED BALITSKY-KOVCHEGOV EVOLUTION

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OUTLINE

I. Balitsky-Kovchegov evolution equation
II. Impact-parameter-dependent computation
III. The problem of Coulomb tails
IV. Collinearly improved BK equation and suppression of large daughter dipoles
V. Results
VI. Conclusions
BK EQUATION
BK EQUATION

BK equation describes the dressing of a color-dipole under the evolution towards higher energies. It has been used to predict structure functions, vector meson production, as well as transverse momentum distributions of partons in hadrons.

Add a bit of energy

High $N_c$ limit

After some time, the initial dipole becomes dressed.

Y. V. Kovchegov, Phys. Rev. D 60, 034008 (1999)
The Balitsky-Kovchegov equation describes the evolution of a color dipole scattering amplitude \( N(\vec{r}, \vec{b}, Y) \) in rapidity

\[
\frac{\partial N(\vec{r}, \vec{b}, Y)}{\partial Y} = \int d\vec{r}_1 K(r, r_1, r_2) \left( N(\vec{r}_1, \vec{b}_1, Y) + N(\vec{r}_2, \vec{b}_2, Y) - N(\vec{r}, \vec{b}, Y) - N(\vec{r}_1, \vec{b}_1, Y) N(\vec{r}_2, \vec{b}_2, Y) \right)
\]

given by \( Y = \ln \frac{x_0}{x} \).

Since the process of gluon emission can be computed under different approximations, we have a number of kernels derived such as

**Running coupling kernel:**

\[
K^{\text{run}}(r, r_1, r_2) = \frac{N_c \alpha_s(r^2)}{2\pi^2} \left( \frac{r^2}{r_1 r_2} + \frac{1}{r_1} \left( \frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{1}{r_2} \left( \frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right)
\]

**Collinearly improved kernel:**

\[
K^{\text{col}}(r, r_1, r_2) = \frac{\overline{\alpha}_s \ r^2}{2\pi \ r_1 r_2} \left[ \frac{r^2}{\text{min}(r_1^2, r_2^2)} \right]^{\pm \pi_s A_1} K_{DLA}(\sqrt{L_{r_1 r_2}})
\]

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Y. V. Kovchegov, Phys. Rev. D 60, 034008 (1999)
For solving this equation numerically, we choose an initial condition

\[ N(r, b, Y = 0) = 1 - \exp \left( -\frac{1}{2} \frac{Q_s^2}{4} r^2 T(b_{q_1}, b_{q_2}) \right), \quad \text{where} \quad T(b_{q_1}, b_{q_2}) = \left[ \exp \left( -\frac{b_{q_1}^2}{2B} \right) + \exp \left( -\frac{b_{q_2}^2}{2B} \right) \right]. \]

There are two free parameters; saturation scale \( Q_s^2 = 0.49 \text{ GeV}^2 \) and variance of the profile distribution \( B_G = 3.22 \text{ GeV}^{-2} \).

- The \( r \) behavior mimics that of the GBW model.
- The \( b \) behavior exhibits the exponential fall-off calculated for the individual quarks.
IMPACT-PARAMETER DEPENDENCE OF THE BK EQUATION
There are two main options for treating the impact-parameter dependence of the scattering amplitude:

**Option a)** Factorizing the impact-parameter dependence. 

\[ N(\vec{r}, \vec{b}, x) \approx T(\vec{b})N(\vec{r}, x) \]

If we factorize the impact-parameter dependence, we can integrate over it and replace it with a multiplicative factor.

\[
\sigma^{q\bar{q}}(\vec{r}, x) = \int d\vec{b}N(\vec{r}, \vec{b}, x) = \sigma_0 N(x, \vec{r})
\]

This factor then stays the same for all energies and dipole sizes and is usually fit to data.

**Option b)** Solving the equation with the impact-parameter dependence on rapidity.

This adds two additional dimensions to the computation. The usual grid size in these two dimensions is 225x20. Which in turn means, that the CPU time gets increased with a factor of 4500.

This is not the only problem. When one tries to run the computation with the usual choice of kernels, one encounters the problems of Coulomb tails.
THE PROBLEM OF COULOMB TAILS
If we start with an exponentially falling initial condition and the usual running coupling kernel.
THE PROBLEM

If we start with an exponentially falling initial condition and the usual running coupling kernel.

Scattering amplitude sliced in \( r = 0.1 \, [\text{GeV}^{-1}] \)

- Initial condition falls exponentially
- Evolution increases the larger dipoles into a power-like growth.
THE PROBLEM

If we start with an exponentially falling initial condition and the usual running coupling kernel.

This growth would then violate the Martin-Froisart bound.

It also makes data description impossible.

(without additional phenomenological factors)
The kernel itself does not depend on $b$. We can however tame the growth in $b$ by suppressing evolution at big sizes of daughter dipoles.

Why?
For high-\(b\), the scattering amplitude is exponentially suppressed at the initial condition.

\[
\frac{\partial N(\vec{r}, \vec{b}, Y)}{\partial Y} \approx 0
\]

\[
\int dr_1 K(r, r_1, r_2)(N(\vec{r}_1, \vec{b}_1, Y) + N(\vec{r}_2, \vec{b}_2, Y) - N(\vec{r}, \vec{b}, Y) - N(\vec{r}_1, \vec{b}_1, Y)N(\vec{r}_2, \vec{b}_2, Y))
\]
HIGH-b SUPPRESSION

For high-\(b\), the scattering amplitude is exponentially suppressed at the initial condition.

\[
\frac{\partial N(\vec{r}, \vec{b}, Y)}{\partial Y} \overset{\sim}{=} 0 = \int dr_1 K(r_1, r_2) (N(r_1, \vec{b}_1, Y) + N(r_2, \vec{b}_2, Y) - N(\vec{r}, \vec{b}, Y) - N(r_1, \vec{b}_1, Y)N(r_2, \vec{b}_2, Y))
\]
For high-\(b\), the scattering amplitude is exponentially suppressed at the initial condition.

\[
\frac{\partial N(\vec{r}, \vec{b}, Y)}{\partial Y} = \int dr_1 K(r, r_1, r_2)(N(r_1, \vec{b}_1, Y) + N(r_2, \vec{b}_2, Y) - N(\vec{r}, \vec{b}, Y) - N(r_1, \vec{b}_1, Y)N(r_2, \vec{b}_2, Y))
\]

The only amplitudes that could be non-zero are those with small impact parameter.

These have \(r_{1,2} \sim 2b\), which is large.
For high-\(b\), the scattering amplitude is exponentially suppressed at the initial condition.

\[
\frac{\partial N(\vec{r}, \vec{b}, Y)}{\partial Y} = \int d\vec{r}_1 K(r, r_1, r_2)(N(\vec{r}_1, \vec{b}_1, Y) + N(\vec{r}_2, \vec{b}_2, Y) - N(\vec{r}, \vec{b}, Y) - N(\vec{r}_1, \vec{b}_1, Y)N(\vec{r}_2, \vec{b}_2, Y))
\]

Therefore if we suppress kernel at high \(r_1\) and \(r_2\), we suppress the evolution at high-\(b\) and maintain the exponential falloff of the scattering amplitude.
HOW TO SUPPRESS LARGE DAUGHTER DIPOLES
One possible solution to this problem is that we can cut the kernel, so that dipoles, that are too big would not contribute to the evolution.

\[
\frac{\partial N(r, \vec{b}, Y)}{\partial Y} = \int d\vec{r}_1 K^{\text{run}}(r, r_1, r_2) \Theta \left( \frac{1}{m^2} - r_1^2 \right) \Theta \left( \frac{1}{m^2} - r_2^2 \right)
\]

\[
(N(r_1, \vec{b}_1, Y) + N(r_2, \vec{b}_2, Y) - N(r, \vec{b}, Y) - N(r_1, \vec{b}_1, Y)N(r_2, \vec{b}_2, Y))
\]
I have then solved the BK equation without neglecting its impact parameter dependence as described by the Eq. 1.28. I have solved it both with the original kernel as well as with the kernel, that incorporates the confinement cuts for gluon mass [38]. I have incorporated the soft contribution to the computation of the structure function in this case and then compared it to data.

Solving this equation has proven to be extremely demanding on computational resources due to a very large phase space region that needs to be covered in each step of the evolution. Future incorporation of an angular asymmetry of the proton will lead to a necessity of parallelising the computation and possibly to shifting to using GPUs rather than CPUs.

For this approach the BK equation and dipole model, the initial condition of the form [37]

\[
n(r, b, Y = 0) = 1 \exp\left(-c r^2 \exp\left(-d b^2\right)\right) \tag{2.7}
\]

was chosen, where 

\[c = 0.0643 \text{ GeV}^2 \text{ and } d = \frac{1}{8} \text{ GeV}^2\]

At first, we tried to use the same setup for this equation that was successful for solving the running coupling BK equation (that is an approximation of the full BK equation with impact parameter dependence).

However, if we try to evolve the scattering amplitude, we observe, that the dependence of the scattering amplitude in \(b\) stops being exponentially decreasing and the evolution shifts this decrease to a power law. Therefore, the resulting size of the proton grows rapidly, as we evolve the scattering amplitude (as shown in Fig. 2.5) superseding the Martin-Froisart bound emerging from the property of unitarity of the cross section [33].

This unphysical behavior emerges from the fact, that the BK equation was postulated in perturbative QCD, where a small value of the strong coupling constant \(\alpha_s\) is assumed. When we however reach the region of large \(b\), the corresponding coupling constant is too large and we reach a purely non-perturbative region.

In this region, the BK equation loses its meaning and we cannot rely anymore on its predictions. To fix this problem, one has to impose confinement onto the kernel of the BK equation. This is usually done with the addition of a cutoff in transverse size to the daughter dipoles that can emerge from the mother dipole [38]. The equation then becomes

\[
\frac{\partial N(r, \vec{b}, Y)}{\partial Y} = \int d\vec{r}_1 K^{run}(r, \vec{r}_1, \vec{r}_2) \Theta\left(\frac{1}{m^2} - r_1^2\right) \Theta\left(\frac{1}{m^2} - r_2^2\right) (N(r_1, \vec{b}_1, Y) + N(r_2, \vec{b}_2, Y) - N(r, \vec{b}, Y) - N(r_1, \vec{b}_1, Y)N(r_2, \vec{b}_2, Y))
\tag{2.8}
\]

Mass of the emitted gluon is a free parameter, that is fitted to data.
By imposing the cutoff of the kernel, we maintain the exponential falloff of the scattering amplitude.

However, as was shown in [Phys. Rev. D84(2011)094022], we still cannot describe the data, since the cutoff is too strong and we need to impose new phenomenological constants to cure this.
The recently proposed collinearly improved kernel is by its nature suppressed at high $r_{i,2}$ and does not require additional dimensional parameters.

\[
K^{\text{col}}(r, r_1, r_2) = \frac{\bar{\alpha}_s}{2\pi} \frac{r^2}{r_1^2 r_2^2} \left[ \frac{r^2}{\min(r_1^2, r_2^2)} \right]^{\pm \bar{\alpha}_s A_1} K_{\text{DLA}}(\sqrt{L_{r_1 r} L_{r_2 r}})
\]

where

\[
K_{\text{DLA}}(\rho) = \frac{J_1(2\sqrt{\bar{\alpha}_s \rho^2})}{\sqrt{\bar{\alpha}_s \rho}}
\]

with $L_{r_1 r} = \ln \left( \frac{r_1^2}{r_2^2} \right)$

$\pm \bar{\alpha}_s A_1$ is positive when $r$ is smaller than the daughter dipoles and negative otherwise and $A_1 = 11/12$

Running coupling is of the usual scheme for the BK computations as in [J. L. Albacete at al, Eur.Phys.J. C71 (2011) 1705] at the minimal scale given by

\[
\bar{\alpha}_s = \alpha_s \frac{N_c}{\pi} \quad \alpha_s = \alpha_s(r_{\text{min}}) \quad r_{\text{min}} = \min(r_1, r_2, r)
\]

with $C = 9$.

The factor in square brackets represents the contribution of single collinear logarithms and DLA term resums double collinear logarithms to all orders.
FIG. 3. Absolute value of the ratio $K_{ci}/K_{rc}$ at a fixed dipole size and orientation with respect to the daughter dipole as a function of the daughter dipole size.

For the collinearly improved kernel, they are

$$K_{ci}^1 = \frac{\bar{\alpha}_s}{2\pi} \frac{r^2}{r'^2},$$

$$K_{ci}^2 = \left[ \frac{r^2}{\min(r'^2_1, r'^2_2)} \right]^{\pm\alpha_s A_1},$$

$$K_{ci}^3 = K_{DLA}(\sqrt{L_{r1}L_{r2}}).$$

The entire collinearly improved kernel is then given by the multiplication of all these factors as

$$K_{ci} = K_{ci}^1 K_{ci}^2 K_{ci}^3.$$
The improved kernel is then given by the multiplication of all these factors as logarithms, and of the running coupling.

For the collinearly improved kernel, they are the daughter dipole as a function of the daughter dipole size.

This term is present already at the LO:

\[ K^1_{ci} = \frac{\bar{\alpha}_s}{2\pi} \frac{r^2}{r_1 r_2}, \]

\[ K^2_{ci} = \left[ \frac{r^2}{\min(r_1^2, r_2^2)} \right]^{\pm \bar{\alpha}_s A_1}, \]

\[ K^3_{ci} = K_{DLA}(\sqrt{L_{r_1 r} L_{r_2 r}}). \]

Resums single collinear logarithms

Resums double collinear logarithms

\[ K_{ci} = K^1_{ci} K^2_{ci} K^3_{ci} \]

\( r = 1 \text{ GeV}^{-1}, \theta_{r,1} = \pi/2 \)
Here we compare the value of the collinearly improved kernel with the running coupling kernel versus $r_1$.

$$K^1_{rc} = \frac{N_c \alpha_s(r^2)}{2\pi^2} \frac{r^2}{r_1^2 r_2^2},$$

$$K^2_{rc} = \frac{N_c \alpha_s(r^2)}{2\pi^2} \frac{1}{r_1^2} \left( \frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right),$$

$$K^3_{rc} = \frac{N_c \alpha_s(r^2)}{2\pi^2} \frac{1}{r_2^2} \left( \frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right),$$

$$K_{rc} = K^1_{rc} + K^2_{rc} + K^3_{rc}.$$
Here we compare the value of the collinearly improved kernel with the running coupling kernel versus $r_1$. The contribution of the three terms is shown in Fig. 4 at $r = 1$ GeV and $\theta_{r_1} = \pi/2$ for each of the two kernels. The fact that the three terms are added in $K_{rc}$, but multiplied in $K_{ci}$ explains numerically the suppression. Even though, the first term is essentially the same for both kernels, the additive character of $K_{rc}$ makes it deviate from the collinearly improved kernel at large $r_1$ values as shown in Fig. 4. There, we can see that even though the kernels are comparable in the low-$r_1$ region, at large $r_1$ values, the $K_{r1}^2$ and $K_{r2}^3$ terms become dominant, whereas in the collinearly improved kernel, the $K_{ci}^1$ term suppresses the total value.

**FIG. 4.** The three constituent terms of the BK kernel for the running coupling (left) and collinearly improved cases (right).

The physics reason of this suppression can be traced back to the fact that large daughter dipoles do not follow the time-ordering prescription (that is, they would live longer than the parent dipole) built in when setting up the resummation that leads to the collinearly improved kernel [39, 51].

### B. Contribution of the kernel terms to the evolution

The suppression for large sizes of the dipole daughter in the kernel is translated as a suppression of the amplitude at large $b$ in the evolution. In this region only large $r_1$, parts. For the collinearly improved kernel, they are

\[
K_{ci} = K_{ci}^1 K_{ci}^2 K_{ci}^3
\]

\[
K_{rc} = K_{rc}^1 + K_{rc}^2 + K_{rc}^3
\]
The first term, $K_{ci}$, is present already at the leading order if one considers a fixed value of the running coupling, $\alpha_s$, of the running coupling, $\alpha_s$.

They would live longer than the parent dipole.

$$K_{ci} = K_{ci}^1 K_{ci}^2 K_{ci}^3$$

$$K_{rc} = K_{rc}^1 + K_{rc}^2 + K_{rc}^3$$

Here we compare the value of the collinearly improved kernel with the running coupling kernel versus $r_\parallel$.

The suppression can be traced back to the fact that large daughter dipoles do not follow the time-ordering prescription built in when setting up the resummation that leads to the collinearly improved kernel.

The physics reason of this suppression can be traced back to the fact that large daughter dipoles do not follow the time-ordering prescription (that is, they would live longer than the parent dipole).
Here we compare the value of the collinearly improved kernel with the running coupling kernel versus $r_1$. 

\[
\begin{align*}
K_{r_1} & = N_c \langle s | (r_1^2) \rangle (r_2^2)^2 \langle 1 | r_2^2 \rangle \\
K_2 & = N_c \langle s | (r_2^2) \rangle (r_1^2)^2 \langle 1 | r_1^2 \rangle \\
K_3 & = N_c \langle s | (r_1^2) \rangle (r_2^2)^2 \langle 1 | r_1^2 \rangle \\
K_{r_1} & = K_1 + K_2 + K_3.
\end{align*}
\]

The parameter $C$ for the running coupling in this kernel was chosen to be $C = 9$ just as in the collinearly improved kernel for the sake of a valid comparison.

There are two main differences responsible for the different behavior of these two kernels. One is the additive character of the constituent terms in the $r_cBK$ kernel. Even though, the first term is essentially the same for both kernels, the additive character of the $r_cBK$ makes it deviate from the collinearly improved kernel at high $r_1$ values as shown in Fig. 11. There, we can see, that even though the kernels are comparable in the low-$r_1$ region, at high values, the $K_2$ and $K_3$ terms become dominant, whereas in the collinearly improved kernel, the $K_1$ term suppresses the total value.

Second difference is illustrated best if we study the influence of adding these three constituent terms one by one to the kernel. In Fig. 12, we compare the impact parameter profile of the scattering amplitude evolved to $Y = 3$ with different kernel constituents. Here we see, that the impact parameter profile is mostly influenced by inclusion of the $K_3$ term with Bessel functions that is responsible for resuming double collinear logarithms, although the term $K_2$ resumming single collinear logarithms also suppresses the high-$b$ region.

We can link the high-$r_1$ suppression of the collinearly improved kernel to the suppression of the scattering amplitude at high impact parameter due to the fact that at high-$b$ region, essentially only high-$r_1$, $2$ region contributes to the total integral. This is true because big impact parameter means that the probing dipole is far away from the target proton and is therefore (at the initial condition) exponentially suppressed. Only dipoles with $r_1(r_2) \ll b$ can be oriented so that their $b_1(b_2)$ is small. Only these contribute to the overall integral. Since $K_1$ is suppressed in this region, the integral will be suppressed as well and scattering amplitude will not grow as fast at high-$b$ (which we can see in Fig. 12).
KERNEL CUTOFF

Here we compare the value of the collinearly improved kernel with the running coupling kernel versus $r_i$.

$|K_c/K_{rc}|$ for $\theta_{r_1} = 1.57$ [rad] and $r = 1$ [GeV$^{-1}$]

Scattering amplitude for $r = 1.0$ [GeV$^{-1}$]

J. Cepila, J. G. Contreras, M. Matas; Phys. Rev. D 99, 051502

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COMPARISON TO DATA
RESULTS

![Graph showing the dependence of $F_2(x, Q^2)$ on $x$ for different values of $Q^2$. The graph includes a legend with various lines corresponding to different $Q^2$ values, such as $Q^2 = 2.0 \text{ GeV}^2 \times 2^0$, $Q^2 = 2.7 \text{ GeV}^2 \times 2^1$, etc.]
RESULTS

\[ J/\Psi, Q^2 = 0.05 \text{ GeV}^2 \]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figures/RESULTS.png}
\caption{Comparison of the computation with data from the H1 Collaboration at HERA at \( \sqrt{s} = 196 \text{ GeV} \).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figures/RESULTS.png}
\caption{Comparison of the computation with data from the H1 Collaboration at HERA at \( \sqrt{s} = 196 \text{ GeV} \).}
\end{figure}
H1 Collaboration [44, 45] is shown in Fig. 3. Note that the parameter \( \lambda_1 \) at \( \langle W \rangle = 55 \) GeV was used to set the value of the amplitude divided by 16, which is known as the skewedness correction [43].

As a final application of the dipole scattering amplitude that was not considered when deriving the correction has been computed using the derivative of the wave function of Large Research, Development, and Innovations Infrastructures.

The potential of the solutions we found, we compute the corrections, and how to apply them to phenomenology, and with a given transverse photon, respectively, and the longitudinal and transverse photons are added. As it is customary (see discussion in Sec. 3 of [39]), we correct the contribution of the real part of the dipole scatterings [41, 42] with parameters as determined in [39].

The dipole scattering amplitudes computed in this work are publicly available in the website https://hep.fjfi.cvut.cz/.

The measurement of the data at the level of 10%.

The agreement is at the level of 10%.
RESULTS
Photoproduction data

- ZEUS (2009)
- H1 (2000)
- LHCb (2015)
- CMS (2019)

Photoproduction

- H1 (2006)
- H1 (2013)
- ALICE p-Pb (2014)
- ALICE p-Pb (2018)

Model, $Q^2 = 0.05 \text{ GeV}^2$

Electroproduction

- H1 (2006)
- Model, $Q^2 = 3.2 \text{ GeV}^2$
- H1 (2006)
- Model, $Q^2 = 7.0 \text{ GeV}^2$
- H1 (2006)
- Model, $Q^2 = 22.4 \text{ GeV}^2$

Electroproduction, $W_{ip} = 100 \text{ GeV}$

- H1 (2006)
- Model, $Q^2 = 3.2 \text{ GeV}^2$
- H1 (2006)
- Model, $Q^2 = 7.0 \text{ GeV}^2$
- H1 (2006)
- Model, $Q^2 = 22.4 \text{ GeV}^2$

SCATTERING AMPLITUDE DATASETS
SCATTERING AMPLITUDE DATASETS

In this work we solved the impact-parameter dependent Balitsky-Kovchegov equation with the recently proposed collinearly improved kernel. We find that the solutions do not present the Coulomb tails that have affected previous studies. We also show that once choosing an adequate initial condition it is possible to obtain a reasonable description of HERA data on the structure function of the proton, as well as on the cross section for the exclusive production of a J/ψ vector meson off proton targets. Here you can find the data sets associated with this work.

If you want to use this data set, please cite the following:

You can download the computed dat sets and an example in Python here: ciBK_data_files.zip.

Contact person: Marek Matas, marek.matas@fjfi.cvut.cz

All the datasets are publicly available at https://hep.fjfi.cvut.cz/bdepBK.php
b-dependent solution of the Balitsky-Kovchegov equation

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If you want to use this data set, please cite the following:


You can download the computed data sets and an example in Python here: cIBK_data_files.zip.

Contact person: Marek Matas, marek.matas@fffi.cvut.cz

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All the datasets are publicly available at [https://hep.fffi.cvut.cz/bdepBK.php](https://hep.fffi.cvut.cz/bdepBK.php)
All the datasets are publicly available at https://hep.ffj.fn.tc/bdepBK.php
CONCLUSIONS

• The predictive power of the the impact-parameter dependent BK equation can be spoiled by the unphysical growth of the so-called Coulomb tails.
• These can be suppressed by suppressing the evolution for large daughter dipoles \( r_1 \) and \( r_2 \).
• The collinearly improved kernel suppresses the Coulomb tails so that the \( b \)-dependent BK equation describes data over a large phase-space and various processes.
• We have currently submitted a paper with all details to arXiv: 1907.12123.
THANK YOU FOR YOUR ATTENTION