BFKL Pomeron loops in photoproduction and hadroproduction of J/psi at large transverse momenta

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Outline

Work done with
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- Motivation and phenomenological context
- Theoretical small-x evolution context:
  non-forward BFKL equation and BKP states
- Evaluation of the lowest order amplitudes
- Double BFKL pomeron evolution, the pomeron loops
- Results, comparison to data
Definition of the process

- Consider high pT vector meson production with a jet, with large rapidity distance

- Integrate out the jet to get contribution to inclusive production

- Proposed by Khoze, Martin, Ryskin, Stirling
Heavy quarkonia hadroproduction

Production mechanisms in QCD:

- Color singlet, collinear: LO, NLO
- Color octet
- Color singlet NNLO*
- Color singlet kT-factorization
- Color singlet with double scattering without correlations

This study:
- Color singlet, double scattering with correlations
Color singlet vs color octet

- Conventional color singlet mechanism: simple and straightforward, but badly underestimates the data.

- Color octet mechanism is able to describe the data but the successful description relies on several multiplicative parameters that are fitted.

- There is still room for alternative approaches.
Example: color singlet beyond NLO: NNLO*
Color singlet – beyond NLO: three gluon fusion contribution (higher twist)

- Conventional color singlet mechanism relies on two gluon fusion followed by gluon emission

- Alternative: fusion of two gluons from the beam and one gluon from the target

- Higher twist suppression but enhancement by double gluon density

- Found to lead to a ~25% contribution to data at moderate pT, but irrelevant at large pT

[Khoze, Martin, Ryskin, Stirling; M. Sadzikowski, LM]
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[Khoze, Martin, Ryskin, Stirling; M. Sadzikowski, LM]
At NNLO: heavy quarkonium + jet with sizable rapidity distance

- **Vector meson vertex:** fusion of three gluons
- Two gluons come from a single parton – no higher twist suppression!
- In the cross-section enhancement factor appears from double hard pomeron evolution between the meson and the jet
- Enters as a part of NNLO correction to color singlet
- It is a gauge invariant contribution in the high energy limit
The correlated double pomeron contribution

- In partonic cross section one finds four gluon t-channel evolution
- In high energy limit, in the LL1/x approximation the evolution described by Bartels-Kwieciński-Praszałowicz (BKP) equation

![Diagram of correlated double pomeron exchange]

- Leading singularity at high energies in large Nc limit: the double pomeron exchange
- The pomerons originate from a single parton ~ correlated double parton density
Two pomeron contribution in hadroproduction and diffractive photoproduction at high $p_T$

- Both described by two pomeron exchange but with different cuts
- The same kinematic part at the lowest order
BKP states in t-channel

- Analysis of four gluon state in the t-channel in high energy limit must take into account:
  - Gluon reggeization
  - Symmetry of the 4-gluon state
  - BKP 4-gluon amplitude with central cut has symmetries: for exchanges of gluons (12), (34) and (12) with (34)
  - Decomposition into eigenstates of BKP evolution
BKP states in t-channel

- Two BFKL pomeron color singlet diffractive cut
- Two cut BFKL pomeron
- D-reggeons, single cut BFKL
Problem to resolve: double non-forward BFKL evolution and integrate over the BFKL pomeron loop
Projection on the two pomeron state

- Project on the BKP state using color basis with adequate symmetries

\[ |1\rangle = N_1 \delta^{ab} \delta^{cd}, \quad |d_R\rangle = N_d \delta^{ab} \delta^{cd}, \quad |2P\rangle = N_{2P} (\delta^{ac} \delta^{bd} + \delta^{ad} \delta^{bc}) \]

\[ \langle A|A'\rangle = \delta_{AA'} + \mathcal{O}(1/N_c^2), \quad \text{Projection operator on } 2P = |2P\rangle\langle 2P| \]
Solving the double non-forward BFKL exchange problem

\[ |\mathcal{M}|^2 = \mathcal{N} \int d^2 q \int d^2 k_1 d^2 k_2 \int d^2 k'_1 d^2 k'_2 \frac{1}{k_1^2 (q - k_1)^2 k_2^2 (q - k_2)^2} \]

\[ \times \Phi_{J/\Psi}(k_1, k_2) \Phi^*_{J/\Psi}(q - k_1, -q - k_2) \delta^{(2)}(k_1 + k_2 - p_T) \]

\[ \times G(k_1, k'_1; q, Y) G(k_2, k'_2; -q, Y) \]

\[ \times \Phi^2_P(k'_1, k'_2, q - k'_1, -q - k'_2) \]
We developed fully numerical approach to solve non-forward BFKL equation.

Integro-differential (w.r.t. rapidity $Y$) equation with two dimensional integral kernel.

Currently, in the numerical approach we use an infrared cut-off $s_0$ on gluon virtuality. Running coupling and other NLL BFKL effects not included yet.

The double pomeron exchange amplitude is obtained by numerical integration over the loop of the non-forward BFKL pomerons.

The numerical approach agrees with a semi-analytic one.
Results: the lowest order

- Analytic results known for diffractive amplitude [Ginzburg, Ivanov]

\[
\text{for } p_T \gg M : \quad M_{diff} \sim \frac{C_1 e q_c g_s^4}{p_T^4} \log\left(\frac{p_T^2}{M^2}\right) (\varepsilon_V^* \varepsilon_\gamma)
\]

- Diffractive cross section at high pT

\[
\frac{d\sigma_{diff}}{dp_T^2} \sim \sum_{\varepsilon_V, \varepsilon_\gamma} |M_{diff}|^2 \sim \frac{C_1^2 q_c^2 \alpha_{em} \alpha_s^4}{p_T^8} \log^2\left(\frac{p_T^2}{M^2}\right)
\]

- Suitable modification of coupling constants and color factor leads to the two pomeron cross section in hadroproduction at the lowest order

\[
\frac{d\sigma_{2P}}{dp_T} \sim \frac{C_2 P \alpha_s^5}{p_T^7} \log^2\left(\frac{p_T^2}{M^2}\right) \sim \frac{1}{p_T^7}
\]
Results: double two BFKL pomeron amplitudes at parton level

Main features of the double BFKL pomeron amplitude at high $p_T \gg M$

- Exponential growth with rapidity

\[ \frac{d\sigma}{dy} \sim \exp(2\Delta y) \]

with $\Delta \sim 0.3$
Results: double two BFKL pomeron amplitudes at parton level

Main features of the double BFKL pomeron amplitude at high $p_T >> M$

- Parton level $p_T$ dependence

Weak effects of the evolution on the leading dependence at high $p_T$
Main features of the double BFKL pomeron amplitude at high $p_T >> M$

- Dominance of low pomeron $q_T < M_T$ in the pomeron loop
It is straightforward to get the pp inclusive cross section from partonic cross sections

\[
\frac{d\sigma(pp \rightarrow J/\psi X)}{dp_TdY} = \int dx_1 \int dx_2 \delta(Y - \log(x_1 \sqrt{S_{pp}/E_T})) \\
\times g(x_1, \mu) \left[ C_q \sum_q q(x_2, \mu) + C_g g(x_2, \mu) \right] \frac{d\hat{\sigma}_0}{dp_T}(x_1x_2S_{pp})
\]

- Non-trivial color coefficients $C_q$ and $C_g$ for quark and gluon partonic targets
- The standard choice of scale for parton and strong coupling constant: $E_T$
Comparison to data: diffractive photoproduction of J/ψ

- Diffractive photoproduction of J/ψ at high pT (data from H1)

- Data well described, conservative uncertainty measure, shape not affected
Comparison to data: hadroproduction of J/ψ

Results compared to CMS data for prompt J/ψ at 13 TeV

Neither normalisation nor shape are well described
Comparison to CMS data: Upsilon

$p+p \rightarrow \Upsilon(1S)$ at 13 TeV

$B d\sigma/dp_T dy$ [pb/GeV]

$0<|y|<0.6$

running $\alpha_s = \alpha_s(E_T)$

CT14nlo PDFs

$s_0 = 0.5$ GeV$^2$

trajectory $\alpha_s = 0.14$

BFKL with 2P exchange

CMS data

$2.5 \times 10^7/p_T^5$ [pb/GeV]

$1.0 \times 10^9/p_T^7$ [pb/GeV]
Comparison to data: hadroproduction of J/ψ

- Results compared to CMS data for prompt J/ψ at 13 TeV: fixed coupling constant, scale set to quark mass

![Graph showing BFKL with 2P exchange compared to CMS data for p+p -> J/ψ at 13 TeV. The graph includes the CMS data points and theoretical curves with different predictions for B(σ/p)[pb/GeV].]
Conclusions

- We obtained for the first time the full solution for two non-forward BFKL pomeron amplitude, with the pomerons correlated by common origin at a point-like parton.

- Two cut BFKL pomeron loop contribution to heavy vector meson hadroproduction was evaluated for this configuration.

- Cross sections were computed for associated diffractive photoproduction of J/psi and associated J/psi and jet production with rapidity separation.

- Good description of diffractive photoproduction of J/psi at large momentum transfer.

- The correlated two pomeron (pomeron loop) mechanism gives small contribution to inclusive hadroproduction of J/psi at large pT.

THANKS!
Backup
Hadroproduction of J/$\psi$: BFKL vs the lowest order

$p+p \rightarrow J/\Psi$ with 2P exchange

running $\alpha_s = \alpha_s(E_T)$
CT14nlo PDFs
$s_0 = 0.5$ GeV$^2$
trajectory $\alpha_s = 0.14$
Distribution of evolution length $y$ in $J/\psi$ hadroproduction

$p_T = 30$ GeV

Graph showing the distribution of $B \frac{d \sigma}{d p_T^2 dy}$ with $y$ on the x-axis and $B \frac{d \sigma}{d p_T^2 dy}$ on the y-axis.
Relation to Bartels triple pomeron vertex with double Pomeron cut
Diagramatics:

Color singlet LO

[Image of various diagrams labeled (a) to (h)]

[Lansberg]
Diagramatics:

Color singlet NLO

(a)  (b)  (c)  (d)

(e)  (f)  (g)  (h)
Diagramatics:

Color singlet NNLO* [Lansberg]
Diagramatics:

Color octet

(a)  
(b)  
(c)  
(d)  

(e)  
(f)  

(g)  
(h)  

[Lansberg]
The correlated double pomeron contribution: how to compute? Step 1

- Very well known starting point: proton-dissociative heavy vector meson photoproduction at high $p_T$ with rapidity gap

- Go to the lowest order
The correlated double pomeron contribution: how? Step 2

- The lowest order amplitudes for quasi-diffractive production and the 3 gluon fusion differ only by coupling constants and color factors, due to symmetry of the color part, the kinematical parts are the same.
The correlated double pomeron contribution: how? Step 3

Dress-up the lowest order amplitude with the BFKL evolution / BFKL Green’s functions
Solving the double non-forward BFKL exchange problem

- The LL BFKL Green’s function with conformal eigenfunctions $E(n, \nu)$ in position space [Lev Lipatov]

\[ \tilde{G}(r_1, r_2, r'_1, r'_2) = \sum_n \int d\nu \, w(n, \nu) \int d^2r_0 E_{n,v}^*(r_{01}^*, r_{02}^*) \exp(\bar{\alpha}_s Y \chi_n(\nu)) E_{n,v}(r'_{01}, r'_{02}) \]

- Momentum representation of the Green’s function

\[ \hat{G}(k, k'; q, Y) = \sum \int d\nu \, w(n, \nu) \langle k | E(q, n, \nu) \rangle \exp(\bar{\alpha}_s Y \chi_n(\nu)) \langle E(q, n, \nu) | k' \rangle \]

- BFKL exchange amplitude with impact factors of particles A and B

\[ \mathcal{M}(q, Y) \sim \langle \Phi_A | \hat{G}(q, Y) | \Phi_B \rangle \]

\[ \mathcal{M}(q, Y) \sim \sum_n \int d\nu \langle \Phi_A | E(q, n, \nu) \rangle \exp(\bar{\alpha}_s Y \chi_n(\nu)) \langle \Phi_B | E(q, n, \nu) \rangle \]
Solving the double non-forward BFKL exchange problem

- Extension to double pomeron exchange amplitude

\[ |\mathcal{M}|^2 \sim \sum_n \sum_{n'} \int d\nu \int d\nu' w(n, \nu) w(n, \nu') \exp(\tilde{\alpha}_s Y \chi_n(\nu)) \exp(\tilde{\alpha}_s Y \chi_n(\nu')) \times \int d^2q \langle \Phi_Q^{2P} \mid E(q, n, \nu) \rangle \otimes \langle E(-q, n', \nu') \rangle \langle E(q, n, \nu) \mid \otimes \langle E(-q, n', \nu') \rangle \rangle \Phi_{J/\psi}^{2P} \]

\[ \Phi_{J/\psi}^{2P}(k_1, k_2, q-k_1, -q-k_2) = \Phi_{J/\Psi}(k_1, k_2) \Phi^*_{J/\Psi}(q-k_1, -q-k_2) \delta^{(2)}(k_1+k_2-p_T) \]

- The pointlike parton (q or g) impact factor: Mueller-Tang prescription generalized to two pomerons

\[ \Phi_Q(k, q) \sim \text{const}(k, q) \rightarrow \langle E(q, n, \nu) \mid \Phi_Q \rangle = \Phi_{M-T}(q, n, \nu) \]

\[ \Phi_Q^{2P}(\{k_i\}, q) \sim \text{const}(\{k_i\}, q) \]

\[ \langle E(q, n, \nu) \mid \otimes \langle E(-q, n', \nu') \rangle \rangle \Phi_Q^{2P} \sim \Phi_{M-T}(q, n, \nu) \Phi_{M-T}(-q, n', \nu') \]