Multiple scattering effects in heavy quarkonia hadroproduction

Leszek Motyka
Jagiellonian University, Krakow

Low x 2019, Nicosia
27.08.2019
Based on work done with Mariusz Sadzikowski, 2015 and with Piotr Kotko, Anna Staśto and Mariusz Sadzikowski, 2019

- 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*

![Graph showing the ratio of \(d\sigma/dP_T\) for different orders of approximation (LO, NLO, NNLO*) versus \(P_T\) (GeV).]
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]
Color singlet – beyond NLO: three gluon fusion contribution (higher twist)

- Conventional color singlet mechanism relies on two gluon fusion followed by gluon emission
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 – **too soft!**

[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

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 pT

**Two pomeron contribution**

![Diagram](image1.png)

**Diffractive photoproduction at high pT**

- 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

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

\[ \langle A|A' \rangle = \delta_{AA'} + \mathcal{O}(1/N_c^2), \]

Projection operator on \( 2P = |2P\rangle\langle 2P| \)
Solving the double non-forward BFKL exchange problem

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

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

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

\[ \times \Phi^2_P(q'_1, k'_2, q - k'_1, -q - k'_2) \]
Solving the double non-forward BFKL exchange problem: numerical approach

- 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]

\[
M_{\text{diff}} \sim \frac{C_1 e q_c g_s^4}{p_T^4} \log\left(\frac{p_T^2}{M^2}\right) (\varepsilon^*_V \varepsilon_\gamma)
\]

- Diffractive cross section at high pT

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

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

\[
\frac{d\sigma_{2P}}{dp_T} \sim \frac{C_2 P \alpha_s^5}{p_T^7} \log^2\left(\frac{p_T^2}{M^2}\right) \sim \frac{1}{p_T^7}
\]
Main features of the double BFKL pomeron amplitude at high $p_T > M$

- Exponential growth with rapidity

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

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

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

$q_T$ – transverse momentum of the pomeron in the loop
From parton to hadron level

It is straightforward to get the pp inclusive cross section from partonic cross sections

\[
\frac{d\sigma(pp \rightarrow J/\psi X)}{dp_Tdy} = \int dx_1 \int dx_2 \delta(Y - \log(x_1 \sqrt{S_{pp}/E_T})) \times g(x_1, \mu) \left[ C_q \sum_q q(x_2, \mu) + C_g g(x_2, \mu) \right] \frac{d\sigma_0}{dp_T}(x_1 x_2 S_{pp})
\]

- 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 $J/\psi$

- Diffractive photoproduction of $J/\psi$ 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

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

- $2.5 \times 10^7 / p_T^5 \text{[pb/GeV]}$
- $1.0 \times 10^9 / p_T^7 \text{[pb/GeV]}$

$0 < |\Upsilon| < 0.6$

running $\alpha_s = \alpha_s(E_T)$
CT14nlo PDFs
$s_0 = 0.5 \text{ GeV}^2$
trajectory $\alpha_s = 0.14$
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
The pT-shape differentiates

- At large pT the quarkonia distribution is hard
- Computations performed with color singlet models: single scattering, uncorrelated 1+2 gluon fusion and correlated 1+2 gluon fusion lead to much too soft distributions → need for color octet contributions at parton level
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
Distribution of evolution length $y$ in $J/\psi$ hadroproduction

$p_T = 30$ GeV

$B \frac{d\sigma}{dp_T} dy$ vs. $y$

- $Y=0$
- $Y=0.3$
- $Y=-0.3$
- $Y=0.6$
- $Y=-0.6$
Relation to Bartels triple pomeron vertex with double Pomeron cut
Diagramatics:

Color singlet LO

[Image of diagrams with labels (a) to (h)]

[Lansberg]
Diagramatics:

Color singlet NLO

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

(e)  (f)  (g)  (h)

[Ref: Lansberg]
Diagramatics:

Color singlet NNLO* [Lansberg]

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

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

Color octet

[Images of diagrams (a) to (h) with labels $Q$ and $S_i^{[8]}$ as per Lansberg]