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

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DIS 2019, Torino
09.04.2019

Outline

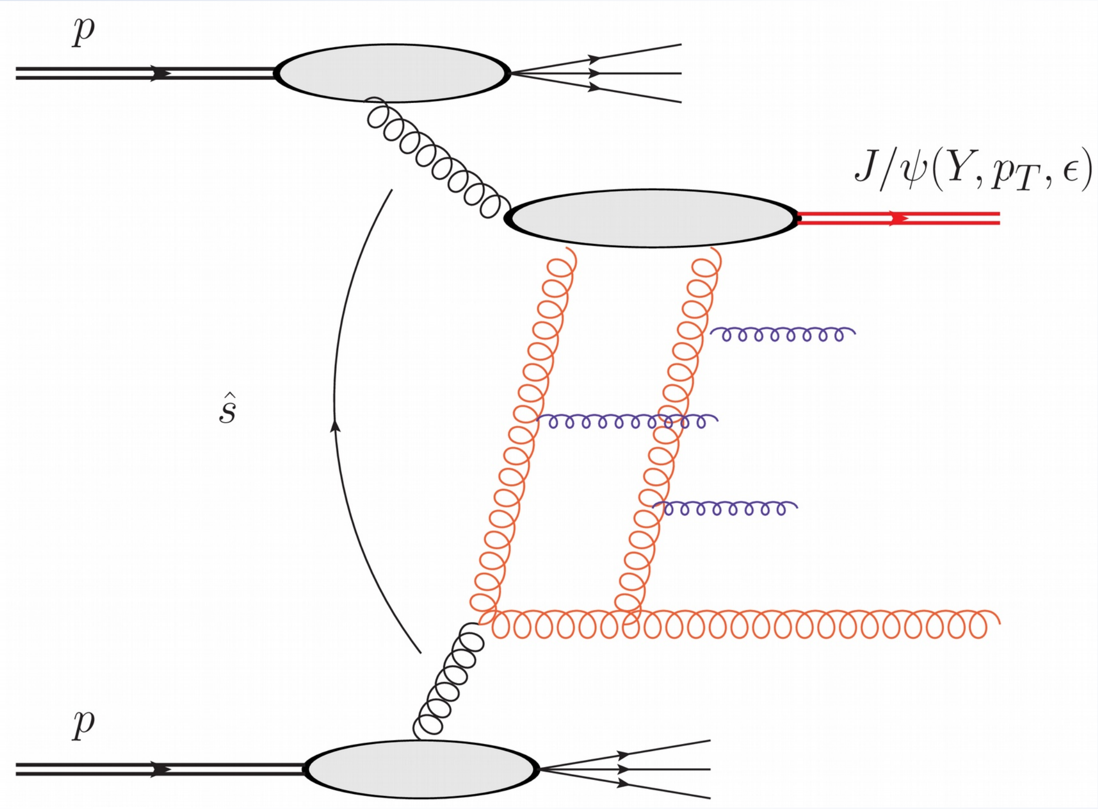
Work done with

Piotr Kotko, Anna Staśto and Mariusz Sadzikowski

- 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:

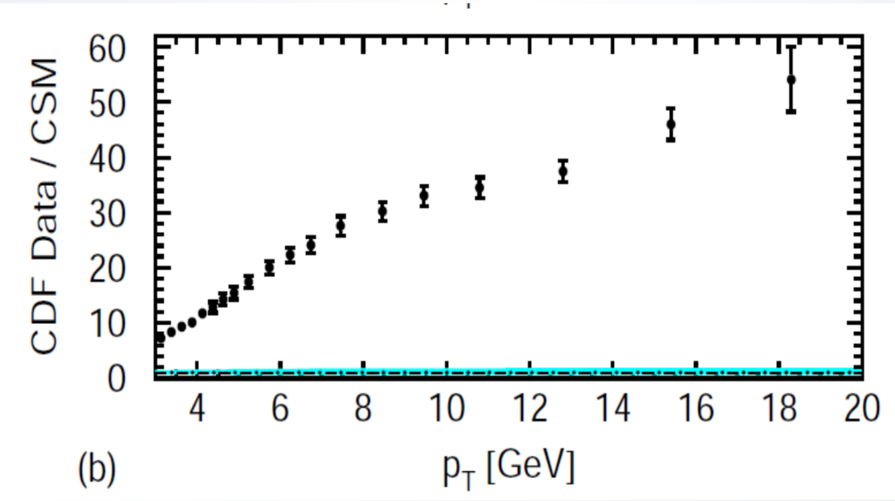
- Color singlet, collinear: LO, NLO
- Color octet
- Color singlet NNLO*
- Color singlet kT-factorization
- Color singlet with double scattering without correlations

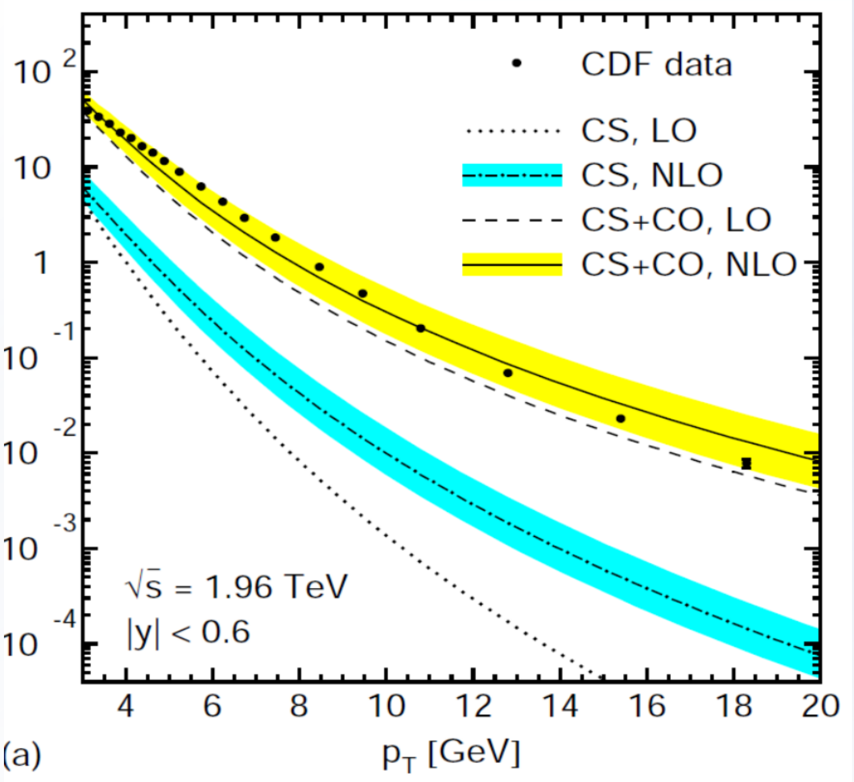
This study:

- Color singlet, double scattering with correlations

Color singlet vs color octet

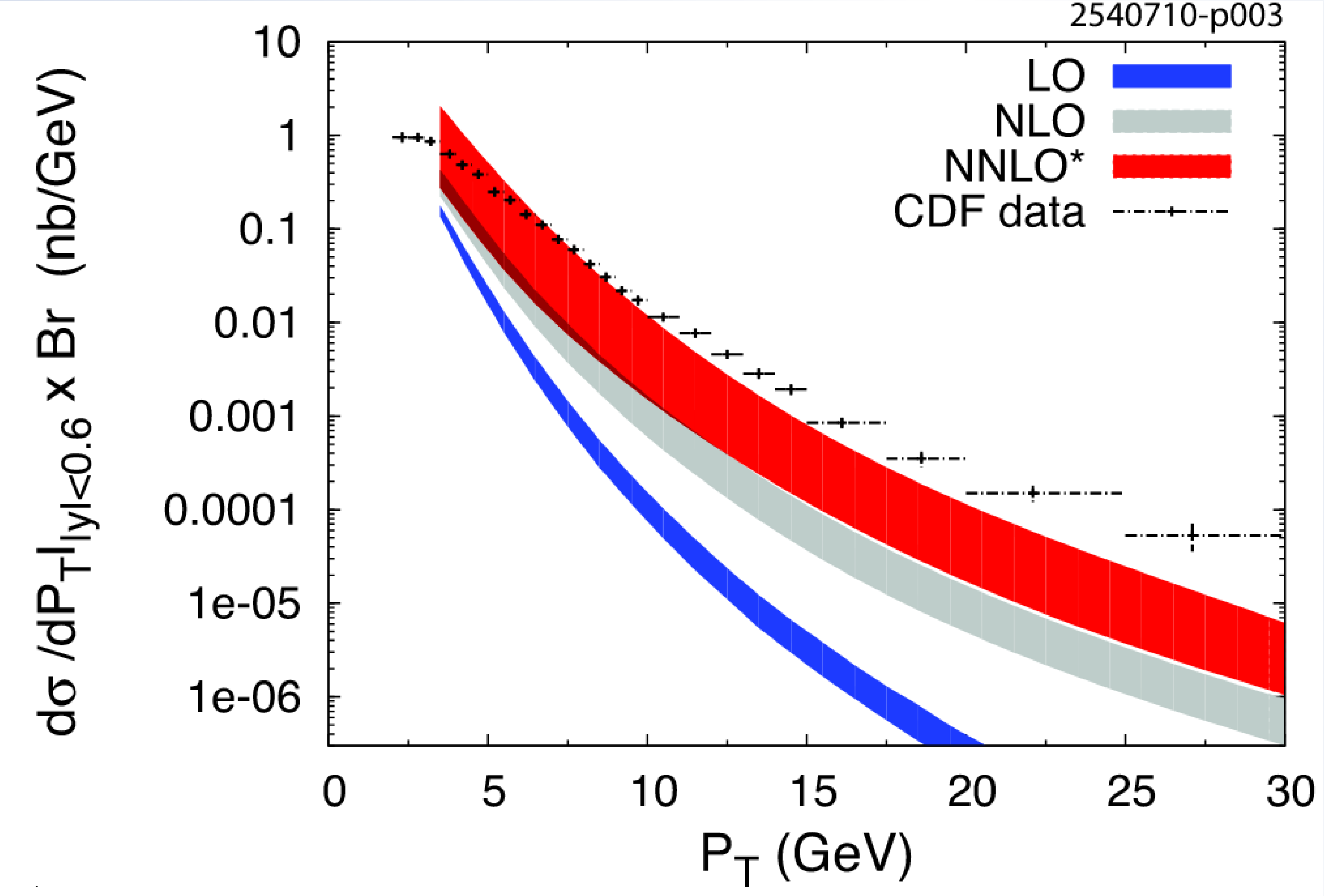
- Conventional color singlet mechanism: simple and straightforward, but badly underestimates the data
- Color octet mechanism is able to describe the data but the successful description relies on several multiplicative parameters that are fitted
- There is still room for alternative approaches





Example: color singlet beyond NLO: NNLO*

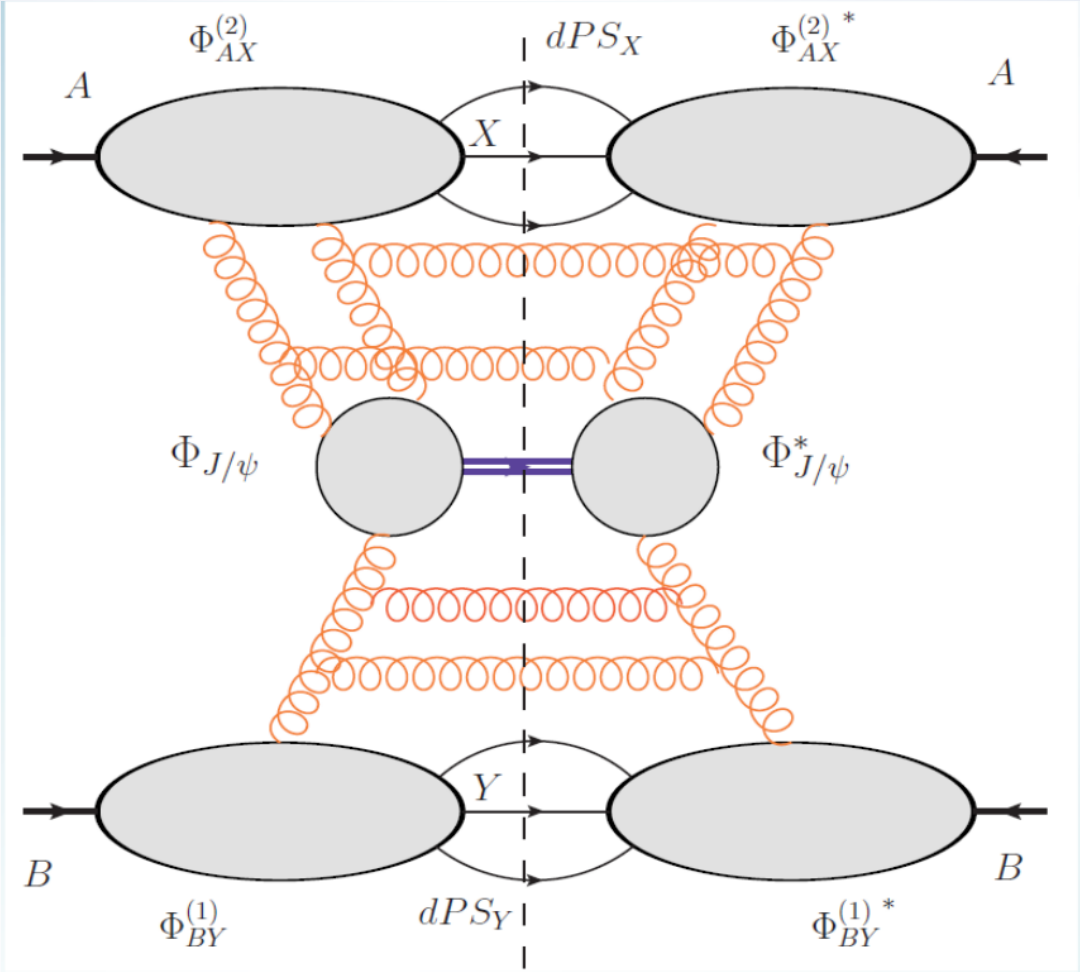
[Lansberg]



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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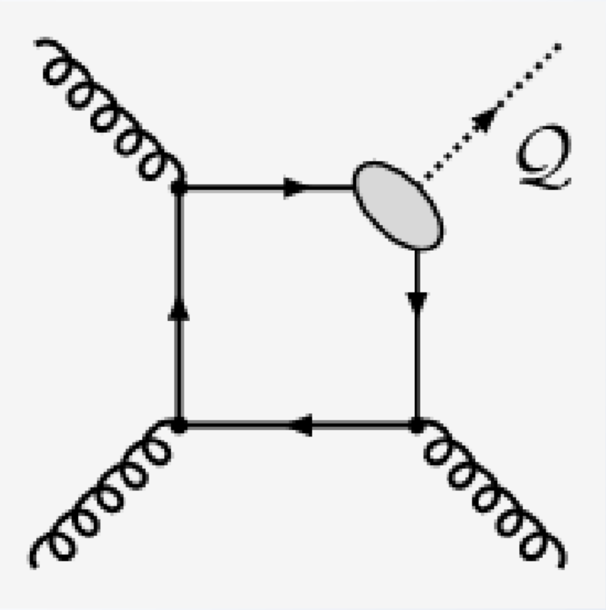

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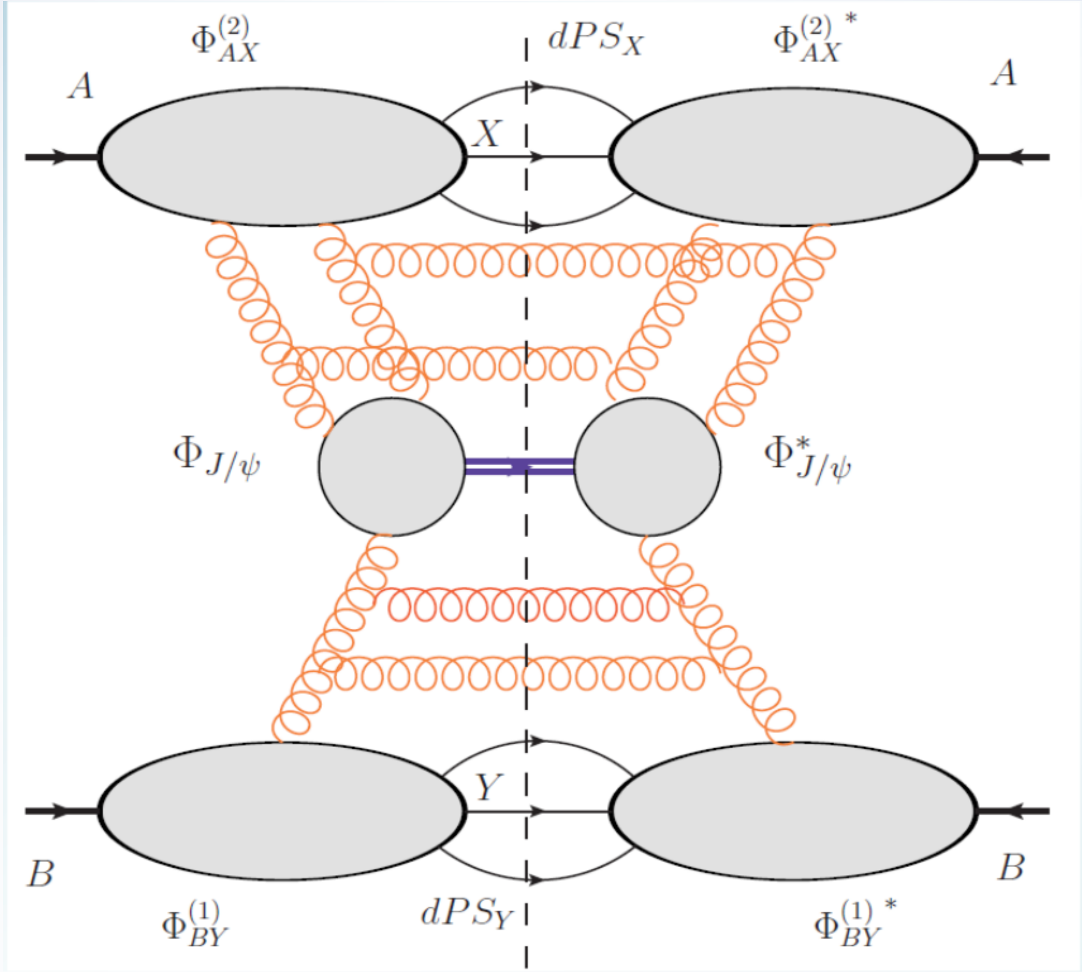
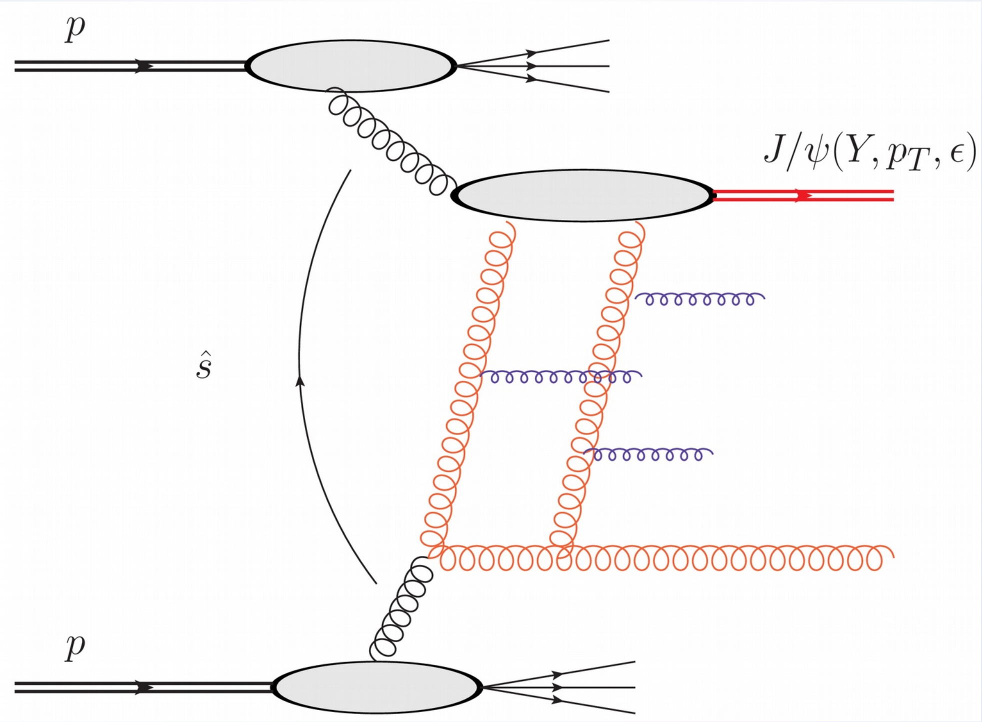
[Khoze, Martin, Ryskin, Stirling; M. Sadzikowski, LM]



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!

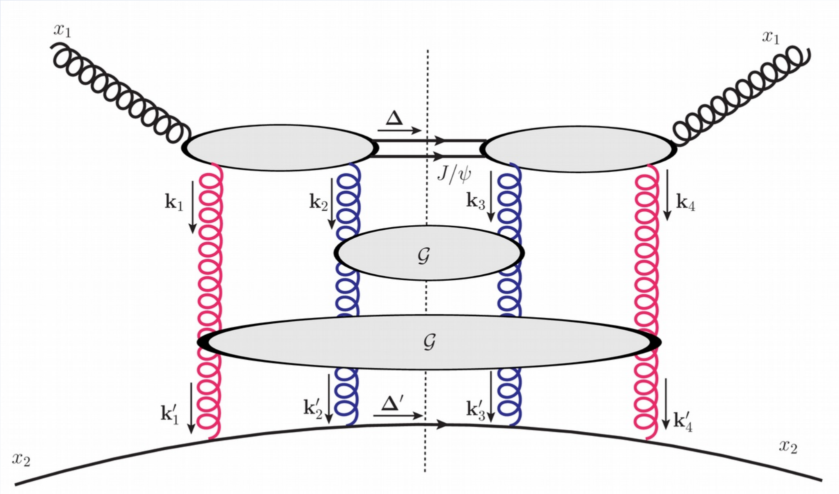
- In the cross-section enhancement factor appears from double hard pomeron evolution between the meson and the jet

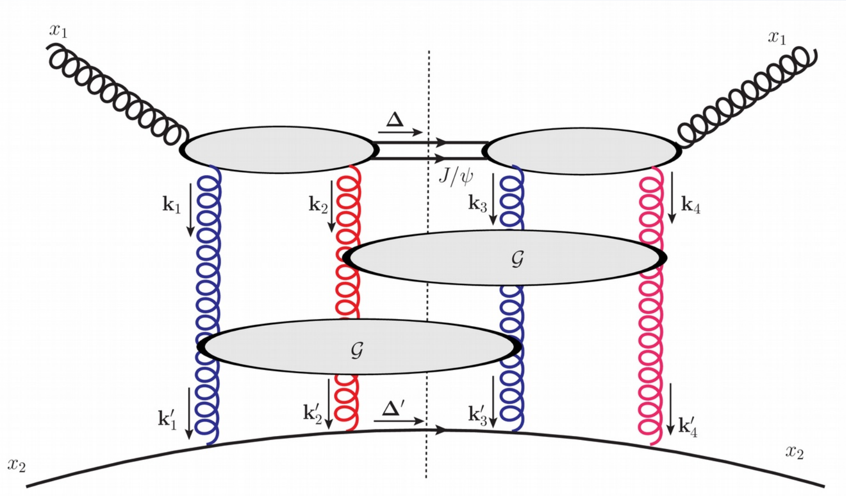
- Enters as a part of NNLO correction to color singlet

- 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

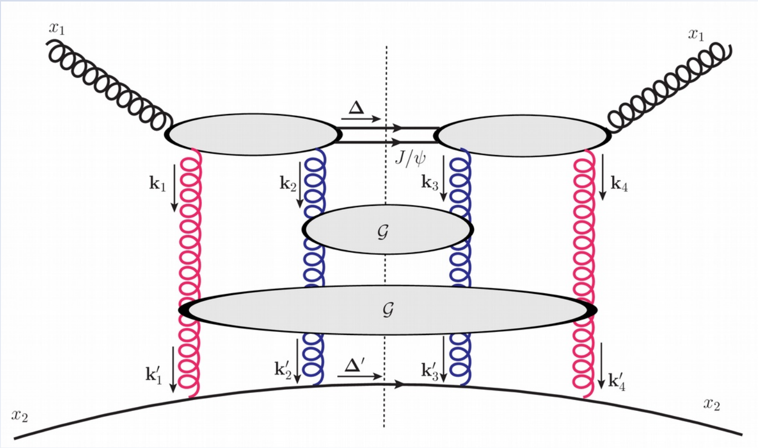


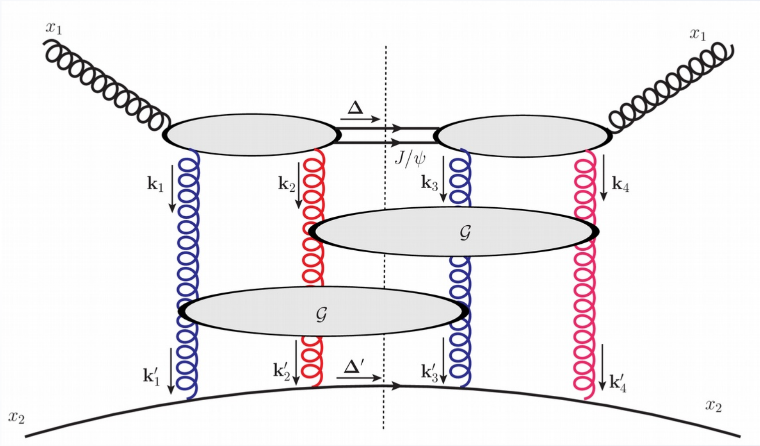


- Leading singularity at high energies in large Nc limit: the double pomeron exchange
- The pomerons originate from a single parton ~ correlated double parton density

Two pomeron contribution in hadroproduction and diffractive photoproduction at high pT

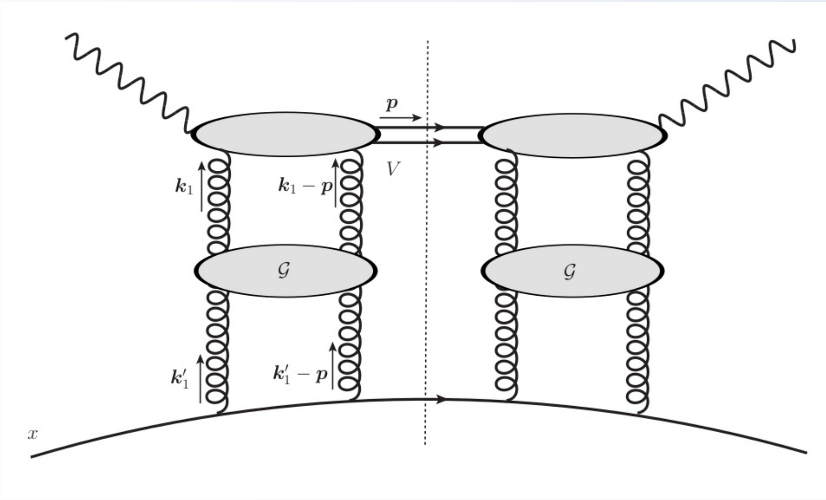
Two pomeron contribution





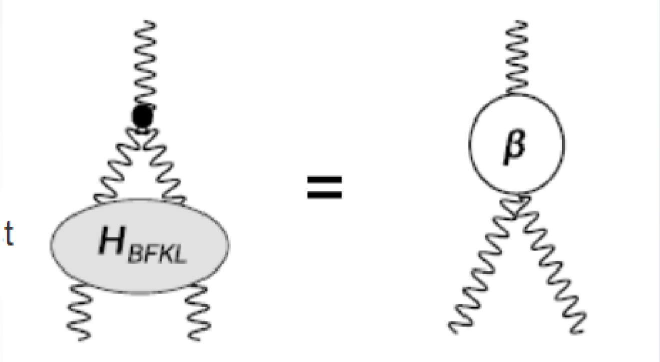
Diffractive photoproduction at high pT

- Both described by two pomeron exchange but with different cuts
- The same kinematic part at the lowest order

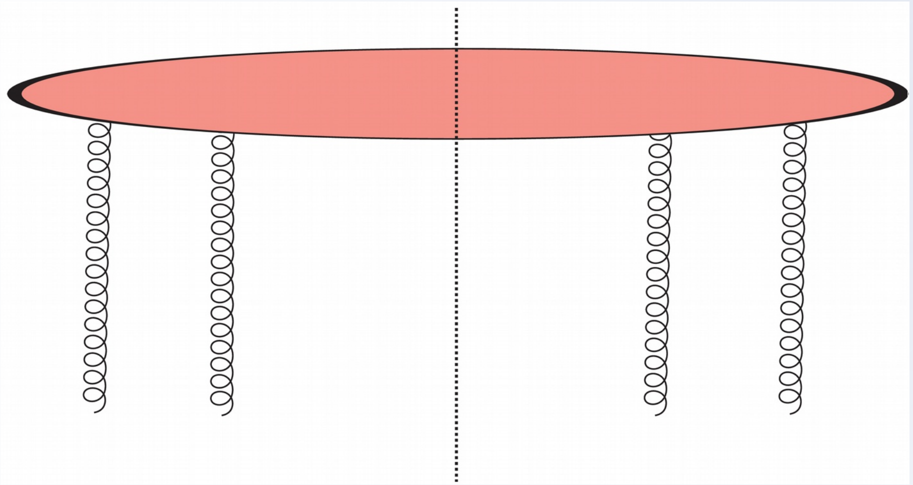


BKP states in t-channel

- Analysis of four gluon state in the t-channel in high energy limit must take into account:

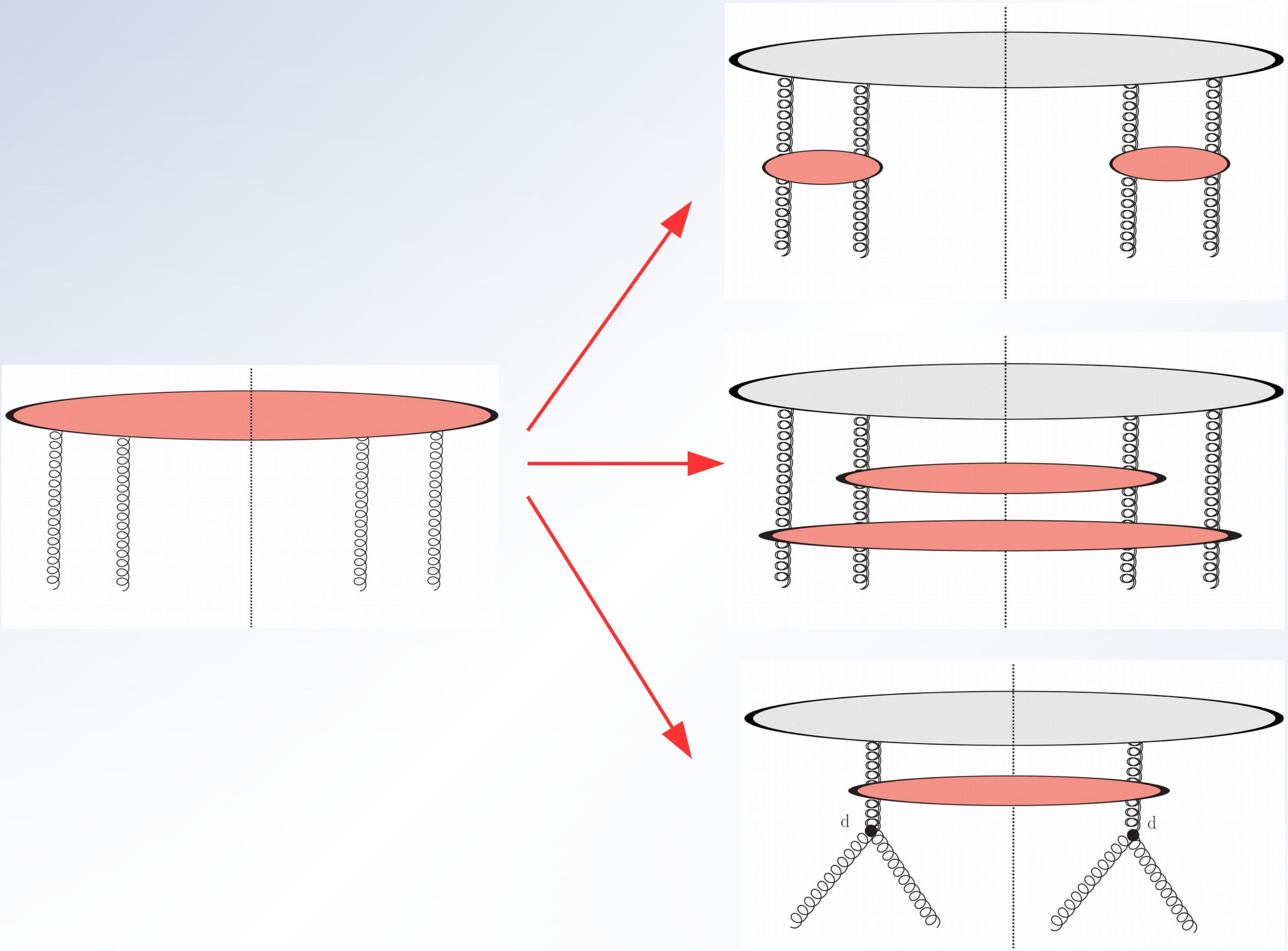


- Gluon reggeization
- Symmetry of the 4-gluon state
- BKP 4-gluon amplitude with central cut has symmetries:
  for exchanges of gluons
  (12), (34) and (12) with (34)



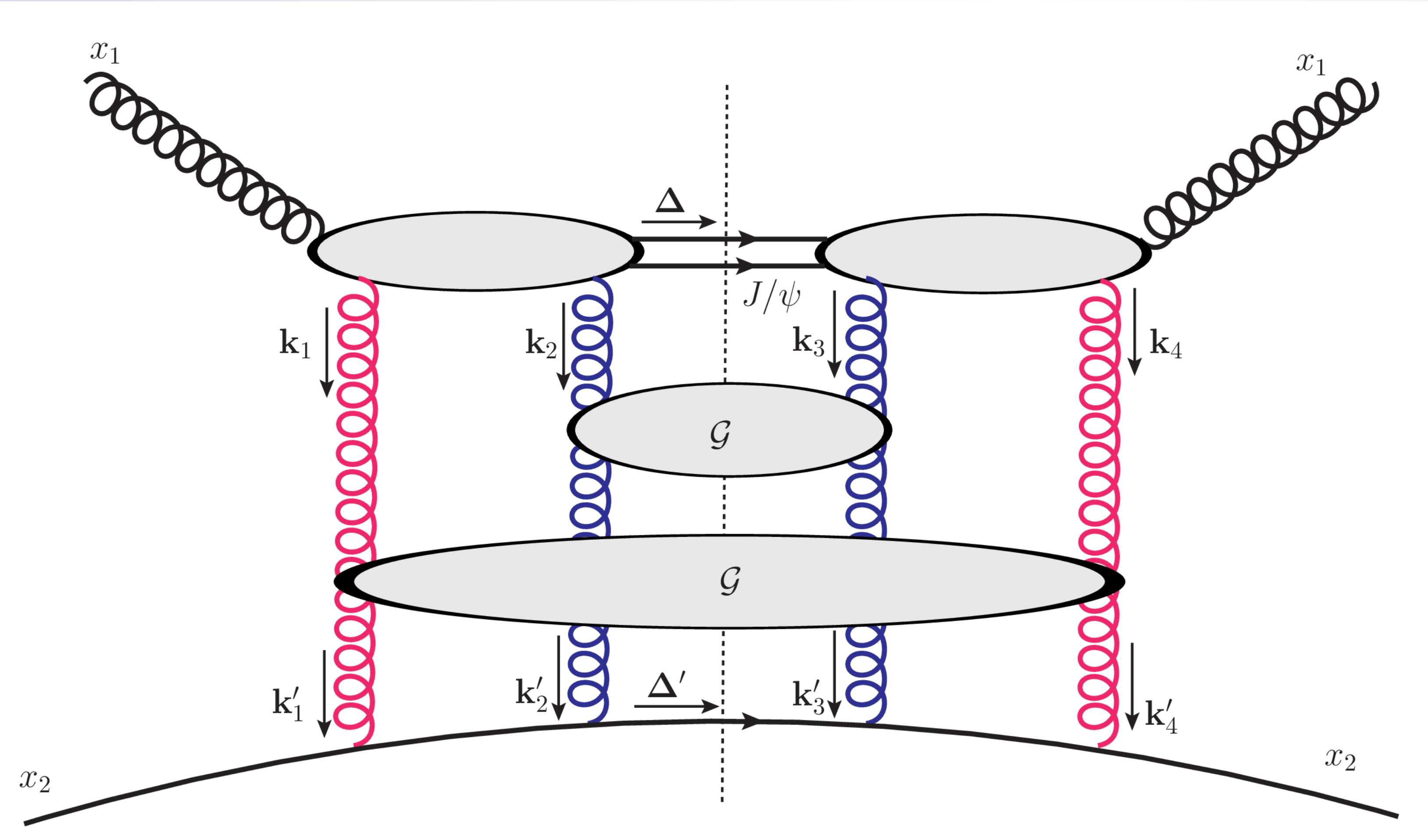
- Decomposition into eigenstates of BKP evolution

BKP states in t-channel



- Two BFKL pomerons color singlet diffractive cut
- Two cut BFKL pomerons
- D-reggeons, single cut BFKL

Problem to resolve: double non-forward BFKL evolution and integrate over the BFKL pomeron loop

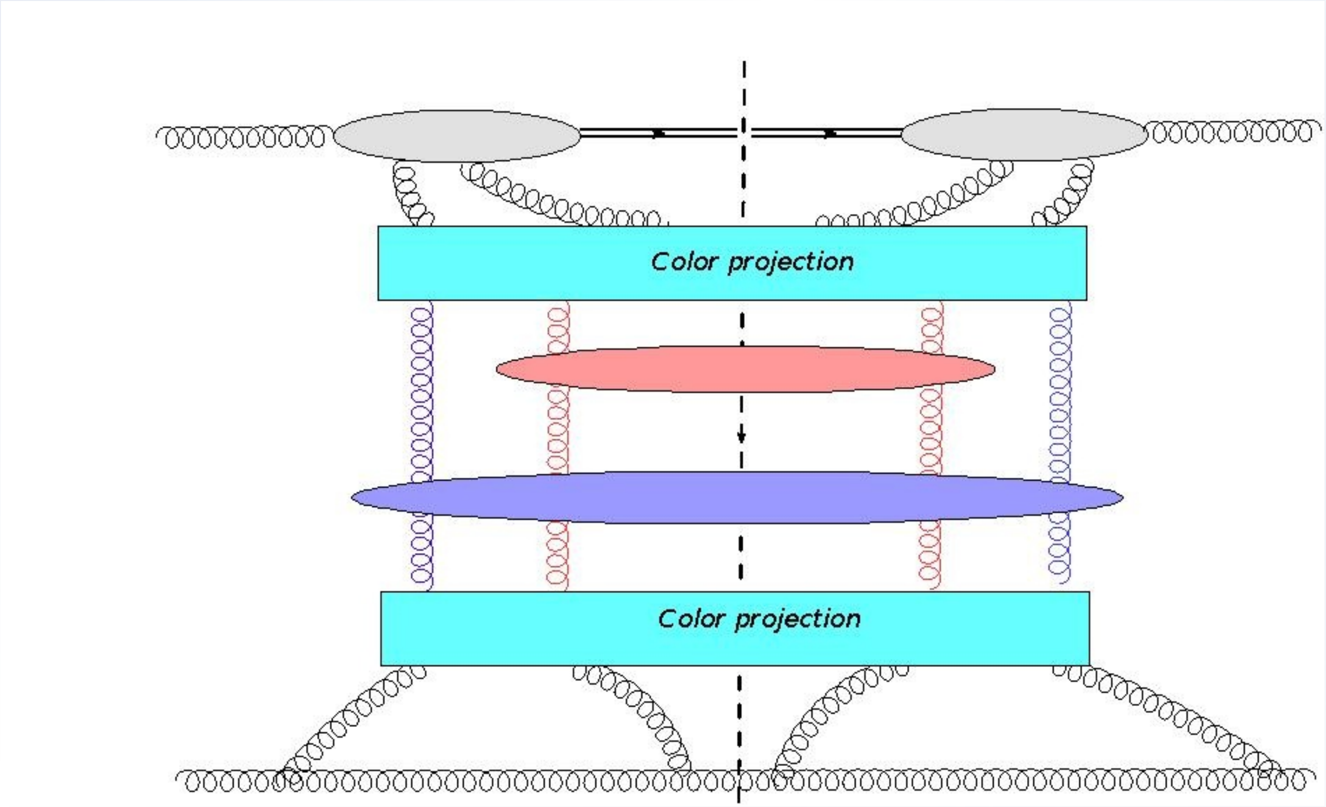


Projection on the two pomeron state

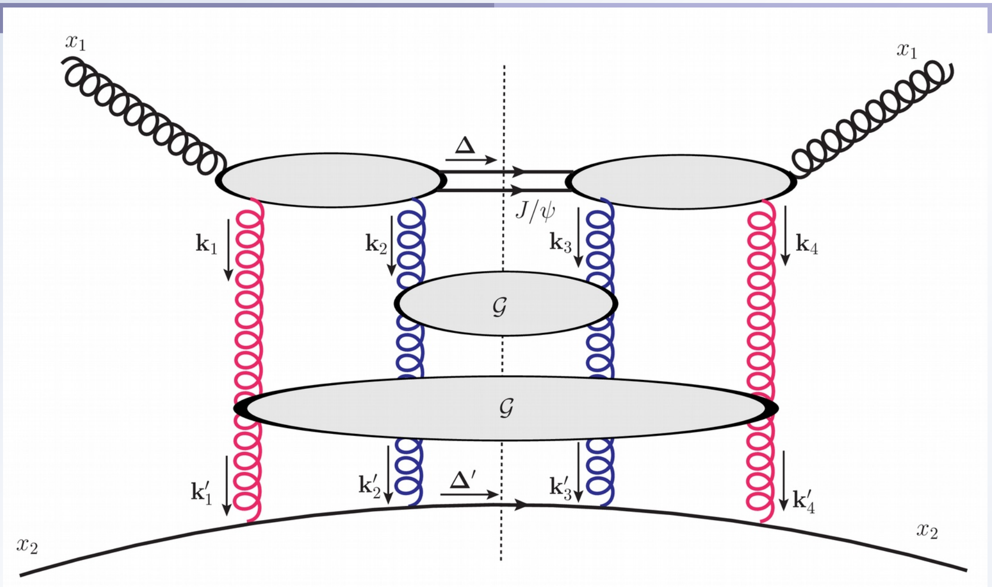
- Project on the BKP state using color basis with adequate symmetries

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

$$\langle A|A'\rangle = \delta_{AA'} + \mathcal{O}(1/N_c^2), \qquad \text{Projection operator on 2P} = |2P\rangle\langle 2P|$$



Solving the double non-forward BFKL exchange problem



$$
\begin{aligned}
|\mathcal{M}|^2 = \mathcal{N} \int d^2\boldsymbol{q} \int d^2\boldsymbol{k}_1 d^2\boldsymbol{k}_2 \int d^2\boldsymbol{k}'_1 d^2\boldsymbol{k}'_2 \, \frac{1}{\boldsymbol{k}_1^2(\boldsymbol{q}-\boldsymbol{k}_1)^2\boldsymbol{k}_2^2(\boldsymbol{q}-\boldsymbol{k}_2)^2} \\
\times \Phi_{J/\Psi}(\boldsymbol{k}_1, \boldsymbol{k}_2)\, \Phi^*_{J/\Psi}(\boldsymbol{q}-\boldsymbol{k}_1, -\boldsymbol{q}-\boldsymbol{k}_2)\, \delta^{(2)}(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{p}_T) \\
\times \mathcal{G}(\boldsymbol{k}_1, \boldsymbol{k}'_1; \boldsymbol{q}, Y)\, \mathcal{G}(\boldsymbol{k}_2, \boldsymbol{k}'_2; -\boldsymbol{q}, Y) \\
\times \Phi_q^{2P}(\boldsymbol{k}'_1, \boldsymbol{k}'_2, \boldsymbol{q}-\boldsymbol{k}'_1, -\boldsymbol{q}-\boldsymbol{k}'_2)
\end{aligned}
$$

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 s0 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]

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

- Diffractive cross section at high pT

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

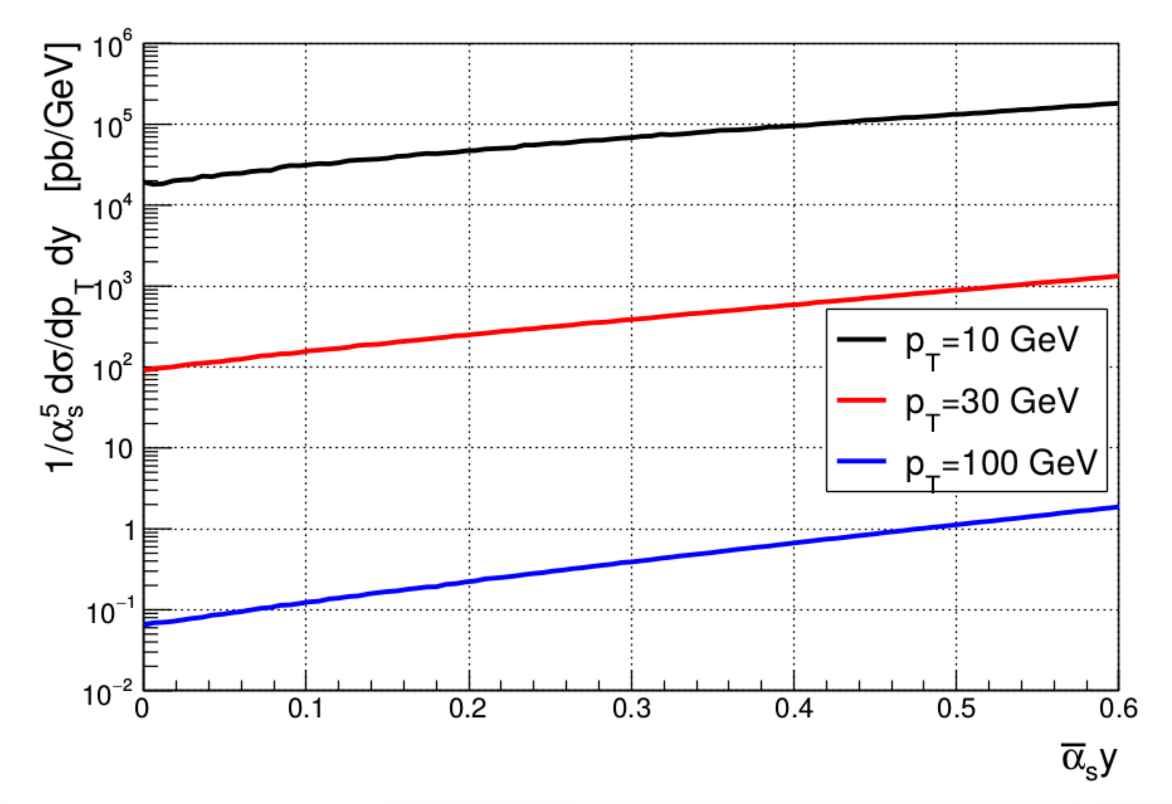
- Suitable modification of coupling constants and color factor leads to the two pomeron cross section in hadroproduction at the lowest order

$$\frac{d\sigma_{2P}}{dp_T} \sim \frac{C_{2P} \alpha_s^5}{p_T^7} \log^2(p_T^2/M^2) \sim \frac{1}{p_T^7}$$

Results: double two BFKL pomeron amplitudes at parton level

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

- Exponential growth with rapidity



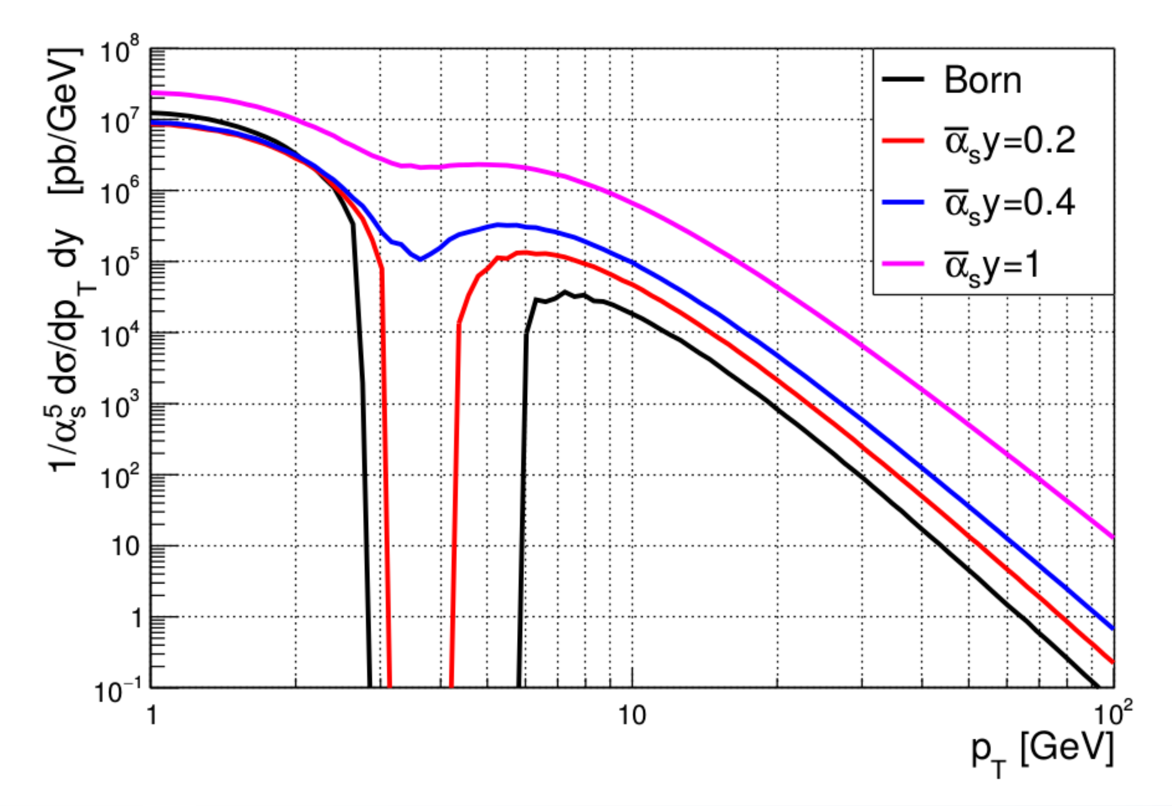
$d\sigma / dy \sim \exp(2\Delta y)$

with $\Delta \sim 0.3$

Results: double two BFKL pomeron amplitudes at parton level

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

- Parton level pT dependence

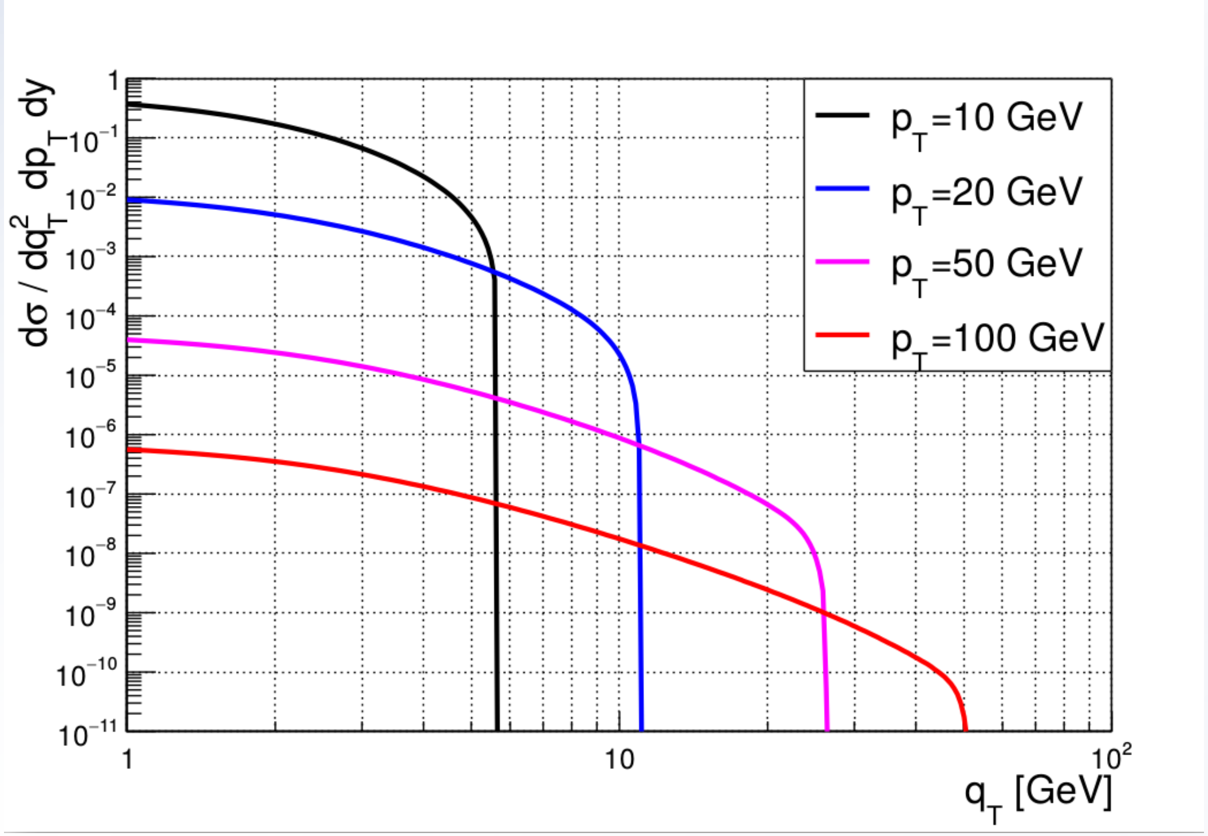


Weak effects of the evolution on the leading dependence at high pT

Results: double two BFKL pomeron amplitudes at parton level

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

- Dominance of low pomeron qT < MT in the pomeron loop



qT – transverse momentum of the pomeron in the loop

From partonic to hadronic level

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

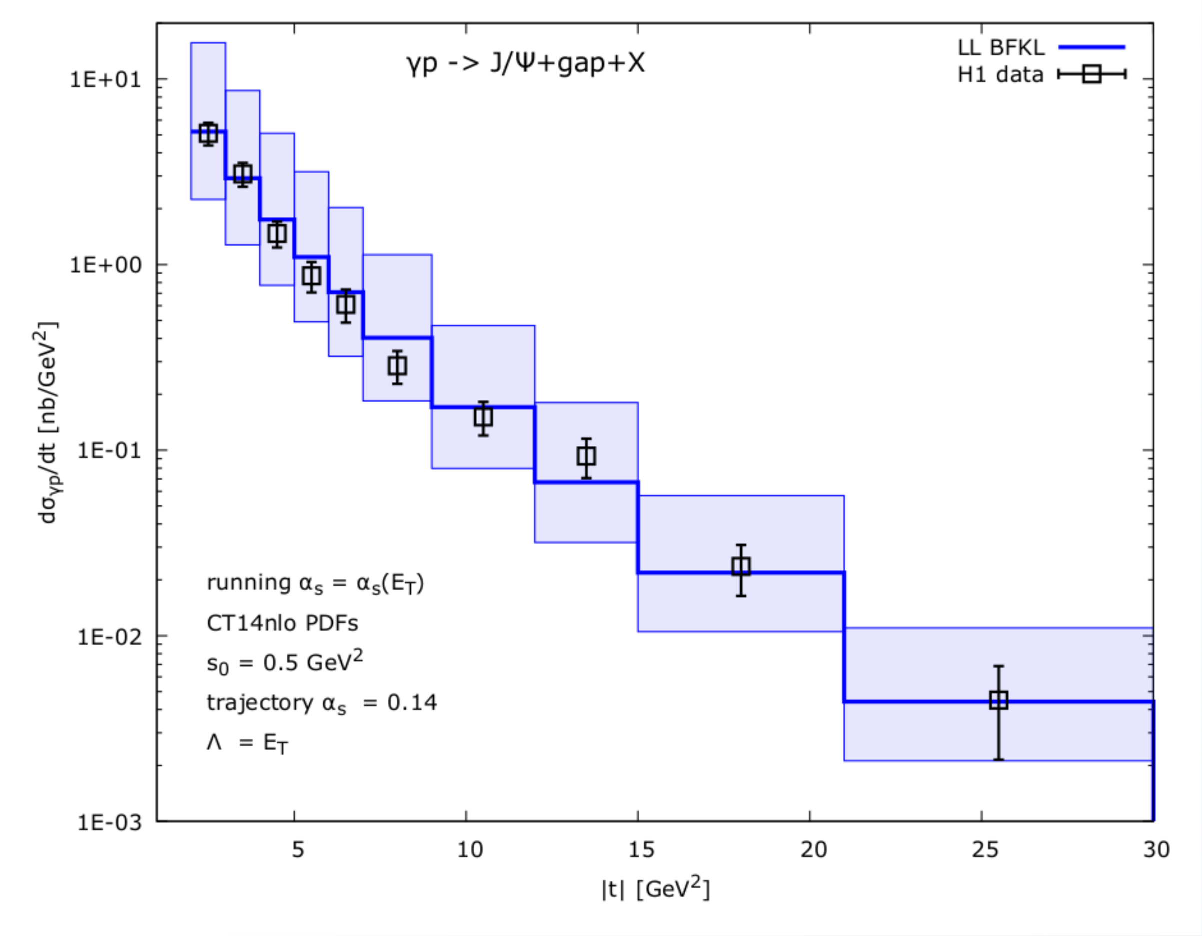
$$\frac{d\sigma(pp \to J/\psi X)}{dp_T dY} = \int dx_1 \int dx_2\, \delta(Y - \log(x_1\sqrt{S_{pp}}/E_T))$$

$$\times\, g(x_1,\mu)\left[C_q \sum_q q(x_2,\mu) + C_g g(x_2,\mu)\right] \frac{d\hat{\sigma}_0}{dp_T}(x_1 x_2 S_{pp})$$

- 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/ψ

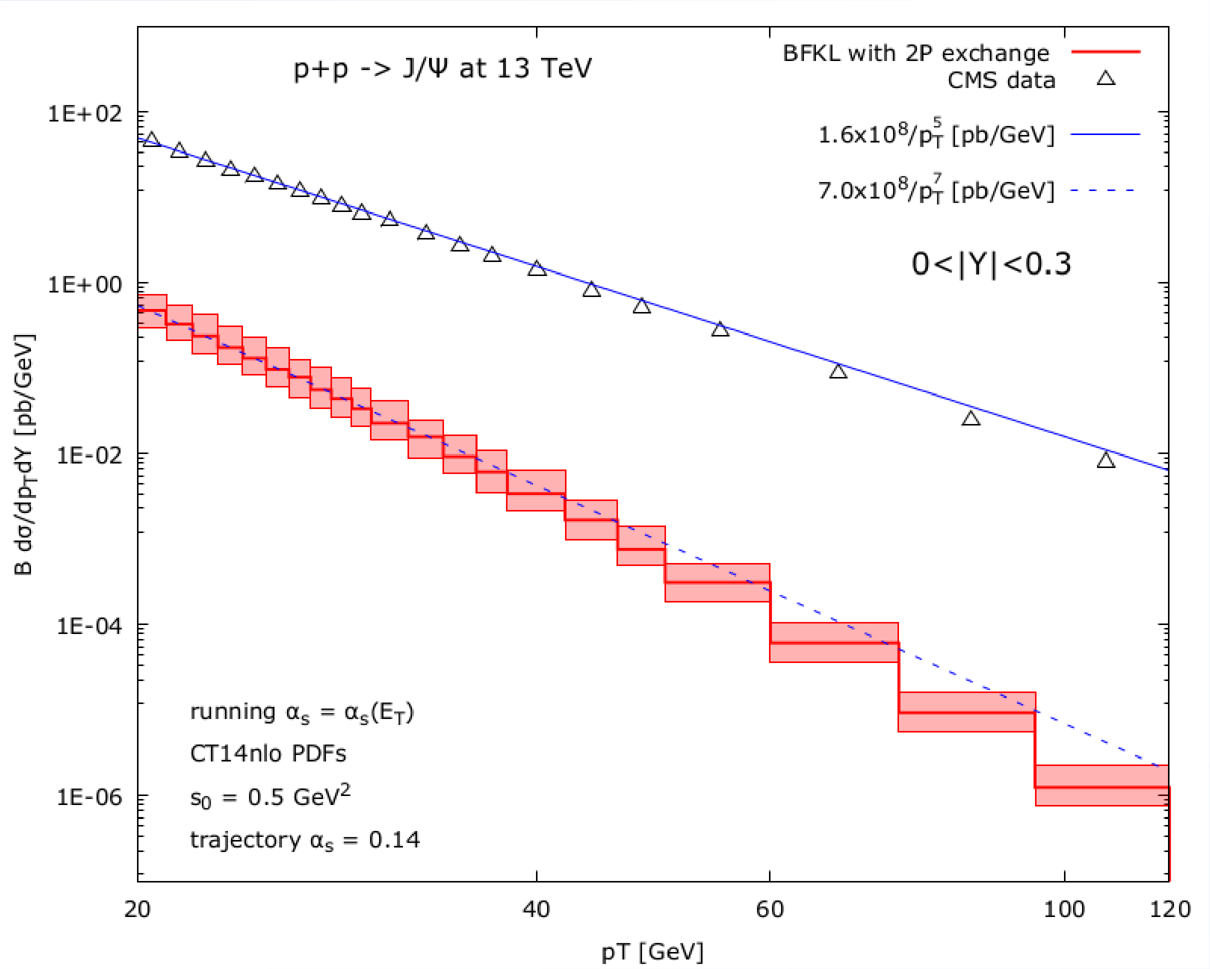
- Diffractive photoproduction of J/ψ at high pT (data from H1)



- Data well described, conservative uncertainty measure, shape not affected

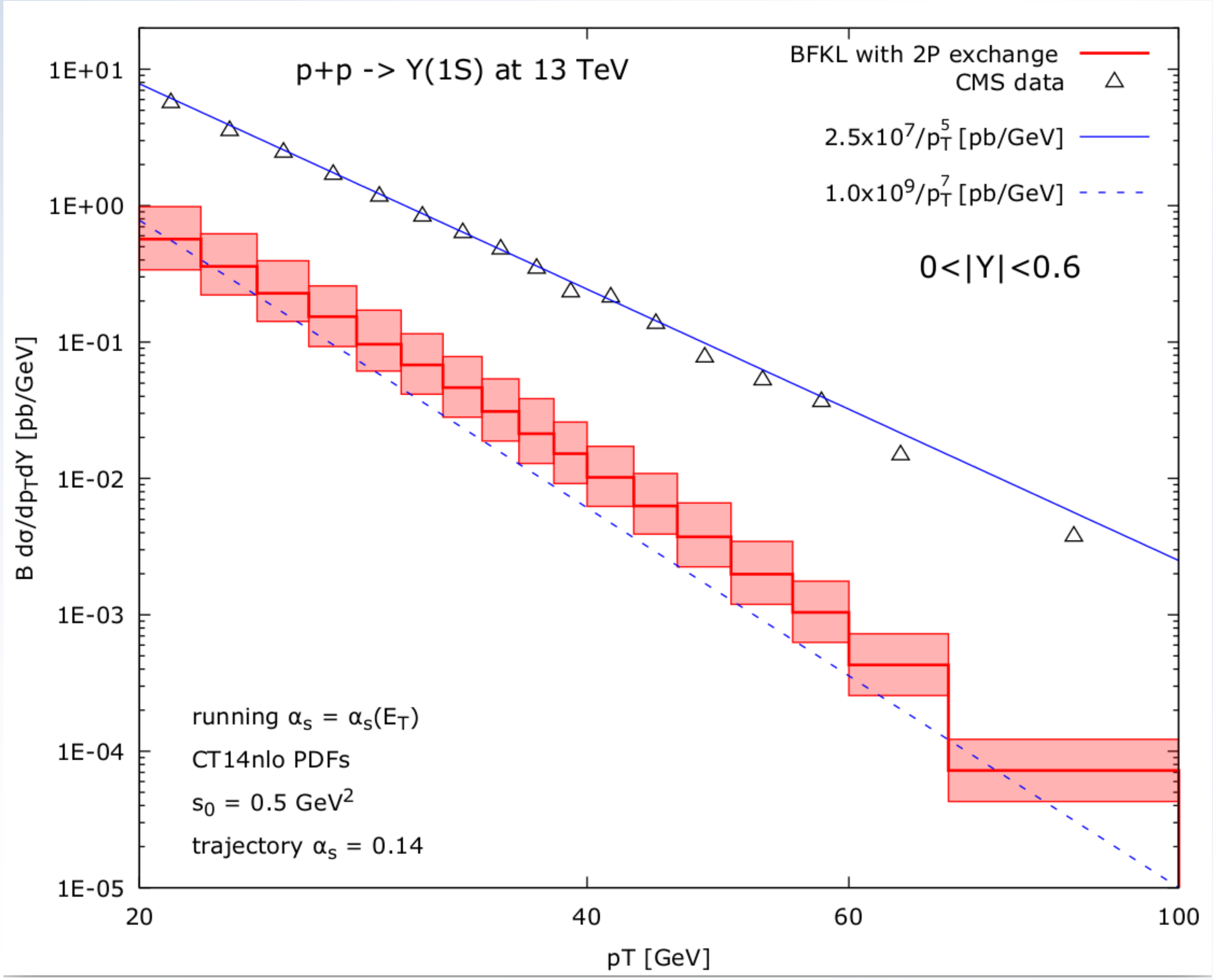
Comparison to data: hadroproduction of J/ψ

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



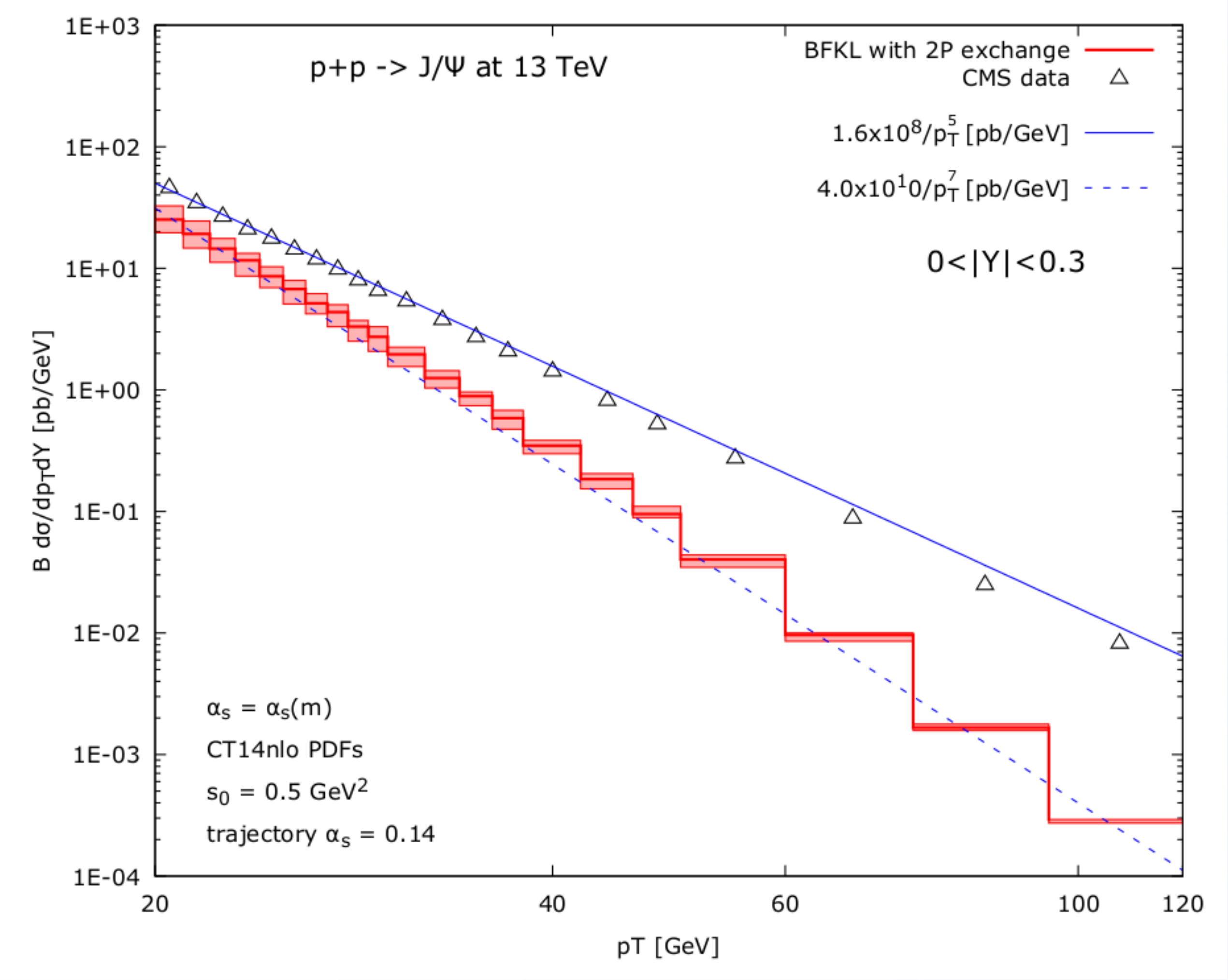
- Neither normalisation nor shape are well described

Comparison to CMS data: Upsilon



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



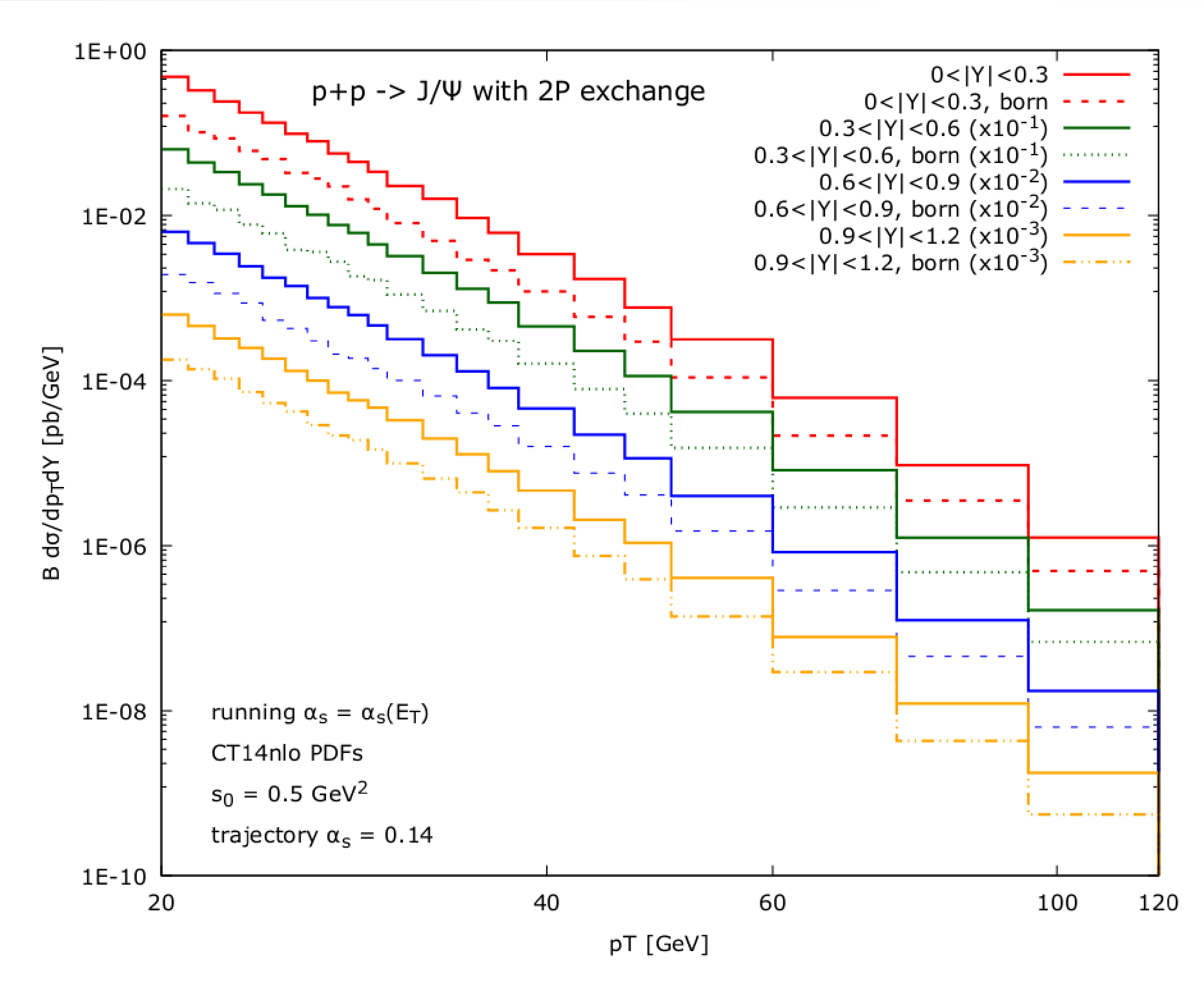
Conclusions

- 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

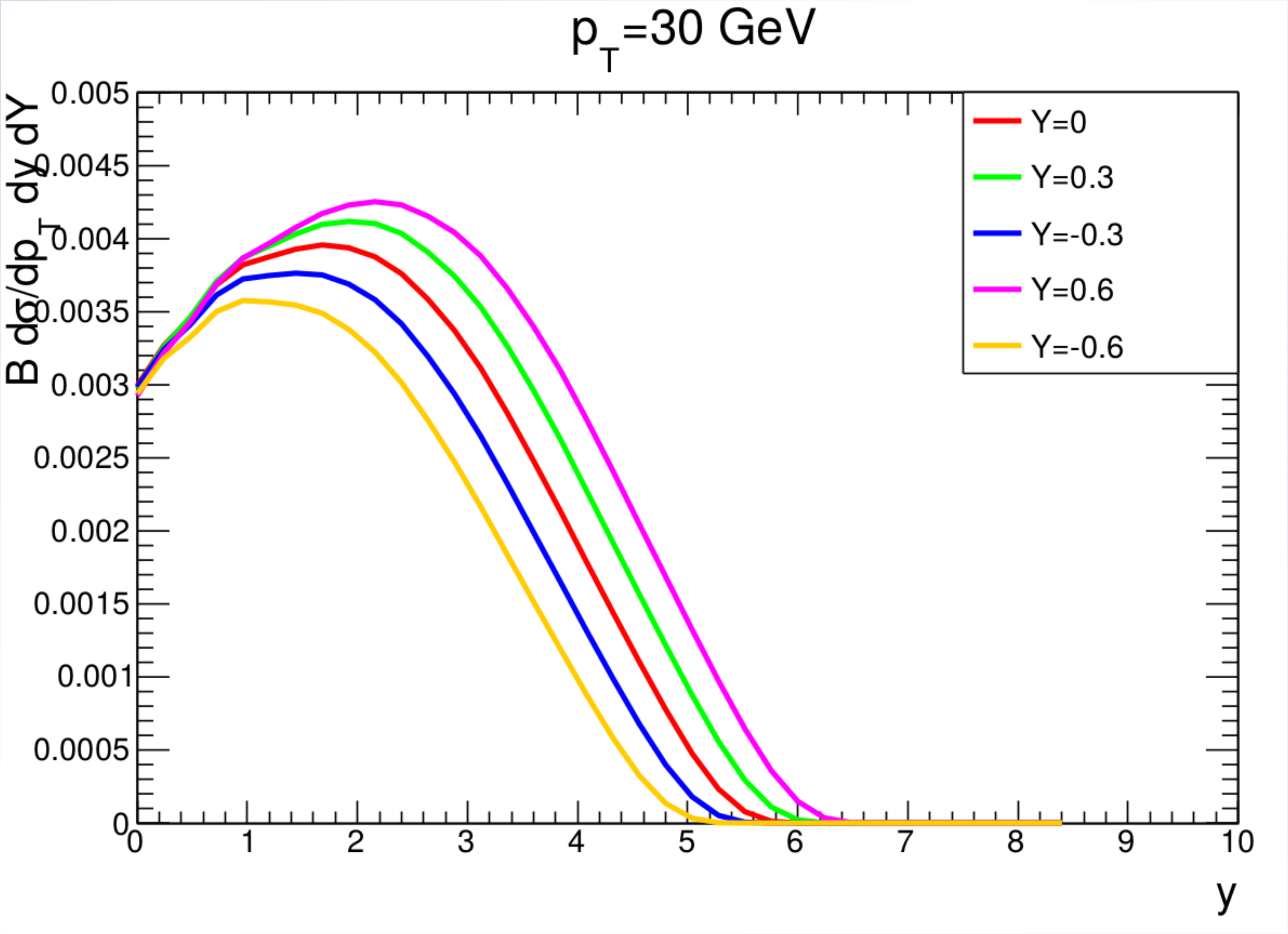
THANKS!

Backup

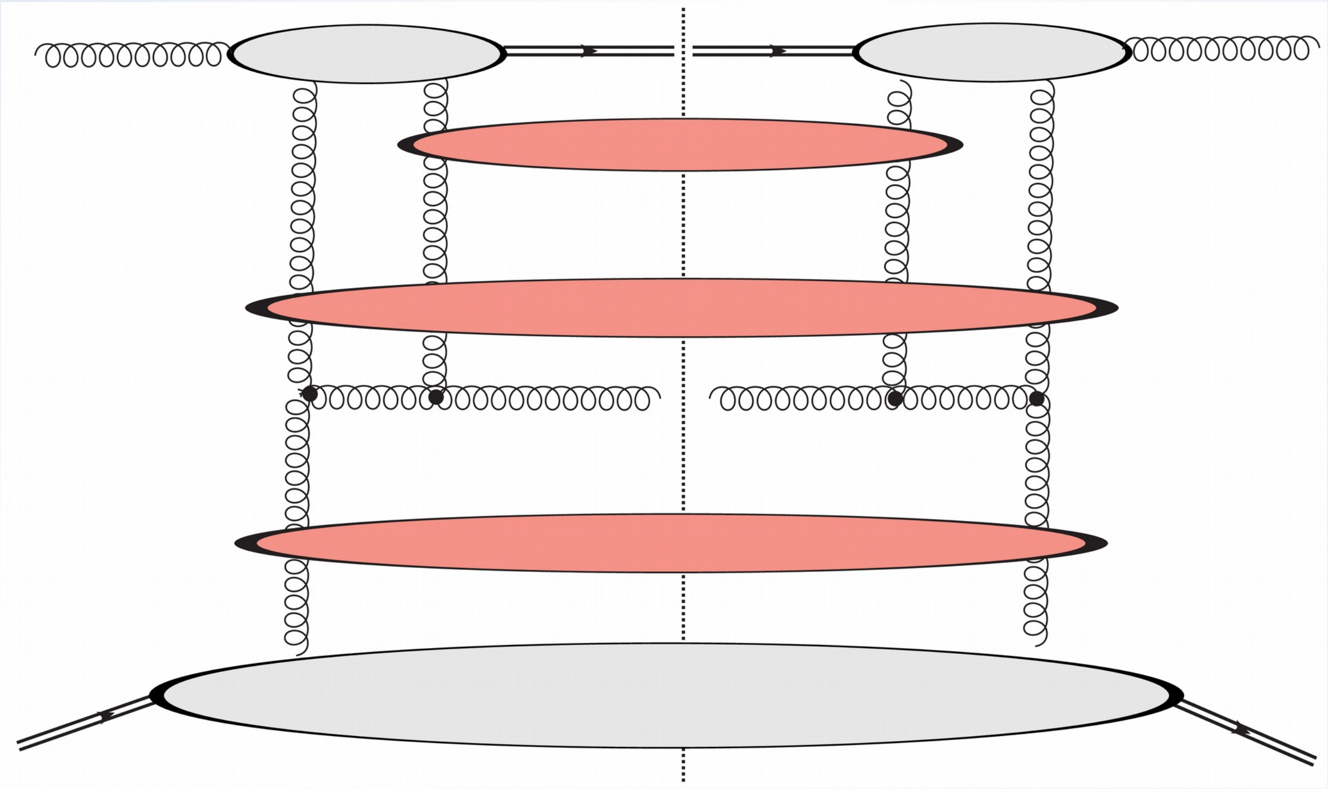
Hadroproduction of J/ψ: BFKL vs the lowest order



Distribution of evolution length y in J/ψ hadroproduction



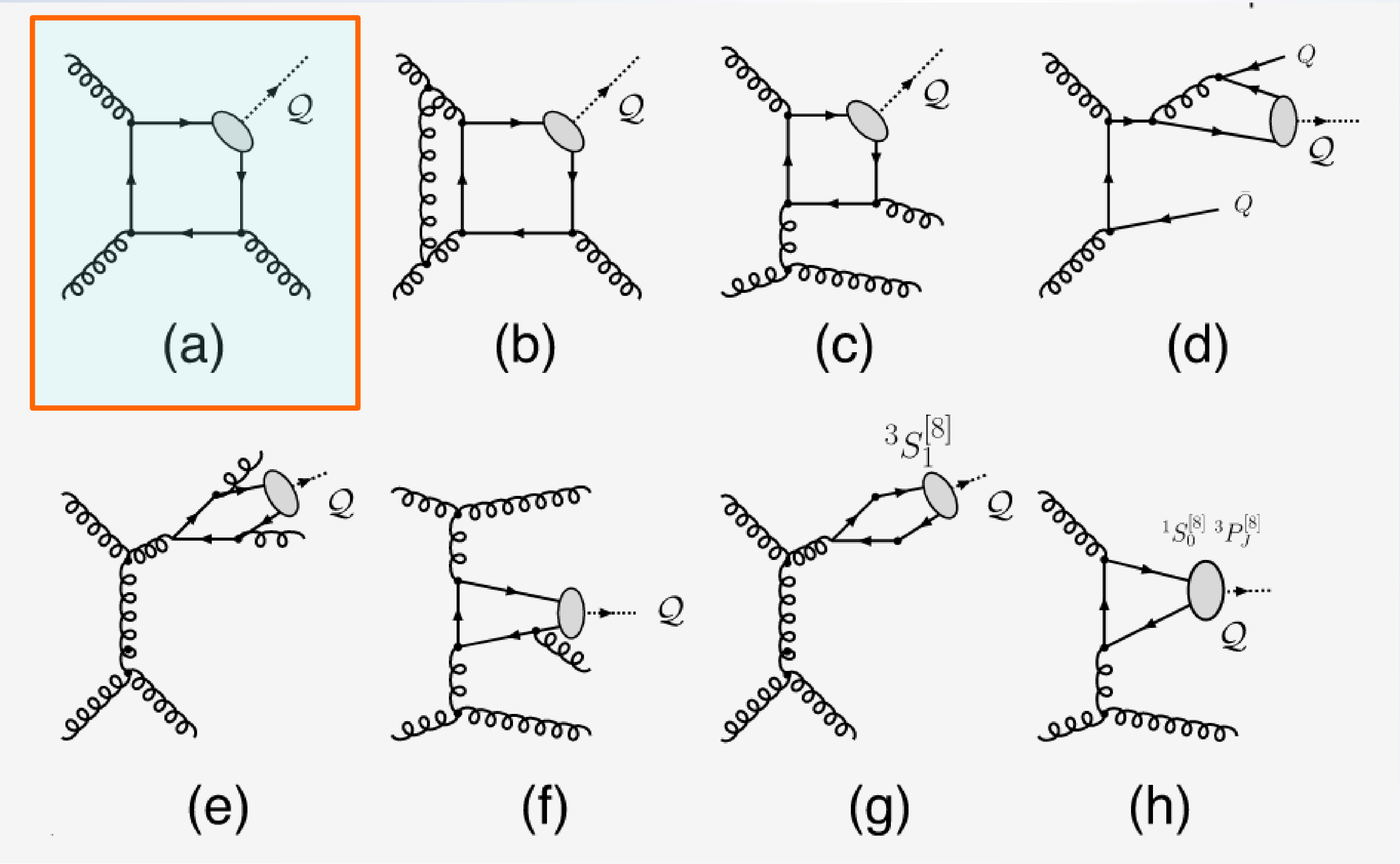
Relation to Bartels triple pomeron vertex with double Pomeron cut



Diagramatics:

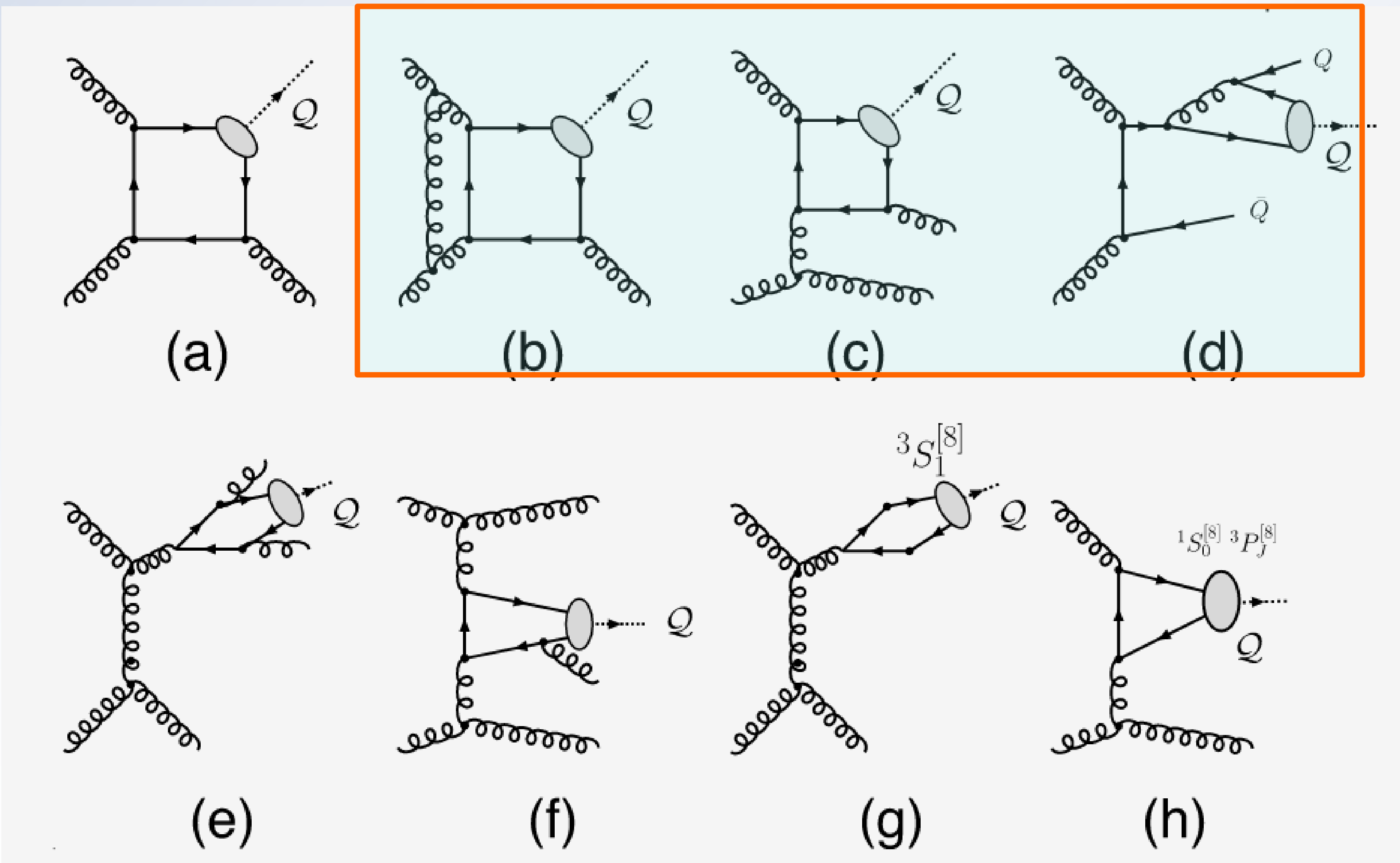
Color singlet LO

[Lansberg]



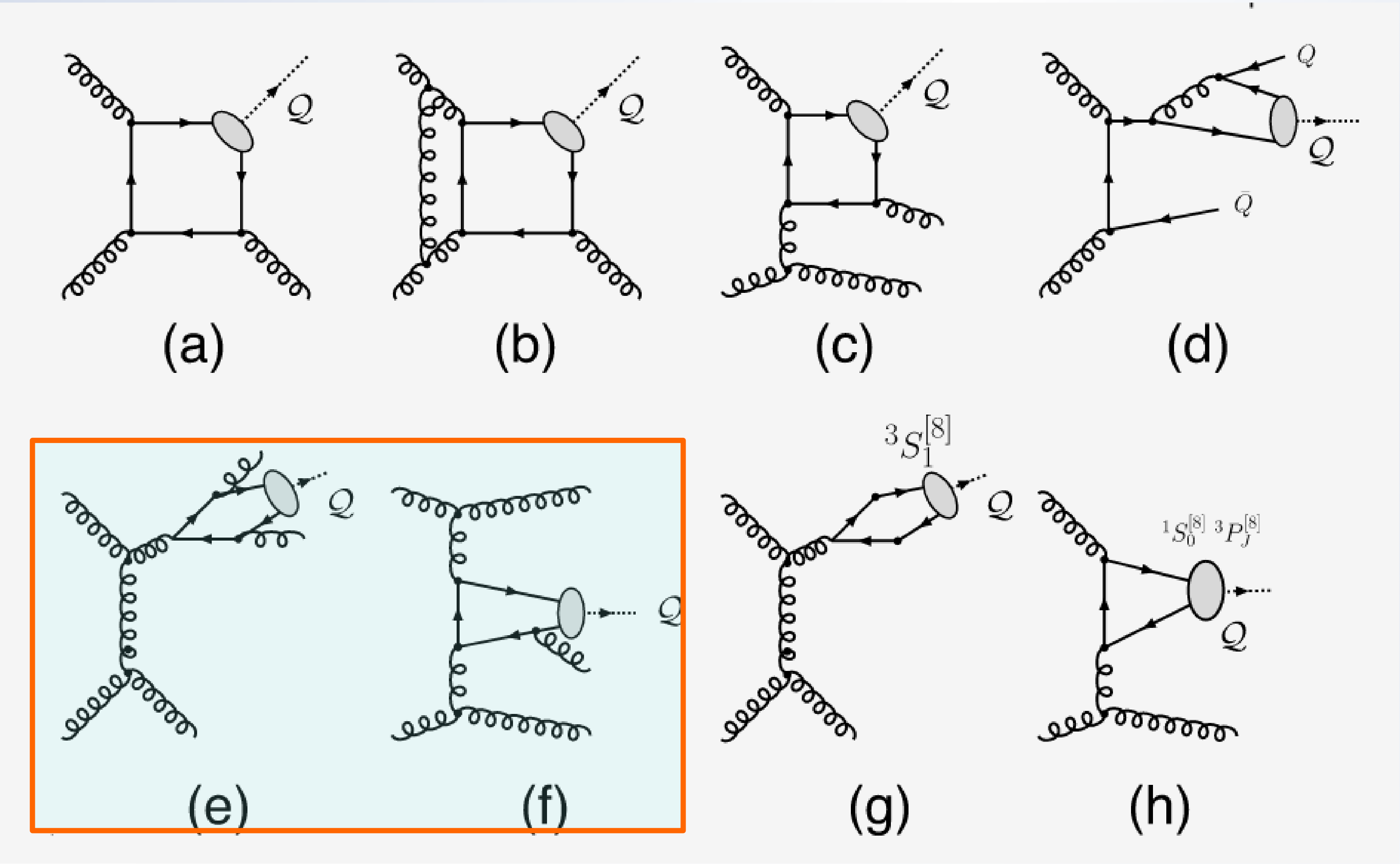
Diagramatics:

Color singlet NLO [Lansberg]



Diagramatics:

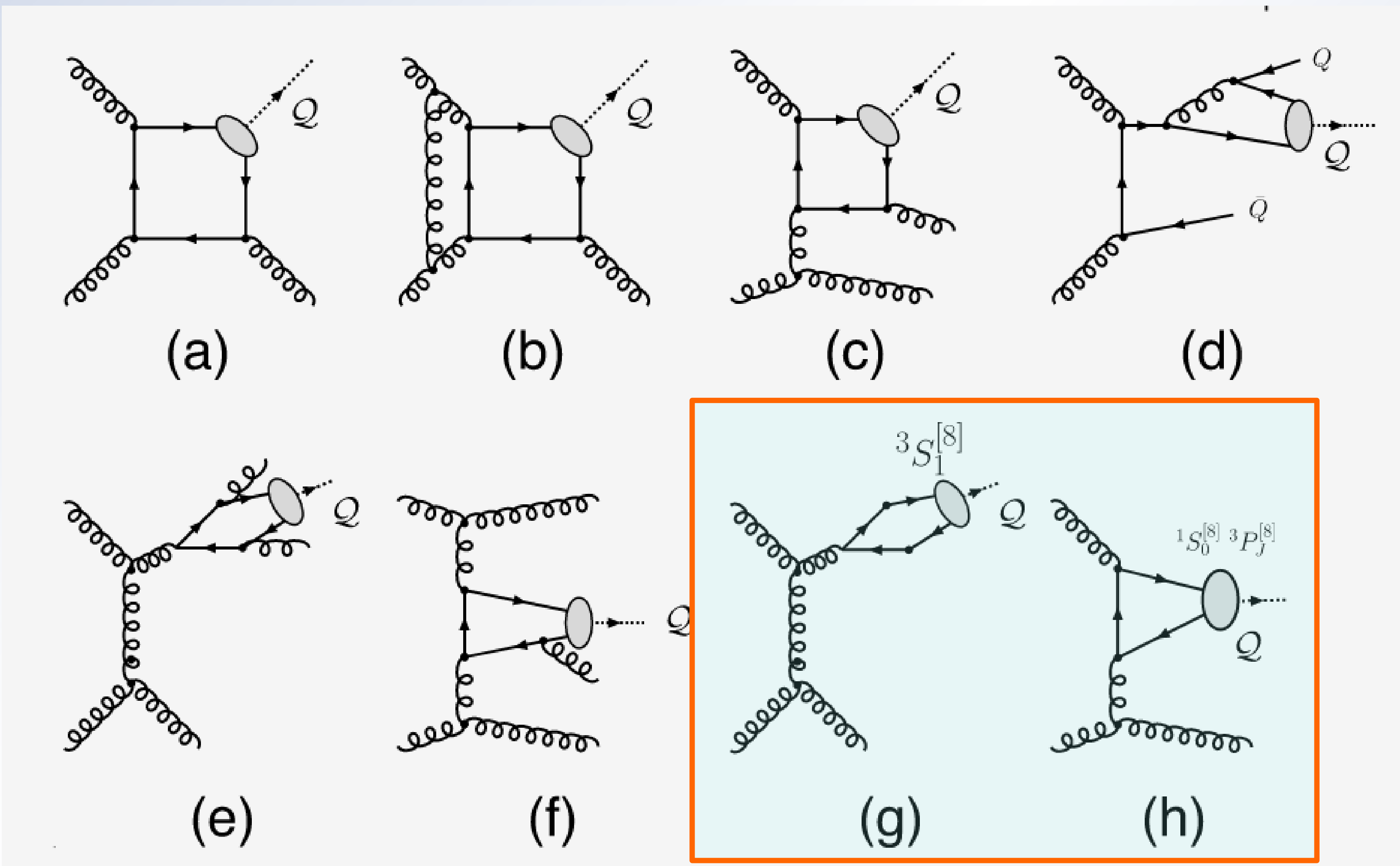
Color singlet NNLO* [Lansberg]



Diagramatics:

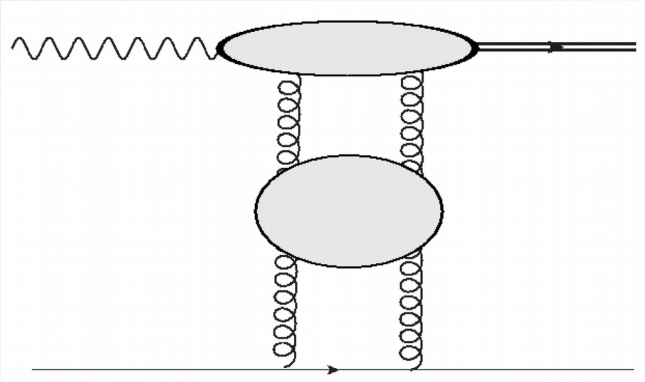
Color octet

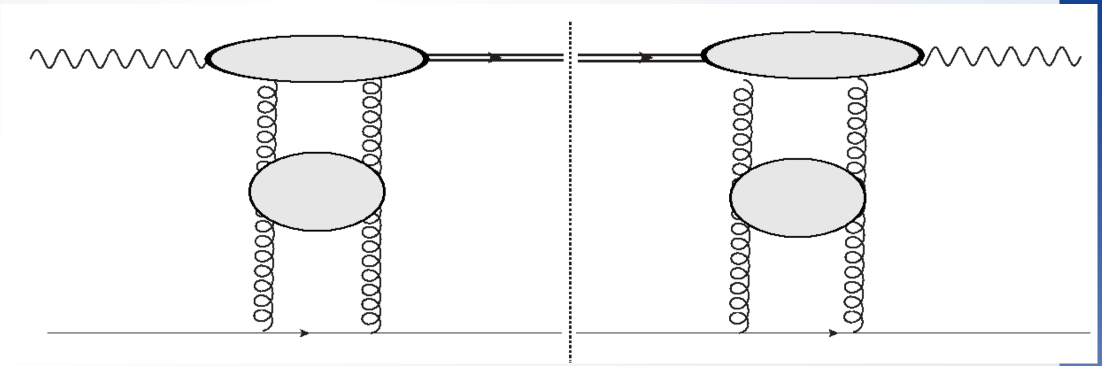
[Lansberg]



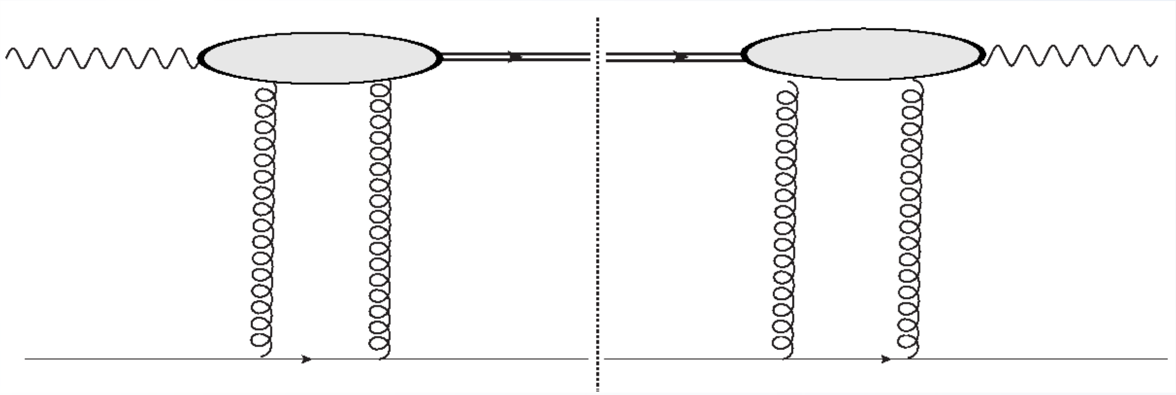
The correlated double pomeron contribution: how to compute? Step 1

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



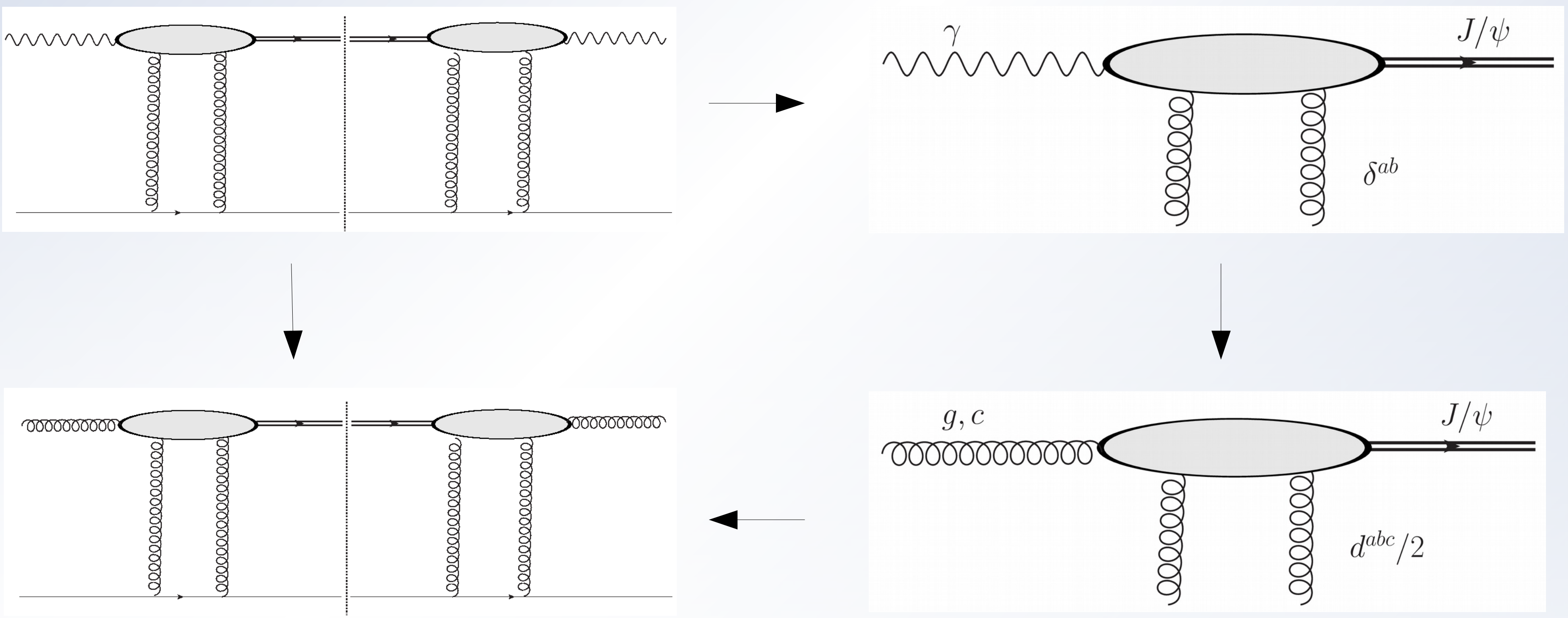


- Go to the lowest order



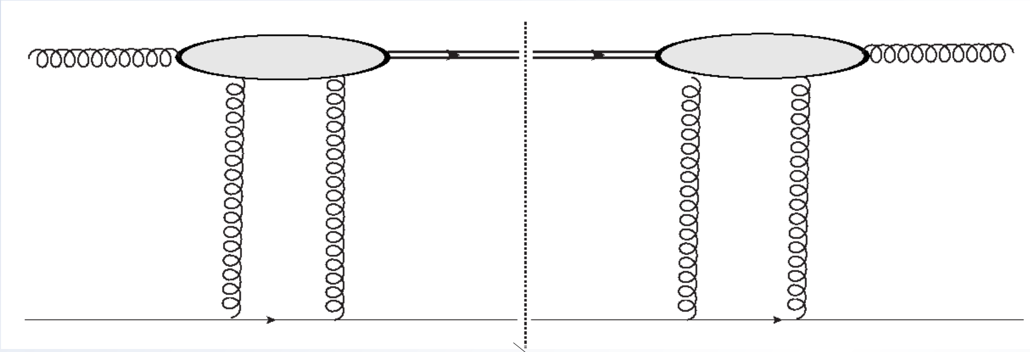
The correlated double pomeron contribution: how? Step 2

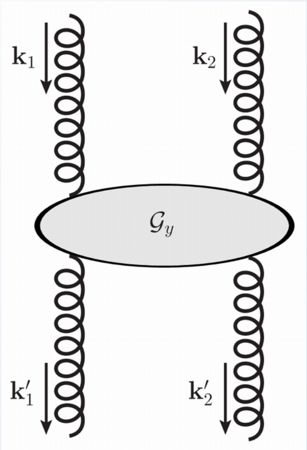
- The lowest order amplitudes for quasi-diffractive production and the 3 gluon fusion differ only by coupling constants and color factors, due to symmetry of the color part, the kinematical parts are the same

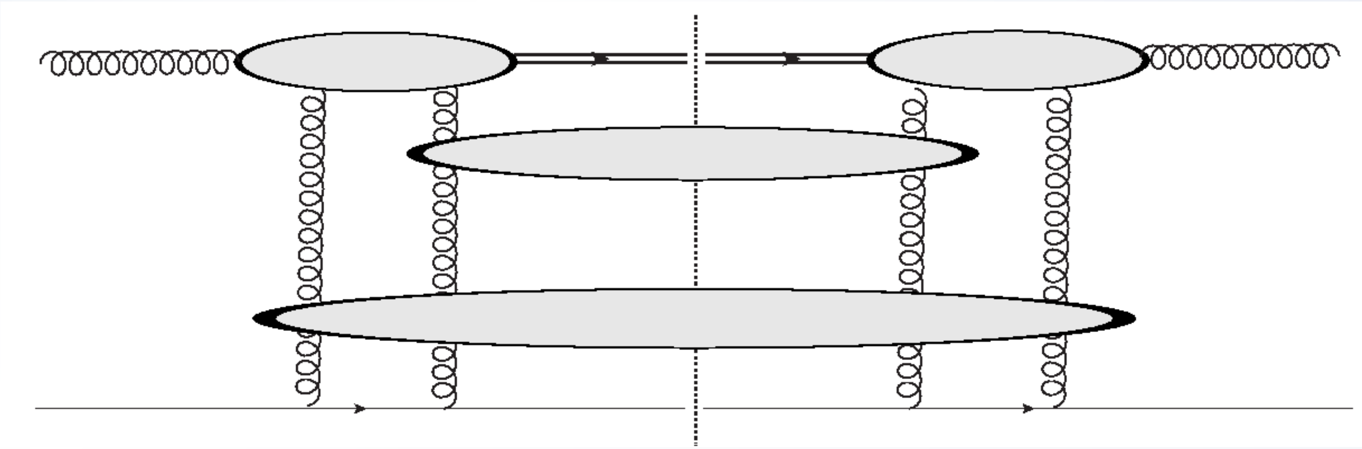


The correlated double pomeron contribution: how? Step 3

- 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,v) in position space [Lev Lipatov]

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

- Momentum representation of the Green's function

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

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

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

$$\mathcal{M}(q, Y) \sim \sum_n \int d\nu\, \langle \Phi_A | E(q,n,\nu) \rangle\, \exp(\bar{\alpha}_s Y \chi_n(\nu))\, \langle \Phi_B | E(q,n,\nu) \rangle$$

Solving the double non-forward BFKL exchange problem

- Extension to double pomeron exchange amplitude

$$|\mathcal{M}|^2 \sim \sum_n \sum_{n'} \int d\nu \int d\nu' \, w(n,\nu) w(n,\nu') \exp(\bar{\alpha}_s Y \chi_n(\nu)) \exp(\bar{\alpha}_s Y \chi_{n'}(\nu'))$$

$$\times \int d^2q \langle \Phi_Q^{2P} [|E(q,n,\nu)\rangle \otimes |E(-q,n',\nu')\rangle][\langle E(q,n,\nu)| \otimes \langle E(-q,n',\nu')|] \Phi_{J/\psi^2}^{2P} \rangle$$

$$\Phi_{J/\psi^2}^{2P}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{q}-\boldsymbol{k}_1, -\boldsymbol{q}-\boldsymbol{k}_2) = \Phi_{J/\Psi}(\boldsymbol{k}_1, \boldsymbol{k}_2) \, \Phi^*_{J/\Psi}(\boldsymbol{q}-\boldsymbol{k}_1, -\boldsymbol{q}-\boldsymbol{k}_2) \, \delta^{(2)}(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{p}_T)$$

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

$$\Phi_Q(k,q) \sim \text{const}(k,q) \longrightarrow \langle E(q,n,\nu)|\Phi_Q\rangle = \Phi_{M-T}(q,n,\nu)$$

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

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