

# The Odderon - a Fundamental Object in QCD ?

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- High Energy behavior: is it 'fundamental' in QCD?
- The (BLV) Odderon solution in pQCD
- The perturbative environment of the Odderon
- 'Unitarization' of the pQCD Odderon (saturation)
- Where and how to look for the pQCD Odderon
- Conclusions

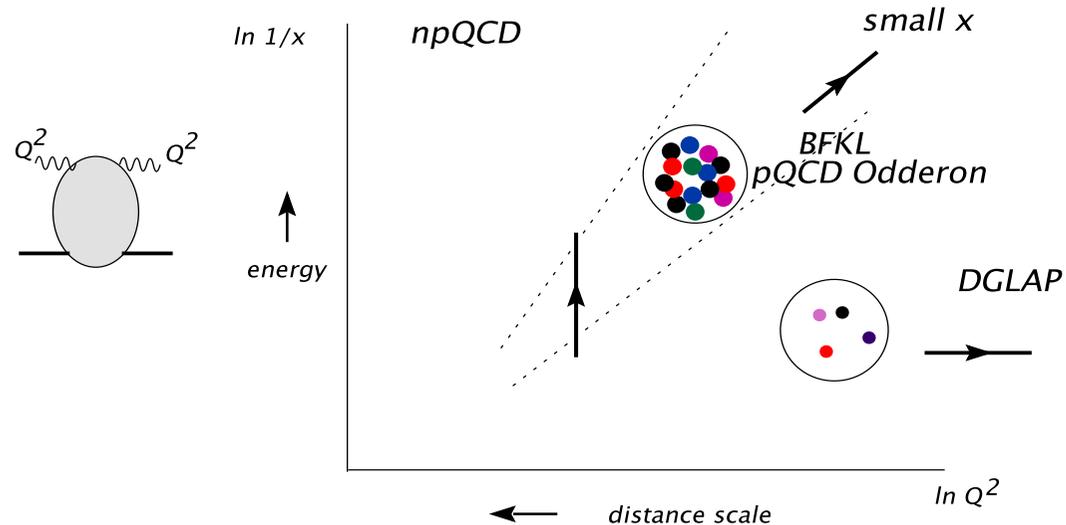
## Introduction

The Odderon was invented (Lukaszuk, Nicolescu ) as (potential) part of the high energy scattering of hadrons.

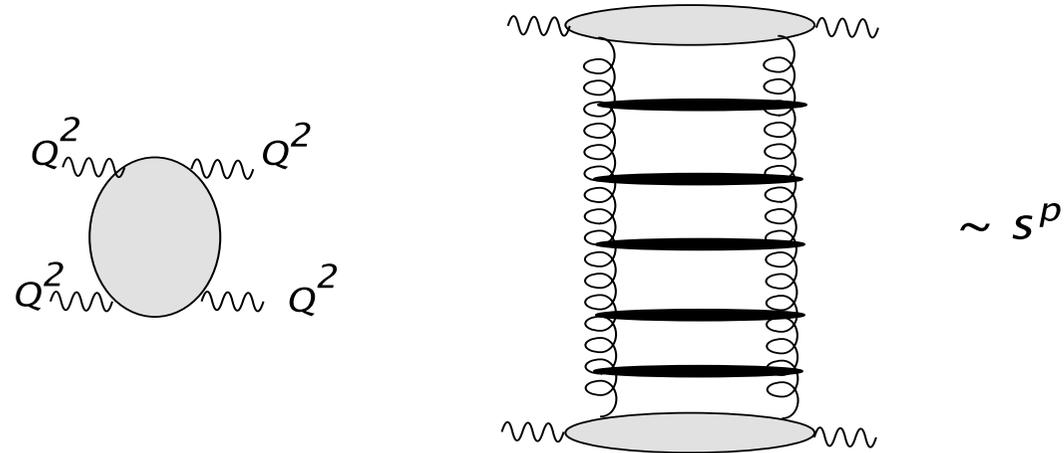
- Long-standing question: does it exist?  
Most convincing evidence in experimental data: difference in  $\frac{d\sigma}{dt}$  between  $pp$  and  $p\bar{p}$ :  
Dip region near  $t = -1.35 \text{ GeV}^2$ .  
This difference could/should be explained by exchange of an Odderon (C-odd, couples differently to  $pp$  and  $p\bar{p}$ ).
- An Odderon solution exists in pQCD.
- How to get from the Odderon in pQCD to the 'real Odderon'?
- Why should we worry, is there anything 'fundamental' about the Odderon in QCD?

## High Energy Behavior: is it fundamental in QCD?

Compared to  $\sim 30$  years ago, there is a change in our perception of the high energy limit. Quantities such as  $\sigma_{tot}$ ,  $\frac{d\sigma}{dt}$  in hadron hadron collisions are nonperturbative. With our present knowledge of QCD: need to start from short distances. Combination of high energy and small-distance limit: two scales. Example: small- $x$  limit at HERA energy,  $s \rightarrow W^2 = Q^2/x, Q^2$ .



At short distances: start with BFKL



Cannot apply this to  $pp$  scattering (only for ultraviolet tail):  
transition to soft region goes via 'unitarization'.

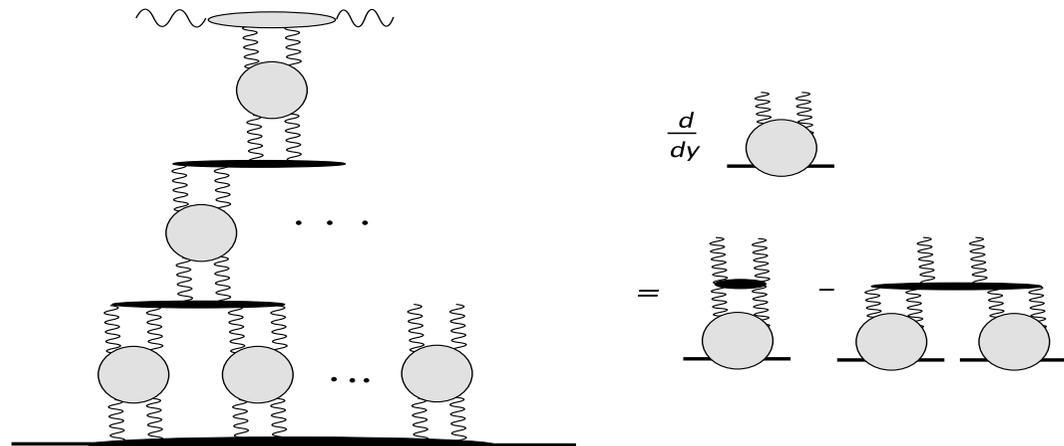
Changes power  $p$ , changes behavior at large impact parameter  $\vec{b}$ .

Recent progress in understanding this unitarization:

Unitarization goes beyond the gluon ladder approximation,  
needs t-channel states with more than two gluons.

Saturation plays crucial role.

Illustration for  $\gamma^* p \rightarrow \gamma^* p$  ( $F_2$  in DIS): fan structure.



Concept of evolution equation replaces ladder summation.

More complicated pictures for  $pp$  scattering.

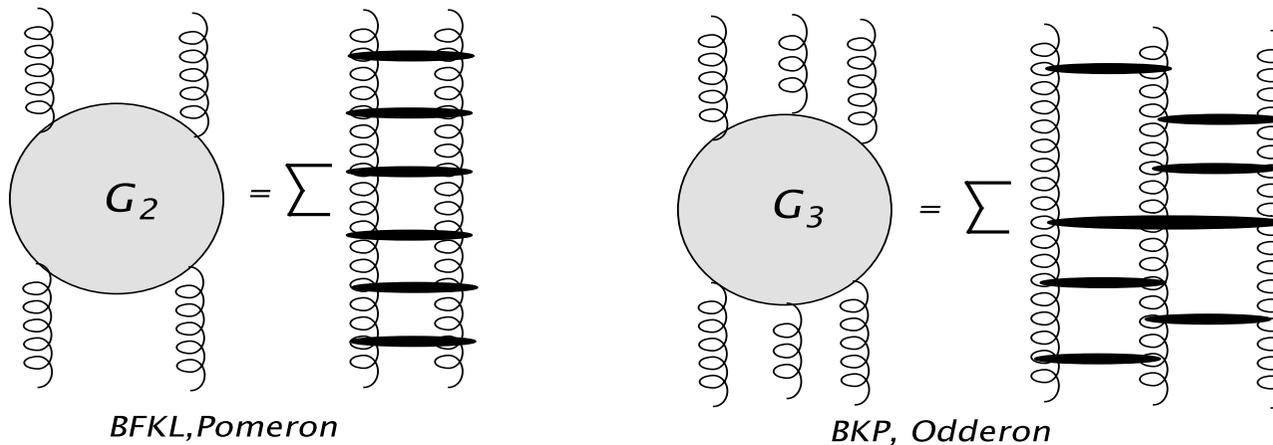
Consequences: transition to soft region needs

- 1) large number of  $t$ -channel is vital
  - 2) nonperturbative modifications at large impact parameter  $b$  not under control yet.
- Need to investigate multi-gluon states (energy spectrum  $\sim$  rapidity evolution)

## The other direction: a conformal field theory

BFKL is the beginning of a  $2 + 1$  dimensional field theory which describes QCD at high energies (lives in rapidity, transverse coordinates).

Define Green's functions of interacting reggeized gluons:  $G_\omega(\vec{r}_1, \dots, \vec{r}_n; \vec{r}'_1, \dots, \vec{r}'_n)$

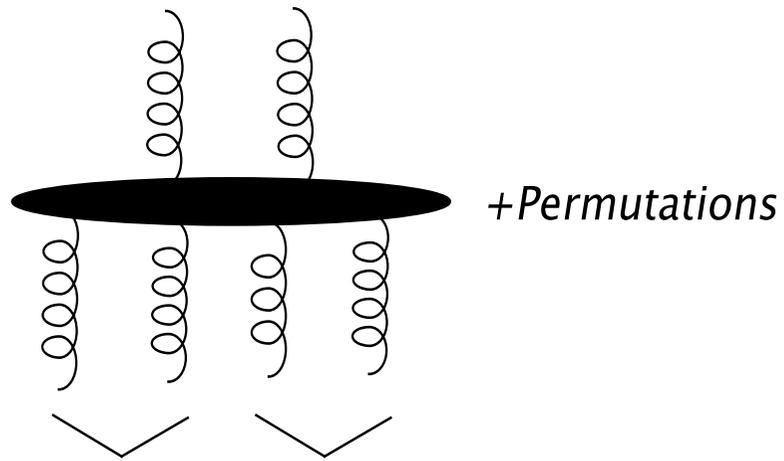


Evolution in time (=rapidity): Schroedinger-like equations  $\partial_y G = G_0 + \sum K_{BFKL} \otimes G$ .

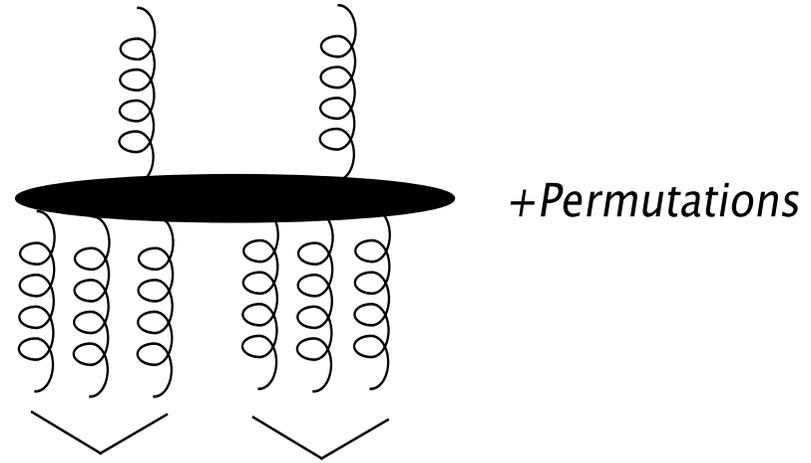
Solution: eigenvalues of the kernel. Known for  $n = 2$ ,  $n = 3$ .

For general  $n$ : in the limit  $N_c \rightarrow \infty$  the problem is exactly soluble: **integrability**

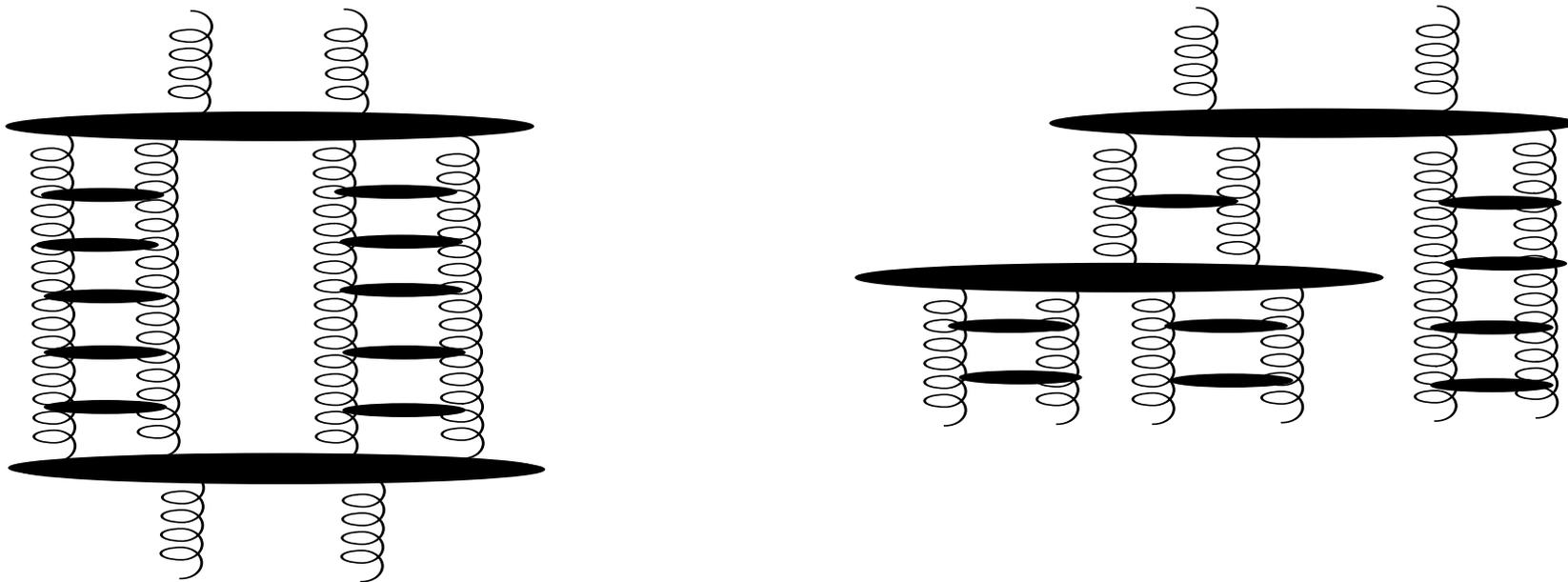
Next step: number changing vertices



*'triple Pomeron'*



Can build general Green's functions:



**Möbius invariance:** use complex coordinates  $\rho = r_1 + ir_2$

$$\rho \rightarrow \frac{a\rho + b}{c\rho + d}, \quad \rho^* \rightarrow \frac{a^*\rho^* + b^*}{c^*\rho^* + d^*}$$

Generators are part of Virasoro algebra:  $L_{\pm 1}, L_0$ , conformal bootstrap (at fixed time).  
 What conformal field theory is behind?

QCD at very high energies (small- $x$ /Regge):

- 2+1 dimensional field theory
- derivation: effective action (Lipatov)
- piece of conformal invariance
- integrable structures: more symmetries?
- ...

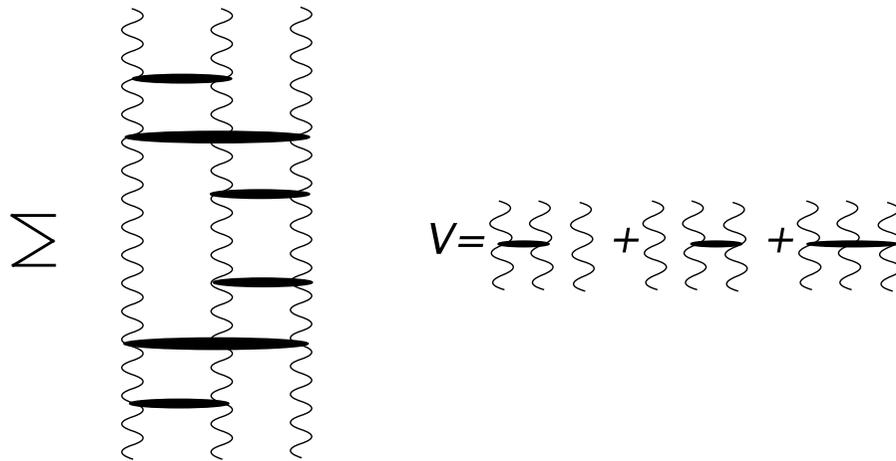
AdS/CFT Correspondence?

Recently found: also the  $SU(2) \times U(1)$  part of the Standard Model has a similar 2+1 dimensional field theory (JB, Lipatov, Peters).

## The (BLV) Odderon solution in pQCD

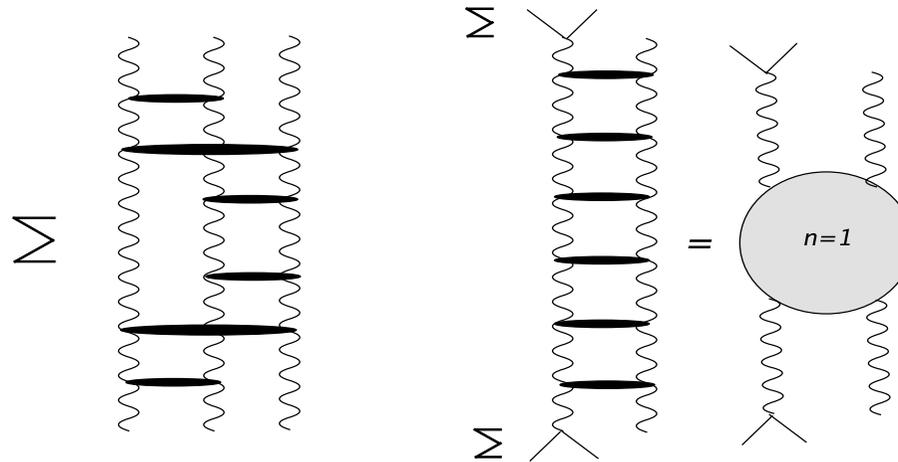
Theoretical basis: BKP equation (generalization of BFKL equation).

Bound state of three reggeized gluons, pairwise interactions with BFKL kernel.



Interest in solution with highest intercept (same as: 'lowest energy in reggeon space').

Lowest energy solution:



Remarkable:

- 1) d-reggeon: degenerate even - signature partner of the gluon  
Bootstrap inside a three gluon color singlet state.
- 2) antisymmetric bound state of the d-reggeon and the gluon
- 3) In leading order:  $\alpha_{\text{odderon-BLV}}(0) = 1$
- 4) More subtle: space of functions ( $\rightarrow$  Vacca's talk)

New features of BFKL dynamics!

Interesting history:

First: search for lowest energy solution with completely symmetric wave function.  
(Variational ansatz, analytic solution).

Result: positive energy, intercept less than one:

$$\alpha_{odderon-JW}(0) = 1 + \omega_{odderon} = 1 - 0.247\alpha_s N_c / \pi,$$

Instead (analytic solution): lowest state has mixed symmetry

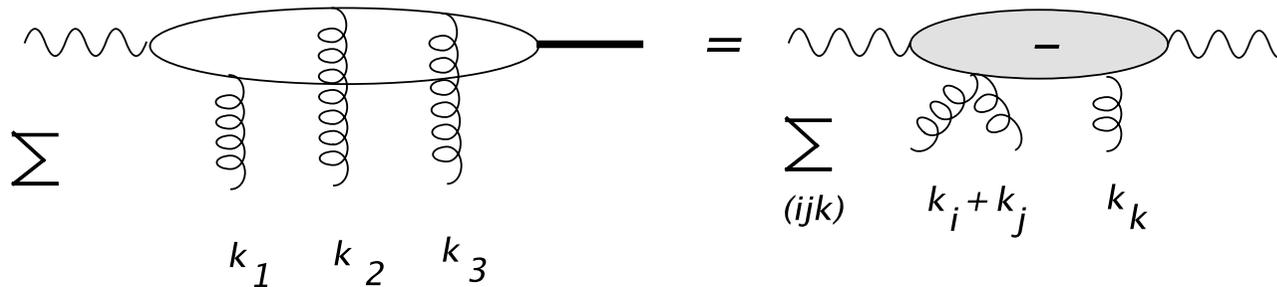
$$\alpha_{odderon-BLV}(0) = 1 + \omega_{odderon} = 1$$

Questions:

- Are there more solutions?
- What about NLO: does the intercept stay at unity?

## The perturbative environment of the Odderon

Coupling to external projectile: the photon impact factor  $\gamma^* \rightarrow \eta_c$   
 (J.Czyzewski, J.Kwiecinski, L.Motyka, M.Sadzikowski)



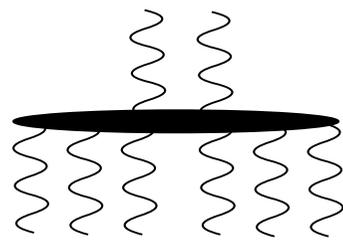
$$\phi(k_1, k_2, k_3) = \sum_{(ijk)} \varphi(k_i + k_j, k_k) - \varphi(k_i + k_j + k_k, 0)$$

Coupling to the external particle 'prepares' the Odderon state!

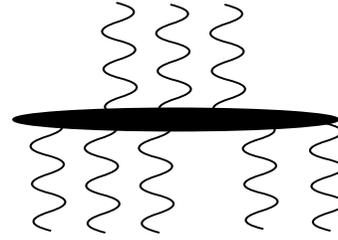
The symmetric JW solution decouples from this vertex.

Important: Odderon seen in dipole model ( $\rightarrow$  Kovchegov )  
 and color glass condensate ( $\rightarrow$  Venogopalan, Hatta ).

Odderon is a new piece in the QCD reggeon field theory. New elements: couplings between Pomeron (two gluon) and Odderon (three gluon)



$P \rightarrow OO$



$O \rightarrow PO$

The  $P \rightarrow OO$  vertex was first calculated in momentum space (JB,C.Ewerz): has the same momentum structure as the  $\gamma^* \rightarrow \eta_c$  vertex.

The  $O \rightarrow PO$  vertex known only in color dipole and CGC approach ( $\rightarrow$  Kovchegov, Hatta).

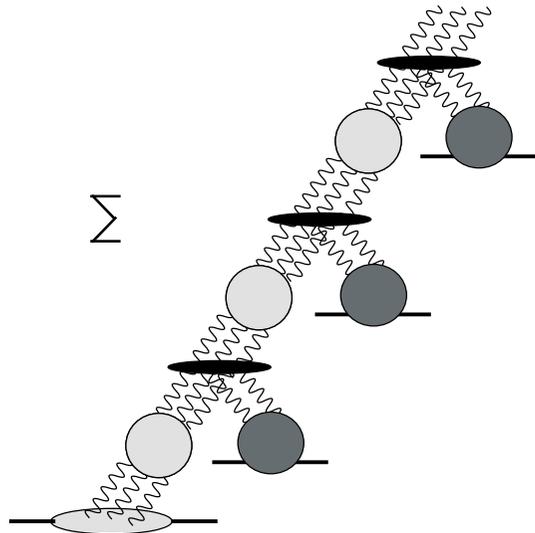
Extend the reggeization program to the Odderon sector (Braunewell, Ewerz).

## The Unitarization of the Odderon

Unitarization of the Odderon:

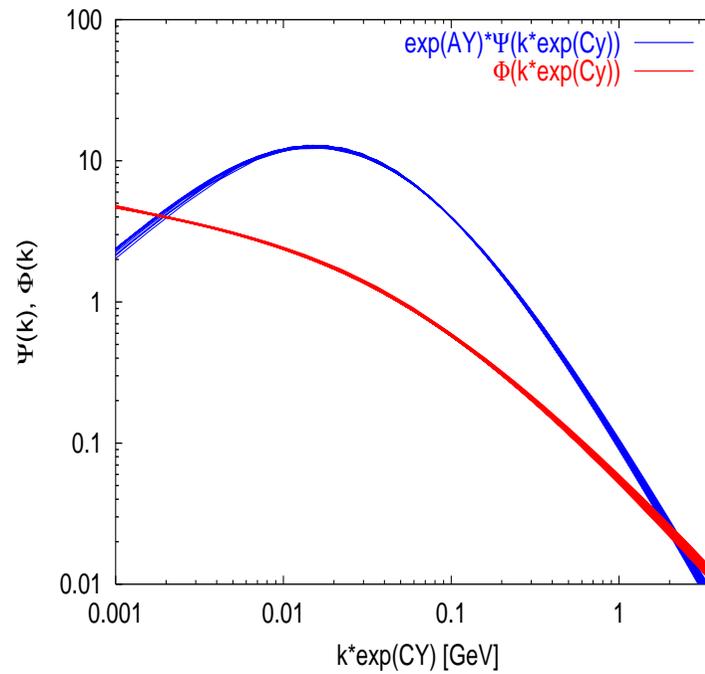
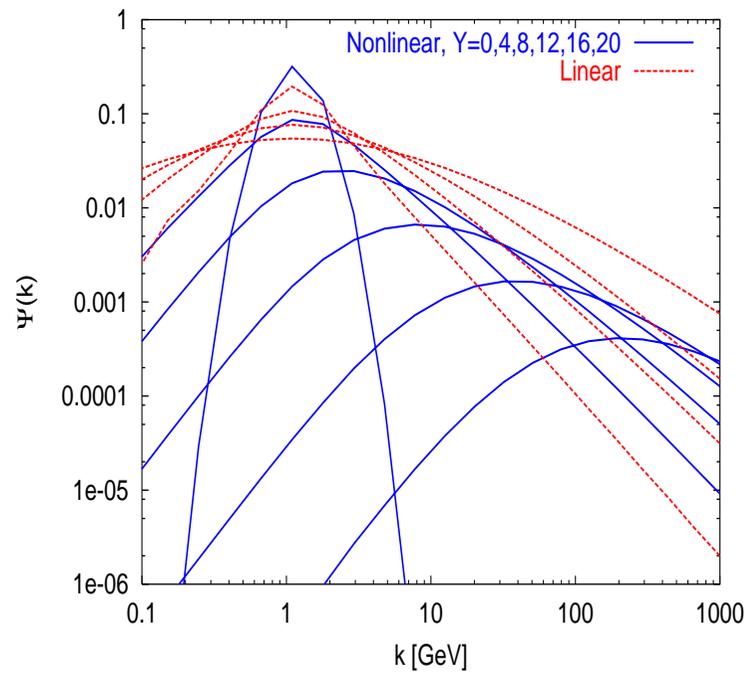
how will the Odderon intercept be affected by the interaction with the Pomeron  
(Kovchegov et al., Hatta et al.)

Recent result by Motyka: solves evolution equation for Odderon in momentum space by matching anomalous dimensions



$$\begin{aligned}\partial_y \Phi_P &= H_{BFKL} \otimes \Phi_P - \bar{\alpha}_s \Phi_P^2 + \frac{1}{2} \bar{\alpha}_s \Psi_O^2 \\ \partial_y \Psi_O &= H_{BFKL} \otimes \Psi_O - 2\bar{\alpha}_s \Psi_O \Phi_P\end{aligned}$$

Finds solution reminiscent of soliton:

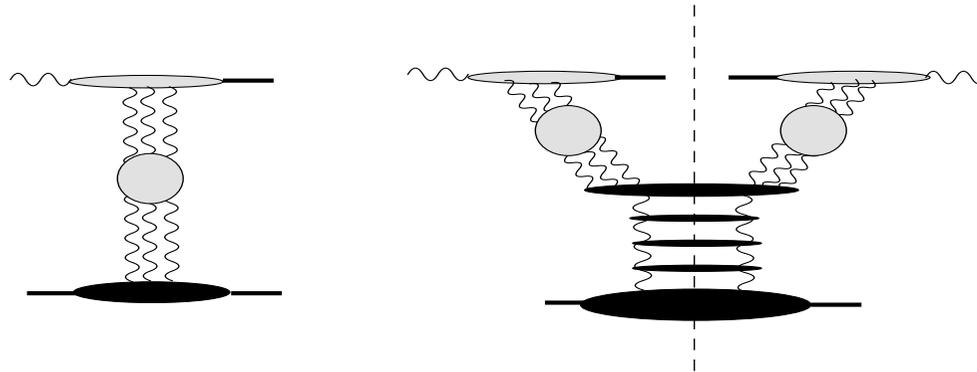


Does this apply to  $pp$  scattering?

## Where and how to look for the pQCD Odderon

1) The Processes  $\gamma^* p \rightarrow \eta_c p$ ,  $\gamma^* p \rightarrow \eta_c X$

(Czyzewski, Kwiecinski, Motyka, Sadzikowski; JB, Colferai, Braun, Vacca )



Dip structure in  $\frac{d\sigma}{dt}$ ; Enhancement of three gluon exchange by factor 5.

Estimated cross section: 1.5 pb for photoproduction, 40 fb for  $Q^2 = 25 \text{ GeV}^2$ .

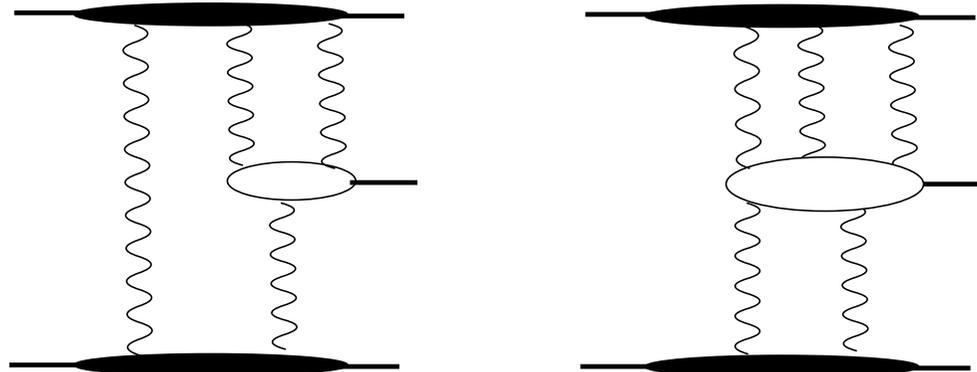
$\gamma^* p \rightarrow \eta_c X$  (new vertex!): 60 pb for photoproduction, 1.5 pb for  $Q^2 = 25 \text{ GeV}^2$ .

Not studied at HERA.

2) Photon-Photon Scattering (Motyka, Kwiecinski; Braunewll, Ewerz ) (→ Ewerz' talk)

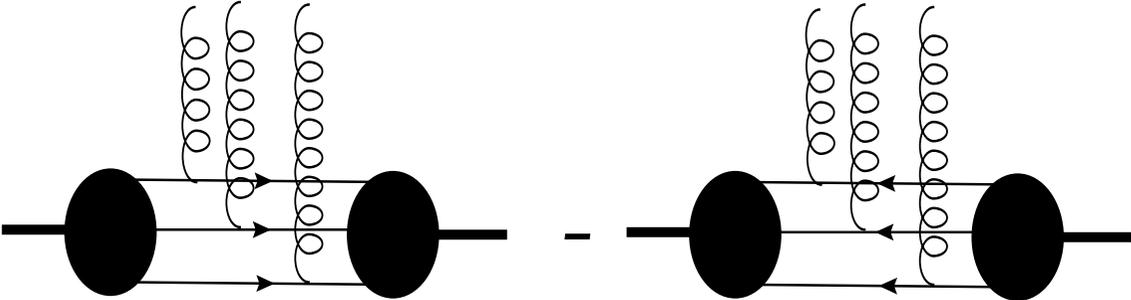
3) Phenomenology on elastic  $pp$  scattering (→ Ewerz' talk)

4) Double Diffractive  $J/\Psi$  production: vertex should be calculated:



Calculation feasible. Background due to  $\gamma$  exchange?

5) Polarization: coupling to the proton



Spin structure?

## Summary

- pQCD predicts an Odderon (in the world of short distances):  
it is a bound state of three reggeized gluons, has novel features beyond BFKL
- From here two directions:
  - Connection with soft physics ( $pp$  scattering): 'unitarization', theoretical progress, but no solution yet (confinement issue)
  - The pQCD Odderon is part of the general QCD reggeon field theory (merges into a string theory?)
- Several places to look for the pQCD ('hard') Odderon.  
Further studies needed.
- Search for the 'real Odderon': dip structure in  $\frac{d\sigma_{pp,p\bar{p}}}{dt}$ :  
Polarization?

Is the Odderon a fundamental object in QCD?