Odderon Searches at LHC

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Regge Limit of Hadronic Scattering

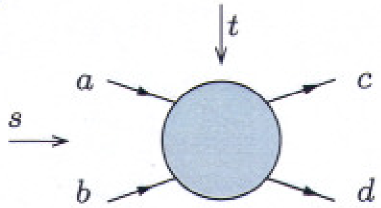
- Regge limit: $s \gg t \simeq M_h^2$
- one of the oldest problems in strong interaction physics
- Regge theory: leading contribution due to Pomeron
- rising total cross sections $\sim s^{0.09}$, small-x structure functions, diffraction

These are nonperturbative (= difficult) problems!

But perturbative QCD approach ($\rightarrow$ resummation) valid when process dominated by large momentum scale

Regge Theory

Consider process



with Mandelstam variables

$$
\begin{aligned}
s &= (p_a + p_b)^2 \\
t &= (p_a - p_c)^2 \\
u &= (p_a - p_d)^2
\end{aligned}
$$

From amplitude $A(s,t)$:

- Optical theorem:

$$\sigma_{\text{tot}} = \frac{1}{s} \operatorname{Im} A_{\text{el}}(s, t=0)$$

- Differential cross section:

$$\frac{d\sigma}{dt} = \frac{1}{16\pi s^2} |A(s,t)|^2$$

Partial wave expansion

$$A(s,t) = 16\pi \sum_{l=0}^{\infty} (2l+1) A_l(t) P_l(z_t)$$

with $z_t = 1 + 2s/(t-4m^2) \simeq 1 + 2s/t$
Use Sommerfeld-Watson transformation:

$$A(s,t) = \frac{1}{2i} \int_C dl (2l+1) \frac{A(l,t)}{\sin \pi l} P(l, z_t)$$

Analytic continuation ($\rightarrow$ signature $\eta = \pm 1$), deformation of contour, high energy limit:

$$A(s,t) = \sum_{\eta=\pm 1} \sum_i A_i^{(\eta)}(s,t)$$

with contribution of a pole at $\alpha_i(t)$

$$A^{(\eta)}(s,t) = \beta^{(\eta)}(t)\, \Gamma(-\alpha^{(\eta)}(t))\, \eta\, \xi^{(\eta)}(t) \left(\frac{s}{s_0}\right)^{\alpha^{(\eta)}(t)}$$

with signature factor

$$\xi^{(\pm 1)}(t) = 1 \pm e^{-i\pi\alpha(t)}$$

The Pomeron

From optical theorem

$$\sigma_{\text{tot}} \sim s^{\alpha(0)-1}$$

Data also require Pomeron with

$$\alpha_{\mathbf{P}}(t) = \alpha_{\mathbf{P}}(0) + \alpha'_{\mathbf{P}} t$$

with $\alpha_{\mathbf{P}} = 1.09$, $\alpha'_{\mathbf{P}} = 0.25\,\text{GeV}^{-2}$

Pomeron is leading contribution to total cross sections.

Pomeron amplitude is predominantly imaginary:

$$(-i)i\left(\frac{-is}{s_0}\right)^{\alpha_{\mathbf{P}}(t)-1}$$

as Feynman rule for Pomeron exchange

Crossing and the Odderon

Consider processes $a+b \to a+b$ and $a+\bar{b} \to a+\bar{b}$.
Define amplitudes

$$A_{\pm}(s,t) = \frac{1}{2}\left(A^{ab}(s,t) \pm A^{a\bar{b}}(s,t)\right)$$

A_+ identical for both processes
$\to$ positive C parity, dominated by Pomeron

A_- changes sign in the two processes
$\to$ negative C parity,
mesonic reggeon contributes to A_-.

Odderon ($\mathbb{O}$) is contribution to A_- which does not vanish rapidly with s.

From crossing and analyticity:

$$(-i)\eta_{\mathbb{O}}\left(\frac{-is}{s_0}\right)^{\alpha_{\mathbb{O}}(t)-1}$$

as Feynman rule for Odderon exchange.
$\to$ Odderon contribution is predominantly real.

Pomeranchuk Theorem

Pomeranchuk theorem in original form

Pomeranchuk

$$\Delta\sigma = \sigma_T^{\bar{p}p} - \sigma_T^{pp} \underset{s\to\infty}{\longrightarrow} 0$$

Note that

$$\Delta\sigma \sim \frac{1}{s} \Im\mathrm{m}\, A_-$$

Original theorem assumes $A_- \to 0$.

Violations of Pomeranchuk theorem discussed already in 1970. Anselm, Danilov, Dyatlov, Levin, ...

Really, the theorem is Eden, Grunberg, Truong

$$\frac{\sigma_T^{\bar{p}p}}{\sigma_T^{pp}} \underset{s\to\infty}{\longrightarrow} 1$$

Consider toy example ($\rightarrow$ maximal Odderon):

$$\begin{aligned} \sigma_T^{pp} &= A \log^2 s + B \log s + C \\ \sigma_T^{\bar{p}p} &= A \log^2 s + B' \log s + C' . \end{aligned}$$

Also, from Froissart-Martin theorem

$$|\Delta\sigma| \leq \mathsf{const} \cdot \log s$$

and obviously $\Delta\sigma < \sigma_T^{pp}, \sigma_T^{p\bar{p}}$.

Cornille-Martin theorem for differential cross section is analogous to Pomeranchuk theorem:

$$\frac{d\sigma^{\bar{p}p}/dt}{d\sigma^{pp}/dt} \underset{s\to\infty}{\longrightarrow} 1$$

The Maximal Odderon

Maximal Odderon introduced by Łukaszuk and Nicolescu in 1973.

Based on maximality principle:
cross sections at high energies saturate asymptotic bound in functional form. For example

$$\sigma_T \longrightarrow C \log^2 s$$

or

$$\Delta\sigma \longrightarrow C_\Delta \log s$$

not violating any general principle.

Possible that $A_-(s) \sim s \log^2 s$, clearly corresponding to an Odderon.

Note:
Name Odderon originally for simple pole at $J = 1$

Joynson, Leader, Nicolescu, Lopez

Odderon in Perturbative QCD

In perturbative QCD the Odderon is described by exchange of three interacting reggeized gluons in the t-channel.

Consider transformation of gluon field $\mathbf{A}_\mu(x) = A_\mu^a(x)t^a$ under charge conjugation,

$$\mathbf{A}_\mu(x) \longrightarrow -\mathbf{A}_\mu^T(x)$$

There are two ways of constructing color singlet states of three gluons.
Even under C:

$$\begin{aligned}\mathcal{P}_{\mu\nu\rho}(x,y,z) &= -i\,\mathrm{tr}\left([\mathbf{A}_\mu(x),\mathbf{A}_\nu(y)]\mathbf{A}_\rho(z)\right)\\ &= \frac{1}{2}f_{abc}A_\mu^a(x)A_\nu^b(y)A_\rho^c(z)\end{aligned}$$

Odd under C:

$$\begin{aligned}\mathcal{O}_{\mu\nu\rho}(x,y,z) &= \mathrm{tr}\left(\{\mathbf{A}_\mu(x),\mathbf{A}_\nu(y)\}\mathbf{A}_\rho(z)\right)\\ &= \frac{1}{2}d_{abc}A_\mu^a(x)A_\nu^b(y)A_\rho^c(z)\end{aligned}$$

- BKP equation (Bartels, Kwiecinski, Praszalowicz)
  For amputated amplitude $f_{\mathbb{O}}^{\{a_n\}} \equiv \mathbf{k}_1^2\,\mathbf{k}_2^2\,\mathbf{k}_3^2\,\phi_{\mathbb{O}}^{a_1a_2a_3}(\omega, \{\mathbf{k}_i, \mathbf{k}_i'\})$

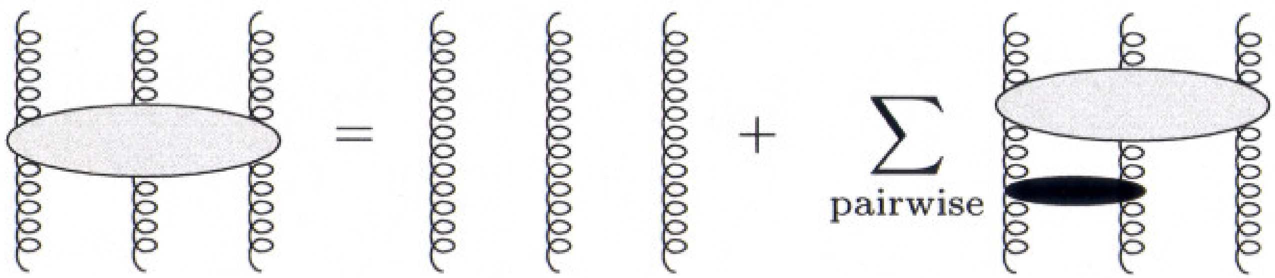
$$\left(\omega - \sum_{i=1}^{3}\beta(\mathbf{k}_i)\right) f_{\mathbb{O}}^{\{a_n\}} = f_{\mathbb{O}}^{(0)\{a_n\}} + \int \frac{d^2\mathbf{l}}{(2\pi)^3} \sum_{(123)} K_{2\to 2}^{\{b_n\}\to\{a_n\}} f_{\mathbb{O}}^{\{b_n\}}(\{\mathbf{k}_i\}, \mathbf{l}),$$

$$K_{2\to 2}^{\{b_n\}\to\{a_n\}} = f_{b_1a_1c}f_{ca_2b_2}\delta_{b_3a_3}K_{2\to 2}(\mathbf{l}, \mathbf{k}_1, \mathbf{k}_2).$$

$$K_{2\to 2}(\mathbf{l}, \mathbf{k}_1, \mathbf{k}_2) = g^2\left[\frac{\tilde{\mathbf{q}}^2}{\mathbf{l}^2(\tilde{\mathbf{q}} - \mathbf{l})^2} - \frac{\mathbf{k}_1^2}{l^2(\mathbf{k}_1 - \mathbf{l})^2} - \frac{\mathbf{k}_2^2}{(\tilde{\mathbf{q}} - \mathbf{l})^2(\mathbf{k}_2 - \mathbf{l})^2}\right],$$

$$\beta(\mathbf{k}_i^2) = -\frac{N_c}{2}g^2\int\frac{d^2\mathbf{l}}{(2\pi)^3}\frac{\mathbf{k}_i^2}{\mathbf{l}^2(\mathbf{l} - \mathbf{k}_i)^2}, \qquad \tilde{q} = k_1 + k_2.$$

$$\left(\omega - \sum_{i=1}^{3}\beta(\mathbf{k}_i)\right)$$



The Odderon Intercept

Two solutions to the BKP equation found explicitly, with different intercepts $\alpha_{\mathcal{O}}$ ($\rightarrow s^{\alpha_{\mathcal{O}}-1}$)

Janik-Wosiek solution

intercept $\alpha_{\mathcal{O}} = 0.96$

Bartels-Lipatov-Vacca solution

intercept $\alpha_{\mathcal{O}} = 1$

The two solutions couple differently to external particles!

BLV- vs. JW- Odderon

For all practical purposes

$0.96 = 1$

→ Couplings to external particles make the crucial difference

In LO:

* BLV couples to all impact factors
* JW requires at least three constituents in scattering particles

Nonperturbative Odderon

Only little is known!

- Regge picture
- Nonperturbative gluon propagators
- Stochastic Vacuum Model using functional approach to high energy scattering

  Dosch, Simonov, Nachtmann ...
- Regge trajectory of the Odderon

  Assume linear trajectory for Odderon,

$$\alpha_{\mathbb{O}}(t) = \alpha_{\mathbb{O}}(0) + \alpha'_{\mathbb{O}} t$$

  assume same slope as for Pomeron, look for suitable 3^{--} glueball state in lattice or other model calculations and extrapolate to $t = 0$.
  $\rightarrow$ intercept of -1.5.

  Kaidalov, Simonov

  Meyer, Teper

Phenomenology

- So far only scarce evidence for Odderon, guidance from experiment missing

- Cross sections typically $\sim \alpha_s^6$
  $\rightarrow$ large uncertainty

- For a long time Odderon only discussed in context of pp scattering
  $\rightarrow$ many contributions, Odderon smaller than others

- Recently: new directions in Odderon phenomenology: exclusive processes

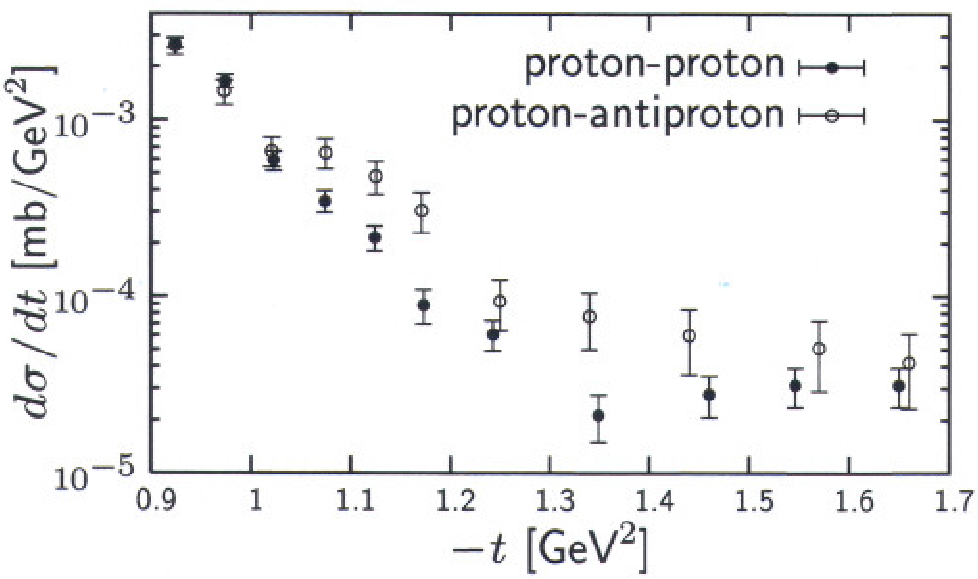
- Caution in applying the perturbative Odderon,
  $\rightarrow$ diffusion problem

Does the Odderon Exist?

Only evidence for Odderon in elastic pp and $p\bar{p}$ scattering,

$$\frac{d\sigma_{el}^{\bar{p}p}}{dt} - \frac{d\sigma_{el}^{pp}}{dt}$$

in the dip region around $t \simeq -1.3\,\mathrm{GeV}^2$ at the ISR ($\sqrt{s} = 52$ GeV)



Only one week of data taking!

pp and $\bar{p}p$ Elastic Scattering

Donnachie-Landshoff description:
Regge fit with Odderon (simple three gluon exchange) + many other contributions

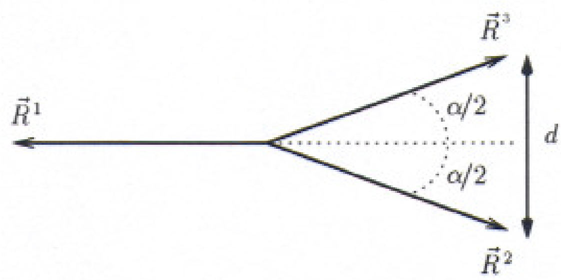
Try different models for Odderon-proton coupling
$\longrightarrow$ proton structure

Dosch, Ewerz & Schatz

- impact factors

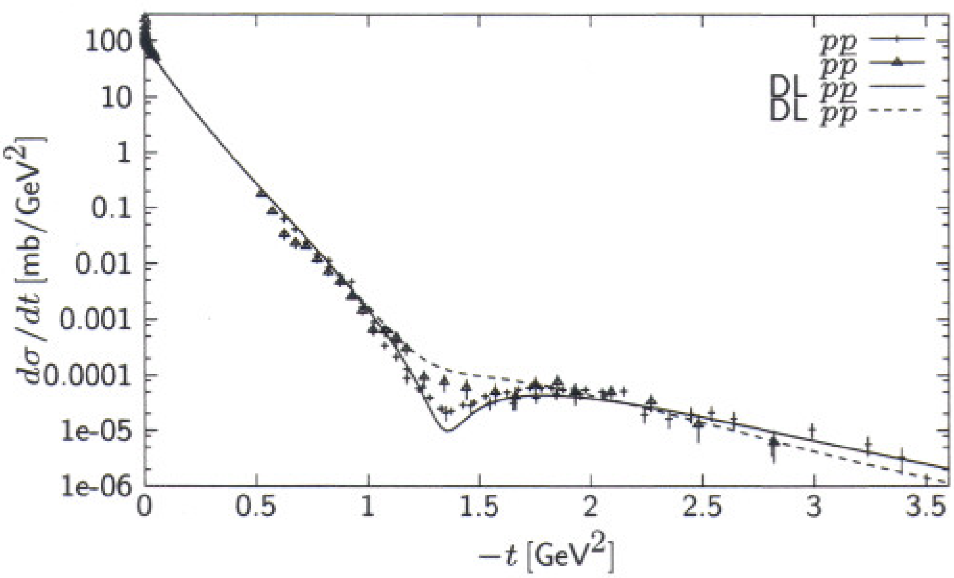
Fukugita & Kwiecinski, Levin & Ryskin

- geometric model for proton (possible diquark cluster?)



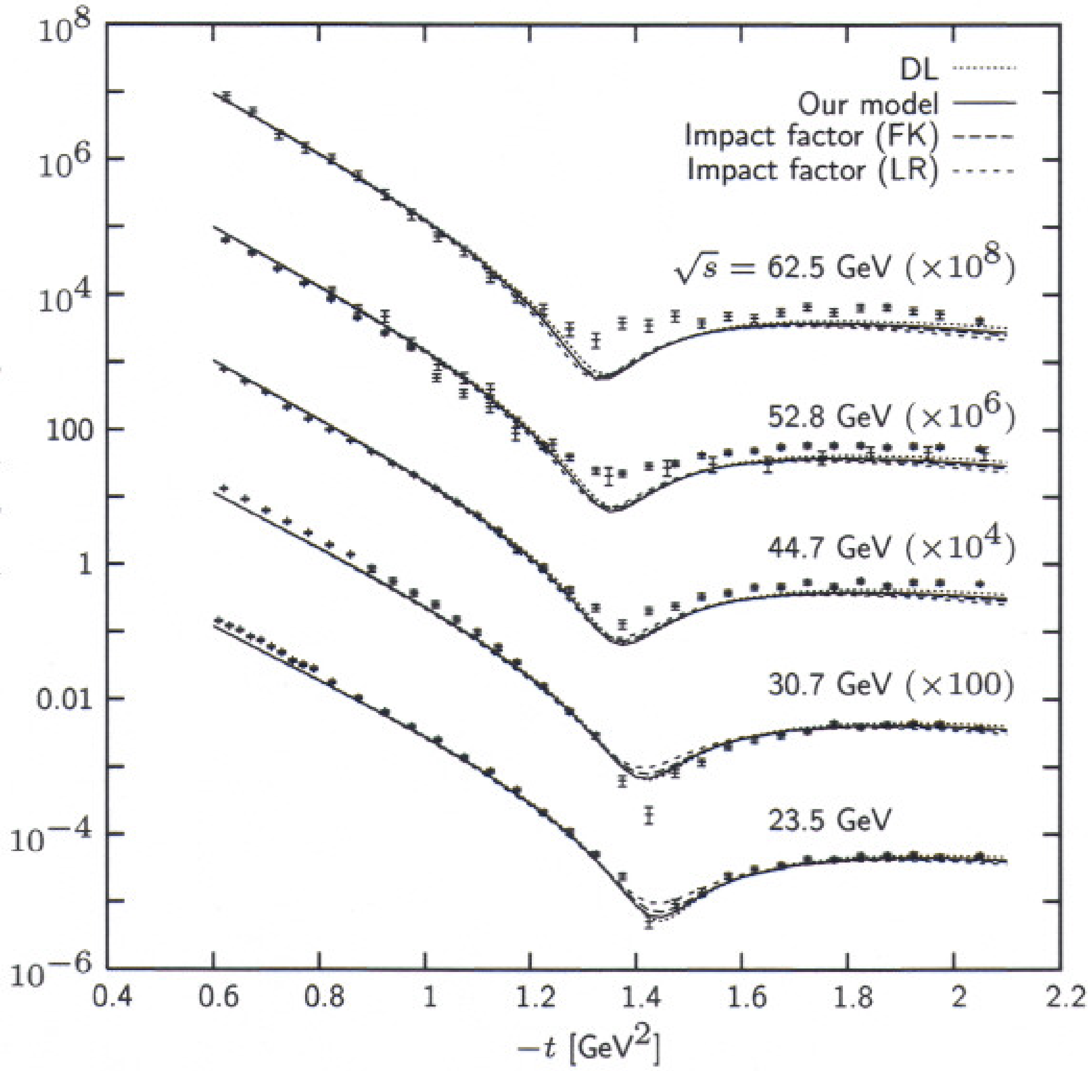
pp and $p\bar{p}$ Elastic Scattering

Differential cross section for pp and $p\bar{p}$ scattering at $\sqrt{s} = 53\,\text{GeV}$ with Donnachie–Landshoff fit



Odderon in DL Fit

All models work well:



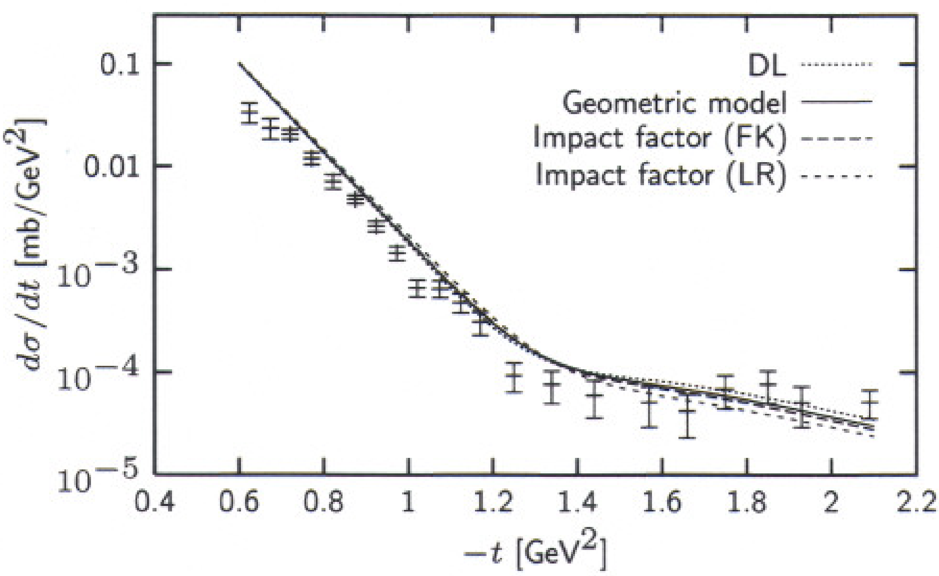
relatively small $\alpha_s \simeq 0.3 - 0.5$

small diquark cluster $\langle d \rangle < 0.35\,\text{fm}$

Other (quite different) fits also describe data, but all fits require some sort of Odderon

$p\bar{p}$ Elastic Scattering

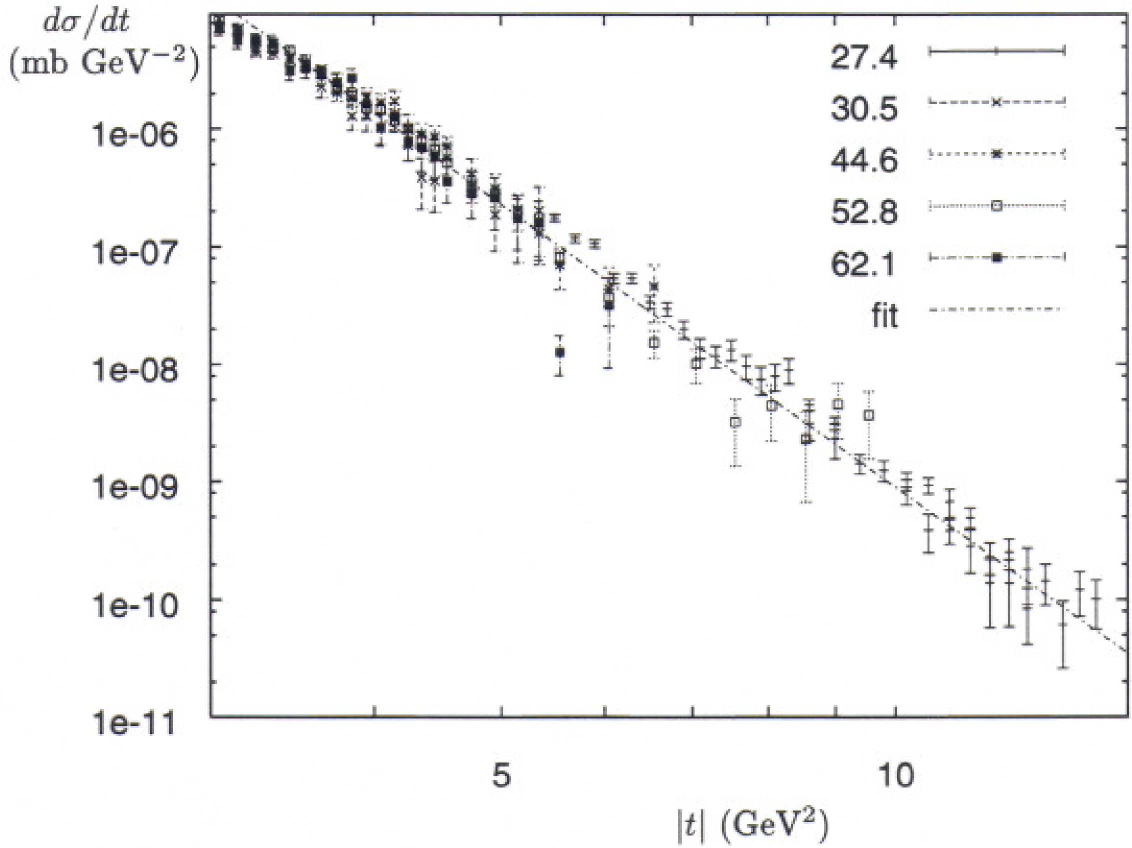
Differential cross section for elastic $p\bar{p}$ scattering at $\sqrt{s} = 53\,\text{GeV}$ as calculated using different couplings of the Odderon to the proton:



Large-t Elastic Scattering

Large-t elastic scattering is energy-independent and extremely well described by

$$\frac{d\sigma}{dt} = 0.09\, t^{-8}$$



This agrees with expectation from Odderon as three-gluon exchange. Donnachie, Landshoff

→ large-t region dominated by Odderon

O-Value of elastic pp scattering at LHC

* intermediate $|t| \sim 1-2\ GeV^2$

→ dip region ("structure region")

very sensitive to Odderon

* large $|t| \nearrow 10\ GeV^2$

→ dominated by Odderon exchange

(possibly 3P contribution ?!)

* small $|t|$

→ related to measurement of

σ_{tot} , ρ-parameter

sensitive to Odderon (semi-theoretical parameter)

Remarks on experimental setup

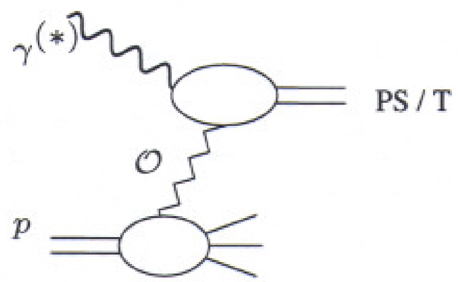
* Proton tagging in CMS (TOTEM) and ATLAS planned at 220/240 m from interaction point; also planned at 420 m (corresponds to 60 GeV long. momentum loss of proton → region for Higgs search)
  * proton tagging → quantum numbers, mass of diffractive system
* ATLAS / CMS require large p_T in central region
* ALICE: identification of small p_T particles in central region possible
  → unique for small mass diffractive system
  but: no proton tagging
* High photon fluxes in pA / AA collisions
  → γp, γA, $\gamma\gamma$ diffractive events

New Ways in Phenomenology

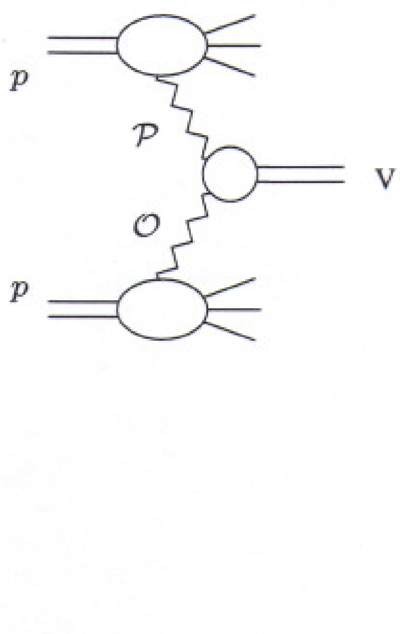
Consider exclusive processes in which the Odderon is the only contribution!

Examples:

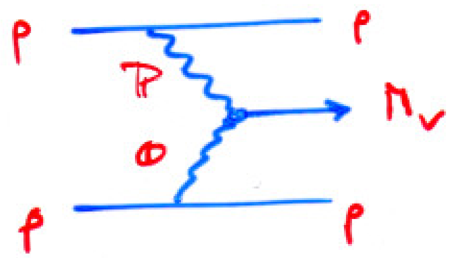
- diffractive pseudoscalar and tensor meson production $\gamma^{(*)} p \to M_{PS/T}\, p$ or



- double diffractive vector meson production $p\,p \to p\,p\,M_V$ (Pomeron-Odderon fusion)



Double-diffractive vector meson production



$$pp \to p + J/\psi + p$$
$$ \phi$$

* For unflavoured mesons $\phi, J/\psi$ reggeon exchange small
* γ exchange under control
* Reggeon and γ exchange important if $p\mathbb{O}$ - coupling is small
* In pp destructive interference in (unlikely) case $\alpha_{\mathbb{P}} = \alpha_{\mathbb{O}}$
  → $p\bar{p}$ better then
* Estimate in Regge theory: for J/ψ at $\sqrt{s} = 2$ TeV

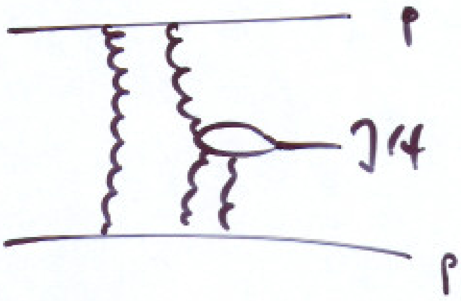
Schäfer, Mankiewicz, Nachtmann

$$\sigma = 3\ \text{mb} \cdot c_0^2 \cdot N$$

$c_0 \leq 0.05$ (from ρ)

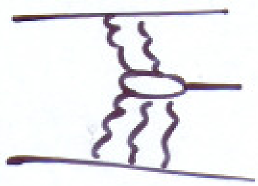
$N \simeq 0.01$ (all uncertainties)

* pQCD estimate: Bzdak, Motyka, Szymanowski, Cudell



← rap. y

* take into account γ-exchange

[note:  is of higher order]

* expected cross section for LHC:

$\mathbb{O}$: 0.3 - 4 nb
γ: 2.4 - 27 nb } for J/ψ, $\left.\frac{d\sigma}{dy}\right|_{y=0}$

with considerable uncertainties:

α_s, gap survival

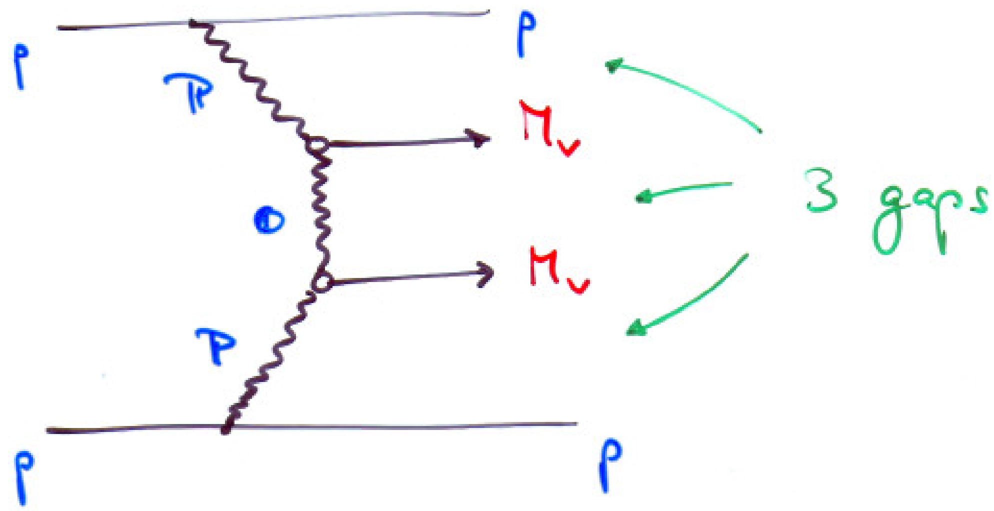
* here assumed that protons stay intact.

→ larger cross sections expected for excitation or breakup of p

Triple-diffractive meson production

CE

In order to avoid potentially small $p\mathbb{O}$-coupling:



* clean signal: $M_V = J/\psi\ ,\ \Upsilon$
* note: possibly small $p\mathbb{O}$-coupling might be main reason for not having seen the Odderon so far.

Odderon in Diffractive Meson Production

Large cross section expected in photoproduction of light mesons

$\longrightarrow$ completely nonperturbative process

Calculation using eikonal approach and model of stochastic vacuum (MSV)

Berger, Donnachie, Dosch, Kilian, Nachtmann & Rueter

Suppression due to diquark clustering absent when proton breaks up

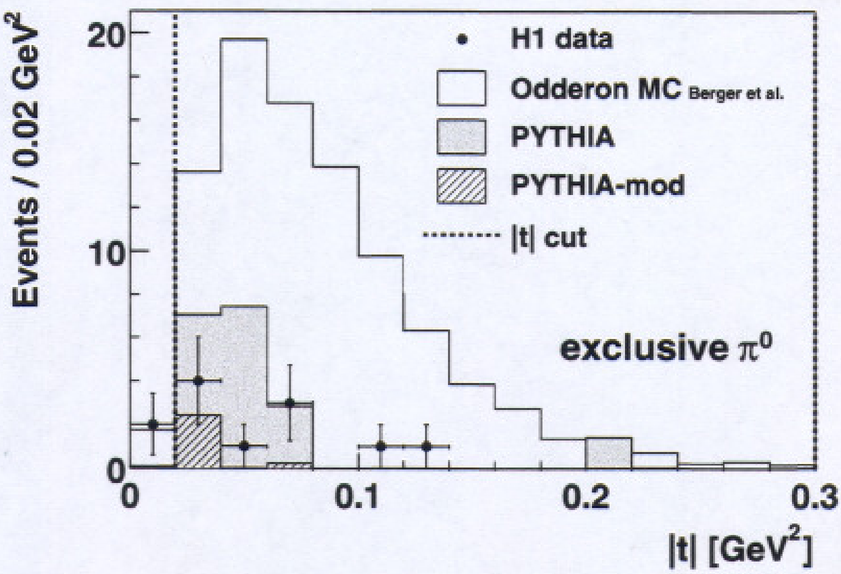
Estimate for $\gamma\, p \to \pi^0\, N^*$ at HERA: $\sigma \simeq 200$ nb

Similarly, $\gamma\, p \to f_2\, X$ at HERA: $\sigma \simeq 21$ nb

$\longrightarrow$ Can we find the Odderon at HERA?

Odderon in Diffractive Meson Production

diffractive pion production:



Does not exactly look like a signal ...

Possible reasons:

Odderon intercept
Odderon-pion coupling ← chiral effects! → suppression $\sim \frac{1}{50}$ (CE, Nachtmann)
Odderon-proton coupling (MSV)

Less uncertainty for heavy mesons like η_c, but much smaller cross sections: $\sim 50\,\mathrm{pb}$ in photoproduction (optimistically)

Czyzewski et al; Engel et al; Bartels et al

Summary

* Odderon should exist if our understanding of high energy scattering is correct.

* Odderon under good control in pQCD, mathematically interesting.

* Important aspect: reggeization due to coupling to external particles

* Nonperturbative Odderon: little known. pO - coupling might tell us about proton structure.

* Experimental evidence for Odderon is weak. Promising are especially exclusive processes.

* Good test:

$$\frac{d\sigma^{el}}{dt}$$

(ideally for pp, $p\bar{p}$ at same energy)