Diffractive Processes at High Energies.

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Contents:

- Introduction.
- Pomeron in QCD.
- Diffraction and small-x physics.
- Hard diffraction in hadronic interactions
- Double Pomeron jet production.
- Conclusions.

Introduction

Study of diffractive processes gives an important information on both nonperturbative and perturbative QCD dynamics.

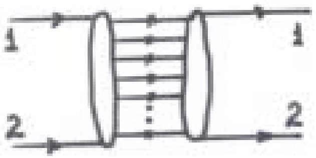
Problems of QCD in nonperturbative region: confinement, chiral symmetry violation. Structure of QCD vacuum.

Some important problems of diffraction:

- The nature of the Pomeron in QCD
- Role of s-channel unitarity and multipomeron exchanges
- QCD and Regge factorizations and their violation in diffractive processes
- Small-x problem and "saturation" of partonic densities as $x \to 0$. Relation to heavy ion collisions.
- Transition from hard to soft regimes

- Two complementary views on diffraction
- S-channel view of diffraction.

Absorption of an initial wave due to many inelastic channels leads by unitarity to diffractive elastic scattering.

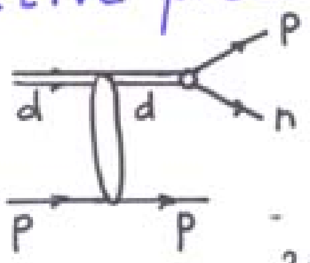


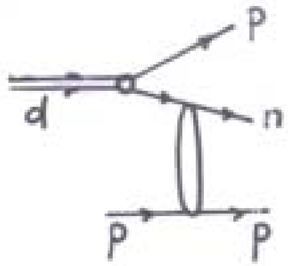
Diffraction is a process, which has a long lifetime $\tau \sim E_L/\mu^2$

E.Feinberg. I.Ya.Pomeranchuk

Diffractive production

Example
Dissociation of a deutron

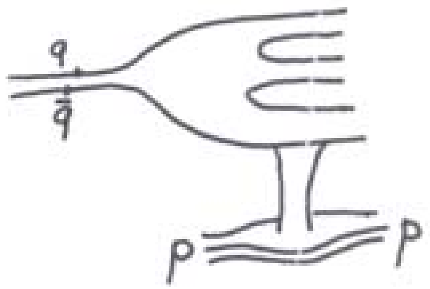




$$\Delta t \approx \frac{2E_L}{M^2 - m_d^2}$$

Inelastic diffraction is due to a difference of amplitudes and is smaller compared to elastic scattering.

Dissociation of a hadron into $q\bar{q}$-pairs (color dipoles).



Good and Walker interpretation of diffraction.

Diffractive part of S-matrix $iD_{ik}(s,b)$ can be diagonalized by an orthogonal matrix Q

b – impact parameter

$$D = Q F Q^T \;;\quad F_{ij} = F_i \delta_{ij}$$

$$\Psi_i = \sum_k Q_{ik} \varphi_k \;;$$

φ_k - eigenstates, which have only elastic scat.

$\Updownarrow$

Quark configurations with fixed transverse separations.

Ψ_1 - initial state.

After diffractive scattering (with $\hat{F} \neq \hat{I} \cdot F$) a final state is a new superposition of eigenstates and thus contains Ψ_i (with $i = 1, 2, \ldots, N$)

Analog of $K_L \to K_S$ regeneration, where K^0 and $\bar{K}^0$ are "diagonal" states.

If all $F_i = \frac{1}{2}$ $(b \leq R)$ - black disc limit - inelastic diffraction is absent.

For $F_i \leq \frac{1}{2}$

$$\sigma^{(el)}(b,s) + \sigma_D^{(in)}(b,s) \leq \frac{1}{2} \sigma^{(tot)}(b,s)$$

Pumplin's bound

Diffractive production is related to the dispersion in the absorption of the diffractive eigenstates

$$\sigma_D^{in}(s,b) = 4\left(\langle F^2\rangle - \langle F\rangle^2\right)$$

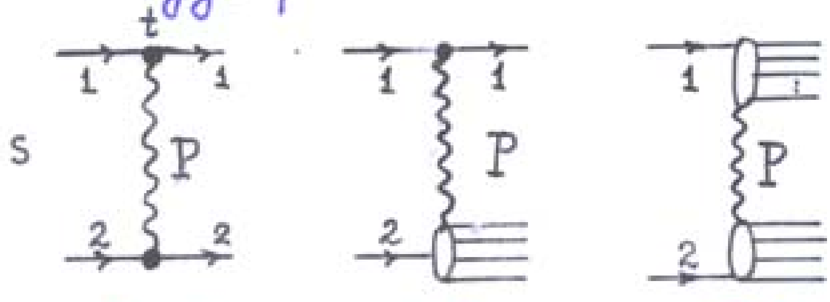
For strong absorption diffractive production is peripheral in b.

In QCD eigen states - dipoles with definite transverse sizes $r_\perp$.

For small $r_\perp$ $F \sim r_\perp^2$. Dependence on s, b ?

- t-channel view

Regge pole model



elastic SD DD

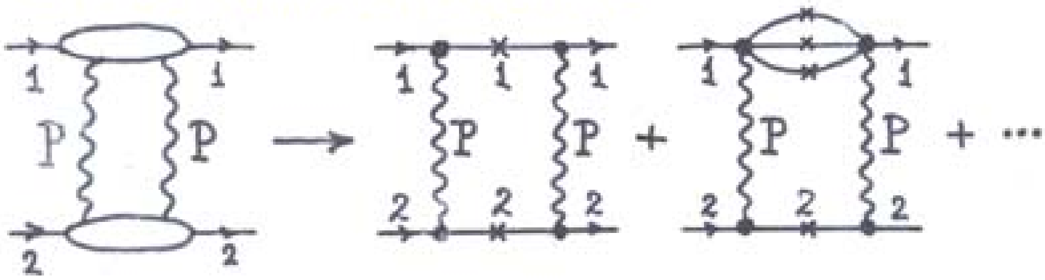
In b-space Regge amplitudes have a gaussian form.

Note that the Pomeron is very non-local object. It corresponds to the process with $\tau \sim E/m^2$.

Pomeron with intercept $\alpha_P(0) > 1$ leads to a violation of unitarity ($s \to \infty$).

Regge cuts (multi-Pomeron exchanges in the t-channel) restore s-channel unitarity.

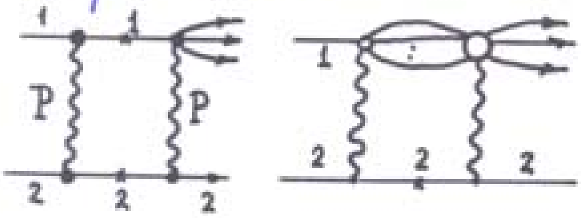
Gribov's technique for evaluation of cuts contributions



Becomes equivalent to GW formulation, but with known s-dependence

Multipomeron contributions to elastic amplitudes are related to amplitudes of diffractive processes.

For inelastic diffraction effects of multipomeron cuts are even more important.



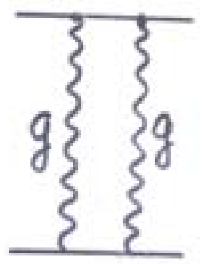
They lead to a peripheral form of amplitudes in b-space.

Gribov diagramme technique and AGK-cutting rules allow for systematic study of multipomeron cuts in diffractive processes and multiparticle production.

Thus an investigation of diffractive processes gives an information on structure hadronic fluctuations and a mechanism of high energy interactions.

• Pomeron in QCD

In QCD the Pomeron is usually related to gluonic exchanges in the t-channel

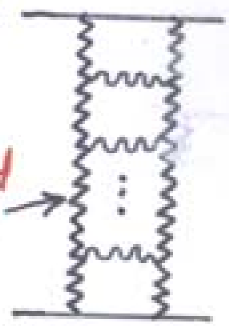


Low, Nussinov

$$\alpha_{\mathbb{P}}(0) = 2S_g - 1 = 1$$

In QCD perturbation theory ladder-type diagrams are important – BFKL - Pomeron

reggeized gluons



In LO $\left(\alpha_s \ln\frac{s}{s_0}\right)^n$

$$\Delta \equiv \alpha_{\mathbb{P}}(0) - 1 = \frac{12\ln 2}{\pi}\alpha_s; \quad \Delta \approx 0.5$$

Large NLO corrections V. Fadin, L. Lipatov M. Ciafalloni et al.

Sources of these corrections were discussed

$$\Delta = 0.15 \div 0.2$$ S. Brodsky et. al

Iterative method of solution of BFKL equation (LO and NLLO) J. Andersen

What is the role of nonperturbative effects?

Are there glueballs on the Pomeron trajectory?

- These problems were investigated in the nonperturbative Wilson loop approach. A. K, Yu. Simonov

In this framework usual ($q\bar{q}$ - $\rho, A_2, \ldots$) trajectory are calculated and agree with experiment.

Predicted spectrum of glueballs in a good agreement with lattice results.

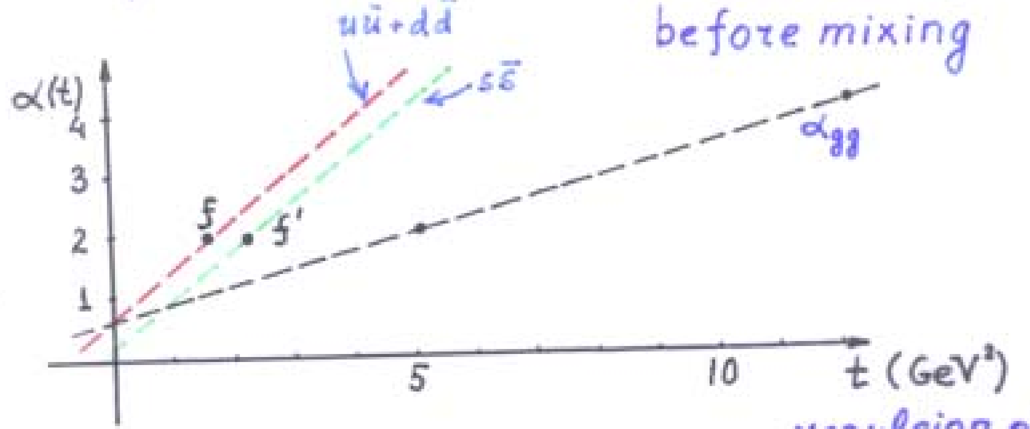
The lowest state 0^+ $M = 1.58$ GeV

Slope of gg-trajectories $\alpha'_{gg} = \frac{4}{9}\alpha'_{q\bar{q}} = 0.4\ \text{GeV}^{-2}$

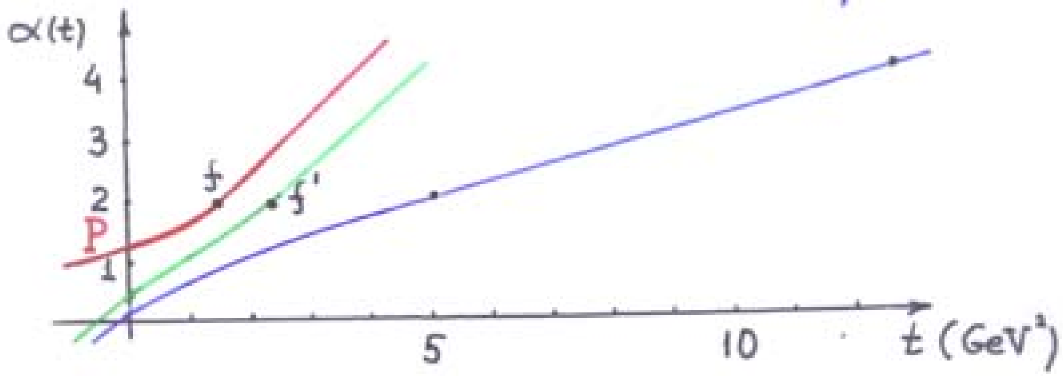
Mixing of gg and $q\bar{q}$ trajectories in the small-t region

Important role of $q\bar{q}$-gluons mixing.

before mixing



repulsion of levels



After mixing and account of semihard interactions of gluons

$\alpha_P(0) = 1.15 \div 1.25$

Very rich physics of the Pomeron (confinement, glueballs, quark-gluon mixing, chiral sym. and role of pions, semihard interactions)

Note that in this approach Pomeron contains both soft and hard effects → physical pomeron.

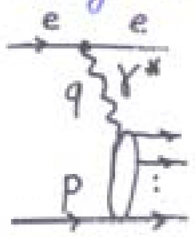
In the region $p_\perp < 1$ GeV notion of point-like quarks and gluons is not a relevant one

- New areas of applications

a) Small-x physics.

Studied experimentally in ep (μp, νp) interactions.

New data from ep collider - HERA allow to investigate the region of very small x



$$Q^2 = -q^2 \; ; \quad x = \frac{Q^2}{2pq} = \frac{Q^2}{W^2+Q^2} \qquad (W^2 \gg m^2)$$

$$W^2 \equiv s = (p+q)^2$$

$$\sigma^{(tot)}_{\gamma^* p}(W^2, Q^2) = \frac{4\pi^2 \alpha_{e.m.}}{Q^2} F_2(x, Q^2)$$

For large Q^2

$$F_2(x, Q^2) \simeq \sum_i e_i^2 x \left(q_i(x, Q^2) + \bar{q}(x, Q^2) \right)$$

Experiments at HERA demonstrated

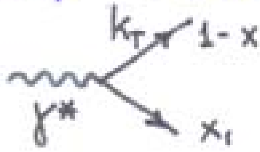
- Fast increase of $F_2(x, Q^2)$ as $x \to 0$

$$\sigma^{(tot)}_{\gamma^* p} \sim \left(\frac{1}{x}\right)^{\lambda(Q^2)} \simeq \left(\frac{W^2}{Q^2}\right)^{\lambda(Q^2)}$$

$\lambda(Q^2)$ increases with Q^2 and ≈ 0.3 at $Q^2 \sim 10^2 GeV^2$

Diffractive dissociation of γ^* exists even at large Q^2. $\Delta_{eff} \approx 0.2$

Two types of $q\bar{q}$-configurations of virtual photons



a) Small size

$$k_T \sim Q, \; r \sim \frac{1}{k_T} \sim \frac{1}{Q};$$

b) Large size

$$k_T \sim \Lambda_{QCD} \ll Q; \; r \sim \frac{1}{\Lambda}$$

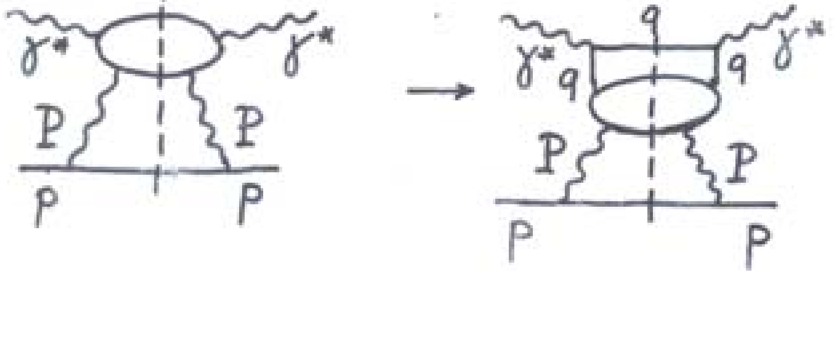
$$\sigma_S \sim \frac{1}{Q^2} \; ; \; \sigma_L \sim \frac{1}{\Lambda^2} \; \left(w_L \sim \frac{1}{Q^2}\right)$$

The model based on this picture and reggeon theory A. Capella, E. Ferreiro, A.K., C. Salgado gives a good simultaneous description of F_2 and diffractive production (F_2^D) in a broad region of Q^2.

(see also E. Gotsman, E. Levin, U. Maor; K. Golec-Biernat, M. Wüsthoff)

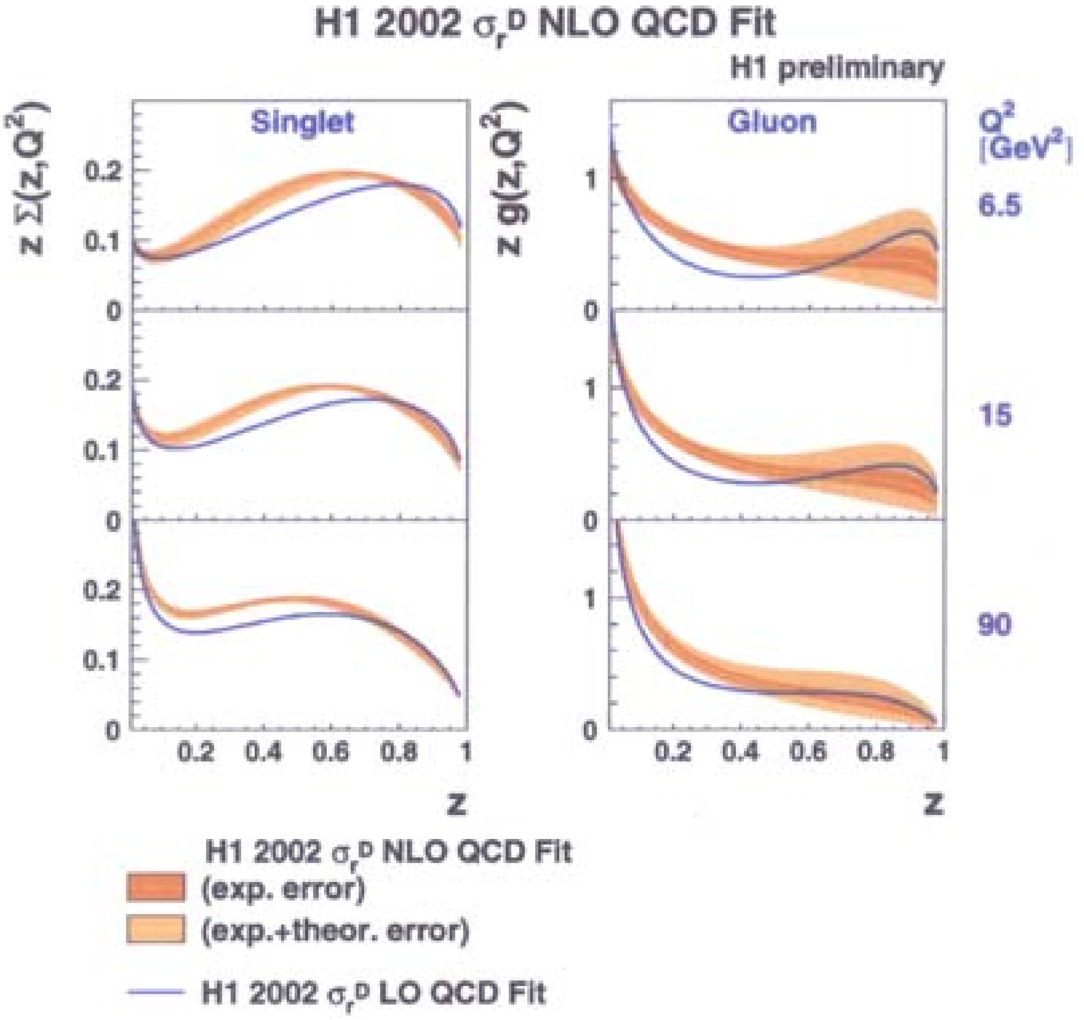
Interaction of small size component can be described in perturbation theory.

At large Q^2 inclusive diffraction dissociation of a photon can be described in terms of quark distributions in the Pomeron.



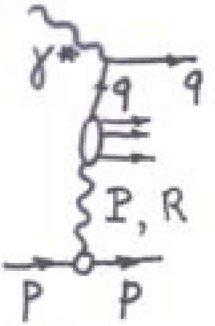
QCD fits of $F_2^{D(3)}$ data

Extraction of the gluon and quark densities in the pomeron from a DGLAP fit to H1 data

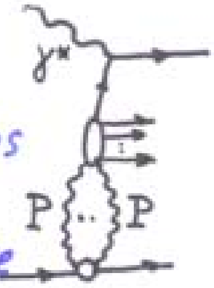


• Structure of the Pomeron and hard diffraction in hadronic interactions.

From analysis of HERA diffractive data it is possible to find distributions of quarks and gluons in the "Pomeron."



These diagrams also contribute



However standard QCD evolution takes place.

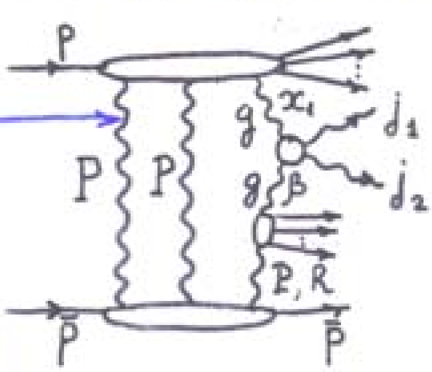
J. Collins

Large uncertainties in the gluonic content of the "Pomeron". New H1 analysis.

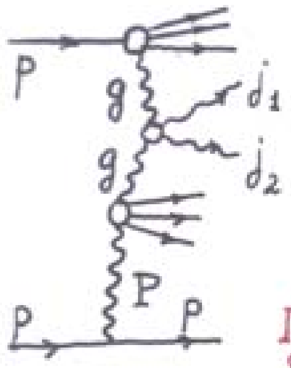
For hadronic interactions situation is more complicated

These exchanges are absent in DIS

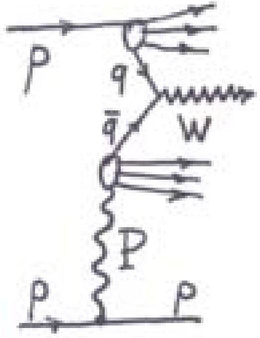
They violate "hard factorization"

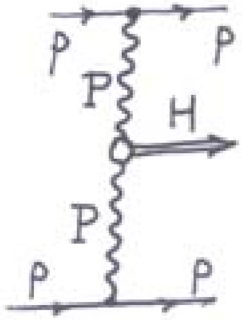


- Hard diffraction in pp

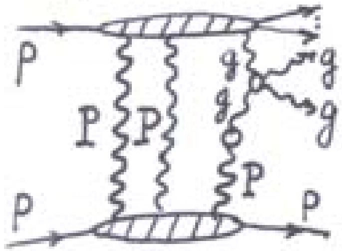


Ingelman Schlein





- In these processes the rescattering effects are important



They strongly reduce cross sections. U. Maor et. al, A. Bialas, R. Peschanski

Violation of both QCD (hard) and Regge factorization.

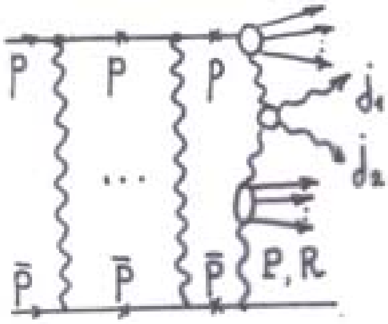
The suppression depends on energy and on the x of a parton (from the upper side) due to different sizes of initial configurations

A.K, V.A. Khoze, A.D. Martin, M.G. Ryskin (2001)

Interesting field for QCD physics at LHC.

Soft color interaction model gives a reasonable value for suppression (but not for β-dependence) R. Enberg

Usually these effects are taken into account in eikonal approximation (elastic rescatterings only)



The suppression factor (survival probability)

$$S^2 = \frac{\int |M(s,b,..)|^2 e^{-\Omega(b)} d^2b}{\int |M(s,b,..)|^2 d^2b}$$

However inelastic intermediate states can play an important role.

see also GLM

Eigen states with small absorption will lead to smaller suppression

Consider this effects in the 2-channel model KMR model (for details see KMR)

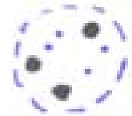
Eigen states absorption cross sections differ strongly (3÷4 times)

In partonic model they correspond to configurations of differen sizes

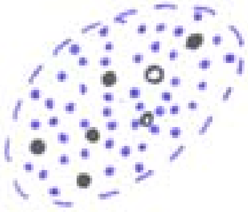
Large size - large σ - state 1

Small(er) size - smaller σ - state 2

Next step: relation to partonic configurations with different x. KKMR



Small size - mostly valence quarks $x \sim 1$



Large size - mostly gluons and sea $x \ll 1$

In this approach it is possible to explain diffractive production of jets at Tevatron CDF

Not only an absolute magnitude but also β-dependence differs from predictions, based on HERA data (Note β^{-1} behaviour of CDF data for small β) Fig. K. Goulianos

Kinematics: $\bar{\xi} = 0.06 \quad M^2 = \bar{\xi} \cdot S = 2 \cdot 10^5\, GeV^2$

$$M_{jj}^2 = x_1 \beta M^2 \sim 10^3\, GeV^2$$

$$x_1 \cdot \beta \simeq 5 \cdot 10^{-3}$$

$\beta \gtrsim 0.25 \rightarrow x_1 \lesssim 0.02$ mostly gluons

$\beta \sim 0.025 \rightarrow x_1 \sim 0.2$ mostly valence q

Thus in this model suppression factor increases as β decreases (for CDF kinemat.)

In this model it is possible to reproduce CDF results without free parameters. Fig.

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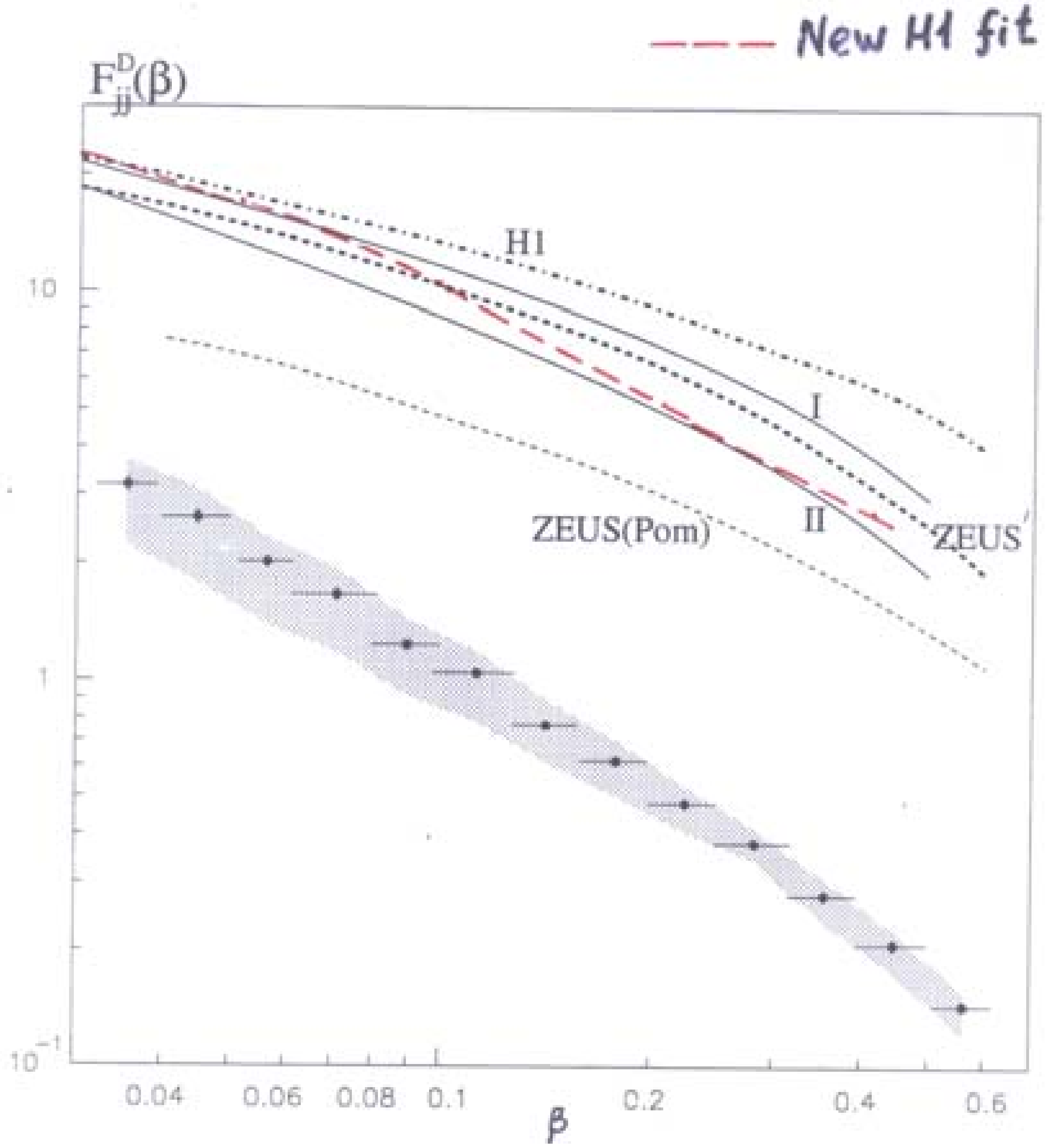
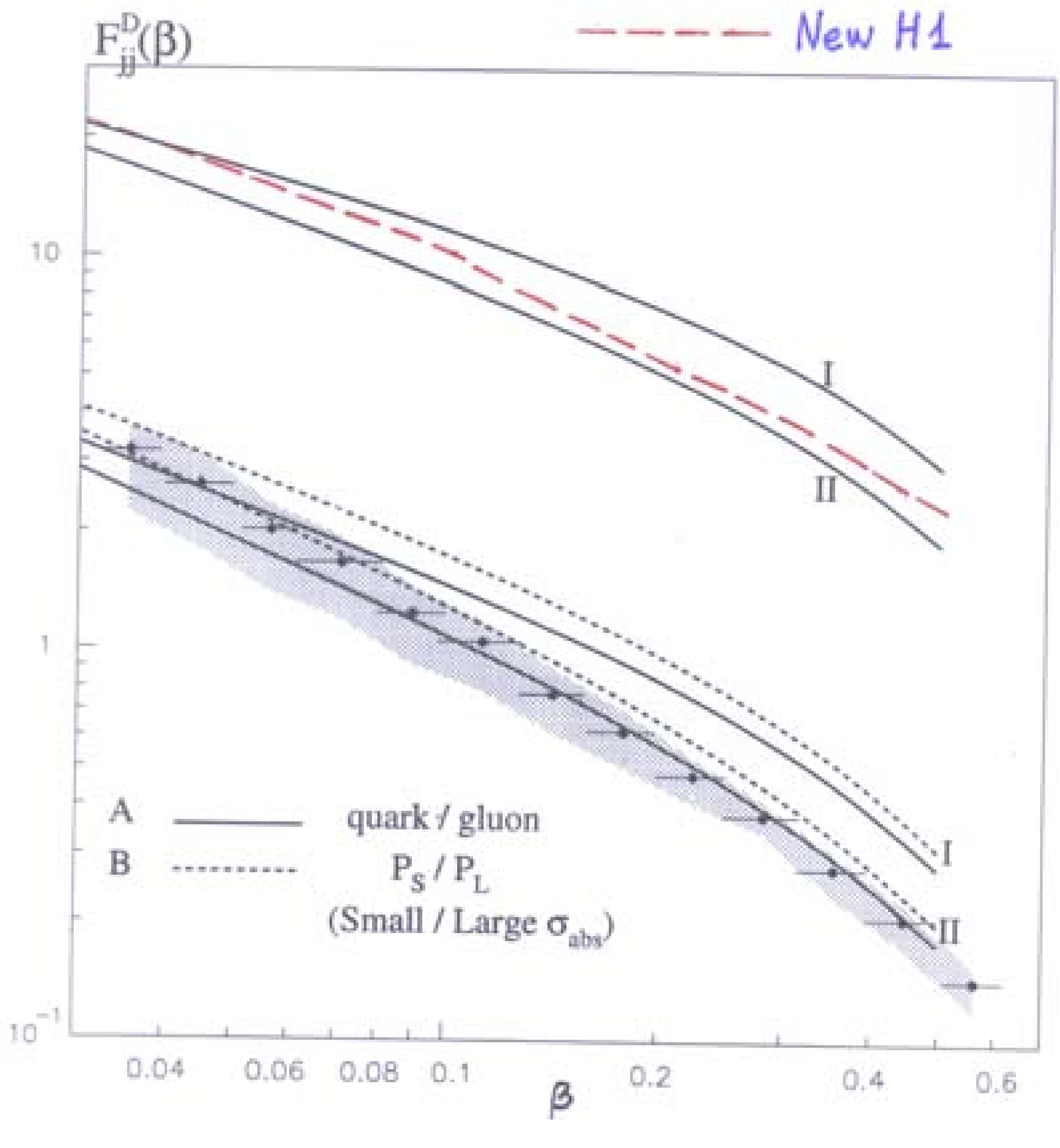
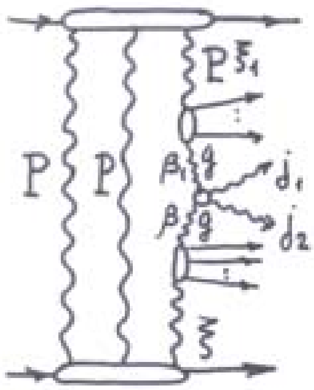


New H1 fit
$F_{jj}^{D}(\beta)$
H1
I
II
ZEUS
ZEUS(Pom)
10
1
10^{-1}
0.04
0.06
0.08
0.1
0.2
0.4
0.6
β

(15)


New H1
$F^D_{jj}(\beta)$
10
1
10^{-1}
I
II
I
II
A quark / gluon
B P_S / P_L
(Small / Large σ_{abs})
0.04
0.06
0.08
0.1
0.2
0.4
0.6
β

- Double Pomeron jet production



This process is observed at Tevatron

Test of factorization by CDF

$$R_1 = \frac{d\sigma^{jj}_{SD}}{d\sigma^{jj}_{in}} = \frac{F_{I\!P}(\xi)\cdot f^g_{I\!P}(\beta)}{x\cdot f^g_p(x)}\,|S_1|^2$$

$x = \xi\cdot\beta$

$$R_2 = \frac{d\sigma^{jj}_{DP}}{d\sigma^{jj}_{SD}} = \frac{F_{I\!P}(\xi_1)\cdot f^g_{I\!P}(\beta_1)}{x_1 f^g_p(x_1)}\,\frac{|S_2|^2}{|S_1|^2}$$

$x_1 = \xi_1\cdot\beta_1$

$$\frac{R_1}{R_2} = \frac{F_{I\!P}(\xi)\, f^g_{I\!P}(\beta)\, x_1 f^g_p(x_1)}{F_{I\!P}(\xi_1)\, f^g_{I\!P}(\beta_1)\, x f^g_p(x)}\cdot\frac{(|S_1|^2)^2}{|S_2|^2}$$

KKMR (PL 2003)

A. Bialas, R. Peschanski

if $\xi = \xi_1,\ \beta = \beta_1\ \ (x = x_1)$

$$R \equiv R_1/R_2 = (|S_1|^2)^2/|S_2|^2$$

For single Regge exchange $(|S_i^2| = 1)$

$$R = 1$$

With account of absorption

$$|S_1|^2 = 0.1\ ,\quad |S_2|^2 = 0.05$$

KMR

$$R = 0.2$$

$$R_{exp} = 0.19 \pm 0.07$$

Conclusions

- Diffractive processes give an important information on different aspects of QCD.
- Pomeron in QCD has a very rich dynamical structure.
- Investigation of hard diffractive processes allows one to study breaking of both Regge and "hard" factorizations and transition from soft to hard regimes in QCD.
- Small-x physics is related to QCD at high density. Shadowing effects are very important in this region.