Diffractive Processes at High Energies.

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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 \( \tau \sim \frac{E_0}{\mu^2} \)

Diffractive production

Example
Dissociation of a deutron

\[ \Delta t \approx \frac{2E_0}{M^2 - m^2} \]

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 can be diagonalized by an orthogonal matrix $Q$

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

$$\Psi_i = \sum_k Q_{ik} \Psi_k ; \quad \Psi_k \text{- eigenstates, which have only elastic scat.}$$

$\Psi_i \text{- initial state.}$

Quark configurations with fixed transverse separations.

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

Analog of $K_L \rightarrow K_S$ 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 $F_i \leq \frac{1}{2}$

$$\sigma^{(el)}(b,s) + \sigma^{(in)}_D(b,s) \leq \frac{1}{2} \sigma^{(tot)}(b,s) \quad \text{Pumplin's bound}$$
Diffractive production is related to the dispersion in the absorption of the diffractive eigenstates

\[ G_D^{\text{in}}(s, b) = 4\left(\langle F^2 \rangle - \langle F \rangle^2\right) \]

For strong absorption diffractive production is peripheral in \( b \).

In QCD eigen states - dipoles with definite transverse sizes \( \tau_\perp \).

For small \( \tau_\perp \) \( F \sim \tau_\perp^2 \). 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 \( T \sim E/m^2 \).

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

\[ \alpha_p(0) = 2 \alpha_s - 1 = 1 \]

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

In LO \( (\alpha_s \ln \frac{\Delta}{\Lambda})^n \)

\[ \Delta = \alpha_p(0) - 1 = \frac{12 \ln 2}{\pi} \alpha_s; \quad \Delta \approx 0.5 \]

Large NLO corrections

Sources of these corrections were discussed

\[ \Delta = 0.15 \div 0.2 \]

Iterative method of solution of BFKL equation (LO and NLO)

S. Brodsky et al.

Low, Nussinov

Reggeized gluons

V. Fadin, L. Lipatov
M. Ciafaloni et al.

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.  
  \[ \text{A.K, Yu. Simonov} \]

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

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

The lowest state \(0^+ \quad M = 1.58 \text{ GeV} \)

Slope of \(gg\) trajectories \(\alpha'_{gg} = \frac{\alpha}{\alpha'} q \approx 0.4 \text{ GeV}^2 \)

Mixing of \(gg\) and \(q\bar{q}\) trajectories in the small-\(t\) region
Important role of $q\bar{q}$-gluons mixing.

\[ \alpha(t) \]

\[ \frac{\tilde{u} + d}{s + \bar{s}} \]

Before mixing

\[ \alpha_{gg} \]

Repulsion of levels

\[ \alpha(t) \]

\[ \frac{f}{s} \]

After mixing and account of semi-hard 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 relevant one
New areas of applications

a) Small-\(x\) physics.

Studied experimentally in \(ep (\mu p, \nu p)\) interactions.

New data from ep collider - HERA allow to investigate the region of very small \(x\), where

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

\[
W^2 = s = (p + q)^2
\]

\[
\sigma^{(tot)}_{\gamma^* p}(W, Q^2) = \frac{4 \pi^3 \alpha_{e.m.}}{Q^2} F_2(x, Q^2)
\]

For large \(Q^2\),

\[
F_2(x, Q^2) = \sum_i e_i^2 x (q_i(x, Q^2) + \bar{q}(x, Q^2))
\]

Experiments at HERA demonstrated

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

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

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

- Diffractive dissociation of \(\gamma^*\) exists even at large \(Q^2\) (\(\Delta_{eff} \approx 0.2\))
Two types of $q \bar{q}$-configurations of virtual photons

a) Small size

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

b) Large size

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

$$\delta_s \sim \frac{1}{Q^2}; \delta_4 \sim \frac{1}{\Lambda^2} \left( \frac{1}{Q^2} \right)$$

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

H1 2002 $\sigma_r^D$ NLO QCD Fit

H1 preliminary

$Q^2$ [GeV$^2$]

6.5

15

90

H1 2002 $\sigma_r^D$ NLO QCD Fit

(exp. error)

(exp.+theor. error)

H1 2002 $\sigma_r^D$ LO QCD Fit
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."

\[ \begin{array}{c}
\gamma^* g \\
\downarrow \\
P, R \\
P \\
P \\
\end{array} \quad \text{These diagrams also contribute} \quad \begin{array}{c}
\gamma^* g \\
\downarrow \\
P, R \\
P \\
P \\
\end{array} \]

However standard QCD evolution takes place. \[ J. \text{Collins} \]

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

For hadronic interactions situation is more complicated

\[ \begin{array}{c}
P \\
\downarrow \\
q_x \quad x_1 \\
P \\
\downarrow \\
q_x \quad x_2 \\
P \\
\downarrow \\
PR \\
P \\
P \\
\end{array} \quad \text{These exchanges are absent in DIS} \quad \begin{array}{c}
P \\
\downarrow \\
q_x \quad x_1 \\
P \\
\downarrow \\
q_x \quad x_2 \\
P \\
\downarrow \\
PR \\
P \\
P \\
\end{array} \]

They violate "hard factorization"
• Hard diffraction in pp

In these processes the rescattering effects are important

They strongly reduce cross sections. 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

Interesting field for QCD physics at LHC. Soft color interaction model gives a reasonable value for suppression (but not for $\beta$-dependence)
Usually these effects are taken into account in eikonal approximation (elastic rescatterings only)

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

The suppression factor (survival probability)

However inelastic intermediate states can play an important role.

Eigen states with small absorption will lead to smaller suppression

Consider this effects in the 2-channel model \textit{KMR} model (for details see \textit{KMR}).

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

In partonic model they correspond to configurations of different sizes

- Large size - large \( \sigma \) - state 1
- Small(er) size - smaller \( \sigma \) - 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 $\beta$-dependence differs from predictions, based on HERA data (Note $\beta^{-1}$ behaviour of CDF data for small $\beta$) Fig. K. Goulianos

Kinematics:

\[
\frac{1}{s} = 0.06, \quad M^2 = \frac{1}{s} S = 2 \times 10^5 \text{GeV}^2
\]
\[
M_{jj}^2 = x_1 \beta M^2 - 10^3 \text{GeV}^2
\]
\[
x_1 \beta \approx 5 \times 10^{-3}
\]

$\beta \geq 0.25 \rightarrow x_1 \approx 0.02$ mostly gluons
$\beta \approx 0.025 \rightarrow x_1 \approx 0.2$ mostly valence $q$

Thus in this model suppression factor increases as $\beta$ decreases (for CDF kinemat.)

In this model it is possible to reproduce CDF results without free parameters. Fig.
$F_{jj}(\beta)$

- **A** quark / gluon
- **B** $P_S / P_L$
  (Small / Large $\sigma_{abs}$)

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**New H1**
Double Pomeron jet production

This process is observed at Tevatron

Test of factorization by CDF

\[ R_1 = \frac{d\sigma_{DP}}{d\sigma_{PP}} = \frac{F_P(\xi) \cdot f_\gamma^g(x)}{x \cdot f_\gamma^g(x)} |S_1|^2 \]

\[ x = \xi \cdot \beta \]

\[ R_2 = \frac{d\sigma_{DP}}{d\sigma_{SD}} = \frac{F_P(\xi_1) \cdot f_\gamma^g(x_1)}{x_1 f_\gamma^g(x_1)} |S_2|^2 \]

\[ x_1 = \xi_1 \cdot \beta_1 \]

\[ \frac{R_1}{R_2} = \frac{F_P(\xi) f_\gamma^g(\beta) x f_\gamma^g(x)}{F_P(\xi_1) f_\gamma^g(\beta_1) x_1 f_\gamma^g(x_1)} |S_1|^2 / |S_2|^2 \]

KKMR

(P. L. 2001)

A. Bialas,
R. Peschanski

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

\[ R = \frac{R_1}{R_2} = \frac{|S_1|^2}{|S_2|^2} \]

For single Regge exchange (\( |S_1|^2 = 1 \))

\[ R = 1 \]

With account of absorption

\[ |S_1|^2 = 0.1, \quad |S_2|^2 = 0.05 \]

\[ R = 0.2 \]

\[ R_{exp} = 0.19 \pm 0.07 \]
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.