SLAC–PUB–8623
September 2000

Jet asymmetry in high energy diffractive production *

C. Merino
Departamento de Física de Partículas, Universidade de Santiago de Compostela, Campus universitario s/n, 15706 Santiago de Compostela, Spain

S. J. Brodsky
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309,USA

J. Rathsman
TH Division, CERN,
CH-1211 Geneva 23, Switzerland

Abstract

We propose the asymmetry in the fractional energy of charm versus anticharm jets produced in high energy diffractive photoproduction as a sensitive test of the interference of the Odderon ($C = -$) and Pomeron ($C = +$) exchange amplitudes in QCD. If measured at HERA, this asymmetry could provide the first experimental evidence of the Odderon.

Contribution to the Proceedings of the
International Euroconference in Quantum Chromodynamics:
15 Years of the QCD—Montpellier Conference (QCD 00)
Montpellier, France
6–12 July 2000

*Research partially supported by the Department of Energy under contract DE–AC03–76SF00515, the European network Quantum Field Theory (1997-2000), and the Swedish Natural Science Research Council, contract F–PD 11264–301.

1 Introduction

The existence of the Odderon, an odd charge-conjugation, zero flavor-number exchange contribution to high energy hadron scattering amplitudes was already discussed many years ago [1]. In Regge theory, the Odderon contribution is dual to a sum over $C = P = -1$ gluonium states in the t-channel [2]. Also in quantum chromodynamics, the Odderon is a basic prediction following simply from the existence of the color-singlet exchange of three reggeized gluons in the $t-$channel [3]. For reactions which involve high momentum transfer, the deviation of the Regge intercept of the Odderon trajectory from $\alpha_{\mathcal{O}}(t=0) = 1$ can in principle be computed [4, 5, 6, 7] from perturbative QCD in analogy to the methods used to compute the properties of the hard BFKL Pomeron [8].

In the past, some tests were proposed to either verify or reject the odderon hypothesis (e.g., to check [9] out the Odderon hypothesis in the range $0.05 \lesssim -t \lesssim 1 Gev^2$, by taking into account a combination of differential cross-sections for $\pi^{\pm}p \to \rho^{\pm}p$ and $\pi^{-}p \to \rho^{0}n$, or of inclusive cross sections for $\pi^{\pm}p \to \rho X$), but no experimental evidence of the Odderon separate existence has ever been published. Now that the recent results from the electron-proton collider experiments at HERA [10] have brought renewed interest in the nature and behavior of both the Pomeron [11, 12] and the Odderon, we propose [13] an experimental test well suited to HERA kinematics which should be able to disentangle the contributions of both the Pomeron and the Odderon to diffractive production of charmed jets.

2 Odderon-Pomeron interference

Consider the amplitude for diffractive photoproduction of a charm quark anti-quark pair. The leading diagram is given by single Pomeron exchange (two reggeized gluons), and the next term in the Born expansion is given by the exchange of one Odderon (three reggeized gluons). Both diffractive photoproduction and leptoproduction can be considered, although in the following we will specialize to the case of photoproduction for which the rate observed at HERA is much larger. Our results can easily be generalized to non-zero Q^2.

We use the conventional kinematical variables, and we denote by $z_{c(\bar{c})}$ the energy sharing of the $c\bar{c}$ pair ($z_c + z_{\bar{c}} = 1$ in Born approximation at the parton level), and we take into account that the finite charm quark mass restricts the range of z. Moreover, ξ is effectively the longitudinal momentum fraction of the proton carried by the Pomeron/Odderon, and the proton mass is neglected.

Regge theory, which is applicable in the kinematic region $s_{\gamma p} \gg M_X^2 \gg M_Y^2$, together with crossing symmetry, predicts the phases and analytic form of high energy amplitudes (see, for example, Refs. [14] and [15]). The amplitude for the diffractive process $\gamma p \to c\bar{c}p'$ with Pomeron (P) or Odderon ($\mathcal{O}$) exchange can be written as

$$\mathcal{M}^{\mathcal{P}/\mathcal{O}}(t, s_{\gamma p}, M_X^2, z_c) \propto g_{pp'}^{\mathcal{P}/\mathcal{O}}(t) \left(\frac{s_{\gamma p}}{M_X^2}\right)^{\alpha_{\mathcal{P}/\mathcal{O}}(t)-1} \frac{\left(1 + S_{\mathcal{P}/\mathcal{O}} e^{-i\pi\alpha_{\mathcal{P}/\mathcal{O}}(t)}\right)}{\sin \pi\alpha_{\mathcal{P}/\mathcal{O}}(t)} g_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c) \tag{1}$$

where $S_{\mathcal{P}/\mathcal{O}}$ is the signature (even (odd) signature corresponds to an exchange which is (anti)symmetric under the interchange $s \leftrightarrow u$), which is $+(-)1$ for the Pomeron (Odderon). In the Regge approach the upper vertex $g_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c)$ can be treated as a local real coupling such that the phase is contained in the signature factor. In the same way the factor $g_{pp'}^{\mathcal{P}/\mathcal{O}}(t)$ represents the lower vertex.

In general the Pomeron and Odderon exchange amplitudes will interfere, as illustrated in Fig. 1. The contribution of the interference term to the total cross-section is zero, but it does contribute to charge-asymmetric rates. Thus we propose to study photoproduction of c-$\bar{c}$ pairs and measure the asymmetry in the energy fractions z_c and $z_{\bar{c}}$. More generally, one can use other charge-asymmetric kinematic configurations, as well as bottom or strange quarks.

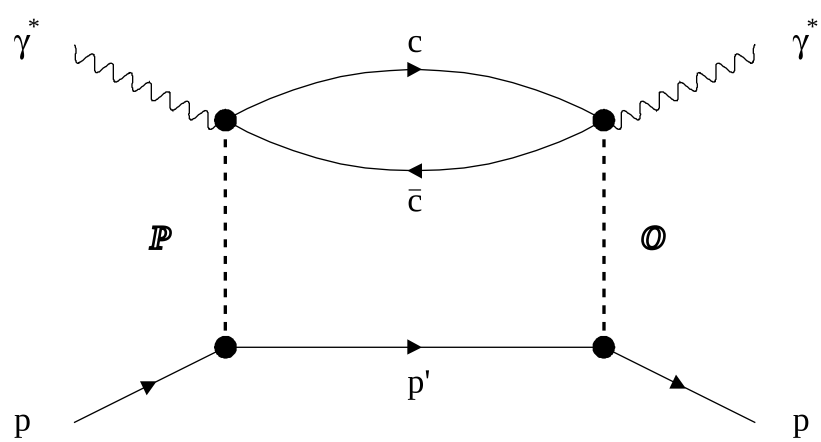

Figure 1: The interference between Pomeron (P) or Odderon ($\mathcal{O}$) exchange in the diffractive process $\gamma p \to c\bar{c}p'$.

Given the amplitude (1), the contribution to the cross-section from the interference term depicted in Fig. 1 is proportional to

$$\begin{aligned}\frac{d\sigma^{int}}{dt dM_X^2 dz_c} &\propto \mathcal{M}^{\mathcal{P}}(t, s_{\gamma p}, M_X^2, z_c)\left\{\mathcal{M}^{\mathcal{O}}(t, s_{\gamma p}, M_X^2, z_c)\right\}^{\dagger} + h.c. \\ &= g_{pp'}^{\mathcal{P}}(t) g_{pp'}^{\mathcal{O}}(t)\left(\frac{s_{\gamma p}}{M_X^2}\right)^{\alpha_{\mathcal{P}}(t)+\alpha_{\mathcal{O}}(t)-2} \frac{2\sin\left[\frac{\pi}{2}\left(\alpha_{\mathcal{O}}(t)-\alpha_{\mathcal{P}}(t)\right)\right]}{\sin\frac{\pi\alpha_{\mathcal{P}}(t)}{2}\cos\frac{\pi\alpha_{\mathcal{O}}(t)}{2}} \\ &\quad \times g_{\mathcal{P}}^{\gamma c\bar{c}}(t, M_X^2, z_c) g_{\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c)\ . \end{aligned} \tag{2}$$

In the same way we can obtain the contributions to the cross-section from the non-interfering terms for Pomeron and Odderon exchange.

The interference term can then be isolated by forming the charge asymmetry,

$$\mathcal{A}(t, M_X^2, z_c) = \frac{\dfrac{d\sigma}{dt dM_X^2 dz_c} - \dfrac{d\sigma}{dt dM_X^2 dz_{\bar{c}}}}{\dfrac{d\sigma}{dt dM_X^2 dz_c} + \dfrac{d\sigma}{dt dM_X^2 dz_{\bar{c}}}}\ . \tag{3}$$

Thus the predicted asymmetry turns out to be

$$\begin{aligned}\mathcal{A}(t, M_X^2, z_c) &= g_{pp'}^{\mathcal{P}} g_{pp'}^{\mathcal{O}}\left(\frac{s_{\gamma p}}{M_X^2}\right)^{\alpha_{\mathcal{P}}+\alpha_{\mathcal{O}}} \frac{2\sin\left[\frac{\pi}{2}\left(\alpha_{\mathcal{O}}-\alpha_{\mathcal{P}}\right)\right]}{\sin\frac{\pi\alpha_{\mathcal{P}}}{2}\cos\frac{\pi\alpha_{\mathcal{O}}}{2}} g_{\mathcal{P}}^{\gamma c\bar{c}} g_{\mathcal{O}}^{\gamma c\bar{c}} \\ &\times\left[\left(g_{pp'}^{\mathcal{P}}\left(\frac{s_{\gamma p}}{M_X^2}\right)^{\alpha_{\mathcal{P}}} g_{\mathcal{P}}^{\gamma c\bar{c}}/\sin\frac{\pi\alpha_{\mathcal{P}}}{2}\right)^2 + \left(g_{pp'}^{\mathcal{O}}\left(\frac{s_{\gamma p}}{M_X^2}\right)^{\alpha_{\mathcal{O}}} g_{\mathcal{O}}^{\gamma c\bar{c}}/\cos\frac{\pi\alpha_{\mathcal{O}}}{2}\right)^2\right]^{-1} . \end{aligned} \tag{4}$$

The main functional dependence in the different kinematic variables is expected to come from different factors in the asymmetry. Thus, the invariant mass M_X dependence is mainly given by the power behavior, $(s_{\gamma p}/M_X^2)^{\alpha_{\mathcal{O}}(t)-\alpha_{\mathcal{P}}(t)}$, and it will thus provide direct information about the difference between $\alpha_{\mathcal{O}}$ and $\alpha_{\mathcal{P}}$. Another interesting question which can be addressed from observations of the asymmetry is the difference in the t-dependence of $g_{pp'}^{\mathcal{O}}$ and $g_{pp'}^{\mathcal{P}}$.

Let's note that in a perturbative calculation at tree-level the interference would be zero in the high-energy limit $s \gg |t|$ since the two- and three-gluon exchanges are purely imaginary and real respectively. This should be compared with the analogous QED process, $\gamma Z \to \ell^+\ell^- Z$, where the interference of the one- and two-photon exchange amplitudes can explain [16] the observed lepton asymmetries, energy dependence, and nuclear target dependence of the experimental data [17] for large angles.

Also it is important to mention that secondary Regge trajectories with the same quantum numbers as the Odderon contribute, in principle, to the asymmetry at the current energies. In fact, the ω contribution seems to be present in the fits to some of the available experimental data. However, due to the intercept values of these secondary Regge trajectories, their contribution will become negligible at higher energies.

The ratio of the Odderon and Pomeron couplings to the proton, $g_{pp'}^{\mathcal{O}}/g_{pp'}^{\mathcal{P}}$, is limited by data on the difference of the elastic proton-proton and proton-antiproton cross-sections at large energy s. Following [18] we use the estimated limit on the difference between the ratios of the real and imaginary part of the proton-proton and proton-antiproton forward amplitudes,

$$|\Delta\rho(s)| = \left| \frac{\Re\{\mathcal{M}^{pp}(s,t=0)\}}{\Im\{\mathcal{M}^{pp}(s,t=0)\}} - \frac{\Re\{\mathcal{M}^{p\bar{p}}(s,t=0)\}}{\Im\{\mathcal{M}^{p\bar{p}}(s,t=0)\}} \right| \leq 0.05 \tag{5}$$

for $s \sim 10^4$ GeV^2 to get a limit on the ratio of the Odderon and Pomeron couplings to the proton. Using the amplitude corresponding to Eq. (1) for proton-proton and proton-antiproton scattering we get for $t = 0$,

$$\Delta\rho(s) = 2\frac{\Re\{\mathcal{M}^{\mathcal{O}}(s)\}}{\Im\{\mathcal{M}^{\mathcal{P}}(s)\} + \Im\{\mathcal{M}^{\mathcal{O}}(s)\}} \simeq -2\left(\frac{g_{pp'}^{\mathcal{O}}}{g_{pp'}^{\mathcal{P}}}\right)^2 \left(\frac{s}{s_0}\right)^{\alpha_{\mathcal{O}}-\alpha_{\mathcal{P}}} \tan\frac{\pi\alpha_{\mathcal{O}}}{2}, \tag{6}$$

where s_0 is a typical hadronic scale ~ 1 GeV^2 which replaces M_X^2 in Eq. (1). In the last step we also make the simplifying assumption that the contribution to the denominator from the Odderon is numerically much smaller than from the Pomeron and therefore can be neglected. The maximally allowed Odderon coupling at t=0 is then given by,

$$\left|g_{pp'}^{\mathcal{O}}\right|_{\max} = \left|g_{pp'}^{\mathcal{P}}\right| \sqrt{\frac{\Delta\rho_{\max}(s)}{2}\cot\frac{\pi\alpha_{\mathcal{O}}}{2}\left(\frac{s}{s_0}\right)^{\alpha_{\mathcal{P}}-\alpha_{\mathcal{O}}}}. \tag{7}$$

Strictly speaking this limit applies for the soft Odderon and Pomeron and are therefore not directly applicable to charm photoproduction which is a harder process, *i.e.* with larger energy dependence. Even so we will use this limit to get an estimate of the maximal Odderon coupling to the proton.

The amplitudes for the asymmetry can be calculated using the Donnachie-Landshoff [19] model for the Pomeron and a similar ansatz for the Odderon [18]. The coupling of the Pomeron/Odderon to a quark is then given by $\kappa_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}\gamma^{\rho}$, *i.e.* assuming a helicity preserving local interaction. In the same way the Pomeron/Odderon couples to the proton with $3\kappa_{pp'}^{\mathcal{P}/\mathcal{O}}F_1(t)\gamma^{\sigma}$ if we only include the Dirac form-factor $F_1(t)$. The amplitudes for the asymmetry can then be obtained by replacing $g_{pp'}^{\mathcal{P}/\mathcal{O}}(t)g_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c)$

in Eq. (1) by,

$$
\begin{aligned}
g_{pp'}^{\mathcal{P}/\mathcal{O}}(t) g_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}}(t, M_X^2, z_c) &= 3\kappa_{pp'}^{\mathcal{P}/\mathcal{O}} F_1(t) \bar{u}(p-\ell)\gamma^\sigma u(p) \left(g^{\rho\sigma} - \frac{\ell^\rho q^\sigma + \ell^\sigma q^\rho}{\ell q} \right) \kappa_{\mathcal{P}/\mathcal{O}}^{\gamma c\bar{c}} \epsilon^\mu(q) \\
&\times \ \bar{u}(p_c) \left\{ \gamma^\mu \frac{\not\ell - \not p_{\bar{c}} + m_c}{(1-z)M_X^2} \gamma^\rho - S_{\mathcal{P}/\mathcal{O}} \gamma^\rho \frac{\not p_c - \not\ell + m_c}{z M_X^2} \gamma^\mu \right\} v(p_{\bar{c}})
\end{aligned}
$$

where $\ell = \xi p$ is the Pomeron/Odderon momentum and $g^{\rho\sigma} - \frac{\ell^\rho q^\sigma + \ell^\sigma q^\rho}{\ell q}$ stems from the Pomeron/Odderon "propagator". Note the signature which is inserted for the crossed diagram to model the charge conjugation property of the Pomeron. The Pomeron amplitude written this way is not gauge invariant and therefore we use radiation gauge also for the photon, *i.e.* the polarization sum is obtained using $g^{\mu\nu} - \frac{q^\mu p^\nu + q^\nu p^\mu}{pq}$. The leading terms in a t/M_X^2 expansion of the squared amplitudes for the Pomeron and Odderon exchange as well as the interference are then given by,

$$
\begin{aligned}
\left(\frac{g_{pp'}^{\mathcal{P}} g_{\mathcal{P}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}}} \right)^2 &\propto \frac{z_c^2 + z_{\bar{c}}^2}{z_c z_{\bar{c}}} \frac{(1-\xi)}{\xi^2} \\
\left(\frac{g_{pp'}^{\mathcal{O}} g_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}} \right)^2 &\propto \frac{z_c^2 + z_{\bar{c}}^2}{z_c z_{\bar{c}}} \frac{(1-\xi)}{\xi^2} \\
\frac{g_{pp'}^{\mathcal{P}} g_{pp'}^{\mathcal{O}} g_{\mathcal{P}}^{\gamma c\bar{c}} g_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}} &\propto \frac{z_c - z_{\bar{c}}}{z_c z_{\bar{c}}} \frac{(1-\xi)}{\xi^2},
\end{aligned}
\tag{8}
$$

with corrections that are of order t/M_X^2 and therefore can be safely neglected. The ratio between the interference term and the Pomeron exchange is thus given by

$$
\frac{g_{pp'}^{\mathcal{O}} g_{\mathcal{O}}^{\gamma c\bar{c}}}{g_{pp'}^{\mathcal{P}} g_{\mathcal{P}}^{\gamma c\bar{c}}} = \frac{\kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}}} \frac{z_c - z_{\bar{c}}}{z_c^2 + z_{\bar{c}}^2} = \frac{\kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}}} \frac{2z_c - 1}{z_c^2 + (1-z_c)^2} \ . \tag{9}
$$

Inserting this into the expression of the asymmetry and making the simplifying assumption that the Odderon contribution can be dropped in the denominator gives

$$
\mathcal{A}(t, M_X^2, z_c) \simeq 2 \frac{\kappa_{pp'}^{\mathcal{O}} \kappa_{\mathcal{O}}^{\gamma c\bar{c}}}{\kappa_{pp'}^{\mathcal{P}} \kappa_{\mathcal{P}}^{\gamma c\bar{c}}} \sin\left[\frac{\pi(\alpha_{\mathcal{O}} - \alpha_{\mathcal{P}})}{2} \right] \left(\frac{s_{\gamma p}}{M_X^2} \right)^{\alpha_{\mathcal{O}} - \alpha_{\mathcal{P}}} \frac{\sin \frac{\pi \alpha_{\mathcal{P}}}{2}}{\cos \frac{\pi \alpha_{\mathcal{O}}}{2}} \frac{2z_c - 1}{z_c^2 + (1-z_c)^2} \ . \tag{10}
$$

To obtain a numerical estimate of the asymmetry, we shall assume that $t \simeq 0$ and use $\alpha_{\mathcal{P}}^{hard} = 1.2$ and $\alpha_{\mathcal{O}} = 0.95$ [6] for the Pomeron and Odderon intercepts, even though a recent paper by J. Bartels, L.N. Lipatov, and G.P. Vacca [20] has presented an Odderon solution in perturbative QCD with precise symmetry properties and intercept one. In addition we will also assume $\kappa_{\mathcal{O}}^{\gamma c\bar{c}} / \kappa_{\mathcal{P}}^{\gamma c\bar{c}} \sim \sqrt{C_F \alpha_s(m_c^2)} \simeq 0.6$, motivated by the

Davies, Bethe, and Maximon calculation [21], and use the maximal Odderon-proton coupling, $\kappa^{\mathcal{O}}_{pp'}/\kappa^{\mathcal{P}}_{pp'} = g^{\mathcal{O}}_{pp'}/g^{\mathcal{P}}_{pp'} = 0.1$, which follows from Eq. (7) for $\alpha^{soft}_{\mathcal{P}} = 1.08$, $s = 10^4$ GeV^2, $s_0 = 1$ GeV^2 and $\Delta\rho_{\max}(s) = 0.05$. Inserting the numerical values discussed above then gives

$$\mathcal{A}(t \simeq 0, M_X^2, z_c) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2z_c - 1}{z_c^2 + (1 - z_c)^2}\,, \tag{11}$$

which for a typical value of $\frac{s_{\gamma p}}{M_X^2} = 100$ becomes a ~ 15 % asymmetry for large z_c as illustrated in Fig. 2. Let's note that the asymmetry can also be integrated over z_c.

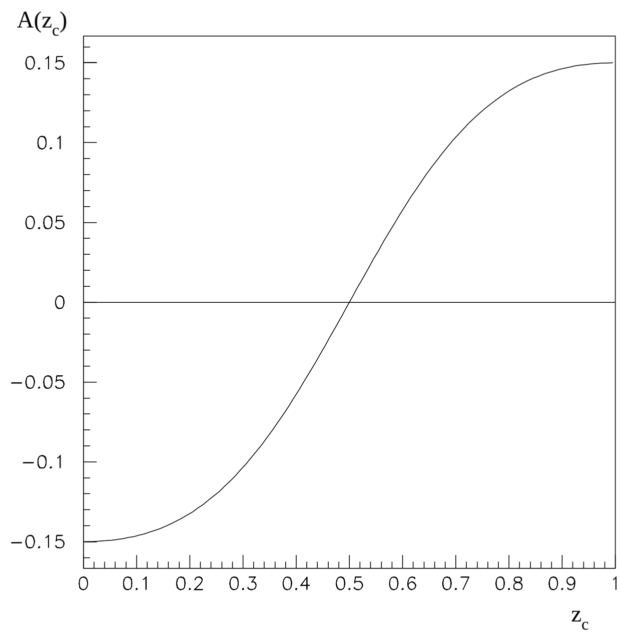

Figure 2: The asymmetry in fractional energy z_c of charm versus anticharm jets predicted by our model using the Donnachie-Landshoff Pomeron for $\alpha_{\mathcal{P}} = 1.2$, $\alpha_{\mathcal{O}} = 0.95$ and $s_{\gamma p}/M_X^2 = 100$.

It should be emphasized that the magnitude of this estimate is quite uncertain, since we are using an Odderon coupling to the proton which is maximal for the soft Odderon in relation to the soft Pomeron, and the hard Odderon and Pomeron could have a different ratio for the coupling to the proton.

3 Conclusions

By observing the charge asymmetry of the quark/antiquark energy fraction (z_c) in diffractive $c\bar{c}$ pair photoproduction or electroproduction, the interference between the Pomeron and the Odderon exchanges can be isolated and the ratio to the sum of the Pomeron and the Odderon exchanges can be measured. Using a model with helicity conserving coupling for the Pomeron/Odderon to quarks, the asymmetry is predicted to be proportional to $(2z_c - 1)/(z_c^2 + (1 - z_c)^2)$. The magnitude of the asymmetry is estimated to be of order 15%. However this estimate includes several unknowns and is thus quite uncertain. This test could be performed by current experiments at HERA, and possibly by COMPASS and STAR, providing the first experimental evidence for the existence of the Odderon.

4 Acknowledgments

It's a pleasure to thank M.A. Braun for his useful comments.

References

[1] V.N. Gribov, V.D. Mur, I.Yu. Kobzarev, L.B. Okun, and V.S. Popov, Phys. Lett. **B32** (1970) 129.

[2] L. Lukaszuk and B. Nicolescu, Nuovo Cimento Letters **8** (1973) 405.

[3] J. Kwiecinski and M. Praszalowicz, Phys. Lett. **94B** (1980) 413; J. Bartels, Nucl. Phys. **B175** (1980) 365.

[4] P. Gauron, L.N. Lipatov, and B. Nicolescu, Z. Phys. **C63** (1994) 253.

[5] N. Armesto and M.A. Braun, Z. Phys. **C75** (1997) 709.

[6] R.A. Janik and J. Wosieck, Phys. Rev. Lett. **82** (1999) 1092.

[7] M.A. Braun, P. Gauron, and B. Nicolescu, hep-ph/9809567.

[8] E.A. Kuraev, L.N. Lipatov, and V.S. Fadin, Sov. Phys. JETP **44** (1976) 443; Sov. Phys. JETP **45** (1977) 199.
Y.Y. Balitski and L.N. Lipatov, Sov. J. Nucl. Phys. **28** (1978) 822.

[9] A.P. Contogouris, L. Jenkovsky, E Martynov, and B. Struminsky, Phys. Lett. **B298** (1993) 432.

[10] H1 Collaboration, T. Ahmed *et al.*, Nucl. Phys. **B429**, 477 (1994); Phys. Lett. **B348** (1995) 681; C. Adloff *et al.*, Z. Phys. **C74** (1997) 221.
ZEUS Collaboration, M. Derrick *et al.*, Phys. Lett. **B315** (1993) 481; J. Breitweg *et al.*, Z. Phys. **C75** (1997) 421; Eur. Phys. J. **C2** (1998) 237.

[11] S.J. Brodsky, L. Frankfurt, J.F. Gunion, A.H. Mueller, and M. Strikman, Phys. Rev. **D50** (1994) 3134.

[12] A. Capella, A.B. Kaidalov, C. Merino, and J. Tran Thanh Van, Phys. Lett. **B337** (1994) 358;
A. Capella, A.B. Kaidalov, C. Merino, D. Petermann, and J. Tran Thanh Van, Phys. Rev. **D53** (1996) 2309.

[13] S.J. Brodsky, J. Rathsman and C. Merino, Phys. Lett. **B461** (1999) 114.

[14] P.D.B. Collins, An introduction to Regge theory and high energy physics, Cambridge University Press (1977).

[15] A.B. Kaidalov, Phys. Rep. **50** (1979) 157.

[16] S.J. Brodsky and J. Gillespie, Phys. Rev. **173** (1968) 1011.

[17] S.C.C. Ting, Proceedings of the International School of Physics Ettore Majorana, Erice (Trapani), Sicily, July 1967.
J.G. Ashbury *et al.*, Phys. Lett. **B25** (1967) 565.

[18] W. Kilian and O. Nachtmann, Eur. Phys. J. **C5** (1998) 317.

[19] A. Donnachie and P.V. Landshoff, Nucl. Phys. **B244** (1984) 322; ibid. **B267** (1986) 690; Phys. Lett. **B185** (1987) 403.

[20] J. Bartels, L.N. Lipatov and G.P. Vacca, hep-ph/9912423.

[21] H.A. Bethe and L.C. Maximon, Phys. Rev. **93** (1954) 768; H. Davies, H.A. Bethe, and L.C. Maximon, Phys. Rev. **93** (1954) 788.