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Diffractive hadroproduction of dijets and *W*'s at the Fermilab Tevatron collider and the Pomeron structure function

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Results from a phenomenological analysis of dijet and W hard diffractive hadroproduction at Fermilab Tevatron energies are reported. The theoretical framework employed here is a modified version of the Ingelman-Schlein approach which includes Dokhshitzer-Gribov-Lipatov-Altarelli-Parisi–evolved structure functions. Different from what has been achieved by the DESY ep HERA reactions, a reasonable overall description of such diffractive hadron processes is obtained only when a complex, quark-rich Pomeron structure function is employed in the calculation.

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I. INTRODUCTION

Regge phenomenology is well known for providing a suitable and economical theoretical framework for the description of *soft* hadron diffractive processes at high energies. Single Pomeron exchange plus a few secondary Reggeon contributions are enough to describe a variety of hadronic reactions (see, for instance, [1] and references therein).

The situation becomes much more intricate when one considers *hard* diffractive processes by which, according to the Ingelman-Schlein (IS) picture [2], the Pomeron structure itself is probed. Difficulties arise when one tries to obtain a unified description for diffractive processes starting with both electron- or positron-proton (ep) and antiproton-proton ($\bar{p}p$) collisions, respectively, studied at the DESY ep collider HERA and Fermilab Tevatron colliders. Although several theoretical approaches have successfuly been employed to describe different aspects of hard diffraction revealed by the ep HERA reactions [3], some of them based on Regge theory, diffractive hadroproduction continues to be one of the most challenging topics in hadron dynamics.

In effect, most of the theoretical approaches which are able to describe the HERA data are not readily translatable to diffractive hadron physics. Models based on the Regge theory, in particular, are presumably affected by a lack of validity for QCD factorization in the hadronic diffraction domain [4]. In spite of these difficulties, such models establish the phenomenological picture most of the event generators currently employed in data analysis of hard diffractive hadroproduction are based upon. Probably this is so because these models have been able to provide an effective description for such processes. In fact, that is one of the underlying assumptions of the present paper.

This Brief Report is a sequel to a previous work [5] in which we have tried to perform a global analysis by a modified version of the IS model, including processes initiated by both ep and $\bar{p}p$ collisions. By that time, the available data were not so stringent such that one could speculate about an unique model to be sufficient. Since then, more and more precise data of diffractive deep inelastic scattering (DIS) have imposed severe restrictions on the Pomeron structure function making more evident the impossibility to readily transfer the partonic densities so obtained to hadronic process calculations.

Our group's analysis of the diffractive DIS data have shown that, at low values of the QCD evolution scale, the Pomeron is predominantly composed by gluons with a hard distribution, in agreement with other studies (see [6] and references therein). This result is corroborated by the calculations of diffractive cross sections for photoproduction [7] and electroproduction [8] of dijets, which yield good agreement with the data once a hard gluonic Pomeron is assumed.

The advent of new data produced by the D0 Collaboration [9] have motivated us to perform a new analysis, this time restricted to the Tevatron data.

Thus, we report here results of a study on diffractive hadroproduction of dijets and W's by using the IS model, with Dokhshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution [10] included, but disconnected from the HERA data analysis just mentioned [6]. In fact, in spite of our efforts it was impossible to reconcile both analyses. We take this failure to produce a unified description as an additional indication of the theoretical problems alluded before.

The interesting point, however, is that if one takes the Pomeron as predominantly composed by quarks at a low QCD evolution scale, a reasonable overall description of diffractive hadroproduction data is achieved. This is what is shown below.

II. CROSS SECTIONS

Our starting point is the generic cross section for a process in which partons of two hadrons, A and B, interact to produce jets (or Ws), $A+B\rightarrow Jets\ \ (W)+X$, that is

$$d\sigma=\sum_{a,b,c,d} f_{a/A}(x_a,\mu^2)dx_a f_{b/B}(x_b,\mu^2)dx_b\frac{d\hat{\sigma}_{ab\rightarrow cd(W)}}{d\hat{t}}d\hat{t}. \tag{1}$$

From this very basic expression we derive all of the others necessary to describe the specific processes we are interested in.

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A. Diffractive dijet production from a single Pomeron exchange

In the case of dijet production, the cross section can be put in terms of the dijet rapidities (η,η') and transversal energy E_T:

$$\left(\frac{d\sigma}{d\eta}\right)_{jj}=\sum_{\text{partons}}\int_{E_{T\text{min}}}^{E_{T\text{max}}}dE_T^2\int_{\eta'_{\text{min}}}^{\eta'_{\text{max}}}d\eta' x_a \times f_{a/A}(x_a,\mu^2)x_b f_{b/B}(x_b,\mu^2)\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)_{jj}, \tag{2}$$

where

$$x_a=\frac{E_T}{\sqrt{s}}(e^{-\eta}+e^{-\eta'}),\quad x_b=\frac{E_T}{\sqrt{s}}(e^{\eta}+e^{\eta'}), \tag{3}$$

with

$$\ln\frac{E_T}{\sqrt{s}-E_Te^{-\eta}}\leqslant\eta'\leqslant\ln\frac{\sqrt{s}-E_Te^{-\eta}}{E_T} \tag{4}$$

and

$$E_{T\ \text{max}}=\frac{\sqrt{s}}{e^{-\eta}+e^{\eta}}, \tag{5}$$

being that $E_{T\ \text{min}}$ and the η range are determined by the experimental cuts.

Equations (2)–(5) express the usual leading-order QCD procedure to obtain the *non-diffractive* dijet cross section (next-to-leading-order contributions are not essential for the present purposes; see Ref. [5]). In order to obtain the corresponding expression for *diffractive* processes, we assume that one of the hadrons, say hadron A, emits a Pomeron whose partons interact with partons of the hadron B. Thus the parton distribution $x_af_{a/A}(x_a,\mu^2)$ in Eq. (2) is replaced by the convolution between a putative distribution of partons in the Pomeron, $\beta f_{a/\mathrm{P}}(\beta,\mu^2)$, and the "emission rate" of Pomerons by A, $f_{\mathrm{P}}(x_{\mathrm{P}},t)$. This last quantity, $f_{\mathrm{P}}(x_{\mathrm{P}},t)$, is the so-called Pomeron flux factor whose explicit formulation in terms of Regge theory is given ahead. The whole procedure implies that

$$x_af_{a/A}(x_a,\mu^2)=\int dx_{\mathrm{P}}\int d\beta\int dt f_{\mathrm{P}}(x_{\mathrm{P}},t) \times\beta f_{a/\mathrm{P}}(\beta,\mu^2)\,\delta\!\left(\beta-\frac{x_a}{x_{\mathrm{P}}}\right), \tag{6}$$

and, defining $g(x_{\mathrm{P}})\equiv\int_{-\infty}^{0}dt f_{\mathrm{P}}(x_{\mathrm{P}},t)$, one obtains

$$x_af_{a/A}(x_a,\mu^2)=\int dx_{\mathrm{P}}g(x_{\mathrm{P}})\frac{x_a}{x_{\mathrm{P}}}f_{a/\mathrm{P}}\!\left(\frac{x_a}{x_{\mathrm{P}}},\mu^2\right). \tag{7}$$

By inserting the above structure function into Eq. (2) one obtains the cross section for diffractive hadroproduction of dijets via a single Pomeron exchange as

$$\left(\frac{d\sigma_{SPE}}{d\eta}\right)_{jj}=\sum_{a,b,c,d}\int_{E_{T_{min}}}^{E_{T_{max}}}dE_T^2\int_{\eta'_{min}}^{\eta'_{max}}d\eta'\int_{x_{\mathrm{P}_{min}}}^{x_{\mathrm{P}_{max}}} \times dx_{\mathrm{P}}g(x_{\mathrm{P}})\beta_af_{a/\mathrm{P}}(\beta_a,\mu^2)x_bf_{b/\bar{p}}(x_b,\mu^2) \times\left(\frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}}\right)_{jj}, \tag{8}$$

where $\beta_a=x_a/x_{\mathrm{P}}$ with x_a and x_b given by Eq. (3) and $x_{\mathrm{P}_{min}}$, and $x_{\mathrm{P}_{max}}$ established by the experimental cuts.

B. Diffractive hadroproduction of $W^{\pm}$

$W^{\pm}$ diffractive production is here considered by the reaction $p+\bar{p}\to p+W(\to e\nu)+X$. It is assumed that a Pomeron emitted by a proton in the positive z direction interacts with a $\bar{p}$ producing $W^{\pm}$ that subsequently decays into $e^{\pm}\nu$. The detection of this reaction is triggered by the lepton (e^+ or e^-) that appears boosted towards negative η (rapidity) in coincidence with a rapidity gap in the right hemisphere.

By using the same concept of the convoluted structure function, the diffractive cross section for the inclusive lepton production for this process becomes [11]

$$\left(\frac{d\sigma_{SD}}{d\eta_e}\right)_{lepton}=\sum_{a,b}\int\frac{dx_{\mathrm{P}}}{x_{\mathrm{P}}}g(x_{\mathrm{P}})\int dE_Tf_{a/\mathrm{P}}(x_a,\mu^2) \times f_{b/\bar{p}}(x_b,\mu^2)\left[\frac{V_{ab}^2G_F^2}{6s\Gamma_W}\right]\frac{\hat{t}^2}{\sqrt{A^2-1}}, \tag{9}$$

where

$$x_a=\frac{M_We^{\eta_e}}{(\sqrt{s}x_{\mathrm{P}})}[A\pm\sqrt{(A^2-1)}], \tag{10}$$

$$x_b=\frac{M_We^{-\eta_e}}{\sqrt{s}}[A\mp\sqrt{(A^2-1)}], \tag{11}$$

and

$$\hat{t}=-E_TM_W[A+\sqrt{(A^2-1)}] \tag{12}$$

with $A=M_W/2E_T$. The upper signs in Eqs. (10) and (11) refer to W^+ production (that is, e^+ detection). The corresponding cross section for W^- is obtained by using the lower signs and $\hat{t}\leftrightarrow\hat{u}$ (see the Appendix in [5]).

C. The Pomeron flux factor

An important element of this approach is the Pomeron flux factor, introduced in Eq. (6). It has some peculiar aspects that deserve to be pointed out.

First of all, the expression for this term was originally proposed to be taken from the invariant cross section of (soft) diffractive dissociation processes as it is given by the triple Pomeron model [2]. The rationale for that can be put in terms of an analogy with the photon flux factor, this one derived from QED. The basic idea is that, similarly to what happens to the electron (or positron) in photoproduction, the proton in a diffractive interaction is scattered at very small angles and practically does not take part in the effective reaction. Analogously to the emission of photons and to the idea of equivalent photon flux defined in QED, one can think of hadron diffraction in terms of Pomeron emission and the "Pomeron flux factor." This picture (and the IS model as a realization of it) has been successfully employed to the hadron vertex in some HERA diffractive processes, such as leading baryon production and diffractive DIS [6], photoproduction [7], and electroproduction [8].

However, such an approach is affected by a problem which is mostly concerned with its energy dependence. As it is theoretically well known from very long, the triple Pomeron integrated cross section violates unitarity [12], although its $x_{\mathbb{P}}$ and t dependences seem to be in good agreement with the available data [13]. In order to overcome this unitarity violation issue, we follow here the "renormalization" procedure originally proposed in [14] and further discussed in [13], that is

$$f_{\mathbb{P}}(x_{\mathbb{P}},t)=\frac{f(x_{\mathbb{P}},t)}{\int_{x_{\mathbb{P}_{min}}}^{x_{\mathbb{P}_{max}}}\int_{t=0}^{\infty} f(x_{\mathbb{P}},t)\,dx_{\mathbb{P}}dt}. \qquad (13)$$

For the "unnormalized" flux factor $f(x_{\mathbb{P}},t)$, we take the Donnachie-Landshoff parametrization [15],

$$f(x_{\mathbb{P}},t)=\frac{9\beta_0^2}{4\pi^2}F_1^2(t)x_{\mathbb{P}}^{1-2\alpha_{\mathbb{P}}(t)} \qquad (14)$$

where $F_1(t)$ is the Dirac form factor,

$$F_1(t)=\frac{(4m^2-2.79t)}{(4m^2-t)}\frac{1}{\left(1-\frac{t}{0.71}\right)^2}. \qquad (15)$$

Notice that, by choosing the renormalization procedure, β_0 does need to be specified since it is crossed out as well as the other constant factors appearing in Eq. (14). Yet about this equation, our choice for the Pomeron trajectory has been $\alpha_{\mathbb{P}}(t)=1.2+0.25t$, which is compatible with both Tevatron and HERA data.

TABLE I. Data versus model predictions. Diffractive W's and dijets were measured at $\sqrt{s}=1800$ GeV by the CDF Collaboration [18,19]. In both cases, $x_{\mathbb{P}}<0.1$ and $E_{T_{min}}=20$ GeV. For the case of W production, $E_{T_{min}}$ refers to the detected lepton while for dijet production it refers to the detected jet.

Yield	Rapidity	Data (%)	Model
W	$-1.1<\eta_e<1.1$	1.15±0.55	0.35
jj	$-3.5<\eta_j<-1.8$	0.75±0.10	0.72

TABLE II. Data versus model results corresponding to the D0 experiment. The experimental data are from Ref. [9] and the model calculations were performed with $E_{T_{min}}=15$ GeV for $\sqrt{s}=1800$ GeV and $E_{T_{min}}=12$ GeV for $\sqrt{s}=630$ GeV. In both cases, $x_{\mathbb{P}}<0.1$.

$\sqrt{s}$ (GeV)	Rapidity	Data (%)	Model
1800	$\|\eta\|>1.6$	0.65±0.04	0.90
1800	$\|\eta\|<1.0$	0.22±0.05	0.37
630	$\|\eta\|>1.6$	1.19±0.08	1.80
630	$\|\eta\|<1.0$	0.90±0.06	0.98

D. The Pomeron structure function

The Pomeron structure function has been established as a three-flavor quark singlet at the initial scale, chosen to be $Q_0^2=2\ \mathrm{GeV}^2$, with the gluon component being generated by DGLAP evolution. Thus, no initial gluon distribution has been assumed. The parametrization used for the initial quark distribuition was

$$\beta\Sigma(\beta,Q_0^2)=[A_1\exp(-A_2\beta^2)+B_1(1-\beta)^{B_2}]\beta^{0.001}+C_1\exp[-C_2(1-\beta)^2](1-\beta)^{0.001}, \qquad (16)$$

which includes different amounts of soft, hard, and superhard profiles according to the chosen parameters. The results presented below were obtained with the following parameters: $A_1=4.75$ and $A_2=228.4$ for the soft part, $B_1=1.14$ and $B_2=0.55$ for the hard one, and finally $C_1=2.87$ and $C_2=100$ for the superhard term.

Wherever necessary, DGLAP evolution of the Pomeron parton densities has been processed by using the program QCDNUM [16]. For the proton (or antiproton, when was the case), the parton densities were taken from the parametrizations given in Ref. [17].

III. RESULTS AND DISCUSSION

In the following, we present our predictions for hard diffractive production of W's and dijets based on the previous discussion. These predictions are compared with experimental data from Refs. [9,18,19] in Tables I–III.

In Table I the difficulty in obtaining a perfect and simultaneous description of both W and dijet production is evident. The situation is much better, however, when one considers only jets. Besides the agreement exhibited in Table I for the CDF experiment, consistency is also found with the D0 results (Tables II and III).

TABLE III. Experimental ratios versus model results corresponding to the D0 experiment. Data are from Ref. [9].

Ratios	Data (%)	Model
630/1800 $\|\eta\|>1.6$	1.8±0.2	2.0
630/1800 $\|\eta\|<1.0$	4.1±0.9	2.7
1800 GeV $\|\eta\|>1.6/\|\eta\|<1.0$	3.0±0.7	2.4
630 GeV $\|\eta\|>1.6/\|\eta\|<1.0$	1.3±0.1	1.8

In Table II both forward and central dijet production at two energies are considered. For all cases, one sees that the model predictions are close to the data, but slightly above. This sort of discrepancy is expected since effects of experimental acceptance were not taken into account in these predicitions. Such effects would certainly reduce these theoretically predicted rates, but it is difficult to estimate to what extent.

In Table III is where the agreement between theory and data is generally better. In this case, two kind of ratios are calculated: ratios between rates at different energies but at the same rapidity range and the reverse, ratios between rates taken at the same energy but different rapidity ranges. The better agreement here could be attributed to the fact that these ratios would cancel the normalization and acceptance effects to some extent.

In summary, we have shown that it is possible to obtain a reasonable overall description of hard diffractive hadroproduction by a model based on the Ingelman-Schlein approach once a quark-rich Pomeron structure function is assumed and its DGLAP evolution performed. This result, i.e., the predominance of quarks in the Pomeron ‘‘valence’’ distribution, already obtained in [5], is in conflict with the parametrizations independently established from HERA data [6–8]. This discrepancy may be seen as an additional indication of factorization breaking [4] in hadronic diffraction. However, if that is the real reason, it is quite intriguing that the consistence between the data and theory shown here is possible at all.

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