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HARD DIFFRACTIVE PROCESSES: QCD MODELS*

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ABSTRACT

We discuss high energy hadron collisions that contain a hard scattering, in the sense that a W , a Z , very heavy quarks, or high P_T jets are produced, yet are diffractive, in the sense that one of the incident hadrons is scattered with only a small energy loss. In our approach, the cross section for such diffractive hard scattering is a part of the normal hard scattering inclusive cross section, as calculated using perturbative quantum chromodynamics. We use Regge phenomenology in combination with perturbative QCD to estimate that a substantial fraction (perhaps 30%) of all hard scattering events are diffractive. Measurement of diffractive hard scattering cross sections would illuminate the short distance gluon and quark content of the Pomeron.

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We discuss high energy hadron collisions that contain a hard scattering, in the sense that a W , a Z , very heavy quarks, or high P_T jets are produced, yet are diffractive, in the sense that one of the incident hadrons is scattered with only a small energy loss. In our approach, the cross section for such diffractive hard scattering is a part of the normal hard scattering inclusive cross section, as calculated using perturbative quantum chromodynamics. We use Regge phenomenology in combination with perturbative QCD to estimate that a substantial fraction (perhaps 30%) of all hard scattering events are diffractive. Measurement of diffractive hard scattering cross sections would illuminate the short distance gluon and quark content of the Pomeron.

1. INTRODUCTION

In this paper, we consider the diffractive production of systems such as very heavy quarks, jets, W 's or Z 's in hadron-hadron collisions. Our treatment uses both perturbative quantum chromodynamics (QCD), to describe the hard scattering in which the W 's, Z 's, heavy quarks or jets are made, and Regge theory to describe diffraction. Our results apply to processes involving any kind of hard scattering at the partonic level. For the sake of definiteness, we will consider the particular case of heavy quark production.

Experiments have suggested¹ that, at least in the case of charm, a good way to find hadrons containing heavy quarks is to look at diffractive events. On the other hand, three of us² have argued that the bulk of the production of sufficiently heavy quarks is described correctly by standard perturbative QCD. Thus, if there is a significant diffractive component of very heavy quark production, then it must be true that this diffractive component is included in the standard perturbative QCD cross section. That is, diffractive production is not to be added to perturbative production: it is part of perturbative production. The issue here is: how big a part is it?

The interplay of Regge theory and perturbative QCD provides one motivation for studying diffractive hard scattering. Until recently, Regge theory and perturbative QCD have been subjects³ without much overlap, with the notable exception of the hypothesis³ that the $x \rightarrow 0$ behavior of structure functions is governed by the normal Regge trajectories. The success of this prediction is not obvious⁴. Another motivation is to examine whether a diffractive trigger in a heavy quark production experiment can enhance the fraction of events which contain a heavy quark. A number of authors have treated diffractive hard scattering recently.^{5,6,7} A complete exposition of our approach may be found in Ref. 8.

We show that the distribution of the heavy quarks produced diffractively is concentrated at small values of the rapidity y . Thus, these quarks, as well as W 's, Z 's, and high p_T jets produced diffractively, should be visible in the central detectors of typical high energy collider experiments. This contrasts with the naive expectation that diffractively produced systems appear only at large rapidity. We emphasize along with the authors of Refs. 5, 6, and 7 that diffractive hard scattering cross sections will probe the short distance character of diffractive amplitudes and provide measurements of the quark and gluon structure functions of the Pomeron.

2. KINEMATICS

We will consider diffractive heavy quark production, as illustrated in Fig. 1:

$$A + B \rightarrow (\bar{Q}Q) + X + C, \quad (2.1)$$

where C is the label for hadron B in the final state, and Q represents a heavy quark of mass M_Q . The heavy quarks will be seen experimentally as heavy hadrons. By a diffractive event, we mean an event in which hadron B goes through the collision nearly unscathed. It is deflected through a small angle, while retaining most of its incident energy. One can also consider diffractive excitation, in which hadron C is different from hadron B .

For a diffractive event, we demand that the invariant momentum transfer t from incident hadron B to final hadron C be no more than a few hundred MeV^2 , and that the momentum fraction z lost by the hadron obey $z \ll 1$. Normally we will integrate over t , so the important variable is z . This is the momentum fraction of hadron B carried by what we shall interpret as an exchanged Pomeron in Fig. 1. The invariant mass squared of the system $(\bar{Q}Q) + X$ is $M^2 \approx zs$; M^2 is

Fig. 1. Diffractive production of very heavy quarks.

large, but is much less than s .

We should point out that, although hadron B is scattered diffractively, the system $(\bar{Q}Q) + X$ cannot be a low mass, diffractively excited version of hadron A. The mass $M \approx [zs]^{1/2}$ of this system must necessarily be very large: $M > 2M_Q \gg 1 \text{ GeV}$. This situation contrasts with the situation for the production of low mass quark flavors.

We have defined the kinematics of the diffraction in terms of the diffracted hadron. However, in a typical experiment at a collider, this hadron will not be observed. The fact that this hadron carries a momentum fraction $(1-z)$ close to 1 will be signaled by the existence of a large rapidity gap between the incident beam and the other hadrons in the final state. Consider a particle in the system $(\bar{Q}Q) + X$ of mass m , transverse momentum k , and minus component of momentum $k^- = \xi zP$. Then $\xi < 1$. The rapidity of this particle obeys

$$y = \frac{1}{2} \ln([k^2 + m^2]/\xi^2 z^2 s) > y_{\min} + \ln(1/z), \quad (2.2)$$

where $y_{\min} = \frac{1}{2} \ln(m^2/s)$ is the minimum rapidity for a particle of this mass in an ordinary event. Thus there is a rapidity gap, $y - y_{\min}$, the size of which is at least $\ln(1/z)$. For particles with transverse momenta that are not unusually small, this gap translates into a gap in the angle of observed particles in the detector.

Fig. 2. Ordinary single diffractive scattering.

3. REGGE THEORY AND DIFFRACTIVE HARD SCATTERING

Consider first the ordinary high-mass diffractive process $A + B \rightarrow C + X$, where we have eliminated the requirement of a heavy quark pair. In the region where z is small and $M_X^2 = zs$ is large, this cross-section is represented as the discontinuity of the Reggeon graph shown in Fig. 2. The zigzag line in Fig. 2 represents a Pomeron which we approximate as an effective factorizable exchange. In QCD, the Pomeron presumably arises from high energy limit of the exchange of complicated gluon ladders, as suggested in the right hand side of the figure. The Reggeon graph gives^{9,10}

$$d\sigma^{\text{diff}}/dtdz = (1/16\pi) |\beta_{BP}(t)|^2 z^{1-2\alpha(t)} \sigma_{\text{tot}}(AP). \quad (3.1)$$

where the cross section for scattering of a Pomeron from hadron A is

$$\sigma_{\text{tot}}(AP) = G_{PPP}(t) \beta_{AP}(0) (M_X^2)^{\alpha(0)-1}. \quad (3.2)$$

With $\alpha(t) \approx 1$, Eqs. (3.1)-(3.2) yield the familiar expectation that $d\sigma^{\text{diff}}/dM_X^2 = M_X^{-2}$ for $M_X^2 \gtrsim 10 \text{ GeV}^2$ and $(M_X^2/s) \lesssim 0.01$. This prediction has been shown by the CERN UA4 collaboration¹¹ to describe data well from ISR to collider energies. For $(M_X^2/s) \gtrsim 0.1$, contributions become important from trajectories other than the Pomeron. We limit our attention therefore to the region $z \lesssim 0.1$.

Now let us consider the case in which heavy quarks are produced. In the usual case, without the diffractive trigger, the cross section is

$$d\sigma^{\text{tot}}[A + B \rightarrow (\bar{Q}Q) + X] = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a; \mu) f_{b/B}(x_b; \mu) d\sigma_{\text{hard}}[a + b \rightarrow (\bar{Q}Q) + X] \quad (3.3)$$

Here a and b label the partons, typically gluons, that take part in the hard scattering. The hard scattering cross section $d\sigma_{\text{hard}}[a + b \rightarrow (\bar{Q}Q) + X]$ is to be computed perturbatively in powers of $\alpha_s(\mu)$, $\mu \approx M_Q$, with the lowest order graphs consisting of the usual gluon fusion graphs¹².

For the leading twist contribution to the diffractive cross section to make heavy quarks, the parton b that enters the hard scattering must be found as a constituent of the Pomeron that was exchanged from the diffractively scattered hadron B , as illustrated in Fig. 3. The heavy quark production occurs inside the subgraph labelled "hard scattering". The hard scattering process depicted is gluon + gluon $\rightarrow Q + \bar{Q} + X$. In general, the gluons can be replaced by partons of any flavor, a and b , and higher orders of perturbation theory for the hard scattering may be used.

The cross-section corresponding to Fig. 3 is obtained by replacing $\sigma_{\text{tot}}(AP)$ in the diffraction formula Eq. (3.1) by the hard scattering formula Eq. (3.3), with B replaced by P and with a suitable change of kinematic variables:

$$d\sigma^{\text{diff}}[A + B \rightarrow C + (\bar{Q}Q) + X]/dtdz = (1/16\pi) |\beta_{BP}(t)|^2 z^{1-2\alpha(t)} \quad (3.4)$$

$$\times \sum_{a,b} \int dx_a f_{a/A}(x_a; \mu) \int d(x_b/z) f_{b/P}(x_b/z, t; \mu) d\sigma_{\text{hard}}[a+b \rightarrow (\bar{Q}Q)+X].$$

The hard scattering cross-section $d\sigma_{\text{hard}}$ is the same as in Eq. (3.3).

Fig. 3. Reggeon graph for diffractive heavy quark production.

The function $f_{b/P}(x_b/z, t; \mu)$ is the distribution of partons in a Pomeron, defined in the usual manner of a parton distribution; x_b/z is the ratio of the minus component of momentum $x_b P$ carried by the parton to the minus component of momentum zP carried by the Pomeron.

The formula (3.4) is an accurate representation of the class of graphs given in Fig. 3. However, we know from the proof of factorization in the non-diffractive case that graphs with different topologies contribute, and that there is a cancellation before the factorized form is obtained. There are graphs with extra Pomerons at the leading twist level. These break the standard factorized form for the cross-section. Factorization, in the usual hard scattering case, is obtained only after a sum is made over graphs in which the Pomerons are cut in all possible ways¹³. However, some of the cuts are not included in the cross section of interest, $d\sigma_{diff}^{[A+B+C+(\bar{Q}Q)+X]}/dtdz$, because they have non-diffractive final states. Thus we cannot expect the diffractive cross-section to satisfy Eq. (3.4) exactly, but only at the level at which multiple Pomeron exchange is ignored.

Similar remarks apply also to the case of ordinary inclusive high-mass diffraction. However, we know^{9-11,14-17} Eq. (3.1) to be a good representation of the data in the range of energies where experiments are performed. Therefore it is likely that Eq. (3.4) is also true to a good approximation.

Another unavoidable limitation of our approach is that the exchange of a simple factorizable Pomeron with $\alpha(0) = 1$ does not describe the observed gradual rise with energy of the total cross section.

In principle, there could be a difference between the t dependences of diffractive heavy quark production at a given z , Eq. (3.4), and the total diffractive cross section at the same z , Eq. (3.1). These differences would be associated with the t dependences of $f_{b/P}(x_b/z, t; \mu)$ in Eq. (3.4) and $G_{PPP}(t)$ in Eq. (3.2). We will discuss the x dependence of $f_{b/P}(x, t; \mu)$ in Sec. 4; we shall assume that the t dependence of this function is either weak or non-existent in the region of t of interest. The triple-Pomeron coupling $G_{PPP}(t)$ has been measured¹⁵ to have the asymptotic value, nearly independent of t ,

$$G_{PPP}(t) = 0.364 \pm 0.025 \text{ mb}^{1/2}. \quad (3.5)$$

Assuming that $G_{PPP}(t)$ and $f_{b/P}(x/z, t; \mu)$ do not depend on t , we may integrate Eqs. (3.1) and (3.4) over t . Cancelling common factors, we derive

$$\frac{d\sigma_{diff}^{[A+B+C+(\bar{Q}Q)+X]}/dz}{d\sigma_{diff}/dz} = \frac{\sum_{a,b} \int dx_a f_{a/A}(x_a; \mu) \int d(x_b/z) f_{b/P}(x_b/z, t; \mu) d\sigma_{hard}^{[a+b+(\bar{Q}Q)+X]}}{\sigma_{tot}(AP)}. \quad (3.6)$$

In order to proceed to quantitative calculations, we must specify the function $\beta_{p\bar{p}}(t)$ in Eq. (3.1). Adopting the relationship

$$\sigma_{\text{tot}}(pp) = \beta_{p\bar{p}}^2(0) , \quad (3.7)$$

we use $\sigma_{\text{tot}}(pp) \approx 40$ mb to derive

$$\beta_{p\bar{p}}(0) = 6.3 \text{ mb}^{1/2} . \quad (3.8)$$

The forward slope of the t dependence of $d\sigma^{\text{diff}}/dt dM_x^2$ is known to be correlated strongly with M_x^2 for small M_x^2 . For $M_x^2 \gtrsim 10 \text{ GeV}^2$, however, it appears to reach a constant level of $\sim 6.5 \text{ GeV}^2$ at ISR energies¹⁴. We therefore parametrize

$$\beta_{p\bar{p}}(t) = 6.3 \text{ mb}^{1/2} \exp[(6.5 \text{ GeV}^2)t/2] . \quad (3.9)$$

Equations (3.2), (3.5) and (3.8) yield

$$\sigma_{\text{tot}}(p\bar{p}) \approx 2.3 \text{ mb} \quad (3.10)$$

for the Pomeron-proton cross section. This value agrees with the result deduced by Field and Fox⁹ but it is about a factor of two larger than the 1 mb value of Kaidalov and Ter-Martirosyan¹⁰ which, in turn, is used by Ingelman and Schlein⁵ and by Fritzsche and Streng⁶.

After integrating Eq. (3.1) over t , we derive

$$\frac{d\sigma^{\text{diff}}}{dM_x^2} = \frac{0.70 \text{ mb}}{M_x^2} . \quad (3.11)$$

This is the result for the diffractive dissociation of only one of the incident hadrons. For the total single diffractive cross section, Eq. (3.11) must be doubled. Our Eq. (3.11) is in agreement with the equivalent expression $d\sigma^{\text{diff}}/dM_x^2 = 0.675 \text{ mb}/M_x^2$ employed in Refs. 5 and 6.

Integrating Eq. (3.11) from $M_x^2 = 10 \text{ GeV}^2$ to $M_x^2 = 0.1s$, we find $\sigma_{\text{diff}}^{\text{tot}}(M_x^2/s < 0.1) = 5.6 \text{ mb}$ at $\sqrt{s} = 540 \text{ GeV}$. When doubled, this result is in acceptable agreement with the value $8.7 \pm 0.8 \text{ mb}$ quoted by the CERN UA4 group¹¹. Correspondingly, we are satisfied that our choices in Eqs. (3.5)-(3.10) comprise a consistent set of parameters. Returning to Eq. (3.6), we note that the absolute magnitude of $d\sigma^{\text{diff}}[A + B + C + (Q\bar{Q}) + X]/dz$ is proportional to the ratio $\sigma_{\text{tot}}^{-1}(A\bar{p}) d\sigma^{\text{diff}}/dz$. Thus, slight overestimates in the values of $\sigma_{\text{tot}}(A\bar{p})$ and $d\sigma^{\text{diff}}/dz$ will tend to cancel. Because we agree on Eq. (3.11) but use a value for $\sigma_{\text{tot}}(p\bar{p})$, Eq. (3.10), which is a factor of 2.3 higher than in Refs. 5 and 6, our estimates for $d\sigma^{\text{diff}}(A + B + C + (Q\bar{Q}) + X)$ will be lower in normalization by the factor 2.3 than those in Refs. 5 and 6, all else being equal.

4. DISTRIBUTION OF PARTONS IN THE POMERON

Although the distribution of partons in a Pomeron, $f_{b/P}(x/z, t, \mu)$, is a non-perturbative quantity, we can find some information on its functional form. First, momentum conservation forces $f_{b/P}(x/z)$ to be zero if $x/z > 1$. Second, we expect the Pomeron to be a mostly gluonic state, with a few sea quarks. Other features are discussed below.

A. Momentum sum rule

According to standard Regge theory, the Pomeron exchanged in Fig. 3 may be thought of as a particle state. The normalization we have used for the Pomeron in Eq. (3.4) is the same as in Eqs. (3.1) and (3.2), where it has the standard particle normalization. Thus it would appear that the distribution of partons in a Pomeron satisfies the momentum sum-rule

$$\sum_b \int d\xi \xi f_{b/P}(\xi, t; \mu) = 1, \quad (4.1)$$

or $\int d\xi \xi f_{g/P}(\xi, t; \mu) \approx 1$, if gluons dominate. We will assume here that the sum rule (4.1) holds. However, we note that no derivation has been given, and that the required derivation may be a subtle matter.

B. Small x/z

Regge theory may be used³ to predict the small- x behavior of parton distributions.

If the $x \rightarrow 0$ behavior of a distribution function $f_{b/H}(x)$ is dominated by a simple Regge pole, R , with intercept $\alpha = \alpha_R(0)$, then the distribution has the following form for small x :

$$f_{b/H}(x; \mu) \approx g_{b/R}(\mu) x^{-\alpha} \beta_{HR}(0). \quad (4.2)$$

The measured behavior of $f_{b/H}(x)$ at small x allows one to determine the parton-Reggeon coupling constant $g_{b/R}(\mu)$. For the valence quark distributions the leading trajectory is the rho trajectory, with $\alpha = 1/2$. For sea quarks and, most importantly, the gluon distribution, the leading trajectory is the Pomeron, with $\alpha = 1$. That is, the gluon distribution function behaves as $1/x$ at small x .

Regge factorization now gives us the small- x behavior of the sea quark and gluon distributions in the Pomeron in terms of the parton-Pomeron coupling:

$$f_{b/P}(x/z, t; \mu) \approx g_{b/P}(\mu) (x/z)^{-\alpha} G_{PPP}(t). \quad (4.3)$$

When Eq. (4.3) is inserted into Eq. (3.4), the result is

$$[d\sigma^{\text{diff}}[A + B + C + (\bar{Q}Q) + X]/dt dz]_{x \ll z}$$

$$= (1/16\pi) G_{\text{PPP}}(t) |\beta_{\text{BP}}(t)|^2 z^{\alpha(0)-2\alpha(t)} \quad (4.4)$$

$$\times \sum_{a,b} \int dx_a f_{a/A}(x_a; \mu) \int dx_b g_{b/B}(\mu) x_b^{-\alpha(0)} d\sigma_{\text{hard}}[a + b + (\bar{Q}Q) + X] .$$

Equation (4.4) enables us to write the diffractive heavy quark production cross section at small x/z directly in terms of the total heavy quark production cross section and measured quantities. Dividing Eq. (4.4) by Eq. (3.1), and using Eqs. (3.2), (3.4), (3.7) and (4.2), we derive

$$\frac{d\sigma^{\text{diff}}[A+B + C+(\bar{Q}Q)+X]_{(x \ll z)}}{d\sigma^{\text{diff}}[A + B + C + X]} = \frac{\sigma^{\text{tot}}[A+B + (\bar{Q}Q)+X]_{(x \ll 1)}}{\sigma^{\text{tot}}[A + B + X]} . \quad (4.5)$$

The heavy quark cross-sections are assumed to be taken in a region where they are dominated by the low- x behavior of the parton distribution in the lower hadron. The formula holds even if we make a sum over the Regge trajectories that couple to hadron B.

In the derivation of Eq. (4.4) it is assumed that the trajectory that dominates the small- x behavior of the gluon distribution function is the same as the trajectory that dominates the total cross-section for hadron-hadron scattering. This trajectory should be the well-known Pomeron. From analyses of ordinary diffractive scattering, it is known that to treat the Pomeron as a simple pole and to use universality of its couplings works to a good approximation, at least if we do not look too closely at the detailed structure of the cross-section as a function of t ¹⁶. However, it is not at all clear that this assumption is correct when a hard scattering is involved.

C. x/z near 1

Let us now turn to the $x/z \rightarrow 1$ limit of the distribution of gluons in the Pomeron $f_{g/P}(x/z, t; \mu)$. The behavior of parton distributions as fractional momenta approach unity is normally estimated by the constituent counting rules¹⁸. To derive these, a hadron is considered to be made up of the minimum number v_{min} of valence partons. Power counting in the simplest hadron graphs gives a behavior $(1-x/z)^n$ where $n = 2v_{\text{min}} - 1$. In the case of the Pomeron, one might consider the Pomeron to be like a two gluon bound state¹⁹. One can then make a simple power counting estimate for $f_{g/P}(x/z)$. Taking the incoming gluons to carry transverse polarization, negligible transverse and minus components of momentum, and finite fractions of the Pomeron's + momentum, we find that the result of this power counting is

$$f_{g/P}(x/z) \propto (1 - x/z)^1 / (k_{T\text{min}})^2 . \quad (4.6)$$

Here $k_{\text{min}} \approx 1 \text{ GeV}$ is an infrared cutoff imposed by hand on the integration over the transverse momentum of the observed gluon.

The power counting result (4.6) is subject to various subtleties. First, an infrared cutoff is necessary, so that the $(1 - x/z)^1$ behavior should not be considered to be a reliable result of perturbative QCD. A second subtlety arises because the two gluon contribution is planar, and the sum over cuts of planar diagrams vanishes in the limit that gives Reggeization of the Pomerons²⁰. To couple two Pomerons, perhaps one must use only non-planar diagrams, which have one more spectator parton. On the other hand, it is not clear to us that the suppression of planar diagrams is strong enough to matter in the present application. Finally, helicity effects can be important in further suppressing the leading twist large x behavior.

We will use $(1 - x/z)^1$ for the $x/z \rightarrow 1$ behavior of the distribution of gluons in a Pomeron in this paper. We are not convinced, however, of the reliability of this result.

D. Parameterization of the gluon distribution

In this subsection, we parametrize the gluon distribution in the Pomeron, using the information developed above. We write $f_{g/P}(\xi)$ in the form

$$f_{g/P}(\xi) = \left\{ \frac{A}{\xi} + B \right\} [1 - \xi] . \quad (4.7)$$

The $1/\xi$ behavior arises from Pomeron dominance at small ξ , and the power $[1 - \xi]$ is estimated from the power counting argument. The coefficient A of the $1/\xi$ behavior is determined from the triple Regge coupling and other factors as discussed above, and the coefficient B is determined by the momentum sum rule.

The coefficient A is given by Eq. (4.3) as

$$A(t; \mu) = g_{b/P}(\mu) G_{PPP}(t) . \quad (4.8)$$

We use Eq. (3.5) for the triple-pomeron coupling $G_{PPP}(t)$. The Regge ansatz Eq. (4.2) allows us to estimate the parton-Pomeron coupling $g_{b/P}(\mu)$. We shall consider the most important case, in which the parton b of interest is the gluon. Equation (4.2) yields

$$x f_{g/p}(x; \mu) / \beta_{pP}(0) \rightarrow g_{g/P}(\mu) \quad \text{as } x \rightarrow 0. \quad (4.9)$$

A standard parametrization for the gluon distribution in a proton at low μ is

$$f_{g/p}(x) \approx 3(1 - x)^5/x . \quad (4.10)$$

This satisfies the energy sum rule $\int dx f_{g/p}(x) = 0.5$ since about half of the momentum of a proton is carried by gluons. We also use $\beta_{pP}(0) \approx 6.3 \text{ mb}^{1/2}$ from Eq. (3.8). Then Eq. (4.9) provides

$$g_{g/P} \approx 0.5 \text{ mb}^{-1/2}, \quad (4.11)$$

and insertion of these results into Eq. (4.8) yields

$$A \approx 0.18. \quad (4.12)$$

Assuming that gluons carry all the momentum of the Pomeron, we can now impose the momentum sum rule (4.1) in order to compute the coefficient B in Eq. (4.7):

$$B \approx 5.46. \quad (4.13)$$

Thus the gluon distribution in the Pomeron is estimated as

$$f_{g/P}(\xi, t; \mu) = \left\{ \frac{0.18}{\xi} + 5.46 \right\} [1 - \xi]. \quad (4.14)$$

We may contrast Eq. (4.14) with the very simple form

$$f_{g/P}(\xi) = \frac{2}{\xi} (1 - \xi), \quad (4.15)$$

which the normalized $f_{g/P}(\xi)$ would have if we had made the assumption that the Pomeron carries only ocean gluons, with the large ξ behavior controlled by Eq. (4.6). Because of the small size of $G_{PPP}(t)$ (i.e. $\ll \beta_{PP}(0)$), our $f_{g/P}(\xi)$ approaches $0.18/\xi$ as $\xi \rightarrow 0$, smaller by about a factor of 10 than the corresponding limit of Eq. (4.15). However, for large ξ , our valence dominated Eq. (4.14) exceeds the expectations of Eq. (4.15), by about a factor of 3. Our Eq. (4.14) is similar to the hard gluon alternative adopted by Ingelman and Schlein⁵ and by Fritzsche and Streng⁶ $f_{g/P}(\xi) = 6(1-\xi)$, but we include a small ocean component at small ξ as required by Regge factorization.

5. PHENOMENOLOGICAL RESULTS

In this section, we use the formulas presented above to calculate the total hard scattering cross section for producing heavy quarks at $s^{1/2} = 540 \text{ GeV}$, the diffractive cross section for producing heavy quarks, and the ratio of these cross sections.

In order to obtain numerical results for diffractive production of heavy flavors, we use Eq. (3.6), with $d\sigma^{\text{diff}}/dz$ specified by Eq. (3.11), and $\sigma_{\text{tot}}(pP)$ given by Eq. (3.10). We include only the contribution from the gluon fusion subprocess $gg + Q\bar{Q}$ ¹². We set $\alpha_s(\hat{s}) = 12\pi/25 \ln(\hat{s}/\Lambda^2)$, where $\hat{s}^{1/2}$ is the c.m. energy of the subprocess $gg + Q\bar{Q}$, and $\Lambda = 0.2 \text{ GeV}$. For the gluon structure function in a proton, we use the density derived by Duke and Owens²¹, with $\Lambda = 0.2 \text{ GeV}$. For the distribution of gluons in a Pomeron, we use our preferred Eq. (4.14). For purposes of comparison, we also

show the diffractive cross sections obtained with a different gluon distribution in the Pomeron, $f(\xi) = 6(1-\xi)^5/\xi$, which is one of the distributions used in Refs. 5 and 6. (The other distribution used by these authors is quite similar to the one we use.)

In principle, the distribution of gluons in the Pomeron, Eq. (4.14), applies at some fairly low value of the scale μ and should then be evolved to $\mu \approx M_Q$ according to the Altarelli-Parisi equation. We have not yet carried out this refinement. When the evolution is done, the predicted diffractive cross sections will generally increase due to the larger number of partons at small x_b/z .

Fig. 4. Cross sections for bottom quark production. The solid curve shows the total cross section for $\bar{p}p \rightarrow Q\bar{Q}X$, with $m_Q = 5.4 \text{ GeV}$, obtained from the subprocesses $gg \rightarrow Q\bar{Q}$ and $\bar{q}q \rightarrow Q\bar{Q}$. The long-dashed and short-dashed curves represent the cross sections σ^{diff} for the diffractive process $\bar{p}p \rightarrow \bar{p}(Q\bar{Q})X'$, for two choices of the gluon distribution of the Pomeron. The notation DIFF1 refers to our preferred gluon distribution, Eq. (4.14), whereas DIFF5 refers to $f(\xi) = 6(1-\xi)^5/\xi$. The diffractive cross sections are integrated over the interval $M^2(Q\bar{Q}X') < 0.1s$. They should be doubled to account for diffractive scattering of either initial hadron.

In Fig. 4 we show the diffractive cross sections $\sigma^{\text{diff}}(\bar{p}p \rightarrow p\bar{b}bX')$ as a function of $\sqrt{s}$. These cross sections are integrated over the range $M^2(b\bar{b}X') < 0.1s$, i.e. $z < 0.1$. They pertain to the diffractive scattering of only one of the initial hadrons; they should be doubled to account for single diffraction of either initial hadron. Also shown in Fig. 4 is the total cross section $\sigma^{\text{tot}}(\bar{p}p \rightarrow b\bar{b}X)$ which we obtain in the usual fashion¹², using the QCD subprocesses $\bar{q}q \rightarrow b\bar{b}$ and $gg \rightarrow b\bar{b}$, and the structure functions of Ref. 21.

For charm, bottom, and top quark production, the diffractive fraction of the total heavy quark cross section is presented in Table 1 for $\sqrt{s} = 540$ GeV and $\sqrt{s} = 2$ TeV. We note that for relatively

Fig. 5 Rapidity distribution, $d\sigma/dy(\bar{p}p \rightarrow QX)$, for bottom quark production at $\sqrt{s} = 540$ GeV. We set $m_b = 5.4$ GeV. The solid curve shows the total rapidity distribution. The long-dashed and short-dashed curves show the rapidity distribution of quarks from the diffractive process $\bar{p}p \rightarrow p(Q\bar{Q})X'$, for two choices of the gluon distribution in the Pomeron. The notation DIFF1 refers to our preferred gluon distribution, Eq. (4.14), whereas DIFF5 refers to $f(\xi) = 6(1-\xi)^5/\xi$. The diffractive results are integrated over the interval $M^2(Q\bar{Q}X') < 0.1s$. They represent diffraction scattering of only one of the incident hadrons. The full diffractive contribution to $d\sigma/dy$ is obtained by adding the results shown to those obtained after reflection about the $y=0$ axis.

light quarks, $M_Q/\sqrt{s} \lesssim 0.1$, the diffractive fraction is substantial, $\gtrsim 15\%$.

In Table 2, we present the fractions of the diffractive cross sections at $\sqrt{s} = 540$ GeV and $\sqrt{s} = 2$ TeV which include a heavy $Q\bar{Q}$ pair. We compare these with the fractions of the total $p\bar{p}$ cross sections which include a heavy pair. We note that except for very heavy quarks these fractions are quite similar. Correspondingly, in our approach, the selection of diffractive events does not improve the probability for isolating heavy flavors. On the other hand, once the reduction in event rate is accepted, $\sigma^{\text{diff}}/\sigma^{\text{tot}} \lesssim 20\%$, diffraction does not impose an additional penalty either, except for very large values of M_Q . The fractions shown in Tables 1 and 2 indicate that it could be possible to obtain a good sample of events from which to try to determine the structure functions of the Pomeron.

In Figs. 5-7 we plot the cross sections $d\sigma/dy$ and $d\sigma^{\text{diff}}/dy$ for production of heavy quarks in $p\bar{p}$ collisions at $s^{1/2} = 540$ GeV and 2 TeV. Cross sections are shown for bottom and top quark production. A top quark mass of 40 GeV is assumed. The curves for $d\sigma^{\text{diff}}/dy$ represent the integral of $d\sigma^{\text{diff}}/dydz$ over the range $z < z_{\text{max}} = 0.1$. The diffractive results are appropriate for the diffraction of only one of the incident hadrons. The full single diffraction contribution, which is symmetric about $y=0$, is obtained upon adding the diffractive contributions shown in Figs. 5-7 to the corresponding contributions obtained from a reflection about the $y=0$ axis. We remark that the heavy quarks are produced with fairly small values of y . They should be observable in the central detectors of

Fig. 6. As for figure 5, but $\sqrt{s} = 2$ TeV.

typical high energy collider experiments. (The results in Figs. 5-7 pertain to either $\bar{p}p \rightarrow QX$ or $\bar{p}p \rightarrow \bar{Q}X$. Thus, if Q and $\bar{Q}$ are not distinguished, the cross sections shown in Figs. 5-7 should be doubled.)

The CERN UA1 collaboration has recently measured the cross section for $b\bar{b}$ production.²² They report a cross section for bottom quarks produced within the rapidity interval $-2 < y < 2$, and with transverse momentum $p_T > 5$ GeV. Their result is²²

$$\sigma(|y| < 2; p_T > 5 \text{ GeV}) = (1.3 \pm 0.1 \pm 0.2) \mu\text{b} . \quad (5.1)$$

With the same selections, we compute

$$\sigma(|y| < 2; p_T > 5 \text{ GeV}) = 0.8 \mu\text{b} , \quad (5.2)$$

with a theoretical uncertainty of perhaps a factor of two in either direction. We regard the agreement between (5.1) and (5.2) as encouraging confirmation that perturbative QCD is reliable for predictions of heavy flavor cross sections for flavors heavier than charm.²³

Fig. 7. As for figure 5, but for top quark production at $\sqrt{s} = 2$ TeV. We set $m_t = 40$ GeV.

Table 1. Fraction of the heavy quark cross section which is diffractive. The numbers should be doubled to account for diffraction scattering of either initial hadron. The diffractive cross section is integrated over the interval $z = (M_x^2/s) < 0.1$.

	$\frac{\sigma^{\text{diff}}(Q\bar{Q})}{\sigma(Q\bar{Q})}$		
$\sqrt{s}$ m_Q	1.5 GeV	5.4 GeV	40 GeV
540 GeV	0.16	0.073	0.76×10^{-3}
2 TeV	0.18	0.09	0.05

Table 2. Fraction of the diffractive cross section which contains a heavy quark pair and, in square brackets, the fraction of the total cross section which contains a heavy quark pair.

	$\frac{\sigma^{\text{diff}}(Q\bar{Q})}{\sigma^{\text{diff}}(M^2/s < 0.1)}$ and $[\frac{\sigma^{\text{tot}}(Q\bar{Q})}{\sigma^{\text{tot}}}]$		
$\sqrt{s}$ m_Q	1.5 GeV	5.4 GeV	40 GeV
540 GeV	0.39×10^{-2} [0.33×10^{-2}]	0.38×10^{-4} [0.73×10^{-4}]	0.33×10^{-10} [0.61×10^{-8}]
2.0 TeV	0.73×10^{-2} [0.74×10^{-2}]	0.19×10^{-3} [0.39×10^{-3}]	0.42×10^{-7} [0.16×10^{-6}]

6. CONCLUSIONS

We have argued that the diffractive hard scattering cross section is a part of the ordinary inclusive hard scattering cross section, Eq. (3.3). Combining Regge phenomenology and perturbative QCD, we estimate that a fairly large fraction of all hard scattering events should be diffractive. It would be very useful if these expectations were to be tested soon. It should be relatively straightforward at collider energies to select events in which a large rapidity gap is present and to measure the cross sections for jet production at large p_T in these events, for W and Z production, for direct photon production, and for heavy flavor production. The data can be used to determine the quark and gluon momentum distributions of the Pomeron.

There is numerical uncertainty in the predictions presented here, mainly due to the fact that the distribution functions for finding partons in a Pomeron are largely unknown. Nevertheless, substantial revision would be necessary in the manner in which we have treated diffraction if it should turn out that experimental measurements differ drastically from our estimates for the diffractive hard scattering cross sections. An important experimentally testable prediction of our physical picture is that similar fractions of gluon induced hard scattering events should be diffractive in each type of hard scattering observed. If, say, 10% of jet events with $E_T \approx 90$ GeV at the Tevatron collider are observed to be diffractive, then about 10% of events in which top quarks with $2M_t = 80$ GeV are produced should be diffractive.

It is important to refine our predictions by using distributions of partons in the Pomeron that have been evolved by the Altarelli-Parisi equation. This is especially important for computations of diffractive hard scattering at very small x or for high mass systems, as would be necessary at SSC energies, $\sqrt{s} = 40$ TeV. We plan to do this in the near future.

We have noted a number of open questions in the theory presented here. The momentum sum rule for the distribution of gluons in a Pomeron has played an important role, but this sum rule lacks a convincing proof. It is not apparent that the small x/z behavior derived for the distribution of gluons in the Pomeron is consistent with the Altarelli-Parisi evolution equation. The $x/z \rightarrow 1$ behavior is not firmly predicted. There are corrections to the simple Regge factorized picture, due to multiple Pomeron exchange, but these corrections have not been explored. To help explore these questions, good simple models of the Pomeron, or a deep understanding of the Pomeron in terms of multiple gluon graphs, or both, are needed. The uncertainties are a sign that more theoretical work is needed. The nature of the questions suggests also the exciting possibility that experimental investigation will lead to a better understanding of the nature of the Pomeron.

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REFERENCES

1. A. Kernan and G. van Dalen, Phys. Rep. 106, 297 (1984).
2. J.C. Collins, D.E. Soper and G. Sterman, Nucl. Phys. B263, 37 (1986).
3. D. J. Gross, in Lectures on Current Algebra and Its Applications, edited by S. B. Treiman, R. Jackiw, and D. J. Gross (Princeton, 1972), p. 349.
4. J. Collins, these proceedings.
5. G. Ingelman and P.E. Schlein, Phys. Lett. 152B, 256 (1985).
6. H. Fritzsch and K.-H. Streng, Phys. Lett. 164B, 391 (1985).
7. K. H. Streng, CERN reports CERN-TH.4264/85 and CERN-TH.4294/85.
8. E. L. Berger, J. C. Collins, D. E. Soper, and G. Sterman, Argonne report ANL-HEP-PR-86-14, submitted to Nucl. Phys. B.
9. R.D. Field and G. Fox, Nucl. Phys. B80, 367 (1974).
10. A. B. Kaidalov and K. A. Ter-Martirosyan, Nucl. Phys. B75, 471 (1974).
11. M. Bozzo et al., Phys. Lett. 136B, 217 (1984); D. Bernard et al., Phys. Lett. 166B, 459 (1986); V. Palladino et al., CERN report CERN/EP 85-154.
12. B. Combridge, Nucl. Phys. B151, 429 (1979); J. Babcock, D. Sivers, and S. Wolfram, Phys. Rev. D18, 162 (1978).
13. C. DeTar, S.D. Ellis, P.V. Landshoff, Nucl. Phys. B87, 176 (1975), J. L. Cardy and G. A. Winbow, Phys. Lett. 52B, 95 (1974).
14. M. G. Albrow et al., Nucl. Phys. B108, 1 (1976).
15. R.L. Cool et al., Phys. Rev. Lett. 47, 701 (1981).
16. K. Goulianos, Phys. Rep. 101, 169 (1983).
17. G. Alberi and G. Goggi, Phys. Rep. 74, 1 (1981).
18. R. Blankenbecler and S. J. Brodsky, Phys. Rev. D10, 2973 (1974); S. J. Brodsky and G. Farrar, ibid. D11, 1309 (1975).
19. F. E. Low, D12, 163 (1975); S. Nussinov, Phys. Rev. D14, 246 (1976); D. Richards, Nucl. Phys. B258, 267 (1985).
20. S. Mandelstam, Nuovo Cim. 30, 1127 (1963).
21. D. Duke and J. Owens, Phys. Rev. D30, 49 (1984).
22. D. Cline, these proceedings.
23. E. L. Berger, J. C. Collins, and D. E. Soper, Oregon report OITS 327 (June, 1986), submitted to Phys. Rev. Letters.

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