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Pomeron flux renormalization in soft and hard diffraction

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ABSTRACT

While the main features of elastic, diffractive and total cross sections are described well by Regge theory, the measured rise of the proton-(anti)proton single diffraction dissociation cross section with energy is considerably smaller than the theoretical prediction based on factorization and a constant triple-pomeron coupling. The observed energy dependence is obtained by renormalizing the pomeron flux "carried" by a nucleon to unity. Double diffraction and double pomeron exchange cross sections are reevaluated and compared to data, and a new interpretation of hard diffraction results emerges in which the hard pomeron obeys the momentum sum rule.

1 Introduction

It is well known that pomeron exchange in Regge theory accounts for the main features of high energy elastic, diffractive and total cross sections [1, 2]. In particular, for proton-(anti)proton interactions, it accounts for the rise of the total cross section and the shrinking of the forward elastic peak with energy, and also describes correctly the mass and t dependence of single diffraction dissociation (SD). Furthermore, the concept of factorization provides relationships between cross sections that pass successfully the test of experimental observation [1].

Encouraged by this success, Ingelman and Schlein [3] proposed to extend factorization to the domain of hard processes involving the pomeron, and calculated the SD high p_T dijet production cross section and rapidity distributions under various assumptions about a pomeron structure function. In their calculation, they assumed that the pomeron has

an independent existence inside a high energy proton (from now on we will use *proton* to refer to proton or antiproton) and defined a "pomeron flux factor", $f_{\mathcal{P}/p}(\xi, t)$, through the expression

$$\frac{d^2\sigma_{SD}}{d\xi\, dt} = \sigma_T^{\mathcal{P}p} \;\; f_{\mathcal{P}/p}(\xi, t) \tag{1}$$

where σ_{SD} is the SD cross section, ξ is the fraction of the momentum of the proton carried by the pomeron, which is related to the pomeron-proton center of mass energy or diffractive mass M by $\xi = M^2/s$, t is the square of the four-momentum transfer or the negative mass squared of the (virtual) pomeron, and $\sigma_T^{\mathcal{P}p}$ is the pomeron-proton total cross section. Using a value for $\sigma_T^{\mathcal{P}p}$ obtained from the SD cross section at fixed target and ISR energies, the pomeron flux was evaluated at higher energies from the SD cross section through the above equation and was used to calculate hard pomeron-proton collisions in the usual way. When later the UA8 experiment studied diffractive dijet production, it was found that [4] while the shape of the rapidity distribution of the jets (we will use rapidity and pseudorapidity or η interchangeably) favors an almost fully *hard* structure function for the pomeron, of the type $Q(\lambda) = 6\lambda(1-\lambda)$, where λ is the momentum fraction of a parton inside the pomeron, rather than a *soft* structure function of the type $Q(\lambda) = 6(1-\lambda)^5$, the rate of jet production can be accounted for by only a fraction of the momentum of the pomeron being carried by hard quarks or gluons. The UA8 rate result is summarized by the "discrepancy factor" required to multiply the pomeron hard-quark or hard-gluon structure function to predict the measured dijet rates. This factor is $0.46 \pm 0.08 \pm 0.24$ $(0.19 \pm 0.03 \pm 0.10)$ for a hard-quark(gluon) dominated pomeron [5].

The discrepancy between the two UA8 results, namely the jet η distribution requiring a hard pomeron structure function while the jet production rate being too small for a pomeron with a fully hard structure function, could be reconciled by noting that the pomeron, being a virtual state, need not observe the momentum sum rule [5, 6]. However, such a picture is not very satisfactory, as it puts into question the notion that the pomeron could have a structure function at all. Below, we show that this discrepancy can be attributed to the pomeron flux factor normalization, and that by *renormalizing* the flux to unity, i.e. to one pomeron per incident proton, the UA8 rate becomes consistent with the momentum sum rule. As a check of our flux normalization procedure, we show that the normalized flux predicts correctly the energy dependence of the SD cross section using an energy independent triple-pomeron coupling. In contrast, an unnormalized flux leads to a SD cross section which increases at a much faster rate than that observed experimentally, and predicts a rate several times higher than the measured cross section at the Tevatron.

2 Pomeron flux factor

It would appear that the flux factor defined by Eq. 1 could be obtained by dividing the SD differential cross section by $\sigma_T^{\mathcal{P}p}$. This is what was done by Ingelman and Schlein in their original calculation [3], and more recently by Bruni and Ingelman in a calculation of the rates expected for diffractive W production at the Tevatron [7]. The latter authors, for example, use a constant pomeron-proton total cross section of 2.3 mb and parameterize the flux factor as

$$f_{\mathcal{P}/p}(\xi, t) = \frac{1}{2}\,\frac{1}{\xi}\left[6.38\ e^{8t} + 0.424\ e^{3t}\right]\frac{1}{2.3} \tag{2}$$

This expression for the pomeron flux leads to a total integrated SD cross section of 9.1 mb for $\xi < 0.05$ at $\sqrt{s}$=546 GeV, in agreement with the value of 9.4 ± 0.7 mb reported by the UA4 experiment [8] (the cross section is multiplied by a factor of 2 to account for the dissociation of *the other* nucleon).

One problem with this approach is that it does not take into account the dependence on ξ, expected in Regge theory, of the pomeron-proton total cross section and of the t slope-parameter. Another problem is that the integral (for the standard diffractive region $\xi < 0.1$) of the flux factor over t and ξ, which represents the total number of pomerons in the proton that participate in the diffractive interaction, grows with energy and has the value of 2.2 (2.6) at $\sqrt{s}$=630 (1800) GeV. One may, therefore, ask the question: what does it really mean to have, say, two pomerons per proton? How can *two* diffractive events be produced in *the same* $p\bar{p}$ collision? Below we will show that this unnormalized flux leads to unphysical results, and that physically consistent results can be obtained only by normalizing the flux to unity. But first we discuss a flux factor that is consistent with Regge theory.

In terms of the pomeron trajectory,

$$\alpha(t) = 1 + \epsilon + \alpha' t \tag{3}$$

the total, the elastic, and the SD $p\bar{p}$ cross sections can be written as (see Fig. 1)

$$\sigma_T = \beta^2(0) s^{\alpha(0)-1} = \sigma_0^{p\bar{p}}\ s^{\epsilon} \tag{4}$$

$$\frac{d\sigma_{el}}{dt} = \frac{1}{16\pi(\hbar c)^2}\ \beta_1^2(t)\beta_2^2(t)\ s^{2[\alpha(t)-1]} = \frac{\sigma_T^2}{16\pi(\hbar c)^2}\ e^{(2\alpha' lns)t}\ F^4(t) \approx \frac{\sigma_T^2}{16\pi(\hbar c)^2}\ e^{b_{el}(s)t} \tag{5}$$

$$F^4(t) \approx e^{b_{0,el}t} \quad \Rightarrow \quad b_{el}(s) = b_{0,el} + 2\alpha' lns \quad (s \text{ in GeV}^2) \tag{6}$$

$$\frac{d^2\sigma_{SD}}{dtd\xi} = \frac{1}{16\pi(\hbar c)^2 s}\ \beta_1^2(t)\left(\frac{s}{M^2}\right)^{2\alpha(t)} \beta_2(0) g(t)\left(M^2\right)^{\alpha(0)} = \frac{\sigma_0^{p\bar{p}}}{16\pi(\hbar c)^2}\ \xi^{1-2\alpha(t)}\ F^2(t)\sigma_T^{\mathcal{P}p} \tag{7}$$

where $\beta(t)$ is the pomeron coupling to the proton, $g(t)$ the triple-pomeron coupling, M the diffractive mass, F(t) the proton form factor, and $\sigma_T^{\mathcal{P}p}$ the pomeron proton total cross section given by (see Eq. 4)

$$\sigma_T^{\mathcal{P}p} = \beta_1(0)g(t)\left(M^2\right)^{\alpha(0)-1} = \sigma_0^{\mathcal{P}p}\left(M^2\right)^{\epsilon} \tag{8}$$

where M^2 is in GeV^2, and in writing $\beta_1(0)g(t) = \sigma_0^{\mathcal{P}p}$ we have assumed that the triple-pomeron coupling constant, $g(t)$, is independent of t [1]. From Eqs. 1 and 7 it is now clear that the flux factor can be expressed in terms of the total cross section, the elastic form factor, and the pomeron trajectory parameters as follows:

$$f_{\mathcal{P}/p}(\xi,t) = \frac{d^2\sigma_{SD}/d\xi\, dt}{\sigma_T^{\mathcal{P}p}} = \frac{\sigma_0^{p\bar{p}}}{16\pi(\hbar c)^2}\xi^{1-2\alpha(t)}F^2(t) \tag{9}$$

For the numerical evaluation of $f_{\mathcal{P}/p}(\xi,t)$ we use values obtained from the recent CDF results in Ref. [9]: $\sigma_T^{\bar{p}p}(s) = 80.03 \pm 2.24$ mb at $\sqrt{s}$=1800 GeV, $\epsilon = 0.115 \pm 0.008$, and $\alpha' = 0.26 \pm 0.02$. The value of ϵ is the weighted average of three values: one obtained from the rise of the total cross section with energy, $\epsilon = 0.112 \pm 0.013$, and the other two from the ξ-dependence of the SD cross section at $\sqrt{s}$ =546 GeV, $\epsilon = 0.121 \pm 0.011$, and at 1800 GeV, $\epsilon = 0.103 \pm 0.017$. The value of α' is obtained from a fit to the form of Eq. 6 of experimentally measured elastic scattering slope parameters at small-t by CDF and at lower energies at the ISR (see [9]). From the above values we obtain $\sigma_0^{p\bar{p}} = \sigma_T^{p\bar{p}}s^{-\epsilon} = 14.3$ mb and $\frac{\sigma_0^{p\bar{p}}}{16\pi(\hbar c)^2} = 0.73\ GeV^{-2}$. Note that at an energy as high as $\sqrt{s}$=1800 GeV the terms in the cross section that fall as $1/\sqrt{s}$ or faster are negligible and therefore Eq. 4 can be used directly to evaluate $\sigma_0^{p\bar{p}}$. The nucleon form factor, $F(t)$, is obtained from elastic scattering. In the small-t region, the t-dependence of elastic scattering is represented well by $F^4(t) \approx e^{b_{0,el}t}$. From the elastic slope parameter at $\sqrt{s}$ =1800 GeV, $b_{el} = 16.98 \pm 0.25\ GeV^{-2}$ [9], using $\alpha' = 0.26$ we obtain (Eq. 6) $b_{0,el} = b_{el} - 2\alpha' lns = 9.2\ GeV^{-2}$ and hence $F^2(t) \approx e^{b_{0,SD}t} = e^{(1/2)b_{0,el}t} = e^{4.6t}$. This is consistent with the value $b_{0,SD} = 4.2 \pm 0.5\ GeV^{-2}$ measured in [9] at $\sqrt{s} = 1800$ GeV. However, this expression underestimates the cross section at large t-values, and this is the reason for using two exponentials in Eq. 2.

Another expression for the flux factor consistent with Regge theory was proposed by Donnachie and Landshoff (DL) [6], who argue persuasively that the pomeron couples to quarks like an isoscalar photon and therefore the relevant form factor is $F_1(t)$, the isoscalar form factor measured in electron-nucleon scattering

$$F_1(t) = \frac{4m^2 - 2.8t}{4m^2 - t}\left[\frac{1}{1-\frac{t}{0.7}}\right]^2 \tag{10}$$

where m is the mass of the nucleon. The DL flux factor is given by

$$f_{\mathcal{P}/p}(\xi,t) = \frac{9\beta_0^2}{4\pi^2}\xi^{1-2\alpha(t)}F_1^2(t) \tag{11}$$

where $\beta_0 \approx 1.8\ GeV^{-1}$ is the pomeron-quark coupling. With this value for β_0 we obtain $\frac{9\beta_0^2}{4\pi^2} = 0.74$, which is to be compared with the value of $\frac{\sigma_0^{p\bar{p}}}{16\pi(\hbar c)^2} = 0.73$ of Eq. 9. Since the discrepancy factor in the UA8 analysis is based on the DL form factor with a pomeron trajectory $\alpha(t) = 1.08 + 0.25t$ [5], we will use this trajectory and Eq. 11 when we recheck the momentum sum rule for the hard pomeron with a normalized pomeron flux. However, in deriving the energy dependence of the SD cross section below, we will make use of the flux given by Eq. 9 with a pomeron trajectory $\alpha(t) = 1.115 + 0.26t$ and $F^2(t) = e^{4.6t}$, since it corresponds to the expression used to derive the integrated SD cross sections from the (more accurate at high energies) CDF data.

3 Single diffraction dissociation

The integral of the SD cross section can be written in terms of M^2 and t as (see Eqs. 1, 7 &8 and use $\xi = M^2/s$)

$$\sigma_{SD} = C\ s^{2\epsilon}\ \sigma_0^{\mathcal{P}p} \int_{t=0}^{t=\infty} \int_{M_0^2}^{M^2=0.1s} \frac{(s/M^2)^{2\alpha' t}}{(M^2)^{1+\epsilon}}\ F^2(t) dt dM^2 \tag{12}$$

where s and M^2 are in GeV^2, C=0.73, $\epsilon = 0.115$, $\alpha' = 0.26$, $F(t)$ the proton form factor, and $M_0^2 = 1.4\ GeV^2$ is the *effective* diffractive threshold [9]. The only unknown parameter in this expression is $\sigma_0^{\mathcal{P}p}$, the pomeron-proton total cross section at $M^2 = 1$ GeV^2. This formula yields a ratio of the diffractive cross section at $\sqrt{s}$=546 to that at $\sqrt{s}$=20 GeV of 4.5, which is much larger than the experimental value of ≈ 1.6 (see discussion on p. 5546 of Ref. [9]). Clearly, the above expression does not give the correct energy dependence for σ_{SD}. The difference from experiment is almost entirely due to the factor $s^{2\epsilon}$, as pointed out in [9]. The SD cross section as given by Eq. 12 becomes larger than the total cross section at higher energies, violating unitarity.

Let us now insist that no more than one pomeron per incident proton be allowed to participate in a diffractive process, i.e let us *re*-normalize the flux factor to unity:

$$f_s(\xi, t) \equiv \frac{f_{\mathcal{P}/p}(\xi, t) d\xi dt}{N(s)} = \frac{f_{\mathcal{P}/p}(\xi, t) d\xi dt}{\int_{M_0^2/s}^{\xi_{max}} \int_{t=0}^{\infty} f_{\mathcal{P}/p}(\xi, t) d\xi dt} \tag{13}$$

The integrated flux factor ($\xi_{max} = 0.1$) of Eq. 9 with $F^2(t) = e^{4.6t}$ is $N(s) = 1$ at $\sqrt{s} = 20$ GeV and increases with energy approximately as $s^{2\epsilon}$ reaching the value of 9.2 at $\sqrt{s} = 1800$ GeV. The normalized integrated SD cross section is given by

$$\sigma_{SD,N} =< \sigma_T^{\mathcal{P}p} >_{f_s} = \sigma_0^{\mathcal{P}p}\ s^{\epsilon} \int \xi^{\epsilon} f_s(\xi, t) d\xi dt \tag{14}$$

where we have used Eq. 8 with $(M^2)^{\epsilon} = s^{\epsilon}\xi^{\epsilon}$. Again, the only unknown in this equation is $\sigma_0^{\mathcal{P}p}$. The total single diffraction cross section calculated from Eq. 14 with $\sigma_0^{\mathcal{P}p}$ =2.6

mb is compared in Fig. 2 with experimental data from ISR [11], UA4 [8], E710 [12], and CDF [9]. For this particular comparison we used data and calculated cross sections for $\xi < 0.05$ in order to reduce possible non-pomeron contributions to the data [1]. Considering the systematic uncertainties represented by the scatter in the data points, the agreement is good. Without renormalizing the pomeron flux, the calculated cross section at $\sqrt{s}$=1800 GeV would be almost an order of magnitude higher! From Eq. 14 it is clear that the normalized cross section rises with energy at a rate slower than s^{ϵ}, staying safely below the total $p\bar{p}$ cross section, as required by unitarity. An approximate expression for the rise of the total SD cross section with energy is given by (see Fig. 2)

$$\sigma_{SD}^{T} = 4.3 + 0.3\, lns \quad \text{mb} \quad (s \text{ in GeV}^2) \tag{15}$$

4 Pomeron-proton total cross section

The pomeron-proton total cross section is related intimately to the normalized single diffraction cross section through Eq. 14. Fitting the data with this equation not only yields the constant $\sigma_0^{\mathcal{P}p}$ but also verifies the assumed $\sim (M^2)^{\epsilon}$ energy dependence, where $M^2 = \hat{\mathrm{S}}$ is the pomeron-proton center of mass energy. From this fit we therefore infer that

$$\sigma_T^{\mathcal{P}p} = 2.6\, \hat{\mathrm{S}}^{\epsilon} \quad \text{mb} \quad (s \text{ in GeV}^2) \tag{16}$$

where $\epsilon = 0.115$ is the offset from unity of the intercept of the pomeron trajectory at $t = 0$. Thus, the pomeron behaves like a hadron. The ratio of $\sigma_0^{\mathcal{P}p}$ to $\sigma_0^{p\bar{p}}$ is

$$\sigma_0^{\mathcal{P}p/p\bar{p}} = 0.18 \tag{17}$$

Since the uncertainty in the value of ϵ affects both the numerator and denominator of this ratio in approximately the same proportion, the value of the ratio is not sensitive to the error in ϵ. The same is true for the ratio of the triple-pomeron to the pomeron-quark coupling constants discussed below.

5 Triple-pomeron coupling constant

From $\sigma_0^{\mathcal{P}p}$ we obtain the value of the triple-pomeron coupling constant (use Eqs. 8 &4), assuming that it is independent of t:

$$g(t) \equiv g(0) = \frac{g(t)\beta(0)}{\beta^2(0)} = \frac{\sigma_0^{\mathcal{P}p}}{(\sigma_0^{p\bar{p}})^{\frac{1}{2}}} = 0.69 \text{ mb}^{\frac{1}{2}} = 1.1 \text{ GeV}^{-1} \tag{18}$$

This value of $g(t)$ is almost a factor of two higher than the value $g(t) = 0.364 \pm 0.025$ mb$^{\frac{1}{2}}$ reported in Ref. [10]. This apparent discrepancy is due to the different parameterization ($\epsilon = 0$ and $\sigma_0^{p\bar{p}} = \sigma_T^{p\bar{p}}$) used in evaluating $g(t)$ from the data in [10].

If the pomeron couples to quarks, as proposed by DL [6], the pomeron-quark coupling constant may be evaluated by equating the coefficients of Eqs. 9 &11, which yields

$$\beta_0 = \frac{\sqrt{\pi\sigma_0}}{6(\hbar c)} = 1.8 \text{ GeV}^{-1} \tag{19}$$

The ratio of the triple-pomeron to the pomeron-quark coupling, $g(t)$ to β_0, is given by

$$\frac{g(t)}{\beta_0} = 0.61 \tag{20}$$

Again, while the values of both $g(t)$ and β_0 are correlated with the value of ϵ, their ratio is insensitive to the uncertainty in ϵ.

6 Double diffraction dissociation

In double diffraction dissociation (DD) both nucleons dissociate, as shown in Fig. 3. Assuming pomeron exchange and factorization, the DD cross section may be obtained from the SD and elastic scattering cross sections using Eqs. 1, 13 &5,

$$\frac{d^3\sigma_{DD}}{dM_1^2\, dM_2^2\, dt} = \frac{1}{d\sigma_{el}/dt}\, \frac{d^2\sigma_1}{dM_1^2 dt}\, \frac{d^2\sigma_2}{dM_2^2 dt} = \left(\frac{\sigma_0^{\mathcal{P}p}}{4\sqrt{\pi}\hbar c}\right)^2 \left(\frac{s^\epsilon}{N(s)}\right)^2 \frac{e^{2\alpha' ln\left[\frac{s\,(1\,GeV^2)}{M_1^2 M_2^2}\right] t}}{(M_1^2 M_2^2)^{1+\epsilon}} \tag{21}$$

where $N(s)$ is the integral of the pomeron flux factor (see Eq. 13). The nucleon form factor, $F(t)$, drops out in the division, so that the t-dependence is given by the slope parameter

$$b_{DD} = 2\alpha' ln\left[\frac{s\,(1\,GeV^2)}{M_1^2 M_2^2}\right] = 2\alpha'\,\Delta y \qquad \left[\text{GeV}^{-2}\right] \tag{22}$$

where Δy is the rapidity gap between the two diffractive clusters (see Fig. 3). If we now apply the requirement $\Delta y > 2.3$, which corresponds to the *coherence* requirement $(M^2/s) < 0.1$ in single diffraction – since $ln(s/M^2) > -ln(0.1) = 2.3$, we obtain the **coherence condition** for double diffraction:

$$\frac{M_1^2\, M_2^2}{s\,(1\,GeV^2)} < 0.1 \tag{23}$$

With this condition as a constraint the b_{DD} parameter is positive for all mass combinations. If Δy were to become negative, which would correspond to mass clusters

overlapping in rapidity, b_{DD} would become negative and the cross section would increase with t. We therefore interpret Eq. 23 to mean that coherence breaks down for rapidity gaps smaller than ~ 2.3 units, and integrate Eq. 21 subject to the coherence condition to obtain the total DD cross section:

$$\sigma_{DD} = K(s) \int_{M_1^2=1.4}^{0.1s/1.4} \int_{M_2^2=1.4}^{0.1s/M_1^2} \frac{dM_1^2\, dM_2^2}{(M_1^2\, M_2^2)^{1+\epsilon}\, ln(s/M_1^2\, M_2^2)} \tag{24}$$

$$\text{where} \quad K(s) = \frac{1}{2\alpha'} \left(\frac{\sigma_0^{\mathcal{P}p}}{4\sqrt{\pi}\hbar c} \right)^2 \left(\frac{s^\epsilon}{N(s)} \right)^2$$

Table 1 lists cross sections at several energies calculated using this equation. The decrease of the cross section with energy is due to the faster increase of the elastic relative to the diffractive cross section.

Table 1: Total double diffraction cross sections.

$\sqrt{s}$ $[GeV]$	σ_{DD}^T $[mb]$
30	3.1
200	2.3
630	1.7
900	1.6
1800	1.3
14000	0.75

A practical way of measuring the inclusive double diffractive cross section at hadron colliders is to look for events with a rapidity gap centered at $y = 0$. Table 2 lists the cross sections expected at the Tevatron, $\sqrt{s} = 1800$ GeV, as a function of the width Δy of the rapidity gap. These cross sections were calculated from Eq. 24 with $M_{1,max}^2 = M_{2,max}^2 = \sqrt{s}\ e^{-\Delta y/2}$. As shown, the cross section decreases slowly as the rapidity gap width increases.

Using the rapidity gap technique, the UA5 collaboration measured the DD cross section at the CERN S$p\bar{p}$S collider and reported values of 3.5 ± 2.5 (4.0 ± 2.2) mb at $\sqrt{s} = 200$ (900) GeV, respectively [14]. These values are within 1 σ of those in Table 1, but are systematically higher. This may be due to an underestimate of the detector acceptance for DD events, which was obtained with a Monte Carlo simulation where single diffractive clusters were generated on each side and were allowed to reach independently and simultaneously mass values up to $M_{max}^2 = 0.05s$. This procedure allows overlapping diffractive clusters in violation of the coherence condition of Eq. 23, resulting in a lower acceptance for DD events and hence a larger cross section.

Table 2: σ_{DD} versus Δy at the Tevatron.

Δy (central)	$\sigma_{DD}^{\Delta y}$ $[mb]$
2.0	0.62
2.5	0.57
3.0	0.52
3.5	0.47
4.0	0.42
4.5	0.39

At the Tevatron, where the energy of $\sqrt{s}$=1800 GeV provides a rapidity range of 15 units, accurate measurements of DD cross sections as a function of rapidity gap width can be performed using minimum bias data triggered by the "beam-beam" counters. Such data are already available in the CDF and D0 experiments. The measurements can best be done by fitting the particle multiplicity distribution in a given region of $\Delta\eta$ centered at $\eta = 0$ and extracting from the fit the number of *excess* events in the zero multiplicity bin. The fraction of these *rapidity gap* events to the total number of events in the sample can then be compared directly with the values in Table 2 divided by the non-diffractive inelastic cross section of 50 mb.

7 Double pomeron exchange

In double pomeron exchange (DPE) two pomerons, one from each incoming hadron, interact to form a diffractive cluster of mass M centered at rapidity y_M (see Fig. 3). The cross section for DPE is obtained from the SD and total cross sections using factorization (see [13]):

$$\frac{d^4\sigma}{d\xi_1 d\xi_2 dt_1 dt_2} = \frac{1}{\sigma_T^{p\bar{p}}} \frac{d^2\sigma_1}{d\xi_1 dt_1} \frac{d^2\sigma_2}{d\xi_2 dt_2} \tag{25}$$

The mass of the cluster and the rapidity of its centroid are related to the variables $\xi_{1,2}$:

$$M^2 = s\,\xi_1\xi_2 \tag{26}$$

$$y_M = \frac{1}{2}\,ln\frac{\xi_1}{\xi_2}$$

The condition $\xi_{1,2} < 0.1$ for SD translates to the condition

$$M^2 < 0.01\,s$$

Using Eqs. 4 &1 with a normalized pomeron flux, and changing the variables from $\xi_{1,2}$ to M^2 and y, we obtain the expression

$$\frac{d^2\sigma}{dM^2 dy_M} = \sigma_0^{p\bar{p}} \left(\frac{\sigma_0^{\mathcal{P}p}}{16\pi(\hbar c)^2} \frac{s^\epsilon}{N(s)} \right)^2 \left\{ (M^2)^{1+\epsilon} \left[(b + \alpha' ln \frac{s}{M^2})^2 - (2\alpha' y_M)^2 \right] \right\}^{-1} \quad (27)$$

where $b = 4.6$ is the slope parameter of the exponential proton form factor, $F(t)$, used here for simplicity. For a given mass M, y_M varies within the range $\pm\frac{1}{2} ln \frac{M^2}{0.01s}$, so that $|2y_M| < ln \frac{s}{M^2}$ and the term in the square brackets is a function decreasing logarithmically with increasing M^2. As a result, the DP cross section falls approximately as $1/M^2$. A numerical integration of this equation for the range 1 GeV^2 $< M^2 < 0.01s$ yields an inclusive DPE cross section of 61, 76, 69 and 50 μb at $\sqrt{s}$= 50, 630, 1800 and 14000 GeV, respectively. The calculated value of 76 μb at 630 GeV is in agreement with the experimental value of 30-150 μb reported by the UA8 experiment [15]. The DP cross section is approximately constant through the entire range from the ISR to the LHC collider energies. On a finer scale, it rises initially with energy and then falls as the lns term in the denominator becomes comparable to b.

8 Hard diffraction

According to our renormalization scheme, all rate predictions for hard processes in diffraction dissociation based on the procedure suggested by Ingelman and Schlein [3] must be scaled down by the integral of the pomeron flux factor at the given energy. Since the flux factor is unity at $\sqrt{s} = 20$ GeV and increases with energy as $\sim s^{2\epsilon}$, the scaling factor varies approximately as $(\sqrt{s}/20)^{4\epsilon}$. This *renormalization* of the flux lowers substantially all theoretical predictions on hard diffraction and changes drastically the interpretation of experimental results in terms of the structure of the pomeron, as discussed below.

8.1 Does the hard pomeron obey the momentum sum rule?

We are now ready to answer the question: does the hard pomeron reported by UA8 obey the momentum sum rule? As mentioned above, the fact that the observed diffractive dijet rate is considerably smaller than the rates predicted for a pomeron with a fully hard-quark(gluon) structure function is generally interpreted as meaning that the momentum sum rule is violated. However, the predicted rates were calculated with the unnormalized DL flux factor of Eq. 11, whose integral over t and ξ within the range $0 < |t| < \infty$ and $1\ GeV^2/s < \xi < 0.1$ is 3.9 (using $\beta_0^2 = 3.5$ GeV^{-2} as in [5]). Therefore, with a normalized

flux factor the predictions of [5] for the dijet rates become 3.9 times smaller. This correction moves the UA8 "discrepancy factors" of $0.46 \pm 0.08 \pm 0.24$ ($0.19 \pm 0.03 \pm 0.10$) for a hard-quark(gluon) dominated pomeron to the values $1.79 \pm 0.31 \pm 0.93$ ($0.74 \pm 0.11 \pm 0.39$), which are consistent with unity and therefore no longer in disagreement with the momentum sum rule.

8.2 Diffractive W's at the Tevatron and HERA physics

Diffractive W production probes the quark structure function of the pomeron. Using the flux factor of Eq. 2, Bruni and Ingelman predicted [7] that the ratio of diffractive to non-diffractive W production at $\sqrt{s}$=1800 GeV is expected to be $\sim$ 17% (0.8%, 0.3%) for a hard-quark (hard-gluon, soft-gluon) pomeron structure function. With the flux factor of Eq. 9, which has a different ξ and t dependence, the predicted rate under the same kinematical conditions goes up to $\sim$ 24%. However, using the flux scaling factor of $(1800/20)^{4\times 0.115}$ at $\sqrt{s}$=1800 GeV, brings the prediction down to $\sim$ 3%, the exact value depending somewhat on the parameters used in Eq. 9. Therefore, in order to probe the pomeron for an *effective* $\sim$ 15% hard-quark component in its structure function, the level predicted by Donnachie and Landshoff [6] on the basis of their analogy between the pomeron and the photon in the way they couple to quarks, the diffractive to non-diffractive W production ratio must be measured with an accuracy smaller than 0.5%.

Hard diffraction has also been under study in e^-p collisions at $\sqrt{s}$ =314 GeV at HERA, where virtual photons from 30 GeV electrons collide with pomerons from 820 GeV protons. Diffractive events are identified by the rapidity gap method and the results are interpreted in terms of the structure function of the pomeron. As discussed above, in drawing conclusions about the pomeron structure from the data by comparing them to theoretical predictions based on the Ingelman-Schlein model, the predictions must be reduced by the flux scaling factor, which at the typical $\gamma^\star p$ center of mass energy of $\sim$ 150 GeV is $\sim$ 2.5.

8.3 Events with a rapidity gap between two jets

The exchange of a hard pomeron, which is a color-singlet or *colorless* QCD construct, between a proton and an antiproton is expected to produce dijet events with a rapidity gap between the two jets. It was estimated [16] that the ratio, R_{jets}, of the cross section for color-singlet exchange to single gluon exchange events with the same kinematics is $\approx 0.1 < |S|^2 >$, where $|S|^2$ is the "survival probability" for the gap, placed at 3–30% [16, 17]. According to this estimate, R_{jets} should not depend strongly on the rapidity

gap width. At the Tevatron collider at $\sqrt{s} = 1800$ GeV, the D0 collaboration reported an upper limit of 1.1% (95% CL) for such events [18], and CDF reported a signal of $R_{jets} = 0.85 \pm 0.12(stat.)^{+0.0024}_{-0.0012}(syst.)$ [19], which is in agreement with the above prediction. Typical rapidity gaps studied were around 2 units.

As can be seen from Table 2, the ratio of all events with a rapidity gap of two units to all the non-diffractive inelastic events at $\sqrt{s} = 1800$ GeV is 1.25% (the first number in the Table divided by the non-diffractive inelastic cross section of 50 mb [9]). This ratio, which we shall call R_{soft}, *is approximately the same as the ratio* R_{jets} measured by CDF! We therefore propose that the exchange of a pomeron produces the same fraction of hard as soft interactions, which implies that the rapidity gap survival probability in dijet production is close to 100%. A test for this model is provided by the rapidity gap width and energy dependence it predicts for R_{jets}. The dependence on the rapidity gap width at $\sqrt{s} = 1800$ GeV is that of Table 2. The dependence on energy is obtained by dividing the DD cross sections given in Table 1 by the corresponding inelastic non-diffractive cross sections, which can be obtained from the formulae given in this paper. At the LHC, $\sqrt{s} = 14$ TeV, we predict that σ_T=128.5 mb, σ_{el}=44.1 mb, $2\sigma_{SD}$=10.0 mb, $\sigma_{DD} = 0.75$ mb, $\sigma_{DP} = 52$ μb, σ_{ND}=73.6 mb, $\sigma_{DD}^{\Delta y=2}$=0.36, and therefore $R_{jets} = R_{soft}$=0.36/73.6 =0.5% (for $\Delta y = 2$), which is less than one half of the prediction for the Tevatron.

9 Conclusion

Regge phenomenology, with simple pomeron exchange and factorization, describes well the general features of elastic, diffractive, and total cross sections. However, the energy dependence of the single diffraction cross section is not predicted correctly by the theory. In fact, in a model of simple factorizable pomeron exchange with a constant triple-pomeron coupling, the diffractive cross section rises at a rate much larger than the total cross section, violating unitarity at the TeV energy scale. Nevertheless, the concept of factorization was extended to "hard diffraction" processes in a model that assumes that a high energy proton carries along a "pomeron flux" that interacts with *the other* proton producing jets, W's, or involving other high p_T phenomena. This model was employed by the UA8 Collaboration to interpret the results of an experiment designed to probe the structure of the pomeron in diffractive dijet production. The UA8 results indicate that the pomeron has a hard partonic structure, but the reported "hard pomeron" does not obey the momentum sum rule. In this paper we show that by renormalizing the pomeron flux carried by a proton to unity, we obtain the correct energy dependence for the single diffraction cross section, and that with a renormalized pomeron flux the UA8 hard pomeron results become consistent with the momentum sum rule.

In addition to single diffraction, we have calculated cross sections for double diffraction and double pomeron exchange and find agreement with available data. Our results for double diffraction show a rapidity gap dependence that can be tested with accurate measurements at the Tevatron. Furthermore, noting that our prediction for the ratio of *soft* rapidity gap events (double-diffractive) to all non-diffractive events, R_{soft}, is close to the measured ratio for *hard* processes containing jets, R_{jets}, we propose that the observed dijets with a rapidity gap are due to the pomeron and that $R_{jets} = R_{soft}$. On the basis of this model, we then use our calculations for double diffraction to predict that the ratio R_{jets} will decrease slowly with energy to become 0.5% (for $\Delta y = 2$) at the LHC.

Pomeron flux renormalization affects all predictions for hard diffraction processes made with an unnormalized flux, like those of Refs. [3, 7]. Such predictions must generally be reduced by the integral of the flux factor used in deriving them, exercising caution with regard to consistency between the parameters of the pomeron trajectory and the other parameters in the flux factor.

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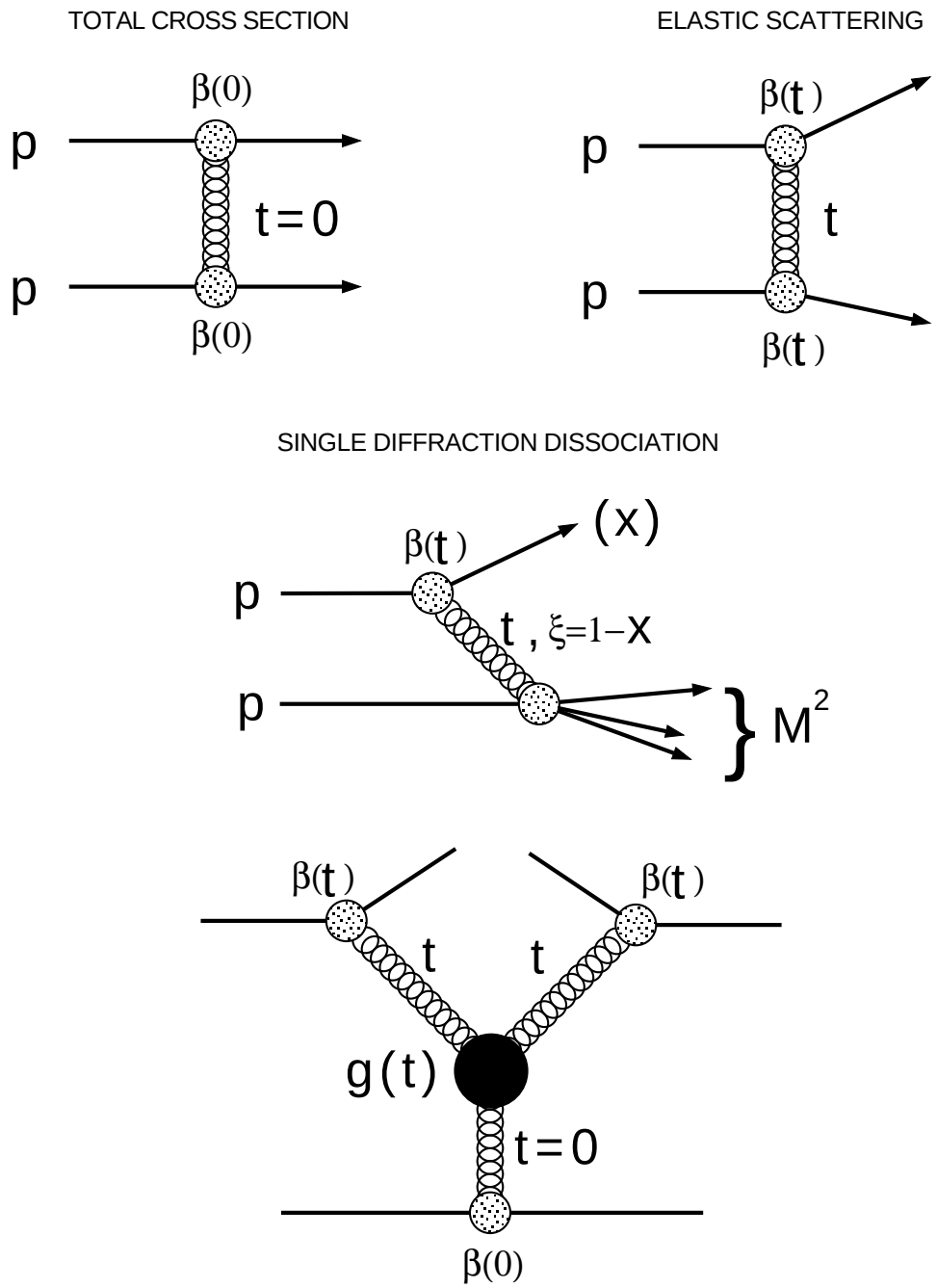

Figure 1: Feynman diagrams for the total, elastic, and single diffraction dissociation cross sections, including the "triple-Regge" diagram for single diffraction.

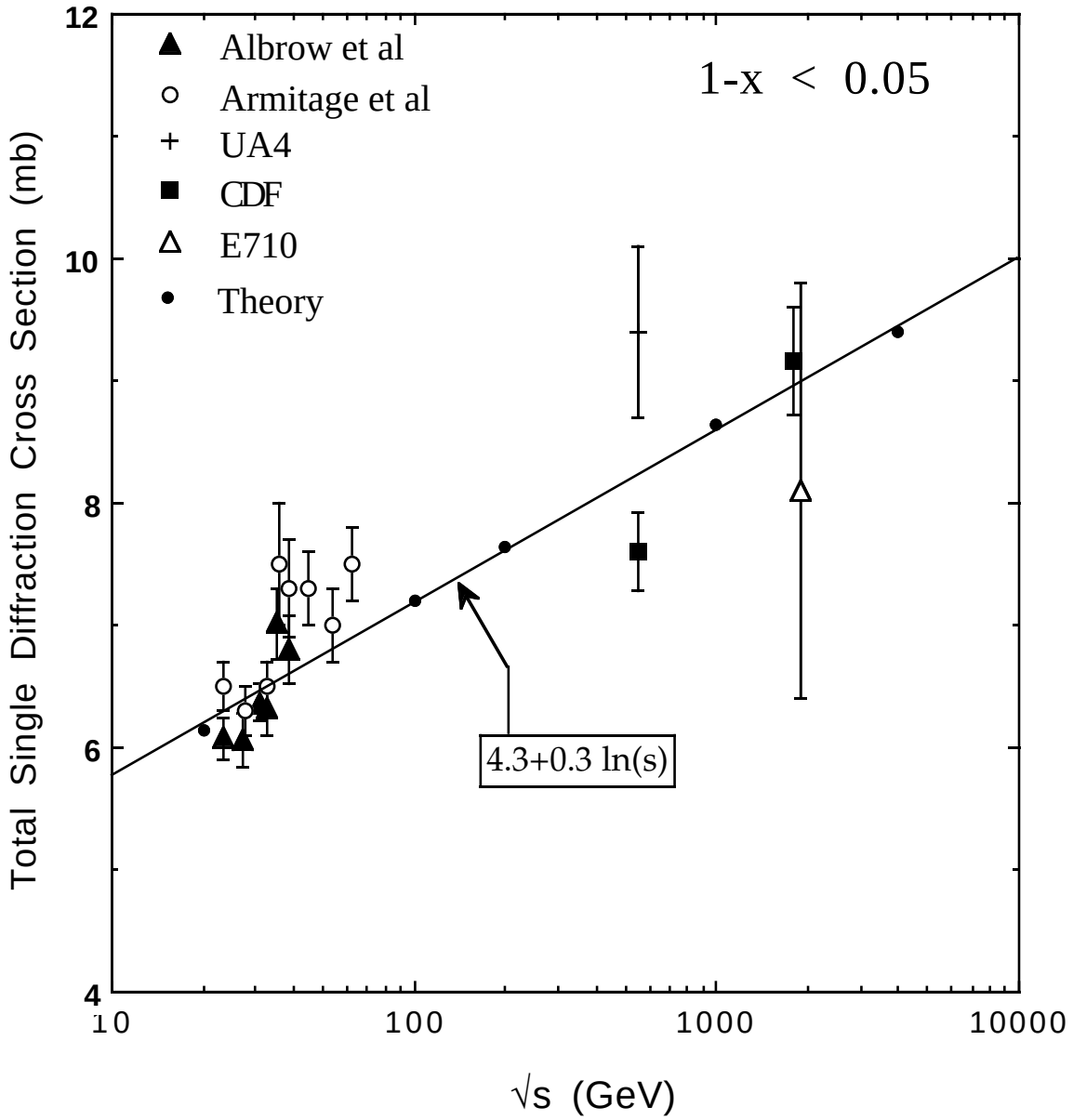

Figure 2: The total $p(\bar{p}) - p$ normalized SD cross section for $\xi < 0.05$, calculated from Eq. 14 with $\sigma_0^{\mathcal{P}p}$=2.6 mb and multiplied by 2, is compared with experimental results.

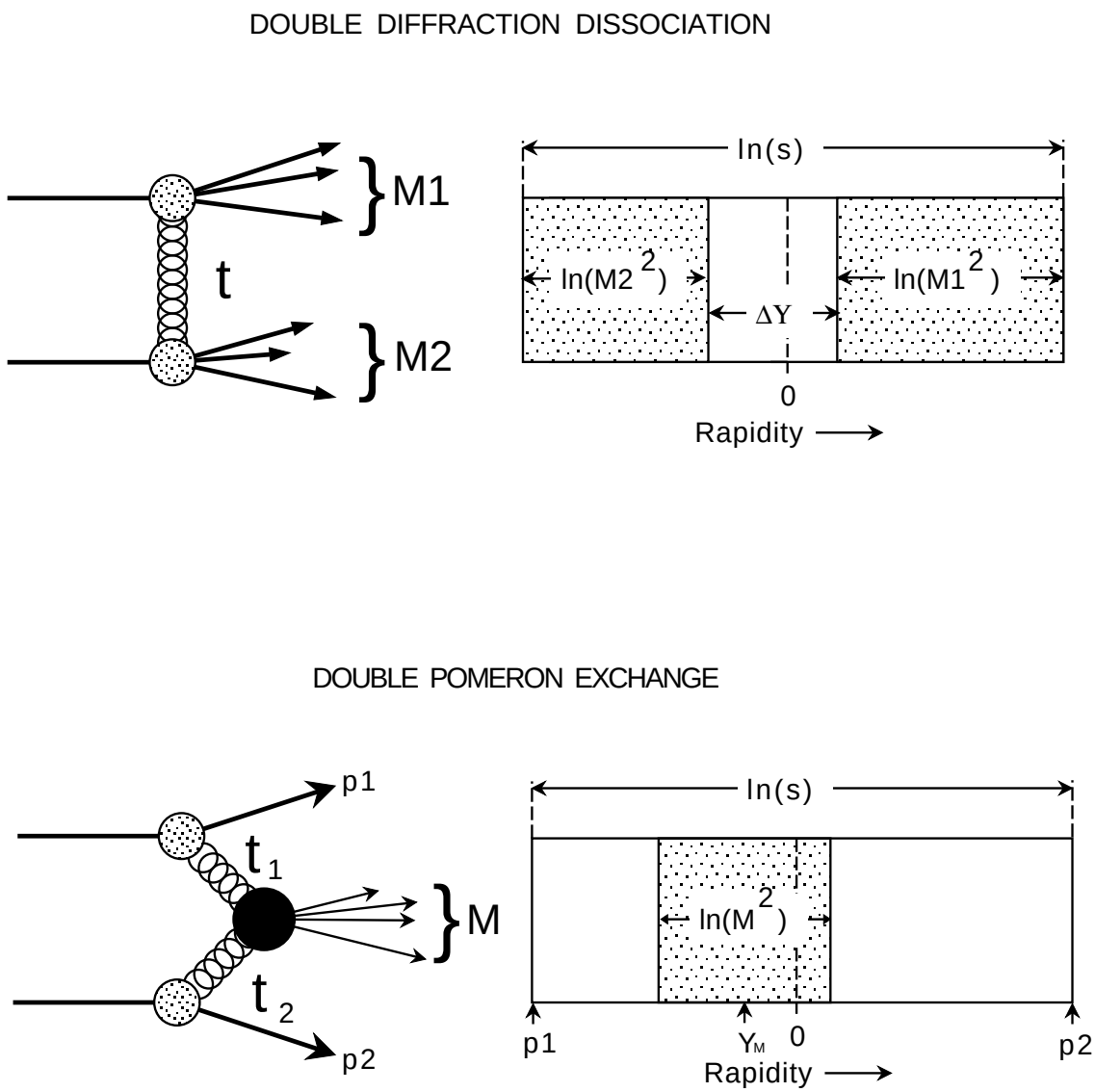

Figure 3: Feynman diagrams, and rapidity regions occupied by the diffractive clusters, for double diffraction dissociation and for double pomeron exchange.