CDF Run 1 Diffractive Results

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Abstract. Results on soft and hard diffraction obtained by the CDF Collaboration in Run 1 of the Fermilab Tevatron $\bar{p}p$ collider are presented. Comparisons are made with theoretical predictions and with results from the DESY ep collider HERA.

I INTRODUCTION

Diffractive events in $\bar{p}p$ collisions are generally characterized by a leading (anti)proton and/or a rapidity gap, defined as a pseudorapidity[3] region devoid of particles (see Fig. 1).

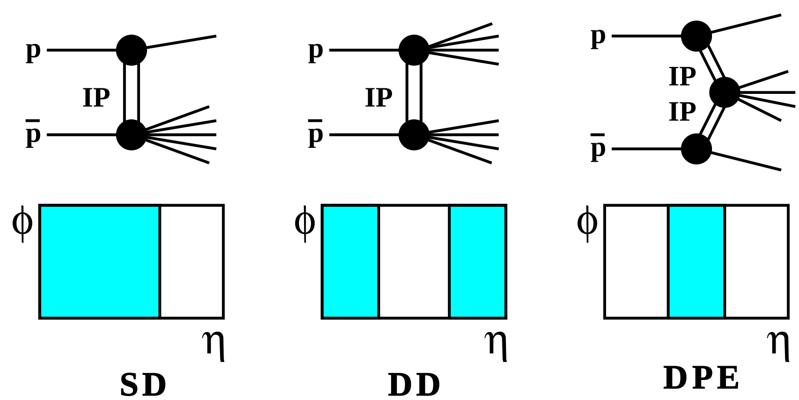

FIGURE 1. Illustrations of (*left*) single diffractive (SD), (*middle*) double diffractive (DD), and (*right*) double pomeron exchange (DPE) events. The shaded areas represent regions of particle production.

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[2] LISHEP 2002 - Session C:Workshop On Diffractive Physics - February 4 - 8 2002 Rio de Janeiro - RJ - Brazil
[3] The pseudorapidity η is defined as $\eta \equiv -\ln(\tan\frac{\theta}{2})$, where θ is the polar angle of a particle with respect to the proton beam direction.

In Regge theory, which has traditionally been used to describe diffraction processes, a rapidity gap is presumed to be associated with the exchange of a pomeron, which in QCD is a color-singlet state with vacuum quantum numbers. Assuming factorization (Regge factorization), the pomeron exchange contribution to the single diffractive (SD) cross section can be expressed as,

$$\frac{d^2\sigma_{SD}}{d\xi dt} = \underbrace{\left[\frac{\beta(t)^2}{16\pi}\xi^{1-2\alpha(t)}\right]}_{f_{I\!P/p}(\xi,t)} \left[g\beta(0)\left(\frac{s\xi}{s_0}\right)^{\epsilon}\right] \tag{1}$$

where ξ is the fractional momentum loss of the proton, t the four momentum transfer squared at the p-$I\!P$ vertex, $\sqrt{s}$ the center-of-mass energy of the $\bar{p}p$ collision, $\alpha(t)$ the pomeron trajectory, $\beta(t)$ the coupling of the pomeron to proton, g the triple-pomeron coupling, and s_0 a constant. The term $f_{I\!P/p}(\xi,t)$ is usually referred to as the pomeron flux factor. Eq. (1) predicts the differential shape of the ξ dependence correctly, but fails to predict the $\sqrt{s}$ dependence of the SD cross section. At $\sqrt{s} = 1800$ GeV, the measured SD cross section was found to be lower than the one given by Eq.(1) by approximately an order of magnitude [1–3]. The recent CDF measurement of the double diffraction (DD) cross section described in section II also tests the Regge theory based on factorization with similar results.

Hard diffraction processes, i.e. those which include a hard (high transverse momentum) partonic scattering, have long been recognized as an interesting place to study the interplay between soft and hard processes. In addition to the question of Regge factorization, another interesting issue in hard diffraction processes is whether they obey QCD factorization, i.e. can be described in terms of parton-parton scattering cross sections convoluted with a universal diffractive (anti)proton structure function. The diffractive structure function depends not only on Q^2 and the Bjorken scaling variable x, but also on ξ and t. As discussed below, QCD factorization has been tested by comparing $\bar{p}p$ hard SD results between two different $\sqrt{s}$ energies, and with expectations from results obtained in diffractive deep inelastic (D-DIS) experiments at HERA, as well as with results on $\bar{p}p$ hard double pomeron exchange (DPE).

The detector components of CDF relevant to diffractive studies are the central tracking chamber (CTC) covering approximately the region $|\eta| < 1.2$, the calorimeters covering the region $|\eta| < 4.2$, and two scintillation beam-beam counter (BBC) arrays covering the region $3.2 < |\eta| < 5.9$.

II SOFT DOUBLE DIFFRACTION

We have measured DD cross sections at $\sqrt{s} = 1800$ and 630 GeV [4] by looking for central rapidity gaps in "minimum-bias" events collected by triggering on a BBC coincidence between the proton and antiproton sides. For practical considerations, we use central rapidity gaps overlapping $\eta = 0$ rather than the largest rapidity

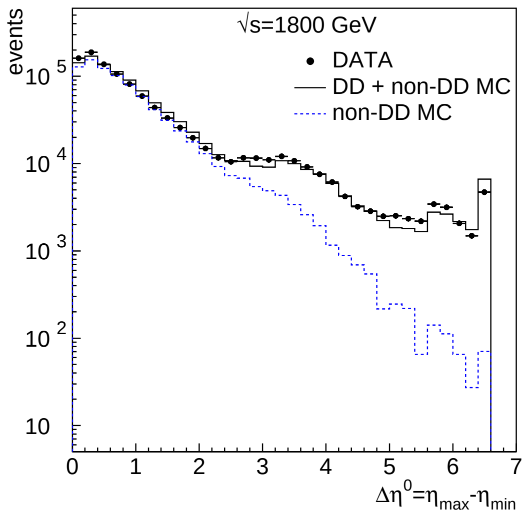

FIGURE 2. Distribution of $\Delta\eta^0 = \eta_{max} - \eta_{min}$ for the 1800 GeV data (points), for DD plus non-DD MC events (solid line), and for only non-DD MC events (dashed line).

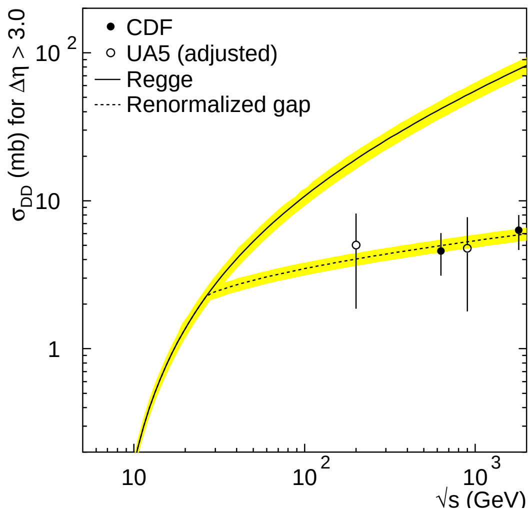

FIGURE 3. The measured total DD cross section as a function of $\sqrt{s}$ (points) compared with predictions from Regge theory based on factorization (solid line) and from the renormalized rapidity gap probability model (dashed line).

gap in the available η-region. In Fig. 2, the distribution of $\Delta\eta^0 \equiv \eta_{max} - \eta_{min}$ for minimum-bias events is shown, where $(\eta_{min})\eta_{max}$ is the η of the "particle" closest to $\eta = 0$ in the (anti)proton direction. A "particle" is a track reconstructed in the CTC, a calorimeter tower above noise level, or a BBC hit. According to Regge theory based on factorization, DD events have approximately flat dependence on $\Delta\eta^0$ in contrast to non-double-diffractive (non-DD) events which are expected to fall exponentially with increasing $\Delta\eta^0$. A mixture of $\Delta\eta^0$ distributions for DD Monte Carlo (MC) events and non-DD MC events fits well the data distribution as shown in Fig. 2, which indicates that Regge theory predicts correctly the $\Delta\eta^0$ dependence. The structure observed in both data and MC $\Delta\eta^0$ distributions is due to the η-dependent thresholds used in the calorimeters to minimize noise contributions.

The DD cross sections for $\Delta\eta^0 > 3$ are found to be $4.43 \pm 0.02(stat) \pm 1.18(syst)$ mb at $\sqrt{s} = 1800$ GeV and $3.42 \pm 0.01(stat) \pm 1.09(syst)$ mb at $\sqrt{s} = 630$ GeV. The extrapolation of the measured DD cross sections for events with $\Delta\eta^0 > 3$ to all gaps with $\Delta\eta > 3$ yields,

$$\sigma_{DD}(\sqrt{s} = 1800 \text{ GeV}, \Delta\eta > 3) = 6.32 \pm 0.03(stat) \pm 1.7(syst) \text{ GeV}$$
$$\sigma_{DD}(\sqrt{s} = \ 630 \text{ GeV}, \Delta\eta > 3) = 4.58 \pm 0.02(stat) \pm 1.5(syst) \text{ GeV}$$

These cross sections are shown in Fig. 3 along with the results from the UA5 Collaboration [5] as a function of $\sqrt{s}$. The DD cross sections measured by the CDF Collaboration are approximately an order of magnitude smaller than those predicted by Regge theory, but are in general agreement with predictions from the renormalized rapidity gap probability model [6]. The renormalized rapidity gap probability model is a generalization of the renormalized pomeron flux model [2] which correctly predicts the $\sqrt{s}$ dependence of the SD cross section.

III HARD SINGLE DIFFRACTION WITH RAPIDITY GAPS

We have measured the ratio of single diffractive (SD) to inclusive rates for W-boson [7], dijet [8], b-quark [9] and J/ψ [10] production at $\sqrt{s} = 1800$ GeV. In these measurements, diffractive events are tagged by a rapidity gap detected in one of the forward calorimeters (FCAL) covering the region $2.4 < |\eta| < 4.2$ and in the adjacent BBC. Using the POMPYT MC simulation [11], the measured SD rate is corrected to correspond to all diffractive events with $\xi < 0.1$. The obtained SD to inclusive ratios are

$$R_W = 1.15 \pm 0.51(stat) \pm 0.20(syst)\ \% \ \ (\xi < 0.1)$$

for $W(\rightarrow e + \bar{\nu}_e)$ events with $p_T^e > 20$ GeV/c, $|\eta^e| < 1.1$ and $\not{E}_T > 20$ GeV,

$$R_{jj} = 0.75 \pm 0.05(stat) \pm 0.09(syst)\ \% \ \ (\xi < 0.1)$$

for dijet events with $E_T^{jet1,2} > 20$ GeV, $1.8 < |\eta^{jet1,2}| < 3.5$ and $\eta^{jet1}\eta^{jet2} > 0$,

$$R_b = 0.62 \pm 0.19(stat) \pm 0.16(syst)\ \% \ \ (\xi < 0.1)$$

for $b(\rightarrow e + X)$ events with the electron of $p_T^e > 9.5$ GeV/c and $|\eta^e| < 1.1$, and

$$R_{J/\psi} = 1.45 \pm 0.24(stat \oplus syst)\ \% \ \ (\xi < 0.1)$$

for $J/\psi(\rightarrow \mu^+\mu^-)$ events with two muons of $p_T^\mu > 2$ GeV/c and $|\eta^\mu| < 1.0$. At $\sqrt{s} = 1800$ GeV, the SD to inclusive ratios are of order 1% for all processes studied.

Since W-boson production is sensitive to the quark content of the pomeron, while dijet and b-quark production are sensitive to the gluon content of the pomeron, we can evaluate the gluon fraction in the pomeron by combining results on diffractive W-boson, dijet and b-quark production. Fig. 4 shows the ratios D of measured to predicted SD to inclusive fractions for W-boson, dijet and b-quark production as a function of the gluon fraction in the pomeron, f_g. The predictions are from POMPYT using the standard pomeron flux[4] and a hard pomeron structure[5]. The least square two-parameter fit to the three CDF results yields $f_g = 0.54^{+0.15}_{-0.14}$ and $D = 0.19 \pm 0.04$. The discrepancy between the CDF-measured ratio D and the D value from HERA [12] indicates a breakdown of QCD factorization. This discrepancy is approximately the same as the one observed between the measured SD cross section and the prediction based on Regge theory and factorization.

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4) The standard pomeron flux is $f_{I\!P/p}(\xi, t) = K\xi^{1-2\alpha(t)}F^2(t)$, where $F(t)$ is the proton form factor, $\alpha(t) = 1.115 + 0.26t$, and $K = 0.73$ GeV^{-2} [2].

5) The hard structure is $\beta f(\beta) = 6\beta(1-\beta)$, where $f(\beta)$ is the parton distribution function of the pomeron and β is the fraction of the momentum of the pomeron carried by a parton.

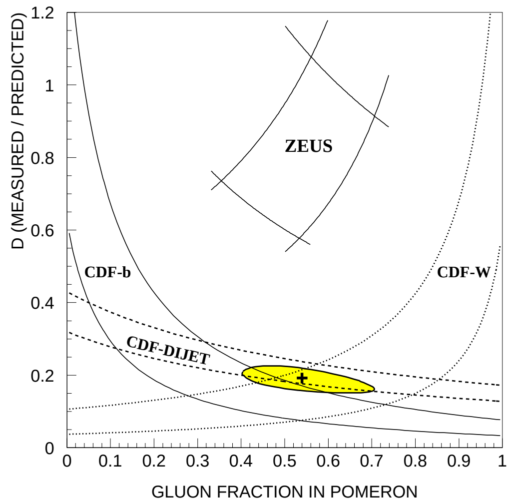

FIGURE 4. The ratio, D, of measured to predicted diffractive rates as a function of the gluon content of the pomeron. The predictions are from the POMPYT MC simulation using a hard pomeron structure. The CDF-W curves were obtained assuming a three-flavor quark structure for the pomeron. The black cross and shaded ellipse are the best fit and 1σ contour of a least square two-parameter fit to the CDF results on diffractive W-boson, dijet and b-quark production.

IV SINGLE DIFFRACTIVE DIJETS WITH LEADING ANTIPROTON

We have studied SD dijet production at $\sqrt{s} = 1800$ and 630 GeV [13,14] using events triggered on a leading antiproton detected in the Roman Pot spectrometer. In leading order QCD, the ratio $R^{SD}_{ND}(x, Q^2, \xi)$ of SD to non-diffractive (ND) dijet production rates is equal to the ratio of the antiproton diffractive to ND structure functions. The diffractive structure function relevant to dijet production integrated over t is given by $F^D_{jj}(x, Q^2, \xi) = x[g^D(x, Q^2, \xi) + \frac{4}{9}q^D(x, Q^2, \xi)]$, where $g^D(x, Q^2, \xi)$ and $q^D(x, Q^2, \xi)$ are the diffractive gluon and quark distribution functions, respectively. Thus, the diffractive structure function may be obtained by multiplying the ND structure function $F_{jj}(x, Q^2)$ by $R^{SD}_{ND}(x, Q^2, \xi)$. The value of x-Bjorken of the struck parton in the antiproton is evaluated from the jet kinematics (including a third jet if $E_T^{jet3} > 5$ GeV) as $x = \sum_{i=1}^{2(3)} E_T^i e^{-\eta^i}/\sqrt{s}$. The obtained diffractive structure function $F^D_{jj}(x, Q^2, \xi)$ can be converted to $F^D_{jj}(\beta, Q^2, \xi)$ by changing variables from x to $\beta = x/\xi$.

Fig. 5 shows the measured $F^D_{jj}(\beta)$ at $\sqrt{s} = 1800$ GeV integrated over the region $0.035 < \xi < 0.095$, $|t| < 1$ GeV^2 and $E_T^{jet1,2} > 7$ GeV. The dashed (dotted) curve is the expectation for $F^D_{jj}(\beta)$ from fit-2 (fit-3) of the diffractive parton distribution functions evaluated by the H1 Collaboration [15] at $Q^2 = 75$ GeV^2, which approximately corresponds to the $\langle E_T^{jet}\rangle^2$ of the CDF data. The measured $F^D_{jj}(\beta)$ and

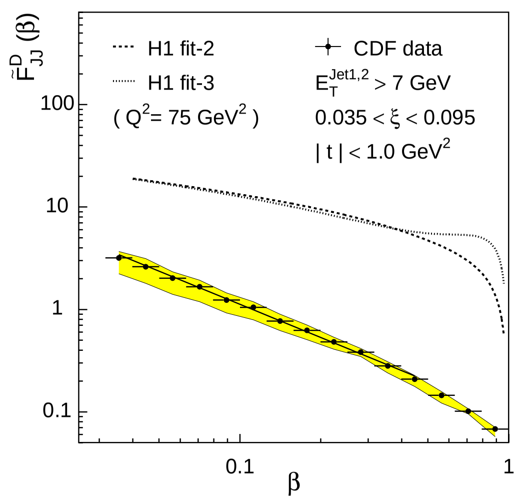

FIGURE 5. Data β distribution (points) compared with expectations from the parton densities of the proton extracted from D-DIS by the H1 Collaboration (dashed and dotted lines). The straight line is a fit to the data of the form β^{-n} in the region $\beta < 0.5$. The lower (upper) boundary of the filled band represents the data distribution obtained by using only the two leading jets (up to four jets of $E_T > 5$ GeV) in evaluating β. The systematic uncertainty in the data normalization is $\pm 25\%$.

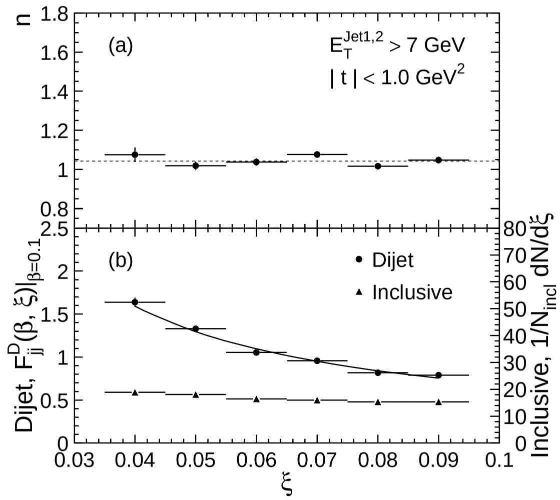

FIGURE 6. Distributions versus ξ: (a) the parameter n of a fit to the diffractive structure function of the form $F^D_{jj}(\beta,\xi)|_\xi = C\beta^{-n}$ for $\beta < 0.5$; (b) the diffractive structure function at $\beta = 0.1$ fitted to the form $F^D_{jj}(\beta,\xi)|_{\beta=0.1} = C\xi^{-m}$ (black points and curve), and the inclusive single-diffractive distribution (triangles). The errors are statistical only. The fits yield $n = 1.0 \pm 0.1$ and $m = 0.9 \pm 0.1$, where the errors are mainly due to the systematic uncertainties in the determination of β.

expectations from the D-DIS analysis by the H1 Collaboration disagree both in normalization and shape indicating a breakdown of QCD factorization. The discrepancy in normalization, defined as the ratio of the integral over β of data to expectation, is $D = 0.06 \pm 0.02$ (0.05 ± 0.02) for fit-2 (fit-3). The relative suppression of the diffractive structure function measured at Tevatron to that measured at HERA is expected in the renormalized pomeron flux model [2,6].

We have also measured the ξ dependence of the diffractive structure function. In the region $\beta < 0.5$, the measured diffractive structure function is well represented by

$$F^D_{jj}(\beta,\xi) = C \cdot \frac{1}{\beta^{1.0\pm0.1}} \cdot \frac{1}{\xi^{0.9\pm0.1}} \tag{2}$$

as shown in Fig. 6, where the errors in the powers of β and ξ dependence are due to the systematic uncertainty in the measurement of β. The observed ξ dependence of F^D_{jj} is much steeper than the $dN/d\xi$ distribution for the inclusive SD data sample, which is rather flat as shown in Fig. 6b. In Regge theory, the flat ξ dependence of the inclusive SD data sample is interpreted as resulting from the mixture of pomeron, reggeon and pion exchanges whose ξ dependences are $\xi^{-\alpha(0)} \sim \xi^{-1.1}$, $\sim \xi^0$ and $\sim \xi$, respectively. The observed ξ dependence of F_{jj}^D indicates that the diffractive dijet production is dominated by pomeron exchange.

The diffractive structure function F_{jj}^D has also been measured at $\sqrt{s} = 630$ GeV and compared with that at 1800 GeV. We find agreement in the β dependence of the measured diffractive structure functions, and a ratio in normalization of $R[\frac{630}{1800}] = 1.3 \pm 0.2(stat)^{+0.4}_{-0.3}(syst)$ in the region $0.1 < \beta < 0.5$, $0.035 < \xi < 0.095$ and $|t| < 0.2$ GeV^2. Within the quoted uncertainties, the measured ratio $R[\frac{630}{1800}]$ is consistent with predictions of the renormalized pomeron flux model [2,6] and the rapidity gap survival model [16].

V DIJET PRODUCTION IN DOUBLE POMERON EXCHANGE

Dijet events with a double pomeron exchange topology have been studied at $\sqrt{s} = 1800$ GeV by the CDF Collaboration using a sample of events triggered on a leading antiproton and requiring two jets in the central pseudorapidity region and a forward rapidity gap in FCAL and BBC on the proton outgoing side.

As mentioned in section IV, the ratio $R_{ND}^{SD}(x_{\bar{p}})$ of SD to ND dijet production rates as a function of $x_{\bar{p}}$ is, in leading order QCD, equal to the ratio of the diffractive to ND structure functions of the antiproton. Similarly, the ratio $R_{SD}^{DPE}(x_p)$ of DPE to SD dijet event rates as a function of x_p is equal to the ratio of the diffractive to ND structure functions of the proton. Therefore, QCD factorization can be tested by comparing the ratios $R_{ND}^{SD}(x_{\bar{p}})$ and $R_{SD}^{DPE}(x_p)$. The variables x_p and $x_{\bar{p}}$ are the Bjorken scaling variables for the proton and antiproton, respectively.

In Fig. 7, the ratio $R_{SD}^{DPE}(x_p)$ is compared with the ratio $R_{ND}^{SD}(x_{\bar{p}})$ as a function of x ($\equiv x_p = x_{\bar{p}}$), where the ratios $R_{SD}^{DPE}(x_p)$ and $R_{ND}^{SD}(x_{\bar{p}})$ are normalized per unit ξ. The data are restricted to the regions $7 < E_T^{jet1,2} < 10$ GeV, $|t_{\bar{p}}| < 1$ GeV^2, $0.035 < \xi_{\bar{p}} < 0.095$, and for DPE $0.01 < \xi_p < 0.03$, where $\xi_{\bar{p}}$ (ξ_p) is the fractional momentum loss of the antiproton (proton), and $t_{\bar{p}}$ is the four momentum transfer squared at the $\bar{p}$-$I\!P$ vertex. The inset in Fig. 7 shows the ξ dependence of the ratios $\tilde{R}_{SD}^{DPE}$ and $\tilde{R}_{ND}^{SD}$, where the tilde over the R indicates the weighted average of the points in the region of x within the vertical dashed lines in the main figure. By considering the extrapolation to $\xi = 0.02$ of a straight line fit to the six $\tilde{R}_{ND}^{SD}$ ratios, the double ratio of $\tilde{R}_{ND}^{SD}$ to $\tilde{R}_{SD}^{DPE}$ is found to be $D \equiv \tilde{R}_{ND}^{SD}/\tilde{R}_{SD}^{DPE} = 0.19 \pm 0.07$. The deviation of D from unity indicates a breakdown of QCD factorization.

We have measured the DPE dijet production cross section by multiplying the DPE to SD dijet event ratio by the SD dijet cross section which is obtained by multiplying the SD dijet to inclusive event ratio by the measured SD inclusive cross section [1]. For the region $0.035 < \xi_{\bar{p}} < 0.095$, $0.01 < \xi_p < 0.03$ and $|t_{\bar{p}}| < 1.0$ GeV^2, the DPE dijet cross section is,

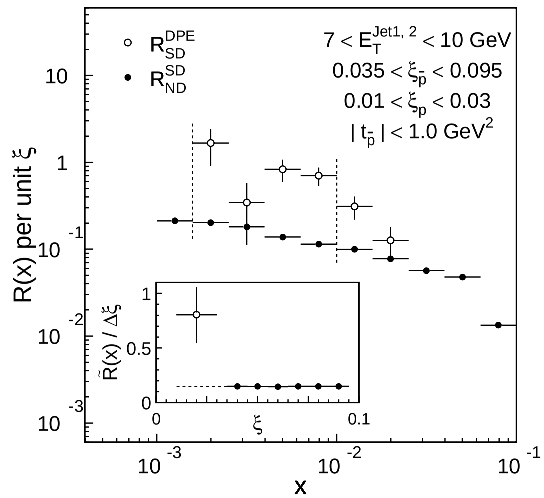

FIGURE 7. Ratios of DPE to SD (SD to ND) dijet event rates per unit ξ, shown as open (filled) circles, as a function x-Bjorken of partons in the p ($\bar{p}$). The errors are statistical only. The SD/ND ratio has a normalization uncertainty of $\pm 20\%$. The inset shows $\tilde{R}(x)$ per unit ξ versus ξ, where the tilde over the R indicates the weighted average of the $R(x)$ points in the region of x within the vertical dashed lines, which mark the DPE kinematic boundary (left) and the value of $x = \xi_p^{min}$ (right).

$$\sigma_{DPE}^{jj}(E_T^{jet1,2} > 7\ \text{GeV}, |\eta^{jet1,2}| < 4.2) = 43.6 \pm 4.4(stat) \pm 21.6(syst)\ \text{nb}$$
$$\sigma_{DPE}^{jj}(E_T^{jet1,2} > 10\ \text{GeV}, |\eta^{jet1,2}| < 4.2) = 3.4 \pm 1.0(stat) \pm 2.0(syst)\ \text{nb}$$

where the systematic uncertainties are largely due to the uncertainties in the SD inclusive cross section and jet energy calibration.

VI CONCLUSIONS

We have made several studies on soft and hard diffraction in Run 1 of the Fermilab Tevatron $\bar{p}p$ collider. In soft single and double diffraction, the measured cross sections are found to be lower than predictions based on Regge theory and factorization, and are in general agreement with predictions from the renormalized rapidity gap probability model [6]. In hard diffraction, a severe breakdown of QCD factorization is observed in comparing $\bar{p}p$ hard single diffraction results with expectations from results obtained in diffractive deep inelastic scattering experiments, and with results from a study of dijet production in $\bar{p}p$ double pomeron exchange events. The observed factorization breakdown is expected in the renormalized rapidity gap probability model [6].

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