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Diffractive Dijet Production at $\sqrt{s}$= 630 and 1800 GeV at the Fermilab Tevatron

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We report a measurement of the diffractive structure function F_{jj}^D of the antiproton obtained from a study of dijet events produced in association with a leading antiproton in $\bar{p}p$ collisions at $\sqrt{s} = 630$ GeV at the Fermilab Tevatron. The ratio of F_{jj}^D at $\sqrt{s} = 630$ GeV to F_{jj}^D obtained from a similar measurement at $\sqrt{s} = 1800$ GeV is compared with expectations from QCD factorization and other theoretical predictions. We also report a measurement of the ξ (x-Pomeron) and β (x of parton in Pomeron) dependence of F_{jj}^D at $\sqrt{s} = 1800$ GeV. In the region $0.035 < \xi < 0.095$, $|t| < 1$ GeV^2, and $\beta < 0.5$, $F_{jj}^D(\beta, \xi)$ is found to be of the form $\beta^{-1.0\pm0.1}\xi^{-0.9\pm0.1}$, which obeys β-ξ factorization.

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In a previous Letter [1], we reported a measurement of the diffractive structure function of the antiproton extracted from events with two jets produced in association with a leading (high momentum) antiproton in $\bar{p}p$ collisions at $\sqrt{s} = 1800$ GeV at the Fermilab Tevatron. Conceptually, diffractive jet production may be thought of as a two-step process, $\bar{p} + p \rightarrow [\bar{p}' + I\!P] + p \rightarrow \bar{p}' + \text{jet}_1 + \text{jet}_2 + X$, where a Pomeron [2], $I\!P$, emitted by the $\bar{p}$ interacts with the proton to produce the jets. In this picture, the structure function of the Pomeron in terms of β (momentum fraction of $I\!P$ carried by its struck parton) at a given value of ξ (momentum fraction of $\bar{p}$ carried by $I\!P$) is directly related to the "diffractive structure function" of the $\bar{p}$ in terms of the familiar Bjorken variable x through the relation $x = \beta\xi$.

A question of paramount importance in hard diffraction is that of the validity of QCD factorization, which would allow cross sections to be expressed in terms of parton-level cross sections convoluted with a unique diffractive structure function. This question was addressed in our previous Letter [1], where we compared our measured diffractive structure function with a prediction based on diffractive parton densities extracted by the H1 Collaboration from a QCD analysis of deep inelastic scattering (DIS) data obtained at the DESY ep collider HERA. A disagreement was found, expressed mainly as a suppression of $\mathcal{O}(10)$ of the overall normalization of our data relative to the prediction. This severe breakdown of QCD factorization is generally attributed to the high densities of low-x partons at the Tevatron, which may lead either to saturation effects [3,4] or to extra partonic interactions in an event spoiling the diffractive rapidity gap [5,6]. Under either scenario, the diffractive structure function is expected to increase as the $\bar{p}p$ collision energy, $\sqrt{s}$, decreases. In this Letter, we report a measurement of the diffractive structure function of the antiproton at $\sqrt{s} = 630$ GeV and compare it with our measurement at $\sqrt{s} = 1800$ GeV and with theoretical expectations. Diffractive dijet production in $\bar{p}p$ collisions at $\sqrt{s} = 630$ GeV has been previously studied by the UA8 Collaboration at the CERN $Sp\bar{p}S$ collider [7], but the results reported were not presented in terms of a normalized Pomeron structure function which could be directly compared with our 1800 GeV measurement.

Another important question in hard diffraction is that of Regge factorization, which allows expressing the diffractive structure function in terms of Pomeron and Reggeon [2] contributions individually obeying β-ξ factorization. Regge factorization is an essential requirement for the Pomeron and Reggeon exchanges to be considered as "particle" exchanges with hadronlike partonic structure functions. The question of β-ξ factorization was not addressed in Ref. [1]. Here we present results on β-ξ factorization using our statistically more significant $\sqrt{s} = 1800$ GeV data.

The present study is similar to our previous diffractive dijet study in experimental setup and in methodology [1]. Briefly, a Roman pot spectrometer (RPS) was employed to trigger the CDF detector on leading antiprotons from $\bar{p}p \rightarrow \bar{p}'X$. In the off-line analysis, the fractional momentum loss ξ of the $\bar{p}$ and the four-momentum transfer squared t were determined with resolutions $\delta\xi = \pm1.5 \times 10^{-3}$ and $\delta t = \pm0.02$ GeV^2 using RPS information and the event vertex. The RPS acceptance at $\sqrt{s} = 630$ GeV is very similar to that at 1800 GeV at the same ξ and for t scaled down by a factor of $(1800/630)^2 = 8.2$. The data were collected in 1995–1996 (Run 1C) with the Tevatron running at $\sqrt{s} = 630$ GeV at an average instantaneous luminosity of $\sim1.3 \times 10^{30}$ cm^{-2} sec^{-1}. After applying off-line cuts requiring a reconstructed track in the RPS, a single reconstructed vertex in the CDF detector within $|z_{\text{vtx}}| < 60$ cm, and a multiplicity of less than 5 in a forward beam-beam counter (BBC) array on the downstream side of the $\bar{p}$ beam, BBC$_{\bar{p}}$, we obtained 184 327 events in the region $0.035 < \xi < 0.095$ and $|t| < 0.2$ GeV^2, which will be referred to below as single diffractive (SD). BBC$_{\bar{p}}$ is one of two 16 channel scintillation counter arrays which covers the region $-5.9 < \eta < -3.2$ [8], where η is the pseudorapidity of a particle defined in terms of the polar angle θ as $\eta = -\ln\tan\frac{\theta}{2}$ (the other BBC array, BBC$_p$, covers the region $3.2 < \eta < 5.9$). The BBC$_{\bar{p}}$ cut is applied to further reject overlap events (caused by multiple interactions in a beam-beam crossing) that pass the single vertex requirement. This cut rejects ≈2.1% of SD events. The nondiffractive (ND) background in the remaining SD sample is ≈2.9%. The BBC$_{\bar{p}}$ cut was not applied in the analysis of the $\sqrt{s} = 1800$ GeV data [1], but a correction was made for the ND background; we have verified that the two methods yield consistent results.

Using the above inclusive SD data set, we selected a SD dijet sample containing 1186 SD events with at least two jets of corrected transverse energy $E_T^{\rm jet} > 7$ GeV. Similarly, a ND dijet sample of 104 793 events was selected from a data set of 2.5×10^6 events collected with a trigger requiring a BBC$_p$-BBC$_{\bar{p}}$ coincidence. The $E_T^{\rm jet}$ was defined as the sum of the calorimeter $E_T \equiv E \sin\theta$ within a cone of radius 0.7 in η-ϕ space [9], where ϕ is the azimuthal angle. The jet energy correction included subtraction of an average underlying event E_T of 0.5 (0.9) GeV for SD (ND) events. These values were determined experimentally, separately for SD and ND events, from the $\sum E_T$ of calorimeter tower energy measured within a randomly chosen η-ϕ cone of radius 0.7 in events of the inclusive SD and ND data samples.

The diffractive dijet sample contains a residual (6.4 ± 2.2)% overlap event, as determined from an analysis of the BBC and forward calorimeter tower multiplicity distributions. Each diffractive data distribution presented below is corrected for the overlap background by subtracting the corresponding ND distribution normalized to the overlap fraction. Another correction is due to the single vertex selection requirement. In addition to rejecting events from multiple interactions, this requirement also rejects single interaction events with multiple vertices caused by reconstruction ambiguities in high multiplicity events. From an analysis of the BBC and forward calorimeter tower multiplicities, the single vertex cut efficiency (fraction of single interaction events retained by the single vertex cut) was determined to be (88.0 ± 1.2)%.

Figure 1 presents the dijet mean E_T and mean η distributions, $E_T^* = (E_T^{\rm jet1} + E_T^{\rm jet2})/2$ and $\eta^* = (\eta^{\rm jet1} + \eta^{\rm jet2})/2$, for the SD (points) and ND (histograms) event samples. As in the 1800 GeV case, the SD E_T^* distribution is somewhat steeper than the ND, and the SD η^* is boosted towards the proton direction (positive η^*). These features indicate that the x dependence of the diffractive structure function of the antiproton is steeper than that of the ND, as discussed further below.

The $\bar{p}$ diffractive structure function is evaluated following the procedure described in our previous Letter [1]. The fraction x of the momentum of the $\bar{p}$ carried by the struck parton is determined from the E_T and η of the jets using the equation $x = (1/\sqrt{s}) \sum_{i=1}^{n} E_T^i e^{-\eta^i}$. The sum is carried out over the two leading jets plus the next highest E_T jet, if there is one with $E_T > 5$ GeV. In leading order QCD, the ratio $R(x)$ of the SD to ND rates is equal to the ratio of the SD to ND structure functions of the $\bar{p}$. The diffractive structure function may therefore be obtained by multiplying $R(x)$ by the known ND structure function. The absolute normalization of the SD dijet sample is obtained by scaling the SD dijet event rate to that of the inclusive diffractive sample and using for the latter the previously measured inclusive diffractive cross section [10]. The normalization of the ND dijet sample is determined from our previously measured 39.9 ± 1.2 mb cross section of the BBC trigger.

Figure 2 shows the normalized ratios $\tilde{R}(x)$ of the number of SD (corrected for RPS acceptance) to ND dijet events at 630 and 1800 GeV for $|t| < 0.2$ GeV^2, $0.035 < \xi < 0.095$, $E_T^{\rm jet1,2} > 7$ GeV and average $E_T^{\rm jet1,2}$ of $E_T^* > 10$ GeV. The tilde over R indicates integration over $(t, \xi, E_T^{\rm jet})$ for SD and $E_T^{\rm jet}$ for ND events. The ratios

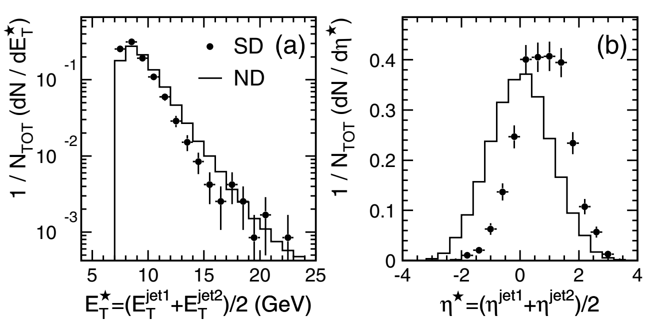

FIG. 1. Mean transverse energy and mean pseudorapidity distributions for single-diffractive (points) and nondiffractive (histograms) events with two jets of $E_T^{\rm jet} > 7$ GeV at $\sqrt{s} =$ 630 GeV.

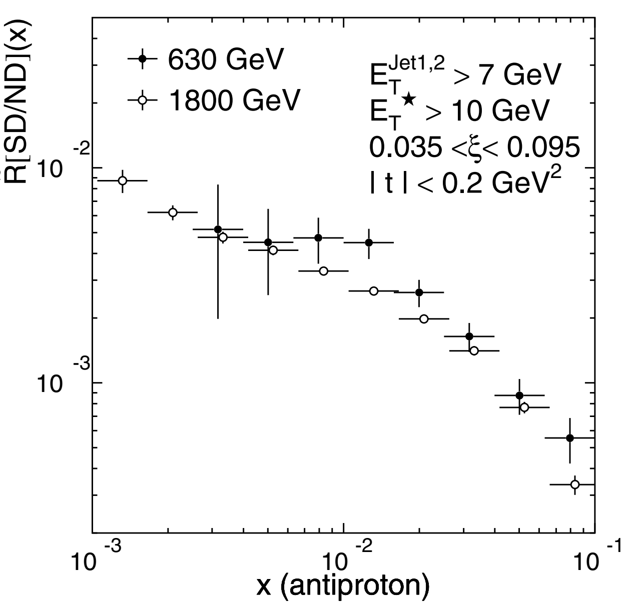

FIG. 2. Ratio of single-diffractive to nondiffractive production rates as a function of x-Bjorken for events with two jets of $E_T > 7$ GeV and mean E_T greater than 10 GeV at $\sqrt{s} =$ 630 GeV (solid points) and 1800 GeV (open circles). The errors are statistical only.

$\tilde{R}(x)$ exhibit similar x dependence at the two energies, but the 630 GeV points lie systematically above the 1800 GeV ones.

The structure function relevant to dijet production can be written as $F_{jj}(x) = x[g(x) + \frac{4}{9}q(x)]$, where $g(x)$ is the gluon and $q(x)$ the quark density, which is multiplied by $\frac{4}{9}$ to account for color factors. The diffractive structure function $\tilde{F}_{jj}^{D}(\beta)$ is obtained by multiplying $\tilde{R}(x)$ by the ND structure function $F_{jj}^{\mathrm{ND}}(x)$ and changing variables from x to β using the relation $x = \beta\xi$. The ND structure function was evaluated using GRV98LO parton densities [11]. Figure 3 shows $\tilde{F}_{jj}^{D}(\beta)$, expressed per unit ξ, for the 630 GeV (black points) and 1800 GeV (open circles) data. The curves are fits of the form $\tilde{F}_{jj}^{D}(\beta) = B(\beta/0.3)^{-n}$ in the range $0.1 < \beta < 0.5$. The value $\beta = 0.1$ corresponds to the limit $x_{\min} = 4 \times 10^{-3}$ imposed on the 630 GeV data to guarantee full detector acceptance for the dijet system from diffractive events associated with the lowest ξ value of 0.035; the upper limit of $\beta = 0.5$ is the value below which the measured $\tilde{F}_{jj}^{D}(\beta)$ at 1800 GeV was found to have a power law behavior [1]. The fits yield $B = 0.262 \pm 0.030$ (0.193 ± 0.005) and $n = 1.4 \pm 0.2$ (1.23 ± 0.04) at $\sqrt{s} = 630$ (1800) GeV, where the quoted uncertainties are statistical. Within these uncertainties, the n parameters are consistent with being equal at the two energies. Fitting the 630 GeV data using the parameter n measured at 1800 GeV yields $B_{630} = 0.255 \pm 0.029$.

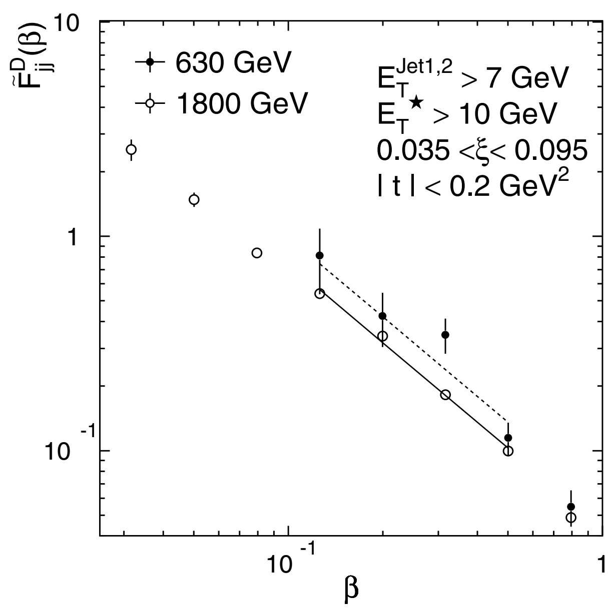

FIG. 3. The diffractive structure function versus β, $\tilde{F}_{jj}^{D}(\beta)$, integrated over the range $0.035 < \xi < 0.095$ and $|t| < 0.2$ GeV^2 and expressed per unit ξ, at $\sqrt{s} = 630$ GeV (solid points) and 1800 GeV (open circles). The errors are statistical only. The lines are fits of the form β^{-n} with the parameter n common at both energies. In the fit region, the systematic uncertainty in the ratio of the 630 to 1800 GeV data is $^{+31}_{-23}\%$ (see text).

The ratio of the 630 to 1800 GeV B parameters is $R_B = 1.3 \pm 0.2$ (stat)$^{+0.4}_{-0.3}$ (syst). The systematic error is due to two contributions: (a) a $\pm 4.5\%$ uncertainty in the ratio of the BBC trigger cross sections at the two energies, combined in quadrature with a $+0.4$ signed uncertainty due to the difference between the experimentally measured inclusive SD cross section at $\sqrt{s} = 1800$ GeV within our (ξ, t) region, $\sigma^{\exp} = 0.57 \pm 0.03$ (stat) mb [obtained from Eqs. (3) and (4) in [10]] and the cross section derived from a global fit to SD cross sections, $\sigma^{\mathrm{fit}} = 0.40 \pm 0.04$ (syst) [12]; (b) a signed uncertainty of -0.3, representing the difference in R_B resulting from using only two or up to four instead of three jets in an event in determining the values of x-Bjorken. Other possible systematic uncertainties, for example those associated with jet energy scale, are less important, as they tend to cancel out in the measurement SD to ND ratios. The measured value of R_B is consistent with unity (factorization), but also with the predictions $R_B^{ren} = (1800^2/630^2)^{2[\alpha(0)-1]} = 1.55$ from [3] using $\alpha(0) = 1.104$ [12] and $R_B = 1.8$ from [6].

To further characterize the diffractive structure function, we have measured its dependence on β and ξ (Fig. 4) using the higher statistics 1800 GeV data sample of events with $E_T^{\mathrm{jet1,2}} > 7$ GeV. In the region $\beta < 0.5$ and $0.035 < \xi < 0.095$, the data are well represented by the factorizable form

$$F_{jj}^{D}(\beta, \xi) = C\beta^{-n}\xi^{-m}. \tag{1}$$

The circle points in Fig. 4a [Fig. 4b] are the values n $[F_{jj}^{D}(\beta, \xi)|_{\beta=0.1}]$ of a fit of Eq. (1) to the data with

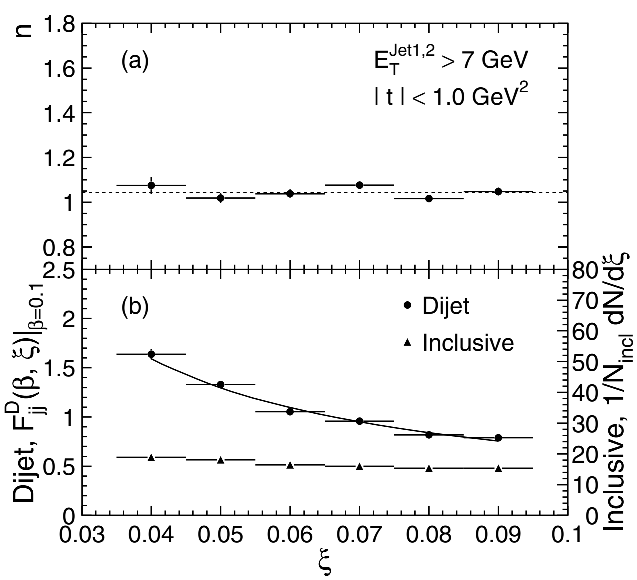

FIG. 4. Distributions versus ξ for 1800 GeV data: (a) the parameter n of a fit to the diffractive structure function of the form $F_{jj}^{D}(\beta, \xi)|_{\xi} = C\beta^{-n}$ for $\beta < 0.5$; (b) the diffractive structure function at $\beta = 0.1$ fitted to the form $F_{jj}^{D}(\beta, \xi)|_{\beta=0.1} = C\xi^{-m}$ (circle-points and curve), and the inclusive single-diffractive distribution (triangles). The errors shown are statistical.

$\beta < 0.5$ within the indicated ξ bin. A straight line one parameter fit to the points in Fig. 4a and a fit of the form ξ^{-m} to those in Fig. 4b yield $n = 1.0 \pm 0.1$ and $m = 0.9 \pm 0.1$, respectively, where the errors are mainly due to the systematic uncertainty in β. The ξ dependence of the inclusive SD data sample is also shown in Fig. 4b (triangles). In Regge theory, the rather flat shape of the inclusive $dN/d\xi$ distribution results from the superposition of a Pomeron exchange contribution, which has a $\xi^{-\alpha(0)} \approx \xi^{-1.1}$ dependence, and a Reggeon exchange contribution, which enters with an effective pion trajectory [12] and is $\sim\xi$. Our measured $\xi^{-0.9\pm0.1}$ dependence indicates that dijet production is dominated by Pomeron exchange.

A similarly steep ξ dependence is exhibited by the $F_2^{D(3)}(\beta, \xi, Q^2)$ structure function extracted from diffractive DIS at HERA in the region $\xi < 0.04$ [13,14]. Our result of $m \approx 1$ shows that a predominantly Pomeron-like behavior, which is generally expected in the small ξ region explored by HERA, is also realized at moderately large ξ values in diffractive dijet production at the Tevatron. Such behavior is predicted by models in which the structure of the generic Pomeron is effectively built from the nondiffractive parton densities by two exchanges, one at the high Q^2 scale of the hard scattering and the other at the hadron mass scale of $\mathcal{O}(1\ \mathrm{GeV}^2)$ [4,6,15].

In summary, we have measured the diffractive structure function of the antiproton from dijet production in $\bar{p}p$ collisions at $\sqrt{s} = 630$ GeV and compare it with that at $\sqrt{s} = 1800$ GeV [1] to test factorization. We find shape agreement and a normalization ratio of $1.3 \pm 0.2\ (\mathrm{stat})^{+0.4}_{-0.3}\ (\mathrm{syst})$, which is compatible with the factorization expectation of unity but also with the predictions of 1.55 and 1.8 of the Pomeron flux renormalization [3] and gap survival probability models [6]. We have also measured the β and ξ dependence of the diffractive structure function at $\sqrt{s} = 1800$ GeV and find that it obeys β-ξ factorization for $\beta < 0.5$. The observed $\xi^{-0.9\pm0.1}$ dependence shows that Pomeron-like behavior extends to moderately high ξ values in diffractive dijet production, which is mainly sensitive to the gluon content of the diffractive structure function. Such behavior is expected in models in which the Pomeron emerges from the quark-gluon sea as a combination of two partonic exchanges, one on a hard scale that produces the dijet system and the other on a soft scale that neutralizes the color flow and forms the rapidity gap [4,6,15].

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