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

The CDF Collaboration

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Abstract

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 with 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, $\bar{p} + p \to [\bar{p}' + I\!P] + p \to \bar{p}' + Jet_1 + Jet_2 + X$, 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 antiproton in terms of the familiar Bjorken variable x through the relation $x = \beta\xi$. A question of interest is whether the Pomeron, which in QCD is a color-singlet construct of (anti)quarks and gluons carrying the quantum numbers of the vacuum, has a unique partonic structure. This question was addressed in our previous Letter [1] by comparing our measured Pomeron structure 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, indicating a severe breakdown of QCD factorization in diffractive processes.

The suppression of the $\bar{p}$ diffractive structure function at the Tevatron relative to that at HERA is generally attributed to low-x partons in the proton interacting with the final state leading $\bar{p}$ and thus spoiling the diffractive signature of the event [3–6]. Consequently, the diffractive structure function is expected to increase as the $\bar{p}p$ c.m.s. energy, $\sqrt{s}$, decreases. An indirect indication of such an effect may have been seen in our measurement of the diffractive structure function of the proton in events with a leading antiproton, whose presence in the event restricts the maximum energy available in the diffractive subsystem [7]. In this Letter, we report a measurement of the diffractive structure function of the antiproton at $\sqrt{s} = 630$ GeV and test QCD factorization by comparing it with our measurement at $\sqrt{s} = 1800$ GeV. In addition, we examine the question of β-ξ factorizarion within the differential form of the diffractive structure function at $\sqrt{s}$ =1800 GeV. Diffractive dijet production in $\bar{p}p$ collisions at $\sqrt{s} = 630$ GeV has been studied by the UA8 Collaboration at the CERN $Sp\bar{p}S$ collider [8], 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.

The present study is identical to our previous diffractive dijet study in the experimental setup used for data collection and in methodology [1]. Briefly, a Roman Pot Spectrometer (RPS) was employed to trigger the CDF detector on leading antiprotons from single diffractive (SD) events, $\bar{p}p \to \bar{p}'X$. In the off-line analysis, the fractional momentum loss ξ of the $\bar{p}$ and the 4-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 1995-96 (Run 1C) with the Tevatron running at $\sqrt{s} = 630$ GeV at an average instantaneous luminosity of $\sim 1.3\times10^{30}$ 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 $|z_{vtx}| < 60$ 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 184327 SD events in the region $0.035 < \xi < 0.095$ and $|t| < 0.2$ GeV^2. BBC$_{\bar{p}}$ is one of two 16 channel scintillation counter arrays which covers the region $-5.9 < \eta < -3.2$ [9], 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$_{\bar{p}}$ multiplicity cut is applied to further reject overlap events that pass the single vertex requirement. The overlap events, consisting of a non-diffractive (ND) event superimposed on a SD, are due to multiple interactions occurring in the same beam-beam bunch crossing. The fraction of SD events rejected by this cut is $\approx 2.1\%$, and the ND background in the remaining SD sample is $\approx 2.9\%$.

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 $E_T^{jet} > 7$ GeV. Similarly, a ND dijet sample of 104793 events was selected from a data set of 2.5 million events collected with a trigger requiring a BBC$_p$-BBC$_{\bar{p}}$ coincidence. The E_T^{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 [10], 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 $(6.4 \pm 2.2)\%$ overlap events, as determined from an analysis of the BBC 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 $(88.0 \pm 1.2)\%$.

Figure 1 presents the dijet mean E_T and mean η distributions, $E_T^* = (E_T^{jet1} + E_T^{jet2})/2$ and $\eta^* = (\eta^{jet1} + \eta^{jet2})/2$, 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 $x = \frac{1}{\sqrt{s}}\sum_{i=1}^{n} E_T^i e^{-\eta^i}$. 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 dijet event rate to that of the inclusive diffractive sample and using for the latter the previously measured inclusive cross section [11]. 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 ratio $\tilde{R}(x)$ of the number of SD dijet events, corrected for RPS acceptance, to the number of ND dijets, after normalizing both SD and ND samples to correspond to the same luminosity (black points). For comparison, $\tilde{R}(x)$ is also shown for our 1800 GeV data (open circles) within the same kinematic region. The tilde over R indicates integration over (t, ξ, E_T^{jet}) for SD and E_T^{jet} for ND events. The integration is carried out over the regions of $|t| < 0.2$ GeV^2, $0.035 < \xi < 0.095$ and $E_T^{jet1,2} > 7$ GeV. To minimize possible normalization shifts between the two data sets resulting from the different underlying event levels at the two energies, or from the influence of the third jet on the E_T values of the leading jets, a cut was imposed on the average dijet transverse energy requiring $E_T^* > 10$ GeV. The ratios $\tilde{R}(x)$ exhibit similar x dependence at the two energies, but the 630 GeV points lie systematically above the 1800 GeV ones. A discrepancy between the two ratios would be evidence for a breakdown of factorization. The observed effect is quantified below after discussion of the relevant systematic errors.

As mentioned above, $R(x)$ represents the ratio of the diffractive to ND parton densities of the antiproton, as viewe by dijet production. The associated structure functions 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 $F_{jj}^{ND}(x)$ and changing variables from x to β using the relation $x = \beta\xi$. The ND structure function was evaluated using GRV98LO parton densities [12].

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 behaviour [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 $B_{630} = 0.255 \pm 0.029$.

The ratio of the 630 to 1800 GeV B parameters is $R_B = 1.3 \pm 0.2\,(\text{stat})^{+0.4}_{-0.3}\,(\text{syst})$. The systematic error is due to two sources. The first source is the uncertainty in the relative normalization between the two energies. This is taken to be the sum in quadrature of a $\pm 4.5\%$ uncertainty in the ratio of the BBC trigger cross sections at the two energies, and a $+0.4$ signed uncertainty resulting from the difference between the experimentally measured inclusive SD cross section at $\sqrt{s} = 1800$ GeV within our (ξ, t) region, $\sigma^{exp} = 0.57 \pm 0.03\,(\text{stat})$ mb (obtained from Eqs. (3) and (4) in [11]), and the cross section derived from a global fit to SD cross sections, $\sigma^{fit} = 0.40 \pm 0.04\,(\text{syst})$ [13]. The second source of systematic uncertainty is 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 of SD to ND ratios, and to an even higher degree in the measurement of the ratio of ratios.

A deviation of R_B from unity quantifies the breakdown of factorization. The measured value of R_B is consistent with factorization, but is also consistent with the prediction $R_B^{ren} = (1800^2/630^2)^{2[\alpha(0)-1]} = 1.55$ of the renormalized Pomeron flux model [3], evaluated using $\alpha(0) = 1.104$ [13] for the Pomeron intercept, and with the value of 1.8 expected in the rapidity gap survival model of [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 $E_T^{jet1,2} > 7$ GeV. In the region $\beta < 0.5$ and $0.035 < \xi < 0.095$, the data are well represented by the factorizable form

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

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 $\beta < 0.5$ 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 associated with the measurement of the β of the struck parton of the antiproton. The observed ξ dependence is steeper than that of the inclusive SD data sample, which 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 [13] and is $\sim \xi$. The 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 $\xi < 0.04$ [14,15]. Our result of $m \approx 1$ shows that a predominantly Pomeron-like behaviour, 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 behaviour is predicted by models in which the structure of the generic Pomeron is effectively built from the non-diffractive 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 $\mathcal{O}(1\text{ GeV}^2)$ [5,6,16].

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 measured previously at $\sqrt{s} = 1800$ GeV to test factorization. We find shape agreement between the two structure functions and a normalization ratio of $1.3 \pm 0.2\,(\text{stat})^{+0.4}_{-0.3}\,(\text{syst})$. Within the quoted uncertainties, this ratio is compatible with the factorization expectation of unity, but is also compatible with the phenomenological predictions of 1.55 and 1.8 of the Pomeron flux renormalization [3] and gap survival probability models [6], respectively. 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 behaviour extends to moderately high ξ values in diffractive dijet production, which is mainly sensitive to the gluon content of the diffractive structure function. Such behaviour 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 [5,6,16].

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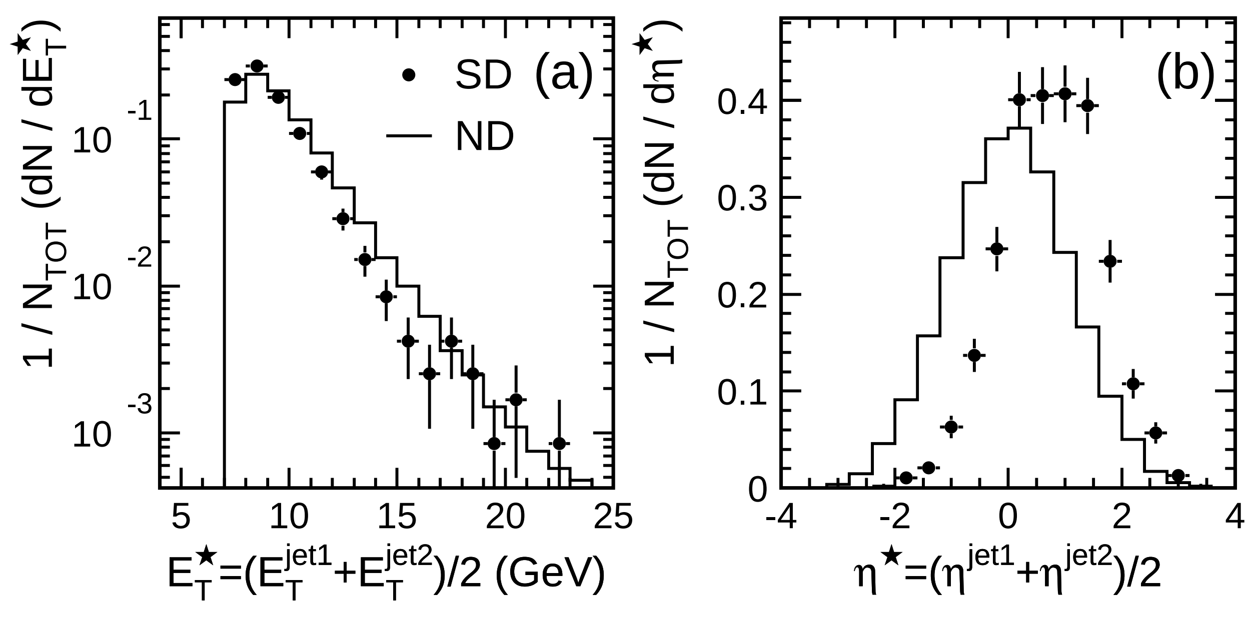

FIG. 1. Mean transverse energy and mean pseudorapidity distributions for single-diffractive (points) and non-diffractive (histograms) events with two jets of $E_T^{jet} > 7$ GeV at $\sqrt{s} = 630$ GeV.

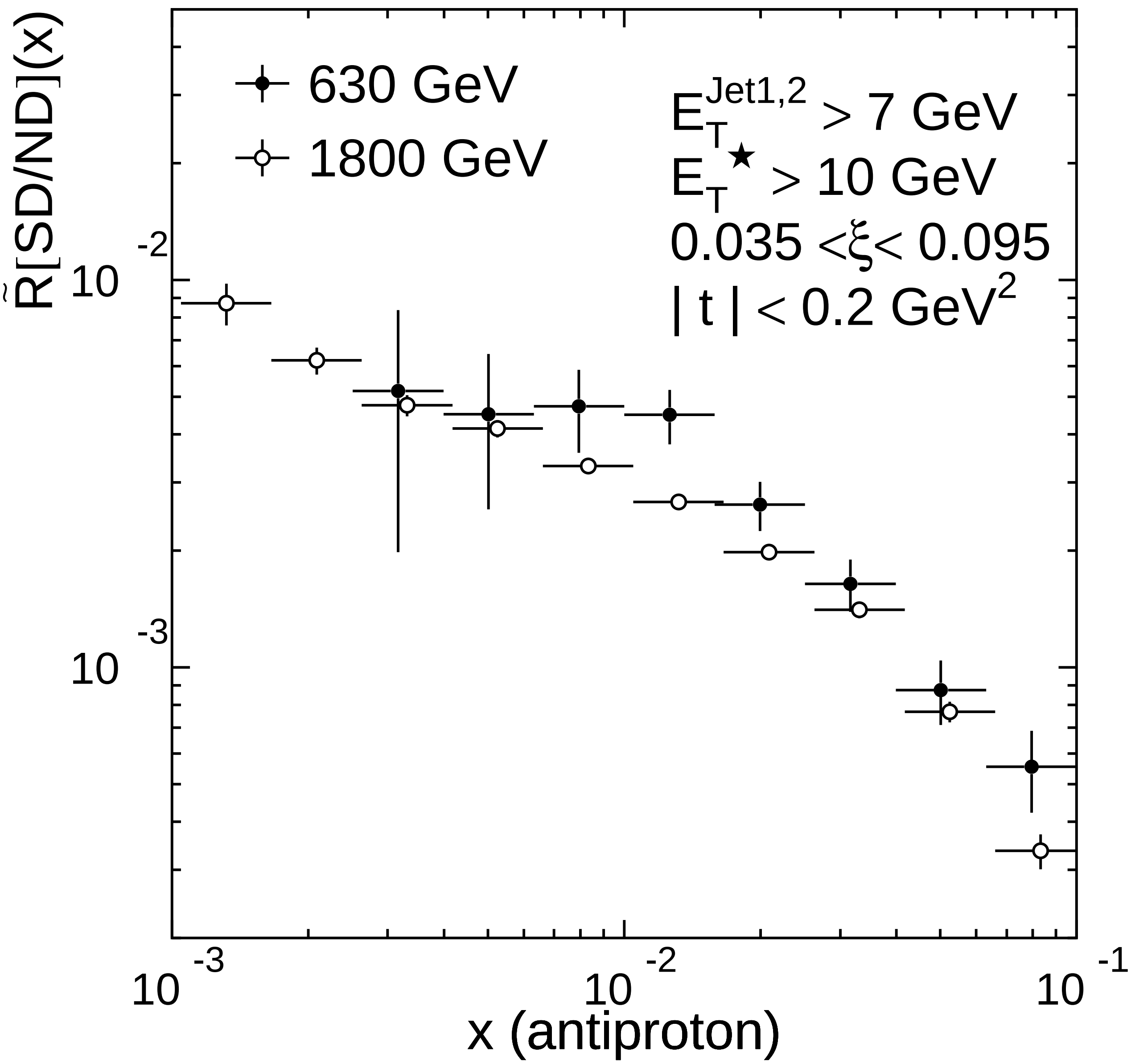

FIG. 2. Ratio of single-diffractive to non-diffractive production rates as a function of x-Bjorken for events with two jets of $E_T > 7$ GeV and mean E_T greater than 10 GeV at $\sqrt{s} = 630$ GeV (black points) and 1800 GeV (open circles). The errors are statistical only.

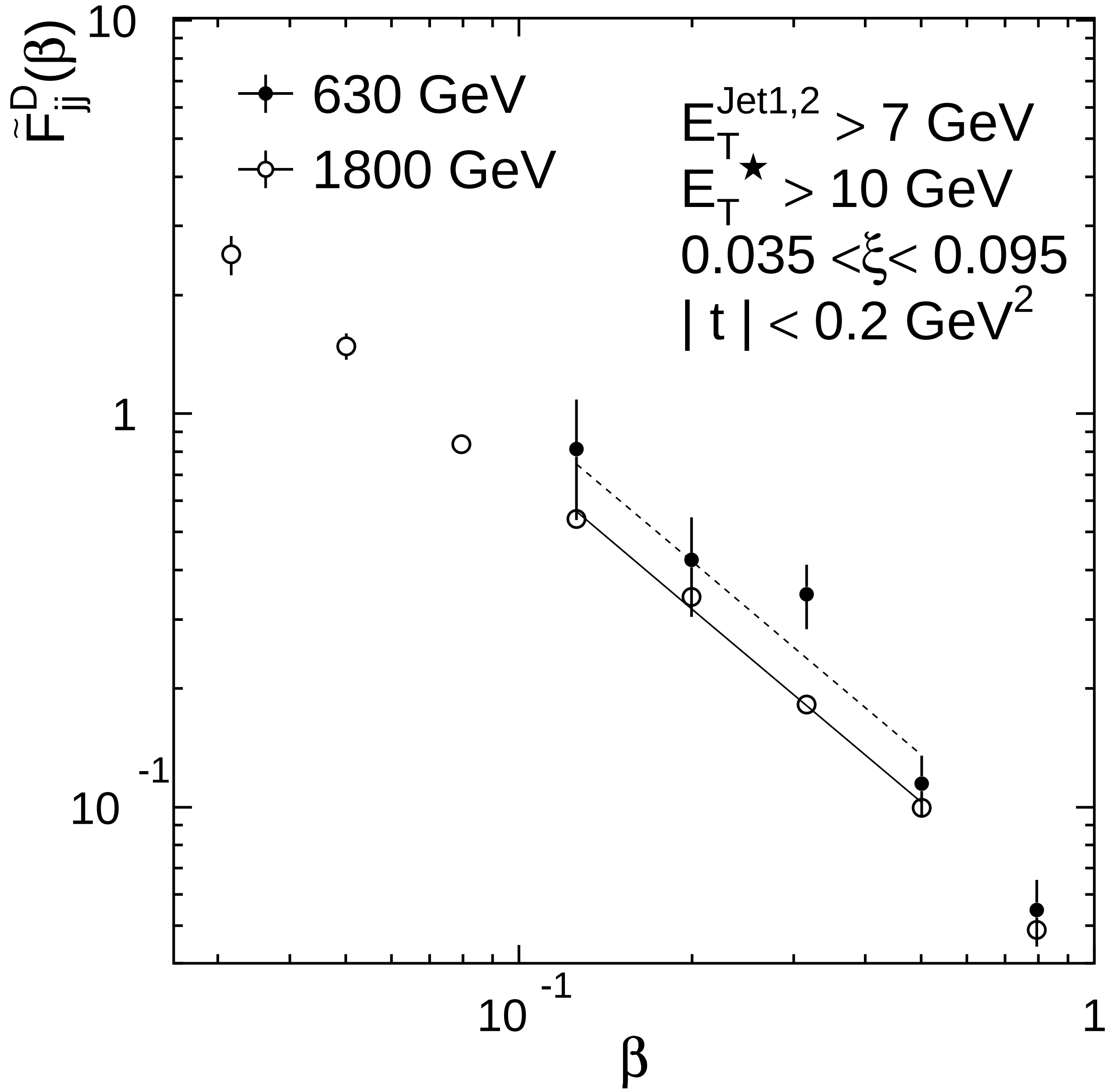

FIG. 3. The diffractive structure function versus β, $\tilde{F}^D_{jj}(\beta)$, integrated over the range $0.035 < \xi < 0.095$ and $|t| < 0.2$ GeV^2 and expressed per unit ξ, at $\sqrt{s} = 630$ GeV (black points) and 1800 GeV (open circles). The errors are statistical only. The lines are fits of the 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).

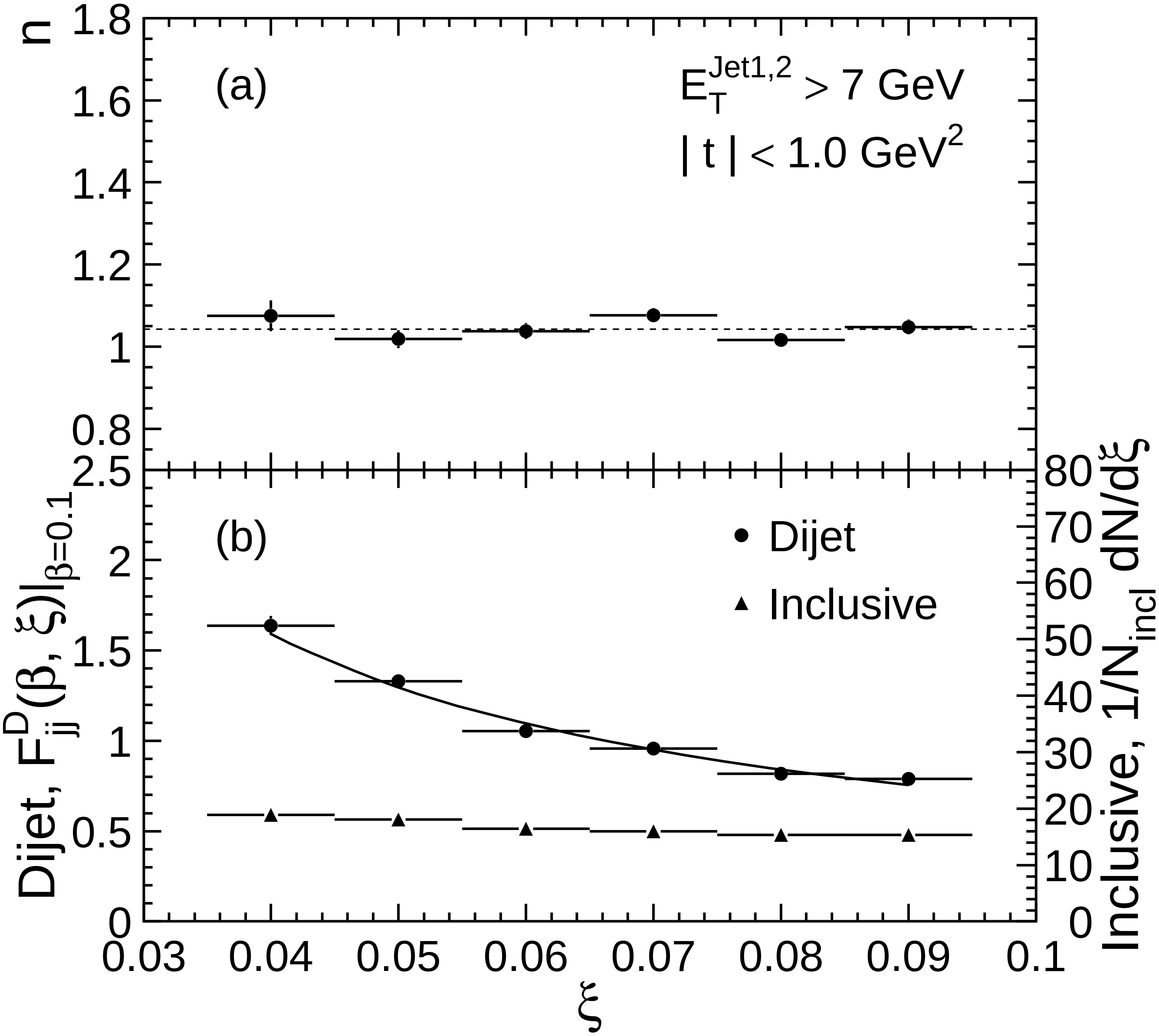

FIG. 4. Distributions versus ξ for 1800 GeV data: (a) the parameter n of a fit to the diffractive structure function of the form $F_{jj}^D(\beta,\xi)|_\xi = C\,\beta^{-n}$ for $\beta < 0.5$; (b) the diffractive structure function at $\beta = 0.1$ fitted to the form $F_{jj}^D(\beta,\xi)|_{\beta=0.1} =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