DIFFRACTIVE STRUCTURE FUNCTIONS AT THE TEVATRON

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We have studied events with a high-\(x_F\) antiproton and two central jets with \(E_T > 7\) GeV in CDF, in pp collisions at \(\sqrt{s} = 1800\) GeV. From the di-jet kinematics we derive the diffractive structure function of the antiproton. We also find an excess of events with a rapidity gap at least 3.5 units wide in the proton direction, which we interpret as di-jet production in double pomeron exchange events. We find non-factorization between our single diffractive results and (a) diffraction in ep at HERA (b) double pomeron exchange.

1 Introduction

There are predominantly three classes of hard diffractive events at the Tevatron (pp collisions at \(\sqrt{s} = 1.8\) TeV). In Single Diffraction, SD, the p or \(\bar{p}\) emerge with \(p_{\text{out}} = (1-\xi)p_{\text{in}}\) with \(\xi < 0.1\) (ideally \(\xi \lesssim 0.05\)). It has small 4-momentum transfer squared \(t = (p_{\text{in}}^4 - p_{\text{out}}^4)^2\). In hard Double Diffraction, DD, between a high \(E_T\) jet at large positive \(\eta\) and one at large negative \(\eta\) there is a rapidity gap of at least 3 units, and in hard Double Pomeron Exchange, DPE, high \(E_T\) jets in the central region have rapidity gaps on both sides, with a leading p and \(\bar{p}\). In SD, we can consider an exchanged entity, which we can call the pomeron \(P\) for convenience (though there can be some other reggeons \(R\) exchanged too), with momentum fraction \(\xi\). If a pair of high \(E_T\) jets are produced, with pseudorapidities \(\eta\), we can calculate the Bjorken-\(x\), \(x_{Bj}\), of the scattering partons from:

\[
x_{Bj} = \frac{1}{\sqrt{s}} \sum_{\text{JETS}} E_T e^{\pm \eta}. \tag{1}
\]

If the interacting partons have fractional momenta \(\beta\) of \(P\), then \(\beta = \frac{x_{Bj}}{\xi}\). If all the hadrons \(i\) in the event are measured, with \(E_T^i\) and \(\eta_i\), then \(\xi\) can also be determined from:

\[
\xi = \frac{1}{\sqrt{s}} \sum_{\text{particles}} E_T^i e^{\pm \eta_i}. \tag{2}
\]

\(^a\)Strictly speaking, the formula should have true rapidity \(y\) not pseudorapidity \(\eta\).
where the +(−) sign is for diffractively scattered ̄p(p). (The p have large positive η.) We define a diffractive structure function \( F(\xi, t, x_{Bj}, Q^2) \). In pomeron language, we measure the parton distribution function in the P. In structure function language, we measure the \( F \) of the p (or ̄p) when we have a large gap or a leading p (or ̄p).

In Run I we measured, using the rapidity gap technique, the diffractive production of di-jets, \( W \), high \( E_T \) b-jets, and \( J/\psi \), and Jet-Gap-Jet JGJ events. Then, for the last two months of the run, we installed scintillating fiber tracking hodoscopes in roman pots to detect diffractively scattered ̄p. We measured ̄pJJ (SD) and ̄pJJG (DPE) events. The central detectors consist of tracking chambers in a 1.5T solenoidal field, surrounded by sampling electromagnetic and hadronic calorimetry used here for measuring particles and jets.

Our studies of diffraction using rapidity gaps can be summarized by saying that for all hard processes (at \( \sqrt{s} = 1.8 \text{ TeV} \)) \emph{approximately} 1% are diffractive. Comparing diffractive \( W \), b-jet and di-jet production we can estimate that at the relevant \( Q^2 \approx M_W^2 \) the gluon fraction in the P is 0.54±0.15. \( W \) are made by q\bar{q} annihilation, b-jets by gg interactions and generic di-jets by a mixture. The soft P at \( Q^2 \approx 0 \) may still be dominated by gluons. Another result is that if one uses a POMPYT Monte Carlo tuned to ep diffractive data and assumes factorization, one predicts a factor \( \approx 5 \) too much hard diffraction at the Tevatron. This is an indication of the breakdown of factorization, implying that one cannot treat hard diffractive processes as the emission of a pomeron with a universally-defined parton distribution function (Ingelman-Schlein model).

Although in this talk I concentrate on CDF results, DØ have presented a study of events with forward rapidity gaps and either forward or central di-jets at both \( \sqrt{s} = 630 \) and 1800 GeV. They compared ratios of these conditions with Monte Carlo predictions with hard, soft or flat g-distributions in the pomeron. None of these choices fits the data. It is possible to compare the data to a prediction with a flat distribution and extract an effective distribution; also to use equ. (1) and (2) to estimate \( x_p \) and \( \xi \). However, what one really wants to do is to tag the P by measuring the quasi-elastic (anti-)proton, so that one can measure the diffractive structure functions directly.

2 Single Diffraction with measured ̄p

Near the end of Run I we installed small (2 cm × 2 cm) scintillating fiber x,y hodoscopes in three roman pots 56 m downstream from CDF. Antiprotons are measured after passing through 81.6 Tm of dipole field. In one low luminosity run at \( \sqrt{s} = 1.8 \text{ TeV} \), 3.1M events were collected which after clean up (single high quality central vertex, single clean pot track with 0.035 < \( \xi < 0.095 \), \( |t| < \)
1.0 GeV\(^2\)) reduces to 1,639k events. Of these, 30.4k = 1.86\% have at least 2 jets with \(E_T > 7\) GeV. For comparison we took 342k non-diffractive events, of which 32.6k = 10.9\% have at least two 7 GeV jets. The main reason why ND events are 6 times richer in jets than SD events is the higher available energy (1800 GeV cf. \(\sqrt{s} = 330 - 550\) GeV). The fraction of diffractive triggers that have di-jets rises with \(\xi\) from 0.013 to 0.022. Interestingly there is no dependence on \(|t|\) from \(|t|_{\text{min}}\) to 3 GeV\(^2\),

\[
t_{\text{min}} = 2 \left[ m_p^2 - (E_{\text{in}}E_{\text{out}} - p_{\text{in}p_{\text{out}}}) \right]. \tag{3}
\]

The \(E_T^{\text{JET}}\) spectrum extends to 35 GeV, and is steeper than the ND jet spectrum. The jets are boosted towards the proton direction (positive rapidity) by about 1 unit, on average.

We can use the jet kinematics to measure Bjorken-\(x\), \(x_{\text{Bj}}\), of the colliding partons, see equ. (1). A 3rd jet is included if it has \(E_T > 5\) GeV. Let the ratio of SD:ND jets be \(R(\frac{SD}{ND})(x_p, \xi)\) and the ND di-jet effective structure function be:

\[
F_{jj}(x_p) = x_p \left[ g(x_p) + \frac{4}{9} \sum q_i(x_p) + \bar{q}_i(x_p) \right]. \tag{4}
\]

For \(F_{jj}(x_p)\) we use the GRV98LO structure function. Then

\[
F_{jj}^D(x_p, \xi) = R(\frac{SD}{ND})(x_p, \xi) \times F_{jj}(x_p) \tag{5}
\]

and through the change of variables \(\beta = \frac{x_p}{\xi}\) we can derive \(F_{jj}^D(\beta, \xi)\).

The ratio \(R(\frac{SD}{ND})(x_p)\) for different \(\xi\) is shown in Fig.1 vs \(x_{\text{Bj}}\) (antiproton) = \(x_p\). It is not flat, showing that when a lower \(x_{\text{Bj}}\) parton gives rise to the jets it is more likely (than a higher \(x_{\text{Bj}}\) parton) to be a diffractive event. The middle part of the distribution, not affected by kinematic boundaries, fits a power law:

\[
R(\frac{SD}{ND})(x_p) = (6.1 \pm 0.1) \times 10^{-3} \times (x_p/0.0065)^{-0.45 \pm 0.02}. \tag{6}
\]
Figure 1. Ratio of diffractive to non-diffractive di-jet event rates as a function of $x_{Bj}$. Different $\xi$ regions are plotted separately and displaced for clarity.

Figure 2. Data $\beta$ distribution (points) compared with expectations from diffractive deep inelastic scattering (H1). The dashed(dotted) lines are from H1 fit 2(3).
When we change variables and plot $F_{jj}^D(\beta)$ vs $\beta$ we find (see Fig.2) a falling distribution with no sign of a $\beta = 1$ peak ("superhard pomeron") and normalization a factor $> 10$ lower than the H1 fits (ep). This is showing a breakdown of (ep $\leftrightarrow$ pp) factorization. The $x_{Bj}(\text{antiproton})$ and $\beta$ distributions appear to be independent of $\xi$ from 0.035 to 0.095; we have a factorizing form for $10^{-3} < \beta < 0.5$:

$$F_{jj}^D(\beta, \xi) = C \beta^{-1.04\pm0.01} \xi^{-m}.$$  (7)

At larger $\beta$, $m$ rises from $\approx 0.85$ at $\beta = 0.03$ to $\approx 1.2$ at $\beta = 1$, similar to the behavior observed at H1 and ZEUS.

3 Double Pomeron Exchange

We now turn to double pomeron exchange, which provides another test of factorization. We take the SD di-jet events and look for rapidity gaps ($\Delta \eta > 3.5$) on the outgoing p-side, by counting hits in the region $2.4 < \eta < 5.9$. We find 132 events with 0 hits, while an extrapolation of the bulk of the multiplicity distribution gives 14 events, so the signal is very significant with a S:N = 10:1. (This is with both jet $E_T > 7$ GeV; with a 10 GeV cut we still have 17 events.) The mean $<\xi_p>$ is slightly larger (within the range 0.035 - 0.095) for these DP events than for the SD events. As well as measuring $\xi_p$ with the pot track, we can estimate it from the sum over all hadrons, see equation (2). By comparing the two we find a correction factor of 1.7 (not all particles are detected and/or well measured). Then we can estimate the $\xi_p$ of the unseen proton as

$$\xi_p = 1.7 \times \frac{1}{\sqrt{s}} \sum E_i^\gamma e^{\eta_i}.$$  (8)

Most of the events have $0.01 < \xi_p < 0.03$ and for definitiveness we make that cut. The $E_T$ spectrum of the jets is like that in SD, but the statistics are poor above 12 GeV. The $\eta$ of the di-jet tends to be negative (towards the $\bar{p}$) as one expects from $\xi_p - \xi_{\bar{p}}$. In fact:

$$\Delta \eta \approx \ln \xi_{\bar{p}} - \ln \xi_p.$$  (9)

The $\Delta \phi$ distribution between the leading jets is slightly more peaked at $180^\circ$ than in SD (and SD more than ND). The fraction of all the central mass carried by the two leading jets, $R_{X}^{jj}$, is a broad distribution with no sign of a peak near 1, which might be expected from a non-factorizing DPE diagram.

Just as before we could plot $R(\text{SD})(x_{\bar{p}})$, now we can plot $R(\text{DPE})(x_p)$ in the same range of $x_{Bj}$. If we had factorization among these processes we would...
expect these quantities to be equal; in fact the latter is a factor ≈5 higher. This does not seem to be due to the different ξ ranges of the p and ¯p, as we saw before no ξ-dependence in $R(\frac{SD}{ND}) (x_p)$.

We can quote a cross section for $0.01 < \xi_p < 0.03$, $0.035 < \xi_p < 0.095$, $-4.2 < \eta^{jet1,2} < +2.4$, $E_T^{jet1,2} > 7(10)$ GeV of $43.6\pm22 (3.4\pm2.2)$ nb, where the error is essentially all systematic resulting from the difficulty of measuring such low $E_T$ jets. Removing the ξ cut to gain statistics, at 95% c.l. < 8.5% of the 7 GeV di-jets are exclusively produced, i.e. with $R_{X}^{JJ} \approx 1$. This is much smaller than a prediction of ≈ 1 µb.

In conclusion, we measured non-factorizing effects in hard diffraction. The “pomeron” does not have a unique structure function; it depends on the environment (ep, p̅p(SD), p̅p(DPE)). In hard diffraction, a more realistic picture than the Ingelman-Schlein model is probably one where a hard scatter takes place (on a very short space-time scale) and before or after (on a much longer space-time scale) soft gluons are exchanged which can create rapidity gaps and can leave the p, p̅ or both in their ground state. These soft color interactions are quite different when the interaction involves an €̅€, €̅€, γ than when it does not.

4 Acknowledgements

I thank Dino Goulianos, Albert de Roeck and the organizers of ISMD 2000 for their invitation, and the Fermilab staff and the staffs of CDF institutions for their contributions. This was a supplementary program (E876) within CDF, and additional support from the U.S. Department of Energy and the Ministry of Education, Science and Culture of Japan is gratefully acknowledged.

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