CDF experimental results on diffraction

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Abstract
Experimental results on diffraction from the Fermilab Tevatron collider obtained by the CDF experiment are reviewed and compared. We report on the diffractive structure function obtained from dijet production in the range $0 < Q^2 < 10,000$ GeV^2, and on the $|t|$ distribution in the region $0 < |t| < 1$ GeV^2 for both soft and hard diffractive events up to $Q^2 \approx 4,500$ GeV^2. Results on single diffractive W/Z production, forward jets, and central exclusive production of both dijets and diphotons are also presented.

1 Introduction

Diffractive processes are characterized by the presence of large rapidity regions not filled with particles ("rapidity gaps"). Traditionally discussed in terms of the "Pomeron", diffraction can be described as an exchange of a combination of quarks and gluons carrying the quantum numbers of the vacuum [1].

At the Fermilab Tevatron collider, proton-antiproton collisions have been used to study diffractive interactions in Run I (1992-1996) at an energy of $\sqrt{s} = 1.8$ TeV and continue in Run II (2003-present) with new and upgraded detectors at $\sqrt{s} = 1.96$ TeV. The goal of the CDF experimental program at the Tevatron is to provide results help decipher the QCD nature of hadronic diffractive interactions, and to measure exclusive production rates which could be used to establish the benchmark for exclusive Higgs production at the Large Hadron Collider (LHC). The study of diffractive events has been performed by tagging events either with a rapidity gap or with a leading hadron. The experimental apparatus includes a set of forward detectors [2] that extend the rapidity [3] coverage to the forward region. The Miniplug (MP) calorimeters cover the region $3.5 < |\eta| < 5.1$; the Beam Shower Counters (BSC) surround the beam-pipe at various locations and detect particles in the region $5.4 < |\eta| < 7.4$; the Roman Pot spectrometer (RPS) tags the leading hadron scattered from the interaction point after losing a fractional momentum approximately in the range $0.03 < \xi < 0.10$.

2 Diffractive dijet production

The gluon and quark content of the interacting partons can be investigated by comparing single diffractive (SD) and non diffractive (ND) events. SD events are triggered on a leading anti-proton in the RPS and at least one jet, while the ND trigger requires only a jet in the calorimeters. The ratio of SD to ND dijet production rates (N_{jj}) is proportional to the ratio of the corresponding

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structure functions (F_{jj}), $R_{\frac{SD}{ND}}(x,\xi,t) = \frac{N_{jj}^{SD}(x,Q^2,\xi,t)}{N_{jj}(x,Q^2)} \approx \frac{F_{jj}^{SD}(x,Q^2,\xi,t)}{F_{jj}(x,Q^2)}$, and can be measured as a function of the Bjorken scaling variable $x \equiv x_{Bj}$ [4]. In the ratio, jet energy corrections approximately cancel out, thus avoiding dependence on Monte Carlo (MC) simulation. Diffractive dijet rates are suppressed by a factor of O(10) with respect to expectations based on the proton PDF obtained from diffractive deep inelastic scattering at the HERA ep collider [1]. The SD/ND ratios (i.e. gap fractions) of dijets, W, b-quark, J/ψ production are all approximately 1%, indicating that the suppression factor is the same for all processes and it is related to the gap formation.

In Run II, the jet E_T spectrum extends to $E_T^{\rm jet} \approx 100$ GeV, and results are consistent with those of Run I [5], hence confirming a breakdown of factorization. Preliminary results indicate that the ratio does not strongly depend on $E_T^2 \equiv Q^2$ in the range $100 < Q^2 < 10,000$ GeV^2 (Fig. 1, left). The relative normalization uncertainty cancels out in the ratio, and the results indicate that the Q^2 evolution, mostly sensitive to the gluon density, is similar for the proton and the Pomeron. A novel technique [6] to align the RPS is used to measure the diffractive dijet cross section as a function of the t-slope in the range up to $Q^2 \simeq 4,500$ GeV/c^2 (Fig. 1, right). The shape of the t distribution does not depend on the Q^2 value, in the region $0 \leq |t| \leq 1$ GeV^2. Moreover, the $|t|$ distributions do not show diffractive minima, which could be caused by the interference of imaginary and real parts of the interacting partons.

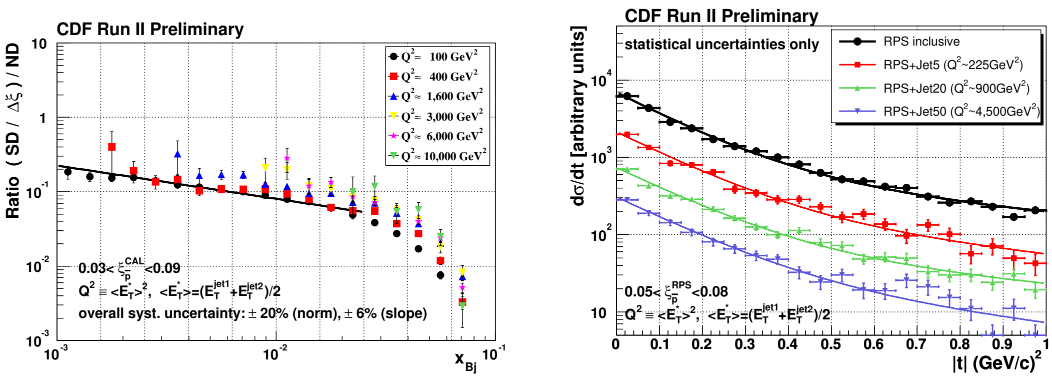

Fig. 1: *Left*: Ratio of diffractive to non-diffractive dijet event rates as a function of x_{Bj} (momentum fraction of struck parton in the anti-proton) for different values of $E_T{}^2 \equiv Q^2$; *Right*: Measured $|t|$-distributions for soft and hard diffractive events.

3 Diffractive W/Z production

Studies of diffractive production of the W/Z bosons are an additional handle to the understanding of diffractive interactions. At leading order (LO) diffractive W/Z bosons are produced by a quark interaction in the Pomeron. Production through a gluon can take place at NLO, which is suppressed by a factor α_s and can be distinguished by the presence of an additional jet.

In Run I, the CDF experiment measured a diffractive W boson event rate $R_W = 1.15 \pm 0.51$ (stat)± 0.20 (syst)%. Combining the R_W measurement with the dijet production event rate (which takes place both through quarks and gluons) and with the b-production rate allows the determination of the gluon fraction carried by the Pomeron which can be estimated to be $54^{+16}_{-14}\%$ [7].

In Run II, the RPS provides an accurate measurement of the fractional energy loss (ξ) of the leading hadron (Fig. 2, left), removing the ambiguity of the gap survival probability. The innovative approach of the analysis [8] takes advantage of the full $W \rightarrow l\nu$ event kinematics including the neutrino. The missing transverse energy ($\not{E}_{\mathrm{T}}$) is calculated as usual from all calorimeter towers, and the neutrino direction (i.e. η_ν) is obtained from the comparison between the fractional energy loss measured in the Roman Pot spectrometer (ξ^{RPS}) and the same value estimated from the calorimeters (ξ^{cal}): $\xi^{RPS} - \xi^{cal} = \frac{\not{E}_{\mathrm{T}}}{\sqrt{s}} \cdot e^{-\eta_\nu}$. The reconstructed W mass (Fig. 2, right) yields $M_W = 80.9 \pm 0.7$ GeV/c^2, in good agreement with the world average value of $M_W = 80.398 \pm 0.025$ GeV/c^2 [9]. After applying the corrections due to the RPS acceptance, trigger and track reconstruction efficiencies, and taking into account the effect of multiple interactions, both W and Z diffractive event rates are calculated: $R_W = 0.97 \pm 0.05(\mathrm{stat}) \pm 0.11(\mathrm{syst})\%$, and R_Z=0.85±0.20 (stat)±0.11 (syst)%.

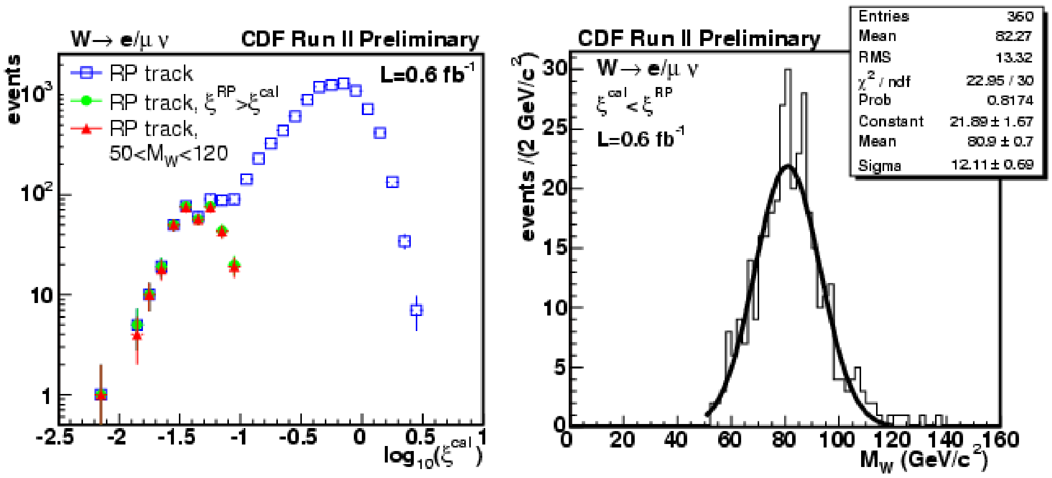

Fig. 2: Calorimeter ξ^{cal} distribution in W events with a reconstructed Roman Pot track (*left*). Due to the neutrino, $\xi^{cal} < \xi^{RPS}$ is expected. The difference $\xi^{RPS} - \xi^{cal}$ is used to determine the W boson mass (*right*).

4 Forward jets

An interesting process is dijet production in double diffractive (DD) dissociation. DD events are characterized by the presence of a large central rapidity gap and are presumed to be due to the exchange of a color singlet state with vacuum quantum numbers. A study of the dependence of the event rate on the width of the gap was performed using Run I data with small statistics. In Run II larger samples are available. Typical luminosities ($\mathcal{L} \approx 1 \div 10 \times 10^{31}$cm^{-2}sec^{-1}) during normal Run II run conditions hamper the study of gap "formation" due to multiple interactions which effectively "kill" the gap signature. Central rapidity gap production was studied in soft and hard diffractive events collected during a special low luminosity run ($\mathcal{L} \approx 10^{29} cm^{-2} sec^{-1}$). Figure 3 (left) shows a comparison of the gap fraction rates, as function of the gap width (i.e. $\Delta\eta$) for minimum bias (MinBias), and MP jet events. Event rate fraction is calculated as the ratio of the number of events in a given rapidity gap region divided by all events: $R_{gap} = N_{gap}/N_{all}$. The fraction is approximately 10% in soft diffractive events, and approximately 1% in jet events. Shapes are similar for both soft and hard processes, and gap fraction rates decrease with increasing $\Delta\eta$. The MP jets of gap events are produced back-to-back (Fig. 3, right).

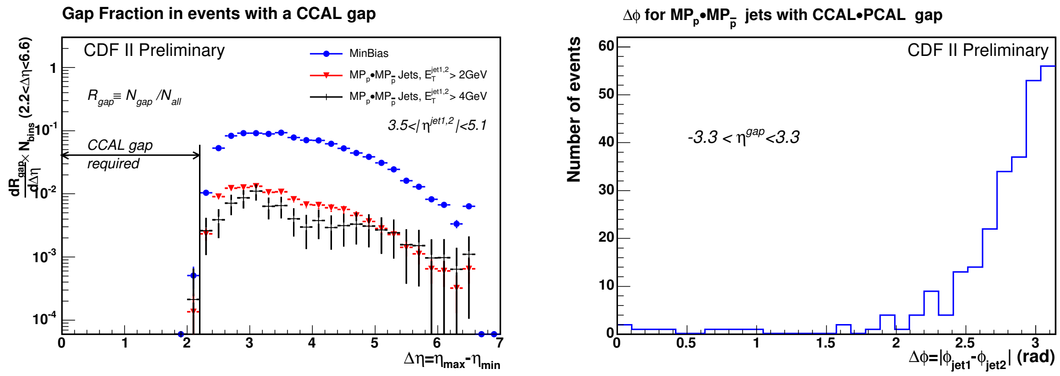

Fig. 3: *Left:* Event rate gap fraction defined as $R_{gap} = N_{gap}/N_{all}$, for minimum bias (MinBias) and MP jet events with $E_T > 2(4)$ GeV; *Right:* Azimuthal angle difference $\Delta\phi$ distribution of the two leading jets in a DD event with a central rapidity gap ($|\eta^{gap}| < 3.3$).

5 Exclusive production

The first observation of the process of exclusive dijet production can be used as a benchmark to establish predictions on exclusive diffractive Higgs production, a process with a much smaller cross section [10]. A wide range of predictions was attempted to estimate the cross section for exclusive dijet and Higgs production. In Run I, the CDF experiment set a limit on exclusive jet production [11]. First observation of this process was made in Run II. The search strategy is based on measuring the dijet mass fraction (R_{jj}), defined as the ratio of the two leading jet invariant mass divided by the total mass calculated using all calorimeter towers. An exclusive signal is expected to appear at large R_{jj} values (Fig. 4, left). The method used to extract the exclusive signal from the R_{jj} distribution is based on fitting the data to MC simulations. The quark/gluon composition of dijet final states can be exploited to provide additional hints on exclusive dijet production. The R_{jj} distribution can be constructed using inclusive or b-tagged dijet events. In the latter case, as the $gg \rightarrow q\bar{q}$ is strongly suppressed for $m_q/M^2 \rightarrow 0$ ($J_z = 0$ selection rule), only gluon jets will be produced exclusively and heavy flavor jet production is suppressed. Figure 4 (center) illustrates the method that was used to determine the heavy-flavor composition of the final sample. The falling distribution at large values of R_{jj} ($R_{jj} > 0.7$) indicates the suppression of the exclusive b-jet events. The CDF result favors the model in Ref. [12] (Fig. 4, right). Details can be found in Ref. [13].

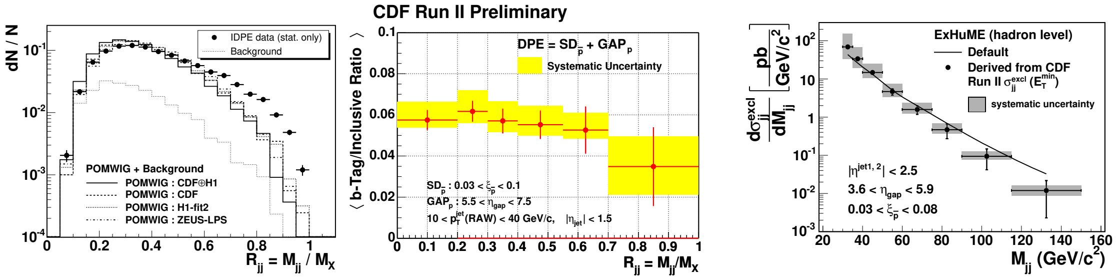

Fig. 4: *Left:* Dijet mass fraction R_{jj} in inclusive DPE dijet data. An excess over predictions at large R_{jj} is observed as a signal of exclusive dijet production; *Center:* Ratio of b-tagged jets to all inclusive jets as a function of the mass fraction R_{jj}. The error band corresponds to the overall systematic uncertainty; *Right:* The cross section for events with $R_{jj} > 0.8$ is compared to predictions.

Exclusive e^+e^- and di-photon production were studied using a trigger that requires forward gaps on both sides of the interaction point and at least two energy clusters in the electromagnetic calorimeters with transverse energy $E_T > 5$ GeV. All other calorimeter towers are required to be below threshold. In the di-electron event selection, the two tracks pointing at the energy clusters are allowed. The CDF experiment reported the first observation of exclusive e^+e^- production [14]. A total of 16 $\gamma\gamma \to e^+e^-$ candidate events are observed, consistent with QED expectations. Exclusive di-photon events can be produced through the process $gg \to \gamma\gamma$. Three candidate events were selected, where one is expected from background sources (i.e. $\pi^0\pi^0$). A 95%C.L. cross section limit of 410 pb can be set [15], about ten times larger than expectations [16].

6 Conclusions

The results obtained during the past two decades have led the way to the identification of striking characteristics in diffraction. Moreover, they have significantly contributed to an understanding of diffraction in terms of the underlying inclusive parton distribution functions. The regularities found in the Tevatron data and the interpretations of the measurements can be extrapolated to the LHC era. At the LHC, the diffractive Higgs can be studied but not without challenges, as triggering and event acceptance will be difficult. Still, future research at the Tevatron and at the LHC holds much promise for further understanding of diffractive processes.

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[3] The terms rapidity and pseudorapidity are used interchangeably. The pseudorapidity η is defined as $-\ln\tan(\theta/2)$, where θ is the polar angle with respect to the proton beam direction. The azimuthal angle is denoted by ϕ, and the transverse energy of a jet, E_T, is defined as $E_T \equiv E \cdot \sin\theta$.

[4] For each event, x_{Bj} is evaluated from the E_T and η of the jets using the equation $x_{Bj} = \frac{1}{\sqrt{s}} \sum_{i=1}^{3} E_T^i e^{-\eta^i}$.

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