CDF results on diffraction from Run I and plans for Run II ⋆

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Abstract

Results on soft and hard diffraction obtained by the CDF Collaboration in Run I of the Fermilab Tevatron $\bar{p}p$ collider are reviewed and compared with results from the DESY ep collider HERA and with theoretical expectations. In addition, the CDF program for diffractive studies in Run II is briefly reviewed with emphasis on the relevant detector upgrades and physics goals.

Key words: diffraction, Pomeron
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1 Introduction

The signature of a diffractive event in $\bar{p}p$ collisions is a leading proton or antiproton and/or a rapidity gap, defined as a region of pseudorapidity, $\eta \equiv -\ln\tan\frac{\theta}{2}$, devoid of particles (see Fig. 1).

In Run I of the Fermilab Tevatron $\bar{p}p$ collider, the CDF Collaboration studied the following diffractive processes:

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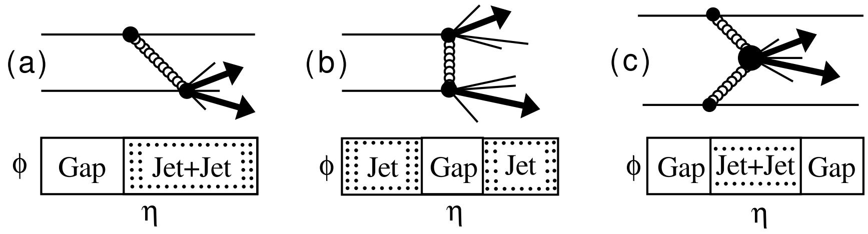

Fig. 1. Dijet production diagrams and event topologies for (a) single-diffraction, (b) double-diffraction, and (c) double Pomeron exchange.

- soft single-diffraction (SD) at $\sqrt{s} = 546$ and 1800 GeV [1] and soft double-diffraction (DD) at $\sqrt{s} = 630$ and 1800 GeV [2]
- W-boson [3], dijet [4], b-quark [5] and J/ψ [6] production at $\sqrt{s} = 1800$ GeV using rapidity gaps to identify diffractive events
- dijets with a rapidity gap between jets at $\sqrt{s} = 630$ [7] and 1800 GeV [8,9]
- dijets with a leading antiproton at $\sqrt{s} = 630$ [10] and 1800 GeV [11]
- dijet production in double Pomeron exchange (DPE) with a leading antiproton and a rapidity gap on the proton side [12]

In addition to the normal variables used to discribe an interaction, two additional variables are needed to describe a diffractive event: the width of the rapidity gap, $\Delta\eta$ [1], and the 4-momentum squared exchanged accross the gap, t. For single diffraction, $\Delta\eta \approx \ln\frac{1}{\xi}$, where ξ is fractional momentum loss of the leading (anti)proton.

In Regge theory, which has traditionally been used to describe diffraction, the rapidity gap is formed as a consequence of the nature of the exchanged Pomeron, which has the quantum numbers of the vacuum and therefore no hadrons are radiated in its exchange. Diffractive cross sections based on single Pomeron exchange factorize into two terms, one that has the form of a total cross section at the c.m.s. energy squared of the diffractive subsystem, s', defined throught the equation $\ln s' = \ln s - \Delta\eta$, and a second term, which is a function of the diffractive variables $\Delta\eta$ and t. The latter is usually referred to as 'Pomeron flux' in single diffraction, or more generally as a 'rapidity gap probability" [13,14].

In QCD, the *generic* Pomeron is a color-singlet combination of quarks and gluon with vacuum quantum numbers. In addition to the question of Regge factorization, another question of interest for hard diffractive processes (those incorporating a hard scattering) is whether they obey QCD factorization. Comparisons among CDF results and between results from CDF and HERA show a rather severe breakdown of QCD factorization in diffraction.

[1] We use pseudorapidity as an approximation to true rapidity.

Below, we present the results obtained from the Run I studies and discuss briefly the CDF plans for diffractive physics in Run II.

2 Soft diffraction

Measurements of pp and $\bar{p}p$ SD cross sections have shown that Regge theory correctly predicts the shape of the rapidity gap dependence for $\Delta\eta > 3$, corresponding to a leading proton fractional momentum loss of $\xi \approx e^{-\Delta\eta} < 0.05$, but fails to predict the correct energy dependence of the overall normalization, which at $\sqrt{s} = 1800$ GeV is found to be suppressed by approximately an order of magnitude relative to predictions based on factorization [1,13,15]. A new CDF measurement of the double diffraction differential cross section gives similar results (see Fig. 2).

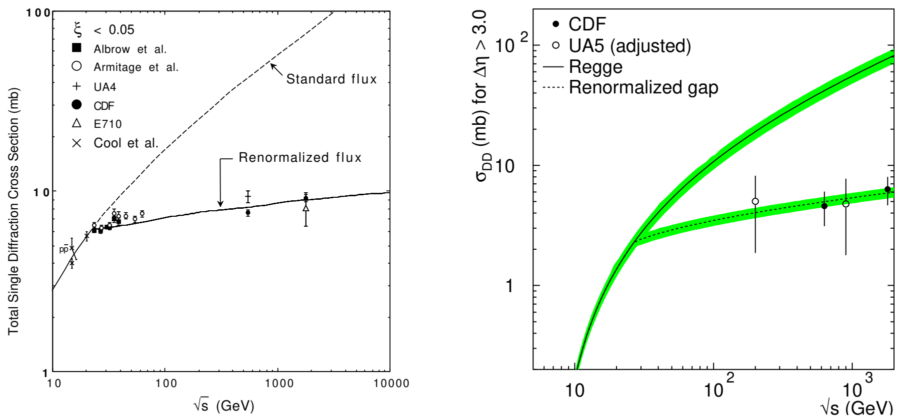

Fig. 2a: The $pp\,(\bar{p}p)$ σ^t_{SD} vs $\sqrt{s}$. Fig. 2b: The $\bar{p}p$ σ^t_{DD} vs $\sqrt{s}$.

The SD and DD cross sections have very similar forms in terms of $\Delta\eta$:

$$d^2\sigma_{SD}/dt\, d\Delta\eta = [K e^{bt} e^{[2\alpha(t)-1]\Delta\eta}] \cdot [\kappa\beta^2(0)(s')^{\alpha(0)-1}] \quad (1)$$

$$d^3\sigma_{DD}/dt\, d\Delta\eta\, d\eta_c = [\kappa\; K\, e^{[2\alpha(t)-1]\Delta\eta}] \cdot [\kappa\beta^2(0)(s')^{\alpha(0)-1}] \quad (2)$$

Here, energy is measured in GeV, $\alpha(t) = \alpha(0) + \alpha' t$ is the Pomeron trajectory, $\beta(t)$ is the coupling of the Pomeron to the proton, $K = \beta^2(0)/16\pi$, $\kappa = g_{I\!PI\!PI\!P}/\beta(0)$, where $g_{I\!PI\!PI\!P}$ is the triple-Pomeron coupling, e^{bt} is the square of the proton form factor, η_c the center of the rapidity gap, and $s' \equiv M_1^2 M_2^2$, where M is the diffractive mass, represents the (reduced) s-value of the diffractive sub-system, since $\ln s' = \ln s - \Delta\eta$ is the rapidity space where particle production occurs. The second factor in the equations can be thought of as the sub-energy total cross section, which allows the first factor to be interpreted as a rapidity gap probability, P_{gap}. For SD, it has been shown that renormalizing the Pomeron flux to unity [13], which is equivalent to normalizing P_{gap} over all phase space to unity, yields the correct energy dependence. The new CDF results show that this also holds for DD, as predicted by a generalization of the Pomeron flux renormalization model [14].

3 Hard diffraction using rapidity gaps

Using forward rapidy gaps to tag diffractive events, CDF measured the ratio of SD to non-diffractve (ND) rates for W-boson [3], dijet [4], b-quark [5] and J/ψ [6] production at $\sqrt{s}$ = 1800 GeV, and using central gaps determined the fraction of jet-gap-jet events as a function of E_T^{jet} and of rapidity gap separation between the two jets ($\Delta\eta^{jet}$) at $\sqrt{s} = 630$ and 1800 GeV.

Forward gaps are defined as no hits in one of the beam-beam counters (BBC), covering the region $3.2 < |\eta| < 5.9$, and no towers with energy $E > 1.5$ GeV in the forward calorimeter (FCAL, $2.4 < |\eta| < 4.2$) adjacent to the BBC with no hits. Using the POMPYT Monte Carlo simulation [16] with a flat gluon or quark Pomeron structure to generate diffractive events, the measured SD/ND ratios were corrected for 'gap acceptance', defined as the ratio of diffractive events with a gap to all diffractive events generated with $\xi = x_{I\!P} < 0.1$ in the selected kinematical range of the hard scattering products. For jet-gap-jet events, the gap was defined as no tracks or calorimeter towers with energy above $\sim$ 300 MeV in the region $|\eta| < 1$. The ND background was estimated using events with both jets at positive or negative η.

Table 1: Ratios of diffractive ($\xi < 0.1$) to non-diffractive rates.

Hard process	$\sqrt{s}$	$R = \frac{\text{DIFF}}{\text{ALL}}$ (%)	Kinematical region
$W(\rightarrow e\nu)$+G	1800	1.15 ± 0.55	E_T^e, $\not{E}_T > 20$ GeV
Jet+Jet+G	1800	0.75 ± 0.1	$E_T^{jet} > 20$ GeV, $\eta^{jet} > 1.8$
$b(\rightarrow e + X)$+G	1800	0.62 ± 0.25	$\|\eta^e\| < 1.1$, $p_T^e > 9.5$ GeV
$J/\psi(\rightarrow \mu\mu)$+G	1800	1.45 ± 0.25	$\|\eta^\mu\| < 0.6$, $p_T^\mu > 2$ GeV
Jet-G-Jet	1800	1.13 ± 0.16	$E_T^{jet} > 20$ GeV, $\eta^{jet} > 1.8$
Jet-G-Jet	630	2.7 ± 0.9	$E_T^{jet} > 8$ GeV, $\eta^{jet} > 1.8$

The results are summarized in Table 1. At $\sqrt{s}$=1800 GeV the DIFF/ALL ratios are of order 1%. Since the processes under study have different sensitivities to the quark and gluon content of the Pomeron, the near equality of the SD to ND ratios indicates that the value of the gluon fraction in the Pomeron, $f_g^{I\!P}$, is not very different from that in the proton. From the W, dijet and b-quark ratios, $f_g^{I\!P}$ was determined to be $0.54^{+0.16}_{-0.14}$ [5]. In addition, a suppression of a factor $D = 0.19 \pm 0.04$ was found in these ratios relative to POMPYT predictions using the standard Pomeron flux. Given that the POMPYT predictions for dfiffractive processes at HERA are approximately correct, the observed large discrepancy between data and POMPYT predictions at the Tevatron indicates a breakdown of QCD factorization. The value of D is approximately the same as that in soft SD (see Fig. 2), as was predicted in Ref. [13].

An independent determination of $f_g^{I\!P}$ was performed by comparing the measured J/ψ DIFF/ALL ratio with that of dijet producion in association with a leading antiproton (discussed in the next section). This comparison, which was made at the same x_{bj} (Bjorken x) value of the parton in the diffracted (surviving) nucleon, yielded $f_g^{I\!P} = 0.59 \pm 0.15$ at $\langle x_{bj} \rangle = 0.0063$, in agreement with the value obtained from the W, dijet and b-quark rapidity gap measurements.

The double ratio of J/ψ to b-quark DIFF/ALL ratios is 2.34 ± 0.35. Since both processes are mainly sensitive to the gluon content of the Pomeron, CDF examined [6] whether the difference in the two ratios could be attributed to the different average x_{bj} values of the two measurements. Given the dependence $x_{bj}^{-0.45}$ of the measured diffractive structure function [11] (see next section), the J/ψ to b-quark double ratio is expected to be equal to $(x_{bj}^{J/\psi}/x_{bj}^{\bar{b}b})^{-0.45}$. Since in these measurements only central J/ψ or b-quark production was considered, the ratio $x_{bj}^{J/\psi}/x_{bj}^{\bar{b}b}$ is approximately proportional to the ratio of the corresponding average p_T value for each process, which is ≈ 6 GeV/c for the J/ψ and ≈ 36 GeV/c for the b-quark (about three times the average p_T of the b-decay electron). The expected value for the double ratio is then $\approx (6/36)^{-0.45} = 2.2$, in agreement with the measured value of 2.34 ± 0.35.

The ratio of jet-gap-jet fractions at $\sqrt{s} = 630$ to 1800 GeV is 2.4 ± 0.8. The $\Delta\eta^{jet}$, E_T^{jet} and x-Bjorken distributions are consistent with being flat [9].

4 Hard single diffraction using a leading antiproton spectrometer

Using a Roman pot spectrometer to detect leading antiprotons and determine their momentum and polar angle (hence the t-value), CDF measured the ratio of SD to ND dijet production rates at $\sqrt{s}$=630 [10] and 1800 GeV [11] as a function of x-Bjorken of the struck parton in the $\bar{p}$. In leading order QCD, this ratio is equal to the ratio of the corresponding structure functions. For dijet production, the relevant structure function is the color-weighted combination of gluon and quark terms given by

$$F_{jj}(x) = x[g(x) + \frac{4}{9}\sum_i q_i(x)]$$

The diffractive structure function, $\tilde{F}^D_{jj}(\beta)$, where $\beta = x/\xi$ is the momentum fraction of the Pomeron's struck parton and the tilde over the F indicates integration over t and ξ, is obtained by multiplying the ratio of rates by the known F^{ND}_{jj} and changing variables from x to β using $x \to \beta\xi$.

Results for $\sqrt{s} = 1800$ GeV are presented in Fig. 3. The comparison of $F^D_{jj}(\beta)$ with predictions based on diffractive parton densities extracted from DIS at HERA confirms the breakdown of factorization observed in the rapidity gap data presented in section 3. The difference in suppression factors between the rapidity gap and Roman pot data can be traced back to differences in kinematical acceptance.

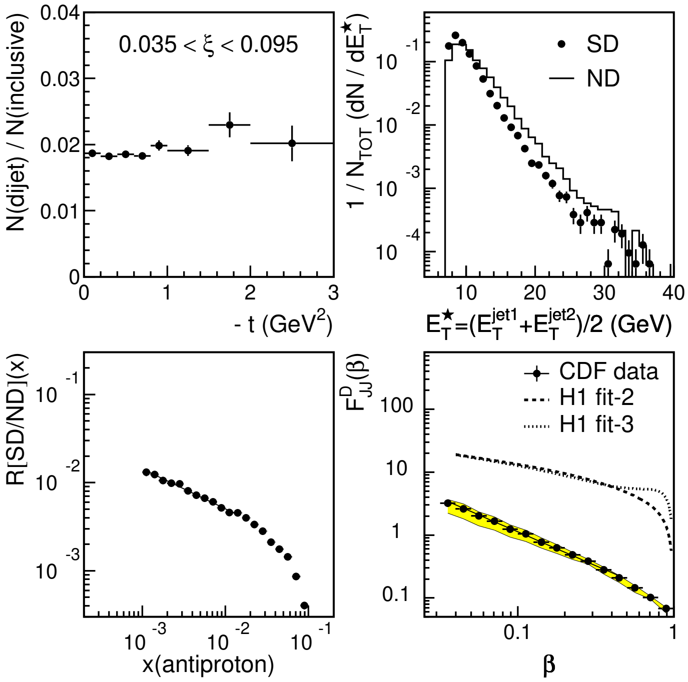

Fig. 3: Inclusive and dijet diffractive results at $\sqrt{s}$ =1800 GeV:
(top left) the ratio of dijet to inclusive SD event rates is independent of t;
(top right) the E_T^{jet} distribution is slightly steeper for SD than for ND events;
(bottom left) the ratio of SD to ND rates goes as $x_{bj}^{-0.45}$ for $x < 0.5\xi$;
(bottom right) the CDF diffractive structure function per unit ξ is steeper than and severely suppressed relative to predictions based on diffractive parton densities extracted by the H1 Collaboration from DIS measurements at HERA.

To further characterize the diffractive structure function, CDF measured its β dependence as a function of ξ and its ξ dependence as a function of β. In the region $\beta < 0.5$ and $0.035 < \xi < 0.095$, the data are well represented by the factorizable form

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

with $n = 1.0 \pm 0.1$ and $m = 0.9 \pm 0.1$, respectively, where the errors are mainly due to the systematic uncertainty associated with the measurement of x-Bjorken of the struck parton of the antiproton. The observed ξ dependence is much steeper than that of the inclusive SD data sample, which in this ξ region is approximately flat [15]. In Regge theory, the flat shape of the inclusive $dN/d\xi$ distribution in this region 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 [15] and is $\sim \xi$. The measured value of $m = 0.9 \pm 0.1$ indicates that dijet production is dominated by Pomeron exchange. Such behaviour is expected in models in which the structure of the Pomeron is effectively built from the ND 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 order 1 GeV^2 [17–19].

Diffractive dijet production was also studied at $\sqrt{s}$=630 GeV [10]. The diffractive structure function was extracted using the same method as at $\sqrt{s}$=1800 GeV, and the measurements of $F_{jj}^D(\beta,\xi)$ at the two c.m.s. energies were compared to test factorization. In the kinematical region of $E_T^{jet1,2} > 7$ GeV, $E_T^* \equiv (E_T^{jet1} + E_T^{jet2})/2 > 10$ GeV, $0.035 < \xi < 0.095$ and $|t| < 0.2$ GeV^2, the 630 to 1800 GeV ratio of the structure functions was found to be

$$R = \frac{F_{jj}^D(\beta,\xi)|_{630\,\mathrm{GeV}}}{F_{jj}^D(\beta,\xi)|_{1800\,\mathrm{GeV}}} = 1.3 \pm 0.2(\mathrm{stat})^{+0.4}_{-0.3}(\mathrm{syst})$$

Within the quoted uncertainties, this ratio is compatible with phenomenological predictions based on the Pomeron flux renormalization [13] and gap survival models [17].

5 Dijet production in double-Pomeron exchange

Factorization was also tested by comparing the ratio of DPE to SD dijet production rates to that of SD to ND. Figure 4 illustrates the event topologies in pseudorapidity space and the corresponding Pomeron exchange diagrans for the two diffractive processes. The comparison of the cross section ratios tests whether the normalization of the diffractive structure function of one of the nucleons is affected by the presence of a rapidity gap associated with the other nucleon.

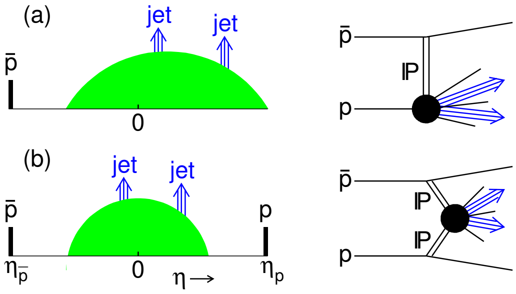

Fig. 4: Illustration of event topologies in pseudorapidity, η, and associated Pomeron exchange diagrams for dijet production in (a) single diffraction and (b) double Pomeron exchange. The shaded areas on the left side represent particles not associated with the jets (underlying event).

The DPE events were extracted from the leading antiproton data by requiring a forward rapidity gap on the proton side using the gap definition given in section 3. At $\langle \xi \rangle = 0.02$ and $\langle x_{bj} \rangle = 0.005$, the double ratio of SD/ND to DPE/SD rates, normalized per unit ξ, was found to be 0.19 ± 0.07, violating factorization [12].

A search for exclusive dijet production in DPE, $p + \bar{p} \to p' + (jet1 + jet2) + \bar{p}'$, yielded an upper limit of 3.7 nb for $0.035 < \xi(\bar{p}) < 0.095$ and jets of $E_T > 7$ GeV and $\eta < 1.7$ [12].

6 Conclusions from Run I

The CDF Run I diffractive studies revealed the following features regarding the process dependence of rapidity gap formation:
(1) In soft single and double diffraction, Regge factorization is violated in such a way as to lead to a scaling behaviour expressed as s-independence of the M^2 distribution of the differential cross sections.
(2) In hard diffraction, a severe breakdown of factorization is observed, expressed as a supression of the the diffractive to non-diffractive production rates relative to predictions from Regge-type models based on factorization or from diffractive parton densities measured at HERA. The suppression factor is approximately equal to that observed in soft diffraction.
(3) The diffractive to non-diffractive productions rates are approximately flavour independent.
The above features lead to the conclusion that the probability of diffractive rapidity gap formation is, to first order, process and flavor independent.

7 Plans for Run II

The CDF program for diffractive studies in Run II will include:

(a) Hard single diffraction

– Process dependence of F^D (compare at the same ξ and x_{bj})

– Q^2 dependence of F_{jj}^D

(b) Double Pomeron exchange

– Soft DPE

– $F_{jj}^D(x_p)$ versus width of gap on the $\bar{p}$ side

– Exclusive dijet and $\bar{b}b$ production

– Low mass exclusive states (glueballs?)

(c) Hard double diffraction

– jet-gap-jet events at high $\Delta\eta^{jet}$ (test BFKL)

(d) Unexpected discoveries!

The Run II program will be implemented by upgrading CDF to include the forward detector system shown schematically in Fig. 4. This system comprises:
1. A Roman Pot Specrometer (RPS) on the antiproton side to detect leading antiprotons and measure ξ and t
2. Beam Shower Counters (BSC) covering the region $5.5 < |\eta| < 7.5$ to be used for triggering on events with forward rapidity gaps
3. Two 'MiniPlug' calorimeters in the region $3.5 < |\eta < 5.5$

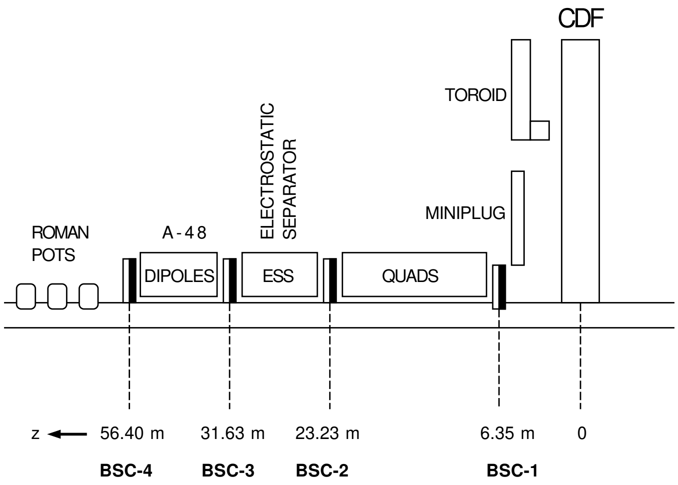

Fig. 5: CDF forward detectors for Run II

The RPS and BSC systems are already installed, and the MiniPlug installation is scheduled for October 2001.

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