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TWENTY YEARS OF DIFFRACTION AT THE TEVATRON

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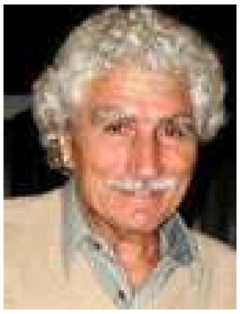

Results on diffractive particle interactions from the Fermilab Tevatron $\bar{p}p$ collider are placed in perspective through a QCD inspired phenomenological approach, which exploits scaling and factorization properties observed in data. The results discussed are those obtained by the CDF Collaboration from a comprehensive set of single, double, and multigap soft and hard diffraction processes studied during the twenty year period since 1985, when the CDF diffractive program was proposed and the first Blois Workshop was held.

Diffractive $\bar{p}p$ interactions are characterized by the presence of at least one large rapidity gap, defined as a region of pseudorapidity[a] devoid of particles. A diffractive rapidity gap, which may be forward (adjacent to a leading nucleon) or central, is presumed to be formed by the exchange of a *Pomeron*[1], which in QCD is a color singlet quark/gluon object with vacuum quantum numbers. Diffraction in which there is a high momentum-transfer partonic scattering in the event is referred to as *hard diffraction*[2, b]. In this paper, we briefly review what we have learned about diffraction from the Collider Detector at Fermilab (CDF) in Run-I (1989-1995) of the Tevatron $\bar{p}p$ collider operating at 1800 GeV c.m.s. energy, and comment on the goals, results already obtained[3, c], and expectations from the 1960 GeV Run-II program, which is currently under way. The CDF results are placed in perspective using a QCD based phenomenological approach, which exploits scaling and factorization properties observed in the data (see Ref.[4]).

[a] We use rapidity, $y = \frac{1}{2}\frac{E+p_L}{E-p_L}$, and pseudorapidity, $\eta = -\ln\tan\frac{\theta}{2}$, interchangeably, since in the kinematic region of interest the values of these two variables are approximately equal.

[b] G. Ingelman, "Hard Diffraction - from Blois 1985 to 2005," in these Proceedings.

[c] See also C. Mesropian, "New Diffraction Results from CDF," in these Proceedings.

1 Run-I Results

In addition to measuring $\bar{p}p$ elastic, single diffraction (SD), and total cross sections at $\sqrt{s} = 540$ and 1800 GeV, CDF studied several soft and hard diffraction processes at $\sqrt{s} = 1800$ GeV, and in some cases at $\sqrt{s} = 630$ GeV [4]. Soft processes studied include:

DD	Double Diffraction	$\bar{p}p \to X + \text{gap} + Y$
DPE	Double Pomeron Exchange	$\bar{p}p \to \bar{p} + \text{gap} + X + \text{gap} + p$
SDD	Single $\oplus$ Double Diffraction	$\bar{p}p \to \bar{p} + \text{gap} + X + \text{gap} + Y$

In the area of hard diffraction, CDF measured SD dijet, W, b-quark and J/ψ production, DD dijet production, and DPE dijet production. Schematic diagrams and event topologies for representative diffractive processes studied in Run-I are shown in Fig. 1.

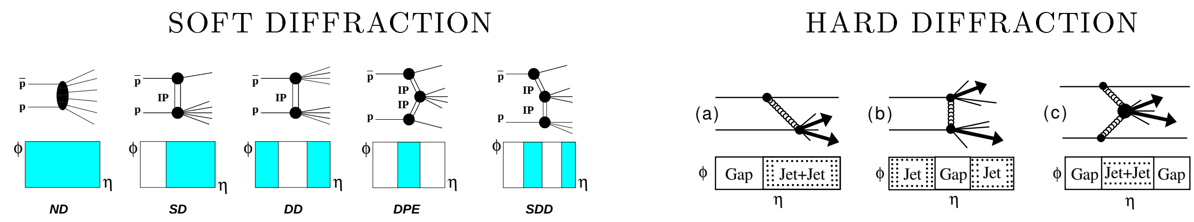

Figure 1: Schematic diagrams and η-ϕ topologies of representative diffractive processes studied by CDF in Run-I. The shaded areas represent regions of pseudorapidity in which *there is* particle production.

Two types of hard diffraction results were obtained in Run-I: diffractive to non-diffractive cross section ratios, using the rapidity gap signature to select diffractive events, and diffractive to non-diffractive structure function ratios, using a Roman Pot Spectrometer (RPS) to trigger on leading antiprotons (see Fig. 2, *left*).

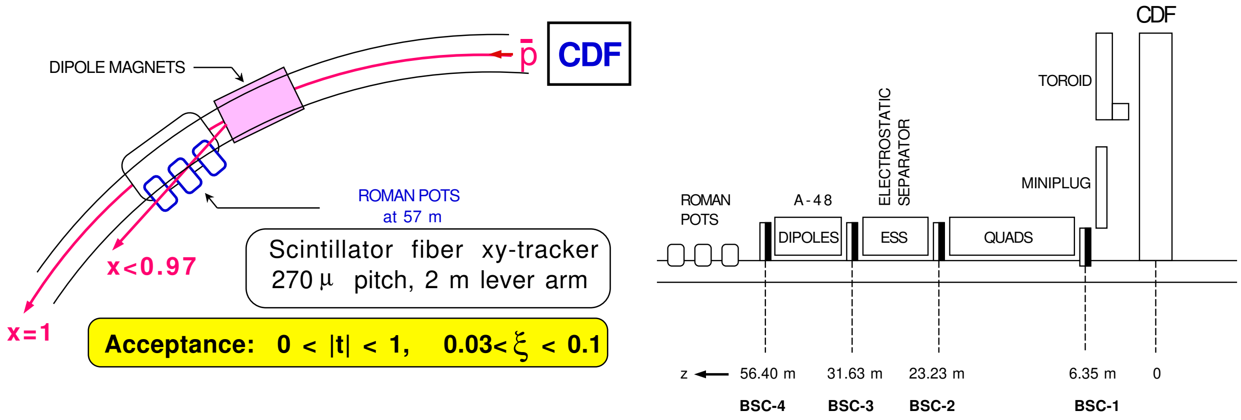

Figure 2: Layout of the CDF detector in Run-I (*left) and in Run-II (*right), showing the special forward detectors used in the diffractive program.

The Run-I diffractive production results exhibit regularities in normalization and factorization properties pointing to the QCD character of diffraction. The result that has attracted the most attention is the breakdown of QCD factorization, indicated by an $\sim \mathcal{O}(10)$ suppression in normalization of the diffractive structure function (DSF) measured from diffractive dijet production at the Tevatron relative to that measured from diffractive deep inelastic scattering (DDIS) at HERA. However, less attention has been paid to the remarkable *s-independence* of the $d\sigma^{SD}/dM^2$ diffractive differential cross section, a scaling property that seems to regulate the magnitude of the breakdown of factorization. This "M^2-scaling" behavior has profound implications about the mechanism of diffraction, favoring a composite over a particle-like Pomeron, as discussed in Ref. [4] and in original references therein.

1.1 *Breakdown of Factorization*

At $\sqrt{s}$ =1800 GeV, the SD/ND ratios (gap fractions) for dijet, W, b-quark, and J/ψ production, as well the ratio of DD/ND dijet production, are all $\approx$ 1%. These ratios are suppressed by a factor of ~10 relative to standard QCD inspired theoretical expectations (*e.g.* 2-gluon exchange), or relative to predictions based on diffractive parton densities measured from DDIS at HERA. This suppression represents a severe breakdown of QCD factorization.

There are two interesting features characterizing the data: (i) despite the overall suppression in normalization, factorization approximately holds among different diffractive processes at fixed $\sqrt{s}$, and (ii) the magnitude of the suppression is comparable to that observed in soft diffraction processes relative to Regge theory expectations. These features indicate that the suppression is in the formation of the rapidity gap. The generalized gap renormalization model provides a good description of the data (see Ref. [4]).

1.2 *Restoration of Factorization in Multigap Diffraction*

Another interesting aspect of the Run-I results is that ratios of two-gap to one-gap cross sections for both soft and hard processes appear to obey factorization. This feature of the data provides both a clue to understanding diffraction and a tool for diffractive studies using processes with multiple rapidity gaps (see Refs. [4,5]).

2 Run-II Program

New diffractive results from CDF obtained in Run-II are presented in these Proceedings by C. Mesropian, but are included here for completeness. The Run-II diffractive program of CDF (see Fig. 2, *right*) is aiming at deciphering the QCD nature of the Pomeron by measuring the dependence of the diffractive structure function on Q^2, x_{Bj}, t, and ξ (fractional momentum loss of the diffracted nucleon) for different diffractive production processes; in addition, the possibility of a composite Pomeron is being investigated by studies of very forward jets with a rapidity gap between jets. Another goal of the program is to measure exclusive production rates (dijet, χ_c^0, $\gamma\gamma$), which could be used to establish benchmark calibrations for exclusive Higgs production at LHC [6,7]. Preliminary results from data collected at $\sqrt{s}$ = 1960 GeV confirm the Run-I DSF results [4,8]. New results from Run-II are the measurement of the Q^2 dependence of the DSF obtained from dijet production and limits on exclusive production rates.

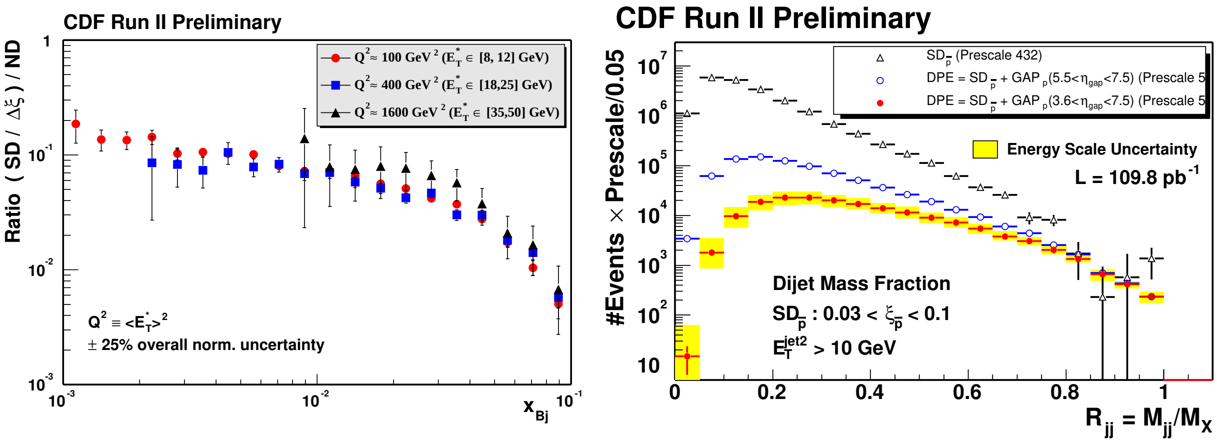

Figure 3: (*left*) Ratio of SD/$\Delta\xi_{\bar{p}}$ over ND rates obtained from dijet data at various Q^2 ranges; (*right*) ratio of dijet mass to total mass "visible" in the calorimeters for dijet production in events with a leading antiproton within $0.3 < \xi_{\bar{p}} < 0.1$ and various gap requirements on the proton side: (triangles) no gap requirement, (open circles) gap in $5.5 < \eta < 7.5$, and (filled circles) gap in region $3.5 < \eta < 7.5$.

2.1 *The Diffractive Structure Function*

In Fig. 3 (*left)*, the ratio of SD/ND rates, which in LO QCD and at fixed x_{Bj} is equal to the ratio of the corresponding structure functions, shows no appreciable Q^2 dependence. This result was foreseen in the renormalization model [9], in which the diffractive structure function is basically the low-x ($x < \xi$) structure function of the diffracted nucleon. More data are currently being analyzed to improve the statistics of this measurement.

Data are at hand and analyses are in progress for the measurement of the t, ξ, and flavor dependence of the DSF using dijet, W, and J/ψ production. In addition, factorization will be tested more accurately than in Run-I by comparing the DSFs obtained from dijet production in SD and DPE.

2.2 *Exclusive Production*

Exclusive Dijet Production

The search for exclusive dijet production is based on measuring the dijet mass fraction M_{jj}, defined as the mass of the two leading jets in an event divided by the total mass reconstructed from all the energy observed in all calorimeters. Fig. 3 (*right*) shows M_{jj} distributions for events with different selection criteria. The signal from exclusive dijets is expected to be concentrated in the region of $R_{jj} > 0.8$, with values of $R_{jj} < 1$ being caused by measurement resolution effects and final state radiation. Background events from inclusive DPE production, $\bar{p}p \to (\bar{p} + gap) + JJ + X + gap$, are expected to contribute to the entire M_{jj} region.

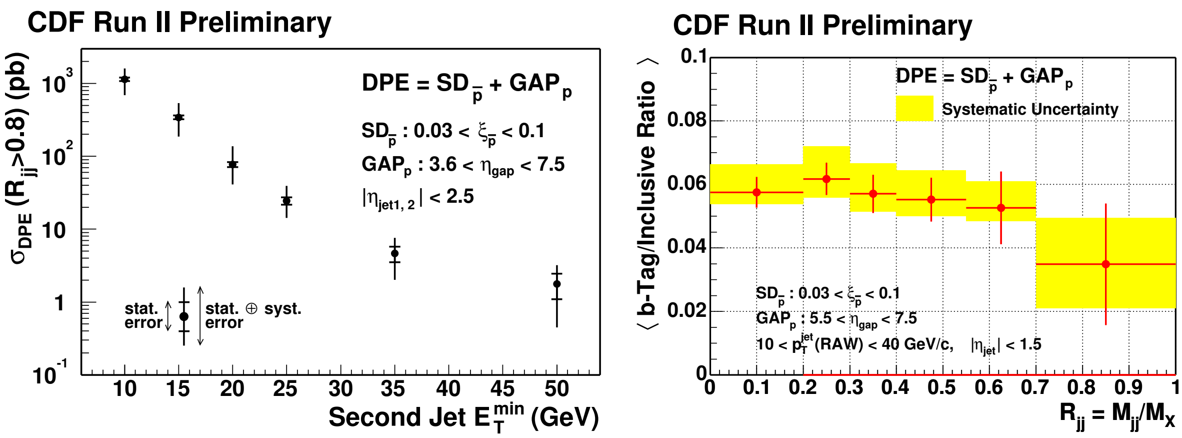

Figure 4: (*left*) Dijet production cross sections for $R_{jj} > 0.8$ in DPE events as a function of E_T^{min}, the E_T of the next to the highest E_T jet; (*right*) the ratio of b-tagged to all jets in the DPE dijet event sample versus the dijet mass fraction.

Since no peak is observed at $R_{jj} > 0.8$ in Fig. 3 (*right)*, CDF reports production cross sections for events with $R_{jj} > 0.8$, which could be used as upper limits for exclusive production. Figure 4 (*left)* shows such cross sections for various kinematic cuts plotted versus E_T^{min}, the next to leading jet E_T. These cross sections agree, within errors, with recent predictions for exclusive dijet production [6,7]. Thus, for the predictions to be correct, the background would have to vanish as $R_{jj} \to 1$. While this is guaranteed by the $J_z = 0$ selection rule for leading order $gg \to q\bar{q}$ jets of $m_q << M_{jet}$, Monte Carlo (MC) simulations are used to deal with the dominant $gg \to gg$ process. To avoid using simulations, one could use $q\bar{q}$ events to estimate the background. This can be done using dijet events in which at least one of the jets is b-tagged. Figure 4 (*right*) shows the ratio of b-tagged to inclusive dijet events versus dijet mass fraction. A suppression is observed as $M_{jj} \to 1$, as would be expected if there were exclusive dijets in the sample. However, background still may exist from the gluon splitting process $gg \to g + g(\to b\bar{b})$. This background could be practically eliminated if both jets were required to be b-tagged. Presently, more data are being collected with an unprescaled b-tagged dijet trigger to yield a large sample of double-b-tagged dijet events with which to measure the rate for exclusive production in a low background environment.

Exclusive χ_c^0 Production

CDF has reported an upper limit of 49 ± 18 (stat) $\pm\ 39$ (syst) pb for exclusive χ_c^0 production from a search for $J/\psi + \gamma$ events from $\bar{p}p \to \bar{p} + \chi_c^0(\to J/\psi + \gamma \to \mu\mu + \gamma) + \bar{p}$. Theoretical predictions of ~ 70 pb have recently been revised to ~ 50 pb [6,7]. More data, collected with a dedicated trigger, are currently being analyzed.

Exclusive $\gamma\gamma$ Production

Data collected with a special trigger are currently being analyzed in search for exclusive $\gamma\gamma$ production. The data at hand are already sufficient for placing an upper limit on the production cross section at a level comparable to that of theoretical predictions [6,7]. With data continuing to come in, the process will hopefully be discoverd soon and be used, along with exclusive dijet production, for calibrating calculations for diffractive Higgs production at LHC.

2.3 Composite Pomeron?

In the generalized renormalization model (see review in Ref. [4]) the hard scattering in hard diffractive processes is controlled by the parton distribution function (PDF) at high Q^2, while the diffractive rapidity gap is formed by the emission of a soft parton that neutralizes the color accross the rapidity region over which the hard exchange occurs. In this *composite Pomeron* model, the color neutralization does not have to extend over the entire rapidity region spanned by hard exchange, as is the case in models with particle-like Pomerons, *e.g.* in the BFKL model [10]. Dijet events with a rapidity gap between jets offer an opportunity to differentiate between particle-like and composite Pomeron models.

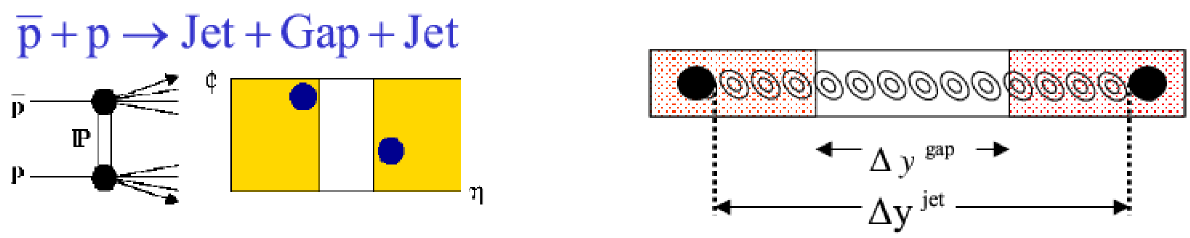

Figure 5: Forward dijet production with a rapidity gap between jets: *(left)* for particle-like Pomerons, the gap extends all the way to the jets, while *(right)* for composite Pomerons, the gap width is generally smaller than the rapidity separation of the jets.

Figure 5 shows schematic diagrams for the process $\bar{p} + p \to Jet + Gap + Jet$. For a particle-like Pomerons (*left*), the gap extends all the way to the jets, while for composite Pomerons (*right*) the gap is smaller than the rapidity separation of the jets. At CDF, the cross section for events with jets in the forward Miniplug calorimeters will be measured as a function of gap position and gap width. This information will then be checked against predictions of various models to determine the nature of Pomeron exchange.

3 Conclusions

A comprehensive set of studies of diffractive processes has been under way at CDF since the program was proposed in 1985, the year of the first *Bois Workshop* on Elastic and Diffractive Scattering. The results obtained on soft and hard diffraction in this twenty year period exhibit regularities that point to the QCD nature of the Pomeron. The most striking feauture of the data is the s-independence of the single diffractive $d\sigma/dM^2$ differential cross section. This scaling behaviour provides a clue to understanding the Pomeron as a composite structure built up from a combination of gluons and/or quarks with the quantum numbers of the vacuum in accordance with QCD color constraints. Results from Run-II already reported at Conferences confirm Run-I results, data at hand are being analyzed to extend the Run-I findings, and studies are being carried out to provide information on rates and backgrounds relevant to formulating a strategic plan for carrying out the diffractive program proposed for the Large Hadron Collider.

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