RESULTS ON DIFFRACTION AT CDF*

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We report recent results on diffraction from the CDF experiment at the Fermilab Tevatron $\bar{p}p$ collider. In events with multiple rapidity gaps, we find that if a single gap survives, *e.g.* is not killed by products of interactions between spectator partons, any additional gaps survive as well. Diffractive structure functions are studied in single-diffractive and double-pomeron-exchange (DPE) dijet production. Exclusive production of dijets and of χ_c^0 in DPE have been studied as benchmark processes for exclusive Higgs production at the LHC.

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1. Introduction

Diffractive interactions are characterized by the exchange of an object referred to as the pomeron ($\mathbb{P}$), which has the quantum numbers of the vacuum. Because the exchange is colorless, a large region in pseudorapidity space is left empty of particles; such a region is called a rapidity gap. In single-diffractive (SD) $\bar{p}p$ interactions, for example, the $\bar{p}(p)$ emits a pomeron which carries away a small fraction of its momentum, ξ, and escapes intact. A large rapidity gap is formed between the forward $\bar{p}(p)$ and the products of the dissociated $p(\bar{p})$, as shown in Fig. 1(b). In the case of double diffraction (Fig. 1(c)), a central rapidity gap is formed between the remains of the p and $\bar{p}$ which are both dissociated. Multiple rapidity gaps can be formed in processes such as double-pomeron exchange (DPE), where both the p and $\bar{p}$ remain intact with forward rapidity gaps and a central mass

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cluster (Fig. 1(d)), or, for instance, in the similar process where one of the incident hadrons is dissociated into a forward mass cluster, *i.e.*, the SDD (single+double diffraction) topology shown in Fig. 1(e).

All of these processes have been studied by the CDF collaboration using data from the Tevatron Run I. Comparisons with results from the HERA *ep* collider have yielded important insight into the nature of diffractive interactions. Data from Run II is being used to continue these studies, as well as to look at processes which may be of even more interest at the LHC, such as exclusive production in DPE.

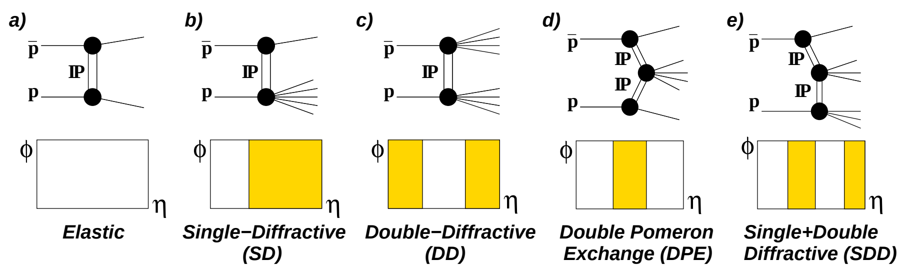

Fig. 1. Event topologies in pseudorapidity (η) *vs* azimuthal angle (ϕ) for (a) elastic, (b) single-diffractive, (c) double-diffractive, (d) double-pomeron exchange, and (e) "single+double diffractive" (SDD) $\bar{p}p$ interactions. Shaded areas represent regions of particle production, while white areas are "rapidity gaps".

The CDF Run I detector is described in detail in Ref. [1]. Most relevant for diffractive analyses are the calorimeters covering the region $|\eta| < 4.2$, charged-particle tracking in the region $|\eta| < 1.1$ inside a 1.4 T solenoid magnetic field, beam–beam counters (BBC's) consisting of scintillator covering the region $3.2 < |\eta| < 5.9$, and Roman-pot detectors installed for the last running period of Run I. Three Roman pots located approximately 57 m downstream in the antiproton direction contain scintillator counters and fiber trackers which are inserted close to the beam inside the vacuum beampipe. Tevatron dipole magnets bend forward $\bar{p}$'s with 90–97% of the beam momentum into the Roman pot detectors.

Changes for the Run II detector include a new plug calorimeter and preshower detector, gas Cherenkov counters covering the region $3.7 < |\eta| < 4.7$ for luminosity measurements, miniplug calorimeters covering $3.5 < |\eta| < 5.1$ [2], and beam-shower counters surrounding the beampipe in forward locations ($5.5 < |\eta| < 7.5$) [3].

2. Multiple rapidity gaps

One obstacle in gaining an understanding of diffraction in a QCD framework is the gap survival probability [4], representing the likelihood that if a rapidity gap is produced by pomeron exchange between two partons, it will not be filled in by products of interactions between spectator partons. In Run I, we performed a series of studies which provide insight into the gap survival probability as well as a tool for removing it from measurements of diffractive processes. First, comparison of hard double-diffractive (DD) interactions characterized by jets on opposite sides of a rapidity gap at center-of-mass (c.m.) energies of $\sqrt{s} = 1800$ and 630 GeV shows evidence that the gap survival probability S decreases with increasing $\sqrt{s}$ [5,6]. Then, in a study of inclusive DD, we showed that the suppression of rapidity gaps is approximately the same as for the jet-gap-jet events, which points to a universality in S across soft and hard diffractive processes [7]. Finally, we addressed the effects of S in events with two rapidity gaps. If the gap survival probability is such that in a given event a single gap would survive, *i.e.*, there are no spectator interactions, then additional gaps should also survive. Our results show this to be the case, and provide a means to study gaps in an environment which is free of the effects of S, namely, in events that already have a gap.

We have studied this by looking at the rate of additional gaps in single-diffractive (SD) events (triggered by a leading $\bar{p}$ in the Roman pots), which would already have a forward rapidity gap associated with the $\mathbb{P}$ emitted by the $\bar{p}$. A second gap is produced if the p also emits a pomeron. One category of such events is double-pomeron exchange, where not only the $\bar{p}$, but also the p survives intact. A study of inclusive DPE is presented in Ref. [8]. We have also studied the category of events (SDD) where the incoming p dissociates in the same way as in a DD interaction [9].

The fraction of Roman-pot-triggered events with a second gap in the SDD topology is shown in Fig. 2. The ratios of SDD to SD rates are higher than expectations from DD fractions in minimum-bias events, suggesting that once one gap is produced, additional gaps are easier to produce. The fractions are also seen to be lower than expectations from Regge theory and factorization, and in good agreement with predictions based on the renormalized gap probability model [10], in which the survival probability does not depend on the number of gaps in an event. Similar results are found for DPE interactions; Fig. 3 shows good agreement between the CDF DPE data and the renormalized gap probability model, as opposed to a model where both rapidity gaps are suppressed.

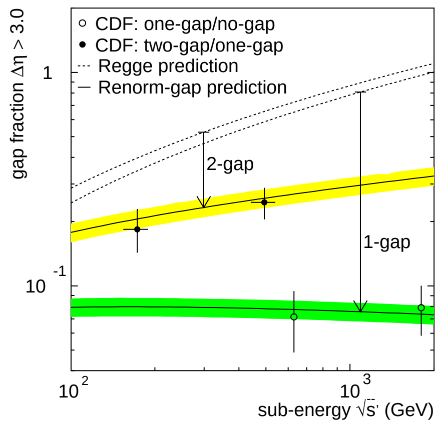

Fig. 2. Ratios of SDD to SD rates (filled circles) and of DD to total cross sections (open circles) as a function of the collision energy of the sub-process, $\mathbb{P}p$ and $\bar{p}p$, respectively. The uncertainties are mainly systematic and are highly correlated among all four data points. The dashed lines are predictions from Regge theory, and the solid lines from the renormalized gap probability model.

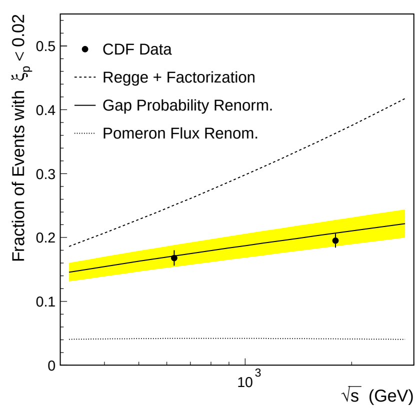

Fig. 3. Fraction of DPE events with $\xi_p < 0.02$ in events with $0.035 < \xi_{\bar{p}} < 0.095$ as a function of $\sqrt{s}$ of the $\bar{p}p$ collision, for CDF data (filled circles), and for predictions from: (solid line) the renormalized gap probability model [10]; (dashed line) standard Regge theory based on factorization; (dotted line) the pomeron flux renormalization model in which the proton and antiproton flux factors are renormalized independently for DPE [11].

Similar results are seen in hard diffraction as well. Though SD dijet production has a cross section about ten times smaller at the Tevatron than at HERA [14], the fraction of dijet events at CDF which have an additional gap (DPE/SD) [12] is in good agreement with the single-gap production results from HERA (Fig. 4), that is, QCD factorization appears to hold for the second gap.

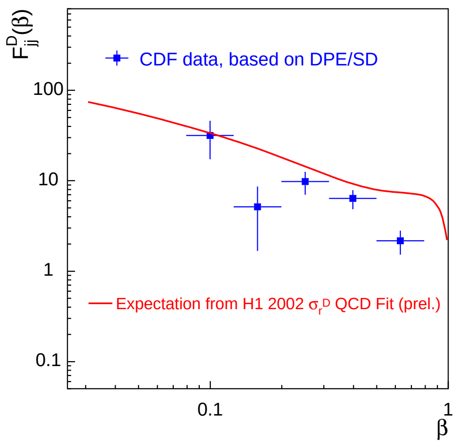

Fig. 4. Comparison of the diffractive structure function of the proton in CDF DPE events [12] with expectations from H1 parton densities from diffractive DIS at HERA [13].

The ability to study diffractive phenomena in an environment where the survival probability does not come into play is a great advantage. An example of a study which could be conducted at the LHC pp collider at $\sqrt{s} = 14$ TeV would be to tag an outgoing diffracted p or forward rapidity gap in one (both) direction(s) as in a SD interaction $pp \to p + \text{gap} + X$ (DPE interaction $pp \to p + \text{gap} + X + \text{gap} + p$) with proton momentum loss fraction(s) such that the remaining subprocess energy $\sqrt{s'}$ of the $\mathbb{P}p$ ($\mathbb{P}\mathbb{P}$) interaction is comparable to Tevatron energies. Because (more than) one gap is already present, additional gaps should be free from any survival probability which would complicate, for example, the production of a rapidity gap between jets in the remaining system X, as shown for DPE in Fig. 5.

These results provide insight into the gap survival probability as well as a tool for eliminating it from measurements of diffractive processes. The ratio of two-gap to one-gap rates, free from survival probability considerations, can be compared to theoretical calculations. Further studies can be conducted at the LHC which will also benefit from the discovery of an environment free of the effects of gap survival probability.

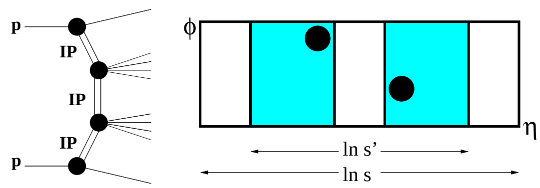

Fig. 5. Schematic diagram and event topology in η-ϕ space of a DPE interaction $pp \to p+\mathrm{GAP}+X+\mathrm{GAP}+p$ at c.m. energy $\sqrt{s}$, where X is a hard DD interaction $\mathbb{PP} \to \mathrm{JET}+\mathrm{GAP}+\mathrm{JET}$ at c.m. energy $\sqrt{s'}$.

3. Single-diffractive dijet production

We have continued our study of SD dijet production, confirming the Run I results on the dependence of the diffractive structure function on ξ, the fraction of the $\bar{p}$ momentum carried by the pomeron. Work is in progress to extend the range of the measurement to smaller ξ. We have also measured the Q^2 dependence and find no appreciable $Q^2(=E_{\mathrm{T}}^2)$ dependence in the range measured, $100 < Q^2 < 1600$ GeV^2. Using jets with higher transverse energy will allow us to reach higher Q^2. Measurements of the diffractive structure function in other processes, such as SD W production which probes the quark content of the pomeron, are in progress. The Run II results are described in detail in [15].

4. Exclusive production in double-pomeron exchange

There has been much interest in exclusive Higgs production as a means for observing relatively light Higgs bosons at the LHC. The clean environment due to the Higgs being produced along with nothing else but the leading protons makes this especially attractive. Although the cross section for exclusive Higgs production is likely too small to be seen at the Tevatron, other processes can be studied and used to constrain predictions for exclusive Higgs production at the LHC. CDF has studied exclusive production of dijets and of χ_c^0 in DPE, and plans to study $b\bar{b}$ and $\gamma\gamma$ production as well.

4.1. Exclusive dijet production

Dijet production in DPE has been studied by CDF in Run I [12] as well as Run II [16]. The Run II sample used requires a rapidity gap in the beam-shower counters on the p side, a Roman-pot $\bar{p}$ trigger, and a single calorimeter tower with $E_{\mathrm{T}} > 5$ GeV. The dijet mass fraction, R_{jj}, is defined as the ratio of the invariant mass of the two leading jets to the mass of the entire system excluding the leading p and $\bar{p}$. If dijets were produced exclusively, R_{jj} would by definition be one, however, to take into account resolution effects, the exclusive region is taken to be $R_{jj} > 0.8$. No significant excess is seen in the exclusive region that would suggest exclusive production by a separate mechanism; rather, the distribution falls smoothly as would be expected for inclusive production (Fig. 6). We find a limit for exclusive dijet production as the cross section for DPE events with $R_{jj} > 0.8$ of $970 \pm 65(\text{stat}) \pm 272(\text{syst})$ pb for leading jet $E_T > 10$ GeV, and $34 \pm 5(\text{stat}) \pm 10(\text{syst})$ pb for leading jet $E_T > 25$ GeV. These limits are very close to theoretically expected exclusive rates [17].

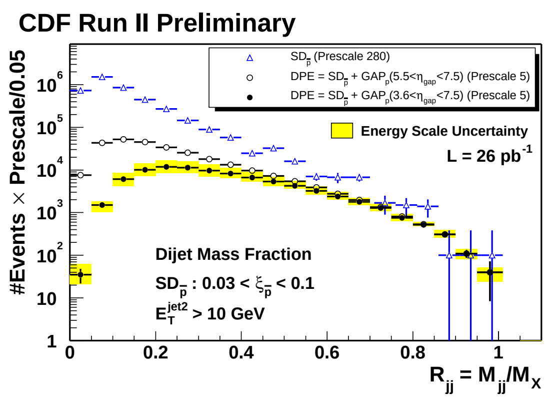

Fig. 6. Number of events as a function of dijet mass fraction in DPE for $5.5 < \eta_{\text{gap}} < 7.5$ (open circles), $3.6 < \eta_{\text{gap}} < 7.5$ (filled circles), and for SD events (triangles).

4.2. Exclusive χ_c^0 production

Because the Higgs boson and the χ_c^0 have quantum numbers in common, exclusive χ_c^0 production is especially interesting as a benchmark for Higgs production. CDF has studied χ_c^0 production in DPE [16] using events selected by a trigger requiring two muons with $p_T > 1.5$ GeV and $|\eta| < 0.6$. Cosmic rays are rejected using timing information. The analysis selects $\mu^+\mu^-$ pairs in the J/ψ mass window, and large rapidity gaps are required on both the p and $\bar{p}$ sides. Ten candidate events are found for exclusive $\chi_c^0 \to J/\psi + \gamma$ (Fig. 7). Since the background from multiplicity fluctuations of inclusive events is unknown, the cross section for the ten events is given as an upper limit on exclusive $J/\psi + \gamma$ production of $\sigma(p\bar{p} \to p + J/\psi + \gamma + \bar{p}) = 49 \pm 18(\text{stat}) \pm 39(\text{syst})$ pb, $|\eta| < 0.6$. These limits are also in agreement with theoretically predicted exclusive rates [17]. Statistics of future measurements should be greatly improved by a new trigger which has been implemented by requiring rapidity gaps plus a muon and a track consistent with the J/ψ mass.

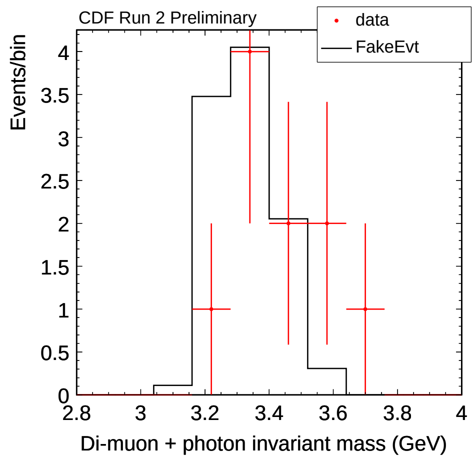

Fig. 7. The invariant mass of the di-muon and γ candidate compared to a sample of MC-generated χ_c^0 events passed through a simulation of the CDF detector.

REFERENCES

[1] F. Abe *et al.* (CDF Collaboration), *Nucl. Instrum. Methods Phys. Res.* **A271**, 387 (1988).

[2] K. Goulianos *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A518**, 42 (2003).

[3] M. Gallinaro *et al.*, Proceedings of the IX Hadron Physics and VII Relativistic Aspects of Nuclear Physics, Rio de Janeiro, Brazil, March 28–April 3 2004, `hep-ph/0407255`.

[4] See for example J.D. Bjorken, *Phys. Rev.* **D47**, 101 (1993).

[5] F. Abe *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **80**, 1156 (1998); **81**, 5278 (1998).

[6] B. Abbott *et al.* (D0 Collaboration), *Phys. Lett.* **B440**, 189 (1998).

[7] T. Affolder *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **87**, 141802 (2001).

[8] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **93**, 141601 (2004).

[9] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **91**, 011802 (2003).

[10] K. Goulianos, `hep-ph/0203141`.

[11] K. Goulianos, *Phys. Lett.* **B358**, 379 (1995).

[12] T. Affolder *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **85**, 4215 (2000).

[13] F.P. Schilling, *Acta Phys. Pol. B* **33**, 3419 (2002).

[14] T. Affolder *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **88**, 151802 (2002); **84**, 5043 (2000).

[15] M. Gallinaro, *Acta Phys. Pol. B* **35**, 465 (2004).

[16] K. Terashi, Proceedings of the DIS'2004, Strbske Pleso, Slovakia.

[17] A.D. Martin *et al.*, `hep-ph/0409258` and references therein.