Exclusice Central Production and Diffractive W/Z Results from CDF II

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Abstract
We report recently published results on central exclusive production of di-jets and di-photons, and exclusive QED production of e^+e^- pairs. In addition, we discuss preliminary results on exclusive photoproduction of charmonium and bottomonium, exclusive QED production of $\mu^+\mu^-$ pairs, and single diffractive W/Z production. All the presented results were extracted from data collected by the CDF II detector from $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV. The implications of these results for the Large Hadron Collider (LHC) are briefly examined.

1 Introduction

We present results obtained by CDF II at the Tevatron [1] in two broad areas: inclusive diffraction and exclusive production. The main goal of the Run II inclusive diffractive program of CDF has been to understand the QCD nature of the Pomeron [2] ($I\!P$) by measuring the diffractive structure function [3] $F^{D4}(Q^2, x_{Bj}, \xi, t)$, where ξ is the 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 the jets. Important results are the observation of a breakdown of QCD factorization in hard diffractive processes, expressed as a suppression by a factor of $\mathcal{O}(10)$ of the production cross section relative to theoretical expectations, and the breakdown of Regge factorization in soft diffraction by a factor of the same magnitude [3]. Combined, these two results support the hypothesis that the breakdown of factorization is due to a saturation of the rapidity gap formation probability by an exchange of a color-neutral construct of the underlying parton distribution function (PDF) of the proton [4]. Historically, such an exchange is referred to as the Pomeron. Renormalizing the "gap probability" to unity over all (ξ, t) phase space corrects for the unphysical effect of overlapping diffractive rapidity gaps and leads to agreement between theory and experiment (see [4]).

Central exclusive production in $p\bar{p}$ collisions is a process in which the p and $\bar{p}$ remain intact and an exclusive state X$_{excl}$ is centrally produced: $p + \bar{p} \rightarrow p + X_{excl} + \bar{p}$. The primary motivation for studying exclusive physics at the Tevatron is to test the feasibility of using exclusive production to search for and study the Higgs boson as well search for other new physics at the LHC [5]. In leading order

[1]The presented results are from the CDF diffractive and exclusive physics program of Run II. This program relies on a system of special forward detectors, which include: a Roman Pot Spectrometer (RPS) equipped with scintillation counters and a fiber tracker to detect and measure the angle and momentum of leading anti-protons, a system of Beam Shower Counters (BSCs) [1] covering the pseudorapidity range 5.5 $< |\eta| <$ 7.5 used to select diffractive events by identifying forward rapidity gaps and reducing non-diffractive background on the trigger level, and two very forward (3.5 $< \; |\eta| \; <$ 5.1) MiniPlug (MP) calorimeters [2], designed to measure energy and lateral position of both electromagnetic and hadronic showers. The ability to measure the event energy flow in the very forward rapidity region is vital for the identification of diffractive events in the high luminosity environment of Run II.

[2]Diffractive reactions are characterized by the exchange of a spin 1 quark/gluon construct with the quantum numbers of the vacuum. In Regge theory, this exchange is the vacuum trajectory traditionally referred to as the Pomeron ($I\!P$). Because the exchange is colorless, a large region in pseudorapidity space is left empty of particles (this region is called a "rapidity gap"). In perturbative QCD, the lowest order prototype of the Pomeron is the color neutral system of two gluons.

QCD, exclusive production occurs through gluon-gluon fusion, while an additional soft gluon screens the color charge allowing the protons to remain intact [6]. This mechanism, historically termed Double Pomeron Exchange (DPE), enables exclusive production of di-jets [3], $\gamma\gamma$ [7], and the χ_c° [8] at the Tevatron, whereas at the LHC, where central masses up to several hundred GeV are attainable, new central exclusive channels open up, as for example W^+W^- and Z^0Z^0. While the main effort at the LHC is directed toward searches for inclusively produced Higgs bosons, an intense interest is developing in exclusive Higgs production, $p + \bar{p} \to p + H + \bar{p}$. This production channel presents several advantages, as for example the production of clean events in an environment of suppressed QCD background for the main Higgs decay mode of $H \to b_{jet} + \bar{b}_{jet}$ due to the $J_z = 0$ selection rule [5]. Exclusive production can also occur through photoproduction ($I\!P$ - γ fusion), yielding charmonium and bottomonium. The same tagging technique can also be utilized to select γp, or γq and γg interactions at the LHC, for which the energy reach and the effective luminosity are higher than for $\gamma\gamma$ interactions.

Additionally, exclusive production of central lepton pairs, $\gamma\gamma \to l^+l^-$ ($l = e, \mu, \tau$), via two-photon exchange has been observed at CDF [9]. Tagging two-photon production offers a significant extension of the LHC physics program.[3] Particularly exciting is the possibility of detecting two-photon exclusive W^+W^-, Z^0Z^0, Higgs boson and new physics production at the LHC [10]. The deployment of forward proton detectors at 200 m and 420 m (FP420 project) from the interaction point of ATLAS and CMS, in order to exploit the above mentioned forward physics scenarios, is currently under consideration [11]. Two-photon exclusive production of lepton pairs will provide an excellent monitoring tool of the tagging efficiency and energy scale of the detectors of the FP420 project. These events can also be used for several systematic studies, including luminosity normalization and contributions from inelastic production or accidental tagging.

2 Central Exclusive Production

Exclusive production is hampered by expected low production rates [5]. As rate calculations are model dependent and generally involve non-perturbative suppression factors, it is sensible to calibrate them against processes involving the same suppression factors but have high enough production rates to be measurable at the Tevatron. The leading order diagrams relating to the exclusive central production processes discussed in this paper are summarized in Fig. 1.

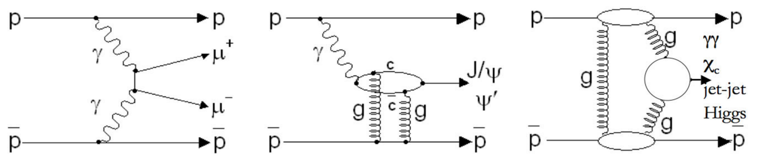

Fig. 1: Leading order diagrams for three types of exclusive process: $\gamma\gamma$ interactions (left), $\gamma I\!P$ fusion or photoproduction (middle), and gg t-channel color-singlet two-gluon exchange (right). Higgs boson production proceeds via the gg diagram.

2.1 Exclusive Di-jet Production

The process of exclusive di-jet production, which has been observed by CDF in Run II data [12], proceeds through the same mechanism as $\gamma\gamma$, χ_c°, and Higgs production, as shown in Fig. 1. The analysis strategy developed to search for exclusive di-jet production is based on measuring the di-jet mass fraction, R_{jj}, defined as the di-jet invariant mass M_{jj} divided by the total mass of the central system: $R_{jj} = M_{jj}/M_X$.[4]

[3]The effective luminosity of high-energy $\gamma\gamma$ collisions reaches $\sim$1% of the pp luminosity, so that the standard detector techniques used for measuring very forward proton scattering should allow for a reliable extraction of $\gamma\gamma$ results.

[4]The mass M_X is obtained from all calorimeter towers with energy above the thresholds used to calculate $\xi_{\bar{p}}^X$, while M_{jj} is calculated from calorimeter tower energies inside jet cones of R=0.7, where R=$\sqrt{\Delta\phi^2 + \Delta\eta^2}$. The exclusive signal is extracted by comparing the R_{jj} distribution shapes of DPE di-jet data and simulated di-jet events obtained from a Monte Carlo (MC) simulation that does not contain exclusive di-jet production.

The POMWIG MC [13] generator along with a detector simulation are used to simulate the DPE di-jets. The signal from exclusive di-jets is expected to appear at high values of R$_{jj}$, smeared by resolution and gluon radiation effects. Events from the inclusive DPE production process p + $\bar{p} \rightarrow p$ + gap +[X + jj] + gap (the leading p is not observed in CDF II) are expected to contribute to the entire R$_{jj}$ region. Any such events within the exclusive R$_{jj}$ range contribute to background and must be subtracted when evaluating exclusive production rates.

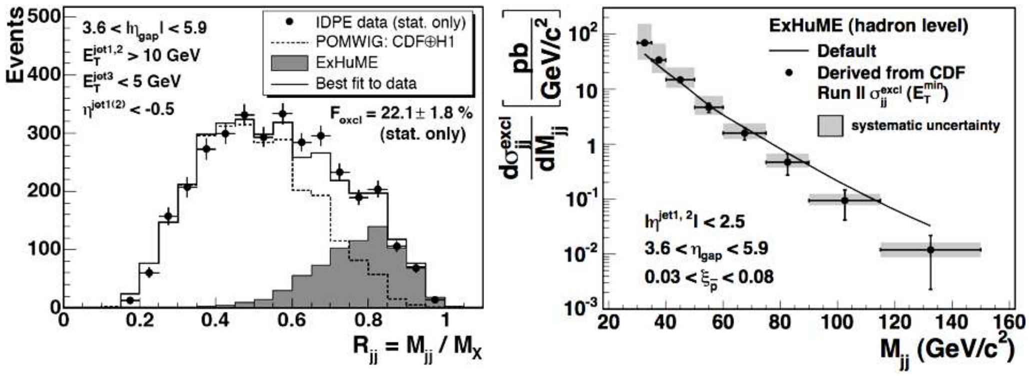

Fig. 2: (Left) The di-jet mass fraction in DPE data (points) and best fit (solid histogram) to a simulated di-jet mass fraction obtained from POMWIG MC events (dashed histogram) and ExHuME di-jet MC events (shaded histogram). (Right) The ExHuME [14] exclusive di-jet differential cross section at the hadron level vs. di-jet mass M$_{jj}$ normalized to measured σ_{jj}^{excl} values. The curve is the cross section predicted by ExHuME.

The process of exclusive di-jet production is important for testing and/or calibrating models for exclusive Higgs production at the LHC. The CDF II collaboration has made the first observation of this process and the main final result is presented in Fig. 2. Details can be found in Ref. [12]. This result favours the model of Ref. [6], which is implemented in the MC simulation ExHuME [14].

2.2 Exclusive e^+e^- Production

The CDF II collaboration has reported the first observation of exclusive e^+e^- production in $p\bar{p}$ collisions [9] using 532 pb^{-1} $p\bar{p}$ data collected at $\sqrt{s} = 1.96$ TeV by CDF II at the Fermilab Tevatron. The definition of exclusivity used requires the absence of any particle signatures in the detector in the pseudorapidity region $|\eta| < 7.4$, except for an electron and a positron candidate each with transverse energy of $E_T \geq 5$ GeV and within the pseudorapidity $|\eta| \leq 2$. With these criteria, 16 events were observed. The dominant background is due to events with unobserved proton dissociation (1.6 ± 0.3 events). The total background expectation is 1.9 ± 0.3 events. The observed events are consistent in cross section and properties with the QED process $p\bar{p} \rightarrow p + (e^+e^-) + \bar{p}$ through two-photon exchange. The measured cross section is $1.6^{+0.5}_{-0.3}(stat) \pm 0.3(syst)$ pb. This agrees with the theoretical prediction of 1.71 ± 0.01 pb obtained using the LPAIR MC generator [15] and a GEANT based detector simulation, CDFSim [16]. Details on the observation of the exclusive e^+e^- signal are reported in reference [9].

2.3 Exclusive $\gamma\gamma$ Production

An exclusive $\gamma\gamma$ event can be produced via $gg \rightarrow \gamma\gamma$ (g = gluon) through a quark loop, with an additional "screening" gluon exchanged to cancel the color of the interacting gluons and so allow the leading hadrons to stay intact. This process is closely related [7, 17] to exclusive Higgs production at the LHC, $p\bar{p} \rightarrow p + H + \bar{p}$, where the production mechanism of the Higgs boson is gg-fusion through a top quark loop. These processes can also be described as resulting from DPE.

A search has been performed for exclusive $\gamma\gamma$ production in p-$\bar{p}$ collisions at $\sqrt{s} = 1.96$TeV, using 532 pb^{-1} of integrated luminosity data taken by CDF II at Fermilab. The event signature requires two electromagnetic showers, each with transverse energy $E_T \geq 5$ GeV and pseudorapidity $|\eta| \leq 1.0$, with no other particles detected. Three candidate events were observed. Each candidate can be interpreted as either a $\gamma\gamma$ or a $\pi^0\pi^0/\eta\eta$ final state with overlapping photons that satisfy the $\gamma\gamma$ selection criteria and thus form a background. The probability that processes other than these fluctuate to ≥ 3 events is 1.7×10^{-4}. Two events clearly favor the $\gamma\gamma$ hypothesis and the third event favors the $\pi^0\pi^0$ hypothesis. On the assumption that two of the three candidates are $\gamma\gamma$ events we obtain a cross section $\sigma(p\bar{p} \rightarrow p + \gamma\gamma + \bar{p}) = 90^{+120}_{-30}(stat) \pm 16(syst)$ fb, for $E_T \geq 5$ GeV and $|\eta| \leq 1.0$, compatible within the theoretical uncertainties with the prediction of 40 fb of Ref. [5]. A comparison between the predictions of the ExHuMe MC and the data shows good agreement both in normalization and in the shapes of the kinematic distributions.

Although two of the candidates are most likely to arise from $\gamma\gamma$ production, the $\pi^0\pi^0$ hypotheses cannot be excluded. A 95% C.L. upper limit is obtained on the exclusive $\gamma\gamma$ production cross section ($E_T \geq 5$ GeV, $|\eta| \leq 1.0$) of 410 fb, which is about ten times higher than the prediction of Ref. [7]. This result may be used to constrain calculations of exclusive Higgs boson production at the LHC. Additional CDF data, collected with a lower E_T threshold, are being analysed. Exclusive $\gamma\gamma$ production has not previously been observed in hadron-hadron collisions. This work is described in more detail in Ref. [18].

2.4 Exclusive $\mu^+\mu^-$ Production

Low Mass Exclusive $\mu^+\mu^-$ ***Production.*** The CDF II collaboration has performed a search for exclusive low mass $\mu^+\mu^-$ final states resulting from three processes: $\gamma\gamma \rightarrow$ non-resonant $\mu^+\mu^-$ "continuum" events, and $J/\psi \rightarrow \mu^+\mu^-$ & $\psi' \rightarrow \mu^+\mu^-$ events arising from $I\!P$ - γ fusion (photoproduction). In addition, evidence for exclusive χ_c° production was sought arising from the decay channel $\chi_c^\circ \rightarrow J/\psi(\rightarrow \mu^+\mu^-) + \gamma$. The invariant mass distribution of the exclusive di-muon events obtained from 1.48 fb^{-1} of data is shown in Fig. 3. The J/ψ and ψ' peaks can be clearly seen above the $\mu^+\mu^-$ continuum.[5] Continuum $\mu^+\mu^-$ production arises from $\gamma\gamma$ interactions. These interactions are simulated

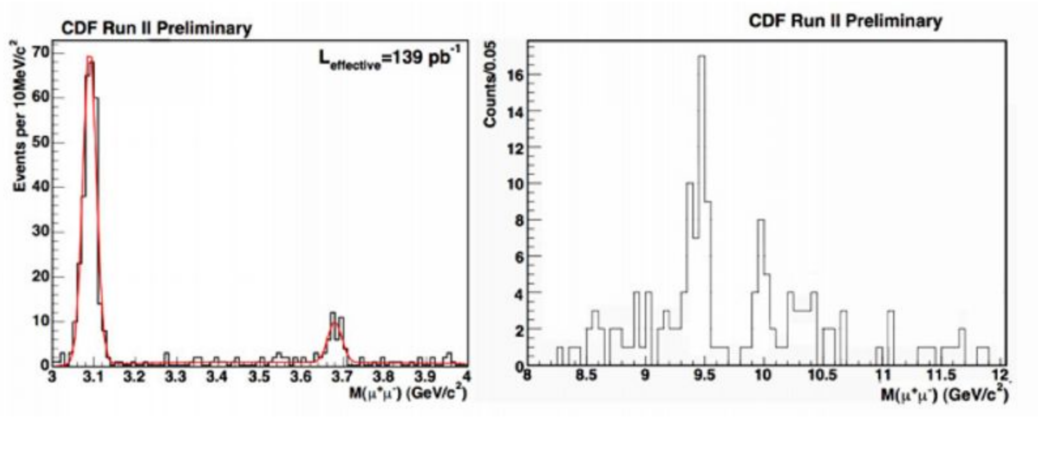

Fig. 3: (Left) The invariant mass distribution obtained from the exclusive $\mu^+\mu^-$ data; the J/ψ peak (left) and the smaller ψ' peak (right) can be clearly seen above the continuum of muon-pair production. (Right) The invariant mass distribution obtained from the exclusive higher mass $\mu^+\mu^-$ data: the Υ (1S) peak (middle-left) and the smaller Υ (2S) (middle) peaks can be clearly seen above the continuum, while he Υ (3S) peak (middle-right) is only barely discernible with these statistics.

by the LPAIR [15] and STARlight MCs [19]. Both give a very good description of the data in shape and in

[5]The offline cuts applied to the muon-pair data are the same as those applied in the e^+e^- case: there should be no activity in the event in the region $|\eta| < 7.4$, and the final state must have two identified muons of $P_T > 1.4$ GeV/c within $|\eta| < 0.6$.

normalization. The events in the J/ψ and ψ' peak of Figure 3, from the process $p\bar{p} \to p + J/\psi(J/\psi') + \bar{p}$, are mainly produced via $I\!P$ - γ fusion. The STARLight MC is used to simulate the photoproduction of the J/ψ and the ψ'.

A J/ψ in the final state can arise from exclusive χ_c° production, $p\bar{p} \to p + (\chi_c^\circ) + \bar{p}$ with $\chi_c^\circ \to J/\psi(J/\psi \to \mu^+\mu^-) + \gamma$. The photon in the χ_c° decay is soft and consequently may not be reconstructed and form a "background" to exclusive J/ψ production via $I\!P$ - γ fusion. The χ_c° contributes to the exclusive J/ψ peak when the soft photon from its decay survives the exclusivity cut. By fitting the shapes of the E_T and $\Delta\phi$ distributions of the di-muon pair of the events in the J/ψ peak of the data with MC generated distributions of J/ψ from photoproduction and χ_c° production, CDF II estimates the χ_c° contribution to the exclusive J/ψ photoproduction peak to be $\approx 10\%$.

Higher Mass Exclusive $\mu^+\mu^-$ Production. The basis of the study of high exclusive muon pairs is somewhat different in that it does not rely on the "standard" exclusivity cuts applied to the low mass data. In this case, one looks for muon pairs that form a vertex with no additional tracks. It is also required that the muons be consistent with $\Delta\phi \approx 0$ and with P_T-sum approximately zero. For 890 pb^{-1} of data (2.3M events), with $\Delta\phi > 120^o$ and a P_T-sum of the two muon tracks less than 7 GeV/c, the mass plot shown in Fig. 3 was obtained. One can clearly discern the $\Upsilon(1\mathrm{S})$ and $\Upsilon(2)$ peaks in this plot. The high mass exclusive muon pair data, with enhanced statistics, is currently under study.

3 Diffractive W/Z Production

Studies of diffractively produced W/ Z boson are important for understanding the structure of the Pomeron. The production of intermediate vector bosons is due to the annihllation of quark-antiquark pairs and thus is a probe of the quark content of the Pomeron. In leading order, the W/Z is produced by a quark in the Pomeron, while production by a gluon is suppressed by a factor of α_S and can be distinguished from quark production by an associated jet [20]. Diffractive dijet production at the Tevatron was found to be suppressed by a factor of $\mathcal{O}(10)$ compared to expectations from the Diffractive Structure Function (DSF) extracted from diffractive deep inelastic scattering (DDIS) at the DESY ep Collider HERA. A more direct comparison could be made by measuring the DSF in diffractive W production at the Tevatron, which is dominated by a $q\bar{q}$ exchange, as in DDIS. In Run I, only the overall diffractive W fraction was measured by CDF [20]. In Run II, both the W and Z diffractive fractions and the DSF are measured.

The CDF Run II analysis is based on events with RPS tracking from a data sample of ~ 0.6 fb^{-1}. In addition to the W/Z selection requirements[6], a hit in the RPS trigger counters and a RPS reconstructed track with $0.03 < \xi < 0.1$ and $|t| < 1$ are required. A novel feature of the analysis is the determination of the full kinematics of the $W \to e\nu/\mu\nu$ decay using the neutrino E_T^ν obtained from the missing E_T, as usual, and η_ν from the formula $\xi^{\mathrm{RPS}} - \xi^{\mathrm{cal}} = (E_T/\sqrt{s})\exp[-\eta_\nu]$, where $\xi^{\mathrm{cal}} = \sum_{\mathrm{towers}}(E_T/\sqrt{s})\exp[-\eta]$. The extracted value of $M_W^{\mathrm{exp}} = 80.9 \pm 0.7$ GeV is in good agreement with the world average W mass of $M_W^{\mathrm{PDG}} = 80.403 \pm 0.029$ GeV [21]. After applying corrections ccounting for the RPS acceptance, $A_{\mathrm{RPS}} \approx 80$ %, the trigger counter efficiency, $\epsilon_{\mathrm{RPStrig}} \approx 75$ %, the track reconstruction efficiency, $\epsilon_{\mathrm{RPStrk}} \approx 87$ %, multiplying by 2 to include production by $p\bar{p} \to W/Z + p$, and correcting the ND event number for the effect of overlaps due to multiple interactions by multiplying by the factor $f_{1-\mathrm{int}} \approx 0.25$, the diffractive fraction of W/Z events was obtained as $R_{W/Z} = 2 \cdot N_{SD}/A_{\mathrm{RPS}}/\epsilon_{\mathrm{RPStrig}}/\epsilon_{\mathrm{RPStrk}}/(N_{\mathrm{ND}} \cdot f_{1-\mathrm{int}})$:

$$R_W(0.03 < \xi < 0.10,\ |t| < 0.1) = [0.97 \pm 0.05\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})]\% \quad (1)$$

$$R_Z(0.03 < \xi < 0.10,\ |t| < 0.1) = [0.85 \pm 0.20\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})]\% \quad (2)$$

[6]The CDF W/Z selection requirements are: $E_T^{e,\mu} > 25$ GeV, $40 < M_T^W < 120$ GeV, $66 < M^Z < 116$ GeV, and vertex z-coordinate $|z_{vtx}| < 60$ cm. In the W case, the requirement of $\xi^{\mathrm{RPS}} > \xi^{\mathrm{CAL}}$ is very effective in removing the overlap evemnts in the region of $\xi^{\mathrm{CAL}} < 0.1$, while a mass cut of $50 < M_W < 120$ GeV has the same effect. In the Z case, we use the ξ^{CAL} distribution of all Z events normalized to the RP-track distribution in the region of $-1 < \log\xi^{\mathrm{CAL}} < -0.4$ ($0.1 < \xi^{\mathrm{CAL}} < 0.4$) to obtain the ND background in the diffractive region of $\xi^{\mathrm{CAL}} < 0.1$.

The R_W value is consistent with the Run I result of $R_W(0.03 < \xi < 0.10,\, |t| < 0.1) = [0.97 \pm 0.47]$ obtained from the published value of $R^W(\xi < 0.1) = [0.15 \pm 0.51 \text{ (stat)} \pm 0.20 \text{ (syst)}]\%$ [20] multiplied by a factor of 0.85 that accounts for the reduced (ξ-t) range in Run II.

4 Conclusion

We present recent results on exclusive central prodction of di-jets, di-leptons, and di-photons reported by the CDF II collaboration, obtained from Run II data collected at the Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.96$ TeV. The results are compared with theoretical expectations, and implications for the possible observation of exclusive Higgs boson production and other interesting new physics processes at the Large Hadron Collider are discussed.

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