We present some precision measurements on electroweak physics performed at the Tevatron collider at Fermilab. Namely we report on the boson-pair production cross sections and on triple gauge boson couplings using proton-anti-proton collisions collected by the CDF and D{\O} experiments at the center-of-mass energy of 1.96 TeV. The data correspond to an integrated luminosity of up to 324 pb$^{-1}$.

1 Introduction

The CDF$^1$ and D{\O}$^2$ experiments study proton-anti-proton collisions at $\sqrt{s} = 1.96$ TeV at the Tevatron collider at Fermilab (Batavia, IL, USA). The Run II of the Tevatron (started in 2001) gives us a unique opportunity to study $W$ and $Z$ boson physics. Compared to the LEP and SLD accelerators, where many of the best measurements of electroweak parameters have been made, the Tevatron offers the advantage to produce a larger number of $W$ bosons and to produce $Z/\gamma^*$ at higher invariant masses.

Study of events containing pairs of vector bosons produce important tests of the non-Abelian structure of the Standard Model (SM). The $SU(2)_L \times U(1)_Y$ structure of the SM implies that the electroweak gauge bosons $W$ and $Z$ can interact with one another through trilinear and quartic gauge boson vertices. Non-SM values of these couplings may increase the di-boson production cross section significantly. Therefore a measurement of this quantity provides a sensitive test of the SM and probes for low energy remnants of new physics.

In this note we review some new results on $W^+W^-$, $WZ$, $ZZ$, $W\gamma$ and $Z\gamma$ production cross section as well as limits on $WWZ$, $WW\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ anomalous couplings.
2  **W and Z signatures**

Due to a large QCD background, decay channels involving quarks are difficult to measure: therefore W and Z bosons are mainly identified through their leptonic decays. These decays are characterized by a high transverse energy ($E_T$) lepton and large transverse missing energy ($\not{E}_T$) for W, or by two high transverse energy leptons for Z. Typically the lepton $E_T$ is required to be greater than 20 - 25 GeV and $\not{E}_T$ greater than 20 - 25 GeV as well.

3  **$W^+W^-$ production cross section**

The first evidence of W pair production was found in $p\bar{p}$ collisions by the CDF Collaboration at $\sqrt{s} = 1.8$ TeV. The properties of W pair production have been extensively studied by the LEP collaborations but the Tevatron offers the possibility to probe much higher masses.

| Lum (pb$^{-1}$) |  |  |  |  |
|---|---|---|---|
| DØ | CDF |
| ($N_{sig}$) | $(N_{bg})$ | $(N_{obs})$ | $(N_{sig})$ | $(N_{bg})$ | $(N_{obs})$ |
| ee | $252$ | $3.42 \pm 0.05$ | $6$ | $184$ | $2.6 \pm 0.3$ | $6$ |
| $\mu\mu$ | $224$ | $2.10 \pm 0.05$ | $4$ | $184$ | $2.5 \pm 0.3$ | $6$ |
| $e\mu$ | $235$ | $11.10 \pm 0.1$ | $15$ | $184$ | $1.9 \pm 1.3$ | $1.3 \pm 1.6$ |
| ee | $184$ | $2.6 \pm 0.3$ | $6$ | $184$ | $2.5 \pm 0.3$ | $6$ |
| $\mu\mu$ | $184$ | $2.10 \pm 0.05$ | $4$ | $184$ | $2.5 \pm 0.3$ | $6$ |
| $e\mu$ | $184$ | $11.10 \pm 0.1$ | $15$ | $184$ | $1.9 \pm 0.4$ | $5$ |

In this note we present the measurement of $W^+W^-$ production cross section in the dilepton decay channel $W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ ($l = e, \mu$). Candidate events are required to have two well identified, oppositely charged, leptons (electrons or muons). Significant backgrounds to $W^+W^-$ production in the dilepton channels include Drell-Yan events with large $\not{E}_T$, $tt$ production and $WZ$, $ZZ$ production. The number of expected signal ($N_{sig}$) and background ($N_{bg}$) events and the number of observed events ($N_{obs}$) are given in Table 1 for CDF and DØ, together with the integrated luminosity for each decay channel. As a final result, the combined cross section for $WW$ production at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV is:

$$
\sigma(p\bar{p} \rightarrow W^+W^-) = \begin{cases} 14.6^{+5.8}_{-4.1} \text{ (stat) } & \pm 0.9 \text{ (lum) pb (CDF)} \\ 13.8^{+3.4}_{-3.8} \text{ (stat) } & \pm 0.9 \text{ (lum) pb (DØ)} \end{cases}
$$

These values are in good agreement with the NLO calculation of $12.4 \pm 0.8$ pb, as shown in Fig. 1. DØ also calculates the probability that the observed events are caused by a fluctuation of the background. This probability amounts to $2.3 \times 10^{-7}$, corresponding to 5.2 standard deviations.

4  **$WZ$ and $ZZ$ pair production**

The presence of unexpected neutral triple gauge boson couplings ($ZZZ$ and $ZZ\gamma$) can result in an enhanced rate of ZZ production, and a anomalous WWZ coupling can increase the WZ production rate above the SM prediction. In general the $WWW$ $(V = Z, \gamma)$ interactions can be described by an effective Lagrangian with arbitrary parameters $g^1_V$, $\lambda_V$ and $\kappa_V$. In the SM $g^1_Z = \kappa_Z = 1$ and $\lambda_Z = 0$. To avoid unitarity violation at high energies, it is necessary to introduce form factors with scale $\Lambda$.

A test for anomalous trilinear boson couplings using $WZ$ events is unique in that $WZ$ diagrams contain only $WWZ$ and not $WW\gamma$ vertices. Anomalous trilinear gauge boson coupling
limits produced using $W^+W^-$ events are sensitive to both vertices and must make an assumption about the relation of the $WWZ$ to the $WW\gamma$ coupling. See for instance the HISZ relations. As this analysis is performed using $W^\pm Z$ event candidates that are unavailable at $e^+e^-$ colliders, it provides a unique measurement of $WWZ$ anomalous coupling limits.

The cleanest $WZ$ signals consist of final states with three charged leptons and a neutrino. Requiring three isolated high transverse momentum ($p_T$) leptons and large $E_T$ associated with the neutrino strongly suppresses all known SM backgrounds. The main background comes from $Z + X$ events, where $X$ is a jet, a photon or a $Z$.

Table 2: Number of signal ($N_{sig}$) and background ($N_{bg}$) events expected and number of events observed ($N_{obs}$) by the DØ experiment for the four tri-lepton channels. The integrated luminosity is also given.

| Decay Channels | $N_{obs}$ | $N_{sig}$  | $N_{bg}$  | lum (pb$^{-1}$) |
|----------------|----------|-----------|-----------|-----------------|
| $eee$          | 1        | 0.44 ± 0.07 | 0.155 ± 0.043 | 320             |
| $e\mu\mu$     | 0        | 0.45 ± 0.04 | 0.073 ± 0.029 | 292             |
| $\mu\mu\mu$   | 2        | 0.62 ± 0.08 | 0.132 ± 0.053 | 289             |
| **Total**      | **3**    | **2.04 ± 0.13** | **0.71 ± 0.08** | –               |

The number of observed candidates ($N_{obs}$), the number of expected signal ($N_{sig}$) and background ($N_{bg}$) events are given in Table 2 for the DØ Collaboration for each trilepton channel. The 2.04 ± 0.13 expected $WZ$ events combined with the 0.71 ± 0.08 estimated background events are consistent with the three candidate events found by DØ. The probability for a background to fluctuate to three or more candidates is 3.5%. The corresponding $\sigma(p\bar{p} \to WZ)$ amounts to 4.5$^{+3.8}_{-2.6}$ pb and the 95% confidence level (C.L.) upper limit is < 13.3 pb.

CDF performed a combined analysis to measure the $WZ$ and $ZZ$ cross sections. They studied events in three categories designed to encompass the main leptonic ratios of the $WZ$ and $ZZ$ decays. The first include events with four charged leptons, which is sensitive to $ZZ \to lll'l'$ ($l = e, \mu, \tau$). The second category includes events with three charged leptons plus $E_T$. It consists predominantly of $ZW \to lll'$, Events from $ZZ \to lll'$, where one lepton is not identified, can also fall in this category. The third category includes events with two charged
The dominant background is $W$ via lepton bremsstrahlung required to suppress events with final state radiation of the photon from the outgoing lepton. In addition to $W W$ production, $W$ lepton bremsstrahlung is used to study the $W Z$ vertex. The final state which is used in this study is $p \bar{p} \rightarrow l l' \nu \nu$ ($l = e, \mu$). In the SM this final state occurs due to $W \gamma$ as well as via lepton bremsstrahlung $W \rightarrow l \nu \rightarrow l l' \nu$. The selection is the same as in the $W$ inclusive cross section measurement and is described elsewhere in these proceedings. In addition to the $W$, a high-energy ($E_{T}^{l} > 7$ GeV) photon isolated from the lepton ($\Delta R(\gamma - l) > 0.7$) is required to suppress events with final state radiation of the photon from the outgoing lepton. The dominant background is $W + \text{jet}$ production where a jet mimics a photon.
Table 5: Number of expected signal ($N_{\text{sig}}$) and background ($N_{bg}$) events and number of observed events ($N_{\text{obs}}$) for $e\nu\gamma$ and $\mu\nu\gamma$ production for DØ and CDF. The first cross section uncertainty is statistical and the second is systematic.

|        | DØ                  | CDF                  |
|--------|---------------------|----------------------|
|        | $e\nu\gamma$       | $\mu\nu\gamma$     |
| Lum (pb$^{-1}$) | $162$ (6.5%)        | $134$ (6.5%)        |
| $N_{\text{sig}}$   | $51.2 \pm 11.5$    | $89.7 \pm 13.7$    |
| $N_{bg}$            | $60.8 \pm 4.5$     | $71.3 \pm 5.2$     |
| $N_{\text{obs}}$    | $112$              | $161$              |
| $\sigma(l\nu\gamma)$(pb)  | $13.9 \pm 2.9$ | $15.2 \pm 2.0$ |

The number of observed candidates ($N_{\text{obs}}$) and the number of expected signal ($N_{\text{sig}}$) and background ($N_{bg}$) events are given in Table 5 for the CDF and DØ collaborations for the electron and muon channels. The resulting cross sections are also given in Table 5. Combining both channels, assuming lepton universality and taking into account correlations of the systematic uncertainties, yields $\sigma(l\nu\gamma) = 18.1 \pm 3.1$ pb for CDF. The theoretical prediction for this cross section and for the kinematic region $E_T^{\gamma} > 7$ GeV and $\Delta R(\gamma - l) > 0.7$ is $19.3 \pm 1.4$ pb. The combined cross section of DØ is measured to be $\sigma(l\nu\gamma) = 14.8 \pm 1.6$ (stat) $\pm 1.0$ (syst) $\pm 1.0$ (lum) pb, in agreement with the SM prediction of $16.0 \pm 0.4$ pb, for the kinematic region $E_T^{\gamma} > 8$ GeV and $\Delta R(\gamma - l) > 0.7$.

Fig. 3 shows the photon $E_T$ spectrum for CDF (left) and DØ (right). The data (black points) are compared with the SM expectations for signal and backgrounds (open histogram). The background estimates are indicated with shaded histograms. The data are in good agreement with the SM expectations, and no enhancement of the photon $E_T$ spectrum is seen at high transverse energy. DØ sets one- and two-dimensional 95% C.L. limits on the coupling parameters $\Delta \kappa_\gamma$ and $\lambda_\gamma$ (see Fig. 4). The one-dimensional limits on each parameter are $-0.93 < \Delta \kappa_\gamma < 0.97$ and $-0.22 < \lambda_\gamma < 0.22$. These limits represent the most stringent constraints on anomalous $WW\gamma$ couplings obtained by direct observation of $W\gamma$ production.
6 $Z\gamma$ production.

In the SM the trilinear gauge couplings of the $Z$ boson to the photon are zero. Therefore photons do not interact with $Z$ bosons at lowest order. Evidence of such an interaction would indicate new physics. The study of $Z$ boson and photon production is a stepping stone for the analysis of $ZZ^*\gamma$ and $Z\gamma^*\gamma$ trilinear gauge couplings.

We present the study of $Z\gamma$ production using $Z$ boson decays to $e^+e^-$ and $\mu^+\mu^-$. The photon may be emitted through initial state radiation (ISR) from one of the partons or produced as final state radiation (FSR) from one of the final leptons. The SM $Z\gamma$ production processes produce photons with a rapidly falling transverse energy $E^\gamma_T$. In contrast anomalous $ZZ^*\gamma$ or $Z\gamma^*\gamma$ couplings which appear in extensions of the SM, can cause production of photons with high $E^\gamma_T$ and can increase the $l^+l^-\gamma$ cross section compared to the SM prediction. In the formalism described in Ref. 15 one assumes that the $ZV\gamma$ ($V = Z, \gamma$) couplings are Lorentz and gauge-invariant. The most general $ZV\gamma$ coupling is parameterized by two CP-violating ($h^V_{10}$ and $h^V_{20}$) and two CP-conserving ($h^V_{30}$ and $h^V_{40}$) complex coupling parameters. The $Z\gamma$ candidate events are selected using the same selection as in the $Z$ inclusive cross section measurement (described elsewhere in these proceedings 12) but with the identification of a photon as described in section 5. The main background to $Z\gamma$ is $Z$+jet production, where the jet is misidentified as a photon.

Table 6: Number of expected signal ($N_{sig}$) and background ($N_{bg}$) events and number of observed events ($N_{obs}$) for $ee\gamma$ and $\mu\mu\gamma$ production for D\$ and CDF.

|        | D\$       | CDF       |
|--------|------------|-----------|
|        | $ee\gamma$ | $\mu\mu\gamma$ | $ee\gamma$ | $\mu\mu\gamma$ |
| Lum (pb$^{-1}$) | 324 (6.5%) | 286 (6.5%) | 168 - 202 (6%) | 175 - 192 (6%) |
| $N_{sig}$  | 109 ± 7   | 128 ± 8   | 31.3 ± 1.6    | 33.6 ± 1.5    |
| $N_{bg}$   | 23.6 ± 2.3 | 22.4 ± 3.0 | 2.8 ± 0.9     | 2.1 ± 0.7     |
| $N_{obs}$  | 138        | 152       | 36            | 35            |

The number of observed candidates ($N_{obs}$) and the number of expected signal ($N_{sig}$) and background ($N_{bg}$) events are given in Table 6 for the CDF and D\$ collaborations for the electron.
The resulting cross sections of CDF are \( \sigma(e^+e^-) = 4.8 \pm 0.8 \text{ (stat)} \pm 0.3 \text{ (syst)} \text{ pb} \) and \( \sigma(\mu^+\mu^-) = 4.4 \pm 0.8 \text{ (stat)} \pm 0.2 \text{ (syst)} \text{ pb} \). The combined cross section measured by CDF is \( \sigma(l^+l^-) = 4.6 \pm 0.6 \text{ pb} \) in agreement with the theoretical prediction including the photon acceptance of 4.5 \pm 0.3 \text{ pb} \[17\]. The combined cross section measured by DØ is \( \sigma(l^+l^-) = 4.2 \pm 0.4 \text{ (stat + syst)} \pm 0.3 \text{ (lum)} \text{ pb} \) in agreement with the theoretical prediction including the photon acceptance of 3.9\(^{+0.1}_{-0.2}\) \text{ pb} \[18\].

### Table 7: One-dimensional 95% C.L. limits on the anomalous \( Z\gamma \) couplings for \( \Lambda = 750 \text{ GeV} \) and 1.0 TeV.

| Coupling | \( \Lambda = 750 \text{ GeV} \) | \( \Lambda = 1.0 \text{ TeV} \) |
|----------|-----------------|-------------------|
| \(|\text{Re}(h_{10,30}^\gamma)|, |\text{Im}(h_{10,30}^\gamma)|\); \( |\text{Re}(h_{20,40}^\gamma)|, |\text{Im}(h_{20,40}^\gamma)|\); \( |\text{Re}(h_{10,30}^\gamma)|, |\text{Im}(h_{10,30}^\gamma)|\); \( |\text{Re}(h_{20,40}^\gamma)|, |\text{Im}(h_{20,40}^\gamma)|\) | 0.24 | 0.23 |
| 0.27 | 0.020 |
| 0.29 | 0.23 |
| 0.030 | 0.019 |

Fig. 5 shows the photon \( E_T^\gamma \) spectrum for CDF (left) and DØ (right). The data (black points) are compared with the SM expectations for signal and backgrounds (open histogram). The data are in good agreement with the SM expectations, and no enhancement of the photon \( E_T^\gamma \) spectrum is seen at high transverse energy.

From the \( E_T^\gamma \) spectrum, 95% C.L. limits are extracted by DØ on each of the CP-violating and CP-conserving anomalous couplings. The one-dimensional limits at 95% C.L. on the real and imaginary parts of \( h_{i0}^V \) (\( i = 1, 2, 3, 4 \)) are given in Table 7. The two-dimensional limit contours in the plane \( h_{30}^V \) and \( h_{40}^V \) at 95% C.L. are shown in Fig. 6. These limits are substantially more restrictive than previous results which have been presented using the same formalism \[19\]. The limits on \( h_{20}^V \) and \( h_{40}^V \) are more than twice as restrictive as the combined results of the four LEP experiments \[20\].

### 7 Conclusion

The Run II of the Tevatron is well underway and the di-boson cross section measurements have already re-established most of the Run I results. In addition limits on the \( WZ \) cross section are extracted by both experiments as well as limits on the triple gauge boson couplings.
Figure 6: Two-dimensional 95% C.L. limits on CP-conserving $ZZ\gamma$ (a) and $Z\gamma\gamma$ (b) couplings for $\Lambda = 1$ TeV obtained with 286-324 pb$^{-1}$ of DØ data. Dashed lines illustrate the unitarity constraints.

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