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Electroweak measurements from the Tevatron

E. Halkiadakis on behalf of the CDF and DØ Collaborations
Rutgers, The State University of New Jersey - Piscataway, NJ, USA

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Summary. — I review the status of electroweak measurements including W and Z bosons produced at the Tevatron. I describe measurements of the W-boson mass, the W production charge asymmetry, diboson production and limits on anomalous trilinear gauge couplings. These analyses use integrated luminosities ranging from 200 pb^{-1} to 3.6 fb^{-1} of data collected by the CDF and DØ Run-II detectors at the Fermilab Tevatron.

PACS 12.15.Ji – Applications of electroweak models to specific processes.
PACS 13.85.Qk – Inclusive production with identified leptons, photons, or other nonhadronic particles.
PACS 14.70.Fm – W bosons.

1. – Introduction

The Fermilab Tevatron is a p-$\bar{p}$ collider at a center-of-mass energy of 1.96 TeV and produces W and Z bosons via q-$\bar{q}$ annihilation at a high rate. Electroweak measurements with W and Z bosons provide us with high-precision tests of the Standard Model (SM) as well as indirect knowledge about the Higgs boson and possible new physics.

In this report, I summarize recent electroweak measurements from the CDF and DØ experiments at the Tevatron using data with integrated luminosities ranging from 200 pb^{-1} to 3.6 fb^{-1}. First, I focus on the high-precision measurements of the W-boson mass and the W production charge asymmetry. Additionally, I present measurements of diboson production which include a first measurement at the Tevatron of $Z\gamma$ in the purely neutral final state and the observation of ZZ production. I also report a summary of limits on anomalous trilinear gauge couplings.

2. – Single-boson production

2˙1. *Precision measurement of the W-boson mass.* – The W-boson mass, m_W, is a fundamental parameter of the SM and its precision measurement is a primary goal of the Tevatron physics program. Together with the mass of the top quark, a precise measurement of m_W is the key to our understanding of the electroweak interaction, in

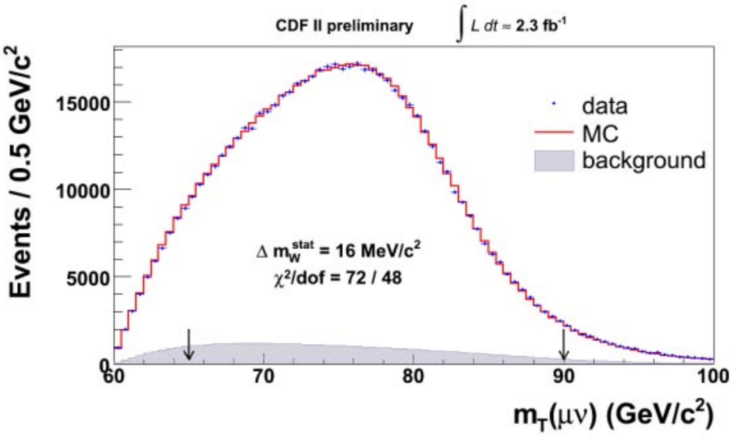


Fig. 1. – The transverse mass distribution of $W \to \mu\nu$ decays from CDF with $2.3\,\mathrm{fb}^{-1}$ of data.

particular the mechanism for electroweak symmetry breaking. In other words, reducing the uncertainty on the measurement of m_W allows us to further constrain the Higgs boson mass.

At the Tevatron, m_W is measured using leptonic W decays and is extracted from a template fit to the transverse mass (m_T), transverse momentum of the lepton (p_T^ℓ) and the transverse missing energy ($\not{E}_\mathrm{T}$) distributions. A fast Monte Carlo simulation is used to model the lineshape of the template distributions, accounting for the complex detector acceptance and resolution effects. We constrain and evaluate our level of understanding of these important detector and physics effects which determine the precision of the measurement of m_W. Examples of these effects, which are rigorously modeled and studied, include the tracker momentum scale and resolution, the calorimeter energy scale and resolution, the intrinsic W-boson transverse momentum and the proton parton distribution functions (PDFs).

Using $200\,\mathrm{pb}^{-1}$ of Tevatron Run-II data which contains a sample of 63964 $W \to e\nu$ decays and 51128 $W \to \mu\nu$ decays the CDF Collaboration measures $m_W = 80413 \pm 34(\mathrm{stat.}) \pm 34(\mathrm{syst.})\,\mathrm{MeV}/c^2$, with a total measurement uncertainty of $48\,\mathrm{MeV}/c^2$ [1]. Combining this measurement with measurements of m_W from Run I of the Tevatron and LEP with uncertainties of $59\,\mathrm{MeV}/c^2$ and $33\,\mathrm{MeV}/c^2$, respectively, give a current world average of $m_W = 80399 \pm 25\,\mathrm{MeV}/c^2$. Additionally, using a dataset corresponding to $1\,\mathrm{fb}^{-1}$ of data, with 499830 $W \to e\nu$ decays the DØ Collaboration recently presented a preliminary measurement of $m_W = 80401 \pm 21(\mathrm{stat.}) \pm 38(\mathrm{syst.})\,\mathrm{MeV}/c^2 = 80401 \pm 43\,\mathrm{MeV}/c^2$, the most precise to date.

Many of the systematic uncertainties in these measurements are limited by the statistics of the control samples used to understand the detector and physics effects and can be improved with an analysis of the larger datasets in hand. Additionally, improvements in the detector model and the production and decay model (for example, by including the input from updated PDF fits) are likely to further reduce the overall systematic uncertainty on future measurements of m_W. CDF has begun analyzing a data sample with an integrated luminosity of $2.3\,\mathrm{fb}^{-1}$, as can be seen in fig. 1. Studies in progress confirm that many of the systematic uncertainties scale with luminosity as expected and we look forward to an updated m_W measurement with a precision better than the current world average of $25\,\mathrm{MeV}/c^2$.

2˙2. *W production charge asymmetry.* – At the Fermilab Tevatron, $W^+(W^-)$ bosons are created primarily by the interaction of u (d) quarks from the proton and $\bar{d}$ ($\bar{u}$) quarks from the anti-proton. Since u-quarks carry, on average, a higher fraction of the proton's momentum than d-quarks, the W^+ tends to be boosted along the proton beam direction and the W^- tends to be boosted along the anti-proton direction. The difference between the W^+ and W^- rapidity distributions results in a charge asymmetry,

$$A(y_W) = \frac{\mathrm{d}\sigma^+/\mathrm{d}y_W - \mathrm{d}\sigma^-/\mathrm{d}y_W}{\mathrm{d}\sigma^+/\mathrm{d}y_W + \mathrm{d}\sigma^-/\mathrm{d}y_W}, \tag{1}$$

where y_W is the W-boson rapidity and $\mathrm{d}\sigma^\pm/\mathrm{d}y_W$ is the differential cross-section for W^+ or W^- boson production. The PDFs describing the internal structure of the proton are constrained by measuring $A(y_W)$. Improvements in PDF uncertainties will reduce the total uncertainties on many important measurements, such as the measurement of the W-boson mass described in the previous section.

Traditionally, the W charge asymmetry measurements at the Tevatron have been made as a function of the pseudorapidity η of the leptons from decays of $W \to l\nu_l$ ($l = e, \mu$) since the W decay involves a neutrino whose longitudinal momentum is not determined experimentally. A recent measurement of the lepton charge asymmetry from DØ uses $W \to e\nu$ decays in $750\,\mathrm{pb}^{-1}$ [2]. As shown in fig. 2, the asymmetry is measured in two bins of electron E_T, $25 < E_T < 35\,\mathrm{GeV}$ and $E_T > 35\,\mathrm{GeV}$, since for a given η the two E_T regions probe different ranges of y_W. For higher E_T, the electron direction is closer to the W direction and gives an improved sensitivity to the PDFs. The data are compared to a next-to-leading-order (NLO) perturbative QCD calculation [3,4] with NLO PDFs from CTEQ6.6 [5] and MRST04 [6]. Figure 2 shows that the measured charge asymmetries tend to be lower than the theoretical predictions for high-η electrons.

Since the lepton charge asymmetry is a convolution of the W production charge asymmetry and the $V - A$ asymmetry from W decays these two asymmetries tend to cancel at large pseudorapidities ($|\eta| < 2.0$). This convolution weakens and complicates the constraint on the proton PDFs. In an analysis by CDF, the complication is resolved by using additional information in the lepton E_T and the $\not{E}_\mathrm{T}$ on an event-by-event basis to measure the asymmetry as a function of the $|y_W|$ instead of the lepton $|\eta|$. Using this new analysis technique [7] CDF presents the first direct measurement of the W production charge asymmetry, which uses $W \to e\nu$ decays and $1\,\mathrm{fb}^{-1}$ of data [8] and is shown in fig. 3. Also shown are the predictions of a NNLO QCD calculation [9] using the MRST 2006 NNLO PDF sets [6] and a NLO QCD calculation using the CTEQ6.1 NLO PDF sets [5], which are in agreement with the measured asymmetry.

These precision measurements of the W charge asymmetry from the Tevatron experiments are testing the accuracy of our knowledge of the proton structure and once included are expected to improve the precision of the global PDFs fits.

3. – Diboson production

The production of dibosons at the Tevatron has similar topologies to beyond the SM searches and therefore contribute as a background to possible new physics, such as in the searches for the Higgs or supersymmetry. Therefore, by making measurements of diboson processes we can test for deviations from SM predictions. These tests can be performed with measurements of the diboson production cross-sections as well as with measurements of triple gauge couplings (TGCs). Couplings between gauge bosons are the

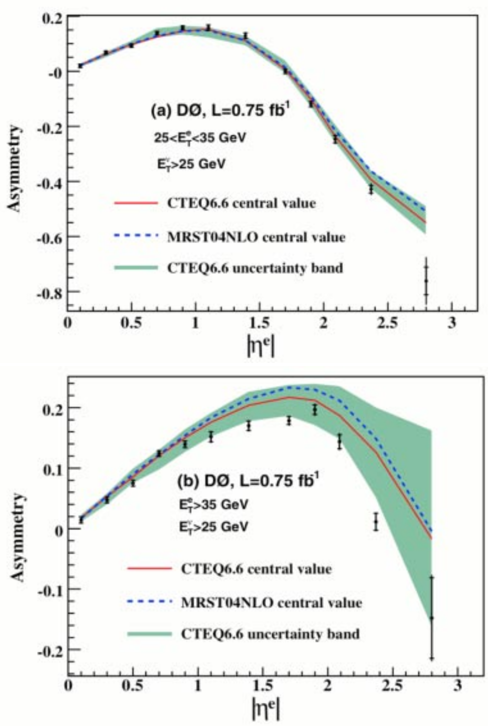


Fig. 2. – The measured electron charge asymmetry distribution from DØ in two electron E_T bins: $25 < E_T < 35\,\mathrm{GeV}$ (left) and $E_T > 35\,\mathrm{GeV}$ (right).

least well-known quantities in the electroweak sector and various SM extensions predict large values of TGCs. The SM allows couplings which involve two W-bosons and either a γ or a Z boson, however, there are no couplings which include only combinations of γ and Z bosons. Measurements of TGCs at the Tevatron are important as they are complementary to the measurements from LEP, exploring a higher $\sqrt{s}$ and different combinations of couplings. What I focus on in this report are the $Z\gamma$ and ZZ processes which probe the $ZZ\gamma$, $Z\gamma\gamma$ and ZZZ couplings and are not permitted in the SM at leading order. A general parameterization is used to describe these anomalous couplings in terms of CP-violating and CP-conserving parameters and are also described by a form factor, with the parameter Λ being the new physics scale responsible for conserving unitarity.

3$\dot{}$1. *$Z\gamma$ production.* – The SM prediction of $Z\gamma$ production is via two tree-level diagrams: initial-state radiation (ISR) and final-state radiation (FSR). The SM cross-section for $Z\gamma$ is very small and due to infrared divergences it depends on the energy threshold of the photon, E_T^γ.

The channels involving two charged leptons ($\ell = \mathrm{e}$ or μ), $ee\gamma$ and $\mu\mu\gamma$, have been extensively studied at Tevatron. Both CDF and DØ apply similar event selection requiring two isolated high-p_T leptons, a photon with $E_T^\gamma > 7\,\mathrm{GeV}$ and a separation requirement between the photon and the leptons of $\Delta R_{\ell\gamma} > 0.7$. The invariant mass of the two leptons is also required to be $M_{\ell\ell} > 40\,\mathrm{GeV}/c^2$ for CDF and $M_{\ell\ell} > 30\,\mathrm{GeV}/c^2$ for DØ.

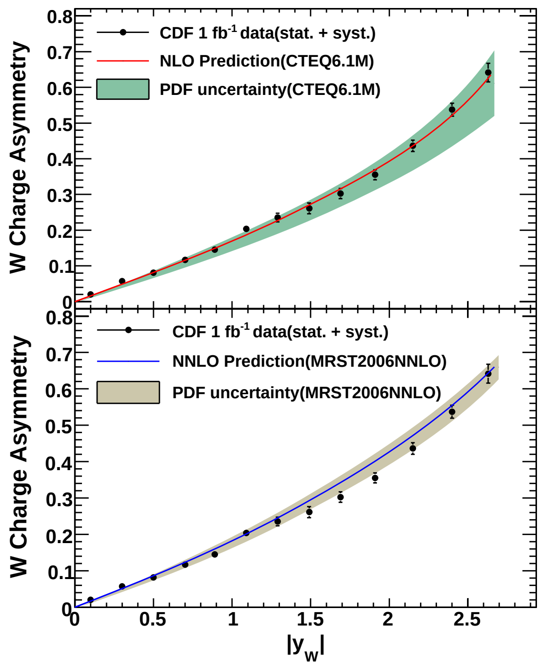


Fig. 3. – The measured W production charge asymmetry from CDF and theoretical predictions from (top) NLO CTEQ6.1 and (bottom) NNLO MRST2006, with their associated PDF uncertainties.

Additionally, CDF separates the ISR from the FSR events by looking at different $M_{\ell\ell\gamma}$ regions; ISR is defined as $M_{\ell\ell\gamma} > 100\,\text{GeV}/c^2$ and FSR is defined as $M_{\ell\ell\gamma} < 100\,\text{GeV}/c^2$. Table I summarizes the cross-section times branching ratio measurements from both CDF and DØ, showing good agreement compared to the NLO prediction [11].

DØ has recently observed with a 5.1σ significance the purely neutral final state of $Z\gamma \to \nu\nu\gamma$ with $3.6\,\text{fb}^{-1}$ of data for the first time at the Tevatron. This is a very challenging analysis. It has a higher acceptance and a higher branching ratio to $\nu\nu$ than to $\ell\ell$ and is also interesting since it is produced uniquely via ISR. The events are selected by making strict requirements of $E_T^\gamma > 90\,\text{GeV}$ and $\not{E}_{\text{T}} > 70\,\text{GeV}$. To suppress backgrounds, events are selected with no jets, and no high-p_T tracks. Additionally,

Table I. – *Summary of measured $Z\gamma$ cross-sections from the Tevatron experiments compared to the theoretical predictions.*

Channel	Experiment ($\int \mathcal{L}$)	Measured $\sigma \times$ BR (pb)	NLO Prediction (pb)
$Z\gamma \to \ell\ell\gamma$	DØ ($1\,\text{fb}^{-1}$) [10]	4.96 ± 0.42 (stat.+syst.)	4.7 ± 0.2 [11]
	CDF, ISR (1.1–2.0 fb^{-1})	1.2 ± 0.2 (stat.+syst.)	1.2 ± 0.1 [11]
	CDF, FSR (1.1–2.0 fb^{-1})	3.4 ± 0.3 (stat.+syst.)	3.3 ± 0.3 [11]
$Z\gamma \to \nu\nu\gamma$	DØ ($3.6\,\text{fb}^{-1}$) [12]	0.032 ± 0.009 (stat.+syst.)	0.039 ± 0.004 [11]

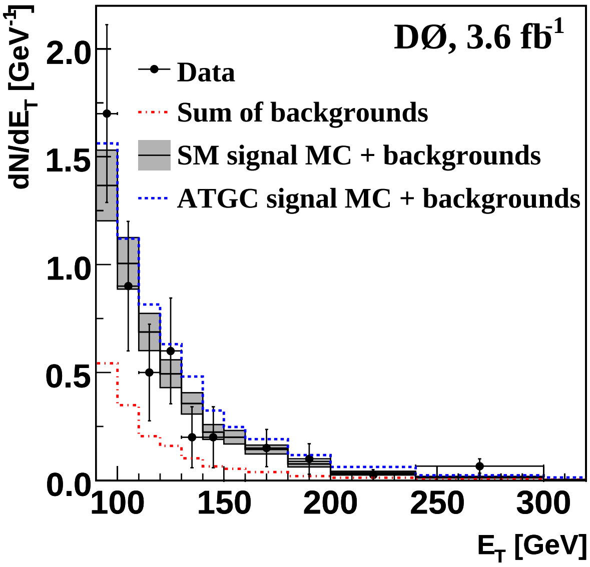


Fig. 4. – The E_T^{γ} distribution from $Z\gamma \to \nu\nu\gamma$ events analyzed by DØ and used to place limits on anomalous TGCs.

there is a challenging non-collision background coming from cosmic ray muons or beam halo muons which undergo bremsstrahlung radiation. This background is removed by requiring that the photon points back to the primary vertex of the event. The measured cross-section times branching ratio for this process is shown in table I and is in agreement with the SM prediction.

The photon E_T^{γ} spectra in these processes are used to probe anomalous TGCs, an example of which is shown in fig. 4 from the DØ analysis of $Z\gamma \to \nu\nu\gamma$ events. This figure shows the consistency with the SM prediction and also shows the effect on the shape of the E_T^{γ} spectrum assuming anomalous couplings near the current bounds. Both CDF and DØ have used the samples described above to set limits at the 95% confidence level (CL) on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings. The CDF results are based upon the $Z\gamma \to \ell\ell\gamma$ channel and were calculated using a scale of $\Lambda = 1.2\,\text{TeV}$ and the limits on the CP-conserving parameters are $|h_{30}^{Z}| < 0.083$, $|h_{30}^{\gamma}| < 0.084$, and $|h_{40}^{\gamma,Z}| < 0.0047$. The DØ results combine both the charged and neutral $Z\gamma$ channels and use a scale factor of $\Lambda = 1.5\,\text{TeV}$, giving combined limits of $|h_{30}^{\gamma,Z}| < 0.033$ and $|h_{40}^{\gamma,Z}| < 0.0017$ [10, 12], representing the best limits from the Tevatron to date. The results are similar for the CP odd couplings.

3$\cdot$2. *ZZ production.* – The ZZ production at the Tevatron is expected to be very small, with a NLO prediction of $1.4 \pm 0.1\,\text{pb}$ [13]. The two experimentally viable modes are: 1) when both Z's decay to charged leptons ($\ell\ell\ell\ell$) and 2) when one Z decays to charged leptons and the other to two neutrinos ($\ell\ell\nu\nu$). Although the $\ell\ell\ell\ell$ channel has a small branching ratio of $\sim 0.5\%$, the contribution from backgrounds is small. The $\ell\ell\nu\nu$ has a roughly six times larger branching ratio of $\sim 3\%$, but suffers from larger backgrounds.

TABLE II. – *Summary of ZZ observed and expected significance results from the Tevatron.*

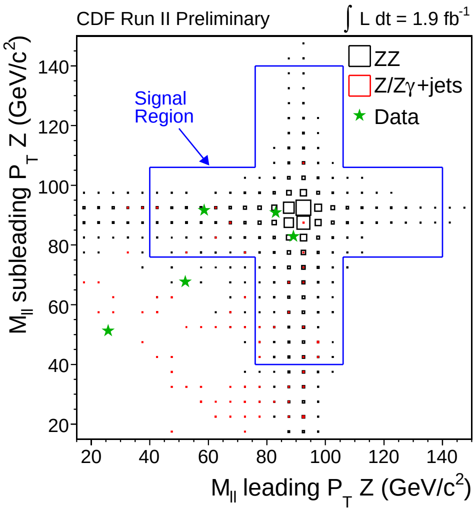
Experiment ($\int \mathcal{L}$)	Channel:	$\ell\ell\nu\nu$	$\ell\ell\ell\ell$	Combined
CDF ($1.9\,\mathrm{fb}^{-1}$) [14]	P-value	0.12	1.1×10^{-5}	5.1×10^{-6}
	Obs. Sig.	1.2σ	4.2σ	4.4σ
	Exp. Sig.			50% chance of 5σ
DØ (1.0–2.7$\,\mathrm{fb}^{-1}$) [15-17]	P-value	0.42×10^{-2}	4.3×10^{-8}	6.2×10^{-9}
	Obs. Sig.	2.6σ	5.3σ	5.7σ
	Exp. Sig.	2.0σ	3.7σ	5.2σ

The analysis strategy from both CDF and DØ is to consider a combination of both of these final states. Last year, CDF made a first measurement of ZZ production using $1.9\,\mathrm{fb}^{-1}$ of data, observing an excess of events with a probability of 5.1×10^{-6} to be due to the expected background. This corresponds to a significance of 4.4 standard deviations (σ), just shy of a 5σ observation (the expected significance for 5σ being 50%). The CDF measured cross-section is $\sigma(p\bar{p} \to ZZ) = 1.4^{+0.7}_{-0.6}$ (stat. + syst.) pb. More recently DØ using $1.7\,\mathrm{fb}^{-1}$ of data in the $\ell\ell\ell\ell$ channel passed the 5σ threshold for observation. Combining this result with the $\ell\ell\nu\nu$ final state with $2.7\,\mathrm{fb}^{-1}$ and a previous $\ell\ell\ell\ell$ analysis with $1\,\mathrm{fb}^{-1}$ of data yields a significance of 5.7σ and a combined cross-section of $\sigma(p\bar{p} \to ZZ) = 1.60 \pm 0.65$ (stat. + syst.) pb. Figure 5 shows the $M_{\ell\ell}$ and $M_{\ell\ell\ell\ell}$ invariant-mass distributions in the $\ell\ell\ell\ell$ channels for CDF and DØ, respectively. A summary of the observed and expected significance results for ZZ production from the Tevatron is shown in table II. Both experiments measure cross-sections for ZZ production consistent with the SM prediction.

Since neither experiment observes an excess of events beyond what is predicted in the SM, they are able to place 95% CL limits on ZZ CP-violating and -conserving anomalous couplings parameters. DØ uses $1.0\,\mathrm{fb}^{-1}$ of data in the $\ell\ell\ell\ell$ channel to set these limits by comparing the number of observed candidate events to the predicted background plus expected signal assuming anomalous trilinear couplings. The DØ results use a scale factor of $\Lambda = 1.2\,\mathrm{TeV}$ with limits of $|f_4^\gamma| < 0.26$, $-0.30 < f_5^\gamma < 0.28$, $|f_4^Z| < 0.28$, $-0.31 < f_5^Z < 0.29$ [16]. CDF's limits are set with an analysis of $1.9\,\mathrm{fb}^{-1}$ of data in the $\ell\ell$jj channel and uses the di-jet invariant mass distribution in the high $p_T^Z > 210\,\mathrm{GeV}/c$ region. The CDF limits also use a scale factor of $\Lambda = 1.2\,\mathrm{TeV}$ and are $|f_4^\gamma| < 0.10$, $|f_5^\gamma| < 0.11$, $|f_4^Z| < 0.12$, $-0.13 < f_5^Z < 0.12$.

4. – Conclusions

With the increasingly large datasets the Tevatron experiments, CDF and DØ, continue to probe our understanding of electroweak production with new sensitivity. Precision W-boson mass measurements continue to further test the SM and help provide new indirect limits on the Higgs mass. Recent precision measurements of the W charge asymmetry is testing the accuracy of our knowledge of the proton structure. We are now measuring diboson production and couplings with greater and greater precision. ZZ



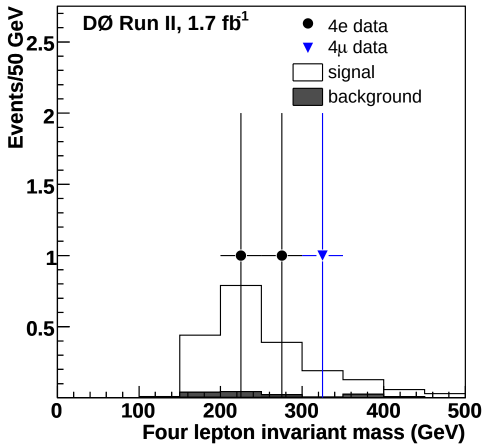


Fig. 5. – Top: the invariant masses of the two lepton pairs ($M_{\ell\ell}$) plotted against each other in the $ZZ \to \ell\ell\ell\ell$ channel from CDF with $1.9\,\mathrm{fb}^{-1}$ of data. Bottom: the four-lepton invariant-mass ($M_{\ell\ell\ell\ell}$) distribution in the $ZZ \to \ell\ell\ell\ell$ channel from DØ with $1.7\,\mathrm{fb}^{-1}$ of data.

production has now been observed and the first observation of $Z\gamma$ production in the purely neutral final state has been made at the Tevatron. New limits have been set on anomalous couplings for $ZZZ/ZZ\gamma/Z\gamma\gamma$ production.

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