DIBOSON PHYSICS AT CDF

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FOR THE CDF COLLABORATION

We have studied diboson events produced by $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using the CDF detector. Our observations of $Z\gamma$, WZ, and ZZ production are consistent with Standard Model predictions, and we set limits on some anomalous couplings.

1. Introduction

The structure of self couplings between gauge bosons in the Standard Model is a direct consequence of electroweak symmetry breaking, so studying these couplings not only confirms the structure of the electroweak sector of the Standard Model, but also presents an opportunity to search for beyond-the-Standard-Model interactions. While direct couplings exist in the Standard Model between W bosons and photons, and between W and Z bosons, there are no Standard Model couplings between the Z boson and the photon, or between the Z boson and itself. Another way to say this is that in the Standard Model, a W boson can radiate a photon or a Z boson, but neither a photon nor a Z boson can radiate either itself or the other. This means that the Standard Model only includes t-channel production of $Z\gamma$ and ZZ diboson final states, while $W\gamma$, WW, and WZ diboson final states can be produced by both s- and t-channel processes at tree level. In this paper we examine diboson production in 1.96 TeV $p\bar{p}$ collisions using the CDF detector, compare this production to Standard Model predictions, and set limits on the strength of some anomalous couplings.

2. $Z\gamma$ Production

Since there is no direct $Z\gamma$ coupling in the Standard Model, the only tree-level diagram for a $Z\gamma$ final state is from initial-state radiation (ISR), where a photon is radiated off an incoming quark. If the Z boson decays into two leptons (electrons or muons), then the dilepton mass will generally be near the Z-boson mass for ISR. In addition, when the Z decays to two leptons, it is possible to get radiation off one of these final-state leptons (FSR for final-state radiation). In the case of FSR, the three-body mass $M_{ll\gamma}$ will generally be near the Z-boson mass. Were there an anomalous coupling between the photon and the Z boson, it would be possible for a Z to radiate a photon or for a photon to radiate a Z, and in this case the two leptons from the Z decay would have a mass near the Z mass, similar to ISR.

To study this, we use the CDF detector[1] to select Z-boson candidate events with photon energies as low as 7 GeV by first identifying the leptonic decays of the Z bosons where the dileptons can be either electrons or muons. One of the leptons is required to be in the central detector ($|\eta| < 1$) [2] to provide a trigger. Once we have identified the trigger lepton, we then require a second oppositely charged lepton of the same flavor with $E_T > 20$ GeV. For the second muon, we accept any high-quality track with $|\eta| < 1$ and minimum-ionizing energy in the calorimeter, regardless of whether or not it is associated with a track stub in the muon chambers. For the second electron, we accept isolated electromagnetic clusters (total energy within $\sqrt{\eta^2 + \phi^2} < 0.4$ less than 1.3 times the energy in the electromagnetic cluster) with $|\eta| < 1.1$ (central) or $1.2 < |\eta| < 2.8$ (plug). In the central region, we require a match between the track and the shower-max detector, and the ratio of hadronic to electromagnetic energy $E_{had}/E_{EM} \leq 0.055 + 0.00045E(\mathrm{GeV})$. Since the tracking efficiency falls off in the plug region, we do not require plug electrons to be matched to a track and therefore we do not require opposite charge, but we require $E_{had}/E_{EM} \leq 0.05$ and for the distribution of energy in the 3×3 towers of the electromagnetic cluster to have a $\chi^2 \leq 25$ with respect to the expectation for an electromagnetic shower.

In Figure 1 we plot the three-body mass on the vertical axis and the dilepton mass on the horizontal axis. FSR-dominated events form the horizontal line near $M_{ll\gamma} = 91$ GeV, and ISR-dominated events form the vertical line near $M_{ll} = 91$ GeV. We find a total of 390 $ee\gamma$ events in 1.07 ± 0.6 $\mathrm{fb}^{-1}$and 388 $\mu\mu\gamma$ events in 2.01 ± 0.12 fb^{-1}. We estimate the QCD photon background to be 93.9 ± 25.8 events, and the QCD background to $Z \rightarrow ee$ to be 13.9 ± 7.1 events. This gives a measured cross section of 4.6 ± 0.2 (statistical) ± 0.3 (systematic) ± 0.3 (luminosity). This agrees with a next-to-leading-order SM calculationof 4.5 ± 0.4.

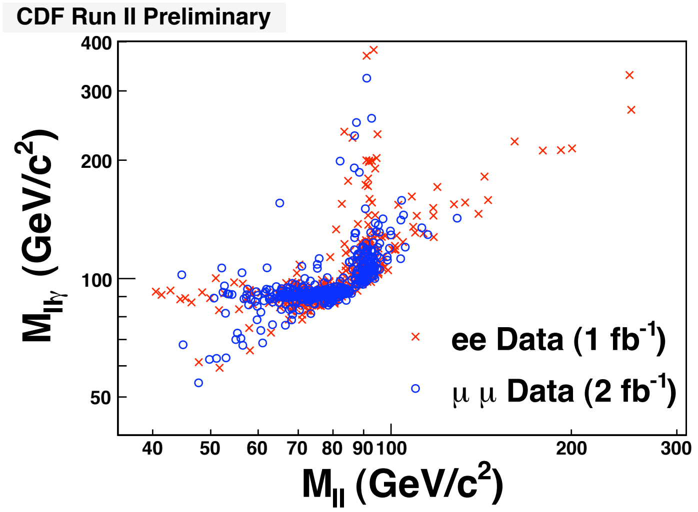

Figure 1. $M_{ll} vs. M_{ll\gamma}$ distribution in the $Z \to \mu\mu + Z \to ee$ datasets for photons with $E_T > 7$ GeV.

Potential $Z\gamma$ couplings have been studied by Gounaris *et al.*[3] and we adopt their notation for classifying the nature of the coupling. If an anomalous coupling between the Z boson and the photon exists, it will produce more events with high E_T photons than expected from the SM. Using the measured photon E_T distribution for ISR-dominated events (events where $M_{ll\gamma} > 100$ GeV/c^2) we are able to set upper limits on the strength of anomalous couplings: $|h_3^Z| < 0.083$, $|h_4^Z| < 0.0047$, $|h_3^\gamma| < 0.084$, $|h_4^\gamma| < 0.0047$.

3. *WZ* Production

To search for WZ diboson production, we look for events where both bosons have decayed leptonically. Because this is a small branching fraction, in order to observe a signal we use as large a lepton acceptance as possible. We find a total of 25 events compared to 21.6 ± 2.6 expected. The 21.6 is composed of 16.5 WZ, 2.5 $Z+$ jets, 1.5 ZZ, 1 $Z\gamma$, and 0.2 $t\bar{t}$. This gives a measured cross section of $\sigma = 4.3^{+1.3}_{-1.0}$ (stat) ± 0.2 (syst) ± 0.3 (lum) pb, compared to a theoretical cross section $\sigma_{NLO} = 3.7 \pm 0.3$ pb.

Using the P_T of the Z from WZ events we can test the WWZ vertex.

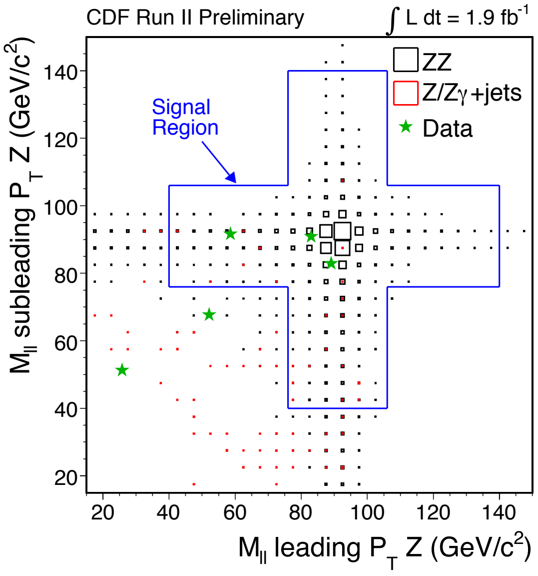

Figure 2. $M_{ll} vs. M_{l'l'}$ distribution for $Z \rightarrow ll + Z \rightarrow l'l'$ events.

If we parameterize the anomalous trilinear gauge coupling as

$$\begin{aligned} \mathcal{L}_{aTGC}/ig_{WWZ} = \quad & \Delta g(W *_{\mu\nu} W^{\mu} Z^{\nu} W_{\mu\nu} W *^{\mu} Z^{\nu}) \\ & + \Delta\kappa W *_{\mu} W^{\nu} Z^{\mu\nu} + \frac{\lambda}{M_W^2} W *_{\rho\mu} W^{\mu}_{\nu} Z^{\nu} \rho \end{aligned}$$

($\Delta g = \Delta\kappa = \lambda = 0$ in the Standard Model), we can set the limits $-0.13 < \lambda < 0.15$, $-0.15 < \Delta g < 0.24$, and $-0.82 < \Delta\kappa < 1.27$.

In addition to looking for leptonic decays of WZ diboson events, we have looked for WZ and WW events where a W boson decays to $l\nu$ and the other boson decays to a pair of jets. This process is dominated by background, so we use a neural net to enhance the signal. We measure a cross section times branching ratio (BR) of $\sigma \times \text{BR} = 1.47 \pm 0.77$ (stat) ± 0.38 (syst) pb, compared to a theoretical expectation of 2.1 pb.

4. *ZZ* Production

The lowest cross section diboson category is ZZ production. We look in the channels where both Z's decay to leptons, and where one Z boson decays leptonically and the other decays into a pair of neutrinos. The first final state is very clean except for the events containing electron candidates in regions of the detector not covered by our tracking detectors ("trackless electrons"), but the second final state has many backgrounds such as $WW \rightarrow ll\nu\nu$. In the first category we expect 2 events without a trackless electron with 2 events observed, and 0.36 events with a trackless electron (0.28 signal and 0.08 background) with 1 event observed. The dilepton masses for the two reconstructed Z's are shown in Figure 2.

The probability of the three observed $ZZ \rightarrow lll'l'$ events coming from a background fluctuation is 1.1×10^{-5}, which corresponds to a significance of 4.2 σ. We also see a signal in the $ll\nu\nu$ channel with a 12% chance of coming from background. When we combine these two channels, we get a significance of 4.4 σ, so this is strong evidence that we have observed ZZ diboson production[4].

5. Summary

We have studied diboson production in $\bar{p}p$ collisions and have found it to be consistent with Standard Model predictions. We have set limits on a number of different couplings that do not appear in the Standard Model (anomalous couplings). Finally, we note that we are now observing processes with cross sections less than a factor of 10 larger than the Standard Model Higgs cross section, so we are closing in on the Standard Model Higgs.

References

1. D. Acosta *et al.*,, Phys. Rev. D **71**, 032001 (2005).
2. The pseudo-rapidity, η, is defined by $\eta = -\log\tan(\theta/2)$, where θ is the polar angle measured with respect to the proton direction. We use ϕ to measure the azimuthal angle.
3. G.J. Gounaris *et al.*, Phys. Rev. D **62**, 073012 (2000).
4. T. Aaltonen, *et al.*, submitted to Phys. Rev. Lett.; hep-ex/0801.4806 (2008).