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DI-BOSON PRODUCTION AND SM/SUSY HIGGS SEARCHES AT THE TEVATRON

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Abstract

The discovery of the Higgs boson would be a major success for the Standard Model (SM) and would provide further insights into the electroweak symmetry breaking mechanism. This report contains the latest results from the DØ and CDF Tevatron experiments on searches for the SM Higgs produced from gluon fusion with $H \to WW$, and in association with a W boson. It also includes searches for a supersymmetric Higgs in the $b\bar{b}$ and $\tau^+\tau^-$ decay channels. The study of di-boson production at the Tevatron is important to understand backgrounds in high mass Higgs searches. It also provides a test of the SM through the measurement of the production cross section and the gauge boson self couplings. This paper includes measurements of the WW, $W\gamma$, and WZ production cross sections, as well as limits on the anomalous couplings associated with the $WW\gamma$ and WWZ interactions. The results are based on sets of up to 320 pb^{-1} of data collected by the DØ and CDF experiments at the $\bar{p}p$ Tevatron collider, running at a center-of-mass energy of 1.96 TeV.

1 Physics Motivation

The Higgs boson is the only scalar elementary particle expected in the standard model (SM). Its discovery would be a major success for the SM and would provide further insights into the electroweak symmetry breaking mechanism. The constraints from precision measurements favor a Higgs boson sufficiently light to be accessible at the Fermilab Tevatron Collider. The Electroweak Working Group (EWWG) has updated, in the Winter of 2005, the constraints on the SM Higgs mass, based on measurements by the LEP, SLD, CDF, and DØ experiments [1]. The preferred mass value, corresponding to the minimum of the solid curve in fig. 1, is at 126 GeV, with an experimental uncertainty of +73 and -48 GeV. Direct measurements at LEP have excluded the SM Higgs boson below 114.4 GeV at the 95% C.L. At the Tevatron, indirect searches involve precision measurements of the top quark and the W mass, while direct searches require high luminosity samples for discovery or exclusion in the low mass range. Although the expected luminosity necessary for its discovery at the Tevatron is higher than obtained thus far, the special role of the Higgs boson in the SM justifies extensive searches for a Higgs-like particle independent of expected sensitivity. The chances for discovery in a small sample improve according to supersymmetric extensions to the standard model [2], which predict an enhancement of the Higgs cross-section relative to that of the SM.

At this stage of the Tevatron experiments, the effort is focused on the understanding of the physics objects, the backgrounds, missing transverse energy ($\not{E}_T$), as well b-tagging and calibration techniques. Di-boson production is, therefore, an important topic of study, not only as a background to high mass Higgs searches, but also as a test of the SM through the measurement of the production cross sections, and the gauge boson self couplings. The DØ [3] and CDF [4] detectors are described elsewhere.

2 Searches for SM/SUSY Higgs Production at the Tevatron

The two most promising mechanisms for Higgs production at the Tevatron $p\overline{p}$ collider, given the center-of-mass energy of $\sqrt{s}$=1.96 TeV, are gluon fusion and associated production with a W or a Z: $gg \to H$, $q\overline{q} \to W/Z + H$. Although the gg process would have the largest cross section, $\sim$ 1 pb at M_H^{SM}=115 GeV, it is only an option in the search for a high mass Higgs boson ($M_H \gtrsim$140 GeV) decaying to WW, since the $H \to b\overline{b}$ decay channel would be overwhelmed with background. For a low mass search, the Tevatron experiments explore WH and ZH associated production, which would give a clear signal with leptons, neutrinos, and b-jets: $q\overline{q} \to W/Z + H \to l\nu/l^+l^-/\nu\overline{\nu} + b\overline{b}$. In the first half of 2003, the DØ and CDF Collaborations performed a joint study on the sensitivity of the Tevatron experiments to either observe or rule out a low mass

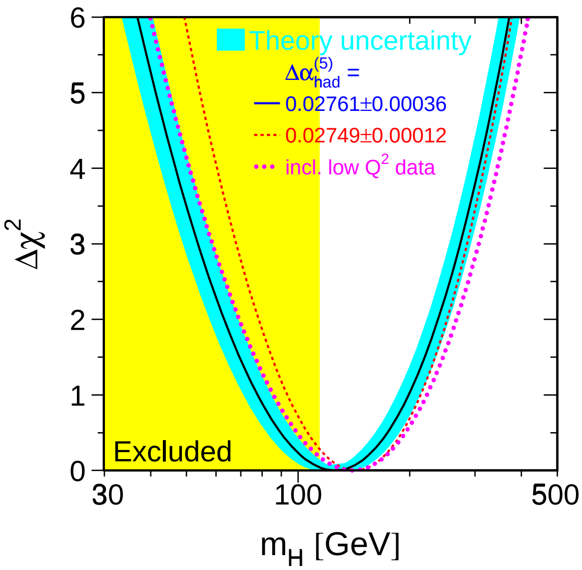

Figure 1: *Constraints to the Higgs boson mass from the Electroweak Working Group.*

SM Higgs [5]. The results of the study are summarized in fig. 2. Given that systematic uncertainties were not taken into consideration in the sensitivity results, the amount of integrated luminosity per experiment for low mass Higgs discovery at 115 GeV would be in the 8-12 fb^{-1} range. Evidence might be found with $\gtrsim$ 3fb^{-1}, while Higgs masses less than ∼130 GeV could be excluded with $\gtrsim$4 fb^{-1}.

In two-Higgs-doublet models of electroweak symmetry breaking, such as the minimal supersymmetric extension of the standard model (MSSM) [2], there are five physical Higgs bosons resulting from symmetry breaking: two neutral CP-even scalers, h and H, with H being the heavier state; a CP-odd, A; and two charged states, $H^{\pm}$. The ratio of vacuum expectation values of the two Higgs fields is defined as tan $\beta = v_2/v_1$ where v_2 and v_1 refer to the fields which couple to the up- and the down-type quarks. At tree level, the couplings of the neutral Higgs bosons to the down-type quarks, such as the bottom quark, are enhanced by a factor of tan β relative to the SM predictions,

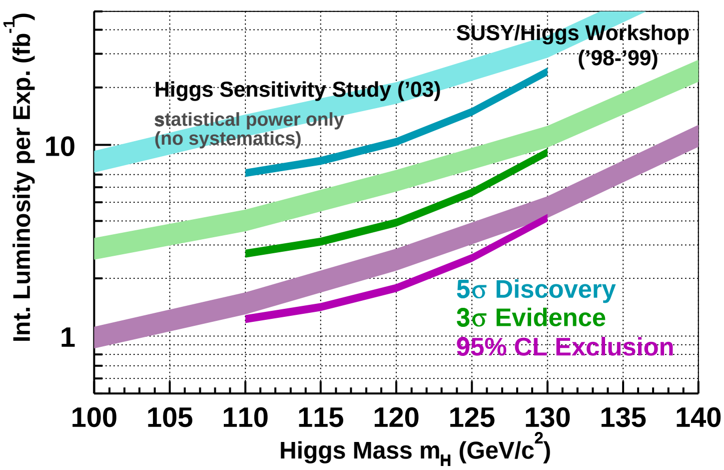

Figure 2: *Results from the Tevatron Higgs sensitivity study.*

thus production cross sections are enhanced by $\tan^2\beta$ [6]. DØ and CDF search for SUSY Higgs production in two channels: $b\bar{b}h/bh \rightarrow b\bar{b}b\bar{b}/bb\bar{b}$, and inclusive Higgs production with $H \rightarrow \tau^+\tau^-$.

The Tevatron accelerator performed very well during 2004, providing more than 0.5 fb^{-1} per experiment since the beginning of Run II. The high instantaneous luminosity values recently achieved at the Tevatron raises the expectations of making strong statements about the Higgs sector by the end of Run II.

3 Di-boson Production and Anomalous Couplings

The study of di-bosons at the Tevatron is not only critical to understand backgrounds in high mass Higgs searches, but also provides a test of the SM through the measurement of the production cross section and the gauge boson self couplings. These couplings are a measure of the strength of the interaction of the W, Z and γ bosons with each other. The model independent way of describing new physics with anomalous couplings is through effective Lagrangians which depend on a number of parameters. The effective Lagrangian for the WWZ and $WW\gamma$ interactions

$$\frac{L_{WWV}}{g_{WWV}} = g_V(W^{\dagger}_{\mu\nu}W^{\mu}V^{\nu} - W^{\dagger}_{\mu}V_{\nu}W^{\mu\nu}) + \kappa_V W^{\dagger}_{\mu}W_{\nu}V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda} \quad (1)$$

depends on three anomalous coupling parameters: g_V, κ_V, and λ_V. The most general Lorenz and gauge invariant $ZV\gamma$ coupling, where V stands for either Z or γ, is described by eight coupling parameters h_i^V (i=1,...,4) [7]. Non-zero values of the the CP violating h_1^V, h_2^V, or the CP conserving h_3^V, h_4^V would result in an increase of the $Z\gamma$ cross section, especially for large photon transverse energies. Partial wave unitarity restricts the $ZV\gamma$ couplings to vanish at high energies. The couplings are therefore parameterized as form-factors:

$$h_i^V = \frac{h_{i0}^V}{(1+\hat{s}/\Lambda^2)^n} \quad (2)$$

where $\hat{s}$ is the square of the $Z\gamma$ invariant mass, Λ is the form-factor scale, and h_{0i}^V are values of couplings at low energy.

Measurements at LEP and at the Tevatron results are complementary. The Tevatron experiments test values of $\hat{s}$ higher than LEP, and the $W\gamma/Z\gamma$ processes independently. While DØ measured the most restrictive limits on h_2^V and h_4^V, LEP obtained the best limits on h_1^V and h_3^V. DØ limits on $WW\gamma/WWZ$ anomalous couplings are the tightest from hadron colliders.

4 Results

4.1 Measurement of WW Production Cross Section

Both DØ and CDF measure the WW production cross section in the three channels: $2e2\nu/2\mu2\nu/e\mu2\nu$. CDF uses a 184 pb^{-1} sample collected from single lepton triggers, and DØ 252, 224, 235 pb^{-1} samples from single or di-lepton triggers [8, 9].

DØ requires two oppositely charged leptons with $p_T > 15$ GeV, and at least one with $p_T >$20 GeV. ZZ and WZ backgrounds are eliminated by removing events in the Z mass window, and requiring a $\not{E}_T$>30, 40, 20 GeV in the ee, $\mu\mu$ and $e\mu$ channels, respectively. Cuts on di-lepton transverse mass, and jet-$\not{E}_T$ angular separation, help to eliminate the $Z\gamma$ and QCD backgrounds. The plots in fig. 3 show, for each channel, that the measured $\not{E}_T$ distributions agree well with the Next-to-Leading Order (NLO) predictions for the signal plus the background contributions, estimated from Monte Carlo generators or extracted from data, in the case of the QCD background [8]. CDF performs a similar analysis and also observes good agreement between the measurement and the predictions for lepton p_T, $\not\!\!E_T$, and di-lepton invariant mass, as illustrated in fig. 4.

In the final sample, DØ observes 25 events compared with $8 \pm 0.6(\text{stat}) \pm 0.6(\text{syst}) \pm 0.5(\text{lum})$ background events, and CDF 17 against $5 \pm 2.2/0.8$. As the probability of a background fluctuation is very small, the observation of the WW signal is well established by the two experiments. The cross sections measured by DØ and CDF are $13.8 \pm 4.3/3.8(\text{stat}) \pm 1.2/0.9(\text{syst}) \pm 0.9(\text{lumin})$ pb and $14.6 \pm 5.8/5.1(\text{stat}) \pm 1.8/3.0(\text{syst}) \pm 0.9(\text{lumin})$ pb, respectively.

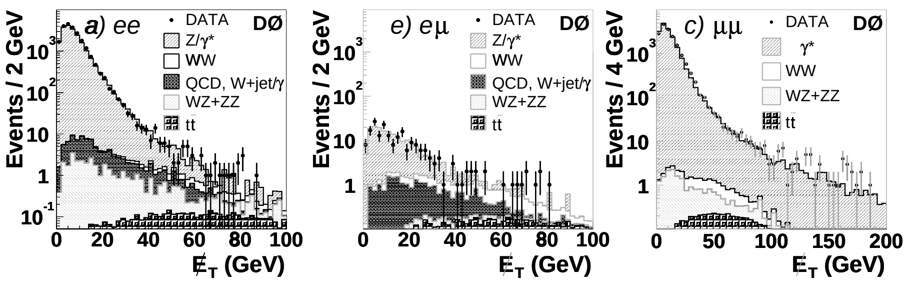

Figure 3: *DØ* $\not\!\!E_T$ *distributions for* WW *events in the three decay channels.*

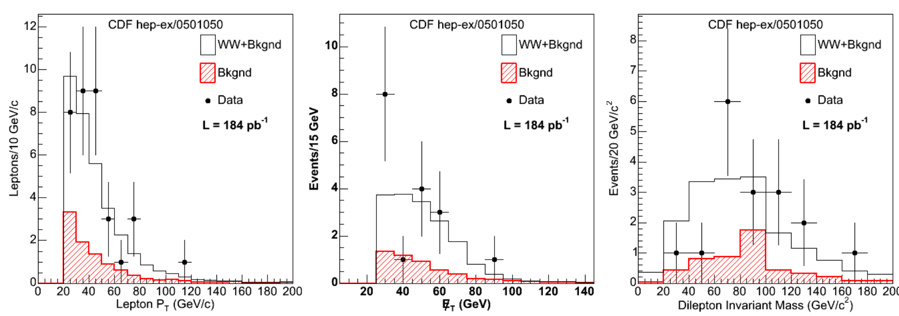

Figure 4: *CDF measurements of lepton* p_T*,* $\not\!\!E_T$*, and di-lepton invariant mass in* WW *events.*

4.2 Search for the SM Higgs boson $H \to WW^\star \to l^+\nu l'^-\overline{\nu}$

The search for the SM Higgs decaying into WW at DØ is based on the same three leptonic channels used in the WW cross section measurement, corresponding to an integrated luminosity of 177, 158, and 147 pb^{-1}. The sample selection includes cuts on the di-lepton invariant mass and event $\not{E}_T$, to remove the Z background, as well as on the sum of the event $\not{E}_T$ and the p_T of the two leptons, to reject Drell-Yan and W+jets events. A $\Delta\phi_{ll}$ <1.5-2 cut between the two leptons was used as a discriminant since the leptons are not back-to-back in Higgs decay due to spin correlations of the W bosons. Two events are observed in the eμ channel, as illustrated in fig. 5, and 9 in the combined sample, compared with a predicted signal [10] of 0.272 ± 0.004 events at M_H=160 GeV, and an expected background [11, 12] of 11.1 ± 3.2 events. The uppermost (blue) line in fig. 5 shows the DØ 95% C.L. limit on the SM Higgs production, $H \to WW$, for masses between 100 and 200 GeV. For M_H=160 GeV, the limit is 5.7 pb. CDF does a similar search on a 184 pb^{-1} sample. The plot on the left of fig. 6 shows the $\Delta\phi_{ll}$ distribution for the combined sample, which consists of 8 observed events, compared with a predicted signal sample of 0.17 ± 0.02 events, and a background sample of 8.9 ± 1. For M_H=160 GeV, the CDF limit is 5.6 pb, as shown in fig. 6. The Tevatron limits are still over an order of magnitude above the SM prediction, due to low statistics.

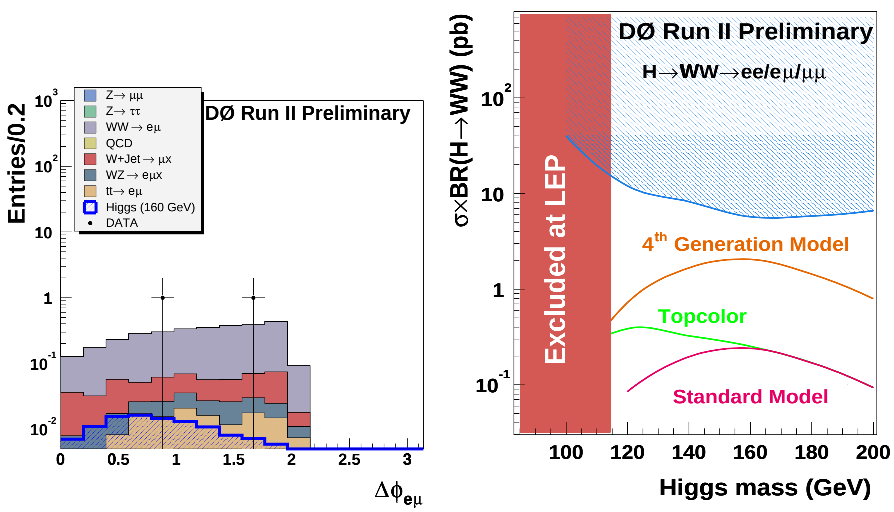

Figure 5: *DØ $\Delta\phi_{e\mu}$ distribution in $H \to WW^\star \to l^+\nu l'^-\overline{\nu}$ events (left). SM Higgs production cross section limit for $H \to WW$ (right).*

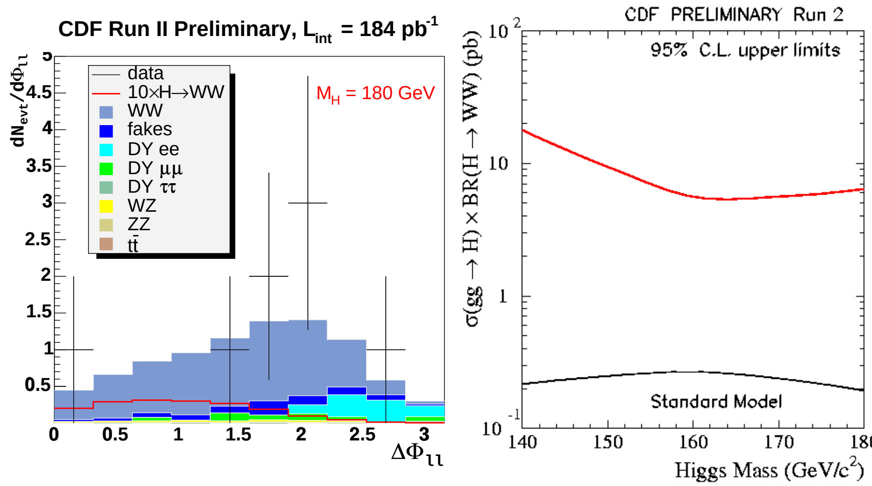

Figure 6: *CDF $\Delta\phi_{ll}$ distribution in $H \to WW^\star \to l^+\nu l'^-\overline{\nu}$ events (left). SM Higgs production cross section limit for $H \to WW$.*

4.3 Search for $Wb\overline{b}$ and SM Higgs Production in association with a W boson

The DØ search for $W + b\overline{b}$ production in the $W \to e\nu$ channel is based on a 174 pb^{-1} sample containing one isolated electron with p_T >20 GeV and $\not{E}_T$>25 GeV [13]. $W + b\overline{b}$ events are the main background for Higgs production associated with a W boson.

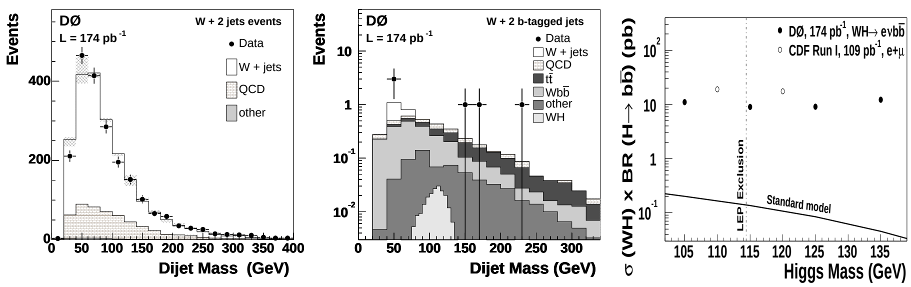

Figure 7: *DØ dijet mass distribution in W+2 jets and W+2 b-tagged jets samples (left). Limit on SM WH production (right).*

The analysis also requires two b-tagged jets with p_T greater than 20 GeV. As illustrated in fig. 7, the measured dijet mass distribution is well described by the prediction for $W + b\overline{b}$ events, added to the estimated background, which includes $W+$ jets, QCD, and $t\bar{t}$ events. The number of observed events decreases from 2540 in the W+2 jets sample before b-tagging, to 76 in the sample with one or more b-tagged jet. In the 2 b-tagged jets sample, 6 events survive, compared with 4.4 ± 1.17 expected background events. Based on this result, shown in fig. 7, a 95% C.L. limit of 6.6 pb is measured on $Wb\bar{b}$ production for p_T^b >20 GeV and an angular separation between b-jets greater than $\Delta R_{b\bar{b}}$ >0.75. By restricting the selection to a ± 25 GeV window around the Higgs mass, DØ establishes a 95% C.L. limit on the SM WH production cross section of 9-12.2 pb for Higgs masses in the range of 105-135 GeV. CDF does a similar search based on a 162 pb^{-1} sample with one electron or muon and $\not\!\!E_T$. The number of observed events decreases from more than 2072 in the W+2 jets sample to 62, when requiring one or more b-tagged jets. Figure 8 shows the CDF upper limit on the SM WH production cross section.

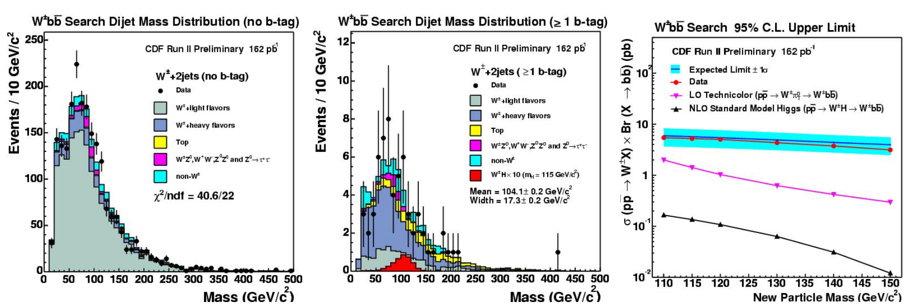

Figure 8: *CDF dijet mass distribution in W+2 jets and W+1 or more b-tagged jets samples (left). Limit on WH production (right).*

4.4 Search for Neutral SUSY Higgs Bosons in Multi-jet Events

Supersymmetry models predict the $hb\bar{b}$ cross section to scale with $\tan^2\beta$ at tree level, making the search for an MSSM Higgs in this channel well worth to pursue even on a small sample. DØ uses a 260 pb^{-1} sample of triple b-tagged multijet events [14]. The main backgrounds are QCD heavy flavor and light jet events, $Z+$ jets, and smaller contributions from other physics processes. The plot on the left in fig. 9 shows the dijet mass distribution of two leading jets in events with at least three b-tagged jets. The measurement agrees very well with the estimated background, shown as a solid line. The predicted signal for a Higgs mass of 120 GeV is shown separately as a dotted line. Since no excess of events is observed, limits on signal production cross section are extracted from this result. For a Higgs mass between 90 and 150 GeV, the limit on the production cross section is 70-20 pb, as shown in the plot at the center of fig. 9. Figure 9 also shows the measured limits on the SUSY parameter tan β versus the mass of the neutral Higgs, m_A. DØ excludes a significant range of tan β, depending on m_A, and the selected MSSM parameter set or scenario. For example, tan β is less than 55 at a 95% C.L. in the case of the maximum mixing scenario. There are other scenarios where the limit on tan β could be even more stringent [14].

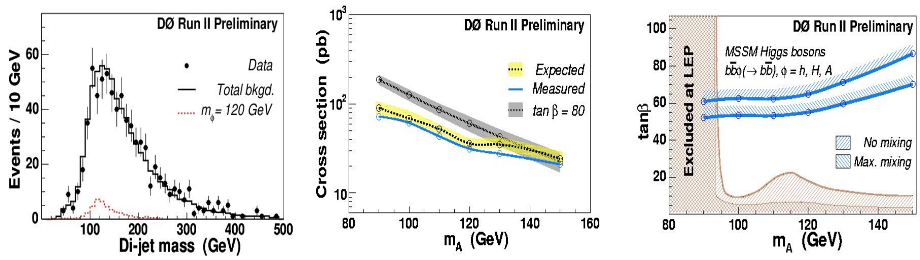

Figure 9: *Dijet mass distribution associated with events with at least three b-tagged jets (left). Limits on the $hb\bar{b}$ production cross section (center). Exclusion limits on tan β (right).*

CDF uses a 195 pb^{-1} sample from τ triggers to search for a MSSM Higgs. One τ decays into hadrons+ν and the other to $e/\mu + 2\nu$. Cuts on the p_T of the leptons, the Z mass window, and the $\hat{H}_T = |p_T(\tau^+)| + |p_T(\tau^-)| + \not{E}_T$ variable are applied to remove the light quark background. The number of observed events in the final sample is 230 compared with the 263.6 ± 30.1 expected from signal (PYTHIA [11] and Tauola [15]) plus background ($Z \to \tau^+\tau^-$, jet$\to \tau$, $t\bar{t}$, di-bosons). Figure 10 shows the measured limit of 19-3 pb, in the mass range 115-200 GeV, on the Higgs production cross section, with $h \to \tau^+\tau^-$. This limit is extracted from the mass-like discriminating variable $m_{vis}(l, \tau, \not{E}_T)$.

4.5 Measurement of $W/Z + \gamma$ Cross Sections and Limits on Anomalous Couplings

DØ measures the $W\gamma$ production cross section in the e and μ channels, using samples of 162 and 134 pb^{-1}, respectively. Cuts on the e and γ transverse mass, angular separation, and event $\not{E}_T$ are applied to remove the backgrounds, dominated by $W+$ jets, and photons as final state radiation from the lepton. The photon p_T distribution shown in fig. 11 for the combined channels in the final sample is in good agreement with the theoretical prediction [16] plus background estimates. The cross section, $14.8 \pm 1.6(\mathrm{stat}) \pm 1.0(\mathrm{syst}) \pm 1.0(\mathrm{lum})$ pb, agrees well with the SM prediction, 16.0 ± 0.4 pb, for $E_T\gamma$ >8 GeV and

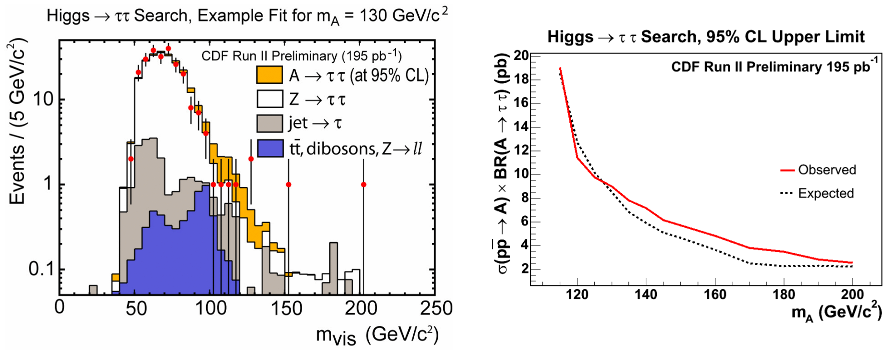

Figure 10: *Mass-like discriminating distribution,* $m_{vis}(l, \tau, \not{E}_T)$ *(left). Limit on the Higgs production cross section with* $h \to \tau^+\tau^-$ *(right).*

$\Delta R_{l\gamma}$ >0.7. Limits on the anomalous couplings $\Delta\kappa_\gamma$ and $\lambda\gamma$ are extracted from the photon p_T spectrum, and are consistent with the zero value expectation from the SM. The point and bars in the λ versus $\Delta\kappa$ plot in fig. 11 indicate the 95% C.L. one dimensional (1D) intervals for each parameter with the other set to zero: $-0.93 < \Delta\kappa_\gamma < 0.97$, $-0.22 < \lambda_\gamma < 0.22$. The ellipse represents the 95% C.L. two dimensional (2D) exclusion limit. These results are the most stringent model independent constrains on $\Delta\kappa_\gamma$ and λ_γ from hadron colliders, and represent an improvement with respect to the Tevatron Run I measurements [17, 18]. While the LEP experiments constrain the $WW\gamma$ and WWZ couplings simultaneously using WW events, single W, or single γ final states in e^+e^- collisions [19], the Tevatron experiments study the $W\gamma$ process directly.

The CDF experiment has measured the $W\gamma$ production cross section [20] in a 200 pb^{-1} sample using the same decay channels as DØ . Figure 12 shows the photon transverse energy spectrum and the transverse mass of the lepton-photon-$\not{E}_T$ system for $W\gamma$ candidates. A total of 195 and 128 events are observed in the e and μ samples, respectively, in agreement with the 194.1 ± 19.1 and 142.4 ± 9.5 events expected from signal plus background. The CDF measured $W\gamma$ cross section of 18.1 ± 3.1 pb is in good agreement with the SM prediction of 19.3 ± 1.4 pb, for $E_T\gamma$ >7 GeV and $\Delta R_{l\gamma}$ >0.7.

DØ also measures the $Z\gamma$ production cross section in the e^+e^- and $\mu^+\mu^-$ channels. The measured cross section of $4.2 \pm 0.4(\mathrm{stat}+\mathrm{syst}) \pm 0.3(\mathrm{lum})$ pb is in good agreement with the NLO prediction [16] of $3.9 \pm 0.1/0.2$ within the errors. Contrary to the $W\gamma$ case, the SM prohibits the $ZZ\gamma$ interactions at tree level, which means that any deviation of the h_i^V trilinear couplings from zero would signal the presence of new physics. DØ has measured the tightest

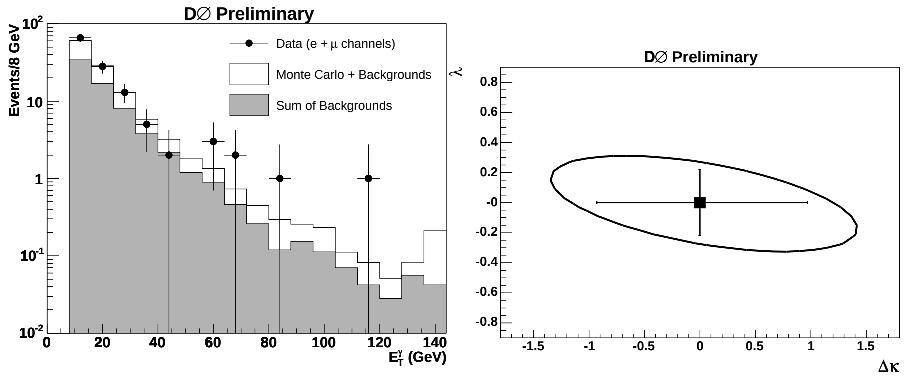

Figure 11: *DØ photon p_T distribution (left). One and two dimensional limits on $WW\gamma$ anomalous couplings (right).*

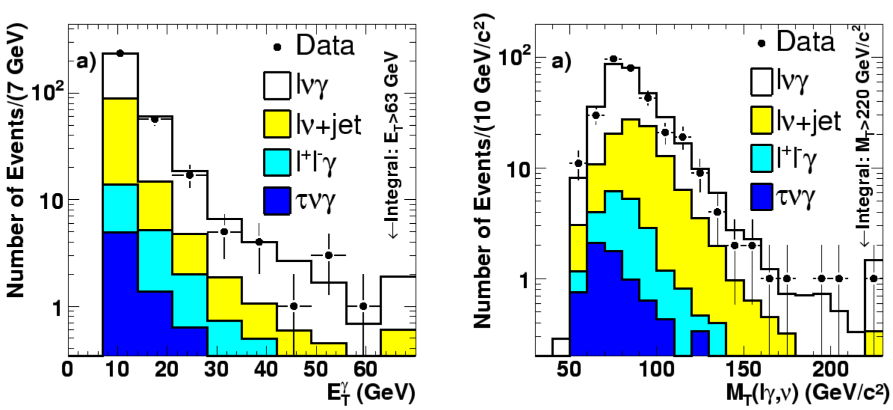

Figure 12: *CDF photon transverse energy spectrum and the transverse mass of the lepton-photon-$\not\!\!E_T$ system for $W\gamma$ candidates.*

1D and 2D upper limits on the trilinear couplings from hadron colliders, which also represent an improvement of a factor of 2-3 with respect to the Run I measurements [17, 18]. No deviation from the zero value SM prediction is observed: $|h_{30}^{\gamma}| < 0.22$, $|h_{40}^{\gamma}| < 0.019$, $|h_{30}^{Z}| < 0.21$, $|h_{40}^{Z}| < 0.019$.

The CDF $Z\gamma$ cross section measurement is based on the same initial sample used in the CDF $W\gamma$ analysis [20]. The number of observed events in the e and μ channels is 36 and 35, respectively, in agreement with the signal plus background SM expectation. The measured cross section of 4.6 ± 0.6 pb is well in agreement with the 4.5 ± 0.3 pb obtained from NLO calculations for $E_T\gamma > 7$ GeV and $\Delta R_{l+\gamma} > 0.7$.

4.6 Search for WZ/ZZ Di-boson Events and Measurement of Limits on Trilinear Couplings

The two Tevatron experiments conducted a search for $W(l\nu)Z(l^+l^-)$ events, in the case of D0, and $WZ(l\nu l^+l^-) + ZZ(l^+l^-l^+l^-/l^+l^-\nu\nu)$ events, in the case of CDF. DØ reports evidence of WZ production, based on the observation of 3 events in 285 and 320 pb^{-1} samples, compared with an expected background of 0.71 ± 0.08. The measured WZ inclusive production cross section by DØ is $4.5 \pm 3.5/2.6$ pb, in agreement with the SM prediction of 3.7 ± 0.1 pb [21]. CDF uses a smaller sample, 194 pb^{-1}, to establish a limit of 15.2 pb to the $WZ + ZZ$ production cross section, based on the observation of 3 events compared with a signal plus background expectation of 3.3 ± 0.43. Figure 13 shows the DØ 1D and 2D limits on Δg_Z, λ_Z, and $\Delta\kappa_Z$, which are also summarized in tab. 1. These results are the most stringent from direct, model independent measurements to date, and about a factor of 2 to 3 better than the DØ Run I results [22]. LEP has measured the $WW\gamma$ and WWZ couplings simultaneously using WW events [19].

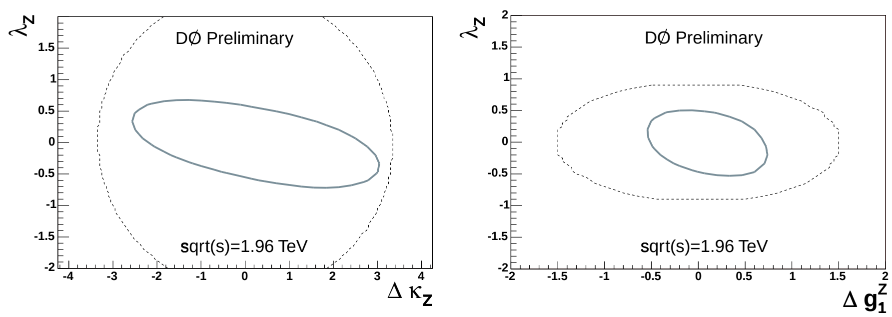

Figure 13: *DØ 1D and 2D limits on Δg_Z, λ_Z, and $\Delta\kappa_Z$.*

Table 1: *DØ preliminary one dimensional 95% C.L. limits on WWZ trilinear couplings.*

Λ=1.0 TeV	Λ=1.5 TeV
-0.53< λ_Z <0.56	-0.48< λ_Z <0.48
-0.57< Δg_Z <0.76	-0.49< Δg_Z <0.66
-2.0< $\Delta\kappa_Z$ <2.4	

5 Conclusions

The hunt for the SM and SUSY Higgs bosons has started at the Tevatron. Di-boson production cross sections have been measured more accurately than before, and the tightest limits on anomalous couplings from hadron colliders have been measured by the DØ experiment. A significant amount of new data will be necessary to exclude the Higgs boson in the low mass range, and even more for discovery. The Tevatron has performed very well during 2004, collecting more than 0.5 fb^{-1} since the beginning of Run II. It is now necessary to improve the particle identification, calibration, and analysis techniques to meet the challenges of the high luminosity environment.

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