Combined Upper Limit on Standard Model Higgs Boson Production at DØ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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The combination of the searches for the Standard Model Higgs boson at a center-of-mass energy of $\sqrt{s}$ =1.96 TeV, using up to 5.4 fb^{-1} of data collected with the D0 detector at the Fermilab Tevatron collider are presented. The major contributing processes include associated production ($WH \rightarrow l\nu bb$, $ZH \rightarrow \nu\nu bb$, $ZH \rightarrow llbb$, and $WH \rightarrow WWW^{(*)}$) and gluon fusion ($gg \rightarrow H \rightarrow WW^{(*)}$). As no significant excess is observed, we proceed to set limits on standard model Higgs boson production. The observed 95% confidence level upper limits are found to be a factor of 4.0 (1.5) higher than the predicted standard model cross section at $M_H = 115(165)$ GeV/c^2 while the expected limits are found to be a factor of 2.8 (1.4) higher than the standard model predicted cross section for the same masses.

1 Introduction

In the Standard Model (SM) of particle physics the Higgs mechanism is responsible for breaking electroweak symmetry, thereby giving mass to the W and Z bosons. It predicts the existence of a heavy scalar boson, the Higgs boson, with a mass that can not be predicted by the SM. Direct searches for the Higgs Boson were performed at the LEP experiments in the process $e^+e^- \rightarrow ZH$ with a centre of mass energy of 206.6 GeV. A direct mass limit at $m_H > 114.4$ GeV/c^2 [1] was set at the 95% confidence level (CL)[1]. The results from a combination of the two Tevatron experiments resulted in an exclusion in the mass range from 160 to 170 GeV/c^2[2].

The results of direct searches for SM Higgs bosons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the DØ experiment are presented [3]. The analyses combined here seek signals of Higgs bosons produced in association with vector bosons ($q\bar{q} \rightarrow W/ZH$), through gluon-gluon fusion (GGF) ($gg \rightarrow H$), through vector boson fusion (VBF) ($q\bar{q} \rightarrow q\bar{q}H$), and in association with top quarks ($t\bar{t} \rightarrow t\bar{t}H$). The analyses utilize data corresponding to integrated luminosities ranging from 2.1 to 5.4 fb^{-1}, collected during the period 2002-2009. The Higgs boson decay modes studied are $H \rightarrow b\bar{b}$, $H \rightarrow W^+W^-$, $H \rightarrow \tau^+\tau^-$ and $H \rightarrow \gamma\gamma$. The searches are organized into 60 analysis subsets comprising different production, decay and final state particle configurations, each designed to isolate a particular Higgs boson production and decay mode. In order to facilitate proper combination of signals, the analyses were designed to be mutually exclusive after analysis selections. The 60 analyses used in this combination are outlined in Table 1. In the cases of $p\bar{p} \rightarrow W/ZH + X$ production, we search for a Higgs boson decaying to two bottom

[1] All limits given in this paper are at 95% CL

quarks, or two tau leptons. The decays of the vector bosons further define the analyzed final states. To isolate $H \to b\bar{b}$ decays, an algorithm for identifying jets consistent with the decay of a heavy-flavor quark is applied to each jet (b-tagging). Several kinematic variables sensitive to displaced jet vertices and jet tracks with large transverse impact parameters relative to the hard-scatter vertices are combined in a neural network (NN) discriminant trained to identify heavy-flavor quark decays and reject jets arising from light-flavor quarks or gluons. By adjusting a minimum requirement on the b-tagging NN output, a spectrum of increasingly stringent b-tagging operating points is achieved, each with a different signal efficiency and purity. For the $WH \to \ell\nu b\bar{b}$, $ZH \to \nu\nu b\bar{b}$ and $ZH \to \ell\ell b\bar{b}$ processes, the analyses are separated into two groups: one in which two of the jets were b-tagged with a loose tag requirement ($WH \to \ell\nu b\bar{b}$ and $ZH \to \ell\ell b\bar{b}$) or one loose and one tight tag requirement ($ZH \to \nu\nu b\bar{b}$) (hereafter called double b-tag or DT) and one group in which only one jet was tagged with a tight tag requirement (single b-tag or ST). The ST selection excludes additional loose-tagged jets, rendering the ST and DT selections orthogonal. The ST selection results in a typical per-jet efficiency and fake rate of about 50% and 0.5%, while the DT selection gives 60% and 1.5%. For these analyses, each lepton flavor of the W/Z boson decay ($\ell = e, \mu$) is treated as an independent channel. In the case of $WH \to \ell\nu b\bar{b}$ production, the primary lepton from the W boson decay may fall outside of the detector fiducial volume or may not be identified. Events of this type are selected by the $ZH \to \nu\nu b\bar{b}$ analysis. For $WH \to WW^+W^-$ production, we search for leptonic W boson decays with three final states of same-signed leptons: $WWW \to e^\pm\nu e^\pm\nu + X$, $e^\pm\nu\mu^\pm\nu + X$, and $\mu^\pm\nu\mu^\pm\nu + X$. In the case of $H \to W^+W^-$ and $q\bar{q}H \to q\bar{q}W^+W^-$ production via vector boson fusion, we search for leptonic W boson decays with three final states of opposite-signed leptons: $WW \to e^+\nu e^-\nu$, $e^\pm\nu\mu^\pm\nu$, and $\mu^+\nu\mu^-\nu$. In addition we also consider final states originating from Higgs boson production in association with a vector boson (WH or ZH), where leptons may originate from the vector boson or Higgs boson decay. In all $H \to W^+W^-$ decays with $M_H < 2M_W$, one of the W bosons will be off mass shell. In all cases, lepton selections include both electrons and muons ($\ell = e, \mu$), while τ leptons are included in the simulation and the selections necessarily have acceptance for secondary leptons from $\tau \to e/\mu$ decays. Finally, we include an analysis that searches for Higgs bosons decaying to two photons and produced via gluon-gluon fusion, vector boson fusion, and associated production mechanisms.

Table 1: List of analysis channels, corresponding integrated luminosities, and final variables. The final variable used for several analyses is a neural-network or boosted decision-tree discriminant output which is abbreviated as NN discriminant and DTree discriminant, respectively.

Production	Final State	Lumi. [fb^{-1}]	Final Variable	# Sub-Channels
WH	$\ell\nu bb$ (ST/DT, 2/3 jet)	5.0	NN discriminant	16
$X + H$	$\tau\tau bb/q\bar{q}\tau\tau$	4.9	DTree discriminant	2
ZH	$\nu\nu bb$ (ST/DT)	5.2	DTree discriminant	4
ZH	$\ell\ell bb$ (ST/DT)	4.2	NN discriminant	16
WH	$\ell^\pm\ell^\pm$	3.6	Likelihood	6
All	$\ell\nu\ell'\nu' + X$	5.4	NN discriminant	3
All	$\gamma\gamma$	4.2	Di-photon Mass	1
$t\bar{t}H$	$t\bar{t}bb$	2.1	Scaled H_T	12

2 Limit Combination

We combine results using the CLs method with a negative log-likelihood ratio (LLR) test statistic [4, 5]. The value of CLs is defined as CLs = CLs+b/CLb where CLs+b and CLb are the confidence levels for the signal-plus-background hypothesis and the background-only hypothesis, respectively. These confidence levels are evaluated by integrating corresponding LLR distributions populated by simulating outcomes via Poisson statistics. Separate channels and bins are combined by summing LLR values over all bins and channels. This method provides a robust means of combining individual channels while maintaining individual channel sensitivities and incorporating systematic uncertainties. Systematics are treated as Gaussian uncertainties on the expected number of signal and background events, not the outcomes of the limit calculations. This approach ensures that the uncertainties and their correlations are propagated to the outcome with their proper weights. The CLs approach used in this combination utilizes binned final-variable distributions rather than a single-bin (fully integrated) value for each contributing analysis. The exclusion criteria are determined by increasing the signal cross section until CLs $= 1 - \alpha$, which defines a signal cross section excluded at 95% confidence level for $\alpha = 0.95$.

3 Systematic Uncertainties

The systematic uncertainties differ between analyses for both the signals and backgrounds. Here only the largest contributions are summarized. Most analyses carry an uncertainty on the integrated luminosity of 6.1%, while the overall normalization of other analyses is determined from the NNLO $Z/\gamma*$ cross section in data events near the peak of $Z \rightarrow \ell\ell$ decays. The $H \rightarrow b\bar{b}$ analyses have an uncertainty on the b-tagging rate of 2-6% per tagged jet. These analyses also have an uncertainty on the jet measurement and acceptances of 7%. All analyses include uncertainties associated with lepton measurement and acceptances, which range from 3-6% depending on the final state. The largest contribution for all analyses is the uncertainty on the background cross sections at 6-30% depending on the analysis channel and specific background. These values include both the uncertainty on the theoretical cross section calculations and the uncertainties on the higher order correction factors. The uncertainty on the expected multijet background is dominated by the statistics of the data sample from which it is estimated, and is considered separately from the other cross section uncertainties. The $H \rightarrow W^+W^-$ and $H \rightarrow \gamma\gamma$ analyses also assign a 11% uncertainty to the NNLO Higgs production cross section associated with the accuracy of the theoretical calculation and arising from uncertainty in PDF and scale. In addition, several analyses incorporate shape-dependent uncertainties on the kinematics of the dominant backgrounds in the analyses. These shapes are derived from the potential deformations of the final variables due to generator and background modeling uncertainties.

4 Derived Upper Limits

We derive limits on SM Higgs boson production $\sigma \times BR(H \rightarrow b\bar{b}/W^+W^-/\tau^+\tau^-)$ via the 60 individual analyses. To facilitate model transparency and to accommodate analyses with different degrees of sensitivity, we present our results in terms of the ratio of 95% C.L. upper

cross section limits to the SM predicted cross section as a function of Higgs boson mass[2]. The individual analyses described in Table 1 are grouped to evaluate combined limits over the range $100 \leq M_H \leq 200$ GeV/c^2. The $X + H \to \tau\tau b\bar{b}/q\bar{q}\tau\tau$ analysis contributes to the region $M_H \leq 145$ GeV/c^2, the $ZH \to \ell\ell b\bar{b}$, $ZH \to \nu\nu b\bar{b}$ $WH \to \ell\nu b\bar{b}$ and $H \to \gamma\gamma$ analyses contribute for $M_H \leq 150$ GeV/c^2, the $WH \to WW^+W^-$ analyses contribute for $M_H \geq 120$ GeV/c^2, the $t\bar{t}H \to t\bar{t}b\bar{b}$ analysis contribues for $M_H \geq 155$ GeV/c^2, and the $H \to WW$ analyses contribute for $M_H \geq 115$ GeV/c^2.
In Table 4 the expected and observed 95% C.L. cross section limit ratio to the SM cross sections for all analyses combined over the probed mass region ($100 \leq M_H \leq 200$ GeV/c^2) are shown.

Table 2: Combined 95% C.L. limits on $\sigma \times BR(H \to \bar{b}b/W^+W^-/\gamma\gamma/\tau^+\tau^-)$ for SM Higgs boson production. The limits are reported in units of the SM production cross section times branching fraction.

M_H (GeV/c^2)	100	105	110	115	120	125	130	135	140	145	150
Expected Limit	2.35	2.40	2.85	2.80	3.25	3.31	3.30	3.35	2.95	2.71	2.46
Observed Limit	3.53	3.40	3.47	4.05	4.03	4.19	4.53	5.58	4.33	3.86	3.20

M_H (GeV/c^2)	155	160	165	170	175	180	185	190	195	200
Expected Limit	1.98	1.41	1.35	1.64	2.05	2.58	3.32	4.19	5.04	6.00
Observed Limit	3.35	1.90	1.53	1.91	1.89	2.20	3.20	3.36	5.71	6.27

5 Conclusion

Upper limits on standard model Higgs boson production derived from 60 Higgs search analyses including data corresponding to 2.1-5.4fb^{-1} were presetend. These analyses were combined and form new limits more sensitive than each individual limit. The observed (expected) 95% C.L. upper limit ratios to the SM Higgs boson production cross sections are 4.0 (2.8) at $M_H = 115$ GeV/c^2 and 1.5 (1.4) at $M_H = 165$ GeV/c^2.

6 Bibliography

References

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