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Higgs Boson Studies at the Tevatron

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Abstract

We present the combination of searches for the Standard Model Higgs boson at a center-of-mass energy of $\sqrt{s}$ = 1.96 TeV, using the full Run 2 dataset collected with the CDF and D0 detectors at the Fermilab Tevatron collider. We also present combined measurements of Higgs Boson production cross sections, branching ratios, and couplings to fermions and bosons. Finally, we present tests of different spin and parity hypotheses for a particle H of mass 125 GeV produced in association with a vector boson and decaying into a pair of b quarks, and place constraints on such hypotheses using the D0 data.

Keywords: Higgs, Tevatron, Boson, D0, Higgs Properties

1. Introduction

In the standard model (SM) of particle physics electroweak symmetry breaking occurs via the Higgs mechanism [1, 2, 3, 4, 5]. It also generates the masses of the W and Z bosons. The 2012 discovery of a Higgs Boson with a mass of approximately 125 GeV by the ATLAS and CMS Experiments at the Large Hadron Collider [6, 7] along with evidence for a particle decaying to $b\bar{b}$ pairs from the CDF and D0 Experiments at the Fermilab Tevatron collider [8] and to fermions at CMS [9] has ushered in a physics program designed to measure the particle's properties.

The CDF and D0 Experiments at the Tevatron each collected approximately 10 fb^{-1} of $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s}$ = 1.96 TeV during Run II from 2001 – 2011. The Tevatron is particularly sensitive to associated production of a Higgs and vector (W or Z) boson where the Higgs Boson decays to a $b\bar{b}$ pair. The Tevatron is able to probe Higgs production cross sections and branching fractions, couplings to other elementary particles, and the spin and parity quantum numbers.

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2. Combination of searches

The Tevatron Higgs Boson searches are typically grouped into categories depending on the Higgs Boson decay mode. For a mass of 125 GeV, the dominant decay mode is to a $b\bar{b}$ pair. Other decay modes that bring additional sensitivity at the Tevatron include WW^*, $\tau^+\tau^-$ and $\gamma\gamma$. The analyses focusing on $H \to b\bar{b}$ decay primarily consider associated Higgs production with a W or Z boson, with the vector boson subsequently decaying leptonically ($WH \to \ell\nu b\bar{b}$, $ZH \to \ell\ell b\bar{b}$, $ZH \to \nu\nu b\bar{b}$). The analyses seeking WW^* decay are mainly sensitive to gluon fusion production ($gg \to H$), with additional contributions from association production and vector boson fusion. In these analyses the most sensitive channels are those where both W bosons decay to leptons ($WW^* \to \ell\nu\ell\nu$). The full combination of CDF's Higgs Boson searches is detailed in Ref. [10], while D0's combination is in Ref [11]. Ref. [12] describes the combination of all CDF and D0 Higgs Boson searches. When we combine all analysis channels at the Tevatron we exclude a SM Higgs Boson at 95% C.L. in the mass ranges 90–109 GeV and from 149–182 GeV. The expected exclusion regions are 90–120 GeV and 140–184 GeV. There is also a clear excess in data above the background expectation that is consistent with the presence of a Higgs Boson in the mass range 115–140 GeV. The p-value for the excess to arise from background fluctuations, as shown in Figure 1, corresponds to 3.0 standard deviations at $m_H = 125$ GeV.

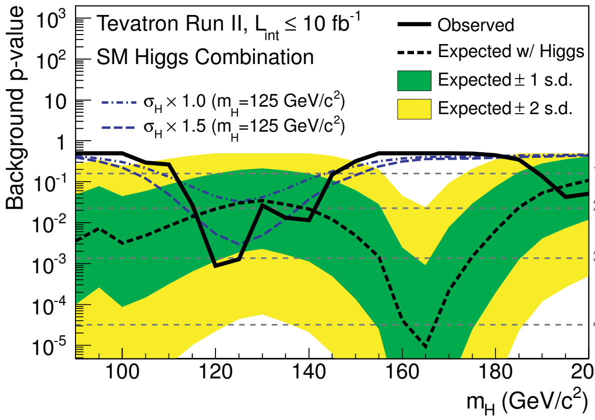

Figure 1: The background p-value as a function of m_H for all the combination of all CDF and D0 SM Higgs boson searches. The dotted black line shows represents the median expected values assuming a SM Higgs boson signal is present, evaluated separately at each m_H. The dark- and light-shaded bands indicate the one and two s.d. fluctuations. The blue lines show the median expected p-values assuming the presence of a SM Higgs boson with $m_H = 125$ GeV, produced at a rate of 1.0 times (short- dashed) and 1.5 times (long-dashed) the SM prediction [12].

We study this excess to determine its compatibility with the SM Higgs Boson hypothesis. We perform a best fit to data for the SM Higgs production cross section using all channels, and then to the cross section times branching fraction ($\mathcal{B}$) for each of the four main decay modes ($b\bar{b}$, WW^*, $\tau^+\tau^-$ and $\gamma\gamma$). The particular channels used for each decay modes combination are detailed in Ref. [12]. Figure 2 shows the results. The best fit value of the Higgs Boson production cross section using all channels is $R^{fit} = 1.44^{+0.59}_{-0.56}$ for $m_H = 125$ GeV, consistent with the SM prediction. When considering only the $H \rightarrow b\bar{b}$ decay mode, the best fit rate is $1.72^{+0.92}_{-0.87}$ for CDF only [10], $1.23^{+1.24}_{-1.17}$ for D0 only [11], and $1.59^{+0.69}_{-0.72}$ for the full Tevatron combination [12].

3. Higgs Boson coupling measurements

The Tevatron results are also sensitive to Higgs Boson couplings to other bosons and to fermions. We introduce scaling factors that we apply to the coupling of the Higgs boson to fermions (κ_f), W bosons (κ_W), Z bosons (κ_Z), or to vector bosons (κ_V). Any deviation from the expected SM values of 1 for all of these factors could be a indication of new physics. We first test

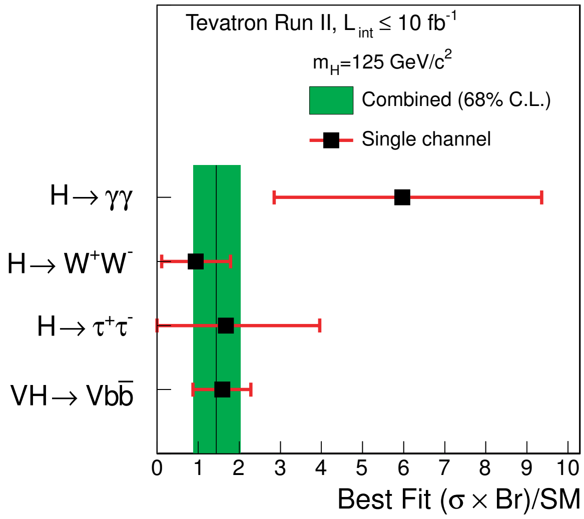

Figure 2: The best-fit values of $R = (\sigma\times\mathcal{B})/SM$ in the Tevatron Higgs boson combined search, focusing on the $H \rightarrow WW^*, H \rightarrow b\bar{b}, H \rightarrow \gamma\gamma$, and $H \rightarrow \tau^+\tau^-$ decay modes for a Higgs boson mass of 125 GeV. The shaded band indicates the one s.d. uncertainty on the best-fit value of R for the combination of all decay channels. [12].

whether custodial symmetry ($\kappa_W/\kappa_Z = 1$) holds by allowing κ_W and κ_Z to vary independently, and we find that the best fit point for (κ_W, κ_Z) is (1.25, ±0.90) as shown in Figure 3. We also allow κ_f and κ_V to vary independently (fixing $\kappa_W = \kappa_Z = \kappa_V$) and find a best fit point of $(\kappa_V, \kappa_f) = (1.05, -2.40)$, with a seconday maximum at $(\kappa_V, \kappa_f) = (1.05, 2.30)$, also shown in Figure 3. Since we are only sensitive to the relative sign of κ_f and κ_Z, we only plot the results for half of the 2-D plane. The Tevatron coupling measurements for both fermions and bosons are in agreement with the SM predictions.

4. Higgs Boson spin and parity studies

It is also important to measure the Higgs Boson spin (J) and parity (P) quantum numbers to determine whether the 2012 discovery is indeed the SM Higgs Boson. The SM predicts a J^P combination of $J^P = 0^+$. Other possibilities include $J^P = 0^-$ and $J^P = 2^+$. Both ATLAS and CMS have released results that strongly favor the SM prediction in bosonic final states [13, 14, 15, 16, 17], although they have not yet probed the $b\bar{b}$ final state. Associated production kinematics are very sensitive to the spin and parity of the particle produced alongside the vector boson, leading to significant differences in the $Vb\bar{b}$ mass distribu-

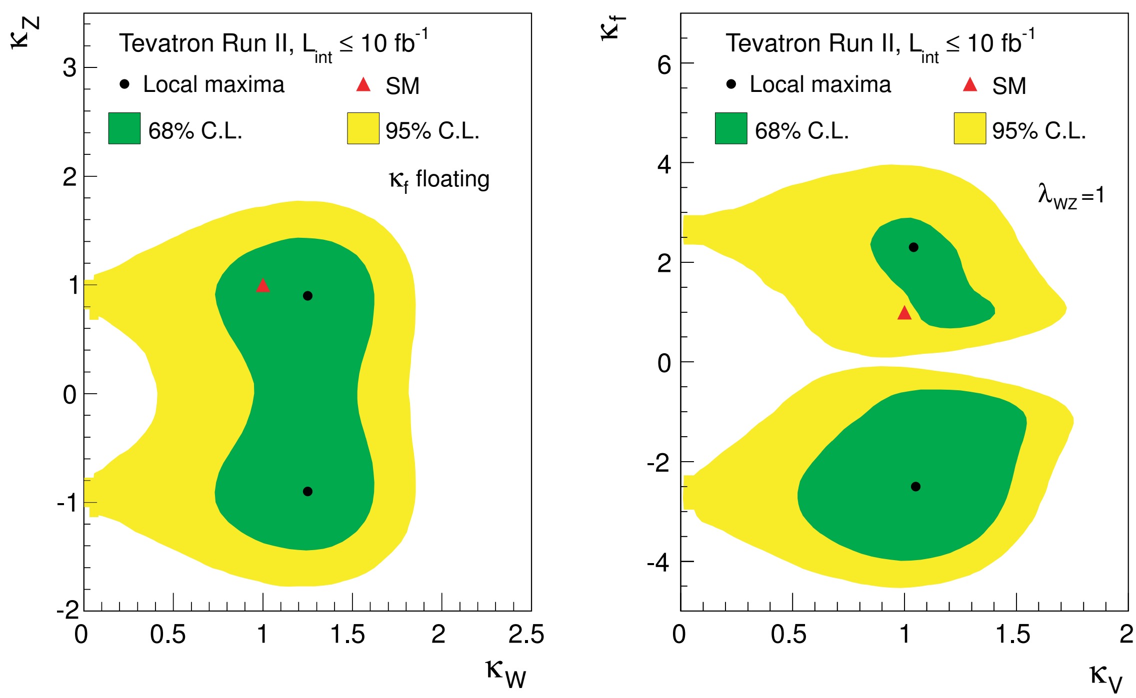

Figure 3: Left: Coupling measurements in the (κ_W, κ_Z) plane for the combined Tevatron SM Higgs Boson searches. Right: Coupling constraints in the (κ_V, κ_f) plane, for the combined Tevatron SM Higgs Boson searches assuming $\kappa_W/\kappa_Z = 1$. The black dots in each plot represent the values that maximize the local posterior probability densities, while the triangles mark the SM prediction [12].

tion [18, 19]. The D0 $WH \to \ell\nu b\bar{b}$, $ZH \to \ell\ell b\bar{b}$, and $ZH \to \nu\nu b\bar{b}$ analyses [20, 21, 22] are thus attractive probes of the Higgs Boson spin and parity. We start from these existing SM VH searches with no modifications to the basic event selection or analysis methodology.

Instead of using a multivariate discriminant trained against the SM Higgs Boson and backgrounds as the final variable as in the published analyses, we use the visible mass of the $V + b\bar{b}$ system for the $ZH \to \ell\ell b\bar{b}$ analysis and the visible transverse mass for the $WH \to \ell\nu b\bar{b}$ and $ZH \to \nu\nu b\bar{b}$ analyses. To reduce background contamination each analysis creates high-purity and low-purity regions based on windows in either the dijet invariant mass or multivariate discriminant output. Nearly all of the signal in each analysis lies within the corresponding high-purity region. For our statistical analysis to determine which J^P combination the data prefer we use the CL_s method with a negative log-likelihood ratio (LLR) as test statistic [23, 24, 25]. The test hypothesis is the $J^P = 2^+$ or $J^P = 0^-$ signal plus the SM backgrounds, while the null hypothesis is the $J^P = 0^+$ (SM Higgs Boson) signal plus the SM background. We perform the statistical analysis for two separate signal normalizations, each expressed via the parameter μ, the ratio to the SM Higgs Boson predicted cross section. The D0 combined analysis [26] can exclude a wide range of possible cross sections of a boson with a non-SM J^P assignment, as shown in Figure 4. For $\mu_{0^-} = \mu_{0^+} = 1$, we exclude the $J^P = 0^-$ hypothesis at the 97.6% C.L. For $\mu_{2^+} = \mu_{0^+} = 1$, we exclude the $J^P = 2^+$ hypothesis at the 99.0% C.L.

We also consider the possibility of a combination of two signals with nearly degenerate mass but different J^P assignments in our data (e.g. $J^P = 0^+$ and $J^P = 0^-$ or $J^P = 0^+$ and $J^P = 2^+$.) These tests can place constraints on theoretical models containing multiple Higgs-like bosons with a mass of 125 GeV, such as those containing a pseudoscalar boson in addition to a SM-like Higgs boson. For these studies we fix the sum of the two cross sections to a specific value of $\mu \times \sigma_{SM}$ and vary the fraction of non-SM signal. We define the non-SM signal fractions as $f_{0^-} = \sigma_{0^-}/(\sigma_{0^+} + \sigma_{0^-})$ and $f_{2^+} = \sigma_{2^+}/(\sigma_{0^+} + \sigma_{2^+})$. In the LLR definition we now modify the test hypothesis to be the sum of the background, the $J^P = 0^-$ signal normalized to $\mu \times \sigma_{SM} \times f_{0^-}$, and the $J^P = 0^+$ signal normalized to $\mu \times \sigma_{SM} \times (1 - f_{0^-})$. The null hypothesis is the sum of the SM background and the $J^P = 0^+$ signal normalized to $\mu \times \sigma_{SM}$ (i.e. the signal is pure $J^P = 0^+$.) We have an equivalent prescription for $J^P = 2^+$. Figure 5 presents the $1 - CL_s$ value as a function of the J^Psignal fraction. For $\mu = 1.0$ D0 excludes a $J^P = 0^-$ ($J^P = 2^+$) signal fraction $f_{0^-} > 0.80$ ($f_{2^+} > 0.67$) at the 95% C.L.

5. Conclusions

We have presented the final combination of Higgs Boson studies at the Fermilab Tevatron using the full RunII dataset. The data exhibit an excess over the background prediction of approximately 3 standard deviations and are consistent with the presence of a SM Higgs boson with a mass of approximately 125 GeV. We also measure the Higgs Boson couplings and find our results in agreement with the SM predictions. The D0 Experiment has tested several models with either a $J^P = 0^-$ or $J^P = 2^+$ boson in $Vb\bar{b}$ final states and finds that the data favor the SM J^P prediction.

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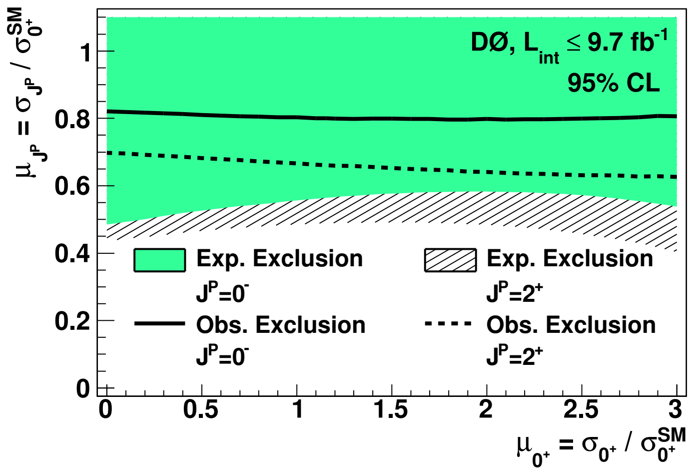

Figure 4: The 95% C.L. expected (shaded area) and observed exclusion (solid line) as functions of the $J^P = 0^-$and $J^P = 0^+$ signal strengths, as well as the 95% C.L. expected exclusion region (hatched area) and observed exclusion (dashed line) as functions of the $J^P = 2^+$ and $J^P = 2^+$ signal strengths. In the statistical analysis, the signal in test hypothesis is the $J^P = 0^-$ or $J^P = 2^+$ signal normalized to the SM Higgs cross section times the value on the vertical axis, and the signal in the null hypothesis is the $J^P = 0^+$ signal normalized to the SM Higgs cross section times the value on the horizontal axis. For each point in the plane that lies in the exclusion region, the test hypothesis is excluded. [26].

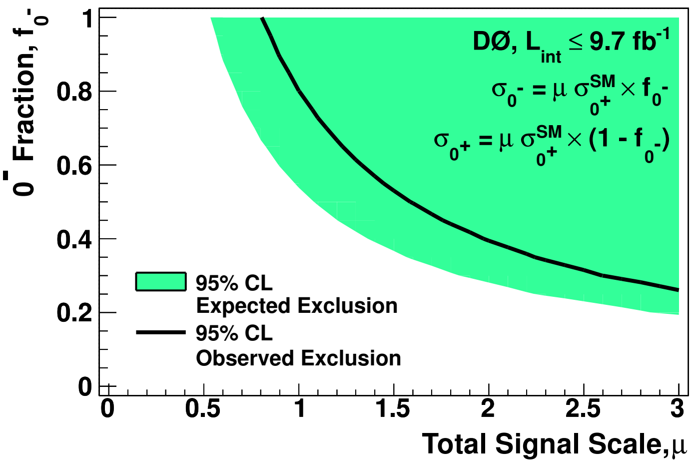

Figure 5: The expected 95% C.L. exclusion (shaded area) and observed 95% C.L. exclusion (solid line) as functions of the $J^P = 0^-$ signal fraction f_{0^-} and the total signal strength in units of the SM Higgs VH production cross section times branching fraction to $b\bar{b}$. The observed exclusion region lies above the line marking the exclusion region. [26].