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Search for the Higgs boson and spin/parity studies of the Higgs-like particle at 125 GeV with D0

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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 II dataset collected with the D0 detector at the Fermilab Tevatron collider. The major contributing processes include associated production (WH or ZH) and gluon fusion ($gg \to H$), in which the Higgs boson further decays to two bottom quarks, two photons, or two weak vector bosons. We also present the final combination of Higgs boson searches at the Tevatron, and measurements of Higgs Boson coupling properties. We further 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 using the D0 detector.

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1. Introduction

In the standard model (SM) of particle physics the Higgs mechanism [1] is responsible for breaking the symmetry between the electromagnetic and weak forces and generating the masses of the W and Z bosons. The 2012 discovery of a Higgs Boson with a mass of 125–126 GeV by the ATLAS and CMS Experiments at the Large Hadron Collider [2, 3] and evidence for a particle decaying to $b\bar{b}$ pairs from the CDF and D0 Experiments at the Fermilab Tevatron collider [4] that is consistent with the ATLAS and CMS results have changed the experimental Higgs programs' primary focus from searches to measuring 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.

2. Combination of searches

The Tevatron Higgs searches can be broadly 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, followed by WW^*. Other decay modes that bring additional sensitivity include $\tau^+\tau^-$ and $\gamma\gamma$. The analyses focusing on $H \to b\bar{b}$ decay consider associated production with a W or Z as the primary production mechanism, with the vector boson subsequently decaying leptonically ($WH \to \ell\nu b\bar{b}$, $ZH \to \ell\ell b\bar{b}$, $ZH \to \nu\nu b\bar{b}$) at both CDF and D0. The analyses seeking WW^* decay consist mostly of gluon fusion production ($gg \to H$), with additional contributions from association production and vector boson fusion. The most sensitive channels with $H \to WW^*$ decay are those where both W bosons decay to leptons ($WW^* \to \ell\nu\ell\nu$). The full list of all CDF analyses and their combination are described in Ref. [5], while those of D0 are in Ref [6]. The Tevatron combination is detailed in Ref. [7]. 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 SM predicted backgrounds 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.

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 ($\mathscr{B}$) 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. [7]. Figure 2 shows the results. The best fit rate for 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. Also of particular interest is the $VH \to Vb\bar{b}$ result. The best-fit $H \to b\bar{b}$ rate is $1.72^{+0.92}_{-0.87}$ for CDF only [5], $1.23^{+1.24}_{-1.17}$ for D0 only [6], and $1.59^{+0.69}_{-0.72}$ for the full Tevatron combination [7].

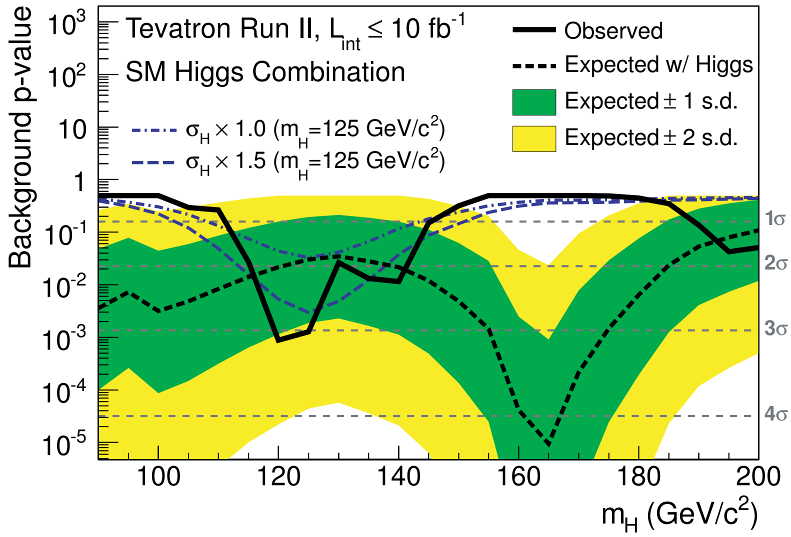

Figure 1: The background p-value as a function of m_H for all of CDF and D0's SM Higgs boson searches in all decay modes combined. The dotted black line shows the median expected values assuming a SM signal is present, evaluated separately at each m_H. The dark- and light-shaded bands indicate the one and two s.d. fluctuations under this scenario. The blue lines show the median expected p-values assuming the SM Higgs boson is present with $m_H = 125$ GeV at signal strengths of 1.0 times (short- dashed) and 1.5 times (long-dashed) the SM prediction [7].

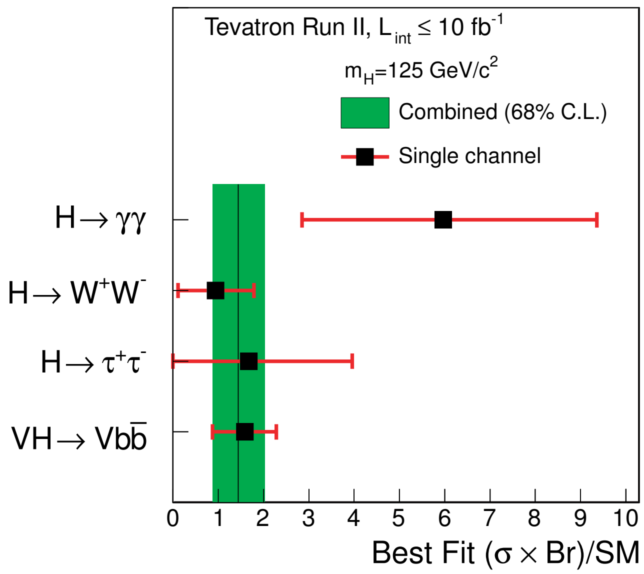

Figure 2: Best-fit values of $R = (\sigma \times \mathscr{B})/SM$ in the combinations of CDF and D0's Higgs boson search channels focusing on the $H \rightarrow WW^*, H \rightarrow b\bar{b}, H \rightarrow \gamma\gamma$, and $H \rightarrow \tau^+\tau^-$ decay modes for a Higgs boson mass of 125 GeV. The shaded band corresponds to the one s.d. uncertainty on the best-fit value of R for the full combination of all decay modes [7].

3. Higgs Boson coupling measurements

The Tevatron results are also sensitive to Higgs Boson couplings to other particles. We introduce scaling factors that modify the coupling of the Higgs boson to fermions (κ_f), W bosons (κ_W), Z bosons (κ_Z), or more generically to vector bosons (κ_V). Any deviations from the expected SM values of 1 for all of these facts could be indications of new physics. We test 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 points for (κ_W, κ_Z) is (1.25, $\pm$0.90) as shown in Figure 3. We also allow κ_f and κ_V to vary simultaneously (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. All of the Tevatron coupling measurements are consistent with the SM predictions within approximately 1 standard deviation.

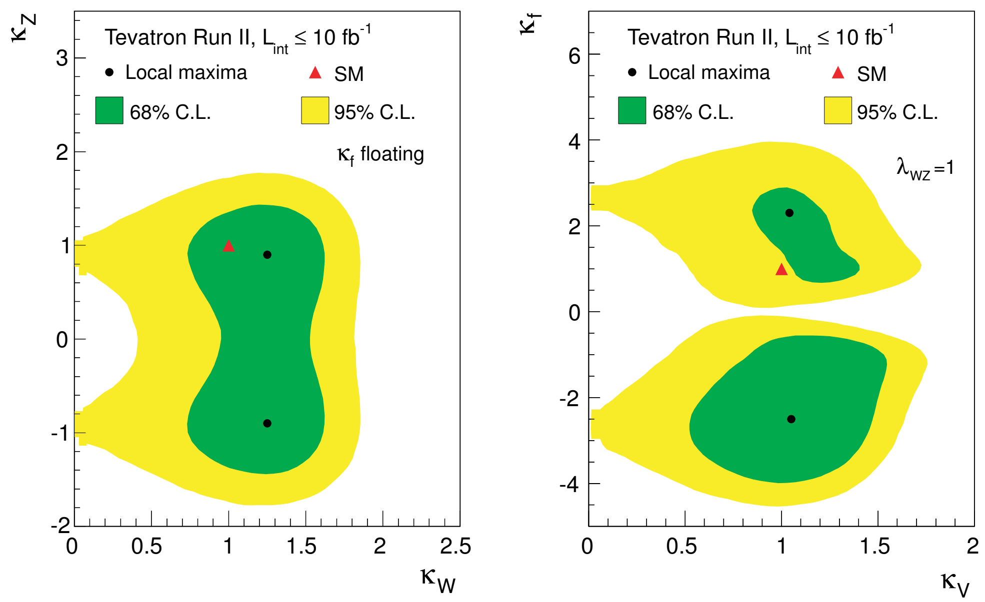

Figure 3: Left: Coupling measurements in the (κ_W, κ_Z) plane for the combined Tevatron SM Higgs Boson searches. Right: Coupling constraints in the (κ_V, κ_f) plane, for the combined Tevatron SM Higgs Boson searches assuming Custodial symmetry ($\kappa_W/\kappa_Z = 1$). In both plots the black dots represent the values that maximize the local posterior probability densities, while the triangle marks the SM prediction [7].

4. Higgs Boson spin and parity measurements

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, 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, particularly the $Vb\bar{b}$ mass distribution [8]. 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 are thus attractive probes of the Higgs Boson spin and parity. We start from the existing analyses [9] 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, however, 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 the test statistic. The test hypothesis is the $J^P = 2^+$ 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. We consider values of $\mu = 1.0$ and $\mu = 1.23$, equal to the best fit value of the SM Higgs cross section times branching fraction to $b\bar{b}$ in the combined D0 SM Higgs Boson search [6]. Figure 4 shows the LLR for the three analyses combined, in which the clear preference for $J^P = 0^+$ is visible. We exclude the $J^P = 2^+$ hypothesis at the 99.2% C.L. for $\mu = 1.0$ and at the 99.9% C.L. for $\mu = 1.23$.

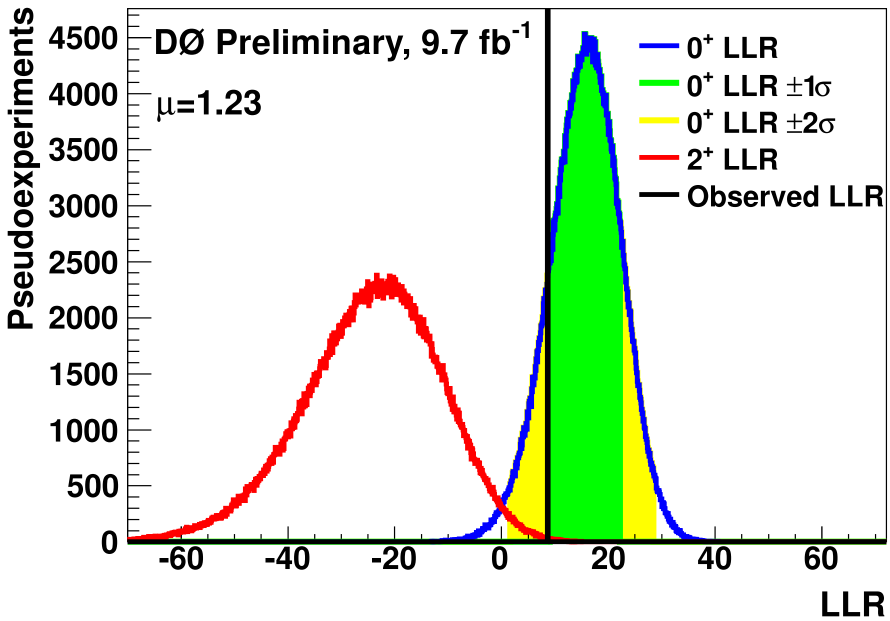

Figure 4: Log-likelihood ratio for the three combined analyses in the D0 spin and parity test. The black line denotes the observed value, and the red and blue distributions represent the predicted pseudoexperiment distributions of the $J^P = 2^+$ and $J^P = 0^+$ hypotheses, respectively. We normalize the signals to 1.23 times the SM Higgs Boson prediction here [10].

5. Conclusions

We have presented the combination of Higgs Boson searches at the Fermilab Tevatron using the full RunII dataset. The data exhibit an excess over the background prediction of approximately 3 standard deviations consistent with the presence of a SM Higgs boson of mass 125 GeV. We also measure the Higgs Boson couplings and find our measurements to be in agreement with the SM predictions. The D0 Experiment has probed the spin and parity of the Higgs Boson in $Vb\bar{b}$ final states and finds that the data favor the SM prediction.

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