OVERVIEW OF HIGGS BOSON STUDIES AT THE TEVATRON

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The CDF and D0 experiments at the Tevatron $p\bar{p}$ Collider collected data between 2002 and 2011, accumulating up to 10 fb^{-1} of data. During that time, an extensive search for the standard model Higgs boson was performed. Combined results from the searches for the standard model Higgs boson with the final dataset are presented, together with results on the Higgs boson couplings and spin and parity.

1 Introduction

The standard model (SM) Higgs boson was introduced to explain electroweak symmetry breaking.[1–5] The search for the Higgs boson was a central part of the D0 and CDF Collaborations' physics program for many years. Recently both experiments finalized their searches and published final results.[6–31]

2 Search for $H \to b\bar{b}$

Due to the overwhelming backgrounds from multijet production, a search for the Higgs boson in the final state with the two b–quarks can not be done in the dominant production mode, ggH, but is performed in the associated production with a vector boson V ($V = W, Z$). The search is divided according to the decay of the associated vector boson: (a) $ZH \to \ell\ell b\bar{b}$, (b) $WH \to \ell\nu b\bar{b}$, and (c) $ZH \to \nu\bar{\nu}b\bar{b}$. One of the main ingredients of the search in these final states is an identification of the jets originating from the b–quarks, i.e. b–tagging. Both the CDF and D0 collaborations use multi–variate analysis (MVA) for b–tagging which improved efficiency for up to 15% over a cut based analysis.[32,33]

To validate our procedures and results we measure the cross sections of SM processes with similar characteristics as the Higgs boson signal. Measured combined cross section of the $VZ \to Vb\bar{b}$ process is $\sigma = (0.68 \pm 0.21) \times \sigma_{SM}$.

3 Combined results from the D0 and CDF experiments

To estimate the sensitivity of the search at the Tevatron experiments we use the log–likelihood ratio (LLR) test statistic for the signal–plus–background ($s + b$) and background–only (b) hypotheses, defined as LLR $= -2\ln(L_{s+b}/L_b)$, and $L_{s+b(b)}$ is the likelihood function for the $s+b(b)$ hypothesis. Figure 1(a) shows the LLR for the combined $VH \to Vb\bar{b}$ channels from both experiments, where data shows broad excess consistent with the dijet mass resolution. For interpretation see Ref. 6. We also measured the cross section of the $VH \to Vb\bar{b}$ process and obtained

$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b}) = 0.19^{+0.08}_{-0.09}$ pb for $M_H = 125$ GeV, to be compared to the SM value of 0.12 ± 0.01 pb.

When all search channels [a] are combined the Tevatron experiments exclude (expect to exclude) the Higgs boson with a mass 90–109 (90–120) GeV and 149–182 (140–184) GeV at the 95% C.L. Figure 1(b) shows LLR from all search channels where an excess in data is consistent with the assumption of the presence of the Higgs boson with a $M_H = 125$ GeV and a cross section of $\sim 1.5(\pm 0.6) \times \sigma_{SM}$. To quantify this excess, we present in Fig. 1(c) local p–values for the background hypothesis, which provide information about the consistency with the observed data. We obtain that the background is inconsistent with the data at the level of 3 standard deviations (s.d.) for $M_H = 125$ GeV. We define signal strength $R = \sigma/\sigma_{SM}$, and we find that our excess is consistent with the presence of a SM Higgs boson with $M_H = 125$ GeV within one s.d. with $R = 1.44^{+0.59}_{-0.56}$. If only $H \to b\bar{b}$ is considered, $R = 1.59^{+0.69}_{-0.72}$.

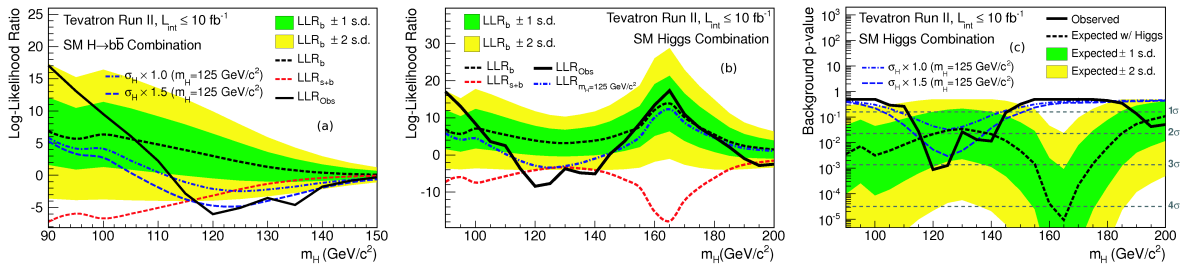

Figure 1 – The LLR distribution for the (a) combined $VH \to Vb\bar{b}$ channels, and (b) all combined channels. (c) p–value for all combined channels.

4 Couplings

After the discovery of a Higgs boson by the LHC experiments[34,35] and evidence in the $b\bar{b}$ final state at the Tevatron experiments,[7] it is important to precisely measure its properties. Any significant deviation may point to a non–SM nature of the newly discovered particle. Since at the Tevatron experiments many production and decay modes are possible, we assumed a simplified model, SM–like with the following: (i) Hff couplings are scaled together by κ_f; (ii) HWW coupling is scaled by κ_W; (iii) HZZ coupling is scaled by κ_Z. For some studies, we scale the HWW and HZZ couplings by $\kappa_W = \kappa_Z = \kappa_V$. Then SM is recovered if $\kappa_f = \kappa_W = \kappa_Z = 1$. Coupling results measurements from the Tevatron experiments are consistent with the SM: (i) assuming $\kappa_W = \kappa_Z = 1$, we find $\kappa_f = -2.64^{+1.59}_{-1.30}$; (ii) assuming $\kappa_f = \kappa_{W(Z)} = 1$, we find $\kappa_W = -1.27^{+0.46}_{-0.29}$ and $\kappa_Z = \pm 1.05^{+0.45}_{-0.55}$, and if they are varied together $(\kappa_W, \kappa_Z) = (1.25, \pm 0.90)$; (iii) to test custodial symmetry we study the ratio $\lambda_{WZ} = \kappa_W/\kappa_Z$, and measure $\lambda_{WZ} = 1.24^{+2.34}_{-0.42}$; (iv) assuming that custodial symmetry holds, $\lambda_{WZ} = 1$, and allowing both κ_V and κ_f to vary, we find $(\kappa_V, \kappa_f) = (1.05, -2.40)$ and $(\kappa_V, \kappa_f) = (1.05, 2.30)$ (see Fig. 2).

5 Spin and Parity

The SM predicts that Higgs boson is a scalar with a positive parity ($J^P = 0^+$). The D0 experiment studied the spin and parity of the particle decaying to a pair of b–quarks, produced in association with a vector boson, with assumptions that a new particle is pseudoscalar, $J^P = 0^-$, or that it is graviton–like particle described with Randall–Sundrum model, $J^P = 2^+$, following specific models described in Ref. 36. Associated production of a new particle X and vector boson at the Tevatron is sensitive to the different kinematics of the various J^P combinations, which give different VX mass distributions for the different J^P choices. We use the invariant mass for

[a] All search channels include $b\bar{b}$, W^+W^-, $\tau^+\tau^-$ and $\gamma\gamma$ decays with all production modes.

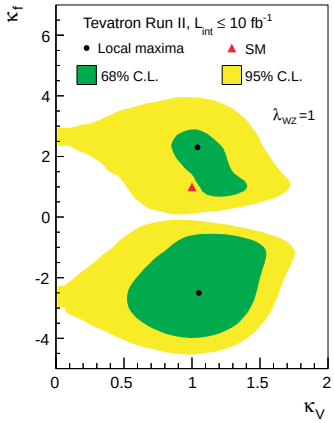

Figure 2 – Two–dimensional constraints in the (κ_W, κ_Z) plane, for the combined Tevatron searches for a SM like Higgs boson with mass 125 GeV.

the $ZH \to \ell\ell b\bar{b}$ channel and the transverse mass of the $\ell\, \not{E}_T\, b\bar{b}$ and $\not{E}_T\, b\bar{b}$ for the $WH \to \ell\nu b\bar{b}$ and $ZH \to \nu\bar{\nu} b\bar{b}$ channels (see Fig. 3(a)). To achieve better sensitivity, we divide data into samples with high and low purity based on dijet invariant mass, $m_{b\bar{b}}$, in the $ZX \to \ell\ell b\bar{b}$ and $VX \to \not{E}_T\, b\bar{b}$ final states, and MVA output used in SM Higgs boson search in the $WX \to \ell\nu b\bar{b}$ final state.

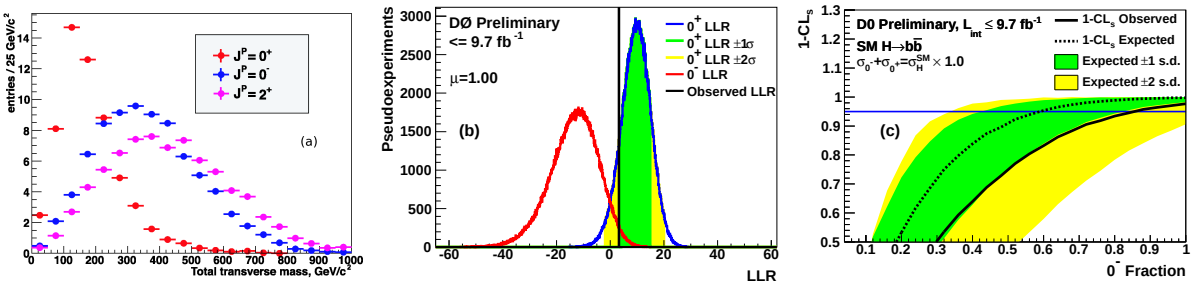

Figure 3 – (a) The transverse mass of the VX system in the $WX \to \ell\nu b\bar{b}$ final state. (b) LLR distributions comparing the $J^P = 0^+$ and the $J^P = 0^-$ hypotheses for the combination of three $VH \to Vb\bar{b}$ final states. (c) $1 - CL_s$ as a function of the $J^P = 0^-$ signal fraction.

Results are combined using the CL_s method with a negative log–likelihood ratio (LLR) test statistic LLR $= 2\ln(\mathrm{L}_{\mathrm{H}_1}/\mathrm{L}_{\mathrm{H}_0})$, where H_i is test or null hypothesis. The CL_s is then $CL_s = CL_{H_1}/CL_{H_0}$. In the context of the models studied, we exclude $J^P = 0^-$ at the 97.9% C.L. (see Fig. 3(b)) and $J^P = 2^+$ at the 99.2% C.L. If we assume that both $J^P = 0^-(J^P = 2^+)$ and $J^P = 0^+$ are mixed in data, and define fraction of the non–SM signal X to be $f_X = \sigma_X/(\sigma_X + \sigma_{0^+})$, we exclude $f_{0^-(2^+)} > 0.85(0.71)$ at 95% C.L. (see Fig. 3(c)).

6 Summary

In summary, we presented combined results from the D0 and CDF Collaborations in the search for the SM Higgs boson. We report an evidence of a Higgs boson when all channels are combined. In addition, we measured various Higgs boson couplings, and found them to be consistent with the SM. We exclude two models of Higgs bosons with exotic spin and parity.

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