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Searches for Low Mass Higgs Boson at the Tevatron

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Summary. — This paper summarized the latest results on the search for the standard model Higgs boson in the low mass regions by the CDF and DØ collaborations, which were presented at the Les Rencontres de Physique de la Vallée d'Aoste conference 2010. The results are based on data samples collected up to 5.4 fb^{-1}.

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1. – Introduction

The last particle predicted by the standard model (SM), which has not yet been observed in experiments, is the Higgs boson. In the SM, the electroweak gauge symmetry is broken through the Higgs mechanism, which postulates the existence of a Higgs field that permeates the entire universe. The SM particles acquire their masses by interacting with the Higgs fields through the exchange of a particle, the Higgs boson. Although the Higgs boson mass is not predicted by the theory, however it can be constrained due to its predicted couplings to the other particles. Global fits to precision electroweak data favors a light Higgs with mass below 157 GeV/c^2 [1]. Direct Higgs searches performed at LEP set a lower limit of 114 GeV/c^2 [2]. If this limit is included into the previous calculation, the upper limit increases to 186 GeV/c^2.

At the Tevatron the Higgs boson can be produced in $p-\bar{p}$ interactions through several processes [3]. The production cross section for Higgs mass between 100-200 GeV/c^2 varies between $\sim$ 1 pb to $\sim$ 0.01 pb, depending on their production mechanisms. The gluon fusion ($gg \rightarrow H$) is the dominant production process followed by the associated productions ($q\bar{q}' \rightarrow WH/ZH$) and the vector boson fusion process ($qq \rightarrow qqH$). In the low Higgs mass region ($m_H < 135$ GeV/c^2), the dominant decay channel is $H \rightarrow b\bar{b}$ ($BR \sim 73\%$ at $m_H = 115$ GeV/c^2), followed by the $H \rightarrow \tau\bar{\tau}$ channel whose branching fraction is $\sim$ 10 times smaller than $H \rightarrow b\bar{b}$. For the Higgs boson mass above 135 GeV/c^2 the decay channel $H \rightarrow W^+W^-$ becomes the dominant decay channel. Although the gluon fusion process has the largest production rate, however it is difficult to search for low mass Higgs boson in this production channel with Higgs decays in $H \rightarrow b\bar{b}$ due to huge QCD multi-jet background. The production and decay modes that have the best discovery sensitivities for a single search channel at low Higgs mass are the associated productions ($q\bar{q}' \rightarrow WH/ZH$) with the decays $H \rightarrow b\bar{b}$ and $W \rightarrow l\nu$ or $Z \rightarrow l^+l^-/\nu\bar{\nu}$ ($l = e$ or μ).

As the predicted Higgs signal is several orders of magnitude smaller than other SM backgrounds, both Tevatron experiments, CDF and DØ , have devised search strategies to optimize the Higgs detection performances. The Higgs acceptance is increased by extending the region of lepton identification in the detector, and the b jet tagging efficiency is improved by developing advanced tagging algorithms. Both experiments also employ multivariate discriminant tools such as artificial neural network (NN), Boosted Decision Tree (BDT) and Matrix Element (ME) probabilities to further discriminate the Higgs signal from the background. To achieve the best search sensitivity, both experiments analysed as much data samples as possible (up to ~ 5.4 fb^{-1} of data sample were analysed when the results were presented at the conference), and the results from all search channels are combined.

2. – Low Mass Higgs Boson Searches

The following sections describe the searches for low mass Higgs boson in various production and decay final states performed by the CDF and DØ experiments.

2·1. *Searches for the Higgs Boson in the* $WH \rightarrow l\nu b\bar{b}$ *Channel.* – CDF and DØ have searched for the SM Higgs boson in the channel where the Higgs boson is assumed to be produced in association with a W boson [4]. The search is focused on the signal events in which the W boson decays leptonically ($W \rightarrow e\nu$ or $W \rightarrow \mu\nu$) and the Higgs boson decays into $b\bar{b}$. Thus the final state signature consists of a high-p_T lepton (e or μ), a pair of b jets and large missing transverse energy ($\not\!\!E_T$) from the escaping neutrino. To select the Higgs events, each candidate event should have an isolated lepton, two or more jets and large $\not\!\!E_T$. At least one of the jets in the selected events is required to be tagged as a b jet candidate. The main sources of background are from productions of $W + bb/cc$, $t\bar{t}$, single Top, di-boson, QCD multi-jet production that fakes a W production signature, and misidentification of non-b jets as b jets (mis-tag) in W boson production with light-flavor jets. To improve the search sensitivity, DØ used a NN based b jet tagging algorithm. This algorithm enables the experiment to have good efficiency in tagging the b jets of the Higgs signal and maintain an over all low mis-tag rate. CDF uses NN to correct the measured jet energy and improves the di-b jet invariant mass (m_{bb}) resolution.

After the event selection, CDF uses a Matrix Element approach to extract the possible signal from the background. This technique uses leading order Matrix Element to compute event probability densities for the signal and backgrounds, thus creating a discriminant for each event. The discriminant distributions are shown in Figure 1. DØ trains a NN algorithm to separate the signal from background. No evidence for a Higgs signal is seen in both searches and upper limits at 95% confidence level (C.L.) are set on its production cross section times branching ratio. For Higgs mass of 115 GeV/c^2, CDF sets an observed (expected) limit of 3.3 (3.8) times the SM predicted cross section, and DØ sets an observed (expected) limit of 5.1 (6.9) times the SM prediction.

2·2. *Searches for the Higgs Boson in the* $ZH \rightarrow l^+l^-b\bar{b}$ *Channel.* – At the Tevatron the Higgs boson can also be produced in association with a Z boson. CDF and DØ have searched for the Higgs boson in this production channel and in the decay modes of $Z \rightarrow l^+l^-$ ($l = e, \mu$) and $H \rightarrow b\bar{b}$. The searches are performed on data samples of 4 fb^{-1} [5]. The events are first selected by requiring a pair of opposite charged electrons or

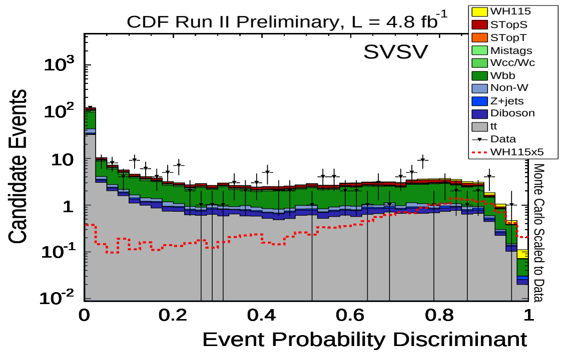

Fig. 1. – Event probability density distributions for the Matrix Element WH analysis by CDF.

muons whose invariant mass is consistent with the Z boson. The selected events are to have at least two jets and at least one jet tagged as a b jet. The dominant backgrounds are the production of Z plus heavy-flavor jets (b or c jets), Z plus light-flavor jets with light-flavor jets mis-identified as b jets, $t\bar{t}$, ZZ, ZW, and events with fake leptons.

Some of the advantages in performing the search in this $ZH \to l^+l^-b\bar{b}$ channel are that all the physics objects in the final state can be detected if they fall within the instrumented region, and the two charged leptons are constrained to the Z mass. Thus CDF and DØ make use of the kinematic constraints to correct the measured jets' energies and improve the di-jet mass m_{bb} resolution. This improvement is illustrated in Figure 2.

To maximize the search sensitivity, both experiments perform the analysis in several sub-channels (i.e. loose and tight lepton identification and single and double b-tagged jets categories). To further enhance the possible Higgs signal over the backgrounds, CDF trains a two-dimensional NN to distinguish ZH signal from Z+jets and $t\bar{t}$, which are the two most dominant backgrounds. DØ uses the BDT algorithm to improve the separation. The discriminant distributions from the BDT are shown in Figure 3. The observed events in the data is consistent with the expected background events. Thus there is no evidence of a Higgs signal in the data. The observed (expected) upper limit at 95% C.L. on $\sigma(p\bar{p} \to ZH) \times BR(H \to b\bar{b})$ for $m_H = 115$ GeV/c^2 is 5.9 (6.8) times the SM prediction for CDF and 8.0 (9.1) times the SM prediction for DØ .

2˙3. *Searches for the Higgs Boson in the* $\not\!\!E_T$+$b\bar{b}$ *Channel.* – CDF and DØ also consider a search for associated Higgs production using a final state signature of $\not\!\!E_T + b\bar{b}$, which is mostly sensitive to the signal of $ZH \to \nu\bar{\nu}b\bar{b}$. The search also has some sensitivity to $WH \to l\nu b\bar{b}$ where the charged lepton is not identified, or an electron that does not pass the electron identification selection is classified as a jet, or a tau lepton that decays hadronically and reconstructed as a jet. For both production channels the Higgs decay considered is $H \to b\bar{b}$. The analyses are performed on data samples of 3.6 fb^{-1} for CDF and 5.2 fb^{-1} for DØ [6]. The main sources of background are from the production of W or Z bosons with jets, single Top quark, $t\bar{t}$, and di-boson. In these processes, the $\not\!\!E_T$ is mostly the result of neutrinos escaping detection. QCD multi-jet production is another source of background. In this case the $\not\!\!E_T$ is due to the mis-measurement of the energy of one or more jets. To reduce the QCD multi-jet background, both experiments look at the correlation between a track based missing transverse momentum $\not\!\!P_T$, which is defined as the opposite of the vector sum of the measured charged particles transverse

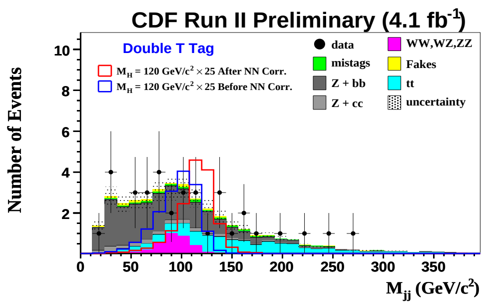

Fig. 2. – m_{jj} mass distribution from a $ZH \to l^+l^-b\bar{b}$ analysis. The blue histogram is the reconstructed $m_{b\bar{b}}$ mass distribution of a ZH simulated sample, with $m_H = 120$ GeV/c^2, before correcting the jets' energy . The red histogram is after applying the correction.

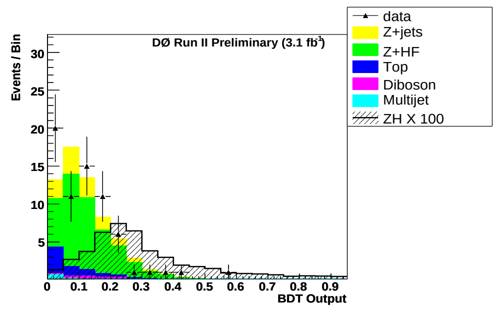

Fig. 3. – Discriminant distributions for the Boosted Decision Tree $ZH \to l^+l^-b\bar{b}$ analysis by DØ .

momentum, and the calorimeter based $\not\!\!E_T$. For collision events with real large missing transverse energy, there will be a strong correlation between the calorimeter based $\not\!\!E_T$ and the track based $\not\!\!P_T$. Whereas for events with no real missing transverse energy, there will be no/weak correlation between $\not\!\!E_T$ and $\not\!\!P_T$.

In this analysis both experiments also apply multivariate algorithms to first separate the QCD multi-jet background from the signal, and then a second training is performed to separate the non-QCD multi-jet background from the signal. The discriminant distributions from the second training for the double b-tagged category from DØ is shown in Figure 4. No evidence of Higgs signal is seen by both experiments in this final state signature search. The observed (expected) upper limit at 95% C.L. on the signal production cross section times branching ratio at $m_H = 115$ GeV/c^2 is 6.1 (4.2) times the SM prediction for CDF, and 3.7 (4.6) times the SM prediction for DØ .

2˙4. *Searches for the Higgs Boson in the All-Hadronic Channel.* – CDF has performed a search for low mass Higgs bosons from WH/ZH production in the decay modes $W \to qq'$ or $Z \to q\bar{q}$ and $H \to b\bar{b}$, and from vector boson fusion ($qq \to qqH$) where the Higgs boson decays into $b\bar{b}$ [7]. The final state signature consists of four jets with at least two b jets. The signal events, which are selected from a data sample of 4 fb^{-1}, are required to have at least four jets with two jets tagged as b jets in the event. The dominant background is from QCD multi-jet production with heavy-flavor jets in the final state. In order to distinguish between signal and background events, CDF uses a NN algorithm. The distributions of the NN output for the expected background contributions and for the data, for one of the double b tagged category of the associated production search, is shown in Figure 5. There is no evidence of the Higgs signal in the most signal like region of the NN output distributions for all the sub-channels considered in this analysis. The observed (expected) upper limit at 95% C.L. on the Higgs production cross section times branching ratio is 10.4 (19.9) times the SM prediction for Higgs mass of 120 GeV/c^2.

2˙5. *Searches for the Higgs Boson in the τ plus jets Final States.* – The search for low mass Higgs boson with tau leptons in the final states has been explored by the DØ experiment. In the first analysis, which uses a data sample of ~ 4 fb^{-1}, the Higgs

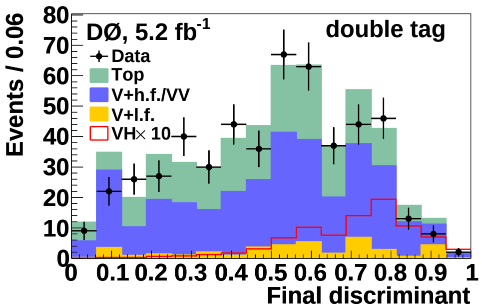

Fig. 4. – Discriminant distributions for the Higgs search in the $\not\!\!E_T + b\bar{b}$ final state by DØ .

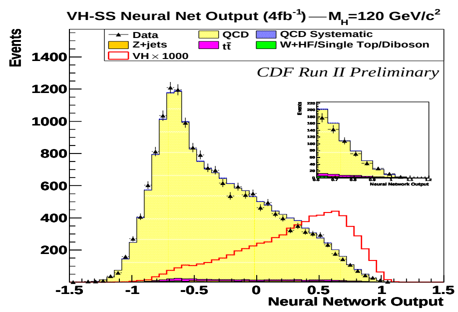

Fig. 5. – Output distributions of the neural network trained for the Higgs search in the all hadronic final state by CDF.

signal is searched in the final state signature that consists of a tau lepton, large $\not\!\!E_T$ and a pair of b jets [8]. The signal contributions come from the WH and ZH associated productions where the W decays into a tau lepton and a neutrino, and the Z boson decays into a pair of tau leptons but with one tau lepton not identified in the detector. The Higgs boson is considered to decay into a pair of b quarks. The signal events are selected with one identified hadronic tau candidate, large $\not\!\!E_T$ and at least two jets with at least one jet tagged as a b jet. The dominant background contributions come from $t\bar{t}$ and $W+bb$ productions. The reconstructed di-jet invariant mass distributions of the selected data events, expected background and predicted Higgs signal, are shown in Figure 6. No evidence of the Higgs signal is observed in the data. An observed (expected) upper limit of 14.1 (22.4) times the SM prediction on the Higgs production cross section times branching ratio is being set for the mass of $m_H = 115$ GeV/c^2 at 95% C.L. .

In the second Higgs search analysis, DØ looks at the final state that contains two tau leptons and two jets [9]. The signal production and decay channels that contribute to this final state include WH/ZH associated productions with $W/Z \to qq$ and $H \to \tau\bar{\tau}$ or $Z \to \tau\bar{\tau}$ and $H \to q\bar{q}$, vector boson fusion ($qq \to qqH$) with $H \to \tau\bar{\tau}$, and gluon fusion $gg \to H$+jets , where the additional jets are originated from QCD initial state radiation and with $H \to \tau\bar{\tau}$. The signal events consist of two tau candidates and at least two jets. One of the tau candidate is required to decay hadronically, and the other tau candidate decays into a muon lepton and neutrinos. Similarly no evidence of the Higgs signal is seen in this analysis. The observed (expected) upper limit at 95% C.L. on the Higgs production cross section times branching ratio is 27.0 (15.9) times the SM prediction for Higgs mass of 115 GeV/c^2.

2·6. *Searches for the Higgs Boson in the Inclusive Di-Photon Final State.* – In the SM, low mass Higgs boson can decay into a pair of photons with a predicted branching ratio of $\sim 0.2\%$. Although its branching ratio is many times smaller than $BR(H \to b\bar{b})$ and $BR(H \to \tau\bar{\tau})$, however the energy resolution of a measured photon is much better than the measurement of a b jet. Additionally the photon's energy is well contained within the detector, whereas for the tau lepton, some of its energy is not measured due to the escaping neutrino. Therefore one may discover the Higgs boson by searching for a mass peak in the di-photon mass spectrum.

CDF and DØ have searched for the Higgs boson in the di-photon final state using data samples of 5.4 fb^{-1} and 4.2 fb^{-1}, respectively [10]. The signal productions that are considered in the search include the gluon fusion, the WH/ZH associated productions, and the vector boson fusion. The main sources of background are QCD di-photon production, γ+jet and di-jet productions where the jet fakes as a photon, and Drell-Yan ($Z/\gamma^* \to e^+e^-$) production where the electron is mis-identified as a photon. To search for the Higgs signal, CDF (DØ) looks for a mass peak in a mass window of ± 12 GeV/c^2 (± 15 GeV/c^2) around the assume Higgs mass. The di-photon invariant mass distribution in the mass window for an assume Higgs mass of 120 GeV/c^2, from CDF, is shown in Figure 7. Both experiments do not observe evidence of a Higgs signal in the di-photon mass distribution. CDF sets an observed (expected) limit of 22.5 (19.4) times the SM prediction for Higgs mass of 120 GeV/c^2, and DØ sets an observed (expected) limit of 13.1 (17.3) times the SM prediction. The limits are given at 95% C.L. .

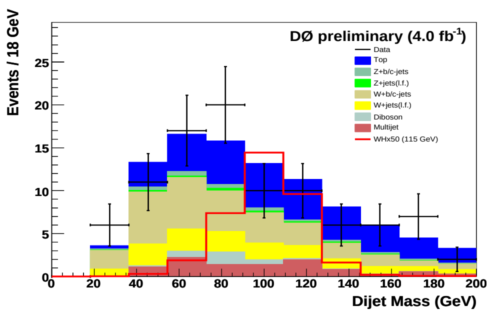

Fig. 6. – Reconstructed di-jet mass distribution for Higgs search in $\tau + \not\!\!E_T + b\bar{b}$ final state by DØ .

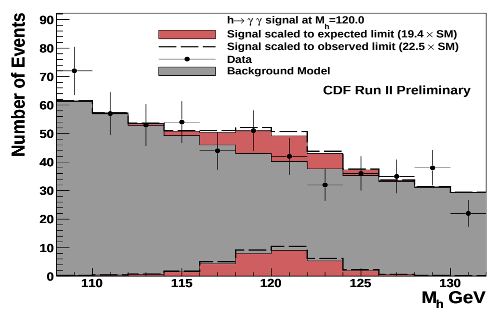

Fig. 7. – Reconstructed di-photon mass distribution for Higgs search in $H \to \gamma\gamma$ decay channel by CDF.

3. – Combined Results from all Searches

In the earlier sections the results on various searches for the SM Higgs boson in the low mass region by the CDF and DØ experiments were presented. Although some channels' sensitivities are similar or are different from others, however each channel is exploring different production and decay modes. The combination of these results will further improve the sensitivity of the the Higgs search. The combined results from each experiment and the Tevatron combined results (combining CDF and DØ 's results) are given in Table I [11, 12, 13]. The Tevatron combined results are also presented in Figure 8. The limits presented in Table I and Figure 8 are the ratios of the upper limit at 95% C.L. on the production cross section times branching ratio to the SM prediction. The combined limit in the low mass region also receives contributions from the high mass searches.

4. – Projection

Over the past few years both Tevatron experiments have improved its sensitivity to the search for the SM Higgs boson by increasing the data size used in the searches and by improving the analysis techniques. By analyzing more data, each experiment gains better understanding of its detector's performance and is then able to discover new

TABLE I. – *CDF, DØ and Tevatron combined upper limit on SM Higgs boson production in the low mass region. The limits are expressed as ratios to the SM prediction.*

	Mass (GeV/c^2)	100	105	110	115	120	125	130	135	140	145	150
CDF	Exp	2.01	2.09	2.14	2.38	2.72	2.84	2.92	2.66	2.51	2.21	1.92
	Obs	2.58	2.62	2.88	3.12	3.37	3.93	3.80	3.80	3.53	2.66	2.26
DØ	Exp	2.35	2.40	2.85	2.80	3.25	3.31	3.30	3.35	2.95	2.71	2.46
	Obs	3.53	3.40	3.47	4.05	4.03	4.19	4.53	5.58	4.33	3.86	3.20
Tev	Exp	1.52	1.58	1.73	1.78	2.1	2.2	2.2	2.1	1.91	1.75	1.49
	Obs	2.11	2.35	2.28	2.70	2.7	3.1	3.1	3.4	3.03	2.17	1.80

ways to improve the Higgs search sensitivity. Some of the improvement techniques are mentioned in earlier sections. The results presented earlier are based on data samples up to ~ 5.4 fb^{-1}. The Tevatron is expected to deliver a total integrated luminosity between 10-12 fb^{-1} by the end of 2011. By doubling the existing data samples, both experiments will be able to make more improvements to the Higgs search. The plot in Figure 9 shows the predicted probability of observing a three sigma evidence of the Higgs signal by the Tevatron, as a function of the Higgs mass, for an integrated luminosity of 5 fb^{-1} and 10 fb^{-1} collected by each experiment [11]. The plot also shows the sensitivities when using the current analysis techniques and when adding in new improvements. The probabilities are calculated by scaling the CDF's expected performance at 5 fb^{-1} and 10 fb^{-1}, to twice the integrated luminosity so as to estimate the performance when both CDF's and DØ 's results are combined. The plot shows that if the Higgs boson exists within the low mass region, there is a $\sim 35\%$ chance of observing a three sigma evidence of the Higgs signal with an integrated luminosity of 10 fb^{-1} collected by both experiments.

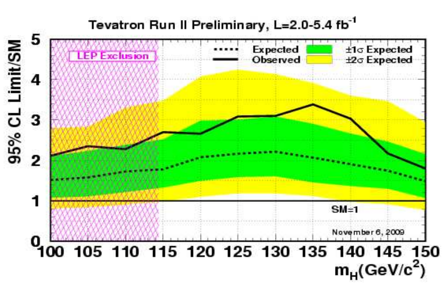

Fig. 8. – Tevatron combined upper limit on SM Higgs boson production in the low mass region.

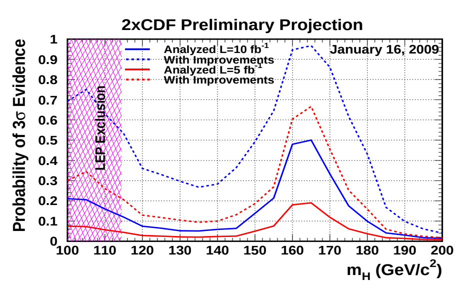

Fig. 9. – Predicted probability of observing a three sigma evidence of the Higgs signal by the Tevatron.

5. – Summary

The CDF and DØ collaborations have searched for the SM Higgs boson in various production and decay channels with data samples up to 5.4 fb^{-1}. No Higgs signal has been observed so far. By combining all the results from both experiments, the observed (expected) 95% C.L. upper limit on the production cross section times branching fraction for a Higgs mass of 115 GeV/c^2 is 2.70 (1.78) times the SM prediction. Both CDF and DØ are working on further improving search techniques. With an integrated luminosity of $\sim$ 10 fb^{-1} from each experiment, there is a $\sim$ 35% chance of observing a three sigma evidence of the Higgs signal in the low mass region, if it exists there.

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