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SEARCH FOR LOW MASS HIGGS BOSON AT THE TEVATRON

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We present the current status of searches for a low mass Standard Model Higgs boson (M_H below $\lesssim$ 135 GeV/c^2) using data collected from $p\bar{p}$ collisions at the Fermilab Tevatron collider at $\sqrt{s}$ = 1.96 TeV. A summary of the latest results from the CDF and D0 collaborations is reported in this paper, focusing in particular on ongoing efforts to increase overall search sensitivity through improvements to the analysis methods.

1 Introduction

The Higgs mechanism is introduced in the Standard Model (SM) to provide mass to fundamental particles, through the spontaneous breaking of the electroweak simmetry. This mechanism implies the existence of a yet experimentally unobserved scalar particle, the Higgs boson, whose search has represented one of the major goals of the high energy physics community over the last decade. The mass of the Higgs boson is a free parameter of the theory, but the strong coupling to massive particles allows to constrain its value: a global fit, which incorporates the measurements of the top quark and W boson masses, as well as additional precision electroweak data provided by LEP, SLD and Tevatron experiments[1], indicates that a light Higgs is preferred, M_H=89^{+35}_{-26} GeV/c^2, with a 95% Confidence Level (C.L.) upper limit of 158 GeV/c^2. On the other hand, results from direct searches at LEP[2] set a 95% lower limit of 114.4 GeV/c^2.

In the last few years CDF and D0 have steadily increased the efforts in extending the potential sensitivity of their searches: the most recent combined results[3] exclude the existence of the Higgs boson with a mass between 158 and 173 GeV/c^2. This interval is expected to further extend, as well as new data will be included. However, a substantial chance to make a signal observation or set an exclusion in the entire explored mass range (100÷200 GeV/c^2) will require several improvements in the analysis methods, beyond the increase of statistics provided by the end of Tevatron operations: a projection of the probability of seeing a 2σ excess, for an integrated luminosity of 10 fb^{-1} per experiment, calculated assuming 30÷40% of sensitivity increase in the analysis techniques with respect to Summer 2010 results, is reported in figure 1.

As of this paper, the observed upper limit at the reference mass of 115 GeV/c^2 is 1.58 times the predicted SM cross section (figure 2): this value refers to the CDF and D0's combined measurements with up to 5.7 fb^{-1} of data[4]. The plan of the two collaborations is to come out with a new more stringent combined limit in the low mass region by Summer 2011, when several search channels will almost double the analyzed integrated luminosity. A summary of the latest public results in the low mass Higgs boson searches is given in this paper, focusing on the most significant improvements which are being implemented and will allow to reach the best sensitivity in the next Tevatron combination.

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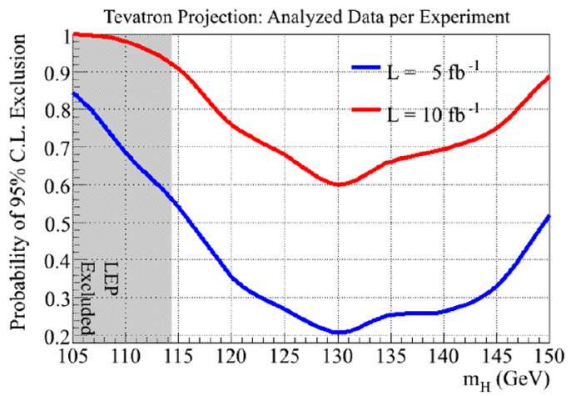

Figure 1: Tevatron probability projections of seeing a 2σ SM Higgs signal excess, for integrated luminosities of 5 fb^{-1} and 10 fb^{-1} per experiment, assuming improvements in the analysis techniques.

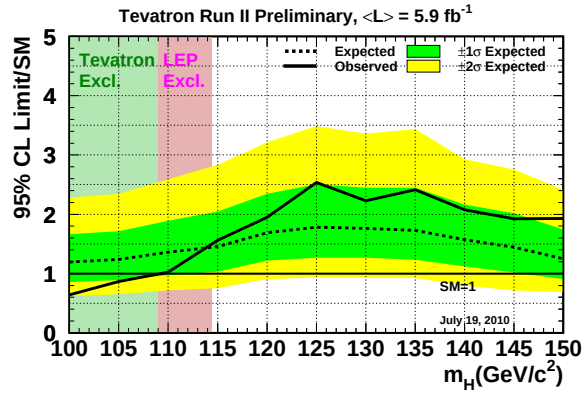

Figure 2: The observed and expected 95% C.L. upper limits on the Higgs production cross section, in units of the SM theoretical cross section, obtained by combining all CDF and D0 analyses with up to 5.7 fb^{-1} of data.

2 Experimental apparatus

A detailed description of the Tevatron collider and CDF and D0 detectors can be found elsewhere [5,6]. The accelerator provides $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with stable and well performing operating conditions: as of May 2011 about 60 pb^{-1} are produced per week, with a typical instantaneous luminosity of 3×10^{32} cm^{-2}s^{-1}; since the beginning or Run II, over 10 fb^{-1} of data have been delivered at the two collision points, and more than 8 fb^{-1} were recorded and made available for the analyses by each experiment. Tevatron collisions are scheduled to stop in September 2011 and we expect that an additional 2 fb^{-1} of data will be delivered by that date.

3 Low Mass Higgs Boson at the Tevatron

At the Tevatron center of mass energy, the dominant Higgs production mode is represented by gluon-gluon fusion, gg→H, followed by the associated production with a W or a Z boson, $q\bar{q}$ →(W/Z)H, and the vector boson fusion, $qq \rightarrow q\mathrm{H}q$. Depending on the mass, the inclusive predicted cross section in the 100÷200 GeV/c^2 interval ranges from about 2 to 0.7 pb: the achievable signal yield is therefore particularly small if compared to the main SM background processes, which are several orders of magnitude larger.

The Higgs search is particularly challenging for $\mathrm{M}_H \lesssim 135$ GeV/c^2, where the decay mode into b quarks becomes dominant (∼73% at M_H=115 GeV/c^2), making difficult the investigation of the direct production: although being the most abundant, the gg→H→ $b\bar{b}$ process is indeed experimentally prohibitive because of the overwhelming non-resonant multijet background. It is then preferred to consider the associated production, whose cross section is smaller of one order of magnitude, but where the leptonic decays of the W and Z boson provide cleaner signatures, easy to trigger on and with a great reduction of the QCD background. The most sensitive channels are represented by WH→ $l\nu b\bar{b}$, ZH→ $\nu\bar{\nu}b\bar{b}$ and ZH→ $llb\bar{b}$, where the Higgs boson is detected through the reconstruction of the jets originating from the b quark hadronization.

Many other additional channels, although less powerful, are considered since they provide a sizeable contribution to the overall sensitivity: these include the all-hadronic associated production, where the W and Z bosons are searched in their hadronic decay, and the low branching ratio (B.R.) decay into a pair of tau leptons or a pair of photons.

No single channel provides by itself the sensitivity to discover the Higgs boson. The best

strategy is to perform dedicated analyses exploiting the specific topological features of the different final states and then combine the results into one single measurement. In order to maximize the sensitivity and optimize the analysis techniques, each channel can be further split into subcategories according to the lepton types or the jet multiplicity in the event selection.

4 Analysis strategies

4.1 Acceptance optimization

One of the main challenges in the Higgs searches is represented by the need to increase as much as possible the total signal acceptance: Tevatron experiments are pursuing this target by including new triggers in the online selection, by relaxing the kinematic cuts and by implementing additional lepton categories or more sophisticated identification algorithms in the event reconstruction. The larger explored phase space requires nevertheless an accurate understanding of the selected data sample, whose composition has to be well described by the background modelings.

An example of the potential gain provided by the increased event acceptance is given by the ongoing update of CDF's ZH$\rightarrow \mu\mu b\bar{b}$ search [7]: the preliminary results, obtained by employing a novel muon identification based on a neural network (NN) algorithm, as well as an extended kinematic selection, as described in figure 3, indicate a sensitivity improvement of the order of 30÷60% beyond the luminosity scaling, in the 100÷150 GeV/c^2 mass range.

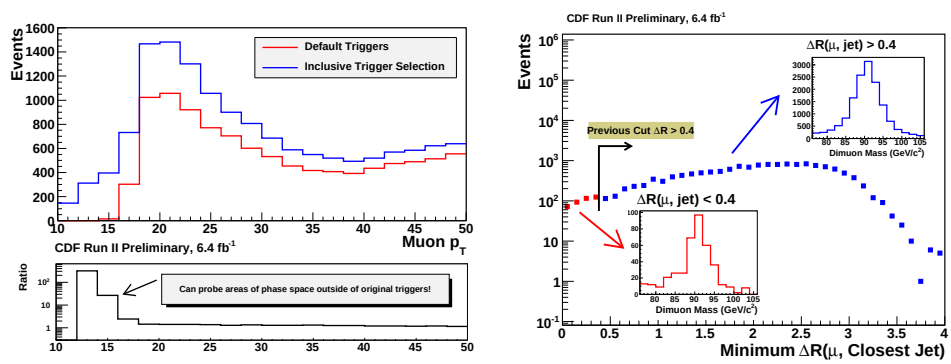

Figure 3: Acceptance increase in the CDF's ZH$\rightarrow \mu\bar{\mu}b\bar{b}$ search. Left: implementation of an inclusive trigger selection. Since no specific cuts on muon candidates are applied, a larger fraction of events is recored, compared to the standard high p_T ($\geq$18 GeV/c) muon trigger. Right: removal of the spatial separation cut ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} > 0.4$) between the muon and the closest jet.

4.2 b-quark identification

When considering final states including b quarks, one fundamental ingredient is the capability of distinguishing jets originated from b quarks from those coming from gluons, light or c quarks.

Both CDF and D0 have developed specific "b-tagging" algorithms, which exploit the relatively long lifetime of b-hadrons and the high position resolution of the silicon detectors. Different approaches are followed: CDF's SecVtx [8] is based on the reconstruction of the b-hadron secondary vertex, obtained by fitting the tracks displaced from the interaction point; CDF's JetProb [9] uses the distribution of the track impact parameters, with respect to the primary vertex, to build a probability that a jet contains a b-hadron; More sophisticated algorithms adopted by both CDF and D0 are based on NNs [10,11] and Boosted Decision Trees (BDT) [15] and combine the information provided by different taggers, with the discriminating power of additional variables, including those related to the leptonic decay of b-hadrons inside the jet.

Table 1: Observed and expected upper limits at 95% C.L. on the Higgs boson production cross section, at the reference mass of 115 GeV/c^2, for the CDF and D0 experiments as of May 2011.

Channel	CDF			D0		
	$\mathcal{L}$ [fb^{-1}]	Exp.limit [σ/σ(SM)]	Obs.limit [σ/σ(SM)]	$\mathcal{L}$ [fb^{-1}]	Exp.limit [σ/σ(SM)]	Obs.limit [σ/σ(SM)]
WH$\rightarrow l\nu b\bar{b}$ [14]	5.7	3.5	3.6	5.3	4.8	4.1
ZH$\rightarrow ll b\bar{b}$ [7]	5.7	5.5	6.0	6.2	5.7	8.0
ZH$\rightarrow \nu\nu b\bar{b}$ [15]	5.7	4.0	2.3	6.2*	4.0	3.4
VH/VBF$\rightarrow b\bar{b}$+jets [16]	4.0	17.8	9.1	-	-	-
H$\rightarrow \tau\tau$+jets [17]	6.0*	15.2	14.7	4.3*	12.8	32.8
H$\rightarrow \gamma\gamma$ [18]	4.2	20.8	24.6	8.2*	11.0	19.9

These multivariate methods benefit of the correlations among the input variables, which help in increasing the signal to background separation; in addition, they have the advantage to provide continuos outputs instead of a simple binary one. This allows to easily modify the definition of a b-tagged jet, by changing the cut on the output distributions, and then alternatively maximize the sample purity or increase the signal acceptance of the analysis selection.

Typical b-tagging efficiencies are 40÷70%, with a corresponding light flavour jet mistag rate of 0.5÷3%.

4.3 Multivariate techniques

Given the small signal to background ratio, the analyses employ multivariate techniques in order to exploit all the event information, by collecting multiple distributions into a single and more powerful discriminating variable: the preferred methods are based on NNs, BDTs and matrix elements (ME). The search sensitivity usually increases by about 20% with respect to simply using one single kinematic distribution as discriminator.

The reliability of these techniques depends on the goodness of the background modeling for the input variables, which need to be carefully verified in dedicated control samples.

5 Results

In table 1 we summarize the expected and observed 95% C.L. upper limits for the different CDF and D0 search channels. More information can be found in the references and in the web pages of the two experiments [12,13]. The items marked with an asterisk refer to the analyses which were updated since Summer 2010 and for which a more detailed description is given here.

5.1 ZH$\rightarrow \nu\nu b\bar{b}$

The signature of this search is based on two b-jets plus an unbalance of transverse energy ($\not\!\!E_T$) due to the undetected neutrinos, coming from the Z boson invisible decay. The analysis is also sensitive to the WH$\rightarrow l\nu b\bar{b}$ channel, when the charged lepton from the W escapes the detection. CDF and D0 apply similar event selections and search strategies: they both require large $\not\!\!E_T$ and 2 or 3 jets, at least one of them b-tagged. NNs (CDF) and BDTs (D0) are implemented to reduce the main background process, represented by QCD multijet production, with $\not\!\!E_T$ coming from jet energy mismeasurements. A second discriminant is then used to separate the signal from the remaining sources of background.

The D0 latest search update has significantly increased the sensitivity thanks to the acceptance gain provided by loosening the b quark identification requirements, followed by a more

clever use of the b-tagger output information. The latter has been employed as additional input variable for the final multivariate algorithm, thus improving the separation between signal and background. This new approach results in a 14% improvement in the expected limit compared to the previous version of the analysis. The final distribution for events containing two b-tagged jets, and the corresponding observed and expected upper limits on the Higgs boson production cross section, as a function of the mass, are shown in figure 4.

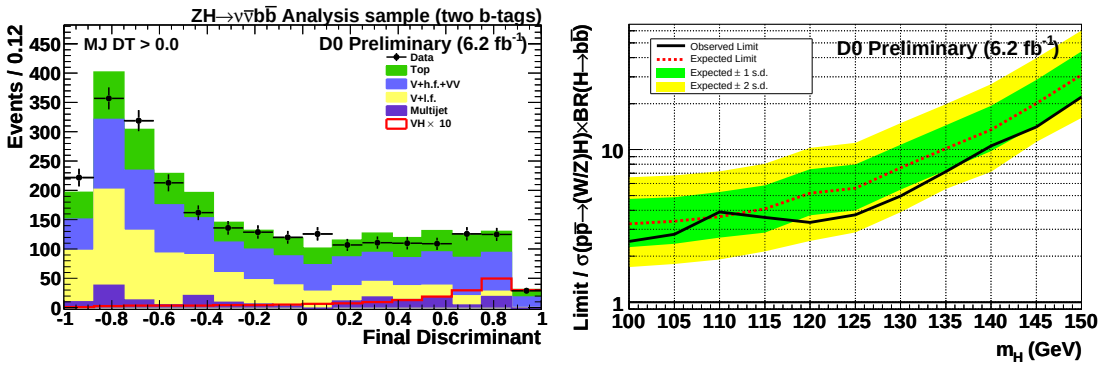

Figure 4: D0's ZH→ $\nu\bar{\nu}b\bar{b}$ search. Left: final discriminant distribution for the double b-tag channel, in the Higgs mass hypothesis of 115 GeV/c^2. Right: observed and expected upper limits on the Higgs boson production cross sections, as a function of the Higgs mass.

5.2 H→ $\tau\tau$+jets

The B.R. of H→ $\tau\tau$ is one order of magnitude smaller than H→ $b\bar{b}$, but the contribution of this search is significant, since several production modes can be simultaneously investigated. In particular, the gluon fusion becomes accessible thanks to the selection of the leptonic decay of one of the two taus, which considerably reduces the multijet background. The requirement of jets in the final state further increases the signal to background ratio and optimizes the search for the vector boson fusion process and the associated production, where the W and Z are allowed to decay hadronically. However, the significance of this channel is affected by the similarity of the H→ $\tau\tau$ signal with the irreducible Z→ $\tau\tau$ background, both characterized by a resonant tau pair in the final state. One additional challenge is represented by the hard discrimination of real hadronically decaying taus from quark/gluon jets: CDF and D0 employ identification algorithms based on BDTs and NNs, respectively.

Both the experiments have recently presented an update of their searches, where the most relevant improvements are related to the refined multivariate techniques adopted to build the final discriminant. The best separation between signal and background is achieved by following a two stage procedure: first several independent BDTs are trained to distinguish the Higgs from the principal sources of background; the different outputs are then combined into one single distribution, chosen to maximize the sensitivity of the search. Figure 5 shows the CDF final discriminant for events containing 2 or more jets in the final state.

5.3 H→ $\gamma\gamma$+X

The diphoton final state suffers from a very low B.R., but it is interesting because the photon identification efficiency and the energy resolution are much better then that of b-jets, and the narrow $M_{\gamma\gamma}$ mass peak can be exploited to reduce backgrounds. The selection is based on the requirement of two high E_T central photons. The dominant background is the direct SM diphoton production, followed by events with misidentified electrons and jets. CDF sets a limit

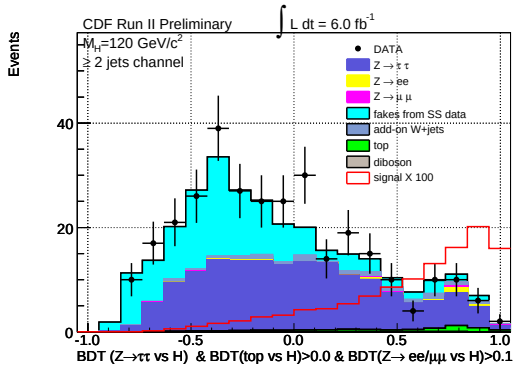

Figure 5: CDF's H→ $\tau\tau$+jets search: final discriminant distribution in the Higgs mass hypothesis of 120 GeV/c^2.

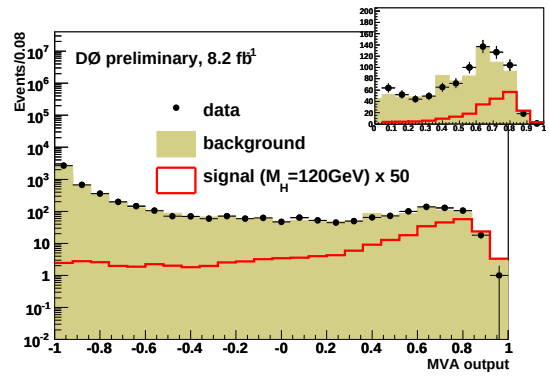

Figure 6: D0's H→ $\gamma\gamma$ search: final discriminant distribution in the Higgs mass hypothesis of 120 GeV/c^2.

by looking for a peak resonance in the $M_{\gamma\gamma}$ distribution; D0 has recently implemented a BDT which collects five kinematic variables, bringing an improvement of the sensitivity of about 20% with respect to the luminosity increase from the previous stage of the analysis.

6 Conclusions

We presented the latest results on the Tevatron searches for a low mass SM Higgs boson. The update of the CDF and D0's combination, currently in progress, will benefit from the ongoing efforts described in this paper to increase the performances beyond the luminosity scale: the projections shown in figure 1 suggest that, with the full data expected by the end of Run II, accompained by the suitable improvements in the analysis techniques, the Tevatron could reach the sensitivity to exclude the presence of the SM Higgs in the entire explored mass range below 150 GeV/c^2, with a sizeable chance to set a 3σ evidence of its existence.

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