Searches for a Low Mass Higgs Boson at the Tevatron

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Summary. — This proceeding presents an overview of recent experimental searches for the standard model Higgs boson. These searches are based on data collected by the CDF and the D0 experiments operating at the Fermilab Tevatron proton-antiproton collider with $\sqrt{s} = 1.96$ TeV. We focus on searches that are sensitive to a low mass Higgs boson production with $m_H \lesssim 140$ GeV/c^2. Using up to 4.2 fb^{-1} of data, both CDF and D0 find no evidence for Higgs boson production, and set 95% confidence level upper limits on Higgs boson production cross section times branching ratio.

PACS 13.85.Rm – Limits on production of particles.
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1. – Introduction

The Higgs boson is the last particle of the standard model (SM) of particle physics which remains to be discovered. The existence of the Higgs boson is expected to be the direct physical manifestation of the mechanism that provides mass to fundamental particles [1]. While the Higgs mechanism is successful in generating masses of particles in the SM, a direct observation of the Higgs boson would be necessary to confirm the predictions of the SM. The mass of the Higgs boson is related to the vacuum expectation value v of the neutral Higgs field by $m_H = \sqrt{2\lambda}v$. Since the Higgs self-coupling parameter, λ, is not specified by the SM, the Higgs boson mass is an unknown quantity.

Direct searches at LEP have excluded the Higgs boson with a mass below 114 GeV/c^2 at 95% confidence level (C.L.) [2]. Global fits to the precision electroweak measurements using data collected at the LEP, SLD and Tevatron allow one to indirectly constrain the Higgs boson mass to values below 163 GeV/c^2 at 95% C.L. [3]. Including the direct limit from LEP raises this upper limit to 191 GeV/c^2. These numbers indicate that the Higgs boson is expected to have a relatively low mass and could be in the reach of the Tevatron experiments. Therefore, the search for the Higgs boson is one of the most active areas of research at the Tevatron.

2. – Higgs boson production at the Tevatron

The Tevatron is a $p\bar{p}$ collider that operates at a center of mass energy of $\sqrt{s}$ = 1.96 TeV. The two general-purpose experiments, CDF and D0, each collected a data sample corresponding to an integrated luminosity of about 5 fb^{-1}. In this paper we review the results that are based on datasets of up to 4.2 fb^{-1}.

A variety of processes can lead to the production of Higgs bosons at the Tevatron, including gluon fusion (the highest production cross section), associated production with W or Z bosons and vector boson fusion. The searches for the Higgs boson are largely driven by possible decays of the Higgs boson and the ease of triggering on its decay products. Since the coupling of the Higgs boson to massive particles depends on their masses, the most frequent decays of the Higgs boson are to the heaviest particles.

If the mass of the Higgs boson is just above the LEP limit, *i.e.* $m_H > 114$ GeV/c^2, than it predominantly decays to $b\bar{b}$. The cross section of QCD production of quarks at hadron colliders is several orders of magnitude higher than $gg \to H$. Therefore, in the range of 100 GeV/c$^2 < m_H <$ 135GeV/c^2 the $gg \to H$ production mode is overwhelmed by a large, essentially irreducible background from QCD multi-jet production. In the case of associated vector boson production, the decay products of the W or Z boson provide additional handles to reduce the amount of the backgrounds, and these are the production channels that yield the most sensitive results in the low mass searches.

Various search channels are optimized for a particular final state, depending on the production mechanism and the decays of the produced particles. The results of individual analyses are combined to increase the overall sensitivity of the Tevatron searches. Both CDF and D0 collaborations search for the Higgs boson in several complementary production channels that individually are not very sensitive to the Higgs boson, but help to increase the Tevatron sensitivity in the combination.

3. – Low mass Higgs boson at the Tevatron

The first step in the Higgs boson searches is to identify, reconstruct and store events using triggering systems. Excellent trigger performance is crucial in order to maintain high efficiency for potential Higgs boson candidates while rejecting the majority of the unwanted events. The CDF and D0 experiments employ three level trigger systems that allow high efficiency in triggering on charged leptons and jets, the imbalance in energy in the plane transverse to the beam ($\not{E}_{\mathrm{T}}$) or photons. The leptonic decays of the W and Z bosons in $\ell\nu b\bar{b}$ and $\ell^+\ell^- b\bar{b}$ channels are primarily detected using the high p_T electron and muon triggers. These triggers generally detect electrons using the electromagnetic calorimeter, while muons are detected by matching tracks found in a central tracker with hits in scintillation counters and drift chambers surrounding the calorimeters. The charged lepton identification efficiency is mainly governed by the geometrical acceptance, resulting in muon coverage up to $|\eta| < 1.5$ at CDF and $|\eta| < 2.0$ at D0. The searches in channels with no charged leptons in the final state, such as $\nu\bar{\nu}b\bar{b}$, rely on triggers that require a presence of large $\not{E}_{\mathrm{T}}$ and jets. Additionally, the sample collected with the $\not{E}_{\mathrm{T}}$+jets trigger helps to recover events where the charged lepton is not identified by the dedicated triggers and leaves a signature of apparent missing transverse energy. Dedicated τ lepton triggers are used to identify the hadronic decays of taus, which search for narrow jets that are matched to a small number of charged tracks. Photons are identified by requiring isolated electromagnetic objects, without a matching track compatible with the cluster energy.

Sophisticated algorithms can be applied offline, after the events are stored, to increase the purity or increase the reconstruction efficiency of physics objects of interest. Efficient identification of jets originating from b quarks plays a crucial role in searches for a low mass Higgs boson. The key element to distinguish the Higgs boson signal from background events is the invariant mass of the $b\bar{b}$ system, which for signal has a sharp peak around the Higgs boson mass, while the backgrounds have smoother distributions. Therefore, improvements in jet energy resolution are crucial for Higgs boson searches in low mass. Since the b quark decays through a weak force, the life-time of b hadrons is long enough to move a considerable distance before decaying to lighter hadrons, typically travelling a few millimeters away from the primary vertex. Reconstruction of the decay products of the b hadron allows one to look for the trajectories of the decay products that have a large impact parameter and identify b jets ("b tagging"). Various algorithms are used by the CDF and D0 collaborations, in order to maximize the b tagging efficiency.

As a last step of the Higgs boson searches, the observed data is compared to the predictions of the signal and backgrounds models. In searches for rare processes at hadron colliders, such as Higgs boson production, the traditional method of a counting experiment does not provide sufficient sensitivity. A better sensitivity can be achieved by a fit to a kinematic distribution that distinguishes the signal process events from backgrounds. The resonance in the dijet invariant mass spectrum yields the most striking feature of the low mass Higgs boson signal events, and searches at LEP and Tevatron have been performed by scanning this spectrum. Additional kinematic and topological features of the signal process can provide further discrimination from backgrounds, increasing the sensitivity of the search. These additional features can be combined into a single discriminating variable using multivariate techniques, such as artificial neural networks (NN), boosted decision trees (BDT) or matrix element techniques (ME). Validation of the techniques is performed in dedicated control samples, as well as by performing the measurements of well known physics processes, *e.g.* the measurement of the top pair production cross section at CDF [4] or the evidence of of WW/WZ production with lepton+jets final states at D0 [5].

4. – Low mass Higgs boson searches at the Tevatron

In the following sections we review the current state of the various Higgs searches at CDF and D0.

4·1. $ZH \to \ell^+\ell^- b\bar{b}$. – This decay mode provides the cleanest experimental signature, since the SM processes rarely produce a similar final state. Additionally, it is possible to fully reconstruct both Z and Higgs bosons, allowing to further constrain the backgrounds. Traditionally the decays of a Z boson to a pair of electrons or muons are considered, since the τ identification at hadron colliders is more challenging. Due to the low branching fraction ($Br(Z \to l^+l^-) \sim 0.07$ for e, μ combined) the number of expected signal events in this channel is relatively low, with an expectation of around 1 event per fb^{-1} (if $m_H = 115$ GeV/c^2) after the analysis cuts. Therefore, the main challenges in this channel are to increase the b tagging and lepton identification efficiencies.

In order to increase the signal acceptance, the CDF and D0 experiments analyse events where both b jets are tagged with a high efficiency and low purity tag ("loose" tagging). Additionally, events where only one jet is b tagged with a lower efficiency but higher purity tag ("tight" tagging) are also analyzed to increase the overall sensitivity. The CDF and D0 experiments also use several categories of leptons which are identified with looser cuts on the information from the lepton detectors. The CDF analysis also uses forward electrons and electrons that are identified based only on calorimeter information.

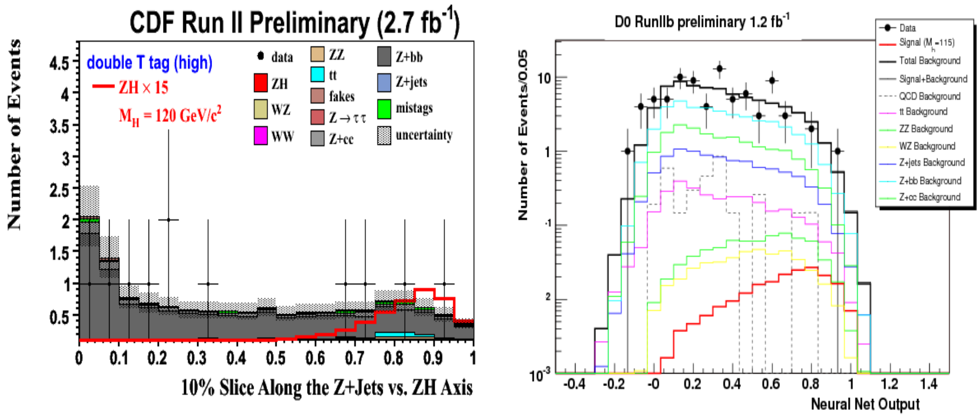


Fig. 1. – Discriminant output distributions used in $ZH \to \ell^+\ell^- b\bar{b}$ searches: (left) a slice of the 2D NN used in the CDF analysis, (right) the NN discriminant used at the D0 experiment.

The CDF analysis exploits the fact that any imbalance of calorimeter energy in the transverse plane is mainly caused by downward fluctuations in the jet energies. By assigning the event $\not{E}_T$ to the jets in the event allows to improve the jet energy measurements and improve the dijet invariant mass resolution. A dedicated neural network is developed for this analysis, which corrects the energy of the dijet system by assigning the $\not{E}_T$ to the jets according to the topology of the event.

Both CDF and D0 experiments employ multivariate techniques to further increase the reach of the Higgs boson searches in this channel. Two approaches are used at CDF: one using a two dimensional NN and another one using ME technique. The D0 experiment uses the output of the BDT discriminant to scan for the presence of the Higgs boson in the muon channel, and the output of a NN discriminant for the electron channel. Figure 1 shows the outputs of the discriminant distributions from CDF and D0.

After analyzing up to 2.7 fb^{-1} at CDF and 2.3 fb^{-1} at D0, the observed data agrees well with the background model both at CDF and D0. The 95% C.L. upper limits on the Higgs boson cross section are therefore derived. The analyses set an observed (expected) limit of 7.1 (9.9)×SM in the NN analysis at CDF and 11 (12.3)×SM in the D0 analysis, assuming $m_H = 115$ GeV/c^2 mass.

4·2. $WH \to \ell\nu b\bar{b}$. – Due to the higher production cross-section compared to Z associated production, and a higher branching fraction ($Br(W^\pm \to l^\pm\nu) \sim 0.22$ for e, μ combined), this final state provides one of the most sensitive channels for Higgs boson searches. The expected number of Higgs boson events in this channel is around 3-4 per fb^{-1} (if $m_H = 115$ GeV/c^2) after the analysis cuts. Similar to $ZH \to \ell^+\ell^- b\bar{b}$ channel, final states with electrons or muons are traditionally considered, although recently the D0 collaboration added a dedicated search for $WH \to \tau\nu b\bar{b}$.

Efficient lepton identification and b-tagging are required in this analysis, in order to enhance the sensitivity of the search. Both experiments have achieved increased signal acceptance by extending the lepton identification algorithms. The D0 analysis increases signal acceptance with muon events from any triggers, achieving close to 100%

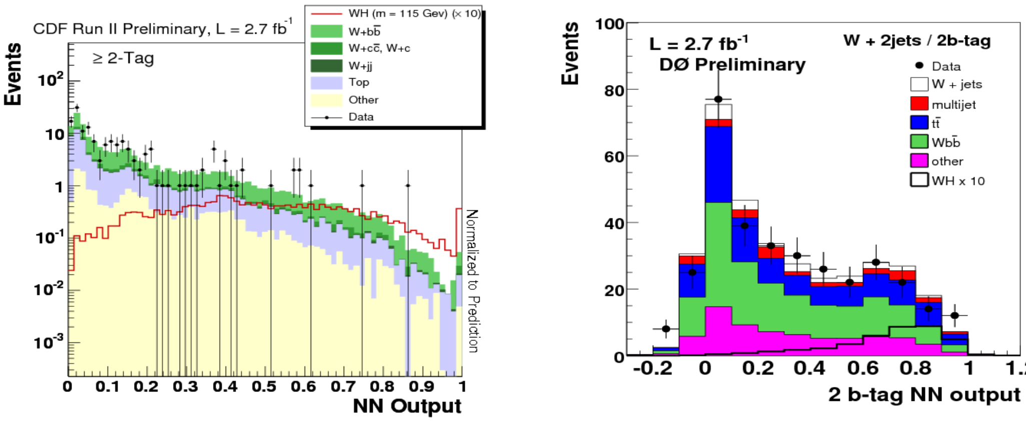


Fig. 2. – Discriminant output distributions used in $WH \to \ell\nu b\bar{b}$ searches: (left) the output of the CDF combined discriminant and (right) the output of the NN discriminant used at the D0.

efficiency of muon detection (single muons, muon+jets, topological triggers). Both CDF and D0 collaboration extend their lepton coverage by accepting events with forward going electrons. The CDF collaboration extends its lepton detector coverage using leptons collected by the $\not{E}_{\mathrm{T}}$+jets triggers, which allows to recover leptons that were not identified at the trigger level. These include muons that went through the regions of the CDF detector that are not covered by the muon detectors, but can be identified using the tracking information, or the corresponding muon detectors are not part of the trigger system.

Additional sensitivity is achieved by the CDF collaboration by incorporating neural network based jet energy corrections and by including events with only one b-tagged jet. The D0 analysis has recently added events with 3 jets in the final state, which further increase the signal acceptance. Both CDF and D0 use multivariate techniques in this channel as the final discriminant. Two approaches are used at CDF: one using a NN and another one using BDT with ME technique. The results of these two analysis are combined at the end. The D0 experiment uses the output of the NN+ME technique. Figure 2 shows the outputs of the discriminant distributions from CDF and D0.

After analyzing 2.7 fb^{-1} at CDF and D0, the observed data agrees well with the background model both at CDF and D0. The 95% C.L. upper limits on the Higgs boson cross section are therefore derived. The analyses set an observed (expected) limit of 5.6 (4.8)×SM in the CDF combined analysis and 6.7 (6.4)×SM in the D0 analysis, assuming $m_H = 115$ GeV/c^2 mass.

4·3. $VH \to \not{E}_{\mathrm{T}}+b\bar{b}$. – The main feature of this channel is the presence of a large energy imbalance in the transverse plane ($\not{E}_{\mathrm{T}}$) and the absence of identified charged leptons from the decays of the vector bosons. The $\not{E}_{\mathrm{T}}$ in the events originates either from the $Z \to \nu\nu$ decays or from $W^{\pm} \to l^{\pm}\nu$ when the charged lepton escapes detection. As a result, the effective production cross-section increases, but the lack of charged leptons weakens the constraints on the backgrounds. The expected number of Higgs boson events in this channel is around 3-4 per fb^{-1} (if $m_H = 115$ GeV/c^2) after analysis cuts.

This channel has an advantage of large number of expected Higgs boson signal events, as described above. However, due to the final event signature, it suffers from contribu-

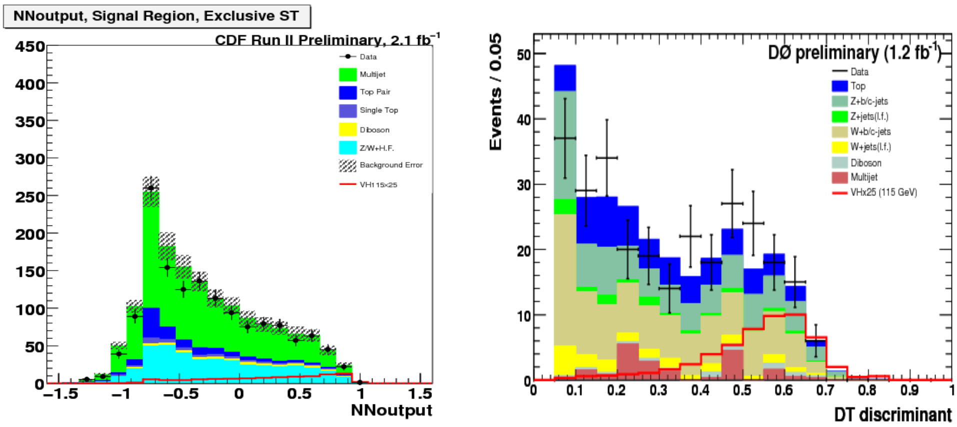


Fig. 3. – Discriminant output distributions used in $VH \to \not{E}_T + b\bar{b}$ searches: (left) the output of the CDF discriminant NN distribution and (right) the output of the BDT discriminant used at the D0.

tion from many background sources, the most prominent of which is the QCD multi-jet production with a presence of fake $\not{E}_T$ originating from mismeasurement of jet energies. Critical issues for this analysis are to achieve a high signal to background ratio and to accurately model the multi-jet production.

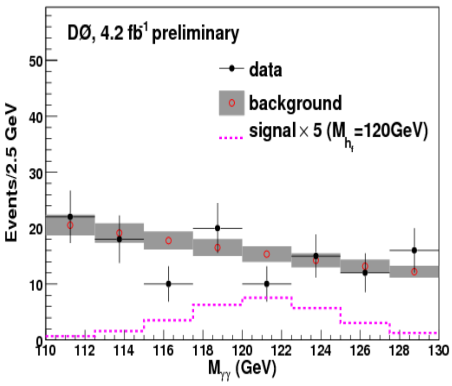
Both CDF and D0 experiments reduce the number of fake $\not{E}_T$ events by comparing the missing energy measured by the calorimeter and the tracker. A dedicated neural network was developed at CDF to drastically reduce the multijet background, by combining several calorimeter and tracker based variables. Data driven techniques are used by both experiments to estimate the contribution of the remaining multijet events. Similar to other searches, also in this channel the CDF analysis includes events where only one of the jets is b-tagged, adding around 10% to the overall sensitivity.

Additional sensitivity is achieved by the CDF collaboration by incorporating track-based jet energy corrections. CDF and D0 also include events with three jets in the final state, which allows to accept signal events where the third jet is produced either from radiation from initial or final state partons or when an e or τ from the W boson decay is reconstructed as a jet. As a final discriminant at CDF the output distribution of a NN is used, while the D0 analysis uses BDT. Figure 3 shows the outputs of the discriminant distributions from CDF and D0.

The CDF and D0 collaborations have analyzed 2.1 fb^{-1} of data, and the observed data agrees well with the background model. The analyses set an observed (expected) limit of 6.9 (5.6)$\times$SM in the CDF analysis and 7.5 (8.4)$\times$SM in the D0 analysis, assuming $m_H = 115$ GeV/c^2 mass.

4$\dot{}$4. *Higgs boson searches in complementary channels.* – Both collaborations perform searches in several channels, which by themselves are not very sensitive, but nevertheless help to increase the combined sensitivity of the Tevatron searches. Some of these channels, such as those involving $H \to \tau\tau$ or $H \to \gamma\gamma$, are also interesting due to the LHC potential.

The D0 collaboration performs a search for Higgs bosons decaying to two photons. The critical issue in this search is to reduce the background of QCD jets that are misidentified as photons. Analyzing 4.2 fb^{-1} of data and scanning the spectrum of diphoton mass for signal excess, the D0 collaboration was able to set an upper expected limit of 18.5×SM. CDF performs a search in $H \to \gamma\gamma$+2 jets channel, which has contributions from various Higgs boson production modes: WH/ZH, vector boson fusion and gluon fusion. Using NN as a final discriminant the sensitivity of 30.5×SM was obtained. A dedicated search for $WH \to \tau\nu b\bar{b}$ performed at D0 achieves a sensitivity of 42.1×SM. The all hadronic mode of the associated Higgs boson production is probed at CDF with the search in $VH \to qqb\bar{b}$ final state. The all hadronic sample provides a very high signal yield, however the background from QCD multijet background is very large. A data driven background model was developed to describe the overwhelming background from QCD multi-jets, and the analysis achieved the sensitivity of around 37×SM using ME discriminant. Higgs boson production in association with top quarks is explored by the D0 collaboration. While the cross section of this process is very small at the Tevatron, it is interesting because it may allow us to study the top Yukawa coupling. The limit obtained by the D0 collaboration by looking at the scalar sum of the transverse momenta of the 4 or 5 leading jets using 2.1 fb^{-1} of data allowed to achieve the sensitivity around 45×SM. Figure 4 shows the outputs of the discriminant distributions in $H \to \gamma\gamma$ from D0 and $VH \to qqb\bar{b}$ from CDF.



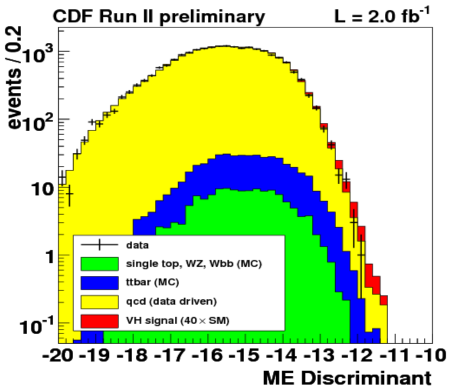
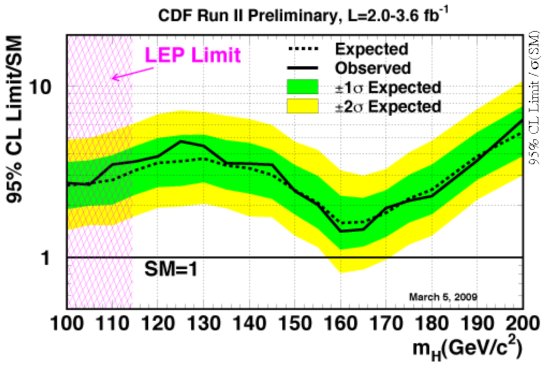


Fig. 4. – Discriminant output distributions used in complementary searches: (left) the diphoton mass in $H \to \gamma\gamma$ (D0), (right) the output of the ME discriminant in $VH \to qqb\bar{b}$ (CDF).

5. – CDF and D0 combined results

The results from various, statistically independent, analyses are combined and then the results from the CDF and D0 experiments are also combined, in order to maximize the experimental reach of the Tevatron. This allows to increase the sensitivity of searches at the Tevatron by doubling the amount of analyzed data. At the time of this meeting the most recent result of the Tevatron combination were not yet finalized. We show the results of combining the results within the CDF and D0 experiments.

Both CDF and D0 collaborations compute the upper limits including systematic uncertainties. These include the rate uncertainties (*e.g.* uncertainties on cross sections for backgrounds and signal) and uncertainties that can affect the shape of the discriminant distributions. The systematic uncertainties are included as nuisance parameters in the calculations. The CDF collaboration uses a Bayesian technique and the D0 collaboration uses a CLs technique to perform the combination. The combination of the results from CDF collaboration sets an upper limit of 3.8 (3.2 expected)×SM. The combination of D0 results sets an upper limit of 5.3 (4.6 expected)×SM. The distributions of the upper limits obtained by the CDF and D0 collaborations are shown in Figure 5. The combined Tevatron expected cross section limit for a Higgs mass of 115 GeV/c^2 should fall below three times the SM prediction.



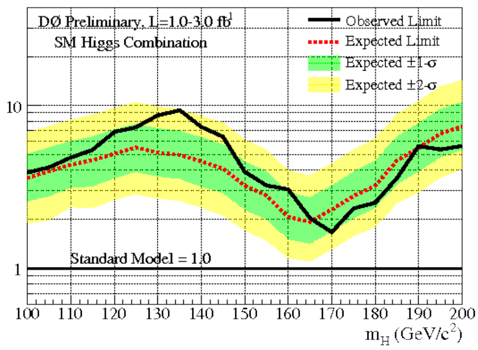


Fig. 5. – The CDF (left) and D0 (right) combined 95% C.L. upper limits as a function of the Higgs boson mass between 100 and 200 GeV/c^2 Solid black: observed limit/SM; Dashed black: median expected limit/SM. Colored bands: ±1, 2 σ distributions around median expected limit.

6. – Conclusions

The most recent results of the low mass Higgs boson searches at Tevatron were presented. While the searches in this mass regime are not yet sensitive to the SM Higgs boson production cross sections, numerous improvements in the analysis techniques were developed over the last year [6, 7], leading to the increase of the Tevatron sensitivity at rate which is much higher than that expected from the larger accumulated dataset alone. With the additional data that will be accumulated by the Tevatron experiments, and a steady rate of improvements, the prospects of the Higgs boson searches at the CDF and D0 are very promising.

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