# Searching for the Standard Model Higgs Boson at the Upgraded Tevatron

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We summarize the status of SM Higgs boson searches at the upgraded Fermilab Tevatron performed by the DØ collaborations and compare it to the expected sensitivity.

## 1 The Standard Model Higgs Boson

The Higgs boson is the only elementary scalar particle expected in the standard model (SM). Its discovery would be a major success for the SM and would provide new experimental insights into the electroweak symmetry breaking mechanism. Direct measurements at LEP have excluded a SM Higgs boson with a mass $m_H < 114.4$ GeV at 95% C.L. but constraints from precision measurements nevertheless favor a Higgs boson sufficiently light to be accessible at the Fermilab Tevatron Collider. The current preferred mass value, as deduced from a fit to electroweak measurements by the LEP, SLD, CDF, and DØ experiments [1] shown in Fig. 1a, is $126^{+73}_{-48}$ GeV. At the Tevatron, indirect searches involve precision measurements of the masses of the top quark and $W$ boson, while direct searches require high luminosity samples for discovery or exclusion in the $115 - 185$ GeV mass range, as shown in Fig. 1b. Although the expected luminosity necessary for its discovery at the Tevatron is higher than obtained thus far, the special role of the Higgs boson in the SM justifies extensive searches for a Higgs-like particle independent of expected sensitivity.

## 2 Searches for SM Higgs Production at the Upgraded Tevatron

At the Tevatron $p\overline{p}$ collider ($\sqrt{s}$=1.96 TeV), the two dominant mechanisms for Higgs production are gluon fusion, and associated production with a $W$ or $Z$ boson: $gg \rightarrow H$, $q\overline{q} \rightarrow W/Z + H$. Although the $gg$ fusion process has the largest cross section, $\sim 1$ pb at $m_H$=115 GeV, it is the most sensitive production mode only at relatively high mass Higgs boson, ($m_H \gtrsim$130 GeV) where it has a significant branching ratio in $WW^*$, as shown in Fig. 1c. At lower masses, the dominant decay $H \rightarrow b\bar{b}$ is swamped by multijet background, so at the Tevatron only the search for a Higgs produced in association with a vector boson has sufficient sensitivity. The $WH$ and $ZH$ channels, would give a clear signal with lepton(s), neutrino(s), and 2 $b$-jets: $q\overline{q} \rightarrow W/Z + H \rightarrow l\nu/ll/\nu\nu + b\bar{b}$.

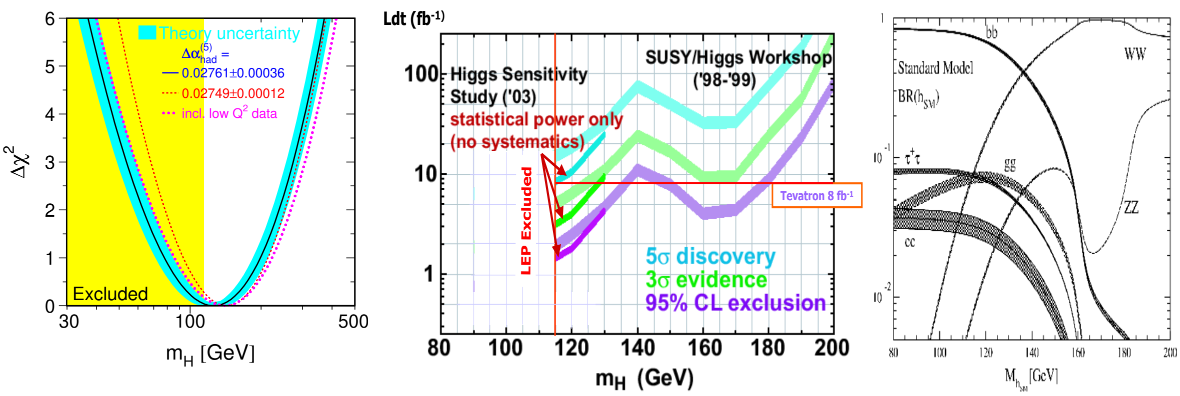


Figure 1: a) Constraints on the Higgs mass from a fit to Electroweak measurements; b) Expected sensitivity to the Higgs boson at the Tevatron; c) Branching ratios ($BR$) of the Higgs boson as a function of $m_H$, in the SM.

Two main studies have been performed to determine the sensitivity of the Tevatron experiments to SM Higgs physics. The first study, in '98-99 [2], explored the whole mass range available with some approximation of the detector response, while the second one (HSS, in '03) was restricted to the low mass region [3] and used a more realistic simulation, since the first data of Tevatron Run II had become available. The most recent study essentially confirmed the findings of the original study, and both results are summarized in Fig. 1b, after combination of all channels of both experiments. The amount of integrated luminosity needed for a Higgs discovery at $m_H = 115$ GeV is approximately 8 fb$^{-1}$. Evidence at 3 $\sigma$ might be found with $\gtrsim 3-4$fb$^{-1}$, while most of the Higgs mass region below $\sim$185 GeV could be excluded at 95% CL with $\sim$ 8 fb$^{-1}$.

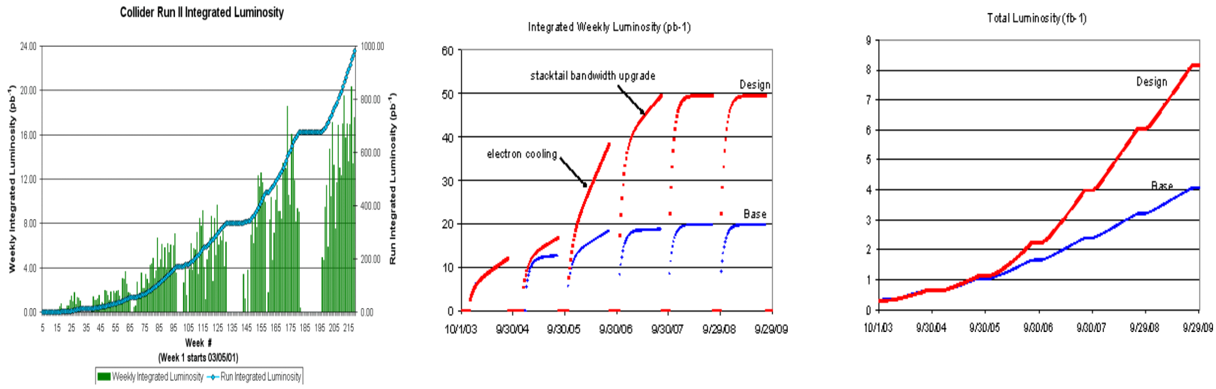


Figure 2: Current and expected performance of the Tevatron: a) integrated luminosity and weekly delivered luminosity since the beginning of Run II; b) Expected weekly delivered luminosity; c) Expected integrated luminosity.

These searches are crucially dependent on performance of the Tevatron accelerator and detectors. After a "warming-up" period, the machine is performing very well since the end of 2003, with larger than designed delivered luminosities. Currently about 1 fb$^{-1}$ has been delivered as shown in Fig. 2a, with weekly integrated luminosity exceeding 20 pb$^{-1}$. Since this figure is the terminal value assumed in the minimal (base) luminosity expectation (cf Fig. 2b), the current performance ensure that a minimal integrated luminosity of 4 fb$^{-1}$ will be achieved by the end of 2009, as shown in Fig. 2c. If the accelerator keeps following the designed luminosity evolution, an integrated luminosity of 8.2 fb$^{-1}$ will be achieved, rendering the potential for a Higgs discovery significant at the Tevatron.

### *2.1 Search for Higgs Production in Association with a $W$ boson, in the $Wb\bar{b}$ Final State*

In this section, we summarize the search by DØ on $WH$ production, which is the most sensitive channel, and compare these results to the expected sensitivity at the end of Run II. Other SM channels ($ZH \rightarrow \nu\nu b\bar{b}, H \rightarrow WW^*$) have also been analyzed, and the comparisons of their results to the corresponding expected sensitivities is similar to the one of the $WH$ channel. We will not describe them here.

CDF and DØ have studied the $Wb\bar{b}$ final state, in which $WH$ production could be observed. The published DØ analysis [4], based on 174 pb$^{-1}$ of data, and its recent preliminary update [5] based on 382 pb$^{-1}$, requires two $b$-tagged jets with $p_T > 20$ GeV and $|\eta| < 2.5$, large transverse missing energy ($\not{E}_T >$ 25 GeV) and an isolated electron with $p_T > 20$ GeV. The measured dijet mass distribution is well described by the expectation, both before (not shown) and after single $b$-tagging (shown in Fig. 3a). The number of observed events is reduced from 153 (2 jets including at least 1 $b$-tagged jet), to 13 events when requesting 2 $b$-tagged jets (Fig. 3b). The number of expected events being 10$\pm$2.4, a 95% C.L. upper cross section limit of 4.6 pb is set on $Wb\bar{b}$ production for $p_T^b > 20$ GeV and an $\eta - \varphi$ separation between $b$-jets $> 0.75$. By restricting the selection to a $\pm 25$ GeV window around the assumed Higgs masses, DØ has established 95% C.L. limits on $WH$ production of 6.9−8.6 pb for $m_H$ between 105 and 135 GeV, as shown in Fig. 3c.

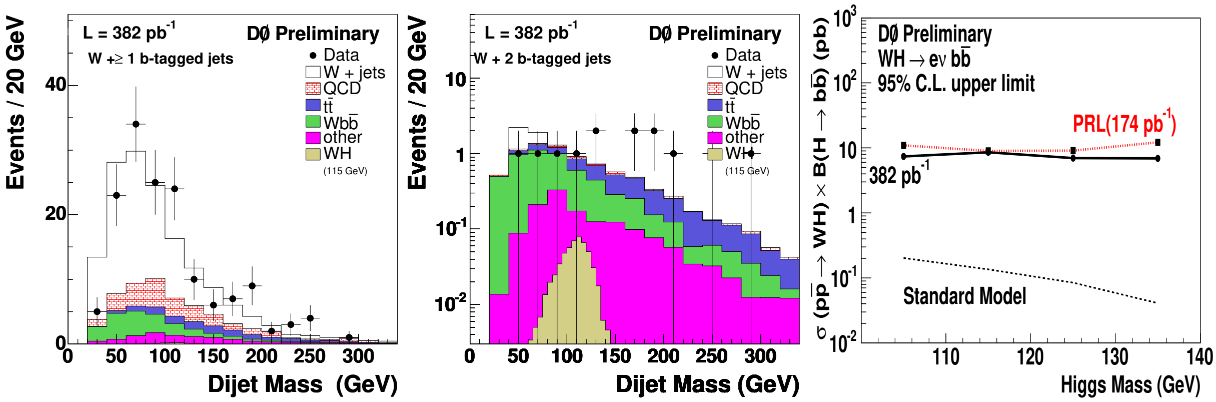


Figure 3: WH results at DØ. a) Distribution of the dijet invariant mass in the $W+$ 2 jets sample after requiring at least one $b$-tagged jet b) Same distribution, after requiring that the 2 jets are $b$-tagged. The expectation obtained from a 115 GeV Higgs is also shown. c) Limit on $WH \times BR(H \to b\bar{b})$ cross section, as a function of $m_H$.

Although the limits are still significantly above the expected SM cross section, the difference in sensitivity compared to the '03 prospective study, shown in Fig. 1b, is a factor 2.5, when taking into account the current integrated luminosity and this specific channel only, as can be seen in Table 1.

| $WH \to e\nu b\bar{b}, m_H = 115$ GeV | DØ Run II, 382 pb$^{-1}$ | HSS[3] scaled to 382 pb$^{-1}$ |
|---|---|---|
| Dijet mass window | [85,135] GeV | [100,136] GeV |
| Dijet mass resolution | $14 \pm 1$ % | 10% |
| Expected signal events (S) | $0.12 \pm 0.03$ | 0.48 |
| Background (B) | $2.37 \pm 0.59$ | 5.79 |
| Significance (S / $\sqrt{B}$) | 0.08 | 0.20 |

Table 1: Comparison of the current $WH \to e\nu b\bar{b}$ analysis, with the expectation of the prospective studies.

This factor is understood for the most part since,

- the current analysis is temporarily restricted to "central" electron ($\eta < 1.1$), while the final coverage, up to 2.5, was used in Ref.[3]. This was estimated to bring a 30% improvement in acceptance. With the first Run II data (177 pb$^{-1}$), in the $W \to e\nu$ cross-section analysis, we have measured 97756 W candidates in the central region, and 21878 W candidates in the endcap regions, with similar signal to background ratio. However only 7/8 of the endcap calorimeters were used, due to a calorimeter readout problem which has been corrected since then. The statistical improvement when including the endcap calorimeters, as derived from these measurements will thus be 26%, i.e. similar to the HSS assumption.

- A "tight" $b$-tagging algorithm is applied in the current analysis, while recent studies have already shown that a significant gain ($\sim$ 40%) can be achieved in $b$-tagging efficiency by loosening it and by using neural network techniques for combining three b-tagging algorithms developed in the collaboration, as can be seen in Fig. 4a. Furthermore, the introduction of the new layer 0 situated closer to the beam in the silicon microvertex detector during the upcoming shutdown is expected to bring further improvement in the $b$-tagging efficiency.

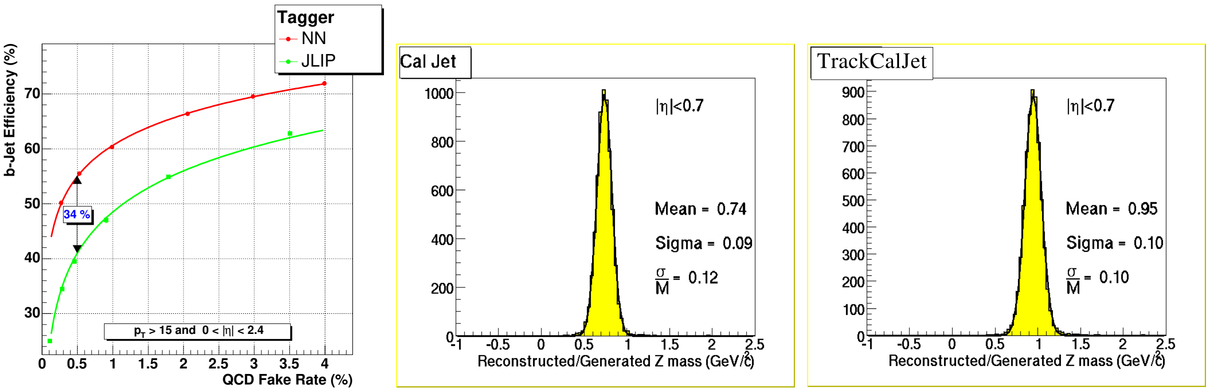


Figure 4: Studies for the WH analysis at DØ: a) Comparison of the $b$-tagging efficiency vs the mistag rate derived on DØ Run II data, between the algorithm used in the first DØ WH analyses (labelled JLIP) and the neural net $b$-tagging still under development (NN). The current observed improvement is 34% in $b$-tagging efficiency, for the mistag rate used in the published analysis; other studies have shown that the sensitivity of the analysis is improved by allowing higher mistag rates, hence higher tagging efficiencies. Simulated $Z \rightarrow qq$ mass reconstruction when using standard calorimetric reconstruction (b) and "track+calorimeter objects" reconstruction (c): the energy scale and the relative resolution are improved significantly, from 0.71 to 0.96 and from 0.12 to 0.10 respectively.

- Several other efficiencies (trigger, lepton-id) are being improved, for an estimated total gain of approximately 30% in acceptance. The trigger will benefit from the upgrade of the level 1 calorimeter trigger (fall 2005), which has the possibility to trigger on better defined objects, hence sharpening the "turn-on" curve. The improvement in electron-id is obtained by relaxing the standard electron-id requirements since the topology of the WH final state is characteristic enough to keep the fake-electron background small compared to the physics background. Removing fiducial cuts on the electron candidate (so-called $\varphi$ cracks) allow to increase the statistics by 15%, without changing significantly the S/B ratio, and this has already been done in DØ Run II new phenomena searches. Identification using an isolated $p_T$ lepton as lepton candidate is providing further improvement, but cannot yet be quantified precisely since this work is still under development.

- The dijet mass resolution used in our WH published results was based solely on calorimeter jets with a generic jet energy scale (i.e. not distinguishing between light and $b$-quark jets). This is being improved by distinguishing these two types of corrections, by implementing a better hadronic calibration at the calorimeter cell level, and by using "tracks+calorimeter objects" reconstruction techniques already developed in the collaboration. An example on simulation of improvement using track+calorimeter objects is given in Fig. 4b and c, where the $Z \rightarrow jj$ mass resolution is improved from 0.12 to 0.10. This has been verified on data using photon+jet events, although the resolution gain is for the moment lower ($\sim$ 10%). In conclusion the improvements obtained so far on simulation and on data are consistent with being able to reach a 10% mass resolution in data, as assumed in the prospective study.

- Since this was the first analysis of this type in DØ, the systematic uncertainties on the signal and on the background (e.g. simulation modelling, jet energy response, $b$-tagging efficiency/mistag) have been estimated conservatively and the total systematic uncertainty is expected to be reduced with the increased statistics below 10%, from their current 15–24% values, thus also improving the sensitivity.

In conclusion, we expect that after implementing the analysis improvements mentioned above, the sensitivity prospects will be met. The situation in the other channels is similar, and a comparable sensitivity has been observed in the corresponding channels analyzed by the

CDF collaboration. Hence, the prospects for discovering a light mass Higgs with 4–8 $pb^{-1}$ of integrated luminosity are good.

## References


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