Search for a High Mass SM Higgs Boson at the Tevatron

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Summary. — The Higgs mechanism accommodates the observed breaking of electroweak symmetry in the standard model (SM). In addition to generating masses for the electroweak W and Z bosons, as well as for fermions, the theory predicts a new scalar Higgs boson with well-determined couplings, but unknown mass. Confirmation of the existence and properties of the Higgs boson would be a key step in elucidating the origins of electroweak symmetry breaking. This paper summarizes the status of the search for a high mass ($m_H > 135$ GeV) SM Higgs boson at Fermilab's Tevatron $p\bar{p}$ accelerator. In the absence of a Higgs signal the Tevatron excludes at the 95% C.L. the production of a SM Higgs boson in the mass range of 158-175 GeV.

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1. – High Mass Searches

No single Higgs search channel has reached SM sensitivity yet. Therefore, all feasible production and decay modes need to explored and combined. Since $\frac{S}{\sqrt{B}}$ ratios are generally very low, it is impossible to perform traditional cut-based analyses. Instead, Multivariate Analysis Techniques (MVA) are required for signal extraction. This includes Matrix Element (ME) calculations, Neural Networks (NN) and Boosted Decision Trees (BDT) [1].
The main Higgs production mode at the Tevatron is through the gluon fusion process ($gg \to H$). Associated production ($q\bar{q} \to VH$) and vector boson fusion ($q\bar{q} \to q\bar{q}H$) contribute to a lesser degree:

- $\sigma(gg \to H) = 0.2 - 1$ pb
- $\sigma(q\bar{q} \to VH) = 0.01 - 0.3$ pb
- $\sigma(q\bar{q} \to q\bar{q}H) = 0.01 - 0.1$ pb

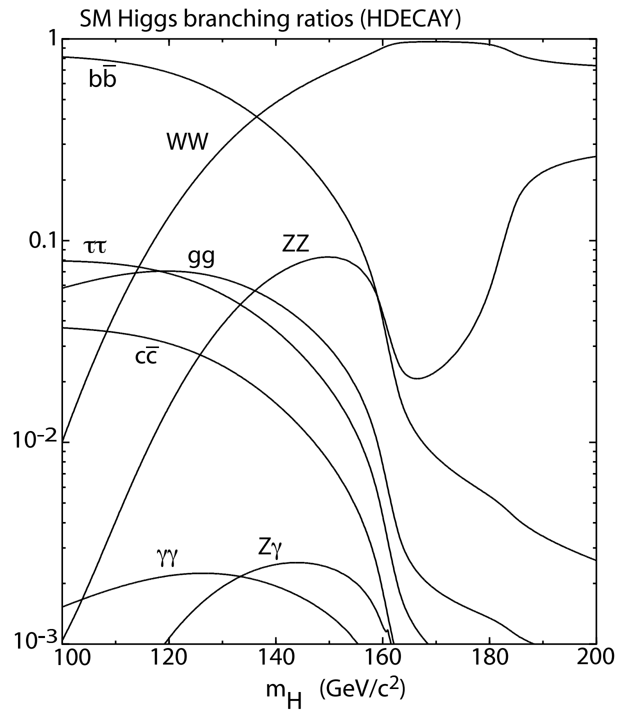

Fig. 1. – SM Higgs-boson branching fractions as a function of the Higgs mass.

Fig. 1 illustrates that for $m_H > 135$ GeV the Higgs boson predominantly decays into pairs of W vector bosons ($H \to WW$), which makes this decay mode the preferred mode for high mass SM Higgs searches at the Tevatron. The case where both W vector bosons decay leptonically presents the most sensitive final state ($H \to WW \to l\nu l\nu$). More recently, the "semi-leptonical" final state has been incorporated ($H \to WW \to l\nu qq$).
The overall strategy of the Tevatron Higgs program is to create as many analysis subchannels as allowed by statistics, in order to tune multivariate discriminants on different mixes of signal and background contributions. The following chapter gives an overview of the high mass Tevatron Higgs search program.

1˙1. $gg \to H \to WW \to l\nu l\nu$. – This channel yields a final state with two oppositely charged leptons (e, μ) and a large amount of missing transverse energy (MET) in the calorimeter. Additionally, one can take advantage of spin correlations. Due to the scalar nature of the Higgs boson, di-lepton pairs from signal tend to be more aligned, while dilepton pairs from SM backgrounds are emitted back-to-back. Background from non-resonant W pair production can be suppressed in this way (Fig. 2).
Backgrounds from Drell-Yan processes ($Z \to ll$) can be suppressed by cutting on MET (Fig. 3).

1˙1.1. CDF Searches. Based on a 5.9 fb^{-1} data set, this analysis is split into 4 subchannels:

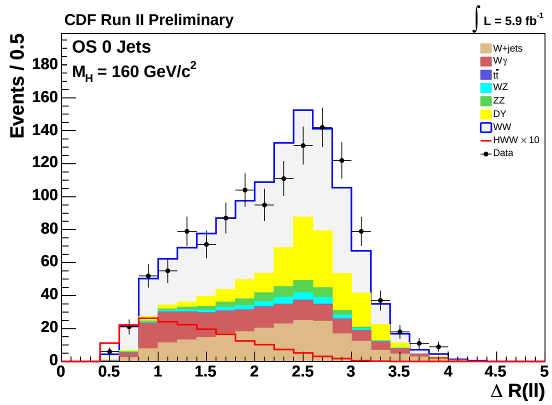

Fig. 2. – dR between the two leptons.

- By requiring no jets in the final state, the main background is due to WW pairs (Fig. 4). This sub-channel uses a likelihood ratio based on ME calculations as an additional MVA input.
- By requiring one jet in the final state, the main background is due to Drell-Yan pairs. This sub-channel gains an additional $\approx 20\%$ in signal from associated production and vector boson fusion processes.
- By requiring at least two jets in the final state, the main background is due to top pair production. This background is suppressed by requiring a tight secondary vertex b-tag.
- Additional signal acceptance is recovered by creating a separate sub-channel for events with low di-lepton invariant mass ($M_{ll} < 16$ GeV). In this case the dominant background is due to $W\gamma$ events.

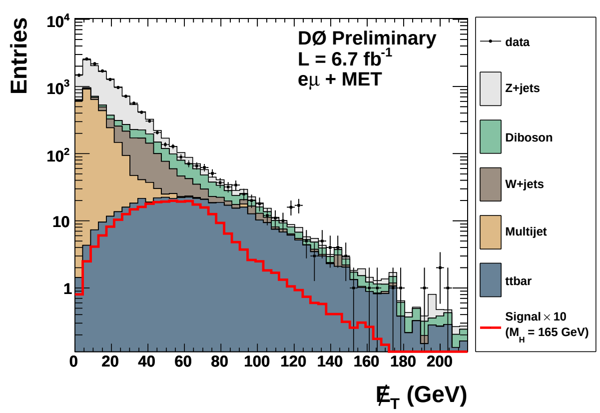

Fig. 3. – Missing transverse energy (MET).

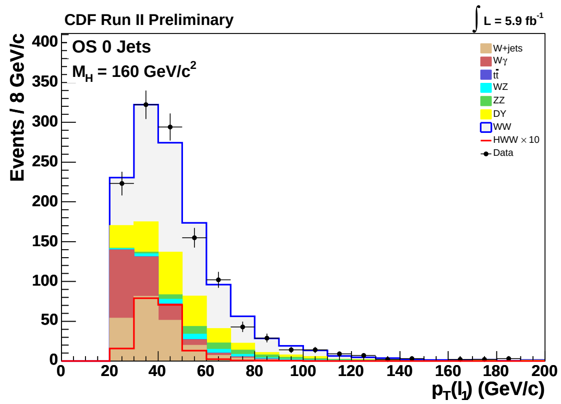

Fig. 4. – Transverse momentum of the leading lepton in the 0 jet sample.

NNs are used to extract the signal. Separate NNs are trained for each sub-channel and each Higgs mass hypothesis. Fig. 5 shows the NN distributions for the 0 jet sample.

1˙1.2. DZero Searches. Various sub-channels are created by separating lepton final states and jet multiplicities:

- Using 6.7 fb^{-1} of data the $H \to WW \to e\nu\mu\nu$ analysis is further split into sub-channels by jet multiplicity (0 jets, 1 jet, $\geq$2 jets). $Z \to \tau\tau$ backgrounds dominate in the 0 jets and 1 jet sub-channels, while $t\bar{t}$ dominates in the $\geq$2 jets case.

- Using 5.4 fb^{-1} of data the $H \to WW \to l\nu l\nu$ analysis is further split into sub-channels by lepton flavor (ee-channel and $\mu\mu$-channel). $Z \to ll$ and W+jets backgrounds dominate.

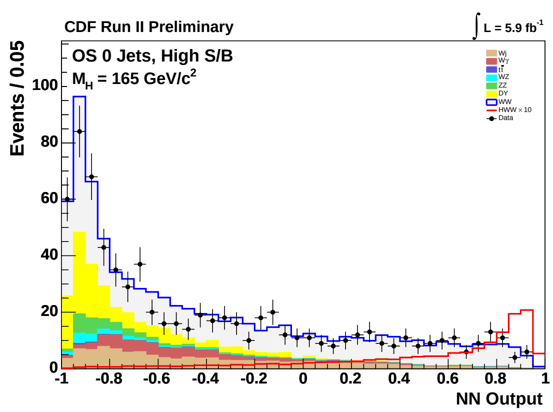

Fig. 5. – NN output for the 0 jet sample.

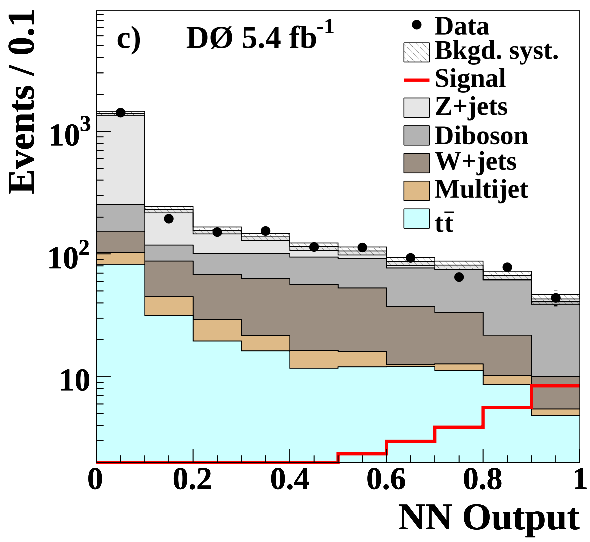

Fig. 6. – NN output for the $l\nu l\nu$ sample ($l = e, \mu$).

Depending on the final-state lepton flavor composition different instrumental and physics backgrounds as well as lepton momentum resolutions come into play. Therefore, separate MVAs are trained for the ee, $\mu\mu$ and $e\mu$ sub-channels. In case of the ee and $\mu\mu$ sub-channels NNs are used for signal extraction (Fig. 6). The $e\mu$ sub-channel uses a BDT (Fig. 7).

1˙2. *Same-Sign Lepton and Trilepton Searches.* – Events with same-sign leptons ($WH \to WWW \to l^{+(-)}l^{+(-)} + X$) and three leptons ($VH \to VWW \to lll + X$)

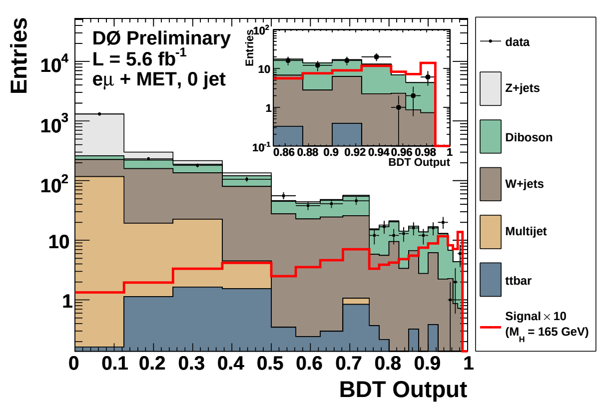

Fig. 7. – Boosted Decision Tree (BDT) output for $e\nu\mu\nu$ sub-channel.

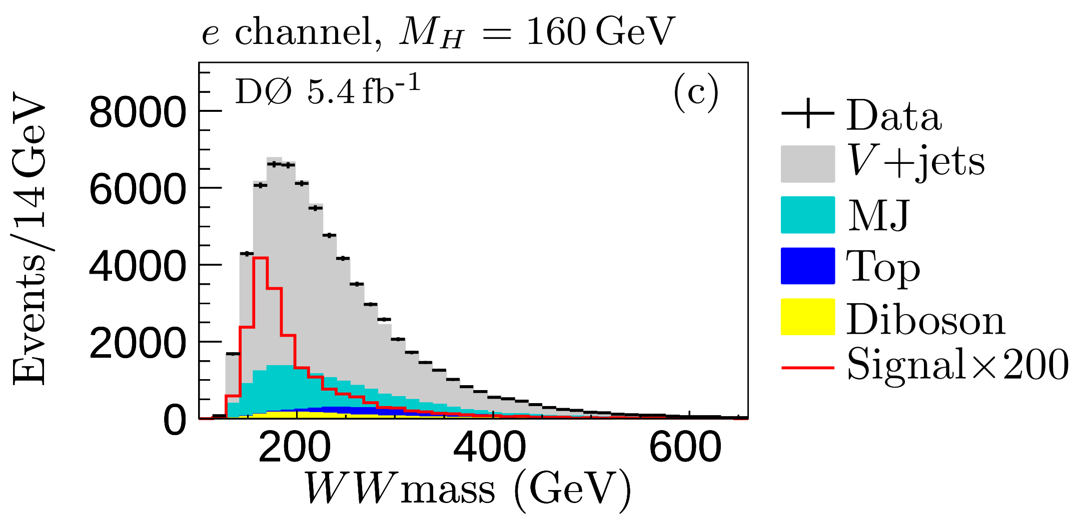

Fig. 8. – WW invariant mass.

in the final state originating from associated production processes are examined in a separate analysis effort.

1˙2.1. CDF Searches. Based on a 5.9 fb^{-1} data set both same-sign and trilepton final states are considered.
The trilepton final states are further split. A sample with same-flavor, opposite-sign dilepton pairs ("inside of Z peak") enhances sensitivity to ZH production, while a sample with same-flavor, same-sign dilepton pairs ("outside of Z peak") enhances sensitivity to WH production. NNs are used for signal extraction.

1˙2.2. DZero Searches. Based on a 5.4 fb^{-1} data set same-sign lepton final states are considered.
This analysis is further divided into sub-channels based on lepton flavors (ee, $e\mu$, $\mu\mu$). Charge flip backgrounds are dominating, requiring good lepton charge ID. A BDT is used for signal extraction.

1˙3. *Hadronic Tau Channel.* – Based on a 5.9 fb^{-1} data set hadronic taus in the final state are considered ($H \to WW \to l\nu\tau_{had}\nu$).

1˙4. *Semi-Leptonic Channel.* – Based on a 5.4 fb^{-1} data set events with semi-leptonic final states are considered ($H \to WW \to l\nu qq$) [2].
This analysis is split into two sub-channels by lepton flavor (e, μ). The large branching fraction of hadronic W decays increases $\sigma\times$BR by $\approx$6. However, large backgrounds mainly from W+jets events require a good background model. By imposing a constraint on the W mass it is possible to reconstruct the z-component of the neutrino momentum (p_z). This allows to reconstruct the Higgs mass for m_H >160 GeV (Fig. 8). A Random Forest is used for signal extraction (Fig. 9).

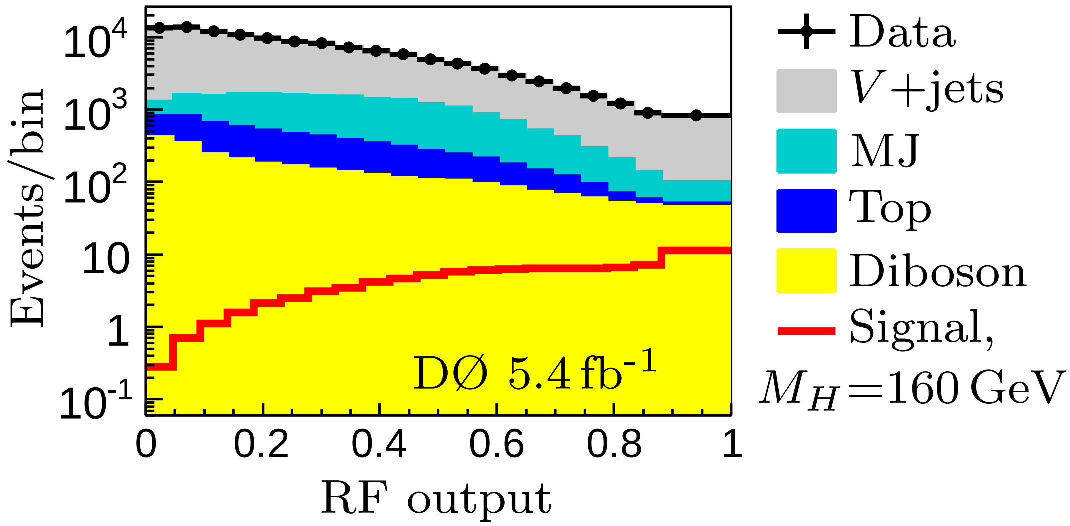

Fig. 9. – Random Forest output.

2. – Combination and Limits

No significant excess of signal-like events is observed in any of the aforementioned search channels. Therefore, MVA outputs are used to set exclusion limits at the 95% C.L [3]. Combining results from both low mass and high mass SM Higgs searches, Fig. 10 shows the combined Tevatron exclusion limits. The production of a SM Higgs boson is excluded at the 95% C.L. in the mass range of 158-175 GeV.

3. – Summary and Outlook

The Tevatron limits presented so far are based on ≈6 fb^{-1} of data. When Tevatron data taking has ended 10 fb^{-1} will be available for analysis. With this data set it will be possible to have $> 2.4\sigma$ expected sensitivity for Higgs masses of 100-200 GeV, and 3 σ expected sensitivity for $m_H = 115$ GeV.

Appendix A.

$gg \to H$ cross sections for this measurements are obtained from Ref. [4] and Ref. [5]. For more details concerning ingredients for the Tevatron Higgs search limits see Ref. [6] and Ref. [7].

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[2] DZero Collaboration, *Phys. Lett.* **106**, 171802 (2011).

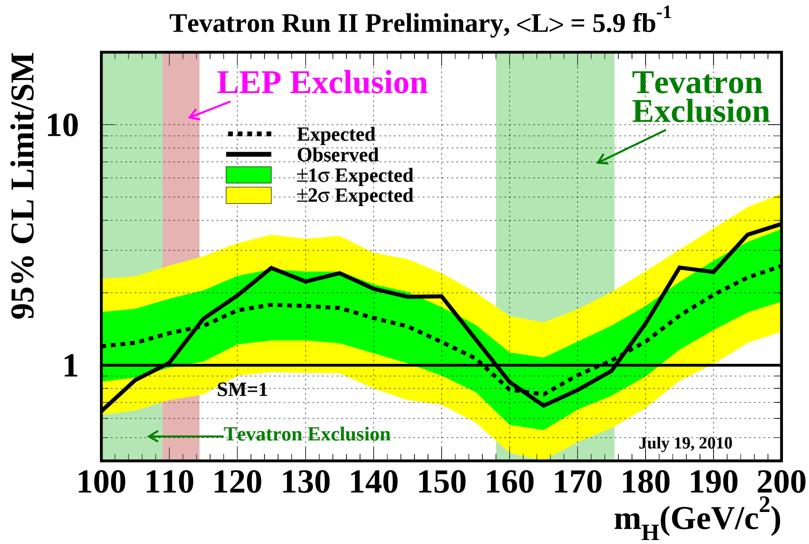

Fig. 10. – Observed and expected (median, for the background-only hypothesis) 95% C.L. upper limits on the ratios to the SM cross section, as functions of the Higgs boson mass for the combined CDF and DZero analyses. The limits are expressed as a multiple of the SM prediction for test masses (every 5 GeV/c^2) for which both experiments have performed dedicated searches in different channels. The points are joined by straight lines for better readability. The band indicate the 68% and 95% probability regions where the limits can fluctuate, in the absence of signal. The limits displayed in this figure are obtained using a Bayesian calculation.

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