Searches for Low Mass Higgs Boson at the Tevatron

Federico Sforza for the CDF and D0 Collaborations
University & INFN Pisa

Abstract. We present the result of the searches for a low mass Standard Model Higgs boson performed at the Tevatron $p\bar{p}$ collider ($\sqrt{s} = 1.96$ TeV) by the CDF and D0 experiments with an integrated luminosity of up to 8.5 fb$^{-1}$. Individual searches are discussed and classified according to their sensitivity. Primary channels rely on the associate production with a vector boson ($WH$ or $ZH$) and the $H \rightarrow b\bar{b}$ decay channel (favored for $M_H \leq 135$ GeV/$c^2$). Event selection is based on the leptonic decay of the vector boson and the identification of $b$--hadron enriched jets. Each individual channel is sensitive, for $M_H = 115$ GeV/$c^2$, to less than 5 times the SM expected cross section and the most sensitive channels can exclude a production cross section of $2.3 \times \sigma_H^S M$. Secondary channels rely on a variety of final states. Although they are from 2 to 5 times less sensitive than any primary channel, they contribute to the Tevatron combination and, in some cases, they pose strong constrains on exotic Higgs boson models.

1 Introduction

The spontaneous symmetry breaking mechanism [1] offers a possible explanation for $W$ and $Z$ boson mass within the Standard Model [2] of particle physics. A new scalar particle, the Higgs boson, is predicted but direct experimental confirmation is missing.

In this paper we summarize the direct searches performed at the Tevatron $p\bar{p}$ collider ($\sqrt{s} = 1.96$ TeV) by the CDF and D0 experiments with the summer 2011 dataset, corresponding to an integrated luminosity of up to 8.5 fb$^{-1}$. Analyses are optimized for the low range of allowed Higgs boson masses: $100 \leq M_H \leq 135$ GeV/$c^2$. This range is favored by indirect constraints coming from the measurement of other SM parameters [3].

2 Low Mass Higgs Analyses

The hadron collider environment is experimentally complex because of the overwhelming background of multi-jet events hiding rare processes such as Higgs boson production. We need a distinct event signature to increase the signal over background ratio and thus the sensitivity. The individual analyses can be classified in two classes on the basis of the final states and the expected sensitivity:

Primary Channels: they identify the most sensitive analyses and they all share common characteristics. The Higgs boson is produced in association with a $W$ or a $Z$ bosons (see Figure 1 for predicted cross sections) and the leptonic decay of the vector boson is used for the online and offline event selection. The Higgs candidates are selected in the $bb$ final state, as Figure 2 shows, this is the favored final state (for $M_H \leq 135$ GeV/$c^2$) because of the Yukawa coupling of the SM Higgs boson to the fermions [1]. More details about the analysis techniques are given (Section 3.1) because of the relevant impact of these analyses.

Secondary Channels: the Higgs is produced via gluon fusion or $t\bar{t}$ associate production (see Figure 2). Each analysis is optimized for a different final state appearing in Figure 2: $\gamma\gamma$, $\tau\tau$, high $b$--jets multiplicity. Each secondary channel analysis is from 2 to 5 times less sensitive than any primary channel but their contribution is not negligible when considered all together. Furthermore, many non SM Higgs boson scenarios predict a production rate which increase in these final states.

3 Primary Search Channels

All primary channels analyses look for the $H \rightarrow b\bar{b}$ decay when produced in association with a $W$ or $Z$ boson that undergo a leptonic decay. They are classified by the following signatures:

$$Z \rightarrow \ell \ell + b\bar{b}, \quad WH \rightarrow \ell \ell + b\bar{b}, \quad W/ZH \rightarrow \ell \ell + b\bar{b} \quad (1)$$

---

*e-mail: federico.sforza@pi.infn.it*
Machine learning algorithms are powerful re-
the use of multivariate techniques: Neural Networks (NN),
of the final discriminant. In the CDF and D0 analyses, each
ffl
The analysis process of the primary channels can be di-
fff
tron experiments can probe sub-picobarn cross sections in

3.1 Analysis Techniques

The analysis process of the primary channels can be di-
vided into four stages: online selection, offline lepton se-
lection, application of b-tagging algorithm and evaluation
of the final discriminant. In the CDF and D0 analyses, each
of these stages have been highly optimized, often thanks to
the use of multivariate techniques: Neural Networks (NN),
Boosted Decision Trees (BDT) or Support Vector Machines
(SVM) [14]. Machine learning algorithms are powerful re-
gression or classification tools as they can exploit the non-
linear correlations between several input variables. The re-
liability of their results is ensured by checking the input
and output distribution between the training samples and
the data in various control regions.

The first stage of the analysis process is the online se-
lection. Collision events are collected and recorded via ded-
pic- ted trigger paths that meet specific physics goals (e.g.
high-P_{T} lepton identification). Combining multiple paths
maximizes the acceptance, however the trigger efficiency
must be parametrized properly on Monte Carlo events.
Es-
pecially in multiple-objects trigger paths (e.g. E_{T} plus jets)
the efficiency function may depend on many variables. At
CDF, for the first time [48] we used a NN to model the
probability distribution of events selected by a large set of
triggers.

The next stage is the offline event selection. We gained
acceptance with the introduction of more lepton categories
(track only reconstruction, likelihood and NN identifica-
tion, etc.) and relaxing the cuts on jets and E_{T} selection [89].
This increased the multi-jet background but multivariate

Background composition is another common feature of
the three primary channels both in CDF and D0 analyses,
we can divide it in three categories: the larger is the W/Z
production in association with light and heavy flavor jets,
after selection this irreducible background can be from 10^{3}
to 10^{4} larger than the expected signal. The second back-
ground is due to multi-jet events faking the E_{T} and the
lepton identification. The contribution of real physics pro-
cesses and detector effects makes this background partic-
ularly difficult to model so the contamination should be
reduced as much as possible at selection level. The last cat-
egory is composed by smaller electroweak processes like
top-quark or diboson production.

Because of the small Higgs production cross section,
the final challenge is the maximization of the acceptance
while keeping the backgrounds under control. Single-top
observation [10,11] and diboson evidence in the heavy fla-
vor final states [12,13] already demonstrate that the Teva-
tron experiments can probe sub-picobarn cross sections in
these channels.

3.2 \( H \rightarrow bb \) Sensitivity

The final expected and observed sensitivity of the individ-
ual primary search channels for different \( M_{H} \) are summa-
rized in Table [1] for CDF and Table [2] for D0. The most
sensitive analysis can exclude at 95% C.L. the presence of
a Higgs boson of \( M_{H} = 115 \text{ GeV}/c^{2} \) produced with a cross
section of 2.3 times the one predicted by the SM.

Individually none of these analyses reaches the SM
sensitivity for any analyzed \( M_{H} \), however each experiment

Venus and the final challenge is the maximization of the acceptance
while keeping the backgrounds under control. Single-top
observation [10,11] and diboson evidence in the heavy fla-
vor final states [12,13] already demonstrate that the Teva-
tron experiments can probe sub-picobarn cross sections in
these channels.

3.1 Analysis Techniques

The analysis process of the primary channels can be di-
vided into four stages: online selection, offline lepton se-
lection, application of b-tagging algorithm and evaluation
of the final discriminant. In the CDF and D0 analyses, each
of these stages have been highly optimized, often thanks to
the use of multivariate techniques: Neural Networks (NN),
Boosted Decision Trees (BDT) or Support Vector Machines
(SVM) [14]. Machine learning algorithms are powerful re-
gression or classification tools as they can exploit the non-
linear correlations between several input variables. The re-
liability of their results is ensured by checking the input
and output distribution between the training samples and
the data in various control regions.

The first stage of the analysis process is the online se-
lection. Collision events are collected and recorded via ded-
pic- ted trigger paths that meet specific physics goals (e.g.
high-P_{T} lepton identification). Combining multiple paths
maximizes the acceptance, however the trigger efficiency
must be parametrized properly on Monte Carlo events.
Es-
pecially in multiple-objects trigger paths (e.g. E_{T} plus jets)
the efficiency function may depend on many variables. At
CDF, for the first time [48] we used a NN to model the
probability distribution of events selected by a large set of
triggers.

The next stage is the offline event selection. We gained
acceptance with the introduction of more lepton categories
(track only reconstruction, likelihood and NN identifica-
tion, etc.) and relaxing the cuts on jets and E_{T} selection [89].
This increased the multi-jet background but multivariate

Background composition is another common feature of
the three primary channels both in CDF and D0 analyses,
we can divide it in three categories: the larger is the W/Z
production in association with light and heavy flavor jets,
after selection this irreducible background can be from 10^{3}
to 10^{4} larger than the expected signal. The second back-
ground is due to multi-jet events faking the E_{T} and the
lepton identification. The contribution of real physics pro-
cesses and detector effects makes this background partic-
ularly difficult to model so the contamination should be
reduced as much as possible at selection level. The last cat-
egory is composed by smaller electroweak processes like
top-quark or diboson production.

Because of the small Higgs production cross section,
the final challenge is the maximization of the acceptance
while keeping the backgrounds under control. Single-top
observation [10,11] and diboson evidence in the heavy fla-
vor final states [12,13] already demonstrate that the Teva-
tron experiments can probe sub-picobarn cross sections in
these channels.

3.2 \( H \rightarrow bb \) Sensitivity

The final expected and observed sensitivity of the individ-
ual primary search channels for different \( M_{H} \) are summa-
rized in Table [1] for CDF and Table [2] for D0. The most
sensitive analysis can exclude at 95% C.L. the presence of
a Higgs boson of \( M_{H} = 115 \text{ GeV}/c^{2} \) produced with a cross
section of 2.3 times the one predicted by the SM.

Individually none of these analyses reaches the SM
sensitivity for any analyzed \( M_{H} \), however each experiment
can combine the three channels to obtain powerful constraints on the $H \rightarrow b\bar{b}$ production and decay. The combination of different channels, across the same experiment, provides also an advantage in the evaluation of the correlated systematic uncertainties. For example effects like Jet Energy Scale (JES) uncertainty or $b$-tag efficiency measurement on $MC$ are shared across all the channels and we fit for their best value [18], in this way a higher statistical sample poses a stronger constraint on these systematics than each channel by itself. Figure 4 shows that the CDF sample poses a stronger constraint on these systematics like $\text{Jet Energy Scale (JES)}$ uncertainty or $b$-tag efficiency measurement. For example $\gamma\gamma$ provides also an advantage in the evaluation of the correlation of di $b$.

| $M_H$ (GeV/c²) | 100 | 105 | 110 | 115 | 120 | 125 | 130 |
|----------------|-----|-----|-----|-----|-----|-----|-----|
| $ZH \rightarrow \ell \ell + b\bar{b}$ |
| Exp.           | 1.8 | 2.0 | 2.2 | 2.6 | 3.1 | 3.7 | 4.8 |
| Obs.           | 1.1 | 2.1 | 2.8 | 2.7 | 3.4 | 4.4 | 6.1 |
| $WH \rightarrow \ell \ell + b\bar{b}$ |
| Exp.           | 2.3 | 2.4 | 2.6 | 2.9 | 3.4 | 4.0 | 4.9 |
| Obs.           | 1.8 | 2.1 | 2.4 | 2.3 | 3.3 | 5.4 | 5.0 |

Table 2. Observed and expected 95% C.L. measured by the D0 experiment using a luminosity up to 8.5 fb⁻¹ for different SM Higgs boson masses in the primary search channels ($\ell\ell + b\bar{b}, \ell\ell + b\bar{b}, \ell\ell + b\bar{b}$).

| $M_H$ (GeV/c²) | 100 | 105 | 110 | 115 | 120 | 125 | 130 |
|----------------|-----|-----|-----|-----|-----|-----|-----|
| $ZH \rightarrow \ell \ell + b\bar{b}$ |
| Exp.           | 3.4 | 3.7 | 4.2 | 4.8 | 5.3 | 6.5 | 8.4 |
| Obs.           | 2.5 | 2.6 | 3.1 | 4.9 | 6.4 | 8.9 | 9.9 |
| $WH \rightarrow \ell \ell + b\bar{b}$ |
| Exp.           | 2.4 | 2.6 | 3.0 | 3.5 | 4.3 | 5.4 | 7.0 |
| Obs.           | 2.6 | 2.9 | 4.1 | 4.6 | 5.8 | 6.8 | 8.2 |
| $VH \rightarrow \ell\ell + b\bar{b}$ |
| Exp.           | 2.8 | 2.9 | 3.1 | 4.0 | 4.5 | 5.4 | 6.9 |
| Obs.           | 2.6 | 2.4 | 2.4 | 3.2 | 3.9 | 5.0 | 7.5 |

4 Secondary Search Channels

The primary channels described in the previous sections play a major role in the Higgs boson searches performed by the CDF and D0 collaborations, however there are a variety of final states worth investigating. The most significant are the $H \rightarrow \gamma\gamma$ [21,22], and $H \rightarrow \tau\tau$ [18,24] decay channels and the $t\bar{t}H \rightarrow t\bar{t}b\bar{b}b$ associate production [25]. For example, even though the diphoton final state has a tiny branching fraction, it can still contribute significantly to the low mass Higgs boson searches due to better mass resolution and detector acceptance relative to b-quark final states; for $M_H = 115$ GeV/c², expected sensitivity of $11 \times \sigma^{SM}_H$ are reached by D0 and $13 \times \sigma^{SM}_H$ by CDF. Similar contribution comes from the $H \rightarrow \tau\tau$ channel (expected sensitivity is $12.8 \times \sigma^{SM}_H$ for D0 and $12.6 \times \sigma^{SM}_H$ for CDF for $M_H = 115$ GeV/c²) because the branching ratio of the SM Higgs boson to a $\tau$ pair is the second highest (7.6% at $M_H = 115$ GeV/c²); the accurate knowledge of the $Z \rightarrow \tau\tau$ process also helps the analysis of this channel. In general each of the secondary channels reach a sensitivity on the order of $12 \times \sigma^{SM}_H$ and the composition of all of them contributes to the final search at the level of an additional primary channel [27,28].

Another reason to pursue these secondary channels is that non-SM theories may predict enhanced yield. For example the $H \rightarrow \gamma\gamma$ analyses can be reinterpreted in the light of a fermiophobic Higgs boson theory where the couplings to the fermions are depressed [26]. Figure 5 shows the exclusion limits posed by the D0 collaboration for this particular model.
5 Results and Future Prospects

The CDF and D0 experiments performed a variety of searches for a low mass Higgs boson. The favored SM decay channel ($H \rightarrow bb$) is analyzed in the associated production modes, $WH$ and $ZH$, where the leptonic decay of the vector boson allows an efficient online selection and offline reconstruction of the candidates. The expected sensitivity, for the best channel and $M_H = 115$ GeV/$c^2$, reaches $2.6 \times \sigma^{SM}_H$. The $H \rightarrow bb$ channels have been combined within each experiment to exclude at 95% C.L. Higgs boson production for $M_H < 105$ GeV/$c^2$

Also the results of a variety of less favorite search channels is analyzed: $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$, $ttH$ associate production. They reach approx $\sigma^{SM}_H$ sensitivity (for $M_H = 115$ GeV/$c^2$). Furthermore they can strongly constrain exotic models, for example the fermiophobic Higgs model has been excluded (at 95% C.L.) up to $M_H < 109$ GeV/$c^2$ [21,22].

Figure 6 shows a plausible scenario of the analysis improvements that can be finalized by the CDF collaboration (similar results are expected from D0) for the Winter 2012 conferences when the full dataset of 10 fb$^{-1}$ will be analyzed.

Acknowledgments

We would like to thank the organizers of the 2011 Hadron Collider Physics Symposium for a wonderful conference with excellent presentations and the CDF and D0 collaborations for the results presented at this conference.

References

1. P.W. Higgs, Phys. Lett. 12 132 (1964); idem, Phys. Rev. Lett. 13 508 (1964); idem, Phys. Rev. 145 1156 (1966); F. Englert and R. Brout, Phys. Rev. Lett. 13 321 (1964); G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, Phys. Rev. Lett. 13 585 (1964).
2. S. L. Glashow, Nucl. Phys. 22, 579 (1961); S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, Elementary Particle Theory, ed. N. Svartholm (Almqvist and Wiksells, Stockholm), 367 (1968).
3. M. Baak et al., [arXiv:1107.0975v1\[hep-ph]].
4. The CDF Collaboration, CDF Notes 10593 and 10572.
5. The D0 Collaboration, D0 Note 6166-CONF.
6. The CDF Collaboration, CDF Note 10596.
7. The D0 Collaboration, D0 Note 6220-CONF.
8. The CDF Collaboration, CDF Note 10583.
9. The D0 Collaboration, D0 Note 6219-CONF.
10. T. Aalton et al. [CDF Collaboration], Phys. Rev. Lett. 103, 092002 (2009).
11. V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 103, 092001 (2009).
12. The CDF Collaboration, CDF Notes 10598.
13. J. F. Grivaz, “Searches for diboson production with heavy-flavor jets in the final state at the Tevatron”, this proceeding.
14. C. M. Bishop., “Pattern Recognition and Machine Learning”, Springer (2006). ISBN 0-38-731073-8.
15. Acosta, D.E. et al. [CDF Collaboration], Phys. Rev. D 71 052003, (2005).
16. Abulencia, A. et al. [CDF Collaboration], Phys. Rev. D 74 072006 (2006).
17. Abazov V.M et al., Nucl. Instrum. Meth. A 620, 400 (2010).
18. The CDF Collaboration, CDF Note 10609.
19. LEP Electroweak Working Group, http://lepewwg.web.cern.ch/LEPEWWG/ 20. W.M. Yao, “Standard Model Higgs Boson Combination at the Tevatron”, this proceeding.
21. T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 108, 011801 (2012). arXiv: 1109.4427[hep-ex].
22. The D0 Collaboration, D0 Note 6177-CONF.
23. T. Aaltonen et al., [The CDF Collaboration],arXiv: 1203.4880.
24. The D0 Collaboration, arXiv:1106.4555v1 [hep-ex].
25. The CDF Collaboration, CDF Note 10574.
26. A. Barroso, L. Brucher, and R. Santos, Phys. Rev. D 60, 035005 (1999); J. Gunion, R. Vega, and J. Wudka, Phys. Rev. D 42, 1673 (1990); A. G. Akeroyd, Phys. Lett. B 368, 89-95 (1996). [hep-ph/9511347].
27. The CDF Collaboration, CDF Note 10609.
28. Conference Note D0 Note 6229-CONF.