Higgs Results from the Tevatron Run II

B. Tuchming *)

CEA Saclay, Dapnia/Spp, 91191 Gif-Sur-Yvette, France

Received 20 October 2004;
final version 31 December 2004

The data taken at the Tevatron experiments have been analyzed to search for Higgs bosons. For the Standard Model Higgs searches, no excess is observed, the data are in good agreement with the expectations, so that limits are set on the production rates. For various theoretical models beyond the Standard Model, there is no excess either, which allows to derive constraints in their respective parameter spaces.

PACS: 62.20
Key words: Higgs Boson, Tevatron

1 Introduction

The Run II of the 1.96 TeV $p\bar{p}$ collider Tevatron started in spring 2001. One of the main physics goal of the Tevatron experiments, CDF and DØ, is the search for Standard Model (SM) and exotic Higgs bosons.

As of summer 2004, both experiments have about 400 pb^{-1} of data available for physics analyses, which is almost four times more than what was collected during Run I (1992-1996). This is a small fraction of what is expected to be recorded by the end of Run II, in 2009: between 4 and 8 fb^{-1} [1].

This proceedings presents the first analyses of the Tevatron data. They are based on a smaller amount of integrated luminosity, less than 200 pb^{-1}. The main goal consists actually in understanding the detector performances and testing and improving the reconstruction algorithms. Jet energy scale, jet energy resolution, b-tagging, missing transverse energy ($\not{E}_T$) reconstruction are steadily improving and not yet optimal. These first data are also used to tune the simulation and check the understanding of the physics backgrounds such as W+jets production, Z+jets production or $b\bar{b}$+jets production. In the following, all exclusion limits are at 95% confidence level.

2 Standard Model Higgs

In the SM, the production cross-sections and the branching fractions as a function of the Higgs mass are well known. Over the relevant mass range, the dominant process is the gluon fusion, $gg \to H$, but one can distinguish two regimes:

- $m_h < 130$ GeV/c^2. The Higgs decays mainly into a pair of b-quarks. Because of the overwhelming QCD background, the relevant process is not $gg \to H \to$

---

*) for the CDF and DØ Collaborations.

$b\bar{b}$, but the associated productions with gauge bosons, either W or Z, decaying leptonically. The main final states are therefore: $e\nu b\bar{b}$, $\mu\nu b\bar{b}$, $eeb\bar{b}$, $\mu\mu b\bar{b}$ and $\nu\nu b\bar{b}$.

- $m_h > 130$ GeV/c^2. The Higgs, produced by gluon fusion, is kinematically allowed to decay into a pair of W bosons. The leptonic channels, $e\nu e\nu$, $\mu\nu\mu\nu$ and $e\nu\mu\nu$, are the main Higgs signatures in this case.

2.1 Measurement of the ratio $(Z+b)/(Z\text{+jets})$

The $Z+b$ production is the dominant background for the ZH search. Moreover, it is a benchmark process for the non-SM associated production of Higgs with b-quarks (see section 3.1). DØ has performed a measurement of the ratio between the production rates of $Z+b$ and Z+jets, in 152 pb^{-1} and 185 pb^{-1} of data for the ee and $\mu\mu$ channel, respectively. By measuring the ratio, many systematics cancel out.

The selection demands two isolated high p_T leptons, $p_T > 15$ and 20 GeV/c for ee and $\mu\mu$ channels, respectively, the di-leptons mass close to 91.2 GeV/c^2, and at least one jet tagged as a b-jet. The background, estimated from the Z-peak side bands, is made of QCD events, where jets are faking leptons, and light quark mistag in Z+jets events. The relative content of $Z+b$ and $Z+c$ events is assessed from the NLO calculations [2]. For jets with $E_T > 20$ GeV and $|\eta| < 2.5$, the results is in good agreement with the NLO expectations [2]:

$$\frac{\sigma(Z+b)}{\sigma(Z+j)} = 0.024 \pm 0.005(\text{stat}) \pm^{0.005}_{0.004}(\text{syst}).$$

2.2 The $Wb\bar{b}$ channel

The $Wb\bar{b}$ signature consists of one high p_T, isolated lepton, a large $\not{E}_T$, and the presence of two b-tagged jet. The transverse mass of the (lepton, $\not{E}_T$) system has also to be compatible with the expected W transverse mass spectrum. The background is made of W+jets events, QCD events with a fake isolated lepton, and top pair production.

DØ has performed the search in the electron channel only, with 174 pb^{-1} of data. The electron is required to be central, isolated, with $p_T > 20$ GeV/c, while $\not{E}_T > 20$ GeV. Two b-tagged jets of $E_T > 20$ GeV and $|\eta| < 2.5$ have to be present. To reduce the top background, exactly two jets are demanded. Cuts on the W transverse mass reduces the QCD background (see Fig. 1). 2 events are observed in the data while the expectation is 2.5 ± 0.5. This allows to set limits on the production of the Higgs and the production of $W + b\bar{b}$:

$$\sigma(Wb\bar{b}) < 20.3 \text{ pb}$$
$$\sigma(WH) \times B(H \to b\bar{b}) < 12.4 \text{ pb, for } m_H = 115 \text{ GeV/c}^2 \text{ }^{1)}.$$

---

[1]) the SM productionl rate is $\sigma(WH) \times B(H \to b\bar{b}) \simeq 0.15$ pb.

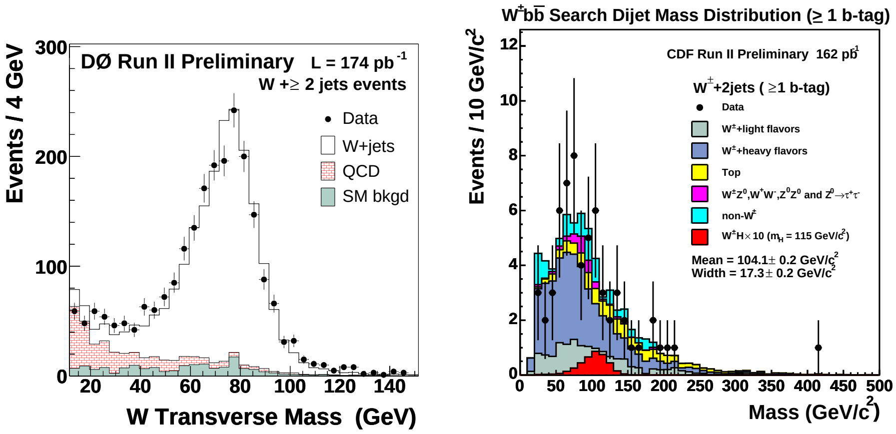

Fig. 1. On the Left: transverse mass spectrum of the W system in DØ $e\nu$ analysis, before b-tagging criteria. On the Right: Di-jet mass spectrum of the $Wb\bar{b}$ candidates, in CDF.

CDF has analyzed 162 pb^{-1} of data in both electron and muon channels. The lepton has to be central and isolated with $p_T > 20$ GeV/c, while $\not{E}_T > 20$ GeV. Exactly two jets with $E_T > 15$ GeV and $|\eta| < 2$ have to be reconstructed. Only one of these jets has to be b-tagged. 61 ± 5 events are expected for this selection while 62 events remain in the data (see Fig. 1). The limit on the production reads:

$$\sigma(WH) \times B(H \to b\bar{b}) < 5 \text{ pb}, \text{ for } m_H = 115 \text{ GeV/c}^2.$$

2.3 The $WW^* \to \ell\nu\ell\nu$ channel

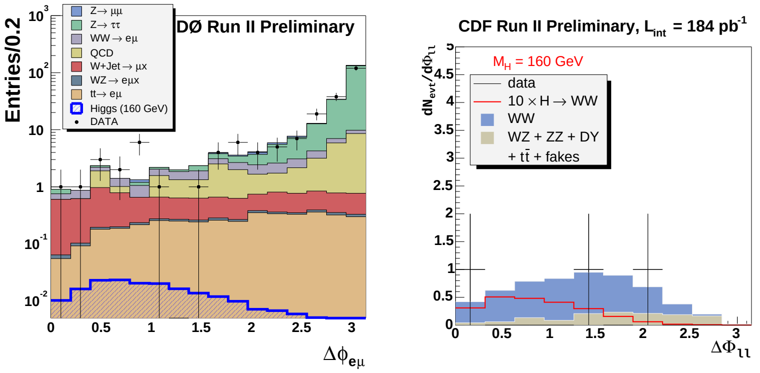

Fig. 2. Distribution of $\Delta\Phi$ after requiring two isolated high p_T leptons for the DØ $e\nu\mu\nu$ channel (left) and after the whole selection for CDF (right).

DØ has made three separate selections for the $e\nu e\nu$ (180 pb^{-1}), $e\nu\mu\nu$ (160 pb^{-1}) and $\mu\nu\mu\nu$ (150 pb^{-1}) channels, while CDF has performed one single $\ell\nu\ell\nu$ analysis ($\ell = e,\ \mu$) in 200 pb^{-1} of data.

Two isolated high p_T leptons and a large $\not{E}_T$ are required: $p_T > 20$ GeV/c and $\not{E}_T > 25$ GeV for $\ell\nu\ell\nu$, $p_T^{1,2} > 12,\ 8$ GeV/c and $\not{E}_T > 20$ GeV for $e\nu e\nu$ and $e\nu\mu\nu$, $p_T^{1,2} > 20,\ 10$ GeV/c and $\not{E}_T > 30$ GeV for $\mu\nu\mu\nu$.

For signal production, because of spin correlation between the two W bosons, the two charged leptons tend to be collinear. Therefore, a small azimuthal angle ($\Delta\Phi$) between the leptons and also a low di-lepton mass helps to discriminate against the background (see Fig. 2). This latter is made of electroweak WW production, Drell-Yan process with mismeasured jets faking $\not{E}_T$, W+jets events with jets faking electrons, and the di-boson production, ZZ or WZ.

In CDF, the di-lepton mass is required to be lower than half of the tested Higgs mass and a maximum likelihood fit on the $\Delta\Phi$ distribution is used to compute the signal production rate and derive limit. In DØ, $\Delta\Phi$ is used for a final cut.

After the selection, no excess is observed (see Table 1) and exclusion limits on the production rates are derived. They are shown in Fig. 3. For $m_H = 160$ GeV/c^2 they read:

$$\sigma(gg \to H) \times B(H \to WW^*) < 5.6 \text{ pb} \quad \text{for CDF}$$
$$\sigma(gg \to H) \times B(H \to WW^*) < 5.7 \text{ pb} \quad \text{for DØ.}$$

	DØ ee $\Delta\Phi < 1.5$	DØ $e\mu$ $\Delta\Phi < 2$	DØ $\mu\mu$ $\Delta\Phi < 1.5$	CDF $\ell^+\ell^-$ $m_H = 160$ GeV/c^2
expected	2.7 ± 0.4	3.1 ± 0.3	5.3 ± 0.6	4.7 ± 0.5
observed	2	2	5	3

Table 1. Expected and observed number of events for the different WW^* channels.

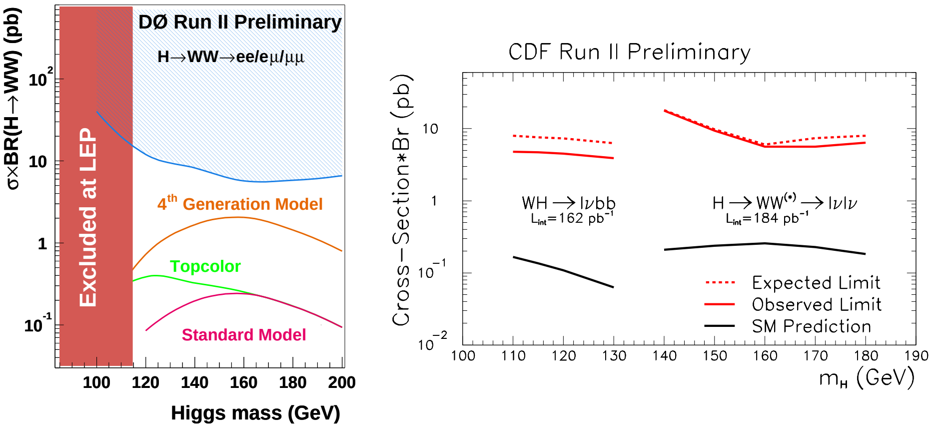

Fig. 3. Exclusion limits on the production rate ($\sigma \times B$) obtained for the WW^* channel at DØ (left) and for the WW^* and $Wb\bar{b}$ channels at CDF (right).

3 Higgs bosons beyond the Standard Model

3.1 Supersymmetric Higgs bosons at large $\tan\beta$

In the Supersymmetric extensions of the SM, at least two Higgs doublets are required to break the electroweak symmetry, $\tan\beta$ being the ratio of their vacuum expected values. This yields five physical Higgs bosons: h and H are neutral and CP-even, A is neutral and CP-odd, and H^+ and H^- are charged.

At large $\tan\beta$ ($\tan\beta > 10$), two of the neutral, either (A, h) or (A, H), have the same mass, and a coupling to b-quarks enhanced by $\tan\beta$ with respect to the SM coupling. These Higgs bosons can be produced in association with b-quarks, the cross-section of this process being proportional to $\tan^2\beta$. As the Higgs bosons decay more than 90% of the time into a pair of b-quarks, the signature is a multi-jet final states with a high b-jet content.

The DØ analysis starts by selecting three or more high p_T jets, (p_T >45, 35, 15 GeV/c for m_A = 100 GeV/c^2). Then, three of these jets are required to be tagged as b-jets. The main backgrounds are the QCD multi-jet productions where the gluon and light flavor jets are faking b-jets, and the $b\bar{b}$ + jets production. In 131 pb^{-1} of data, no excess is observed, which would show up as a peak in di-jet mass distribution (Figure 4) in case of signal production. Therefore exclusion limits in the plane (m_A,$\tan\beta$) are derived, as shown in Fig. 4.

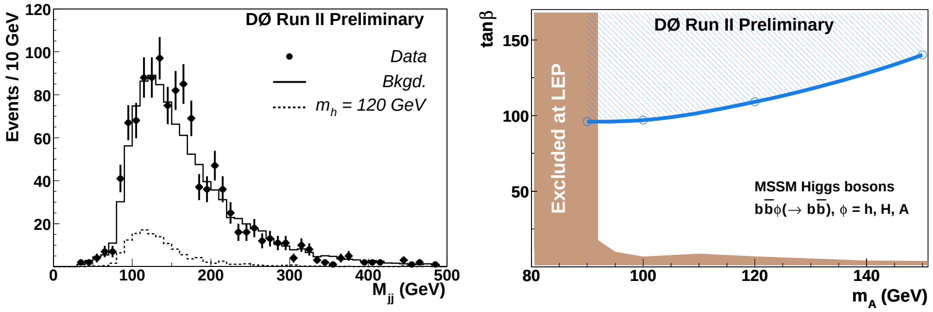

Fig. 4. On the left: invariant mass spectrum of the two leading jets after the 3 b-tag requirement. On the right: the excluded region in the (m_A,$\tan\beta$) plane

.

3.2 Higgs decaying to $\gamma\gamma$

At Tevatron, only models beyond the SM can yield a sizable and observable $H \to \gamma\gamma$ signature [3]. This can occur when the Higgs does not couple to fermions (fermiophobic Higgs) or couples to the top-quark only (topcolor Higgs) [4].

The DØ selection requires two high p_T isolated photons, $p_T > 25$ GeV/c, either in the central calorimeter ($|\eta| < 1.05$) or the endcap calorimeter ($1.5 < |\eta| < 2.4$). The p_T of the di-photon system is demanded to be higher than 35 GeV/c.

The main sources of background arise from QCD events in which either two jets are misidentified as photons, or when one genuine photon is produced along with one jet misidentified as a photon. Some Drell-Yan, $Z/\gamma^* \to ee$ events in which both electrons are misidentified as photons can also pass the selections. The expected number of real di-photon events is small.

For a data sample of 190 pb^{-1}, the observed numbers of events agree, within the uncertainties, with the expectations, as shown in Table 2. This allows to put limits for the topcolor and fermiophobic scenarii, the branching ratio, $\mathrm{B}(H \to \gamma\gamma)$, being considered as a free parameter. They are displayed in Fig. 5.

type of di-photon event	central-central	central-endcap	endcap-endcap
QCD background	42.7 ± 28.0	64.0 ± 45.7	13.1 ± 10.0
Drell-Yan	1.4 ± 1.3	3.0 ± 3.0	6.7 ± 3.0
Direct di-photon	8.3 ± 0.6	1.8 ± 0.1	1.0 ± 0.1
total background	52.4 ± 28.0	68.8 ± 45.8	20.8 ± 10.4
observed events	93	97	41

Table 2. Expected and observed number of events of DØ di-photon analysis. The main source uncertainty for the background is the photon misidentification rate.

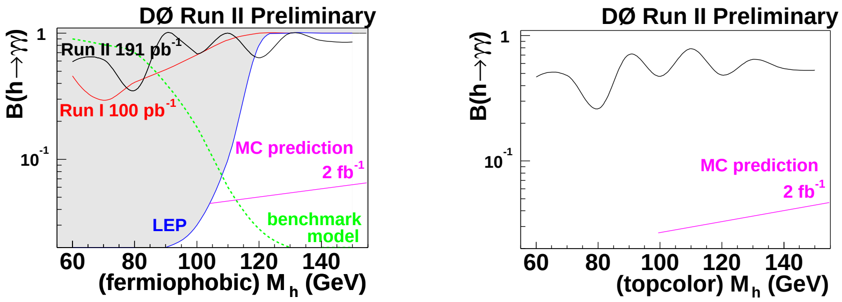

Fig. 5. Exclusion limit in the plane (m_H, $\mathrm{B}(H \to \gamma\gamma)$) for the fermiophobic and the topcolor model.

3.3 Doubly-charged Higgs bosons

Doubly-charged Higgs bosons appear in left-right symmetric models, in Higgs triplet models, and in Little-Higgs models [5]. At Tevatron, they can be either singly or pair produced. The dominant decay mode into a pair of same charged leptons has been looked for in the CDF ($\simeq 240\ \mathrm{pb}^{-1}$) and DØ ($\simeq 105\ \mathrm{pb}^{-1}$) data.

The analysis requires the presence of one pair of same charge leptons, either electrons or muons. Their p_T have to be greater than 30, 25 and 15 GeV/c for the CDF ee, CDF $\mu\mu$ and DØ $\mu\mu$ selections, respectively. DØ requires that the leptons be isolated and their azimuthal opening angle fulfill $\Delta\Phi < 0.8\pi$, while CDF demands that the di-lepton mass be higher than 80 GeV/c^2 for the $\mu\mu$ and $e\mu$ samples, and higher than 100 GeV/c^2 for the ee sample. The dominant background are the QCD jet production, especially heavy flavor production followed by semi-leptonic decays, WZ production, W+jets production and Drell-Yan, $Z/\gamma^* \to ee$, where the same-sign track comes from a photon conversion.

The number of expected and observed events are given in Table 3. No excess is present, therefore exclusion limits are derived. To this end, CDF performs the counting of events, while DØ takes into account the expected mass distribution of the signal and the background [6]. For Left-Right models, these limits are quoted in Table 3 and displayed in Fig. 6.

	CDF, $\mathcal{L}$ =240 pb^{-1}				DØ, $\mathcal{L}$ =106 pb^{-1}			
	expected	observed	H_L^{++}	H_R^{++}	expected	observed	H_L^{++}	H_R^{++}
ee	1.5 ± 0.9	0	133	113	1.5 ± 0.4	3	118	98
$\mu\mu$	0.8 ± 0.5	0	136					
$e\mu$	0.4 ± 0.2	0	115					

Table 3. Expected background and observed number of candidates in the different channels. The lower mass limits (in GeV/c^2) assuming exclusive decays for the left-handed and right-handed doubly-charged Higgs are also quoted.

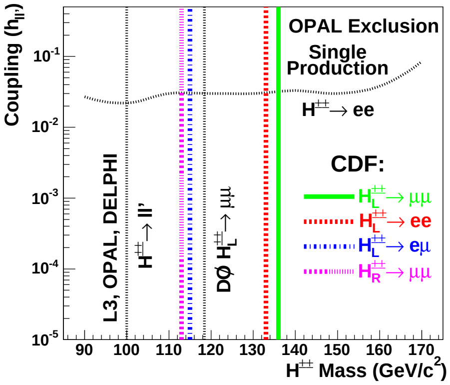

Fig. 6. Doubly-charged Higgs lower mass limits versus lepton coupling, assuming exclusive decay to a given di-lepton pair. The previous existing world limits are also displayed.

4 Prospects for the Standard Model Higgs bosons

The analyses presented in the previous sections do not have yet the sensitivity to reach the SM Higgs cross-section. As shown in Fig. 7, a larger integrated luminosity and the combination of both experiments in all channels will be needed either to exclude at 95% C.L., or make à 3σ evidence or a 5σ discovery, for a given Higgs mass [7]. According to the Tevatron luminosity upgrade plan [1], see Fig. 7, by the end of 2009, the range 115-130 GeV/c^2 will be covered for exclusion and a 3σ evidence is allowed up to 125 GeV/c^2. In the most optimistic scenario ("design"), a 3σ evidence is possible up 130 GeV/c^2 while a 5σ discovery can occur up to

120 GeV/c^2. It is worthwhile to notice that, in 2004, Tevatron has delivered an integrated luminosity above the design, i.e. optimistic, scenario.

Fiscal Year	Design luminosity (fb^{-1})	Base luminosity (fb^{-1})
FY03	0.33	0.33
FY04	0.64	0.56
FY05	1.2	0.93
FY06	2.7	1.4
FY07	4.4	2.2
FY08	6.4	3.3
FY09	8.5	4.4

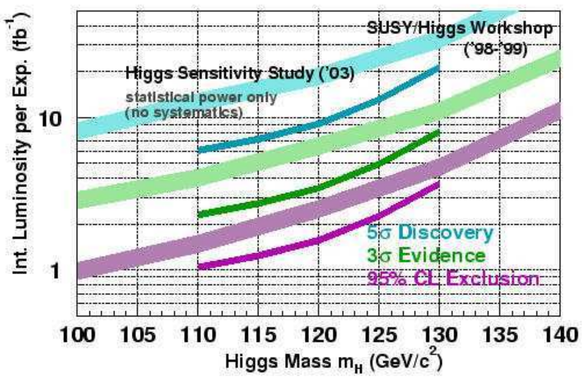

Fig. 7. On the left: Tevatron luminosity upgrade plan [1]. On the right: integrated luminosity per experiment, needed for exclusion or discovery as a function of the Higgs mass. The thick bands correspond to the Susy/Higgs Workshop [8]. The thinest bands are the updates obtained by the Higgs sensitivity study [7].

5 Conclusion

With a few hundreds inverse picobarns of data, the CDF and DØ experiments have demonstrated their ability to perform the search for Higgs bosons in many channels. Results are quite encouraging and show that the hunt for Higgs bosons has started at Tevatron. Given the steadily improving performance of the accelerator, a lot more interesting results will be established in the coming years.

References

[1] The Run II Luminosity Upgrade at the Fermilab Tevatron, v2.0, January 2004, http://www-bdnew.fnal.gov/doereview04/RunII_Upgrade_Plan_v2.0.pdf

[2] J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock, Phys. Rev. D **69**, 074021 (2004)

[3] S. Mrenna and J. D. Wells, Phys. Rev. D **63**, 015006 (2001),

[4] see for example: G. Landsberg and K. T. Matchev, Phys. Rev. D **62**, 035004 (2000)

[5] see for example: J. F. Gunion, C. Loomis and K. T. Pitts, hep-ph/9610237; N. Arkani-Hamed, *et al.*, JHEP **0208**, 021 (2002)

[6] T. Junk, Nucl. Instrum. Meth. A **434**, 435 (1999).

[7] L. Babukhadia *et al.* [CDF and D0 Working Group Members Collaboration], FERMILAB-PUB-03-320-E

[8] M. Carena *et al.*, [Higgs Working Group Collaboration],