Higgs Searches at the Tevatron *

Gavin Davies (On behalf of the CDF and DØ collaborations)

Imperial College London, SW7 2AZ

The CDF and DØ experiments have carried out a wide range of Higgs searches, using an integrated luminosity of approximately 1 fb^{-1}. As no significant excess of signal above the expected background is observed in any of the various final states examined, limits at 95% confidence level (CL) are presented.

PACS numbers: PACS numbers come here

1. Introduction

The Higgs mechanism breaks electroweak symmetry within the Standard Model (SM) by introducing a scalar field to generate particle masses. The existence of an additional neutral particle (the Higgs boson) is also predicted, though its mass is not. Direct searches at LEPII have excluded a SM Higgs boson with mass below 114 GeV at 95 % confidence level (CL). Including the latest Tevatron results on the top and W mass, the favoured Higgs mass is 76^{+33}_{-24} GeV, and including the LEPII exclusion, the mass is predicted to be below 182 GeV at 95% CL [1].

Standard Model Higgs production at the Tevatron is dominated by gluon fusion, with smaller contributions from associated production with a W or Z boson. Cross sections are of order 0.1 to 1 pb. At low mass (below 135 GeV) the dominant Higgs decay mode is to $b\bar{b}$, so searches use associated production to avoid the huge SM background to the gluon fusion production. Above 135 GeV decays to WW^* dominate, and gluon fusion production can be utilised.

Many models beyond the SM, including Supersymmetry, predict larger Higgs production cross sections, some within reach even with the present data sets. The Minimal Supersymmetric extension of the SM (MSSM)[2] introduces two Higgs doublets and so contains five physical Higgs bosons. Two of them are CP-even scalars, h and H, of which h is the lighter and

* Presented at PIC 2007 Annecy

SM like. The other three consist of a charged Higgs pair, $H^{\pm}$, and a CP-odd scalar, A, the mass of which is one of the two free parameters of the model at tree level. The production cross section of the Higgs in the MSSM is proportional to the square of the second free parameter of the model, tanβ, the ratio of the two vacuum expectation values of the Higgs doublets. Large values of tanβ thus result in significantly increased production cross sections compared to the SM. Moreover, in the large tan β limit one of the CP-even scalars and the CP-odd scalar are degenerate in mass, leading to a further cross section enhancement. The main production mechanisms for such neutral Higgs bosons are the $gg, b\bar{b} \to \phi$ and $gg, q\bar{q} \to \phi + b\bar{b}$ processes, where $\phi = h, H, A$. The branching ratio of $\phi \to b\bar{b}$ is around 90% and $\phi \to \tau^+\tau^-$ is around 10%. The overall experimental sensitivity is however similar for the two channels, due to the lower background in the τ channel. Other extensions to the SM such as Top-color [3] or Fermiophobic Higgs models [4] also lead to enhanced decays of Higgs $\to \gamma\gamma$.

The rest of this note summarises the current analyses based on an integrated luminosity of around 1 fb^{-1}. All results are preliminary, and more information is available from the public pages of CDF and DØ [5, 6].

2. Searches for $gg \to H \to WW^*$

Both CDF and DØ search in the di-lepton (ee, $\mu\mu$ and eμ) modes. To reduce backgrounds from Z/$\gamma*$, more than 20, 25 GeV (DØ, CDF) of missing transverse energy is required. The top pair background is reduced be vetoing events with at least two jets or high total jet energy. The QCD background, including semi-leptonic quark decays and jets faking electrons, is reduced by requiring lepton isolation and a di-lepton mass above 15, 16 GeV (CDF, DØ). The remaining background is SM WW production and the opening angle, $\Delta\phi(l, l)$, between the leptons is used as the discriminating variable as the spin-0 Higgs tends to produce more co-linear leptons. The $\Delta\phi(l, l)$ distribution from the DØ ee analysis after all other cuts is shown in Fig. 1. No excess is observed, and limits are set. This analysis is most sensitive to a Higgs mass of 160 GeV, where the DØ 95 % CL observed limit is 3.7 times the predicted SM cross section (4.2 expected). The CDF cut-based analysis sets an observed limit of 9.2 times the SM cross section for a 160 GeV Higgs (6.0 expected).

To improve the background discrimination CDF have also developed a matrix element (ME) analysis. First, the lepton definitions were loosened, increasing the expected number of signal events by a factor of 1.6. Then the matrix element probabilities are calculated for each selected event to be Higgs signal or WW, ZZ, Wγ or W+jet background. A likelihood ratio discriminant is constructed from these probabilities:

$$LR(x_{obs}) = \frac{P_H(x_{obs})}{P_H(x_{obs}) + \Sigma_i k_i P_i(x_{obs})} \tag{2.1}$$

where x_{obs} are the observed leptons and missing energy, P_H is the probability for one of the Higgs mass hypotheses, and k_i are the expected background fractions, with $\Sigma_i k_i = 1$. This discriminant is shown in Fig. 1, and produces good signal-background separation at high likelihood. Fitting this discriminant sets a significantly tighter limit than the CDF cut-based analysis, with the observed 95% CL exclusion limit of 3.4 (4.8 expected) times the SM cross section for a Higgs mass of 160 GeV.

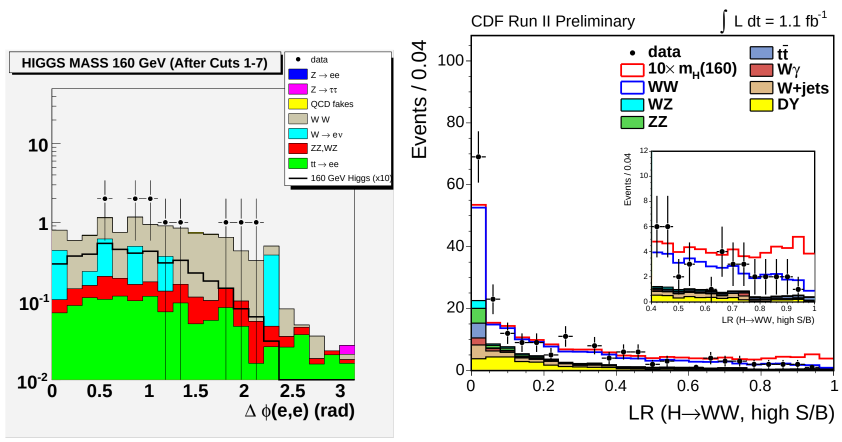

Fig. 1. The $\Delta\phi(l,l)$ distribution from the DØ $H \to WW^*$ search (left), and likelihood ratio from the CDF analysis.

3. Searches for $ZH \to ll\mathrm{b}\bar{\mathrm{b}}$

Below around 135 GeV, the Higgs decays primarily to $\mathrm{b}\bar{\mathrm{b}}$, and so associated production is used. Higgs production with a Z boson has a lower cross section than associated production with a W, but the leptonic (e or μ) Z decays provide a clean Z signal, even with loose lepton requirements and p_T cuts (15 GeV is typical). Two jets are then required above 15 GeV (DØ) or one above 25 and one above 15 GeV (CDF). After this pre-selection, the sample is dominated by Z+jets, and identifying b-jets is crucial to reducing this background, as it is for all low mass SM Higgs searches. DØ uses a neural net tagger based on lifetime information giving high efficiency, 50-70%, for a mistag rate of 0.3-4.5%. CDF use secondary vertex reconstruction, achieving efficiencies of 40-50% for a mistag rate of 0.5-1.5%. To search for the ZH signal, DØ require two b-tagged jets then use the di-jet mass distribution, the main variable giving discrimination between Z+jet and ZH (Fig. 2), in the limit setting. No excess over expected background is observed, and the observed limit is 23 times the SM Higgs cross section (22 expected) for a 115 GeV Higgs. CDF form exclusive 'two loose' or 'one tight' b-tagged samples and further improved the di-jet mass distribution by balancing the measured missing energy with the jets. A 2-dimensional neural net is then used, trained to separate ZH from top backgrounds, and ZH from Z+jets. These improvements yielded an equivalent gain of around 2.5 times more luminosity compared to the previous CDF analysis. The output for the ZH vs Z+jets projection in the double-tagged sample is shown in Fig. 2. Fitting this output allows a 95 % CL limit to be set, corresponding to 16 times the expected SM Higgs cross section (16 expected).

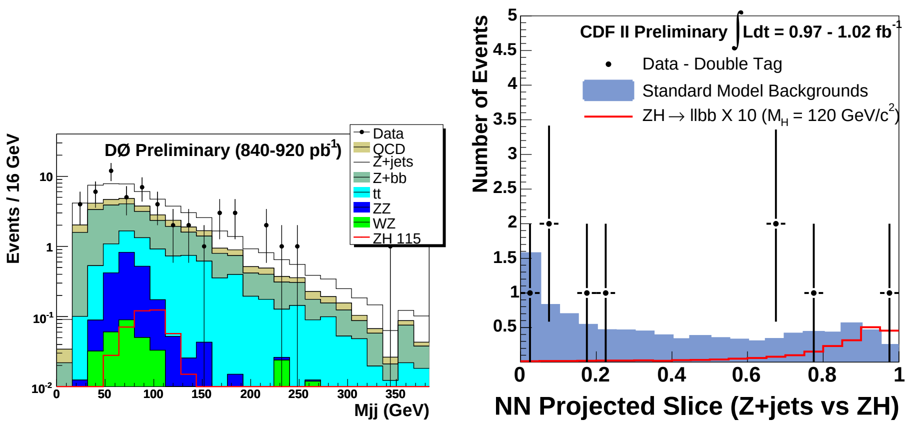

Fig. 2. The di-jet mass distribution from the DØ ZH search (left), and the ZH vs Z+jets neural net output for the double-tag sample in the CDF search.

4. Searches for $ZH \rightarrow \nu\nu b\bar{b}$

Despite the large Z branching ratio to neutrinos this channel is experimentally very challenging. Events must be triggered on jets plus missing energy, and tight cuts used to reject background. DØ require two jets of at least 20 GeV and at least 50 GeV of missing energy. CDF require one jet above 60 GeV, one above 20 GeV and at least 75 GeV of missing energy. Understanding the remaining instrumental background, in the form of fake missing energy from mis-measured jets, remains the main challenge and is determined from data. DØ study the asymmetry of the missing energy as measured with all calorimeter cells and with jets. CDF require that the missing energy is not aligned with the jets, and cut on the ratio of the missing to total jet energy. Both experiments fit the di-jet mass distribution to extract limits for the Higgs cross section, and separate the limit into expected contributions from $ZH \rightarrow \nu\nu b\bar{b}$ and $WH \rightarrow l\nu b\bar{b}$ where the lepton is not reconstructed. DØ sets a 95 % CL limit corresponding to 14 times the SM (9.6 expected) for a 115 GeV Higgs; the CDF limits correspond to 16 times the SM (15 expected) for the same mass point.

5. Searches for $WH \rightarrow l\nu b\bar{b}$

Searches for Higgs production in association with a leptonically decaying W provide the most stringent constraints on a low mass Higgs. Both experiments have performed cut-based analyses splitting the data into exclusive one and two b-tag channels; CDF use a neural net to improve the purity in the single-tag sample. The di-jet mass is then used as the discriminating variable in the limit setting. CDF set a 95 % CL limit corresponding to 26 times the SM cross section (17 expected) for a 115 GeV Higgs. DØ further optimised their search in the muon channel using trigger redundancy, allowing events to pass any trigger and gaining around 50 % more signal. The di-jet mass for the double tagged sample is shown in Fig. 3. The DØ 95 % CL limits correspond to 11 times the SM cross section (8.8 expected) for a 115 GeV Higgs.

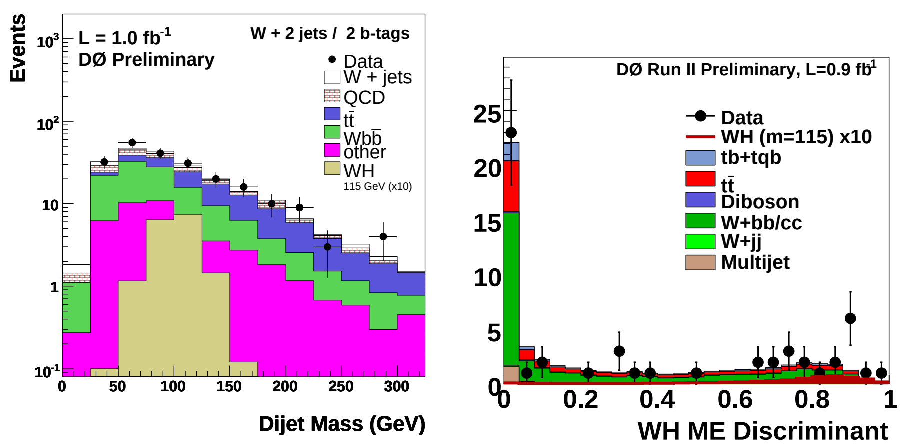

Fig. 3. The di-jet mass distribution (left) and the matrix element discriminant (right) from the DØ $WH \rightarrow l\nu b\bar{b}$ analyses (double tag samples).

DØ also carried out an analysis using the matrix element approach developed for the recent evidence for single top quark production [7]. As in equation 2.1, a discriminant is constructed from the event probabilities, and fitted to set a limit on the Higgs cross section. This discriminant is shown for the double b-tagged sample in Fig. 3. The event selection was optimised for a single top event topology, and so a further 20 - 30 % gain is expected after re-optimisation.

6. Higgs $\rightarrow \tau^+\tau^-$

The main background sources in this channel are $Z \rightarrow \tau^+\tau^-$ (irreducible), $W+$ jets, $Z \rightarrow \mu^+\mu^-/e^+e^-$ with multi-jet and di-boson events also contributing. DØ has performed a search in the channel where one of the τ leptons decays to a μ. The event selection requires only one isolated muon, separated from the hadronic τ with opposite sign. The τ identification is performed with a neural network. A 20 GeV cut on M_W, the reconstructed W boson mass, removes most of the remaining W background. The final separation of signal from background is achieved with a set of neural networks, optimized for different Higgs masses and trained on the visible mass, m_{vis}, and τ and μ kinematics. The data are found to be in good agreement with the background-only expectation. Fig. 4 shows the resulting 95 % CL exclusion in the $\tan\beta - m_A$ plane.

CDF has performed a similar search, including channels where one τ lepton decays to an electron. The event selection includes an isolated electron/muon, τ identification with a variable cone-size algorithm and jet background suppression with a cut on $|p_T^l| + |p_T^{had} + |E_T^{miss}| > 55$ GeV. Most of the W background is removed by cuts on the relative directions of the visible τ decay products and the missing E_T. Limits on cross section times branching ratio and exclusion regions are derived from the m_{vis} distribution, the latter is shown in Fig. 5 in the $\tan\beta - m_A$ plane. Due to a small excess in the region of 130 GeV $< m_{vis} <$ 160 GeV, the limits are weaker than expected. However, when all channels $(e\tau, \mu\tau, e\mu)$ and possible search windows are considered the significance of the observed excess is found to be less than two standard deviations.

7. Higgs $+b \rightarrow b\bar{b}b$

DØ has carried out a search in this channel using a multi-jet event sample corresponding to an integrated luminosity of 0.9 fb^{-1}. Candidate events are required to contain at least three jets with $p_T > 15$ GeV, the leading jet must further be above 40 GeV and the second jet above 25 GeV. At least three jets must be identified as b-jets by the standard DØ neural network b-tagging algorithm. A signal is searched for in the invariant mass spectrum of the two leading b-tagged jets. The dominant background is multi-jet production and is estimated from the data outside the signal

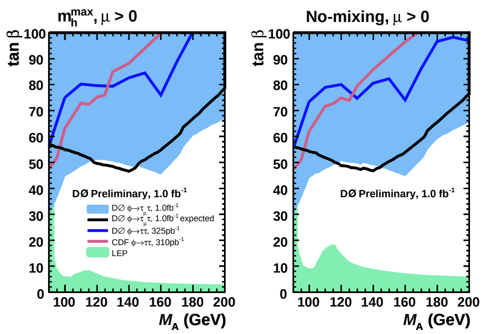

Fig. 4. Excluded region in the tan$\beta - m_A$ plane from DØ for a positive mass parameter μ in the m_h^{max} (left) and the no-mixing (right) scenarios. Also shown is the LEP limit [8] and the previous CDF [9] and DØ [10] results for $\phi \to \tau\tau$.

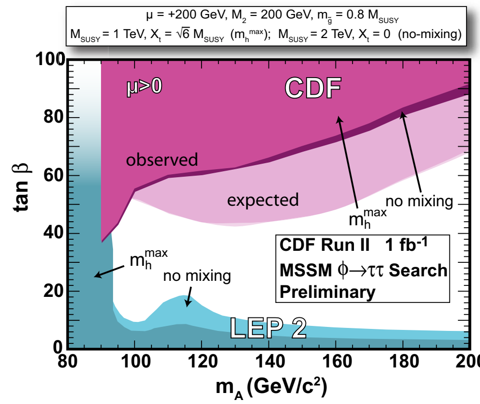

Fig. 5. Excluded region in the tan$\beta - m_A$ plane from CDF in the m_h^{max} and no-mixing scenarios for $\mu > 0$.

search region. The signal acceptance is found to be 1.7-2.6% depending on the Higgs mass. As no significant excess is observed, limits are set. Cross sections down to 20 pb are excluded for Higgs masses up to 170 GeV.

8. Limits on non-SM Higgs $\to \gamma\gamma$

DØ has searched for Higgs bosons in $3\gamma + X$ final states in data corresponding to an integrated luminosity of 0.8 fb^{-1}. The event selection includes three isolated photons with $E_T > 15$ GeV within $|\eta| < 1.1$ (central calorimeter). The combined transverse momentum of the three photons is further required to be larger than 25 GeV. 0 events are selected with a total expected background of 1.1 ± 0.2 events. The background is dominated by direct triple photon production with a small contribution from QCD and $Z/W + X$ processes. No excess is observed and hence excluded fermiophobic Higgs masses are calculated. This search excludes a fermiophobic Higgs below 80 GeV for a charged Higgs mass below 100 GeV and tan$\beta = 30$.

9. Conclusions and Prospects

CDF and DØ have performed searches for the SM and non-SM Higgs bosons over a range of masses with an integrated luminosity of approximately 1 fb^{-1}. No significant excess over expected background was observed, so limits were set.

A Tevatron combined SM limit was produced in Summer 2006, and will be updated soon to include the latest results. However, DØ have combined their results, and these DØ-only limits are tighter than the previous Tevatron combination. The expected limits are 5.9 times the SM cross section for a Higgs mass of 115 GeV, and 4.2 times the SM at 160 GeV. Thus, using a variety of optimisations in triggering, lepton identification and jet resolutions, combined with advanced analysis techniques limits have been improved faster than the gain from increasing luminosity. Further improvements are underway, including the addition of new analysis channels, and 95 % CL exclusion limits could be possible with around 3 fb^{-1} per experiment at 115 and 160 GeV, assuming no signal is seen.

The searches for non-SM Higgs bosons also show very promising sensitivity and have already produced new powerful limits on $h/H/A \to \tau\tau/b\bar{b}$ and $h \to \gamma\gamma$. New MSSM results can be expected shortly from both experiments and work will focus on combining the results from the different channels of both experiments as well as improvements to the analyses themselves, as discussed for the SM case. We are confidently looking forward to exploring the almost 3 fb^{-1} of data per experiment which has already been written to tape, and the 8 fb^{-1} total per experiment expected by the end of Run II.

10. Acknowledgements

I would like to thank my colleagues from the CDF and DØ Collaborations for providing material for this talk and the organisers of PIC 2007 for a very interesting conference.

REFERENCES

[1] http://lepewwg.web.cern.ch/LEPEWWG/

[2] Dimopoulos S and Georgi H 1981 *Nucl. Phys.* B **193** 150

[3] Hill C T 1991 *Phys. Lett.* B **266** 419

[4] Haber H E, Kane G L and Sterling T 1979 *Nucl. Phys.* B **161** 493

[5] http://www-cdf.fnal.gov

[6] http://www-d0.fnal.gov

[7] Abazov V M *et al.* 2007 *Phys. Rev. Lett.* **98** 181802

[8] Schael S *et al.* 2006 *Eur. Phys. J.* C **47** 547-587

[9] Abulencia A *et al.* 2006 *Phys. Rev. Lett.* **96** 011802

[10] Abazov V M *et al.* 2006 *Phys Rev. Lett.* **97** 121802