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Beyond the Standard Model Higgs Searches at the Tevatron

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The CDF and D0 Collaborations at the Tevatron have an extensive programme of searches for "Beyond-the-Standard-Model" Higgs bosons. Recent results, using data sets corresponding to integrated luminosities of up to 4.2 fb^{-1}, from such searches are reported. Good agreement between data and Standard Model backgrounds is found in all of the various final states examined. We thus proceed to set limits at 95% Confidence Level (C.L.).

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1. Introduction

The search for Higgs bosons, both within and beyond the Standard Model (SM), is one of the main priorities for particle physics and as such is a key aspect of the Run II physics programme at the Tevatron. Many of the hypothesised Beyond-the-Standard Model (BSM) theories predict sizable Higgs production cross sections and clean search channels.

The Minimal Supersymmetric extension of the SM (MSSM) [1] introduces two Higgs doublets, and so contains five physical Higgs bosons: h, H, A and $H^{\pm}$. The mass of A is a free parameter at tree level. The Higgs production cross section in the MSSM is proportional to the square of the second free parameter of the model, $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. A large value of $\tan\beta$ can thus result in significantly increased production cross sections. Moreover, in the large $\tan\beta$ limit, A and one of either h or H are degenerate in mass, leading to a further factor 2 enhancement in cross section. $H^{\pm}$ can be pursued in searches for deviations from the SM expectation in top decays. Other possible extensions to the SM, such as next-to-MSSM [2] , can lead to final state topologies which would have escaped previous searches, and so dedicated searches have been carried out. More exotic scenarios including fermiophobic models [3] with enhanced Higgs decay to $\gamma\gamma$ or WW and doubly-charged Higgs production have also been searched for. This note summarises the analyses presented at HCP2009, based on integrated luminosities of up to 4.2 fb^{-1}. More information, along with the latest results, is available from the CDF and D0 public web pages [4, 5].

2. Limits on neutral SUSY Higgs at high $\tan\beta$

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%. Searches for $h/H/A$ in final states with τ-leptons or b-quarks, or indeed combinations there-of, are therefore well motivated; the overall experimental sensitivity is similar for the different channels, due to the lower background in the τ channel.

2.1 Higgs $\to \tau^+\tau^-$

CDF [6] and D0 [7] have searched in the three channels, $e\tau_{had}$, $\mu\tau_{had}$, eμ where the τ decay products are indicated and τ_{had} indicates a hadronic τ decay, using datasets of 1.8 fb^{-1} and 1.0 fb^{-1} respectively. D0 extended the μ channel to 2.2 fb^{-1} of data. The signal is two high-p_T τ leptons, with missing transverse momenta in the same hemisphere as the e/μ and τ-candidate. The $W+$ jets background can be reduced by cutting on the transverse W mass (D0) and the azimuthal angle between the visible lepton and the missing transverse energy (CDF). Multijet backgrounds are estimated from orthogonal data samples. Tau identification at CDF is carried out using a variable cone-sized algorithm whilst D0 use a series of NNs. The final dominant background is $Z \to \tau^+\tau^-$ and is estimated from Monte Carlo. Both experiments use the visible mass, $M_{\text{vis}} = \sqrt{(P_{\tau_1} + P_{\tau_2} + \not{P}_T)^2}$, calculated using the four-vectors of the visible tau decay products $P_{\tau_{1,2}}$ and of the missing momentum $\not{P}_T = (\not{E}_T, \not{E}_x, \not{E}_y, 0)$, as the discriminating variable. As good agreement between data and expectation is observed we proceed to set limits, initially in a model independent way on the production cross section times branching ratio. To take into account radiative corrections limits on

$\tan\beta$ as a function of m_A are then set for the two standard scenarios: the $m_h^{\max}$ scenario [1] and the no-mixing scenario [2]. In the MSSM the width of the Higgs boson can become larger than in the SM. D0 included this effect, but as $\Gamma_A/m_A < 0.1$ for $m_A < 200$ GeV in these scenarios, the effect of the width is small.

2.2 Higgs $+b \to \tau^+\tau^- b$

D0 has performed a recent search using 2.7 fb^{-1} of Run II data in the channel where one tau lepton decays to a μ [8]. The dominant backgrounds are $t\bar{t}$ and multijet production. The multijet background is estimated from data and the $t\bar{t}$ background is modeled using ALPGEN [9] interfaced with PYTHIA [10]. $t\bar{t}$ events are removed using a neural network based on kinematic variables. Multijet events are removed using an unbinned log-likelihood ratio. The likelihood and anti-$t\bar{t}$ neural network are combined to form the final discriminant used to derive limits on cross section times branching ratio and exclusion regions in the MSSM parameter space, see Fig. 1.

2.3 Higgs $+b \to b\bar{b}b$

CDF and D0 have carried out searches in this channel, looking for three b-tagged jets, in data samples of 1.9 fb^{-1} and 1.0 fb^{-1} [11] respectively, with an update to 2.6 fb^{-1} from the latter. The signal corresponds to an excess over background in the dijet invariant mass formed from the two Higgs candidate jets. Though the requirement of a third b-tag reduces the QCD background, the so-called '3tag' sample remains QCD dominated and its composition is determined using both simulation and data. Heavy flavour jets as well as mis-tagged light jets can contribute. CDF use dijet invariant mass and secondary vertex mass templates, whilst D0 use multiple b-tagging criteria with known efficiencies to determine the relative contribution of the different backgrounds. As the Higgs boson width can become considerably larger than the experimental resolution both experiments explicitly include this effect, with a consequent decrease in sensitivity at large values of $\tan\beta$ as the invariant mass spectrum is broadened. To increase sensitivity D0 include multiple possible Higgs' jet-pairings, split the analysis into exclusive three-, four-, and five-jet samples and use a likelihood discriminant (tailored for either low or high mass) based on kinematic information. Again model independent limits on cross section are are initially set before interpretation in the standard scenarios. This channel is more sensitive than the $\phi \to \tau^+\tau^-$channel to the details of the radiative corrections and so greater dependence on the scenarios is observed.

2.4 Combined limits

D0 has produced combined limits from the three neutral MSSM Higgs searches, although in the combination an earlier version of the Higgs $+b \to \tau^+\tau^- b$ analysis using only the 1.2 fb^{-1} RunIIa dataset was included. In total nineteen sub-channels with between 1.0 and 2.6 fb^{-1} of data are included. CDF and D0 have combined the Higgs $\to \tau^+\tau^-$ analyses mentioned above, producing both model independent limits as well as interpretations in the usual scenarios. Fig. 1 shows the excluded region at 95% C.L. in one MSSM benchmark scenario [12]. These combinations place the strongest limits on neutral MSSM Higgs in the $\tan\beta - m_A$ plane to date at a hadron collider.

[1] $M_{\rm SUSY}$= 1 TeV, X_t = 2 TeV, M_2 = 0.2 TeV, $\mu = \pm 0.2$ TeV, and m_g = 0.8 TeV.

[2] $M_{\rm SUSY}$= 2 TeV, X_t = 0 TeV, M_2 = 0.2 TeV, $\mu = +0.2$ TeV, and m_g = 1.6 TeV where X_t is the mixing parameter, M_2 is the gaugino mass term, m_g is the gluino mass and $M_{\rm SUSY}$ is a common scalar mass.

3. Charged Higgs bosons

CDF [14] has carried out a search for H^+ using 2.2 fb^{-1} of data in the low tanβ region which is dominated by the decay $H^+ \rightarrow c\bar{s}$ [14]. The search is conducted in the lepton+jets $t\bar{t}$ channels. Mass templates for H^+ and W^+ are fit to the dijet mass distribution in data to derive upper limits on the branching ratio of $t \rightarrow H^+b$. The dominant background is $t\bar{t}$ which is modeled with PYTHIA. The upper limits on the branching ratio, Br($t \rightarrow H^+b$), shown in Fig. 1, range from 0.3 to 0.1 depending on the H^+ mass. D0 has carried out charged Higgs searches with 1.0 fb^{-1} of data in the $H^+ \rightarrow c\bar{s}$, $H^+ \rightarrow \tau^+\nu$ and $H^+ \rightarrow t\bar{b}$ channels [15]. As well as limits on the branching ratio the results are interpreted in various MSSM scenarios including CP violating cases.

4. Next-to-MSSM

In the nMSSM [2] the branching ratio of Higgs$\rightarrow b\bar{b}$ is greatly reduced. Instead the Higgs predominantly decays to a pair of lighter neutral pseudoscalar Higgs bosons, a. D0 has conducted two searches with 4.2 fb^{-1} of data [16]. Firstly for the case with $2M_\tau < M_a \leq 3M_\pi$ where the a dominantly decays to two muons. Secondly, for the case where $2M_\tau < M_a \leq 2M_b$ and the a predominantly decays to a pair of tau leptons. No excess is observed and limits are calculated on the cross section times branching ratio, see Fig. 1.

5. Limits on non-SM Higgs $\rightarrow \gamma\gamma$

Both CDF [17] and D0 have carried out searches for fermiophobic Higgs bosons via their decay to either W^+W^- or $\gamma\gamma$. The former is based on re-interpretation of the SM $WH \rightarrow WWW^*$ searches. The latter offer the greatest sensitivity, taking advantage of the excellent mass resolution in the di-photon channel. Dominant backgrounds include photon+jets and jet-jet processes, where a jet fakes a photon, as well as direct di-photon production. The most recent searches exclude masses below $\approx$ 105 GeV, illustrating that the Tevatron experiments are already achieving close to single LEP experiment levels of sensitivity. In addition the Tevatron searches are already probing regions of the parameter space inaccessible at LEP.

6. Conclusions

The results presented at this conference by the CDF and D0 collaborations, together with the continuing excellent performance of the experiments and the Tevatron, are very encouraging for the Higgs searches at Run II. We are confidently looking forward to some 10 fb^{-1} on tape by the end of RunII, typically more than tripling the data sets presented here. As well as the larger data sets analysis improvements are underway, as in the SM Higgs searches. The neutral MSSM searches are starting to probe particularly interesting regions of parameter space, with additional sensitivity expected via the re-interpretation of the SM Higgs searches in the MSSM context.

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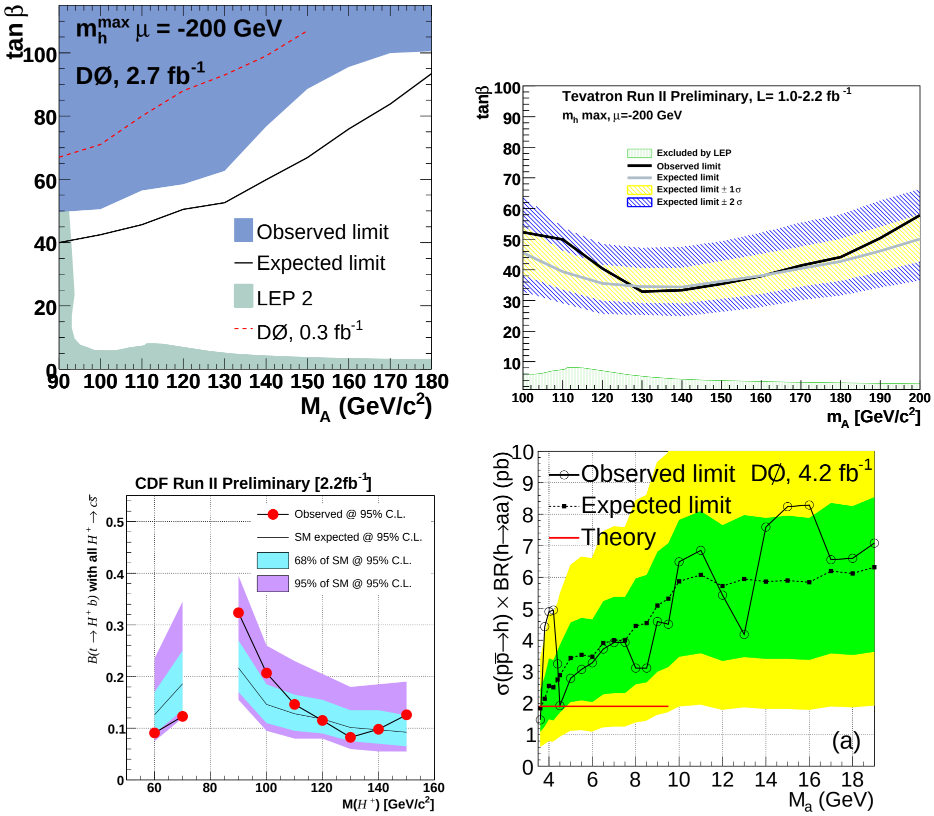

Figure 1: Upper left) Excluded region in the $\tan\beta - m_A$ plane from the D0 $bh \to b\tau^+\tau^-$ analysis for a negative mass parameter μ in the m_h^{max} scenario [12]. Upper right) Excluded region in the $\tan\beta - m_A$ plane from the combined CDF and D0 $h \to \tau^+\tau^-$ searches for a negative mass parameter μ in the m_h^{max} scenario [12]. Also shown is the limit from LEP [13]. Lower left) The expected and observed 95% C.L. upper limits on the branching ratio, Br($t \to H^+ b$) from CDF. Br($H^+ \to c\bar{s}$) is assumed to be 100%. Lower right) The expected and observed limits and $\pm$ 1 and 2 s.d. bands for $\sigma(p\bar{p} \to h + X) \times$ BR($h \to aa$) and $M_h = 100$ GeV from D0.

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