NON-STANDARD MODEL HIGGS SEARCHES AT THE TEVATRON

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The CDF and D0 experiments at Fermilab's Tevatron have been actively searching for the Higgs bosons that appear in extensions of the minimal standard model. Here we present the results of searches for the neutral and charged Higgs bosons of the minimal supersymmetric standard model, as well as searches for doubly charged Higgs bosons that are predicted by other types of extensions. Up to 900 pb^{-1} of Run 2 data have been analyzed and have provided no signs of Higgs boson production; these null results are used to set limits on Higgs production scenarios within the context of particular models.

Keywords: Higgs; MSSM; Tevatron.

1. Introduction

Electroweak symmetry breaking is effected in the standard model (SM) by the "Higgs mechanism," in which a scalar doublet field with non-zero vacuum expectation value spontaneously breaks the $SU(2)\otimes U(1)$ symmetry and enables the W and Z bosons to acquire their measured mass. This mechanism also gives rise to a scalar particle (the Higgs boson) of unspecified mass. Direct searches for the SM Higgs boson at LEP2 have bounded the mass from below at 114 GeV/c^2;[1] precision electroweak measurements have bounded it from above at 166 GeV/c^2.[2]

Higgs bosons are also predicted in the many extensions of the SM that have been conceived to address its shortcomings. One of these extensions is the minimal supersymmetric standard model (MSSM), in which massive superpartners of the SM particles serve to cancel the quadratic divergences of the loop corrections to the Higgs mass-squared. In the MSSM two scalar doublet Higgs fields are required, giving rise to five physical bosons: the CP-even h^0 and H^0 (with $m_h < m_H$ by definition), the CP-odd A^0, and the charged $H^{\pm}$. The neutral Higgs bosons are often referred to collectively as ϕ^0.

A free parameter of the MSSM that plays an important part in determining the phenomenology of the Higgs sector is $\tan\beta$, the ratio of the vacuum expectation values of the two doublet fields. Large (small) values of $\tan\beta$ enhance the Higgs couplings to down-type (up-type) fermions. Small values of $\tan\beta$ are strongly disfavored by LEP2 data;[3] the consequences of this at the Tevatron are (for example) that we expect ϕ^0 to decay predominantly to $b\bar{b}$ and $\tau^+\tau^-$, and that the cross section for $gg, bb \to \phi^0$ production can be on the order of 10 pb. Another important consequence of the MSSM is that there is an upper limit on m_h of around 135 GeV/c^2.

2. Experimental considerations

The efficient identification of bottom quarks and tau leptons form the linchpin of MSSM Higgs search strategies, given the expected ϕ^0 decay modes mentioned above. Bottom quarks are typically tagged by exploiting the long lifetime of B-hadrons; the presence of displaced secondary vertices and/or tracks with large impact parameters with respect to the primary vertex can signal the presence of a b quark. Large-acceptance silicon microstrip detectors provide CDF and D0 with the precision tracking necessary for identifying these signatures. Tau tagging requires good performance and geometrical coverage from a number of different subdetectors — muon chambers and electromagnetic calorimetry for identifying leptonic tau decays, and hadronic calorimetry and tracking for distinguishing hadronic tau decays from QCD jets.

3. Neutral Higgs searches

3.1. *Searches for $b(\bar{b})\phi^0 \to b(\bar{b})b\bar{b}$*

D0 has performed a search for ϕ^0 produced in association with one or more b quarks, with subsequent ϕ^0 decays to $b\bar{b}$. The reason for considering the associated production mechanism is that "bare" $\phi^0 \to b\bar{b}$ production is swamped by QCD $b\bar{b}$ background. A multijet event sample in which three jets were identified as containing a displaced secondary vertex was selected from 260 pb^{-1} of data. The invariant mass of the two highest-p_T jets in each event is shown in Fig. 1 along with the distribution expected from the SM. No distortion of the spectrum from a $b\bar{b}$ resonance is seen.

3.2. *Searches for $\phi^0 \to \tau^+\tau^-$*

Both CDF and D0 have searched for ϕ^0 decays to $\tau^+\tau^-$, which provides a clean enough signature to obviate the need for associated

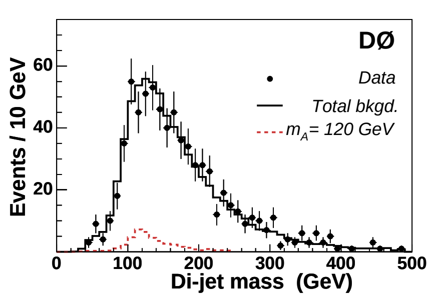

Fig. 1. Invariant mass distribution of the two highest-p_T jets in a sample of triply b-tagged events at D0.

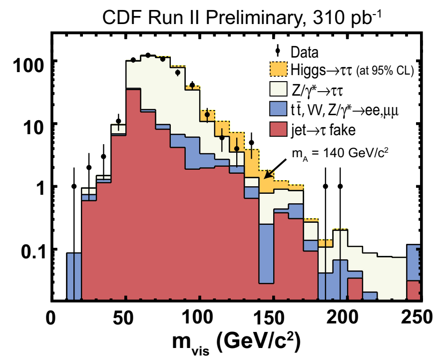

Fig. 2. Tau pair visible mass distribution (see Eq. 1) in a 310 pb^{-1} event sample from CDF.

b production. The high-p_T e or μ from a leptonic τ decay provides the "seed" for the event; an additional narrow, isolated hadron jet completes the $\tau^+\tau^-$ signature.[a] The visible mass of the tau pair, defined as

$$m_{\text{vis}} = \sqrt{(p_{\tau_1}^{\text{vis}} + p_{\tau_2}^{\text{vis}} + \not{p}_T)^2} \qquad (1)$$

where the p's represent four-momenta, was used to discriminate SM processes from a possible Higgs signal; see Fig. 2 for an example from 310 pb^{-1} of CDF data. Neither CDF nor D0 observed any evidence for $\phi^0 \to \tau^+\tau^-$ production.

3.3. *Combined results*

The null results from the $b\bar{b}$ and $\tau^+\tau^-$ searches from CDF and D0 allow one to set 95% CL upper limits on the cross section for neutral MSSM Higgs production. These limits can in turn be interpreted as exclusions for points in the MSSM parameter space that predict a cross section larger than the observed limit. This is shown in Fig. 3 for two benchmark MSSM scenarios described in Ref. 4. One should note how the sensitivity

[a]Leptonic τ decays yield cleaner events, but the branching ratio is only about 1/3. Tau pair searches often employ the technique of requiring a leptonic decay from one τ and a hadronic decay from the other in order to achieve acceptable signal-to-background ratios.

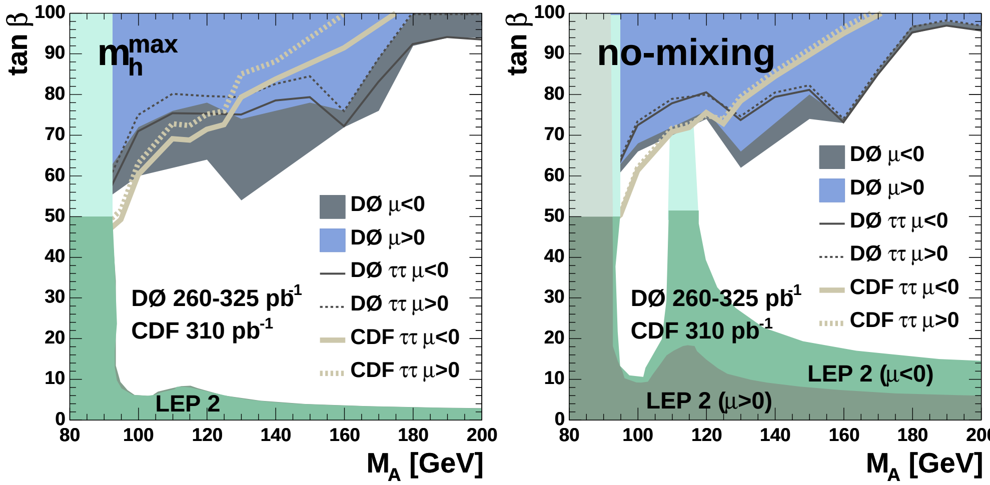

Fig. 3. 95% CL exclusions in the (m_A,$\tan\beta$) plane from CDF, D0, and LEP2 for the $m_h^{\rm max}$ (left) and no-$\tilde{t}$-mixing (right) scenarios. The exclusion areas are shown for two different values of the SUSY Higgs mass parameter μ.

of LEP2 to low values of $\tan\beta$ and/or m_A is complemented well by the Tevatron's coverage of large values of $\tan\beta$ and m_A.

3.4. *New results*

A recent D0 search for $\phi^0 \to \tau^+\tau^-$ in association with one or more b quarks in 286 pb^{-1} of data yielded cross section upper limits around 40 pb,[b] competitive with the $b(\bar{b})b\bar{b}$ analysis described in Sec. 3.1. This indicates that a future combination of the two analyses will prove fruitful. In addition, D0 also updated their $b(\bar{b})b\bar{b}$ analysis with a larger dataset (900 pb^{-1}) and an improved b-tagging algorithm, improving their cross section limit in this channel to around 20 pb.

4. Charged Higgs searches

If the mass of the charged Higgs is less than $m_t - m_b$ then it may be observable in the decay $t \to H^+b$. The branching ratio for this decay can be quite large for $\tan\beta < 1$ and $\tan\beta > 50$, but is small for intermediate values. Since the decay modes for the H^+ (mainly $c\bar{s}$ and $\tau^+\nu_\tau$) are quite different from the decay modes of the W in the SM $t \to W^+b$ decay, measurements of the top pair cross section in different exclusive final states constrain the charged Higgs sector of the MSSM. These constraints were explored in detail by CDF using a 193 pb^{-1} data sample;[5] more recently they have performed a study of the decay $t \to \tau^+\nu_\tau b$ in order to constrain $BR(t \to H^+b)$ at large $\tan\beta$, where $BR(H^+ \to \tau^+\nu_\tau) \approx 1$. The results are shown in Fig. 4.

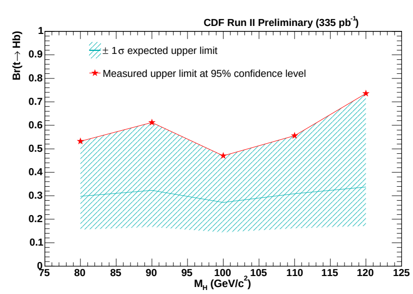

Fig. 4. 95% CL upper limit on $BR(t \to H^+b)$ assuming $BR(H^+ \to \tau^+\nu_\tau) = 1$, for different values of the charged Higgs mass.

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[b]The actual cross section limit depends on the Higgs mass.

5. Doubly charged Higgs searches

Doubly charged Higgs bosons can appear in left-right symmetric models,[6] Higgs triplet models,[7] and "Little Higgs" models.[8] They are pair-produced via a Drell-Yan process and decay predominantly to like-signed lepton pairs, leading to a distinctive four-lepton final state. CDF and D0 have published searches for $H^{\pm\pm}$ decays to electrons and muons[9] and CDF has searched for quasi-stable $H^{\pm\pm}$ bosons that do not decay inside the CDF detector.[10] More recently CDF has searched for $H^{\pm\pm}$ decays to $e\tau$ and $\mu\tau$ in 350 pb^{-1} of data. No excess of events above the SM expectation was observed, enabling one to set a 95% CL lower limit on the doubly charged Higgs mass assuming 100% branching ratio into either $e\tau$ or $\mu\tau$. This result and the results for other $H^{\pm\pm}$ decay modes (assuming only a left-handed lepton coupling) can be found in the symmetric Table 1.

Table 1. $H^{\pm\pm}$ 95% CL lower mass limits

	electron	muon	tau
electron	133 GeV/c^2		
muon	115 GeV/c^2	136 GeV/c^2	
tau	114 GeV/c^2	112 GeV/c^2	n/a

6. Conclusions and outlook

Despite active searching, no evidence for non-SM Higgs production has yet been observed at the Tevatron. This has led to exclusions in the large $\tan\beta$ and m_A region of the MSSM parameter space — a region outside the LEP2 reach. At the time of the ICHEP '06 conference, about 1 fb^{-1} had been analyzed by the CDF and D0 experiments; with the expected yearly doubling of the Tevatron integrated luminosity, up to 8 fb^{-1} per experiment will have been collected by the end of Run 2. Given the enhanced cross sections and couplings discussed in Sec. 1, the Tevatron therefore has a real chance at discovering a Higgs boson if the MSSM is an accurate model of Nature. A non-observation of a Higgs boson at Tevatron Run 2 would severely constrain the MSSM parameter space and would consequently play an important part in guiding the search strategies at the LHC.

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