# Searches for Non-Standard-Model Higgs Bosons at the Tevatron

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The Standard Model of particle physics has a number of asymmetries suggestive of a more fundamental theory, where the symmetries are restored. If the symmetry breaking scale is the electroweak scale, new Higgs bosons beyond that of the Standard Model could be observed at the Tevatron. Recent Tevatron searches have set the most stringent limits on new Higgs bosons in a variety of models.

## 1 Introduction

In the Standard Model (SM), the only symmetry broken by the Higgs mechanism is the electroweak symmetry. However, the SM possesses unexplained features suggestive of a more fundamental theory, with additional symmetries broken at a mass scale that is as yet beyond our reach. Two examples are the symmetry between fermions and bosons (supersymmetry) and between left- and right-handed fermion couplings to the weak gauge bosons (left-right symmetry). These models predict additional Higgs bosons that could be observable at the Tevatron. Recent Tevatron searches have probed for neutral Higgs bosons predicted by supersymmetry, and for doubly charged Higgs bosons in left-right symmetric models.

## 2 Higgs Boson Searches in Supersymmetric Models

A self-consistent supersymmetric theory requires two complex Higgs doublets separately coupling to up-type and down-type fermions. Out of the eight degrees of freedom, three result in the longitudinal components of the $W^{\pm}$ and $Z$ bosons. The remaining five result in the following physical states: two neutral CP-even bosons, denoted by $h$ and $H$ in order of increasing mass; one neutral CP-odd boson ($A$); and two charged bosons ($H^{\pm}$).

The vacuum expectation values (vev's) of the Higgs fields give bosons and fermions their non-zero masses. The ratio of vev's with up-type to down-type couplings is the supersymmetric parameter $\tan\beta$. An important prediction of supersymmetry is that down-type couplings to Higgs bosons include a factor of $\tan\beta$. Thus, down-type couplings are significantly enhanced at large $\tan\beta$, resulting in large production cross sections at the Tevatron. In particular, for $\tan\beta = 50$ the cross section of a 100 GeV Higgs boson is about two orders of magnitude larger than in the SM. In addition, $h$ ($H$) and $A$ are approximately mass-degenerate for $m_A$ less than (greater than) about 100 GeV, effectively doubling the production cross section.

Tevatron searches focus on the dominant decay modes of $b\bar{b}$ and $\tau\tau$ and are generally interpreted for a few different scenarios. All scenarios maximize the Higgs-boson mass as a function of $\tan\beta$ in order to avoid the direct LEP limits. They either have non-vanishing ("$m_h^{max}$") or vanishing ("no-mixing") stop mixing, and probe both positive and negative values of the Higgs mixing parameter at the electroweak scale ($\mu$).

## 2.1 Searches for $H \to \tau\tau$

CDF and DØ [1] have searched for Higgs bosons decaying to tau pairs in final states where one tau decays to an electron ($\tau_e$) or muon ($\tau_\mu$) and the other tau decays either hadronically ($\tau_h$) or to a different-flavor lepton. Because most of the sensitivity comes from final states with $\tau_h$, these searches rely on identifying and measuring hadronic tau decays.

CDF's $\tau_h$ identification starts from a reconstructed high-momentum "seed" track. Additional tracks within a narrow $\eta - \phi$ cone are associated with the tau decay, and the total momentum outside this cone (and within a larger cone) is required to be small. The defined tau cone shrinks with increasing tau momentum, accounting for the larger boost. The tau momentum is measured by combining the track momenta (typically from charged pions) with the electromagnetic calorimeter momenta (typically from neutral pions), with a correction for the expected charged-pion contribution to the electromagnetic momenta.

DØ subdivides the $\tau_h$ decays into cases where a single charged track matches either energy deposited in the hadronic calorimeter (consistent with a charged pion) or energy in both the electromagnetic and hadronic calorimeters (consistent with both charged and neutral pions), or where there are three charged tracks with invariant mass less than the tau mass (1.7 GeV). In each of these cases, DØ uses a neural network discriminant to separate tau decays from direct hadron production. In the case where there is significant measured electromagnetic energy, an additional neural network discriminates tau decays from direct electron production.

Figure 1 shows the CDF ditau invariant mass spectrum in events with one leptonic and one hadronic tau decay. No excess consistent with Higgs production is observed in the CDF or DØ data, so limits are set in the $m_A - \tan\beta$ plane for the $m_h^{max}$ and no-mixing scenarios with $\mu > 0$ and $\mu < 0$ (Fig. 2).

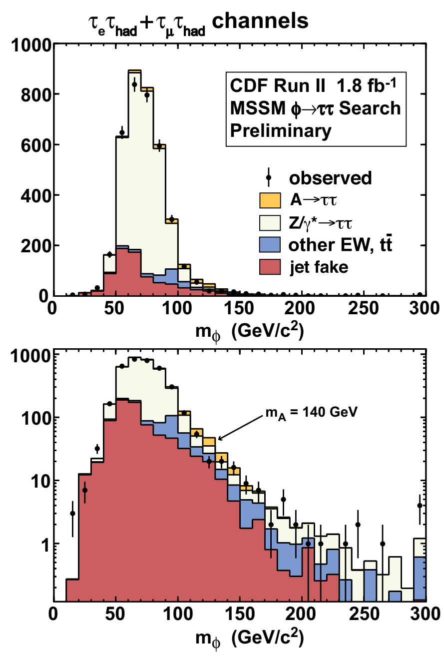


Figure 1: The CDF $\tau_h\tau_l$ invariant mass distribution on linear (top) and log (bottom) scales.

## 2.2 Searches for $(b)bH \to (b)bbb$

The $p\bar{p} \to H \to b\bar{b}$ process is overwhelmed by direct $b\bar{b}$ production, so searches for this Higgs decay channel probe the processes $gb \to Hb \to bbb$ and $q\bar{q}/gg \to bbH \to bbbb$. CDF and DØ [2] require at least three identified $b$ quarks in the final state, making $b$-quark identification a key component of the analysis. In addition, $b$-jet energy resolution is important to resolve the Higgs mass peak from the background continuum, though for $\tan\beta \gtrsim 100$ the intrinsic width is larger than the detector resolution.

CDF identifies $b$ quarks using the significance of the jet vertex displacement with respect to the collision vertex, combined with the

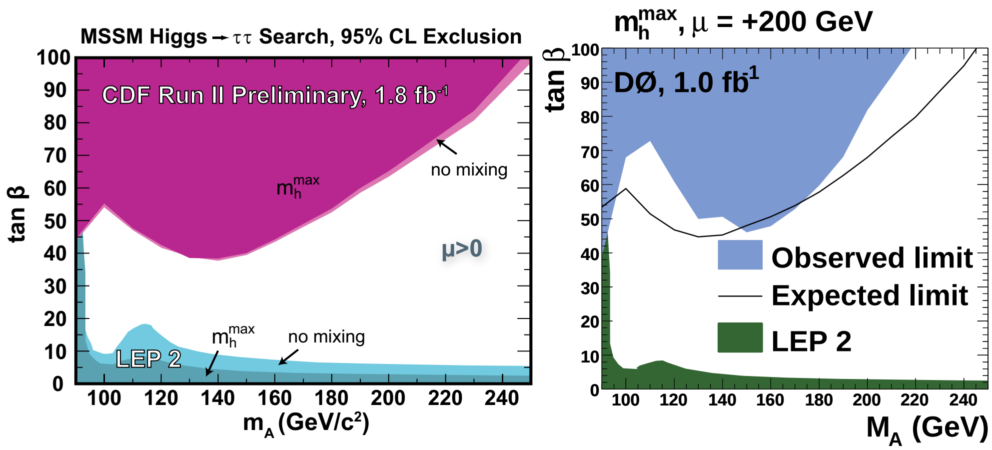


Figure 2: CDF (left) and DØ (right) limits in the $m_A - \tan\beta$ plane. CDF examines the $m_h^{max}$ (dark pink) and no-mixing (light pink) scenarios with $\mu > 0$ and $\mu < 0$ (not shown). The $\mu < 0$ limits are similar. DØ examines the $m_h^{max}$ and no-mixing (not shown) scenarios for $\mu > 0$. The no-mixing limits are similar.

invariant mass of the tracks used in the jet vertex reconstruction (the mass of $b$-quark vertices is higher than that of lighter quarks). The background to the sample is predominantly heavy-flavor quark production, whose mass distributions are predicted using a combination of data and PYTHIA MC. The results of a detailed measurement of azimuthal correlations in $b\bar{b}$ production are used to tune the gluon splitting contribution in the MC. The mass spectrum of the two highest $E_T$ $b$-jets shows no deviation greater than $2\sigma$ between data and MC, so mass limits are set in the $m_A - \tan\beta$ plane for $\mu = -200$ GeV in the $m_h^{max}$ scenario. The $\tan\beta$ limit increases from $\approx 80$ to $\approx 100$ for $m_A$ increasing from 110 GeV to 180 GeV.

DØ uses a neural network discriminant to identify $b$ quarks. The background is estimated separately for each jet multiplicity using the measured $b$-quark identification efficiency and control samples with and without identified $b$-jets. Six variables are used in a likelihood to separate Higgs signal from background, and the resulting mass spectrum shows good agreement between data and predicted background, with a small excess around 180 GeV (Fig. 3). The probability for this excess to correspond to a background fluctuation is 4.4%. Limits are set in the $m_A - \tan\beta$ plane for $\mu = \pm 200$ GeV for the $m_h^{max}$ (negative $\mu$ only) and no-mixing scenarios. In the $m_H^{max}$ scenario, the limits range from $\tan\beta > 55$ for $m_A \approx 125$ GeV to $\tan\beta > 100$ for $m_A \approx 200$ GeV.

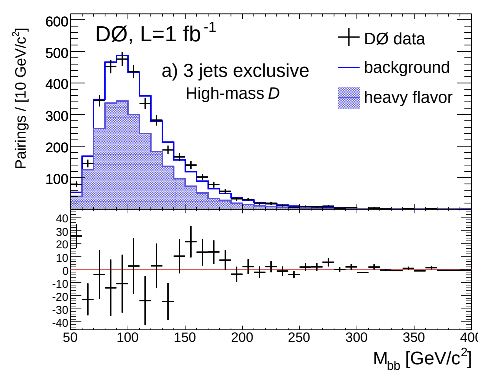


Figure 3: The DØ $m_{bb}$ distribution in the final state with exactly three jets, all identified as originating from a $b$ quark.

## 3 Higgs Boson Searches in Left-Right Symmetric Models

Left-right symmetric theories postulate the breaking of an SU(2) symmetry into the observed $\mathrm{SU(2)_L}$ weak symmetry and an unobserved $\mathrm{SU(2)_R}$ symmetry. The $\mathrm{SU(2)_R}$ symmetry is broken by the vev of a weak $\mathrm{SU(2)_R}$ Higgs triplet. The corresponding neutral Higgs boson couples only to neutrinos and bosons, and results in the see-saw mechanism producing small neutrino masses. The triplet includes a doubly charged Higgs boson $H^{\pm\pm}$ that couples to like-sign lepton pairs. In a supersymmetric model, these Higgs bosons can have masses of $\mathcal{O}(100\text{ GeV})$, and thus be observable at the Tevatron collider.

### 3.1 Searches for $H^{\pm\pm} \to l^{\pm}l^{\pm}$

Doubly charged Higgs bosons are predominantly produced in pairs at the Tevatron. Events with four leptons in the final state have negligible background, and searches typically require fewer than four leptons to increase signal acceptance. The DØ collaboration has recently performed a search in the three-muon final state [3], excluding $H^{\pm\pm}$ masses above 150 (127) GeV for Higgs bosons coupling to left-(right-) handed muons with 100% branching ratio. This result increases the earlier limit from DØ and complements CDF [4], H1 [5], OPAL, and DELPHI searches in all $H^{\pm\pm}$ dilepton decay channels, and for long-lived $H^{\pm\pm}$ (Fig. 4).

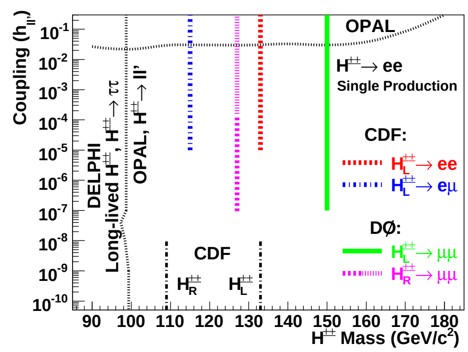


Figure 4: Limits from direct searches for $H^{\pm\pm}$ production, assuming exclusive decay to a given lepton pair. Not shown are: CDF limits of $m_{H_L^{\pm\pm}} > 114$ GeV and 112 GeV for decay to $e\tau$ and $\mu\tau$, respectively; and the H1 limit of $m_{H_L^{\pm\pm}} > 141$ GeV for a coupling $h_{e\mu} = 0.3$.

## 4 Summary

There is strong motivation for additional Higgs bosons beyond that of the SM, and recent Tevatron searches have probed for their existence. In addition to the supersymmetric and doubly-charged Higgs boson searches described here, DØ has searched for fermiophobic Higgs bosons. With 2-10 times unsearched data available, more than one Higgs boson could be awaiting discovery at the Tevatron.

## References


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[4] D. Acosta *et al.* (CDF Collaboration), arXiv:0808.2161 (2008); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **95** 071801 (2005); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **93** 221802 (2004).

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