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Beyond Standard Model Higgs Bosons Searches at the Tevatron

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This paper reviews recent searches by the DØ and CDF Collaborations for non-Standard Model Higgs bosons at a center-of-mass energy of $\sqrt{s}$=1.96 TeV using up to 4.3 fb^{-1} of the Fermilab Tevatron data. Searches for charged and neutral Higgs bosons predicted in the Minimal Supersymmetric Standard Model (MSSM) and Next-to-MSSM (NMSSM) will be discussed.

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1. Introduction

Although the Standard Model (SM) of particle physics has been very successful in describing particles and their interactions, it is incomplete and several extensions to the model predict additional Higgs bosons. Within these extended models, the Higgs behaves similar to the SM Higgs but tends to exhibit different couplings with other particles. In particular, the branching ratios (BR) of the various Higgs decays can be enhanced significantly. This paper focuses on searches for the Higgs bosons by the CDF and DØ Collaborations in $p\bar{p}$ collisions at the Fermilab Tevatron in Run II within two main frameworks: the Minimal Supersymmetric Standard Model (MSSM) and a slightly extended, richer model of Next-to-MSSM (NMSSM).

2. MSSM Higgs Boson

The Higgs sector in MSSM requires two Higgs doublets, which yields five physical Higgs bosons after electroweak symmetry breaking: two neutral CP-even Higgs (h°, H°), one CP-odd Higgs (A°), and a pair of charged Higgs ($H^{\pm}$). The three neutral Higgs bosons are commonly denoted as $\phi(=h,H,A)$. At tree-level, the MSSM Higgs is fully specified by two free parameters conventionally chosen to be the mass of the CP-odd Higgs, m_A, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. However, radiative corrections introduce dependencies on additional SUSY parameters. Within the region of low m_A, the inclusive Higgs production cross section is enhanced by a factor depending on $\tan\beta$. In most parameter space, ϕ decays to $b\bar{b}$ ($\tau\tau$) pairs with branching ratios on the order of 90% (10%). Although the τ-mode has a smaller BR, it provides a much cleaner signature than the b-mode, which suffers from large multijet backgrounds. Nonetheless, both CDF and DØ study both modes and thereby are capable of probing several MSSM benchmark scenarios and extending the search region covered by LEP [1].

Recent searches for charged Higgs bosons focus on top quark decays, where $t \to H^{\pm}b$, using scenarios where the charged Higgs is sufficiently light such that its mass is less than the top mass. Two main decay modes for the charged Higgs exists depending on the value of $\tan\beta$. At large $\tan\beta$, the dominant decay is via the tauonic model, which contains a τ lepton and a neutrino, $H^{\pm} \to \tau\nu$, while smaller $\tan\beta$ values consider the leptophobic model with a charm and strange quark final state, $H^{\pm} \to c\bar{s}$. The Tevatron collider experiments have searched for $H^{\pm}$ in each of these models.

2.1 $b\phi \to bb\bar{b}$ Searches

Since a direct $\phi \to b\bar{b}$ search is difficult given the large multijet background, both DØ and CDF consider ϕ production in association with at least one b-jet. CDF selects events from 2.2 fb^{-1} of data, requiring three b-tagged jets [2]. Contributions from heavy-flavor multijet backgrounds and any possible signal are modeled through a two-dimensional fit of the data to the dijet mass spectrum of the two leading jets, m_{12} and a quantity, x_{tags}, which is sensitive to the flavor of the jets. Subsequently, CDF searches for enhancements in m_{12} and sets mass-dependent limits on the product of the production cross section and branching ratio ($\sigma\times$BR), as shown in Fig. 1 (left). The limits, which assume a negligible Higgs width, currently indicate a positive deviation at Higgs masses of about 140 GeV with a p-value of 0.9%. After considering trial factors, CDF measures a 5.7% probability to observe such an excess at any mass. As the limits are model independent, they

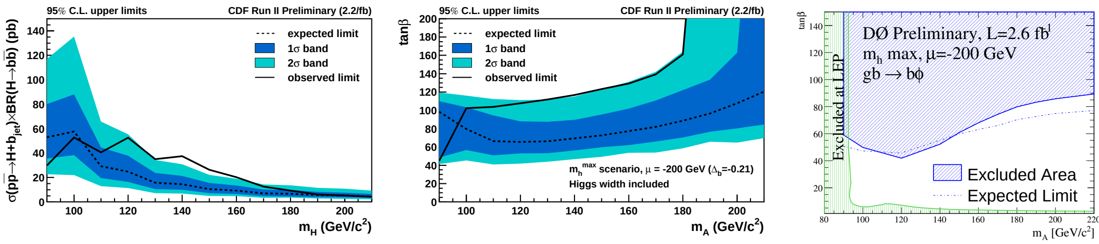

Figure 1: Search for $b\phi \to bb\bar{b}$. Results are shown of the 95% C.L. cross section limits (left) and MSSM $\tan\beta$ exclusion for m_h^{max} and $\mu < 0$ (middle) by CDF and corresponding MSSM exclusion by DØ (right).

are applicable to any narrow scalar decaying to $b\bar{b}$ final states produced in association with a b-jet. As shown in Fig. 1 (middle), these results are translated into a MSSM exclusion in the representative m_h^{max} scenario with $\mu<0$ and include effects of the Higgs width obtained from FEYNHIGGS [3]. Here, the growing width for increasing $\tan\beta$ tends to spread the events over a larger region of m_{12}, yielding limits on $\tan\beta$ between 105-140 within the Higgs mass range of 110-170 GeV.

DØ performed a similar search with 2.6 fb^{-1} of data by requiring triple b-tagged jets [4]. A six-variable likelihood is used to discriminate Higgs boson b-jets from multijet backgrounds. The search relies on the shape difference between signal and background by using a combination of data and simulated (MC) samples. Specifically, the shape from double b-tagged data is used with the ratio of the simulated shapes of the triple-to-double b-tagged events in order to predict the shape of the triple b-tagged data. The search sensitivity is improved by separating the analysis into three-, four-, and five-jet channels. As no excess is observed in the dijet invariant mass, exclusion limits on $\tan\beta$ are set at 95% C.L. for m_h^{max} and $\mu<0$, as shown in Fig. 1 (right).

2.2 $\phi \to \tau\tau$ and $b\phi \to b\tau\tau$ Searches

The CDF search for $\phi \to \tau\tau$ considered integrated luminosities of 1.8 fb^{-1} and required the τ-pairs to decay into $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, and $\tau_e\tau_\mu$, where τ_e, τ_μ (τ_{had}) are the leptonic (hadronic) decays of the tau [5]. The analysis requires an isolated e or μ oppositely charged from a τ_{had}. The hadronic taus are categorized according to their decay mode and selected using a variable-size cone algorithm. Additional selections are imposed to help reject backgrounds including a requirement on the relative direction of the visible τ decay product and $\not\!\!E_{\rm T}$, which reduces the W+jets background. After selections, the irreducible background from $Z \to \tau\tau$ remains, and the visible mass, defined as the invariant mass of the visible τ decay products and the missing momentum four-vector approximated by $\not\!\!P_{\rm T} = (\not\!\!E_{\rm T}, \not\!\!E_{\rm x}, \not\!\!E_{\rm y}, 0)$, is used to search for an enhancement of signal over background. Since the data agree with background, mass-dependent $\sigma\times$BR upper limits are calculated at 95% C.L. and translated into exclusions within the (m_A, $\tan\beta$) plane for representative MSSM scenarios.

DØ carried out a similar analysis using 1.0 fb^{-1} of data considering $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, and $\tau_e\tau_\mu$ final states [6]. Additionally, DØ extended its search in the $\tau_\mu\tau_{had}$ mode using a total 2.2 fb^{-1} dataset [7]. Hadronic taus, oppositely charged and separated from an isolated μ, are split by their decay types and discriminated from the jet background using a τ-identification algorithm based on neural networks (NN). A series of selections are imposed to help suppress backgrounds further. Since no excess in data is observed across the visible mass spectrum, 95% C.L. upper limits on $\sigma\times$BR and (m_A, $\tan\beta$) exclusions in MSSM benchmark scenarios are derived.

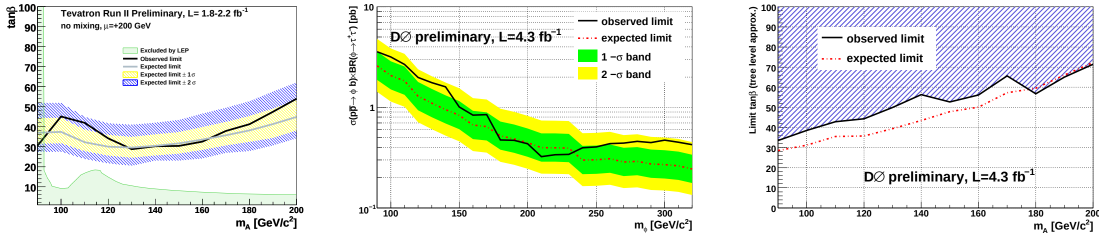

Figure 2: Tevatron combined 95% C.L. exclusion limits in (m_A, tanβ) plane for the $\phi \to \tau\tau$ search (left). Limits on $\sigma \times$BR (middle) and resulting tree-level MSSM exclusion (right) for the $b\phi \to b\tau\tau$ search by DØ.

The exclusion results are similar for both DØ and CDF, and each experiment reaches sensitivities of tan$\beta \sim$ 40-50 for $m_A <$ 180 GeV. Subsequently, Tevatron combined limits have been extracted in the inclusive di-τ channel [8], which probe tan$\beta \sim$ 30 at low m_A and are on the order of the top-to-bottom quark masses, m_{top}/m_b. The result is shown in Fig. 2 (left).

DØ also updated a separate search in the $b\phi \to b\tau_\mu\tau_{had}$ channel using 4.3 fb^{-1} of data [9]. Here, the search techniques developed for both the $\phi \to \tau_\mu\tau_{had}$ and $b\phi \to bb\bar{b}$ channels are used on the final decay products. The backgrounds are dominated by $Z \to \mu\mu$ and $Z \to \tau\tau$ events as well as those from multijet and $t\bar{t}$ processes. In order to discriminate against each, neural networks are applied. Here, the NN-based b-tagging algorithm helps suppress Z+jets events and two additional NN discriminants are constructed to respectively separate $t\bar{t}$ and multijet events from any possible signal. The final discriminant, which is a geometrical mean of these three discriminants, is used to determine mass-dependent limits for $\sigma \times$BR at the 95% C.L. and tree-level MSSM exclusions in tanβ vs. m_A space. These results are also given in Fig. 2 (middle, right).

2.3 Charged Higgs Searches

Both DØ and CDF have searched for charged Higgs bosons produced in top quark decays by selecting on high-p_T leptons, $\not{E}_{\mathrm{T}}$, and b-tagged jets characteristic of top pair production topologies. CDF focused on the leptophobic model with 2.2 fb^{-1} of data [10] while DØ considered both leptophobic and tauonic scenarios with 1.0 fb^{-1} of data [11]. As the data agree with background expectations, CDF extracts 95% C.L. upper limits on top quark decay branching ratio at BR($t \to H^+b$) < 0.1 to 0.3 for $M_{H^\pm}$ between 60-150 GeV. DØ places comparable limits including BR($t \to H^+b$) < 0.15 to 0.19 in the tauonic model for $M_{H^\pm}$ within the range of 80-160 GeV.

3. NMSSM Higgs Boson

Searches for Higgs boson (h) production in extended models of NMSSM [12] have also been performed at the Tevatron. Here, the $h \to b\bar{b}$ mode is greatly reduced and h predominantly decays into a pair of lighter neutral pseudo-scalar Higgs bosons (a). The DØ study used 4.2 fb^{-1} of data [13] dividing the search into two modes depending on the mass of a (M_a). Within the mass region $2m_\mu \lesssim M_a \lesssim 2m_\tau$, the $aa \to 4\mu$ decay dominates. The signature consists of two pairs of extremely collinear muons due to the low a mass. Since no excess of data events is observed relative to the total expected background, the search requires BR($a \to \mu\mu$) < 7% for $M_h \approx$ 100 GeV, assuming BR($h \to aa$)$\sim$1. For masses within $2m_\tau \lesssim M_a \lesssim 2m_b$, the search focuses on $aa \to 2\mu 2\tau$ decays. As no excess is observed in data, limits on $\sigma(p\bar{p} \to h) \times$BR($h \to aa$) are determined.

CDF searched for charged Higgs in top quark decays, $t \to H^\pm b \to W^\pm Ab \to W^\pm \tau\tau b$, within NMSSM using 2.7 fb^{-1} of data [14] assuming the mass of the light pseudo-scalar (A) is less than $2m_b$. Events with low-p_T isolated tracks created by the τ decay products are selected. Since data in the signal region are consistent with backgrounds arising mainly from underlying event sources, 95% C.L. exclusion limits are set on BR($t \to H^\pm b$) for $90 < M_{H^\pm} < 160$ GeV and $4 < M_A < 9$ GeV.

4. Conclusion

CDF and DØ have actively searched for the Higgs boson in models beyond the SM. Studies with up to 4.3 fb^{-1} of data have been reported here. For the MSSM Higgs searches, the Tevatron has reached sensitivities of tan$\beta\sim$30 for $m_A < 160$ GeV. Forthcoming searches with larger datasets should also provide further insights into the deviations from expectation observed at low m_A. The Tevatron has already delivered more than 9 fb^{-1} of data and as more is collected, both DØ and CDF expect to probe significant regions of MSSM parameter space. The experiments look forward to exciting results ahead in its Run II Higgs search program.

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