BEYOND THE STANDARD MODEL HIGGS BOSON SEARCHES AT THE TEVATRON

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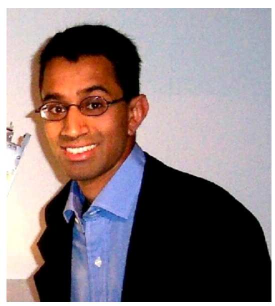

This paper reviews recent searches for beyond the Standard Model Higgs bosons by the DØ and CDF collaborations in $p\bar{p}$ collisions at the Fermilab Tevatron at $\sqrt{s} = 1.96$ TeV. Results from both experiments for searches of Fermiophobic Higgs as well as for Higgs within SUSY at high $\tan\beta$ are presented. As no significant excess is observed in data with respect to predicted backgrounds, strong model-dependent limits are set for each.

1 Introduction

The Standard Model (SM) of particle physics has been very successful in describing particles and their interactions. However, the SM is incomplete and proposed extensions to the model predict the existence of one or more Higgs bosons. Within these extended models, the Higgs behaves similarly to the SM Higgs but tends to exhibit different couplings to other particles. In particular, the branching ratios of the various Higgs decays can be enhanced significantly. This paper focuses on searches for the Higgs bosons at the Tevatron in Run II within the context of three different frameworks: Fermiophobic Higgs model, the Minimal Supersymmetric Standard Model (MSSM), and a slightly richer model of Next-to-MSSM (NMSSM).

2 Fermiophobic Higgs Boson

In Fermiophobic Higgs models, the Higgs primarily couples to bosons such that the Higgs-to-fermion branching ratios are substantially suppressed. For a relatively light Higgs boson, $m_h \lesssim$ 110 GeV, the Higgs predominantly decays to a $\gamma\gamma$ pair, and at higher masses, to a W boson pair.

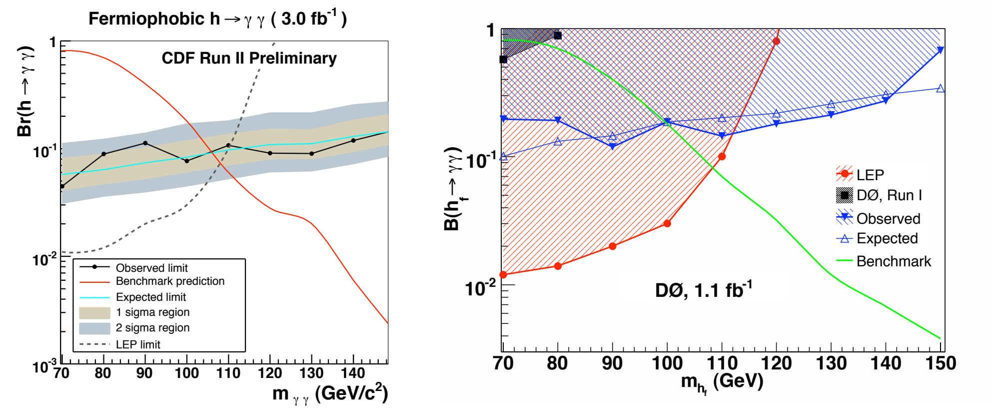

Figure 1: 95% C.L. limits on BR(h_f) as a function of Fermiophobic Higgs mass for CDF (left) and DØ (right).

The latter search is performed in the $WH \to WWW^*$ channel, where the Higgs is produced in association with a W boson.

Considering 2.7 fb^{-1} of the Run II data, CDF has searched in the $WH \to WWW^*$ channel by looking for like-sign dilepton (e, μ) pairs [1]. The search is based on data-driven methods separated into control regions to estimate backgrounds from fake leptons and residual photon conversions. The search sensitivity is improved by implementing an 8-variable Boosted Decision Tree (BDT), which is trained at each Higgs signal mass between 110 to 200 GeV in intervals of 10 GeV. After selections, events in data agree with background expectations, and the results are interpreted in the framework of a search for a Fermiophobic Higgs. Here, the limit on the ratio of $\sigma(p\bar{p} \to WH)\times$BR$(H \to WW)$ with theory near 8.8 has been reached at $m_h = 120$ GeV.

Similarly, the DØ search for $WH \to WWW^*$ is based on 1.0 fb^{-1} of data [2] and selects like-sign isolated dilepton pairs, e or μ, with $p_T^{e,\mu} > 15$ GeV. Track quality cuts are imposed in order to improve the charge measurement. The sample is divided according to the three final states: ee, $\mu\mu$, and $e\mu$. The dominant physics background process includes $WZ \to l\nu ll$, where a lepton (l) is lost from the Z boson, and is estimated from MC events normalized using its theoretical cross section. Additionally, two instrumental backgrounds arise from a) "charge flips" where the charge of one of the leptons is misreconstructed and b) jets misidentified in QCD multijet events. Each of these backgrounds is estimated from a combination of MC and data separated into different control regions. As events in data agree with background predictions, DØ places mass-dependent limits on $\sigma \times$ BR and reaches similar sensitivities as CDF.

Both DØ and CDF also performed a Fermiophobic Higgs search in the decay $h_f \to \gamma\gamma$. The DØ search considers 1.1 fb^{-1} of data [3]. Primary backgrounds originate from QCD direct $\gamma\gamma$ production as well as γ+jet and dijet events where one or both jets are misidentified as photons. In order to distinguish signal photon candidates from such backgrounds, a neural network is applied using calorimeter shower shape and preshower cluster variables. The latter is based on energy-weighted cluster depositions in the preshower whose width is narrower for photons than for jets. On the other hand, CDF result is based on 3.0 fb^{-1} dataset that searches for a very narrow peak in the diphoton mass spectrum, $M_{\gamma\gamma}$, which is fitted with a smooth function [4]. As no excess of events is observed in the $M_{\gamma\gamma}$ distribution for either experiment, mass-dependent limits on BR(h_f) are set, as shown in Fig. 1. For such couplings, CDF sets 95% C.L. lower limit on the Fermiophobic Higgs of $m_{h_f} > 106$ GeV while DØ excludes masses upto 100 GeV. The result reported by CDF is the stringent limit to date by a hadron collider for the model. Moreover, both DØ and CDF improve the LEP limits on BR($h_f \to \gamma\gamma$) at intermediate masses ($m_{h_f} \gtrsim 130$ GeV), extending the sensitivity into the region not accessible by LEP.

3 MSSM Higgs Boson

The Higgs sector in MSSM predicts two Higgs doublets, which leads to five Higgs bosons after electroweak symmetry breaking: two neutral CP-even Higgs (h^0, H^0), one CP-odd Higgs (A^0), and a pair of charged Higgs bosons ($H^{\pm}$). At tree level, the MSSM Higgs is fully specified by two free parameters, which are chosen to be the mass of the CP-odd Higgs, m_A, and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. Radiative corrections, however, introduce a dependence on additional SUSY parameters. The Higgs boson production cross section is enhanced in the region of low m_A and high $\tan\beta$ by a factor proportional to $\tan^2\beta$. Moreover, at least two of the three neutral Higgs bosons, commonly denoted as $\phi(=h, H, A)$, are nearly degenerate in mass, leading to a further increase in cross section. In most parameter space, ϕ decays to $b\bar{b}$-quark ($\tau\tau$-lepton) pairs with branching fractions on the order of 90% (10%). Although the τ-mode has a smaller BR, it provides a much cleaner signature whereas the b-mode suffers from large QCD multijet backgrounds. Nonetheless, both CDF and DØ are well-situated to study both modes, and the Tevatron searches can probe several MSSM benchmark scenarios to extend the search region covered by LEP [5].

3.1 $\phi b \to b\bar{b}b$ Searches

A direct $\phi \to b\bar{b}$ search is difficult given the large multijet background. Instead, CDF and DØ consider searches for ϕ production in association with at least one b-jet. DØ selects events with 2.6 fb^{-1} of data, requiring three b-tagged jets using a NN b-tagger, which combines several *dca* and vertex-based tagging algorithms [6]. A six-variable likelihood is then used to discriminate Higgs boson b-jet pairs from multijet backgrounds. The background is estimated from 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 triple b-tagged composition in data. The search sensitivity is improved by separating the analysis into three-, four-, and five-jet channels. After all selections, background yields agree with data and thus, the dijet invariant mass is used to set $\tan\beta$ exclusion limits at 95% C.L. for representative MSSM scenarios. Here, Fig. 2 (left) shows the DØ exclusion for m_h^{max} and $\mu < 0$, where enhanced production for the $3b$ mode yields the strongest limits.

CDF performed a similar analysis in 1.9 fb^{-1} of data by requiring triple b-tagged jets using a displaced vertex algorithm [7]. The search requires vertex mass fits to two- and three-jet distributions to estimate the quark content within the heavy-flavor multijet backgrounds. Subsequently, CDF searches for enhancements in the mass of the two leading jets and as data agrees with background predictions, mass-dependent cross section limits are set. These limits are translated into a MSSM exclusion, which is shown in Fig. 2 (right) for m_h^{max} and $\mu < 0$.

3.2 $\phi \to \tau\tau$ and $\phi b \to \tau\tau b$ Searches

Searches for $\phi \to \tau\tau$ have been performed by DØ [8] with integrated luminosities of 1.0 fb^{-1} and by CDF [9] with 1.8 fb^{-1}. These searches require 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. Moreover, DØ has extended its search in the $\tau_\mu\tau_{had}$ mode using a total 2.2 fb^{-1} dataset [10].

The CDF analysis requires an isolated e or μ oppositely charged from a τ_{had}. The hadronic taus are split according to their decay mode and selected using a variable-size cone algorithm. Backgrounds originating from multijet events are suppressed by requiring $H_T > 50$ (45) GeV for $\tau_e\tau_{had}$ ($\tau_\mu\tau_{had}$) modes, where H_T is the scalar sum of the lepton and hadronic p_T with the missing transverse energy, $\not{E}_T$. The W+jets background is removed by placing a requirement on the relative direction of the visible τ decay product and $\not{E}_T$. After selections, the irreducible background from $Z \to \tau\tau$ remains, and the visible mass, defined as the invariant mass of

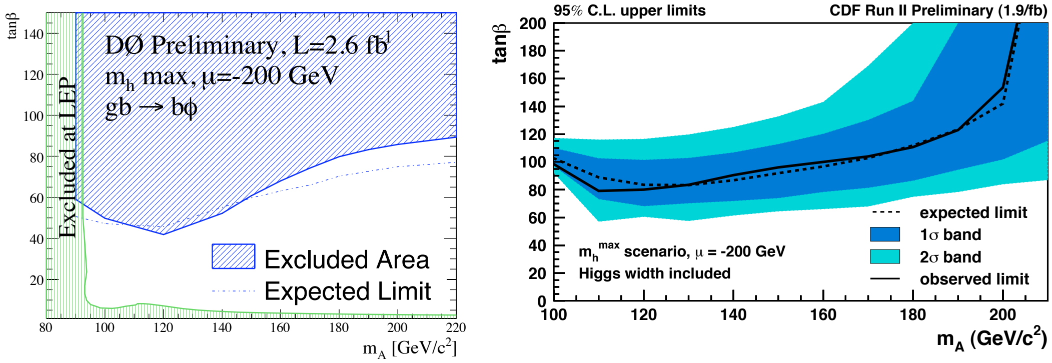

Figure 2: 95% C.L. exclusion limits in the (m_A, $\tan\beta$) plane in m_h^{max} and $\mu < 0$ MSSM scenario for $\phi b \to b\bar{b}b$ searches at DØ (left) and CDF (right). The effects of non-negligible Higgs boson width are included for each.

the visible τ decay products and the missing momentum four-vector approximated by $\not{P}_{\rm T} = (\not{E}_T, \not{E}_{\rm x}, \not{E}_{\rm y}, 0)$, is exploited to search for an enhancement of signal over backgrounds. The visible mass is shown in Fig. 3. Since no significant excess is observed in data, regions of (m_A, $\tan\beta$) are excluded in MSSM benchmark scenarios, also shown in Fig. 3.

DØ performed similar searches, which for the 2.2 fb^{-1} $\tau_\mu\tau_{had}$ analysis selects events with an isolated μ oppositely charged and separated from a τ_{had}. The hadronic taus are categorized by decay types and discriminated from the jet background using a τ-identification algorithm based on neural networks (NN). The NN input variables use isolation and shower shape parameters as well as correlations built between calorimeter clusters and tracks. An additional series of selections are imposed to help suppress backgrounds dominated by heavy-flavor multijet events where a jet can be misidentified as a τ candidate. This includes $M_T < 40$ GeV to reject $W(\to l\nu)$+jet events, where M_T is the transverse mass reconstructed from the lepton and missing transverse momentum vector. Since data events agree with the sum of predicted backgrounds across the visible mass spectrum, exclusions at 95% C.L. within the (m_A, $\tan\beta$) plane are derived in MSSM benchmark scenarios. These results are summarized in Fig. 4. From these searches, both CDF and DØ reach similar sensitivities of $\tan\beta \sim 40-50$ for low m_A (<180 GeV).

A separate search in the $\phi b \to \tau\tau b$ channel has been carried out by DØ using 1.2 fb^{-1} of data [11]. Since the final state contains a τ-pair with an additional b-quark, the techniques developed for both the $\phi \to \tau\tau$ and $\phi b \to b\bar{b}b$ searches are used. The backgrounds are initially dominated by QCD multijet, $Z \to \mu\mu$ and $Z \to \tau\tau$ events. These are largely reduced by imposing a single b-tag, yielding a final dataset primarily composed of multijet and $t\bar{t}$ backgrounds. As no excess in the final data sample is observed, regions of $\tan\beta \sim 60$ (100) at $m_A \sim 90$ (160) GeV are excluded in MSSM benchmark scenarios. The results are both competitive and complementary to the other ϕ search modes and contribute to the overall Tevatron sensitivity.

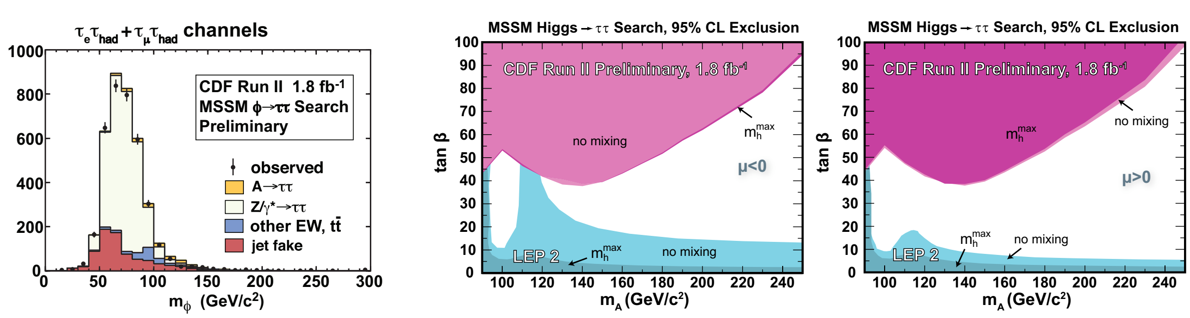

Figure 3: CDF search for $\phi \to \tau\tau$. Results are shown for the visible mass spectrum in $\tau_e\tau_{had} + \tau_\mu\tau_{had}$ final states (left) and for MSSM $\tan\beta$ exclusions for $\mu < 0$ (middle) and $\mu > 0$ (right) in the no-mixing and m_h^{max} scenarios.

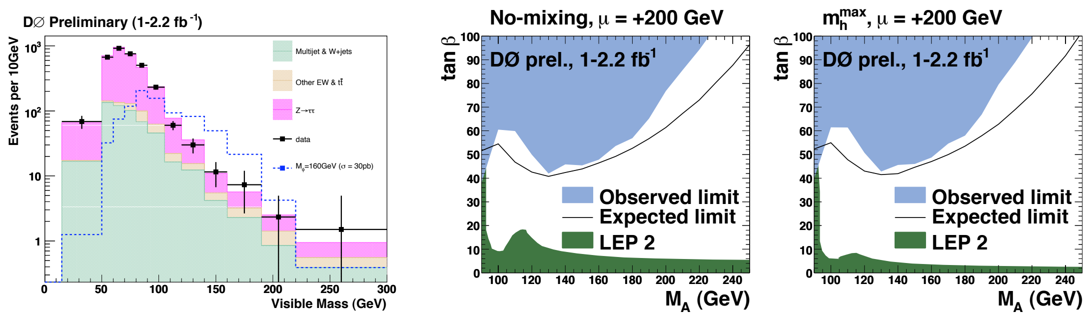

Figure 4: DØ search for $\phi \to \tau\tau$. Results are shown for the visible mass spectrum in $\tau_\mu \tau_{had}$ final state (left) and MSSM exclusions in the (m_A, $\tan\beta$) plane in the no-mixing (middle) and m_h^{max} (right) scenarios for $\mu > 0$.

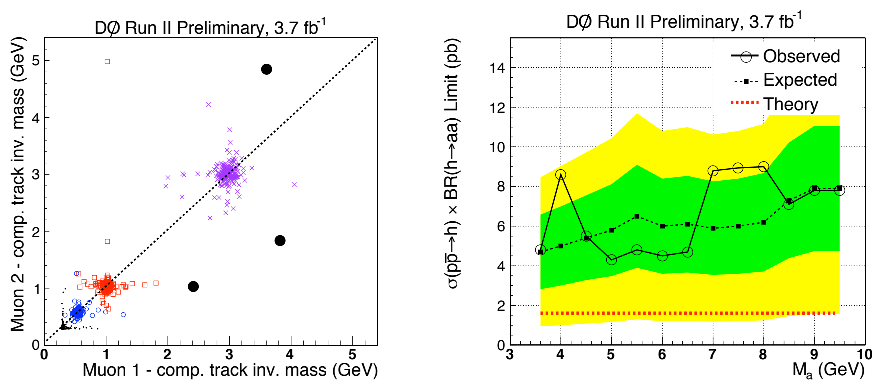

Figure 5: DØ search for $h \to aa \to \mu\mu\mu\mu$ or $\mu\mu\tau\tau$. Left: invariant mass of the muon and companion track for leading vs. second-leading p_T muons. Shown are data (solid big black dots), and various generated signal masses: 0.2143 GeV (small black dots), 0.5 GeV (open blue circles), 1 GeV (open red squares), and 3 GeV (purple crosses). Right: expected and observed limits on $\sigma\times$BR vs. M_a with ± 1 (green) and 2σ (yellow) bands for $M_h = 100$ GeV.

4 NMSSM Higgs Boson

DØ has also recently added a new search channel for Higgs boson (h) production in extended, richer models of NMSSM [12] using 3.7 fb^{-1} of data [13]. Here, the $h \to b\bar{b}$ mode is greatly reduced and the h dominantly decays to a pair of lighter neutral pseudo-scalar Higgs bosons (a). The DØ study is divided into two search modes depending on the mass of a (M_a).

Within the mass region $2M_\mu \lesssim M_a \lesssim 2M_\tau$ ($\sim$ 3.6 GeV), the BR($a \to \mu^+\mu^-$) is $\sim$100% and the study focuses on 4μ final states. The signal signature consists of two pairs of extremely collinear muons due to the low a mass. In order to detect such a topology, the object-ID for muons is redefined by requiring a "companion track" with $p_T > 4$ GeV associated with each muon track of $p_T > 10$ GeV, within $\Delta R < 1$. Further, the typical single μ isolation criteria is modified to consider the isolation for each "μ-companion track" pair. Dominant backgrounds include a) muons from π/K in-flight decays or from heavy-flavor decays, which are estimated from data using control samples without the μ isolation requirement, and b) $Z/\gamma^* \to \mu\mu$ events, where additional fake companion tracks are reconstructed. After selections, three events are observed in data, consistent with the total background of 1.5$\pm$0.5 events. In particular, no clustering of isolated data events is observed in the muon-companion track invariant mass distribution for the leading vs. second-leading p_T muons, as shown in Fig. 5 (left), which is expected for signal. Therefore, assuming a Higgs cross section of 1000 fb at $M_h = 120$ GeV, the search excludes BR($a \to \mu\mu$) $\gtrsim$ 10 at 95% C.L. for large BR($h \to aa$).

A second topology is studied within the mass range $2M_\tau \lesssim M_a \lesssim 2M_b$ (~ 9.0 GeV). Here, BR($a \rightarrow \mu^+\mu^-$) is suppressed and a dominantly decays to τ-pairs. Since the 4τ decay channel is limited by the ability to efficiently trigger on low p_T leptons, the search focuses on the $2\mu2\tau$ final-state. The signature is comprised of a pair of collinear muons reconstructed back-to-back in azimuthal ϕ with respect to substantial $\not\!\!E_T$ (> 25 GeV) arising from the $a \rightarrow \tau^+\tau^-$ decay. Selections on the muon are tightened in order to ensure the $\not\!\!E_T$ is accurately corrected for the transverse momentum of the muons. The QCD background is estimated from data where events must pass all selections except with $\not\!\!E_T < 25$ GeV, while contributions from diboson, W+jets, and $t\bar{t}$ production are determined from simulated PYTHIA samples. A counting experiment is performed by fitting the dimuon mass spectrum and counting the events for data, signal, and background within a 2σ window. As no excess is observed in data, limits on $\sigma(p\bar{p})\times$ BR($h \rightarrow aa$) are determined. These are shown in Fig. 5 (right) relative to the reference SM Higgs cross section for $M_h = 100$ GeV. Here, the current limits from the Tevatron are still a factor of $\sim$4 larger than the expected Higgs production. Moreover, approximately 40 fb^{-1} of data would be needed in order to reach sensitivity to the expected signal level.

5 Conclusion

CDF and DØ have actively searched for the Higgs boson in models beyond the SM across a comprehensive set of search channels. Studies with integrated luminosities of up to 3.7 fb^{-1} have been reported here, and in the absence of signal, each experiment has established strong model- and mass-dependent limits. For the MSSM Higgs searches, sensitivities of $\tan\beta \sim 40-50$ for $m_A < 180$ GeV have been reached. Updates to these searches as well as a combination of the different channels, and among experiments for an overall Tevatron limit, is expected soon. Moreover, the DØ studies on NMSSM Higgs production represent a new search at the Tevatron. The collider has already delivered more than 6 fb^{-1} of data and as more is collected, both DØ and CDF expect to continually improve the sensitivity. If a key value of (m_A, $\tan\beta$) is achieved, the experiments look forward to the prospects for a Higgs boson discovery in the Run II program.

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