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# Searches for Beyond the Standard Model Higgs Bosons in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV

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**Abstract.** The recent results on various Beyond the Standard Model (BSM) Higgs boson searches performed by the DØ experiment at the Tevatron are presented here. In particular, the Higgs bosons in supersymmetric models and fermiophobic scenario have been investigated. No significant excess over the Standard Model (SM) expectations have been observed and accordingly limits have been established on the corresponding model parameters.

**Keywords:** Higgs, Fermiophobic, MSSM, NMSSM, DØ, Tevatron
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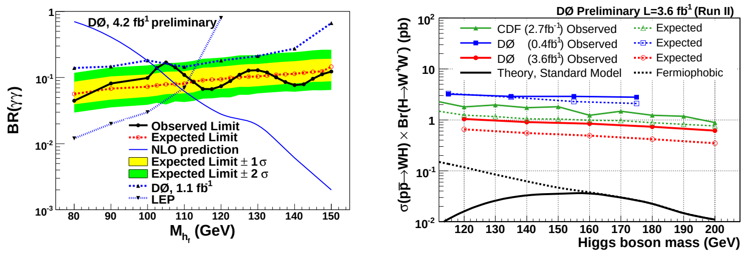
## INTRODUCTION

Besides the Standard Model Higgs Boson searches, the DØ physics program is enriched with various well motivated BSM Higgs boson searches. The searches are primarily focused on the Higgs bosons from three different models: the Fermiophobic Higgs model, the Minimal Supersymmetric Standard Model or MSSM and the next to Minimal Supersymmetric Standard Model or NMSSM. The analyses summarized here are performed with 1-4.2 $\mathrm{fb}^{-1}$ of $p\bar{p}$ collision data recorded with the DØ detector during Run II of the Tevatron Collider at Fermilab.

## FERMIOPHOBIC HIGGS SEARCH

The Fermiophobic model assumes zero couplings of the Higgs boson to fermions while the Higgs couplings to the gauge bosons remain the same as in the SM. In such models, Higgs boson production via gluon fusion is absent and the Higgs bosons are mainly produced in association with a $W^{\pm}$ or a $Z^0$ boson (VH) and via vector boson fusion (VBF). DØ has performed the searches for such Fermiophobic Higgs bosons ($h_f$) in two different channels: $h_f \rightarrow \gamma\gamma$ and $W^{\pm}h_f(\rightarrow W^+W^-)$ with 4.2 $\mathrm{fb}^{-1}$ and 3.6 $\mathrm{fb}^{-1}$ datasets respectively.

In the inclusive $h_f \rightarrow \gamma\gamma$ search, both both VH and VBF production modes are considered. The background events for this channel are contributed by $Z^0/\gamma^* \rightarrow e^+e^-$, $\gamma$+jet and QCD dijet production processes. Here the invariant mass ($M_{\gamma\gamma}$) distribution from two reconstructed photons (with $p_T > 20$ GeV) has been utilized as the final discriminating variable. The observed limits on the production cross section have been translated into the benchmark model expectations and a Fermiophobic Higgs boson mass




(a) (b)

**FIGURE 1.** (a) The limits on $Br(h_f \to \gamma\gamma)$ as a function of Higgs boson mass ($M_{h_f}$); $M_{h_f} < 102.5$ is excluded at 95% CL. (b) The 95% CL limits on $\sigma(p\bar{p} \to W^{\pm}h_f) \times Br(h_f \to W^+W^-)$ as a function of Higgs boson mass. The previous DØ results are also shown for comparison.

below 102.5 GeV is excluded at 95% CL (see Fig. 1(a)).

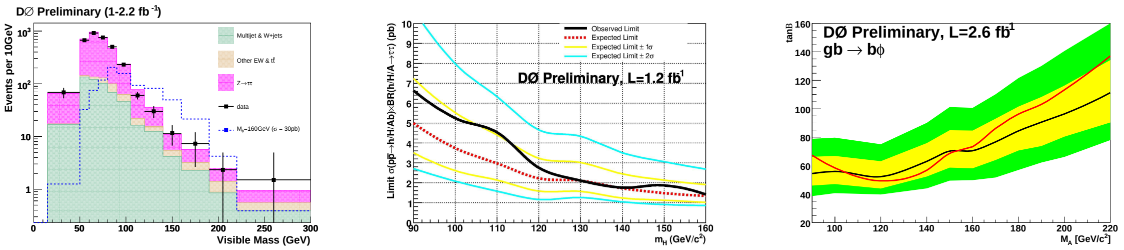
In the Fermiophobic Higgs models, the $BR(h_f \to W^+W^-)$ becomes nearly 100% for a Higgs boson mass above 100 GeV [1]. The signatures of $W^{\pm}h_f(\to W^+W^-)$ events have been looked for in the events containing two like-signed leptons, $l^{\pm}l^{\pm}$ (electrons or muons). The physics processes like $W^{\pm}Z^0 \to l^{\pm}l^{\pm}l^{\mp}$ and $Z^0Z^0 \to l^{\pm}l^{\mp}l^{\pm}l^{\mp}$ along with the misreconstructed $Z^0/\gamma^* \to e^+e^-/\mu^+\mu^-$ events are the most dominant background processes for this search channel. The observed and expected limits on $\sigma(p\bar{p} \to W^{\pm}h_f) \times Br(h_f \to W^+W^-)$ are compared to the SM and Fermiophobic model predictions in Fig. 1(b).

## SEARCH FOR NEUTRAL MSSM HIGGS BOSONS

The MSSM[2][3] requires two doublet Higgs fields to generate masses to both "up"-type and "down"-type fermions. After electroweak symmetry breaking, such a two-Higgs-doublet model predicts the existence of five physical Higgs bosons: two CP-even Higgs bosons, h and H, one CP-odd Higgs boson, A and a pair of charged Higgs bosons, $H^{\pm}$. At the tree level, the MSSM Higgs phenomenology can fully be described by two free parameters: $m_A$, the mass of the CP-odd Higgs boson and $\tan\beta$, the ratio of vacuum expectation values of the Higgs fields to the "up"-type and "down"-type fermions respectively.

The couplings of neutral Higgs bosons to bottom quark (b) and tau lepton ($\tau$) i.e., "down"-type fermions scale as $\tan\beta$ with respect to their SM values. Therefore for high $\tan\beta$, the production cross sections involving b quarks are enhanced of a factor $\tan^2\beta$. Moreover, the CP-odd Higgs boson A becomes degenerate with either one of the other neutral Higgs bosons, h/H which leads to a total $2\cdot\tan^2\beta$ enhancement in production cross section relative to the SM prediction. At high $\tan\beta$, the neutral Higgs bosons ($h/H/A \equiv \Phi$) decay predominantly into $b\bar{b}$ (Br≈90%) or $\tau^+\tau^-$ (Br≈10%) pairs.

Three different analyses *viz.*, $\Phi \to \tau^+\tau^-$, $\Phi b(\bar{b}) \to \tau^+\tau^- b(\bar{b})$ and $\Phi b(\bar{b}) \to bbb(\bar{b})$ are presented here consisting of 2.2, 1.2 and 2.6 fb$^{-1}$ datasets respectively. The inclusive $\Phi \to \tau^+\tau^-$ search considers the events where one of the tau leptons decays into a muon ($\tau_\mu$) while the other tau lepton decays hadronically ($\tau_{had}$). The hadronically decaying tau leptons are classified into three different types depending on their detector signatures and




(a) (b) (c)

**FIGURE 2.** (a) The visible mass distribution (see text) for inclusive $p\bar{p} \to \Phi(\to \tau^+\tau^-)$ searches. (b) Limits on $\sigma(p\bar{p} \to \Phi b(\bar{b})) \times BR(\Phi \to \tau^+\tau^-)$ vs $M_\Phi$. (c) The tree level limits on $\tan\beta - m_A$ from $\Phi b(\bar{b}) \to bbb(\bar{b})$ search channel.

are selected through the usage of neural network discriminants ($NN_\tau$). The background events for this channel are dominated by $Z^0/\gamma^* \to \tau^+\tau^-$, $Z^0/\gamma^* \to \mu^+\mu^-$ and multijet QCD production processes. The $W^\pm$+jet events are rejected by requiring $M_T(p_T^\mu, \not{E}_T) <$ 40 GeV. The said analysis with 1.2 $fb^{-1}$ Run IIb dataset is combined with earlier analysis [4] with 1 $fb^{-1}$ of Run IIa dataset which considers additional final states *viz.*, $\tau_e\tau_{had}$ and $\tau_e\tau_\mu$. The distribution for the combined visible mass i.e., $\sqrt{(P_{\tau 1} + P_{\tau 2} + \not{P}_T)^2}$, where $P_{\tau 1,2}$ is the four vector of the visible tau decay products and $\not{P}_T = (\not{E}_T, \not{E}_x, \not{E}_y, 0)$, is shown in Fig. 2(a). In the $\Phi b(\bar{b}) \to \tau^+\tau^- b(\bar{b})$ search, the events are characterized by an isolated muon, a hadronic tau jet candidate (same $NN_\tau$ selection as in $\Phi \to \tau^+\tau^-$) and a b-tagged jet. Multijet QCD, $t\bar{t}$ and $Z^0/\gamma^* \to \tau^+\tau^- b/c$ are the dominating background processes and they are reduced further by applying a 2D neural network discriminant. Fig. 2(b) shows the limits on $\sigma(p\bar{p} \to \Phi b(\bar{b})) \times BR(\Phi \to \tau^+\tau^-)$ at 95% CL. In the $\Phi b(b) \to bbb(\bar{b})$ search, the events are required to have 3-5 jets ($p_T > 20$ GeV and $|\eta| < 2.5$) three of which are b-tagged. The overwhelmingly large QCD background contributions are determined through usage of both data and Monte Carlo (MC) distributions. The invariant mass distribution from the jet pairs are considered here after applying a likelihood discriminant for further separation between signal and background processes. The cross section limits are translated into the $\tan\beta - m_A$ space assuming a simple $2 \cdot \tan^2\beta$ enhancement over the SM and are shown in Fig 2(c).

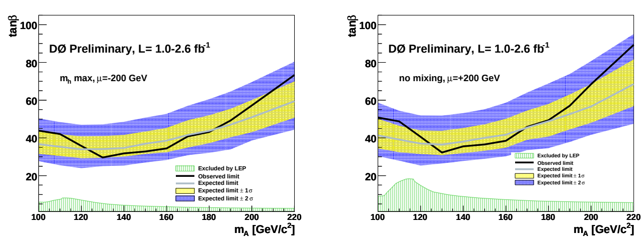



**FIGURE 3.** Combined limits on MSSM parameter space for different benchmark scenario: $m_h^{max}$, $\mu$=-200 GeV (left) and no-mixing, $\mu$=+200 GeV(right).

Finally, all three above mentioned searches are combined taking into account systematic uncertainties, including the correlations across channels and analyses. Fig. 3 shows the combined results interpreted in different benchmark scenarios[5].

## NMSSM HIGGS SEARCH

In the next-to-MSSM (NMSSM) [6], at lower masses the Higgs boson predominantly decays into a pair of lighter neutral pseudoscalars, a. The result is a suppression of $h \rightarrow b\bar{b}$ branching ratio. Depending on its mass, the neutral pseudoscalar can decay into a pair of muons ($2M_\mu < M_a < 3M_\pi$) or taus ($2M_\tau < M_a < 2M_b$). Thus the final state signatures would consist of two muon pairs or two tau pairs. However, because of the difficulties with the $4\tau$ final state, the search is performed in the $h \rightarrow a(\rightarrow \tau^+\tau^-)a(\rightarrow \mu^+\mu^-)$ final state. Due to the extreme collinearity of the $\mu^+\mu^-$ pair from the pseudoscalar decay and the finite angular resolution of the DØ muon system, each muon pair in 4 muon channel is required to contain one muon trajectory associated with a companion track. A requirement of $\Delta R > 1$ between the muon pairs is applied to ensure that these muon pairs are well separated from each other. For the $2\tau + 2\mu$ channel however both the muons in a muon pair are required to be reconstructed and should be close to each other within $\Delta R < 1$. It is to be noted here that $2\tau + 2\mu$ analysis does not require explicit tau reconstruction (compromised by the collinearity of the taus). Instead, the $\not{E}_T$ requirements are used to predominantly select the events with tau candidates.

For $M_a < 2M_\tau$, the 4 muon channel sets an upper limit of 10 fb on $\sigma(p\bar{p} \rightarrow hX)Br(h \rightarrow aa)Br(a \rightarrow \mu^+\mu^-)^2$. Assuming $Br(h \rightarrow aa) \approx 100\%$ and the SM $\sigma(p\bar{p} \rightarrow hX) \approx 1.9$ pb (for $M_h = 100$ GeV), the corresponding upper limit on $Br(a \rightarrow \mu^+\mu^-) \approx 7\%$. However, in the NMSSM the $BR(a \rightarrow \mu^+\mu^-)$ is expected to be larger than 10% for $M_a < 2m_c$ and depending on the branching ratio of $a \rightarrow c\bar{c}$ possibly even up to $2m_\tau$. Thus the recently reported[7] DØ result severely constrains the region $2M_\mu < M_a < 2M_\tau$. For $M_a > 2m_\tau$, the limits set by the $2\tau + 2\mu$ channel are a factor of 1-4 larger than the expected production cross section.

## CONCLUSIONS

DØ has made rigorous BSM Higgs bosons searches in most of the promising channels. Neither of the searches presented here observe a statistically significant excess over the SM background expectations. Accordingly at 95% CL, the most restrictive limits have been established on relevant parameters for different theories. Improved analysis techniques along with the rapidly increasing datasets are expected to enhance the sensitivity of future BSM Higgs searches. For the most recent results see Ref. [8].

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