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Searches for Non-SM Higgs at the Tevatron

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We present the non-standard model Higgs boson searches at both DØ and CDF experiments. We concentrate on three topics, reported by DØ and CDF recently: the searches for the minimal supersymmetric Higgs boson using $p\bar{p} \to hb\bar{b} \to b\bar{b}b\bar{b}$ and $p\bar{p} \to hX \to \tau\tau X$, and for long-lived doubly charged Higgs boson.

1 Introduction

Tevatron is currently the only place where we can search for not only the standard model (SM) Higgs boson but also non-SM Higgs bosons. CDF and DØ have started searching for the exotic Higgs bosons including supersymmetric Higgs bosons and doubly charged Higgs bosons. DØ recently updated the results of the minimal supersymmetric standard model (MSSM) Higgs boson search using $hb\bar{b} \to b\bar{b}b\bar{b}$ final state. CDF updated its search for MSSM Higgs bosons using $hX \to \tau\tau X$ final state, and long-lived doubly charged Higgs bosons.

2 Search for MSSM Higgs bosons

In two-Higgs-doublet models of electroweak symmetry breaking, such as the MSSM [1], there are five physical Higgs bosons: two neutral CP-even scalars, h and H; a neutral CP-odd state, A; and two charged states, $H^{\pm}$. The ratio of the vacuum expectation values of the two Higgs fields is defined as $\tan\beta = v_2/v_1$, where v_2 and v_1 refer to the Higgs fields that couple to the up-type and down-type fermions, respectively. At tree level, the coupling of the A boson to down-type quarks, such as the b quark, is enhanced by a factor of $\tan\beta$ relative to the standard model (SM), and the production cross section is therefore enhanced by $\tan^2\beta$ [2]. The Tevatron is currently sensitive to $\tan\beta$ in the range $\tan\beta > 50$. In this region of $\tan\beta$, the A boson is nearly degenerate in mass with either the h or the H boson, and their widths are small compared to the di-jet mass resolution. Consequently, we cannot distinguish between the h/H and the A, and the total cross section for signal is assumed to be twice that of the A boson. LEP experiments have excluded at the 95% C.L. a light Higgs boson with mass $m_h \leq 92.9$ GeV [3]. The major decay modes of h are a b quark pair production(90%) and τ lepton pair production(8%). The $p\bar{p} \to hb\bar{b}$ with $h \to b\bar{b}$ or $h \to \tau\tau$ decay are considered the most promising channels at Tevatron.

2.1 Search for MSSM Higgs bosons in hbb channel at DØ

The analysis is based on 260 pb^{-1} of data collected using the DØ detector from November 2002 to June 2004. The dedicated trigger is designed for maximizing signal acceptance while providing reasonable trigger rate. Events with up to five jets are selected. Depending on the hypothesized Higgs boson mass, the jet p_T selections are chosen to optimize the expected signal significance. Jets containing b quarks are identified using a secondary vertex (SV) tagging algorithm. The b tagging efficiency is $\approx 55\%$ for central b-jets of p_T>35 GeV with a light quark (or gluon) tag rate of about 1%.

The signal bh events, with $h \to b\bar{b}$, were generated for Higgs boson masses from 90 to 150 GeV using PYTHIA event generator [4]. The p_T and rapidity spectra of the Higgs bosons from PYTHIA were adjusted to those from NLO calculation [5]. The multijet production is the major source of background and is determined from data. As a cross-check, we also compared the data with ALPGEN [6] event generator. All other backgrounds are expected to be small and are simulated with PYTHIA.

There are two main categories of multijet background. One contains genuine heavy-flavor jets, while the other has only light-quark or gluon jets that are mistakenly tagged as b-quark jets, or correspond to gluons that branch into nearly collinear $b\bar{b}$ pairs. Using the selected data sample, before the application of b-tagging requirements, the probability to b-tag a jet ("mis-tag" function) is measured as a function of its p_T and $|\eta|$. The mis-tag function is corrected by subtracting heavy-flavor contributions. This mis-tag function is used to estimate the mis-tagged background, by applying it to every jet reconstructed in the full data sample. The triple b-tagged data are compared with this background expectation and no signal evidence is found. Figure 1 shows the expected MSSM Higgs boson production cross section as a function of m_A for $\tan\beta = 80$. The MSSM cross section shown in Figure 1 corresponds to no mixing in the scalar top quark sector [7], or $X_t = 0$, where $X_t = A_t - \mu \cot\beta$, A_t is the tri-linear coupling, and the Higgsino mass parameter $\mu = -0.2$ TeV. We also interpret our results in the "maximal mixing" scenario with $X_t = \sqrt{6} \times M_{SUSY}$, where M_{SUSY} is the mass scale of supersymmetric particles, taken to be 1 TeV. Results for both scenarios of the MSSM are shown in Figure 1 as limits in the $\tan\beta$ versus m_A plane. The present DØ analysis excludes a significant portion of the parameter space, down to $\tan\beta$= 50, depending on m_A and the MSSM scenario assumed.

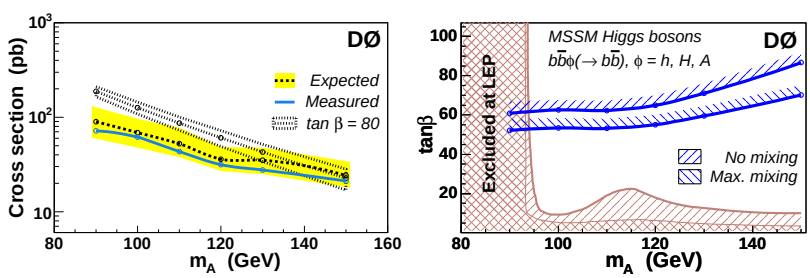

Figure 1: The upper limits on the signal cross section as a function of Higgs boson mass (left) and the 95% C.L. upper limit on $\tan\beta$ as a function of Higgs boson mass (right).

2.2 Search for MSSM Higgs bosons in $hX \to \tau\tau X$ channel at CDF

Using the data collected by the CDF detector from March 2002 to January 2004, corresponding to an integrated luminosity of about 200 pb^{-1}, MSSM Higgs searches for the $hX \to \tau\tau X$ is presented. The signal consists of a tau pair in which one of the taus decays to hadrons and a neutrino (τ_h) while the other decays to an electron (τ_e) or a muon (τ_μ) and two neutrinos. The data are collected with a set of dedicated τ-triggers which select a lepton (e or μ) candidate

with $p_T > 8$ GeV and an isolated track from τ_h decay. The τ, which decays to hadrons, are reconstructed by charged tracks and neutral pions inside special τ narrow cone. The invariant mass of τ_h and the track multiplicity of the τ_h is required to be less than 1.8 GeV and equal to 1 or 3, respectively. The further selections are done on the event topology using missing transverse energy ($\not\!\!E_T$), p_T of τ_e or τ_μ and τ_h. An example is the scalar sum $\hat{H}_T = |p_T^{vis}(\tau_1)| + |p_T^{vis}(\tau_2)| + \not\!\!E_T$, where $p_T^{vis}(\tau)$ is visible transverse momentum of the tau decay products not including neutrinos. Requiring $\hat{H}_T$ >50 GeV leads to significant background reduction with small signal loss.

The signal processes $gg \to h$ and $bb \to h$ is simulated using PYTHIA event generator. We generate Higgs masses between 115 GeV and 200 GeV for $\tan\beta$ =30. The backgrounds from $Z \to l^+l^-$, (l=e,μ,or τ), di-boson production, and $t\bar{t}$ production are estimated using Monte Carlo samples. The Backgrounds from jet to τ misidentification are estimated using a fake rate function obtained from independent jet samples, as a function of the jet energy, psuedorapidity, and track multiplicity. The biggest source of background is $Z \to \tau\tau$ events, which can only be distinguished from the Higgs signal by the di-τ mass. We define a mass-like discriminating variable $m_{vis}(l,\tau_h^{vis}, \not\!\!E_T)$. It is constructed using the four-momentum of the lepton (e or μ), the four-momentum of the visible decay products of the $\tau_h(\tau_h^{vis})$ and $\not\!\!E_T$ (also treated as a four vector). After combining the $\tau_e\tau_h$ and $\tau_h\tau_\mu$ channels, we perform a binned likelihood fit of the $m_{vis}(l,\tau_h^{vis}, \not\!\!E_T)$ distribution to extract a Higgs signal. The uncertainties in background estimation are incorporated in the imposed Gaussian constraints. Several signal templates were generated to cover the studied mass region. Figure 2 shows the $m_{vis}(l,\tau_h^{vis}, \not\!\!E_T)$ distribution for data and various backgrounds. The limits on Higgs production cross section times branching fraction at 95 % C.L. are presented in Figure 2.

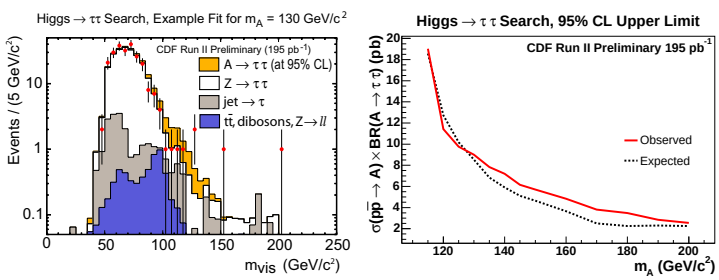

Figure 2: Observed $m_{vis}(l,\tau_h^{vis}, \not\!\!E_T)$ distributions for various background (left) and limits on the production product $\sigma(p\bar{p} \to h) \times B(A \to \tau\tau)$ (right).

3 Search for long-lived doubly charged Higgs bosons at CDF

A number of models like the left-right symmetric model requires a Higgs triplet containing a doubly-charge Higgs boson ($H^{\pm\pm}$), which could be light in the minimal supersymmetric left-right model. The dominant production mode at the Tevatron is expected to be $p\bar{p} \to \gamma^*/Z + X \to H^{++}H^{--}$. The partial width in the leptonic decay mode is proportional to the coupling to the lepton and Higgs mass. DØ and CDF published the $H^{\pm\pm}$ mass limits from direct searches in the di-lepton decay channels for the short lived $H^{\pm\pm}$ [8, 9]. We present here the case where $H^{\pm\pm}$ boson is long-lived ($c\tau$ >3 m), resulting in the $H^{\pm\pm}$ boson decaying outside the detector. DELPHI experiment [10] excludes $m_{H^{\pm\pm}}$ <99.6 GeV (99.3 GeV) at the 95% C.L. for $H^{\pm\pm}$ bosons with coupling to left-(right-) handed leptons.

The analysis is based on 292 pb^{-1} of data collected using the CDF Run II detector. We use an inclusive muon trigger requiring a track with $p_T > 18$ GeV, and a matching with a track in the muon chamber. We select two tracks, each with p_T >20 GeV, and at least one of the tracks to have a matching muon. Since the charge of tracks collected by drift chamber

is proportional to the ionization deposited by the particle per unit length(dE/dx), $H^{\pm\pm}$ boson deposits four times more dE/dx in the drift chamber than a single charge track like a μ. The $H^{\pm\pm}$ boson is modeled by quadrupling the dE/dx of the cosmic ray muons. The dE/dx from the low momentum protons are used as a controlled sample. We calculate the geometric and kinematic acceptance for a pair of $H^{\pm\pm}$ boson using the PYTHIA generator.

Since no data remained after selecting large dE/dx, we set 95% C.L. upper limits on the $H^{\pm}$ pair production cross section, as shown Figure 3. The theoretical cross sections are computed separately for $H^{\pm}$ bosons that couple to left- and right-handed particles($H_L^{\pm}$ and $H_R^{\pm}$). We exclude the long-lived $H_L^{\pm}$ and $H_R^{\pm}$ bosons below a mass of 133 GeV and 109 GeV, respectively. When the two states are degenerate in mass, we exclude $H^{\pm}$ <146 GeV at the 95 % C.L.

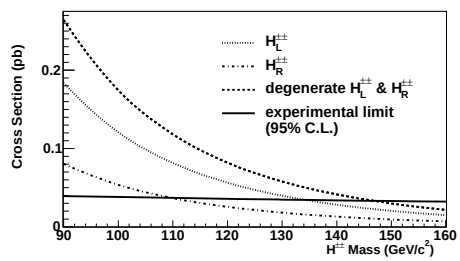

Figure 3: The comparison of the experimental cross section upper limit with the theoretical cross section for pair production of $H^{\pm}$ bosons.

4 Conclusion

We reported on searches for several types of exotic Higgs bosons. We have excluded significant area of theoretical parameters. DØ and CDF are expected to collect more data and employ advanced analysis techniques, therefore, will continue exploring the Higgs domain.

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