A search for the production of neutral Higgs bosons decaying into $\tau^{+}\tau^{-}$ final states is presented in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. The integrated luminosity used for the study is about 2.2 fb$^{-1}$, collected by the DØ Experiment at the Fermilab Tevatron Collider. No significant excess is observed over the background expectation. The results are interpreted in the Minimal Supersymmetric Standard Model (MSSM) and regions in the ($m_A$, tan$\beta$) parameter space for two MSSM benchmark scenarios are excluded.

1. INTRODUCTION

Neutral Higgs bosons produced in $p\bar{p}$ collisions at the Tevatron can decay into $\tau^{+}\tau^{-}$ final states. The cross-section times branching ratio of the $h \rightarrow \tau^{+}\tau^{-}$ final state in the Standard Model (SM) is too small to play any role in SM Higgs boson searches due to the large irreducible background from Drell-Yan production in the interesting (low mass) region. This, however, is different in the Minimal Supersymmetric Standard Model (MSSM), which predicts two Higgs doublets leading to five Higgs bosons: a pair of charged Higgs boson ($H^{\pm}$); two neutral CP-even Higgs bosons ($h,H$) and a CP-odd Higgs boson ($A$). At tree level, the Higgs sector of the MSSM is fully described by two parameters, which are chosen to be the mass of the CP-odd Higgs boson, $m_A$, and tan$\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. The Higgs boson production cross-section is enhanced in the region of low $m_A$ and high tan$\beta$ due to the enhanced Higgs boson coupling to down-type fermions \cite{1}. In addition, two of the three neutral Higgs bosons, commonly denoted by $\phi$, are often nearly degenerate in mass, leading to a further increase in the cross-section. In the low $m_A$, high tan$\beta$ region of the parameter space, Tevatron searches can therefore probe several MSSM benchmark scenarios extending the search regions covered by LEP \cite{2}.

Searches for neutral Higgs bosons decaying into tau lepton pairs, $\phi (= H, h, A) \rightarrow \tau\tau$, have been performed by the DØ Collaboration with integrated luminosities of $L = 1.0$ fb$^{-1}$ in Run IIA \cite{3} and $L = 1.2$ fb$^{-1}$ in Run IIB \cite{4}. The Run IIA search requires the tau pairs to decay into $\tau_\ell\tau_{\ell\text{had}}$, $\tau_\mu\tau_{\mu\text{had}}$, or $\tau_\tau$, and the Run IIB search requires the tau pairs to decay into $\tau_\mu\tau_{\mu\text{had}}$, where $\tau_\ell$ and $\tau_\mu$ are the leptonic decays of the tau and $\tau_{\mu\text{had}}$ is the hadronic decay mode. These studies together represent a data set of $L = 2.2$ fb$^{-1}$.

The search strategy relies primarily on implementing an efficient tau identification algorithm in conjunction to a series of selections that remove backgrounds, which are dominated by electroweak $Z/\gamma^* \rightarrow \tau\tau$ and $Z/\gamma^* \rightarrow \mu\mu$ processes, as well as those from heavy-flavor multijet events where a jet can be misidentified as a $\tau$ candidate.

2. FINAL RESULTS

The visible mass, $M_{\text{vis}}$, is used to search for the signal in the data sample. This variable is defined as:

$$M_{\text{vis}} = \sqrt{(P_{\tau_1} + P_{\tau_2} + E_T)^2},$$

and is calculated using the four vectors of the visible tau decay products, $P_{\tau}$, and of the missing momentum $P_T = (E_T, E_x, E_y, 0)$. $E_x$ and $E_y$ indicate the components of $E_T$. No significant excess is seen over the background expectation and thus limits on the production cross section for neutral Higgs boson times the branching fraction into tau leptons are given for neutral Higgs bosons in the mass range 90 to 300 GeV.
The $M_{vis}$ spectrum shown in Fig. 1 is also used as the input to the limit calculator `collie` using the $CL_s$ method at 95% Confidence Level. These limits are shown in Fig. 1 assuming a Higgs boson with SM width. Correlations in systematic uncertainties between the different tau decay channels that have been studied are taken into account. The combination of the 2.2 fb$^{-1}$ data set analyzed at DØ in Run II provides a 10-20% improvement in the cross section across the range of Higgs boson masses studied compared to the results from the 1.0 fb$^{-1}$ data set only.

Figure 1: (a) Distribution of the visible mass after all selections. The data, shown with error bars, are compared to the sum of the expected backgrounds. Also shown, in blue open histogram, is the signal for a Higgs mass of 160 GeV assuming a signal cross section times branching fraction of 30 pb. (b) Expected and observed upper limits on the production cross section times branching ratio for $\phi \rightarrow \tau \tau$ production as a function of $m_\phi$ assuming the SM width of the Higgs boson. Results (square marker) correspond to an integrated luminosity of $L=2.2$ fb$^{-1}$ and are compared to the DØ Run IIa $L=1.0$ fb$^{-1}$ result (asterisk marker).

3. INTERPRETATION OF RESULTS IN MSSM

Using the limits set on the cross section for neutral Higgs production, regions of the ($m_A$, tan$\beta$) parameter space can be excluded in the the MSSM. Through radiative corrections beyond tree level, the masses and couplings of the Higgs boson depend on additional SUSY parameters. Assuming a CP-conserving Higgs sector, limits on tan$\beta$ as a function of $m_A$ can be derived in two benchmark scenarios given by [6] and defined in [1]:

- $m_h^{max}$ scenario
- No-mixing scenario

The cross section, width, and branching ratios for the Higgs boson have been calculated using the `FEYNHIGGS` program [7] version 2.6.4. The excluded region in the ($m_A$, tan$\beta$) space in each scenario is given in Fig. 2 for the case of $\mu > 0$. The region excluded by the LEP experiments [2] is also shown. The $\mu < 0$ case, which is presently disfavored [8], is not considered. At large tan$\beta$, the $A$ boson is nearly degenerate in mass with either the $h$ or $H$ boson and thus, the production cross sections for $gg \rightarrow \phi$ and $b\bar{b} \rightarrow \phi$ are added at each ($m_A$, tan$\beta$) point.

4. CONCLUSION

The search for the production of neutral Higgs bosons decaying into $\tau^+\tau^-$ final states in the DØ Experiment is presented with 2.2 fb$^{-1}$ integrated luminosity. The result shows 25% improvement in the Higgs cross-section limits around the mass range 200 GeV compared to the published result in 1.0 fb$^{-1}$ data set, and a sensitivity to tan$\beta$ about 60 for low $m_A$ bins and 40-50 for the rest of $m_A < 200$ GeV has been reached.
Figure 2: Region in the \((m_A, \tan\beta)\) parameter space that has been excluded at 95% CL for \(\mu > 0\) in two MSSM benchmark scenarios: (a) \(m_{h^{\text{max}}}\) and (b) no-mixing. Shown also by the green shaded region is the excluded region by LEP \[2\].

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