Search for Higgs decays to tau lepton pairs at the Tevatron

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Abstract. We present a search for neutral supersymmetric Higgs bosons decaying to \( \tau^+\tau^- \) pairs produced in \( p\overline{p} \) collisions at \( \sqrt{s} = 1.96 \) TeV. The data have been collected with the CDF II and D0 detectors at the Tevatron collider at Fermilab (1 fb\(^{-1}\) of integrated luminosity per experiment). No significant excess above the standard model backgrounds is observed. We set exclusion limits on MSSM parameters \( m_A \) and \( \tan\beta \) in several benchmark scenarios.

PACS. 14.80.Cp Non-standard-model Higgs bosons – 13.85.Rm Limits on production of particles – 12.60.Fr Extensions of electroweak Higgs sector – 12.60.Jv Supersymmetric models

1 Introduction

The Higgs mechanism provides the scheme for the electroweak symmetry breaking, that is accepted in the standard model (SM) as well as some of its supersymmetric extensions, such as Minimal Supersymmetric Standard Model (MSSM) [1]. The Higgs boson, if it exists, remains to be found, and the Tevatron experiments are actively searching for it. Due to low production cross-section predicted for Higgs in the SM, the SM Higgs cannot be observed with the amount of data collected to date. The production of MSSM Higgs may be enhanced relative to that of the SM by several orders of magnitude for certain areas of MSSM parameter space [2], making discovery of a MSSM Higgs at the Tevatron possible with less integrated luminosity.

In MSSM, the Higgs sector is comprised of two doublets of complex scalar fields. These correspond to the five physical particles: two charged bosons \( H^\pm \), one neutral CP-odd boson \( A \) and two more neutral CP-even \( h \) (light) and \( H \) (heavy) particles. At the tree level, two free parameters are sufficient to describe properties of these bosons. Most often, these parameters are chosen to be the mass of the CP-odd state \( m_A \), and the ratio of vacuum expectation values of Higgs coupling to down-type and to up-type fermions denoted \( \tan\beta \). At low \( m_A \) and high \( \tan\beta \) the \( A \) is almost mass-degenerate with either \( h \) or \( H \), and the production cross-section of the \( \phi \) is enhanced by \( \tan^2\beta \). It is conventional to use \( \phi \) to denote any of the \( A, h, \) or \( H \).

The MSSM Higgs at the Tevatron is expected to be primarily produced in the gluon fusion process, and the second most significant process is \( bb \to \phi \). It decays roughly 90\%(10\%) of times into \( b\overline{b}(\tau\tau) \) pair. The analyses presented in this paper are devoted to the latter channel. CDF has searched for the Higgs decaying into the final states \( \tau_e\tau_{\text{had}}, \tau_\mu\tau_{\text{had}} \) and \( \tau_e\tau_\mu \), where the subscript denotes either the corresponding leptonic, or a hadronic \( \tau \) decay. The D0 analysis uses the \( \tau_\mu\tau_{\text{had}} \) final state.

2 Data and Monte Carlo Samples

The analyses are based on the data collected at the Tevatron in \( p\overline{p} \) collisions at \( \sqrt{s} = 1.96 \) TeV. Both CDF and D0 experiments used data samples that correspond to the integrated luminosity of \( \sim 1 \) fb\(^{-1}\).

The data of CDF have been collected using dilepton triggers for the \( \tau_e\tau_\mu \) final state, and lepton+track triggers. At D0, single muon triggers have been used, that require hits in the muon system in conjunction with a high-momentum track in the central tracking volume.

For background estimates and efficiency calculation both experiments have used Monte Carlo samples created with PYTHIA event generator [3] and GEANT detector simulation [4].

3 Backgrounds

The largest and irreducible background in this search comes from events with \( Z/\gamma^* \to \tau\tau \). This background is estimated using Monte Carlo simulation.

The QCD multi-jet events and \( W+\)jet events constitute the second largest source of the background. These contributions can be controlled with well chosen selection criteria.

Finally, there is a number of small backgrounds that are taken into account, such as di-boson and \( tt \) production, and \( Z \to ee, \mu\mu \).
Table 1. Event count in data and predicted background

|          | CDF | D0 |
|----------|-----|----|
| $\tau_\ell\tau_{\text{had}}$ | $\tau_\mu\tau_{\text{had}}$ | $\tau_\nu\tau_{\text{had}}$ |
| Backg.   | 1196±19 | 1002±13 | 369±4 | 1287±130 |
| Data     | 1215  | 1000  | 374    | 1144    |

4 Analysis

4.1 Event Reconstruction and Selection

The analysis of each experiment is only briefly described in this paper, a complete report can be found in [5] and [6] for the CDF and D0, respectively.

For the reconstruction of a leptonic tau decay trigger leptons are used both at CDF and D0. These leptons are required to match a high-momentum track. They also have to pass isolation requirements on the total amount of energy deposited in the calorimeter and scalar sum of charged track momenta detected by the tracking system in a cone around the leptons.

The $\tau$ leptons decaying hadronically are identified by detection of collimated jets. The primary $\tau$ decay channels contributing to this signature are the $\pi^\pm\nu_\tau$, $\pi^\pm\pi^0\nu_\tau$ and $\pi^\pm\pi^\mp(\nu\pi^0)\nu_\tau$. The jets detected in calorimeter are thus matched to one or three charged tracks, the angular size of the jets is limited to a narrow cone and, in case of CDF, isolation requirements on detected particles outside of the $\tau$ jet cone are imposed. The D0 experiment identifies $\tau$ leptons with neural networks developed on $Z \to \tau\tau$ events. With such selection, multi-jet QCD backgrounds are suppressed.

Other backgrounds are reduced by several requirements at the event level. Events at D0 have to pass $W$-veto that removes $W \to \mu\nu$ events, with $m_W$ reconstructed using the momentum of the muon and the vector of the missing energy. Similar backgrounds are suppressed by CDF with the requirement that rejects events where the missing energy points away from the combined direction of the reconstructed $\tau\tau$ decay products. Other methods used by CDF and D0 to eliminate lesser backgrounds can be found in [5] and [6].

After applying event reconstruction and selection to the data samples, both CDF and D0 find that the observed yields in the data match the expected counts of background events within uncertainties (see Table 1). Note that CDF errors are statistical only, while the errors of D0 also include systematics.

4.2 Results for $\sigma(p\bar{p} \to \phi X) \cdot Br(\phi \to \tau\tau)$

The selected data samples have been searched for the signs of the Higgs signal in the mass range from 90 to 250(200) GeV/c$^2$ by CDF(D0).

CDF used the binned likelihood fitting technique looking for a peak in the distribution of the invariant mass of the visible $\tau\tau$ decay products and the vector of the missing energy. A small excess of events has been observed in the $\tau_\ell \tau_{\text{had}}$ sample at the mass of about 140 GeV/c$^2$. The statistical significance of the excess is approximately two standard deviations.

Neural network analysis has been developed by D0 and used event parameters such as the visible mass (defined as at CDF), transverse momenta and pseudorapidities of the decay products. The distribution of the neural network output for the data has been compared to the expectation for the background, and no statistically significant deviation has been observed.

The data of both CDF and D0 are consistent with background-only observation. Consequently, both experiments set a 95% C.L exclusion limit on $\sigma(p\bar{p} \to \phi X) \cdot Br(\phi \to \tau\tau)$, the product of the Higgs boson production cross-section and the decay rate of the Higgs.
to $\tau$-pair. This limit is dependent on the Higgs boson mass. The limit from CDF is shown in Fig. 1. The observed exclusion is slightly weaker than expected for given statistics due to the $2\sigma$ event excess mentioned above. The limit from D0 is presented in Fig. 2.

### 5 Interpretation of Results within MSSM

The measured limits on the $\sigma(p\bar{p} \rightarrow \phi X) \cdot Br(\phi \rightarrow \tau\tau)$ can be used to derive exclusions on the free parameters of the MSSM. As the number of the parameters is large, the common approach to interpreting results of Higgs searches is to fix most of the MSSM parameters to agreed-upon values and then derive the exclusion regions in the plane $(m_A, \tan\beta)$, the two parameters most directly related to MSSM Higgs properties. There are several ways to fix MSSM parameters corresponding to the most indicative cases. These are called MSSM benchmark scenarios [7]. Out of the scenarios described in [7], CDF and D0 employ the $m_h^{max}$ and the no-mixing scenario with the case of the mixing parameter of the Higgs doublets $\mu$ being positive and negative. The $m_h^{max}$ scenario is defined as the set of MSSM parameters that maximizes the value of the mass of the lightest Higgs boson. The second scenario, no-mixing, is similar to $m_h^{max}$, but with the mixing parameter for the stop quarks set to zero. Total of four cases are considered.

The CDF exclusion regions for the four scenarios are drawn in Fig. 3 and the results from D0 are found in Fig. 4 and 5. In the studied mass region the $\tan\beta$ values above 40-60 are excluded in the considered MSSM scenarios. While no signal is observed and the data are consistent with the SM backgrounds, the measurements presented here provide the most constraining to date limits on Higgs decays to $\tau\tau$ channel.

### References

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Fig. 4. D0 exclusion area for $\tan \beta$ as a function of $m_A$ for benchmark scenarios with $\mu < 0$ overlaid with the LEP results and previous MSSM Higgs searches at the Tevatron with lower luminosity.

Fig. 5. D0 exclusion area for $\tan \beta$ as a function of $m_A$ for benchmark scenarios with $\mu > 0$ overlaid with the LEP results and previous MSSM Higgs searches at the Tevatron with lower luminosity.