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Searches for Minimal Supersymmetric Standard Model Higgs bosons at the Tevatron

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This paper presents recent searches for minimal supersymmetric standard model (MSSM) Higgs bosons in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. These results have been obtained by the D0 and CDF experiments. We show analyses with up to 7.3 fb^{-1} of integrated luminosity. They probe a significant portion of the MSSM parameter space, being able to exclude $\tan\beta > 25$ for low mass Higgs bosons $m_A < 170$ GeV$/c^2$.

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1. Introduction

While in the standard model (SM) only one Higgs boson doublet breaks the $SU(2)$ symmetry, there are two Higgs boson doublets in the minimal supersymmetric standard model (MSSM) [1]. This leads to five physical Higgs bosons remaining after electroweak symmetry breaking; three neutrals: h, H, and A, collectively denoted as ϕ, and two charged, $H^{\pm}$. At the tree level, the mass spectrum of the Higgs bosons is determined by two parameters conventionally chosen to be $\tan\beta$, the ratio of the two Higgs doublet vacuum expectation values, and M_A, the mass of the pseudoscalar Higgs boson A. Although $\tan\beta$ is a free parameter in the MSSM, large values ($\tan\beta \gtrsim 20$) are preferred. The top quark to bottom quark mass ratio suggests $\tan\beta \approx 35$ [2], and the observed density of dark matter also points towards high $\tan\beta$ values [3]. At high values of $\tan\beta$, two of the neutral Higgs bosons (A and h or H) are approximately degenerate in mass. They share similar couplings to quarks, enhanced by $\tan\beta$ compared to the SM couplings for down-type fermions, while the couplings to up-type fermions are suppressed. The enhancement of couplings to down-type fermions has several consequences. First, the main decay modes of this Higgs boson pair are $\phi \to b\bar{b}$ and $\phi \to \tau\tau$ with branching ratios $\mathscr{B}(\phi \to b\bar{b}) \approx 90\%$ and $\mathscr{B}(\phi \to \tau\tau) \approx 10\%$, respectively. Then, their production in association with b quarks is enhanced by approximately $\tan^2\beta$ compared to the SM, which could make this production rate measurable at a hadron collider.

Experiments at the CERN e^+e^- Collider (LEP) excluded MSSM Higgs boson masses below 93 GeV/c^2 [4]. We present here recent searches from the D0 and CDF experiments which extend the exclusion to higher masses for high $\tan\beta$. These experiments exploit the two Higgs boson decay modes $\phi \to \tau\tau$ and $\phi \to b\bar{b}$ to perform several searches with different sensitivity and backgrounds, the $\phi \to b\bar{b}$ searches are nevertheless more sensitive to radiative corrections, hence to the MSSM parameters. The inclusive Higgs boson searches are performed by the two experiments in different $\tau\tau$ final states distinguished by the decay of tau leptons: $\tau \to \mu\nu_\mu\nu_\tau$ (τ_μ), $\tau \to e\nu_e\nu_\tau$ (τ_e) and hadronic τ decays (τ_h). Both experiments have dedicated $\tau_{\rm h}$-tagging algorithms [6, 7]. The $\phi \to b\bar{b}$ mode can only be used when searching for the associated production $bg \to b\phi \to bb\bar{b}$ where the additional associated b-quark greatly reduces the multijet background (MJ). Eventually, D0 experiment also perform searches in the $bg \to b\phi \to b\tau\tau$ final states.

2. Inclusive searches in the di-tau channels

Both D0 and CDF experiments consider three different channels depending on the decay of the tau pair: $\tau_\mu\tau_{\rm h}$, $\tau_{\rm e}\tau_{\rm h}$, and $\tau_\mu\tau_{\rm e}$. The different analyses follow a similar strategy requiring exactly two oppositely charged well identified leptons. In addition μ and e must be isolated while $\tau_{\rm h}$ are required to be $\tau_{\rm h}$-tagged. CDF searches employ 1.8 fb^{-1} of integrated luminosity [8]. D0 results [9] are based on an integrated luminosity of 5.4 fb^{-1} but limited to the most sensitive channels $\phi \to \tau_\mu\tau_{\rm h}$ and $\phi \to \tau_{\rm e}\tau_\mu$.

A set of cuts are imposed to suppress MJ, W+jets and, to a lower extent, $t\bar{t}$ backgrounds, the $Z \to \tau\tau$ background being irreducible. Both experiments search for an excess in the $M_{\rm vis}$ distribution where $M_{\rm vis} = \sqrt{(p_{\tau\tau} + \not{p}_T)^2}$, with $p_{\tau\tau}$ the 4-vector of the two reconstructed leptons pair and $\not{p}_T \equiv (\not{E}_T, \not{E}_x, \not{E}_y, 0)$. $M_{\rm vis}$ distributions are shown on Fig. 1 for D0 and CDF experiments.

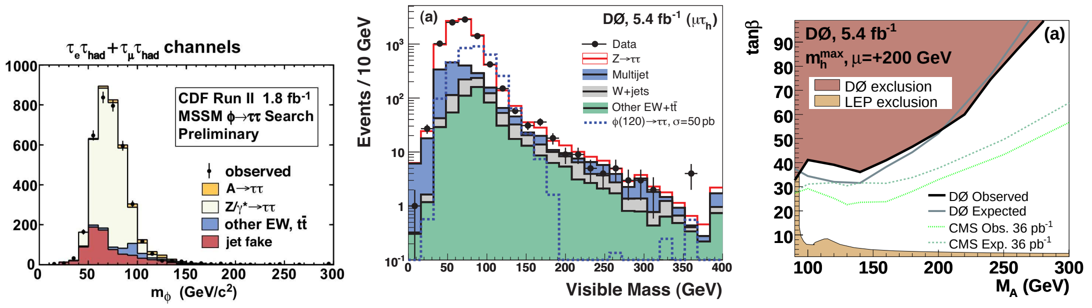

Figure 1: Left: M_{vis} distribution at CDF in the combined $\tau_e\tau_h$+$\tau_\mu\tau_h$ channel. Middle: M_{vis} distribution at D0 for all channels combined. Right: constraints in the $(\tan\beta, m_A)$ plane in the MSSM m_h-max scenario.

For both experiments no excess of data over expected background is observed. They both proceed to set model independent limits on $\sigma(\phi \to \tau\tau) \times \mathscr{B}(\phi \to \tau\tau)$ as a function of the Higgs boson mass (assuming its natural width is negligible compared to the experimental resolution) and translate this limit in several MSSM benchmark scenarii [10], hence putting constraints in the $(m_A, \tan\beta)$ plane. The constraints from the D0 collaboration, based on the largest dataset than the ones from CDF, are shown on Fig. 1.

3. $b\phi \to bb\bar{b}$ searches

An inclusive search $\phi \to b\bar{b}$ is extremely difficult due to the abundant MJ background. Therefore, both experiments focus on the $bb\bar{b}$ final state where an additional b quark in the acceptance greatly reduces the MJ background. Both experiments require three b-tagged jets in the final selection. The MJ background dominates the sample and is very challenging to model. Hence, D0 and CDF employ a data-driven method to derive the MJ distributions. They both search for a peak in the the Higgs jet-pair invariant mass distribution. The Higgs jet-pair is selected at D0 using a likelihood ($\mathscr{LH}$) method while CDF selects the two leading jets. D0 further applies a cut on $\mathscr{LH}$ to increase the search sensitivity. The jet-pair invariant mass distribution is modelled by using the MJ sample with exactly two b-tagged jets. To get the final shape, a correction is required and it is found to depend on the parton flavour composition of the event. At CDF, the final shape is obtained by applying a b-tag efficiency (or b-tag fake) correction while at D0 this correction is derived from the monte carlo (MC) simulation. In both experiment, the composition of the signal sample is determined from a fit to data.

The analysis is performed with an integrated luminosity of 2.6 fb^{-1} by CDF [11] and 5.2 fb^{-1} at D0 [12]. Both experiments does not observe any significant excess of data over the predicted background and set limit on the $\sigma(bg \to b\phi) \times \mathscr{B}(\phi \to b\bar{b})$. Limits on the different MSSM scenarii are also derived (taking into account the Higgs natural width). Examples of these limits are shown on Fig. 2.

4. $b\phi \to b\tau\tau$ searches

This channel is studied for by the D0 experiment in two different final states: $b\tau_e\tau_h$ and $b\tau_\mu\tau_h$.

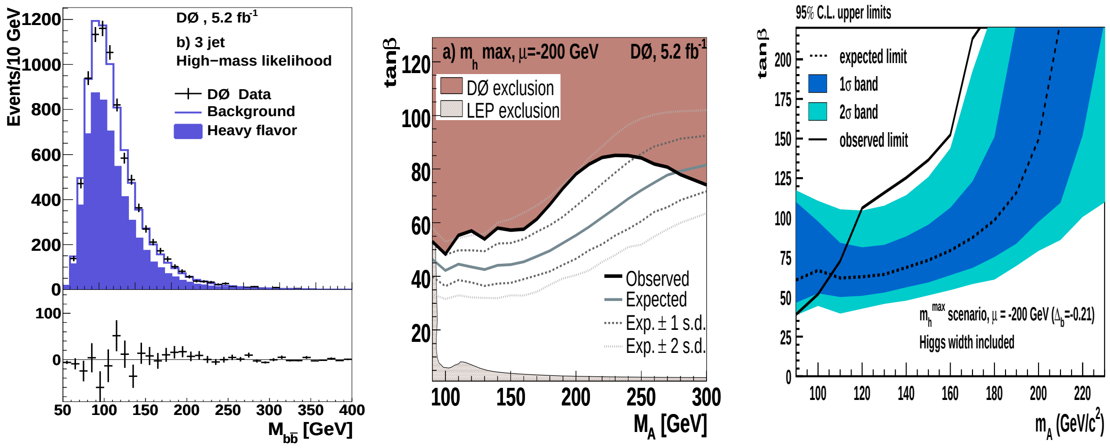

Figure 2: Right: Invariant mass of the best Higgs jet-pair at D0, background is fitted assuming no Higgs signal. Middle: constraints in the $(\tan\beta, m_A)$ plane in the MSSM $m_{\rm h}$-max scenario ($\mu < 0$) obtained by D0. Left: constraints in the $(\tan\beta, m_A)$ plane in the MSSM $m_{\rm h}$-max scenario ($\mu < 0$) obtained by CDF.

The former [13] uses an integrated luminosity of 3.7 fb^{-1} while the latter [14] analyses 7.3 fb^{-1}.

The dominant backgrounds are coming from $Z \to \tau\tau$, W+jets, MJ and $t\bar{t}$. The two analysis employs a similar strategy. The W+jets background is efficiently suppressed by a cut on the transverse mass formed by the $\ell \equiv \mu/e$ and the $\not{E}_T$. Then, they developed multivariate discriminants against the main backgrounds, *i.e.* *MJ* and $t\bar{t}$, and combined them in a final discriminant $\mathscr{D}_f$ which is used to perform for the search for a potential signal. In the case of the $b\tau_\mu\tau_{\rm h}$ analysis, b-tagging information are also included in $\mathscr{D}_f$. For this channel, the Z background is constrained from data using a $Z \to \mu\mu$ control sample. Such a $\mathscr{D}_f$ discriminant distribution is presented on Fig. 3 for the $b\tau_\mu\tau_{\rm h}$ channel.

No excess of data over predicted background is observed and limits are placed on $\sigma(bg \to b\phi) \times \mathscr{B}(\phi \to \tau\tau)$. They are subsequently converted into constraints on the MSSM benchmark scenarii including the effect of the natural Higgs boson width. These results are presented on Fig. 3.

5. Conclusion

D0 and CDF have actively searched for MSSM Higgs bosons. We presented here results with up to 7.3 fb^{-1} of integrated luminosity. In the absence of excess of data over expected background from SM processes, we set limits, strongly constraining the MSSM parameter space. We reach sensitivities down to $\tan\beta \approx 20$ for low mass Higgs bosons.

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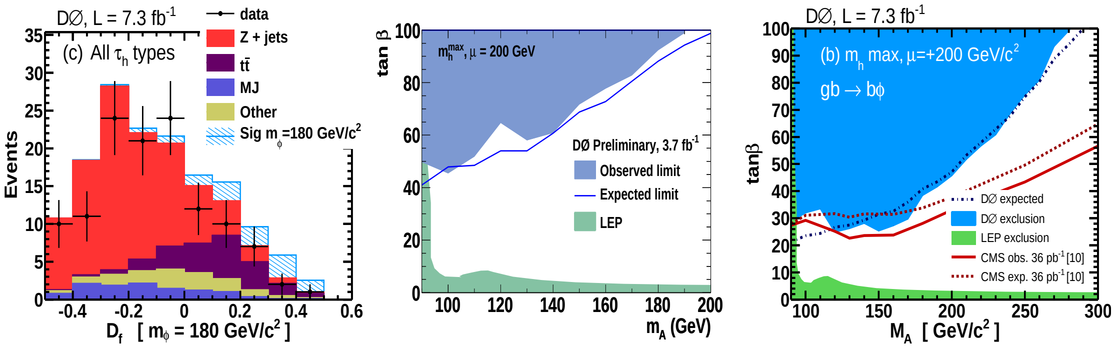

Figure 3: Right: $\mathscr{D}_f$ discriminant in $b\tau_\mu\tau_\mathrm{h}$ analysis for a Higgs boson mass of 180 GeV/c^2. Middle: constraints in the $(\tan\beta, m_A)$ plane in the MSSM m_h-max scenario ($\mu > 0$) obtained by D0. Left: constraints in the $(\tan\beta, m_A)$ plane in the MSSM m_h-max scenario ($\mu > 0$) obtained by CDF.

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