SEARCH FOR HIGGS BOSONS BEYOND THE STANDARD MODEL AND SUPERSYMMETRY AT THE TEVATRON

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Abstract

Recent results from the CDF and DØ Collaborations on the searches for Higgs bosons beyond the Standard Model and for Supersymmetric particles at the Run II of the Fermilab Tevatron collider are presented. The analysed datasets correspond to an integrated luminosity of 200-800 pb^{-1} collected from proton anti-proton collisions at a center of mass energy of 1.96 TeV. No significant excess over the Standard Model expectations are observed and limits on parameters of the various models under study are set.

1 Introduction

The predictions of the Standard Model of elementary particles and fundamental interactions (SM) have been successfully tested over the past decades. All the SM particles have been discovered, except the scalar Higgs boson predicted in the minimal version of the SM and responsible for the electroweak symmetry breaking. This mechanism introduces defects in the model, such as the hierarchy problem, and from theoretical arguments new physics is expected to appear at the TeV scale. Models beyond the SM, such as Supersymmetry (SUSY), have been proposed. They generally predict the emergence of new particles with a mass within the reach of the Tevatron Run II. At the Run II, the Tevatron is colliding protons and anti-protons at a center-of-mass energy of 1.96 TeV, it is the highest energy collider currently running. With more than 1 fb^{-1} of data delivered so far to the experiments, CDF and DØ, it is an optimal place to search for new phenomena at the energy frontier. In this report, results from the CDF and DØ Collaborations on the search for Higgs bosons beyond the SM and particles predicted in SUSY models are presented. Limits are given at the 95% Confidence Level.

2 Higgs bosons beyond the Standard Model

CDF and DØ search for Higgs bosons predicted in various extensions of the SM: the minimal Supersymmetric extension of the Standard Model (MSSM), left-right symmetric models predicting doubly charged Higgs bosons, and fermiophobic models. While the reader could refer to [1)] and [2)] for a complete overview, the following focuses on the Higgs sector of the MSSM. It consists of two complex Higgs doublets leading to five physical Higgs bosons: three are neutral (h, H and A) and two are charged (H^+ and H^-). At tree level, the Higgs sector depends on two free parameters generally taken as the pseudoscalar Higgs boson mass (m_A) and the ratio of the vacuum expectation values of the Higgs doublets (tanβ).

2.1 Neutral Higgs bosons

Generally, the Yukawa couplings of the Higgs bosons to the down-type fermions are enhanced by a factor of tanβ respective to the SM ones, scaling the production cross section as $\tan^2\beta$. Since the pseudoscalar Higgs boson and either h or H are nearly mass degenerate at high tanβ and have similar couplings, they are not distinguished in the search strategy. Independently of the mass, the neutral Higgs bosons mostly decay to a bottom quark pair (90%) or a tau lepton pair.

CDF published a search for Higgs boson production [3)] via the main production mechanism gg or $b\bar{b} \rightarrow \phi$ (ϕ= h, H or A) in the $\phi \rightarrow \tau^+\tau^-$ decay channel, one tau decaying hadronically (τ_h) and the other leptonically. The data ($\mathcal{L}_{int}$=310 pb^{-1}) was collected with triggers selecting one lepton, e or μ, and one isolated track. The hadronic tau decays are collimated with a few attached tracks, making their identification particularly challenging at hadron colliders. CDF achieves tau identification with sequential cuts reaching efficiencies of about 40% and a misidentification rate below 1.5%, depending on the jet energy. Fig. 1 (left) illustrates the characteristic 1-prong and 3-prongs tau decays in τ_h candidates. Background events (mainly $Z \rightarrow \ell\ell$, multijet, W+jets) are further reduced with topological requirements on the tau decay products. The number of observed events (487 events, rather pure in $Z \rightarrow \tau\tau$ events) are compatible with the SM expectation. Binned likelihood fits of the partially reconstructed ditau system mass are performed to set limits in the m_A-tanβ parameter space, Fig. 2.

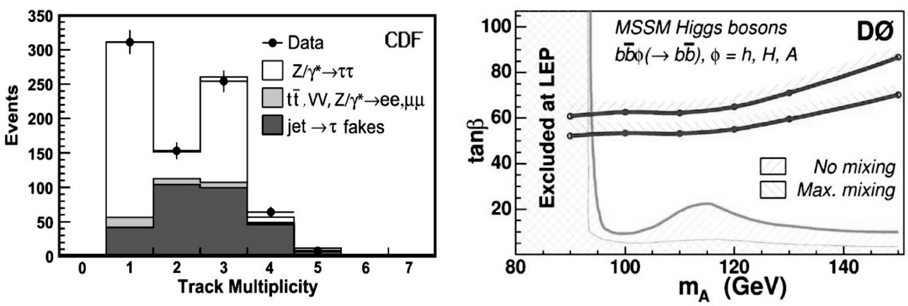

Figure 1: *(left) Track multiplicity for hadronically decaying taus selected in the CDF ditau Higgs bosons search; (right) limits in the m_A-tanβ plane obtained in the published DØ multijet final state analysis for two benchmark scenarios.*

DØ completed a new search in the $\phi \rightarrow \tau\tau$ decay channel [4] in three final states: $e\tau_h$, $\mu\tau_h$ and $e\mu$. The data ($\mathcal{L}_{int}$=325 pb^{-1}) was collected with single lepton triggers (e or μ) and dilepton triggers ($e\mu$). DØ identifies τ_h with Neural Network techniques and classifies them in different types: single π-like, ρ-like and 3-prongs decays. This technique gives a good handle on the jets faking τ_h: for a tau misidentification of 1.5%, the tau efficiency is above 70%, depending on the tau type and its energy. After further background reduction, the irreducible $Z \rightarrow \tau\tau$ background (and the multijet background in the $e\tau_h$ subchannel) dominates the selected sample. No evidence of signal is observed and limits on the production cross section times branching fraction are set, using the visible mass as a discriminating variable. The sensitivity is optimised by splitting samples per tau type and W mass like range. The DØ ditau analysis alone significantly improves the observed upper limit previously set by CDF for Higgs boson masses above about 125 GeV/c^2.

The DØ ditau analysis is combined with the published DØ analysis searching for neutral Higgs bosons produced in association with b quarks in the multijet final state [5], gg or $q\bar{q} \rightarrow b\bar{b}\phi$ with $\phi \rightarrow b\bar{b}$, Fig. 1 (right). The combined limits are displayed on Fig. 2. The sensitivity of the multijet channel in the $\mu > 0$ hypothesis is very low and does not contribute to the actual limits.

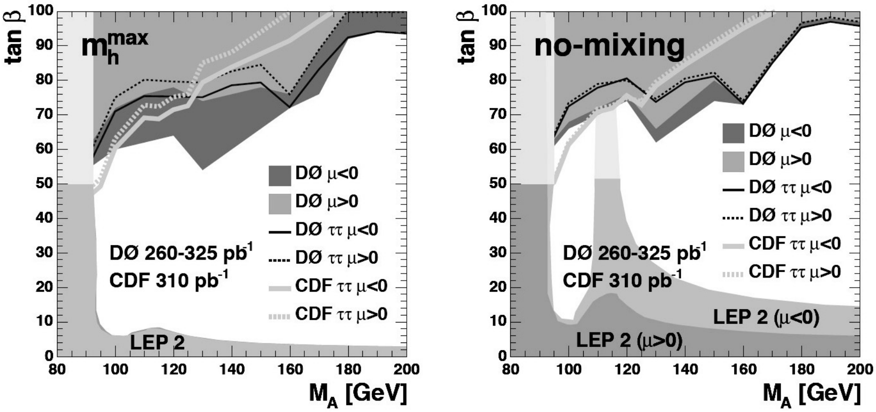

Figure 2: *Excluded regions in the m_A-tanβ plane for the m_h^{max} and the no-mixing scenarios for μ=±200 GeV. The combined limits of the ditau and multijet DØ analyses are displayed. For completeness, the limits set respectively by the CDF and DØ ditau analyses alone are also shown. Results from the CERN e^+e^- collider LEP are only available for tanβ less than 50.*

2.2 Charged Higgs bosons

At the Tevatron, the direct production of charged Higgs pairs is predicted to be small though the $H^{\pm}$ could be copiously produced in the decay of the top quark $t \rightarrow H^{\pm}b$, if kinematically allowed, competing with the standard $t \rightarrow W^{\pm}b$ decay channel.

CDF searches for evidence of $H^{\pm}$ [6] using its top pair production cross section measurement ($\mathcal{L}_{int}$=193 pb^{-1}). The respective numbers of events expected in the dilepton, lepton+jets with one b-tag, lepton+jets with more than one b-tag and lepton+tau channels would vary according to the model hypothesis. This analysis allows the H^+ to decay to $\bar{\tau}\nu$, $W^+\phi(\rightarrow b\bar{b})$, $c\bar{s}$ and $t^{\star}\bar{b}$. No evidence of signal is observed over the studied mass range 80-160 GeV/c^2. Fig. 3 shows the limits set in the tanβ-$m_{H^{\pm}}$ plane for one benchmark scenario. Generally, the limits at high tanβ depend significantly on the model parameters, the Yukawa coupling at the tbH vertex could be strongly suppressed, while the limits at low tanβ are more robust.

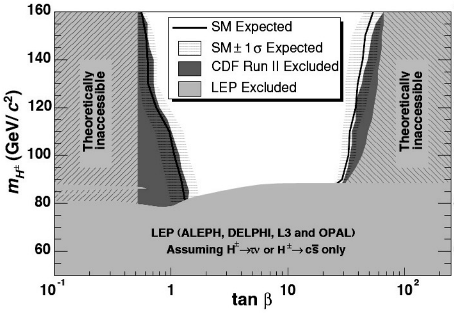

Figure 3: *Exclusion regions in the* $\tan\beta$*-*$m_{H^\pm}$ *plane obtained in the CDF charged Higgs search for one particular benchmark scenario. In this scenario, the branching ratio* $BR(t \to H^\pm b)$ *is enhanced at large* $\tan\beta$ *and, at low* $\tan\beta$*, where the* $H^\pm \to W^\pm\phi$ *decay is open, the value of* m_ϕ *is maximised.*

3 Supersymmetric particles

Supersymmetry extends the SM particle spectrum with the SUSY partners of the gauge fields ($\tilde{\chi}^\pm$, $\tilde{\chi}^0$ and $\tilde{g}$) and the partners of the matter fields ($\tilde{q}$ and $\tilde{\ell}$). The properties of the additionnal particles depend on more than a hundred free parameters in the unconstrained MSSM. At present, the mechanism of the breaking is unknown and several scenarios are under consideration, such as the minimal supergravity model (mSUGRA) and the gauge mediated SUSY breaking (GMSB). They largely reduce the number of free parameters and predict a wide variety of new phenomena that could be observed at the Tevatron. While the reader could refer to [1] and [7] for a complete overview of the SUSY searches pursued by the CDF and DØ Collaborations, the following focuses on major MSSM results assuming the R-parity is conserved. Under this hypothesis, the weakly interacting lightest supersymmetric particle (LSP) is stable, leading to signatures with large missing transverse energy (MET). Note that, two new searches with R-parity violated, decay via λ_{121} and λ_{122} at CDF [8] and neutral long lived particles at DØ [9], are not covered in the present report.

3.1 Squarks and gluinos

At hadronic colliders, the production of colored particles, such as the squarks and gluinos, is favored. Despite the large SM background (multijet, W+jets and Z+jets events), DØ performs a generic search, assuming the five lightest $\tilde{q}$ flavors have similar masses [10]. The final state depends on the mass hierarchy: if the squarks are lighter than the gluinos, the main production mechanism is $\tilde{q}\tilde{q}^\star$ decaying to $q\tilde{\chi}_1^0 + \bar{q}\tilde{\chi}_1^0$; if the gluinos are lighter, $\tilde{g}\bar{\tilde{g}}$ decaying to $q\bar{q}\tilde{\chi}_1^0 + \bar{q}q\tilde{\chi}_1^0$

dominates; in the intermediate region, the $\tilde{q}\tilde{g}$ rate increases. This leads respectively to two, four and three jets with MET signature. The initial dataset ($\mathcal{L}_{int}$=310 pb^{-1}) is selected with jets+MET triggers. After a common preselection, DØ optimises one analysis per jet multiplicity which reduces the SM background with kinematic cuts as well as a lepton veto. No evidence of signal is observed and limits in the gluino-squark mass plane in the mSUGRA model (tanβ=3, A_0=0 and $\mu < 0$) assuming ten squarks species are derived, Fig. 4. Although this model is already severely constrained by LEP, the Tevatron is now exploring uncovered regions.

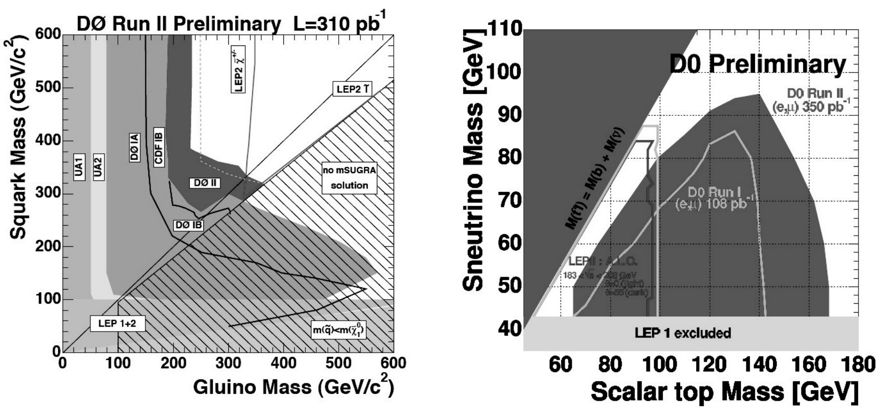

Figure 4: *(left) The (red) dark area represents the exclusion limits set by the DØ generic squarks and gluinos search in the gluino-squark mass plane and the (green) dashed line is the corresponding expected limit; (right) exclusion limits in the stop-sneutrino mass plane set in the DØ stop pair production decaying to* $b\bar{b} + e^{\mp}\mu^{\pm} + MET$ *analysis.*

The stop quark is of particular interest at the Tevatron. Unlike the squarks of the first generations, due to the large top quark mass, the mixing in the stop sector is expected to be large and the lighter stop could be the lightest of all squarks. At DØ a new search for stop pairs in the $b\bar{b} + e^{\mp}\mu^{\pm}$ + MET final state has been performed [11]. It assumes the stop to be lighter than the chargino which decays by sneutrino exchange. The signal selection is based on isolation requirements (e, μ and MET). The requirements on minimum transverse momentum (p_T) of the electron and muon are soft (8 and 12 GeV) to increase the sensitivity in the low $\Delta m = m_{\tilde{t}} - m_{\tilde{\nu}}$ region. Background reduction is optimised in three Δm regions. No evidence of signal is observed in the analysed dataset ($\mathcal{L}_{int}$=350 pb^{-1}). The limits are derived using two variables sensitive to Δm: the number of non-isolated tracks and the scalar p_T sum of the reconstructed objects, Fig. 4 (right). This channel is presently being combined with the $b\bar{b} + \mu^{\mp}\mu^{\pm}$+MET analysis previously completed at DØ [12].

Similarly, one sbottom quark could be relatively light and DØ has a dedicated analysis for direct $\tilde{b}$ pair production search [13]. It assumes the direct decay of the sbottom, assumed to be the NLSP, into the LSP: $\tilde{b} \rightarrow b\tilde{\chi}_1^0$. It is a source of two acoplanar b-jet events with MET. The initial dataset ($\mathcal{L}_{int}$=310 pb^{-1}) is selected with jets+MET triggers. DØ uses a single b-tagged sample to extract signal events. The main background left are $Z(\rightarrow \nu\bar{\nu}) + jj$, $W(\rightarrow \tau\nu) + j$ and $Z(\rightarrow \nu\bar{\nu}) + b\bar{b}$. For high sbottom mass, the jet p_T and MET distributions are expected to rise above the SM expectations and the analysis is optimised accordingly. No evidence of signal is observed in the data and limits in the sbottom-neutralino mass plane are derived. As a result, a scalar bottom quark lighter than $\sim$ 200 GeV/c^2 is excluded for a neutralino mass up to $\sim$ 80 GeV/c^2. This result improves by $\sim$50 GeV/c^2 the limit previously set by CDF in Run I.

3.2 Charginos and neutralinos

At hadron colliders, charginos and neutralinos can be produced together through electroweak processes leading to rather small cross section. However, the subsequent decays $\tilde{\chi}_1^{\pm} \rightarrow \ell\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow \ell\ell\tilde{\chi}_1^0$ (via either sleptons or SM vector bosons) leads to a striking signature with three leptons (e, μ or τ) in the final state together with MET. The low SM background rate motivates the current CDF and DØ searches in this final state.

DØ published [14] an analysis in the trilepton channel with at least two identified leptons (e or μ): $ee\ell$, $\mu\mu\ell$, like sign $\mu\mu$ and $e\mu\ell$ channels. The lepton identification efficiency being crucial in this final state, the third lepton (ℓ) is not identified and an additional isolated track is required instead, covering the e, μ and partially τ decays. W and Z boson mass veto efficiently reject SM sources of leptons. A final combined cut on the MET and the third lepton track p_T optimally reduce the remaining backgrounds finally dominated by multijet and diboson events. In the 320 pb^{-1} of data analysed, three events are observed, in agreement with the SM expectations. This result, expressed in upper limits on the cross section times branching fraction, Fig. 5 (left), is to be compared to the Run I upper limit of about 1.5 pb^{-1}. Assuming a mSUGRA inspired model ($m_{\tilde{\chi}_1^{\pm}} \sim m_{\tilde{\chi}_2^0} \sim 2m_{\tilde{\chi}_1^0}$) with degenerate slepton masses, the $\sigma \times BR(3\ell)$ can be expressed as a function of $m_{\tilde{\chi}_1^{\pm}}$ and $m_{\tilde{\ell}}$ with a small dependence on the other model parameters. The chargino mass limits are therefore derived in several scenarios accounting for the slepton mass. If the slepton is slightly heavier than the $\tilde{\chi}_2^0$, the leptonic decays are maximised ("3l-max" scenario) and the charginos mass limits set by DØ improves on the LEP limits. However, in scenarios less favorable no limits are set. This is the case if the sleptons are heavy ("large-m_0" scenario), enhancing the decay of charginos and neutralinos through the SM vector bosons. In contrast, if the squarks are heavy ("heavy-squarks" scenario) negative interferences in the $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production vanish and the cross section is maximal.

At high tanβ, the mixing of the $\tilde{\tau}$ could be large and one $\tilde{\tau}$ could be lighter than the $\tilde{e}$ or the $\tilde{\mu}$, favoring a three-τ final state. Part of this final state is included in previous channels. However, DØ dedicated analyses to the hadronically decaying taus through the additional $e\tau_h\ell$ and $\mu\tau_h\ell$ channels [15]. Preliminary results show that the combination of the six analyses could improve the sensitivity of DØ on the chargino mass by about 2 GeV compared to the published results.

CDF is currently completing a trilepton search pursued in the ee+track [16], eee or $ee\mu$ [17] and $\mu\mu e$ or $\mu\mu\mu$ [18] channels with an integrated luminosity of 224, 346 and 346 pb^{-1} respectively. In particular, the former is being reoptimised [19] with an enlarged dataset ($\mathcal{L}_{int}$=607 pb^{-1}) and the latter is being extended [20] with another dataset selected with low p_T dimuon triggers ($\mathcal{L}_{int}$=312 pb^{-1}) so that each lepton p_T threshold is lowered down to 5 GeV, increasing the reach. The number of observed events, 1 and 0 respectively, are consistent with the SM expectations.

At the Tevatron, the trilepton analyses do not have enough sensitivity yet to improve the LEP limits in mSUGRA scenarios with non enhanced branching ratio to leptons. The sensitivity projections, Fig. 5 (right), show this search will largely benefit from the increasing dataset and a combination between the CDF and DØ results [21].

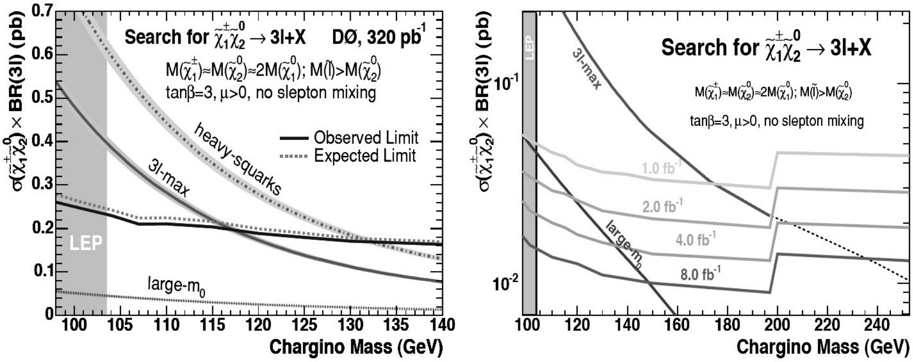

Figure 5: *Upper limit on the $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ cross section times trilepton branching ratio as a function of the chargino mass: (left) in the published DØ search and (right) expected with CDF and DØ by extrapolating the current DØ trilepton analysis results for 1, 2, 4 and 8 fb^{-1} delivered per experiment.*

If SUSY is broken via gauge interactions (GMSB), the gravitino is almost massless and could become the LSP leading to signatures rather different from the one expected in mSUGRA. In the R-parity conservation hypothesis, assuming the NLSP (the $\tilde{\chi}_1^0$ in that case) decays promptly into the LSP and a photon, $\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma$, charginos and neutralinos cascade decays could be a copious source of two energetic photon events with large MET. This signature has negligible SM backgrounds other than misreconstructed events.

DØ recently updated a GMSB search based on this signature [22]. This new analysis is performed on a larger dataset ($\mathcal{L}_{int}$=760 pb^{-1}) and the purity of the selected central diphoton sample benefits from an improved photon identification: the misreconstruction of the photon primary vertex rate is decreased by the use of a calorimeter pointing algorithm. Remaining backgrounds are reduced with requirements on the MET. The number of observed events is in agreement with the SM expectations and results are interpreted within one Snowmass Slope benchmark scenario where the SUSY breaking scale Λ is the only parameter, Fig. 6. Regarding to chargino mass, the limit set by this analysis alone improves by 11 GeV/c^2 the published combined limit recently obtained by CDF and DØ at the Run II Tevatron [23]. It is the most stringent limit to date in this framework.

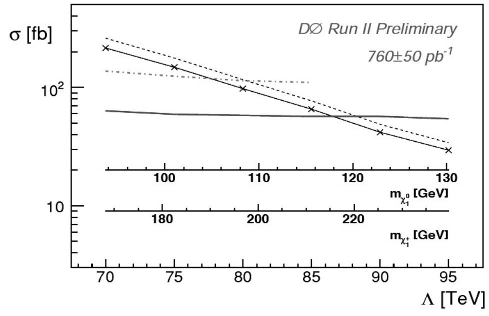

Figure 6: *Limit on GMSB Snowmass Slope breaking scale for the new diphoton + MET analysis pursued at DØ (plain blue bold line).*

4 Summary and perspectives

Our current understanding of Nature suggests the emergence of new physics at the TeV scale, making the Tevatron an ideal place to search for the unknown. Although no significant deviations from the Standard Model expectations have been observed to date, both CDF and DØ continue the quest and, more than ruling out parameter space of exotic models, the always growing dataset and the gain in our knowledge of the detectors may reveal an unexpected surprise.

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