Printed ISSN 1330–0016
Online ISSN 1333–9133
CD ISSN 1333–8390
CODEN FIZBE7

TEVATRON SEARCHES FOR HIGGS AND SUPERSYMMETRY

DANIEL R. CLAES

Department of Physics & Astronomy, University of Nebraska, U.S.A.
E-mail address: dclaes@unlhep.unl.edu

Received 24 October 2007; Accepted 20 February 2008
Online 18 June 2008

Results are presented of searches for Standard Model and MSSM Higgs, as well as supersymmetric particles. A broad variety of signatures were explored by the CDF and DØ experiments, using approximately 2 fb^{-1} of reconstructed $p\bar{p}$ data from collisions at 1.96 TeV at Fermilab's Tevatron. No significant deviation from background sources has been observed in any of the searches, and new limits have been set on the production cross sections.

PACS numbers: 11.30.Pb, 13.85.Rm, 14.80.Bn, 14.80.Cp, 14.80.Ly UDC 539.126
Keywords: Higgs, supersymmetry, Tevatron searches

1. Introduction

Fermilab's Tevatron is a $p\bar{p}$ collider operating at a center of mass energy of 1.96 TeV. Particle searches have intensified as the Tevatron's two experiments, DØ and CDF, accumulate data making a number of interesting production cross sections accessible for the very first time. With an integrated luminosity of 3 fb^{-1} recorded per experiment, and roughly 2 fb^{-1} of it reconstructed, results are summarized for both Higgs and supersymmetric searches performed on 1 - 1.9 fb^{-1} of this data, collected roughly from April 2003 through February 2007. Additional details for all analysis can be found on the corresponding websites [1, 2]. All reported cross section limits are derived at 95% CL. Comprehensive descriptions of the CDF and DØ detectors can be found elsewhere [3, 4].

2. Standard model Higgs

Direct searches at LEP exclude Higgs' masses below 114.4 GeV [5], while global electroweak fits place an indirect upper limit of 144 GeV [6]. A SM Higgs should be light enough to be produced at the Tevatron. Though direct Higgs production by gluon fusion, $gg \to H$, is the dominant production mechanism (0.7 pb for a 115 GeV Higgs), the combined Vector Boson (VB) associated production (WH and ZH) can also be significant, particularly at low Higgs mass.

Since the Higgs' mass determines the possible decay channels, searches are guided by either of two assumptions: *For Higgs masses below* 135 GeV, $H \to b\bar{b}$ decays dominate and the QCD background is overwhelming. If the associated vector boson in WH and ZH production decays leptonically, efficient b-tagging and missing transverse energy ($\not\!\!E_T$) cuts can reduce the background substantially and make searches in these channels viable. *At sufficiently high mass*, $H \to WW^{(*)}$ decays become kinematically possible. Muon or electron identification in the subsequent leptonic decays help suppress the QCD background.

In the low-mass $H \to b\bar{b}$ search, the b-quark lifetime provides a means of distinguishing heavy flavor jets. Signal to background ratios can improve by as much as a factor of 10 ($\approx$1:1000 $\to$ 1:100) by requiring a single tag; with a two tag requirement $S/B \approx$1:50 is achievable. Algorithms either consider the impact parameter (*w.r.t.* the reconstructed primary vertex) of tracks associated with a jet, or fully reconstructed secondary vertices in the silicon tracker [7, 8]. CDF achieves a 50% (40%) efficiency with a 1.5% (0.5%) mistag rate for its loose (tight) tags. Feeding reconstructed information from either algorithm into a neural net can improve the performance. DØ achieved a 70% (50%) efficiency with a 4.5% (0.3%) mistags.

2.1. $WH \to \ell\nu b\bar{b}$

Associated WH production, with the W decaying to leptons and Higgs to b-jets motivates a search for one or two tagged b-jets. The W is identified by requiring a central, isolated electron or muon and $\not\!\!E_T$. Both CDF and DØ searched 1.7 fb^{-1} of data, combining the results from non-overlapping samples of their data: DØ studied four exclusive samples (e or μ with either 1 tight or two loose b-tags) and CDF two (two jets tagged by secondary vertices, or one jet by a secondary vertex and the other by a jet probability b-tag). All selected candidates are well described by the known contributing SM processes (W production in association with two heavy flavor jets and $t\bar{t}$ production). No significant excess is observed, and the upper limits from both experiments are comparable (Fig. 1). The horizontal line at 1 gives an indication of how far these individual searches still are from observing (or truly constraining) the SM Higgs. For a Higgs mass of 115 GeV, the expected (observed) values for $\sigma_{95}/\sigma_{\rm SM}$ = 9.05 (11.1) [DØ] and 9.95 (10.1) [CDF].

2.2. $ZH \to \nu\bar{\nu}b\bar{b}$

The large $Z \to \nu\bar{\nu}$ and $H \to b\bar{b}$ branching ratios provide excellent sensitivity for ZH associated production. The H's recoil against the accompanying Z suggests a signature of acoplanar jets (QCD jet pairs will tend to be aligned back-to-back); CDF tightens this requirement by allowing no more than two observed jets in their search through 1.7 fb^{-1} of data. The event selection required at least one b-tagged

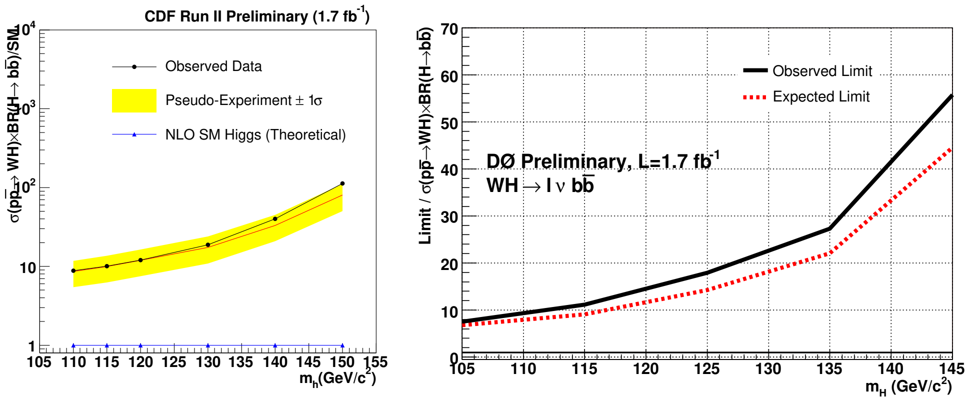

Fig. 1. The observed (and expected) cross-sections normalized to the SM prediction for CDF (left) and DØ (right).

jet and large missing transverse energy $\not{E}_T > 55$ GeV. The prevalent physics backgrounds are VB production associated with heavy flavor jets and $t\bar{t}$. Multijet events, with mis-measured jets, dominate the instrumental backgrounds. The number of selected events, and all their kinematic distributions, are consistent with SM expectations. CDF's expected value for $\sigma_{95}/\sigma_{\rm SM} = 9.7$ at $m_H = 115$ GeV.

2.3. $ZH \to \ell\ell b\bar{b}$

The associated Z can be directly reconstructed when it decays into a pair of isolated high-p_T leptons. Candidate events selected by muon or electron pairs in the Z-peak were required to have one or two b-tagged jets. The main background sources are Z plus heavy jets and $t\bar{t}$ production. No real $\not{E}_T$ is expected in such signatures, and CDF discards events with $\not{E}_T$ not attributable to jet mis-measurements (placing cuts on $\not{E}_T$ projections along the direction bisecting the leptons' opening angle), improving the invariant jet mass resolution. DØ required either one tight or two loose b-tags. CDF sequentially applied two separate neutral nets trained to reject the main backgrounds (Z plus jets and $t\bar{t}$). Once again, with no unexplained excess observed in about 1 fb^{-1} of data, $\sigma(p\bar{p} \to ZH) \times BR(H \to b\bar{b})$ limits are reported by both experiments. The individual experimental reaches in this search are no better than $16-20 \times$ SM predictions near $m_H = 115$ GeV.

2.4. $H \to WW \to \ell\nu\ell\nu$

Direct production of a heavy Higgs, with its dominant decay mode $H \to WW$ into leptonic final states, can produce a signature of two leptons with $\not{E}_T$. Since a W-pair produced in a (spin-0) Higgs decay favors final state leptons with directions aligned (small azimuthal separation $\phi_{\ell\ell}$), and most SM background processes (pairs from Z-decays) give back-back-back leptons, this topological cut helps suppress backgrounds. At the tree level there are no jets, and CDF discards events with two or more jets. Since the square of the theoretical matrix element gives the probability of an interaction as a function of observables (like final-state momenta) CDF used a leading-order matrix element technique to define a likelihood ratio in establishing its cross section estimates.

This search is most sensitive near $m_H = 160$ GeV where the branching fraction to WW first turns on (and briefly peaks near 100%). Both experiments individually reach an expected $\sigma_{95}/\sigma_{\rm SM} \approx 3.1$ for $m_H = 160$ GeV.

2.5. $WH \to WWW^{(*)} \to \ell^{\pm}\nu\ell^{\pm}\nu + X$

A heavy Higgs produced in association with a W-boson results in WWW states. A distinctive signature of same-charge di-leptons could be exploited. Data selection demands two *like-sign* isolated leptons plus $\not\!\!E_T$. In addition DØ builds a likelihood variable from the dilepton invariant mass, $\not\!\!E_T$, and the opening angles between leptons and the leptons and the $\not\!\!E_T$.

The background due to mis-identified charge is estimated from data by the frequency of discrepancies between redundant checks on charge: solenoid vs. toroid tracks (muons), and solenoid tracks vs. their $\Delta\phi$ match to the calorimeter (electrons). In each channel explored (ee, $e\mu$, and $\mu\mu$) the number of observed events is completely described by background. Weak signal levels at the current luminosity (1.0 fb^{-1}), however, result in a ratio of observed to SM cross sections no better than about 18 (at $m_H = 160$ GeV).

3. Combined Tevatron limit

Although the individual analyses performed by each experiment are far from placing constraints on a SM Higgs, the statistical power of combining them all is clear in Fig. 2 [9]. The 95% CL upper limits on the observed (expected) cross sections are a factor of 7.7 (4.2) higher than the SM cross sections for $m_H = 115$ GeV and only a factor of 1.4 (2.5) higher for $m_H = 160$ GeV.

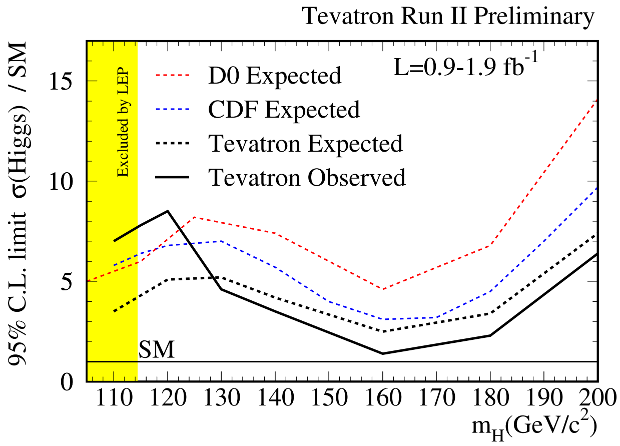

Fig. 2. Expected and observed 95% CL cross-section ratios for the combined CDF and DØ analyses.

4. MSSM Higgs

In two Higgs doublet models (such as is required by the MSSM – Minimum Supersymmetric Model) electroweak symmetry breaking results in four massive scalar bosons (h, H, $H^{\pm}$) and one massive pseudoscalar (A) Higgs boson, often collectively denoted by ϕ. An important parameter is $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$, the ratio of the vacuum expectation values of the neutral Higgs bosons (assumed to couple exclusively to the *up* and *down*-type quarks). The MSSM is fully parametrized at tree level by the values of $\tan\beta$ and m_A. Enhanced $\phi^0 bb$ and $\phi^0 \tau\tau$ couplings at large $\tan\beta$ mean potentially large Higgs production rates at the Tevatron for MSSM Higgs.

4.1. $\phi b(b) \to bbb(b)$

Since $\phi \to b\bar{b}$ processes are swamped by heavy flavor production, searches focus on ϕb associated production. Selecting three b-tagged jet events, DØ and CDF have looked for evidence of signal in the invariant mass distributions of the two leading b-jets in, respectively 0.90 and 0.98 fb^{-1} of data. The background distribution's shape is inferred from samples of double-tagged events convoluted with the measured mistag rate, normalized to the three b-tagged sample outside the signal mass window. CDF used the additional discriminator $m_{\rm diff} = M^{\rm jet1}_{\rm vertex} + M^{\rm jet2}_{\rm vertex} - M^{\rm jet3}_{\rm vertex}$ comparing the mass of the tracks associated with each jet that originated from the displaced vertex. With no excess events to account for, the expected and observed cross-section limits are reported (Fig. 3 *top*).

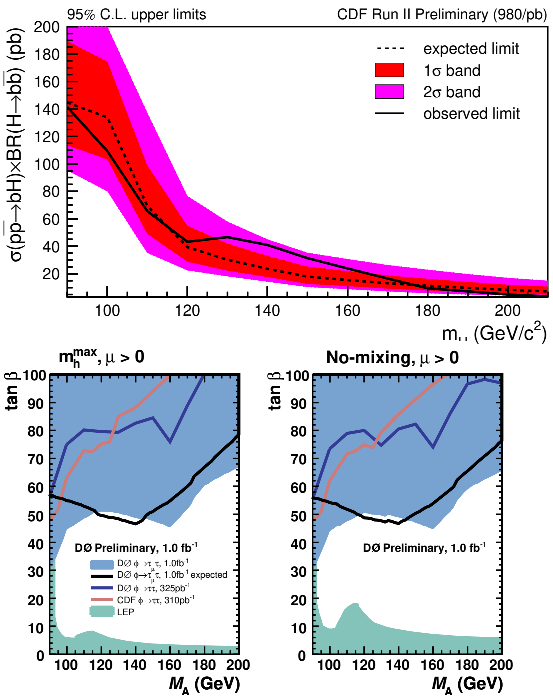

Fig. 3. (top) CDF's $\sigma(p\bar{p} \to bH) \times BR(H \to b\bar{b})$. Errors on the expected limit are shown as shaded bands. (Bottom) Limits by DØ in the $\tan\beta$ – m_A plane. In the $m_\phi = 90 - 200$ GeV mass region both experiments exclude $\tan\beta$ values greater than about 40-50.

4.2. Neutral MSSM Higgs $A \to \tau_\ell \, \tau_{had}$

A search for neutral MSSM Higgs decaying to taus is reported by both experiments for 1 fb^{-1} of data. Under the requirement that one τ decay leptonically, its lepton isolated from the opposite sign hadronic tau, DØ has completed analysis for the μ channel employing three NNs to discriminate three topologies of τ decays from background jets: *EM* clusters without tracks, hadronic clusters matched to single tracks, and hadronic clusters with multiple tracks. A cut on the visible mass $m_{\text{vis}} = \sqrt{p_{\tau_1} + p_\mu + p_T^{\text{miss}}} > 20$ GeV removed the remaining W background. CDF explored the e and $e\mu$ channels as well, utilized a variable sized cone algorithm to define hadronic taus (ranging from 0.175 radians for $E_{\text{vis}} < 30$ GeV to 0.05 radians for $E_{\text{vis}} > 100$ GeV). W events were removed by a cut on the projection of the $\not{E}_T$ onto the bisector of the tau opening angle.

While a small excess was reported in CDFs $e\tau$ and $\mu\tau$ channels, it is a $<$ 2σ effect not observed in their own $e\mu$ analysis, nor in the DØ analysis. Both experiments are in fact in good agreement with SM background estimates, and produce similar exclusions (see Fig. 3 *bottom*).

4.3. Fermiophobic Higgs

A production mechanism unique to hadron colliders $p\bar{p} \to h_f H^\pm \to h_f h_f W^\pm \to \gamma\gamma\gamma(\gamma) + X$ is accessible to the Tevatron provided $m_{H^\pm}$ is not too large. DØ requires three photons ($p_T > 30$ GeV, 20 GeV and 15 GeV) and applies a cut on the vector sum of the photon $p_T > 25$ GeV. No events are observed in the 1.0 fb^{-1} data set, with background estimates of 1.1 ± 0.2 event.

A search for associated VB production through inclusive di-photon states $p\bar{p} \to VV \to h_f \to \gamma\gamma + X$ and $p\bar{p} \to h_f W^\pm(Z) \to \gamma\gamma + X$ was conducted by DØ selecting two photons with $p_T > 25$ GeV and cutting on their vector sum (> 35 GeV) in the signal region. With no excess events, a limit was placed on $m_h > 92$ GeV at the 95% CL.

5. Supersymmetry

Tevatron experiments have performed detailed analysis on MSSM, particularly in its most constrained form, mSUGRA (minimal supergravity), controlled by five parameters: m_o, $m_{1/2}$, A^0, $\tan\beta$, and sign(μ). A neutralino LSP (lightest SUSY particle), $\tilde{\chi}_1^0$, is generally assumed.

5.1. Stop $\to$ *Charm +* $\not{E}_T$

If light enough, $\tilde{t} \to c\tilde{\chi}_1^0$ and stop pair production would lead to acoplanar jets in the final state. To overcome the enormous QCD background, DØ applied heavy-flavor jet tagging and required large $\not{E}_T$. Final optimization was made with mass-dependent cuts on H_T and the separation angles between jets. For $m_{\tilde{t}} = 135$ GeV and $m_{\tilde{\chi}_1^0} = 75$ GeV, 66 candidate events were observed, with 64.21 ± 3.22 expected background. An excluded domain in the plane of the stop and neutralino masses is derived (Fig. 4).

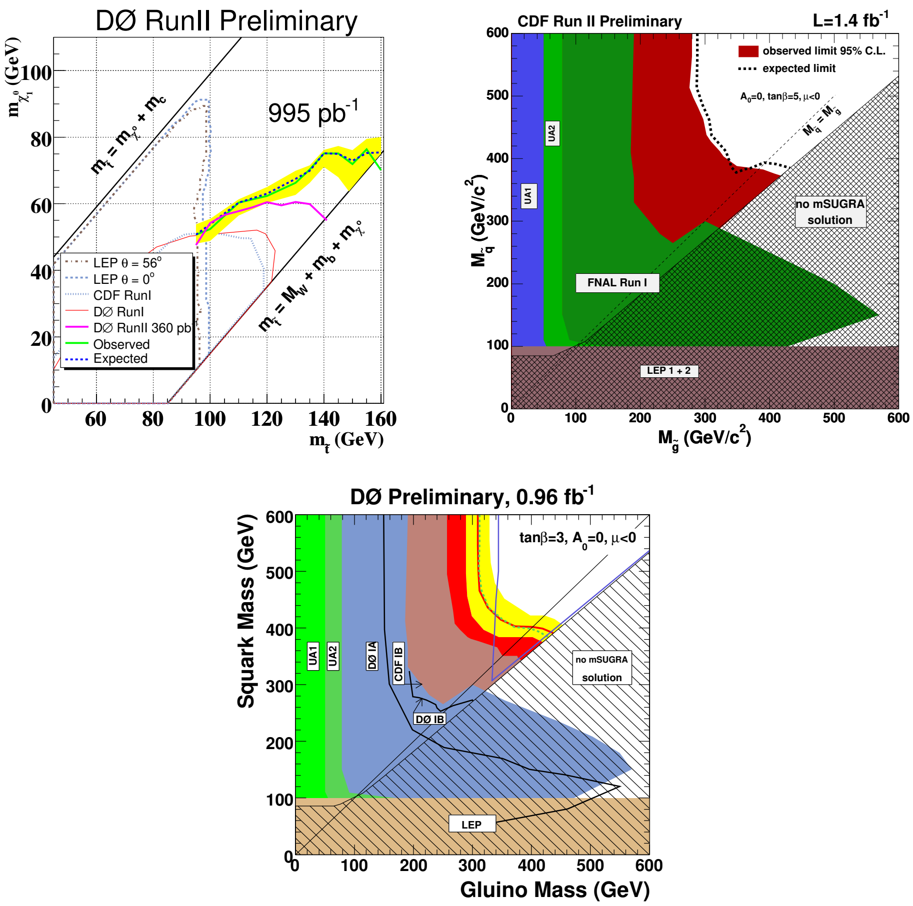

Fig. 4. DØ 's exclusion contour in the plane of the stop and $\tilde{\chi}_1^0$ mass (left), CDF's (right) and DØ 's (bottom) in the plane of generic squark and gluino masses. Direct comparisons are complicated by the different SUSY parameters assumed.

5.2. A search for long-lived stop

Promptly decaying stops were assumed in the above analysis. In some models involving extra dimensions, the stop may in fact be the LSP, eliminating the $\not{E}_T$ signature. Instead such a charged massive particle would appear as a high p_T, low velocity, highly ionizing "muon track." This distinctive signature allows using generic CHAMP searches to set limits on a stable stop. In its analysis of 1.0 fb^{-1} of data, CDF used TOF measurements to separate signal from muons (from W decay) and calculated candidate masses from the track momentum and measured TOF β. The distribution of candidate masses is consistent with expected backgrounds. With no candidates with a mass above 10 GeV, a stable stop below 250 GeV has been excluded.

5.3. *Squarks/gluinos* $\rightarrow$ *jets* + $\not\!\!E_T$

A search scanning the mSUGRA parameter space for $\tilde{q}$ and $\tilde{g}$ cascade decays was conducted by both CDF and DØ . At low m_0 where gluinos are heavier than squarks, $\tilde{q}\tilde{q}$ production dominates and the squarks are expected to decay by $\tilde{q} \rightarrow q\tilde{\chi}_1^0$, producing predominately events with two acoplanar jets and $\not\!\!E_T$. For high m_0 where the squarks are heavier, $\tilde{g}\tilde{g}$ production dominates, the gluinos decay by $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$, and mulitjet ($\geq$ jets) events result.

CDF and DØ have performed three separate analyses: 2-jet, 3-jet (for the intermediate m_0 region), and $>$ 3-jet. The main backgrounds are the associated production of Ws with jets (where the lepton from $W \rightarrow \ell\nu$ is not identified), the associated production of Zs and jets ($Z \rightarrow \nu\nu$ constitutes an irreducible $\not\!\!E_T$ background), and instrumental effects (arising from QCD multijet production with jet energy mismeasurements faking the $\not\!\!E_T$). In addition to jets and $\not\!\!E_T$, the selection criteria included a cut on H_T, a veto on isolated leptons, and topological cuts on the angles between the $\not\!\!E_T$ and jet directions.

The two collaborations report similar results: $m_{\tilde{g}} < 290$ GeV (CDF), 309 GeV (DØ) for any $m_{\tilde{q}}$ and $m_{\tilde{g}} < 380$ GeV (CDF), 402 GeV (DØ) for $m_{\tilde{q}} \approx m_{\tilde{g}}$, though direct comparisons are difficult. DØ 's search was based on a $\tan\beta = 3$, CDF on $\tan\beta = 3$, and the theoretical uncertainties were dealt with differently.

5.4. *Squarks/gluinos* $\rightarrow \tau_{had}$ + *jets* +$\not\!\!E_T$

In some regions of mSUGRA parameter space (*e.g.*, $A_0 = -2m_0$, $\tan\beta = 15$, $\mu < 0$), the squarks decay through chargino and neutralino states to final state leptons. With squarks lighter than gluinos in this same region, $\tilde{q}\tilde{q}$ production dominates, and the lighter $\tilde{\tau}_1$ states are the lightest sleptons (suppressing decays to other sleptons).

DØ preformed a selection of two or more jets and at least one hadronic τ with 0.96 fb^{-1} of data. Final optimization of $E_T > 175$ GeV and $E_T^{\rm jet1} + E_T^{\rm jet2} + E_T^{\tau} > 325$ GeV produced 2 candidates while the expected background was 1.7$\pm$ 0.2. The exclusion contour (see Fig. 5 *left*) shows the mSUGRA plane is constrained in the region of $m_0 = 90 - 110$ GeV up to $M_{1/2}$ values near 150 GeV. At $m_0 = 110$ GeV, squark masses under 366 GeV are excluded.

5.5. *Chargino/neutralino* $\rightarrow$ *trileptons*

Associated production of the lightest chargino (decaying by $\tilde{\chi}^{\pm} \rightarrow \ell\nu\tilde{\chi}_1^0$) and second lightest neutralino (with $\tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$) lead to final states containing three leptons and $\not\!\!E_T$. Background (diboson production with leptonic decays, and Drell-Yan with the conversion of a bremsstrahlung photon) is small, yet low rates and low p_T leptons remain a challenge.

Using 0.9 – 1.7 pb^{-1}, DØ studied four different samples: $ee\ell$, $\mu\mu\ell$, $e\mu\ell$ and like-sign $\mu\mu$. To maximize signal efficiency, the third lepton was identified by an isolated track. CDF identified 14 different samples: (combinations of e, μ, τ, and isolated

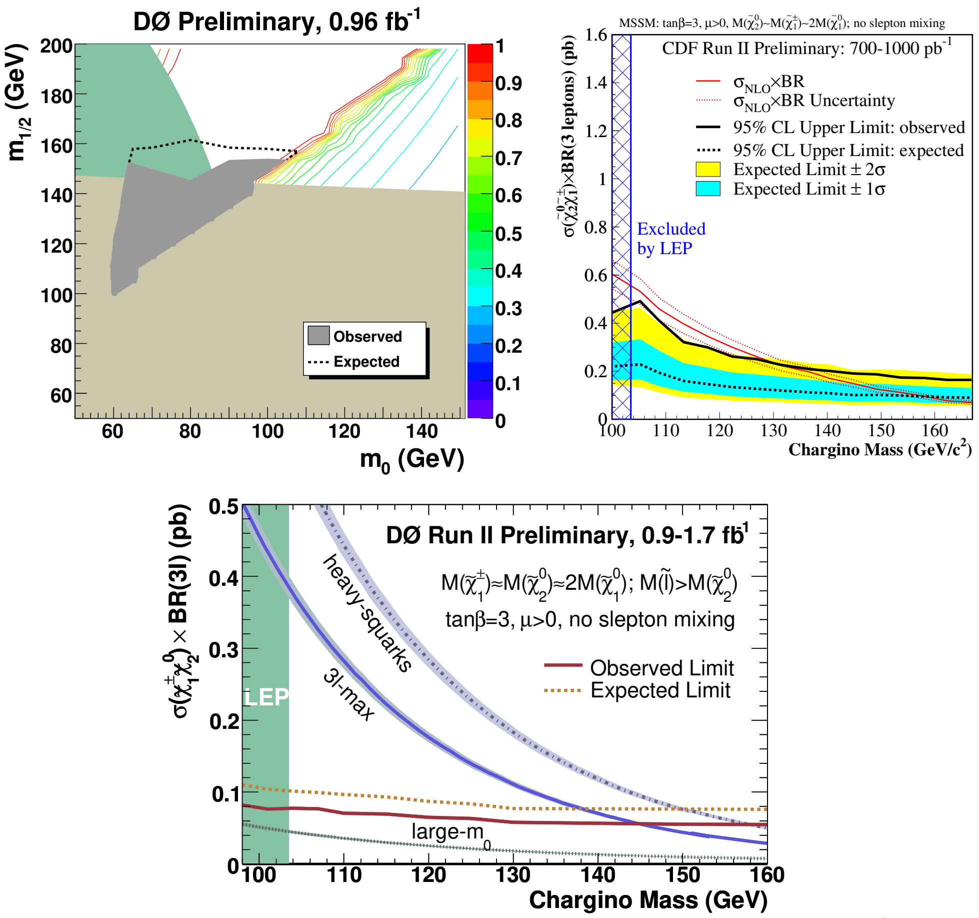

Fig. 5. Limit on the associated production cross section times branching fraction into three leptons by CDF (left) and DØ (right). Theoretical expectations in various mSUGRA scenarios are also indicated (bottom).

track) × (low-p_T/high-p_T triggers). Optimization was based on mSUGRA signals with low slepton, chargino, and neutralino masses ($\tan\beta = 3$). CDF fixed m_0 at 60 GeV, while DØ adjusted m_0 so that slepton masses were just above the mass of $\tilde{\chi}_1^0$. The results for both experiments are shown in Fig. 5. The DØ lower limit on chargino mass in in the "3ℓ-mass scenario" is 145 GeV. The CDF limit for the low m_0 considered is 126 GeV.

6. *Conclusions*

With 2 fb^{-1} of data, and many channels being analyzed, the CDF and DØ experiments are rapidly approaching the sensitivity of expected SM Higgs signals. With results reported on integrated luminosities between 0.9 fb^{-1} and 1.9 fb^{-1}, the combined Tevatron expected cross-section limits are about a factor of four above the SM expectation for a Higgs mass of 115 GeV, and only 2.5 for a mass of 160 GeV. With Tevatron running approved through 2009 and a final data set of 6 - 7 fb $^{-1}$ expected for each experiment, the Tevaton may yet see signs of the Higgs existence, or begin to constrain it.

Broad searches continue for the signatures of MSSM Higgs as well as supersymmetric decays (from squarks, gluinos, charginos, neutralinos and sleptons), but to date, none have been observed. New limits have been set on SUSY masses and mSUGRA parameters.

References

[1] CDF Higgs results: http://www-cdf.fnal.gov/physics/new/hdg/hdg.html ; CDF SUSY results: http://www-cdf.fnal.gov/physics/exotic/exotic.html.

[2] DØ Higgs results: http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm ; DØ SUSY results: http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm.

[3] CDF Collaboration, arXiv:0708.3642; submitted to Phys. Rev. D.

[4] DØ Collaboration, Nucl. Instr. and Methods A **565** (2006) 463.

[5] LEP Working Group for Higgs Searches, Phys. Lett. B **565** (2003) 61.

[6] http://lepewwg.web.cern.ch/LEPEWWG/.

[7] C. Neu, *Proc. Int. Workshop on Top Quark Physics*, January 12 – 15, 2006, Coimbra, Portugal published by POS; CDF public note 6315.

[8] http://www-d0.fnal.gov/phys_id/bid/d0_private/bid.html.

[9] CDF and DØ Collaborations, CDF public note 8383; DØ Note 5227.

TEVATRON SEARCHES FOR HIGGS AND SUPERSYMMETRY
TRAŽENJE HIGGSA I SUPERSIMETRIJE TEVATRONOM

Results are presented of searches for Standard Model and MSSM Higgs, as well as supersymmetric particles. A broad variety of signatures were explored by the CDF and DØ experiments, using approximately 2 fb^{-1} of reconstructed $p\bar{p}$ data from collisions at 1.96 TeV at Fermilab's Tevatron. No significant deviation from background sources has been observed in any of the searches, and new limits have been set on the production cross sections.

Predstavljamo ishode traženja Higgsa i supersimetričnih čestica prema standardnom modelu i prema MSSM. Primjenjuje se široka lepeza znakova u CDF i DØ eksperimentima, rabeći oko 2 fb^{-1} analiziranih podataka za $p\bar{p}$ sudare na 1.96 TeV u Tevatronu Fermilab-a. U tim traženjima nismo našli odstupanja od šuma, i postavili smo nove granice za udarne presjeke.