CDF note 9229

Search for Gluino and Squark Production in Multijets Plus Missing $\not\!\mathrm{E}_\mathrm{T}$ Final States

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URL http://www-cdf.fnal.gov

(Dated: March 4, 2008)

We present preliminary results on a search for squarks and gluinos in proton-antiproton collisions with a center-of-mass energy of 1.96 TeV and based on 2.0 fb^{-1} of data collected by the CDF detector in the Tevatron Run II. Events with multiple jets of hadrons and large missing transverse energy in the final state are studied within the framework of minimal supergravity and assuming R-parity conservation. No excess with respect to Standard Model predictions is observed and new limits on the gluino and squark masses are extracted.

I. INTRODUCTION

Supersymmetry (SUSY) [1] is regarded as one of the most promising fundamental theories to describe physics at arbitrarily high energies beyond the Standard Model (SM). Over the last decades, the Minimal Supergravity (mSUGRA) [2] scenario has been extensively studied. In mSUGRA, symmetry breaking is achieved via gravitational interactions and the vast SUSY parameter space is reduced to only five parameters that determine the low energy phenomenology from the scale of Grand Unification(GUT): the common scalar mass m_0, the common gaugino mass $m_{1/2}$, the common soft trilinear SUSY breaking parameters A_0, the ratio of the Higgs vacuum expectation values at the electroweak scale tanβ, and the sign of the Higgsino mass term sgn(μ). When R-parity [3] is conserved, supersymmetric particles have to be produced in pairs and ultimately decay into the lightest supersymmetric particle (LSP), usually identified as the lightest neutralino $\tilde{\chi}_1^0$, which constitutes a valid candidate for cold dark matter.

At the Tevatron, the production of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), superpartners of quarks and gluons, constitutes one of the most promising channels because of the strong couplings involved. The cascade decay of gluinos and squarks into quarks and gluons will result in a final state consisting of several jets plus missing transverse energy ($\not\!\!E_{\mathrm{T}}$) coming from the neutralinos, which leave CDF undetected. In this document, we discuss preliminary results on a search for squarks and gluinos carried out on 2.0 fb^{-1} of data collected by the CDF detector in Run II. A complete set of plots and results are collected at `http://www-cdf.fnal.gov/physics/exotic/exotic.html`.

II. SIGNAL AND BACKGROUND SAMPLES

A mSUGRA scenario with $A_0 = 0$, sgn(μ)=-1 and tanβ=5 is assumed. The gluino-squark mass plane is scanned via variations of the parameters m_0 (0-500 GeV/c^2) and $m_{1/2}$ (50-200 GeV/c^2). The PYTHIA [4] Monte Carlo program is used to generate samples for each mSUGRA point, and ISASUGRA 7.74 is implemented to predict the SUSY spectrum at the TeV scale. Light-flavor squark masses are considered degenerate, while 2-to-2 processes involving stop ($\tilde{t}$) and sbottom ($\tilde{b}$) production are excluded to avoid a strong theoretical dependence on the mixing in the third generation. Each squark/gluino production subprocess (corresponding to one of the final states $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{q}\bar{\tilde{q}}$, $\tilde{q}\tilde{g}$ and c.c.) is normalized to next-to-leading order (NLO) predictions as estimated using PROSPINO V.2 [5]. The cross sections are computed using CTEQ6.1M PDFs and the renormalization/factorization scale is set to the average mass of the two final-state supersymmetric particles.

SM backgrounds are dominated by QCD multijet processes where the observed $\not\!\!E_{\mathrm{T}}$ comes from partially reconstructed jets in the final state. Monte Carlo samples have been generated using PYTHIA TUNE A, and data in a low $\not\!\!E_{\mathrm{T}}$ region are used to determine the absolute normalization. Other sources of backgrounds are Z and W production in association with jets, and top and diboson production. For these processes, $\not\!\!E_{\mathrm{T}}$ might result from mis-reconstructed jets, the presence of neutrinos and muons in the final state, or both. ALPGEN v2.1 [6] interfaced with parton shower from PYTHIA is used to estimate W and Z+jets backgrounds, taking the normalization from the measured inclusive Drell-Yan cross sections [7]. Top and diboson processes are estimated using PYTHIA TUNE A Monte Carlo samples normalized to the NLO theoretical predictions [8]. Finally, the generated samples are recontructed using the full CDF detector simulation.

III. EVENT SELECTION

Events are required to have a reconstructed primary vertex with z-position within 60 cm of the nominal interaction point, $\not\!\!E_{\mathrm{T}}$ >70 GeV and a tracking activity consistent with the energy measured in the calorimeter to reject cosmics and beam-halo background.
Depending on the relative masses of squarks and gluinos, different event topologies are expected. If squarks are significantly lighter than gluinos, $\tilde{q}\tilde{q}$ production is enhanced. The squark tends to decay according to $\tilde{q} \rightarrow q\tilde{\chi}_1^0$, and a dijet topology is favoured, along with $\not\!\!E_{\mathrm{T}}$ due to the two neutralinos in the final state. If gluinos are lighter than squarks, $\tilde{g}\tilde{g}$ process dominates. Gluinos decay via $\tilde{g} \rightarrow q\bar{q}\chi_1^0$, leading to topologies containing a large number of jets (≥ 4) and moderate $\not\!\!E_{\mathrm{T}}$. For $\mathrm{M}_{\tilde{\mathrm{g}}} \approx \mathrm{M}_{\tilde{\mathrm{q}}}$, a topology with at least three jets in the final state is expected. Three different analyses are carried out in parallel, requiring at least 2, 3 or 4 jets in the final state, respectively. In each case, the transverse energy of the jets must be above 25 GeV, and one of the leading jet is required to be central ($|\eta|$ <1.0). A minimum azimuthal distance between the jets and the $\not\!\!E_{\mathrm{T}}$ is required to reduce the QCD multijets contribution. Lepton vetoes are applied to reject boson+jets, dibosons and $\mathrm{t\bar{t}}$ backgrounds, where W and Z bosons in the event can decay semileptonically into electrons, that can be misidentified as jets, or muons, that can produce large $\not\!\!E_{\mathrm{T}}$. An electron veto is applied requiring the jet electromagnetic fraction, defined as the ratio between the transverse electromagnetic energy of the jet and its total transverse energy, to be less than 0.9 for the first two, three and four leading jets, in case of 2-jet, 3-jet and 4-jet analysis, respectively. Muons are identified as isolated [11] tracks. A minimum azimuthal distance between the highest $\mathrm{p_T}$ isolated

track and the $\not\!\!E_T$ is required to reduce $W \to \mu\nu$ contribution, and events are rejected if the invariant mass of the two highest isolated tracks falls in a mass window consistent with the Z boson mass.

For each final state, a dedicated study has been carried out to define the selection criteria that enhance the sensitivity to the mSUGRA signals. The signal significance, $\mathrm{S}/\sqrt{\mathrm{B}}$, with S denoting the signal and B the background number of events, is maximized. Jet transverse energies, $\not\!\!E_T$ and $\mathrm{H_T}$, defined as the sum of the transverse energy of the jets, are the variables employed in the optimization. Table 1 summarizes the thresholds applied on these variables in the different analyses.

IV. CONTROL REGIONS

Monte Carlo predictions for SM processes are tested in background-dominated regions, referred as control regions, defined by reversing the selection requirements introduced to suppress specific background processes. Two different types of control regions are identified:

- *QCD-dominated region*: at least one of the leading jets is required to be aligned with the $\not\!\!E_T$ azimuthal direction.

- *EWK/Top-dominated region*: lepton vetoes are reversed, and at least one electron or muon, identified via the presence of an electromagnetic cluster or isolated track, is required in the event.

Figure 1 shows, for the 4-jet analysis, the $\not\!\!E_T$ and $\mathrm{H_T}$ distributions in the QCD-dominated sample (top), electron-enhanced sample (middle), and electron and muon enhanced sample (bottom). The shaded band indicates the total systematic uncertainty on the background estimation (see below).

Variable [GeV]	4-jet	3-jet	2-jet
$\mathrm{H_T}$	280	330	330
$\not\!\!E_T$	90	120	180
$\mathrm{E_T^{jet1}}$	95	140	165
$\mathrm{E_T^{jet2}}$	55	100	100
$\mathrm{E_T^{jet3}}$	55	25	–
$\mathrm{E_T^{jet4}}$	25	–	–

TABLE I: Set of thresholds employed in the analysis.

Good agreement is found between data and SM Monte Carlo predictions. Similar agreement is observed in all control samples considered for each analysis separately.

V. SYSTEMATIC UNCERTAINTIES

The dominant systematic uncertainty on the signal efficiencies and SM background yields comes from the 3% uncertainty on the jet energy scale. This translates into a 15% and 30% uncertainty on the signal and background estimations, respectively. Systematic uncertainties related to the modeling of the initial and final state radiation (ISR/FSR) in mSUGRA signal, boson+jets and $t\bar{t}$ Monte Carlo samples translates into an uncertainty on the signal efficiency between 3% to 6%, depending on the $\tilde{q}/\tilde{g}$ masses, and a 10% (8%) uncertainty on the boson+jets (top) background contribution. Other uncertainties specific for the different background processes include: a 10% uncertainty on the diboson production cross section due to the uncertainties on PDFs and the choice of renormalization scale, a 10% uncertainty on the $t\bar{t}$ theoretical cross section, and a 2% systematic uncertainty on boson+jets production cross section. Finally, a 6% uncertainty on the integrated luminosity is also included.

Systematic uncertainties on the mSUGRA cross sections are dominated by PDFs and renormalization scale uncertainties. The Hessian method [9] is used to compute the uncertainty due to PDFs, which varies between 20% and 34%, depending on the mSUGRA point. The uncertainty due to the renormalization and factorization scale is determined by re-evaluating the cross section using twice and half the nominal scale set in PROSPINO for each production subprocess. The resulting systematic uncertainty varies between 17% and 23%, depending on the mSUGRA point.

VI. RESULTS

The number of observed and SM expected events corresponding to a total integrated luminosity of 2.0 fb^{-1} are reported in Table 2, separately for the three analyses. Good agreement is found between data and Monte Carlo predictions. Figure 2 shows the $\not{E}_{\mathrm{T}}$ and $\mathrm{H_T}$ distributions for the 4-jet, 3-jet and 2-jet analyses. All selection criteria have been applied except the one on the variable that is represented. The figures show the comparison of the data and the SM prediction, including the total systematic uncertainty. For illustration purposes, one representative mSUGRA point is shown for each analysis region. In case of the 4-jet region, a point with $\mathrm{M}_{\tilde{g}} = 287\ \mathrm{GeV/c^2}$ and $\mathrm{M}_{\tilde{q}} = 438\ \mathrm{GeV/c^2}$ is considered. For the 3-jet region, a point with $\mathrm{M}_{\tilde{g}} = 249\ \mathrm{GeV/c^2}$ and $\mathrm{M}_{\tilde{q}} = 270$

GeV/c^2 is chosen. Finally, in case of the 2-jet region, we chose a point with $M_{\tilde{g}} = 349$ GeV/c^2 and $M_{\tilde{q}} = 385$ GeV/c^2.

No significant deviation from the SM predictions is observed, and the results are thus translated into exclusion limits on gluino and squark production as a function of gluino and squark masses. A Bayesian approach at 95% C.L. is used, where statistical and systematic uncertainties on signal efficiency and background contributions are considered in the limit calculation, including also the uncertainty on the total luminosity, and fully taking into account the correlations. Figure 3 shows, as an example, PROSPINO NLO cross sections as a function of the squark masses, for $M_{\tilde{g}} = 230$ GeV/c^2, and as a function of the gluino mass for $M_{\tilde{g}} \approx M_{\tilde{q}}$, respectively. The yellow band indicates the total systematic uncertainties on the NLO predictions. The cross sections are compared to observed and expected 95% C.L. limits, as obtained in this analysis. Cross sections in the range 1 pb to 0.1 pb, depending on the gluino and squark masses considered, are excluded.

Exclusion limits on quarks and gluino masses are also computed. In this case, a Bayesian approach at 95% C.L. is also employed where, in addition to signal and background uncertainties, the uncertainties on the PROSPINO NLO predictions, as illustrated in Fig. 3, are also considered in the limit calculation. The obtained exclusion limits from different squark and gluino masses are mapped out in Fig. 4, where exclusion regions, as determined by other experiments, are also presented. In a mSUGRA scenario with $A_0 = 0$, $\mu < 0$ and $\tan\beta = 5$, this search excludes masses up to 392 GeV/c^2 at 95% C.L. in the region where gluino and squark masses are similar, gluino masses up to 280 GeV/c^2 for every squark mass, and gluino masses up to 423 GeV/c^2 for squark masses below 378 GeV/c^2.

The results of this analysis in terms of $M_{\tilde{g}}$-$M_{\tilde{q}}$ can also be translated into the mSUGRA parameters at the GUT scale. Figure 5 shows the excluded regions in the m_0-$m_{1/2}$ plane for $\tan\beta=5$, $A_0=0$ and $\mu<0$. This search improves on the limits from indirect searches as determined by LEP2 [10] for m_0 values between 75 and 250 GeV/c^2 and for $m_{1/2}$ values between 130 and 170 GeV/c^2.

VII. CONCLUSION

We have presented preliminary results on searches for squarks and gluinos in proton-antiproton collisions with a center-of-mass energy of 1.96 TeV at the Tevatron, based on 2.0 fb^{-1} of data collected by the CDF detector in Run II. In a mSUGRA scenario with $A_0 = 0$, $\mu < 0$ and $\tan\beta = 5$, we exclude masses up to about 392 GeV/c^2 at 95% C.L. in the region where gluino and squark masses are similar, gluino masses up to 280 GeV/c^2 for every squark mass, and gluino

Region	Observed data Evts	SM Expected Evts (stat. $\oplus$ syst.)
4-jets	45	48 ± 17
3-jets	38	37 ± 12
2-jets	18	16 ± 5

TABLE II: Observed number of data events for the three selection analyses in 2.0 fb^{-1}, compared with the expected events from SM processes. The quoted systematic uncertainty on the background include 6% uncertainty on the luminosity.

masses up to 423 GeV/c^2 for squark masses below 378 GeV/c^2.

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

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http://lepsusy.web.cern.ch/lepsusy/

[11] where a track is considered isolated if the scalar p_T sum of all additional tracks in a cone of radius R = 0.4 is less than 2 GeV/c

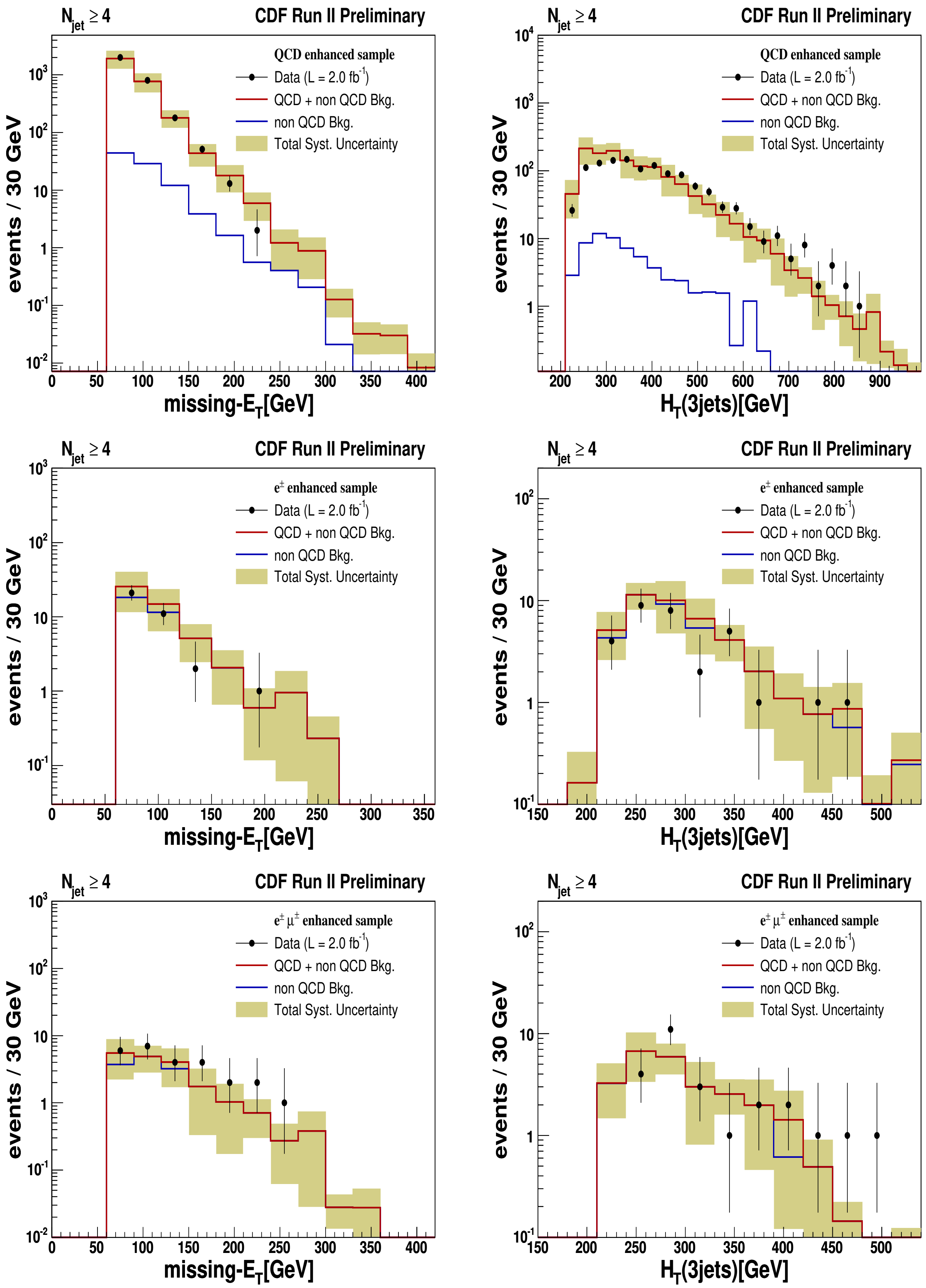

FIG. 1: $\not\!\!E_T$ and H_T distributions in the QCD-dominated sample (top), electron-enhanced sample (middle), electron and muon enhanced sample (bottom), for the 4-jet region, after all selection cuts except the one on the variable that is represented. The data are compared to the SM predictions including the total systematics uncertainties. In addition, the non-QCD background contribution is shown separately.

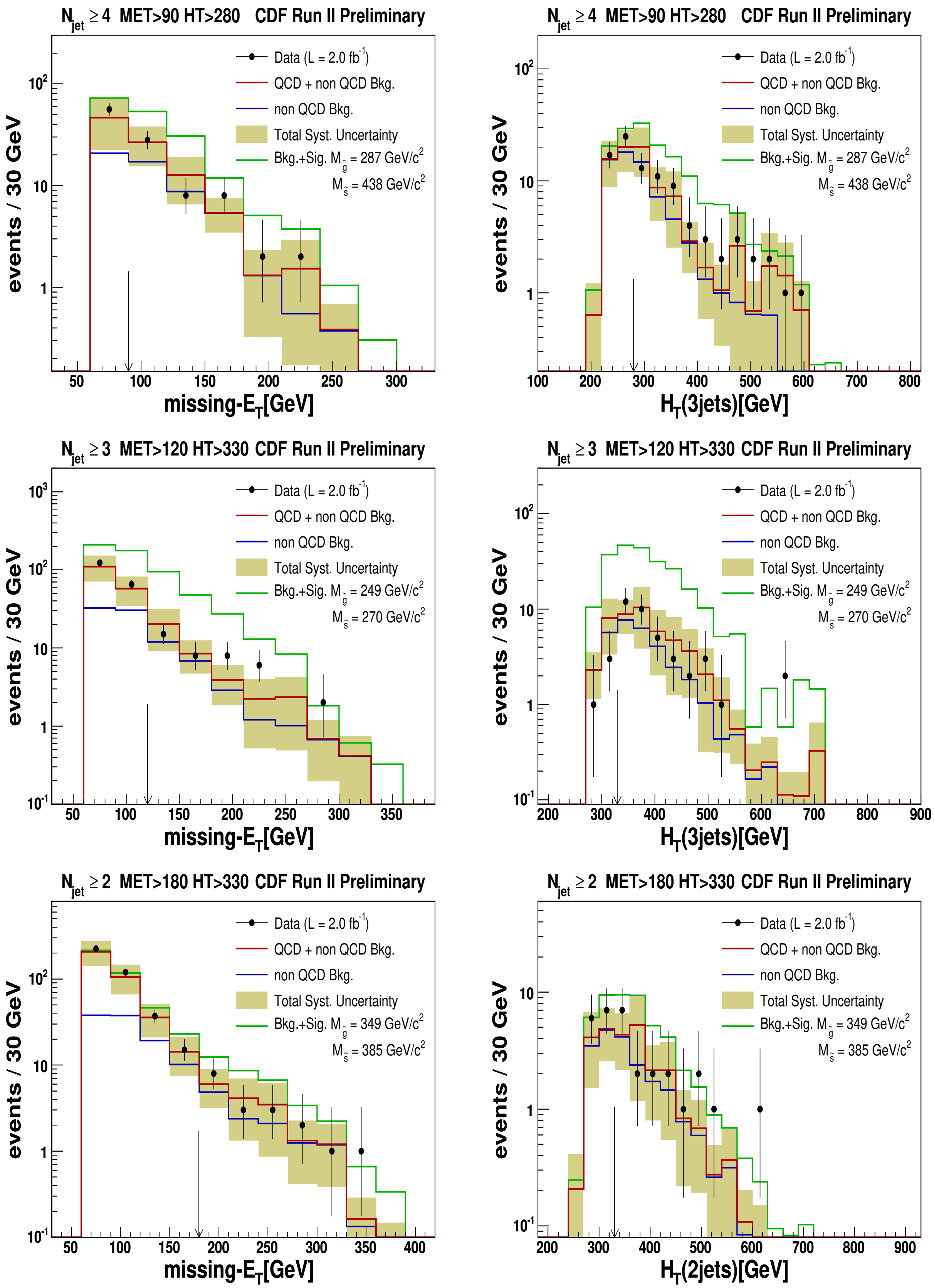

FIG. 2: $\not{E}_T$ and H_T distributions after all selection cuts for the 4-jet(top), the 3-jet(middle) and the 2-jet (bottom) analyses. The data are compared to the SM predictions including the total systematics uncertainties. In addition, the non-QCD background contribution is shown separately. Distributions for a representative signal point are shown for the three analysis regions. In these plots, all cuts have been applied except the one on the variable that is represented.

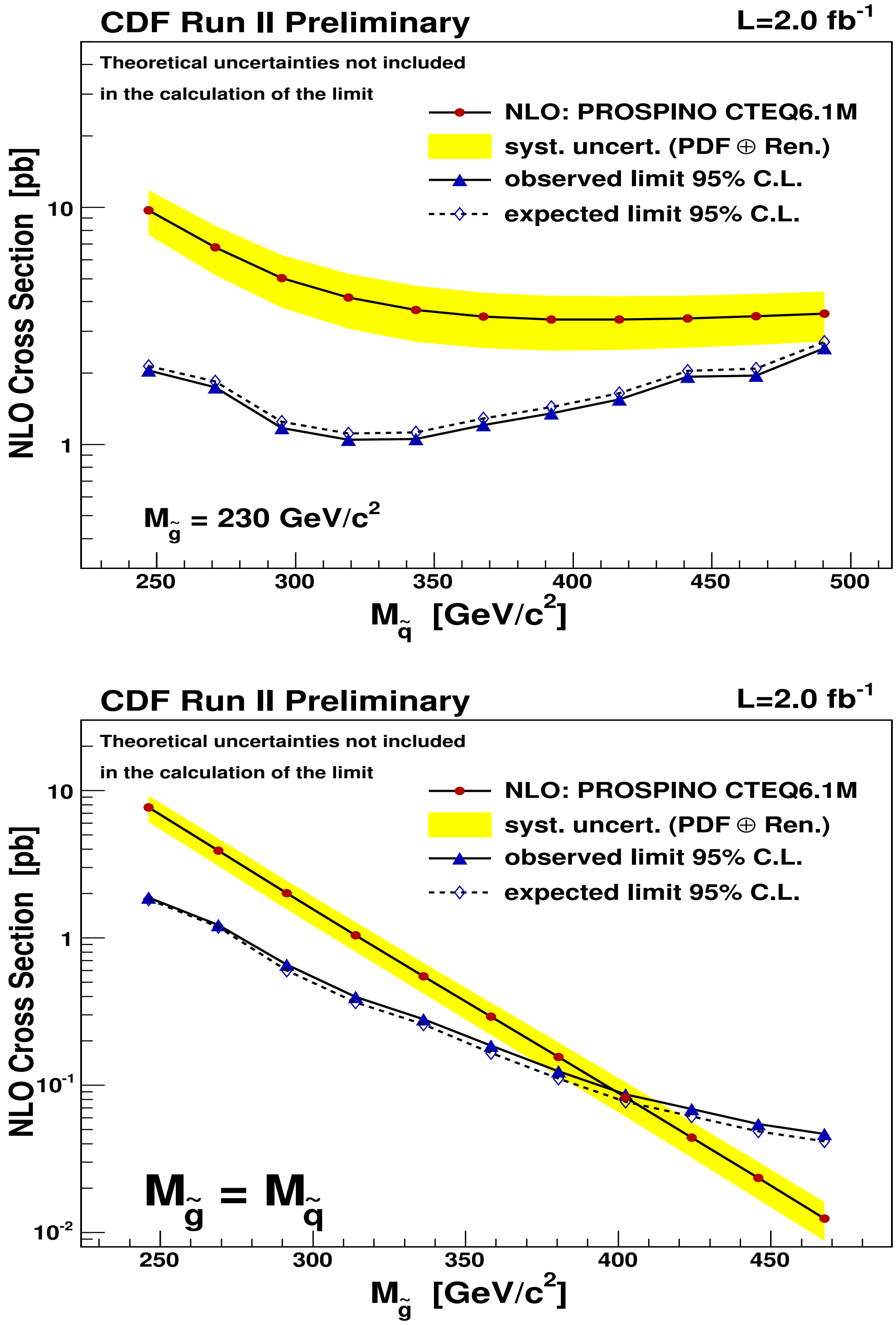

FIG. 3: Cross section as a function of gluino/squark masses in the case of $M_{\tilde{g}} = 230$ GeV/c^2 (top) and $M_{\tilde{q}} \approx M_{\tilde{g}}$ (bottom). The observed and expected limits at 95% C.L. are also shown. The yellow band indicates the total systematic uncertainties on the NLO prediction.

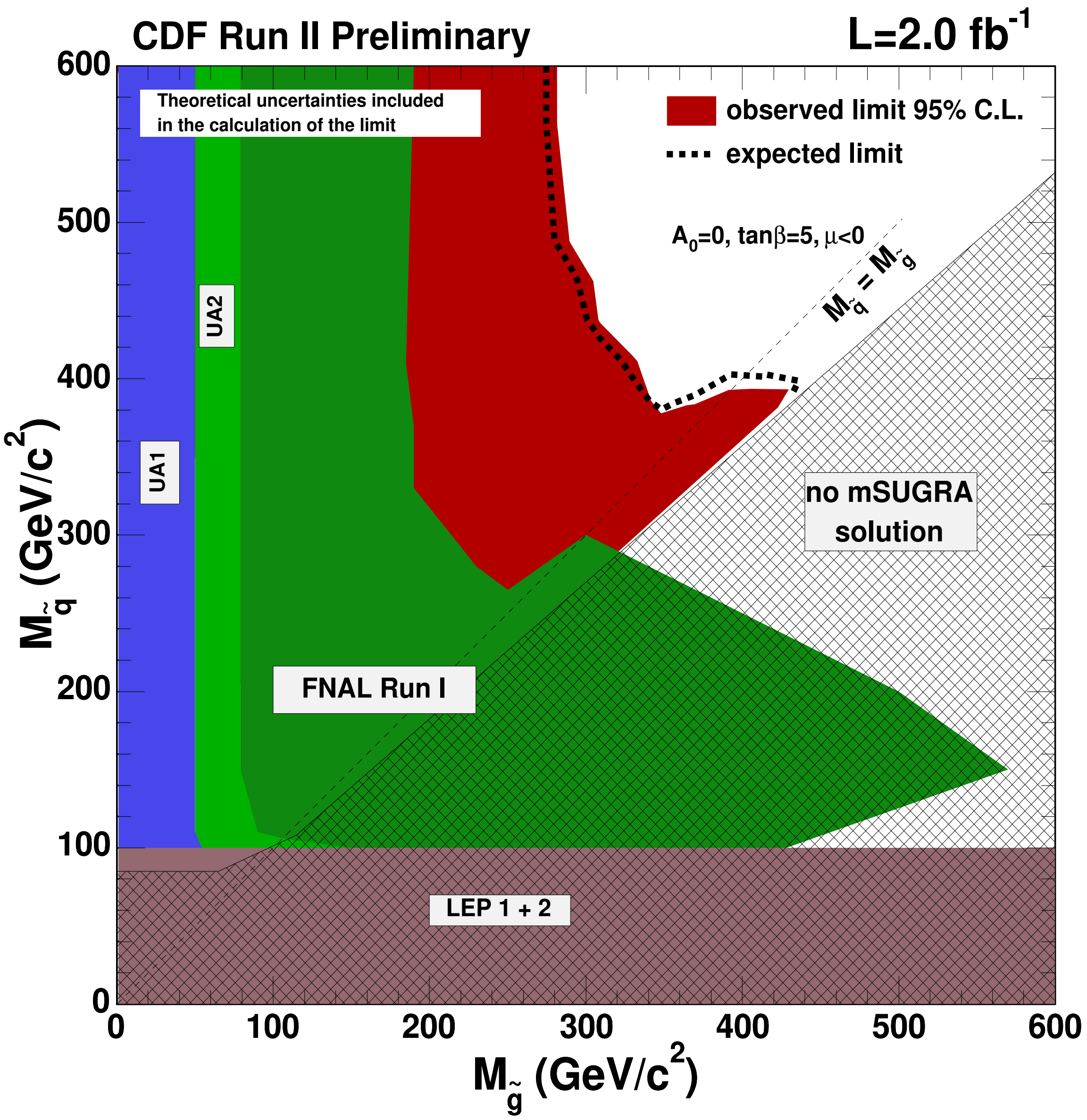

FIG. 4: Observed(red region) and expected (dashed-line) exclusion limits at the 95 % C.L in the $M_{\tilde{q}}$ - $M_{\tilde{g}}$ mass plane. Regions excluded by previous experiments are shown, together with no-mSUGRA solution region.

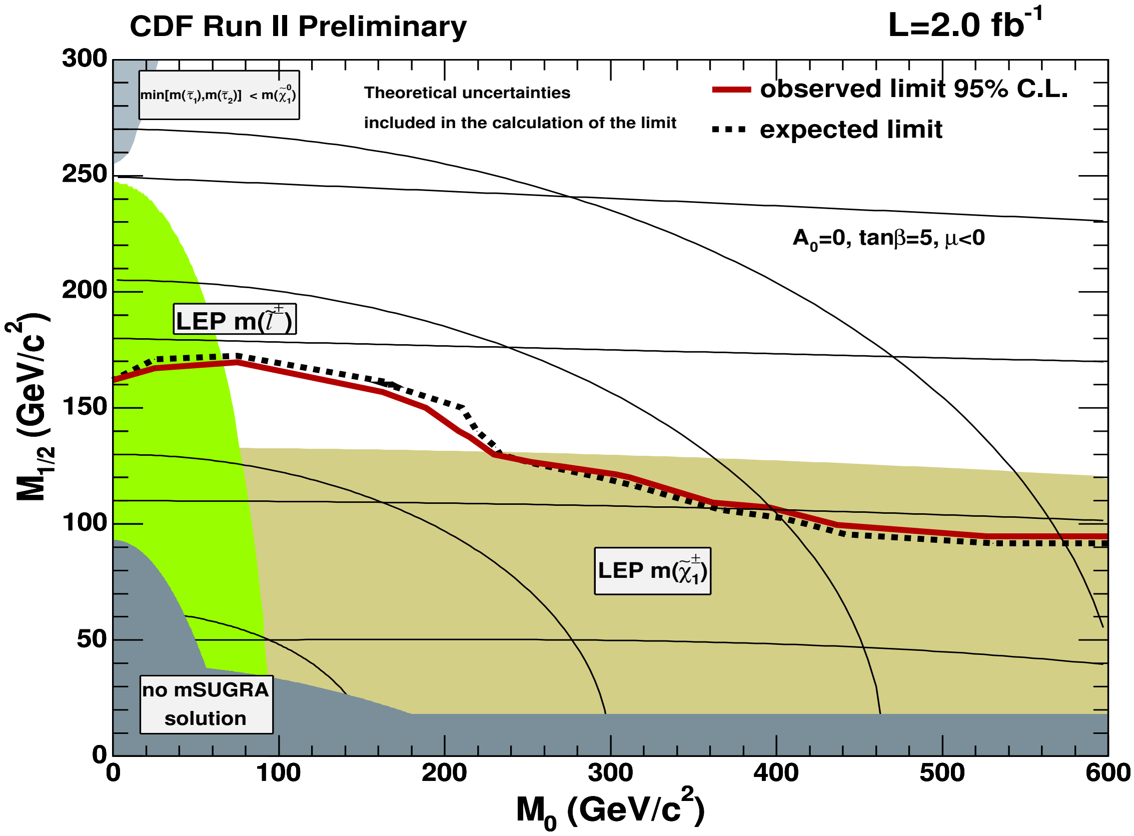

FIG. 5: Observed(solid line) and expected (dashed line) exclusion limits at the 95% C.L. in the (m_0,$m_{1/2}$) plane. The light-grey region indicates the region where $m(\tilde{\tau}) < m(\tilde{\chi}_1^0)$. The beige and green regions are excluded by LEP2 chargino and slepton searches[10], respectively. No mSUGRA solution is found in the dark-grey region. The black lines are the iso-mass curves for gluinos (horizontal) and squarks (elliptic) corresponding to masses of 150, 300, 450 and 600 GeV/c^2.