SEARCH FOR SUSY WITH $\not{E}_T$ AND JETS AT CDF

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Events with signatures involving large missing transverse energy ($\not{E}_T$) are among the quintessential search modes for R-parity conserving supersymmetry. CDF has conducted two recent analyses for supersymmetry which use $\not{E}_T$ and jets. The $\not{E}_T$ and monojet signature is employed to determine process independent limits for the production of new physics beyond the Standard Model and then applied to models of spontaneous breaking of supersymmetry to determine limits on the supersymmetry breaking parameter and the gravitino mass. Direct searches for scalar top and scalar bottom quarks within the framework of supersymmetric models are performed using a signature of $\not{E}_T$ and two heavy flavor jets. Since the data is found to be consistent with Standard Model expectations, limits are determined in the mass planes $m(\tilde{\chi}_1^0) - m(\tilde{t}_1)$ and $m(\tilde{\chi}_1^0) - m(\tilde{b}_1)$.

1. New Physics and Gravitinos

Several theories beyond the Standard Model[1] contain light, neutral particles which have extremely small interaction cross sections. These particles typically pass through detectors unobserved producing a signature with an imbalance in transverse energy (E_T) quantified as missing transverse energy ($\not{E}_T$).

CDF has performed a search for physics beyond the Standard Model by examining events with large $\not{E}_T$ and a high E_T jet.[2] Trigger induced systematic effects are reduced by increasing the 35 GeV trigger threshold to $\not{E}_T \geq 50$ GeV. A high E_T jet is obtained by selecting events which contain a leading jet with $E_T \geq 80$ GeV. The effects of jet energy mismeasurement and additional instrumental backgrounds are reduced by requiring that the angle between the $\not{E}_T$ direction and the nearest jet satisfy $\Delta\phi(\not{E}_T, \text{jet}) \geq 90°$. Events with identified electrons or muons are removed. The $\not{E}_T$ spectrum and the estimated backgrounds after all selection criteria have been applied are shown in the left plot of Figure 1. The number of observed events is 379 while 380 ± 129 background events are determined. The 95% confidence level (CL) upper limit for the product of acceptance and cross section for new physics as a function of $\not{E}_T^{min}$, the $\not{E}_T$ threshold, are shown in the top right plot of Figure 1. To determine a process specific cross section limit, the pertinent acceptance is calculated.

Theories in which supersymmetry is broken via standard model gauge interactions can produce signatures with large $\not{E}_T$ and high E_T jets. In models with gravity where supersymmetry is realized locally, the gravitino ($\tilde{G}$) acquires a mass $m_{\tilde{G}}$.[3] A
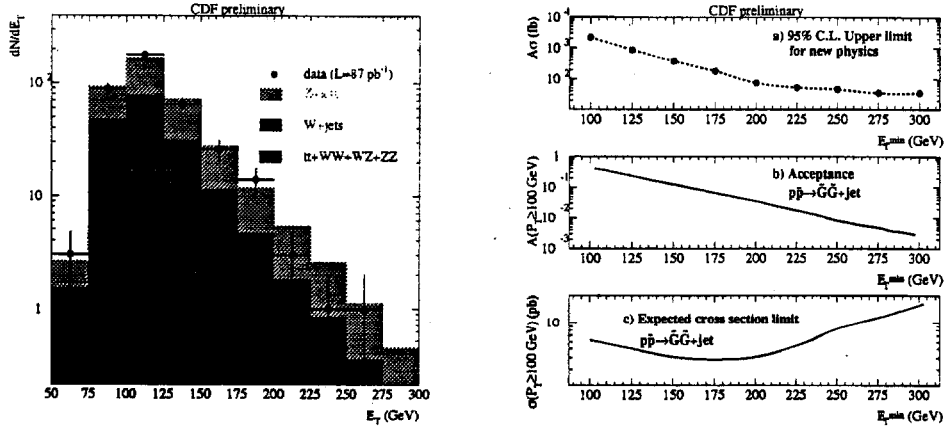
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Fig. 1. Left plot: Distribution of $\not{E}_T$ for data compared to background expectations. Right plot: 95% CL upper limit for acceptance times production cross section of new physics (top), the signal acceptance for $\tilde{G}\tilde{G}$ jet processes with $p_T^{\tilde{G}\tilde{G}} \geq 100$ GeV/c (middle), and the expected 95% CL upper limit for the cross section of $\tilde{G}\tilde{G}$ jet production with $p_T^{\tilde{G}\tilde{G}} \geq 100$ GeV/c (bottom).

gravitino with mass much less than the electroweak scale may be created when the scale at which the breaking of supersymmetry is transmitted is much less than the Planck scale. If R-parity is conserved, this naturally provides for a gravitino which can be the LSP. If sufficiently light ($m_{\tilde{G}} \ll 10^{-4}$ eV/c^2), the gravitino may appear at the Tevatron in signatures characterized by large $\not{E}_T$.

Pair production of gravitinos in conjunction with jets may occur through the processes $q\bar{q} \rightarrow \tilde{G}\tilde{G}g$, $qg \rightarrow \tilde{G}\tilde{G}q$, $\bar{q}g \rightarrow \tilde{G}\tilde{G}\bar{q}$, and $gg \rightarrow \tilde{G}\tilde{G}g$. The resulting signature for such events would be large $\not{E}_T$ and a jet.[2] In order to determine acceptances for $\tilde{G}\tilde{G}$ jet production, the theoretical predications[4] calculated at the supersymmetry breaking scale $\sqrt{F} = 200$ GeV are employed together with a CDF detector simulation. The dependence on $\not{E}_T^{min}$ in the calculated acceptances and cross sections is minimized by specifying the value of the transverse magnitude of the vector sum of the two gravitino momenta before further radiation, $p_T^{\tilde{G}\tilde{G}}$. For the acceptances and cross sections, $p_T^{\tilde{G}\tilde{G}} \geq 100$ GeV/c. The signal acceptance resulting from the simulations is shown in the middle right plot of Figure 1.

The expected 95% CL cross section upper limit for $\tilde{G}\tilde{G}$ jet production as a function of $\not{E}_T^{min}$ is shown in the bottom right plot of Figure 1. The value of $\not{E}_T^{min}$ is selected which results in the optimal reach in cross section. For $\not{E}_T^{min} = 175$ GeV, 19 events are observed with an estimated background of 21.6 ± 7.0. Incorporating a 20% uncertainty from the acceptance and a 4% uncertainty from the luminosity, the 95% CL upper limit for the number of signal events is 16.9. With an acceptance of 6.2%, the 95% CL upper limit for the $\tilde{G}\tilde{G}$ jet production cross section with $p_T^{\tilde{G}\tilde{G}} \geq 100$ GeV/c is 3.1 pb. Together with the cross section calculated from theory

of 12.6 ± 4.0 pb for $\sqrt{F} = 200$ GeV with a 32% systematic uncertainty, the 95% CL limit on the supersymmetry breaking scale is determined to be $\sqrt{F} \geq 217$ GeV. This value for $\sqrt{F}$ corresponds to gravitino masses residing above 1.1×10^{-5} eV/c^2.

2. Supersymmetric Top and Bottom

Theoretical considerations suggest that the scalar top quark ($\tilde{t}$) may be the lightest scalar quark and potentially lighter than the top quark. The dependence of the splitting in the $\tilde{t}$ mass eigenvalues on the top quark mass due to the mixing of chiral scalar top states can cause widely disparate values allowing $\tilde{t}_1$ to be much lighter than $\tilde{t}_2$. The values which anchor the mass spectrum are determined by scaling of the renormalization group equations from high energies ($\sim M_p$) down to the electroweak regime (~ 1 TeV). The effect on the renormalization group equations of the top Yukawa coupling is to drive the masses of the scalar top quarks lower than the first two families.

Although the splitting between $\tilde{b}$ mass eigenvalues due to the bottom mass and the influence of the bottom Yukawa coupling are weaker, values of supersymmetric parameters exist which cause large mixing among the scalar bottom quarks. Through a judicious choice of the ratio of the vacuum expectation values of the Higgs fields, $\tan \beta$, large mixing between the states can occur leading to considerable splitting among the $\tilde{b}$ mass eigenvalues and a small mass for the lighter mass eigenstate. This condition can appear in the $\tilde{b}$ sector when $\tan \beta$ is large.

At the Tevatron, the principal mechanisms for pair production of third generation scalar quarks are $q\bar{q}$ annihilation and gluon fusion. Several potential decay modes exist for $\tilde{t}_1$.[5] The process $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ occurring via Feynman diagram loops and ordinarily suppressed dominates if $m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{t}_1} < m_b + m_\ell + m_{\tilde{\nu}}$. For $\tilde{b}$, if $m_t, m_{\tilde{\chi}_1^+} > m_{\tilde{b}} > m_b + m_{\tilde{\chi}_1^0}$, the decay mode $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ is open and dominant.

A signature of two heavy flavor jets, missing transverse energy, and the absence of leptons is utilized at CDF to search for pair produced scalar top and scalar bottom quarks decaying to $c\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$, respectively.[6] Events characterized by two or three hard jets with $E_T \geq 15$ GeV and $|\eta| \leq 2$ and no additional jets with $E_T > 7$ GeV and $|\eta| \leq 3.6$ are selected. Systematic effects caused by the $\not{E}_T$ trigger threshold are suppressed by increasing the $\not{E}_T$ requirement from 35 GeV to 40 GeV. The effects of jet energy mismeasurement and QCD background are reduced by ensuring that the jets are well separated from the direction of $\not{E}_T$ as well as from each other. The angles are restricted between $\not{E}_T$ and any jet ($\Delta\phi(\not{E}_T, j) > 45°$), $\not{E}_T$ and the leading jet ($\Delta\phi(\not{E}_T, j_1) < 165°$), and the two highest E_T jets ($45° < \Delta\phi(j_1, j_2) < 165°$). Events containing electrons and muons are rejected. Jets arising from c and b quarks are identified using the jet probability algorithm[7] which gives the probability, $\mathcal{P}_{jet}$, that the ensemble of tracks in a jet is consistent with originating from a primary vertex. For events corresponding to $\tilde{t}$ decays, $\mathcal{P}_{jet} \leq 0.05$. For $\tilde{b}$ decays, $\mathcal{P}_{jet} \leq 0.01$.

For the scalar top quarks search, 11 observed events are found and a background of 14.5 ± 4.2 is estimated. Since there is no excess of observed events over Standard
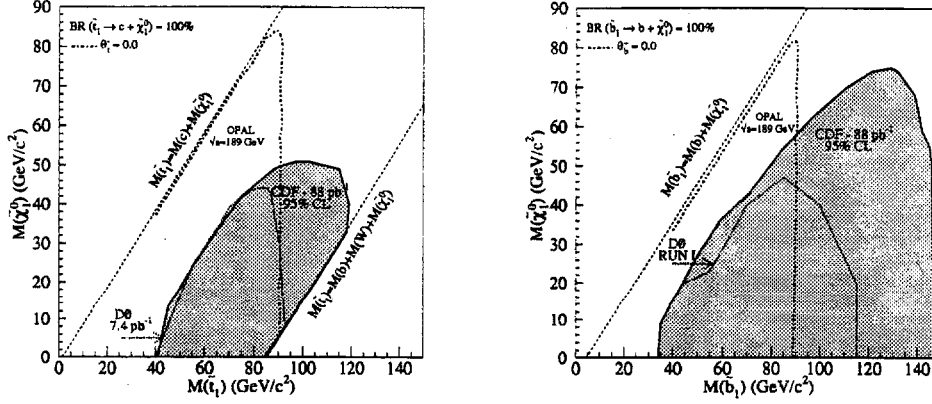
Fig. 2. Left plot: CDF 95% CL exclusion region in $m(\tilde{\chi}_1^0) - m(\tilde{t}_1)$ plane for $\tilde{t}_1 \to c\tilde{\chi}_1^0$. Right plot: CDF 95% CL exclusion region in $m(\tilde{\chi}_1^0) - m(\tilde{b}_1)$ plane for $\tilde{b}_1 \to b_1\tilde{\chi}_1^0$.

Model backgrounds, a 95% CL exclusion region in the $m(\tilde{\chi}_1^0) - m(\tilde{t}_1)$ plane is determined using a background subtraction method.[8] The results are shown in the left plot of Figure 2. The break in sensitivity between the 95% CL excluded region and the kinematic limit is primarily due to requiring $\not{E}_T \geq 40$ GeV. However, the recent analysis performed by OPAL[9] without a $\not{E}_T$ restriction supplement the coverage obtained by CDF and are shown in the figure. For $m(\tilde{\chi}_1^0) = 40$ GeV/c^2, the maximum scalar top quark mass excluded is 119 GeV/c^2 at the 95% CL.

Once the selection criteria for the scalar bottom quarks search are applied, 5 events are observed and an expected background of 5.8 ± 1.8 is determined. The 95% CL excluded region in the $m(\tilde{\chi}_1^0) - m(\tilde{b}_1)$ plane is shown in the right plot of Figure 2. The OPAL results[9] for this decay channel are superimposed. For $m(\tilde{\chi}_1^0) = 40$ GeV/c^2, the maximum scalar bottom quark mass excluded is 146 GeV/c^2 at 95% CL.

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