First Search for Multijet Resonances in $\sqrt{s} = 1.96$ TeV $p\bar{p}$ Collisions

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We present the first model independent search for three-jet hadronic resonances within multijet events in $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions at the Fermilab Tevatron using the CDF II detector. Pair production of supersymmetric gluinos and squarks with hadronic R-parity violating decays is employed as an example of a new physics benchmark for this signature. Selection criteria based on the kinematic properties of an ensemble of jet combinations within each event help to extract signal from copious QCD background. No significant excess outside the top quark mass window is observed in data with an integrated luminosity of 3.2 fb^{-1}. We place 95% confidence level limits on the production cross section $\sigma(p\bar{p} \to XX') \times \mathrm{BR}(\tilde{g}\,\tilde{g} \to 3\text{ jet} + 3\text{ jet})$ where X, $X' = \tilde{g}$, $\tilde{q}$, or $\tilde{\bar{q}}$, with $\tilde{q}$, $\tilde{\bar{q}} \to \tilde{g} + \text{jet}$, as a function of gluino mass, in the range of 77 GeV$/c^2$ to 240 GeV$/c^2$.

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Most searches for new physics at high energy hadron colliders use signatures that require leptons, photons, or missing transverse energy ($\not\!\!E_T$) [1] in order to suppress backgrounds from QCD. Final states with multijets and $\not\!\!E_T$ have also been explored [2,3].

In this Letter, we present a first new physics search in an entirely hadronic channel with no $\not\!\!E_T$ signature using data collected with the Collider Detector at Fermilab (CDF). This data set corresponds to an integrated luminosity of 3.2 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Tevatron collider. The search utilizes a novel approach [4,5]: an ensemble of all possible jet triplets within an event consisting of at least six jets is used to extract a signal from the multijet QCD backgrounds. We model the possible new physics origin for this signature with pair production of $SU(3)_C$ adjoint Majorana fermions each one decaying into three quarks [6,7]. This search is sensitive to models such as hadronic R-parity violating supersymmetry (RPV SUSY) [4] with a gluino, chargino, or neutralino lightest superpartner, as well as the hadronic decay modes of pairs of top quarks or fourth generation quarks and it complements existing di-jet resonances searches at hadron colliders. Moreover, it does not require any b-quark jet identification which is an important tool, often used for top quark identification.

The CDF II detector is a multipurpose particle detector consisting of tracking and calorimeter systems [8]. The data were collected using an online event selection that requires at least four calorimeter jets [9] with uncorrected transverse energy $E_T > 15$ GeV. A jet is formed by a cluster of calorimeter towers and reconstructed with a cone algorithm using a fixed cone of $\Delta R = 0.4$ [10], with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ [1]. In the online selection an additional request is made for the sum of the transverse energy of all clusters to be larger than 175 GeV. At the analysis level, jet energies are corrected to account for effects such as nonlinearities in the detector response and multiple $p\bar{p}$ collisions in an event [11].

Events are selected with at least six jets with transverse momentum (p_T) greater than 15 GeV$/c$ and $|\eta| < 2.5$. The scalar sum of the most energetic six jets' p_T, $\sum p_T$, is required to be greater than 250 GeV$/c$ and events with $\not{E}_T > 50$ GeV are removed. Multiple interactions, resulting in the reconstruction of more than one primary vertex in the same event, contribute to the multijet background. We require at least one primary vertex and discard events with more than four primary vertices. To further reduce this background, we require jets in an event to originate from near the same point on the beam line. We associate tracks with each jet where possible [12] by requiring ΔR between the track and the jet to be less than 0.4. The mean z coordinate of all tracks associated with each jet ($\bar{z}_j$ for the jth jet), and the associated standard deviation [$\delta(z_j)$] are determined. Events with jets that have $|\bar{z}_j| > 60$ cm are discarded. We then evaluate the standard deviation of the $\bar{z}_j$ of all jets in the event [$\delta(z_{\rm all})$] and select events that have at least four jets with $\delta(z_j) < 4$ cm, and $\delta(z_{\rm all}) < 0.5$ cm, consistent with the resolution of tracks associated with jets. Once the selection is applied, pileup effects are significantly reduced. Since we select events with at least six jets, we consider an ensemble of 20 (or more) possible jet triplets. We discard those triplets that have more than one jet with no z information. In addition, all jets in the triplet must have $\delta(z_j) < 2.5$ cm, and originate from within 10 cm of the primary vertex of the event.

The biggest challenge of this analysis is to reduce the large multijet QCD background. To extract signal from this background, we apply the following technique: for every accepted triplet we calculate the invariant mass, M_{jjj}, and scalar sum p_T, $\sum_{jjj} p_T$. Triplets made of uncorrelated jets tend to have $M_{jjj}c \approx \sum_{jjj} p_T$, while signal triplets should have M_{jjj} as close to the mass of the decaying particle as allowed by jet energy resolution. We then select triplets with $\sum_{jjj} p_T - M_{jjj}c > \Delta$, Δ being a diagonal offset as illustrated in Fig. 1. The diagonal offset values are optimized for the best signal over background ratio separately

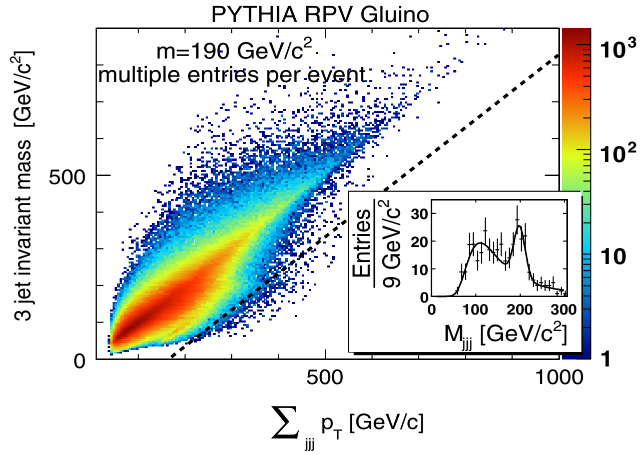

FIG. 1 (color online). Distribution of M_{jjj} versus $\sum_{jjj} p_T$ for a pair-produced RPV gluino with invariant mass 190 GeV$/c^2$ generated with PYTHIA MC generator. Triplets to the right of a diagonal offset ($\sum_{jjj} p_T - M_{jjj}c = \Delta$), indicated by the dashed line, are kept. The inset shows the M_{jjj} distribution for the RPV signal MC simulation and with no QCD background after a diagonal offset of 195 GeV$/c$ along with a Gaussian plus a Landau fit; the Landau shows the combinatorial contribution within the signal jet ensemble. The QCD background distribution resembles that of the combinatorial contribution, because they are both due to effectively uncorrelated triplets.

for each hadronic resonance mass in this search. The optimized diagonal offset selection greatly reduces the QCD background and the contribution from incorrect combinations of jets. We note that for a small fraction of events it is possible for multiple triplets to pass all selection criteria.

The QCD background is estimated from a 5-jet data sample, which is statistically independent of the signal sample of ≥ 6 jets (for brevity referred to as 6-jet). The 5-jet M_{jjj} distribution is rescaled by the ratio of the 6-jet to 5-jet population in each $\sum_{jjj} p_T$ bin. A Landau function is chosen [4] to fit the scaled 5-jet M_{jjj} distribution. The Landau parameters extracted from the scaled 5-jet M_{jjj} distribution vary by less than 2 GeV$/c^2$ from similar fits to the 6-jet sample, indicating that the scaled 5-jet sample describes the background in the 6-jet sample well. The contribution to the background from $t\bar{t}$ pair production is estimated using the PYTHIA Monte Carlo (MC) generator [13] followed by the CDF detector simulation [14]. These events were generated assuming a top quark mass of 172.5 GeV$/c^2$ and production cross section of 7.5 pb. To ensure a proper fit to the QCD background, the fit is blinded to the mass region corresponding to the top quark, 153 GeV$/c^2 < M_{jjj} < 189$ GeV$/c^2$. Additionally, we find that truncating the Landau fit for lower values of Δ gives an improved description of the QCD background. The Landau parameters extracted from the fits vary smoothly as functions of the diagonal offset value. We now have a firm prediction for the QCD background and fix the parameters when we fit for signal.

The signal is modeled using the PYTHIA MC generator. The process $p\bar{p} \rightarrow XX'$ where $X, X' = \tilde{g}, \tilde{q}$, or $\bar{\tilde{q}}$ is simulated at several gluino mass values, ranging from $74\ \mathrm{GeV}/c^2$ to $245\ \mathrm{GeV}/c^2$ with hadronic *uds* RPV SUSY decays turned on, allowing gluino decays to three light jets. Two scenarios of squark masses are considered ($0.5\ \mathrm{TeV}/c^2 < m_{\tilde{q}} < 0.7\ \mathrm{TeV}/c^2$, $m_{\tilde{q}} = m_{\tilde{g}} + 10\ \mathrm{GeV}/c^2$) and were found to give equivalent acceptances.

The acceptance of the trigger, reconstruction, and selection requirements for signal events is determined by fitting the pair-produced RPV gluino MC simulation with a Landau plus Gaussian function, corresponding to the combinatorial contribution and signal peak, respectively. An example is shown in the inset of Fig. 1. The Gaussian is integrated in a $\pm 1\sigma$ range to extract the number of signal triplets. This procedure is repeated for various diagonal offset values and the optimal offset for each hadronic resonance mass is determined. The acceptance, calculated for these optimal offset values, is 5×10^{-5}, constant within 20% across all gluino mass points.

The expected sensitivity of this analysis in the absence of signal is determined with a set of background-only experiments (pseudoexperiments). A pseudoexperiment is constructed with the background modeled by a Landau function whose parameters are chosen randomly from within the range allowed by the background shape fits, with the expected amount of $t\bar{t}$ added. Each pseudoexperiment is fit with the Landau background shape parameters fixed, and a signal Gaussian whose position is determined by the mass point being fit, and whose amplitude and width are allowed to vary within a range determined by the expected signal shape. The number of signal triplets allowed by each pseudoexperiment is extracted by integrating the Gaussian in the same way as in the acceptance calculation.

Two broad categories of systematic uncertainties are accounted for in extracting a cross section: uncertainties in the shape of the M_{jjj} distribution and uncertainties in the acceptance of the signal. Shape uncertainties, determined from background and signal fits, are incorporated in the pseudoexperiments themselves. Acceptance uncertainties arise from modeling the signal Monte Carlo simulation and include effects of initial and final state radiation [15] (20%), parton distribution functions (PDFs) from CTEQ [16] (10%), jet energy scale [11] (31%), and luminosity [17] (6%) uncertainties. The overall acceptance uncertainty due to these sources is 38%.

We search for a hadronic resonance in the data for an invariant mass (m) 77–240 GeV/c^2 in 9 GeV/c^2 steps, consistent with jet energy resolution. For each mass, jet triplets are selected by the optimal diagonal offset value. The data M_{jjj} distribution is fit in exactly the same way as the pseudoexperiments. Figure 2 shows the M_{jjj}

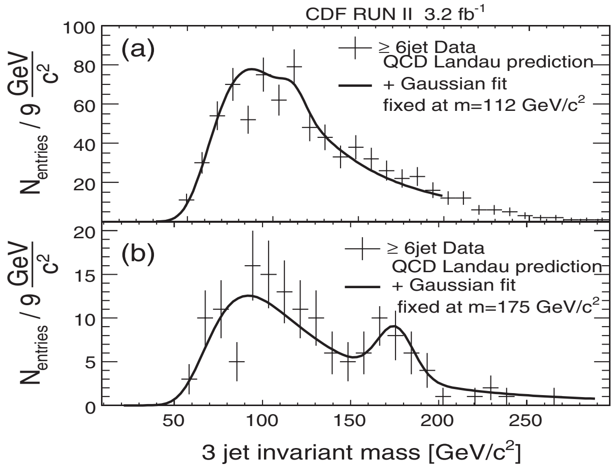

FIG. 2. M_{jjj} distributions in 3.2 fb^{-1} data fitted to a Landau (parameters are extracted from fits to the scaled 5-jet M_{jjj} distribution) plus a Gaussian at (a) 112 GeV/c^2 (optimal diagonal offset value 155 GeV/c) and (b) 175 GeV/c^2 (optimal diagonal offset value of 190 GeV/c). The fit function in panel (b) includes a Gaussian fixed at $m = 175\ \mathrm{GeV}/c^2$.

distribution for $m = 112\ \mathrm{GeV}/c^2$ and $175\ \mathrm{GeV}/c^2$. The latter fit shows a noticeable excess consistent in mass with the hadronic decay of the top quark. The Gaussian component of the fit integrated from 165 GeV/c^2 to 185 GeV/c^2, corresponding to a $\pm 1\sigma$ window around the Gaussian peak, gives 11 ± 5 triplets. The number of expected QCD background triplets in the same mass window from the Landau function is 8 ± 1. The $t\bar{t}$ contribution to background is evaluated using PYTHIA. It is cross-checked with higher order $t\bar{t}$ MC generators ALPGEN [18] and MC@NLO [19], samples that varied the amount of initial and final state radiation, as well as samples that varied the PDFs within their uncertainties. These studies lead us to expect between 0.5 and 1.1 triplets from $t\bar{t}$ production in the aforementioned mass range. We note that ~10% of the triplets in the top mass window originate from two or more combinations in a jet ensemble of a given event, consistent with the PYTHIA $t\bar{t}$ simulation. We evaluate the significance of the excess using the pseudoexperiment method described above, which includes systematic uncertainties on signal acceptance as well as the shape of the M_{jjj} distribution. The observed excess is 2 standard deviations (2σ) above the prediction. Additional cross-checks, such as requiring one of the jets to have originated from a b-quark, suggest that the excess is consistent with coming from top quarks.

We do not observe a significant deviation from standard model backgrounds anywhere in the data. A Bayesian approach is used to place 95% confidence level limits on $\sigma(p\bar{p} \rightarrow XX') \times \mathrm{BR}(\tilde{g}\tilde{g} \rightarrow 3\ \mathrm{jet} + 3\ \mathrm{jet})$ where $X, X' = \tilde{g}, \tilde{q}$, or $\bar{\tilde{q}}$, with $\tilde{q}, \bar{\tilde{q}} \rightarrow \tilde{g} + \mathrm{jet}$, versus gluino mass, shown in Fig. 3. The largest excess observed is the one previously noted located near the top quark mass. We find that our

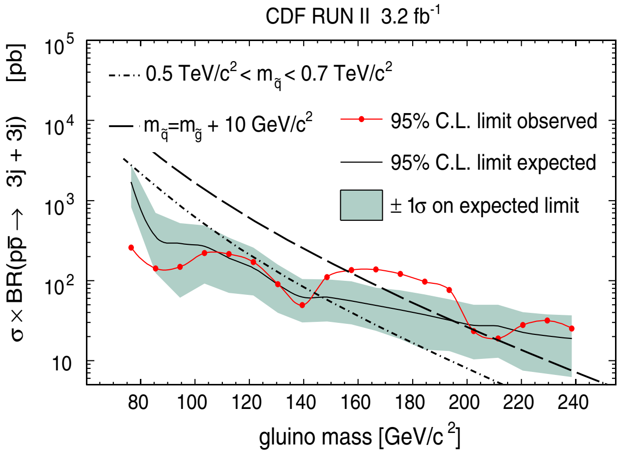

FIG. 3 (color online). The observed (points) and expected (solid black line) 95% confidence level limits on the production cross section $\sigma(p\bar{p} \to XX') \times \mathrm{BR}(\tilde{g}\,\tilde{g} \to 3\ \mathrm{jet} + 3\ \mathrm{jet})$ where X, $X' = \tilde{g}$, $\tilde{q}$, or $\bar{\tilde{q}}$, including systematic uncertainties. The shaded bands represent the total uncertainty on the limit. Also shown is the model cross section from PYTHIA corrected by an NLO k factor (dash-dotted line for $0.5\ \mathrm{TeV}/c^2 < m_{\tilde{q}} < 0.7\ \mathrm{TeV}/c^2$, dashed line for $m_{\tilde{q}} = m_{\tilde{g}} + 10\ \mathrm{GeV}/c^2$).

background estimate has a 2.3% probability of producing such a deviation. Comparisons to the theoretical cross section for $\sigma(p\bar{p} \to XX') \times \mathrm{BR}(\tilde{g}\,\tilde{g} \to 3\ \mathrm{jet} + 3\ \mathrm{jet})$ from PYTHIA corrected by a next-to-leading-order (NLO) k factor calculated using PROSPINO [20] are shown in the dashed and dash-dotted lines for two different squark mass scenarios. For a decoupled squark mass ($0.5\ \mathrm{TeV}/c^2 < m_{\tilde{q}} < 0.7\ \mathrm{TeV}/c^2$) we exclude gluinos below a mass of $144\ \mathrm{GeV}/c^2$ (dashed line). In the case of a squark mass which is nearly degenerate with the gluino mass ($m_{\tilde{q}} = m_{\tilde{g}} + 10\ \mathrm{GeV}/c^2$) we exclude gluinos below $155\ \mathrm{GeV}/c^2$ (dash-dotted line).

We have performed a first search for three-jet hadronic resonances in a six or more jet final state using a data sample with an integrated luminosity of 3.2 fb^{-1} collected by the CDF II detector. A novel technique is introduced that exploits kinematic features within an ensemble of jet combinations that allows us to extract signal from the QCD background. We observe no significant excess in the data in an invariant mass range from $77\ \mathrm{GeV}/c^2$ to $240\ \mathrm{GeV}/c^2$ and place 95% confidence level limits on the production cross section $\sigma(p\bar{p} \to XX') \times \mathrm{BR}(\tilde{g}\,\tilde{g} \to 3\ \mathrm{jet} + 3\ \mathrm{jet})$ where X, $X' = \tilde{g}$, $\tilde{q}$, or $\bar{\tilde{q}}$, with $\tilde{q}$, $\bar{\tilde{q}} \to \tilde{g} + \mathrm{jet}$, versus gluino mass. The results are presented as limits on RPV gluinos decaying to three jets, but are more widely applicable to any new particle with a three-jet decay mode. Two different squark mass scenarios have been considered: decoupled squarks and squarks nearly degenerate in mass with the gluino. We can exclude gluinos below $144\ \mathrm{GeV}/c^2$ and $155\ \mathrm{GeV}/c^2$, respectively.

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[1] CDF uses a (z, ϕ, θ) coordinate system with the z axis in the direction of the proton beam; ϕ and θ are the azimuthal and polar angle, respectively. The pseudorapidity is defined as $\eta = -\ln(\tan\frac{\theta}{2})$, and the transverse momentum and energy as $P_T = p\sin\theta$ and $E_T = E\sin\theta$, respectively. Missing transverse energy ($\not{E}_T = |\vec{\not{E}}_T|$) is defined as $\vec{\not{E}}_T = -\sum_i E_T^i \hat{\mathbf{n}}_\mathbf{i}$ where $\hat{\mathbf{n}}_\mathbf{i}$ is a unit vector in the transverse plane that points from the beam line to the ith calorimeter tower.

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