Search for New Physics with a Dijet Plus Missing E_T Signature in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present results of a signature-based search for new physics using a dijet plus missing transverse energy ($\not\!E_T$) data sample collected in 2 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the CDF II detector at the Fermilab Tevatron. We observe no significant event excess with respect to the standard model prediction and extract a 95% C.L. upper limit on the cross section times acceptance for a potential contribution from a nonstandard model process. The search is made by using novel, data-driven techniques for estimating backgrounds that are applicable to first searches at the LHC.

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Events featuring two energetic jets and significant missing transverse energy ($\not\!\!E_T$) [1] are a potential signature for phenomena not included in the standard model (SM), such as supersymmetry [2], universal extra dimensions [3], and leptoquark production [4]. In general, any model predicting pair production of unstable particles whose decay products are a single parton and a noninteracting particle could be observable as an event excess above the SM expectation in the dijet + $\not\!\!E_T$ channel. In this Letter, we report on a signature-based search for new physics contributions to the dijet + $\not\!\!E_T$ final state in CDF run II data collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV corresponding to an integrated luminosity of 2 fb^{-1}. This search features newly developed techniques for obtaining data-driven predictions of SM background contributions to the search samples. These techniques evade large systematic uncertainties inherent in Monte Carlo–based background estimates such as those affiliated with the modeling of jet energy scale and resolution.

In contrast with previous CDF [5] and D0 [6] searches in this final state, no *a priori* optimization of the kinematic selection criteria is performed to maximize sensitivity to a particular model. Here the criteria are chosen to encompass the widest possible kinematic range consistent with the trigger used to collect the data sample. We perform a simple counting experiment on this inclusive sample, comparing the number of observed events against the SM expectation, to search for indications of potential non-SM contributions. A second, analogous counting experiment is made on a subsample of the highest energy events from within the inclusive sample, which is more sensitive to some classes of non-SM production processes. The tighter kinematic selections that define this event subset are chosen to give a fixed (15%) uncertainty on the data-driven SM background prediction made for this sample. From here forward, we refer to these sets of candidate events as our loose and tight samples. Based on the counting experiment results, we place 95% C.L. upper limits on the cross section times acceptance ($\sigma \times A$) for a generic, non-SM process that contributes events to the candidate samples. Finally, we use the generic limit on $\sigma \times A$ to extract a lower limit on leptoquark mass for the specific case of scalar leptoquark production, which serves as a sensitivity benchmark for the result.

A detailed description of the CDF II detector can be found in Ref. [7]. The data sample was collected by using a three-level trigger system based on a minimum $\not\!\!E_T$ requirement of 45 GeV. Reconstructed candidate events are required to have $\not\!\!E_T > 80$ GeV to ensure full trigger efficiency. Jets are reconstructed from energy deposits in the calorimeter by using a cone-based algorithm with fixed radius of 0.7 in $\eta - \phi$ space. The measured jet E_T is corrected for detector effects and contributions from multiple $p\bar{p}$ interactions per bunch crossing [8]. Events in the candidate samples are required to have two reconstructed jets with $|\eta| < 2.4$ and $E_T > 30$ GeV and no additional jets with $|\eta| < 3.6$ and $E_T > 15$ GeV. In addition, the scalar sum of the two jet transverse energies, $H_T = E_T(\text{jet 1}) + E_T(\text{jet 2})$, must be greater than 125 GeV. A separation of at least 0.5 radians in azimuthal angle is required between the $\not\!\!E_T$ and both jets to help suppress multijet background events containing significant $\not\!\!E_T$ from poorly measured jets. Events from beam-related backgrounds and cosmic rays are removed by using standard criteria [9] to tag reconstructed tracks and jets inconsistent with having been produced by particles originating from $p\bar{p}$ collisions. The subset of events that satisfy tighter kinematic thresholds of $\not\!\!E_T > 100$ GeV and $H_T > 225$ GeV define the tight candidate sample.

Several SM processes capable of producing a high $\not\!\!E_T$ signature in our detector contribute events to our candidate samples. The largest SM background is Z + jets where the Z boson decays into a pair of neutrinos. This process results in a signature indistinguishable from that of potential signal, and its relative contribution to the candidate samples is therefore irreducible. The next most significant SM contribution is from W + jets in which the W decays via a charged lepton (e, μ, or τ) and neutrino. We suppress this background by rejecting events that contain either an isolated track [9] with $p_T > 10$ GeV/c (μ or τ candidate) or a jet with $E_T > 15$ GeV and electromagnetic energy fraction above 90% (e candidate).

The W/Z + jets backgrounds are modeled by using separate data samples collected with single lepton triggers. We estimate the number of background events from W/Z + jets production in our dijet + $\not\!\!E_T$ candidate samples by using cross section measurements obtained from $Z(\rightarrow \ell\ell)$ + jets and $W(\rightarrow \ell\nu)$ + jets ($\ell = e$ or μ) events with fully reconstructed leptons. The measured cross sections contain contributions from diboson production where two jets are produced in the hadronic decay of the second boson, and potential diboson contributions to the dijet + $\not\!\!E_T$ samples are therefore included within the resulting background estimates. Events in the samples used to make these measurements are required to have at least one electron ($E_T > 25$ GeV) or one muon ($p_T > 20$ GeV/c) passing standard selection criteria [7]. We select $W \rightarrow \ell\nu$ candidates by requiring $\not\!\!E_T > 25$ GeV ($\not\!\!E_T > 20$ GeV) for electrons (muons) and $Z \rightarrow \ell\ell$ candidates by requiring a second lepton satisfying a looser set of selection criteria [7]. We then apply the full set of dijet + $\not\!\!E_T$ selections described previously to the selected W/Z candidates to obtain $W(\rightarrow \ell\nu)$ + jets and $Z(\rightarrow \ell\ell)$ + jets event samples. To be consistent with the criteria used in selecting dijet + $\not\!\!E_T$ signal events, reconstructed tracks and calorimeter energy deposits associated with the charged lepton(s) are removed prior to application of the isolated track veto and $\not\!\!E_T$ requirements.

To extract W/Z + jets cross sections from these samples, we correct for the acceptance of the $W \to \ell\nu$ (25%–32%) or $Z \to \ell\ell$ (15%–33%) pieces of the selection criteria by using simulated ALPGEN [10] events run through a full detector simulation based on Ref. [11]. Acceptances depend on the specific lepton ($\ell = e$ or μ) decay channel and the associated loose or tight dijet + $\not\!\!E_T$ selection criteria. To account for observed differences in lepton reconstruction and identification efficiencies between data and simulation, corrections of up to 10% per lepton are applied to the simulated acceptances. Uncertainties on these efficiency corrections are small ($\sim$ 1%–2%) compared with those coming from candidate sample statistics and the methods used to estimate sample background contributions. The observed agreement in the cross section measurements made by using high-statistics $W(\to e\nu)$ + jets and $W(\to \mu\nu)$ + jets candidate samples provides validation of the techniques used to estimate $W \to \ell\nu$ background contributions. To minimize statistical uncertainties, cross sections used to estimate backgrounds are combined measurements from both lepton decay channels.

Estimates of dijet + $\not\!\!E_T$ candidate sample backgrounds from Z + jets production, in which the Z boson decays to neutrinos, are taken directly from measured $Z(\to \ell\ell)$ + jets cross sections based on the difference in Z branching ratios for charged leptons and neutrinos. A second, independent background estimate is obtained from measured $W(\to \ell\nu)$ + jets cross sections incorporating a theoretical prediction for $R_{(W/Z)}$, the ratio of W + jets and Z + jets production cross sections. We determine $R_{(W/Z)}$ with a next-to-leading order (NLO) calculation by using the MCFM generator [12]. The value of $R_{(W/Z)}$, which depends on the specific choice of jet requirements, is calculated to be 8.7 ± 0.2 (8.2 ± 0.2) for the loose (tight) dijet + $\not\!\!E_T$ sample. Final background estimates are obtained by combining the two statistically independent, consistent results.

Similarly, measured $W(\to \ell\nu)$ + jets cross sections are used to extract W + jets background estimates for the dijet + $\not\!\!E_T$ candidate samples. The probability for the charged lepton in these events to fail the lepton veto criteria is obtained from simulation ($\sim$ 20% for electrons, $\sim$33% for muons, and $\sim$55% for taus) and applied as an acceptance factor on the measured cross section. Smaller backgrounds from Z + jets, where the Z boson decays into a pair of charged leptons that both fail lepton veto criteria, are estimated from measured $Z(\to \ell\ell)$ + jets cross sections by using the same technique. Since the same measured cross sections are used to estimate all W/Z + jets backgrounds, uncertainties on these predictions are fully correlated. Small event contributions from $t\bar{t}$ and single-top production are obtained directly from simulation. We use a measured run II cross section [13] for $t\bar{t}$ and a NLO cross section calculation [14] for single-top production to normalize these estimates.

The dominant multijet topology contributing events to our candidate samples is three-jet events in which the third jet is either not reconstructed or has an E_T below our jet threshold (15 GeV). The magnitude of this background is estimated from data by using three-jet events in which the observed $\not\!\!E_T$ points in the direction of the least-energetic jet. We perform a linear extrapolation of the $\not\!\!E_T$ distribution obtained from the least-energetic jets in these events into the region where the E_T falls below the threshold for defining jets. A large sample of multijet events simulated with PYTHIA [15] is used to establish the validity of the technique. Before performing the extrapolation, corrections obtained from simulation are applied to the distribution to remove W/Z + jets contributions. The same simulated PYTHIA event sample is used to determine the relative fraction of events originating from other multijet topologies (20%), and the background estimates obtained from three-jet data are scaled by this factor to incorporate all contributions. We assign a conservative 100% uncertainty to this scale factor that minimally affects combined uncertainties on the multijet background estimates, which are dominated by the small statistics of the three-jet candidate samples.

Background contributions from the process in which a photon is produced in association with jets are obtained from a simulated event sample generated with PYTHIA. The estimates are normalized by using a run II D0 measurement of the γ + jets cross section [16]. The uncertainty on this measurement is the leading source of uncertainty on the γ + jets background estimates. Finally, the small, residual noncollision background is estimated by using timing information from the hadronic calorimeter.

Estimated SM backgrounds and the number of observed events for the loose and tight dijet + $\not\!\!E_T$ candidate samples are shown in Table I. The dominant uncertainty source on the combined SM background predictions is the statistical size of the $W(\to \ell\nu)$ + jets and $Z(\to \ell\ell)$ + jets candidate samples (4.6% and 12.2% on the total background estimates for the loose and tight samples, respectively). Other non-negligible uncertainty contributions are from

TABLE I. Estimated SM backgrounds and the number of observed data events for loose ($H_T > 125$ GeV, $\not\!\!E_T > 80$ GeV) and tight ($H_T > 225$ GeV, $\not\!\!E_T > 100$ GeV) candidate samples.

Background	Loose sample	Tight sample
$Z \to \nu\bar{\nu}$	888 ± 54	86.4 ± 12.7
$W \to \tau\nu$	669 ± 42	50.6 ± 8.0
$W \to \mu\nu$	399 ± 25	32.9 ± 5.2
$W \to e\nu$	256 ± 16	14.0 ± 2.2
$Z \to \ell\ell$	29 ± 4	1.7 ± 0.2
Top quark production	74 ± 9	10.8 ± 1.7
Multijet production	49 ± 30	9.0 ± 9.0
γ + jets	75 ± 11	4.8 ± 1.1
Noncollision	4 ± 4	1.0 ± 1.0
Total expected	2443 ± 151	211.2 ± 29.8
Data observed	2506	186

background estimates used in the $W(\to \ell\nu)$ + jets and $Z(\to \ell\ell)$ + jets cross section measurements (2.4% and 4.0%), input parameters to the theoretical calculation of $R_{(W/Z)}$ (1.8% and 1.8%), and statistics of the three-jet samples used to perform the linear extrapolation for determining multijet backgrounds (1.2% and 4.3%). Final combined uncertainties on predicted SM backgrounds for the loose and tight candidate samples are 6.2% and 14.1%. As illustrated in Fig. 1, the data-driven background model is further validated by using the $W(\to \ell\nu)$ + jets candidate samples to predict kinematic distributions obtained from dijet + $\not\!\!E_T$ candidate events. Correct missing E_T models are obtained for each specific background contribution by removing lepton energy deposits not contained within dijet + $\not\!\!E_T$ candidate events originating from that process.

We observe no significant excess in data relative to SM predictions in either the loose or tight candidate samples constraining potential contributions from new physics processes. An upper limit on the number of non-SM signal events contained within each sample is obtained by using a Bayesian approach with a flat prior for the number of signal events and priors based on gamma distributions for both the acceptance and number of SM background events [17]. These limits are directly translatable into upper limits on $\sigma \times A$ for any new physics process that contributes events to our candidate samples. The limits do not assume central values for signal acceptance, which is detector-dependent and varies significantly for different processes. Quoted limits are based on specific choices for acceptance uncertainties, which vary less among the different processes. For a 15% signal acceptance uncertainty we obtain a 95% C.L. upper limit of 0.18 pb (0.02 pb) on $\sigma \times A$ for the loose (tight) candidate sample. Increasing the signal acceptance uncertainty by a factor of 2 leads to a 25% degradation in the quoted limits.

For the case of scalar leptoquark pair production where each leptoquark decays into a quark and a neutrino, we provide an example of the detector-dependent acceptance calculation required to extract model limits. We simulate signal acceptance by using PYTHIA in conjunction with a full detector simulation. The loose (tight) dijet + $\not\!\!E_T$ selection criteria yield an acceptance of 14% (4%) to a first-generation leptoquark with a mass of 150 GeV$/c^2$. Acceptance increases as a function of leptoquark mass ($M_{\rm LQ}$), rising to 20% (9%) at 200 GeV$/c^2$. The relative acceptance uncertainty is 13% (20%) independent of $M_{\rm LQ}$ and comes from potential variations in parton distribution functions (PDFs), ambiguity in the absolute jet energy scale [8], modeling of initial and final state radiation, data sample luminosity, and selection efficiencies. Mass limits are based on a NLO production cross section calculation [18] by using the CTEQ6.1M PDF set [19] and $\mu = M_{\rm LQ}$ for the renormalization and factorization scales. Cross section uncertainties due to PDF modeling (from the full set of CTEQ6.1M eigenvectors) and scale choice (from varying μ between $M_{\rm LQ}/2$ and $2 \times M_{\rm LQ}$) are added in quadrature. We determine the sample with best *a priori* sensitivity to the leptoquark model at each mass point and set a 95% C.L. lower mass limit based on where the cross section limit from the more sensitive sample intersects the lower uncertainty band of the NLO calculation. Figure 2 shows the cross section limits as a function of leptoquark mass, which result in lower mass limits of 187 GeV$/c^2$ for first- and second-generation $q\nu$ scalar leptoquarks (corresponding to an upper cross section limit of 0.33 pb at this mass point). This result significantly improves upon the previous CDF limit [5] and is only slightly looser than the D0 lower mass limit of 205 GeV$/c^2$ [6] obtained from an optimized search on a 25% larger data sample.

In summary, this Letter presents a signature-based search for potential non-SM contributions to the dijet + $\not\!\!E_T$ final state. New techniques for obtaining data-driven estimates of SM background contributions to the search samples are described. These techniques, which circumvent uncertainties intrinsic to Monte Carlo models,

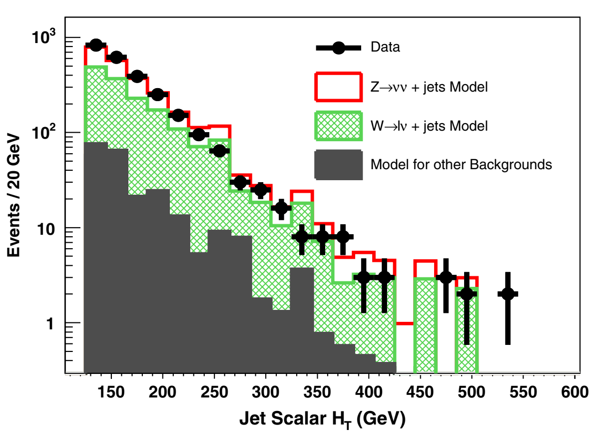

FIG. 1 (color online). Scalar sum of jet transverse energies (H_T) for events in the loose dijet + $\not\!\!E_T$ candidate sample compared against the predicted distribution from the data-driven background model.

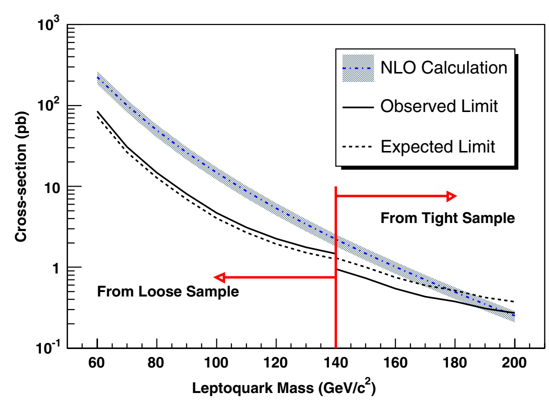

FIG. 2 (color online). 95% C.L. upper cross section limits on first- and second-generation $q\nu$ scalar leptoquark pair production (q being u, d, s, or c) as a function of leptoquark mass ($M_{\rm LQ}$).

are favored for first LHC searches in these channels. No data excess is observed, and we set a 95% C.L. upper limit on the cross section times acceptance for potential non-SM production processes. For the specific case of first- and second-generation scalar leptoquark production, we obtain a 95% C.L. lower mass limit of 187 GeV/c^2.

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[1] We use a coordinate system where θ is the polar angle to the proton beam, ϕ is the azimuthal angle about this beam axis, and η is the pseudorapidity defined as $-\ln\tan(\theta/2)$. Missing transverse energy $\not{E}_T$ is defined as the magnitude of $-\sum_i E_T^i \hat{n}_i$, where $\hat{n}_i$ is a unit vector in the azimuthal plane that points from the beam line to the ith calorimeter tower and E_T^i is the transverse component of the measured energy in the tower, defined as $E^i \cdot \sin\theta$.

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