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Search for $t\bar{t}$ resonances in the lepton plus jets final state in $pp$ collisions at $\sqrt{s} = 1.96$ TeV

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Search for $t\bar{t}$ resonances in the lepton plus jets final state in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

DØ Collaboration
We present a search for a narrow-width heavy resonance decaying into top quark pairs ($X \rightarrow t\bar{t}$) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using approximately $0.9$ fb$^{-1}$ of data collected with the DØ detector at the Fermilab Tevatron Collider. This analysis considers $t\bar{t}$ candidate events in the lepton plus jets channel with at least one identified $b$ jet and uses the $t\bar{t}$ invariant mass distribution to search for evidence of resonant production. We find no evidence for a narrow resonance $X$ decaying to $t\bar{t}$. Therefore, we set upper limits on $\sigma_X \cdot B(X \rightarrow t\bar{t})$ for different hypothesized resonance masses using a Bayesian approach. For a Topcolor-assisted technicolor model, the existence of a leptophobic $Z'$ boson with mass $M_{Z'} < 700$ GeV and width $\Gamma_{Z'} = 0.012M_{Z'}$ can be excluded at the 95% C.L.
jets, where \( \ell = e \) or \( \mu \) final state. The event signature is one isolated electron or muon with high momentum transverse to the beam axis \( (p_T) \), large transverse energy imbalance \( (E_T) \) due to the undetected neutrino, and at least four jets, two of which result from the hadronization of b quarks. The analyzed dataset corresponds to an integrated luminosity of 913 fb\(^{-1}\) in the \( e + \text{jets} \) channel and 871 ± 53 fb\(^{-1}\) in the \( \mu + \text{jets} \) channel, collected with the DØ detector between August 2002 and December 2005. The analysis uses events with at least three reconstructed jets. Backgrounds from light-quarks are further reduced by identifying b jets. After b tagging, the dominant physics background for a resonance signal is non-resonant SM tt production. Smaller contributions arise from the direct production of W bosons in association with jets (W + jets), as well as instrumental background originating from multijet processes with jets faking isolated leptons. The search for resonant production in the tt invariant mass distribution is performed using Bayesian statistics to compare SM and resonant production to the observed mass distribution.

Previous searches performed by the CDF and DØ Collaborations in Run I found no evidence for a tt resonance [6,7]. In these studies, a Topcolor model was used as a reference to quote mass limits. According to this model [5], a large top quark mass can be generated through the formation of a dynamical tt condensate, Z', due to a new strong gauge force with large coupling to the third generation of fermions. In one particular model, Topcolor-assisted technicolor [8], the Z' boson has large couplings only to the first and third generation of quarks and has no significant couplings to leptons. Limits obtained on \( \sigma_X \cdot B_X \rightarrow b \bar{b} \) are used to set a lower bound on the mass of such a leptophobic Z' boson. In Run I CDF found \( M_Z' > 480 \text{ GeV} \) with 106 pb\(^{-1}\) of data [6], and DØ obtained \( M_Z' > 560 \text{ GeV} \) using 130 pb\(^{-1}\) [7], both at the 95% CL and for a resonance with width \( \Gamma_{Z'} = 0.012 M_{Z'} \).

2. DØ detector

The DØ detector [9] has a central-tracking system consisting of a silicon microstrip tracker and a central fiber tracker, both located within the cone of the given jet. The information is combined in jet-matching algorithm [20]. The CTEQ6L1 parton distribution functions [17] for ten different choices of the resonance mass \( M_X \) between 350 GeV and 1 TeV. In all cases, the width of the resonance is set to \( \Gamma_X = 0.012 M_X \). This qualifies the X boson as a narrow resonance since its width is smaller than the estimated mass resolution of the DØ detector of 5–10%. The generated resonance is forced to decay into tt.

Standard Model tt and diboson backgrounds (WW, WZ, and ZZ) are generated with PYTHIA [17]. Single top quark production is generated using the COMPTOR generator [18]. A top quark mass of 175 GeV is used for both resonant and SM top production processes. W + jets and Z + jets events are generated using ALPGEN [19] to model the hard interaction and PYTHIA for parton showering, hadronization and hadron decays. To avoid double counting between the hard matrix element and the parton shower, the MLM jet-matching algorithm is used [20]. The CTEQ6L1 parton distribution functions [21,22] are used for all samples. The generated events are processed through the full GEANT3-based [23] simulation of the DØ detector and the same reconstruction program as used for data.

The SM tt, single top quark, diboson, and Z + jets backgrounds are estimated completely from Monte Carlo (MC) simulation, to obtain the total acceptance as well as the shape of the reconstructed tt invariant mass distribution. Trigger inefficiencies and differences between data and MC lepton and jet identification efficiencies are accounted for by weighting the simulated events [15]. Jet b-tagging probabilities are measured in data and parametrized as functions of \( p_T \) and \( \eta \). They are used to weight each simulated event according to its event b-tagging probability. Finally, the expected yields are normalized to the SM theoretical prediction. A tt production of \( \sigma_{\text{SM}} = 6.77 \pm 0.60 \text{ pb} \) for \( m_t = 175 \text{ GeV} \) [24] is used. Z + jets, single top quark and diboson samples are normalized to their next-to-leading-order cross sections [25–27].

The W + jets background is estimated from a combination of data and MC information. The expected number of W + jets events in the b-tagged sample is computed as the product of the estimated number of W + jets before b tagging and the expected event b-tagging probability. The former is obtained from the observed number of events with real leptons in data, computed using the angle, and \( y \) the rapidity. The selected events must contain three or more jets with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.5 \). At least one of the jets is required to have \( p_T > 40 \text{ GeV} \). Events with mismeasured lepton momentum are rejected by requiring the \( E_T \) to be acollinear with the lepton direction in the transverse plane: \( \Delta \phi(e, E_T) > 2.2–0.045 \text{ GeV}^{-1} E_T \) and \( \Delta \phi(\mu, E_T) > 2.1–0.035 \text{ GeV}^{-1} E_T \) [15].

To improve the signal-to-background ratio, at least one jet is required to be identified as a b jet. The tagging algorithm uses the impact parameters of tracks matched to a given jet and information on vertex mass, the decay length significance, and the number of participating tracks for any reconstructed secondary vertex within the cone of the given jet. The information is combined in a neural network to obtain the output variable, NN, which tends towards one for b jets and towards zero for light quark jets [16]. In this analysis we consider jets to be b-tagged if NNb > 0.65 which corresponds to a tagging efficiency for b jets of about 55% with a tagging rate for light quark jets of less than 1%.

We independently analyze events with three and four or more jets and separate singly tagged and doubly tagged events, since the channels have different signal-to-background ratios and systematic uncertainties.

4. Signal and background modeling

Simulated events are used to determine selection efficiencies for the resonant tt production signal and for background sources except those in which instrumental effects give fake leptons and \( E_T \) in multijet production events. Samples of resonant tt production are generated with PYTHIA [17] for ten different choices of the resonance mass \( M_X \) between 350 GeV and 1 TeV. In all cases, the width of the resonance is set to \( \Gamma_X = 0.012 M_X \). This qualifies the X boson as a narrow resonance since its width is smaller than the estimated mass resolution of the DØ detector of 5–10%. The generated resonance is forced to decay into tt.

Standard Model tt and diboson backgrounds (WW, WZ, and ZZ) are generated with PYTHIA [17]. Single top quark production is generated using the COMPTOR generator [18]. A top quark mass of 175 GeV is used for both resonant and SM top production processes. W + jets and Z + jets events are generated using ALPGEN [19] to model the hard interaction and PYTHIA for parton showering, hadronization and hadron decays. To avoid double counting between the hard matrix element and the parton shower, the MLM jet-matching algorithm is used [20]. The CTEQ6L1 parton distribution functions [21,22] are used for all samples. The generated events are processed through the full GEANT3-based [23] simulation of the DØ detector and the same reconstruction program as used for data.

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The W + jets background is estimated from a combination of data and MC information. The expected number of W + jets events in the b-tagged sample is computed as the product of the estimated number of W + jets before b tagging and the expected event b-tagging probability. The former is obtained from the observed number of events with real leptons in data, computed using the
matrix method \cite{12}, and then subtracting the expected contribution from other SM production processes. The $b$-tagging probability is obtained by combining the $W +$ jets flavor fractions estimated from MC with the event $b$-tagging probability, estimated from $b$-tag rate functions. The shape of the reconstructed invariant mass distribution is obtained from the MC simulation.

The multijet background is completely determined from data. The total number of expected events is estimated by applying the matrix method to the each of the $b$-tagged subsamples. The shape is derived from events with leptons failing the isolation requirements. A summary of the prediction for the different background contributions in the combined $\ell +$ jets channels, along with the observed number of events in data, is given in Table 1. Systematic uncertainties are discussed below.

5. Reconstruction of the $t\bar{t}$ invariant mass distribution

The $t\bar{t}$ invariant mass is reconstructed from the four-momenta of up to the four highest $p_T$ jets, the lepton momentum, and the neutrino momentum. The latter is obtained from the transverse missing energy and a $W$-mass constraint. The neutrino transverse momentum is identified with the missing transverse momentum, given by $E_T$ and its direction. The neutrino momentum along the beam direction, $p_T^\nu$, is estimated by solving the equation $M_W^2 = (p_T + p_T^\nu)^2$, where $p_T$ ($p_T^\nu$) is the lepton (neutrino) four momentum. If there are two solutions, the one with the smaller $|p_T^\nu|$ is taken; if no solution exists, $p_T^\nu$ is set to zero. This method gives better sensitivity for high mass resonances than a previously applied constrained kinematic fit technique \cite{7}, since for $M_{jj} \gtrsim 700$ GeV the jets from the hadronically decaying $W$ boson are more likely to be reconstructed in a single jet instead of two jets and in such cases the assumptions made in the kinematic fit are invalid. The sensitivity for lower resonance masses is slightly reduced from that for the constrained fit. The direct reconstruction also allows the inclusion of data with fewer than four jets in the case that some jets are merged, further increasing the sensitivity. The expected $t\bar{t}$ invariant mass distributions for three different resonance masses are compared to the SM expectation in Fig. 1.

6. Systematic uncertainties

The systematic uncertainties can be classified as those affecting only normalization and those affecting the shape of any of the signal or background invariant mass distributions. The systematic uncertainties affecting only the normalization include the theoretical uncertainty on the SM prediction for $\sigma_t$ (9%), the uncertainty on the integrated luminosity (6.1%) \cite{28}, and the uncertainty on the lepton identification efficiencies.

The systematic uncertainties affecting the shape of the invariant mass distribution as well as the normalization are studied in signal and background samples. These include uncertainties on the jet energy calibration, jet reconstruction efficiency, and $b$-tagging parameterizations for $b$, $c$ and light jets. The effect due to the top quark mass uncertainty is computed by changing $m_t$ in the simulation of $t\bar{t}$ to 165 GeV and 185 GeV, normalized to their corresponding theoretical cross sections. The effect is scaled to correspond to a top quark mass uncertainty of $\pm 5$ GeV. The difference in the $t\bar{t}$ acceptance due to the top quark mass variation is also included in the systematic uncertainty. The fraction of heavy flavor in the $W +$ jets background is measured in control samples, and a corresponding uncertainty on the $W +$ jets flavor composition is used. Also the uncertainties on the $b$-fragmentation and the uncertainties of the efficiencies used in the matrix method are taken into account.

Table 2 gives a summary of the relative systematic uncertainties on the total SM background normalization for the combined $\ell +$ jets channels. The sample dependence of the background composition and the use of data- and MC-based methods to estimate the backgrounds, induce a sample dependent overall luminosity uncertainty. The effect of the different systematic uncertainties on the shape of the $t\bar{t}$ invariant mass distribution cannot be inferred from this table, but is included in the analysis.

7. Result

After all selection cuts, 319 events remain in the $e +$ jets channel and 288 events in the $\mu +$ jets channel. The sums of all SM and multijet instrumental backgrounds are $303 \pm 22$ and $251 \pm 19$.
The distributions are separated into 3 jets and apply a Bayesian approach to calculate 95% C.L. upper limits on the combined signal acceptance and background yields is a multi-

...elements, respectively. Invariant mass distributions are computed for events with exactly one b tag and for events with more than one b tag. Additionally, the distributions are separated into 3 jets and ≥ 4 jets samples. The measured invariant mass distributions and corresponding background estimations are shown in Fig. 2 for the 3 jets and ≥ 4 jets samples.

Finding no significant deviation from the SM expectation, we apply a Bayesian approach to calculate 95% C.L. upper limits on σX · B(X → t¯t) for hypothesized values of MX between 350 and 1000 GeV. A Poisson distribution is assumed for the number of observed events in each bin, and flat prior probabilities are taken for the signal cross section times branching fraction. The prior for the combined signal acceptance and background yields is a multi-

...sage limit for a Topcolor-assisted technicolor Z’ boson of 780 GeV.

8. Conclusion

A search for a narrow-width heavy resonance decaying to t¯t in the ℓ+jets final states has been performed using data corresponding to an integrated luminosity of about 0.9 fb⁻¹, collected with the DØ detector at the Tevatron collider. By analyzing the reconstructed ℓt invariant mass distribution and using a Bayesian method, model independent upper limits on σX · B(X → t¯t) have been obtained for different hypothesized masses of a narrow-width heavy resonance decaying into t¯t. Within a Topcolor-assisted tech-
nicolor model, the existence of a leptophobic $Z'$ boson with $M_{Z'} < 700$ GeV and width $\Gamma_{Z'} = 0.012 M_{Z'}$ is excluded at the 95% C.L.

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