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Search for scalar leptoquarks and T-odd quarks in the acoplanar jet topology using 2.5 fb$^{-1}$ of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV

DØ Collaboration

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In this Letter, a search for new particles in the topology consisting of exactly two jets and missing transverse energy ($E_T$) resulting from the decay of those particles is a promising channel to discover physics beyond the SM.

A search for new physics in the acoplanar jet topology has been performed in 2.5 $fb^{-1}$ of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, recorded by the DØ detector at the Fermilab Tevatron Collider. The numbers of events with exactly two acoplanar jets and missing transverse energy are in good agreement with the Standard Model expectations. The result of this search has been used to set a lower mass limit of 205 GeV at the 95% C.L. on the mass of a scalar leptoquark when this particle decays exclusively into a quark and a neutrino. In the framework of the Little Higgs model with T-parity, limits have also been obtained on the T-odd quark mass as a function of the T-odd photon mass.

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of 136 GeV [2] for $\beta = 0$ was obtained by the DØ Collaboration with 310 pb$^{-1}$ of Run II data. The CDF Collaboration also set a lower mass limit of 117 GeV [3] with 191 pb$^{-1}$ of Run II data. Those limits, as well as the results presented in this Letter, apply for first- and second-generation scalar leptoquarks. For the third-generation, tighter limits were obtained by increasing the signal sensitivity using heavy-flavor quark tagging [4].

The second category is the Little Higgs (LH) model [5], which provides an interesting scenario for physics at the TeV scale, predicting the existence of additional gauge bosons, fermions, and scalar particles with masses in the 100 GeV–5 TeV range. Electroweak precision constraints are satisfied by introducing a discrete symmetry called T-parity [6]. This symmetry is constructed such that all the SM states are even, while most new states of the LH model with T-parity (LHT) are odd. In the LHT model, six new Dirac T-odd quarks (T-quarks or $\tilde{Q}$) are the partners of the left-handed T-even quarks of the SM. In most of the parameter space, the lightest T-odd particle (LTP) is the so-called “heavy photon” ($\tilde{A}_H$) which is stable and weakly interacting. From SM precision measurements, it is possible to set a lower mass limit of $\sim$80 GeV on the mass of $\tilde{A}_H$ [7]. The new particle spectrum of the LHT model has similar properties to spectra of supersymmetric models. The LTP, just as the Lightest Supersymmetric Particle in SUSY models with R-parity conservation, is a dark matter candidate which escapes undetected. However, it is possible to set a lower mass limit $\sim$80 GeV on the mass of $\tilde{A}_H$, based on the branching ratio that this branching ratio is 100%. Pair production of T-quarks therefore leads to a final state with two quarks and two LTP, giving the missing transverse energy signature. The only direct constraint from collider data on the T-quark mass is the $\sim$100 GeV lower limit on the mass of the supersymmetric partner of the first two generations quarks from LEP [8] which can also be applied to T-quarks. The parton distribution functions (PDFs) used in the MC generators are the CTEQ6L1 PDFs. The LQ mass in the MC simulation was not simulated, since it can be conservatively neglected in the parameter space accessible at the Tevatron. Concerning the signal efficiency, one of the signal efficiencies is derived using Monte Carlo (MC) generators and passed through a full detector simulation chain as the data. The parton distribution functions (PDFs) used in the MC generators are the CTEQ6L1 PDFs. A data event from a randomly selected beam crossing was overlaid on each event to simulate the additional minimum bias interactions and detector noise. The ALCGEN generator [14] was used to simulate $W/Z$ + jets and $t\bar{t}$ production. It was interfaced with PYTHIA [15] for the simulation of initial and final state radiation (ISR/FSR) and of jet hadronization. Pairs of vector bosons and electroweak top quark production were simulated with PYTHIA and COMPTHEP [16], respectively. The next-to-leading order (NLO) cross sections were computed with MCFM5.1 [17]. The QCD background was not simulated, since it can be conservatively neglected in the final stage of this analysis.

Leptoquark pair production and decays were simulated with PYTHIA and the CTEQ6L1 PDFs. The LQ mass in the MC simulation ranged from 60 to 240 GeV. The NLO cross sections of this process were computed from a program based on [18] with a renormalization and factorization scale ($\mu_{R,\mu}$) equal to the LQ mass, and using the CTEQ6L1M PDF sets.

For the LHT model, it has been shown in [9] that T-quark pair production and decay to $q \tilde{A}_H$ is very similar to squark pair production and decay to $q\tilde{g}$, where $\tilde{g}$ is the lightest neutralino. Signal efficiencies were therefore determined using MC events generated with PYTHIA corresponding to the production and decay of these supersymmetric particles. It has been checked that the spin differences between the T-odd particles of the LHT model and the supersymmetric particles do not modify the signal efficiencies. Therefore, MC simulations of such events were performed to cover the $Q$–$\tilde{A}_H$ mass plane accessible at the Tevatron. Concerning the signal normalization, the cross section of first and second generation T-quark pair production is equal to four times the cross section of heavy quark pair production, if no other new particles predicted by the LHT model are involved in the T-quark production. The NLO cross sections of this signal were therefore calculated using MCFM5.1, with $\mu_{R,\mu}$ equal to the T-quark mass, and the CTEQ6L1M PDF sets.

The analysis strategy follows closely the “dijet” analysis from Ref. [19]. Events were recorded using triggers requiring two acoplanar jets and large $E_T$ or $H_T$, where $H_T$ is the vector sum of the jet transverse momenta ($H_T = \sum_{jets} p_T$). The trigger requirements evolved during the Run II data taking period in order to take into account the increasing peak instantaneous luminosity of the Tevatron. At the last stage of the trigger selection, the requirements were typically the following: (1) $E_T$ or $H_T$ greater than 30 GeV and their separation from all jets greater than 25$^\circ$; (2) an azimuthal angle between the two highest $p_T$ jets less than 170$^\circ$. Offline, events where $E_T$ was higher than 40 GeV were then selected.

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8 The pseudorapidity $\eta$ is defined as $-\ln(\tan(\theta/2))$, with $\theta$ being the polar angle with respect to the proton beam direction.
where CPF0 is the fraction of track/Δ φ(1) jets [19]. This was accomplished by requiring CPF0 for jets had to be higher than 35 GeV. Finally, jets were required to be greater than 50 degrees and lower than 170 degrees, respectively.

The best primary vertex (PV0) was defined as the vertex with the smallest probability to be due to a minimum bias interaction [20]. The longitudinal position of PV0 was required to be less than 60 cm from the detector center to ensure efficient vertex reconstruction. Good jets were defined as jets with a fraction of energy in the electromagnetic layers of the calorimeter lower than 0.95. The acoplanarity, i.e. the azimuthal angle between the two leading jets, jet1 and jet2, ordered by decreasing transverse momentum, was required to be less than 165 degrees. Then, the two leading jets, jet1 and jet2, selected by requiring the DCA($\chi^2$) of the track-measured distance of closest approach between the track and PV0 on the beam direction and in the plane transverse to the beamline, was required to be less than 165 degrees. Then, the two leading jets were required to be in the central region of the detector, with $|\eta_{\text{det}}| < 0.8$, where $\eta_{\text{det}}$ is the jet pseudorapidity calculated under the assumption that the jet originates from the detector center. After this preselection, the transverse momenta of the two leading jets had to be higher than 35 GeV. Finally, jets were required to originate from the best primary vertex, based on their associated tracks [19]. This was accomplished by requiring CPF0 > 0.75, where CPF0 is the fraction of track $p_T$ sum associated with the jet which comes from PV0, CPF0 = $\sum p_T^{\text{track}}(\text{PV0})/\sum p_T^{\text{track}}$ (any PV).

At this stage, the QCD multijet background is still dominant. To further reject those events, the selection criteria on $\vec{E}_T$ was increased to 75 GeV. The requirement that the azimuthal angle between the $\vec{E}_T$ and the first jet, $\Delta \phi(\vec{E}_T, \text{jet}_1)$, exceeds 90 degrees, was used to remove events where a jet was mismeasured and generating $\vec{E}_T$ aligned to that jet. Also, the minimal azimuthal angle $\Delta \phi_{\text{min}}(\vec{E}_T, \text{any jet})$ and the maximal azimuthal angle $\Delta \phi_{\text{max}}(\vec{E}_T, \text{any jet})$ between jets and $\vec{E}_T$ directions had to be greater than 50 degrees and lower than 170 degrees, respectively.

To suppress $W(\rightarrow l\nu)+\text{jets}$ events, a veto on events containing an isolated electron or muon with $p_T > 10$ GeV was applied. Events with an isolated track were then rejected to further reduce that background. Isolated tracks were required to have $p_T > 5$ GeV, to originate from PV0 with $\Delta C A(z) < 5$ cm and $\Delta C A(r) < 2$ cm, where $\Delta C A(z)$ and $\Delta C A(r)$ are the positions of the projection of the distance of closest approach between the track and PV0 on the beam direction and in the plane transverse to the beamline, respectively.

The number of hits in the CFT used to reconstruct the track was required to be at least 8. Finally, good quality tracks were selected by requiring the $\chi^2$/dof of the track-fit reconstruction to be lower than 4. A hollow cone with inner and outer radii of 0.06 and 0.5 was constructed around each track that passed those criteria. If no other track with $p_T > 0.5$ GeV and the same quality criteria as above was found in this hollow cone, the track was considered isolated. The use of a hollow, rather than full cone also allowed rejection of tau leptons decaying into three charged particles.

Events with exactly two jets with $p_T > 15$ GeV and $|\eta_{\text{det}}| < 2.5$ in the final state were then selected. This criterion rejects a large fraction of the remaining $t\bar{t}$ events, and increases the signal sensitivity at large $T$-quark and leptoquark masses once large $E_T$ and $H_T$ are required, with $H_T = \sum p_T$, where the sum is also over all jets with $p_T > 15$ GeV and $|\eta_{\text{det}}| < 2.5$. Table 1 summarizes the number of events observed and expected from MC simulations at each stage of the analysis. Fig. 1 shows comparisons between data and MC simulations: the distribution of the number of jets, and the $E_T$ and $H_T$ distributions after applying all the selection criteria described above.

Finally, the two final cuts on $E_T$ and on $H_T$ were optimized for different signals by minimizing the expected upper limit on the cross section in the absence of signal. To this end and also for

<table>
<thead>
<tr>
<th>Cut applied</th>
<th>Data</th>
<th>Background</th>
<th>Signal</th>
<th>Signal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>208 055</td>
<td>30 752 ± 5350</td>
<td>166 ± 21</td>
<td>0.302 ± 0.037</td>
</tr>
<tr>
<td>1st leading jet $p_T &gt; 35$ GeV</td>
<td>122 456</td>
<td>25 352 ± 4410</td>
<td>152 ± 19</td>
<td>0.276 ± 0.034</td>
</tr>
<tr>
<td>2nd leading jet $p_T &gt; 35$ GeV</td>
<td>79 985</td>
<td>14 538 ± 2530</td>
<td>144 ± 18</td>
<td>0.262 ± 0.032</td>
</tr>
<tr>
<td>$E_T &gt; 75$ GeV</td>
<td>6509</td>
<td>5219 ± 909</td>
<td>125 ± 16</td>
<td>0.228 ± 0.028</td>
</tr>
<tr>
<td>$\Delta \phi(\vec{E}_T, \text{jet}_1) &gt; 90^\circ$</td>
<td>6386</td>
<td>5148 ± 897</td>
<td>124 ± 15</td>
<td>0.226 ± 0.028</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{min}}(\vec{E}_T, \text{any jet}) &gt; 50^\circ$</td>
<td>3857</td>
<td>1343 ± 602</td>
<td>93 ± 12</td>
<td>0.170 ± 0.021</td>
</tr>
<tr>
<td>$\Delta \phi_{\text{max}}(\vec{E}_T, \text{any jet}) &lt; 170^\circ$</td>
<td>2855</td>
<td>2568 ± 448</td>
<td>81 ± 10</td>
<td>0.147 ± 0.018</td>
</tr>
<tr>
<td>Isolated electron veto</td>
<td>2347</td>
<td>2129 ± 371</td>
<td>79 ± 9</td>
<td>0.144 ± 0.018</td>
</tr>
<tr>
<td>Isolated muon veto</td>
<td>2007</td>
<td>1880 ± 328</td>
<td>79 ± 9</td>
<td>0.144 ± 0.018</td>
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<tr>
<td>Isolated track veto</td>
<td>1472</td>
<td>1398 ± 244</td>
<td>73 ± 9</td>
<td>0.133 ± 0.017</td>
</tr>
<tr>
<td>Exactly two jets</td>
<td>957</td>
<td>858 ± 150</td>
<td>40 ± 6</td>
<td>0.089 ± 0.011</td>
</tr>
<tr>
<td>Final $H_T$ cut optimized</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Final $E_T$ cut optimized</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

* First and second jets are also required to be central ($|\eta_{\text{det}}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.

![Fig. 1. Distribution of the number of jets (a) and distributions of $E_T$ (b) and $H_T$ (c) before the final optimization of the cuts on these two quantities; for data (points with error bars), for SM background (full histogram with shaded band corresponding to the total uncertainty), and for signal MC (dashed histogram). The signal drawn corresponds to pair production of scalar leptoquarks with $M_{LQ} = 200$ GeV.](image-url)
the final limit computation, the CLs modified frequentist method has been used [21]. For the leptoquark search, two benchmarks were defined corresponding to low \(m_{\text{LQ}} = 140 \text{ GeV}\) and high \(m_{\text{LQ}} = 200 \text{ GeV}\) leptoquark masses. As summarized in Table 2, the optimized values were determined to be \(H_T > 150 \text{ GeV}\) and \(E_T > 75 \text{ GeV}\) for the low mass selection, and \(H_T > 300 \text{ GeV}\) and \(E_T > 125 \text{ GeV}\) for the high mass selection. In the T-quark search, five \(H_T - E_T\) cut combinations were used to optimally scan the \((Q, A_H)\) mass plane as summarized in Table 2. In all cases, the contribution of the QCD multijet background was estimated to be small enough to be conservatively neglected. The number of events observed are in good agreement with the SM expectations.

The uncertainty coming from the JES corrections on the SM backgrounds and signal predictions ranges from 5% for low \(H_T\) and \(E_T\) cuts to 10% for high \(H_T\) and \(E_T\) cuts. The uncertainties due to the jet energy resolution, to the jet track confirmation, and to jet reconstruction and identification efficiencies range between 2% and 4%. The systematic uncertainty due to the isolated track veto was measured to be 3%. All these uncertainties account for differences between data and MC simulation, both for signal efficiencies and background contributions. The trigger was found to be fully efficient for the event samples surviving all analysis requirements within an uncertainty of 2%. The uncertainty on the luminosity measurement is 6.1% [22]. All of these uncertainties are fully correlated between signal and SM backgrounds. A 15% systematic uncertainty was set on the \(W/Z + \text{jets and } t\bar{t}\) NLO cross sections. The uncertainty on the signal acceptance due to the PDF was determined using the full set of CTEQ6.1M eigenvectors, with the individual uncertainties added in quadrature. The effect of the renormalization and factorization scale was studied by calculating the signal cross sections for \(\mu_R = Q, \mu_F = Q/2\) and \(\mu_R = \mu_F = 2 \times Q\). The PDF and \(\mu_R, \mu_F\) effects were added in quadrature to compute minimum, \(\sigma_{\text{min}}\), and maximum, \(\sigma_{\text{max}}\), signal cross sections.

For the leptoquark search, Fig. 2 shows the 95% C.L. observed and expected upper limits on scalar leptoquark production cross sections. The intersection with the minimal NLO cross section gives a lower mass limit of 205 GeV for \(\beta = 0\). The corresponding \(95\%\) CL signal cross section upper limit. The first uncertainty is statistical and the second one is systematic.
pected limit is 207 GeV. Those limits are 214 GeV and 222 GeV, respectively, for the nominal signal cross section.

For the T-quark search, Fig. 3 shows the 95% C.L. excluded regions in $\tilde{Q} - \tilde{A}_H$ mass plane assuming that the branching fraction of the decay $\tilde{Q} \to q\tilde{A}_H$ is 100%. The largest excluded T-quark mass, 404 GeV, is obtained for large mass difference between the T-quarks and the LTP.

In summary, a search for scalar leptoquarks and for T-quarks produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV has been performed with a 2.5 fb$^{-1}$ data sample. This search was conducted in events containing exclusively two jets and large missing transverse energy. The results are in good agreement with the SM background expectations, and 95% C.L. limits have been set on the leptoquark and T-quark masses. For a single-generation scalar leptoquark, a lower mass limit of 205 GeV has been obtained for $\beta = 0$, improving the previous limit by 69 GeV. In the LHT model, limits on T-quark mass were obtained as a function of the $\tilde{A}_H$ mass assuming 100% branching ratio for the decay $\tilde{Q} \to q\tilde{A}_H$. T-quark masses up to 404 GeV are excluded when the mass difference between T-quarks and the LTP is large. Those are the most stringent direct limits to date on the T-quarks mass.

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