Search for top+jet resonances in $t\bar{t}+$jet(s) at CDF.

The CDF Collaboration

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We present a search for a heavy new particle $M$ produced in association with a top quark ($pp \rightarrow Mt/M\bar{t}$) and decaying via $M \rightarrow \bar{t}q/\bar{t}q$, leading to a resonance in the $t\bar{t}$/t$+$jet system of $t\bar{t}+$extra jet events. We use events with exactly one lepton, missing transverse energy and at least five jets in data with an integrated luminosity of 8.7 fb$^{-1}$. We find the data to be consistent with the Standard Model and set cross-section upper limits from 0.61 pb to 0.02 pb for resonances ranging from 200 GeV to 800 GeV. We reinterpret these cross-section limits for specific physics models as exclusions in mass-coupling space.

I. INTRODUCTION

We present a search for top+jet resonances in $t\bar{t}+$jet events using the CDF detector [1]. Recently, CDF reported a measurement of the top-quark production forward-backward asymmetry ($A_{FB}$) that is significantly larger than predicted by the SM [2]; DØ sees a consistent result [3].

A wide class of models [4] have been built to explain such a discrepancy, most involving the production of a new heavy mediating particle $M$ that enhances $A_{FB}$. Such new particles may also be singly produced in association with a top(antitop)-quark and further decay to a anitop(top)-quark and an additional jet.

$$pp \rightarrow Mt(\bar{t}) \rightarrow \bar{t}jt(\bar{t}j\bar{t})$$

Such a decay would look like a top+jet resonance in $t\bar{t}+jet$ events.

II. SIGNAL AND SELECTION

Our signal is similar to $t\bar{t}$ with an additional jet, in the lepton + jets channel the detector signature is $\ell + \nu + qq' + bb' + q$. To isolate such a final state we require:
FIG. 1: Validation in the $t\bar{t}$ region, with exactly four jets and at least one $b$-tag.

- Exactly one tight electron or muon with $p_T > 20$ GeV
- At least 5 jets with $E_T > 20$ GeV and $|\eta| < 2.0$
- At least 1 SCVTX [5] tag
- $E_T \geq 20$ GeV.

III. MODELING AND BACKGROUNDS

We model the $M$ resonance signal using MADGRAPH [6] to describe the hard process and PYTHIA [7] for the showering. The dominant backgrounds with our selection are $t\bar{t}$ and $W$+jets. The $t\bar{t}$ and diboson background samples are generated using PYTHIA, $W$+jets and $Z$+jets using ALPGEN [8]+PYTHIA, and the QCD sample is modeled from jet events in the data.

We validate our background in three control regions:

- $t\bar{t}$ region: Exactly four jets and at least one $b$-tag. This validates the overall background normalization, as well as the modeling of $m_{t\bar{t}}$; the requirement of exactly four jets depletes the sample of potential signal contamination, Figure 1.

- $t\bar{t} + j$ region: At least five jets and exactly zero $b$-tags. This validates the modeling of additional jet radiation, which is the source of SM events with at least five jets. The requirement of exactly zero $b$-tags suppresses the signal, Figure 2.

- Low $H_T$ region: At least five jets and small $H_T (< 225$ GeV). This region directly probes the $t\bar{t}$+jet contribution, which is partially suppressed in the $t\bar{t}$+jet region by the low $H_T$ requirement, Figure 3.

Our signal region is then defined as $N_{jets} \geq 5$ and at least 1 tag.

We consider several sources of systematic uncertainty, including jet energy scale, contributions from additional interactions, uncertainty in descriptions of initial and final state radiation, differences in Monte Carlo generators for $t\bar{t}$ background and the $Q^2$ systematics for $W$+jets backgrounds. The impact of these systematics are listed in Table I.

IV. RECONSTRUCTING THE RESONANCE MASS.

We construct the resonance mass, $m_{t\bar{t}}$, using the top kinematic fitter. From the $N (\geq 5)$ jets we pick the 4 jets that have highest likelihood match to a $t\bar{t}$ topology, the remaining $N-4$ are paired with the $t/\bar{t}$, the highest invariant mass of a jet + $t/\bar{t}$ is chosen as our analysis variable, $m_{t\bar{t}}$. Figure 4 shows this reconstruction for the backgrounds, data and example signal resonances of 300, 500 and 800 GeV/c$^2$ in the signal region.
FIG. 2: Validation in the $W^{+}\text{jets}$ region, with at least 5 jets and exactly 0 $b$-tag.

FIG. 3: Validation in the $t\bar{t} + j$ region, with at least 5 jets, at least 1 $b$-tag, and $H_T < 225\text{GeV}$.

TABLE I: Impact of systematic uncertainties on each background source and an example signal of 500 GeV in the signal region.

<table>
<thead>
<tr>
<th>Systematic</th>
<th>$t\bar{t}$</th>
<th>$W^{+}\text{jets}$</th>
<th>Total</th>
<th>$M$ (500 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>550.55</td>
<td>78.64</td>
<td>669.17</td>
<td>339.09</td>
</tr>
<tr>
<td>JES</td>
<td>17%</td>
<td>15%</td>
<td>16%</td>
<td>9%</td>
</tr>
<tr>
<td>Radiation</td>
<td>6%</td>
<td>5%</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>-</td>
<td>-</td>
<td>19%</td>
<td>2%</td>
</tr>
<tr>
<td>Nvtx</td>
<td>3%</td>
<td>2%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>$t\bar{t}$ Generator</td>
<td>6%</td>
<td>-</td>
<td>5%</td>
<td>-</td>
</tr>
<tr>
<td>Normalization</td>
<td>10%</td>
<td>30%</td>
<td>12%</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Uncertainty</strong></td>
<td><strong>22%</strong></td>
<td><strong>38%</strong></td>
<td><strong>21%</strong></td>
<td><strong>10%</strong></td>
</tr>
</tbody>
</table>
FIG. 4: Resonance mass reconstruction, $m_{t\bar{t}j}$, for backgrounds, data and example signal resonances of 300, 500 and 800 GeV/$c^2$ in the signal region scaled to a cross-section of (left) 0.1 pb with log-scale and (right) 1 pb on a linear scale.

V. RESULTS: LIMITS ON CROSS SECTION

To extract the most likely signal cross-section, we perform a binned maximal-likelihood fit to the $m_{t\bar{t}j}$ distribution, varying each background rate within uncertainties, allowing shape and rate variation due to systematic uncertainties described above. The signal and background rates are fitted simultaneously. The CLs method [9] is used to set 95% cross-section upper limits. The median expected upper limit is extracted in the background-only hypothesis.

We find that the observed limits are consistent with what we would expect if the data were drawn from the standard model. We estimate 95% C.L. upper limits on the cross-section of such resonances, see Figure 5.

FIG. 5: Upper limits at 95% CL on $t\bar{t} + j$ production via a heavy new mediator $M$, as a function of the mediator mass. Also shown are theoretical predictions, assuming a unit coupling.
VI. RESULTS

We convert limits on top+jet resonance to exclusion of specific models in mass-coupling space, see Fig. 6

(a) Singlet models.

(b) Triplet models.

FIG. 6: Excluded region in mass-coupling space for two specific models, where the $M$ particle is part of a new singlet (a) or colored triplet [4] (b). Also shown are regions [10] which are consistent with the observed anomalous $A_{FB}$ and constraints from top-quark pair production and single-top production cross-section measurements.


[10] This region simultaneously satisfies the observed high-$m_t$ $A_{FB}$, low-$m_t$ $A_{FB}$, and the $t\bar{t}$ cross-section better than the Standard Model. Mathematically, it is defined as the region with $\chi^2 < 2.8$, where $\chi^2$ is defined in Equation 22 in Ref. [4]. $\chi^2$ for the Standard Model is 2.8.