Search for $t\bar{t}$ resonances in semileptonic final states

P. Turner

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Search for $t\bar{t}$ resonances in semileptonic final states in pp collisions at $\sqrt{s}=8$ TeV

Paul Turner on behalf of the CMS Collaboration

University of Illinois at Chicago

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August 15, 2013
Search for $t\bar{t}$ resonances in semileptonic final states

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Outline

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Massive new particles can manifest as resonances in the production of \( t\bar{t} \) pairs at the Large Hadron Collider (LHC).

Each result in a distorted \( t\bar{t} \) invariant mass spectrum w.r.t. the SM expectation. This allows for a model independent search for beyond standard model (BSM) physics by looking at the \( t\bar{t} \) invariant mass!
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Specific BSM models:
- Colorons, axigluons, gravitons in Randall-Sundrum model extensions, ...
- Leptophobic Topcolor $Z' -$ Harris et. al.
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We present a model-independent search for the production of heavy resonances decaying into $t\bar{t}$ using data recorded in 2012 by the Compact Muon Solenoid (CMS) detector in pp collisions at $\sqrt{s}=8$TeV at the LHC.

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- Superconducting solenoid, 6m internal diameter, 3.8T
- Silicon Pixel and Strip Tracker
- Lead Tungstate Crystal Electromagnetic Calorimeter (ECAL)
- Brass/Scintillator hadron calorimeter (HCAL)
- Gas-ionization muon chambers are embedded in the steel return yoke of the solenoid
- Forward calorimetry complements the barrel and endcap detectors
Data consists of $19.6 \text{ fb}^{-1}$ integrated luminosity of pp collisions at $\sqrt{s} = 8 \text{ TeV}$ collected by the CMS experiment in 2012.

→ Heavy resonance means boosted topology!

**Electron Channel Trigger**
- Electron $w/p_T > 30\text{GeV}$
- Jet $w/p_T > 100\text{GeV}$
- Jet $w/p_T > 25\text{GeV}$

**Muon Channel Trigger**
- Muon $w/p_T > 40\text{GeV}$
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Offline Selection

- One electron (muon) with $p_T > 35$ GeV (45 GeV), $|\eta| < 2.5$ (2.1)
  - No isolation requirement!
- Veto on second lepton
- At least two jets $|\eta| < 2.4$
  - Leading jet $p_T > 150$ GeV, other jets $p_T > 50$ GeV
- $H_T^{lep} = E_T^{miss} + p_T^{lep} > 150$ GeV (Scalar)
- $E_T^{miss} > 50$ GeV
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Offline Selection

- 2D Cut: \( \Delta R(\text{lep}, \text{closestjet}) > 0.5 \) or \( p_{T,\text{rel}}(\text{lep}, \text{closestjet}) > 25 \text{GeV} \)

→ Do not cut hard on lepton isolation!
Offline Selection

- Triangular (topological) cut (removes events when $E_T^{\text{miss}}$ opposite to electron or jet)

\[- \frac{1.5}{75 \text{ GeV}} E_T^{\text{miss}} + 1.5 < \Delta \Phi\{ (\text{e or j}), E_T^{\text{miss}} \} < \frac{1.5}{75 \text{ GeV}} E_T^{\text{miss}} + 1.5\]
Event Selection

Number of jets distribution in the electron (muon) channel of the high-mass analysis.
Event Selection

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Distance $\Delta R$ between the electron (muon) and the closest jet.

2D Cut : $\Delta R$ (lepton, closest jet) > 0.5
or $p_{T,rel}$ (lepton, closest jet) > 25 GeV
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Each candidate has a list of jets, lepton, and $E_T^{\text{miss}}$ (neutrino)

- $t_{\text{had}}$ reconstructed with at least one jet
- $t_{\text{lep}}$ reconstructed with at least one jet, $E_T^{\text{miss}}$, and one lepton
- Permute jet assignments to generate hypotheses
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$\chi^2$ Cut

- Select hypothesis with minimal $\chi^2$, Cut on $\chi^2 < 10$
  - $\chi^2 = \chi^2_{lep} + \chi^2_{had}$
Top Jet Candidate

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Selection Summary

→ Increase the acceptance for our signal by allowing events with low jet multiplicity and non-isolated leptons. This causes the number of qcd events to dominate.

→ Introduce two alternative cuts: 2D and triangular. This controls QCD.

→ $\chi^2$ cut controls W+jets

→ Events are separated based on b-tagging. The aim is to have complementary channels with different W+jets/$t\bar{t}$ relative contributions.
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Monte Carlo Samples

- MadGraph-pythia combination is used to generate high-mass resonances with $\Gamma/m = 0.01$ and $\Gamma/m = 0.10$, where $\Gamma$ is the width of the resonance, $m=0.5,0.75,1,1.25,1.5,2,$ and $3$ TeV resonance mass.
- Pythia 8 is used to generate a KK gluon excitation.
- Pythia and MadGraph used to generate backgrounds.
- All samples include in-time and out-of-time pileup, re-weighted to reflect actual pileup conditions determined from data.
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### Cross-Sections

<table>
<thead>
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<th>Process</th>
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<th>Generator</th>
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<td>approx. NNLO</td>
<td>POWHEG</td>
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<td>NNLO</td>
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<td>POWHEG</td>
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<tr>
<td>Single $\bar{t}$, tW production</td>
<td>11.1</td>
<td>approx. NNLO</td>
<td>POWHEG</td>
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### Number of Events

<table>
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<th>Sample</th>
<th>Electron+Jets Channel</th>
<th>Muon+Jets Channel</th>
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<td>$g_{KK}, M=2\text{TeV}/c^2$</td>
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<td>$g_{KK}, M=3\text{TeV}/c^2$</td>
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<td>Single Top</td>
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<td>$t\bar{t}$</td>
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<tr>
<td>$W+\text{jets}(+b)$</td>
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<td>$W+\text{jets}(+c)$</td>
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<td>$W+\text{jets}(+\text{light})$</td>
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<td>$Z+\text{jets}$</td>
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<tr>
<td>Total Background</td>
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</tr>
<tr>
<td>Data 2012</td>
<td>5346</td>
<td>4820</td>
</tr>
</tbody>
</table>
Invariant Mass Distributions

Muon Channel:

Electron Channel:
Statistical Analysis

- Statistical analysis is defined by using a bin likelihood of the invariant mass of the reconstructed $t\bar{t}$ system

$$L(\beta | data) = \prod_{i=1}^{N_{bins}} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$$

$$\mu_i = \sum_k \beta_k T_{k,i}$$

- $T_{k,i}$ is the i-bin content for k-template.
- Lognormal distributions are used as prior for all the systematic uncertainties.
Summary of Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Uncertainty</th>
<th>Type</th>
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<tbody>
<tr>
<td>ttbar cross section</td>
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<td>Single top cross section</td>
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<td>$W_{light}$ +jets cross section</td>
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<td>$W_{heavy}$ +jets cross section</td>
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<td>Normalization</td>
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<tr>
<td>$Z$+jets cross section</td>
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<td>muon trigger and id</td>
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<td>Normalization &amp; Shape</td>
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<td>Jet Energy Scale</td>
<td>±1σ($p_T$, η)</td>
<td>Normalization &amp; Shape</td>
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<td>Jet Energy Resolution</td>
<td>±1σ(η)</td>
<td>Normalization &amp; Shape</td>
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<tr>
<td>Mistag Rate</td>
<td>±1σ</td>
<td>Normalization &amp; Shape</td>
</tr>
<tr>
<td>Pileup</td>
<td>CTEQ6 (CT10) set</td>
<td>Normalization &amp; Shape</td>
</tr>
<tr>
<td>PDFs</td>
<td>$2Q^2$ and $0.5Q^2$</td>
<td>Normalization &amp; Shape</td>
</tr>
<tr>
<td>Scale ($Q^2 = M(t)^2 + \Sigma p_T(jet)^2$) for $t\bar{t}$</td>
<td>$2Q^2$ and $0.5Q^2$</td>
<td>Normalization &amp; Shape</td>
</tr>
<tr>
<td>Scale ($Q^2 = M(t)^2 + \Sigma p_T(jet)^2$) for $W/Z$+jets</td>
<td>2 and $0.5 \times$ default</td>
<td>Normalization &amp; Shape</td>
</tr>
</tbody>
</table>

Search for $t\bar{t}$ resonances in semileptonic final states

P. Turner

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Bayesian statistical method used to extract 95% C.L. upper limits on $Z' \rightarrow t\bar{t}$ cross-section

Expected limits given by background-only pseudo-experiments ($\mu = 0$). Expected limit is given by the median of the distribution of upper limits, 68% and 95% give the $\pm 1$ and $\pm 2$ standard deviations.

Limits are calculated for threshold and boosted analysis separately, then combined where the transition between threshold and boosted is based on the expected sensitivity.
The 95% CL upper limits for narrow resonances. Theoretical prediction Harris et. al.
The 95% CL upper limits for resonances with 10% width. Theoretical prediction Harris et al.
The 95% CL upper limits for Kaluza-Klein excitations of the gluon. Theoretical prediction Agashe et. al.
Conclusions

- We have presented a model-independent search for the production of heavy resonances decaying into $t\bar{t}$
- We have combined the results of two complementary analyses optimized for the threshold and boosted regions
- No evidence for a massive resonance is found, therefore we set model-independent limits on the production cross section of non-SM particles decaying to $t\bar{t}$

<table>
<thead>
<tr>
<th></th>
<th>0.5 TeV</th>
<th>2 TeV</th>
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<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>Narrow</td>
<td>$1.91^{+0.76}_{-0.53}$ pb</td>
<td>1.94 pb</td>
</tr>
<tr>
<td>Wide</td>
<td>$1.69^{+0.67}_{-0.45}$ pb</td>
<td>1.71 pb</td>
</tr>
</tbody>
</table>
In addition, we set the following limits at 95% C.L. on the production of non-SM particles in specific models.

- Topcolor $Z'$ bosons with a width of 1.2 and 10% are excluded at 95% C.L. for masses below 2.10 TeV and 2.68 TeV.
- Kaluza-Klein excitations of a gluon with masses below 2.54 TeV in the Randall-Sundrum model are excluded and an upper limit of $0.101 \text{ pb} (0.150_{-0.055}^{+0.072} \text{ pb expected})$ is set on the production cross section times branching fraction for resonance of 2 TeV.

Compared to the results of previous analyses, the upper limits on the masses of these specific resonances have been improved by several hundred GeV.
The CMS Collaboration (2013)
Search for $t\bar{t}$ resonances in semileptonic final states in pp collisions at $\sqrt{s} = 8$ TeV

*CMS PAS B2G-12-006* Available on the CERN CDS information server

R. M. Harris and S. Jain
Cross Sections for Leptophobic Topcolor Z decaying to top-antitop

K. Agashe et al.
LHC Signals from Warped Extra Dimensions
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Figure: Distribution of the reconstructed mass of the leptonically decaying top quark in the muon channel of the high-mass analysis.
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Figure: Distribution of the reconstructed mass of the leptonically decaying top quark in the electron channel of the high-mass analysis.
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Figure: Distribution of the reconstructed mass of the hadronically decaying top quark in the muon channel of the high-mass analysis.
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