Search for resonances decaying to a top quark pair at $\sqrt{s} = 13$ TeV with the ATLAS detector

Kuan-Yu Lin (Michigan State University)
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Outline

- Theoretical motivation
- Two search analysis:
  - All-jets final states (arXiv:1902.10077, accepted by PRD)
4 types of Z’
Top-assisted technicolor

- Only couples to first and third generation quarks
- Couples stronger to up-type quarks than down-type quarks
- Cross-section increases with width
Kaluza Klein boson

- Randall-Sundrum: warped extra-dimension
- Alleviates hierarchy problem of Higgs mass
- Right handed top quark closer to IR brane to gain large Yukawa coupling with Higgs

raoulma.github.io/index.html
• Simplified models allow dark matter to annihilate through a mediator (vector or axial for results shown today) to ordinary matter

• Using measured DM relic density, we can search for the DM mediator through its couplings to quarks to constrain other free parameters in the model
All-jets final states
Event selection

- Two **independent** selection optimized for different Z’ mass
- Resolved:
  - ≥ 6 calo jets. At least 5 $p_T > 75$ GeV and two $|\eta| < 1.6$ plus loosely b-tagged
  - Assign these jets into 2 buckets based on top mass criterion and each bucket has exactly 1 loose b-tagged jet
  - Categorize events based on W mass criterion and tight b-tagging
- Boosted:
  - 1 $p_T > 500$ GeV & 1 $p_T > 400$ GeV large-radius jets separated by azimuthal angle > 1.6. Each jet contains ≥ 1 b-tagged track jet
  - Categorize events based on large-radius jet mass,subjettiness $\tau_{32}$ of the 2 $p_T$ leading large-radius jet and tight b-tagging
Lower $p_T$, lower mass
Boosted selection - mass categorization
Resolved: signal region
Boosted: R1, tight $\tau_{32}$ & 2 b-tag

**ATLAS Simulation**
$\sqrt{s} = 13$ TeV

- $m(Z'_{TC2})=0.75$ TeV resolved
- $m(Z'_{TC2})=1$ TeV resolved
- $m(Z'_{TC2})=2$ TeV boosted
- $m(Z'_{TC2})=3$ TeV boosted

**ATLAS Simulation**
$\sqrt{s} = 13$ TeV

- $m(G_{X})=0.75$ TeV resolved
- $m(G_{X})=1$ TeV resolved
- $m(G_{X})=2$ TeV boosted
- $m(G_{X})=3$ TeV boosted
$m_{t\bar{t}}$ spectrum

- $t\bar{t}$ estimated by MC
- Multi-jet estimated by Data
  - 2D sideband (ABCD) method
    - Resolved: mass criteria of buckets vs. number of tight b-tag jets
    - Boosted: large-R jet mass vs. number of tight b-tagged track jets
$m_{t\bar{t}}$ spectrum
Top-color Z’ exclusion limit

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- **ATLAS**
  - Observed 95% CL upper limit
  - Expected 95% CL upper limit
  - Expected 95% CL upper limit ± 1σ
  - Expected 95% CL upper limit ± 2σ
  - LO Z’\(_{TC2}\) γ=1.2% cross–section × 1.3
  - NLO Z’\(_{TC2}\) γ=3% cross–section
  - NLO Z’\(_{TC2}\) γ=1% cross–section

\[ \sigma \times B \text{ [pb]} \]

\[ m_{Z'} \text{ [TeV]} \]
Lepton+jets final states
Event selection

• Exactly one e/µ with $p_T > 30$ GeV, $E_T^{miss} > 20$ GeV and $E_T^{miss} + m_W > 60$ GeV. At least one b-tagged track jet with $p_T > 10$ GeV

• Boosted:
  • At least one jet with $p_T > 25$ GeV, $\Delta R$(jet,e/µ) < 1.5 => $j_{sel}$
  • At least one top tagged large-radius jet with $p_T > 300$ GeV, $\Delta \phi$(jet,e/µ) > 2.3, $\Delta R$(jet, $j_{sel}$) > 1.5

• Resolved (considered if boosted selection fails):
  • At least 4 jets with $p_T > 25$ GeV
  • Passing kinematic optimization algorithm which assign 3 jets into hadronic top decay and 1 to leptonic top decay

• Categorize events based on number of b-tagged track jets with angular matching
Resolved signal $m_{\bar{t}t}$

ATLAS Simulation, $\sqrt{s}=13$ TeV

Resolved

- before boosted-veto
- after boosted-veto

$m(Z')=0.5$ TeV
$m(Z')=1.0$ TeV
$m(Z')=1.5$ TeV
Boosted signal $m_{t\bar{t}}$

ATLAS Simulation, $\sqrt{s}=13$ TeV
Boosted

- $m(Z')=1.0$ TeV
- $m(Z')=1.5$ TeV
- $m(Z')=2.0$ TeV
- $m(Z')=3.0$ TeV
Leptonic top mass

**ATLAS**

 resolved, e+jets

Boosted, e+jets

Momentum of the leptonic top [GeV]

Events / 20 GeV

Data / Bkg.

Data

$t\bar{t}$

W+jets

Multi-jet

Others

$Z'_{TC_2}$ 0.5 TeV

Bkg. uncertainty

$Z'_{TC_2}$ 3 TeV (x 50)

Bkg. uncertainty
Hadronic top mass

**ATLAS**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- resolved, e+jets

**ATLAS**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- boosted, e+jets

Data / Bkg.

Events / 20 GeV

Events / 10 GeV

Mass of the hadronic top [GeV]

Large-R jet mass [GeV]
\( \text{m}_{\text{t}\bar{t}} \) spectrum (resolved, e vs. \( \mu \))

- \( \text{t}\bar{t} \) estimated by MC
- Multi-jets estimated by matrix method from data
  - Loose e/\( \mu \) region
  - Control region by inverting cuts on \( E_T^{\text{miss}} \) and \( E_T^{\text{miss}} + m_T^W \)
- W+jets estimated by
  - Shape: Sherpa MC
  - Corrections in total yields and flavor components: charge asymmetry data
$m_{t\bar{t}}$ spectrum (e, resolved vs. boosted)
Top-color $Z'$ exclusion limit

\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)

- Expected 95% CL upper limit
- Observed 95% CL upper limit
- Expected 95% CL upper limit $\pm 1 \sigma$
- Expected 95% CL upper limit $\pm 2 \sigma$
- LO $Z'_{\text{TC2}} \Gamma=1.2\%$ cross section $\times 1.3$
- NLO $Z'_{\text{TC2}} \Gamma=3\%$ cross section
- NLO $Z'_{\text{TC2}} \Gamma=1\%$ cross section

\( \sigma \times B \text{ [pb]} \)

\( m_{Z'} \text{ [TeV]} \)
• Top color $Z'$, Kaluza Klein gluon & graviton, and vector & axial DM mediators searched by all-jets & lepton+jets final states at 13 TeV

• Both searches have similar signal sensitivity but lepton+jets performed slightly better at low mass
Back-up
Topcolor assisted technicolor

• Has its root in top-color models
  • QCD SU(3) comes from the symmetry breaking of SU(3)_1×SU(3)_2
  • Coupling of SU(3)_1 << SU(3)_2. The later couples to third generation quarks
  • t̅t̅ condensate to generate large top quark mass and EWSB
• Topcolor assisted technicolor introduces U(1)_1×U(1)_2
  • Coupling U(1)_1 << U(1)_2. The later couples to third generation quarks
  • U(1)_2 gives attractive force between t̅t̅ but repulsive force between b̅b̅
  • The t̅t̅+b̅b̅ condensate gives top quark larger mass than bottom quark
Summary of mass limits

### All-jets

<table>
<thead>
<tr>
<th>Signal</th>
<th>Expected excluded mass [TeV]</th>
<th>Observed excluded mass [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z'_{TC2}) ((\Gamma = 1%))</td>
<td>([0.57, 2.8])</td>
<td>([0.58, 3.1])</td>
</tr>
<tr>
<td>(Z'_{TC2}) ((\Gamma = 3%))</td>
<td>([0.51, 3.6])</td>
<td>([0.53, 3.6])</td>
</tr>
<tr>
<td>(Z'_{med}) (vector)</td>
<td>([0.75, 1.07] \cup [2.0, 2.1])</td>
<td>([0.74, 0.97] \cup [2.0, 2.2])</td>
</tr>
<tr>
<td>(Z'_{med}) (axial-vector)</td>
<td>([1.99, 2.04])</td>
<td>([0.80, 0.92] \cup [2.0, 2.2])</td>
</tr>
<tr>
<td>(g_{KK}) ((\Gamma = 10%))</td>
<td>(&lt; 3.5)</td>
<td>(&lt; 3.4)</td>
</tr>
<tr>
<td>(g_{KK}) ((\Gamma = 20%))</td>
<td>(&lt; 3.4)</td>
<td>(&lt; 3.4)</td>
</tr>
<tr>
<td>(g_{KK}) ((\Gamma = 30%))</td>
<td>(&lt; 3.3)</td>
<td>(&lt; 3.4)</td>
</tr>
<tr>
<td>(g_{KK}) ((\Gamma = 40%))</td>
<td>(&lt; 3.2)</td>
<td>(&lt; 3.4)</td>
</tr>
</tbody>
</table>

### Lepton+jets

Summary of 95 % Confidence Level mass exclusion ranges on benchmark models

<table>
<thead>
<tr>
<th>Model</th>
<th>Observed excluded mass [TeV]</th>
<th>Expected excluded mass [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z'_{TC2}) (1% width)</td>
<td>(&lt; 3.0)</td>
<td>(&lt; 2.6)</td>
</tr>
<tr>
<td>(Z'_{DM,ax})</td>
<td>(&lt; 1.2)</td>
<td>(&lt; 1.4)</td>
</tr>
<tr>
<td>(Z'_{DM,vec})</td>
<td>(&lt; 1.4)</td>
<td>(&lt; 1.6)</td>
</tr>
<tr>
<td>(G_{KK})</td>
<td>([0.45, 0.65])</td>
<td>([0.45, 0.65])</td>
</tr>
<tr>
<td>(g_{KK}) (15% width)</td>
<td>(&lt; 3.8)</td>
<td>(&lt; 3.5)</td>
</tr>
<tr>
<td>(g_{KK}) (30% width)</td>
<td>(&lt; 3.7)</td>
<td>(&lt; 3.2)</td>
</tr>
</tbody>
</table>
ATLAS vs CMS Z' limits

\[ \sqrt{s} = 13 \text{ TeV}, \, 36.1 \text{ fb}^{-1} \]

- ATLAS:
  - \( \bar{t}t \rightarrow (q\bar{q}')(q'\bar{q}) \) observed 95% CL upper limit
  - \( \bar{t}t \rightarrow (q\bar{q}')(q'\bar{q}) \) expected 95% CL upper limit
  - \( \bar{t}t \rightarrow (q\bar{b})(q'\bar{b}) \) observed 95% CL upper limit
  - \( \bar{t}t \rightarrow (q\bar{b})(q'\bar{b}) \) expected 95% CL upper limit

- CMS:
  - 35.9 fb\(^{-1}\) (13 TeV)
  - Observed
  - Expected
  - ±1 s.d. exp.
  - ±2 s.d. exp.
  - Z' 1% width (NLO)

LO \( Z_\text{TC2} \) \( \Gamma = 1.2\% \) cross-section \times 1.3
NLO \( Z_\text{TC2} \) \( \Gamma = 3\% \) cross-section
NLO \( Z_\text{TC2} \) \( \Gamma = 1\% \) cross-section

\( JHEP 04 (2019) 031 \)
CMS results

JHEP 04 (2019) 031
All-jets: exclusion limits

\( \sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1} \)

**Width** \( \simeq 5.6\% \text{ mass} \)
All-jets: exclusion limits

\[ \text{BR}(g_{KK} \rightarrow tt) \approx 92.5\% \]

Width = 30\% mass

\[ \text{BR}(g_{KK} \rightarrow tt) \text{ varies from 18\% to 68\%} \]

Width = 3\% ~ 6\% mass
Lepton+jets: exclusion limits

 BR\( (g_{KK} \to tt) \approx 92.5\% \)
 Width = 30% mass

 Width = \( \frac{3}{M_{\text{Pl}}} \)

 BR\( (g_{KK} \to \bar{t}t) \) varies from 18% to 68%
 Width = 3% ~ 6% mass
Lepton+jets: exclusion limits

**ATLAS**

$t\bar{t} = 13$ TeV, $36.1$ fb$^{-1}$

- Expected 95% CL upper limit
- Observed 95% CL upper limit
- Expected 95% CL upper limit ± 1 σ
- Expected 95% CL upper limit ± 2 σ
- LO KK gluon $\Gamma=30\%$ cross section

**ATLAS**

$t\bar{t} = 13$ TeV, $36.1$ fb$^{-1}$

- Expected 95% CL upper limit
- Observed 95% CL upper limit
- Expected 95% CL upper limit ± 1 σ
- Expected 95% CL upper limit ± 2 σ
- LO KK gluon $\Gamma=15\%$ cross section
Lepton+jets: exclusion limits

Width $\approx 5.6\%$ mass
All-jets: selection efficiency times acceptance

$\sqrt{s} = 13$ TeV
All SRs
$Z'_{TC2}$

$m_{t\bar{t}}$ is at Parton level before FSR
Lepton+jets: selection efficiency times acceptance

**ATLAS** Simulation

$\sqrt{s} = 13$ TeV, $Z' \to t\bar{t}$

![Graph of Acceptance x Efficiency vs. $m_{t\bar{t}}$ (TeV)](attachment:image1)

- **Resolved**
- **Boosted**
- **Combination**

**ATLAS** Simulation

$\sqrt{s} = 13$ TeV, Kaluza–Klein gluon ($\Gamma = 30\%$) → $t\bar{t}$

![Graph of Acceptance x Efficiency vs. $m_{t\bar{t}}$ (TeV)](attachment:image2)
Leptonic top mass (muon)

**ATLAS**

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- Resolved, $\mu +$jets
- Boosted, $\mu +$jets
Hadronic top mass (muon)
Which top matched to b-tagged jet(s)?

- **Leptonic top**
- **Hadronic top**
- **Both top**

$m_{t\bar{t}}$ spectrum (resolved, e)
$m_{\tau\tau}$ spectrum (resolved, $\mu$)
$m_{t\bar{t}}$ spectrum (boosted, e)

ATLAS
\( \sqrt{s} = 13 \) TeV, 36.1 fb\(^{-1}\)

Boosted e (cat. 1)
Post-Fit

Boosted e (cat. 2)
Post-Fit

Boosted e (cat. 3)
Post-Fit

Events / 100 GeV

Data / Pred.

$\tilde{m}_{t\bar{t}}$ [GeV]

$\tilde{m}_{t\bar{t}}$ [GeV]

$\tilde{m}_{t\bar{t}}$ [GeV]
$m_{tt}$ spectrum (boosted, $\mu$)
### All-jets: Systematic uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Resolved ((Z'_{TC2} \ m = 0.75 \ TeV))</th>
<th>Boosted ((Z'_{TC2} \ m = 3 \ TeV))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>&lt; 0.01</td>
<td>+0.03 /−0.03</td>
</tr>
<tr>
<td>(b)-tagging efficiency</td>
<td>+0.05 /−0.04</td>
<td>+0.07 /−0.07</td>
</tr>
<tr>
<td>Small- and large-(R) JES and JER</td>
<td>+0.20 /−0.24</td>
<td>+0.21 /−0.09</td>
</tr>
<tr>
<td>(t\bar{t}) modeling</td>
<td>+0.34 /−0.33</td>
<td>+0.10 /−0.09</td>
</tr>
<tr>
<td>Multijet estimation</td>
<td>+0.25 /−0.27</td>
<td>+0.16 /−0.13</td>
</tr>
<tr>
<td>Extrapolation</td>
<td>−</td>
<td>+0.34 /−0.33</td>
</tr>
<tr>
<td>PDF</td>
<td>+0.07 /−0.08</td>
<td>+0.10 /−0.10</td>
</tr>
<tr>
<td>Pileup reweighting</td>
<td>+0.07 /−0.05</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Simulation statistical uncertainty</td>
<td>±0.41</td>
<td>-</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>±0.92</td>
<td>±0.67</td>
</tr>
<tr>
<td>Data statistical uncertainty</td>
<td>±0.39</td>
<td>±0.74</td>
</tr>
</tbody>
</table>
**Lepton+jets: systematic uncertainties**

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Background [%]</th>
<th>$Z'_{TC2}$, 2 TeV [%]</th>
<th>$Z'_{TC2}$, 3 TeV [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>resolved</td>
<td>boosted</td>
<td>resolved</td>
</tr>
<tr>
<td>$t\bar{t}$ extra QCD radiation</td>
<td>4.0</td>
<td>2.4</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}$ QCD NNLO</td>
<td>0.8</td>
<td>7.4</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}$ cross-section</td>
<td>5.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}$ generator</td>
<td>1.7</td>
<td>3.8</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}$ parton shower</td>
<td>0.6</td>
<td>3.2</td>
<td>-</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>2.6</td>
<td>2.7</td>
<td>-</td>
</tr>
<tr>
<td>Anti-$k_t$ $R = 0.4$ JER</td>
<td>1.1</td>
<td>0.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Anti-$k_t$ $R = 0.4$ JES</td>
<td>5.8</td>
<td>0.9</td>
<td>7.0</td>
</tr>
<tr>
<td>Anti-$k_t$ $R = 1.0$ JER</td>
<td>0.1</td>
<td>4.0</td>
<td>5.3</td>
</tr>
<tr>
<td>Anti-$k_t$ $R = 1.0$ JES</td>
<td>0.3</td>
<td>6.0</td>
<td>3.7</td>
</tr>
<tr>
<td>$b$-tagging efficiency</td>
<td>3.2</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$b$-tagging extrapolation</td>
<td>2.4</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.9</td>
<td>1.9</td>
<td>2.1</td>
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<tr>
<td>Pile-up</td>
<td>4.4</td>
<td>0.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Total</td>
<td>11.6</td>
<td>12.8</td>
<td>11.7</td>
</tr>
</tbody>
</table>
More plots & tables

- All-jets final states: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-24/