Search for new resonances coupling to third generation quarks at CMS

Sheila Amaral
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Purdue University Northwest
on behalf of CMS collaboration
CMS experiment has a rich search program for BSM

- this talk focus on recent results with top quark(s) in final state:
  - Channels with large top BR: \( t \rightarrow ℓνb \) and \( t \rightarrow bqq \)

<table>
<thead>
<tr>
<th>Final state</th>
<th>Luminosity</th>
<th>Result</th>
</tr>
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<tbody>
<tr>
<td>tt resonances</td>
<td>ℓνbbjj</td>
<td>2.6 fb(^{-1})</td>
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<td>LQ3 ( \rightarrow tt )</td>
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$t\bar{t}$ resonances

B2G-16-015

JHEP 07 (2017) 001
Two boosted channels:
- Semileptonic
- All-hadronic:

Top tagging variables: $m_{SD}$, $\tau_{32}$

Special isolation criteria
tt resonances

Search for tt resonance:

→ Z’ resonance with width \( \Gamma/M \) = 1%, 10%, 30%

→ Kaluza-Klein excitation of gluon \( g_{\text{KK}} \)

Semileptonic channel:

- Divided into e and \( \mu \), and according to the number of b-tagged and top-tagged jets;
- Main background: QCD (non-top multijet), derived from data

All-Hadronic channel:

- Divided depending on \( \Delta y_{\text{tt}} \) and number of jets with a b-tagged subjet;
- Main background: ttbar

\( M_{\text{tt}} \) from lepton, \( E_T^{\text{miss}} \), jets

No significant deviation from SM background expectation!
tt resonances

Observed 95% CL mass limits (with lepton+jets and fully hadronic combination):

<table>
<thead>
<tr>
<th>Signal</th>
<th>Observed exclusion</th>
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<tr>
<td>Narrow $Z'$ (1%)</td>
<td>[0.6 – 2.5] TeV</td>
</tr>
<tr>
<td>Wide $Z'$ (10%)</td>
<td>[0.5 – 3.9] TeV</td>
</tr>
<tr>
<td>Extra wide $Z'$ (30%)</td>
<td>[0.5 – 4.0] TeV</td>
</tr>
<tr>
<td>KK gluon</td>
<td>[0.5 – 3.3] TeV</td>
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The combination of the semileptonic and fully hadronic channels improves the exclusion limits for resonances with masses above 2 TeV compared to those of previous analyses at 8 TeV!
$Z' \to tT$

B2G-16-013

JHEP 09 (2017) 053
First search for heavy spin-1 resonance decay into a vector-like T quark and a top quark!!!

Search for Tt resonance in full-hadronic: \( T \rightarrow bW \rightarrow Z' \) resonance width = 1% and mass range [1.5 - 2.5] TeV
\( T \rightarrow T \) quark width fixed to 1 MeV and mass range [0.7 - 1.5] TeV

If kinematically allowed \( Z' \rightarrow tT \) would dominate \( Z' \rightarrow tt \)

3-jet topology:
- Two signal categories: 1 or 2 b-tags in top jet
- Sensitive to \( T \rightarrow tH \) and \( T \rightarrow tZ \)

- Large R
- High \( p_T \)
- \( \tau_{32} \) (3-prong)
$M_{Z'}$ reconstructed from tagged jets

- 2 b-tag category dominates: almost same signal efficiency, but much less background
- Upper cross-section limits for various (Z',T)-mass combinations
- Scan of BR (T → bW, tH, tZ): Each plane is B(T→bW) vs B(T→tH) and B(T→tZ) = 1-B(T→bW)-B(T→tH) for different (Z',T)-mass

Observed cross section limits are in all cases within 2 standard deviations of the expected values!
Two benchmarks theory models: More data needed for exclusion!

Heavy spin-1 Resonance $\rho_L^0 \to Tt$ : Composite Higgs boson model

$T'$ branching fractions: $bW$: $tH$: $tZ = 0\% : 50\% : 50\%$

Heavy KK gluon $G^* \to Tt$: Warped extra-dimension model

$T'$ branching fractions: $bW$: $tH$: $tZ = 50\% : 25\% : 25\%$

No significant deviation from SM expectation!
W' resonances

B2G-16-009
B2G-17-010
PLB 777 (2017) 39
Search for right-handed $W'$ with narrow width (3%) 

Similar to $Z' \rightarrow tt$, except only one boosted top! 
  - Critical (larger QCD background)

**All-hadronic B2G-16-009**
- Critical (larger QCD background)

**Semileptonic: B2G-17-010**
- Lepton + $E_T^{miss} + b$-jet

**Energetic b-jet**

All-hadronic B2G-16-009
QCD estimated from data!
Limits on 2015 data similar to Run I
**Improvement w.r.t. B2G-16-009 (2015 data):**

- Refined event categorization: Type B: $p_T(t) > 650$ GeV and $p_T(j_1+j_2) > 700$ GeV, otherwise Type A

**Semileptonic B2G-17-010**

![Graphs showing CMS data for W' → tb process with event categorization](image)
$W' \rightarrow tb$

Hadronic channel with 2015 data: $W'_R$ masses excluded below 2.0 TeV

Semileptonic channel with 2016 data: $W'_R$ masses excluded up to 3.4 (3.6) TeV

These result are the most stringent limits to date!

First search in this channel at 13 TeV
Scan over left- ($a_L$) and right-handed ($a_R$) couplings $\Rightarrow W'$ invariant mass with arbitrary couplings

- Both $W'_R$ and $W'_L$ could contribute

$$\mathcal{L} = \frac{V_{q_iq_j}}{2\sqrt{2}} g_w q_i \gamma_\mu (a^R_{q_iq_j} (1 + \gamma^5) + a^L_{q_iq_j} (1 - \gamma^5)) W'q_j + \text{H.c.}$$

Mass limits interpreted as a function of both couplings

Black line: contours of equal $W'$ mass separated by 200 GeV
Excited top

B2G-16-025

PLB 778 (2018) 349
Pair production of spin-3/2 excited top quarks in

- Semileptonic channel
- Full 2016 dataset (35.7 fb$^{-1}$)

Resolved selection: $\mu/e + E_T^{\text{miss}} +$ boosted $W$ jet + small-cone jets

First search at 13 TeV!
Reconstruction of $t^*$ quark is based on the quality of jet-parton assignment:

$$S = \left( \frac{m_{q\bar{q}'} - M_W}{\sigma_W} \right)^2 + \left( \frac{m_{q\bar{q}'b} - M_t}{\sigma_{t,\text{had}}} \right)^2 + \left( \frac{m_{\ell\nu\bar{b}} - M_t}{\sigma_{t,\text{lep}}} \right)^2 + \left( \frac{m_{q\bar{q}'bg} - m_{\ell\nu\bar{b}g}}{\sigma_{t^*}} \right)^2$$

- **Combined mass limit:** 1.2 TeV
- **Best limits to date at 13 TeV!**
3rd-generation Leptoquark

B2G-16-028
Submitted to EPJC
Pair production of LQ$_3$s
- Boson which decay into a lepton and a quark

Exclusive decay mode $\rightarrow t\tau$

$\mu/e + E_T^{\text{miss}} + \tau_h + \text{boosted W jet} + \text{small-cone jets final state}$
$LQ_3 \rightarrow t\tau$

$S_T$ variable: scalar sum of the $p_T$ of selected $\mu/e$, $\tau$, jets and $E_T^{\text{miss}}$

Different categories cover a wide range of leptoquark masses!

Signal characterized high-$p_T$ $\Rightarrow$ high $S_T$
- SM populate lower $S_T$ region

No excess observed!
LQ₃ → tτ

LQ₃s excluded for masses below 1.2 TeV for B=0 and below 750 GeV over the full B range

These results provide the most stringent limits to date!
Summary

- Rich search program for states with decays to 3\textsuperscript{rd} generation quarks
  - LQ3, Z', W', t*, ...
- Reconstruction techniques for boosted topologies efficiently used
- No deviation from SM yet
- Many more results expected soon!
Backup
Resonances decaying into Higgs/W/Z discussed yesterday (talk of ...)

focus today on **new resonances coupling to 3rd generation quarks**

For heavy resonances the bosons get high boost $\Rightarrow$ **very collimated decay products**

$\Rightarrow$ can be merged into a single object (jet)

Possibly **boosted objects**: require new triggers (non-isolated lepton) and reconstruction strategies (jet $p_T$ cleaning, jet substructure, ...)

![Diagram of non-boosted and boosted resonances](image)
Boosted Leptons

นอกจาก decay of heavy resonances lead to boosted tops

- **Leptonic decay → non-isolation leptons**

- **Methods used: special lepton isolation criteria**
  - variable $p_T$-dependent cone size, “mini isolation"
    - Sum relative $p_T$ inside cone $R_{\text{min}}$ around lepton
    - $R_{\text{min}} \sim 1/p_T$, $0.05 < R_{\text{min}} < 0.2$
  - Non-isolated leptons (“2D-cut”): Relative transverse momentum & angular separation
    - $p_{T,\text{rel}} > 40$ GeV $|| \Delta R(\text{jet}, \ell) > 0.4$
**Boosted jets**

- **Hadronic decay** → “fat jets” with substructure

- **Methods commonly used: top tagging**
  - Reconstruction of anti-kT jets with R=0.8 (AK8) reclustered with CA algorithm
  - m_{SD} jet mass using softdrop algorithm (top: 110 < m_{SD} < 210 GeV)
    - Removal of soft wide-angle radiation within large-cone jets
    - Reconstruction of subjets
  - n-subjettiness $\tau_N$ measure of probability that jet contains “N” subjets
    - The ratio $\tau_{32} = \tau_3 / \tau_2$ → discriminator between jets with 3-prongs from jets with 2-prongs (top: $\tau_{32} < 0.69$)
  - Pileup mitigation using “pileup jet particle identification” (PUPPI)
    - Combines local shape information, event pileup properties and tracking information before the AK8 jet clustering
  - Subjet b-tagging

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**Diagram and Graphs**

- **CMS**
  - AK8 jets with $p_T > 500$ GeV, $|\eta| < 2.4$, $\tau_{32} < 0.69$
  - Data
  - Matched to top quark
  - Unmatched to top quark
  - $Z'$ 3 TeV ($\tau_{32} < 0.69$)
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