Searches for new resonances coupling to third generation quarks at CMS

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**Introduction**

- Analyses use third generation quarks as a probe for new physics
- Heavy resonance decaying to third generation quarks
  - $Z' \rightarrow t\bar{t}$
  - $W' \rightarrow tb$
- With an intermediate VLQ
  - $Z' \rightarrow tT$
- Leptoquark pair production
  - $LQ \rightarrow \tau t$
  - $LQ \rightarrow \mu t$
Introduction

- Searches generally involve tagging heavy boosted objects (ex. top, W, H) merged into a single jet
  - Softdrop mass
    - Decluster until softdrop condition is met
    - Groomed mass variable and subjets identified
  - N-subjettiness
    - Identify subjet axes, and extract \( \tau_N \) variables
    - \( \tau_3/\tau_2 \) - “three-prong” like
    - \( \tau_2/\tau_1 \) - “two-prong” like
  - Subjet b tagging
    - Attempt to b tag softdrop subjets
    - Identify one or two subjets

Softdrop condition

\[
\min\left(\frac{p_{T1} + p_{T2}}{p_{T1} + p_{T2}}\right) > z(\Delta R_{12}/R_0)^\beta
\]

N-subjettiness

\[
\tau_N = \frac{1}{d} \sum_i p_{Ti} \min\{\Delta R_{1,i}, \Delta R_{2,i}, ..., \Delta R_{N,i}\}
\]
Search for a heavy $Z'$ resonance decaying to a top quark pair

Search in multiple channels
- Two hadronictops (all hadronic)
- One hadronic top and one semileptonic top (semileptonic)
- Two semileptonic tops (dileptonic)

Consider two signal hypotheses
- Heavy $Z'$ and RSgluon
- Heavy resonance leads to merged objects
  - Use boosted hadronic top identification
  - Lepton isolation starts to break down

Link: CMS-PAS-B2G-17-017
\( Z' \rightarrow t\bar{t} \)

- Require two top tagged jets
  - \( \tau_3 / \tau_2 \), Softdrop mass, Subjet b tag (0, 1, or 2)
- Select on rapidity difference
  - \( \Delta R < 1.0 \), \( \Delta R > 1.0 \)
- Estimate QCD background using anti tag and probe
  - Invert Nsubjettiness selection

### Graphs

1. **Jet Momentum [GeV]**
   - **t-tag mistag rate**
     - \( \Delta y \) inclusive
     - PUPPI t-tag

2. **Events**
   - **Pull**
     - \( m_{tt} \) [GeV]
   - **Events**
     - **36 fb\(^{-1} \) (13 TeV)**
       - Data
       - NTMJ
       - \( Z' \) 4.0 TeV, 1% width
     - **Events**
       - **Preliminary** CMS

### Background
- The all-hadronic channel has a substantial background from QCD multi-jet events
- An anti-tag and probe technique is used to select a region enriched in QCD
- The mistag rate is then measured using the probe jet
- The mistag rate is then used to estimate the QCD background in the signal region
- A “mass-modified” procedure is used to ensure the jet kinematics in the QCD control region match that of the signal region
- The data derive QCD background is then validated with QCD MC
$Z' \rightarrow t\bar{t}$

- Selection
  - One lepton (e or $\mu$)
  - Two jets, one with high $p_T$
  - Hadronic top tag categories (0 or 1)
  - High $p_T^{miss}$
  - No lepton isolation cut
- Use BDT selection to separate $W$+jets
- 10 inputs
- Reconstruct $t\bar{t}$ system using $\chi^2$

\[
\chi^2 = \left[ \frac{M_{lep} - \overline{M}_{lep}}{\sigma_{M_{lep}}} \right]^2 + \left[ \frac{M_{had} - \overline{M}_{had}}{\sigma_{M_{had}}} \right]^2
\]
**Z’ → t̅t**

- **Selection**
  - Two opposite sign leptons (e or μ)
  - Two jets, one with high $p_T$
  - At least one b tag
  - High $p_T^{\text{miss}}$
  - No lepton isolation cut
- Use $\Delta R_{\text{sum}} \equiv \Delta R_{j_{11}} + \Delta R_{j_{12}}$ to categorize events
  - Boosted: $\Delta R_{\text{sum}} < 1$
  - Resolved: $1 < \Delta R_{\text{sum}} < 2$
  - Background CR: $\Delta R_{\text{sum}} > 2$
- Set limits using $S_T$ distribution

\[
S_T \equiv \sum_{i=1}^{N_{\text{jet}}} p_{T_i} + \sum_{i=1}^2 p_{T_i} + p_{T}^{\text{miss}}
\]
$Z' \rightarrow t\bar{t}$

- Limits set using RSGluon and $Z'$ signal hypotheses
- Limits extended
  - 3.8 TeV for the narrow $Z'$ hypothesis
  - 4.6 TeV for the RSGluon hypothesis
W' → tb

- Search for a heavy W' resonance decaying to a top quark and bottom quark
  - Semileptonic final state
- Set generic limits of left- and right-handed W' couplings

\[ \mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_{\mu} \left[ a_R^{f_i f_j} (1 + \gamma^5) + a_L^{f_i f_j} (1 - \gamma^5) \right] W'_{\mu} f_j + h.c. \]

Link: physletb.2017.12.006

W' → tb

- Selection
  - One lepton (e or µ)
  - Two jets, one with high $p_T$
  - B tag categories (1,2)
  - High $p_T^{\text{miss}}$
  - No lepton isolation cut
- Use kinematic categorization for limit setting
  - Top $p_T$, $(j_1 + j_2) p_T$
$W' \rightarrow tb$

- Backgrounds from Monte Carlo with data control regions
  - Investigate dilepton $t\bar{t}$ to check top $p_T$ spectrum
  - Use 0 b tag region to investigate $W+$jets shape and normalization
- Limits set on $W'_R$ hypothesis
  - $M_{W'_R} >> M_{\nu_R}$ -- Exclude $M_{W'_R} < 3.4$ TeV
  - $M_{W'_R} < M_{\nu_R}$ -- Exclude $M_{W'_R} < 3.6$ TeV
- Limits set in $a_L, a_R$ plane
  - Left- and right-handed $W'$ couplings
Z' → tT

- Search for a heavy Z' resonance decaying to a top and a T VLQ in the lepton+jets channel
  - T decays in to bW,tH,tZ analyzed
  - Use multiple boosted jet categories
    - H_{1b}, H_{2b}, Z, W
- Reconstruct Z' based on presence of a hadronic top tag
  - Event contains hadronic top tag
    - Leptonic top from lepton, MET, and AK4 jet
  - Event does not contain hadronic top tag
    - AK4 jets are assigned to either leptonic or hadronic top
  - Construct $\chi^2$ to assign AK4 jets

$$\chi^2 = \left[ \frac{M_{\text{lep}} - \overline{M}_{\text{lep}}}{\sigma_{M_{\text{lep}}}} \right]^2 + \left[ \frac{M_{\text{had}} - \overline{M}_{\text{had}}}{\sigma_{M_{\text{had}}}} \right]^2$$

Link: CMS-PAS-B2G-17-015
$Z' \rightarrow t\bar{t}T$

- Primary backgrounds $t\bar{t}$ and $W+$jets
  - Invert boson mass selection to simultaneously constrain
    - $W+$jets sideband from 0 b jets category
    - $t\bar{t}$ sideband from $\geq 1$ b jet category
  - Shape taken from simulation
• Set limits using two benchmark models
  • Extra dimension model
  • Composite model
• best sensitivity for $T \rightarrow tH$

Higgs 2b muon channel

$T \rightarrow bW$ and $T \rightarrow tZ$ also covered by:
and
LQ → ℓt

- Searches for third generation scalar leptoquarks
  - Non-zero lepton and baryon numbers
- Decay to third generation quark and lepton
  - top+τ
  - top+µ

Link: CMS-PAS-B2G-16-027, arxiv:1803.02864

CMS Collaboration, “Search for third-generation scalar leptoquarks decaying to a top quark and a τ lepton at $\sqrt{s} = 13$ TeV”
LQ → ττ

- Selection
  - One lepton (e or μ)
  - Three jets
  - τ tag categories (1 or ≥ 2)
    - N_τ = 1
      - Limits set using the hadronic top p_T^{top} variable in bins of S_T
    - N_τ ≥ 2
      - Counting experiment
- Background estimation
  - Invert τ isolation to extract misidentified τ background
  - Extrapolate to signal region using ratio from MC
- Prompt τ background from simulation

\[
N_{SR, data}^{tt} = \left( N_{CR}^{data} - N_{other, MC}^{CR} \right) \frac{N_{SR}^{ττ, MC}}{N_{CR}^{ττ, MC}}
\]
LQ → μt

- **Selection**
  - Two oppositely charged muons
  - At least two jets, one b tagged
  - High $S_T$
  - High $M_{μμ}$
- **Additional lepton categories**
  - One additional electron or muon
    - Set limits using $M_{LQ} \equiv \frac{1}{2} (M_{LQ}^{lep} + M_{LQ}^{had})$
    - Reconstruct using $χ^2$
    - All remaining events
      - Set limits using $S_T$
      - Background estimate from data
        - Define zero muon control region
        - Extrapolate from control region using MC ratio as a function of $S_T$

\[
χ^2 = \left( \frac{M_t - \bar{M}_t}{σ_M} \right)_{lep}^2 + \left( \frac{M_t - \bar{M}_t}{σ_M} \right)_{had}^2 + \left( \frac{ΔM_{LQ}^{rel} - ΔM_{LQ}^{rel}}{σ_{ΔM}} \right)^2
\]
LQ → ℓt

• Limit combination

LQ → τt

LQ → µt

Combined limits
Summary

• Exciting new results from CMS
  • Heavy bosons to 3\textsuperscript{rd} generation quarks
    • $Z' \rightarrow t\bar{t}, W' \rightarrow tb$
  • Including an internal VLQ
    • $Z' \rightarrow tT$
  • Leptoquark pair production
    • $LQ \rightarrow \tau t, LQ \rightarrow \mu t$
  • New methods push sensitivity beyond expected improvement
• Looking forward to new results using 2017 and 2018 data
Backup