Searches for new heavy particles coupling to third-generation quarks at CMS

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Introduction

4th generation of fermionic quarks

- Not chiral (H boson), but vector currents: Vector-Like Quarks
- T, B, X_{5/3}, ...
- Preferred decay to 3rd-generation quarks
- Decay modes:
  - T → tH, tZ, bW
  - B → bH, bZ, tW

Recent highlights from CMS

- Z' → tt, combination of all final states
- TT/BB: multi-class DNN jet-tagger
- Single B/X_{5/3}: Dominant at high M_{VLQ}
- Z' → Tt: Covers new region in Z' phase space

New heavy vector bosons

- Z', W', g_{KK}
- Decay to VLQs or SM quarks
Searches in CMS

Vector-like quarks
- $TT \rightarrow tH, \ tZ, \ bW$
- $BB \rightarrow bH, \ bZ, \ tW$
- Single $B/X_{5/3} \rightarrow tW$
- Single $B \rightarrow bH$
- Single $T \rightarrow tZ$

Heavy vector bosons
- $Z' \rightarrow tt$
- $W' \rightarrow tb$
- $Z' \rightarrow Tt, \ T \rightarrow tZ, \ tH$
- $W' \rightarrow Bt / bT, \ T/B \rightarrow t/b + H$
Jet tagging

- Very heavy particles decay → collimated final states
- Reconstructed in large-R jet with distinct substructure
  - Groomed jet mass $M$ at $W/Z/H/t$ mass
  - $N$-subjettiness $\tau_N$: Measure for probability to have $\leq N$ subjets
  - $b$-tagging applied to subjets
Heavy $Z' \rightarrow tt$

all-jets, $1\ell +$ jets

- Analyze all $t\bar{t}$ decay modes

**all-jets channel**

- $t$-tagging powerful tool
- Require $\geq 2$ $t$-tags with subjet $b$-tags
- Categories in $|\Delta y|$ between tags

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Heavy $Z' \rightarrow tt$

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$1\ell +$ jets channel

- $W+$jets suppressed by BDT
- $Z'$ reconstructed
  - $\ell, \nu, \text{jet for } t_\ell$
  - t-tag or small-R jets for $t_h$
- Categories in $N_t$
Heavy $Z' \rightarrow tt$

$2\ell + \text{jets}$, combination

$2\ell$ channel

- b-tagging needed
- Depending on boost: $\ell$ close to jets
- Sum of $\Delta R(\ell_i, j)$ defines SRs, CRs
- $S_T$ sensitive variable

Full combination

- 3 channels statistically independent
- Combination maximizes sensitivity
- Interpreted in different signal models ($Z'$, $g_{KK}$)
Heavy $Z' \rightarrow tt$

combined limits

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

CMS

$\sigma_{g_{KK}} \times B(g_{KK} \rightarrow t\bar{t}) \text{ [pb]}$

- Observed
- Expected
- $\pm 1 \text{ s.d. exp.}$
- $\pm 2 \text{ s.d. exp.}$

$g_{kk} (\text{LO} \times 1.3)$ Combination

$M_{g_{KK}} \text{ [TeV]}$
**Heavy t/b partners (TT, BB)**

- **BEST algorithm**: DNN multi-class jet tagger
- **Boost large-R jet constituents into different rest frames**: $t$, $W$, $Z$, $H$

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Heavy t/b partners (TT, BB)

all-jets

Best algorithm: DNN multi-class jet tagger

Boost large-R jet constituents into different rest frames: t, W, Z, H

Event shape variables into DNN: 6 possible tags: qg, b, t, W, Z, H

35.9 fb⁻¹ (13 TeV)
Heavy t/b partners (TT, BB) all-jets

- BEST algorithm: DNN multi-class jet tagger
- Boost large-R jet constituents into different rest frames: t, W, Z, H
- Event shape variables into DNN: 6 possible tags: qg, b, t, W, Z, H
- Categories in $N_{\text{tags}}$ (126)

**Search:** arXiv:1906.11903

**BEST:** Phys. Rev. D 94, 094027

Data / BG

![CMS plot showing event categories andcategories](image-url)
• BEST algorithm: DNN multi-class jet tagger
• Boost large-R jet constituents into different rest frames: t, W, Z, H
• Event shape variables into DNN: 6 possible tags: qg, b, t, W, Z, H
• Categories in $N_{\text{tags}}$ (126)
• Complementary cut-based analysis optimized for $\text{TT} \rightarrow bW \ bW$
• Similar sensitivity as in $\ell+$-jets final state
Heavy t/b partner (X_{5/3} / B)

1\ell + jets

- Single production dominant at high VLQ masses
- Target VLQ \rightarrow tW
- VLQ reconstruction
  - Resolved: small-R jets, \ell, p_T^{miss}
  - Boosted: t-tagged jet = hadronic t
Heavy t/b partner ($X_{5/3}/B$)

$1\ell + \text{jets}$

- Single production dominant at high VLQ masses
- Target VLQ $\to tW$
- VLQ reconstruction
  - Resolved: small-R jets, $\ell, p_T^{\text{miss}}$
  - Boosted: t-tagged jet = hadronic t

- Unique signature: forward jet
- CR without forward jet: background enriched and similar shape as SR

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Heavy t/b partner ($X_{5/3} / B$)

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- Single production dominant at high VLQ masses
- Target VLQ $\rightarrow tW$
- VLQ reconstruction
  - Resolved: small-$R$ jets, $\ell$, $p_T^{\text{miss}}$
  - Boosted: t-tagged jet = hadronic $t$
- Unique signature: forward jet
- CR without forward jet: background enriched and similar shape as SR
- Take background shape from data

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Heavy t/b partner \((X_{5/3} / B)\)

1\(\ell\) + jets

\begin{align*}
\sigma \times B(X_{5/3} \rightarrow tW) [\text{pb}] \\
\text{CMS} & \quad \text{Obs} 95\% \text{ CL upper limits} \\
X_{5/3} + t, \text{RH} & \quad \text{Exp} 95\% \text{ CL upper limits.} \\
(\Gamma/m)_{\text{VLQ}} = 1\% & \quad \pm 2 \text{ std. deviation} \\
\text{Theory} & \quad \pm 1 \text{ std. deviation}
\end{align*}

35.9 fb\(^{-1}\) (13 TeV)
Heavy $Z' \rightarrow Tt$

$1\ell + \text{jets}$

- Previously unexplored decay mode
- Dominant if $2M_T > M_{Z'} > M_t + M_T$
- Optimized for $T \rightarrow tH, tZ$
- $Z'$ reconstruction: $t\bar{t} + W/Z/H$
  - boosted regime: $t$-tag for $t_h$
  - resolved regime: small-R jets for $t_h$
  - tagged jet for $W/Z/H$
- Tagging efficiencies measured in data
- $t\bar{t}, W+$-jets constrained by data in CRs

\[35.9 \text{ fb}^{-1} (13 \text{ TeV})\]
Heavy $Z' \to Tt$

$1\ell + \text{jets}$

$G^* \to (pp \sigma 2 - 10 1 - 10 10 2 10 95\% \text{ CL upper limits}$

$\text{Expected}$
$68\% \text{ expected}$
$95\% \text{ expected}$

$\text{Observed}$

$tT \to G^* = 1.2 \text{ TeV}$

$T_{G^* \text{ model, } M_T = 1.2 \text{ TeV}}$

$W_b : H_t : Z_t = 0.5 : 0.25 : 0.25$

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

$Z' \to (pp \sigma 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 \text{ Ht})$

$= 1.3 \text{ TeV}$

$T_M = 1.5 \text{ TeV}$

$Z'M_{CMS} (13 \text{ TeV})$

$-135.9 \text{ fb}$

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Conclusion

- Heavy new particles predicted to solve open questions of SM
- Partners of quarks or gauge bosons
- Strong coupling to 3rd-generation quarks
- CMS searches cover multitude of decay channels
- New final states and improved analysis techniques
- Jet-substructure crucial in all searches
- Masses in multi-TeV range excluded
back-up
Heavy t/b partners (TT, BB)

1\ell, 2\ell(SS), \geq 3\ell + jets

- All T/B decays considered: tZ, tH, bW
- 1\ell final state
  - b-tagging, large-R tagging crucial
  - min(M_{b\ell}) and S_T sensitive variables
  - Categories in N_W, N_H
- 2\ell(SS) final state
  - Rare signature in SM background
  - counting experiment
- \geq 3\ell final state
  - Categories in \ell flavors
  - S_T sensitive variable
- Combination maximizes sensitivity
- Non-prompt \ell rate estimated from data
Heavy t/b partners (TT, BB)

$1\ell, 2\ell(\text{SS}), \geq 3\ell + \text{jets}$

- **All**
- **$1\ell$**
- **$2\ell$**
- **$\geq$**
- **Co**
- **No**

$\beta(bW)$

35.9 fb$^{-1}$ (13 TeV)

$B(bW)$

CMS

$\beta(tH)$

$W^+, Z, H$

$b, t, \bar{t}$

$\Gamma_{2/3}$

$W^−, Z, H$

95% CL observed T quark mass limit (GeV)

Nonprompt

CMS

JHEP 08 (2018) 177
Heavy t partner ($X_{5/3}X_{5/3}$)

1$\ell$, 2$\ell$ SS + jets

- Targets $X_{5/3} \rightarrow tW$ decay mode
- $b$-, $W$-, $t$-tagging employed
- Kinematic cuts on large had. activity

1$\ell$ + jets

- categories in $e/\mu$, $N_b$, $N_W$, $N_t$
- $\min(M_{\ell b})$ sensitive variable
- $W+$jets, $t\bar{t}$ fitted in control regions

2$\ell$ SS + jets

- Number of jets + add. $\ell \geq 5$
- Low event yield $\rightarrow$ counting experiment
- Non-prompt and charge-misID background derived from data
Heavy t partner ($X_{5/3}X_{5/3}$)

$1\ell, \ 2\ell \text{ SS } + \text{jets}$

- Ta
- $b^-$, Kir
- $1\ell + \text{jets}$
  - cal
  - $m_i$
  - $W^+$
- $2\ell \text{ SS } +$
  - Nu
  - $L_1$
  - No

background derived from data

CMS

$B(X_{5/3} \rightarrow tW) = 1$

Right-handed

SS dilepton and
1-lepton combination

35.9 fb$^{-1} (13 \text{ TeV})$

95\% CL upper limits

- Observed
- Expected
- 68\% expected
- 95\% expected
- Signal cross section

$\sigma(X_{5/3}X_{5/3})$ [pb]

$\min[M(l,b)] \text{ [GeV]}$

35.9 fb$^{-1} (13 \text{ TeV})$

Data

- QCD
- $X_{5/3}X_{5/3}$ LH (0.9 TeV)
- $X_{5/3}X_{5/3}$ RH (1.2 TeV)
- EWK
- Bkg uncertainty
- TOP

$e/\mu + \text{jets}$

$\geq 1 \ t, \geq 1 \ W$

$1 \ b, \geq 4 \ j$
Heavy t partner (T)  

$2\ell + \text{jets}$

- Optimized for $T \rightarrow tZ \rightarrow (qqb)(\ell\ell)$
- Utilizing $b$-, $W$-, $t$-tagging
- 3 regimes for $t$ reconstruction:
  - fully merged: 1 $t$-tag
  - semi-merged: 1 $b$-tag, 1 $W$-tag
  - resolved: 3 jets, 1 $b$-tag
- $T$ reconstructed from $t$ and $Z \rightarrow \ell\ell$
- $M_{tZ}$ sensitive variable
- Categories with / without forward jet
- DY+jets background estimated in CR with $b$-tag veto
- Also sensitive to $Z' \rightarrow Tt \rightarrow (tZ)t$

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Heavy $t$ partner ($T$)

$2\ell +$ jets

- Optimized for $T \rightarrow tZ \rightarrow (qqb)(\ell\ell)$
- Utilizing $b$-, $W$-, $t$-tagging
- 3 regimes for $t$ reconstruction:
  - fully merged: 1 $t$-tag
  - semi-merged: 1 $b$-tag, 1 $W$-tag
  - resolved: 3 jets, 1 $b$-tag
- $T$ reconstructed from $t$ and $Z \rightarrow \ell\ell$
- $M_{tZ}$ sensitive variable
- Categories with / without forward jet
- DY+jets background estimated in CR with $b$-tag veto
- Also sensitive to $Z' \rightarrow Tt \rightarrow (tZ)t$

$|m_{TZ}|$ [GeV]

35.9 fb$^{-1}$ (13 TeV)

- $\sigma(pp \rightarrow Tbq) = 135.9$ fb
- CMS


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BSM particles coupling to 3$^{rd}$ gen. quarks

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Heavy $W' \rightarrow Tb / tB$

- Target $T/B \rightarrow t/b + H$ decay
- Optimized for highly boosted topology
  - Substructure information crucial
- $b$, $H$, $t$-tagging used
- $W'$ reconstructed from $b$, $H$, and $t$-tag
- $M_{W'}$ sensitive variable
- Control regions defined by anti-tags
- QCD background estimated from data

![Diagram showing $W'$ decay](image_url)

![Graph showing events vs. $m_{tb}$](image_url)
Heavy $W' \rightarrow Tb / tB$

- $\text{Target T/B} \rightarrow t/b + H$ decay
- Optimized for highly boosted topology
- Substructure information crucial
- $b-, H-, t$-tagging used
- $W'$ reconstructed from $b-, H-, t$-tag
- $M_{W'}$ sensitive variable
- Control regions defined by anti-tags
- QCD background estimated from data

![Graph showing CMS results with limits on $m_{VLQ}$](graph.jpg)

- $T \rightarrow W' \tau$ and $W' \rightarrow tHb$
- $m_{VLQ} \sim 2/3 m_{W'}$
- Observed limit (95% CL) and Expected limit (95% CL)
- 68% expected and 95% expected
- $W'$ signal with PDF+scale uncertainty

**Data**
- QCD estimate
- MC
- $W'$ (1500 GeV) → VLQ (1000 GeV)
- $W'$ (2000 GeV) → VLQ (1300 GeV)
- $W'$ (2500 GeV) → VLQ (1500 GeV)
- $W'$ (3000 GeV) → VLQ (1800 GeV)
- $\sigma_{(Data-Bkg)/2}$ limit (95% CL)

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Heavy $W' \rightarrow tb$

1$\ell +$ jets

- Sensitive to $t \rightarrow \ell \nu q$ decay
- Optimized separately for $e/\mu$ channel
  - Larger QCD contamination in $e$ channel
- $b$-tagging on hardest jet
- $W'$ reconstruction
  - Can reconstruct $\nu$ from $\ell$, $M_W$
  - $t$ cand. from $\ell$, $\nu$, jet with $M_{\ell\nu q} \approx M_t$
  - $W'$ from $t$ and hardest jet with $b$-tag
- Quality / kinematic cuts on $W'$ cand.
- $M_{W'}$ sensitive variable
- Categories in $N_b$, $p_T$
- $W+$jets flavor fractions from CR
Heavy $W' \rightarrow tb$

$1\ell + \text{jets}$

- sel
- Op
- b-t
- $W'$
- Qu
- $M_V$
- Ca
- $W'$+jets flavor fractions from CR

CMS

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

- $W'_{R}$ signal ($M_{R} >> M_{W'_{R}}$)
- $W'_{R}$ signal ($M_{R} > M_{W'_{R}}$)
- Observed signal (95% CL)
- Expected limit (95% CL)

68% expected
95% expected