Probing top quark couplings in associated top quark production

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Experimental status of the following SM processes - sensitive to (rare) top couplings:

**top quark coupling to Z boson:**
1. $ttV$
2. $tZq$

**top quark coupling to photon:**
3. $tt\gamma$
4. $t\gamma$

**EFT in top physics**
(1. $ttV$: reinterpretation)

5. $tW$ & $tt$ dilepton
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For further ATLAS+CMS reports on interesting processes probing top couplings:
see talks by N.Faltermann ($ttH$ and $tH$) and G.Mohanty (CPV and FCNC)

**This talk:**

- 1. $ttV$: reinterpretation
- 2. $tZq$
- 3. $tt\gamma$
- 4. $t\gamma$
- 5. $tW$ & $tt$ dilepton

*Also covered by M. Alhroob*
Associated production of top quark pairs and vector bosons

- CMS: arXiv:1711.02547

NEW!
ttZ

Ignoring 0 or 1 lepton final states

- $t \rightarrow (q+q) \ b$ or $(\text{lepton}+\nu) \ b$
- $t \rightarrow (q+q) \ b$ or $(\text{lepton}+\nu) \ b$
- $Z \rightarrow \text{lepton} + \text{lepton}$

2 to 4 leptons
ttZ… and ttW

Ignoring 0 or 1 lepton final states

- $t \rightarrow (q+q) \ b$ or $(\text{lepton}+\nu) \ b$
- $t \rightarrow (q+q) \ b$ or $(\text{lepton}+\nu) \ b$
- $Z \rightarrow \text{lepton}+\text{lepton}$

2 to 4 leptons

Requiring at least one top quark + W boson to decay into leptons to reduce multijet background:

- $t \rightarrow (q+q) \ b$ or $(\text{lepton}+\nu) \ b$
- $t \rightarrow (\text{lepton}+\nu) \ b$
- $W \rightarrow \text{lepton}+\nu$

2 or 3 leptons

competing multi-lepton final state

- ttW may not look so interesting in terms of SM couplings …but it is for EFT: see in 2 slides
- Instead of treating as background:
  - add 2 leptons (same sign) region ; fit ttW contribution together
Main backgrounds: ZZ, WZ, tt+X, t+X

Luminosity: \( \sim 36 \text{ fb}^{-1} \)

Signal extraction — more leptons, less jets:

- simultaneous fits to several control regions: \( N_{\text{leptons}}, N_{\text{jets}}, N_{\text{b-jets}} \)

Boosted Decision Trees for signal to background separation in dilepton final states

- ATLAS: for opposite sign same flavour ttZ enriched (using e.g. \( \eta \) of the dilepton system, \( p_T/E_T \) jet sums, global event variables)

- CMS: for same-sign dilepton (using e.g. jet, leptons, global event variables)

Background from control regions in data: e.g. “fake leptons” (tight-loose ID), ttbar (opposite sign different flavour requirement)
Observation: significance (obs and exp) for ttW and ttZ above 5 s.d. in both experiments

Both ATLAS and CMS measurements compatible (slightly above) SM predictions
In terms of EFT

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i O_i + \cdots, \quad \Rightarrow \quad \sigma = \sigma_{\text{SM}} + C_i \sigma^{(1)}_i + C_i^2 \sigma^{(2)}_i \]

- From a large number of operators affecting ttV cross sections
  - constrains from other processes (e.g. tt cross section, properties…)
  - conservation laws (e.g. baryon and lepton numbers)
  - no new physics couplings to light quarks
  - ignore operators that affect backgrounds too much (except ttH)…
  - 8 operators left
New physics constrains:
- considering only dim-6 operators that modify $t\bar{t}Z$, $t\bar{t}W$ and \textit{(as important background)} $t\bar{t}H$
- varying one coefficient at a time

\textbf{Example:}
In terms of EFT

- New physics constrains:
  - considering only dim-6 operators that modify ttZ, ttW and (as important background) ttH
  - varying one coefficient at a time

**Results:**

<table>
<thead>
<tr>
<th>Wilson coefficient</th>
<th>Best fit [TeV$^{-2}$]</th>
<th>68% CL [TeV$^{-2}$]</th>
<th>95% CL [TeV$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{c}_{uW}/\Lambda^2$</td>
<td>1.7</td>
<td>$[-2.4, -0.5]$ and $[0.4, 2.4]$</td>
<td>$[-2.9, 2.9]$</td>
</tr>
<tr>
<td>$</td>
<td>\bar{c}_{H}/\Lambda^2 - 16.8$ TeV$^{-2}</td>
<td>$</td>
<td>15.6</td>
</tr>
<tr>
<td>$</td>
<td>\bar{c}_{3G}/\Lambda^2</td>
<td>$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\bar{c}_{3G}/\Lambda^2$</td>
<td>$-0.4$</td>
<td>$[-0.6, 0.1]$ and $[0.4, 0.7]$</td>
<td>$[-0.7, 1.0]$</td>
</tr>
<tr>
<td>$\bar{c}_{uG}/\Lambda^2$</td>
<td>0.2</td>
<td>$[0, 0.3]$</td>
<td>$[-1.0, -0.9]$ and $[-0.3, 0.4]$</td>
</tr>
<tr>
<td>$</td>
<td>\bar{c}_{uB}/\Lambda^2</td>
<td>$</td>
<td>1.6</td>
</tr>
<tr>
<td>$\bar{c}_{Hu}/\Lambda^2$</td>
<td>$-9.3$</td>
<td>$[-10.3, -8.0]$ and $[0, 2.1]$</td>
<td>$[-11.1, -6.5]$ and $[-1.6, 3.0]$</td>
</tr>
<tr>
<td>$\bar{c}_{2G}/\Lambda^2$</td>
<td>0.4</td>
<td>$[-0.9, -0.3]$ and $[-0.1, 0.6]$</td>
<td>$[-1.1, 0.8]$</td>
</tr>
</tbody>
</table>
Not only top quark pairs, also single top : tZq

- ATLAS: PLB 780 (2018) 557
- CMS: PLB 779 (2018) 358
Single top associated to a Z boson

Examples:

- Z radiated off a light quark
- Non-resonant
- Triple-boson coupling

... and also ttZ
Single top associated to a Z boson

- Using 3 lepton final states
- Multivariate analyses for signal to background separation
- Control regions (N_{jets}, N_{b-jets}) to better constrain main backgrounds:
  - ttV, WZ, fake leptons
- ATLAS
  - trains a neural network against fake leptons
  - LO MC
  - narrow Z mass requirement to M(\text{lepton}^{+}\text{lepton}^{-})
- CMS
  - uses NLO MC
  - includes non-resonant contribution tllZ

Using ~36 fb-1 of data at 13 TeV

Also covered by M. Alhroob
Single top associated to a Z boson

\[ \sigma(tZq) = 600\pm170 \text{ (stat)} \pm 140 \text{ (sys)} \text{ fb} \]

4.2 (5.4) s.d. observed (expected) significance

\[ \sigma(tllq) = 123^{+33}_{-31} \text{ (stat)}^{+29}_{-23} \text{ (sys)} \text{ fb} \]

3.7 (3.1) s.d. obs (exp) significance

NNLO prediction:
\[ 800 \pm 6.1^{-7.4}_{+7.0} \text{ (scale)} \text{ fb} \]

Corrected for t and Z branching fractions

NNLO prediction:
\[ 94.2^{+1.9}_{-1.8} \text{ (scale)} \pm 2.5 \text{ (PDF)} \text{ fb} \]

with \( l = e, \mu, \tau \) corrected for t branching fraction

Also covered by M. Alhroob
Associated production of top quark pair and a photon

- ATLAS: JHEP 11 (2017) 086
- CMS: JHEP 10 (2017) 006
• Based on ~20 fb-1

• Semileptonic: \( tt \rightarrow Wb + Wb \rightarrow (q+q') b \rightarrow (q+q') b + (\text{lepton}+\nu) b \)
  
  • at least for jets, large missing \( E_T \)

• Main backgrounds:
  
  • \( tt + \text{jet} \), with a jet faking (or containing) a photon
  
  • \( V + \text{photon} \)
  
  • \( tt \) or \( V \), with a jet or an electron faking a photon

• Template fits for signal to background separation
**ttγ cross section using 8 TeV data**

**ATLAS**
- Photon $p_T > 15$ GeV, $|\eta| < 2.4$
- Template variable: $p_T^{\text{iso}} = \sum_{\text{tracks}} p_T$ within 0.2 rad around $\gamma$
- Also differential cross section

**CMS**
- Photon $p_T > 25$ GeV, $|\eta| < 1.4$
- Template variables:
  - $M_3 = \text{invariant mass of the 3 jets giving the highest } \sum_{\text{jets}} p_T$
- Charged hadron $\gamma$ isolation for fake photon determination

Fiducial: $\sigma(\text{ttγ}) = 139\pm7(\text{stat.})\pm17(\text{syst.}) \text{ fb}$

[ NLO: 151\pm24 fb ]

Total: $\sigma(\text{ttγ}) = 515\pm108 \text{ fb}$

[ NLO: 592\pm71(\text{scale})\pm30(\text{PDF}) \text{ fb} ]
Not only top quark pairs, also single : $t\gamma q$

- CMS: TOP-17-016, submitted to PRL
Again, not only top-photon coupling:

- Now ttγ becomes the main background followed by V+γ and fakes

- Statistically & systematically challenging
  - Focus on muon channel to improve signal efficiency
  - Use BDT for signal to background separation
• Event selection:
  • One isolated muon ($p_T > 26$ GeV, $|\eta| < 2.4$)
  • At least two jets, one b-tagged
  • One isolated photon ($p_T > 25$ GeV, $|\eta| < 1.44$)
    - separated from jets and muon with $\Delta R > 0.5$
  • $E_T^{\text{miss}} > 30$ GeV
  • BDT variables e.g. jets and lepton $\eta$, angles, distance separation, reconstructed top mass…

Fiducial cross section for $\gamma p_T > 25$ GeV, $|\eta| < 1.44$, $\Delta R > 0.5$:

$$\sigma(t\gamma) x B(t \to \mu v b) = 115 \pm 17 \text{(stat.)} \pm 30 \text{(syst.)} \text{ fb}$$

[ SM: $81 \pm 74 \text{ fb}$ ]
Search for new physics in top quark production

• CMS: TOP-17-020
So far, LHC top quark-releated analyses have two approaches:

- (SM) measurements
  - examples: those presented in this talk
- Searches for specific new physics model dependent/independent
  - examples: FCNC searches, exotic final stated including top quarks, anomalous couplings in differential distributions

**reinterpreted in terms of EFT**
Search for new physics in top quark dilepton events

- So far, LHC top quark-related analyses have two approaches
  - (SM) measurements
    - examples: those presented in this talk
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- **New approach:**
  - Event selection: 2 isolated leptons, opposite sign+b-jet: mostly tt, tW events, different N_{jet}, N_{b-jet} categories as before
  - **Not one single observable: analysis fully designed to access the 6-dim operators relevant for top production**
  - first global analysis using tW + tt dilepton final states

reinterpreted in terms of EFT
Search for new physics in top quark dilepton events
Search for new physics in top quark dilepton events

**Example effects:**

- $O_{G}$ doesn't affect $tW$; kinematic distributions not too sensitive: use yields to check for the effect of $O_{G}$ in $t\bar{t}$ production
Search for new physics in top quark dilepton events

Example effects:

- $O_G$: doesn’t affect $tW$; kinematic distributions not too sensitive: use yields to check for the effect of $O_G$ in $tt$ production

- $O_{uG,cG}$: affects $tt$ & $tW$; kinematic distributions discriminate FCNC x SM production: neural network $NN_{FCNC}$
Search for new physics in top quark dilepton events

Example effects:

- $O_G$: doesn't affect $tW$; kinematic distributions not too sensitive: use yields to check for the effect of $O_G$ in $tt$ production
- $O_{uG,cG}$: affects $tt$ & $tW$; kinematic distributions discriminate FCNC $x$ SM production: neural network $NN_{\text{FCNC}}$
- $O_{\phi q,tW}$: affects $tW$ kinematic distributions; neural network $NN_{\text{jet,b-jet}}$ to discriminate ($tt + DY$) from $tW$; discriminate SM from New Physics effects
Search for new physics in top quark dilepton events

**Example effects:**

- \( \mathcal{O}_G \): doesn’t affect tW; kinematic distributions not too sensitive: use yields to check for the effect of \( \mathcal{O}_G \) in \( tt \) production

- \( \mathcal{O}_{qG,cG} \): affects \( tt \) & tW; kinematic distributions discriminate FCNC × SM production: neural network NN\(_{\text{FCNC}}\)

- \( \mathcal{O}_{\phi,q,tW} \): affects tW kinematic distributions; neural network NN\(_{\text{jet,b-jet}}\) to discriminate (tt ‘bkg’ + DY) from tW; discriminate SM from New Physics effects

- \( \mathcal{O}_{tG} \): as above + affects differently \( tt \) and tW cross sections: use yields!

  *Multivariate analysis: SM-signal / SM-background / New Physics separation!*
Search for new physics in top quark dilepton events

**Some effects:**

- \( O_G \): doesn’t affect \( tW \); kinematic distributions not too sensitive: use yields to check for the effect of \( O_G \) in \( tt \) production
- \( O_{uG,cG} \): affects \( tt \) & \( tW \); kinematic distributions discriminate FCNC x SM production: neural network \( \text{NN}_{\text{FCNC}} \)
- \( O_{\phi q,tW} \): affects \( tW \) kinematic distributions; neural network \( \text{NN}_{\text{jet,b-jet}} \) to discriminate (\( tt \) ‘bkg’ + DY) from \( tW \); discriminate SM from New Physics effects
- \( O_G \): as above + affects differently \( tt \) and \( tW \) cross sections: use yields!

**Example likelihood:**

**Results:**

assuming new physics
scale \( \Lambda = 1 \text{ TeV} \)
Summary and conclusions
Conclusions

- **Increased precision on ATLAS and CMS measurements**
  - top quark couplings accessed in rare processes, this talk:
    - top pairs and single top production in association with vector bosons
    - top pairs and single top production in association with photons
  - Some processes still statistically dominated:
    - naturally improving with current data taking
    - good prospects for more detailed measurements, e.g. differential associated production cross section

- **Tools to interpret these measurements also improving**
  - e.g. accurate SM predictions,
  - EFT (global) studies using multiple processes: ttW and ttZ cross sections imposing limits to 8 Wilson operators
  - also tZq already analyzed, in terms of EFT, e.g. arXiv:1804.07773

- **New approach on the experimental side**
  - model-independent measurements: analysis designed to be more sensitive to EFT-Lagrangian terms
  - Improved chances of finding new physics!