EFT Interpretations of Top and Higgs Measurements at LHC and First Steps Towards Global Analyses

Alexander Grohsjean

Top Quark Physics at the Precision Frontier 2019
Fermilab
From Bumps ...

K. Mimasu

"UV"!

SM

E
new states might (just) exist beyond the LHC energy reach

- indirect effects in kinematic tails, e.g., LEP limits on ~ TeV $Z'$

- small effects that require precise theoretical control on signal and background predictions
SMEFT in a Nutshell

♦ SM effective field theory (SMEFT)

$$L = L_{SM}^{(4)} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \ldots$$

♦ operator expansion:
  - heavy BSM states are integrated out
  - only local operators from SM fields left

♦ truncated at dimension 6 (leading B & L preserving interactions)

♦ order-by-order: self-consistent, renormalizable QFT

♦ can be matched to UV theories of new physics
### Dimension-6 SMEFT Operators

#### Table 2: Dimension-six operators other than the four-fermion ones.

<table>
<thead>
<tr>
<th>$X^3$</th>
<th>$\phi^6$ and $\phi^4 D^2$</th>
<th>$\psi^2 \phi^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{G}$</td>
<td>$f_{ABC}G_{\mu}^{A}G_{\rho}^{B}G_{\nu}^{C}u$</td>
<td>$Q_{G}$&lt;br&gt;$(\phi^2 \phi)^3$&lt;br&gt;$(\phi^4 \phi)(\bar{q}<em>L \gamma</em>\mu \phi)$&lt;br&gt;$(\phi^4 \phi)(\bar{q}<em>R \gamma</em>\mu \phi)$&lt;br&gt;$(\phi^4 \phi)(\bar{q}<em>u \gamma</em>\mu \bar{q}_d)$&lt;br&gt;$(\phi^4 \phi)(\bar{q}<em>d \gamma</em>\mu \bar{q}_u)$&lt;br&gt;$(\phi^4 \phi)(\bar{q}<em>d \gamma</em>\mu \bar{q}_d)$&lt;br&gt;$(\phi^4 \phi)(\bar{q}<em>u \gamma</em>\mu \bar{q}_u)$</td>
</tr>
<tr>
<td>$Q_{\bar{G}}$</td>
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</tr>
<tr>
<td>$Q_{W}$</td>
<td>$\epsilon_{IJK} W_{\mu}^{I} W_{\nu}^{J} W_{\rho}^{K}$</td>
<td>$Q_{W}$&lt;br&gt;$Q_{W}$&lt;br&gt;$Q_{W}$&lt;br&gt;$Q_{W}$&lt;br&gt;$Q_{W}$&lt;br&gt;$Q_{W}$&lt;br&gt;$Q_{W}$</td>
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<tr>
<td>$Q_{\bar{W}}$</td>
<td>$\epsilon_{IJK} \bar{W}<em>{\mu}^{I} \bar{W}</em>{\nu}^{J} \bar{W}_{\rho}^{K}$</td>
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</tr>
</tbody>
</table>

#### Table 3: Four-fermion operators.

<table>
<thead>
<tr>
<th>$(LL)(LL)$</th>
<th>$(RR)(RR)$</th>
<th>$(LL)(RR)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{uu}$</td>
<td>$(\bar{q}<em>u \gamma</em>\mu \bar{q}_u)(\bar{q}<em>u \gamma</em>\mu \bar{q}_u)$</td>
<td>$Q_{uu}$</td>
</tr>
<tr>
<td>$Q_{ud}$</td>
<td>$(\bar{q}<em>u \gamma</em>\mu \bar{q}_d)(\bar{q}<em>d \gamma</em>\mu \bar{q}_u)$</td>
<td>$Q_{ud}$</td>
</tr>
<tr>
<td>$Q_{(1)}$</td>
<td>$(\bar{q}<em>u \gamma</em>\mu \bar{q}_u)(\bar{q}<em>u \gamma</em>\mu \bar{q}_u)$</td>
<td>$Q_{(1)}$</td>
</tr>
<tr>
<td>$Q_{(2)}$</td>
<td>$(\bar{q}<em>u \gamma</em>\mu \bar{q}_d)(\bar{q}<em>d \gamma</em>\mu \bar{q}_u)$</td>
<td>$Q_{(2)}$</td>
</tr>
<tr>
<td>$Q_{(3)}$</td>
<td>$(\bar{q}<em>u \gamma</em>\mu \bar{q}_u)(\bar{q}<em>u \gamma</em>\mu \bar{q}_u)$</td>
<td>$Q_{(3)}$</td>
</tr>
</tbody>
</table>

- complete, non-redundant set of operators:
  - dimension-6: 59 (76 real)
  - depending on CP/flavor assumptions
The Challenge

- Top Quark
- Standard Model
- SUSY
- Higgs Boson
- ...

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The Challenge

- **Top Quark**
- **Higgs Boson**
- **Standard Model**
- **SUSY**
- **EFT**
- **...**
The Challenge

- Top Quark
- Standard Model
- SUSY
- EFT

Higgs Boson

...
Simplified Template Cross Sections (STXS)

- evolution from inclusive cross section measurements

```
  ggF  VBF  (EW_{qqH})  (H + leptonic V)  VH  ttH  bbH  tH
```

arXiv:1610.07922
Simplified Template Cross Sections (STXS)

- evolution from inclusive cross section measurements
  - define several kinematic regions at generator level
  - maximize experimental sensitivity to e.g. BSM effects
  - minimize theory dependence

\[
\begin{align*}
\text{ggF} & \quad \text{VBF} & \quad (EW_{qqH}) & \quad (H + \text{leptonic } V) \\
0\text{-jet} & \quad 1\text{-jet} & \quad \geq 2\text{-jet} & \quad \geq 2\text{-jet VBF cuts} & \quad \\
\quad \quad \quad \text{p}_{\text{T}}^2 [0, 60] & \quad \text{p}_{\text{T}}^2 [0, 60] & \quad \text{p}_{\text{T}}^2 [0, 25] & \quad \geq 2 \text{-jet VBF cuts} & \quad \\
\quad \quad \quad \text{p}_{\text{T}}^2 [60, 120] & \quad \text{p}_{\text{T}}^2 [60, 120] & \quad \geq 3 \text{-jet } VH \text{ cuts} & \quad \text{Rest} & \quad \\
\quad \quad \quad \text{p}_{\text{T}}^2 [120, 200] & \quad \text{p}_{\text{T}}^2 [200, \infty] & \quad & \quad & \quad \\
\quad \quad \quad \text{BSM} & \quad \text{BSM} & \quad & \quad & \quad \\
\end{align*}
\]
Connecting STXS with EFT

\[ gg \rightarrow H \text{ (0-jet)} \]
\[ gg \rightarrow H \text{ (1-jet, } p_T^{H} < 60 \text{ GeV)} \]
\[ gg \rightarrow H \text{ (1-jet, } 60 \leq p_T^{H} < 120 \text{ GeV)} \]
\[ gg \rightarrow H \text{ (1-jet, } 120 \leq p_T^{H} < 200 \text{ GeV or VBF-like)} \]
\[ gg \rightarrow H \text{ (2-jet, } p_T^{H} < 200 \text{ GeV)} \]
\[ gg \rightarrow H \text{ (}\geq\text{ 1-jet, } p_T^{H} \geq 200 \text{ GeV)} \]
\[ gg/qq \rightarrow Hqq \text{ (} p_T^{H} \geq 200 \text{ GeV)} \]
\[ gg/qq \rightarrow Hll/Hll \]
\[ gg/qq \rightarrow t\bar{t}H \]

**ATLAS Preliminary**
\[ \sqrt{s} = 13 \text{ TeV, } 36.1 \text{ fb}^{-1} \]
\[ H \rightarrow \gamma\gamma \text{ and } H \rightarrow ZZ^{*} \rightarrow 4l \]
\[ m_H = 125.09 \text{ GeV, } |y|_H < 2.5 \]

Ratio normalized to SM

Measurements
Stat. uncertainty
Syst. uncertainty
SM prediction

**ATLAS CONF-2017-049**
Connecting STXS with EFT

- coefficients A,B from LO MC
  - HEL as effective Lagrangian (SILH basis with flavor-universal couplings)

\[ \sigma_{EFT}/\sigma_{SM} = 1 + \sum_i c_i A_i + \sum_{ij} c_i c_j B_{ij} \]
Connecting STXS with EFT

coefficients A,B from LO MC

- HEL as effective Lagrangian (SILH basis with flavor-universal couplings)
Connecting STXS with EFT

**Historical Note:**

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ATLAS CONF-2017-049

- Coefficients A, B from LO MC
  - HEL as effective Lagrangian (SILH basis with flavor-universal couplings)

\[
\frac{\Gamma_f}{\Gamma_{4\ell}} \approx \frac{\Gamma_{SM}}{\Gamma_{4\ell}^{SM}} \left[ 1 + \sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j - \left( \sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j \right) \right]
\]

\[
\frac{\sigma_{EFT}}{\sigma_{SM}} = 1 + \sum_i c_i A_i + \sum_{ij} c_i c_j B_{ij}
\]

\[
B_{4\ell} = \frac{\Gamma_{4\ell}}{\sum_j \Gamma_j} \approx \frac{\Gamma_{SM}}{\sum_j \Gamma_j^{SM}} \left[ 1 + \sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j - \left( \sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j \right) \right]
\]
15 dim-6 operators affecting Higgs physics

- neglect CP-odd ones (-4)
- neglect Higgs self-couplings/Yukawa couplings to down-type quarks and leptons (-3)
- neglect Higgs field normalization as sensitivity not good enough for global change in rate (-1)
- $C_{ww} + c_B = 0$ from precision electroweak parameter $S$ (-1)

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expression</th>
<th>HEL coefficient</th>
<th>Vertices</th>
</tr>
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<tbody>
<tr>
<td>$O_g$</td>
<td>$</td>
<td>H</td>
<td>^2 G_{\mu\nu}^A G^{A\mu\nu}$</td>
</tr>
<tr>
<td>$O_\gamma$</td>
<td>$</td>
<td>H</td>
<td>^2 B_{\mu\nu} B^{\mu\nu}$</td>
</tr>
<tr>
<td>$O_u$</td>
<td>$y_u</td>
<td>H</td>
<td>^2 \bar{u}_R H u_R + \text{h.c.}$</td>
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<tr>
<td>$O_{HW}$</td>
<td>$i (D^\mu H) \sigma^a (D^\nu H) W^a_{\mu\nu}$</td>
<td>$c_{HW} = \frac{m_W^2}{s_W^2} \bar{c}_{HW}$</td>
<td>$HWW, HZZ$</td>
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<td>$i (H^\dagger D^\mu H) \partial^\nu B_{\mu\nu}$</td>
<td>$c_B = \frac{m_W^2}{s_W^2} \bar{c}_B$</td>
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probe 6 remaining operators
Constraining Higgs EFT from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$

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<td>^2 \bar{u}_t Hu_R + h.c.$</td>
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<tr>
<td>$O_B$</td>
<td>$i (H^\dagger D^\mu H) \partial^\nu B_{\mu\nu}$</td>
<td>$c_{CB} = \frac{m_W^2}{s^2} \bar{c}_B$</td>
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Constraining Higgs EFT from $H \to \gamma\gamma$ and $H \to ZZ$

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Observed HEL constraints with $H \to ZZ^*$ and $H \to \gamma\gamma$

- $\text{cG} \ [10^{-4}]$ ~ $4\times$ c. t. previous limits

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

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STXS Examples from CMS: $H \rightarrow 4l$ (2016-2018)

- targeting four production modes: $ggH$, VBF, VH, $t\bar{t}H/tH$
- first results with revised categorization (stage 1.1)

CMS PAS-HIG-19-001

♦ first ττ stage 1 measurement in multiple ggF & VBF bins

CMS Preliminary

Observation
SM expectation
scale @ PDF @ αs @ BR uncertainties

μ_{proc}:
- 0.40 ± 0.07
- 0.34 ± 0.13
- 1.26 ± 1.56
- 1.80 ± 1.01
- 0.47 ± 0.01
- 0.36 ± 0.03
- 1.00 ± 0.30
- 1.17 ± 1.47
- 1.41 ± 1.05
- 1.06 ± 2.76

Best fit μ_{proc} = σ_{proc}/σ_{SM}

CMS PAS-HIG-18-032
The Challenge

- Top Quark
- Higgs Boson
- Standard Model
- EFT
- SUSY
- ...

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Direct Measurement of $t\bar{t}$ Spin Density Matrix

- top ideal quark for spin measurements
  - decays before forming bound states
  - spin transferred to daughter particles
  - leptons represent an ideal probe of top spin
Direct Measurement of $t\bar{t}$ Spin Density Matrix

- top ideal quark for spin measurements
  - decays before forming bound states
  - spin transferred to daughter particles
  - leptons represent an ideal probe of top spin

- powerful probe of BSM physics
  \[ O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^a t) \hat{f} G_{\mu\nu}^a \]
  \[ \rightarrow \text{high sensitivity to EFT, e.g. chromomagnetic dipole moment (CMDM)} \]
Direct Measurement of $t\bar{t}$ Spin Density Matrix

- top ideal quark for spin measurements
  - decays before forming bound states
  - spin transferred to daughter particles
  - leptons represent an ideal probe of top spin

- powerful probe of BSM physics
  → high sensitivity to EFT, e.g. chromomagnetic dipole moment (CMDM)

\[ O_{tG} = y_t g_s (\overline{Q} \sigma^{\mu \nu} T^a t) \tilde{g} G^{a}_{\mu \nu} \]

- 15 coefficients completely characterize spin dependence of $t\bar{t}$ production
  - probe by measuring unfolded 1D angular distributions

\[ \frac{1}{\sigma} \frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2} \left( 1 + B^+ \cdot \hat{l}^+ + B^- \cdot \hat{l}^- - \hat{l}^+ \cdot C \cdot \hat{l}^- \right) \]
Top Quark Polarization

- polarization consistent with zero for each axis
  - not yet sensitive to small level of polarization in the SM

\[
\frac{1}{\sigma} \frac{d\sigma}{d\Omega^+ + d\Omega^-} = \frac{1}{(4\pi)^2} \left( 1 + B_+ \hat{\ell}^+ + B_- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot \mathbb{C} \cdot \hat{\ell}^- \right)
\]
spin correlations consistent with SM along each axis

\[
\frac{1}{\sigma} \frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2} \left( 1 + B^+ \cdot \hat{e}^+ + B^- \cdot \hat{e}^- - \hat{e}^+ \cdot C \cdot \hat{e}^- \right)
\]
Probing Strong Top-Quark Couplings

- 95% CL limits on CMDM operator from simultaneous fit to all measured differential cross sections to constrain systematics

\[-0.07 < C_{tG}/\Lambda^2 < 0.16 \text{ TeV}^{-2}\]

- Strongest direct limits to date, additional operator constraints in preparation
Measuring Top-EWK Couplings

- electroweak-top interactions from $t\bar{t}Z$ production
  - split events with 3/4 leptons into jet/b-jet multiplicity bins
Measuring Top-EWK Couplings

- electroweak-top interactions from $t\bar{t}Z$ production
- translate cross-section measurements into limits of
  - 4 independent EFT operators

### Tensor Couplings (Quad.)

\[
\begin{align*}
C_{tZ} &= \Re \left( -\sin \theta_W C_{tZ}^{(33)} + \cos \theta_W C_{tZ}^{(33)} \right) \\
C_{tZ}^{[I]} &= \Im \left( -\sin \theta_W C_{tZ}^{(33)} + \cos \theta_W C_{tZ}^{(33)} \right) \\
C_{\phi t} &= C_{\phi t}^{(33)} \\
C_{\phi Q} &= C_{\phi Q}^{(33)} - C_{\phi q}^{(33)}
\end{align*}
\]

- \( C_{tZ} \) = tensor couplings (quad.)
- \( C_{tZ}^{[I]} \) = tensor couplings (quad.)
- \( C_{\phi t} \) = vector couplings (lin.)
- \( C_{\phi Q} \) = vector couplings (lin.)

### Vector Couplings (Lin.)

\[
\begin{align*}
O_{uB}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} u_j) \phi B_{\mu\nu} \\
O_{uW}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \phi W_{\mu\nu}^I \\
O_{\phi u}^{(ij)} &= (\phi \slashed{D}_\mu \phi) (\bar{u}_i \gamma^\mu u_j) \\
O_{\phi q_1}^{(ij)} &= (\phi \slashed{D}_\mu \phi) (\bar{q}_i \gamma^\mu q_j) \\
O_{\phi q_2}^{(ij)} &= (\phi \slashed{D}_\mu \phi^I) (\bar{q}_i \gamma^\mu \tau^I q_j)
\end{align*}
\]
Measuring Top-EWK Couplings

♦ electroweak-top interactions from $t\bar{t}Z$ production

♦ translate cross-section measurements into limits of
  - 4 independent EFT operators
  - main impact on $p_T^Z$ and $\cos(\Phi_Z^*)$ → use to reweight NLO SM simulations

\[ c_{tZ} = \text{Re} \left( -\sin \theta_W C_{uB}^{(33)} + \cos \theta_W C_{uW}^{(33)} \right) \]
\[ c_{tZ}^{[l]} = \text{Im} \left( -\sin \theta_W C_{uB}^{(33)} + \cos \theta_W C_{uW}^{(33)} \right) \]
\[ c_{\phi t} = C_{\phi t} = C_{\phi u}^{(33)} \]
\[ c_{\phi Q} = C_{\phi Q} = C_{\phi q}^{(33)} - C_{\phi q}^{(33)} \]

Tensor couplings (quad.): $C_{tZ}/C_{tZ}^{[l]}$

\[ O_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j) \bar{\varphi} B_{\mu\nu} \]
\[ O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \bar{\varphi} W_{\mu\nu}^I \]

Vector couplings (lin.): $C_{\phi t}/C_{\phi Q}$

\[ O_{\varphi u}^{(ij)} = (\varphi^\dagger i \bar{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j) \]
\[ O_{\varphi q}^{(ij)} = (\varphi^\dagger i \bar{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j) \]
\[ O_{\varphi q}^{(ij)} = (\varphi^\dagger i \bar{D}_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j) \]
Measuring Top-EWK Couplings

- electroweak-top interactions from $t\bar{t}Z$ production
- translate cross-section measurements into limits of additional bins of $p_T^Z$ and $\cos(\phi^*_Z)$ for enhanced sensitivity
most stringent direct constraints on electroweak dipole moments and top-Z vector couplings (individual limits)
Probing Simultaneously $t\bar{t}$ and $tW$ Production

- Constraint separately 6 EFT couplings in dilepton final states.

\[
O_{tW} = (\bar{q} \sigma^{\mu\nu} \tau^i t) \phi W^i_{\mu\nu}, \\
O^{(3)}_{\phi q} = (\phi^+ \tau^i D_\mu \phi)(\bar{q} \gamma^\mu \tau^i q)
\]

\[
O_{u(c)G} = (\bar{q} \sigma^{\mu\nu} \lambda^a t) \phi G^a_{\mu\nu}, \\
O_G = f_{abc} G^{av}_\mu G^{bp}_\nu G^{c\mu}_\rho.
\]

\[
O_{tG} = (\bar{q} \sigma^{\mu\nu} \lambda^a t) \phi G^a_{\mu\nu}
\]
Analysis Strategy

♦ different categories of jet and b-jet multiplicities

<table>
<thead>
<tr>
<th>Eff. coupling</th>
<th>Channel</th>
<th>1-jet, 0-tag</th>
<th>1-jet, 1-tag</th>
<th>Categories</th>
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<tbody>
<tr>
<td>$C_C$</td>
<td>ee</td>
<td>—</td>
<td>—</td>
<td>Yield</td>
</tr>
<tr>
<td></td>
<td>$e\mu$</td>
<td>Yield</td>
<td>Yield</td>
<td>Yield</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu$</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$C_{qg}^{(3)}$, $C_{tW}$, $C_{tG}$</td>
<td>ee</td>
<td>—</td>
<td>NN$_{10}$</td>
<td>NN$_{21}$</td>
</tr>
<tr>
<td></td>
<td>$e\mu$</td>
<td>NN$_{10}$</td>
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<td>$C_{uG}$, $C_{cG}$</td>
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<td>$\mu\mu$</td>
<td>—</td>
<td>—</td>
<td>NN$_{FCNC}$</td>
</tr>
</tbody>
</table>

♦ dedicated NNs
  - to distinguish $tW$ from $t\bar{t}$ topologies
  - to split FCNC from SM backgrounds
EFT Limits from Combined $t\bar{t}$ and $tW$ Production

- limits on one operator at a time
- sensitivity not yet at the level of more dedicated approaches (e.g. CMS PAS-TOP-18-006)
- first step towards more global approaches

\[ -0.07 < C_{tG}/\Lambda^2 < 0.16 \text{ TeV}^2 \]

\[ \text{BR}(t\rightarrow ug) < 0.1\% \]

\[ \text{BR}(t\rightarrow cg) < 0.53 \% \]

arXiv:1903.11144
Probing $t\bar{t}t\bar{t}$ Production

- not yet observed ($\sigma_{SM} \sim 9fb$ @ NLO) at LHC
  - $O(10^5)$ smaller than $t\bar{t}$
Probing $\bar{t}t\bar{t}t$ Production

- not yet observed ($\sigma_{SM} \sim 9fb @ NLO$) at LHC
  - $O(10^5)$ smaller than $tt$
- high sensitivity to four heavy-quark operators
  - quadratic cross section contributions
    up to $\sim 6 fb$ for coefficient strengths of 1

\[ \mathcal{O}_{tt}^1 = (\bar{t}_R \gamma^\mu t_R) (\bar{t}_R \gamma^\mu t_R) \]
\[ \mathcal{O}_{QQ}^1 = (\bar{Q}_L \gamma^\mu Q_L) (\bar{Q}_L \gamma^\mu Q_L) \]
\[ \mathcal{O}_{Qt}^1 = (\bar{Q}_L \gamma^\mu Q_L) (\bar{t}_R \gamma^\mu t_R) \]
\[ \mathcal{O}_{Qt}^8 = (\bar{Q}_L \gamma^\mu T^A Q_L) (\bar{t}_R \gamma^\mu T^A t_R) \]
EFT Sensitivity of $t\bar{t}t\bar{t}t$

- single lepton and opposite-sign dilepton final states
- two dedicated boosted decision trees:
  - identify 3 jet combinations from all-hadronic top decays rather than ISR/FSR (dijet/trijet masses, b-tagging, jet angles, …)
EFT Sensitivity of $t\bar{t}t\bar{t}$

- single lepton and opposite-sign dilepton final states
- two dedicated boosted decision trees:
  - identify 3 jet combinations from all-hadronic top decays rather than ISR/FSR (dijet/trijet masses, b-tagging, jet angles, …)
  - distinguish $t\bar{t}t\bar{t}$ from dominant $t\bar{t}$ background with separate BDTs per final state
combine results with same sign dilepton and trilepton analysis (EPJC 78 (2017) 140)

- observed limit of $3.6 \sigma_{\text{SM}}$, significance of 1.4 S.D.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected limit $\times \sigma_{\text{ttt}}^{\text{SM}}$</th>
<th>Observed limit $\times \sigma_{\text{ttt}}^{\text{SM}}$</th>
<th>Expected limit (fb)</th>
<th>Observed limit (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lepton</td>
<td>$9.4^{+4.4}_{-2.9}$</td>
<td>$10.6$</td>
<td>$86^{+40}_{-26}$</td>
<td>$97$</td>
</tr>
<tr>
<td>Dilepton</td>
<td>$7.3^{+4.5}_{-2.5}$</td>
<td>$6.9$</td>
<td>$67^{+41}_{-29}$</td>
<td>$64$</td>
</tr>
<tr>
<td>Combined (this analysis)</td>
<td>$5.7^{+2.9}_{-1.8}$</td>
<td>$5.2$</td>
<td>$52^{+26}_{-17}$</td>
<td>$48$</td>
</tr>
<tr>
<td>Multilepton [25]</td>
<td>$2.5^{+1.4}_{-0.8}$</td>
<td>$4.6$</td>
<td>$23^{+12}_{-8}$</td>
<td>$42$</td>
</tr>
</tbody>
</table>
| Combined (this analysis + multilepton) | $2.2^{+1.1}_{-0.7}$                                   | $3.6$                                                    | $20^{+10}_{-6}$     | $33$                |}

constraint heavy-fermion EFT coefficients (inserting at most one additional EFT vertex)

- 95% C.L. intervals (contribution of other operators marginalized)

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expected $C_k/A^2$ (TeV$^{-2}$)</th>
<th>Observed (TeV$^{-2}$)</th>
<th>Chin. Phys. C42 (2018) 023104</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_{tt}^1$</td>
<td>$[-2.5, 2.4]$</td>
<td>$[-3.7, 3.5]$</td>
<td>[-2.92, 2.80]</td>
</tr>
<tr>
<td>$O_{QQ}^1$</td>
<td>$[-1.5, 1.4]$</td>
<td>$[-2.2, 2.0]$</td>
<td>[-4.97, 4.90]</td>
</tr>
<tr>
<td>$O_{tq}^1$</td>
<td>$[-5.7, 4.5]$</td>
<td>$[-8.0, 6.8]$</td>
<td>[-10.3, 9.33]</td>
</tr>
</tbody>
</table>
A Global Analysis within the LHC WGs

- individual measurements of top, Higgs and electroweak processes not easily lend themselves to EFT interpretation
  - e.g. “backgrounds” of $t\bar{t}Z$ cross sections like $t\bar{t}W$, $t\bar{t}H$, $tqZ$, $tHq$,...
    also affected by EFT
  - considerable statistical overlap between different measurements

- consistent treatment crucial
  - theory model
  - systematic uncertainties
  - correlations across measurements

- intrinsically small effects
  - precise theoretical control
  - excellent experimental precision

→ a global effort including the experimental and theoretical LHC communities desirable
Towards Global Analysis

♦ LHC Higgs working group (STXS framework):
  • excellent scalability → easy to add new results
  • benefit from new theory developments
  • sensitivity driven by categorization

♦ LHC Top working group:
  • common EFT model: dim6top (arXiv 1802.07237)
  • re-interpretation of unfolded results
  ◆ good scalability, easy combinable beyond LHC
  ◆ treat background SM-like
  ◆ full phase space results sensitive to efficiency/acceptance differences
    → fiducial, particle level
  • measurements at detector level
    ◆ good sensitivity
    ◆ probe EFT in all contributing processes
    ◆ so far relying on MC reweighing → further developments crucial
    ◆ several options for later combinations
Summary

♦ precision SMEFT measurements will be an essential part of the LHC heritage

♦ the LHC has entered an EFT era
  • large variety of 13 TeV results already available

♦ first strategies for more global LHC SMEFT measurements established

♦ need to combine efforts across existing research groups

♦ right time to re-think and improve research strategies

♦ still many unexplored processes
Flavor Changing Neutral Currents

♦ large variety of analysis searching for FCNC through Higgs/Z/photon/gluon
  • $\bar{t}t$ decay and single top production

♦ multivariate analysis techniques standard to probe tiny signal

♦ combine all possible final states to set limits on e.g. BR ($t\rightarrow H_u/c$)

arXiv: 1812.11568
Limits on BSM Models of FCNC

ATLAS+CMS Preliminary

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9] JHEP 07 (2017) 003</td>
<td></td>
</tr>
</tbody>
</table>

September 2018

Each limit assumes that all other processes are zero

Theory predictions from arXiv:1311.2028

Start probing models predicting highest branching fractions
Rare Process: $t\bar{t}Z/t\bar{t}W$

- measurement of $t\bar{t}X$ cross sections at 13 TeV using 35.9 fb$^{-1}$
  - $t\bar{t}W$ from same-sign dilepton events
  - $t\bar{t}Z$ from final states with 3 and 4 leptons

- split events according to number of jets and $b$-tagged jets

- train BDT for same-sign dilepton events ("D") to separate $t\bar{t}W$ from non-prompt leptons

- fit across categories to extract $\sigma_{t\bar{t}W}$ vs $\sigma_{t\bar{t}Z}$
ttZ 2016 + 2017

- improved analysis strategy:
  - more inclusive trigger
  - multivariate lepton identification (x2 syst. red.)
  - better lepton and efficiency measurements
  - (~15% higher prompt-lepton efficiency)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty range (%)</th>
<th>Correlated in 2016 and 2017</th>
<th>Impact on the ttZ cross section (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.5</td>
<td>×</td>
<td>2</td>
</tr>
<tr>
<td>PU modeling</td>
<td>1–2</td>
<td>✓</td>
<td>1</td>
</tr>
<tr>
<td>Trigger</td>
<td>2</td>
<td>×</td>
<td>2</td>
</tr>
<tr>
<td>Lepton ID efficiency</td>
<td>4.5–6</td>
<td>✓</td>
<td>4</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1–9</td>
<td>✓</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0–1</td>
<td>✓</td>
<td>1</td>
</tr>
<tr>
<td>B tagging light flavor</td>
<td>0–4</td>
<td>×</td>
<td>1</td>
</tr>
<tr>
<td>B tagging heavy flavor</td>
<td>1–4</td>
<td>×</td>
<td>2</td>
</tr>
<tr>
<td>Choice in $\mu_R$ and $\mu_F$</td>
<td>1–4</td>
<td>✓</td>
<td>1</td>
</tr>
<tr>
<td>PDF choice</td>
<td>1–2</td>
<td>✓</td>
<td>1</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>1.5</td>
<td>✓</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Parton shower</td>
<td>1–8</td>
<td>✓</td>
<td>1</td>
</tr>
<tr>
<td>WZ cross section</td>
<td>10–20</td>
<td>✓</td>
<td>3</td>
</tr>
<tr>
<td>WZ + heavy flavor</td>
<td>8</td>
<td>✓</td>
<td>1</td>
</tr>
<tr>
<td>ZZ cross section</td>
<td>10</td>
<td>✓</td>
<td>1</td>
</tr>
<tr>
<td>$t\bar{t}X$ bg.</td>
<td>10–15</td>
<td>✓</td>
<td>3</td>
</tr>
<tr>
<td>$X\gamma$ background</td>
<td>20</td>
<td>✓</td>
<td>1</td>
</tr>
<tr>
<td>Nonprompt background</td>
<td>30</td>
<td>✓</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Rare SM background</td>
<td>50</td>
<td>✓</td>
<td>2</td>
</tr>
<tr>
<td>Stat. unc. in nonprompt bg.</td>
<td>5–50</td>
<td>×</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Stat. unc. in rare SM bg.</td>
<td>5–100</td>
<td>×</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td></td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>
 Flavor Changing Neutral Currents

- forbidden at tree level in SM
- suppressed by GIM mechanism at higher orders
- many BSM models predict sizable FCNC branching fraction

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>2HDM FC / FV</th>
<th>MSSM / w. RPV</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR(t → cg)</td>
<td>$10^{-12}$</td>
<td>$10^{-8} / 10^{-4}$</td>
<td>$10^{-7} / 10^{-6}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>BR(t → cZ)</td>
<td>$10^{-14}$</td>
<td>$10^{-10} / 10^{-6}$</td>
<td>$10^{-7} / 10^{-6}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>BR(t → cγ)</td>
<td>$10^{-14}$</td>
<td>$10^{-9} / 10^{-7}$</td>
<td>$10^{-8} / 10^{-9}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>BR(t → cH)</td>
<td>$10^{-15}$</td>
<td>$10^{-5} / 10^{-3}$</td>
<td>$10^{-5} / 10^{-9}$</td>
<td>$10^{-4}$</td>
</tr>
</tbody>
</table>

- large variety of searches for enhanced couplings of top quarks to u/c quarks via g, Z, γ, H in top production and decay

arXiv:1311.2028
FCNC Interpretation in Terms of EFT

- set limits on trilinear top-quark-boson couplings

\[ L = \sum_{q=u,c} \frac{g}{\sqrt{2} c_W} \frac{\kappa_{tZq}}{\Lambda} (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_{\mu\nu} \]

arXiv:1812.11568

significant improvement compared to 8 TeV result