Learning to pinpoint effective operators at the LHC: a study of the $t\bar{t}b\bar{b}$ signature

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ArXiv: 1807.02130

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1. Introduction

2. SMEFT: $\bar{t}t\bar{b}b$ and its virtues
   a. Four-quark operators
   b. Complementarity to four top

3. Sensitivity study: individual operators

4. Learning the effective operators

5. Conclusion and outlook
1. Introduction: SMEFT

- Lack of direct evidence for BSM physics at the LHC → Standard Model Effective Field Theory (SMEFT):
  - model-independent interpretation
  - New physics at high energy scales
  - Heightened energy dependence and modified kinematics

Extend SM Lagrangian up to dim. 6:
(→ Leading B & L conserving contributions)

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)} \]

\[ M^2 \equiv \Lambda^2 \gg p^2 \]

\[ \frac{g^2_*}{p^2 - M^2} \]
1. Introduction: SMEFT

- Warsaw basis of dim. 6 operators (B. Grzadkowsk, et al. [JHEP 1010 (2010) 085])
- Depending on flavor assumptions, tens to hundreds of independent operators
  → For a given final-state, many simultaneous contributions possible!

### Intrinsically large SMEFT parameter space

- high-multiplicity final states with complex inter-correlated kinematics

= multi-class machine learning algorithms
2. $t\bar{t}b\bar{b}$ in SMEFT: four-heavy-quark operators

- $t\bar{t}b\bar{b}$ is sensitive to a set of four-quark dim. 6 operators.
- MFV-inspired approach to separate 4-Heavy, 2-Heavy-2-Light and 4-Light operators
- We focus on 4-Heavy operators
  - 2H2L are constrained much more by $t\bar{t}$ and $b\bar{b}$ production via $q\bar{q}$ initial state
2. $t\bar{t}b\bar{b}$ in SMEFT: comparison to four top

- Some operators can be constrained by four top as well

  *ex: C. Zhang Chin. Phys. C42 (2018), no. 2 023104*

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\[ C_{QQ}^{(+)} = \frac{1}{2} C_{QQ}^{1} + \frac{1}{6} C_{QQ}^{8} \]

Degeneracy in four-top, lifted for $t\bar{t}b\bar{b}$!
2. $t\bar{t}b\bar{b}$ in SMEFT: comparison to four top

- Some operators can be constrained by four top as well

  \[ \begin{align*}
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  O_{QtQb}^8 &= (\bar{Q} T^A t) \bar{e} (\bar{Q} T^A b).
  \end{align*} \]

\[ C_{QQ}^{(+)} = \frac{1}{2} C_{QQ}^1 + \frac{1}{6} C_{QQ}^8 \]

Degeneracy in four-top, lifted for $t\bar{t}b\bar{b}$!

Pre-requisite:

$t\bar{t}b\bar{b}$ has a sufficiently large production cross section ($\sim 3$ pb) to exploit differential kinematical information with 300 fb-1 (after Run III)!

(for comparison: $\sigma_{tttt} \sim 9$ fb)
2. $t\bar{t}b\bar{b}$ in SMEFT: comparison to four top

<table>
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<tr>
<td></td>
<td>4-top (300 fb$^{-1}$) ($M_{\text{cut}} = 4$ TeV)</td>
<td>4-top (35.8 fb$^{-1}$) (no $M_{\text{cut}}$)</td>
<td>global fit (no $M_{\text{cut}}$)</td>
<td>$t\bar{t}b\bar{b}$ (300 fb$^{-1}$) ($M_{\text{cut}} = 2$ TeV)</td>
</tr>
<tr>
<td>$C_{qq}^1$</td>
<td>$[-2.8, 2.5]$</td>
<td>$[-2.2, 2.0]$</td>
<td>$[-5.4, 5.2]$</td>
<td>$[-2.1, 2.3]$</td>
</tr>
<tr>
<td>$C_{qq}^8$</td>
<td>$[-8.4, 7.4]$</td>
<td>n.a.</td>
<td>$[-21, 16]$</td>
<td>$[-4.5, 3.1]$</td>
</tr>
<tr>
<td>$C_{qt}^1$</td>
<td>$[-2.2, 2.3]$</td>
<td>$[-3.5, 3.5]$</td>
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<td>$[-7.9, 6.6]$</td>
<td>$[-11, 8.7]$</td>
<td>$[-3.9, 3.8]$</td>
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$\mu_{4t} < 1.87$  \hspace{1cm} $\mu_{4t} < 5.22$
3. Deriving constraints on individual operators: **Sensitivity study**
Strategy

Cross section measurement in the fiducial detector volume → CMS ttbb/ttjj @ 13 TeV

Strategy

\[ \sigma_{t\bar{t}b,CMS} = 88 \pm 12(\text{stat.}) \pm 29(\text{syst.}) \text{ fb} \]

\[ \sigma [\text{pb}] = 0.078 (1 + 0.0011 C + 0.0049 C^2) \]

Strategy

Selection of kinematic phase space to enrich in EFT contributions (using $m_{4b}$) → reconstructed phase space needed!
Strategy

- Identify sensitive variable and apply a cut
- Derive cross section dependence on the Wilson coefficients in this EFT-enriched phase space

\[ \bar{b} \bar{t} W^- W^+ \]

<table>
<thead>
<tr>
<th>\text{SM only}</th>
<th>SM + EFT ( C_{qb} = 10 \text{ TeV}^2 )</th>
<th>SM + EFT ( C_{qb} = 20 \text{ TeV}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>2.0</td>
<td>2.5</td>
<td></td>
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\[ M_{tb} \text{ [TeV]} \]
Learning effective operators: Combine kinematic information of the ttbb final state into machine learning tools
→ Select EFT enriched phase space
Strategy

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<tr>
<th>$\Delta R$</th>
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<tr>
<td>$m_{\text{inv}}(b_1,b_2,\text{add}_1,\text{add}_2)$</td>
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![Histogram of discriminator $p(T_L) + p(T_R)$](image-url)
Summary of individual limits

Summary of the obtained (projected) 95% CL constraints on all relevant operators (one-by-one).

![Graph showing 95% CL limits for various operators](image)
4. Improving sensitivity with multiple effective operators simultaneously

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**Case study:** operators with right-handed top currents ($t_R$) or left-handed top currents ($t_L$)
Learning the effective operators

- Combine all available kinematics in a (shallow) neural network (NN) to select EFT enriched phase space.

- Instead of a binary classifier (SM vs EFT), we exploit multi-class structure to also distinguish amongst EFT operators with left-handed top quark currents ($t_L$) and with right-handed top quark currents ($t_R$)!

- **Important note**: training performed on pure SM and pure EFT (only quadratic contribution, no interference!). Including interference in the training is an interesting case-study for the future!

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18 kinematic input observables

50 nodes (10% dropout) 3 output classes

\[ \sum_{i=1}^{3} P_i = 1 \]
Learning the effective operators

How to combine the network outputs?

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<th>Desired Discrimination</th>
<th>Combined NN Output used for limits</th>
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<tr>
<td>only $t_L$ operator</td>
<td>$\frac{P(t_L)}{P(t_L)+P(SM)}$</td>
</tr>
<tr>
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<td>$\frac{P(t_R)}{P(t_R)+P(SM)}$</td>
</tr>
<tr>
<td>including both $t_L$ and $t_R$ operators</td>
<td>$P(t_L) + P(t_R)$</td>
</tr>
<tr>
<td>$t_L$ vs $t_R$</td>
<td>$\frac{P(t_L)}{P(t_L)+P(t_R)}$</td>
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One operator at a time:
dedicated SM vs $t_L/t_R$ outputs

Multiple operators: SM vs EFT and $t_L$ vs $t_R$ outputs
Learning the effective operators

**multiple operators**

2-dim phase space of NN outputs

- **x-axis**: SM vs EFT ($t_L$ and $t_R$)
- **y-axis**: $t_L$ vs $t_R$
Learning the effective operators

*multiple operators*

Case-study: Consider two non-zero Wilson coefficients: $C_{tb}^1$ and $C_{Qb}^1$

→ Assume an observation of the SM: $(C_{tb}^1, C_{Qb}^1) = (0,0)$
Learning the effective operators

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Case-study: Consider two non-zero Wilson coefficients: $C_{tb}^1$ and $C_{Qb}^1$

→ Assume an observation of EFT signal: $(C_{tb}^1, C_{Qb}^1) = (5,3)$
Learning the effective operators

multiple operators

Case-study: Consider two non-zero Wilson coefficients: $C^1_{tb}$ and $C^1_{Qb}$

→ Assume an observation of EFT signal: $(C^1_{tb}, C^1_{Qb}) = (5,3)$
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Summary

• $t\bar{t}\bar{b}\bar{b}$ is an indispensable component in a global fit of the top-quark interactions in the SMEFT at the LHC!
  o Large enough cross section to exploit differential information
  o First direct constraints on a specific set of operators

• Multi-class machine learning algorithms are a suitable tool for interpreting LHC data in this framework!
  o Intrinsically large SMEFT parameter space
  o High-multiplicity final states with inter-correlated information

• Probing multiple SMEFT couplings simultaneously allow to pinpoint (or constrain) more efficiently the origin (absence) of a possible excess!
Backup
Introduction: $t\bar{t}b\bar{b}$ production

I associate $t\bar{t}b\bar{b}$ to:

A. Higgs boson measurements
B. SM measurements
C. Theory calculations (simulations)
D. BSM searches
Introduction: $t\bar{t}b\bar{b}$ production

**A.** $t\bar{t}b\bar{b}$ is important background for $t\bar{t}H$ ($H \rightarrow b\bar{b}$). Recent discovery of this Higgs production mode


**B.** $t\bar{t}b\bar{b}$ ($t\bar{t}b\bar{b}$/ttjj) has therefore been measured by CMS and ATLAS (7, 8 & 13 TeV)


**C.** Difficult modeling (different mass scales, collinear splitting,...) → large effort from theory community


**D.** ??? → Indispensable component in global fit of top-quark interactions!
**t\(\bar{t}\)b\(\bar{b}\) in SMEFT: comparison to four top**

- Some operators can be constrained by four top as well

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</table>

\(C_{QQ}^{(+) = \frac{1}{2} C_{QQ}^1 + \frac{1}{6} C_{QQ}^8}\)

Degeneracy in four-top, lifted for \(t\bar{t}b\bar{b}\)!

<table>
<thead>
<tr>
<th>Operator</th>
<th>4-top ((M_{cut} = 2 \text{ TeV}))</th>
<th>4-top ((M_{cut} = 3 \text{ TeV}))</th>
<th>4-top ((M_{cut} = 4 \text{ TeV}))</th>
<th>this work ((M_{cut} = 2 \text{ TeV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{QQ}^1)</td>
<td>([-3.9, 3.5])</td>
<td>([-2.9, 2.6])</td>
<td>([-2.8, 2.5])</td>
<td>([-2.1, 2.3])</td>
</tr>
<tr>
<td>(C_{QQ}^8)</td>
<td>([-11.8, 10.5])</td>
<td>([-8.8, 7.8])</td>
<td>([-8.4, 7.4])</td>
<td>([-4.5, 3.1])</td>
</tr>
<tr>
<td>(C_{Qt}^1)</td>
<td>([-3.2, 3.3])</td>
<td>([-2.4, 2.4])</td>
<td>([-2.2, 2.3])</td>
<td>([-2.1, 2.3])</td>
</tr>
<tr>
<td>(C_{Qt}^8)</td>
<td>([-7.4, 5.8])</td>
<td>([-5.4, 4.3])</td>
<td>([-5.1, 4.1])</td>
<td>([-3.9, 3.8])</td>
</tr>
</tbody>
</table>

\(\rightarrow @ 300 \text{ fb}^{-1}\)
Model building and generator software details

Dimension-6 four-fermion EFT operators
Feynrules model provided by LHC TOP WG

LO matrix element calculation
MadGraph

Parton showering
Pythia 8

Detector simulation and event reconstruction
Delphes

Visible phase space at particle level

Phase space after event reconstruction and selection
EFT validity

\[
\frac{C_i}{\Lambda^2} E^2 \equiv C_i E^2 < C_i M_{\text{cut}}^2 \lesssim (4\pi)^2
\]

Fix \( \Lambda = 1 \) TeV and express limits in [TeV\(^{-2}\)]

All energy scales associated to the final state are imposed to be below \( M_{\text{cut}} \).
\( \rightarrow H_T \) (scalar sum of all visible final state objects) is a good example.

\( M_{\text{cut}} = 2 \) TeV
Strategy

Cross section measurement in the fiducial detector volume
→ CMS ttbb/ttjj @ 13 TeV

Selection of kinematic phase space to enrich in EFT contributions (using $m_{4b}$)
→ reconstructed phase space needed!

Learning effective operators: Combine kinematic information of the ttbb final state into machine learning tools
→ Select EFT enriched phase space
→ Distinguish amongst EFT operators!
Cross section in the fiducial detector volume


Integrated luminosity = 2.3 fb$^{-1}$
Visible phase space definition:
$\sigma_{t\bar{t}b\bar{b},CMS} = 88 \pm 12(stat.) \pm 29(syst.)$ fb

Projections for 300 fb$^{-1}$: scaled stat. unc. and fixed syst. unc. of 10%
measured xsec = prediction of MadGraph
Cross section in the fiducial detector volume


Integrated luminosity = 2.3 fb$^{-1}$

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measured xsec = prediction of MadGraph

$\sigma_{\text{fit}} = \sigma_{\text{SM}} \left(1 + p_1 \cdot C_i + p_2 \cdot C_i^2\right)$
Cross section in the fiducial detector volume

$$\sigma_{fit} = \sigma_{SM} \left( 1 + p_1 \cdot C_i + p_2 \cdot C_i^2 \right)$$

Color singlet operators have small interference but larger squared order contributions

Color octet operators have larger interference (SM ~ gluon induced) but suppressed squared order contributions (color factor 2/9)
Tailoring the kinematical phase space

Step 1: move to the reconstructed phase space: **Dileptonic decays of the top quarks**

Step 2: identify quantities that are sensitive to the EFT operators \((\Delta R, M_{\text{inv}}, p_T, \eta) \to M_{4b}\)

Step 3: Make a selection on this quantity and derive the effective cross section dependence
Tailoring the kinematical phase space

Question: What cut to choose on M4b?
Answer: The one that optimizes the sensitivity!
→ increase relative population of EFT contributions
→ without blowing up statistical uncertainty on the SM measurement

M_{4b} > 1.1 \text{ TeV} \ (< 2 \text{ TeV!!})
Learning the effective operators

multiple operators

The NN has indeed learned to distinguish amongst $t_L$ and $t_R$ operators!
Tailoring the kinematical phase space

Prospects for 300 fb$^{-1}$ after event reconstruction/selection and $M_{4b} > 1.1$ TeV

$\sigma [\text{fb}] = 0.2977 \ (1 + 0.0052 \ C + 0.0332 \ C^2)$

$\chi^2$

cross section [fb]

$C_{Qb}^1 \in [-3, +3] \ \text{TeV}^{-2}$

$xsec: C_{Qb}^1 \in [-6, +6] \ \text{TeV}^{-2}$

→ Improvement with a factor $\sim 2!$
Learning the effective operators

*one operator at a time*

Once again the cut value is chosen to optimize the sensitivity

\[ \sigma \text{ [fb]} = 0.2064 ( 1 - 0.0016 C + 0.0671 C^2 ) \]

\[ \sigma \text{ [fb]} = 0.2026 ( 1 + 0.0166 C + 0.0153 C^2 ) \]

\[ C_{Qb}^1 \in [-2.1, +2.3] \text{ TeV}^{-2} \]

\[ M_{4b}: C_{Qb}^1 \in [-3, +3] \text{ TeV}^{-2} \]

\[ C_{Qb}^8 \in [-5, +4.3] \text{ TeV}^{-2} \]

\[ M_{4b}: C_{Qb}^8 \in [-6.5, +7] \text{ TeV}^{-2} \]

→ significant further improvement!
Learning the effective operators

one operator at a time

Question: What cut to choose on the NN output?
Answer: The one that optimizes the sensitivity!

→ increase relative population of EFT contributions
→ without blowing up statistical uncertainty on the SM measurement

NN output > 0.83
Backup: Neural Network training

- 18 inputs + RELU + 1 hidden layer (50 neurons) + RELU + Dropout (10%) + 3 outputs + SOFTMAX (sum=1)
- Mini-batches of size 128, training for 100 epochs
- Loss function: Categorical cross entropy
- Optimizer: Stochastic gradient descent
  - Initial learning rate = 0.005
  - Decay = $10^{-6}$
  - Nestrov momentum = 0.8
Outlook

• Fully marginalized limits when more precise measurements become available

• Method is generic and can be applied to other topologies / final states!

• Increased complexity of the network (Deep learning) or more advanced machine learning techniques may result in better sensitivity.

• Question for the future: How much can we push these algorithms to distinguish different EFT operators.
  o We demonstrated a distinction between $t_L$ and $t_R$ operators
  o Distinguish color singlet operators from color octet ones would be possible if one includes interference effects during the training phase! (becomes dependent on the value of the Wilson coefficient $\rightarrow$ Parametrized learning approach?)
  o Can you (ideally) distinguish each individual operator or are some of them indistinguishable?