Common standards for the EFT interpretation of top-quark measurements at the LHC

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(DESY)

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with much support and feedback from
top-EFT enthusiasts in ATLAS and CMS,
and LHC TOP WG conveners

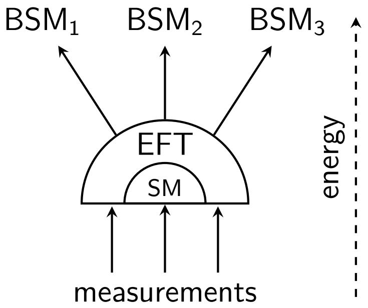
CERN, 16 May 2018
LHC TOP WG meeting

The standard model effective field theory

systematically parametrizes the theory space
in direct vicinity of the SM

- based on SM fields and symmetries
- in a low-energy limit
- systematic and renormalizable when global

(...) if one writes down the most general possible Lagrangian, including all *terms consistent with assumed symmetry principles, (...) the result will simply be the most general possible S-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry.* [*Phenomenological Lagrangians*, Weinberg '79]



The standard model effective field theory

systematically parametrizes the theory space in direct vicinity of the SM

- based on SM fields and symmetries
- in a low-energy limit
- systematic and renormali

Identify new physics through correlated deviations in precisely measured observables.

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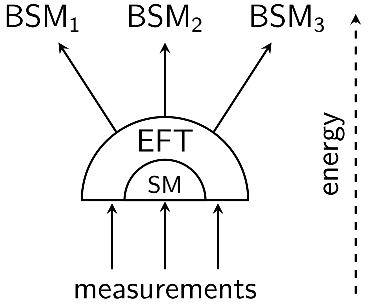


Common framework for top physics at the LHC

First steps

Delimit an initial scope

- focus a priori on processes and operators involving top quarks
- determine which contributions are relevant
- prioritize the study of flavour structures

Fix notation

- define d.o.f. natural for top physics at the LHC
- fix notation, normalization, and indicative allowed ranges
- provide simulation tools as TH/EXP interface

Discuss analysis strategies (one example)

- address the challenges of a global EFT
- highlight useful experimental outputs

Delimit an initial scope

Relevant operators

Focus a priori on processes and operators involving a top quark
Use the *Warsaw* basis of dim-6 operators as reference [Grzadkowski et al '10]

Four-quark operators (11)

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu \tau^I q_j)(\bar{q}_k\gamma_\mu \tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$\mathcal{O}_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$\mathcal{O}_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

Two-quark operators (9)

$$\mathcal{O}_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu \tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$\mathcal{O}_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$\mathcal{O}_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}\,W^I_{\mu\nu},$$
$$\mathcal{O}_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi\,W^I_{\mu\nu},$$
$$\mathcal{O}_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} u_j)\quad\tilde{\varphi}\,B_{\mu\nu},$$
$$\mathcal{O}_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} T^A u_j)\,\tilde{\varphi}\,G^A_{\mu\nu},$$

Two-quark-two-lepton operators (8)

$$O_{lq}^{1(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_j\gamma^\mu \tau^I l_j)(\bar{q}_k\gamma^\mu \tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_j\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_j\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$\mathcal{O}_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$\mathcal{O}_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu} u_l),$$
$$\mathcal{O}_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l),$$

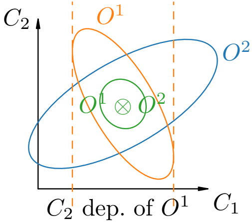
$+ \not{B}$ and $\not{L}$ operators (4 or 5)

Others should be sufficiently constrained by processes involving no tops.

Relevant contributions

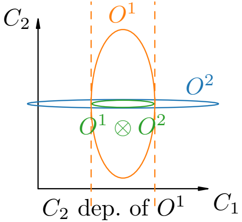
Use present sensitivities and constraints
(rather than theoretical prejudices)
to decide which contributions are relevant.

1. work on an obs.-by-obs. basis (O^k)
2. evaluate all tree-level contributions
3. discard dependences when irrelevant
4. compute higher orders in SM couplings where necessary



C_2 dep. of O^1
should be kept

Note the relevance of d.o.f.'s in a measurement may change as constraints are collected!



C_2 dep. of O^1
can be dropped

BSM flavour assumptions (FCNCs treated separately)

To prioritize the study of flavour structures

Lepton sector (not critical)

- rather loose $[U(1)_{l+e}]^3$ aka flavour diagonality
- could easily be restricted to $U(3)_{l+e}$, $U(3)_l \times U(3)_e$, or ...

Quark sector (baseline and variants)

mostly restrict the large number of four-quark operators

Baseline: $U(2)_q \times U(2)_u \times U(2)_d$ among first two generations

$\equiv$ SM flavour symmetry in the limit $y_{u,d,s,c} \to 0$, $V_{\text{CKM}} \to \mathbb{I}$

forces the first two generations to appear as $\sum_{i=1,2} \bar{q}_i q_i, \;\; \bar{u}_i u_i, \;\; \bar{d}_i d_i$

Extended: $U(2)_{q+u+d}$ [sugg. by J.A.Aguilar-Saavedra]

- allows light right-handed charged currents $\sum_{i=1,2} \bar{u}_i d_i$
- allows light chirality flipping currents $\sum_{i=1,2} \bar{q}_i u_i, \;\; \bar{q}_i d_i$

Restricted: *top-philic* scenario [sugg. by A.Wulzer]

- assumes NP generates all operators with tops and bosons
- then project that over-complete set on the Warsaw basis with EOM, etc.

Fix notation

Top-specific d.o.f. definitions

Match SM interference structures
and interactions with physical gauge bosons

- $$\begin{pmatrix} O_{\varphi q}^{1(33)} \\ O_{\varphi q}^{3(33)} \end{pmatrix} = \begin{pmatrix} (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_3 \gamma^\mu q_3) \\ (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_3 \gamma^\mu \tau^I q_3) \end{pmatrix} = \begin{pmatrix} -1 & 1 \\ 1 & 1 \\ 0 & 1 \\ 0 & 1 \end{pmatrix}^T \begin{pmatrix} \frac{+e}{2s_w c_w} & (\bar{t}\gamma^\mu P_L t) & Z_\mu & (v+h)^2 \\ \frac{-e}{2s_w c_w} & (\bar{b}\gamma^\mu P_L b) & Z_\mu & (v+h)^2 \\ \frac{g}{\sqrt{2}} & (\bar{t}\gamma^\mu P_L b) & W_\mu^+ & (v+h)^2 \\ \frac{g}{\sqrt{2}} & (\bar{b}\gamma^\mu P_L t) & W_\mu^- & (v+h)^2 \end{pmatrix}$$

  $c_{\varphi Q}^- \equiv C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$ enters in $pp \to t\bar{t}Z$
  $c_{\varphi Q}^3 \equiv C_{\varphi q}^{3(33)}$ enters in $t \to bW^+$
  $c_{\varphi Q}^+ \equiv C_{\varphi q}^{1(33)} + C_{\varphi q}^{3(33)}$ enters in $e^+e^- \to b\bar{b}$ (or $pp \to b\bar{b}Z$)

- $$\begin{pmatrix} O_{qq}^{1(ii33)} \\ O_{qq}^{1(i33i)} \\ O_{qq}^{3(ii33)} \\ O_{qq}^{3(i33i)} \end{pmatrix} = \begin{pmatrix} 1 & 1/6 & 0 & 1/2 \\ 0 & 1/6 & 1 & -1/6 \\ 0 & 1 & 0 & 3 \\ 0 & 1 & 0 & -1 \end{pmatrix}^T \begin{pmatrix} (\bar{q}_i \gamma^\mu q_i)\,(\bar{Q}\gamma_\mu Q) \\ (\bar{q}_i \gamma^\mu \tau^I q_i)\,(\bar{Q}\gamma_\mu \tau^I Q) \\ (\bar{q}_i \gamma^\mu T^A q_i)\,(\bar{Q}\gamma_\mu T^A Q) \\ (\bar{q}_i \gamma^\mu \tau^I T^A q_i)\,(\bar{Q}\gamma_\mu \tau^I T^A Q) \end{pmatrix}$$

  $c_{Qq}^{1,1} \equiv C_{qq}^{1(ii33)} + \frac{1}{6} C_{qq}^{1(i33i)} + \frac{1}{2} C_{qq}^{3(i33i)}$ interferes with EW NC
  $c_{Qq}^{3,1} \equiv C_{qq}^{3(ii33)} + \frac{1}{6} (C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)})$ interferes with EW CC
  $c_{Qq}^{1,8} \equiv C_{qq}^{1(i33i)} + 3 C_{qq}^{3(i33i)},$ interferes with QCD
  $c_{Qq}^{3,8} \equiv C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$ doesn't interfere with EW CC

Counting and constraints

	benchmark	extended	restricted
four heavy quarks	$11 + 2$ CPV		5
two light and two heavy quarks	14	$+10 + 10$ CPV	} 5
two heavy quarks and two leptons	$(8 + 3$ CPV$)\times 3$		
two heavy quarks and bosons	$9 + 6$ CPV		$9 + 6$ CPV

Indicative direct constraints

[many from TopFitter]

c^1_{td}	$\equiv C^{1(33ii)}_{ud}$	$[-4.95, 5.04]$ [35]
c^8_{td}	$\equiv C^{8(33ii)}_{ud}$	$[-11.8, 9.31]$ [35]
Two-heavy ($9 + 6$ CPV d.o.f.)		
$c^{[I]}_{t\varphi}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C^{(33)}_{u\varphi}\}$	
$c^{-}_{\varphi q}$	$\equiv C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$	$c^1_{\varphi q}$ $[-3.1, 3.1]$ [36], $[-8.3, 8.6]$ [37]
$c^3_{\varphi Q}$	$\equiv C^{3(33)}_{\varphi q}$	$[-4.1, 2.0]$ [36], $[-8.6, 8.3]$ [37]
$c_{\varphi t}$	$\equiv C^{(33)}_{\varphi u}$	$[-9.7, 8.3]$ [36], $[-9.1, 9.1]$ [37]
$c^{[I]}_{\varphi tb}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C^{(33)}_{\varphi ud}\}$	
$c^{[I]}_{tW}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C^{(33)}_{uW}\}$	c_{tW} $[-4.0, 3.5]$ [36], $[-4.1, 4.1]$ [37]
$c^{[I]}_{tZ}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$	c_{tB} $[-6.9, 4.6]$ [36], $[-7.6, 7.6]$ [37]
$c^{[I]}_{bW}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C^{(33)}_{dW}\}$	
$c^{[I]}_{tG}$	$\equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C^{(33)}_{uG}\}$	c_{tG} $[-1.32, 1.24]$ [36]

[$\Lambda = 1$ TeV]

Two-heavy two-lepton ($8 + 3$ CPV d.o.f. $\times 3$ lepton flavours)

Indicative indirect constraints

B decays, dilepton production, EWPO, EDMs, CP asymmetries

[D.Marzocca; W.Dekens, J.de Vries, V.Cirigliano, E.Mereghetti]

Tree-level UFO implementations

As TH/EXP interfaces

- dedicated `dim6top` (https://feynrules.irmp.ucl.ac.be/wiki/dim6top)
  - $O(90)$ d.o.f.'s of the extended flavour scenario + $O(300)$ FCNCs
- `SMEFTsim` alternative (http://feynrules.irmp.ucl.ac.be/wiki/SMEFT) [Brivio,Jiang,Trott '17]
  - implementing Warsaw operators
  - providing restriction cards for emulating d.o.f.'s

Benchmark dependences (cross checked among the two models)

e.g. linear contributions to total rates: permil of the SM rate, $\Lambda = 1$ TeV

		$pp \to t\bar{t}$	$pp \to t\bar{t}\,b\bar{b}$	$pp \to t\bar{t}\,t\bar{t}$	$pp \to t\bar{t}\,e^+\nu$	$pp \to t\bar{t}\,e^+e^-$	$pp \to t\bar{t}\,\gamma$	$pp \to t\bar{t}\,h$
SM	sm	5.2×10^2 pb	1.9 pb	0.0098 pb	0.02 pb	0.016 pb	1.4 pb	0.4 pb
c^1_{QQ}	`cQQ1`	−0.25	−1.9	-1×10^2		−1.6	−0.67	−0.71
c^8_{QQ}	`cQQ8`	−0.16	−3.2	−34		−0.91	−0.5	−0.27
c^1_{Qt}	`cQt1`	−0.15	−5.6	1×10^2		−0.76	−0.19	−0.55
c^8_{Qt}	`cQt8`	−0.053	−1.8	−41		−0.18	−0.095	−0.15
c^1_{Qb}	`cQb1`	−0.0055	0.72	−0.052		−0.015	−0.007	−0.026
c^8_{Qb}	`cQb8`	0.14	3.9	0.12		0.35	0.16	0.56
c^1_{tt}	`ctt1`			-1.8×10^2				
c^1_{tb}	`ctb1`	−0.0095	0.46	−0.059		−0.02	−0.026	−0.039
c^8_{tb}	`ctb8`	0.13	3.5	0.11		0.26	0.31	0.56
c^1_{QtQb}	`cQtQb1`							
c^8_{QtQb}	`cQtQb8`							
c^{1I}_{QtQb}	`cQtQb1I`							
c^{8I}_{QtQb}	`cQtQb8I`							
$c^{3,8}_{Qq}$	`cQq83`	2.7	−0.11	4.7	−85	−20	8.5	15
$c^{1,8}_{Qq}$	`cQq81`	12	7.1	25	2.6×10^2	71	40	75
c^8_{tq}	`ctq8`	13	8.2	27	2.6×10^2	62	51	74
c^8_{Qu}	`cQu8`	7.4	4.4	18		21	41	44
c^8_{tu}	`ctu8`	7.4	3	16		14	22	45
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]

Discuss analysis strategies

Warning: illustrative theorist view!

- to show how the challenges of a global EFT could be addressed
- to fix ideas on what are useful outputs from a TH perspective

An example of EFT analysis strategy

Exploiting a (particle-level) fiducial volume close enough to the detector level for unfolding to be very model independent.

to be checked!

$\longrightarrow$ facilitates re-interpretations

- in an evolving global EFT picture
- with more sophisticated predictions
- with less restrictive assumptions (about flavour, non-top operators, etc.)
- outside experimental collaborations

$\longrightarrow$ facilitates multidimensional EFT analyses

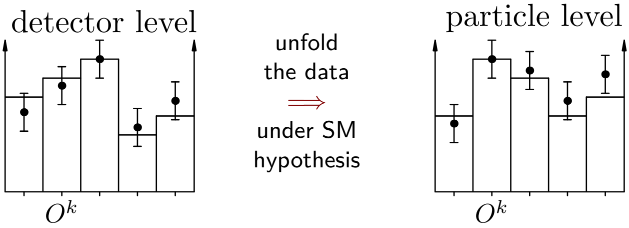
$\longrightarrow$ but may sometimes be impractical or suboptimal

An example of EFT analysis strategy

For O^k observables

total rate, binned p_T, η, m_{xy}, etc. distributions,
binned MVA output, ratios, asymmetries, *optimal observables*,...

Unfold



Note that *forward folding* could actually be advantageous.

Provide

- observable definitions (code if non-standard)
- statistical uncertainties
- systematics breakdown and correlations

($\rightarrow$ re-interpretable in any model)

Global EFT interpretation

- Compute EFT predictions to the particle level

$$O^k = B_l^k + \frac{C_i}{\Lambda^2} S_i^k + \frac{C_i C_j}{\Lambda^4} S_{ij}^k + \cdots$$

SM bkg composition

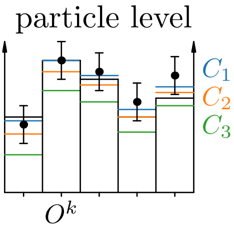
linear dim-6 contributions (EFT-SM interf.)

quadratic dim-6 contributions

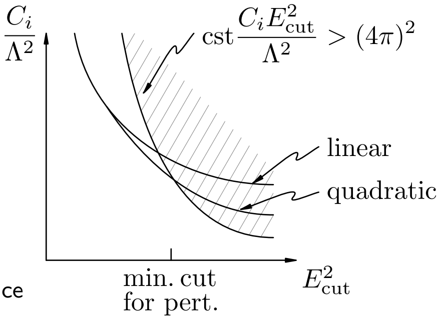
higher powers, and higher-dim. operators

- Obtain and release likelihoods in the full $\{C_i\}$ space

  $\equiv$ **global** constraints to combine with other measurements

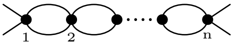


- also quote **individual** constraints
  - → information about sensitivity and the magnitude of approximate degeneracies



- quote both the **linear** and **quadratic** dim-6 approx.
  - → information about the importance of higher powers of dim-6 coeff. (barring interference suppressions)

- quote limits as functions of $\boldsymbol{E}_{\textbf{cut}}$ on a characteristic energy scale
  - → valid interpretation for models [Contino et al '16]
    with lower scales,
    with [dim>6] > [dim-6] without E_{cut}
  - → perturbativity possibly ensured by minimal E_{cut}

$$\sum_n \left[\right.$$


$$\left. \right] \sim \sum_n \left[\text{cst}\, \frac{C_i E_{\text{cut}}^2}{(4\pi)^2 \Lambda^2} \right]^n$$

Summary

Covered

Delimit an initial scope

- focus a priori on top-quark processes and operators
- use constraints and sensitivities to identify relevant contributions
- prioritize the study of flavour structures

Fix notation

- define d.o.f. natural for top physics at the LHC
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Discuss analysis strategies (one example)

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More details in [1802.07237]

Next steps

Explorations on the EXP side

- setup tools
- imagine new clever techniques
- define strategies
- learn in the making
- make new requests to TH

Specific cases

- think about observable/process sensitivities and complementarities
- share plans with theorists: channels, observables, deliverables
  → identify specific issues
  → examine whether new computations are needed

Further NLO QCD progresses

- extending existing results
- with firmer LO bases
- step by step, process by process

A prescription for theory uncertainties