# Global EFT fits in the top sector

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VBSCAN EFT meeting
05/03/2018

# SMEFT

## New Interactions of SM particles

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arxiv:1008.4884

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$ |
| $Q_{\widetilde{G}}$ | $f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |
| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde{G}}$ | $\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde{W}}$ | $\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde{B}}$ | $\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde{W}B}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$ |

| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$ | $Q_{qqq}^{(1)}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$ | $Q_{qqq}^{(3)}$ | $\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |

- Top EFT
- Global top EFT fits

# Top-quark operators and how to look for them

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$

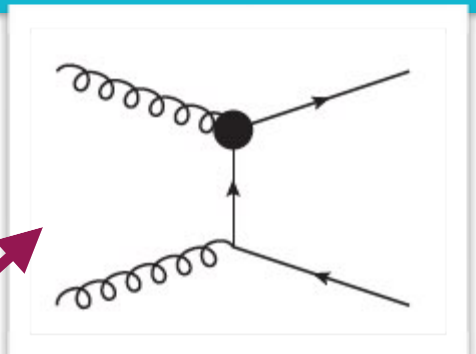
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$$

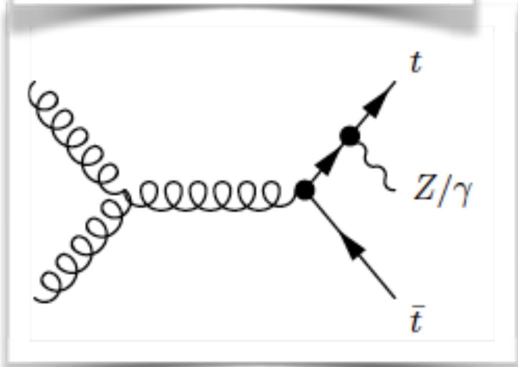
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

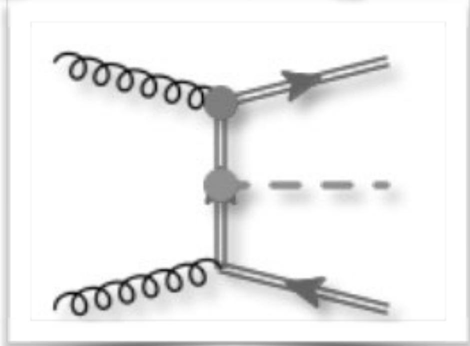
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$









see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)

**Operators entering various processes: A strategy is needed**

# Input from the LHCTopWG

Interpreting top-quark LHC measurements
in the standard-model effective field theory

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→ Input from a lot of theorists

**Abstract**

This note proposes common standards and prescriptions for the effective-field-theory interpretation of top-quark measurements at the LHC.

arXiv:1802.07237

# Top EFT note

## Contents



Warsaw basis

3 scenarios with different flavour assumptions

Constraints from LHC, EWPO, indirect constraints

Public UFO implementations and benchmark results already given for LHC13

Separate discussion of FCNC

arXiv:1802.07237

# Benchmark results for 13 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 | $5.2 \times 10^{2}$ pb | 1.9 pb | 0.0098 pb | 0.02 pb | 0.016 pb | 1.4 pb | 0.4 pb |
| $c^{1}_{QQ}$ | cQQ1 | $-0.25$ | $-1.9$ | $-1 \times 10^{2}$ | | $-1.6$ | $-0.67$ | $-0.71$ |
| $c^{8}_{QQ}$ | cQQ8 | $-0.16$ | $-3.2$ | $-34$ | | $-0.91$ | $-0.5$ | $-0.27$ |
| $c^{1}_{Qt}$ | cQt1 | $-0.15$ | $-5.6$ | $1 \times 10^{2}$ | | $-0.76$ | $-0.19$ | $-0.55$ |
| $c^{8}_{Qt}$ | 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 | | | $-1.8 \times 10^{2}$ | | | | |
| $c^{1}_{tb}$ | 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 | $2.6 \times 10^{2}$ | 71 | 40 | 75 |
| $c^{8}_{tq}$ | ctq8 | 13 | 8.2 | 27 | $2.6 \times 10^{2}$ | 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 |
| $c^{8}_{Qd}$ | cQd8 | 5 | 3 | 11 | | 17 | 7.3 | 29 |
| $c^{8}_{td}$ | ctd8 | 5 | 2.1 | 10 | | 12 | 10 | 28 |
| $c^{3,1}_{Qq}$ | cQq13 | 3.3 | 3 | 5.8 | $1.1 \times 10^{2}$ | 22 | 11 | 18 |
| $c^{1,1}_{Qq}$ | cQq11 | 0.94 | $-1.4$ | $-7.7$ | $-5.9$ | $-5$ | 3 | 5.4 |
| $c^{1}_{tq}$ | ctq1 | 0.65 | 2.4 | $-7.9$ | 8.7 | 0.84 | 3.7 | 4.8 |
| $c^{1}_{Qu}$ | cQu1 | 0.57 | 1.5 | $-5.2$ | | 1.5 | 2.9 | 4.3 |
| $c^{1}_{tu}$ | ctu1 | 1.1 | $-0.29$ | $-3.8$ | | 2.3 | 3.3 | 6.6 |
| $c^{1}_{Qd}$ | cQd1 | $-0.19$ | 0.55 | $-4$ | | $-0.66$ | $-0.3$ | $-1.4$ |
| $c^{1}_{td}$ | ctd1 | $-0.37$ | $-1.3$ | $-5$ | | $-0.91$ | $-1.3$ | $-2.1$ |
| $c_{t\varphi}$ | ctp | | $-0.00035$ | $-9.1$ | $-0.034$ | $-0.0093$ | | $-1.2 \times 10^{2}$ |
| $c^{-}_{\varphi Q}$ | cpQM | $-0.063$ | 1 | $-41$ | $-0.76$ | $-1 \times 10^{2}$ | $-0.13$ | $-0.29$ |
| $c^{3}_{\varphi Q}$ | cpQ3 | 0.68 | 22 | 0.065 | 0.46 | 3.7 | 1.5 | 1.8 |
| $c_{\varphi t}$ | cpt | $-0.024$ | 2.8 | 42 | $-0.36$ | 68 | $-0.058$ | $-0.16$ |
| $c_{\varphi tb}$ | cptb | | | | | | | |
| $c_{tW}$ | ctW | 0.98 | 1 | $-34$ | 13 | 1.1 | 69 | 9.4 |
| $c_{tZ}$ | ctZ | $-0.54$ | 0.028 | 27 | $-0.048$ | $-3.6$ | $-55$ | $-4.3$ |
| $c_{bW}$ | cbW | | | | | | | |
| $c_{tG}$ | ctG | $2.7 \times 10^{2}$ | $2.5 \times 10^{2}$ | $3.8 \times 10^{2}$ | $2.4 \times 10^{2}$ | $3.1 \times 10^{2}$ | $2.4 \times 10^{2}$ | $8.4 \times 10^{2}$ |
| $c^{I}_{t\varphi}$ | ctpI | | $-7.3 \times 10^{-7}$ | 0.045 | $-0.00064$ | $-0.00029$ | | 0.045 |
| $c^{I}_{\varphi tb}$ | cptbI | | | | | | | |
| $c^{I}_{tW}$ | ctWI | $4.8 \times 10^{-6}$ | 0.032 | $-1.6$ | $-0.19$ | 0.29 | 0.91 | 0.031 |
| $c^{I}_{tZ}$ | ctZI | $-1.4 \times 10^{-6}$ | 0.1 | $-1.2$ | 0.0098 | 3.2 | $-0.56$ | $-0.057$ |
| $c^{I}_{bW}$ | cbWI | | | | | | | |
| $c^{I}_{tG}$ | ctGI | $-0.00098$ | 0.48 | 0.66 | 0.031 | $-0.7$ | 0.019 | $-2.4$ |
| $c^{3(1)}_{Ql}$ | cQl31 | | | | 0.011 | 0.06 | | |
| $c^{-(1)}_{Ql}$ | cQlM1 | | | | $-0.0062$ | $-9.8$ | | |
| $c^{(1)}_{Qe}$ | cQe1 | | | | | $-1.5$ | | |
| $c^{(1)}_{tl}$ | ctl1 | | | | $-0.0023$ | $-3.6$ | | |
| $c^{(1)}_{te}$ | cte1 | | | | | $-6.7$ | | |

arXiv:1802.07237

Results at 13 TeV for all degrees of freedom for each process including interference ($1/\Lambda^2$) and squared terms ($1/\Lambda^4$), interference between operators

Public UFO for top EFT

https://feynrules.irmp.ucl.ac.be/wiki/dim6top

# What’s next?

Use SMEFT to parametrise and look for deviations from SM predictions

Use as many experimental measurements as possible
Cross-sections+differential distributions

Use the best SM predictions
QCD/EW corrections

Need for precision also in SMEFT

Need for precision calculations
Automated tools for the EFT

# How can we improve EFT predictions?

- SMEFT@NLO
  - Mixing between operators: anomalous dimension matrix: Jenkins et al arXiv:1308.2627,1310.4838, Alonso et al. 1312.2014
  - Additional operators at NLO: e.g. chromomagnetic dipole in single top production

Recent progress in top physics:

- top pair Franzosi and Zhang (arxiv:1503.08841)
- single top Zhang (arxiv:1601.06163), de Beurs, Laenen, Vreeswijk, EV (arXiv:1807.03576)
- ttZ/γ Bylund, Maltoni, Tsinikos, EV, Zhang (arXiv:1601.08193)
- ttH Maltoni, EV, Zhang (arXiv:1607.05330)
- tZ/Hj Degrande, Maltoni, Mimasu, EV, Zhang (arXiv:1804.07773)

All automated within MadGraph5_aMC@NLO
R2+UV counterterms: NLOCT Degrande (arxiv:1406.3030)

# Towards a complete implementation@NLO

**Based on:**

- Warsaw basis
- Degrees of freedom for top operators as in dim6top

**Current status:**

- 73 degrees of freedom (top, Higgs, gauge):
  - CP-conserving
  - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- Successful validation at LO with dim6top (in turn validated with SMEFTsim)
- 0/2F@NLO operators validated (with previous partial NLO implementations) → **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
- 4F@NLO operators validation: on-going

**Future plans**

- Full NLO model release (4F@NLO)
- Other flavour assumptions
- CP-violating effects

Work in progress with:
C. Degrande, G. Durieux, F. Maltoni, K. Mimasu, C. Zhang

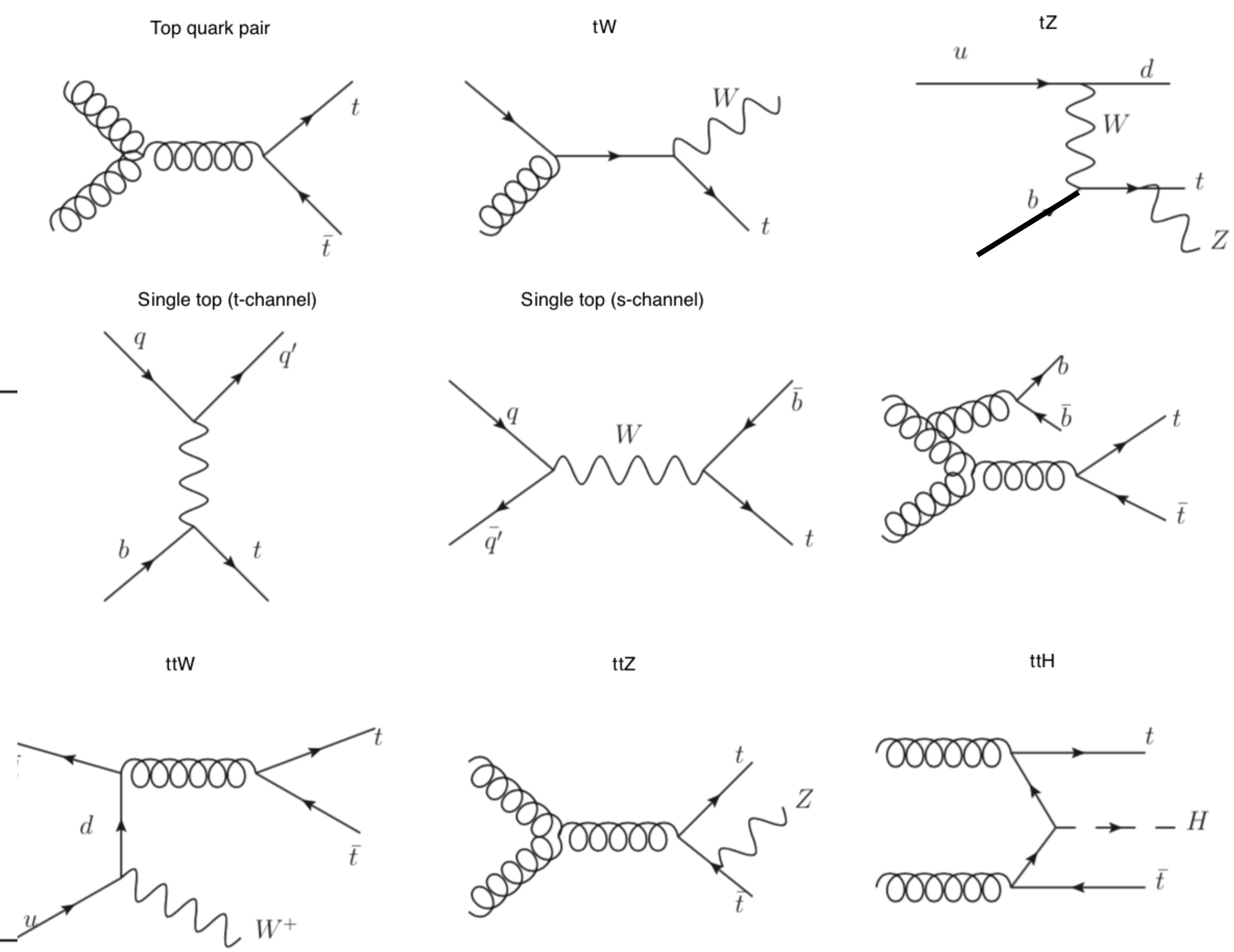
- Top EFT
- Global top EFT fits

# A global top fit@NLO

| Class | Notation | Degree of Freedom | Operator Definition | Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $t\bar{t}$ | single-top | $tW$ | $tZ$ | $t\bar{t}W$ | $t\bar{t}Z$ | $t\bar{t}H$ | $t\bar{t}t\bar{t}$ | $t\bar{t}b\bar{b}$ |
| $QQQQ$ | 0QQ1 | $c^1_{QQ}$ | $2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$ | | | | | | | | ✓ | ✓ |
| | 0QQ8 | $c^8_{QQ}$ | $8C^{3(3333)}_{qq}$ | | | | | | | | ✓ | ✓ |
| | 0Qt1 | $c^1_{Qt}$ | $C^{1(3333)}_{qu}$ | | | | | | | | ✓ | ✓ |
| | 0Qt8 | $c^8_{Qt}$ | $C^{8(3333)}_{qu}$ | | | | | | | | ✓ | ✓ |
| | 0Qb1 | $c^1_{Qb}$ | $C^{1(3333)}_{qd}$ | | | | | | | | | ✓ |
| | 0Qb8 | $c^8_{Qb}$ | $C^{8(3333)}_{qd}$ | | | | | | | | | ✓ |
| | 0tt1 | $c^1_{tt}$ | $C^{(3333)}_{uu}$ | | | | | | | | ✓ | |
| | 0tb1 | $c^1_{tb}$ | $C^{1(3333)}_{ud}$ | | | | | | | | | ✓ |
| | 0tb8 | $c^8_{tb}$ | $C^{8(3333)}_{ud}$ | | | | | | | | | ✓ |
| | 0QtQb1 | $c^1_{QtQb}$ | $C^{1(3333)}_{quqd}$ | | | | | | | | | ✓ |
| | 0QtQb8 | $c^8_{QtQb}$ | $C^{8(3333)}_{quqd}$ | | | | | | | | | ✓ |
| $QQqq$ | 081qq | $c^{1,8}_{Qq}$ | $C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 011qq | $c^{1,1}_{Qq}$ | $C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$ | (✓) | | | | (✓) | (✓) | (✓) | ✓ | ✓ |
| | 083qq | $c^{3,8}_{Qq}$ | $C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$ | ✓ | (✓) | | (✓) | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 013qq | $c^{3,1}_{Qq}$ | $C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$ | (✓) | ✓ | | ✓ | (✓) | (✓) | (✓) | ✓ | ✓ |
| | 08qt | $c^8_{tq}$ | $C^{8(ii33)}_{qu}$ | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 01qt | $c^1_{tq}$ | $C^{1(ii33)}_{qu}$ | (✓) | | | | (✓) | (✓) | (✓) | ✓ | ✓ |
| | 08ut | $c^8_{tu}$ | $2C^{(i33i)}_{uu}$ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | 01ut | $c^1_{tu}$ | $C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$ | (✓) | | | | | (✓) | (✓) | ✓ | ✓ |
| | 08qu | $c^8_{Qu}$ | $C^{8(33ii)}_{qu}$ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | 01qu | $c^1_{Qu}$ | $C^{1(33ii)}_{qu}$ | (✓) | | | | | (✓) | (✓) | ✓ | ✓ |
| | 08dt | $c^8_{td}$ | $C^{8(33ii)}_{ud}$ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | 01dt | $c^1_{td}$ | $C^{1(33ii)}_{ud}$ | (✓) | | | | | (✓) | (✓) | ✓ | ✓ |
| | 08qd | $c^8_{Qd}$ | $C^{8(33ii)}_{qd}$ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ |
| | 01qd | $c^1_{Qd}$ | $C^{1(33ii)}_{qd}$ | (✓) | | | | | (✓) | (✓) | ✓ | ✓ |
| $QQ+V,G,\varphi$ | 0tG | $c_{tG}$ | $\mathrm{Re}\{C^{(33)}_{uG}\}$ | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| | 0tW | $c_{tW}$ | $\mathrm{Re}\{C^{(33)}_{uW}\}$ | | ✓ | ✓ | ✓ | | | | | |
| | 0bW | $c_{bW}$ | $\mathrm{Re}\{C^{(33)}_{dW}\}$ | | (✓) | (✓) | (✓) | | | | | |
| | 0tZ | $c_{tZ}$ | $\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$ | | | | ✓ | | ✓ | | | |
| | 0ff | $c_{\varphi tb}$ | $\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$ | | (✓) | (✓) | (✓) | | | | | |
| | 0fq3 | $c^3_{\varphi Q}$ | $C^{3(33)}_{\varphi q}$ | | ✓ | ✓ | ✓ | | | | | |
| | 0pQM | $c^-_{\varphi Q}$ | $C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$ | | | | ✓ | | ✓ | | | |
| | 0pt | $c_{\varphi t}$ | $C^{(33)}_{\varphi u}$ | | | | ✓ | | ✓ | | | |
| | 0tp | $c_{t\varphi}$ | $\mathrm{Re}\{C^{(33)}_{u\varphi}\}$ | | | | | | | ✓ | | |

34 d.o.f.

CP-conserving




Rich phenomenology

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

# Global fit Setup

## Theory

(N)NLO QCD+ NLO EW for SM
NLO QCD for SMEFT
State-of-the-art PDFs without top data

## Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions
Parton-level

## Global SMEFT fit of the top-quark sector

Based on NNPDF
Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

## Methodology

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added
Plan to extend to Higgs, gauge sector etc

## Output

# Observables and theory predictions

## Data

Top-pair production
W-helicities

4 tops, ttbb, top-pair associated production

Single top
t-channel, s-channel, tW, tZ

| Dataset | $n_{dat}$ |
|---|---|
| ATLAS_tt_8TeV_ljets [ $m_{t\bar{t}}$ ] | 7 |
| CMS_tt_8TeV_ljets [ $y_t$ ] | 10 |
| CMS_tt2D_8TeV_dilep [ $(m_{t\bar{t}}, y_t)$ ] | 16 |
| CMS_tt_13TeV_ljets2 [ $y_{t\bar{t}}$ ] | 8 |
| CMS_tt_13TeV_dilep [ $y_{t\bar{t}}$ ] | 6 |
| CMS_tt_13TeV_ljets_2016 [ $y_t$ ] | 11 |
| ATLAS_WhelF_8TeV | 3 |
| CMS_WhelF_8TeV | 3 |
| CMS_ttbb_13TeV | 1 |
| CMS_tttt_13TeV | 1 |
| ATLAS_tth_13TeV | 1 |
| CMS_tth_13TeV | 1 |
| ATLAS_ttZ_8TeV | 1 |
| ATLAS_ttZ_13TeV | 1 |
| CMS_ttZ_8TeV | 1 |
| CMS_ttZ_13TeV | 1 |
| ATLAS_ttW_8TeV | 1 |
| ATLAS_ttW_13TeV | 1 |
| CMS_ttW_8TeV | 1 |
| CMS_ttW_13TeV | 1 |
| CMS_t_tch_8TeV_dif | 6 |
| ATLAS_t_tch_8TeV [ $y_t$ ] | 4 |
| ATLAS_t_tch_8TeV [ $y_t$ ] | 4 |
| ATLAS_t_sch_8TeV | 1 |
| CMS_t_tch_13TeV_dif [ $y_t$ ] | 4 |
| CMS_t_sch_8TeV | 1 |
| ATLAS_tW_inc_8TeV | 1 |
| CMS_tW_inc_8TeV | 1 |
| ATLAS_tW_inc_13TeV | 1 |
| CMS_tW_inc_13TeV | 1 |
| ATLAS_tZ_inc_13TeV | 1 |
| CMS_tZ_inc_13TeV | 1 |
| Total | 102 |

One distribution from each dataset, to avoid double counting

## Theoretical predictions

| Process | SM | SMEFT |
|---|---|---|
| $t\bar{t}$ | NNLO QCD | NLO QCD |
| single-$t$ ($t$-ch) | NNLO QCD | NLO QCD |
| single-$t$ ($s$-ch) | NLO QCD | NLO QCD |
| $tW$ | NLO QCD | NLO QCD |
| $tZ$ | NLO QCD | LO QCD + NLO SM $K$-factors |
| $t\bar{t}W(Z)$ | NLO QCD | LO QCD + NLO SM $K$-factors |
| $t\bar{t}h$ | NLO QCD | LO QCD + NLO SM $K$-factors |
| $t\bar{t}t\bar{t}$ | NLO QCD | LO QCD + NLO SM $K$-factors |
| $t\bar{t}b\bar{b}$ | NLO QCD | LO QCD + NLO SM $K$-factors |

Baseline fit includes:

- Best available SM predictions
- NLO EFT predictions
- $O(1/\Lambda^4)$ terms

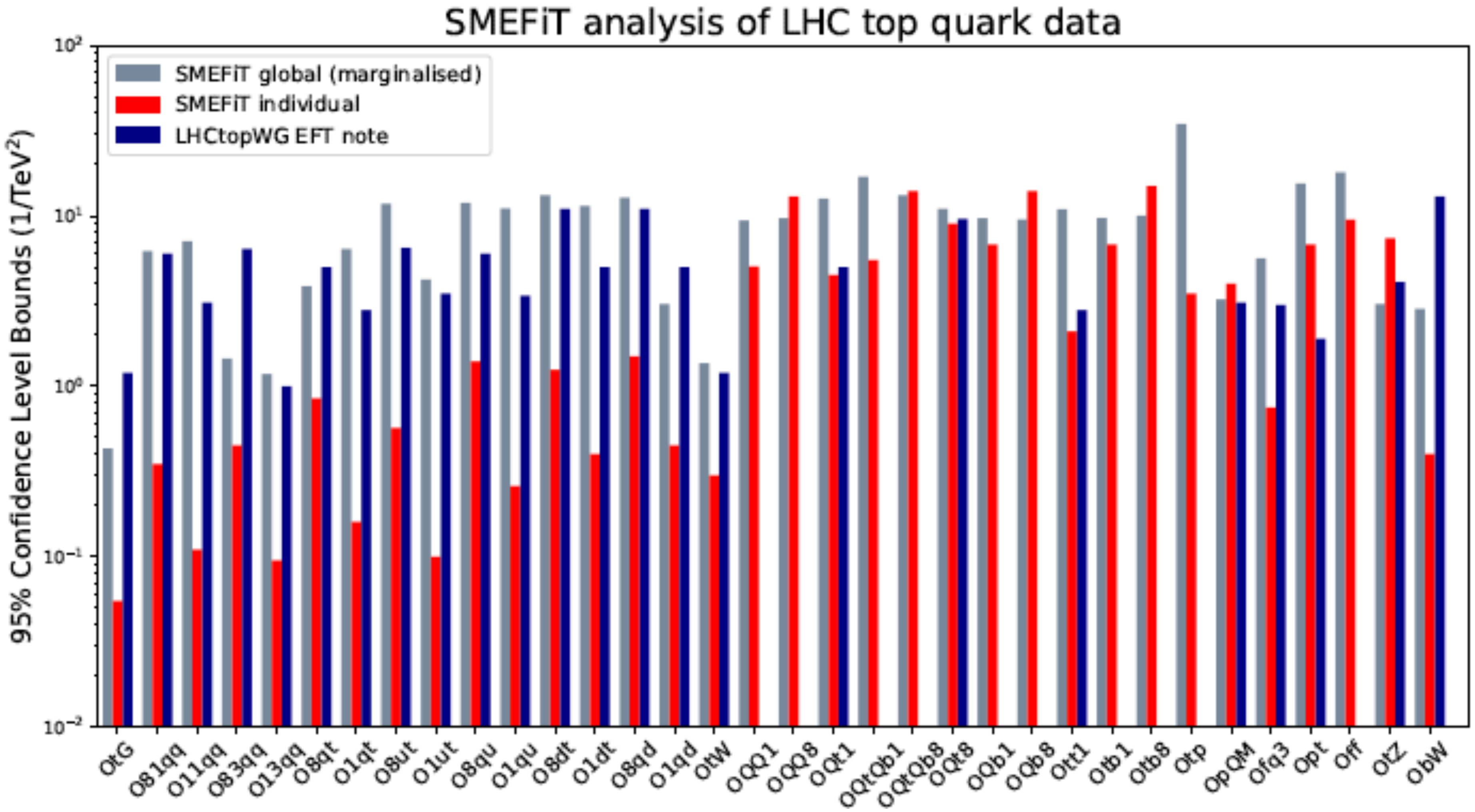
# Methodology

- Based on the MC replica method used by NNPDF for PDF fits
  - Construct sampling of the probability distribution in the data space.
  - Sampling of the probability distribution in the SMEFT space by minimising the error function.

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\rm dat}} \sum_{i,j=1}^{N_{\rm dat}} \left(\mathcal{O}_i^{(\rm th)}\left(\{c_l^{(k)}\}\right) - \mathcal{O}_i^{(\rm art)(k)}\right) ({\rm cov}^{-1})_{ij} \left(\mathcal{O}_j^{(\rm th)}\left(\{c_l^{(k)}\}\right) - \mathcal{O}_j^{(\rm art)(k)}\right)$$

- Cross validation to avoid over-fitting: for each replica, the data is randomly split with equal probability into the training and validation sets. The latter is monitored during the fit, to avoid over-fitting.

- Closure test: feed pseudo-data generated with known EFT parameters to the fit, and ensure that the fit reproduces the correct parameters.



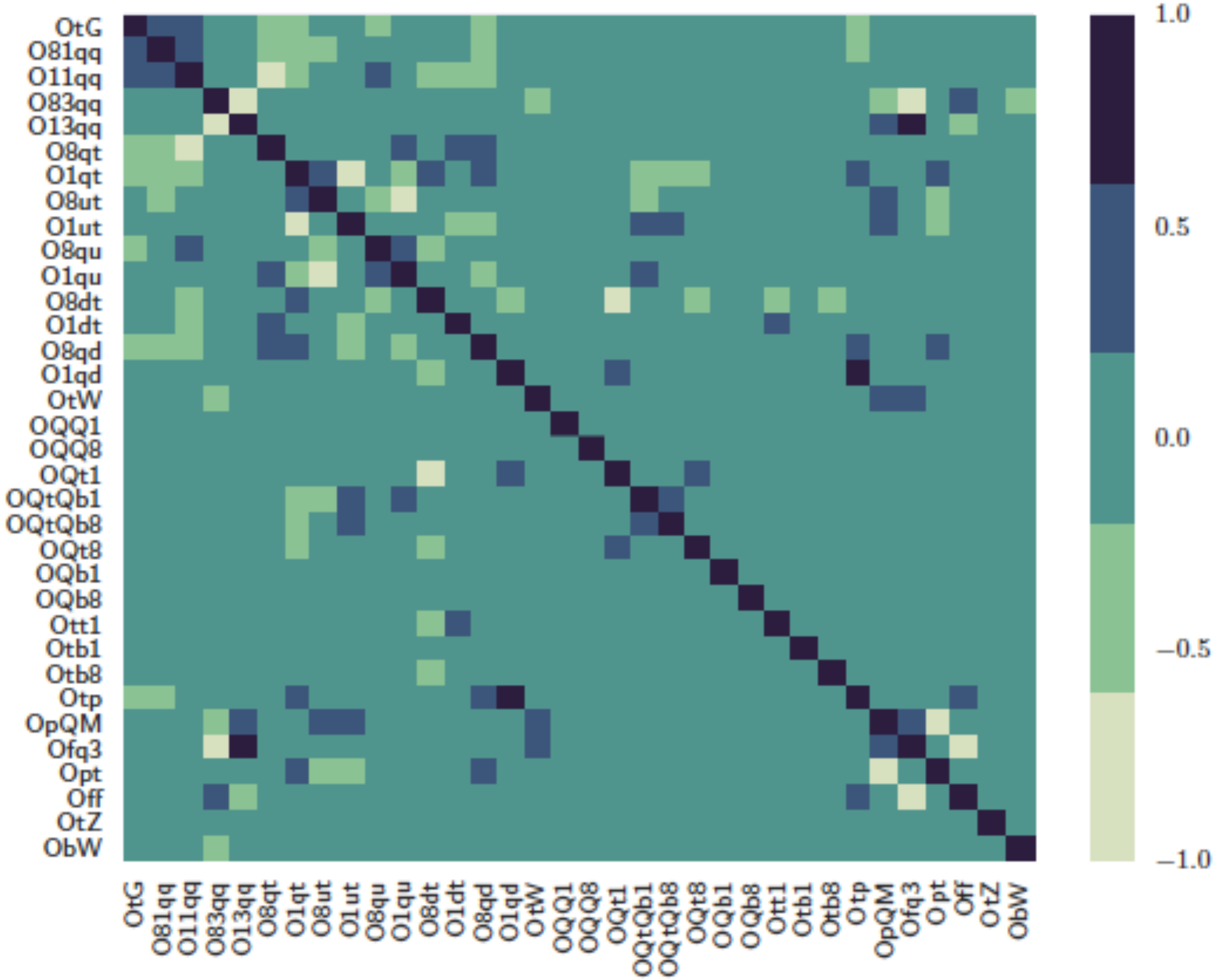

First limits reported for some operators

Improvement for some operators: e.g. $O_{tG}$, $O^{83}_{qq}$, $O_{bW}$

Individual limits more stringent than marginalised ones

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

# Correlations between EFT coefficients




Strong (anti-)correlations between different operators (ignored by individual constraints)

# Some considerations

- $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
  - $1/\Lambda^2$ suppressed due to helicity Azatov et al arXiv:1607.05236
  - $1/\Lambda^4$ can be large for loosely constrained operator coefficients/strongly coupled theories

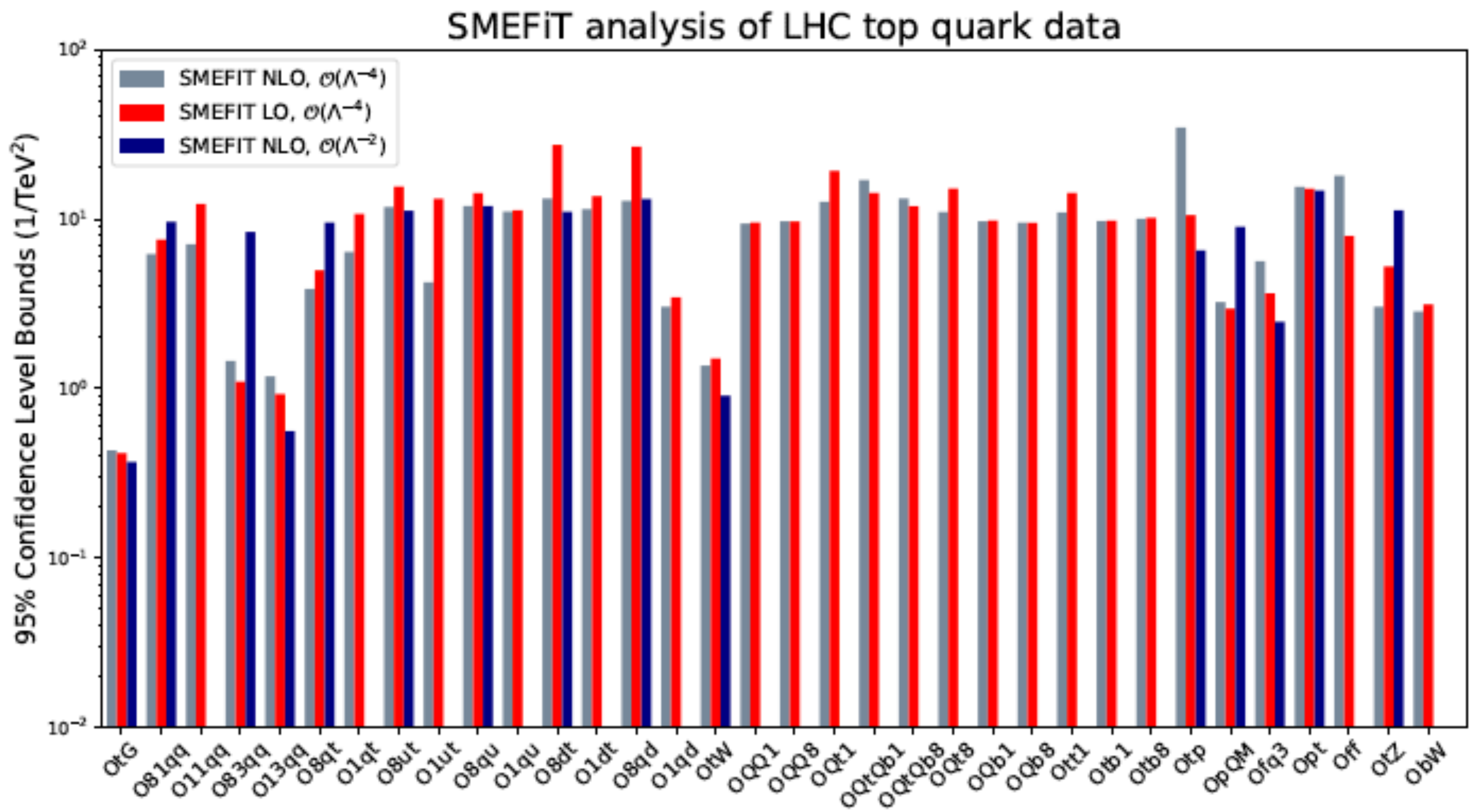
$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

E<Λ satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

- Validity of the EFT expansion: $E<\Lambda$
  - Ensure results are not dominated by high energy regions
  - report limits as a function of the max scale probed Contino et al arXiv:1604.06444

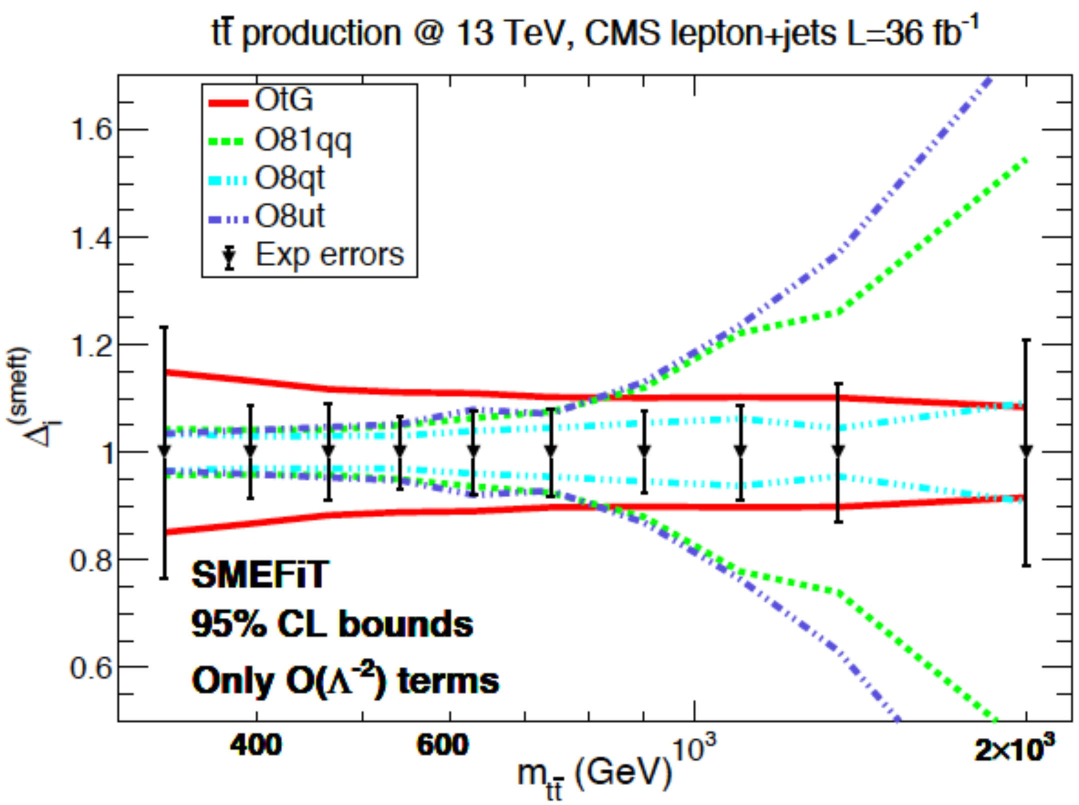
# Impact of higher-order terms

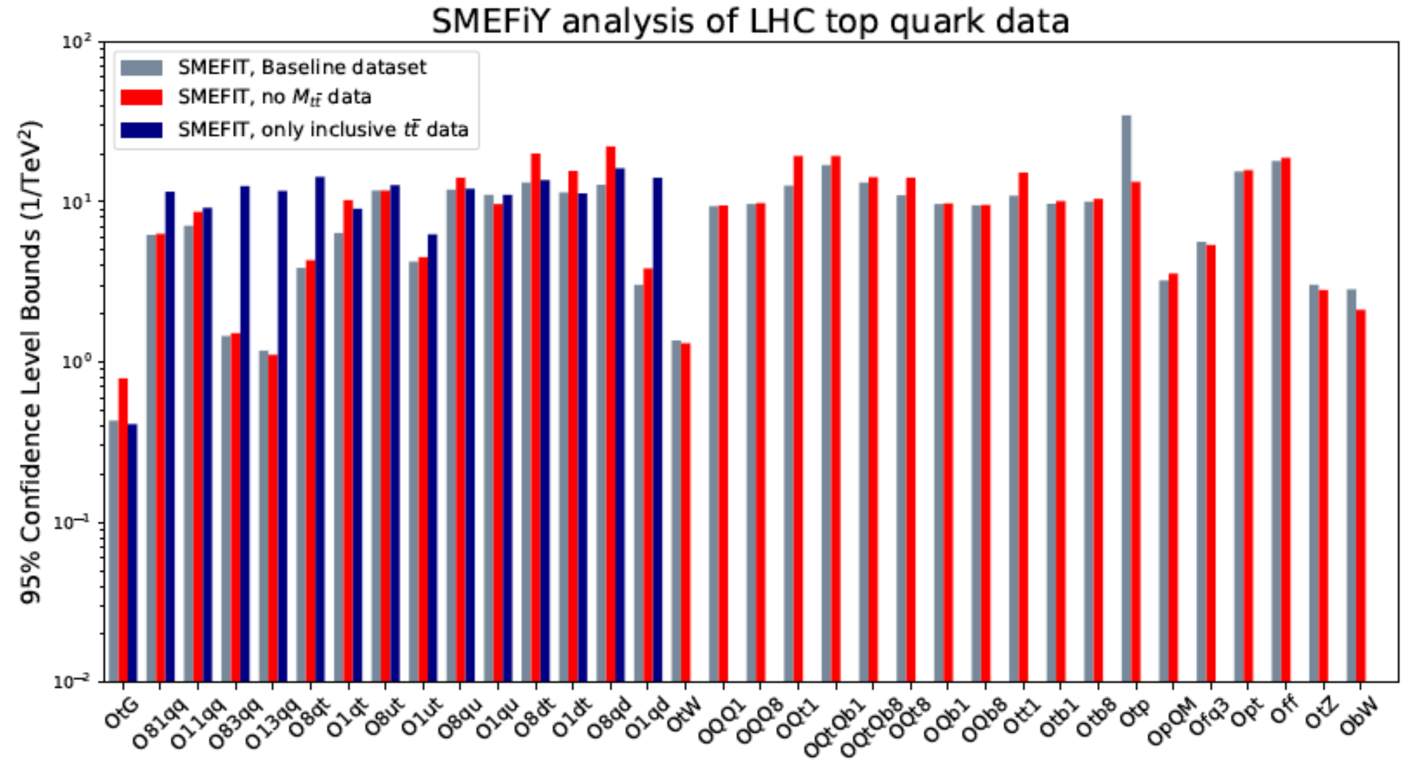
Fit allows to check the impact of NLO QCD corrections and of including the $O(1/\Lambda^4)$ terms




Non-trivial impact of the two effects, can be different operator-by-operator

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965




$m_{tt}$ distribution (bins above 1 TeV) → Use $y_{tt}$ as a check

# Summary & Outlook

- NLO SMEFT implementation:
  - Imminent release of SMEFT@NLO with 73 d.o.f's
    - **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
  - Extensively validated and user friendly
- First application of the NLO implementation:
  - A global fit in the top sector
    - NLO SMEFT predictions
    - Wide range of LHC top data
    - Robust and reliable fitting procedure based on NNPDF methodology
- Extension of the fit to include EWPO, Higgs, diboson, VBS data is straightforward and constitutes the next step
- Fitting UV models a posteriori under study