Current status of the
Standard Model Effective Field Theory (SMEFT)

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What is a scale of New physics?

Before the LHC start we knew a scale ~1 TeV from

No lose theorem!

From the unitariry of VV->VV (V: W,Z) amplitudes: $\left|\mathrm{Re}(a_l)\right| \leq \frac{1}{2}$

Either light Higgs $M_H \lesssim 710\ \mathrm{GeV}$

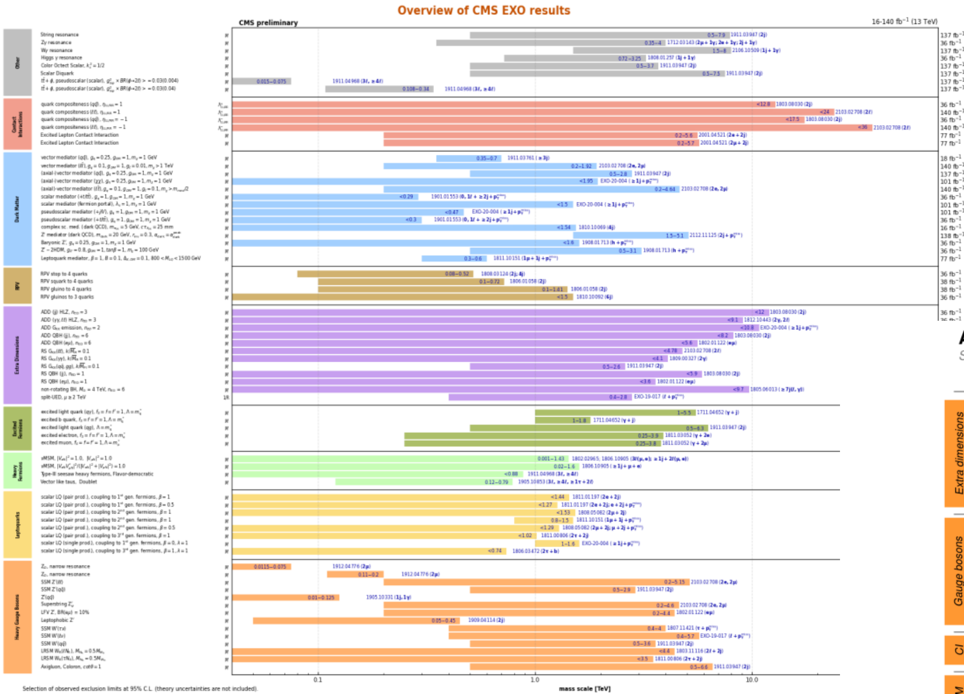
or

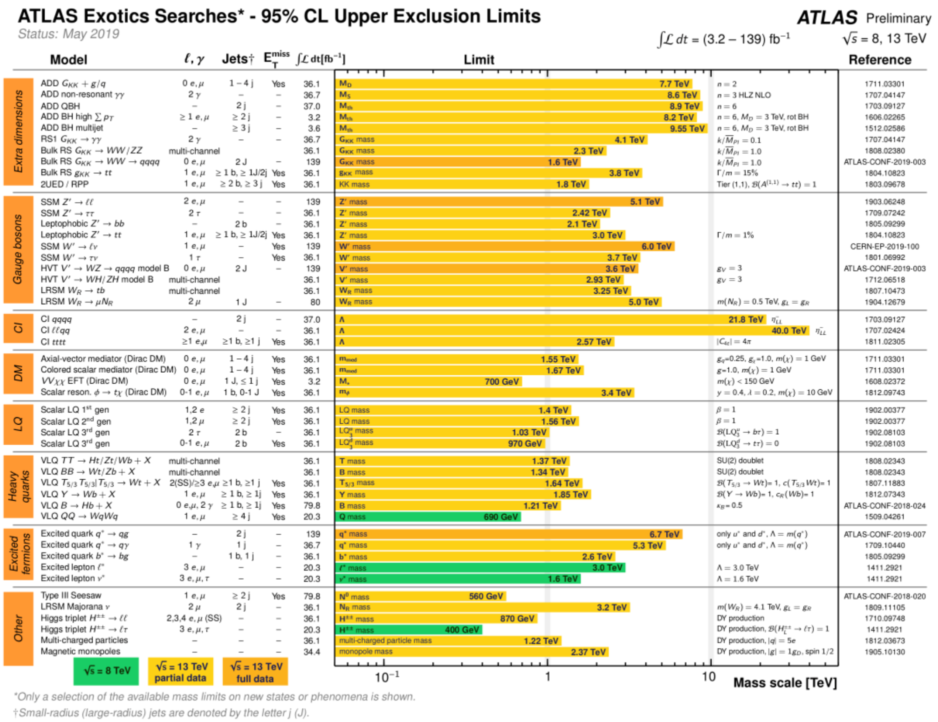
New Physics at $\sqrt{s} \lesssim 1.2\ \mathrm{TeV}$

The Higgs boson was found !

We do not have solid arguments for a new scale
We do not know if a new scale (if exists) would be accessible at the LHC/FCC energies

Many limits already in TeV energy range





Two possibilities to search for BSM

Collision energy E > production thresholds

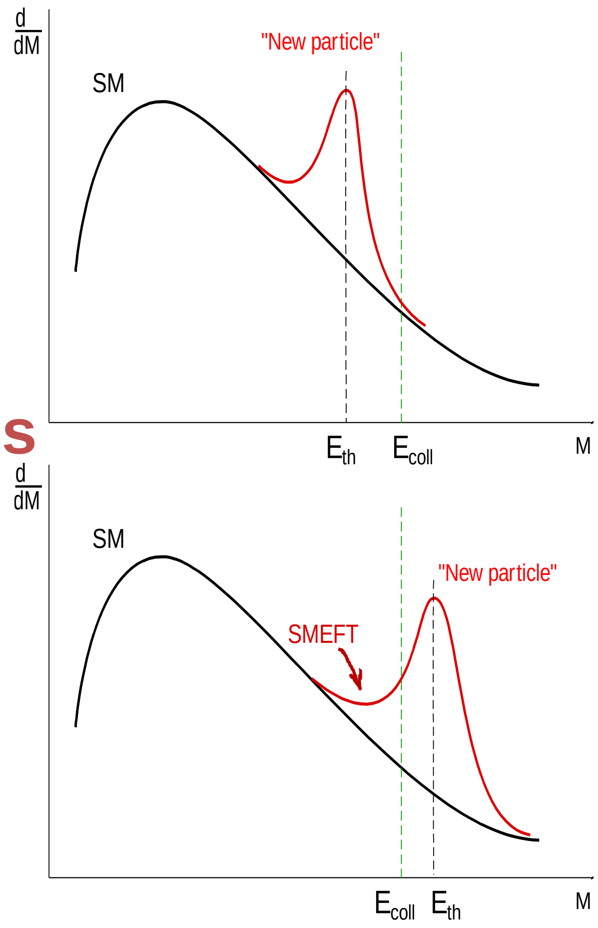
$\Rightarrow$**New particles, new resonances**

Z', W', π_T, ρ_T , KK states, squarks, sleptons, vector like fermions, excited states…

Collision energy E < production thresholds

Modification of SM decay widths, production cross sections, kinematical distributions)

Effective field theories – the way to proceed



The main idea –
integrating out heavy degrees of freedom

UV full theory

↓

EFT

φ_H – heavy degrees of freedom , $M\varphi_H \geq \Lambda$

φ_L – light degrees of freedom , $M\varphi_L << \Lambda$

integrating out = integrating over

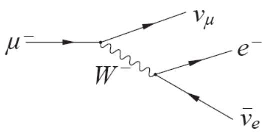
$$Z_{UV}[J_L , J_H] = \int [D\varphi_L][D\varphi_H] \exp [\, i \int d^4x \, [L_{UV}(\varphi_L, \varphi_H) + J_L \varphi_L + J_H \varphi_H \,]$$

↓

$$Z_{EFT}[J_L] = Z_{UV}[J_L , 0] = \int [D\varphi_L] \exp [\, i \int d^4x \, [L_{EFT}(\varphi_L) + J_L \varphi_L]$$

$L_{EFT}(\varphi_L)$ is a point like Lagrangian

Obvious for integrating out heavy bosons
(like in integrating out W, Z in Fermi 4-fermion theory)



$$L = \frac{G_F}{\sqrt{2}} \bar{\mu}\gamma_\sigma(1-\gamma_5)\nu_\mu \bar{e}\gamma_\sigma(1-\gamma_5)\nu_e + h.e.$$

tree-generated [TG] operators

Arzt, C, M. B. Einhorn, and J. WudkaNucl. Phys. B 433, 41–66 (1995)

Less obvious for integrating out heavy fermions

The decoupling theorem

T. Appelquist, J. Carazzone, Phys. Rev. D11, 2856 (1975)

For any 1PI Feynman graph with external vector mesons only but containing internal fermions, when all external momenta (i.e. p^2) are small relative to M^2, then apart from coupling constant and field strength renormalization the graph will be suppressed by some power of m relative to a graph with the same number of external vector mesons but no internal fermions.

loop-generated [LG] operators

Einhorn, Martin, Wudka (2013), Nucl. Phys. B 876, 556–574

SM Effective Field Theory (SMEFT)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{i,d>4} \frac{c_i^{(d)}(\mu)}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

$c_i^{(d)}$ - dimensionless coefficients
$O_i^{(d)}$ - operators constructed from SM fields preserving SM gauge invariance, and (optionally) other symmetries

S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979)

W. Buchmuller and D. Wyler, Nucl. Phys. B268, 621 (1986)

There is only one dim-5 operator which violates lepton number conservation (Weinberg operator). Corresponding Wilson coefficient is strongly suppressed

$$\left(\overline{L^c_{L\alpha}}\widetilde{H}^*\right)\left(\widetilde{H}^\dagger L_{L\beta}\right) + \text{h.c.}$$

$C^{(5)}/\Lambda \leq 10^{-15}$ GeV^{-1} from neutrino mass differences

$$L_L = (\nu_L, \ell_L)^T \quad \widetilde{H} = i\sigma_2 H^*$$

Assumptions

- **Lorenz and Poincare invariance, point like Lagrangian**

- **gauge group is the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ and the linear realization of the mechanism of electroweak symmetry breaking**

- **the only remaining degrees of freedom are the SM fields**

- **the scale of New physics $\Lambda \gg v_{SM}$**

-**various assumptions on flavor structure (MVF, $U(3)^5$…)**

Several issues

Operator basis ?

Squired terms $(1/\Lambda^2)^2$?

NLO corrections ?

Unitarity and validity of computation for particular observables ?

…

Operator basis

Operator basis, all operators allowed by the symmetries and then reduced using equations of motion (field redefinition) , integration by parts identities, and Fierz transformations

At dimension-6 there are 59 (Warsaw basis) independent CP conserving operators for one generation of fermions excluding baryon and lepton number violating operators
(There are about 80 operators in the original Buchmuller-Wyler basis)

B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, JHEP 10 (2010) 085

Number gauge-invariant operators is 84 for 1 generation of fermions,
76 baryon- and lepton-number conserving operators, 59 CP conserving operators

B. Henning, X. Lu, T. Melia, and H. Murayama 1512.03433, JHEP 09, 019 (2019)

2499 dimension-6 operators for three generations
(1350 of which CP-even and 1149 CP-odd)
Global SMEFT fit will have to explore a huge parameter space with potentially a large number of flat directions.

R. Alonso, E. E. Jenkins, A. V. Manohar, and M. Trott, JHEP 04 (2014) 159

One can split all the operators on symmetry preserve (B and L number, FCNC) and symmetry violating sectors (much suppressed Wilson coefficients).

Simple example

Einhorn, Wudka 1307.0478

Model: $L = ½ (\partial_\mu \varphi)^2 - ¼ \lambda \varphi^4$

Equation of motion: $\partial_\mu \partial^\mu \varphi + \lambda \varphi^3 = 0$

Operators at D=6 : φ^6; $(\partial^2 \varphi)^2$; $\varphi^2 (\partial \varphi)^2$

How many independent operators?

Simple example

Einhorn, Wudka 1307.0478

Model: $L = \frac{1}{2} (\partial_\mu \varphi)^2 - \frac{1}{4} \lambda \varphi^4$

Equation of motion: $\partial_\mu \partial^\mu \varphi + \lambda \varphi^3 = 0$

Operators at D=6 : φ^6; $(\partial^2 \varphi)^2$; $\varphi^2 (\partial \varphi)^2$

How many independent operators?

1. $(\partial^2 \varphi)^2 - \lambda^2 \varphi^6 = (\partial^2 \varphi - \lambda \varphi^3)(\partial^2 \varphi + \lambda \varphi^3) = 0$

2. $0 = \partial^\mu (\varphi \varphi^2 \partial_\mu \varphi) = \varphi^2 (\partial_\mu \varphi)^2 + \varphi \partial^\mu (\varphi^2 \partial_\mu \varphi) = 3 \varphi^2 (\partial \varphi)^2 + \varphi^3 \partial^2 \varphi = 3 \varphi^2 (\partial \varphi)^2 - \lambda \varphi^6$

Both operators $(\partial^2 \varphi)^2$ and $\varphi^2 (\partial \varphi)^2$ are equivalent to the operator $\lambda \varphi^6$

‘Warsaw’ basis

B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, JHEP 10 (2010) 085

15 4-boson operators; 19 2-boson&2-fermion operators

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\sigma^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\sigma^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\sigma^I \widetilde{H}\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p\sigma^I\gamma^\mu q_r)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
Q_{HWB}	$H^\dagger\sigma^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\sigma^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

25 4-fermion operators

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\sigma^I q_r)(\bar{q}_s\gamma^\mu\sigma^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\sigma^I l_r)(\bar{q}_s\gamma^\mu\sigma^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

SMEFT in the TOP sector

28 operators are involved directly to the top sector

Aguilar Saavedra et al.,1802.07237

2-Quark Operators (9)

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

4-Quark Operators (11)

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

2-Quark-2-Lepton Operators (8)

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

Notations

$$\mathcal{L} = \sum_a \left(\frac{C_a}{\Lambda^2} {}^{\ddagger}O_a + \text{h.c.} \right) + \sum_b \frac{C_b}{\Lambda^2} O_b$$

In addition 5 baryon- and lepton-number-violating operators:

$$^{\ddagger}O_{duq}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{q^c}_{k\gamma} \varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$^{\ddagger}O_{qqu}^{(ijkl)} = (\overline{q^c}_{i\alpha} \varepsilon q_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma},$$
$$^{\ddagger}O_{qqq}^{1(ijkl)} = (\overline{q^c}_{i\alpha} \varepsilon q_{j\beta})(\overline{q^c}_{k\gamma} \varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$^{\ddagger}O_{qqq}^{3(ijkl)} = (\overline{q^c}_{i\alpha} \tau^I \varepsilon q_{j\beta})(\overline{q^c}_{k\gamma} \tau^I \varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$^{\ddagger}O_{duu}^{(ijkl)} = (\overline{d^c}_{i\alpha} u_{j\beta})(\overline{u^c}_{k\gamma} e_l)\,\epsilon^{\alpha\beta\gamma},$$

Squired terms $(1/\Lambda^2)^2$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{C_j^{(8)}}{\Lambda^4} O_j^{(8)} + \ldots$$

$$\sigma = \sigma^{\rm SM} + \sum_i \left(\frac{c_i^{(6)}}{\Lambda^2} \sigma_i^{(6\times {\rm SM})} + {\rm h.c.} \right) + \sum_{ij} \frac{c_i^{(6)} c_j^{(6)*}}{\Lambda^4} \sigma_{ij}^{(6\times 6)} + \sum_j \left(\frac{c_j^{(8)}}{\Lambda^4} \sigma_j^{(8\times {\rm SM})} + {\rm h.c.} \right) + \ldots$$

1. Without an operator basis at dimension eight for the higher-dimensional contribution, it is not possible to calculate the fulll term of $1/\Lambda^4$, and it should thus be treated as an uncertainty.

2. In some cases, the interference between SM amplitudes and EFT ones could be suppressed (for instance, for certain helicities) or even vanishingly small (for instance, in the case of FCNCs). The dominant contribution could then arise at the quadratic level.

3. Repeat this procedure twice, with and without including the quadratic EFT contributions. The comparison between those two sets of results can explicitly establish where quadratic dimension-six EFT contributions are subleading compared to linear ones.

But the problem is even more involved since the SMEFT contributions come from production, from decay, and from the width in Breit-Wiegner denominator

SMEFT at NLO

$$\sigma(\mu_0) = \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i(\mu_0)\sigma_i(\mu_0) + \sum_{i,j} \frac{1\text{TeV}^4}{\Lambda^4} C_i(\mu_0)C_j(\mu_0)\sigma_{ij}(\mu_0)$$

EFT with Dim 6, 8 … operators formally are not renormalizable. But the renormalization can be performed consistently in each order in $1/\Lambda^2$. Due the gauge invariance and other symmetries the counter-terms have the same structure as the original operators. Because of NLO QCD and EW corrections the operators are mixed.

M. Ghezzi, R. Gomez-Ambrosio, G. Passarino and S. Uccirati, 1505.03706

C. Hartmann and M. Trott, 1507.03568

….

59×59 anomalous dimension mixing matrix for the Wilson coefficients

E. E. Jenkins, A. V. Manohar and M. Trott, 1308.2627, 1310.4838

Directions of studies

1. Limits on Wilson coefficients of the operators contributing to certain process/processes

2. Global analysis
(concrete operator may contribute to different processes, several operator may contribute to the same process)

3. Limits on a concrete set of operators following from a certain UV model

NLO corrections to h → γγ decay in SMEFT

Dedes, Paraskevas, Rosiek, Suxho, Trifyllis, 1805.00302

$$\mathcal{R}_{h\to\gamma\gamma} = \frac{\Gamma(\text{SMEFT}, h\to\gamma\gamma)}{\Gamma(\text{SM}, h\to\gamma\gamma)} \equiv 1 + \delta\mathcal{R}_{h\to\gamma\gamma}$$

$$\Gamma(\text{SM}, h\to\gamma\gamma) = \frac{G_F\,\alpha_{\text{EM}}^2\,M_h^3}{128\sqrt{2}\pi^3}|I_{\gamma\gamma}|^2 \qquad I_{\gamma\gamma} \equiv I_{\gamma\gamma}(r_f, r_W) = \sum_f Q_f^2 N_{c,f} A_{1/2}(r_f) - A_1(r_W)$$

$$A_{1/2}(r_f) = 2r_f[1+(1-r_f)f(r_f)]\,, \qquad A_1(r_W) = 2 + 3r_W[1+(2-r_W)f(r_W)]$$

$$f(r) = \begin{cases} \arcsin^2\left(\frac{1}{\sqrt{r}}\right), & r\geq 1\,, \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-r}}{1-\sqrt{1-r}}\right) - i\pi\right]^2, & r\leq 1 \end{cases} \qquad r_f \equiv \frac{4m_f^2}{M_h^2}\,, \qquad r_W \equiv \frac{4M_W^2}{M_h^2}$$

$$\begin{aligned}
\delta\mathcal{R}_{h\to\gamma\gamma} = \sum_{i=1}^{6}\delta\mathcal{R}_{h\to\gamma\gamma}^{(i)} \simeq\ & 0.06\left(\frac{C_{1221}^{\ell\ell} - C_{11}^{\varphi\ell(3)} - C_{22}^{\varphi\ell(3)}}{\Lambda^2}\right) + 0.12\left(\frac{C^{\varphi\Box} - \frac{1}{4}C^{\varphi D}}{\Lambda^2}\right) \\
& - 0.01\left(\frac{C_{22}^{e\varphi} + 4C_{33}^{e\varphi} + 5C_{22}^{u\varphi} + 2C_{33}^{d\varphi} - 3C_{33}^{u\varphi}}{\Lambda^2}\right) \\
& - \left[48.04 - 1.07\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}}{\Lambda^2} - \left[14.29 - 0.12\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}}{\Lambda^2} \\
& + \left[26.62 - 0.52\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}}{\Lambda^2} \\
& + \left[0.16 - 0.22\log\frac{\mu^2}{M_W^2}\right]\frac{C^{W}}{\Lambda^2} \\
& + \left[2.11 - 0.84\log\frac{\mu^2}{M_W^2}\right]\frac{C_{33}^{uB}}{\Lambda^2} + \left[1.13 - 0.45\log\frac{\mu^2}{M_W^2}\right]\frac{C_{33}^{uW}}{\Lambda^2} \\
& - \left[0.03 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C_{22}^{uB}}{\Lambda^2} - \left[0.01 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C_{22}^{uW}}{\Lambda^2} \\
& + \left[0.03 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C_{33}^{dB}}{\Lambda^2} - \left[0.02 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C_{33}^{dW}}{\Lambda^2} \\
& + \left[0.02 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C_{33}^{eB}}{\Lambda^2} - \left[0.01 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C_{33}^{eW}}{\Lambda^2} + \ldots\,,
\end{aligned}$$

$$\mu = M_W$$

Largest corrections and strongest limits for the operators appeared at tree level

$$\frac{|C^{\varphi B}|}{\Lambda^2} \lesssim \frac{0.003}{(1\ \text{TeV})^2}\,, \qquad \frac{|C^{\varphi W}|}{\Lambda^2} \lesssim \frac{0.011}{(1\ \text{TeV})^2}\,, \qquad \frac{|C^{\varphi WB}|}{\Lambda^2} \lesssim \frac{0.006}{(1\ \text{TeV})^2}\,,$$

$$\frac{|C_{33}^{uB}|}{\Lambda^2} \lesssim \frac{0.071}{(1\ \text{TeV})^2}\,, \qquad \frac{|C_{33}^{uW}|}{\Lambda^2} \lesssim \frac{0.133}{(1\ \text{TeV})^2}\,.$$

Weaker limits for the operators appeared at loop level

NLO corrections to h → bb decay in SMEFT

Cullen, Pecjak, Scott 1904.06358

$$\Gamma(h \to b\bar{b}) \equiv \Gamma = \Gamma^{(0)} + \Gamma^{(1)}$$

$$V^{\rm SM}(H) = \lambda(H^\dagger H - v^2/2)^2 \qquad \langle H^\dagger H\rangle \equiv \frac{1}{2}v_T^2 = \frac{v^2}{2}\left(1 + \frac{3C_H \hat{v}_T^2}{4\lambda}\right) \qquad Q_H = (H^\dagger H)^3$$

$$\mu\frac{d}{d\mu}C_i(\mu) = \sum_j \gamma_{ij}C_j \qquad \tilde{C}_i(\mu) \equiv \Lambda_{\rm NP}^2 C_i(\mu) \qquad \hat{v}_T \equiv \frac{2M_W \hat{s}_w}{e}$$

$$\Gamma^{(4,0)} = \frac{N_c m_H m_b^2}{8\pi \hat{v}_T^2},$$

$$\Gamma^{(6,0)} = 2\Gamma^{(4,0)}\left[C_{H\Box} - \frac{C_{HD}}{4}\left(1 - \frac{\hat{c}_w^2}{\hat{s}_w^2}\right) + \frac{\hat{c}_w}{\hat{s}_w}C_{HWB} - \frac{\hat{v}_T}{m_b}\frac{C_{bH}}{\sqrt{2}}\right]\hat{v}_T^2$$

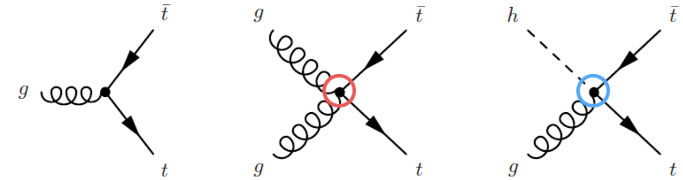
Size of relevant NLO corrections to different terms in LO decay width

	SM	$\tilde{C}_{HWB}$	$\tilde{C}_{H\Box}$	$\tilde{C}_{bH}$	$\tilde{C}_{HD}$
NLO QCD-QED	18.2%	17.9%	18.2%	18.2%	18.2%
NLO large-m_t	-3.1%	-4.6%	3.2%	3.5%	-9.0%
NLO remainder	-2.2%	-1.9%	-1.2 %	0.6%	-2.0%
NLO correction	12.9%	11.3%	20.2%	22.3%	7.1%

SMEFT operators lead to additional vertexes (i=j=3)

$$\mathcal{L}_{gtt} = -g_s \bar{t}\,\frac{\lambda^a}{2}\gamma^\mu t\, G^a_\mu - g_s \bar{t}\,\lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t}\left(d_V^g + i d_A^g \gamma_5\right) t\, G^a_\mu$$

$$^{\ddagger}O^{(ij)}_{uG} = \left(\bar{q}_i \sigma^{\mu\nu} T^A u_j\right) \tilde{\varphi} G^A_{\mu\nu}$$



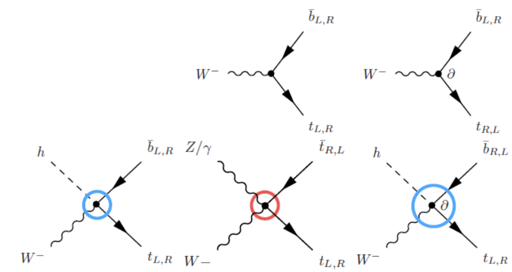
$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^\mu \left(f_V^L P_L + f_V^R P_R\right) \mathrm{t} W^-_\mu - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{\sigma^{\mu\nu}\partial_\nu W^-_\mu}{M_W}\left(f_T^L P_L + f_T^R P_R\right)\mathrm{t} + \mathrm{h.c.}$$

$$^{\ddagger}O^{(ij)}_{u\varphi} = \bar{q}_i u_j \tilde{\varphi}\left(\varphi^\dagger \varphi\right),$$

$$^{\ddagger}O^{(ij)}_{\varphi ud} = (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i \gamma^\mu d_j),$$

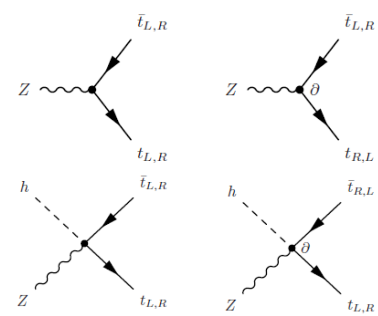
$$^{\ddagger}O^{(ij)}_{uW} = \left(\bar{q}_i \sigma^{\mu\nu} \tau^I u_j\right) \tilde{\varphi} W^I_{\mu\nu}$$

$$^{\ddagger}O^{(ij)}_{dW} = \left(\bar{q}_i \sigma^{\mu\nu} \tau^I d_j\right) \varphi W^I_{\mu\nu}$$



$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\gamma^\mu\left(X^L_{tt} P_L + X^R_{tt} P_R - 2 s_W^2 Q_t\right) t\, Z_\mu$$
$$-\frac{g}{2c_W}\bar{t}\,\frac{i\sigma^{\mu\nu} q_\nu}{M_Z}\left(d_V^Z + i d_A^Z \gamma_5\right) t\, Z_\mu\,,$$

$$\mathcal{L}_{\gamma tt} = -eQ_t \bar{t}\gamma^\mu t\, A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu} q_\nu}{m_t}\left(d_V^\gamma + i d_A^\gamma \gamma_5\right) t\, A_\mu$$



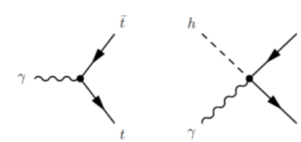
$$O^{1(ij)}_{\varphi q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j),$$

$$O^{3(ij)}_{\varphi q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j),$$

$$O^{(ij)}_{\varphi u} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j),$$

$$^{\ddagger}O^{(ij)}_{uW} = \left(\bar{q}_i \sigma^{\mu\nu} \tau^I u_j\right) \tilde{\varphi} W^I_{\mu\nu},$$

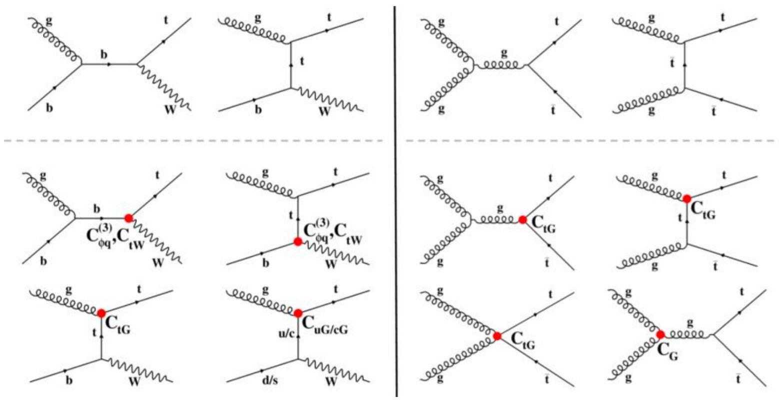
$$^{\ddagger}O^{(ij)}_{uB} = \left(\bar{q}_i \sigma^{\mu\nu} u_j\right) \tilde{\varphi} B_{\mu\nu}$$



Top quark pair (tt) and single top quark in association with a W boson (tW)

tW **tt**

CMS 1903.11144



$$O_{\phi q}^{(3)} = (\phi^+ \tau^i D_\mu \phi)(\bar{q}\gamma^\mu \tau^i q), \qquad L_{eff} = \frac{C_{\phi q}^{(3)}}{\sqrt{2}\Lambda^2} g v^2 \bar{b}\gamma^\mu P_L t W_\mu^- + h.c.,$$

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^i t)\tilde{\phi} W_{\mu\nu}^i, \qquad L_{eff} = -2\frac{C_{tW}}{\Lambda^2} v \bar{b}\sigma^{\mu\nu} P_R t \partial_\nu W_\mu^- + h.c.,$$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^a t)\tilde{\phi} G_{\mu\nu}^a, \qquad L_{eff} = \frac{C_{tG}}{\sqrt{2}\Lambda^2} v\,(\bar{t}\sigma^{\mu\nu}\lambda^a t)\, G_{\mu\nu}^a + h.c.,$$

$$O_G = f_{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}, \qquad L_{eff} = \frac{C_G}{\Lambda^2} f_{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu},$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^a t)\tilde{\phi} G_{\mu\nu}^a, \qquad L_{eff} = \frac{C_{u(c)G}}{\sqrt{2}\Lambda^2} v\,(\bar{u}\,(\bar{c})\,\sigma^{\mu\nu}\lambda^a t)\, G_{\mu\nu}^a + h.c.$$

Czakon, Mitov 2014 (NNLO)

$$\sigma_{SM}^{t\bar{t}} = 832^{+20}_{-29}\,(\text{scales}) \pm 35\,(\text{PDF} + \alpha_S)\ \text{pb}$$

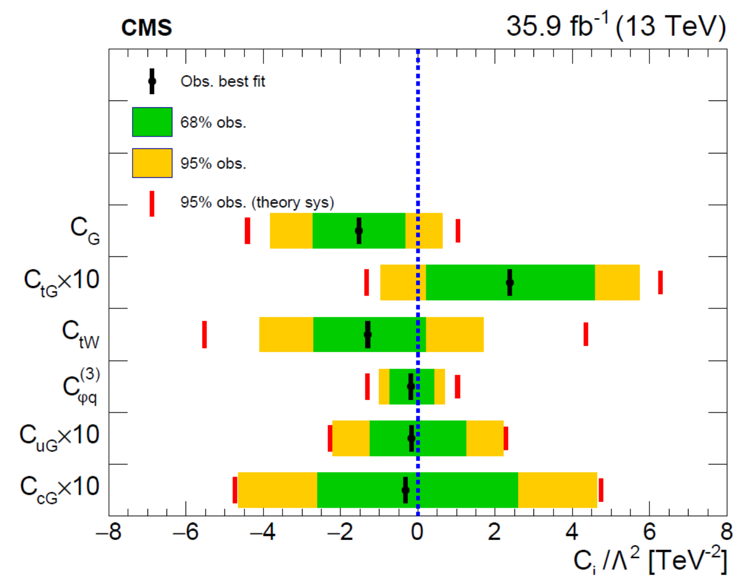
Kidonakis, 1506.04072 (NNLO)

$$\sigma_{SM}^{tW} = 71.7 \pm 1.8\,(\text{scales}) \pm 3.4\,(\text{PDF} + \alpha_S)\ \text{pb}$$

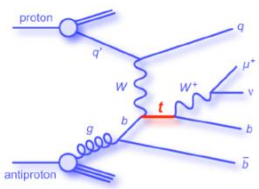
For the first time, both tt and tW production are used simultaneously in a model independent search for effective couplings in SMEFT approach (constraints presented, obtained by considering one operator at a time)

Durieux, Maltoni, Zhang, 1412.7166; Franzosi , Zhang, 1503.08841; Zhang, 1601.06163; CMS 1903.11144

Channel	Contribution	C_G	$C_{\phi q}^{(3)}$	C_{tW}	C_{tG}	C_{uG}	C_{cG}
$t\bar{t}$	$\sigma_i^{(1)-LO}$	31.9 pb	—	—	137 pb	—	—
	$K^{(1)}$	—	—	—	1.48	—	—
	$\sigma_i^{(2)-LO}$	102.3 pb	—	—	16.4 pb	—	—
	$K^{(2)}$	—	—	—	1.44	—	—
tW	$\sigma_i^{(1)-LO}$	—	6.7 pb	−4.5 pb	3.3 pb	0	0
	$K^{(1)}$	—	1.32	1.27	1.27	0	0
	$\sigma_i^{(2)-LO}$	—	0.2 pb	1 pb	1.2 pb	16.2 pb	4.6 pb
	$K^{(2)}$	—	1.31	1.18	1.06	1.27	1.27



Anomalous Wtb couplings



Operators contributing to tWb interactions

Boos, Dubinin, Sachwitz, Schreiber 0001048;
Aguilar-Saavedra 0811.3842

$$O_{\phi q}^{(3,3+3)} = \frac{i}{2}\left[\phi^\dagger(\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I)\phi\right](\bar{q}_{L3}\gamma^\mu \tau^I q_{L3}), \qquad O_{\phi\phi}^{33} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{t}_R \gamma^\mu b_R),$$

$$O_{dW}^{33} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I b_R)\phi\, W_{\mu\nu}^I, \qquad O_{uW}^{33} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I t_R)\tilde{\phi}\, W_{\mu\nu}^I,$$

Kane, Ladinski, Yaun

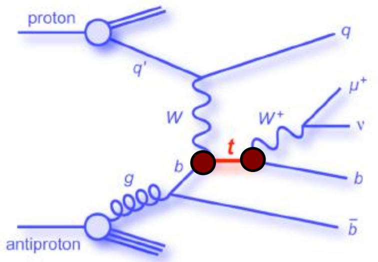
$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^\mu\left(f_V^L P_L + f_V^R P_R\right)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{\sigma^{\mu\nu}\partial_\nu W_\mu^-}{M_W}\left(f_T^L P_L + f_T^R P_R\right)t + \text{h.c.}$$

where $f_{LV} = V_{tb} + C_{\phi q}^{(3,3+3)*}\frac{v^2}{\Lambda^2}, \quad f_{RV} = \frac{1}{2}C_{\phi\phi}^{33*}\frac{v^2}{\Lambda^2}, \quad f_{LT} = \sqrt{2}C_{dW}^{33*}\frac{v^2}{\Lambda^2}, \quad f_{RT} = \sqrt{2}C_{uW}^{33}\frac{v^2}{\Lambda^2}.$

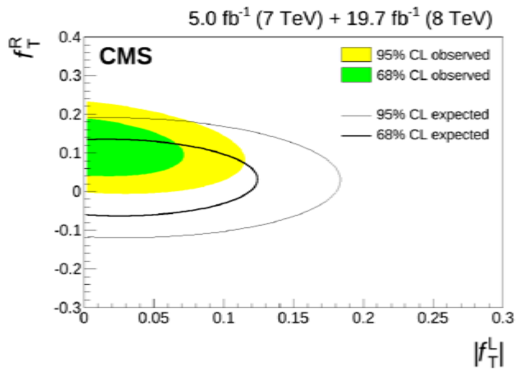
CM: $f_{LV} = Vtb$, $f_{RV} = 0$, $f_{LT} = 0$, $f_{RT} = 0$

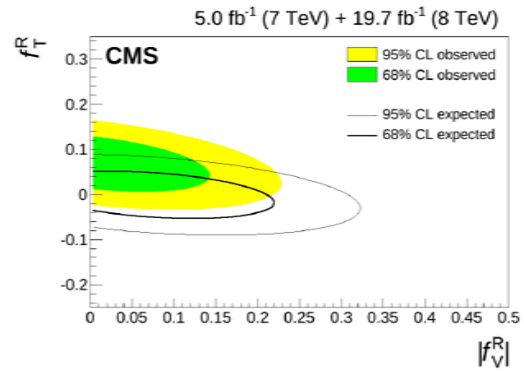
Natural size $|1-f_L^V|, f_R^V \sim v^2/\Lambda^2$ **Natural size $f_L^T, f_R^T \sim v^2/\Lambda^2$**

Anomalous Wtb couplings

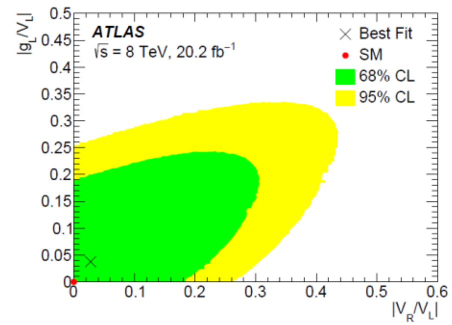


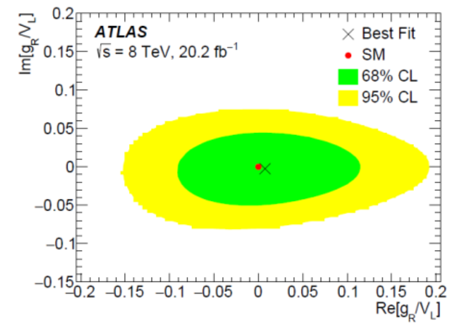
CMS limits



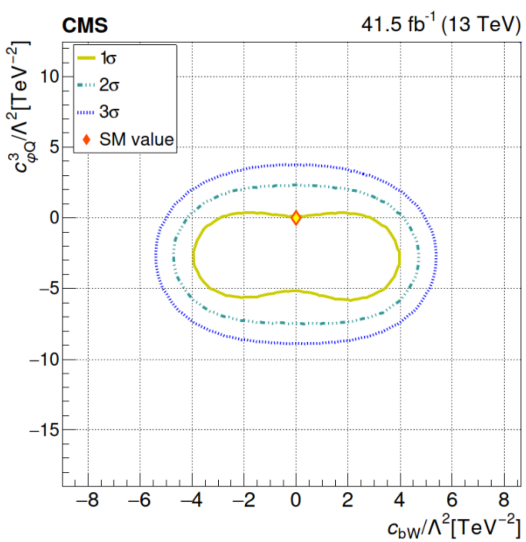


ATLAS limits





CMS limits (2012.04120 13 TeV 41.5 fb^{-1})



ATLAS limits (2403.02126 13 TeV 140 fb^{-1})

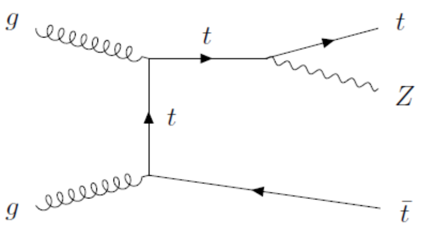
$C^3_{\phi Q}$	[–0.87, 1.42]
$\Re C_{tW}$	[–0.9, 1.4]
$C^{(3)}_{HQ}$	[–0.95, 2.0]

ttZ in SMEFT

Bylund, Maltoni, Tsinikos, Vryonidou, Zhang, 1601.08193

Contributions in [fb]

13TeV	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$
$\sigma_{i,LO}^{(1)}$	$286.7^{+38.2\%}_{-25.5\%}$	$78.3^{+40.4\%}_{-26.6\%}$	$51.6^{+40.1\%}_{-26.4\%}$	$-0.20(3)^{+88.0\%}_{-230.0\%}$
$\sigma_{i,NLO}^{(1)}$	$310.5^{+5.4\%}_{-9.7\%}$	$90.6^{+7.1\%}_{-11.0\%}$	$57.5^{+5.8\%}_{-10.3\%}$	$-1.7(2)^{+31.3\%}_{-49.1\%}$
K-factor	1.08	1.16	1.11	8.5
$\sigma_{i,LO}^{(2)}$	$258.5^{+49.7\%}_{-30.4\%}$	$2.8(1)^{+39.7\%}_{-26.9\%}$	$2.9(1)^{+39.7\%}_{-26.7\%}$	$20.9^{+44.3\%}_{-28.3\%}$
$\sigma_{i,NLO}^{(2)}$	$244.5^{+4.2\%}_{-8.1\%}$	$3.8(3)^{+13.2\%}_{-14.4\%}$	$3.9(3)^{+13.8\%}_{-14.6\%}$	$24.2^{+6.2\%}_{-11.2\%}$
$\sigma_{i,LO}^{(1)}/\sigma_{SM,LO}$	$0.376^{+0.3\%}_{-0.3\%}$	$0.103^{+1.9\%}_{-1.8\%}$	$0.0677^{+1.7\%}_{-1.6\%}$	$-0.00026(4)^{+89.5\%}_{-167.2\%}$
$\sigma_{i,NLO}^{(1)}/\sigma_{SM,NLO}$	$0.353^{+1.3\%}_{-2.4\%}$	$0.103^{+0.7\%}_{-0.8\%}$	$0.0654^{+1.1\%}_{-2.1\%}$	$-0.0020(2)^{+22.9\%}_{-38.0\%}$
$\sigma_{i,LO}^{(2)}/\sigma_{i,LO}^{(1)}$	$0.902^{+8.4\%}_{-6.7\%}$	$0.036(1)^{+0.2\%}_{-1.1\%}$	$0.056(2)^{+0.6\%}_{-0.3\%}$	$-104(16)^{+60.8\%}_{-815.2\%}$
$\sigma_{i,NLO}^{(2)}/\sigma_{i,NLO}^{(1)}$	$0.787^{+3.3\%}_{-12.8\%}$	$0.042(4)^{+5.6\%}_{-3.9\%}$	$0.067(6)^{+7.6\%}_{-4.8\%}$	$-14(1)^{+29.0\%}_{-29.1\%}$



$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \sum_{i\le j} \frac{C_i C_j}{(\Lambda/1\text{TeV})^4}\sigma_{ij}^{(2)}$$

Contributing operator combinations
(not restricted from other searches)

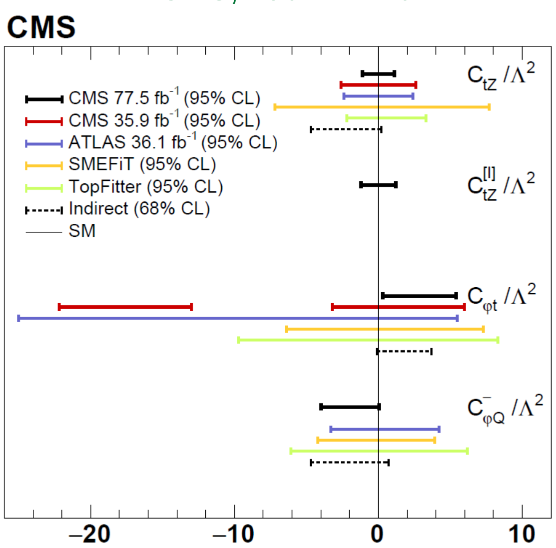
$$c_{tZ} = \text{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)$$

$$c_{tZ}^{[I]} = \text{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)$$

$$c_{\phi t} = C_{\phi t} = C_{\phi u}^{(33)}$$

$$c_{\phi Q}^{-} = C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)},$$

CMS, 1907.11270



tttt in SMEFT

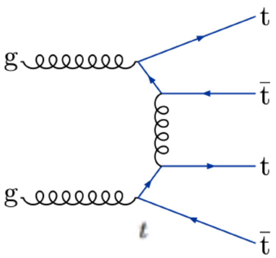
Relevant set of 4 top operators

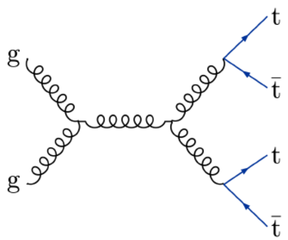
$$\mathcal{O}^1_{\rm tt} = (\bar{\rm t}_{\rm R}\gamma^\mu {\rm t}_{\rm R})\left(\bar{\rm t}_{\rm R}\gamma_\mu {\rm t}_{\rm R}\right),$$

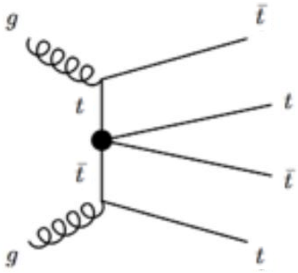
$$\mathcal{O}^1_{\rm QQ} = (\bar{\rm Q}_{\rm L}\gamma^\mu {\rm Q}_{\rm L})\left(\bar{\rm Q}_{\rm L}\gamma_\mu {\rm Q}_{\rm L}\right),$$

$$\mathcal{O}^1_{\rm Qt} = (\bar{\rm Q}_{\rm L}\gamma^\mu {\rm Q}_{\rm L})\left(\bar{\rm t}_{\rm R}\gamma_\mu {\rm t}_{\rm R}\right),$$

$$\mathcal{O}^8_{\rm Qt} = \left(\bar{\rm Q}_{\rm L}\gamma^\mu T^A {\rm Q}_{\rm L}\right)\left(\bar{\rm t}_{\rm R}\gamma_\mu T^A {\rm t}_{\rm R}\right)$$







Alwall et al.,1405.0301

NLO cross section $\sigma^{\rm SM}_{\rm t\bar{t}t\bar{t}} = 9.2\ {\rm fb}$

CMS, 1906.02805

$$\sigma_{\rm t\bar{t}t\bar{t}} = \sigma^{\rm SM}_{\rm t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_k C_k \sigma^{(1)}_k + \frac{1}{\Lambda^4}\sum_{j\le k} C_j C_k \sigma^{(2)}_{j,k}$$

Operator	$\sigma^{(1)}_k$ (fb TeV^2)	$\sigma^{(2)}_{j,k}$ (fb TeV^4) $\mathcal{O}^1_{\rm tt}$	$\mathcal{O}^1_{\rm QQ}$	$\mathcal{O}^1_{\rm Qt}$	$\mathcal{O}^8_{\rm Qt}$
$\mathcal{O}^1_{\rm tt}$	0.39	5.59	0.36	−0.39	0.3
$\mathcal{O}^1_{\rm QQ}$	0.47		5.49	−0.45	0.13
$\mathcal{O}^1_{\rm Qt}$	0.03			1.9	−0.08
$\mathcal{O}^8_{\rm Qt}$	0.28				0.45

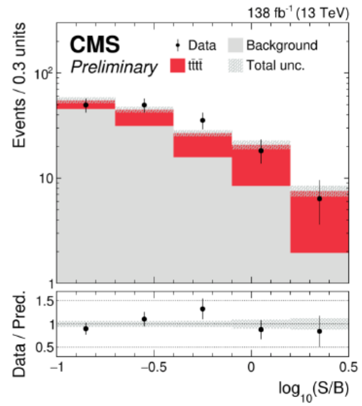
95% CL intervals for Wilson coefficients

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\rm tt}$	[−2.0, 1.8]	[−2.1, 2.0]
$\mathcal{O}^1_{\rm QQ}$	[−2.0, 1.8]	[−2.2, 2.0]
$\mathcal{O}^1_{\rm Qt}$	[−3.3, 3.2]	[−3.5, 3.5]
$\mathcal{O}^8_{\rm Qt}$	[−7.3, 6.1]	[−7.9, 6.6]

4 tops in SM

2212.03259

$\sqrt{s}$ (TeV)	$\sigma^{\rm NLO}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\rm NLO+NLL}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\rm NLO+NLL'}_{t\bar{t}t\bar{t}}$ (fb)	$K_{\rm NLL'}$
13	$11.00(2)^{+25.2\%}_{-24.5\%}$ fb	$11.46(2)^{+21.3\%}_{-17.7\%}$ fb	$12.73(2)^{+4.1\%}_{-11.8\%}$ fb	1.16
13.6	$13.14(2)^{+25.1\%}_{-24.4\%}$ fb	$13.81(2)^{+20.7\%}_{-20.1\%}$ fb	$15.16(2)^{+2.5\%}_{-11.9\%}$ fb	1.15
$\sqrt{s}$ (TeV)	$\sigma^{\rm NLO(QCD+EW)}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\rm NLO(QCD+EW)+NLL}_{t\bar{t}t\bar{t}}$ (fb)	$\sigma^{\rm NLO(QCD+EW)+NLL'}_{t\bar{t}t\bar{t}}$ (fb)	$K_{\rm NLL'}$
13	$11.64(2)^{+23.2\%}_{-22.8\%}$ fb	$12.10(2)^{+19.5\%}_{-16.3\%}$ fb	$13.37(2)^{+3.6\%}_{-11.4\%}$ fb	1.15
13.6	$13.80(2)^{+22.6\%}_{-22.9\%}$ fb	$14.47(2)^{+18.5\%}_{-19.1\%}$ fb	$15.82(2)^{+1.5\%}_{-11.6\%}$ fb	1.15

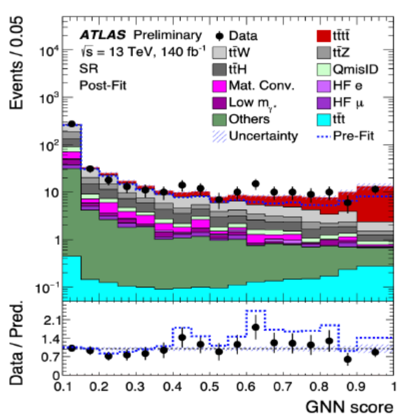


5.5 (4.9) σ observed (expected)

CMS PAS TOP-22-013

$$\sigma(pp \to t\bar{t}t\bar{t}) = 17.9\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.4}_{-2.1}\,(\text{syst})\,\text{fb}$$

~ 5.5 σ



6.1 (4.3) σ observed (expected)

$$\sigma_{t\bar{t}t\bar{t}} = 22.5\,^{+6.6}_{-5.6}$$

ATLAS 2303.15061

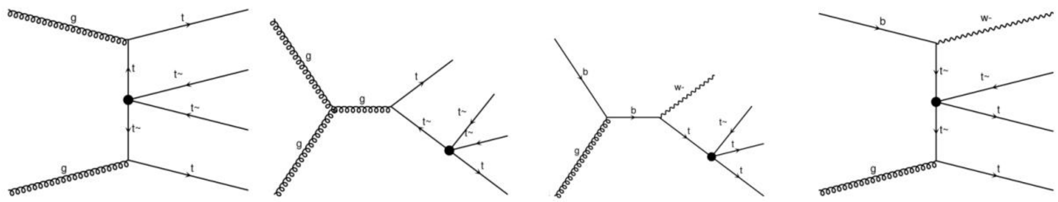
~ 6.1 σ

4 top discovery

4tops and 3tops

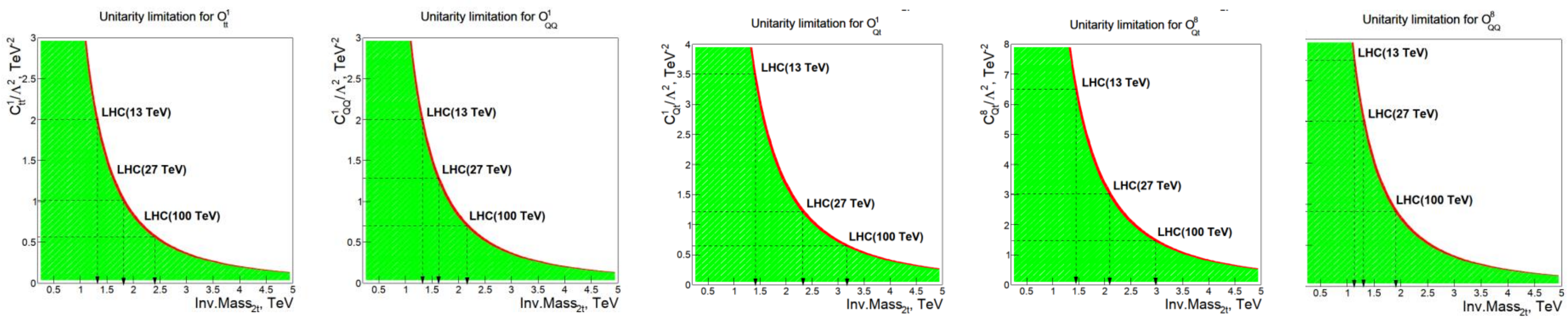
E.B., L.Dudko 2107.07629;
A.Aleshko, E.B., V.Bunichev, L.Dudko 2309.12514

$$\begin{aligned}
O^1_{tt} &= (\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R),\\
O^1_{QQ} &= (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L),\\
O^1_{Qt} &= (\bar{Q}_L\gamma^\mu Q_L)(\bar{t}_R\gamma_\mu t_R),\\
O^8_{Qt} &= (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{t}_R\gamma_\mu T^A t_R),\\
O^8_{QQ} &= (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{Q}_L\gamma_\mu T^A Q_L),
\end{aligned}$$



(a) (b)

Partial wave unitarity bounds $|a_0| = C_i/\Lambda^2 \cdot k_i \cdot M_{tt} < ½$



13 TeV, 138 fb^{-1}

model	C^1_{tt}	C^1_{QQ}	C^1_{Qt}	C^8_{Qt}	C^8_{QQ}
4t,nocut,1D	[-1.1,1.1]	[-2.2,2.1]	[-2.0,2.0]	[-5.7,4.6]	[-5.0,4.8]
4t,cut,1D	[-1.2,1.2]	[-2.4,2.3]	[-2.2,2.2]	[-6.8,5.0]	[-6.0,5.7]
3t,nocut,1D	[-3.7,3.7]	[-2.5,2.9]	[-2.6,2.7]	[-5.3,5.6]	[-5.1,6.1]
3t,cut,1D	[-4.3,4.2]	[-2.9,3.2]	[-3.1,3.2]	[-6.9,7.3]	[-6.4,7.7]
3+4t,nocut,1D	[-1.1,1.0]	[-2.0,2.0]	[-1.8,1.8]	[-4.7,4.2]	[-4.2,4.5]
3+4t,cut,1D	[-1.2,1.2]	[-2.2,2.2]	[-2.1,2.1]	[-5.8,4.8]	[-5.2,5.4]
4t,nocut,5D	[-0.95,0.90]	[-1.8,1.7]	[-1.6,1.6]	[-4.8,3.6]	[-4.2,4.0]
4t,cut,5D	[-1.0,1.0]	[-2.0,1.9]	[-1.8,1.9]	[-5.7,4.1]	[-4.6,4.4]
3t,nocut,5D	[-3.1,3.0]	[-2.0,2.4]	[-2.1,2.2]	[-4.3,4.6]	[-4.2,5.1]
3t,cut,5D	[-3.5,3.4]	[-2.3,2.7]	[-2.5,2.7]	[-5.6,6.1]	[-5.1,6.5]
3+4t,nocut,5D	[-0.95,0.90]	[-1.6,1.6]	[-1.5,1.5]	[-4.0,3.3]	[-3.5,3.7]
3+4t,cut,5D	[-1.0,1.0]	[-1.8,1.8]	[-1.7,1.7]	[-4.8,3.8]	[-4.1,4.3]

Expected 1D limits with unitary cuts

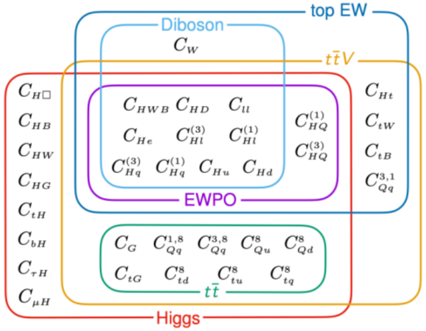
Energy, model	C^1_{tt}	C^1_{QQ}	C^1_{Qt}	C^8_{Qt}	C^8_{QQ}
13 TeV, 4t	[-1.2, 1.2]	[-2.4, 2.3]	[-2.2, 2.2]	[-6.8, 5.0]	[-6.0, 5.7]
13 TeV, 3t	[-4.3, 4.2]	[-2.9, 3.2]	[-3.1, 3.2]	[-6.9, 7.3]	[-6.4, 7.7]
13 TeV, 3+4t	[-1.2, 1.2]	[-2.2, 2.2]	[-2.1, 2.1]	[-5.8, 4.8]	[-5.2, 5.4]
14 TeV, 4t	[-1.1, 1.0]	[-2.1, 2.0]	[-1.9, 1.9]	[-5.8, 4.2]	[-5.2, 4.9]
14 TeV, 3t	[-2.5, 2.5]	[-1.6, 2.0]	[-1.8, 1.9]	[-3.9, 4.4]	[-3.7, 5.1]
14 TeV, 3+4t	[-1.1, 1.0]	[-1.5, 1.7]	[-1.5, 1.6]	[-3.8, 3.6]	[-3.5, 4.3]
27 TeV, 4t	[-0.90, 0.83]	[-1.7, 1.6]	[-1.6, 1.6]	[-4.9, 3.6]	[-4.4, 4.2]
27 TeV, 3t	[-2.0, 2.0]	[-1.3, 1.5]	[-1.4, 1.6]	[-3.3, 3.9]	[-2.7, 4.1]
27 TeV, 3+4t	[-0.88, 0.83]	[-1.2, 1.3]	[-1.3, 1.3]	[-3.2, 3.2]	[-2.6, 3.5]
100 TeV, 4t	[-0.68, 0.66]	[-1.3, 1.3]	[-1.2, 1.2]	[-3.8, 3.0]	[-3.7, 3.6]
100 TeV, 3t	[-1.3, 1.4]	[-0.89, 1.0]	[-1.0, 1.1]	[-2.1, 2.6]	[-1.8, 2.7]
100 TeV, 3+4t	[-0.67, 0.64]	[-0.85, 0.94]	[-0.93, 0.94]	[-2.1, 2.3]	[-1.8, 2.5]

Similar results for 4tops Degrande et.al 2402.06528

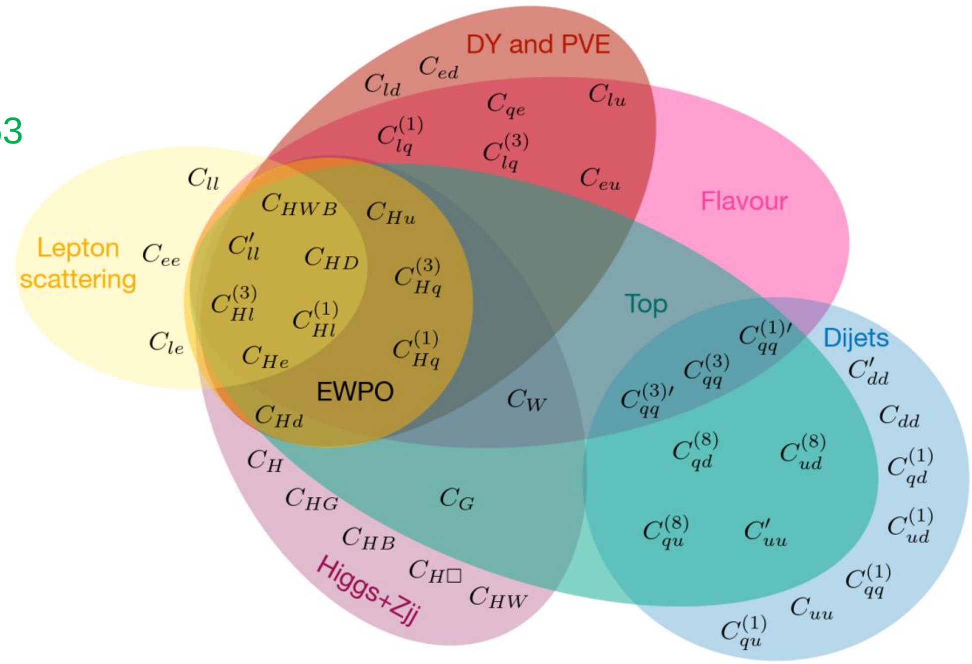
Towards global fits in SMEFT

Bounds on SMEFT Wilson coefficients at leading order and next-to-leading order

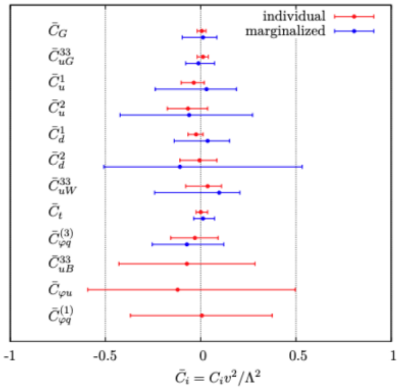
Constraints from
- electroweak precision observables (EWPO) (Z-pole)
- lepton scattering (WW)
- Higgs, top, flavour, dijet, Drell-Yan, Diboson
- measurements from parity violation experiments (PEV)



Bartocci, Biekoetter, Hurth 2311.04963



Towards global fits in SMEFT



TopFitter

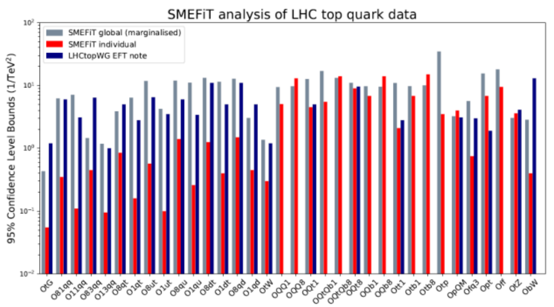
Top pair, single-top production, ttZ/γ from the LHC run I and II and Tevatron

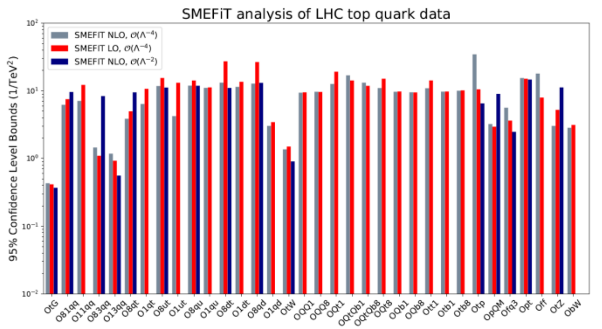
Buckley, Englert, Ferrando, Miller, Moore, Russell, White, 1512.03360

Global fits to the SMEFT from the top sector.

SMEFiT

Hartland, *Maltoni, Nocera, Rojo,* Slade, Vryonidou, Zhang, 1901.05965

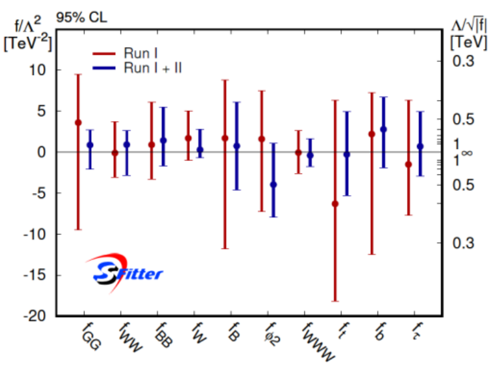




Sfitter

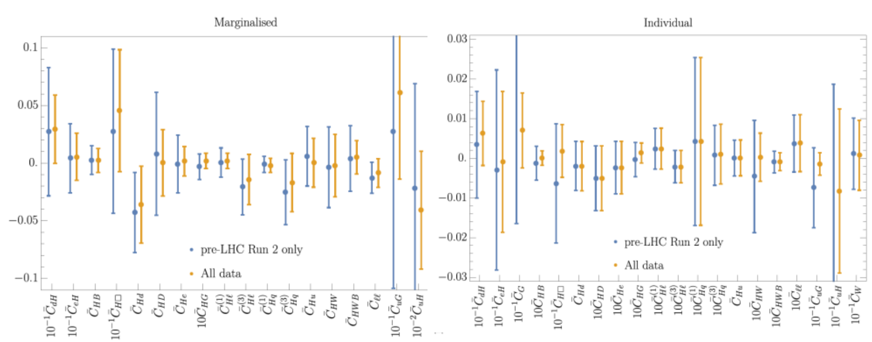
Biekoetter, Corbett, Plehn,1812.07587

Global fits to the SMEFT from the Higgs sector.



Global SMEFT Fit to Higgs, Diboson and Electroweak Data

Ellisa, Murphyc, Sanzd, Youe, 1803.03252

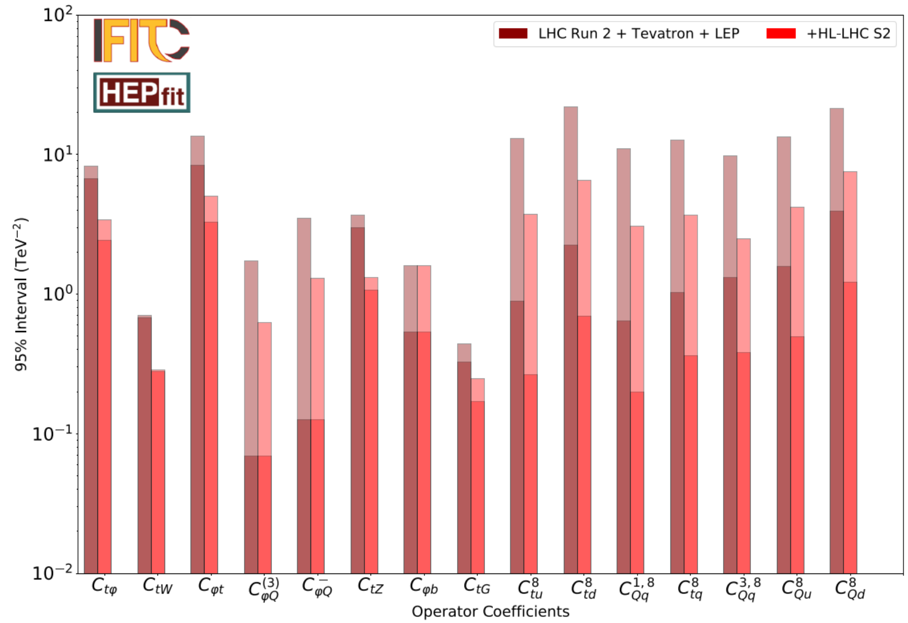


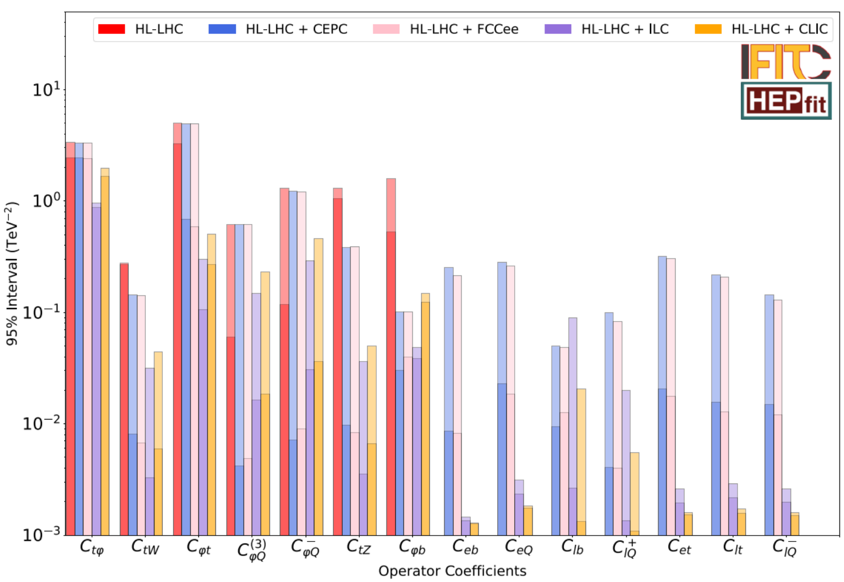
Towards global fits in SMEFT

The top-quark sector in the global SMEFT fit

Blasa, Duc, Grojean et. al
Contribution to Snowmass 2021, 2206.08326v5

Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	Experiment	SM	Ref.
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS	[133]	[134]
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS	[133]	[135]
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS	[136]	[137]
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS	[138]	[139]
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS	[140, 141]	[142]
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS	[143]	[144]
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS	[145]	[145]
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS	[136, 146]	[147]
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC	[148, 149]	[150]
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC	[151]	[150]
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC	[148, 149]	[150]
$t \to Wb$	F_0, F_L	8 TeV	20 fb^{-1}	LHC	[152]	[153]
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron	[154]	[155]
$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD	–	[54]





a single-parameter fit - solid bars;
the global or marginalised bounds – full bars (shaded region in each bar)

Towards global fits in SMEFT

Flavor symmetry assumption for dim 6 operators:

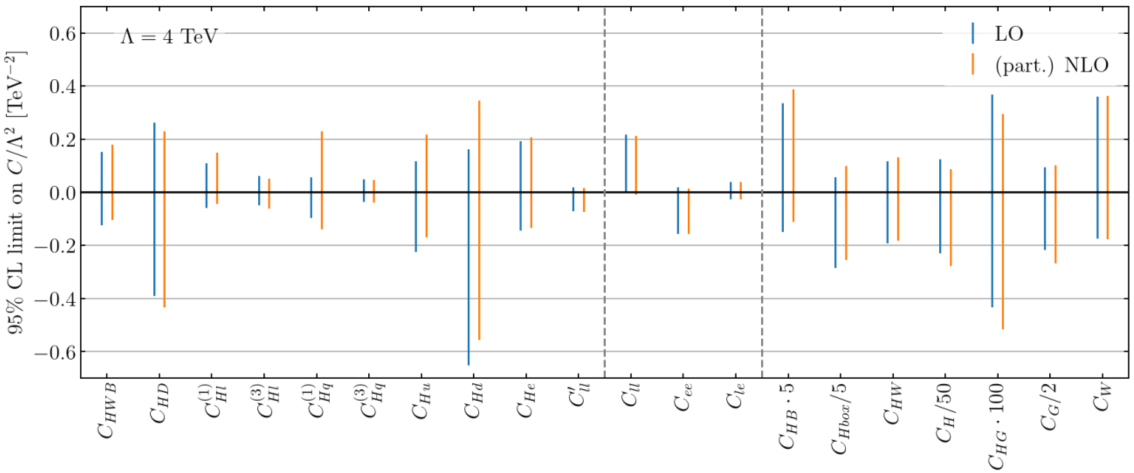
$U(3)^5 = U(3)_\ell \times U(3)_q \times U(3)_e \times U(3)_u \times U(3)_d$

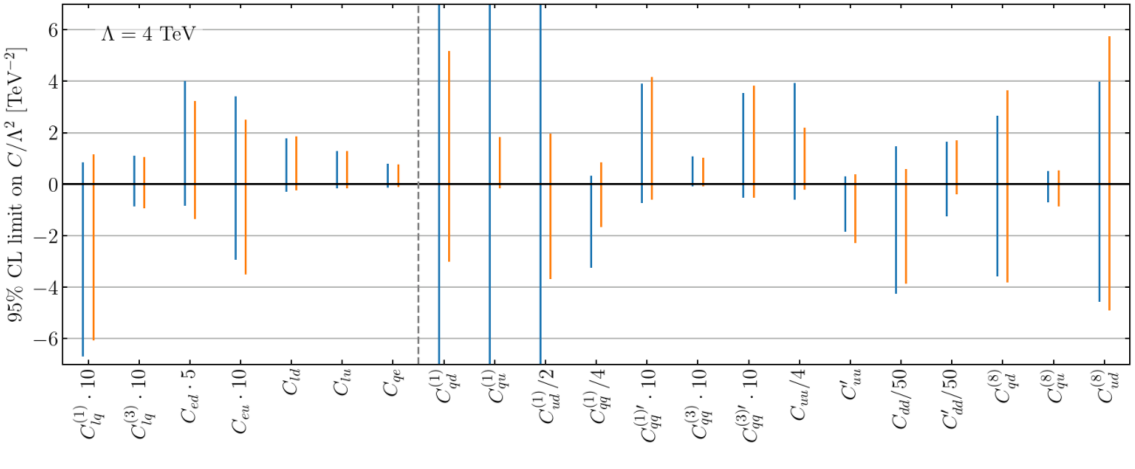
2499 operators → 47 operators

41 (CP even) + 6 (CP odd)

Comparison of limits at LO and NLO

Bartocci, Biekoetter, Hurth 2311.04963





From UV theory to SMEFT

Number of SMEFT operators is huge.
EFT Lagrangian from the concrete UV model contains much less operators

Example: $L_{QED} = \bar{\psi}(i\,\gamma_\mu D^\mu - m_e)\psi, \quad D_\mu = \partial_\mu - ie\,A_\mu$

$E_\gamma \ll m_e$, Lagrangian Euler-Heisenberg

$L_{eff} = -1/4\, F_{\mu\nu}F^{\mu\nu} + a/m_e^4\,(F_{\mu\nu}F^{\mu\nu})^2 + b/m_e^4\,(F_{\mu\nu}F^{\nu\alpha}\,F_{\alpha\beta}F^{\beta\mu})$

Matching: $a = -\alpha^2/36, \; b = 7\,\alpha^2/90$

Other operators do not appear

Off-shell matching – effective actions of light degrees of freedom are the same (mostly used in practice)

$$\Gamma_{UV}[\varphi] = \Gamma_{SMEFT}[\varphi]$$

On-shell matching – S-matrix elements (amplitudes) are the same

$$\langle\varphi_{in}|\, S_{UV}\, |\varphi_{out}\rangle = \langle\varphi_{in}|\, S_{SMEFT}\, |\varphi_{out}\rangle$$

Z'

Dawson, Forslund, Schnubel 2404.01375

Generic Z' model

$$\mathcal{L}_{Z'} = -\frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}M_{Z'}^2 Z'_\mu Z'^\mu - \frac{\epsilon}{2}B_{\mu\nu}Z'^{\mu\nu} + (g_{H,2})^2 Z'_\mu Z'^\mu |H^\dagger H| - Z'_\mu \mathcal{J}^\mu$$

$$\mathcal{J}^\mu = (ig_H)\left(H^\dagger \overleftrightarrow{D}^\mu H\right) + \sum_f \left(g_{ij}^{fL}\bar{f}_L^i \gamma^\mu f_L^j + g_{ij}^{fR}\bar{f}_R^i\gamma^\mu f_R^j\right)$$

After Integrating out Z'

$$\delta\mathcal{L} = -\frac{1}{2M_{Z'}^2}\left(\mathcal{J}_\mu + \epsilon j_\mu\right)^2 - \frac{1}{2M_{Z'}^4}\left(1-\epsilon^2\right)\left[\partial_\mu\left(\mathcal{J}_\nu + \epsilon j_\nu\right)\right]^2 + \frac{1}{M_{Z'}^4}\left(g_{H,2}^2 + \frac{g'^2\epsilon^2}{4}\right)\left(H^\dagger H\right)\left(\mathcal{J}_\mu + \epsilon j_\mu\right)^2$$

$$j_\mu = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) + g'\sum_f Y_f \bar{f}\gamma^\mu f$$

Matching with SMEFT operators of dim 6

$$\frac{C_{ll}[ijkl]}{\Lambda^2} = -\frac{1}{2M_{Z'}^2}(g_{ij}^{lL} + \epsilon g' Y_l \delta_{ij})(g_{kl}^{lL} + \epsilon g' Y_l \delta_{kl}),$$

$$\frac{C_{lq}^{(1)}[ijkl]}{\Lambda^2} = -\frac{1}{M_{Z'}^2}(g_{ij}^{lL} + \epsilon g' Y_l \delta_{ij})(g_{kl}^{qL} + \epsilon g' Y_q \delta_{kl}),$$

$$\frac{C_{qq}^{(1)}[ijkl]}{\Lambda^2} = -\frac{1}{2M_{Z'}^2}(g_{ij}^{qL} + \epsilon g' Y_q \delta_{ij})(g_{kl}^{qL} + \epsilon g' Y_q \delta_{kl}).$$

$$\frac{C_{lf}[ijkl]}{\Lambda^2} = -\frac{1}{M_{Z'}^2}(g_{ij}^{lL} + \epsilon g' Y_l \delta_{ij})(g_{kl}^{fR} + \epsilon g' Y_f \delta_{kl}),$$

$$\frac{C_{qf}^{(1)}[ijkl]}{\Lambda^2} = -\frac{1}{M_{Z'}^2}(g_{ij}^{qL} + \epsilon g' Y_q \delta_{ij})(g_{kl}^{fR} + \epsilon g' Y_f \delta_{kl}).$$

$$\frac{C_{\varphi\Box}}{\Lambda^2} = \frac{1}{8M_{Z'}^2}\left(2g_H + \epsilon g'\right)^2,$$

$$\frac{C_{\varphi D}}{\Lambda^2} = \frac{1}{2M_{Z'}^2}\left(2g_H + \epsilon g'\right)^2.$$

$$\frac{C_{ff}[ijkl]}{\Lambda^2} = -\frac{1}{2M_{Z'}^2}(g_{ij}^{fR} + \epsilon g' Y_f \delta_{ij})(g_{kl}^{fR} + \epsilon g' Y_f \delta_{kl}),$$

$$\frac{C_{ff'}[ijkl]}{\Lambda^2} = -\frac{1}{M_{Z'}^2}(g_{ij}^{fR} + \epsilon g' Y_f \delta_{ij})(g_{kl}^{f'R} + \epsilon g' Y_{f'} \delta_{kl}),$$

$$\frac{C_{ud}^{(1)}[ijkl]}{\Lambda^2} = -\frac{1}{M_{Z'}^2}(g_{ij}^{uR} + \epsilon g' Y_u \delta_{ij})(g_{kl}^{dR} + \epsilon g' Y_d \delta_{kl}).$$

$$\frac{C_{\varphi l}^{(1)}[ij]}{\Lambda^2} = -\frac{1}{2M_{Z'}^2}(2g_H + \epsilon g')(g_{ij}^{lL} + \epsilon g' Y_l \delta_{ij}),$$

$$\frac{C_{\varphi q}^{(1)}[ij]}{\Lambda^2} = -\frac{1}{2M_{Z'}^2}(2g_H + \epsilon g')(g_{ij}^{qL} + \epsilon g' Y_q \delta_{ij}),$$

$$\frac{C_{\varphi f}[ij]}{\Lambda^2} = -\frac{1}{2M_{Z'}^2}(2g_H + \epsilon g')(g_{ij}^{fL} + \epsilon g' Y_f \delta_{ij}).$$

+ More operators of dim 8

In some concrete cases the operators start from D=8.
Extra dimensional gravity is an example.

E.B., Bunichev, Volobuev, Smolaykov PRD 79 (2009)

$$L_{eff} = \lambda\; J_{SM} * \Delta * J_{SM}, \quad \lambda = \frac{1}{2} g^2 M^{-d} \left(\sum_{n\neq 0} \frac{(\psi^{(n)}(y_B))^2}{M_n^2} \right)$$

Models with gravity in the bulk $\quad J_{SM} \to T_{\mu\nu} = 2\frac{\delta L_{SM}}{\delta\gamma^{\mu\nu}} - \gamma_{\mu\nu} L_{SM}$

After integrating out heavy KK gravitational modes

$$L_{eff} = \frac{C}{M^4} T^{\mu\nu} \tilde{\Delta}_{\mu\nu,\rho\sigma} T^{\rho\sigma}$$

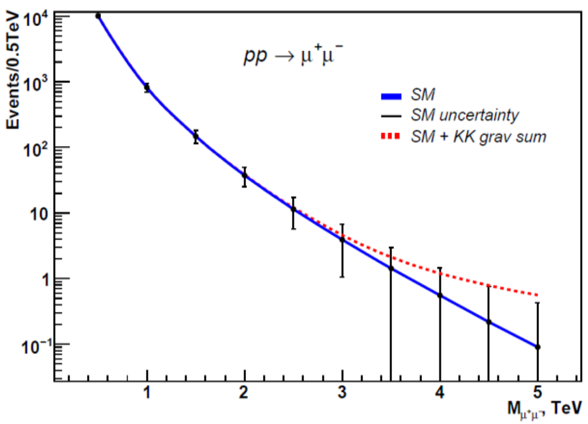
$$\tilde{\Delta}_{\mu\nu,\rho\sigma} = \eta_{\mu\rho}\eta_{\nu\sigma} + \eta_{\mu\sigma}\eta_{\nu\rho} - \left(\frac{2}{3} - \delta\right)\eta_{\mu\nu}\eta_{\rho\sigma}$$

$$T^{\Psi}_{\mu\nu} = \frac{i}{4}\left(\bar{\Psi}\gamma_\mu\partial_\nu\Psi + \bar{\Psi}\gamma_\nu\partial_\mu\Psi - \partial_\nu\bar{\Psi}\gamma_\mu\Psi - \partial_\mu\bar{\Psi}\gamma_\nu\Psi\right) - \\ -\eta_{\mu\nu}\left(\frac{i}{2}\bar{\Psi}\gamma^\rho\partial_\rho\Psi - \frac{i}{2}\partial_\rho\bar{\Psi}\gamma^\rho\Psi - m_\Psi\bar{\Psi}\Psi\right)$$

$$T^{Z}_{\mu\nu} = -Z_{\mu\rho}Z_{\nu\sigma}g^{\rho\sigma} + m_Z^2 Z_\mu Z_\nu + \eta_{\mu\nu}\left(\frac{1}{4}Z_{\rho\sigma}Z^{\rho\sigma} - \frac{m_Z^2}{2}Z^\rho Z_\rho\right)$$

$$T^{W}_{\mu\nu} = -W^+_{\mu\rho}W^-_{\nu\sigma}g^{\rho\sigma} - W^+_{\nu\rho}W^-_{\mu\sigma}g^{\rho\sigma} + m_W^2\left(W^+_\mu W^-_\nu + W^+_\nu W^-_\mu\right) + \\ +\eta_{\mu\nu}\left(\frac{1}{2}W^+_{\rho\sigma}W^{-\rho\sigma} - m_W^2 W^+_\rho W^{-\rho}\right)$$

$$T^{\Phi}_{\mu\nu} = \partial_\mu\Phi\partial_\nu\Phi - \eta_{\mu\nu}\left(\frac{1}{2}\partial^\rho\Phi\partial_\rho\Phi - \frac{m_\Phi^2}{2}\Phi^2\right)$$



Dilepton invariant mass at LHC 14TeV (L= 100 fb^{-1}) at C/M^4 = 3•10^{-3} TeV^{-4}

The scalar leptoquarks S_1 and S_3

$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}} \quad \text{and} \quad S_3 \sim (\bar{\mathbf{3}}, \mathbf{3})_{\frac{1}{3}}$$

Gherardia, Marzoccab, Venturini 2003.12525

$$\mathcal{L}_{\text{LQ}} = |D_\mu S_1|^2 + |D_\mu S_3|^2 - M_1^2|S_1|^2 - M_3^2|S_3|^2 + \\ + \left((\lambda^{1L})_{i\alpha}\bar{q}_i^c\epsilon\ell_\alpha + (\lambda^{1R})_{i\alpha}\bar{u}_i^c e_\alpha\right) S_1 + (\lambda^{3L})_{i\alpha}\bar{q}_i^c\epsilon\sigma^I\ell_\alpha S_3^I + \text{h.c.} +$$

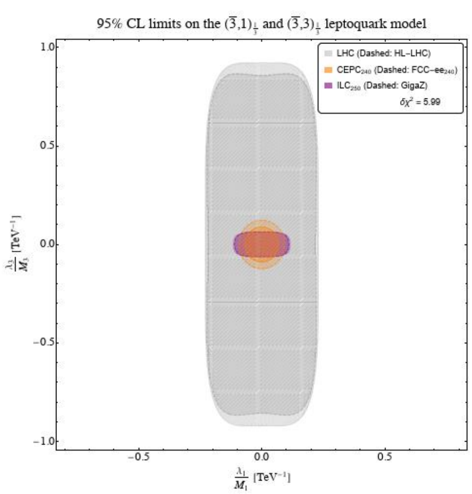
Tree level matching conditions after Integrating out leptoquarks

$$\left[c_{lq}^{(1)}\right]_{\alpha\beta ij} = \frac{\lambda_{i\alpha}^{1L*}\lambda_{j\beta}^{1L}v^2}{4M_1^2} + \frac{3\lambda_{i\alpha}^{3L*}\lambda_{j\beta}^{3L}v^2}{4M_3^2}, \quad \left[c_{lq}^{(3)}\right]_{\alpha\beta ij} = -\frac{\lambda_{i\alpha}^{1L*}\lambda_{j\beta}^{1L}v^2}{4M_1^2} + \frac{\lambda_{i\alpha}^{3L*}\lambda_{j\beta}^{3L}v^2}{4M_3^2},$$

$$\left[c_{lequ}^{(1)}\right]_{\alpha\beta ij} = \frac{\lambda_{j\beta}^{1R}\lambda_{i\alpha}^{1L*}v^2}{2M_1^2}, \quad \left[c_{lequ}^{(3)}\right]_{\alpha\beta ij} = -\frac{\lambda_{j\beta}^{1R}\lambda_{i\alpha}^{1L*}v^2}{8M_1^2}, \quad [c_{eu}]_{\alpha\beta ij} = \frac{\lambda_{i\alpha}^{1R*}\lambda_{j\beta}^{1R}v^2}{2M_1^2}.$$

In the universal Yukawa these five Wilson coefficients only depend on two ratios: λ_1/M_1 and λ_3/M_3

Global 4-fermion fit:



Blasa, Duc, Grojean et. al
Contribution to Snowmass 2021, 2206.08326

Concluding remarks

In the absence (so far) of any manifestation of BSM physics at the LHC, the Standard Model Effective Field Theory (SMEFT) is the consistent theoretical framework to go beyond the SM in model independent way allowing to perform systematically experimental data analyses.

SMEFT is based on the linear realization of the mechanism of electroweak symmetry breaking. We did not consider HEFT based on a non-linear realization of the mechanism of electroweak symmetry breaking being not favored (but not excluded) by current data.

SMEFT allows to compute consistently higher order perturbative corrections. Several NLO computations in SMEFT have been done. NLO corrections not only significantly reduce the scale uncertainties, but also allow more accurate obtain the shapes of differential distributions.

Without SMEFT it is challenging to compare limits predicted in various theoretical studies and/or obtained at various experiments.

Concrete BSM extensions lead to certain operators with possibly predicted ratios between their strengths based on a matching procedure.

Lot of studies are in progress and remain to be done

Reviews

Brivio, Trott Phys.Rept. (2019)

Boos Phys.Usp. (2022)

Falkowski EPJ C (2023)

Isidori, Wilsch, Wyler Rev.Mod.Phys. (2024)

…

Thank you !

Back up slides

Subsidiary bosons for BSM evaluations

New Physics (NP) contributions to the SM vertex

$$\Gamma_\mu = \Gamma_\mu^{SM} + \Gamma_\mu^{NP_1} + \Gamma_\mu^{NP_2} + \ldots$$

Example: anomalous Wtb vertex

$$L_{Wtb} = \frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(f_V^L P_L + f_V^R P_R)t\, W_\mu^- + \frac{g}{\sqrt{2}}\bar{b}\frac{\sigma^{\mu\nu}}{m_W}(f_T^L P_L + f_T^R P_R)t\, W_{\mu\nu}^- + h.c.$$

W boson SM	$\frac{g}{2\sqrt{2}} f_V^L \gamma^\mu (1 - \gamma_5)$
W boson subsidiary 1	$\frac{g}{2\sqrt{2}} f_V^R \gamma^\mu (1 + \gamma_5)$
W boson subsidiary 2	$\frac{g}{2 m_W \sqrt{2}} f_T^L \sigma^{\mu\nu} q_\nu (1 + \gamma_5)$
W boson subsidiary 3	$\frac{g}{2 m_W \sqrt{2}} f_T^R \sigma^{\mu\nu} q_\nu (1 - \gamma_5)$

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