Effective Field Theories at LHC
– EFT predictions and fits –

Ilaria Brivio

Università & INFN Bologna

Swiss National Science Foundation

COMETA

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Lectures plan

1. Theory recap of SMEFT at dim-6
   - basic EFT principles and context
   - operator bases and Feynman rules for dim6 SMEFT
2. Constraints from LEP observables
   - Input parameter schemes for the EW sector
   - Z-pole EWPOs
   - W^+W^- and Bhabha scattering
   - m_W and oblique parameters
3. LHC data and global fits
   - the need for global analyses. most commonly included datasets
   - SMEFT predictions for LHC, and theory uncertainties incl. EFT validity
   - basics of statistical methods for EFT fits
   - some playing around with `SMEFiT`
4. More precision
   - higher orders in loops: features of NLO SMEFT predictions
   - higher orders in the EFT: dim8

Recap of SMEFT at dim6

Some useful references for Part 1

- A. Manohar. "Introduction to effective Field Theories"
  arXiv: 1804.05863
- I. Brivio. "SMEFTsim 3.0 - a practical guide"
  arXiv: 2012.11343
- J. Rojo. "The Standard Model Effective Theory: towards a pedagogical primer"
  `juanrojocom.files.wordpress.com/2020/02/smeft-drstp-2.pdf`
- G. Isidori, F. Wilsch, D. Wyler.
  "The Standard Model effective field theory at work". arXiv: 2303.16922
- I. Brivio, M. Trott. "The Standard Model as an effective field theory"
  arXiv: 1706.08945

The Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

1 X^3		2 φ^6 and $\varphi^4 D^2$ 3		$\psi^2\varphi^3$ 5	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

4 $X^2\varphi^2$		6 $\psi^2 X\varphi$		$\psi^2\varphi^2 D$ 7	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

The Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

8a $(\bar{L}L)(\bar{L}L)$		8b $(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$ 8c	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

8d $(\bar{L}R)(\bar{R}L)$ 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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Feynman rules in the Warsaw basis

sticking to unitary gauge for practicity.

FR are not always obvious, due to

- redefinitions performed to make kinetic terms canonical and diagonal
- redefinitions performed to specify input parameter sets

To keep track of which operators enter where, **public tools** are available

- SMEFTviz by R. Balasubramanian and S. Swatman [in-browser]
  `rahulb.web.cern.ch/SMEFTviz.html`
- SMEFTsimFeyn by G. Boldrini [python]
  `github.com/GiacomoBoldrini/SMEFTsimFeyn`
- SMEFTsim interactive FR database [Mathematica]
  `notebookarchive.org/smeftsim-interactive-feynman-rules-database--2022-01-5jz62qa/`

all based on the SMEFTsim implementation of the Warsaw basis in UFO models.

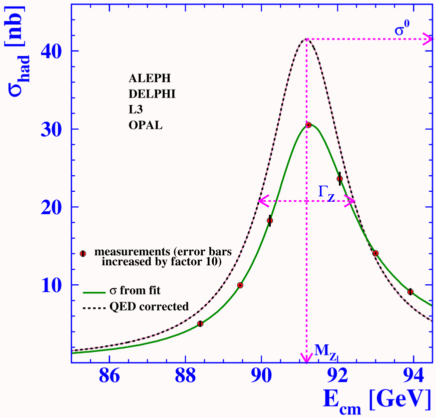
Constraints from LEP

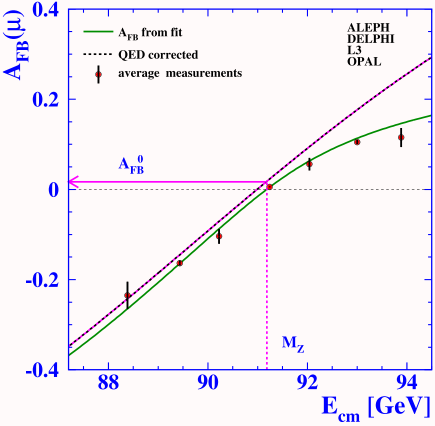
Useful references for Part 2

- ALEPH, DELPHI, L3, OPAL, SLD collaborations. “Precision electroweak measurements on the ZZ resonance” arXiv:hep-ex/0509008
- L. Berthier, M. Trott “Towards consistent Electroweak Precision Data constraints in the SMEFT” arXiv: 1502.02570
- IB, M. Trott, “Scheming in the SMEFT... and a reparameterization invariance!” arXiv: 1701.06424
- E. Celada, T. Giani, J. ter Hoeve, L. Mantani, J. Rojo, A. N. Rossia, M. Thomas, E. Vryonidou, “Mapping the SMEFT at high-energy colliders: from LEP and the (HL-)LHC to the FCC-ee” arXiv: 2404.12809
- IB, M. Trott. “The Standard Model as an effective field theory”, Appendix A arXiv: 1706.08945
- E. Bagnaschi, J. Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You, “SMEFT analysis of m_W”. arXiv: 2204.05260

Z lineshape measurements at LEP

LEP-SLD EWPO combination, hep-ex/0509008





SMEFT corrections to EWPOs (m_W, m_Z, G_F scheme)

$$g_V = T_3/2 - Q s_\theta^2 \qquad g_A = T_3/2$$

$$\delta g_V = \delta g_Z\, g_V + Q\delta s_\theta^2 + \Delta_V \qquad \delta g_A = \delta g_Z\, g_A + \Delta_A$$

$$\delta g_Z = \frac{g^2}{g^2+g'^2}\frac{\delta g}{g} + \frac{g'^2}{g^2+g'^2}\frac{\delta g'}{g'} = -\frac{\Delta G_F}{2} + \Delta m_Z^2 + \frac{s_{2\theta}}{2}\bar{C}_{HWB}$$

$$\delta s_\theta^2 = \frac{s_{2\theta}^2}{2}\left(\frac{\delta g'}{g'} - \frac{\delta g}{g}\right) + \frac{s_{4\theta}}{4}\bar{C}_{HWB} = -c_\theta^2 \Delta m_Z^2 + \frac{s_{4\theta}}{4}\bar{C}_{HWB}$$

$$\Delta_V^\ell = -\frac{1}{4}(\bar{C}_{Hl}^1 + \bar{C}_{Hl}^3 + \bar{C}_{He}) \qquad \Delta_A^\ell = -\frac{1}{4}(\bar{C}_{Hl}^1 + \bar{C}_{Hl}^3 - \bar{C}_{He})$$

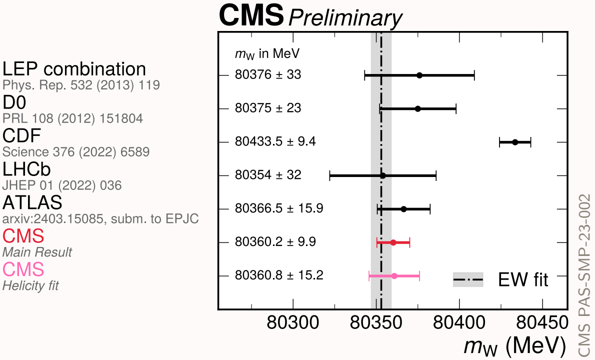
$$\Delta_V^\nu = -\frac{1}{4}(\bar{C}_{Hl}^1 - \bar{C}_{Hl}^3) \qquad \Delta_A^\nu = -\frac{1}{4}(\bar{C}_{Hl}^1 - \bar{C}_{Hl}^3)$$

$$\Delta_V^u = -\frac{1}{4}(\bar{C}_{Hq}^1 - \bar{C}_{Hq}^3 + \bar{C}_{Hu}) \qquad \Delta_A^u = -\frac{1}{4}(\bar{C}_{Hq}^1 - \bar{C}_{Hq}^3 - \bar{C}_{Hu})$$

$$\Delta_V^d = -\frac{1}{4}(\bar{C}_{Hq}^1 + \bar{C}_{Hq}^3 + \bar{C}_{Hd}) \qquad \Delta_A^\ell = -\frac{1}{4}(\bar{C}_{Hq}^1 + \bar{C}_{Hq}^3 - \bar{C}_{Hd})$$

$$\delta g_V^{W\ell} = \frac{\delta g}{g} + \bar{C}_{Hl}^3 = -\frac{\Delta G_F}{2} + \bar{C}_{Hl}^3 \qquad \delta g_V^{Wq} = \frac{\delta g}{g} + \bar{C}_{Hq}^3 = -\frac{\Delta G_F}{2} + \bar{C}_{Hq}^3$$

m_W interpretation

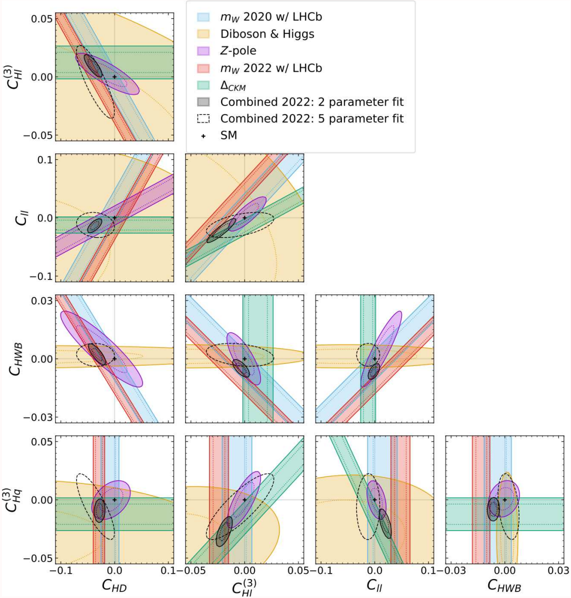


in SMEFT, taking $\{\alpha, m_Z, G_F\}$ inputs:

$$\frac{\delta m_W}{m_W} = \frac{\delta v}{v} + \frac{\delta g}{g} = -\frac{t_{2\theta}}{4}\left[\frac{1}{2t_\theta}\bar{C}_{HD} + 2\bar{C}_{HWB} + t_\theta\left(2\bar{C}^3_{Hl} - \bar{C}'_{ll}\right)\right]$$

$$= -\frac{t_{2\theta}t_\theta}{2}\left[\frac{g^2}{8\pi}\left(S - 2c^2_\theta T\right) + \Delta G_F\right]$$

m_W interpretation

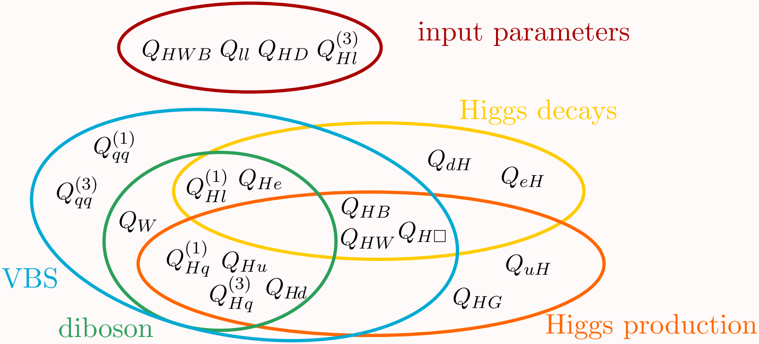


Bagnaschi et al 2204.05260

LHC observables and Global Fits

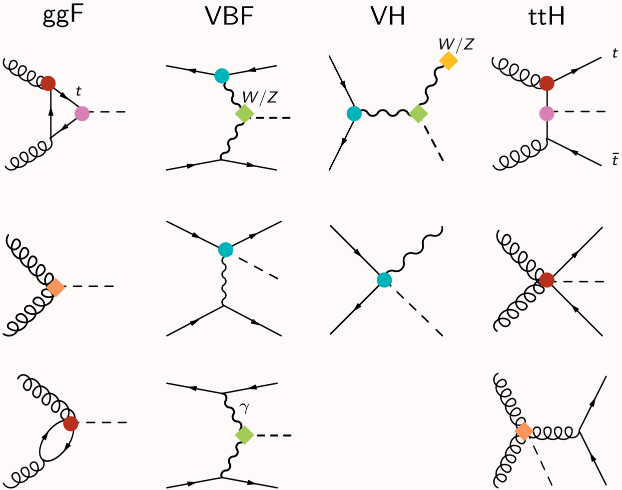
SMEFT for EW and Higgs sectors

leading Warsaw basis operators in Higgs and EW processes: ~ 20



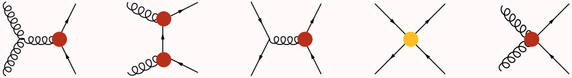
$+$ CP odd $+$ flavor indices $+$ others entering through loop corrections . . .

SMEFT in Higgs production

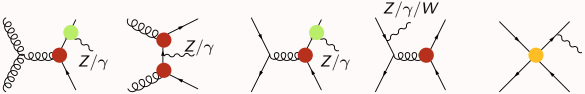


SMEFT affecting top quark interactions

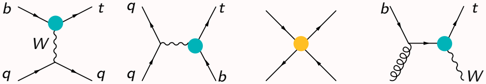
$t\bar{t}$



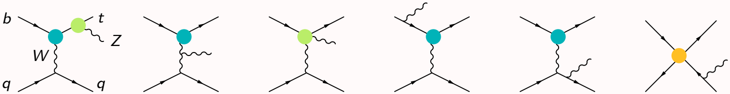
$t\bar{t}V$



$tj,\ tW$



tZj



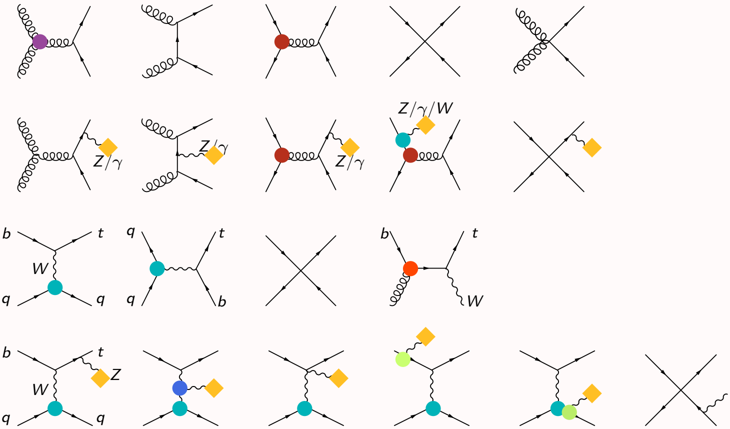
SMEFT entering top processes in other interactions

$t\bar{t}$

$t\bar{t}V$

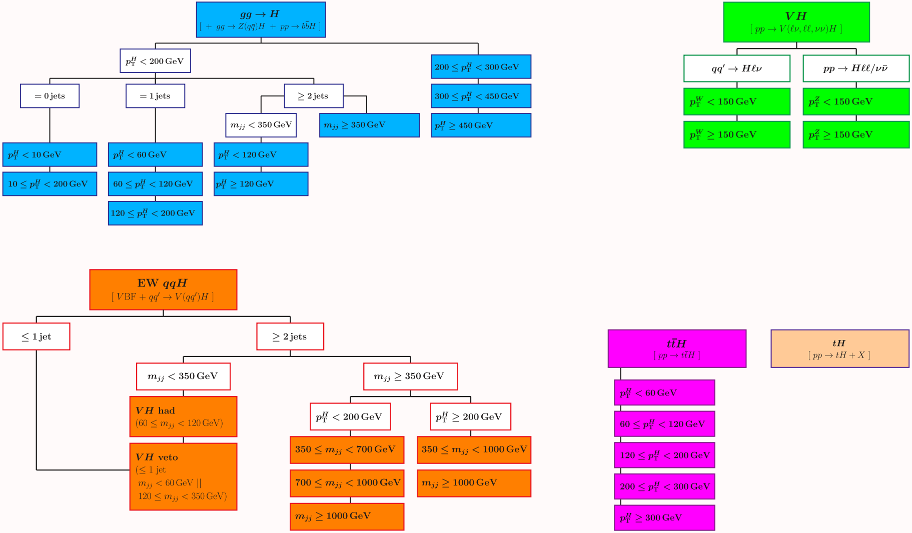
$tj,\ tW$

tZj



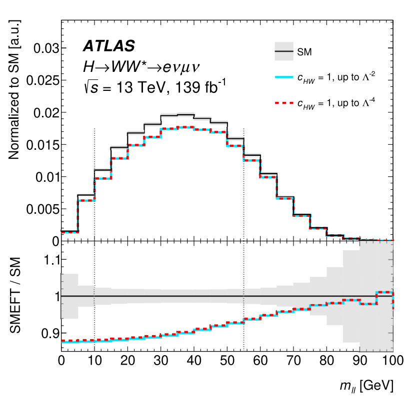
Simplified Template Cross Sections (STXS)

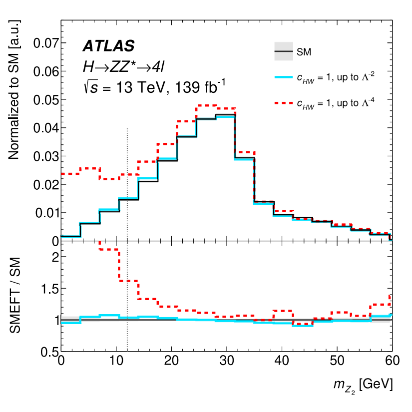
from: ATLAS H10 2207.00348 (stage 1.2)



SMEFT corrections in acceptances

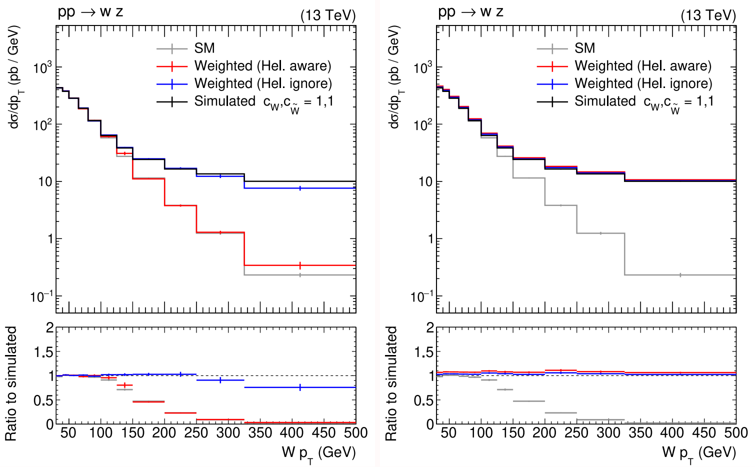
ATLAS 2402.05742





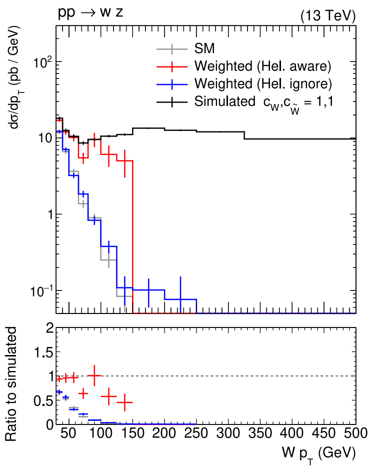
Direct simulation vs reweighting

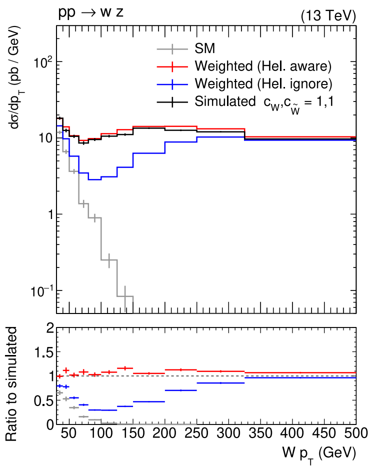
LHC EFT WG 2406.14620



Direct simulation vs reweighting

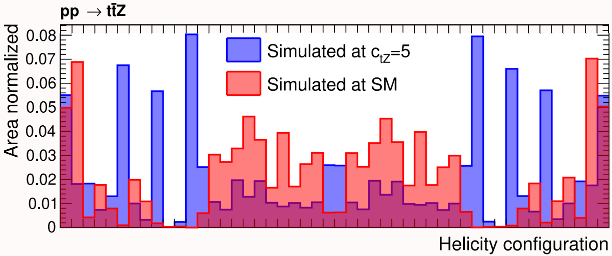
LHC EFT WG 2406.14620

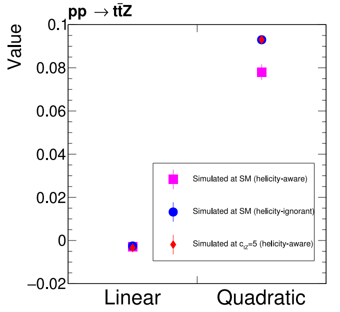




Direct simulation vs reweighting

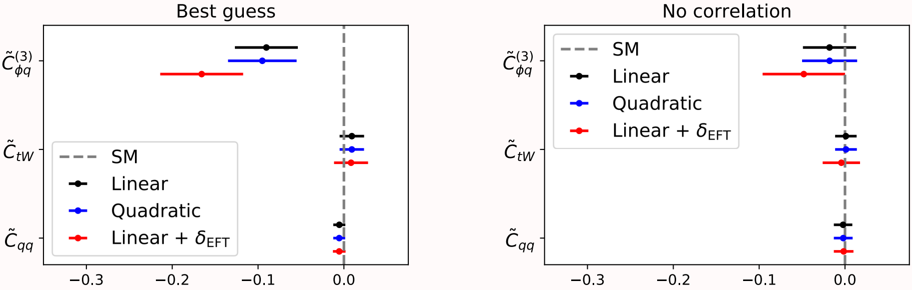
LHC EFT WG 2406.14620





Importance of correlations in fit results

Bißmann,Erdmann,Grunwald,Hiller,Kröninger 1912.06090



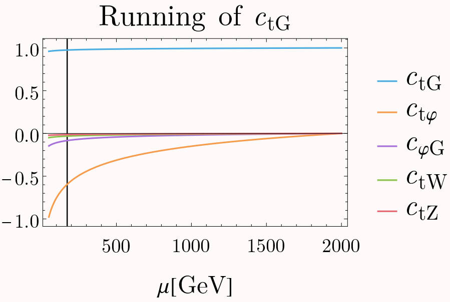
toy fit to ATLAS/CMS measurements of single-top + top decay.
different correlation assumptions concern theory and systematic uncertainties.

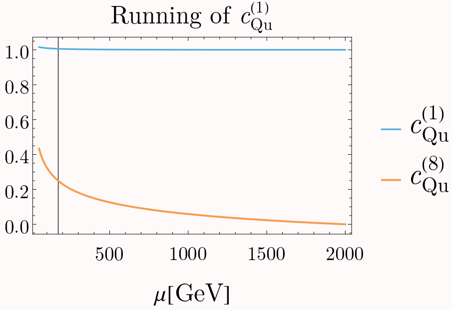
"best guess": 90% correlation among sys and among th

Scale uncertainties on SMEFT contributions

each operator behaves differently → uncertainty on constrained direction

$$pp \to \bar{t}t \text{ @LHC. } C_i(2\,\mathrm{TeV}) = 1,\ \Lambda = 2\,\mathrm{TeV}$$



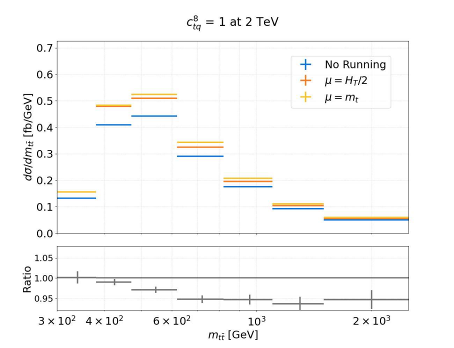


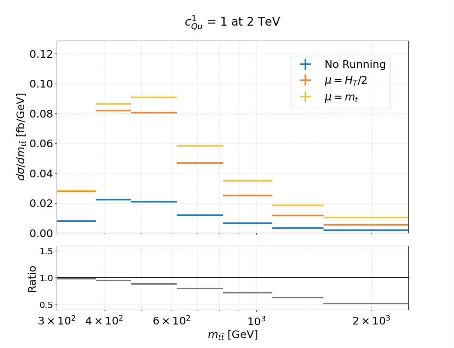
Aoude,Maltoni,Mattelaer,Severi,Vryonidou 2212.05067

Scale uncertainties on SMEFT contributions

each operator behaves differently → uncertainty on constrained direction

$$pp \to \bar{t}t \text{ @LHC. } C_i(2\,\mathrm{TeV}) = 1,\ \Lambda = 2\,\mathrm{TeV}$$





Aoude, Maltoni, Mattelaer, Severi, Vryonidou 2212.05067

Scale dependence

SMEFT operators **run and mix** (Alonso),Jenkins,Manohar,Trott '13

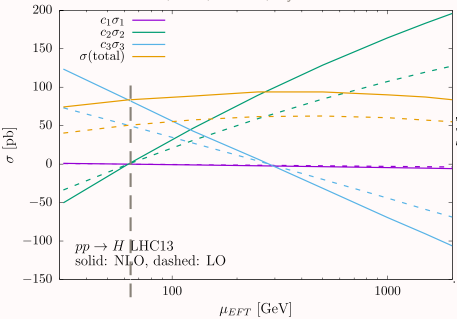
→ bounds are put on $C(\mu_0)$ defined at a certain scale μ_0.

→ residual scale dependence present, depends on process and operator

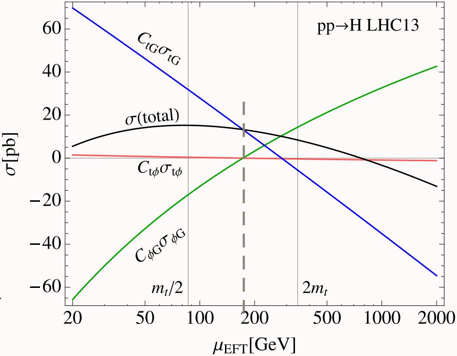
→ typically smaller in (absolute) size for NLO calculations

$gg \to h$

Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460



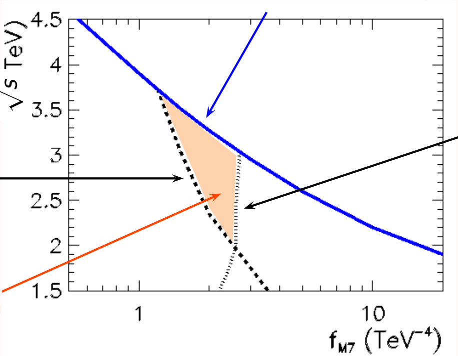
Maltoni,Vryonidou,Zhang 1607.05330



$O_1 = O_{t\phi}/y_t^3 \quad O_2 = O_{\phi G}\, g_s^2/y_t^2 \quad O_3 = O_{tG}/y_t$

Unitarity constraints

Kalinowski et al 1802.02366



unitarity bound for ssWW VBS

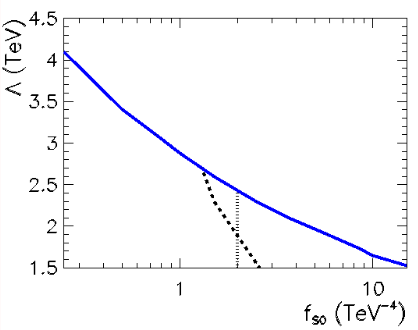
EFT consistency: $f \leqslant f^2$ for corrections to VBS

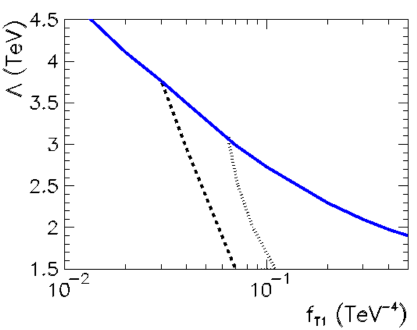
observability in ssWW

interesting region

dim8 operator: $f_{M7} = C_{M7}/\Lambda^4$

Kalinowski et al 1802.02366

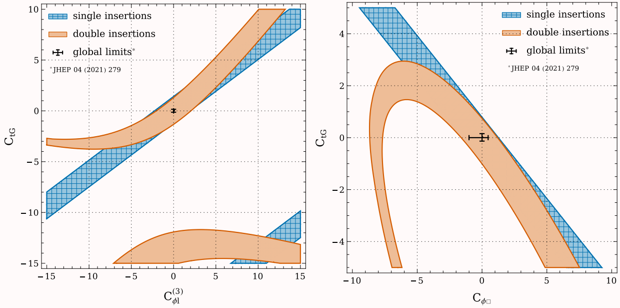




Uncertainties from missing higher EFT orders

- on dim6 constraints with quadratics, through double insertions etc

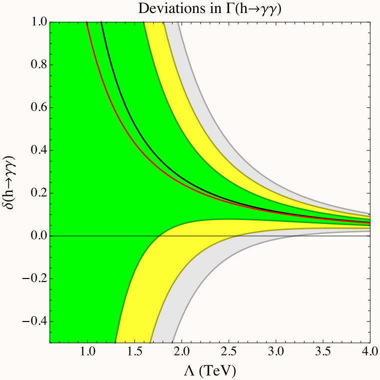
Asteriadis, Dawson, Fontes 2212.03258

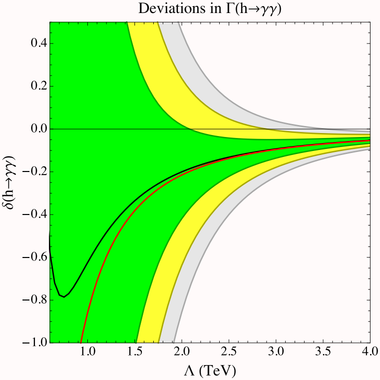


- on neglected effects from dim8 (and higher)

Missing higher-orders error band

Hays, Helset, Martin, Trott 2007.00565

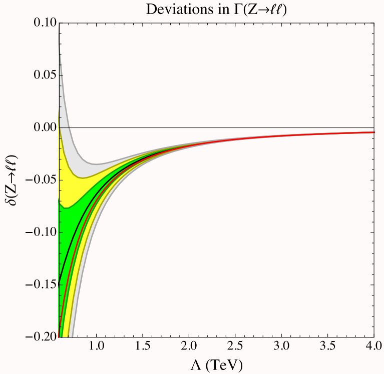




red, black lines correspond to "partial" quadratics and linear-only for a fixed benchmark.
the colored bands are obtained varying the coefficients giving Λ^{-4} contributions within a fixed prior.

Missing higher-orders error band

Hays,Helset,Martin,Trott 2007.00565

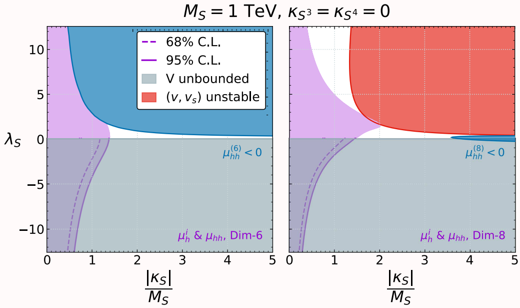


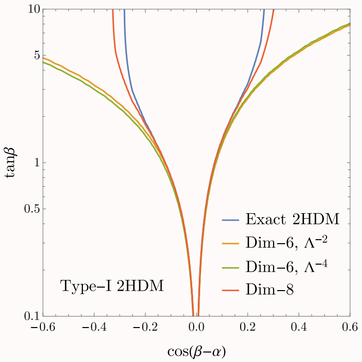
red, black lines correspond to "partial" quadratics and linear-only for a fixed benchmark.
the colored bands are obtained varying the coefficients giving Λ^{-4} contributions within a fixed prior.

Inserting (partial) dim8 contributions in the fit

Ellis,Mimasu,Zampedri 2304.06663

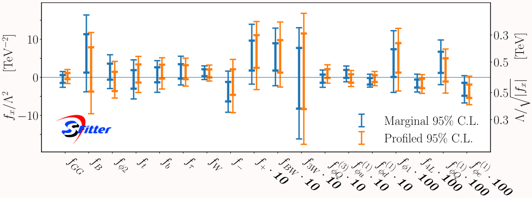
Dawson,Fontes,Homiller,Sullivan 2205.01561

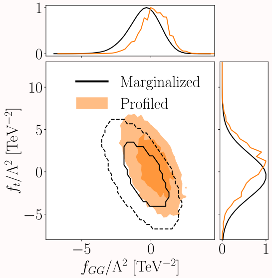


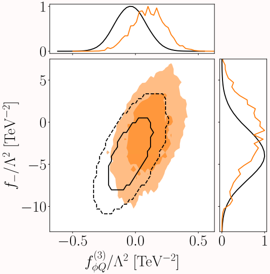


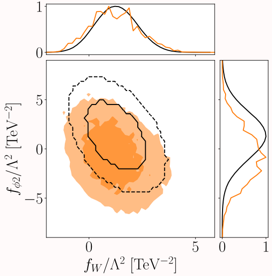
Profiling vs Marginalizing

IB,Bruggisser,Elmer,Geoffray,Luchmann,Plehn 2208.08454



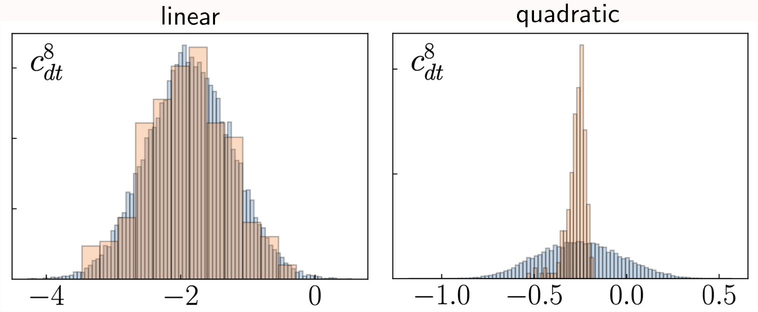






MC replica method

Kassabov,Madigan,Mantani,Moore,Morales,Rojo,Ubiali 2303.06159
see also Costantini,Madigan,Mantani,Moore 2404.10056

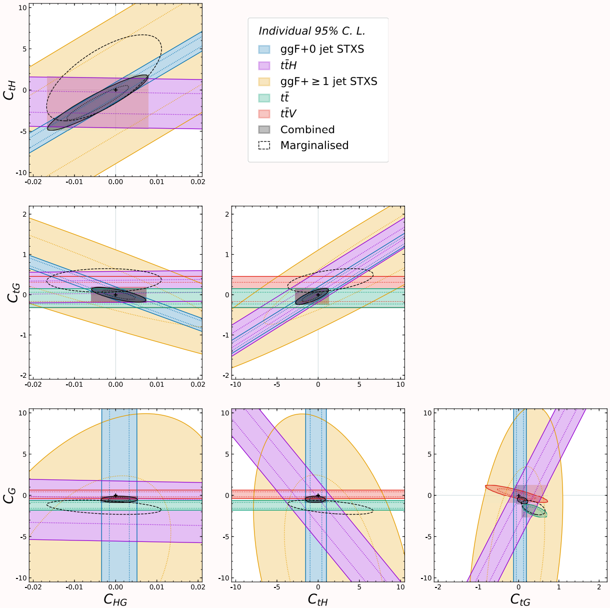


1-parameter fit to $m_{t\bar{t}}$

- nested sampling
- MC replica

Select results from global fits

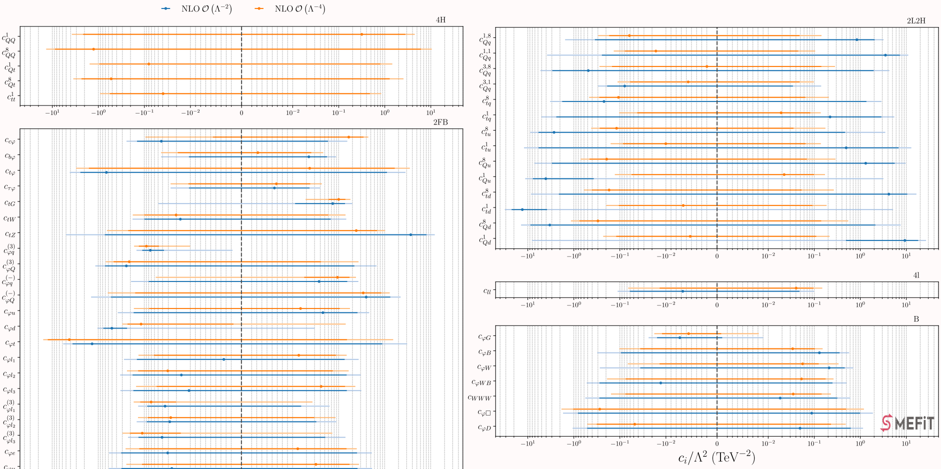
Complementarities in top + Higgs



Ellis, Madigan, Mimasu, Sanz, You 2012.02779

EWPO + Higgs + top combination

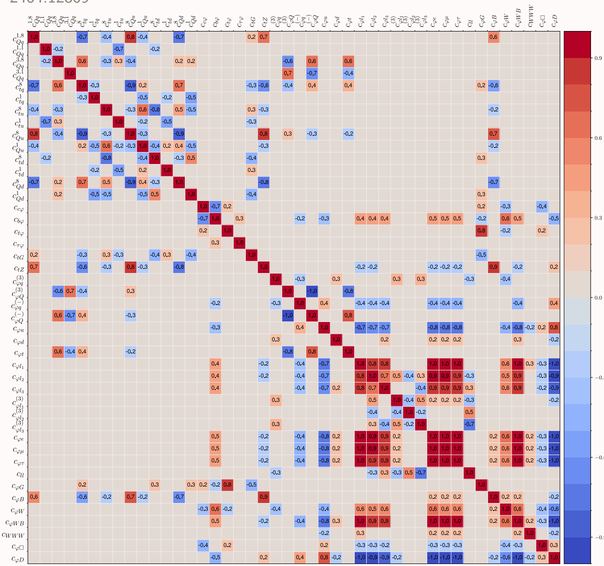
Celada et al, SMEFiT 2404.12809



Correlation matrices

Celada et al, SMEFiT 2404.12809

Linear fit

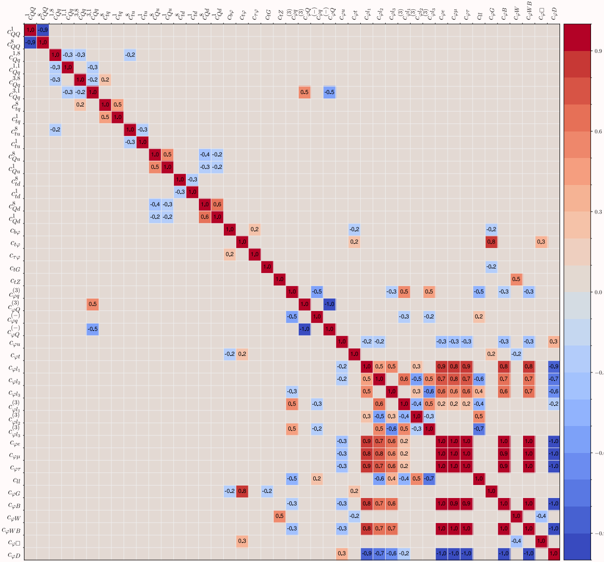


Correlation: NLO $\mathcal{O}\left(\Lambda^{-2}\right)$

Correlation matrices

Celada et al, SMEFiT 2404.12809

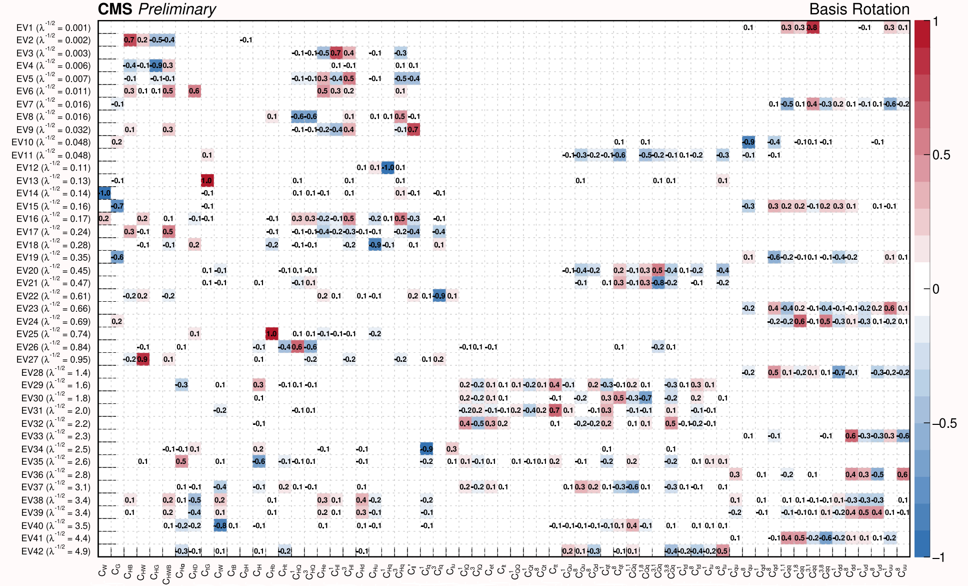
Quadratic fit



Correlation: NLO $\mathcal{O}\left(\Lambda^{-4}\right)$

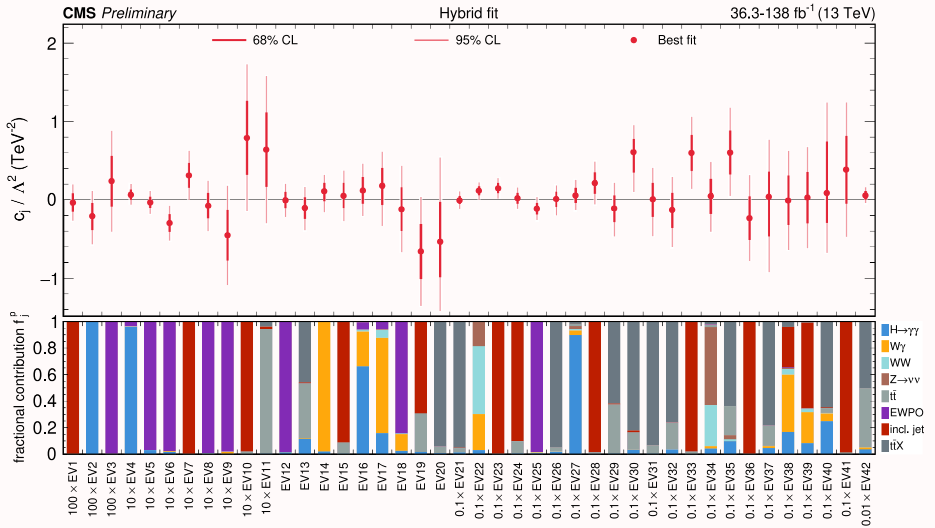
EW+Higgs+top+multi-jet: PCA

CMS SMP-24-003



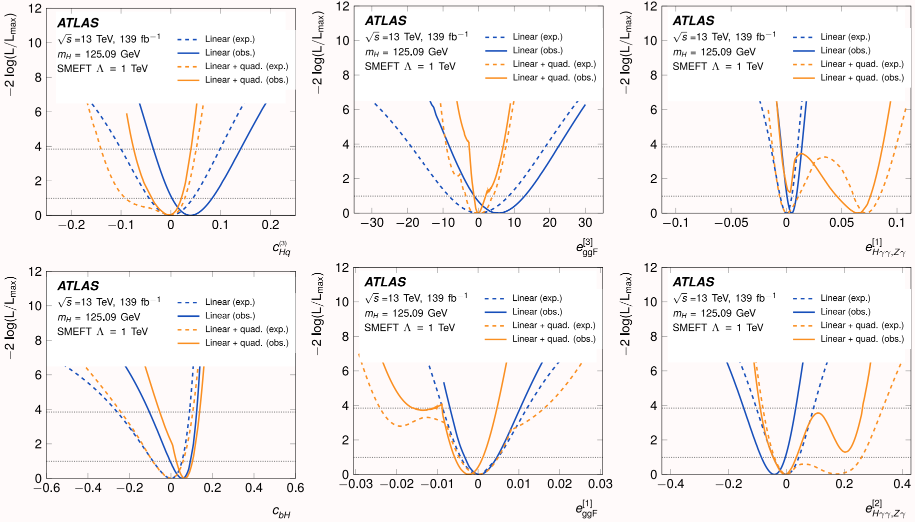
EW+Higgs+top+multi-jet: Fisher

CMS SMP-24-003



Likelihood shapes: linear vs quadratics

Higgs-only combination ATLAS 2402.05742



Some playing around with SMEFiT

recommended: copy the jupyter notebook to your Colab
(all package dependences tested)

`colab.research.google.com/drive/1qvCwkYGf6hq2g6OjLNkqLcLH4vi3cTIG?usp=sharing`

Higher orders

One loop corrections

SMEFT operators **run and mix** (Alonso),Jenkins,Manohar,Trott '13

→ bounds are put on $C(\mu_0)$ defined at a certain scale μ_0.

→ residual scale dependence present, depends on process and operator

→ typically smaller in (absolute) size for NLO calculations

$h \to \bar{b}b$ Cullen,Pecjak,Scott 1904.06358

$$\frac{\Gamma^{LO}_{SMEFT}(m_H)}{\Gamma^{LO}_{SM}(m_H)} = \Delta^{\rm LO}(m_H, m_H) = (1 \pm 0.08) + \frac{(\bar{v}^{(\ell)})^2}{\Lambda^2_{\rm NP}} \Big\{ (3.74 \pm 0.36)\tilde{C}_{HWB} + (2.00 \pm 0.21)\tilde{C}_{H\Box} - (1.41 \pm 0.07)\frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}}\tilde{C}_{bH} + (1.24 \pm 0.14)\tilde{C}_{HD}$$

$$\pm 0.35\tilde{C}_{HG} \pm 0.19\tilde{C}^{(1)}_{Hq} \pm 0.18\tilde{C}_{Ht} \pm 0.11\tilde{C}^{(3)}_{Hq} \pm 0.08\frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}}\tilde{C}^{(1)}_{qtqb} \pm 0.03\frac{\tilde{C}_{tW}}{\bar{e}^{(\ell)}} \pm 0.03(\tilde{C}_{HW} + \tilde{C}_{tH}) + \dots \Big\},$$

[uncertainties from ×2 variations of both SM and C scales. $\tilde{C}$ defined at $\mu_0 = m_H$]

One loop corrections

SMEFT operators **run and mix** (Alonso),Jenkins,Manohar,Trott '13

→ bounds are put on $C(\mu_0)$ defined at a certain scale μ_0.

→ residual scale dependence present, depends on process and operator

→ typically smaller in (absolute) size for NLO calculations

$h \to \bar{b}b$

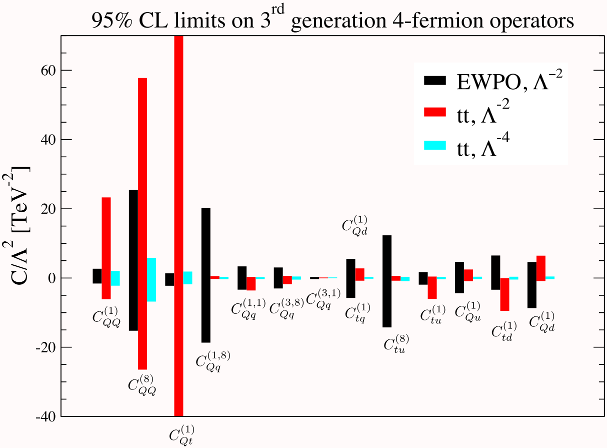
Cullen,Pecjak,Scott 1904.06358

$$\Delta^{\rm NLO}(m_H, m_H) = 1.13^{+0.01}_{-0.04} + \frac{(\bar{v}^{(\ell)})^2}{\Lambda^2_{\rm NP}} \Big\{ \left(4.16^{+0.05}_{-0.14}\right) \tilde{C}_{HWB} + \left(2.40^{+0.04}_{-0.09}\right) \tilde{C}_{H\Box}$$
$$+ \left(-1.73^{+0.04}_{-0.03}\right) \frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}} \tilde{C}_{bH} + \left(1.33^{+0.01}_{-0.04}\right) \tilde{C}_{HD} + \boxed{\left(2.75^{+0.49}_{-0.48}\right) \tilde{C}_{HG}}$$
$$+ \left(-0.12^{+0.04}_{-0.01}\right) \tilde{C}^{(3)}_{Hq} + \left(-0.08^{+0.05}_{-0.01}\right) \tilde{C}_{Ht} + \left(0.06^{+0.00}_{-0.05}\right) \tilde{C}^{(1)}_{Hq}$$
$$+ \left(0.03^{+0.02}_{-0.01}\right) \frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}} \tilde{C}^{(1)}_{qtqb} + \left(0.00^{+0.07}_{-0.04}\right) \frac{\tilde{C}_{tG}}{g_s} + \left(-0.03^{+0.01}_{-0.01}\right) \tilde{C}_{tH}$$
$$+ \left(0.03^{+0.01}_{-0.01}\right) \tilde{C}_{HW} + \left(-0.01^{+0.01}_{-0.00}\right) \tilde{C}_{tW} + \ldots \Big\}.$$

[uncertainties from $\times 2$ variations of both SM and C scales. $\tilde{C}$ defined at $\mu_0 = m_H$]

Sensitivity to more operators

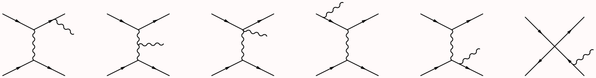
Dawson,Giardino 2201.09887



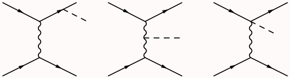
More interconnections among sectors

Example: Higgs and top

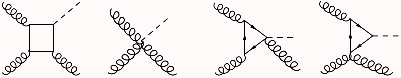
$gg \to tZj$



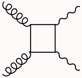
$gg \to thj$



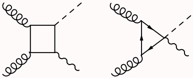
$gg \to hg$



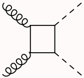
$gg \to ZZ, \gamma\gamma$



$gg \to Zh$

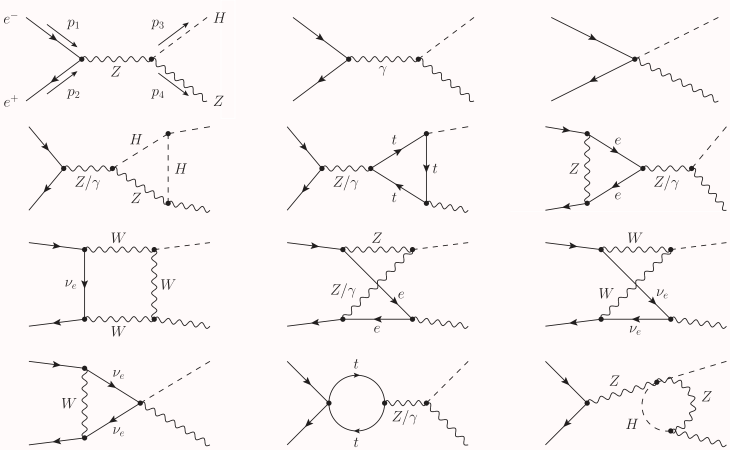


$gg \to hh$



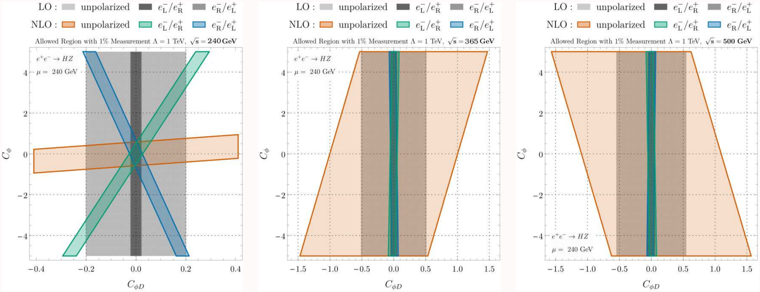
Example: $e^+e^- \to ZH$ at NLO

Asteriadis, Dawson, Giardino, Szafron 2409.11466



Example: $e^+e^- \to ZH$ at NLO

Asteriadis, Dawson, Giardino, Szafron 2409.11466



Asteriadis, Dawson, Giardino, Szafron 2409.11466