SMEFT predictions for the LHC

Ilaria Brivio

Università & INFN Bologna

Swiss National Science Foundation

COMETA

INFN Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

Lectures plan

- Effective Field Theories: motivation and intuitive idea
- SMEFT generalities
- SMEFT at $d = 6$: Warsaw basis
- Basics of SMEFT predictions at LO
- EWSB, Field and couplings redefinitions
- Flavor structure
- EW input parameter schemes
- SMEFT corrections in propagators
- A concrete example: $h \to \mu^+ \nu_\mu \bar{\nu}_e e^-$
- Automation of SMEFT predictions
- Higher orders

Useful references

- I. Brivio, M. Trott. "The Standard Model as an effective field theory" arXiv: 1706.08945
- G. Isidori, F. Wilsch, D. Wyler. "The Standard Model effective field theory at work". arXiv: 2303.16922
- 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`
- A. Manohar, "Effective Field Theories" arXiv: 9508245
- A. Manohar. "Introduction to effective Field Theories" arXiv: 1804.05863
- T. Cohen. "As scales become separated: lectures on Effective Field Theory" arXiv: 1903.03622

more refs in a separate pdf

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

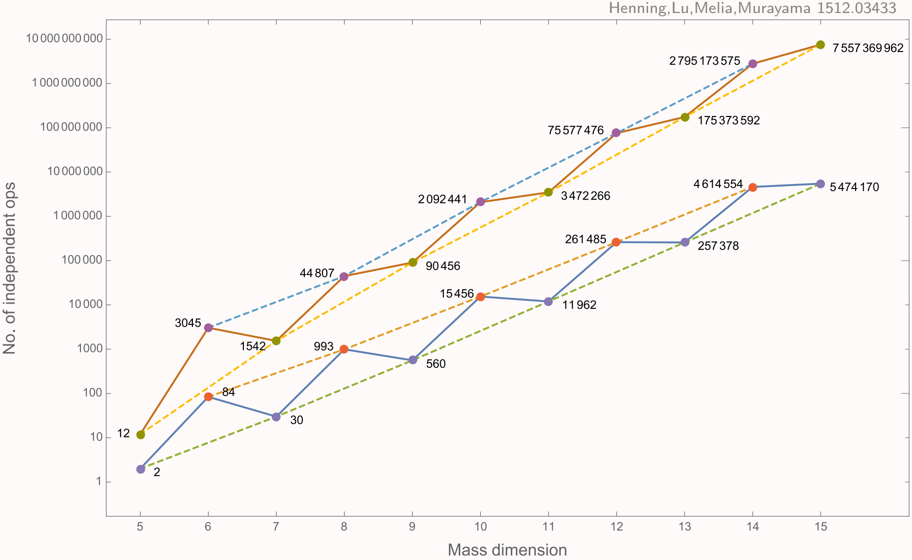
The Warsaw basis

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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

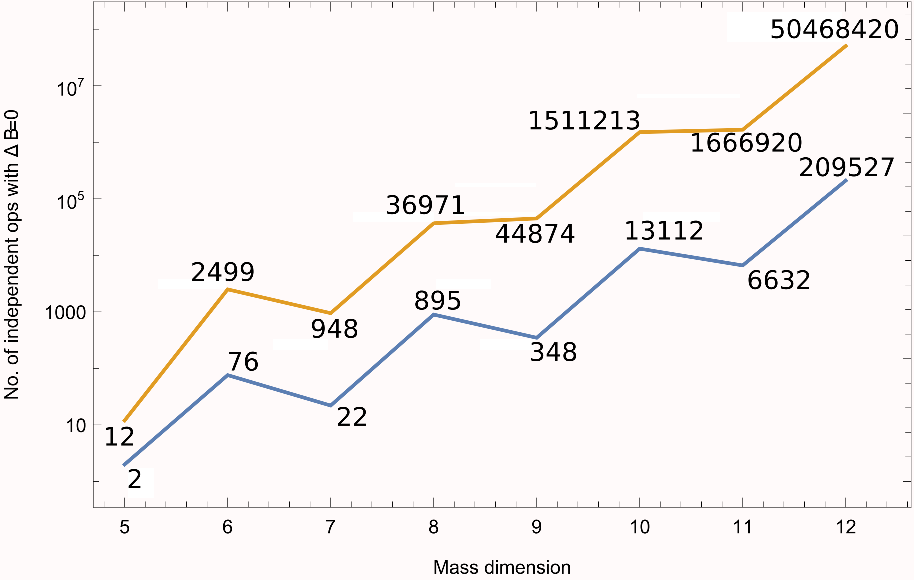
SMEFT: number of independent parameters



SMEFT: number of independent parameters

imposing $\Delta B = 0$

Henning,Lu,Melia,Murayama 1512.03433



A very large flavorful parameter space

Classification within Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

Class	CP	$\not{CP}$	Total
X^3	2	2	4
$\varphi^6 + \varphi^4 D^2$	3	-	3
$\varphi^2 X^2$	4	4	8
$\varphi^2\psi^2$	27	27	54
$\varphi X\psi^2$	72	72	144
$\varphi^2 D\psi^2$	51	30	81
$(\bar{L}L)(\bar{L}L)$	171	126	297
$(\bar{R}R)(\bar{R}R)$	255	195	450
$(\bar{L}L)(\bar{R}R)$	360	288	648
$(\bar{L}R)(\bar{R}L)$	81	81	162
$(\bar{L}R)(\bar{L}R)$	324	324	648

- most parameters from **fermionic** terms
- **flavor** has dramatic impact on counting

Examples:

$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi$	9 + 9
$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	6 + 3
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	27 + 18
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	45 + 36
$(\bar{l}_i^I e_j)(\bar{d}_k q_l^I)$	81 + 81

SMEFT corrections to LHC processes

$$\int d\Phi \quad \int \text{PDFs} \quad |A_{SMEFT}|^2 \longrightarrow \text{shower/hadr.} \longrightarrow \text{detector} \longrightarrow \text{obs.}$$

SMEFT corrections to LHC processes

$$\int d\Phi \quad \int \text{PDFs} \quad |A_{SMEFT}|^2 \longrightarrow \text{shower/hadr.} \longrightarrow \text{detector} \longrightarrow \text{obs.}$$

could PDF fits absorb SMEFT away?

- SMEFT effects within unc. for Run I-II
- can be sizeable for HL-LHC pred.

Carrazza et al 1905.05215
Greljo et al. 2104.02723
Iranipour,Ubiali 2201.07240
Hammou et al 2307.10370

$\varepsilon \cdot A$

acceptances for SM and SMEFT differ if Lorentz structure changes

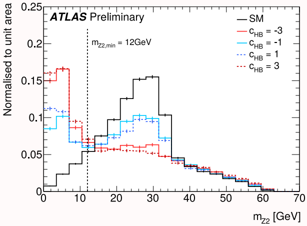
ATLAS 2004.03447
ATLAS-CONF-2020-053
ATL-PHYS-PUB-2022-037

EFT impact can depend on jet def.

Haisch et al 2204.00663

ME-PS matching has to include soft/collinear em. from EFT

Goldouzian et al 2012.06872
Haisch et al 2204.00663

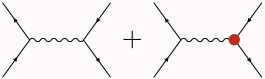


ATL-PHYS-PUB-2022-037

SMEFT corrections to LHC processes

$$\int d\Phi \quad \int \mathrm{PDFs} \quad |A_{SMEFT}|^2 \longrightarrow \text{shower/hadr.} \longrightarrow \text{detector} \longrightarrow \text{obs.}$$

$$A_{SMEFT} = A_{SM} + \sum_i \left(C_i^{(6)}/\Lambda^2\right) A_i$$



$$|A_{SMEFT}|^2 = |A_{SM}|^2 + \sum_i \frac{C_i^{(6)}}{\Lambda^2} 2Re\left(A_{SM} A_i^\dagger\right) + \sum_{i,j} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} |A_i A_j^\dagger|$$

$\times$ (SM K-factor) interference/linear quadratics

- A_{SMEFT} typically computed up to 1-loop in QCD / EW
- $\int d\Phi \int \mathrm{PDFs}\, |A_{SMEFT}|^2$

  can be computed with **Monte Carlo gen.** up to 1-loop in QCD

SMEFT Lagrangian after first redefinitions

after expanding around the true vacuum v_T and requesting:
canonical h and gauge kinetic terms + diagonal gauge boson masses

the relevant Lagrangian terms in unitary gauge are

$$V(h) = h^2\,\lambda v_T^2\left[1+\Delta m_h^2\right] + h^3\,\lambda v_T\left[1+\frac{3}{2}\Delta m_h^2 - \frac{\bar C_H}{4\lambda}\right] + h^4\,\frac{\lambda}{4}\left[1+2\Delta m_h^2 - \frac{9\bar C_H}{2\lambda}\right] - \frac{3}{4}\,\frac{h^5\,\bar C_H}{v_T}\,.$$

$$\mathscr{L}_{\text{gauge mass}} = W_\mu^- W^{+\mu}\,\frac{v_T^2 g_W^2}{4} + Z_\mu Z^\mu\,\frac{v_T^2(g_W^2+g_1^2)}{4}\left(1+\Delta m_Z^2\right)$$

and a covariant derivative is

$$D_\mu = \partial_\mu + iQ\frac{g_1 g_W}{\sqrt{g_1^2+g_W^2}}A_\mu\left[1+\frac{\Delta\alpha}{2}\right]$$
$$+\, i\sqrt{g_1^2+g_W^2}\,Z_\mu\left[T_3\left(1-\frac{\Delta\alpha}{2}\right) - \frac{g_1^2 Q}{g_1^2+g_W^2}\left(1-\frac{g_W^2}{g_1^2}\,\frac{\Delta\alpha}{2}\right)\right] + \dots$$

with

$$\Delta\kappa_H = \bar C_{H\Box} - \frac{\bar C_{HD}}{4} \qquad\qquad \Delta m_h^2 = 2\Delta\kappa_H - \frac{3}{2\lambda}\,\bar C_H$$

$$\Delta m_Z^2 = \frac{2g_W g_1}{g_W^2+g_1^2}\,\bar C_{HWB} + \frac{\bar C_{HD}}{2} \qquad\qquad \Delta\alpha = -\frac{2g_W g_1}{g_W^2+g_1^2}\,\bar C_{HWB}$$

Parameter counting with flavor symmetries

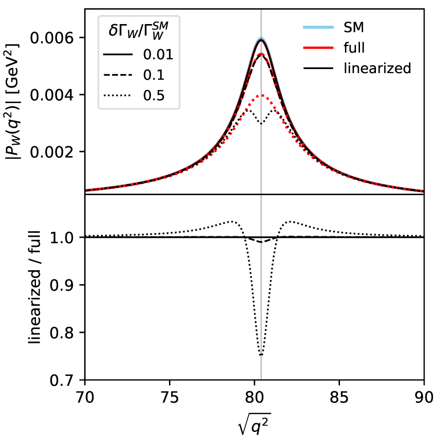
Example operator	fl. general	$\mathbf{U(3)^5}$	$\mathbf{U(2)^3 \times U(3)^2}$
$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi$	$9+9$	$1+1\ (y)$	$2+2\ (y{,}1)$
$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	$6+3$	1	2
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	$27+18$	2	2
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	$45+36$	1	2
$(\bar{l}_i^j e_j)(\bar{d}_k q_l^j)$	$81+81$	$1+1\ (y^2)$	$2+2\ (y^2, y)$

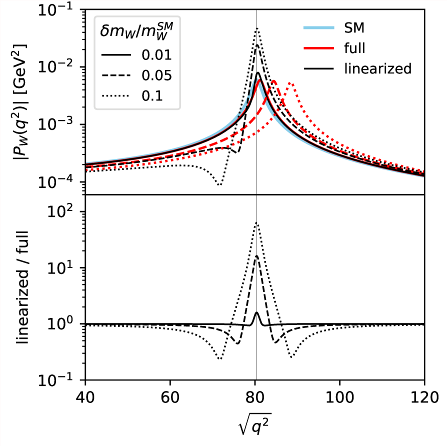
$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

$$U(2)^3 \times U(3)^2 = U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e \qquad V_{CKM} = \mathbb{1}$$

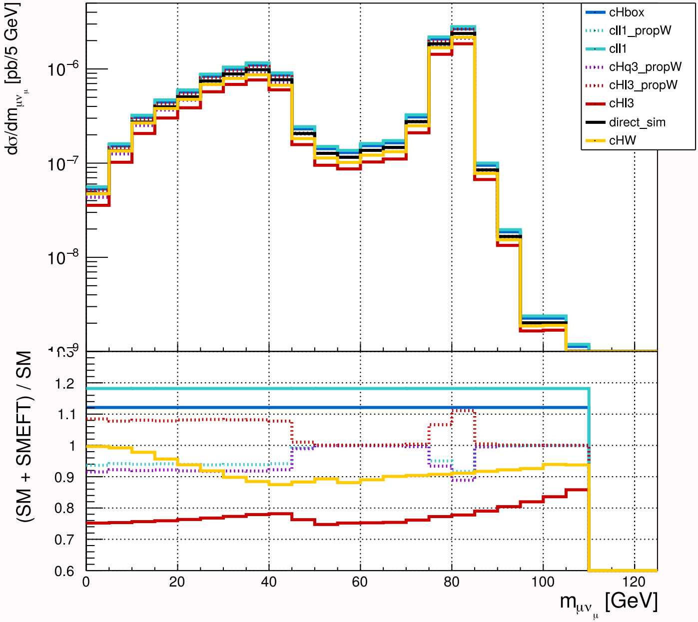
Propagator corrections

$$\frac{i(-\eta^{\mu\nu}+q^\mu q^\nu/m_W^2)}{p^2-m_W^2+i\Gamma_W m_W}\left[1+\frac{i m_W\,\Delta\Gamma_W}{p^2-m_W^2+i\Gamma_W m_W}-\frac{(2m_W-i\Gamma_W)\,\Delta m_W}{p^2-m_W^2+i\Gamma_W m_W}\right]+\mathcal{O}(\Lambda^{-4})$$

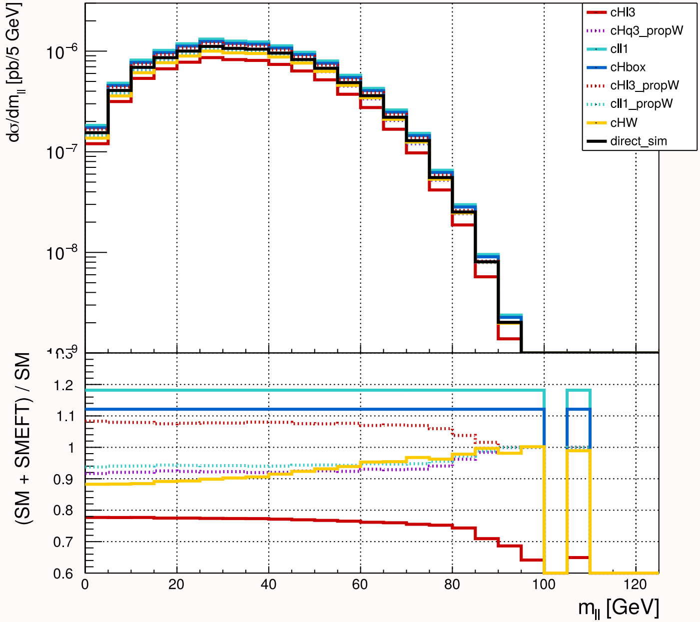




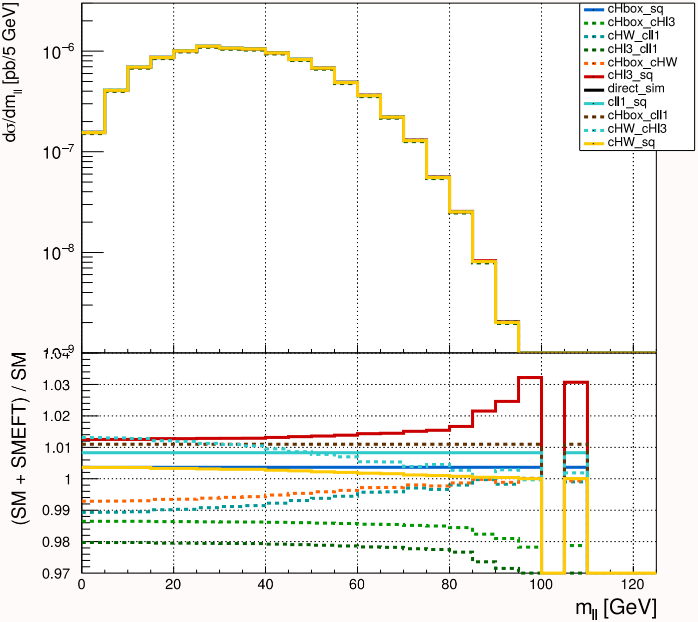
SMEFT effects in $h \to \mu^+ \nu_\mu \bar{\nu}_e e^-$



SMEFT effects in $h \to \mu^+ \nu_\mu \bar{\nu}_e e^-$



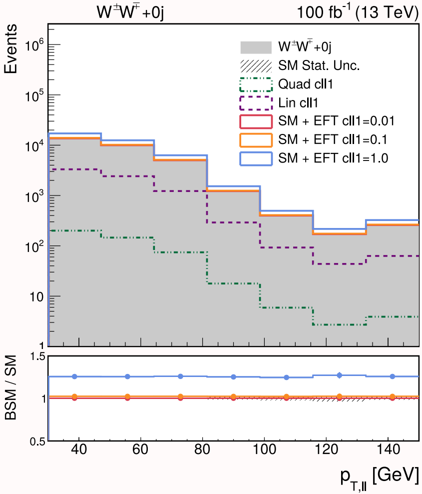
SMEFT effects in $h \to \mu^+ \nu_\mu \bar{\nu}_e e^-$

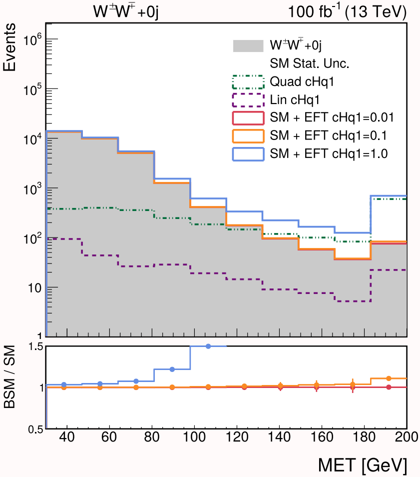


SMEFT effects: rescaling vs. shape change

Bellan,Boldrini,Brambilla,IB et al 2108.03199

parton level simulation of $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$ with $\{m_W, m_Z, G_F\}$ inputs





Predictions to 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

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

$$\pm 0.35\tilde{C}_{HG} \pm 0.19\tilde{C}^{(1)}_{Hq} \pm 0.18\tilde{C}_{Ht} \pm 0.11\tilde{C}^{(3)}_{Hq}$$

$$\pm 0.08\frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}}\tilde{C}^{(1)}_{qtqb} \pm 0.03\frac{\tilde{C}_{tW}}{\bar{e}^{(\ell)}} \pm 0.03(\tilde{C}_{HW} + \tilde{C}_{tH}) + \dots \Big\},$$

[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

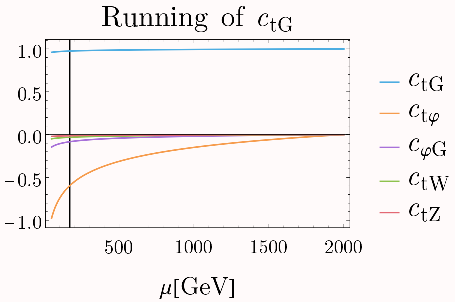
$$\begin{aligned}\Delta^{\rm NLO}(m_H,m_H) = 1.13^{+0.01}_{-0.04} + \frac{(\bar{v}^{(\ell)})^2}{\Lambda^2_{\rm NP}}\Big\{ &\left(4.16^{+0.05}_{-0.14}\right)\tilde{C}_{HWB} + \left(2.40^{+0.04}_{-0.09}\right)\tilde{C}_{H\Box} \\ &+ \left(-1.73^{+0.04}_{-0.03}\right)\frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}}\tilde{C}_{bH}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

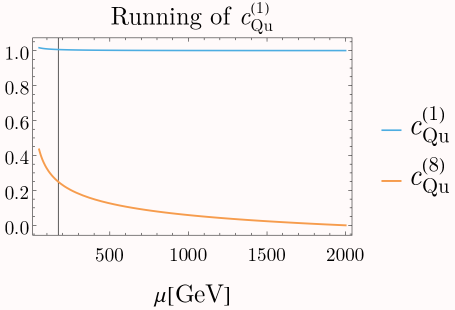
[uncertainties from $\times 2$ variations of both SM and C scales. $\tilde{C}$ defined at $\mu_0 = m_H$]

Impact of RG running and mixing

Aoude, Maltoni, Mattelaer, Severi, Vryonidou 2212.05067

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

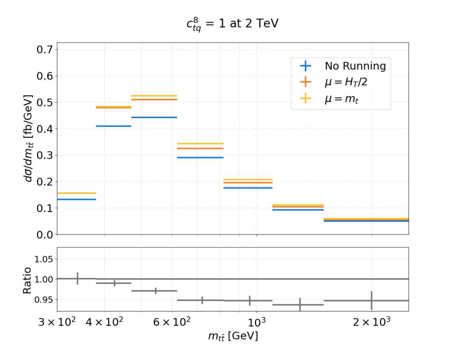


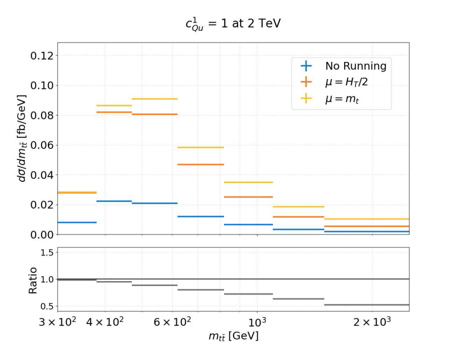


Impact of RG running and mixing

Aoude, Maltoni, Mattelaer, Severi, Vryonidou 2212.05067

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





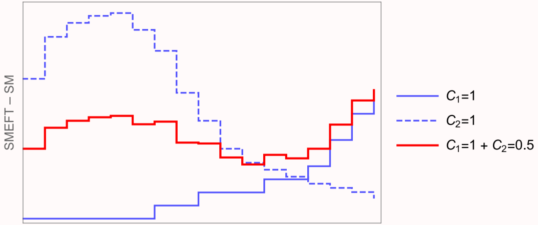
Automation of SMEFT predictions

Most used: MadGraph5_aMC@NLO

- ✔ maximal flexibility in terms of processes
- ✔ interaction orders syntax facilitates **morphing**
- ✔ offers an integrated **reweighting** module — Gainer et al. 1404.7129, Mattelaer 1607.00763
- ✔ supports polarized matrix elements — Buarque-Franzosi,Mattelaer,Ruiz,Shil 1912.01725
- ✔ recent updates (from 2.9.0) — Mattelaer, Ostrolenk 2102.00773
  optimized **phase space integrator** + new algorithm for amplitude evaluation
  → faster and more agile for EFT, when several diagrams are 0

Morphing of EFT signal

@ LHC one is typically interested in <u>kinematic distributions</u>
→ final shape is a superposition of SMEFT effects depending on C_k



the parameterization has to be **polynomial** in C_k in each bin:

$$n^i(C_1, C_2) = n^i_{SM} + C_1\, a^i_1 + C_2\, a^i_2\, (+C_1^2\, b^i_1 + C_2^2\, b^i_2 + C_1 C_2\, b^i_{12})$$

→ morphing = **determine n^i_{SM}, a^i_k, (b^i_k, b^i_{kl}) for each bin i**

→ for N coeff. requires: $(1+N)$ event generations for SM + interferences
$N(N+1)/2$ for quadratics

much more efficient than evaluating n_i on N-dimensional grid!

Reweighting procedure

1. simulate a process in a certain setup (A) $\rightarrow$ unweighted events
2. "convert" to a different model/parameter space point (B) by scaling **weight** W event by event

$$W_B = \frac{|A_B|^2}{|A_A|^2} W_A$$

- ✔ re-use event samples: much **faster** than re-generating
- ✔ relation between W_B from W_A has arbitrary **numerical precision**
- ✔ **smaller stat. uncertainties** in ratios/sums/diffs of SM(EFT) components

$$\text{two indep. sim.} \rightarrow \quad \sigma\left[\frac{n(B)}{n(A)}\right] = \sqrt{\sigma\left[n(B)\right]^2 + \sigma\left[n(A)\right]^2}$$

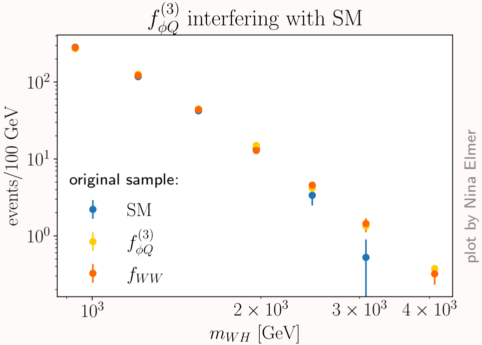
$$n(B) \text{ from rwgt of } n(A) \rightarrow \quad \sigma\left[\frac{n(B)}{n(A)}\right] = 0 \qquad \text{[fully correlated]}$$

essentially recycling phase-space integration, re-evaluating only matrix element

Reweighting procedure – caveats

⚠ **phase space sampling** has to be adequate for both A and B

⚠ too small statistics in a given bin can lead to large over/under-estimations



→ SM sample missing statistics in 3 highest bins

→ statistics is important to integrate properly over non-shown variables

⚠ MG5 uses **dynamical phase sp. integration**: adapts to process, doesn't "factorize" dependence reduced with large # events (smaller stat error)

UFO models for SMEFT

most used:

`SMEFTsim` IB,Jiang,Trott 1709.06492, IB 2012.11343

- only tree level
- full Warsaw basis (incl ~~CP~~) in various flavor version
- full dependence on m_ψ, CKM, leading spurions

`SMEFT@NLO` Degrande,Durieux,Maltoni,Mimasu,Vryonidou,Zhang 2008.11743

- up to 1-loop QCD
- full Warsaw basis with CP and $U(3)_d \times U(2)_u \times U(2)_q \times U(1)^3_{l+e}$
- 5-flavor scheme $(m_b = 0 = y_b, V_{CKM} = \mathbb{1})$

`dim6top` Durieux,Zhang 1802.07237

- only tree level, same flavor sym as in `SMEFT@NLO` + expl. breakings
- only top operators, including FCNC

more with alternative operator sets/bases (also dim8) in FeynRules database

validation protocol Durieux et al 1906.12310

based on dedicated MG5 module that performs single-event comparisons

→ extensive cross-comparisons performed for `SMEFTsim`, `SMEFT@NLO`, `dim6top`

SMEFTsim

Simulations with other Monte Carlo generators

- **Sherpa** ⇝ more talks at indico.cern.ch/event/971724/

  supports UFO and interaction order specifications Höche,Kuttimalai,Schumann,Siegert 1412.6478

- **POWHEG-BOX**

  hard-coded matrix elements. some processes available in SMEFT NLO QCD:
  - EW Higgs production — Mimasu,Sanz,Williams 1512.02572
  - diboson — Baglio,Dawson,(Homiller,Lewis) 1812.00214, 1909.11576
  - $\ell\ell$ Drell Yan up to dim 8 — Alioli,Dekens,Girard,Mereghetti 1804.07407; Alioli,Boughezal,Mereghetti,Petriello 2003.11615
  - HH — Heinrich,Jang,Scyboz 2204.13045

  MG5 – POWHEG-BOX interface — Nason,Oleari,Rocco,Zaro 2008.06364

  ME produced by MG up to NLO QCD → run in POWHEG

- **JHUGen**: H production + $H \to 4\ell, \tau\tau$, on- and off-shell Gritsan,Roskes,Sarica,Schulze, Xiao,Zhou 2002.09888

  anomalous couplings mapped to SMEFT: Warsaw, Higgs b. (via JHUGenLexicon)
  LO, reweighting possible (via MELA)

- **VBFNLO**

  hard-coded matrix elements. EW+QCD diboson, triboson, VBS, VBF for H,Z,W,γ
  anomalous couplings mapped to SMEFT: HISZ basis dim 6 + Éboli basis dim 8

  Hagiwara et al PRD48(1993)2182, Éboli et al hep-ph/0009262

What is SMEFTsim?

- **Purpose**: enable MC event generation in SMEFT, with a general tool that automates theory manipulations and implements all $\mathcal{L}_6$ in Warsaw basis
- **Scope**: complete tree-level $\mathcal{O}(\Lambda^{-2})$ predictions, in unitary gauge
- consists of **FeynRules model + 10 UFOs** (pre-exported)

`general` `MFV` `U35` `top` `topU3l`

$\times$

$\{\alpha_{\rm em}, m_Z, G_F\}$ $\{m_W, m_Z, G_F\}$

- original version: IB,Jiang,Trott 1709.06492
- since 2020, version 3.x.x IB 2012.11343
  - new features: propagator corrections, more flavors...
  - a dedicated github website and repository smeftsim.github.io

Flavor in SMEFTsim

- all operators defined in the **up basis**

$$Y_d \equiv Y_d^{(d)} V^\dagger \,, \quad Y_u \equiv Y_u^{(d)} \,, \quad Y_l \equiv Y_l^{(d)}$$

- CKM implemented using Wolfenstein parameterization
- symmetries can be imposed:
  - ✔ much fewer free parameters
  - ✔ LHC cannot distinguish all quark flavors anyway
  - ✔ FV/FUV/FCNC are not a primary target
  - ✔ implement a possible "flavor power counting"

Bordone,Catà,Feldmann 1910.02641
Faroughy,Isidori,Wilsch,Yamamoto 2005.05366
Greljo,Palavrić,Thomsen 2203.09561

→ directly hard-coded into 5 alternative `SMEFTsim` versions

`general` no symmetry → 

`top` $U(2)_q \times U(2)_u \times U(2)_d \times U(1)^3_{l+e}$

`topU3l` $U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e$

`MFV` $U(3)^5$ + extra spurion insertions − ~~CP~~

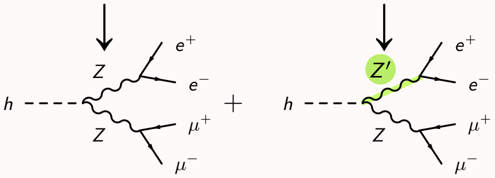
`U35` $U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$

SMEFTsim flavor structures: parameter counting

	general		U35		MFV		top		topU3l	
	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$
$\mathscr{L}_6^{(1)}$	4	2	4	2	2	-	4	2	4	2
$\mathscr{L}_6^{(2,3)}$	3	-	3	-	3	-	3	-	3	-
$\mathscr{L}_6^{(4)}$	8	4	8	4	4	-	8	4	8	4
$\mathscr{L}_6^{(5)}$	54	27	6	3	7	-	14	7	10	5
$\mathscr{L}_6^{(6)}$	144	72	16	8	20	-	36	18	28	14
$\mathscr{L}_6^{(7)}$	81	30	9	1	14	-	21	2	15	2
$\mathscr{L}_6^{(8a)}$	297	126	8	-	10	-	31	-	16	-
$\mathscr{L}_6^{(8b)}$	450	195	9	-	19	-	40	2	27	2
$\mathscr{L}_6^{(8c)}$	648	288	8	-	28	-	54	4	31	4
$\mathscr{L}_6^{(8d)}$	810	405	14	7	13	-	64	32	40	20
tot	2499	1149	85	25	120	-	275	71	182	53

Propagator corrections in SMEFTsim

$$\mathcal{A} \propto \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z} = \frac{1}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \left[1 - \frac{i m_Z}{q^2 - m_Z^2 + i m_Z \Gamma_Z^{SM}} \delta\Gamma_Z \right] + \mathcal{O}(\delta\Gamma_Z^2)$$



Dummy fields W', Z', h', t' are added whose propagator is **the pure linearized shift**

Gröber,Mattelaer,Mimasu – Les Houches 2017 1803.10379

Insertions controlled by interaction order `NPprop` in dummy vertices

→ e.g. interference piece `NPprop<=2 NPprop^2==2`

Loop-generated SM Higgs couplings

SMEFTsim is a purely LO UFO model. cannot do $gg \to h, h \to \gamma\gamma \dots$ in SM
$\to$ cannot compute interference terms?!

$\to$ implemented as point-vertices in $m_t \to \infty$ limit [ok for Higgs prod+decay]

γ $$\mathscr{L} = \frac{e^2}{8\pi^2} f_{\gamma\gamma}\left(\frac{m_h^2}{4m_W^2}, \frac{m_h^2}{4m_t^2}\right)\mathcal{O}_{\gamma\gamma} + \frac{e^2}{4\pi^2} f_{Z\gamma}\left(\frac{m_h^2}{4m_W^2}, \frac{m_h^2}{4m_t^2}, \frac{m_Z^2}{4m_W^2}\right)\mathcal{O}_{Z\gamma}$$

two relevant $d = 5$ operators:

$$\mathcal{O}^{(1)}_{\gamma\gamma} = A_{\mu\nu}A^{\mu\nu}\frac{h}{v}\,, \qquad \mathcal{O}^{(1)}_{Z\gamma} = Z_{\mu\nu}A^{\mu\nu}\frac{h}{v}\,,$$

$f_{\gamma\gamma}\left(\frac{m_h^2}{4m_W^2}, \frac{m_h^2}{4m_t^2}\right)$, $f_{Z\gamma}\left(\frac{m_h^2}{4m_W^2}, \frac{m_h^2}{4m_t^2}, \frac{m_Z^2}{4m_W^2}\right)$ computed to order m_t^{-2}, m_W^{-6}.

Loop-generated SM Higgs couplings

`SMEFTsim` is a purely LO UFO model. cannot do $gg \to h, h \to \gamma\gamma \dots$ in SM
$\to$ cannot compute interference terms?!

$\to$ implemented as point-vertices in $m_t \to \infty$ limit [ok for Higgs prod+decay]

G $$\mathscr{L} = \frac{g_s^2}{48\pi^2}\left[O_{gg}^{(1)} - \frac{7}{60m_t^2}\mathcal{O}_{gg}^{(2)} + \frac{g}{5m_t^2}\mathcal{O}_{gg}^{(3)} + \frac{1}{30m_t^2}\mathcal{O}_{gg}^{(4)} + \frac{3}{5m_t^2}\mathcal{O}_{gg}^{(5)}\right]$$

complete basis of HG operators up to $d=7$: "top-EFT"

Neill 0908.1573
Harlander,Neumann 1309.2225
Dawson,Lewis,Zeng 1409.6299

$$\mathcal{O}_{gg}^{(1)} = G^a_{\mu\nu}G^{a\mu\nu}\frac{h}{v},$$

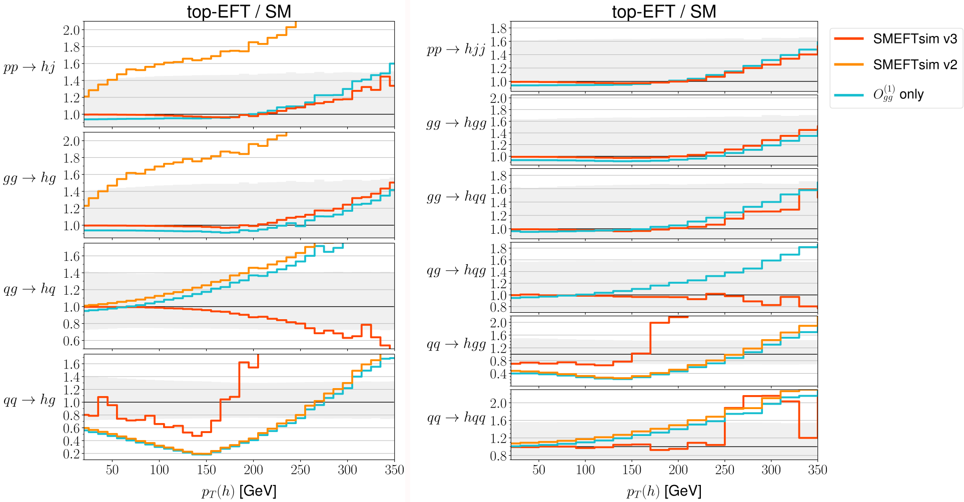
$$\mathcal{O}_{gg}^{(2)} = D_\sigma G^a_{\mu\nu}D^\sigma G^{a\mu\nu}\frac{h}{v}, \quad \mathcal{O}_{gg}^{(3)} = f_{abc}G^{a\nu}_{\mu}G^{b\sigma}_{\nu}G^{c\mu}_{\sigma}\frac{h}{v},$$

$$\mathcal{O}_{gg}^{(4)} = D^\mu G^a_{\mu\nu}D_\sigma G^{a\sigma\nu}\frac{h}{v}, \quad \mathcal{O}_{gg}^{(5)} = G^{a\mu\nu}D_\nu D^\sigma G^a_{\sigma\mu}\frac{h}{v}.$$

$\to$ complete basis for hg^2, hg^3, hg^4 vertices at $\mathcal{O}(m_t^{-2})$

$\to$ full momentum dependence: Higgs can be off-shell

Loop-generated SM Higgs couplings



- hG vertices ok for $h + 2j$ production up to $p_T(h) \lesssim 250\,\mathrm{GeV}$
- $hZ\gamma$, $h\gamma\gamma$ ok for h decays

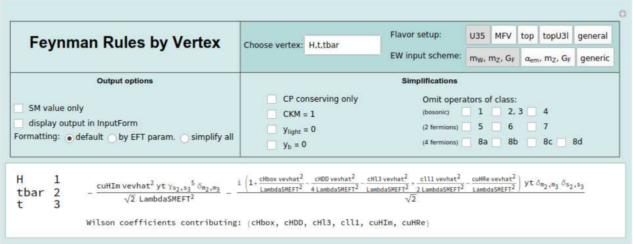
Interactive Feynman rules database

- download from **Notebook Archive**

`notebookarchive.org/smeftsim-interactive-feynman-rules-database--2022-01-5jz62qa/`

notebook + working material (zip folder)

- 2 tools to get immediately FR by operator or by vertex



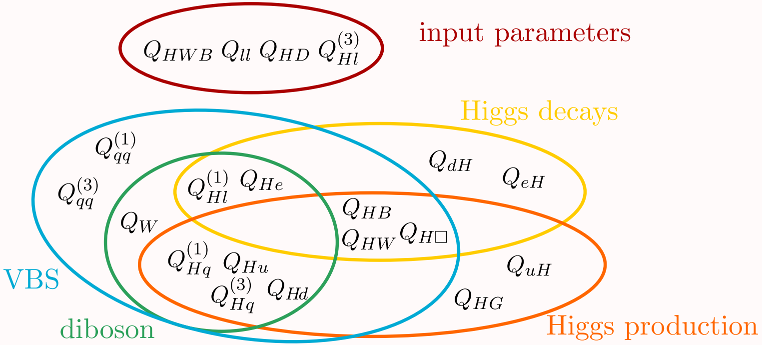
2 more tools to visualize vertices!

- SMEFTviz by R. Balasubramanian and S. Swatman
- SMEFTsimFeyn by G. Boldrini

Pheno and Global Fits

SMEFT for EW and Higgs sectors

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

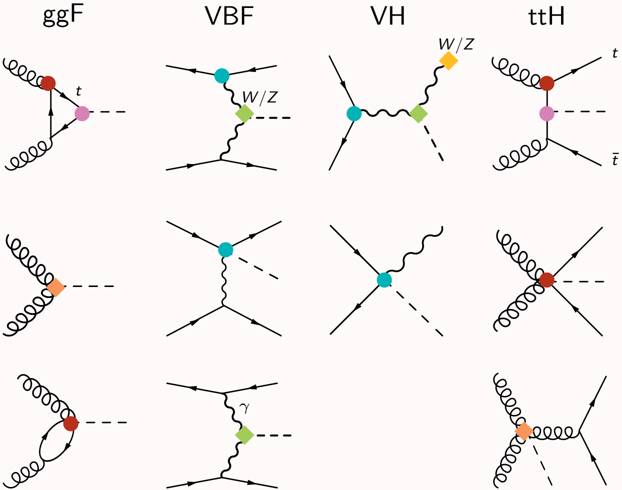


$+$ CP odd $+$ flavor indices $+$ others entering through loop corrections ...

SMEFT in Higgs production

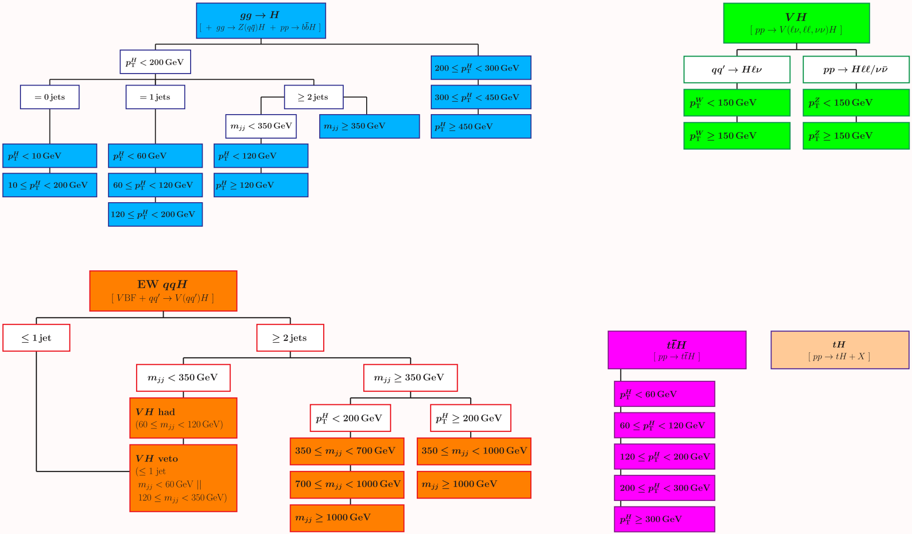
ggF VBF VH ttH

SMEFT in Higgs production



Simplified Template Cross Sections (STXS)

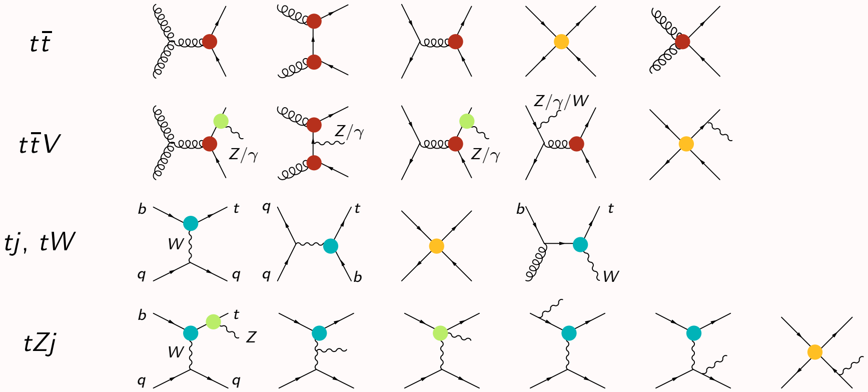
from: ATLAS H10 2207.00348 (stage 1.2)



up to ~ 60 invariants in Warsaw basis. relevant operators: much less!

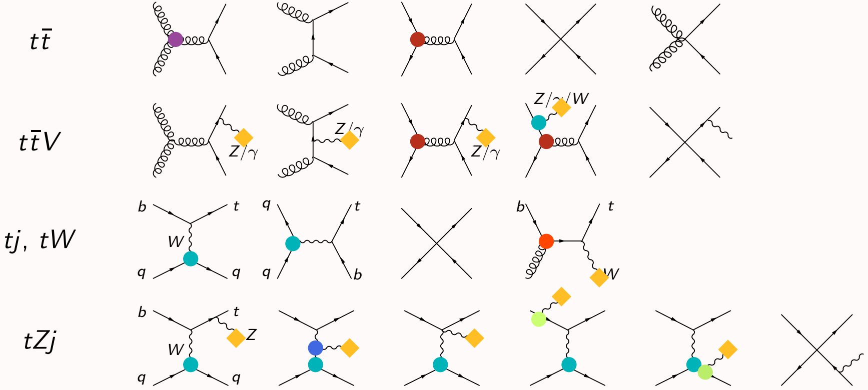
\# depends on – flavor symmetry + scheme
– **processes considered**
– interference/quadratics
– LO/NLO QCD

top WG 1802.07237, Aguilar-Saavedra 0811.3842 (Willenbrock),Zhang 1404.1264,1601.06163,1008.3869, Englert et al 1506.08845,1512.03360,1607.04304 Maltoni et al 1601.08193,1804.07773,1901.05965, 2008.11743, de Beurs et al 1807.03576 Brivio et al 1910.03606



Interplay of top and Higgs + EW

1. top operators → Higgs / EW processes
2. non-top operators → top processes



Interplay of top and Higgs + EW

1. top operators → Higgs / EW processes
2. non-top operators → top processes

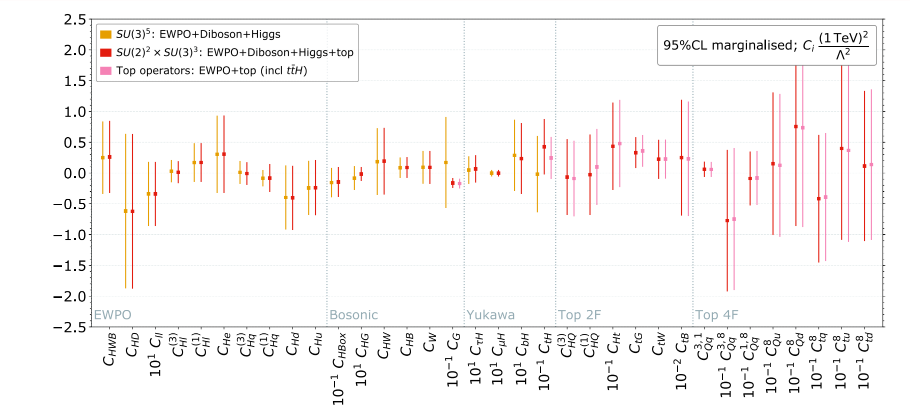
$\sim$ 10 extra operators (un-suppressed, $SU(2)_d \times SU(3)_l \times SU(3)_e$, Warsaw b.)

- $C_G \leftrightarrow$ multi-jet
- –
- C_{bG}
- $C_{Hq}^{(3)}$ ★
- $C_{Hq}^{(1)}, C_{Hu}, C_{Hd}$ ★
- C_{Hb} ★
- $C_W \leftrightarrow$ VV, VBF Z/W, VBS
- $C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{He}$ ($QQ\ell\ell$ op.) ★ $\leftrightarrow$ EWPO, VH, VBF, $h \to 4\ell$, VV, VBS ...

$+\ C_{HWB}, C_{HD}, C'_{ll}$ from EW inputs!

Top + EW + Higgs: global results

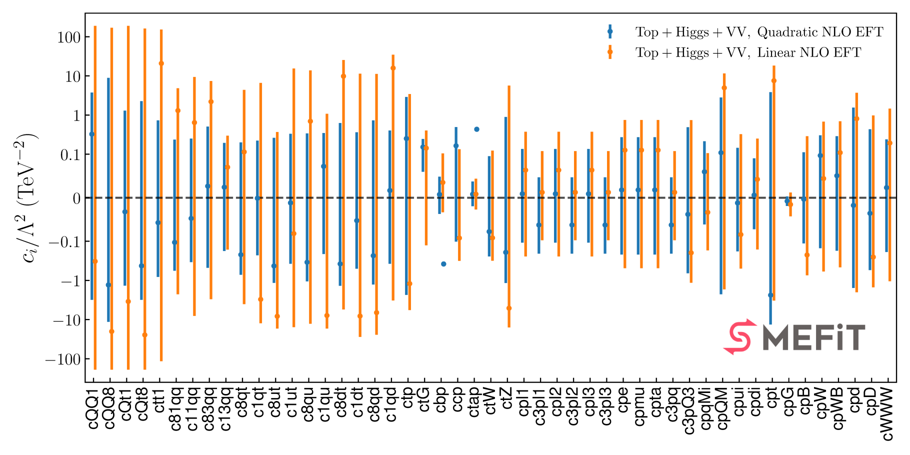
Ellis,Madigan,Mimasu,Sanz,You 2012.02779



34 param, linear, LO + ggH

Top + EW + Higgs: global results

Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006

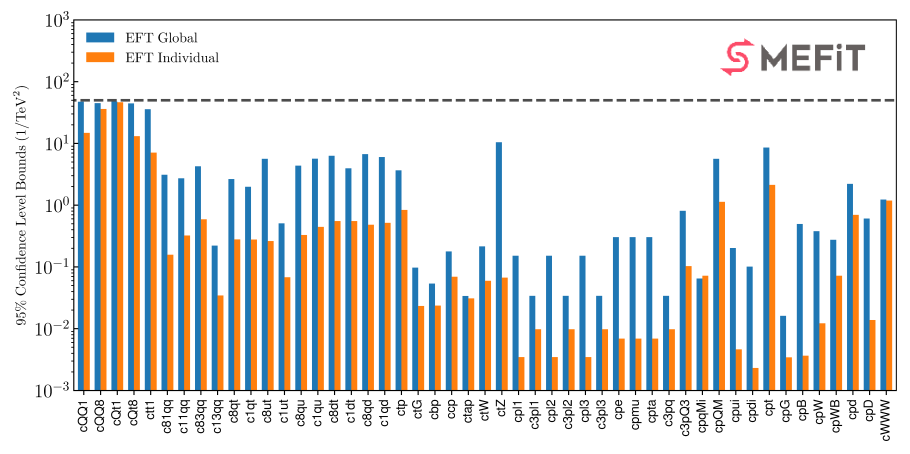


49 param, linear+quadratic, NLO QCD

Top + EW + Higgs: global results

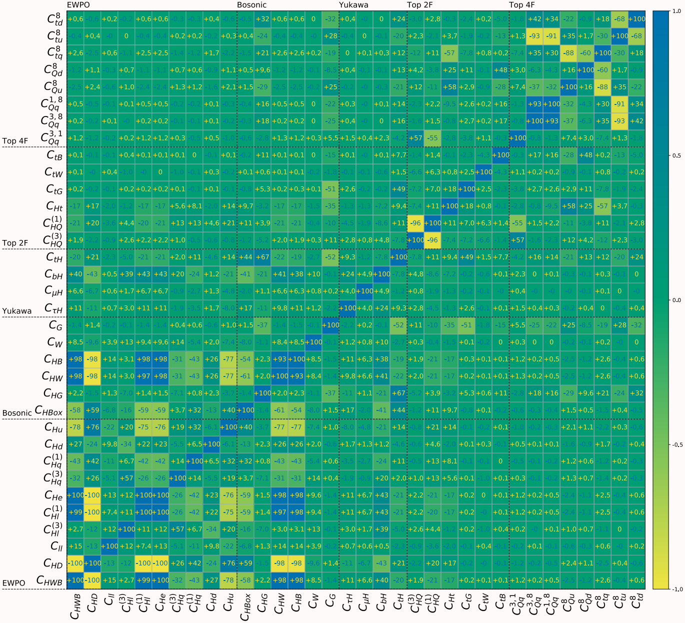
Linear bounds

Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006

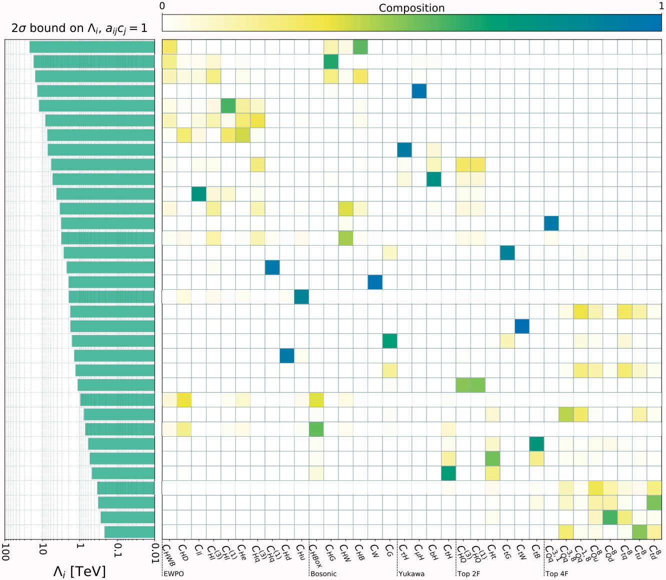


49 param, linear+quadratic, NLO QCD

Top + EW + Higgs: correlation map



Principal Component Analysis

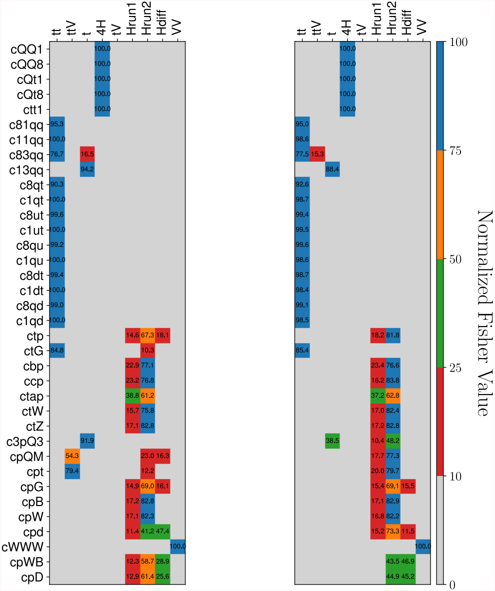


Relative constraining power (%)

	EWPO	LEP WW	Run 1, μ_H	Run 2, μ_H	STXS	LHC WW&	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
	6	–	15	29	50	–	–	–	–	–
	35	–	13	28	23	–	–	–	–	–
	59	–	7	16	18	–	–	–	–	–
	–	–	5	94	1	–	–	–	–	–
	99	–	–	–	–	–	–	–	–	–
	95	–	–	–	–	3	–	–	–	–
	99	–	–	–	–	–	–	–	–	–
	–	–	21	45	33	–	–	–	–	–
	74	–	2	4	14	6	–	–	–	–
	18	–	8	19	55	–	–	–	–	–
	73	22	–	–	–	3	–	–	–	–
	7	2	5	53	4	29	–	–	–	–
	–	–	–	3	–	–	–	–	96	–
	7	–	2	39	2	46	–	–	3	–
	–	–	–	10	4	–	–	57	–	28
	94	2	–	–	–	2	–	–	–	–
	–	2	–	–	–	11	86	–	–	–
	65	14	2	4	10	4	1	–	–	–
	–	–	–	–	–	–	–	99	–	–
	–	–	–	–	–	–	–	84	15	–
	–	–	–	13	6	–	–	48	–	32
	90	5	–	–	1	2	–	–	–	–
	–	–	–	5	2	–	–	79	–	13
	–	–	–	–	–	–	–	3	78	18
	2	3	27	40	12	6	–	4	–	4
	–	–	1	2	–	–	–	15	4	77
	4	4	14	33	23	7	1	12	–	2
	–	–	1	3	1	–	–	4	–	89
	–	–	3	10	4	–	–	28	2	53
	1	–	8	27	16	2	–	32	–	12
	–	–	–	–	–	–	–	58	–	41
	–	–	–	–	–	–	–	90	–	10
	–	–	–	–	–	–	–	61	–	38
	–	–	–	–	–	–	–	95	–	5

Ellis,Madigan,Mimasu,Sanz,You 2012.02779

Fisher information

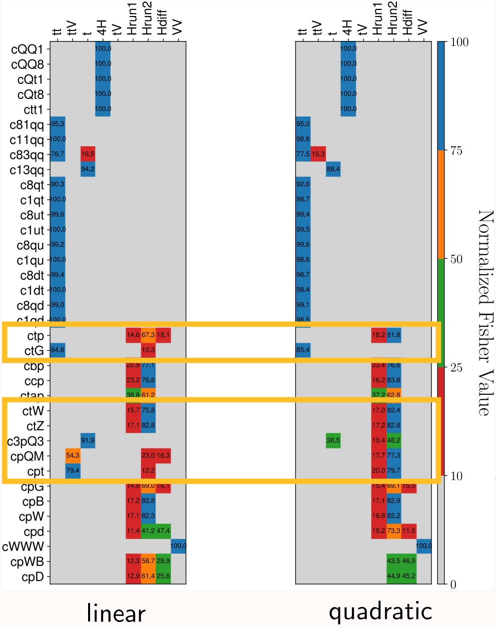


linear quadratic

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang 2105.00006

Fisher information

Ethier,Maltoni,Mantani,Nocera,Rojo,Slade,Vryonidou,Zhang 2105.00006



C_{tG} mostly constrained by $t\bar{t}$

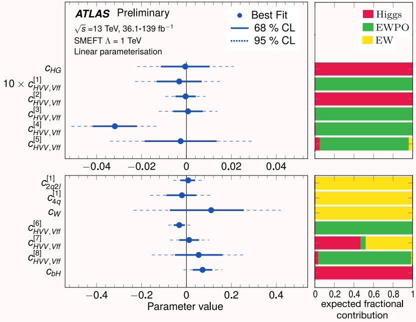
ttV op. constrained by $h \to \gamma\gamma$, single-t, $t\bar{t}V$

SMEFT combined analyses in ATLAS and CMS

LHC experiments gearing up to do dedicated combination

important in order to use the full experimental information:
better uncertainty and correlation estimates

ultimate goal:
a cross-experiment cross-sector combined study



ATL-PHYS-PUB-2022-037

CMS-TOP-19-001