

The SMEFT program at the LHC

Ilaria Brivio

Institut für Theoretische Physik,
Universität Heidelberg



Effective Field Theories: basics

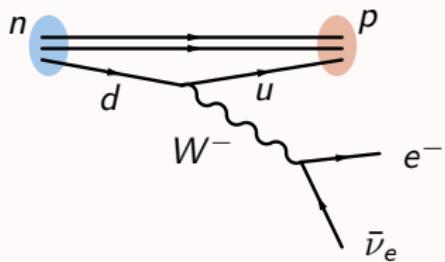
EFT = field theory that describes the **IR limit** of an underlying UV sector in terms of only the light degrees of freedom

Effective Field Theories: basics

EFT = field theory that describes the **IR limit** of an underlying UV sector in terms of only the light degrees of freedom

classical example: **Fermi's interaction** for β -decays

“True” theory: Electroweak interactions



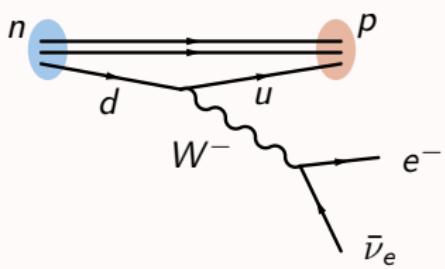
$$\mathcal{A} \left(\frac{1}{m_W^2} \right)$$

Effective Field Theories: basics

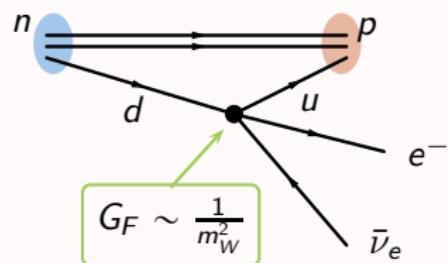
EFT = field theory that describes the **IR limit** of an underlying UV sector in terms of only the light degrees of freedom

classical example: **Fermi's interaction** for β -decays

"True" theory: Electroweak interactions



$$E \ll m_W$$



$$\mathcal{A} \left(\frac{1}{m_W^2} \right)$$

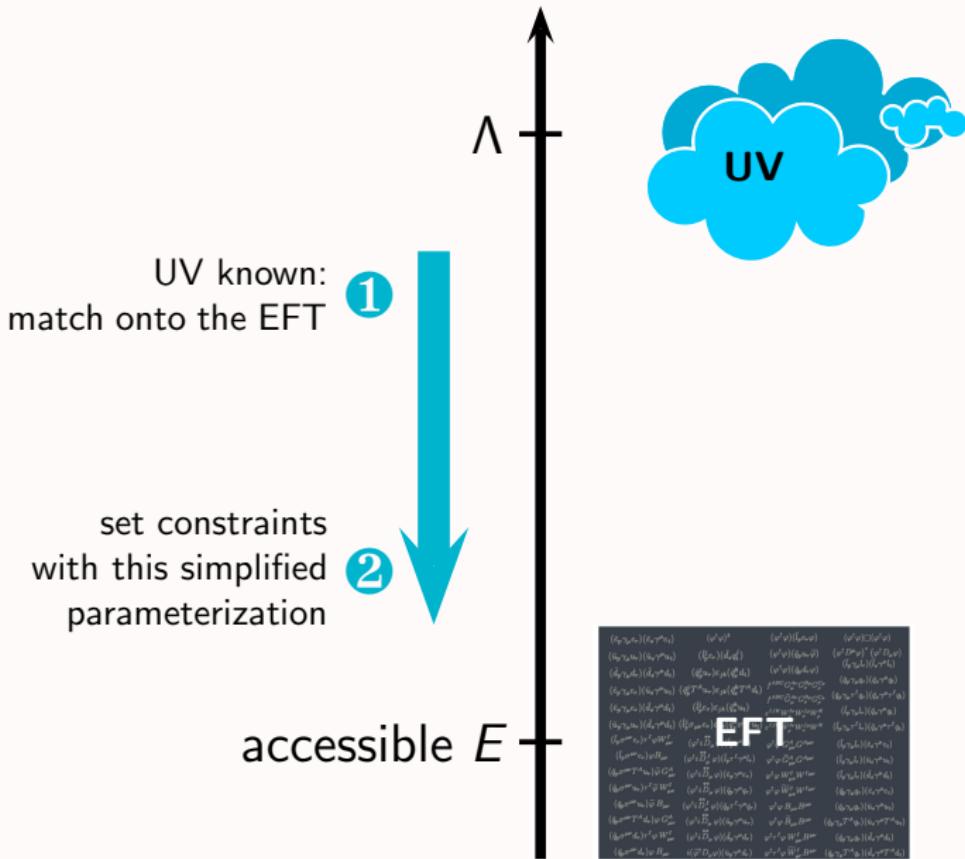
$$\mathcal{A}(0) + \frac{1}{m_W^2} \left(\cancel{\text{X}} + \dots \right) + \mathcal{O}(m_W^{-4})$$

Top-down and bottom-up

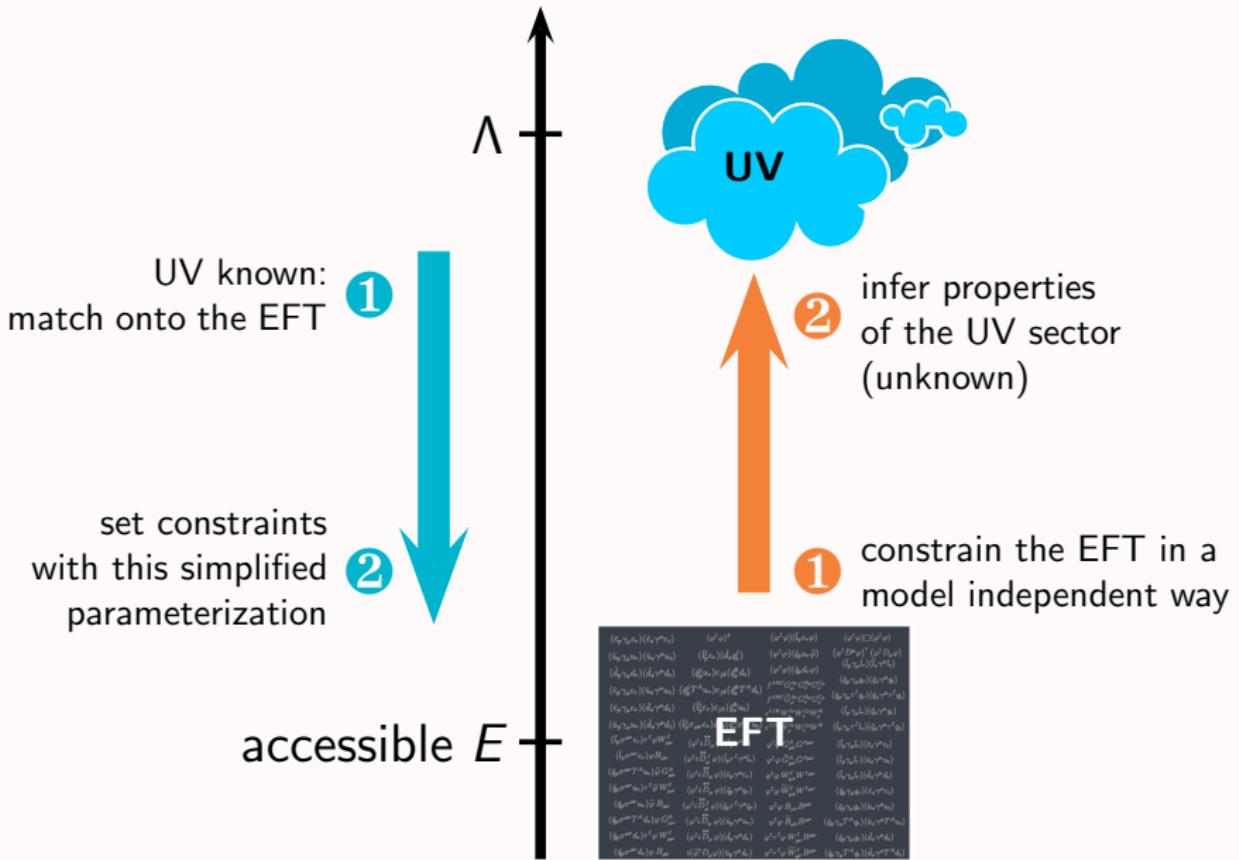
accessible $E+$



Top-down and bottom-up



Top-down and bottom-up



Standard Model Effective Field Theory:
The EFT constructed with **Standard Model** field & symmetries

→ expansion in **canonical dimensions** d (Taylor series in v/Λ or E/Λ)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \dots$$

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

C_i = Wilson coefficients

$\mathcal{O}_i^{(d)}$ = gauge-invariant operators

At each order, $\mathcal{O}_i^{(d)}$ form a complete, non-redundant **basis**

SMEFT describes ∼ **any beyond-SM physics living at $\Lambda \gg v$**
(nearly decoupled)

d=6: the Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\square}$	$(\varphi^\dagger \varphi) \square (\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

d=6: the Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

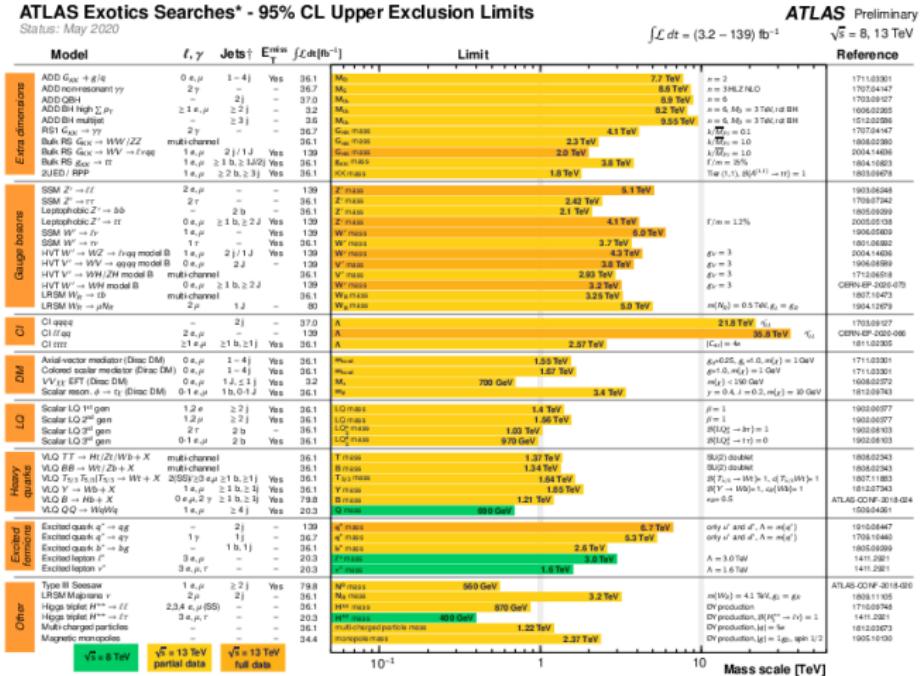
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s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

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

SMEFT for indirect searches at LHC

new physics seems indeed
nearly decoupled

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: May 2020



*Only a selection of the available mass limits on new states or phenomena is shown.

\dagger Small-radius (large-radius) jets are denoted by the letter j .

SMEFT for indirect searches at LHC

new physics seems indeed
nearly decoupled

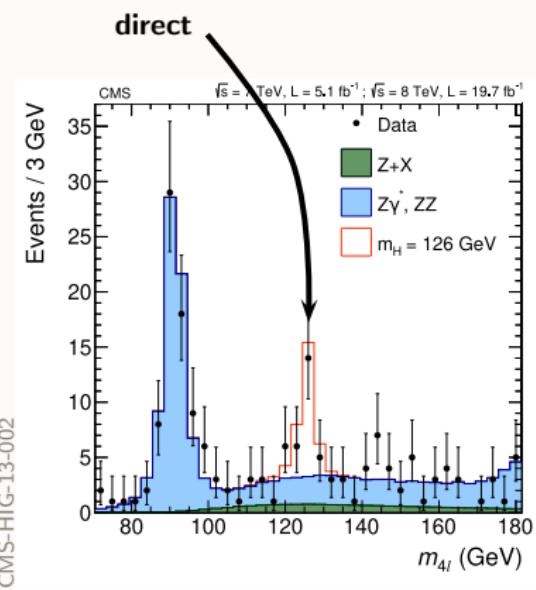
collider physics is entering a
precision era



SMEFT for indirect searches at LHC

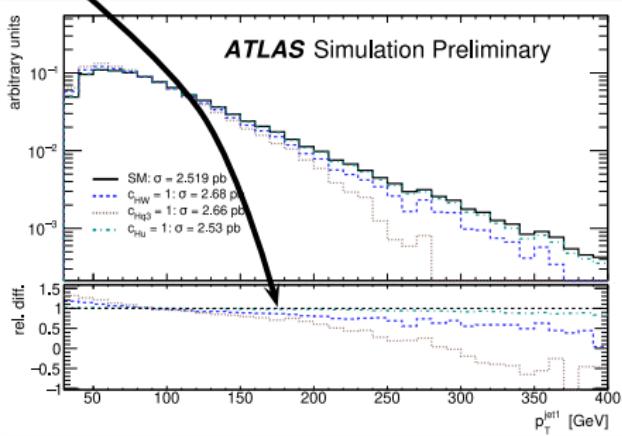
new physics seems indeed
nearly decoupled

collider physics is entering a
precision era



indirect

indirect searches
more and more competitive
with direct ones



SMEFT for indirect searches at LHC

new physics seems indeed
nearly decoupled

collider physics is entering a
precision era



indirect searches
more and more competitive
with direct ones



SMEFT-based searches at the LHC are crucial

- + a proper **QFT** :
renormalizable order by order, well-defined radiative corrections and RGE
- + minimal commitment to a specific UV
- + systematically includes **all** BSM effects, compatible with assumptions
- + **universal language** for data interpretation: can connect to other experiments

Challenges

1. being **sensitive** to indirect BSM effects

$$\text{in bulk } \sim \frac{v^2}{\Lambda^2} = \frac{v^2 g_{UV}}{M^2}. \quad g_{UV} \simeq 1, \quad M \simeq 2 \text{ TeV} \rightarrow 1.5\%$$

$$\text{on tails } \sim \frac{E^2}{\Lambda^2} \simeq \frac{E^2 g_{UV}}{M^2} \quad E \simeq 1 \text{ TeV}, M \simeq 3 \text{ TeV} \rightarrow 10\%$$

Challenges

1. being **sensitive** to indirect BSM effects

$$\text{in bulk } \sim \frac{v^2}{\Lambda^2} = \frac{v^2 g_{UV}}{M^2}. \quad g_{UV} \simeq 1, \quad M \simeq 2 \text{ TeV} \rightarrow 1.5\%$$

$$\text{on tails } \sim \frac{E^2}{\Lambda^2} \simeq \frac{E^2 g_{UV}}{M^2} \quad E \simeq 1 \text{ TeV}, M \simeq 3 \text{ TeV} \rightarrow 10\%$$

2. making sure that, if we observe one, we **interpret it correctly**

- ▶ retaining all relevant contributions: all operators, NLO corrections...
 - ↓
 - handling many parameters in predictions and fits
 - understanding the theory structure
- ▶ correct understanding of uncertainties and correlations
- ▶ systematic mapping to BSM models

Combine, combine, combine

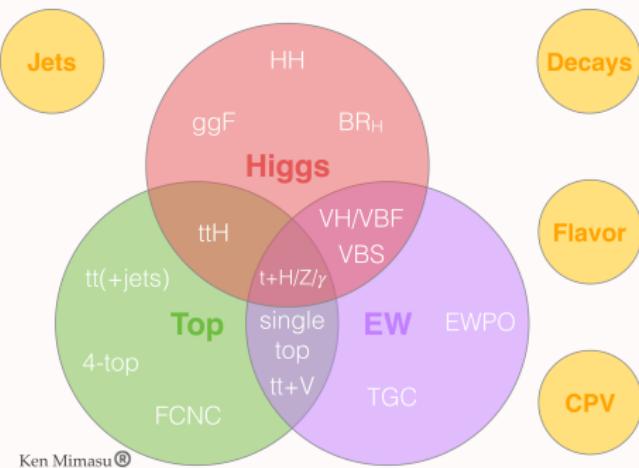
2499 parameters in the most general case

can be reduced

- ▶ assuming symmetries: flavor, CP
- ▶ taking advantage of kinematic suppressions

beyond this **combining**
different measurements is necessary

- ▶ to access as many operators as we can
- ▶ to avoid bias in interpretation
i.e. miss a potential deviation or
assign it to the wrong op.

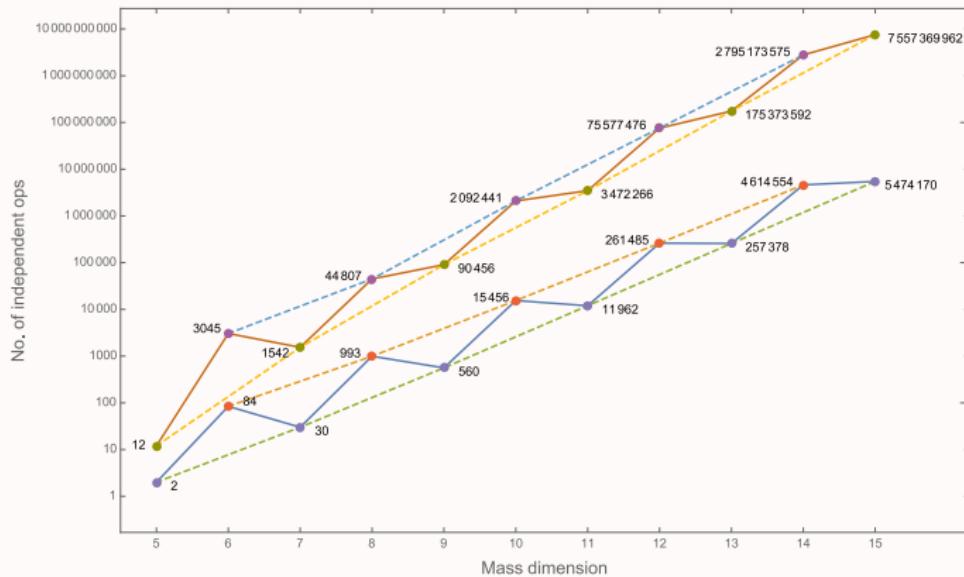


Theoretical understanding

Theory progress

parameters known for all orders

Lehman(Martin) 1410.4193,1510.00372
Henning,Lu,Melia,Murayama 1512.03433
Marinissen,Rahn,Walewijn 2004.09521



Theory progress

parameters known for all orders

complete bases up to $d = 9$

5: Weinberg PRL43(1979)1566

6: Buchmller,Wyler Nucl.Phys.B268(1986)621, Grzadkowski et al 1008.4884

7: Lehman 1410.4193, Henning,Lu,Melia,Murayama 1512.0343

8: Li,Ren,Shu,Xiao,Yu,Zheng 2005.00008, Murphy 2005.00059

9: Li,Ren,Xiao,Yu,Zheng 2007.07899, Liao,Ma 2007.08125

Theory progress

- # parameters known for all orders
- complete bases up to $d = 9$
- interplay with helicity amplitudes
 - Shadmi,Weiss 1809.09644
 - Henning,Melia 1901.06747,1902.06754,1902.06747
 - Ma,Shu,Xiao 1902.06752
 - Aoude,Machado 1905.11433
 - Durieux,Kitahara,(Machado),Shadmi,Weiss 1909.10551,2008.09652
 - Durieux,Machado 1912.08827
 - Craig,Jiang,Li,Sutherland 2001.00017

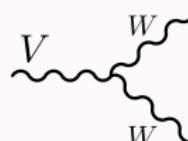
Theory progress

- # parameters known for all orders
- complete bases up to $d = 9$
- interplay with helicity amplitudes
- geometric formulation Alonso,Jenkins,Manohar 1511.00724,1605.03602
Dedes,Materkowska,Paraskevas,Rosiek,Suxho 1704.03888
Helset,Paraskevas,Trott 1803.08001
Corbett,Helset,Trott 1909.08470
(Hays),Helset,Martin,Trott 2001.01453,2007.00565
Corbett,Helset,Martin,Trott 2102.02819

2 and 3 point functions can only have

[limited # of independent Lorentz structures] $\times (H^\dagger H)^n$

e.g. TGC:

$$\begin{aligned} & \varepsilon_{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu} \\ & \varepsilon_{ijk} (H^\dagger \sigma^i H) W_\mu^{j\nu} W_\nu^{k\rho} B_\rho^\mu \\ & (D_\mu H^\dagger D_\nu H) B^{\mu\nu} \\ & (D_\mu H^\dagger \sigma^i D_\nu H) W^{i\mu\nu} \\ & \varepsilon_{ijk} (H^\dagger \sigma^i H) (D_\mu H^\dagger \sigma^j D_\nu H) W^{k\mu\nu} \\ & (H^\dagger \sigma^i H) (D_\mu H^\dagger \sigma^i D_\nu H) (H^\dagger \sigma^j H) W^{j\mu\nu} \end{aligned}$$


→ can write operators up to arbitrarily high dimension

Theory progress

- # parameters known for all orders
- complete bases up to $d = 9$
- interplay with helicity amplitudes
- geometric formulation
- RGE up to $d = 6$ + a subset of $d = 8$ Chala,Guedes,Ramos,Santiago 2106.05291

Alonso,Jenkins,Manohar,Trott 1308.2627,1310.4838,1312.2014

Grojean,Jenkins,Manohar,Trott 1301.2588

Alonso,Chang,Jenkins,Manohar,Shotwell 1405.0486

Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706

Miro,Ingoldby,Riembau 2005.06983

Baratella,Fernandez,Pomarol 2005.07129,2010.13809

Theory progress

- # parameters known for all orders
- complete bases up to $d = 9$
- interplay with helicity amplitudes
- geometric formulation
- RGE up to $d = 6 +$ a subset of $d = 8$
- flavor structure

Brivio,Jiang,Trott 1709.06492
Bordone,Catà,Feldmann 1910.02641
Faroughy,Isidori,Wilsch,Yamamoto 2005.05366
Brivio 2012.11343

Theory progress

- # parameters known for all orders
- complete bases up to $d = 9$
- interplay with helicity amplitudes
- geometric formulation
- RGE up to $d = 6 +$ a subset of $d = 8$
- flavor structure
- NLO SMEFT
 - $\mu \rightarrow e\gamma$: Pruna,Signer 1408.3565
 - $h \rightarrow \gamma\gamma$, WW : Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
Hartmann,Trott 1505.02646,1507.03568
 - Dedes,Paraskevas,Rosiek,Suxho,Trifyllis 1805.00302
 - Dawson,Giardino 1807.11504
 - $h \rightarrow ZZ$, $Z\gamma$: Dawson,Giardino 1801.01136, Dedes,Suxho,Trifyllis 1903.12046
 - $h \rightarrow f\bar{f}$: (Cullen,Gauld),Pecjak,Scott 1512.02508,1904.06358,2007.15238
 - $gg \rightarrow h(j)$: Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460
Grazzini,Ilnicka,Spira 1806.08832
 - Γ_Z : Hartmann,Shepherd,Trott 1611.09879, Dawson,Giardino 1808.05948
 - Z, W pole obs: Dawson,Giardino 1909.02000
 - $t \rightarrow bW$: Boughezal,Chen,Petriello,Wiegand 1907.00997
 - + several NLO QCD (DY, VV, $t\bar{t}(V)$, single- t ...)

Theory progress

- # parameters known for all orders
- complete bases up to $d = 9$
- interplay with helicity amplitudes
- geometric formulation
- RGE up to $d = 6 +$ a subset of $d = 8$
- flavor structure
- NLO SMEFT
- connection to WET/LEFT Jenkins,Manohar,Stoffer 1709.04486
Dekens,Stoffer 1908.05295

Theory progress

automation ▶ basis handling

Falkowski et al 1508.05895 Aebischer et al 1712.05298
Criado 1901.03501

▶ matching & running

(Celis),Fuentes-Martin,(Ruiz-Femenia),Vicente,Virto
1704.04504,2010.16341
Aebischer,Kumar,Straub 1804.05033
Fuentes-Martin,König,Pages,Eller Thomsen,Wilsch 2012.08506
Cohen,Lu,Zhang 2012.07851

▶ Feynman rules

Dedes,(Materkowska),Paraskevas,Rosiek,Suxho,(Trifyllis)
1704.03888,1904.03204, Brivio,Jiang,Trott 1907.04692
Corbett 2010.15852

▶ LO predictions

Alloul,Fuks,Sanz 1310.5150 Durieux,Zhang 1802.07237
Brivio,(Jiang,Trott) 1907.04692,2012.11343

▶ NLO QCD predictions

Degrande,Durieux,Maltoni,Mimasu,Vryonidou 2008.11743

Global fits

LHC constraints on SMEFT: status

Higgs + EW

Alves et al 1211.4580, 1805.11108, Butter et al 1604.03105
Corbett et al 1509.01585, de Blas et al 1608.01509, 1710.05402, 1910.14012
Ellis,Murphy,Sanz,You 1803.03252 da Silva Almeida et al 1812.01009
Biekötter,Corbett,Plehn 1812.07587, Dawson,Homiller,Lane 2007.01296

top

Englert et al 1506.08845, 1512.05560, 1901.03164 + ICHEP2020 proc.
Cirigliano,Dekens,deVries,Mereghetti 1605.04311 Hartland et al 1901.05965
Durieux,Irles,Miralles,Peñuelas,Pöschl 1907.10619, Brivio et al 1910.0306

Higgs + EW + top

Ellis, Madigan, Mimasu, Sanz, You 2012.02779
Ethier, Maltoni, Mantani, Nocera, Rojo 2105.00006

top + B physics

Bißmann,(Erdmann),Grunwald,Hiller,Kroöninger 1909.13632, 2012.10456
Bruggisser,Schäfer,Westhoff,VanDyk 2101.07273

diboson (+ VBS)

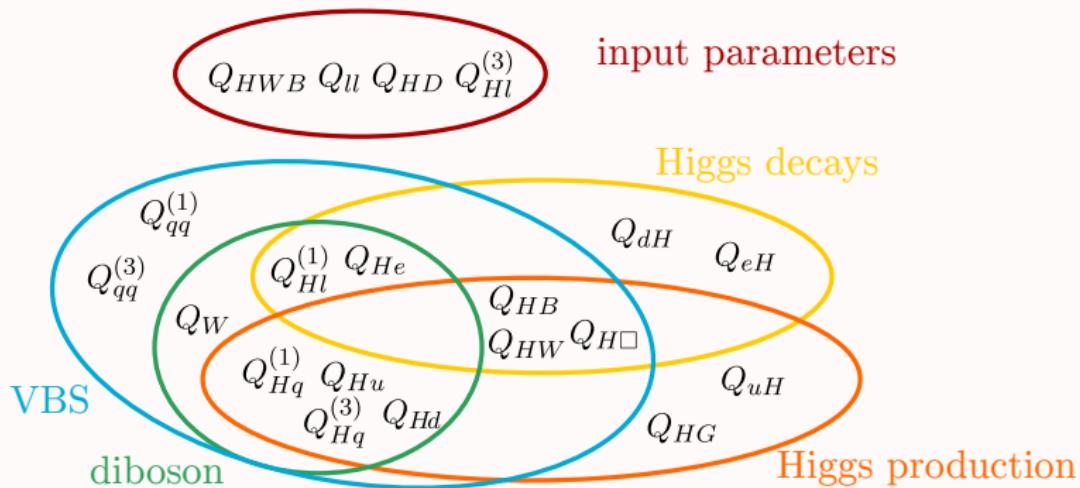
Baglio,Dawson,Homiller,(Lane,Lewis) 1812.00214, 1909.11576, 2003.07862
Ethier,Gomez-Ambrosio,Magni,Rojo 2101.03180

impact analysis of NLO corrections and quadratic SMEFT terms

various techniques: information geometry, bayesian reweighting, replica model, Partial Component Analysis. . .

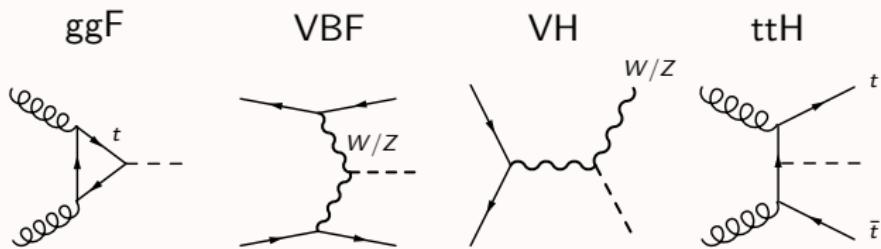
SMEFT for EW and Higgs sectors

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

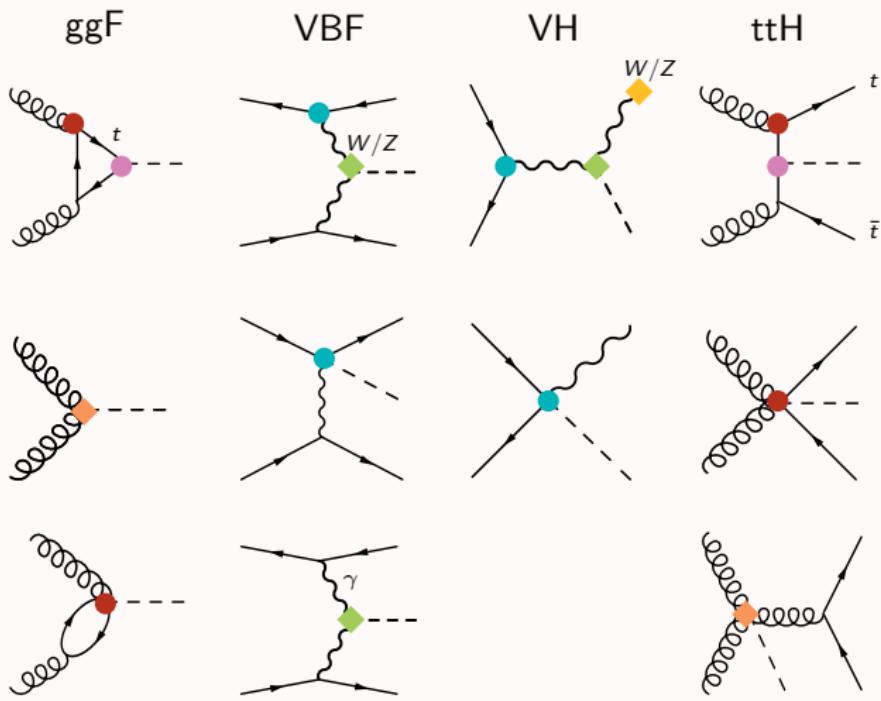


+ CP odd + flavor indices + others entering through loop corrections ...

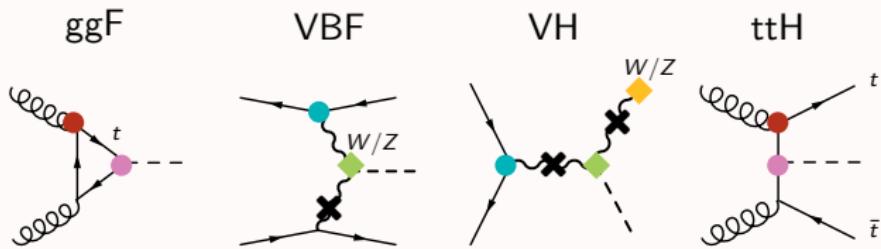
SMEFT in Higgs production



SMEFT in Higgs production



SMEFT in Higgs production



propagator corrections: relevant when particle \sim on-shell

$$\sim \frac{i}{q^2 - m^2 + i\Gamma m} \left[1 - \frac{i\Gamma m}{q^2 - m^2 + i\Gamma m} \left(\frac{\delta\Gamma}{\Gamma} + \left(1 + \frac{2im}{\Gamma} \right) \frac{\delta m}{m} \right) \right]$$



Simplified Template Cross Sections (STXS)

Higgs combinations:

$$n_k = \mathcal{L}_k \sum_{i,f} (\sigma_i \cdot B_f) (\varepsilon \cdot A)_{if}$$

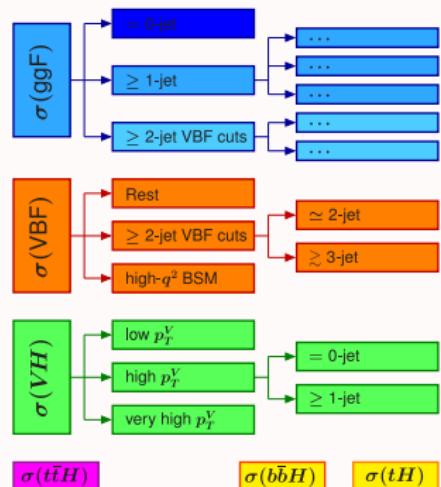
lumi ← ↓ ↗ acceptance
prod xs $i \rightarrow h$ ↓ ↗ efficiency
Brivio,Corbett,Trott 1906.06949 decay BR $h \rightarrow f$

ATLAS HIGG-2018-28
ATLAS-CONF-2020-053

fit to $n_k \rightarrow (\sigma_i \cdot B_f)$ for defined i, f categories.

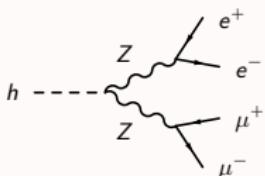
STXS define production categories :
unfolded XS organized in “macro-bins”
→ minimize selection cuts + modeling bias
better reproducibility

- defined in stages: finer and finer bins
- include $f = \{\gamma\gamma, 4\ell, 2\ell 2\nu, \tau\tau, b\bar{b}\}$

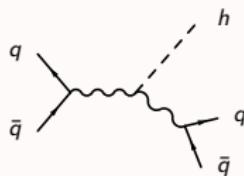


LesHouches 2015 1605.0469,
LHCXSWG 1610.0792,
Berger et al. 1906.02754

SMEFT corrections in Higgs processes: example



$h \rightarrow 2e2\mu$ width



STXS 1.1 bin $p_{Th} < 200$

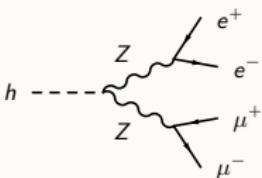
$60 \leq m_{jj} \leq 120$

$m_{jj} \geq 350$

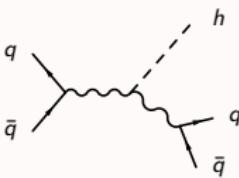
$$\frac{X_{SMEFT}}{X_{SM}} = 1 + \sum_{\alpha} \frac{X_{\alpha}}{X_{SM}} \bar{C}_{\alpha} + \mathcal{O}(\Lambda^{-4})$$

$$X = \Gamma, \sigma \quad \bar{C}_{\alpha} = \frac{v^2}{\Lambda^2} C_{\alpha}$$

SMEFT corrections in Higgs processes: example



$h \rightarrow 2e2\mu$ width



STXS 1.1 bin $p_{Th} < 200$

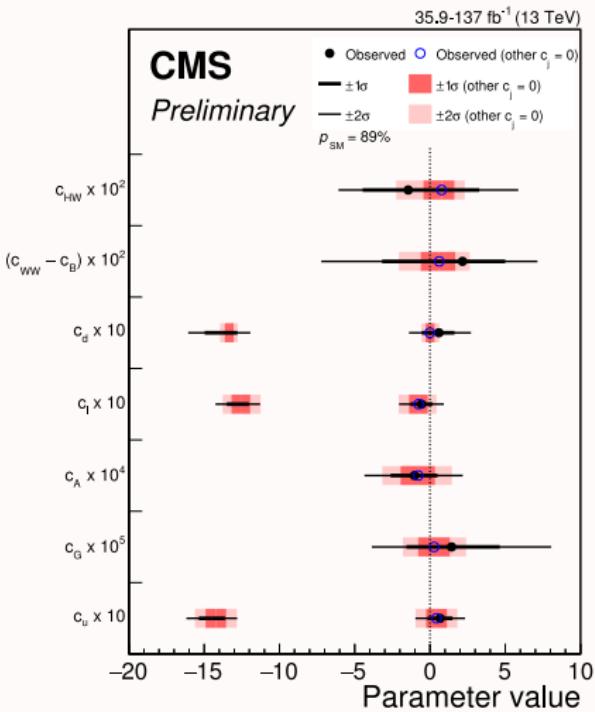
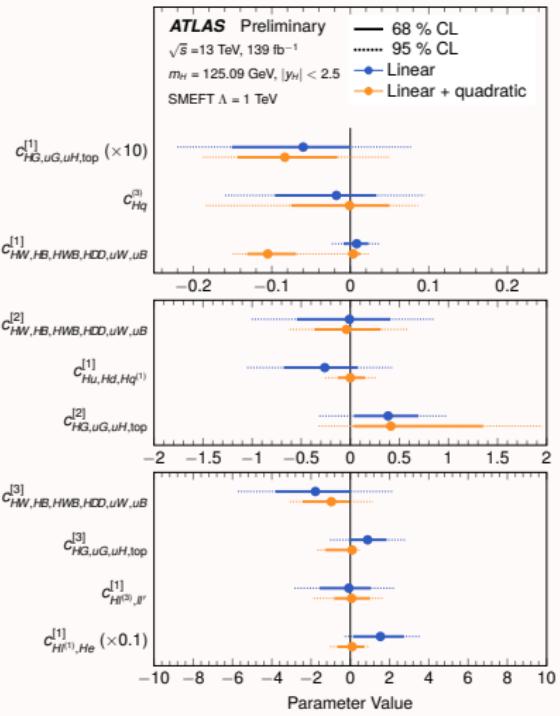
$60 \leq m_{jj} \leq 120$

$m_{jj} \geq 350$

	direct	propagators	direct	propagators	direct	propagators
\bar{C}_{He}	-1.724	0.153		0.0526		$5.32 \cdot 10^{-5}$
$\bar{C}_{HI}^{(1)}$	2.144	0.153		0.0526		$5.32 \cdot 10^{-5}$
$\bar{C}_{HI}^{(3)}$	-3.856	1.147	-6	1.258	-6	$1.351 \cdot 10^{-3}$
$\bar{C}_{Hq}^{(1)}$		-0.39	-0.197	-0.135	0.109	$-1.363 \cdot 10^{-4}$
$\bar{C}_{Hq}^{(3)}$		-1.353	25.66	-1.329	-5.345	$-1.423 \cdot 10^{-3}$
\bar{C}_{Hu}		-0.203	1.926	-0.070	-0.323	$-7.092 \cdot 10^{-5}$
\bar{C}_{Hd}		0.150	-0.608	0.0518	0.103	$5.24 \cdot 10^{-5}$
\bar{C}'_{II}	3	-0.839	3	-0.936	3	$-1 \cdot 10^{-3}$

Brivio,Corbett,Trott 1906.06949, Brivio 2012.11343, ATLAS-CONF-2020-053

Higgs fits by ATLAS & CMS

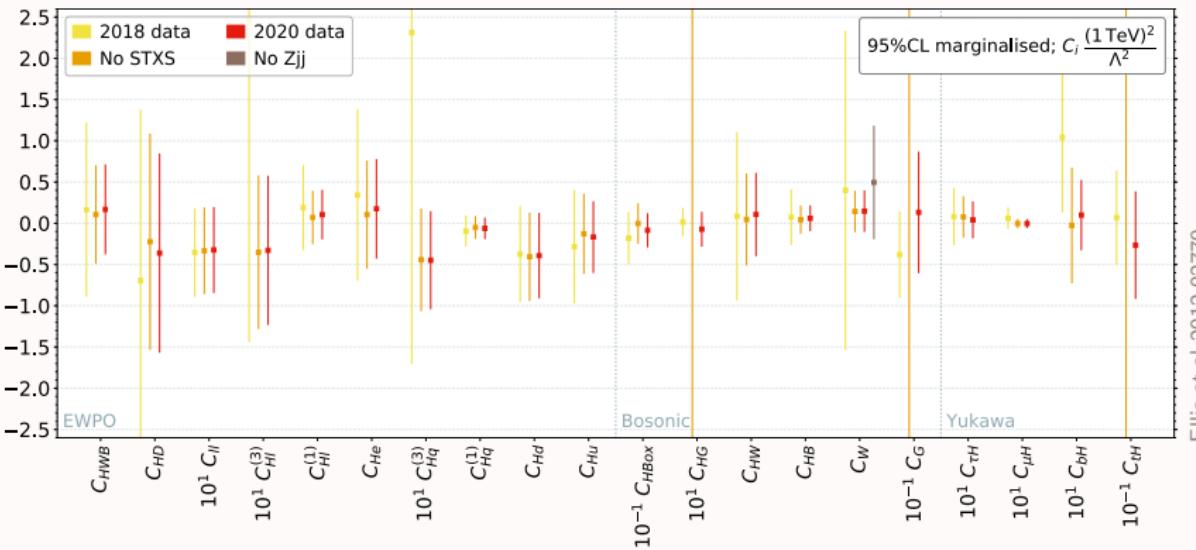


Higgs + EW interplay has been studied extensively

historically the first two sectors to be combined in global fits

typically: EWPO from LEP

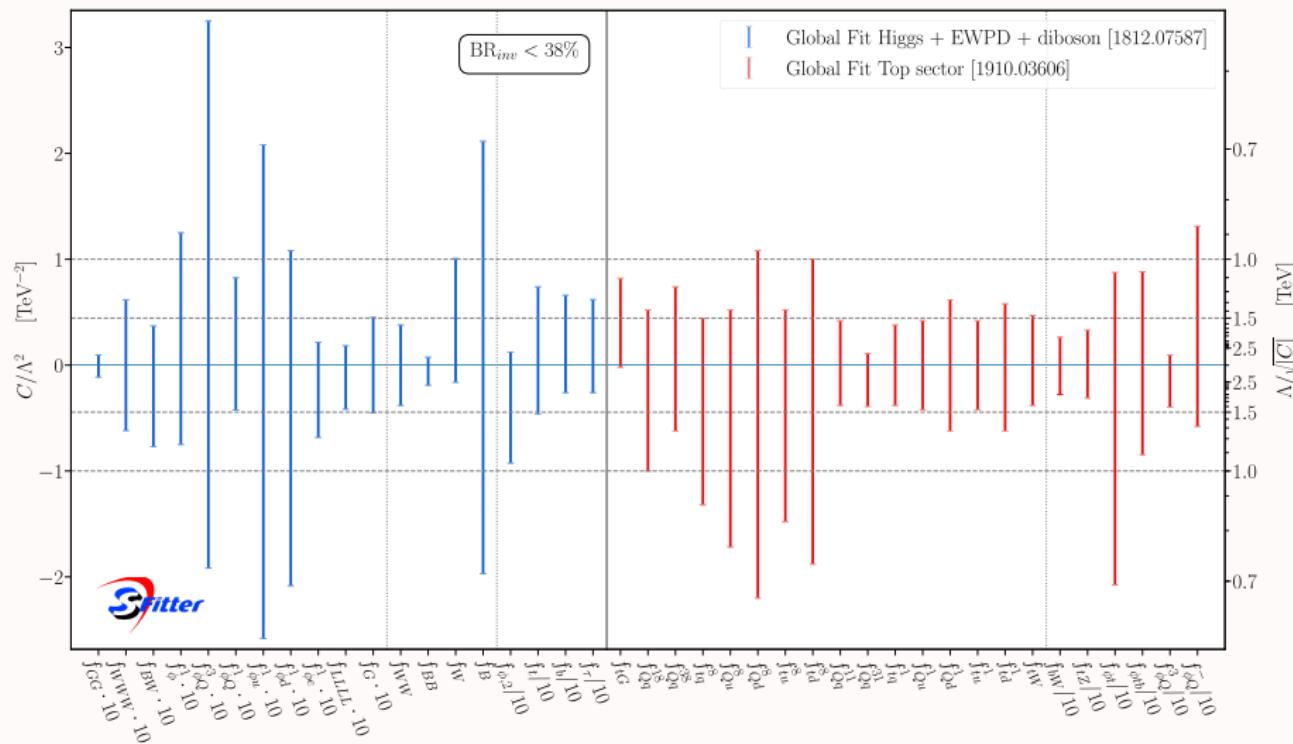
- + diboson measurements (LEP2/LHC)
- + Higgs production/decay rates (STXS)



Ellis et al 2012.02779

EW + Higgs vs top

EWPD + LHC Run I + II, 95% C.L.



Operators affecting top quark interactions

also studied extensively in the literature.

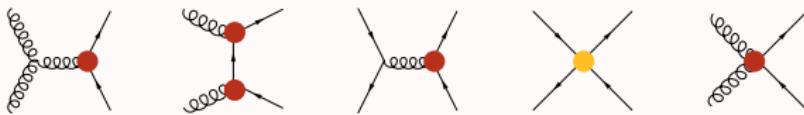
~ 20 relevant operators

depends on – flavor symmetry + scheme

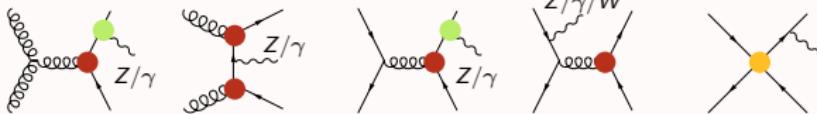
- **processes considered**
- interference/quadratics
- LO/NLO QCD

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

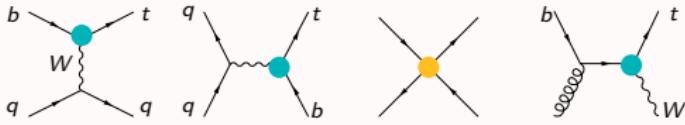
$t\bar{t}$



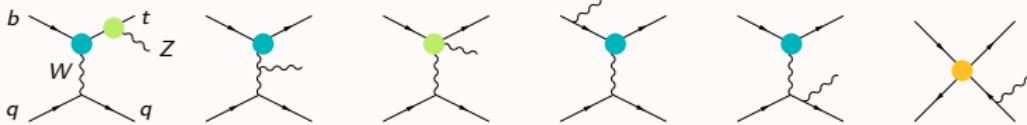
$t\bar{t}V$



tj, tW

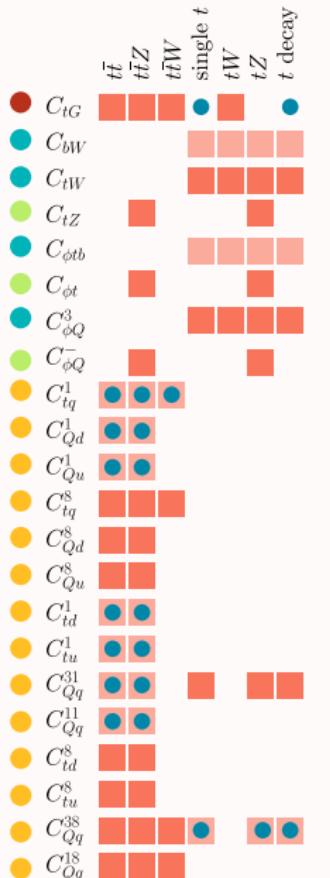


tZj



Operators affecting top quark interactions

Brivio, Bruggisser, Maltoni, Moutafis, Plehn,
Vryonidou, Westhoff, Zhang 1910.03606



- $SU(2)_q \times SU(2)_u \times SU(2)_d$
- top interactions only
- up to NLO QCD, quadratic SMEFT

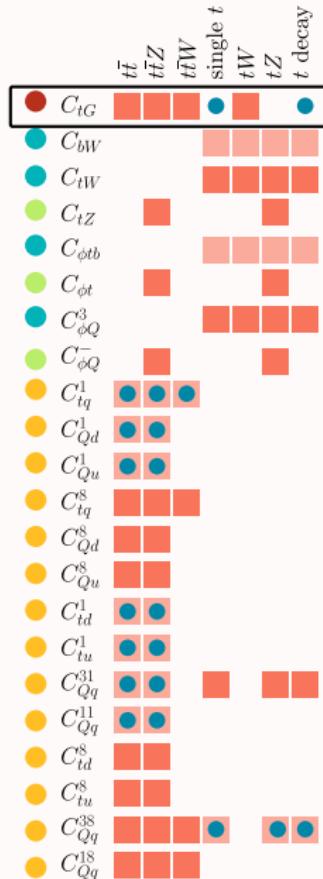


22 param.

■ interferes at LO QCD
■ only quadratic
● interferes at NLO QCD

Operators affecting top quark interactions

Brivio, Bruggisser, Maltoni, Moutafis, Plehn,
Vryonidou, Westhoff, Zhang 1910.03606



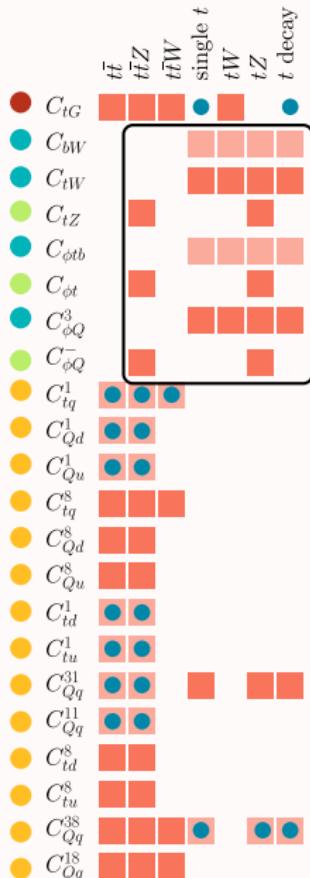
- $SU(2)_q \times SU(2)_u \times SU(2)_d$
 - top interactions only
 - up to NLO QCD, quadratic SMEFT
- ↓
22 param.

C_{tG} is the most constrained (mostly $t\bar{t}$)

- interferes at LO QCD
- only quadratic
- interferes at NLO QCD

Operators affecting top quark interactions

Brivio, Bruggisser, Maltoni, Moutafis, Plehn,
Vryonidou, Westhoff, Zhang 1910.03606



- $SU(2)_q \times SU(2)_u \times SU(2)_d$
- top interactions only
- up to NLO QCD, quadratic SMEFT



22 param.

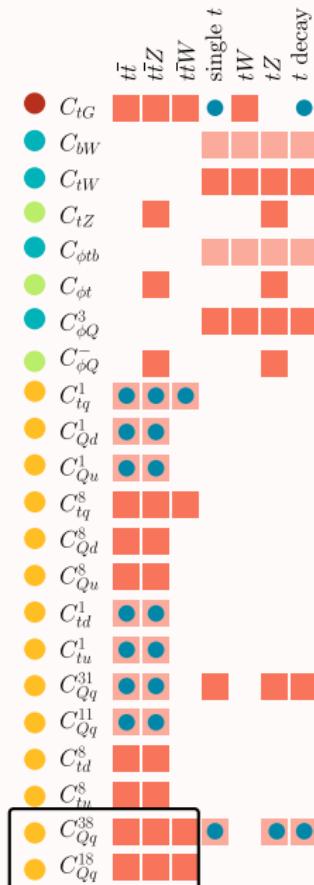
C_{tG} is the most constrained (mostly $t\bar{t}$)

$t\bar{t}Z$, single- $t \rightarrow$ sensitivity to EW couplings

- interferes at LO QCD
- only quadratic
- interferes at NLO QCD

Operators affecting top quark interactions

Brivio, Bruggisser, Maltoni, Moutafis, Plehn,
Vryonidou, Westhoff, Zhang 1910.03606



- $SU(2)_q \times SU(2)_u \times SU(2)_d$
- top interactions only
- up to NLO QCD, quadratic SMEFT



22 param.

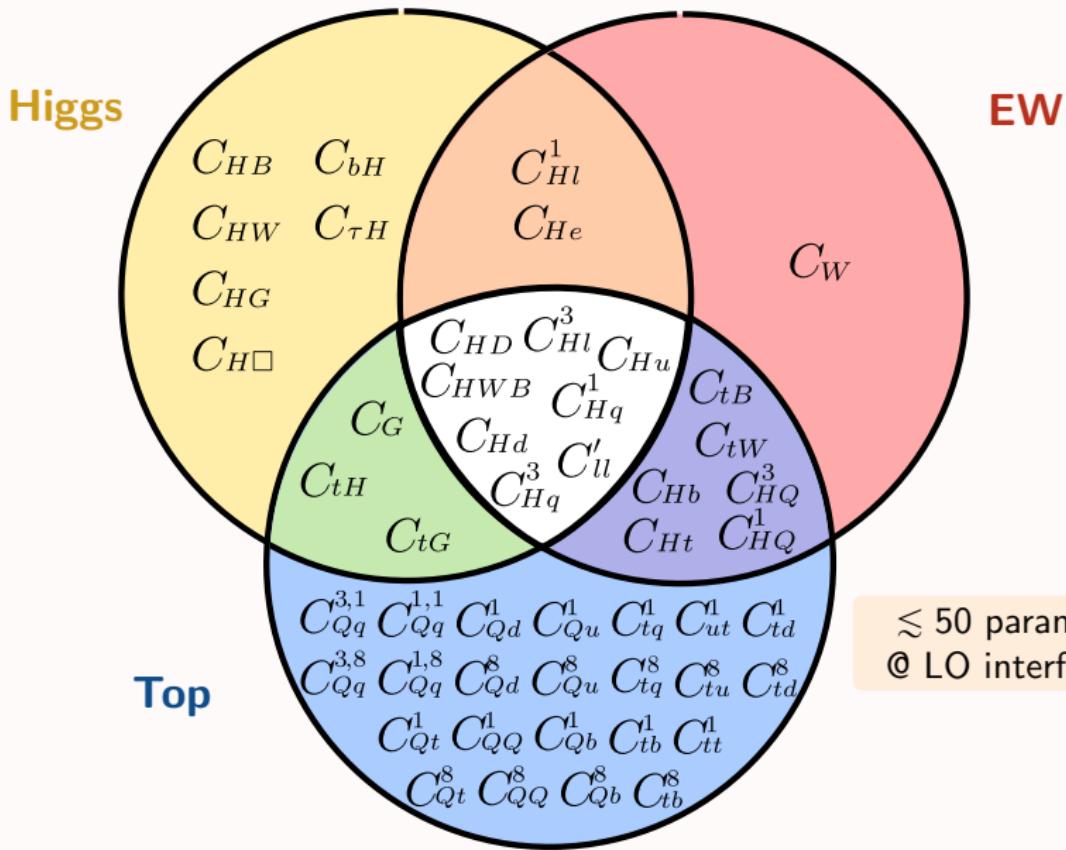
C_{tG} is the most constrained (mostly $t\bar{t}$)

$t\bar{t}Z$, single- $t \rightarrow$ sensitivity to EW couplings

→ break degeneracies among $qqQQ$ op.

- orange interferes at LO QCD
- light orange only quadratic
- dark blue interferes at NLO QCD

Next step: top + EW + Higgs

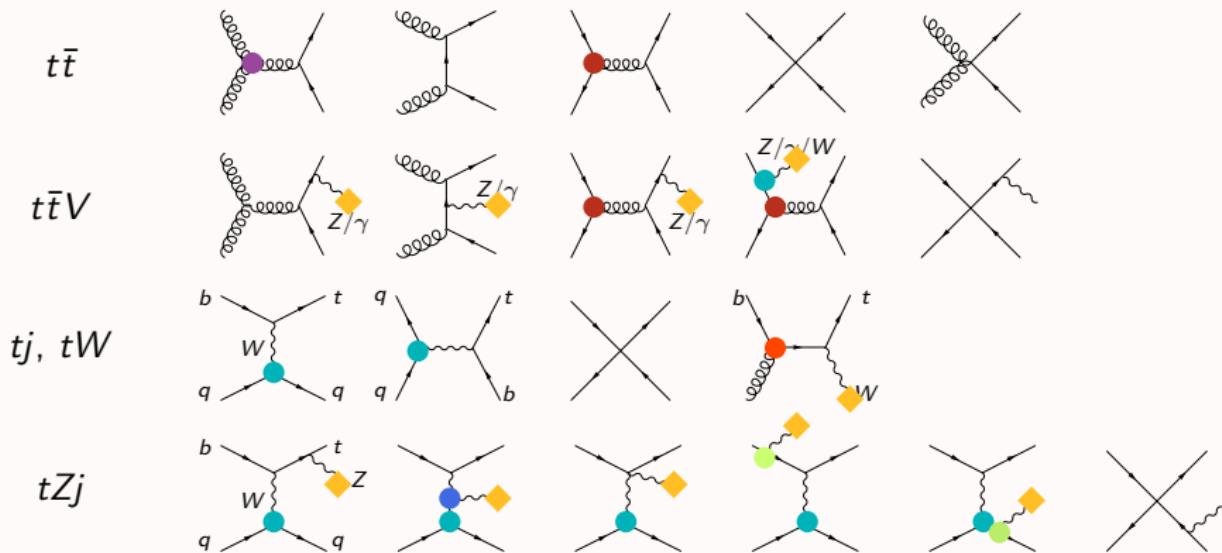


Combining Higgs and top

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

Combining Higgs and top

1. top operators \rightarrow Higgs / EW processes
2. non-top operators \rightarrow top processes



Combining Higgs and top

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

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

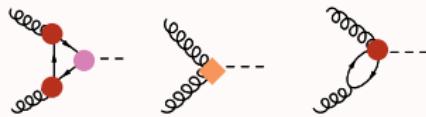
- $C_G \leftrightarrow$ multi-jet
 - —
 - C_{bG}
 - $C_{Hq}^{(3)}$ ★
 - $C_{Hq}^{(1)}, C_{Hu}, C_{Hd}$ ★
 - C_{Hb} ★
 - $C_W \leftrightarrow$ VV, VBF Z/W, VBS
 - ◆ $C_{HI}^{(1)}, C_{HI}^{(3)}, C_{He}$ ($QQ\ell\ell$ op.) ★ \leftrightarrow EWPO, VH, VBF, $h \rightarrow 4\ell, VV, VBS \dots$
- + C_{HWB}, C_{HD}, C'_{II} from EW inputs!

Combining Higgs and top

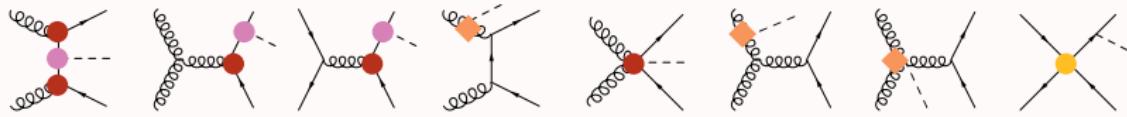
1. top operators → Higgs / EW processes
2. non-top operators → top processes

Grazzini,Ilnicka,Spira,(Wiesemann) 1612.00283,
1806.08832,
(Maltoni),Vryonidou,Zhang 1607.05330, 1804.09766
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460

$gg \rightarrow h$



$t\bar{t}h$



$h \rightarrow \gamma\gamma$

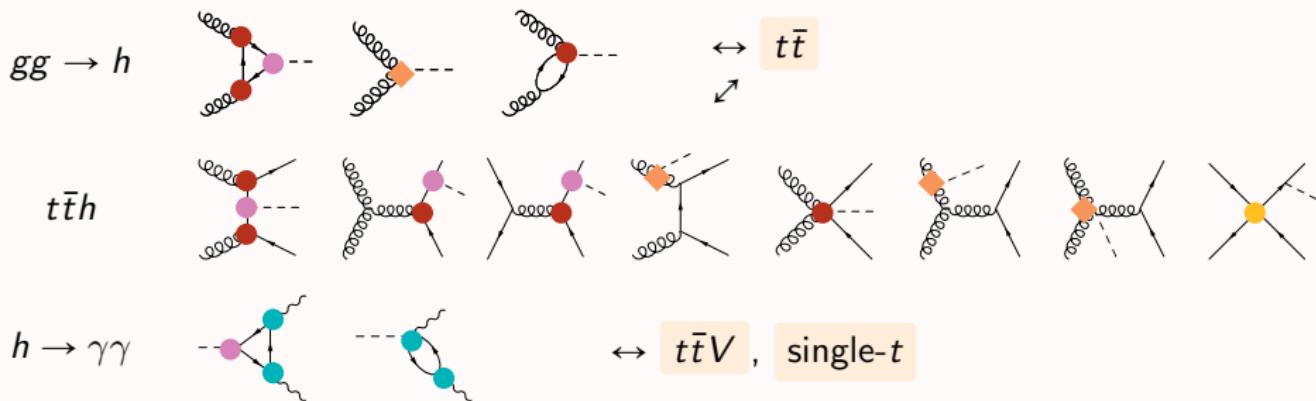


Combining Higgs and top

1. top operators → Higgs / EW processes

2. non-top operators → top processes

Grazzini,Ilnicka,Spira,(Wiesemann) 1612.00283,
1806.08832,
(Maltoni),Vryonidou,Zhang 1607.05330, 1804.09766
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460



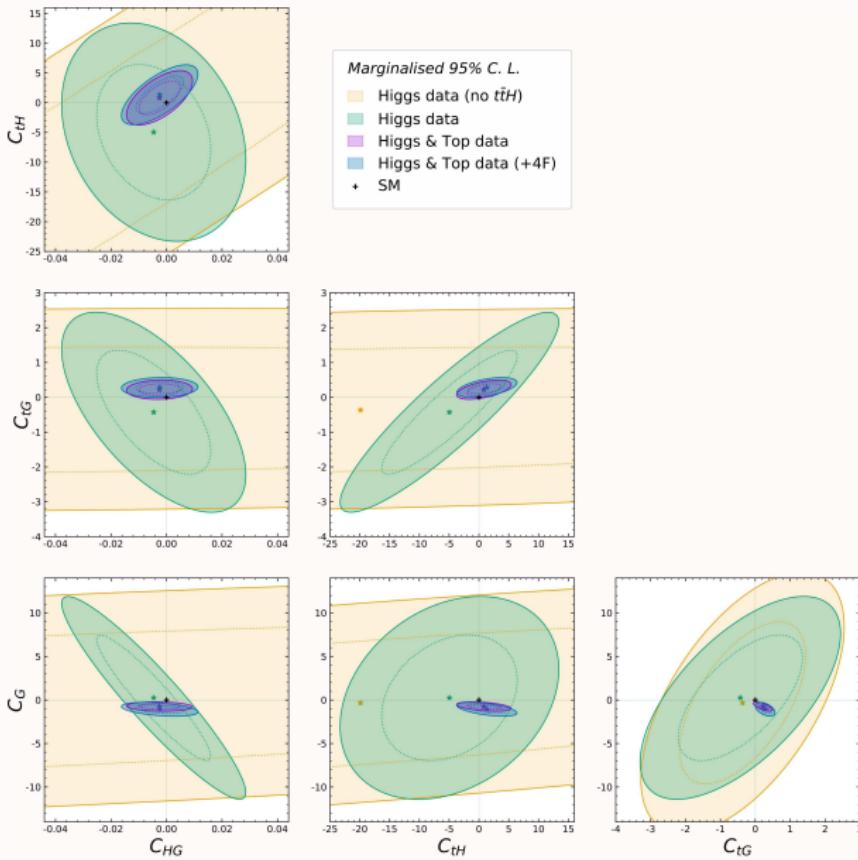
new: ● C_{tH} operator → $t\bar{t}H$ vertex ↔ interplay with C_{HG} ◇

● $C_{tG} \rightarrow t\bar{t}G + t\bar{t}GG + t\bar{t}GH + t\bar{t}GGH$

● $C_{tW}, C_{tB}, C_{HQ}^{(3)}, C_{HQ}^{(1)}, C_{Ht} \rightarrow t\bar{t}V + t\bar{t}VH$

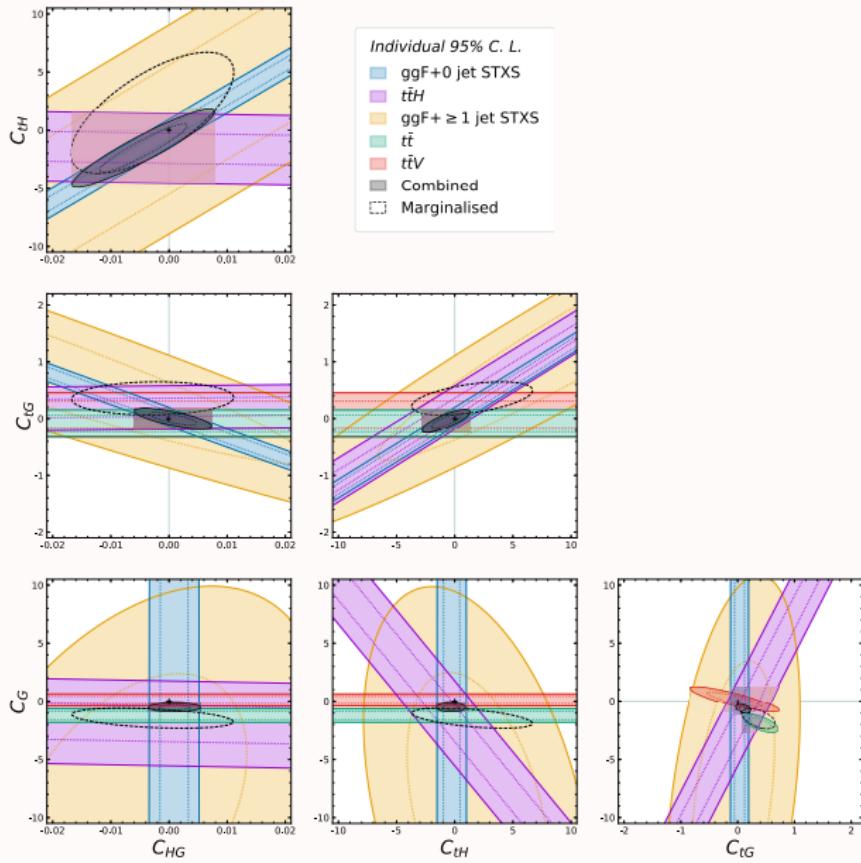
Example: complementarities in top + Higgs

Ellis, Madigan, Mimasu, Sanz, You 2012.02779



Example: complementarities in top + Higgs

Ellis, Madigan, Mimasu, Sanz, You 2012.02779



Example: complementarities in top + Higgs

Ellis, Madigan, Mimasu, Sanz, You 2012.02779

EWPO		Bosonic				Yukawa		Top 2F		Top 4F			
Top 4F	C_{tb}^8	+0.6	+0.2	+0.6+0.6	+0.4	+32	+0.6+0.6	0	-57+0.4	0	+24	+2.8	+0.2
	C_{tr}^8	+0.4	0	+0.2+0.2	+0.3+0.4+2.6	+28	0	+20	+2.5	+3.7	+1.3	-0.3 -0.1	
	C_{tq}^8	+2.6	+0.6	+2.5+2.5	+1.7	+21	+2.6+2.6+2.0	19	0	+0.1+0.3+12.7	+11	-57	
	C_{Qd}^8	+1.1	+0.7	+0.7+0.6	+1.1+0.5+9.6	+25	0.4	+13.4	+2.7+2.5+11	+46	3.0	+16+100 -0+0.1+7	
	C_{Qu}^8	+2.4	+1.0	+1.3+1.2	+2.1+1.5+2.7	+25	+2.1	+12.1	+58+2.9	+27	+7.4 -17 -37	+102+16 -88+35	
	$C_{Q\bar{d}}^{1,8}$	-0.5	+0.1	+0.5+0.5	+0.1	+16	+0.5+0.5	0	-22+0.3	+0.1+14	+2.2	+2.6+0.2+16	
	$C_{Q\bar{q}}^{3,8}$	+0.2	+0.1	+0.2+0.2	+0.1	+18	+0.2+0.2	0	-29+0.4	0	+16	+1.5+2.7+0.2+11	
	$C_{Q\bar{Q}}^{3,1}$	+1.2	+0.2	+1.2+1.2+1.2+0.3	+0.5	+13	+1.2+3.0+3.5+5.5+1.5+0.4+2.3	+57	-55	+1.3	+100	+7.4+3.0 +1.3	
	C_{tb}	-0.1	+0.4+0.1+0.1+0.1	0	+0.5	+11	+0.1+0.1	0	+11+0.1	+0.1+7.7	+1.4	+100	
	C_{tW}	-0.1	+0.6	0	+0.3	+0.1+0.6+0.1+0.1	+1.5	+6.3	+0.8+2.9+100	+1.1+0.2+0.2	+0.8	+0.2	
Top 2F	C_{tG}	+0.2	+0.2+0.2+0.2+0.1	+0.1	+0.1	+5.3+0.7+0.3+0.1	+51	+2.6	+49	+7.0+18+100+2.5	+2.7+2.6+2.9+11	+1.1+0.2+0.2	
	C_{Ht}	+17	+13	+13	+5.6+0.1	+14+0.7	+1.7	+35	+9.4	+10.1+18+0.8	+5.8	+25+3.7+3.7	
	$C_{HO}^{(1)}$	+20	+4.4	+20	+13+13+4.6+21	+11+3.9+21	+11	+11	+11+0.6	+100+11+7.0+6.3+1.4	+55+1.5+2.2+11	+11 +2.8	
	$C_{HO}^{(3)}$	-1.9	+2.6	+2.2+2.2+1.0	+0.1	+2.0+1.9+0.3+11+2.8+0.6+4.8	+100	-96	+57	+12+4.2	+2.3	+0.4	
	C_{HO}	+21	+2.0+1.1+1.1	+2.0+11+11	+1.2+4.4+6.7	+52	+8.3	+100	+11+9.4+49+11.5+7.1	+16+14	+13+12	+2.4	
Yukawa	C_{bh}	+40	+4.3	+0.5+39+43+43	+43+20	+1.2+1	+11+2.1	+41+38+10	+24+4.9+100	+4.8	+0.1+2.3	0	+0.3 0
	$C_{\mu H}$	+6.6	+0.6+1.7+6.7+6.7	+1.3	+1.3	+1.1+6.6+6.3+0.8+0.2+4.0+100+4.9	+6.6	+6.6	+6.6	+0.4	+0.3	0	
	C_{tH}	+11	+0.7+3.0+11+11	+1.7	+17	+9.8+11+1.2	+100+0.4+24+9.5+2.6	+2.6	+0.1+1.5+0.4+0.9	+0.4 0	+0.4	+0.4	
Bosonic	C_G	+1.4	+0.4+0.6	+1.0+1.5+0.6	+1.0+0.7	+100	+0.7	+57+11	+10+0.1	+5.5+1.5	+2.5	+20+3.3	
	C_W	+8.5	+3.9+13+9.4+9.6+1.4	+2.0	+0.1	+8.4+0.5+100	+1.7+0.8+10	+5.3	+0.3+0.1	0	+0.3 0	+0.2 0	
	C_{HB}	+94	+9.6+1.4+3.1+98+98	+31+41+26+77	+54	+2.1+93+100+8.5	+11+6.3+36	+1.9+1.9+2.1	+11+0.3+0.1+0.1+1.2+0.2+0.5	+2.6	+0.6	+0.6	
	C_{HW}	+94	+9.6+1.4+3.0+97+98	+31+41+26+77	+61	+2.0+100+93+9.4	+9.8+0.6+41	+2.2+2.0+2.1	+11+0.2+0.1+0.1+1.3+0.2+0.5	+2.6	+0.6	+0.6	
	C_{HG}	+2.2	+1.3+1.4+1.5	+0.6+2.3	+100+2.0+2.3	+37	+1+1+2	+67	+3.9+0.6+1	+18+16	+9.6+21	+3.2	
EWPO	C_{HBox}	+54	+59	+1+59+59+1.7+32	+40+100	+61+54	+1.5+17	+41+44	+11+9.7	+0.1	+1.5+0.5	+0.4	
	C_{Hu}	+76	+2+20+75+76	+19+32	+100+40	+77+77	+1.0	+1.0+2.1	+21+14	+21+14	+2.2	+1.1	
	C_{Hd}	+27	+9.6+3.6+22+23	+6.5+100	+2.3+2.6+26	+4.7+1.3+1.2	+4.6	+0+0.3	+0.5+0.1+0.1	+1.7	+0.4	+0.4	
	C_{H^1}	+42	+6.7+4.2+1.4+100+6.5+32+0.6+4.3	+4.3	+0.4	+2+11	+13+0.1	0	+1.2+0.6	+0.2	+1.2+0.6	+0.2	
	C_{H^3}	+35	+26+57+26+26+100+14	+19+3.7+3.7	+31+1+14+0.4	+20+2.0+1.0+1.3+5.6+0.1	+0.1+0.3	+1.3+0.7	+0.2	+1.3+0.7	+0.2	+0.2	
	C_{He}	+10	+3.0+1.3+1.2+100+100+20	+2+23+2.6	+5+1.5+98+98+9.6	+11+6.7+43	+1+2+2.1	+17+0.2	0	+0.1+1.2+0.2+0.5	+2.5	+0.6	
	C_{H^1}	+93	+100+7.6+11+100+100+20	+42+22+75	+59+1+4+97+98+9.4	+11+6.7+43	+1+2+2.2	+17+0.2	+0.2	+0.1+1.2+0.2+0.5	+2.5	+0.6	
	C_{H^3}	+2.7	+12+100+11+12+1.7+6.7	+34+20+21	+3+3.0+3.1+1.3	+3+0.1+1.7+39	+2.6+4.4	+0.2	+0.4+0.2	+0.3+1.0+0.7	0	+0.2	
	C_{Hl}	+15	+10+12+7.6+1.3	+1+1+9.8+2.1	+1+1+14+1.4+3.9	+0.7+0.6+0.5	+1+1+1	+1+1+21	+20+17	+0.8	+0.1	+0.6+0.2	
	C_{HD}	+10	+100+15+2.7+9.9+100+20	+1+1+26+42+20+76+59	+98+98+98+9.5	+11+6.6+40	+1+1+1	+1+1+21	+20+17	+2.4+1.1	+0.4	+0.6+0.2	
	C_{HWB}	+10	+100+15+2.7+9.9+100+20	+1+1+26+42+20+76+59	+98+98+98+9.5	+11+6.6+40	+1+1+1	+1+1+21	+20+17	+2.4+1.1	+0.4	+0.6+0.2	

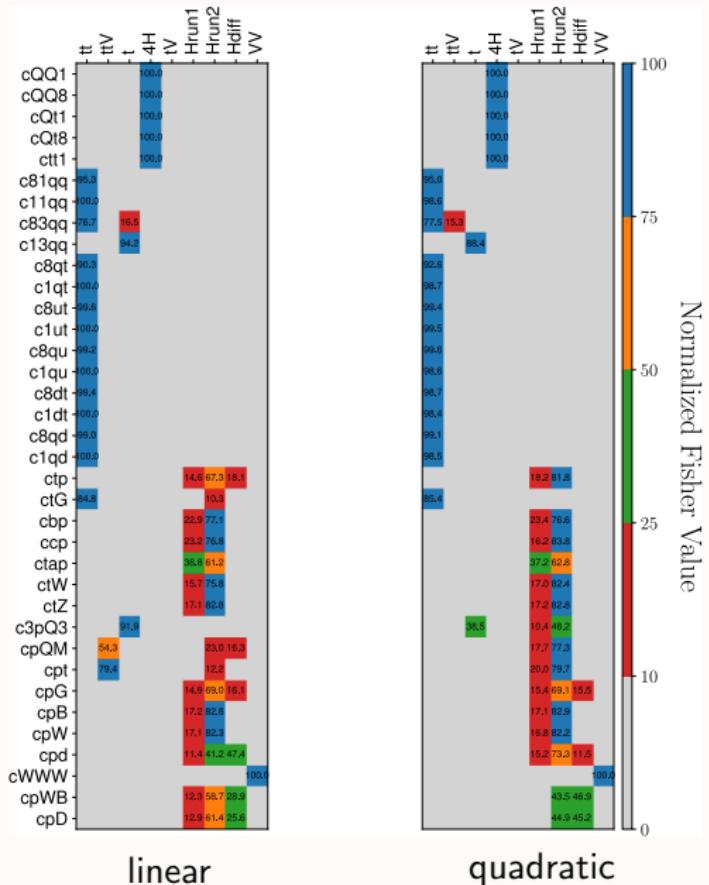
Example: complementarities in top + Higgs

Ellis Madigan, Mimashu Sanz, You 2012.02779

		EWPO				Bosonic				Yukawa				Top 2F				Top 4F						
		$C_{8t\bar{t}}$	C_8	$C_{8u\bar{u}}$	$C_{8d\bar{d}}$	$C_{8q\bar{q}}$	$C_{8\tau\bar{\tau}}$	$C_{8\mu\bar{\mu}}$	$C_{8e\bar{e}}$	C_{4B}	$C_{4B\bar{B}}$	C_{4Q}	$C_{4Q\bar{Q}}$	C_{4U}	C_{4D}	C_{4G}	C_{4H}	$C_{4H\bar{H}}$	C_{4W}	$C_{4B\bar{B}H\bar{H}}$	$C_{4Q\bar{Q}H\bar{H}}$	$C_{4U\bar{U}H\bar{H}}$	$C_{4D\bar{D}H\bar{H}}$	
Top 4F	$C_{8t\bar{t}}$	+0.6	+0.2	+0.6	+0.6	+0.4	+32	+0.6	-0.6	+0	-37	+0.4	+0.4	+2.0	+0.2	+42	+34	+18	+68	+100				
	C_8	+0.4	0	+0.7	+0.7	+0.3	+0.3	+0.4	-2.3	+2.8	0	-20	-2.3	+3.7	-1.5	-0.3	-0.4	+35	+17	+30	+100	+48		
	$C_{8u\bar{u}}$	+2.6	+0.6	+2.5	+2.5	+1.7	+21	+2.6	+2.6	-0.2	-10	0	+0.1	+0.3	+1.1	-5.7	+0.8	+0.2	+35	+30	-85	+60	+100	+18
	$C_{8d\bar{d}}$	+1.1	+0.7	+0.7	+0.6	+1.1	+1.0	+0.5	+9.6	-0.4	-10	-0.4	+1.2	+4.2	+2.5	+1.1	+48	+3.0	+16	+100	+60	+17		
	$C_{8q\bar{q}}$	+2.4	+1.0	+1.3	+1.2	+2.1	+1.5	-2.9	+2.5	-1	-12	-1	+0.8	+0.2	+50	+2.0	-7	+7.0	-37	+32	+100	+10	-88	+35
	$C_{8\tau\bar{\tau}}$	+0.5	+0.1	+0.5	+0.5	+0.1	+16	+0.5	+0.5	0	-2	-0.3	+0.1	+1.6	+2.2	+2.4	+0.2	+16	+9.5	+100	-32	+30	-91	+34
	$C_{8\mu\bar{\mu}}$	+0.2	+0.1	+0.2	+0.2	+0.1	+18	+0.2	+0.2	0	-7	-0.4	0	+1.6	+1.5	+2.7	+0.2	+17	+100	+93	-37	+35	-93	+42
	$C_{8e\bar{e}}$	+0.1	+0.2	+2.1	+2.1	+0.3	+0.5	+1.3	+1.2	+0.3	+5.5	+1.5	+1.5	+0.4	+2.3	+5.7	-5.5	+1.1	+100	+30	+17.4	+3.0	+1.3	
	C_{4B}	+0.1	+0.6	+0.1	+0.1	+0.1	+0.5	+11	+0.1	-0.3	0	-1	-0.1	+0.1	+1.7	+1.6	+1.6	+0.8	+100	+17	+16	-2	+4.0	+0.2
	C_{4H}	+0.1	+0.4	0	+0.3	+0.1	+0.1	+0.6	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.1	+0.2
Top 2F	$C_{4t\bar{t}}$	+0.2	+0.2	+0.2	+0.2	+0.1	+0.1	+5.3	+0.2	+0.3	+2	+51	+2	+5	+4.9	+7.0	+18	+100	+2.5	+2.7	+2.6	+2.0	+11	
	C_{4H}	+1.7	+1.7	+1.7	+1.7	+5.6	+8.1	+14	+9.7	+11	+3.7	+11	+1.1	+1.1	+1.1	+1.1	+100	+18	+0.8	+50	+25	+57	+3.7	
	$C_{4H}^{(1)}$	+2.0	+4.4	+2.0	+2.0	+13	+13	+4.6	+21	+11	+3.0	+21	+2.1	+2.1	+2.1	+2.1	+1.1	+96	+100	+11	+7.0	+6.3	+1.4	+5.7
	$C_{4H}^{(3)}$	+1.9	+2.6	+2.2	+2.2	+1.0	+1.0	+7.0	+1.9	+0.5	+1.1	+2.8	+0.5	+0.5	+0.5	+0.5	+57	+17.4	+2.2	+2.3	+11	+2.8		
	$C_{4H}^{(4)}$	+2.1	+2.1	+2.1	+2.1	+2.0	+1.1	+14	+4.1	+4.7	+3.0	+51	+2	+5	+100	+18	+100	+11	+9.6	+4.9	+1.5	+7.7	+16	+14
Yukawa	C_{4H}	+40	+1	+0.5	+39	+43	+43	+20	+2.0	+1.2	+21	+1	+4.1	+30	+10	+24	+4.8	+4.8	+0.1	+2.3	0	+0.1	+0.1	+0
	$C_{4\mu\bar{\mu}}$	+6.6	+0.6	+1.7	+6.7	+6.7	+6.7	+1.3	+1.3	+1.3	+1.3	+1.3	+6.6	+6.6	+6.3	+0.8	+0.8	+0.8	+0.4	+0.4	+0.1	+0.1	0	
	$C_{4\tau\bar{\tau}}$	+1.1	+0.7	+3.0	+1.1	+1.1	+1.7	+17	+1.1	+1.1	+9.4	+11	+1.2	+10	+4.0	+28	+9.3	+2.0	+2.6	+0.1	+1.5	+0.4	+0.4	
	C_{4G}	+1.4	+1.4	+0.6	+0.6	+1.4	+1.5	+1.4	+0.6	+0.6	+1.4	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5	+2.0	
	C_{4W}	+0.5	+3.9	+13	+9.4	+9.4	+14	+2.0	+2.0	+2.0	+2.0	+2.0	+8.4	+8.5	+100	+1.2	+0.8	+10	+0.1	+0.1	+0.1	+0.1	+0.2	
Bosonic	C_{4HB}	+90	+90	+13	+34	+34	+34	+2.0	+2.0	+2.0	+2.0	+2.0	+57	+57	+57	+1.1	+1.1	+1.1	+0.3	+0.3	0	+0.1	+0.2	
	C_{4HW}	+80	+80	+14	+3.0	+9.8	+9.8	+1.1	+1.1	+2.0	+2.0	+2.0	+57	+57	+57	+1.1	+1.1	+1.1	+0.3	+0.3	+0.1	+0.1	+0.6	
	C_{4Hg}	+80	+80	+14	+3.0	+9.7	+9.8	+2.1	+2.1	+2.0	+2.0	+2.0	+61	+2.0	+100	+93	+8.6	+9.8	+6.6	+4.1	+2.2	+2.0	+2.1	+2.6
	$C_{4Hg}^{(2)}$	+2.2	+2.2	+1.3	+1.3	+1.3	+1.3	+0.8	+0.8	+2.3	+3	+3	+1.1	+1.1	+1.1	+67	+3.0	+5.3	+0.6	+11	+18	+116	+29	+9.6
	C_{4Box}	+0.9	+59	+1	+59	+59	+37	+3.2	+3.1	+40	+100	+61	+54	+1.5	+17	+11	+4.1	+11	+9.7	+0.1	+1.5	+0.5	+0.4	
EWPO	C_{4Hu}	+0	+76	+2.2	+20	+75	+76	+19	+19	+32	+104	+40	+77	+77	+1.0	+1.0	+1.0	+21	+14	+21	+14	+0.1	+2.1	+1.1
	C_{4Hd}	+17	+2.0	+9.8	+34	+22	+23	+6.5	+100	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+4.6	+4.6	+0.1	+0.3	+0.5	+0.1	+1.7	+0.4
	$C_{4Hq}^{(1)}$	+1.1	+4.2	+6.7	+6.7	+6.7	+14	+1.0	+6.6	+5.2	+32	+0.0	+3	+4.3	+0.6	+0.6	+1.1	+1.1	+1.1	+0.1	+1.1	+1.1	+2.0	+0.2
	$C_{4Hq}^{(3)}$	+0.2	+26	+57	+26	+26	+100	+14	+19	+3.7	+31	+31	+14	+0.6	+20	+2.0	+1.6	+13	+5.6	+0.1	+1.1	+0.3	+1.3	+0.7
	C_{4He}	+10	+100	+13	+12	+100	+100	+0.2	+2	+25	+76	+59	+1.5	+98	+98	+9.6	+11	+6.7	+4.3	+2.2	+2.1	+1	+0.2	+0.1
EWPO	$C_{4H\tau\bar{\tau}}$	+99	+100	+17	+4.4	+11	+100	+100	+0.2	+2	+25	+75	+59	+1.6	+97	+98	+9.6	+11	+6.7	+4.3	+2.2	+2.0	+1	+0.2
	$C_{4H\mu\bar{\mu}}$	+100	+100	+16	+26	+42	+2	+76	+59	+59	+98	+98	+0.1	+0.1	+0.1	+0.1	+1.1	+2.1	+20	+17	+1.1	+2.0	+1.1	+0.6
	$C_{4H\eta\bar{\eta}}$	+100	+100	+15	+27	+99	+100	+0.2	+2	+27	+78	+58	+2.0	+99	+98	+9.5	+11	+6.8	+4.0	+1.9	+1.1	+2.0	+1.1	+0.6

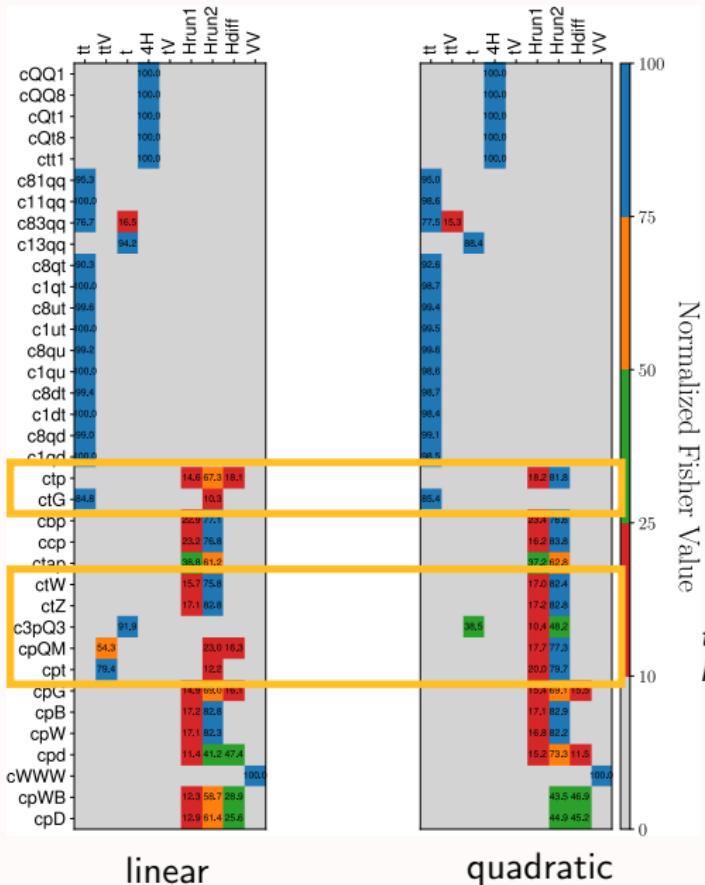
Example: complementarities in top + Higgs

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



Example: complementarities in top + Higgs

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



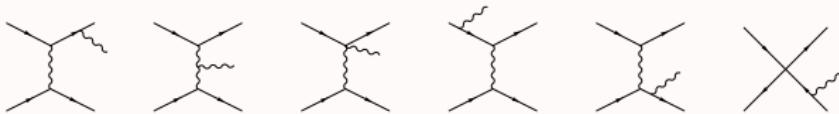
C_{tG} mostly constrained by $t\bar{t}$

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

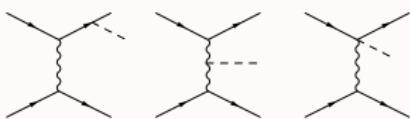
Increasing complexity & interplay

the top enters several more processes at higher orders / with lower rates

$gg \rightarrow tZj$



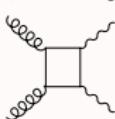
$gg \rightarrow thj$



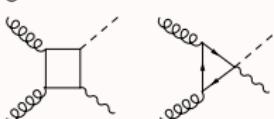
$gg \rightarrow hg$



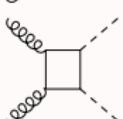
$gg \rightarrow ZZ, \gamma\gamma$



$gg \rightarrow Zh$



$gg \rightarrow hh$



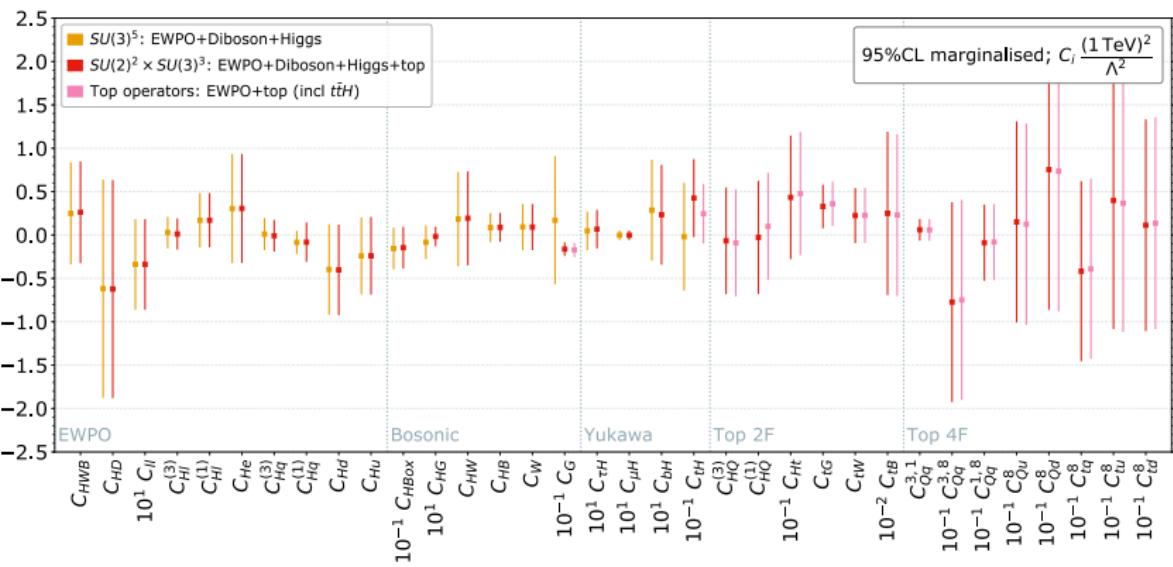
Maltoni,Mandal,Zhao 1812.08703

Degrade,Maltoni,Mimasu,Vryonidou,Zhang 1804.07773

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

Top + EW + Higgs: global results

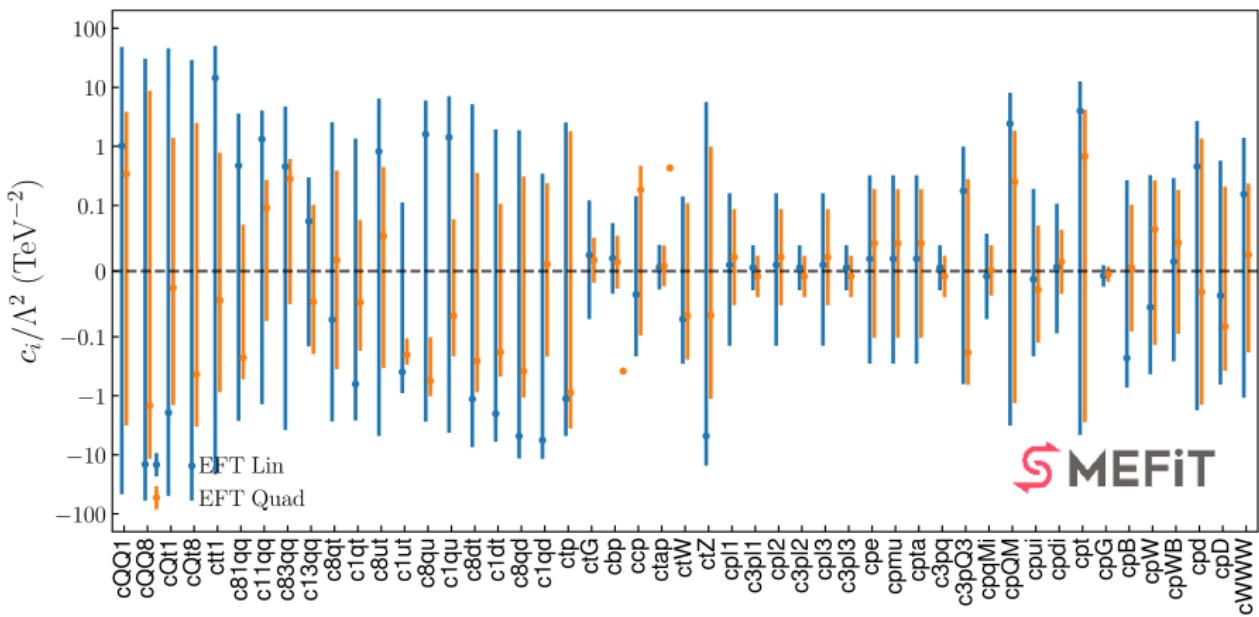
Ellis, Madigan, Mimasu, Sanz, You 2012.02779



34 param, linear, LO + ggH

Top + EW + Higgs: global results

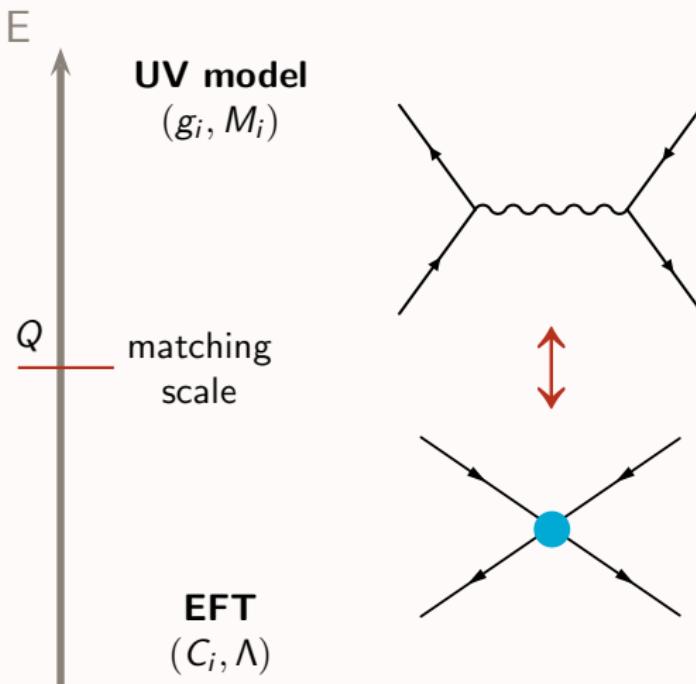
Ethier, Maltoni, Mantani, Nocera, Rojo 2105.00006



49 param, linear+quadratic, NLO QCD

Matching to UV models

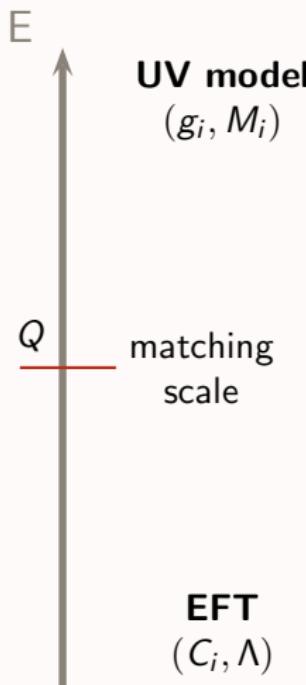
Matching



imposing all matrix elements are
equal at $\mu = Q$

C_i, Λ as function of (g_i, M_i)

Matching



done efficiently up to 1-loop in UV model
via functional methods:

Covariant Derivative Expansion or

Universal One-Loop Effective Action

$$S_{\text{eff}}[\phi] = S[\Phi_0] + \frac{i}{2} \text{Tr} \log \left(-\frac{\delta^2 S}{\delta \Phi^2} \Big|_{\Phi_0} \right)$$

light fields

heavy fields. $\Phi = \Phi_0 + \eta$

Matching SMEFT to UV models: status

CDE / UOLEA: up to 1-loop

Henning,Lu,Murayama 1412.1837,1604.01019
del Aguila,Kunszt,Santiago 1602.00126
Drozd,Ellis,Quevillon,You 1512.03003
Boggia,Gomez-Ambrosio,Passarino 1603.03660
Ellis,Quevillon,(Vuong),You,Zhang
1604.02445,1706.07765,2006.16260
Fuentes-Martin,Portoles,Ruiz-Femenia 1607.02142
Zhang 1610.00710, Cohen,Lu,Zhang 2011.02484
(Krämer),Summ,Voigt 1806.05171,1908.04798

matching via amplitudes up to 1-loop

Craig,Jiang,Li,Sutherland 2001.00017

automated matching

Criado 1710.06445, Bashki,Chakrabortty,Kumar Patra 1808.04403
Cohen,Lu,Zhang 2012.07851
Fuentes-Martin,König,Pagès,Thomsen,Wilsch 2012.08506

complete tree-level dictionary

de Blas,Criado,Pérez-Victoria,Santiago 1711.10391

“v-improved” matching

(Brehmer),Freitas,López-Val,Plehn 1510.03443, 1607.08251

reduced fits

Gorbahn,No,Sanz 1502.07352, Drozd,Ellis,Quevillon,You 1504.02409
Ellis,(Madigan,Mimasu,Murphy),Sanz,You 1803.03252,2012.02779
Dawson,Homiller,Lane 2007.01296,2102.02823
Bakshi,Chakrabortty,Englert,Spannowsky,Stylianou 2009.13394
Anisha,Bakshi,Chakrabortty,Kumar Patra 2010.04088

Example: SM + vector triplet

Brivio, Bruggisser, Geoffray, Luchmann, Kilian, Krämer, Plehn, Summ in preparation

$$\begin{aligned}\mathcal{L}_V = & -\frac{1}{4} V_{\mu\nu}^i V^{i\mu\nu} - \frac{g_M}{2} V_{\mu\nu}^i W^{i\mu\nu} + \frac{m_V^2}{2} V_\mu^i V^{i\mu} + \frac{g_H}{2} V_\mu^i (H^\dagger i \overleftrightarrow{D}^{i\mu} H) \\ & + \frac{g_I}{2} V_\mu^- \bar{\ell} \gamma^\mu \sigma^i \ell + \frac{g_q}{2} V_\mu^- \bar{q} \gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V_\mu^i V^{i\mu}\end{aligned}$$

Example: SM + vector triplet

Brivio, Bruggerisser, Geoffray, Luchmann, Kilian, Krämer, Plehn, Summ in preparation

$$\begin{aligned}\mathcal{L}_V = & -\frac{1}{4} V_{\mu\nu}^i V^{i\mu\nu} - \frac{g_M}{2} V_{\mu\nu}^i W^{i\mu\nu} + \frac{m_V^2}{2} V_\mu^i V^{i\mu} + \frac{g_H}{2} V_\mu^i (H^\dagger i \overleftrightarrow{D}^{i\mu} H) \\ & + \frac{g_I}{2} V_\mu^- \bar{\ell} \gamma^\mu \sigma^i \ell + \frac{g_q}{2} V_\mu^- \bar{q} \gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V_\mu^i V^{i\mu}\end{aligned}$$

field redefinition to
remove kinetic mixing

$$\begin{cases} V_\mu^i \rightarrow \frac{1}{\sqrt{1-g_M^2}} V_\mu^i \\ W_\mu^i \rightarrow W_\mu^i - \frac{g_M}{\sqrt{1-g_M^2}} V_\mu^i \end{cases}$$

constraints
on g_i
↑
SMEFT fit

Warsaw basis, matching up to 1-loop in model

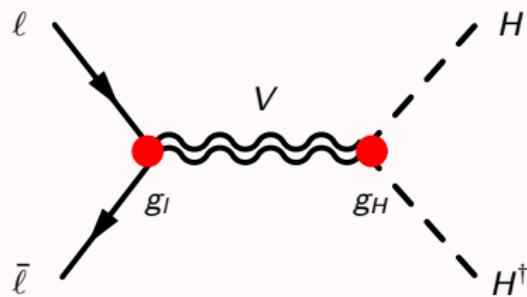
Example: SM + vector triplet

Brivio, Bruggisser, Geoffray, Luchmann, Kilian, Krämer, Plehn, Summ in preparation

$$\begin{aligned}\mathcal{L}_V = & -\frac{1}{4} V_{\mu\nu}^i V^{i\mu\nu} - \frac{g_M}{2} V_{\mu\nu}^i W^{i\mu\nu} + \frac{m_V^2}{2} V_\mu^i V^{i\mu} + \frac{g_H}{2} V_\mu^i (H^\dagger i \overleftrightarrow{D}^{i\mu} H) \\ & + \frac{g_I}{2} V_\mu^- \bar{\ell} \gamma^\mu \sigma^i \ell + \frac{g_q}{2} V_\mu^- \bar{q} \gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V_\mu^i V^{i\mu}\end{aligned}$$

e.g. $Q_{HI}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^i H)(\bar{\ell} \gamma^\mu \sigma^i \ell)$

$$(C_{HI}^{(3)})_{ij} = -\frac{g_I g_H}{4 m_V^2} \delta_{ij}$$



Example: SM + vector triplet

Brivio, Bruggisser, Geoffray, Luchmann, Kilian, Krämer, Plehn, Summ in preparation

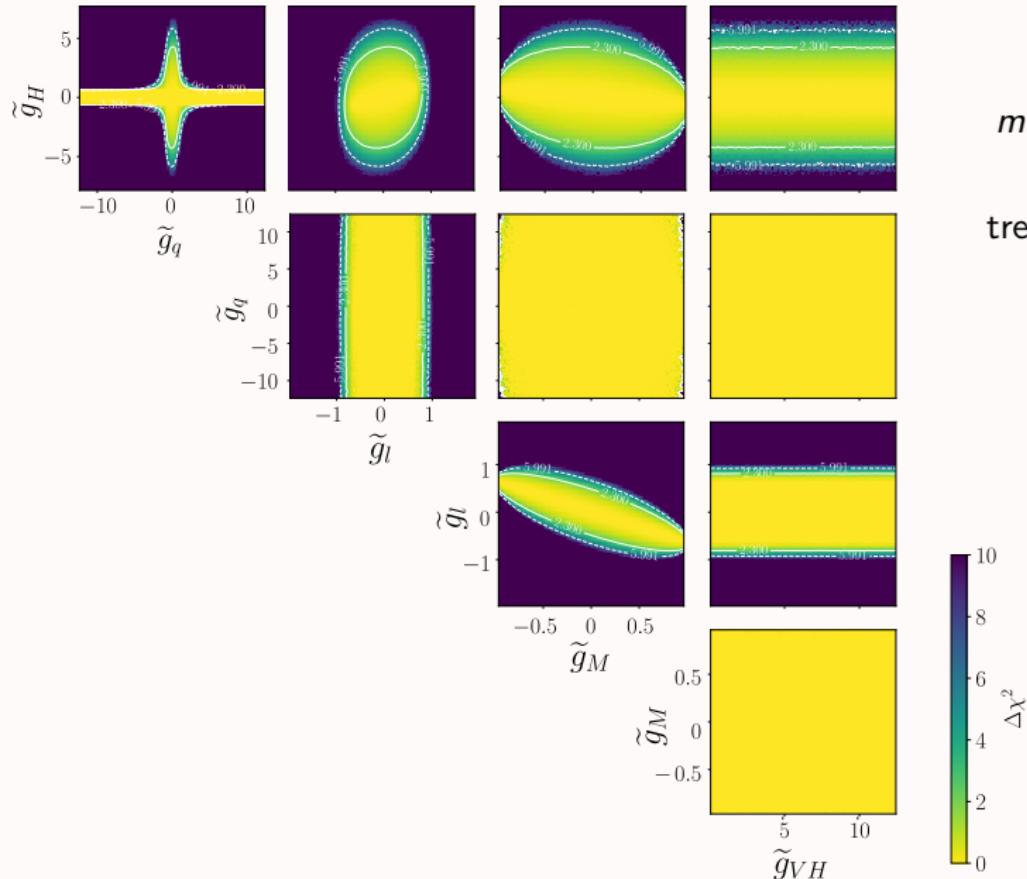
$$\begin{aligned}\mathcal{L}_V = & -\frac{1}{4} V_{\mu\nu}^i V^{i\mu\nu} - \frac{g_M}{2} V_{\mu\nu}^i W^{i\mu\nu} + \frac{m_V^2}{2} V_\mu^i V^{i\mu} + \frac{g_H}{2} V_\mu^i (H^\dagger i \overleftrightarrow{D}^{i\mu} H) \\ & + \frac{g_I}{2} V_\mu^- \bar{\ell} \gamma^\mu \sigma^i \ell + \frac{g_q}{2} V_\mu^- \bar{q} \gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V_\mu^i V^{i\mu}\end{aligned}$$

e.g. $Q_{HI}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^i H)(\bar{\ell} \gamma^\mu \sigma^i \ell)$

$$\begin{aligned}(C_{HI}^{(3)})_{ij} = & -\frac{g_I g_H}{4 m_V^2} \delta_{ij} + \frac{1}{36864 \pi^2 m_V^2} \frac{\delta_{ij}}{1 - g_M^2} \left[g_w^4 (288 + 1531 g_M^2 + 2989 g_M^4) \right. \\ & + g_w^3 (2642 g_H g_M + 2340 g_I g_M + 7942 g_H g_M^3 + 6732 g_I g_M^3) \\ & + g_w^2 (g_I^2 (-102 + 3054 g_M^2) + g_H^2 (49 + 5711 g_M^2)) \\ & + g_w g_M (1080 g_H^3 + 5400 g_H^2 g_I + 2304 g_H g_I^2 + 432 g_I^3 + 1440 h_H g_{VH} + 1440 g_I g_{VH}) \\ & + g_H g_I (1080 g_H^2 - 360 g_H g_I + 432 g_I^2 + 1440 g_{VH} + (1 + g_w^2)(2160 + 12600 g_M^2)) \\ & \left. + 1440 g_M^2 g_{VH} \right] + \frac{3}{3032 \pi^2 m_V^2} (g_I - g_H)(g_I + g_w g_M)(Y_e Y_e^\dagger)_{ij}\end{aligned}$$

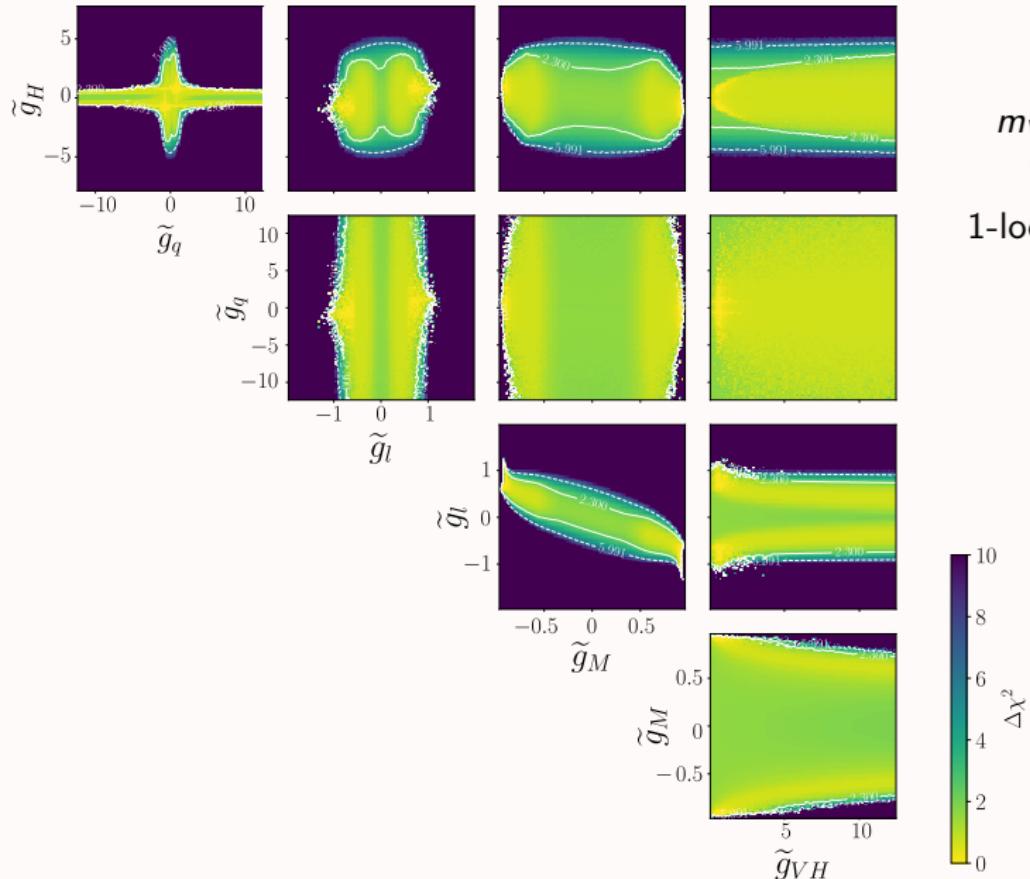
Heavy vector triplet: tree vs loop matching

PRELIMINARY



Heavy vector triplet: tree vs loop matching

PRELIMINARY

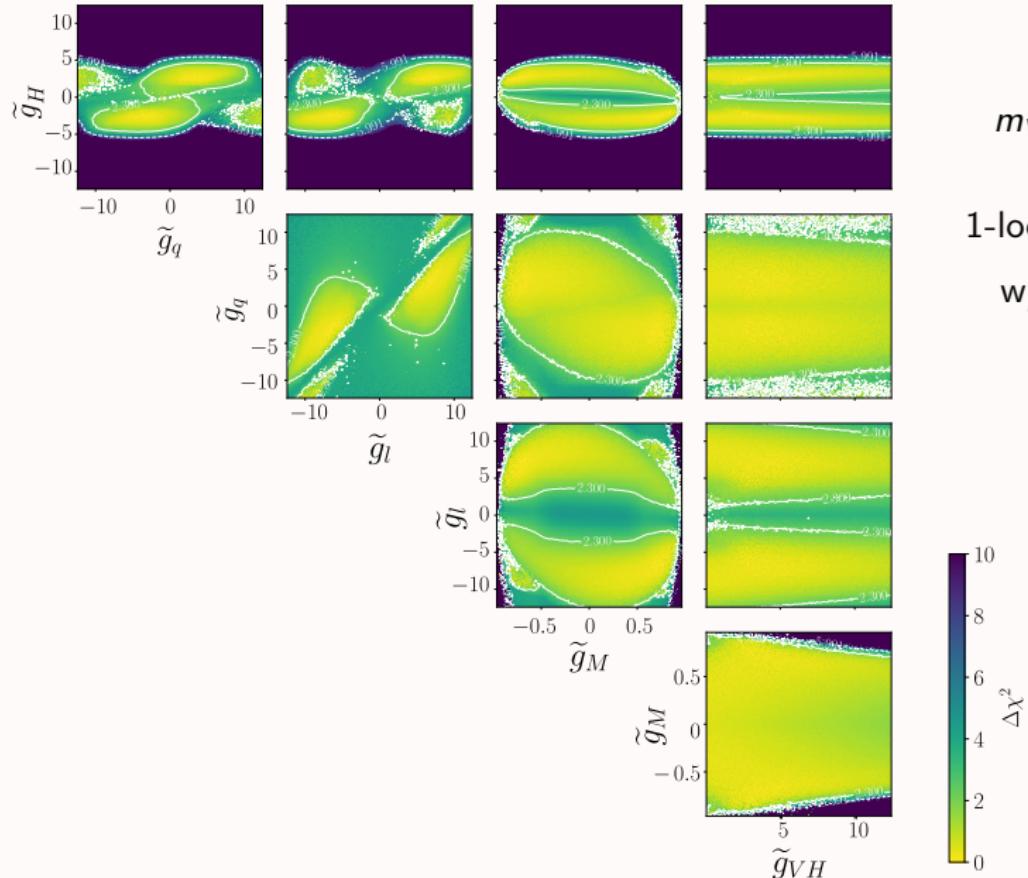


$$m_V = 4 \text{ TeV}$$
$$Q = m_V$$

1-loop matching

Heavy vector triplet: tree vs loop matching

PRELIMINARY



$$m_V = 4 \text{ TeV}$$
$$Q = m_V$$

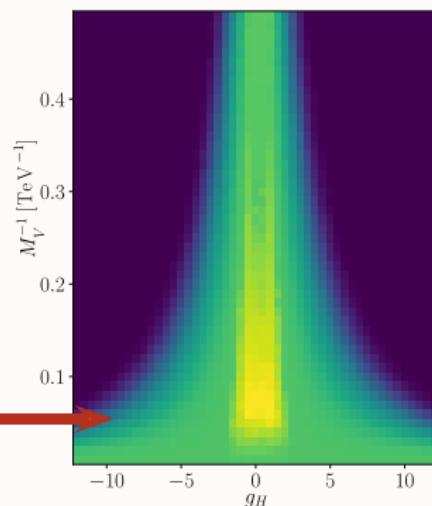
1-loop matching
w/o EWPD

Heavy vector triplet mass as free parameter

HVT interacts with SM also proportionally to EW gauge coupling g_2

→ in the matching we can distinguish $\tilde{g}_i \leftrightarrow m_V$

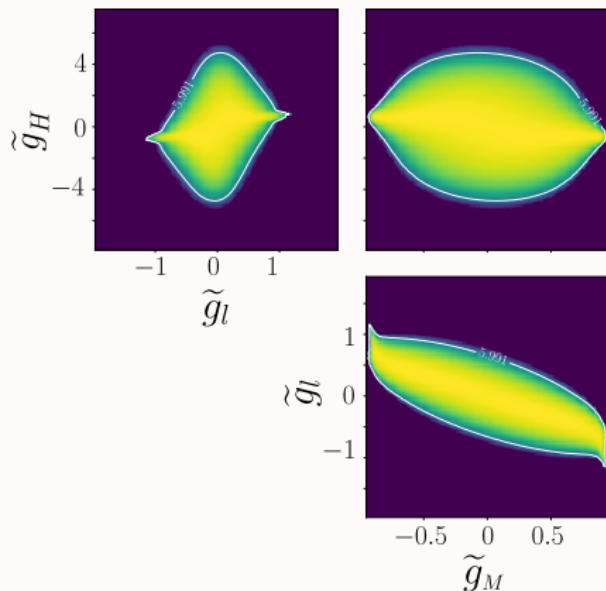
→ m_V can be a free parameter in the fit



(g_H, m_V^{-1}) projection from 3-param. fit

Heavy vector triplet: matching scale dependence

PRELIMINARY

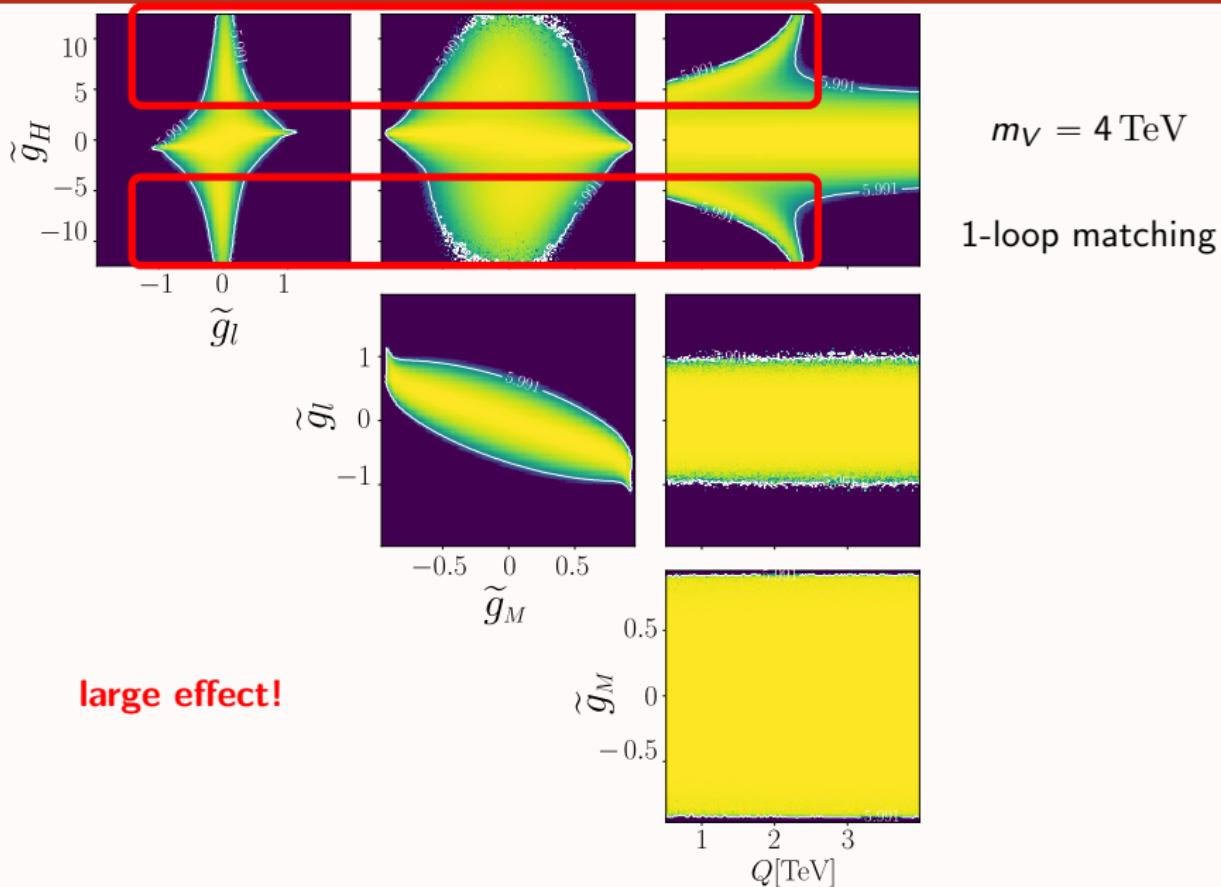


$m_V = 4 \text{ TeV}$

1-loop matching

Heavy vector triplet: matching scale dependence

PRELIMINARY

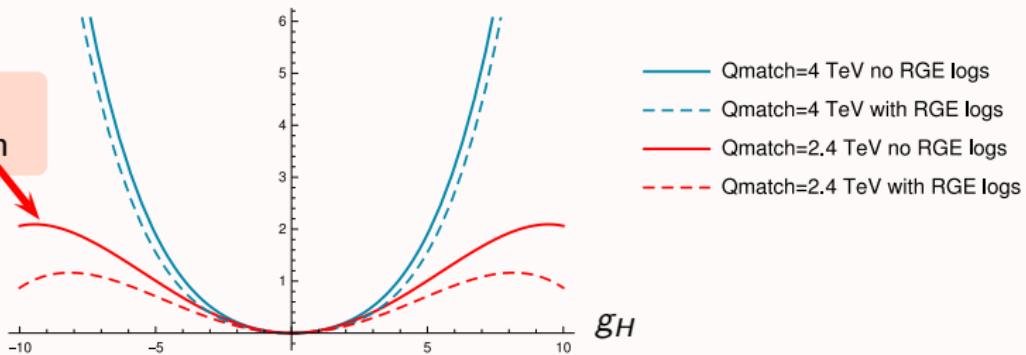


Heavy vector triplet: matching scale dependence

extra “leaves” around lines where $f_{\phi 2} \simeq 0 \simeq f_{u\phi}$

$f_{\phi 2} (1/\text{TeV}^2) - f_{u\phi}$ similar

tree-loop
compensation



$$f_{\phi 2} \simeq 0.04 g_H^2 \left(1 + 0.1 \log \frac{m_V}{Q} \right) + 10^{-3} g_H^4 \left(1 - 2.4 \log \frac{m_V}{Q} \right)$$

flips sign for $Q \lesssim m_V/1.52$

What next?

Challenges for the future

theory

- ▶ towards higher orders both in loops and EFT
- ▶ automated NLO EW calculations
- ▶ better understanding of interplay with models
- ▶ understanding effects in PDF, non-perturbative aspects of LHC processes
- ▶ SMEFT vs HEFT

global fits. challenge: flavor indices

- ▶ incorporating B physics
- ▶ incorporating low energy measurements

experiments

- ▶ coordination for cross-sector combinations
- ▶ better measurements: more precise and more differential

$h \rightarrow WW + WW:$
ATLAS-PHYS-PUB-2021-010

More differential information

more statistics



finer binning
higher-dim. histograms



better shape analyses
interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!

More differential information

more statistics



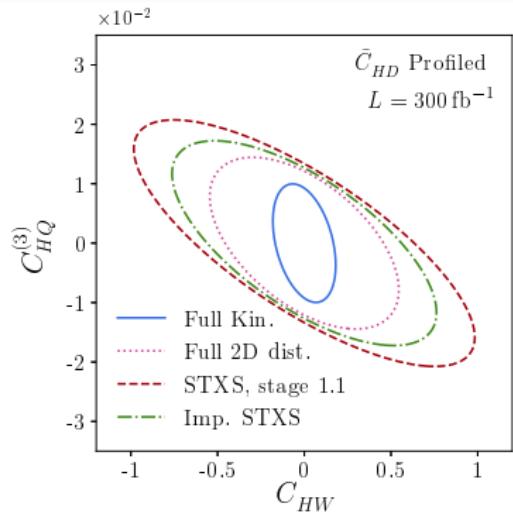
finer binning
higher-dim. histograms



better shape analyses
interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!

- extract **more information** from each measurement



Brehmer, Dawson, Homiller, Kling,
Plehn 1908.06980

More differential information

more statistics



finer binning
higher-dim. histograms



better shape analyses
interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!

- ▶ extract **more information** from each measurement
- ▶ more discriminating power between different shapes → operators

More differential information

more statistics



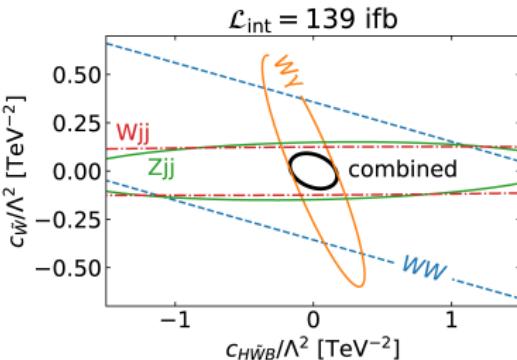
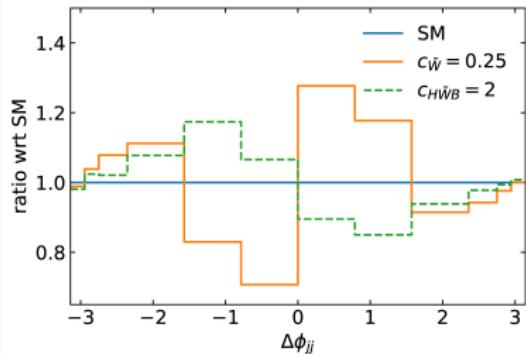
finer binning
higher-dim. histograms



better shape analyses
interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!

- ▶ extract **more information** from each measurement
- ▶ more discriminating power between different shapes \rightarrow operators
- ▶ access to CP properties



More differential information

more statistics



finer binning
higher-dim. histograms



better shape analyses
interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!

- ▶ extract **more information** from each measurement
- ▶ more discriminating power between different shapes → operators
- ▶ access to CP properties
- ▶ access to polarizations → crucial for VBS, diboson
 - single out Goldstone boson contributions
 - more direct access to EWSB

More differential information

more statistics



finer binning
higher-dim. histograms



better shape analyses
interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!

- ▶ extract **more information** from each measurement
- ▶ more discriminating power between different shapes → operators
- ▶ access to CP properties
- ▶ access to polarizations → crucial for VBS, diboson
 - single out Goldstone boson contributions
 - more direct access to EWSB
- ▶ ...

Summary

- ▶ SMEFT is the best framework for indirect searches of new physics at LHC
 - current direct bounds consistent with $(v/\Lambda_{BSM}) \ll 1$
 - collider physics entering **precision era**
- ▶ Combining different measurements is key to constraining as many coefficients as possible and avoiding bias
- ▶ Studies in EW, Higgs and top sectors are theoretically advanced
 - all relevant observables understood
 - state-of-the-art fits 30-50 parameters
 - first SMEFT analyses by experiments
- ▶ matching to simplified models
 - ▶ **matching scale** dependence can be sizeable (at least for HVT)
 - ▶ non-SM singlets → can fit over the new physics mass as well