The SMEFT program at the LHC

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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

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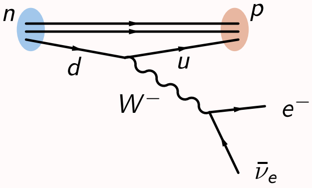
classical example: **Fermi's interaction** for β-decays

"True" theory: Electroweak interactions



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

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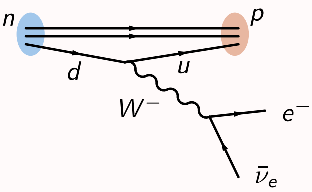
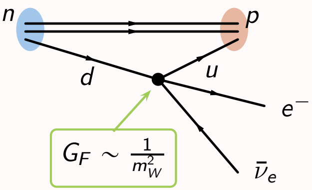
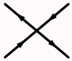


$\mathcal{A}\left(\frac{1}{m_W^2}\right)$

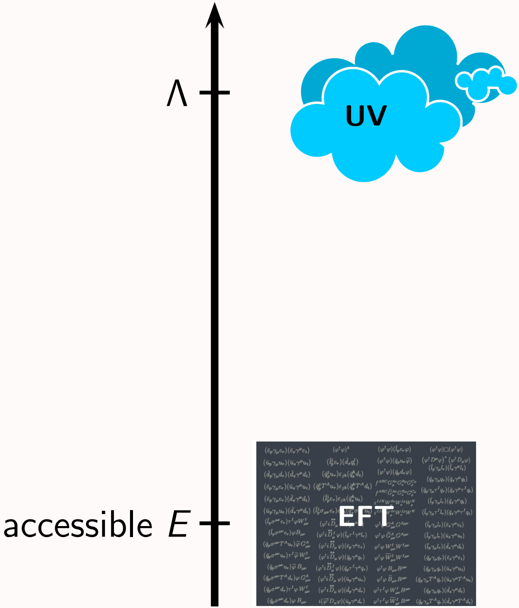
$\mathbf{E} \ll \mathbf{m_W}$

EFT: Fermi's interactions

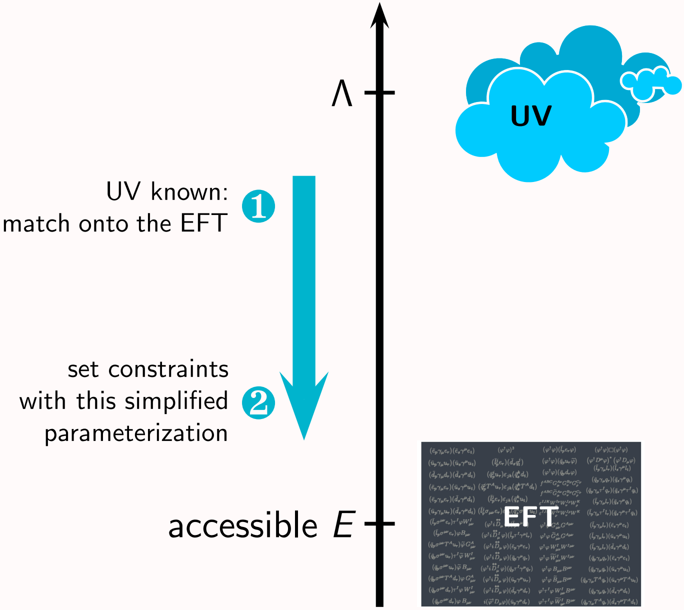


$\mathcal{A}(0) + \frac{1}{m_W^2}\Big($  $+ \dots\Big) + \mathcal{O}\left(m_W^{-4}\right)$

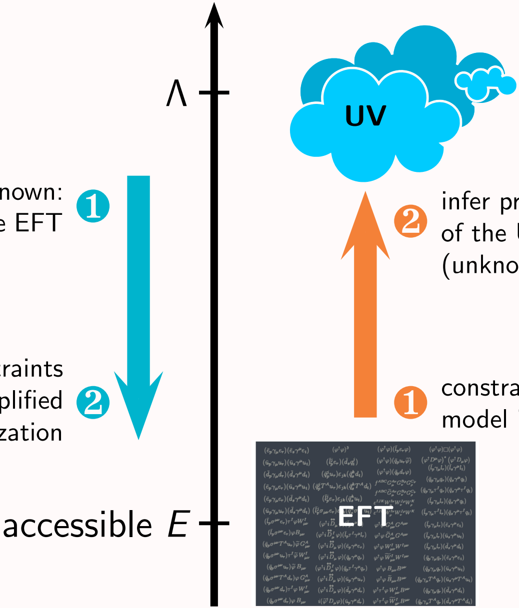
Top-down and bottom-up



Top-down and bottom-up



Top-down and bottom-up



UV known: match onto the EFT ❶

set constraints with this simplified parameterization ❷

constrain the EFT in a model independent way ❶

infer properties of the UV sector (unknown) ❷

SMEFT

Standard **M**odel **E**ffective **F**ield **T**heory:
The EFT constructed with **Standard Model** field & symmetries

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

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

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

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

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

d=6: the Warsaw basis

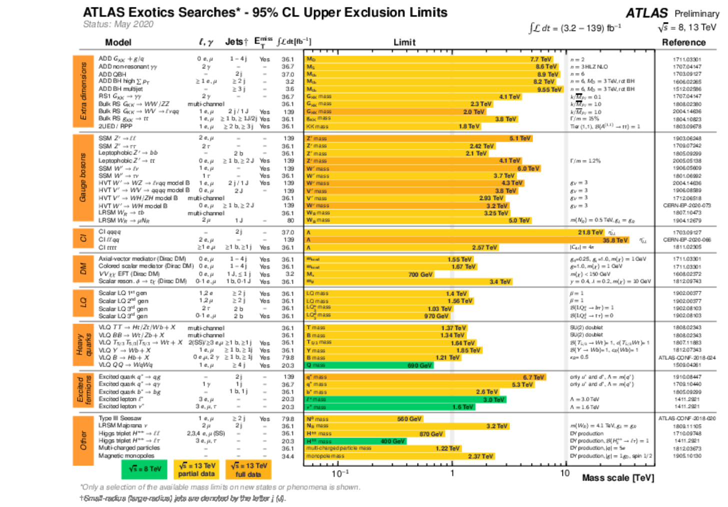
Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	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 for indirect searches at LHC

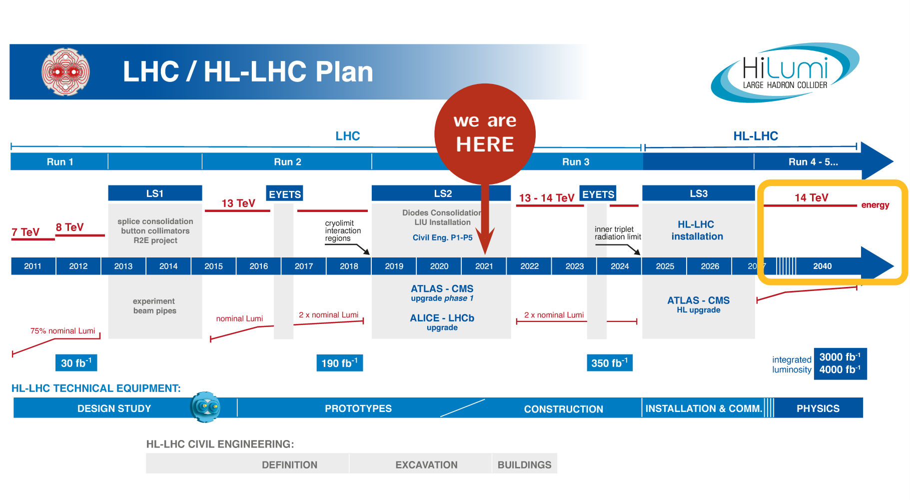
new physics seems indeed
nearly decoupled



SMEFT for indirect searches at LHC

new physics seems indeed nearly decoupled

collider physics is entering a precision era



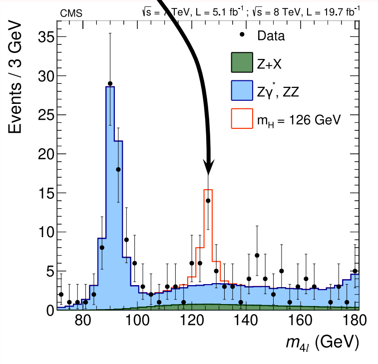
SMEFT for indirect searches at LHC

new physics seems indeed nearly decoupled

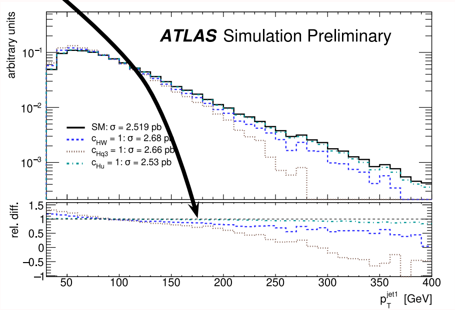
collider physics is entering a precision era

indirect searches
more and more competitive with direct ones

direct



indirect



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

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

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

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

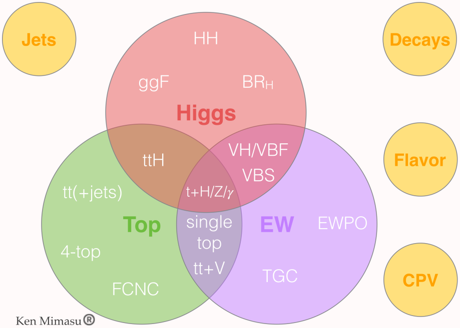
Combine, combine, combine

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.

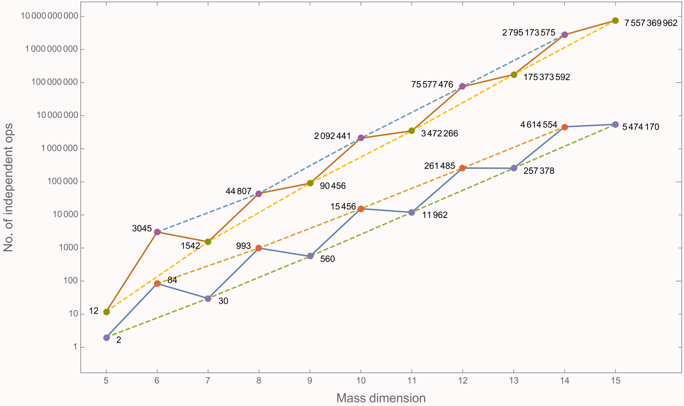


Theoretical understanding

Theory progress

☑ # parameters known for all orders

Lehman(Martin) 1410.4193,1510.00372
Henning,Lu,Melia,Murayama 1512.03433
Marinissen,Rahn,Waalewijn 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: $\varepsilon_{ijk}\, W_\mu^{i\nu}\, W_\nu^{j\rho}\, W_\rho^{k\mu}$

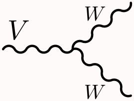
$\varepsilon_{ijk}(H^\dagger\sigma^i H)\, W_\mu^{j\nu}\, W_\nu^{k\rho}\, B_\rho^\mu$

$(D_\mu H^\dagger D_\nu H)\, B^{\mu\nu}$

$(D_\mu H^\dagger \sigma^i D_\nu H)\, W^{i\mu\nu}$

$\varepsilon_{ijk}(H^\dagger\sigma^i H)\,(D_\mu H^\dagger\sigma^j D_\nu H)\, W^{k\mu\nu}$

$(H^\dagger\sigma^i H)\,(D_\mu H^\dagger\sigma^i D_\nu H)\,(H^\dagger\sigma^j H)\, W^{j\mu\nu}$



$\rightarrow$ 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
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- ☑ 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

$\mu \to e\gamma$: Pruna,Signer 1408.3565
$h \to \gamma\gamma, WW$: Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
Hartmann,Trott 1505.02646,1507.03568
Dedes,Paraskevas,Rosiek,Suxho,Trifyllis 1805.00302
Dawson,Giardino 1807.11504
$h \to ZZ, Z\gamma$: Dawson,Giardino 1801.01136, Dedes,Suxho,Trifyllis 1903.12046
$h \to f\bar{f}$: (Cullen,Gauld),Pecjak,Scott 1512.02508,1904.06358,2007.15238
$gg \to h(j)$: 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
$t \to bW$: Boughezal,Chen,Petriello,Wiegand 1907.00997
+ several NLO QCD (DY, VV, $t\bar{t}(V)$, single-t...)

Theory progress

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- ☑ 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,Pagès,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

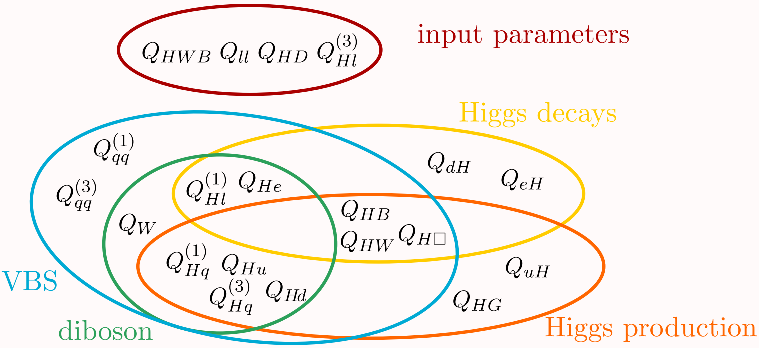
- diboson (+ VBS)

  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. . .

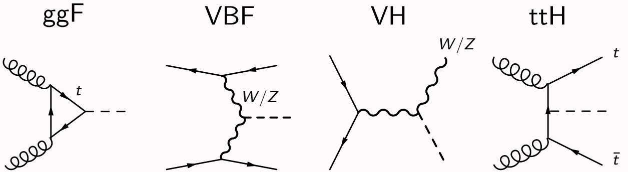
SMEFT for EW and Higgs sectors

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

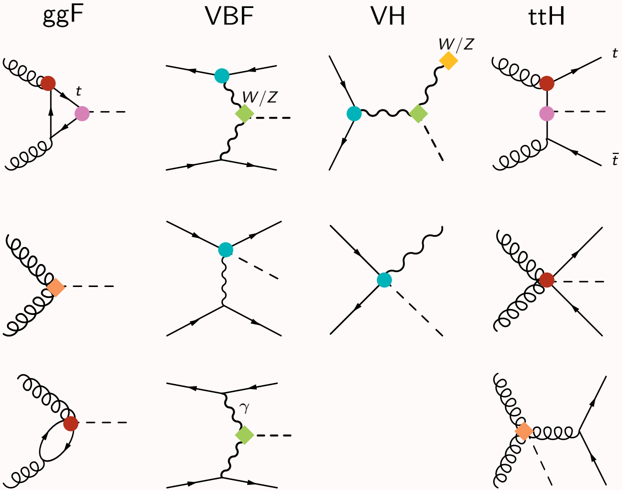


+ CP odd + flavor indices + others entering through loop corrections ...

SMEFT in Higgs production

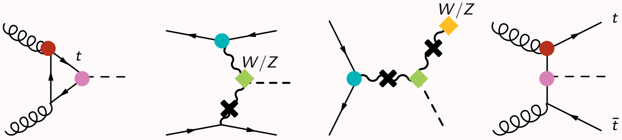


SMEFT in Higgs production



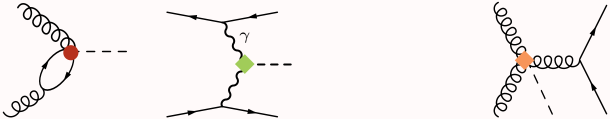
SMEFT in Higgs production

ggF VBF VH ttH



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

prod xs $i \to h$

decay BR $h \to f$

efficiency

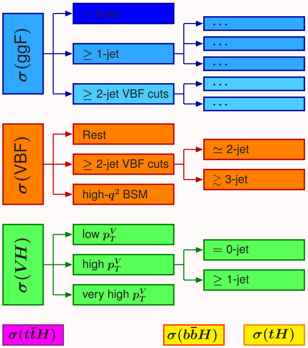
acceptance

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

Brivio,Corbett,Trott 1906.06949

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

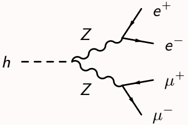
STXS define **production categories**:
unfolded XS organized in "macro-bins"
→ minimize selection cuts + modeling bias
better reproducibility

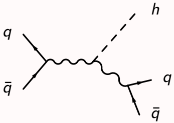


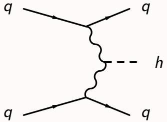
LesHouches 2015 1605.0469,
LHCHXSWG 1610.0792,
Berger et al. 1906.02754

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

SMEFT corrections in Higgs processes: example







$h \to 2e2\mu$ width

STXS 1.1 bin $p_{Th} < 200$

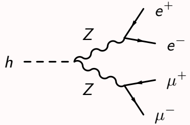
$60 \leqslant m_{jj} \leqslant 120$

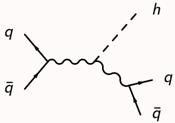
$m_{jj} \geqslant 350$

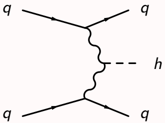
$$\frac{X_{SMEFT}}{X_{SM}} = 1 + \sum_\alpha \frac{X_\alpha}{X_{SM}} \bar{C}_\alpha + \mathcal{O}(\Lambda^{-4})$$

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

SMEFT corrections in Higgs processes: example



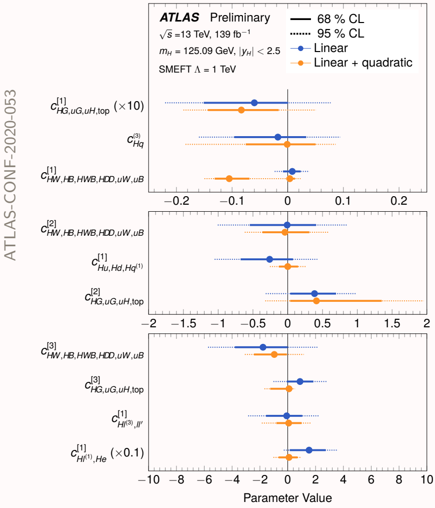


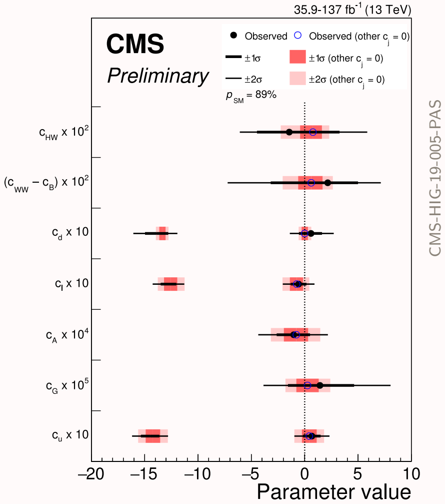


	$h \to 2e2\mu$ width		STXS 1.1 bin $p_{Th} < 200$, $60 \leqslant m_{jj} \leqslant 120$		STXS 1.1 bin $p_{Th} < 200$, $m_{jj} \geqslant 350$	
	direct	propagators	direct	propagators	direct	propagators
$\bar{C}_{He}$	-1.724	0.153		0.0526		$5.32 \cdot 10^{-5}$
$\bar{C}_{Hl}^{(1)}$	2.144	0.153		0.0526		$5.32 \cdot 10^{-5}$
$\bar{C}_{Hl}^{(3)}$	-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	$5.24 \cdot 10^{-5}$
$\bar{C}'_{ll}$	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

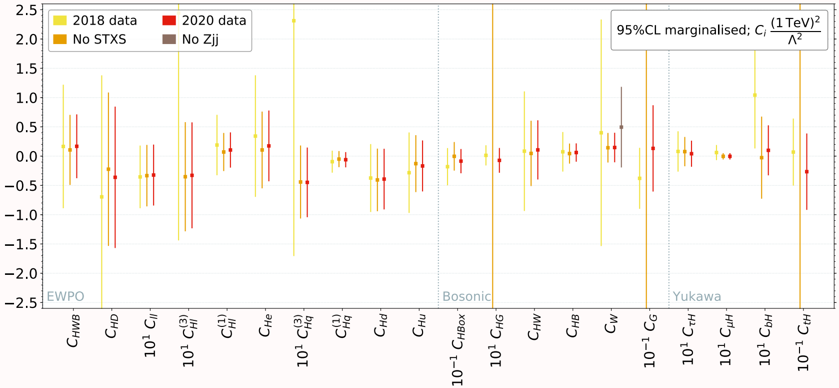




Higgs + EW interplay has been studied extensively

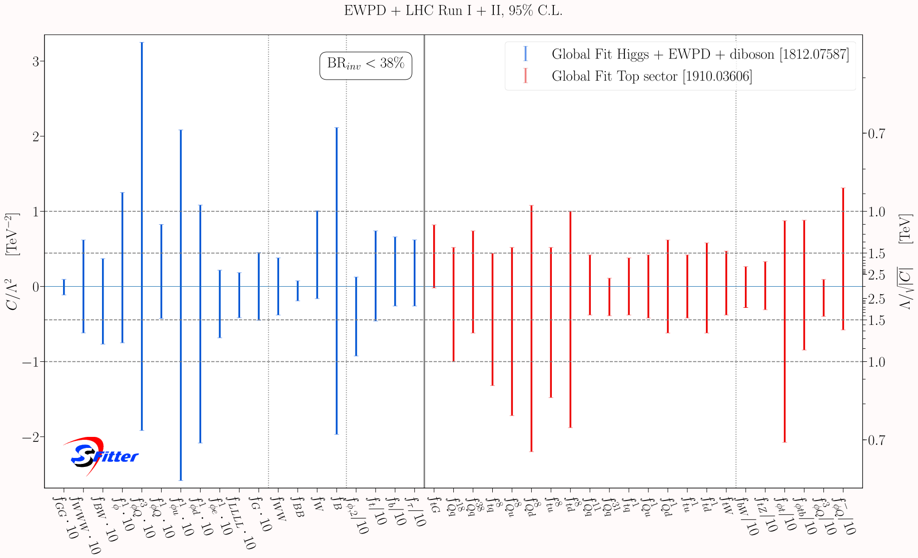
historically the first two sectors to be combined in global fits

typically: EWPO from LEP
+ diboson measurements (LEP2/LHC)
+ Higgs production/decay rates (STXS)



Ellis et al 2012.02779

EW + Higgs vs top



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

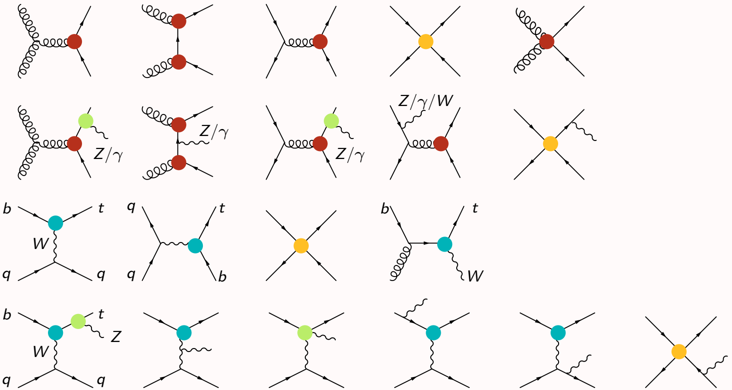
top WG 1802.07237, Aguilar-Saavedra 0811.3842 (Willenbrock),Zhang 1404.1264,1601.06163,1008.3869, Englert et al 1506.08845,1512.03360,1607.04304 Maltoni et al 1601.08193,1804.07773,1901.05965, 2008.11743, de Beurs et al 1807.03576 Brivio et al 1910.03606

$t\bar{t}$

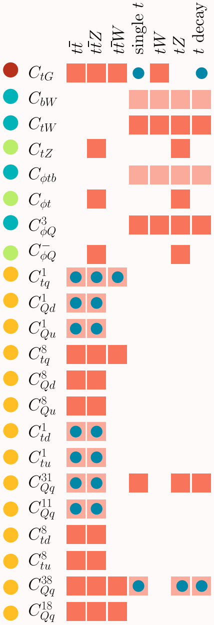
$t\bar{t}V$

tj, tW

tZj



Operators affecting top quark interactions

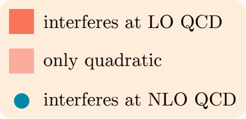


Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang 1910.03606

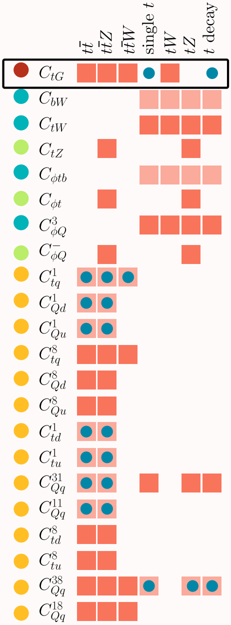
- $SU(2)_q \times SU(2)_u \times SU(2)_d$
- top interactions only
- up to NLO QCD, quadratic SMEFT

$\downarrow$

22 param.



Operators affecting top quark interactions



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

- $SU(2)_q \times SU(2)_u \times SU(2)_d$
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↓

22 param.

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

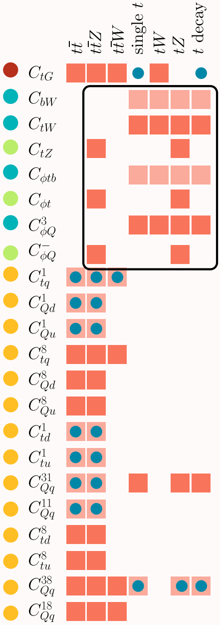
interferes at LO QCD

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

↓

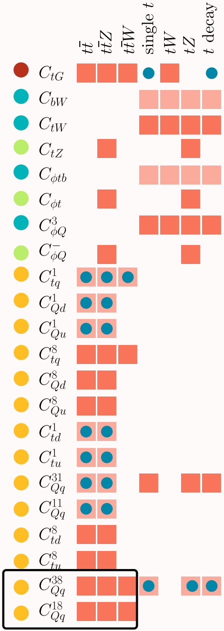
22 param.

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

$t\bar{t}Z$, single-t → 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

$\downarrow$

22 param.

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

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

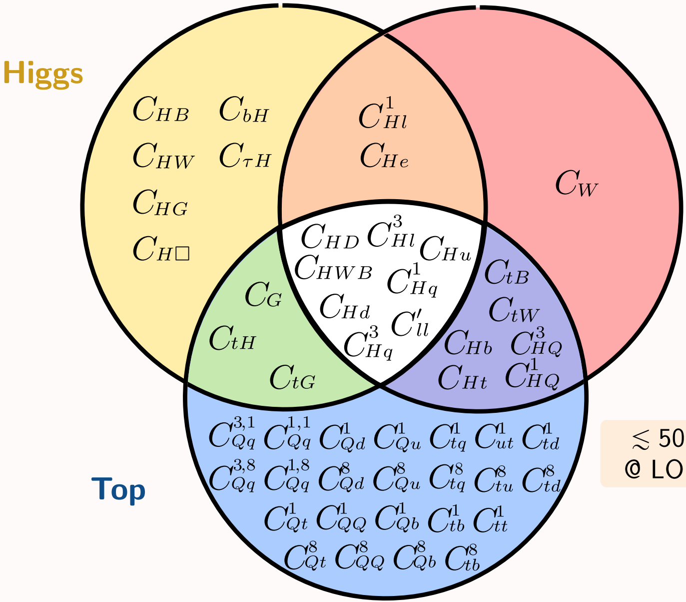
$\rightarrow$ break degeneracies among $qqQQ$ op.

interferes at LO QCD

only quadratic

interferes at NLO QCD

Next step: top + EW + Higgs



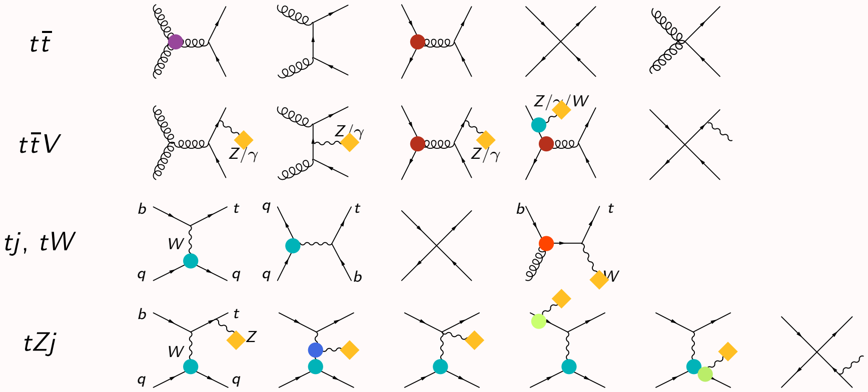
$\lesssim$ 50 parameters
@ LO interference

Combining Higgs and top

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

Combining Higgs and top

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



Combining Higgs and top

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 ...

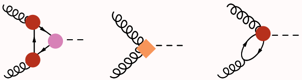
$+\ C_{HWB}, C_{HD}, C'_{ll}$ from EW inputs!

Combining Higgs and top

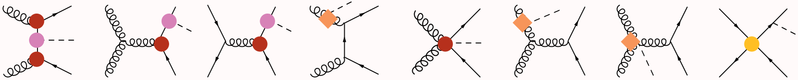
1. **top operators → Higgs / EW processes**
2. non-top operators → top processes

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

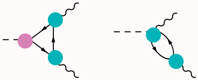
$gg \to h$



$t\bar{t}h$



$h \to \gamma\gamma$



Combining Higgs and top

1. top operators → Higgs / EW processes
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Grazzini,Ilnicka,Spira,(Wiesemann) 1612.00283, 1806.08832,
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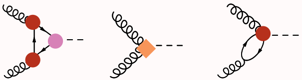
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460

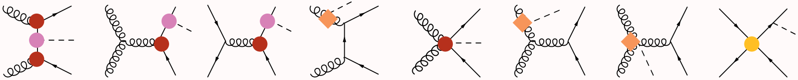
$gg \to h$



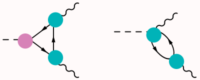
↔ $t\bar{t}$

↗

$t\bar{t}h$



$h \to \gamma\gamma$



↔ $t\bar{t}V$, single-t

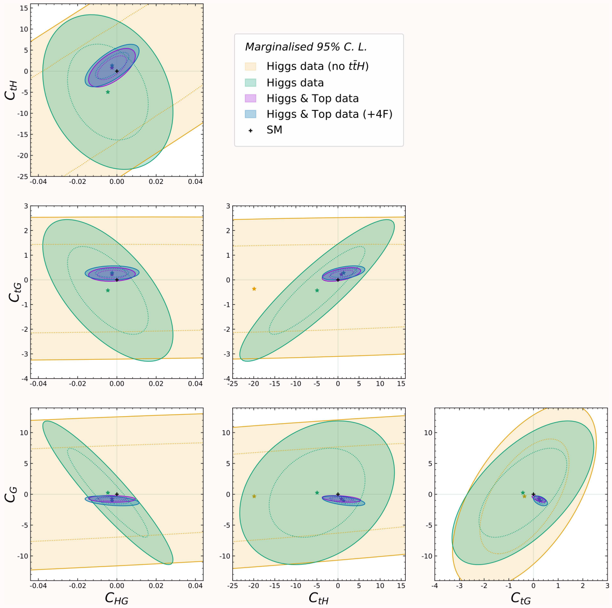
new: ● C_{tH} operator → $t\bar{t}H$ vertex ↔ interplay with C_{HG} ◆

↗

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

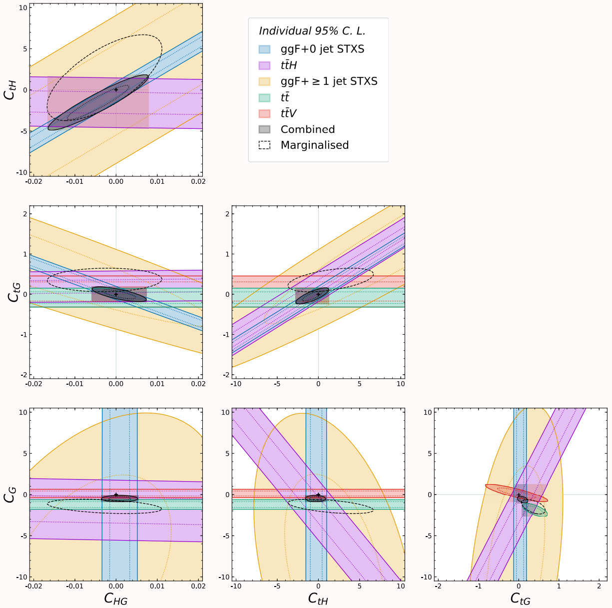
● $C_{tW}, C_{tB}, C_{HQ}^{(3)}, C_{HQ}^{(1)}, C_{Ht} \to t\bar{t}V + t\bar{t}VH$

Example: complementarities in top + Higgs



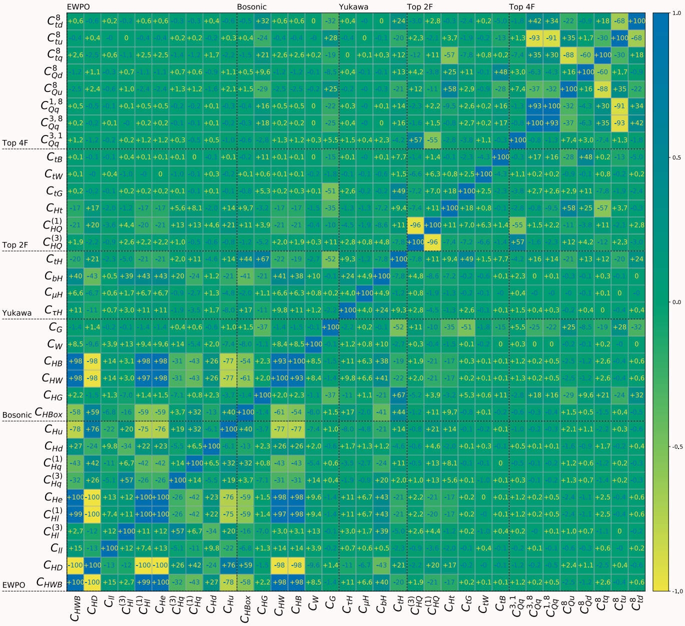
Ellis, Madigan, Mimasu, Sanz, You 2012.02779

Example: complementarities in top + Higgs



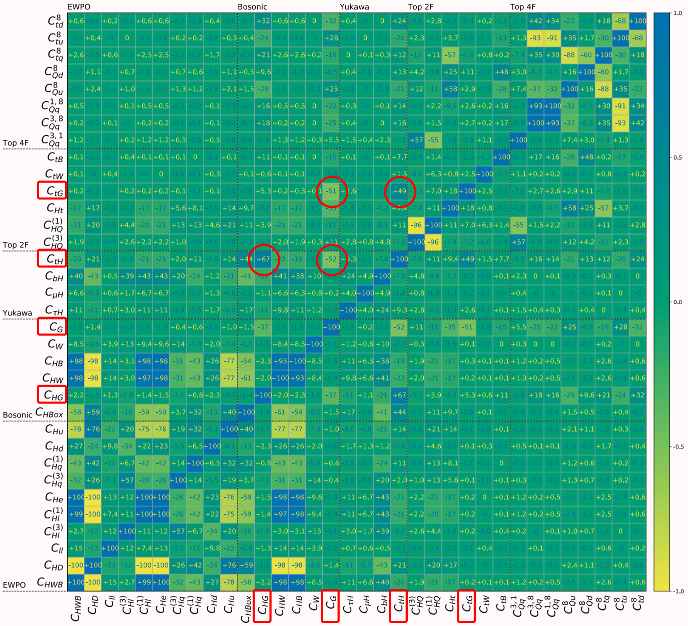
Ellis, Madigan, Mimasu, Sanz, You 2012.02779

Example: complementarities in top + Higgs



Ellis,Madigan,Mimasu,Sanz,You 2012.02779

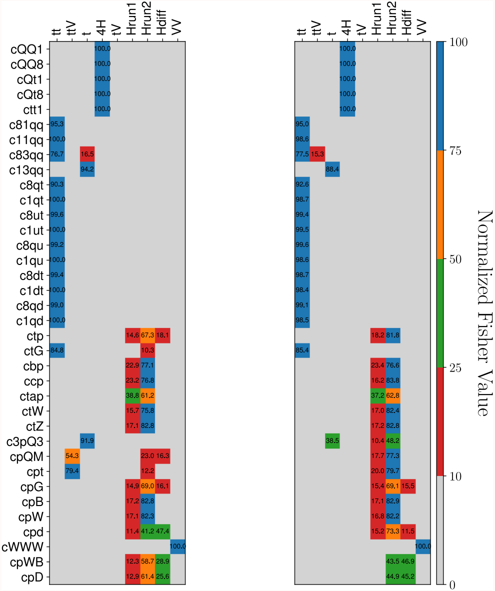
Example: complementarities in top + Higgs



Ellis, Madigan, Mimasu, Sanz, You 2012.02779

Example: complementarities in top + Higgs

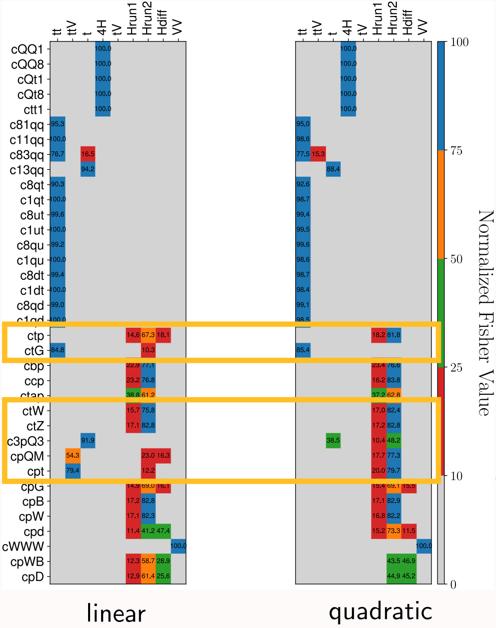
Ethier,Maltoni,Mantani,Nocera,Rojo,Slade,Vryonidou,Zhang 2105.00006



linear quadratic

Example: complementarities in top + Higgs

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



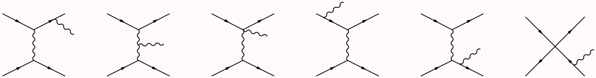
C_{tG} mostly constrained by $t\bar{t}$

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

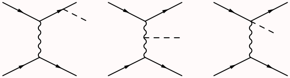
Increasing complexity & interplay

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

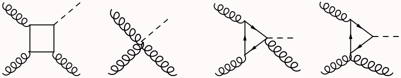
$gg \to tZj$



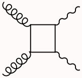
$gg \to thj$



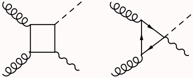
$gg \to hg$



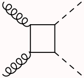
$gg \to ZZ, \gamma\gamma$



$gg \to Zh$



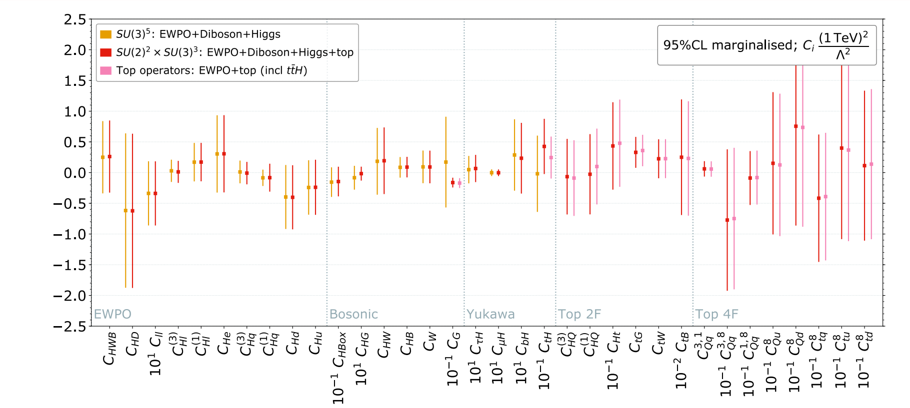
$gg \to hh$



Maltoni,Mandal,Zhao 1812.08703
Degrande,Maltoni,Mimasu,Vryonidou,Zhang 1804.07773
Hartland,Maltoni,Nocera,Rojo,Slade,Vryonidou,Zhang 1901.05965

Top + EW + Higgs: global results

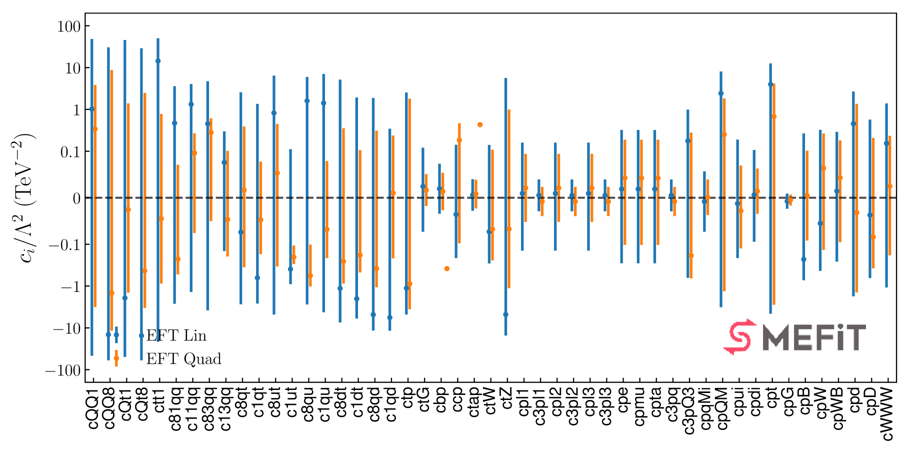
Ellis,Madigan,Mimasu,Sanz,You 2012.02779



34 param, linear, LO + ggH

Top + EW + Higgs: global results

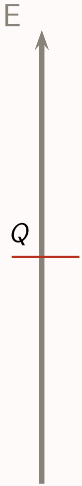
Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006



49 param, linear+quadratic, NLO QCD

Matching to UV models

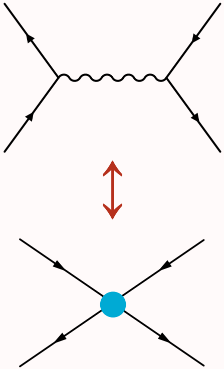
Matching



UV model
(g_i, M_i)

matching scale

EFT
(C_i, Λ)

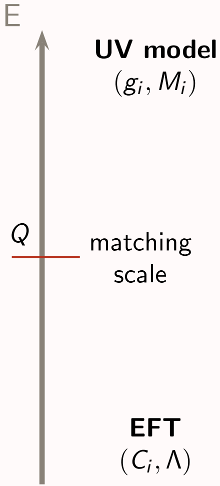


imposing all matrix elements are equal at $\mu = Q$

$\downarrow$

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

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

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

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

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↓

field redefinition to remove kinetic mixing

$$\begin{cases} V^i_\mu \to \dfrac{1}{\sqrt{1-g_M^2}}V^i_\mu \\ W^i_\mu \to W^i_\mu - \dfrac{g_M}{\sqrt{1-g_M^2}}V^i_\mu \end{cases}$$

↓

Warsaw basis, matching up to 1-loop in model

constraints on g_i $\uparrow$ SMEFT fit

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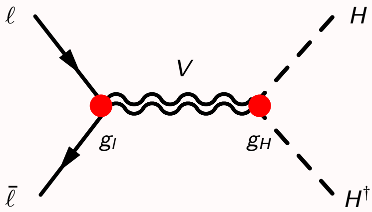
e.g. $Q^{(3)}_{Hl} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{\ell}\gamma^\mu\sigma^i\ell)$

$(C^{(3)}_{Hl})_{ij} = -\frac{g_l g_H}{4m_V^2}\delta_{ij}$



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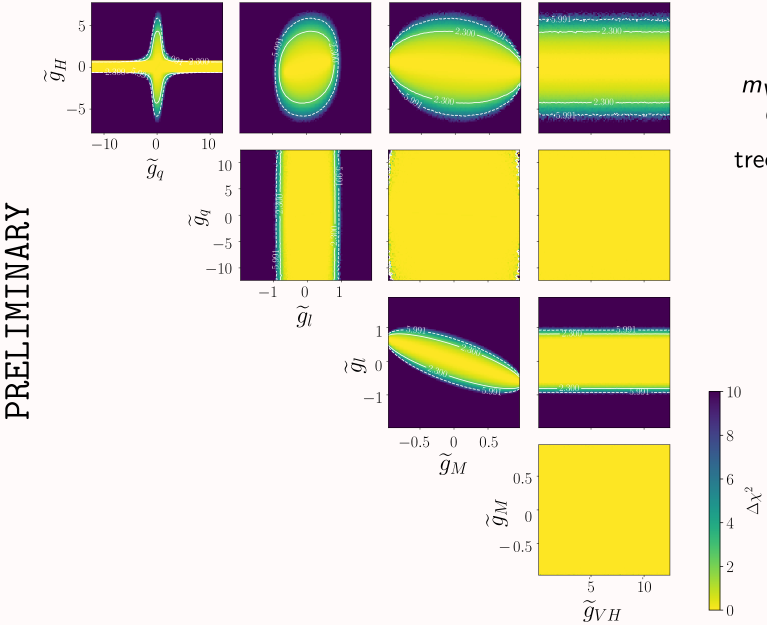
e.g. $Q_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{\ell}\gamma^\mu \sigma^i \ell)$

$$(C_{Hl}^{(3)})_{ij} = -\frac{g_l g_H}{4 m_V^2}\delta_{ij} + \frac{1}{36864\pi^2 m_V^2}\frac{\delta_{ij}}{1-g_M^2}\Big[g_w^4 (288 + 1531 g_M^2 + 2989 g_M^4)$$
$$+ g_w^3 (2642 g_H g_M + 2340_g l g_M + 7942 g_H g_M^3 + 6732 g_l g_M^3)$$
$$+ g_w^2 (g_l^2 (-102 + 3054 g_M^2) + g_H^2 (49 + 5711 g_M^2))$$
$$+ g_w g_M (1080 g_H^3 + 5400 g_H^2 g_l + 2304 g_H g_l^2 + 432 g_l^3 + 1440 h_H g_{VH} + 1440 g_l g_{VH})$$
$$+ g_H g_l (1080 g_H^2 - 360 g_H g_l + 432 g_l^2 + 1440 g_{VH} + (1 + g_w^2)(2160 + 12600 g_M^2))$$
$$+ 1440 g_M^2 g_{VH} \Big] + \frac{3}{3032\pi^2 m_V^2} (g_l - g_H)(g_l + g_w g_M)(Y_e Y_e^\dagger)_{ij}$$

Heavy vector triplet: tree vs loop matching

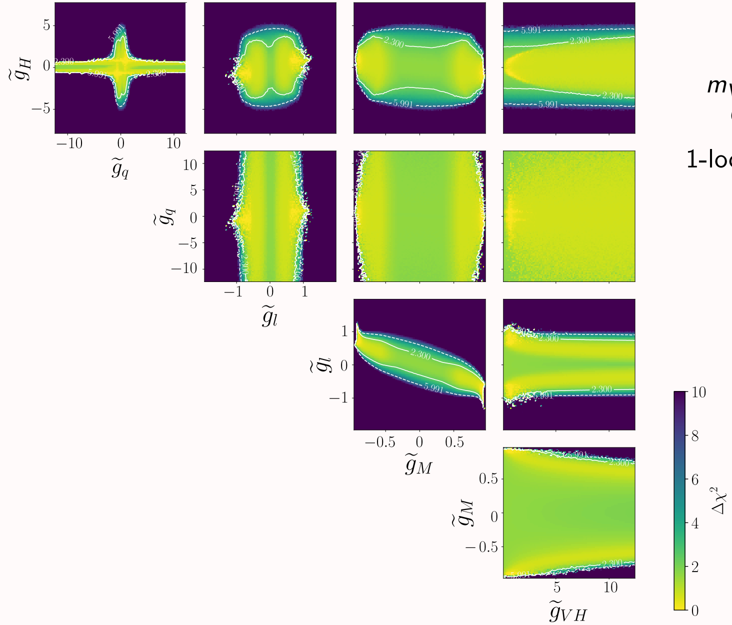


$m_V = 4\,\mathrm{TeV}$
$Q = m_V$

tree matching

Heavy vector triplet: tree vs loop matching

PRELIMINARY



$m_V = 4\,\mathrm{TeV}$
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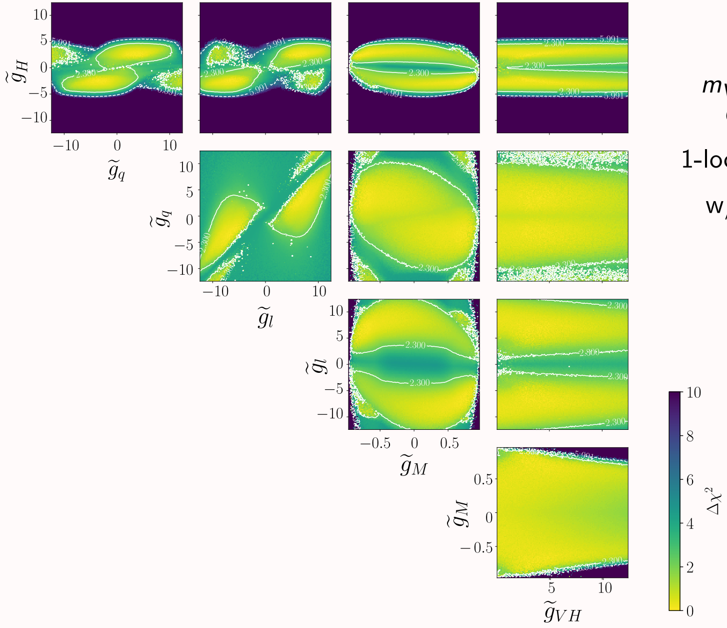
1-loop matching

Heavy vector triplet: tree vs loop matching

PRELIMINARY



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

1-loop matching

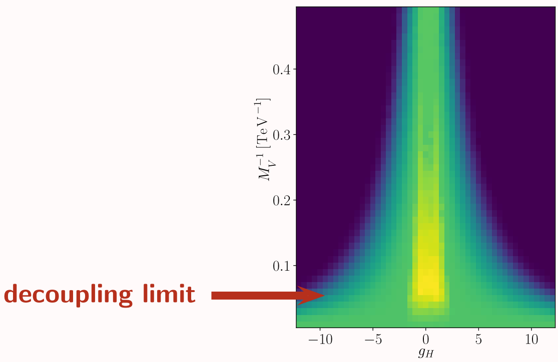
w/o EWPD

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 $\tilde{g}_i \leftrightarrow m_V$

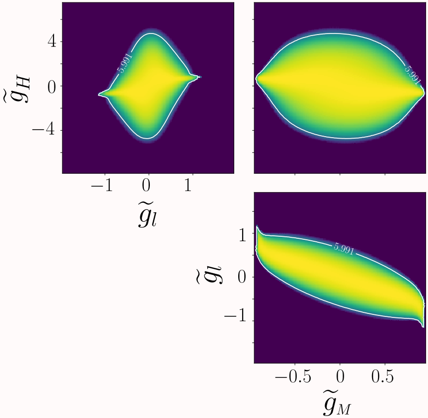
→ m_V can be a free parameter in the fit



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

Heavy vector triplet: matching scale dependence

PRELIMINARY



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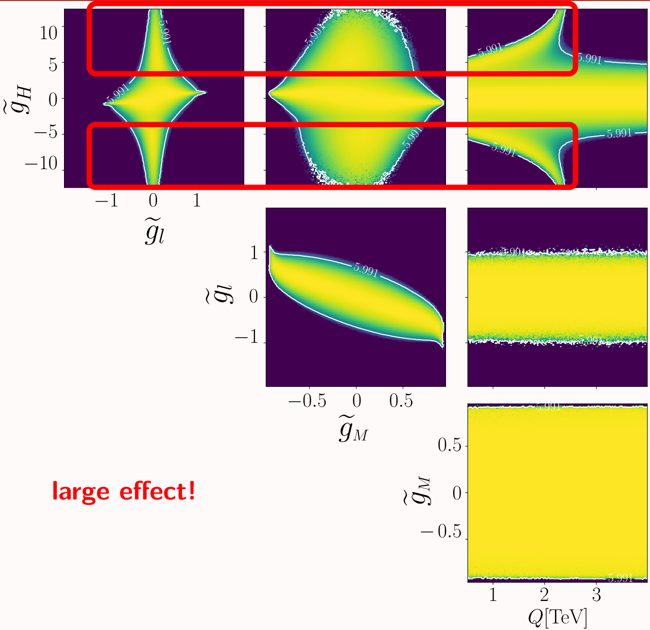
1-loop matching

Heavy vector triplet: matching scale dependence



PRELIMINARY

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

1-loop matching

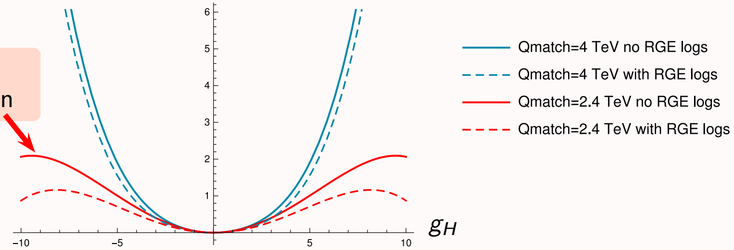
large effect!

Heavy vector triplet: matching scale dependence

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

$f_{\phi 2}$ $(1/\mathrm{TeV}^2)$ – $f_{u\phi}$ 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

$h \to WW + WW$:
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!

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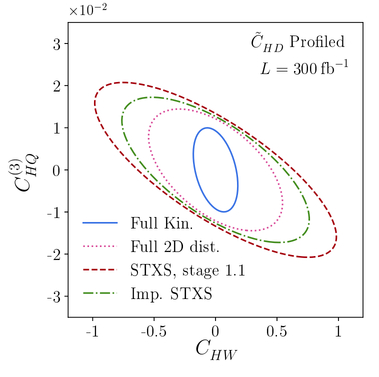

Brehmer,Dawson,Homiller,Kling, Plehn 1908.06980

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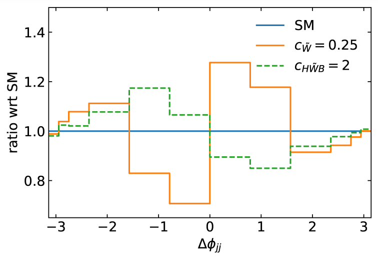

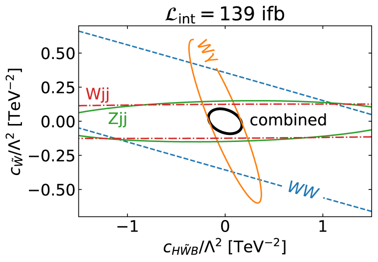

Biekötter,Gregg,Krauss,Schönherr 2102.01115

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  → single out Goldstone boson contributions
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- ...

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