SMEFT precision for global LHC fits

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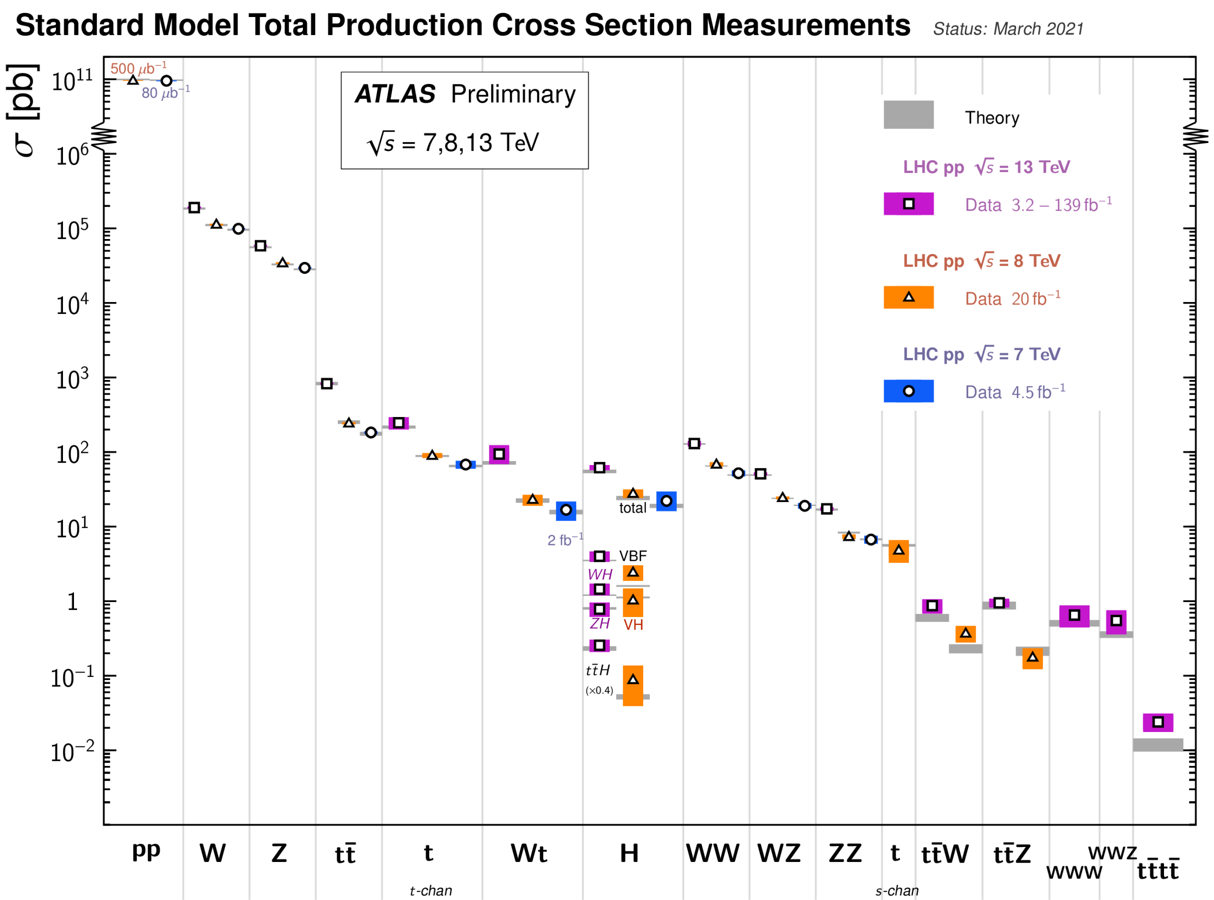
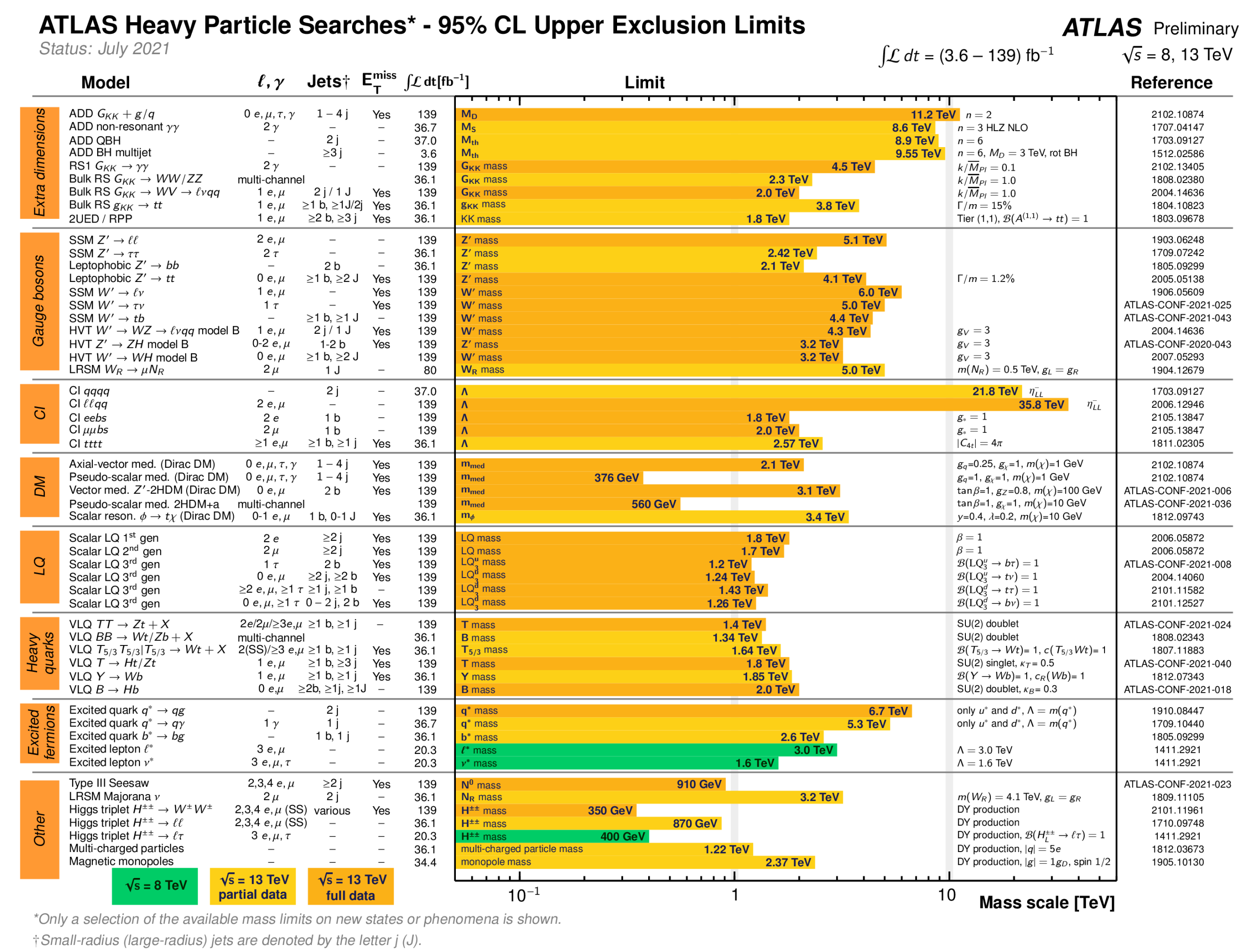
LHC: the story so far

Rediscovering the SM



Searching for the unknown



Good agreement with the SM predictions
No sign of new light particles

What can New Physics be?

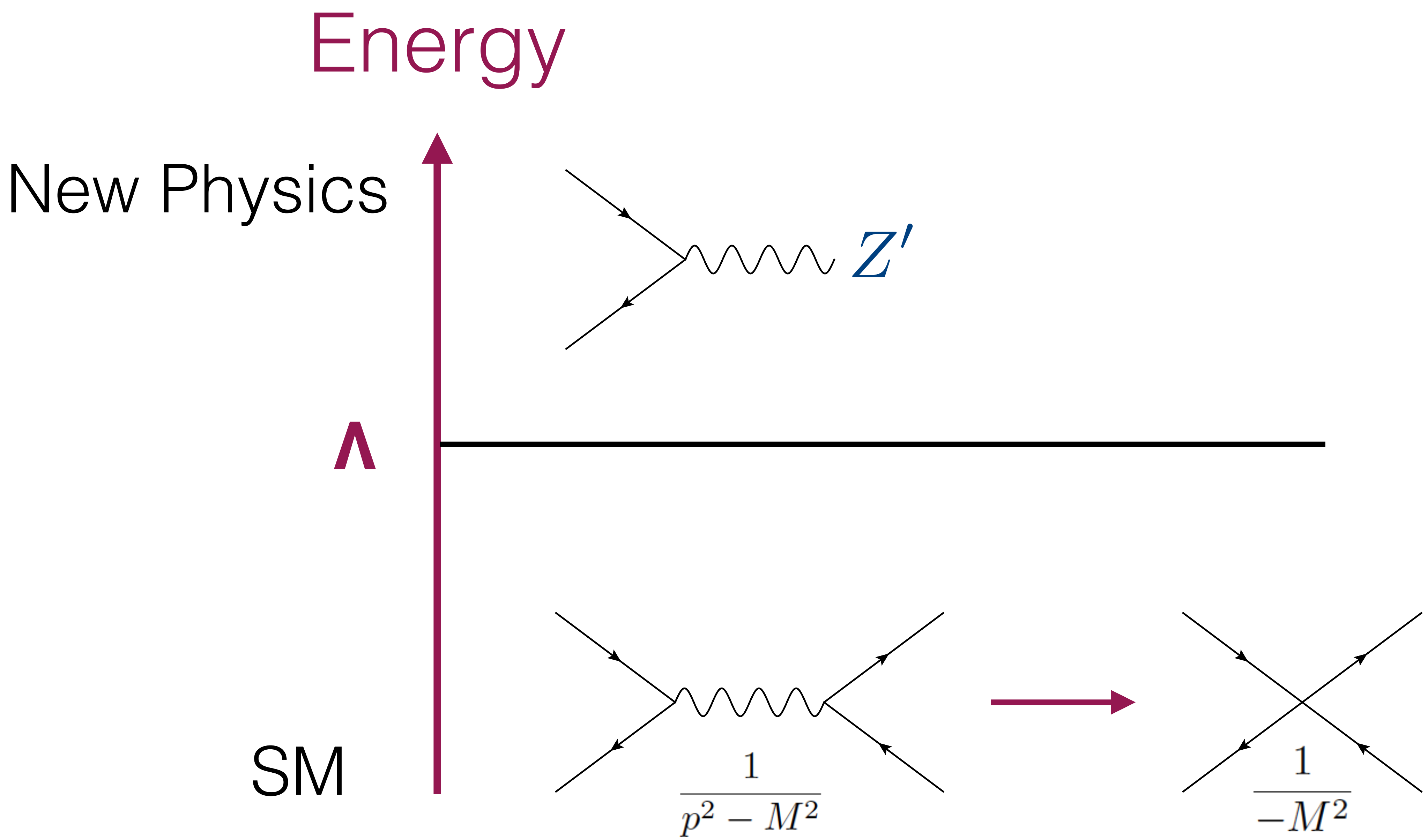
Possibilities and how to deal with them:

Weakly coupled: Small rates means that more Luminosity can help

Exotic: Need new ways to search for it, going beyond standard searches or even beyond high-energy colliders

Heavy: Not enough energy to produce it
Need indirect searches → **SMEFT opens new directions**

SMEFT: What is it all about?

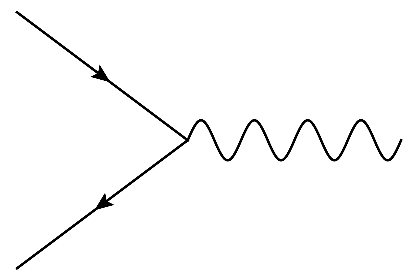


$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

SMEFT: What is it all about?

Energy

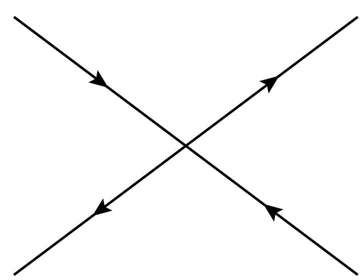
New Physics



$$\mathcal{L}(\phi, Z')$$

Λ~M

SM

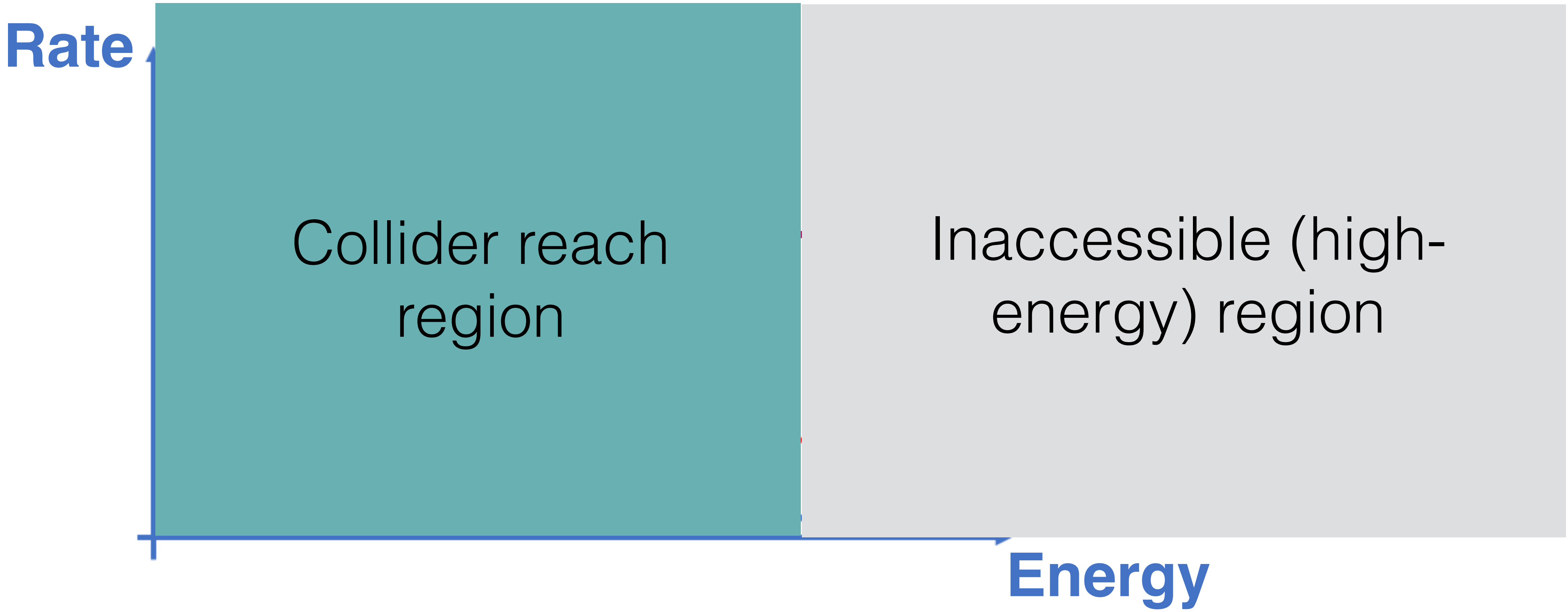


$$\frac{1}{-M^2}$$

$$\mathcal{L}_{SM}(\phi) + \mathcal{L}_{dim6}(\phi) + \ldots$$

$$\mathcal{L}_{dim6} = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

How to find new physics with EFT?



Effective Field Theory (EFT): The way to probe New Physics beyond the direct collider energy reach

Effective Field Theory

Energy

UV physics (heavy particles) $\mathcal{L}_{NP}(\phi, \underbrace{\boldsymbol{Z', X, Q, S}}_{\textbf{new}} \dots)$

Λ

Effective Field Theory $\mathcal{L}_{SM}(\phi) \boxed{+ \mathcal{L}_{dim6}(\phi)} + \dots$

Standard Model $\mathcal{L}_{SM}(\phi)$

Effective Field Theory reveals high energy physics through precise measurements at low energy.

SMEFT basics

New Interactions of SM particles

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

dim-6: 59 operators

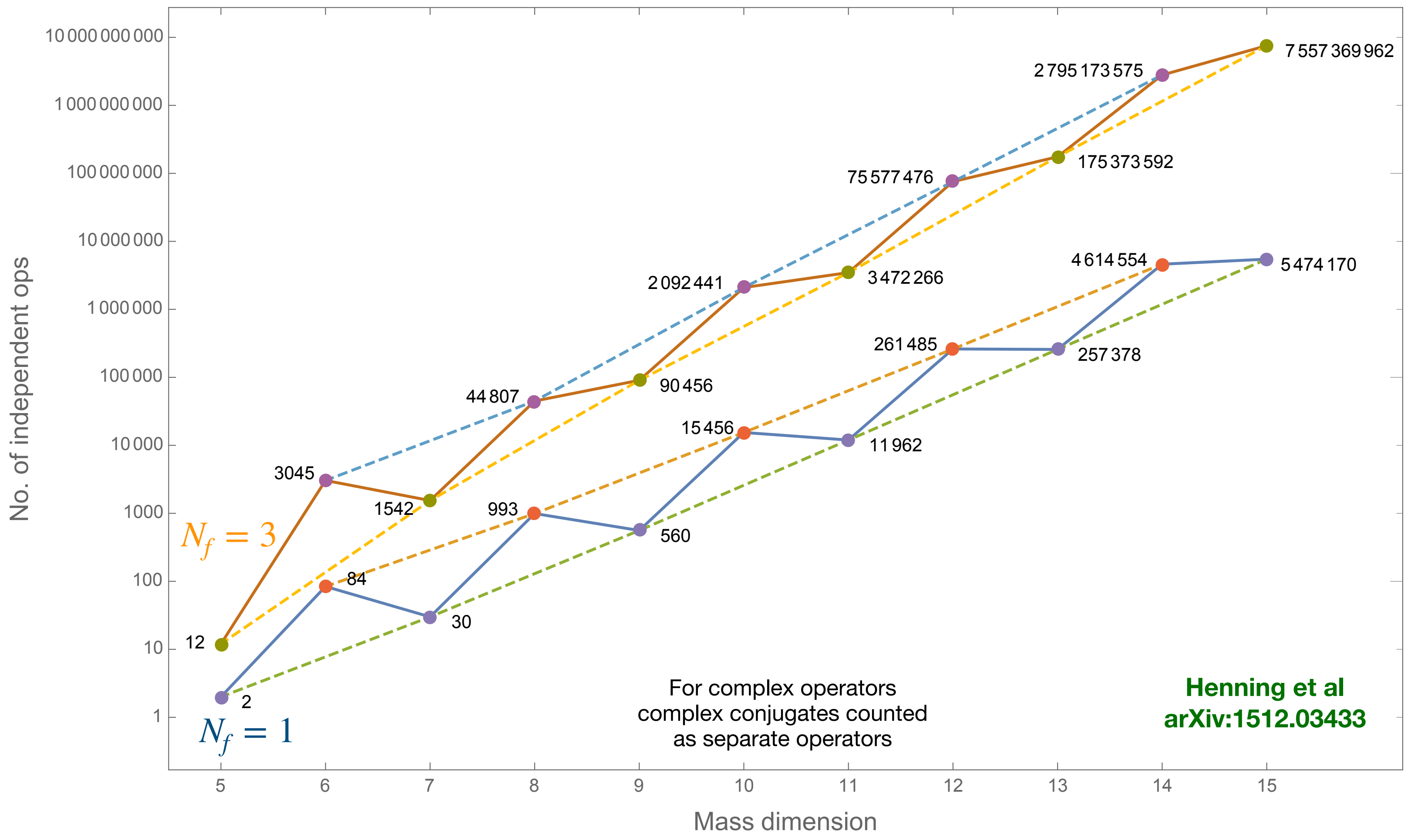
Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arXiv: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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

SMEFT@higher dimensions



Dimension-7 Lehman arXiv: 1410.4193

Dimension-8 Li et al arXiv: 2005.00008

Dimension-9 Li et al arXiv: 2012.09188

Code to generate a basis (non-redundant set) at arbitrary dimension in SMEFT:

Li et al arXiv:2201.04639

Let's take a tour of SMEFT

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$ → Processes and observables

→ Sensitivity → Measurements → Constraints → UV

Huge effort to improve each one of these steps!

EFT pathway to New Physics

$$\Delta\text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2}\sum_i c_i^6(\mu)\, a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise EFT predictions

Precise SM predictions

Precise experimental measurements

SMEFT@dim6

59 operators in flavour universal scenario

2499 if fully general

Is there any hope?

- Not all operators enter in all observables
- Many observables available
- We can make “reasonable” assumptions

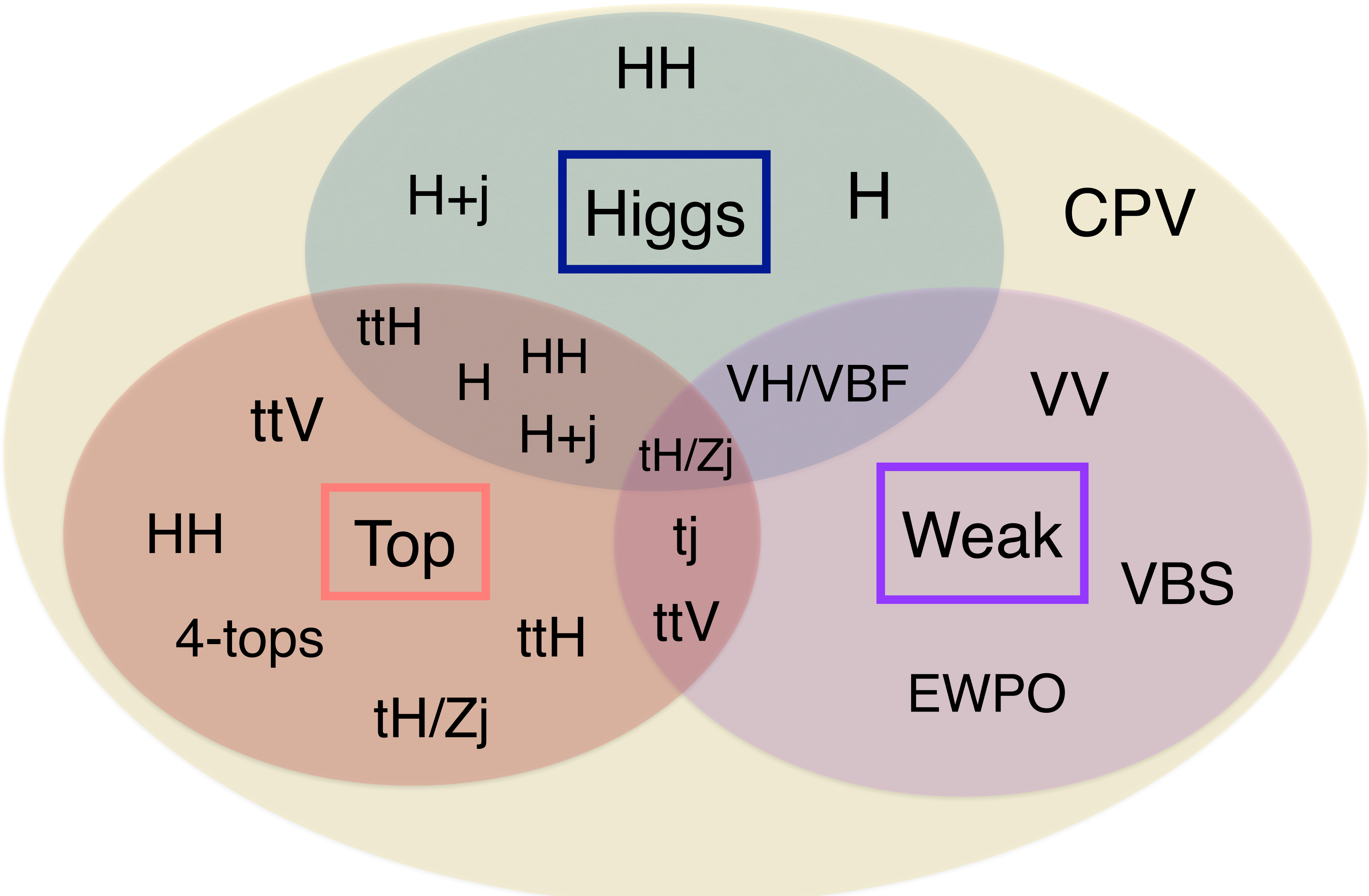
no B,L violation

Flavour (universality, MFV)

CP conservation

<100 operators for the LHC

Global nature of EFT



Adapted from K. Mimasu

Examples of operators

Dimension-6 operators of the SMEFT:

Class	Example	Interaction	Impact
X^3	$\epsilon_{IJK} W^I_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$	gauge boson self-coupling	diboson
H^6	$(\varphi^\dagger \varphi)^3$	Higgs potential, self-coupling	di-Higgs
$\psi^2 H^3$	$(\varphi^\dagger \varphi)\ (\bar{q}_i\, u_j\, \tilde{\varphi})$	Higgs-fermion (Yukawa)	ttH, H→bb
$\psi^2 H^2 D$	$(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{q}_i\, \gamma^\mu\, q_j)$	gauge-fermion (Z,W)	Z,W production
$X^2 H^2$	$(\varphi^\dagger \varphi)\ G^a_{\mu\nu} G^{\mu\nu}_a$	gauge-Higgs	ggH, H→VV
$H^4 D^2$	$(\varphi^\dagger\, D^\mu \varphi)^* (\varphi^\dagger\, D^\mu \varphi)$	Higgs-Z	m_Z (LEP)
$\psi^2 X H$	$(\bar{q}_i\, \sigma^{\mu\nu}\, u_j\, \tilde{\varphi}) B_{\mu\nu}$	dipole	ffV, ffVH
ψ^4	$(\bar{q}_i\, \gamma^\mu\, q_j)(\bar{q}_k\, \gamma_\mu\, q_l)$	four fermion	ffff scattering

Aspects of EFT predictions

* Higher Orders in $1/\Lambda^4$
  * squared dim-6 contributions
  * double insertions of dim-6
  * dim-8 contributions
* Higher Orders in QCD and EW
  * EFT is a QFT, renormalisable order-by order in $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$

Application: Top quark and SMEFT

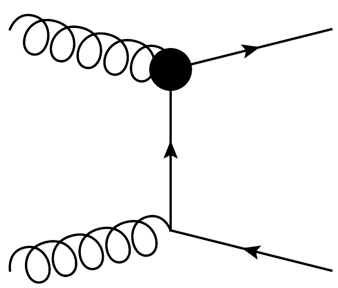
Why study the top quark ?

1. Heaviest known particle: Strong coupling to the Higgs
2. Portal to new physics: e.g. EWSB, composite Higgs
3. LHC is a top factory: precise access to top properties through a lot of production channels

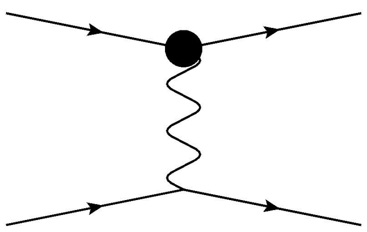
Tops at the LHC

Rich phenomenology:

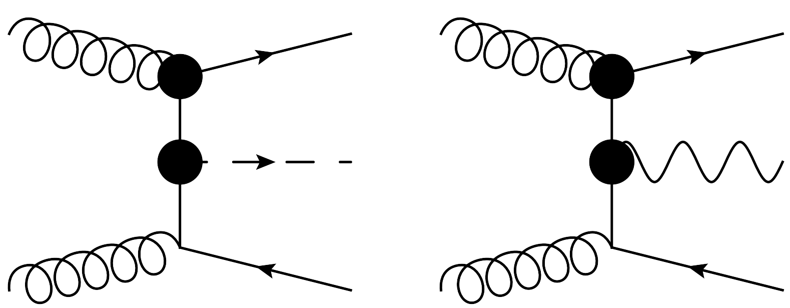
pair production



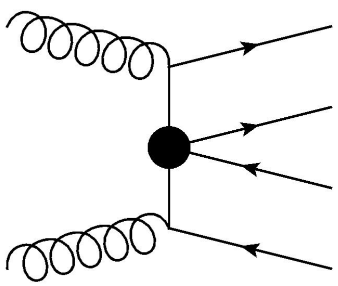
single



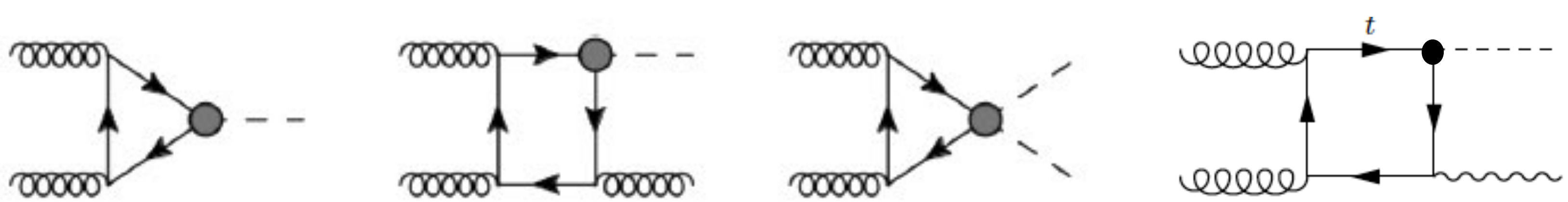
associated production



4 tops



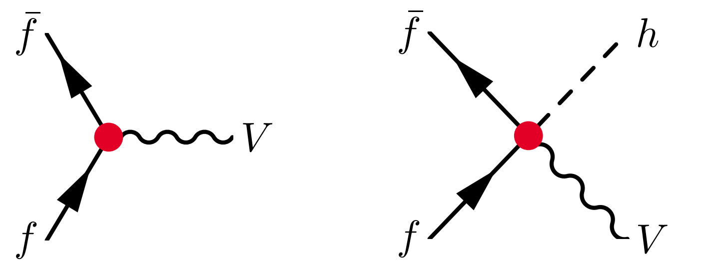
top loops



connection to Higgs physics

Operator map

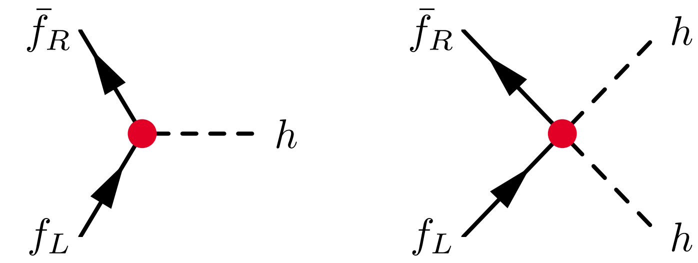
currents $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$



$C_{\phi f}$

- Shift SM $f\bar{f}V$ couplings
- $f\bar{f}Vh$ contact interactions

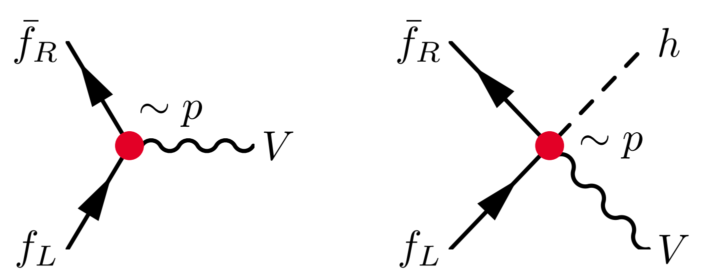
Yukawa $(\bar{q}\, t\, \tilde{\varphi})(\varphi^\dagger \varphi)$



$C_{t\phi}$

- Decouple m_t & y_t
- $t\bar{t}hh(h)$ contact interactions

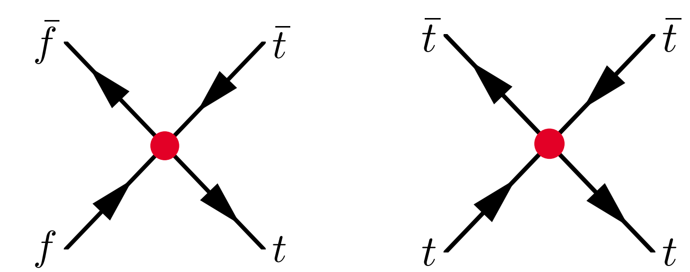
dipole $(\bar{q}\, \sigma_{\mu\nu}\, t\, \tilde{\varphi})V^{\mu\nu}$



C_{tV}

- Chirality flipping $f\bar{f}V$ couplings
- $f\bar{f}V(V)h$ contact interactions
- W, B & G fields

4 fermion $(\bar{q}\gamma_\mu q)(\bar{Q}\gamma^\mu Q)$



C_{ft}

- Contact interactions
- 2-heavy-2-light or 4-heavy
- Numerous (~O(20) w/ top)

From K. Mimasu

How to look for top operators?

$$O^{(3)}_{\varphi Q} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

$$O^{(1)}_{\varphi Q} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

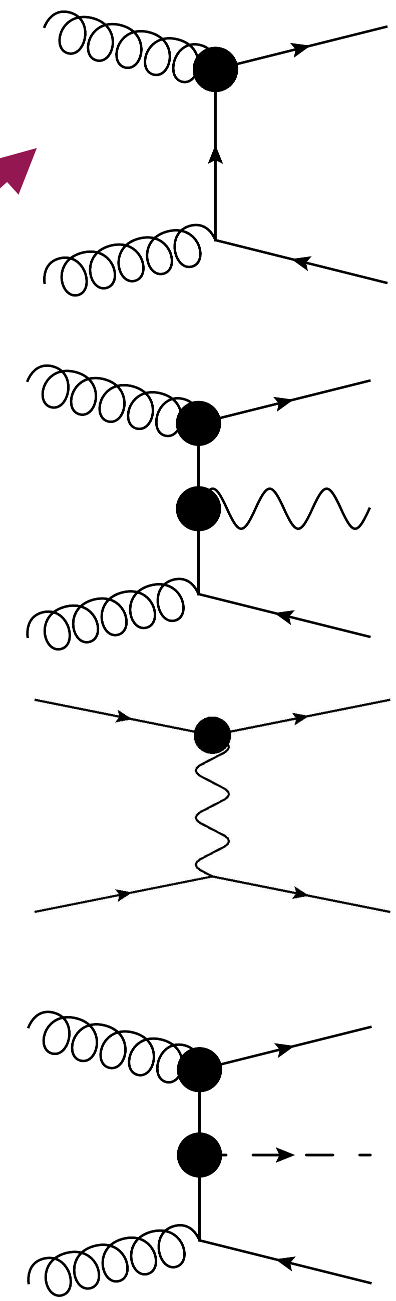
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

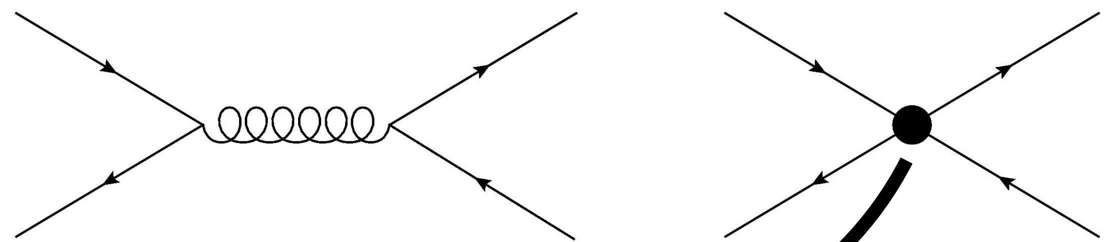
$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$



see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

Operators entering various processes: Global approach needed

EFT in top pair production



Cross-section

4-fermion operators

$$
\begin{aligned}
O_{Qq}^{1,8} &= (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i) & O_{Qq}^{1,1} &= (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i) \\
O_{Qq}^{3,8} &= (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i) & O_{Qq}^{3,1} &= (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i) \\
O_{tu}^{8} &= (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i) & O_{tu}^{1} &= (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i) \\
O_{td}^{8} &= (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i) & O_{td}^{1} &= (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)\ ; \\
O_{Qu}^{8} &= (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i) & O_{Qu}^{1} &= (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i) \\
O_{Qd}^{8} &= (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i) & O_{Qd}^{1} &= (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i) \\
O_{tq}^{8} &= (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t) & O_{tq}^{1} &= (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)\ ;
\end{aligned}
$$

Octets Singlets

Different chiralities and colour structures

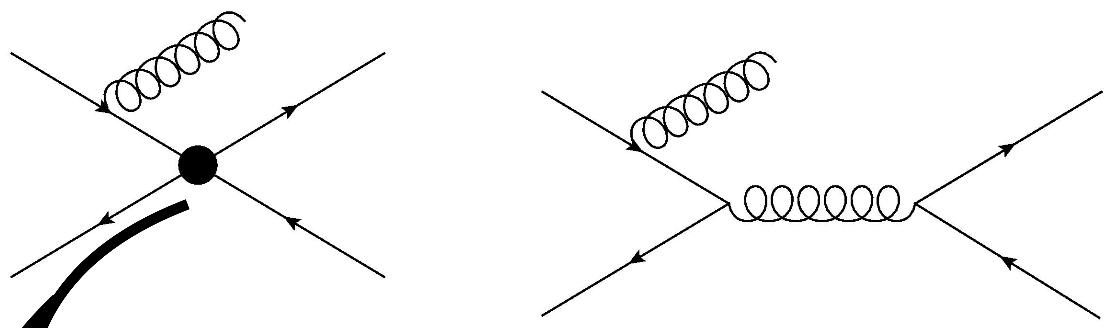
c_t	$\mathcal{O}(\Lambda^{-2})$ LO	NLO	
c_{tu}^{8}	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$	
c_{td}^{8}	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$	
c_{tq}^{8}	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$	
c_{Qu}^{8}	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$	
c_{Qd}^{8}	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$	
$c_{Qq}^{8,1}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$	
$c_{Qq}^{8,3}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$	
c_{tu}^{1}	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$	$[0.41^{+13\%}_{-17\%}]$
c_{td}^{1}	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$	$[-0.15^{+10\%}_{-13\%}]$
c_{tq}^{1}	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$	$[0.50^{+3\%}_{-2\%}]$
c_{Qu}^{1}	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$	$[0.57^{+6\%}_{-5\%}]$
c_{Qd}^{1}	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$	$[-0.19^{+6\%}_{-5\%}]$
$c_{Qq}^{1,1}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$	$[0.39^{+9\%}_{-12\%}]$
$c_{Qq}^{1,3}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$	$[1.05^{+17\%}_{-22\%}]$

Interesting interference patterns

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

New observables in $t\bar{t}$

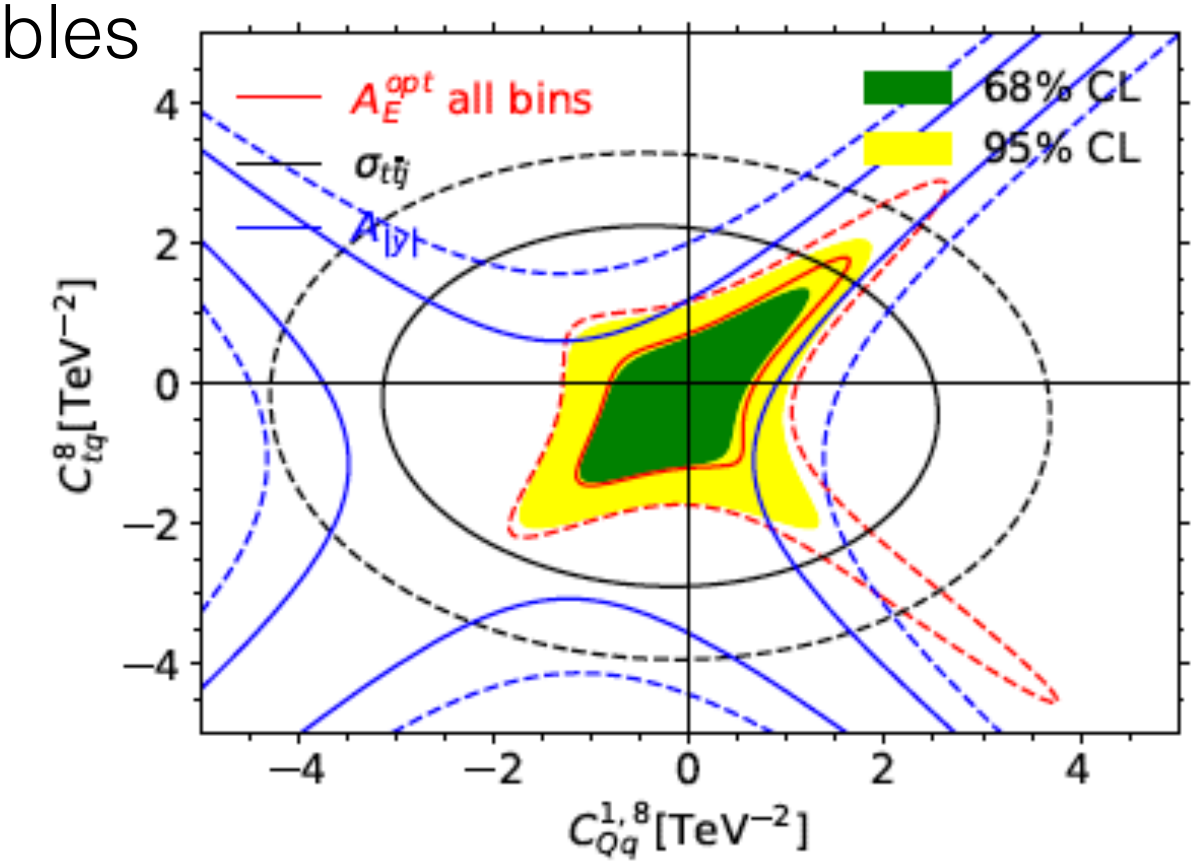
LHC can probe more sensitive observables



$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$

$$O_{tq}^{8} = (\bar{t}\gamma_\mu T^A t)(\bar{q}_i \gamma^\mu T^A q_i)$$

Different top chiralities



Basan, Berta, Masetti, EV, Westhoff arXiv:2001.07225

An asymmetry observable

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$

Optimised sensitivity
Broken degeneracies

How to compute these results?

Computing tools for SMEFT: SMEFT@NLO

Automated one-loop computations in the SMEFT

Céline Degrande,[1,*] Gauthier Durieux,[2,†] Fabio Maltoni,[1,3,‡]
Ken Mimasu,[1,§] Eleni Vryonidou,[4,¶] and Cen Zhang[5,6,**]

We present the automation of one-loop computations in the standard-model effective field theory at dimension six. Our implementation, dubbed SMEFT@NLO, contains ultraviolet and rational counterterms for bosonic, two- and four-fermion operators. It presently allows for fully differential predictions, possibly matched to parton shower, up to one-loop accuracy in QCD. We illustrate the potential of the implementation with novel loop-induced and next-to-leading order computations relevant for top-quark, electroweak, and Higgs-boson phenomenology at the LHC and future colliders.

Standard Model Effective Theory at One-Loop in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang, arXiv:2008.11743

The implementation is based on the Warsaw basis of dimension-six SMEFT operators, after canonical normalization. Electroweak input parameters are taken to be G_F, M_Z, M_W. The CKM matrix is approximated as a unit matrix, and a $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$ flavor symmetry is enforced. It forbids all fermion masses and Yukawa couplings except that only of the top quark. The model therefore implements the five-flavor scheme for PDFs.

A new coupling order, `NP=2`, is assigned to SMEFT interactions. The cutoff scale `Lambda` takes a default value of 1 TeV^{-2} and can be modified along with the Wilson coefficients in the `param_card`. Operators definitions, normalisations and coefficient names in the UFO model are specified in definitions.pdf. The notations and normalizations of top-quark operator coefficients comply with the LHC TOP WG standards of 1802.07237. Note however that the flavor symmetry enforced here is slightly more restrictive than the baseline assumption there (see the dim6top page for more information). This model has been validated at tree level against the `dim6top` implementation (see 1906.12310 and the comparison details).

Current implementation

UFO model: SMEFTatNLO_v1.0.tar.gz

- 2020/08/24 - v1.0: Official release including notably four-quark operators at NLO.

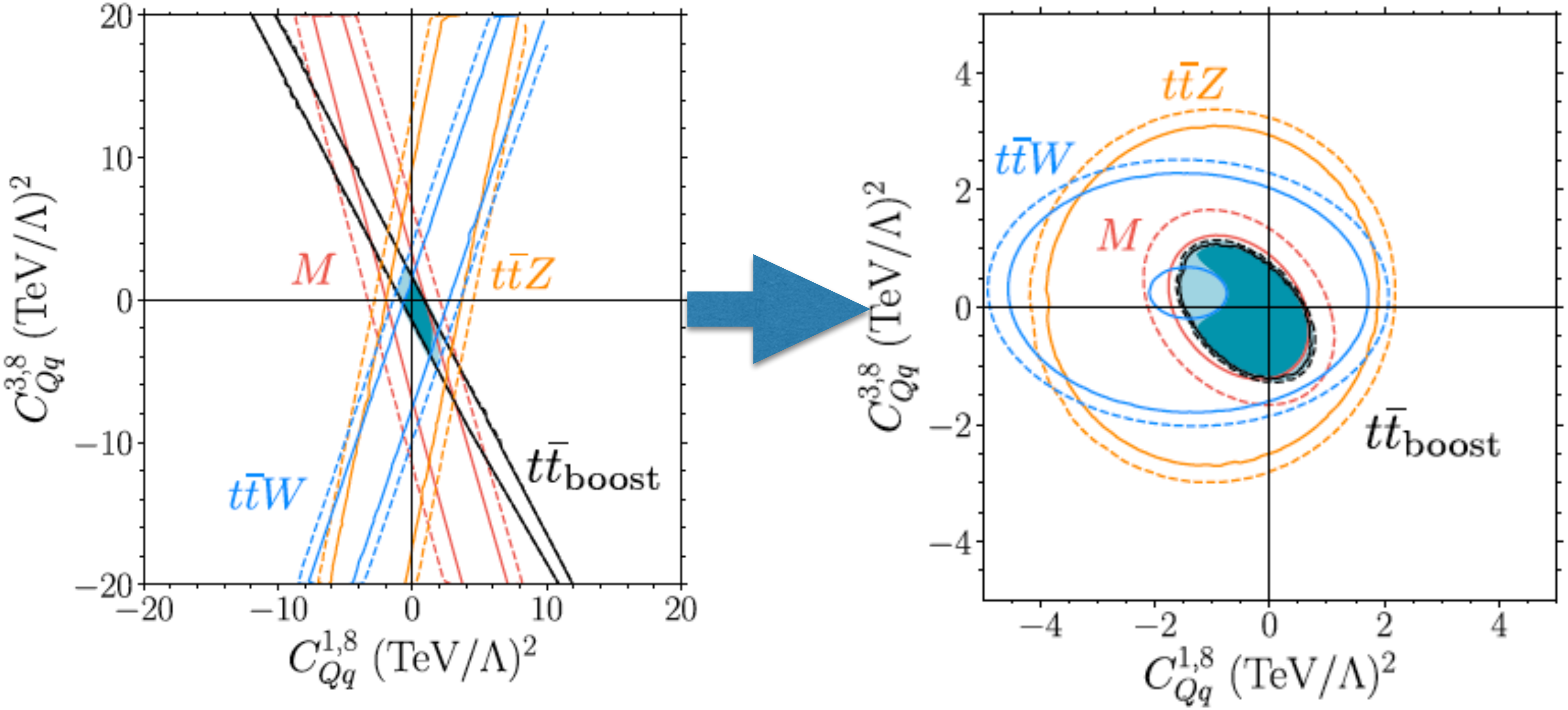
Support

Please direct any questions to smeftatnlo-dev**[at]**cern**[dot]**ch.

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

Probing top operators



Linear

Quadratic

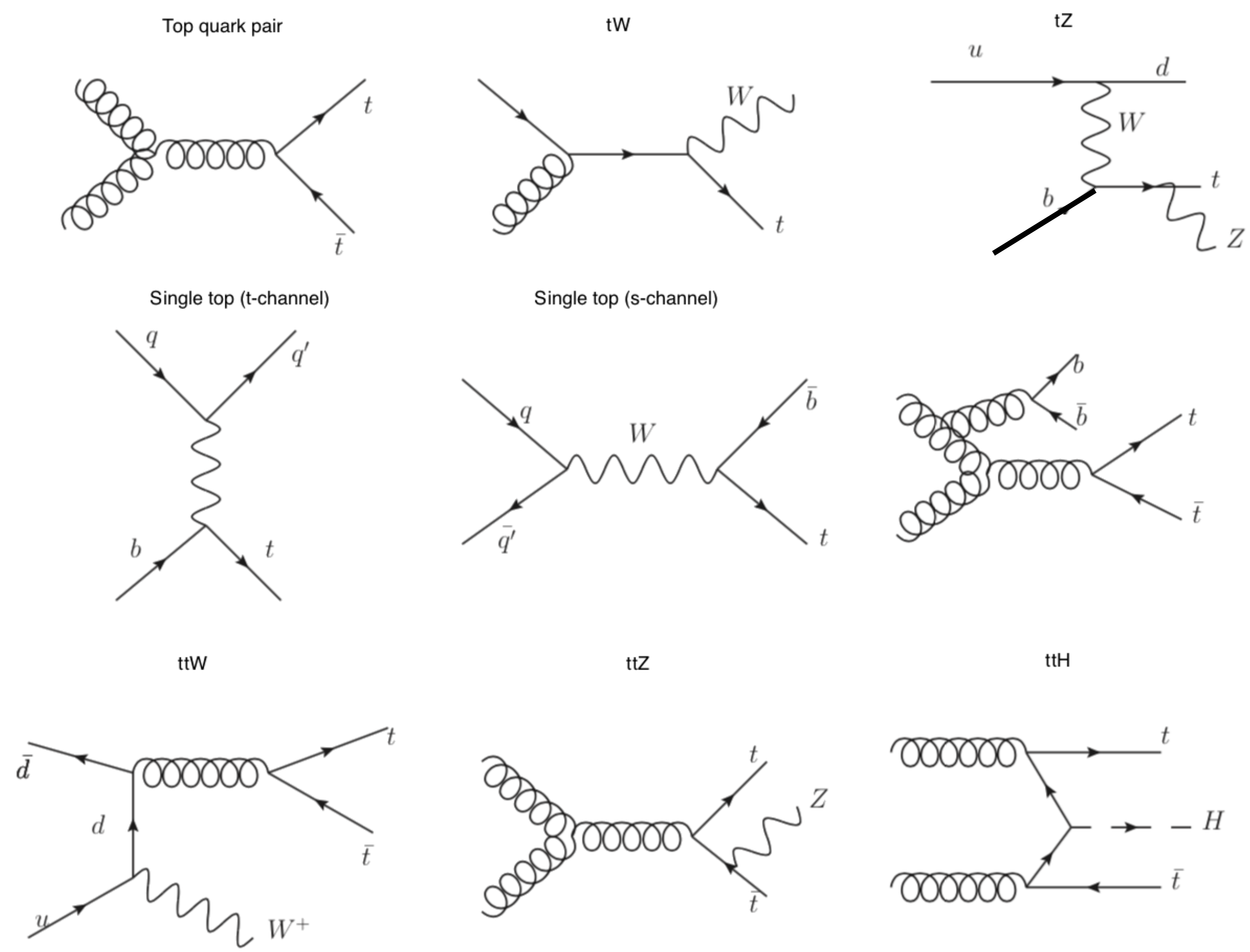
$$O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i)$$
$$O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i)$$

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

A global top fit

Class	Notation	Degree of Freedom	Operator Definition
$QQQQ$	OQQ1	c^{1}_{QQ}	$2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$
	OQQ8	c^{8}_{QQ}	$8C^{3(3333)}_{qq}$
	OQt1	c^{1}_{Qt}	$C^{1(3333)}_{qu}$
	OQt8	c^{8}_{Qt}	$C^{8(3333)}_{qu}$
	OQb1	c^{1}_{Qb}	$C^{1(3333)}_{qd}$
	OQb8	c^{8}_{Qb}	$C^{8(3333)}_{qd}$
	Ott1	c^{1}_{tt}	$C^{(3333)}_{uu}$
	Otb1	c^{1}_{tb}	$C^{1(3333)}_{ud}$
	Otb8	c^{8}_{tb}	$C^{8(3333)}_{ud}$
	OQtQb1	c^{1}_{QtQb}	$C^{1(3333)}_{quqd}$
	OQtQb8	c^{8}_{QtQb}	$C^{8(3333)}_{quqd}$
$QQqq$	O81qq	$c^{1,8}_{Qq}$	$C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$
	O11qq	$c^{1,1}_{Qq}$	$C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$
	O83qq	$c^{3,8}_{Qq}$	$C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$
	O13qq	$c^{3,1}_{Qq}$	$C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$
	O8qt	c^{8}_{tq}	$C^{8(ii33)}_{qu}$
	O1qt	c^{1}_{tq}	$C^{1(ii33)}_{qu}$
	O8ut	c^{8}_{tu}	$2C^{(i33i)}_{uu}$
	O1ut	c^{1}_{tu}	$C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$
	O8qu	c^{8}_{Qu}	$C^{8(33ii)}_{qu}$
	O1qu	c^{1}_{Qu}	$C^{1(33ii)}_{qu}$
	O8dt	c^{8}_{td}	$C^{8(33ii)}_{ud}$
	O1dt	c^{1}_{td}	$C^{1(33ii)}_{ud}$
	O8qd	c^{8}_{Qd}	$C^{8(33ii)}_{qd}$
	O1qd	c^{1}_{Qd}	$C^{1(33ii)}_{qd}$
$QQ+V,G,\varphi$	OtG	c_{tG}	$\mathrm{Re}\{C^{(33)}_{uG}\}$
	OtW	c_{tW}	$\mathrm{Re}\{C^{(33)}_{uW}\}$
	ObW	c_{bW}	$\mathrm{Re}\{C^{(33)}_{dW}\}$
	OtZ	c_{tZ}	$\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$
	Off	$c_{\varphi tb}$	$\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$
	Ofq3	$c^{3}_{\varphi Q}$	$C^{3(33)}_{\varphi q}$
	OpQM	$c^{-}_{\varphi Q}$	$C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$
	Opt	$c_{\varphi t}$	$C^{(33)}_{\varphi u}$
	Otp	$c_{t\varphi}$	$\mathrm{Re}\{C^{(33)}_{u\varphi}\}$

List of operators



Rich phenomenology

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Global fit Setup

Theory

Accurate predictions for the SM and the EFT

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions

Global SMEFT fit of the top-quark sector

Faithful uncertainty estimate
Avoid under- and over-fitting
Validated on pseudo-data (closure test)

Methodology

Constraints on New Physics scale
Fit results can be used to bound specific UV complete models

Output

Top observables

Data

Top-pair production W-helicities, asymmetry

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	n_{dat}	Ref
ATLAS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	7	[46]
CMS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	10	[47]
CMS_tt2D_8TeV_dilep	**8 TeV, 20.3 fb^{-1}**	dileptons	$1/\sigma d^2\sigma/dy_{t\bar{t}}dm_{t\bar{t}}$	16	[48]
ATLAS_tt_8TeV_dilep (*)	**8 TeV, 20.3 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[54]
CMS_tt_13TeV_ljets_2015	**13 TeV, 2.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	8	[51]
CMS_tt_13TeV_dilep_2015	**13 TeV, 2.1 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[53]
CMS_tt_13TeV_ljets_2016	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	10	[52]
CMS_tt_13TeV_dilep_2016 (*)	**13 TeV, 35.8 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	7	[56]
ATLAS_tt_13TeV_ljets_2016 (*)	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	9	[55]
ATLAS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[49]
CMS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[50]
ATLAS_CMS_tt_AC_8TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	6	[57]
ATLAS_tt_AC_13TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	5	[58]

Single top t-, s-channel

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	N_{dat}	Ref
CMS_t_tch_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	t-channel	$\sigma_{\mathrm{tot}}(t), \sigma_{\mathrm{tot}}(\bar{t})$	2	[83]
ATLAS_t_tch_8TeV	**8 TeV, 20.2 fb^{-1}**	t-channel	$d\sigma(tq)/dy_t$	4	[85]
CMS_t_tch_8TeV_dif	**8 TeV, 19.7 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	6	[84]
CMS_t_sch_8TeV	**8 TeV, 19.7 fb^{-1}**	s-channel	$\sigma_{\mathrm{tot}}(t+\bar{t})$	1	[87]
ATLAS_t_sch_8TeV	**8 TeV, 20.3 fb^{-1}**	s-channel	$\sigma_{\mathrm{tot}}(t+\bar{t})$	1	[86]
ATLAS_t_tch_13TeV	**13 TeV, 3.2 fb^{-1}**	t-channel	$\sigma_{\mathrm{tot}}(t), \sigma_{\mathrm{tot}}(\bar{t})$	2	[88]
CMS_t_tch_13TeV_inc	**13 TeV, 2.2 fb^{-1}**	t-channel	$\sigma_{\mathrm{tot}}(t), \sigma_{\mathrm{tot}}(\bar{t})$	2	[90]
CMS_t_tch_13TeV_dif	**13 TeV, 2.3 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	4	[89]
CMS_t_tch_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t)}\rvert$	5	[91]

4 tops, ttbb, top-pair associated production

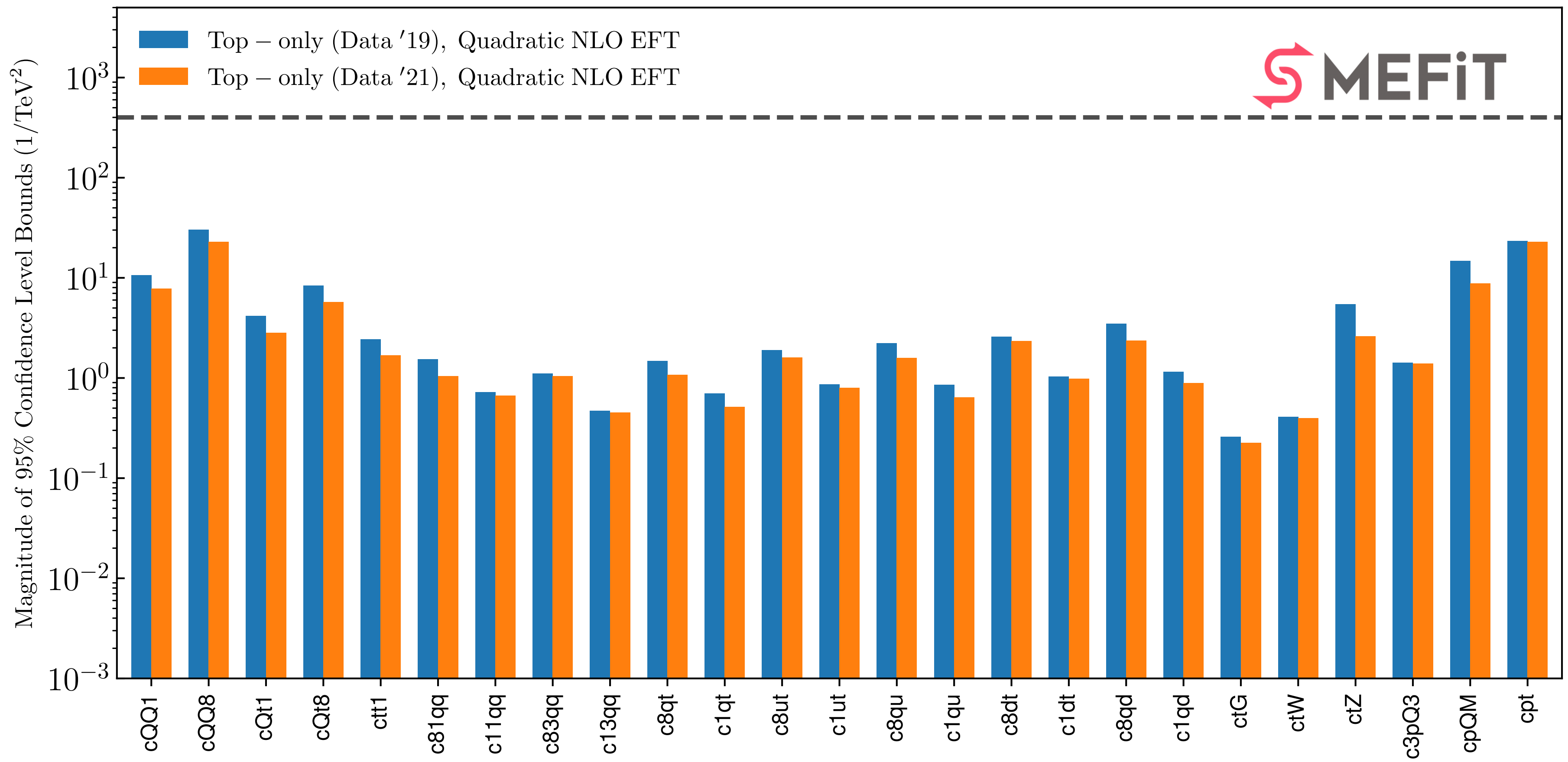
Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	N_{dat}	Ref
CMS_ttbb_13TeV	**13 TeV, 2.3 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}b\bar{b})$	1	[70]
CMS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}b\bar{b})$	1	[79]
ATLAS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}b\bar{b})$	1	[78]
CMS_tttt_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}t\bar{t})$	1	[71]
CMS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}t\bar{t})$	1	[76]
ATLAS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}t\bar{t})$	1	[77]
CMS_ttZ_8TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}Z)$	1	[72]
CMS_ttZ_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}Z)$	1	[73]
CMS_ttZ_ptZ_13TeV (*)	**13 TeV, 77.5 fb^{-1}**	total xsec	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[81]
ATLAS_ttZ_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}Z)$	1	[74]
ATLAS_ttZ_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}Z)$	1	[75]
ATLAS_ttZ_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}Z)$	1	[80]
CMS_ttW_8_TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}W)$	1	[72]
CMS_ttW_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}W)$	1	[73]
ATLAS_ttW_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}W)$	1	[74]
ATLAS_ttW_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}W)$	1	[75]
ATLAS_ttW_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\mathrm{tot}}(t\bar{t}W)$	1	[80]

tW, tZ

Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	N_{dat}	Ref
ATLAS_tW_8TeV_inc	**8 TeV, 20.2 fb^{-1}**	inclusive (dilepton)	$\sigma_{\mathrm{tot}}(tW)$	1	[95]
ATLAS_tW_inc_slep_8TeV (*)	**8 TeV, 20.2 fb^{-1}**	inclusive (single lepton)	$\sigma_{\mathrm{tot}}(tW)$	1	[101]
CMS_tW_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	inclusive	$\sigma_{\mathrm{tot}}(tW)$	1	[96]
ATLAS_tW_inc_13TeV	**13 TeV, 3.2 fb^{-1}**	inclusive	$\sigma_{\mathrm{tot}}(tW)$	1	[97]
CMS_tW_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\mathrm{tot}}(tW)$	1	[98]
ATLAS_tZ_13TeV_inc	**13 TeV, 36.1 fb^{-1}**	inclusive	$\sigma_{\mathrm{tot}}(tZq)$	1	[100]
ATLAS_tZ_13TeV_run2_inc (*)	**13 TeV, 139.1 fb^{-1}**	inclusive	$\sigma_{\mathrm{fid}}(t\ell^+\ell^-q)$	1	[102]
CMS_tZ_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\mathrm{fid}}(Wb\ell^+\ell^-q)$	1	[99]
CMS_tZ_13TeV_2016_inc (*)	**13 TeV, 77.4 fb^{-1}**	inclusive	$\sigma_{\mathrm{fid}}(t\ell^+\ell^-q)$	1	[103]

Category	Processes	n_{dat}
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z$, $t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**

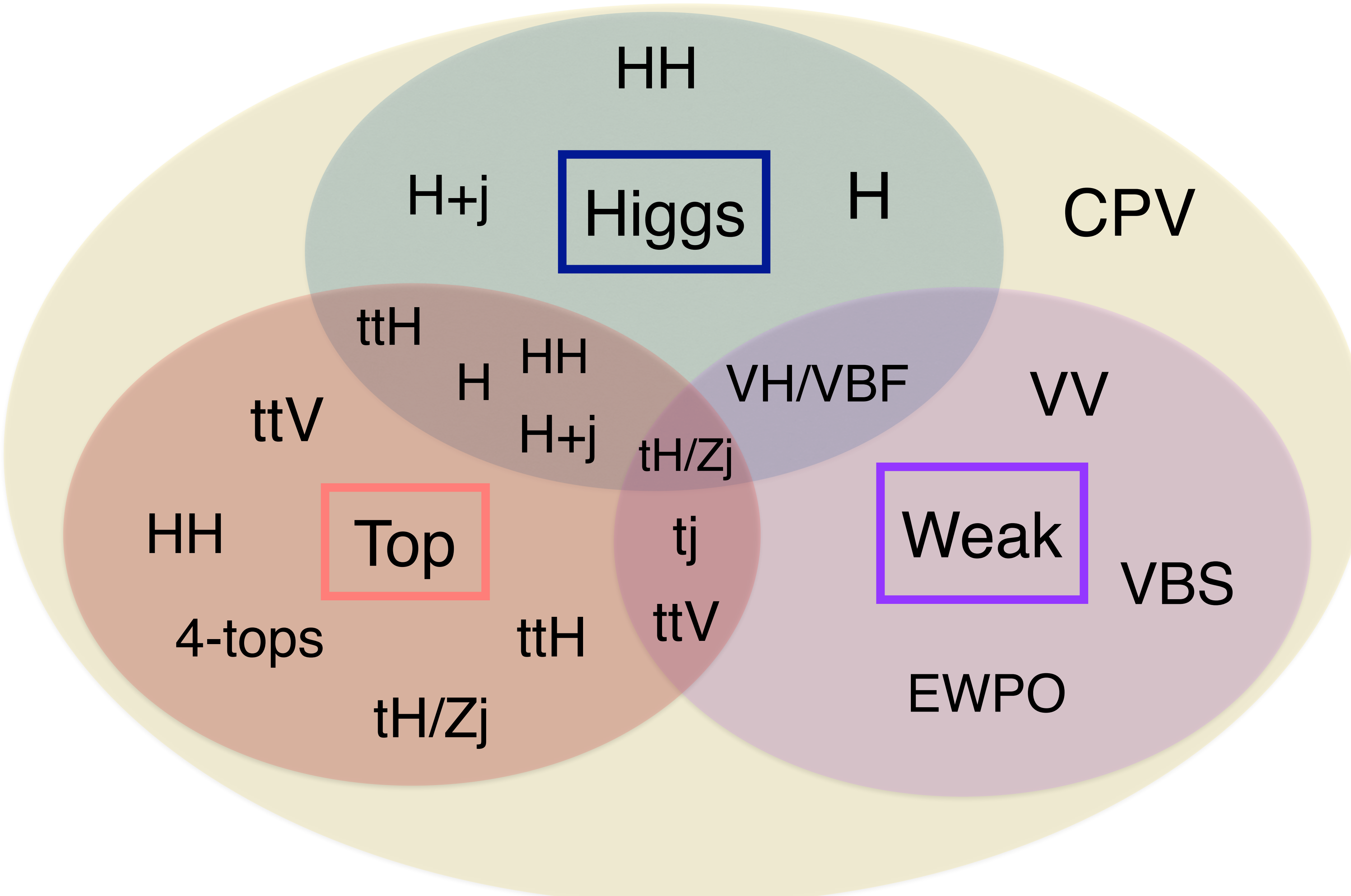
Global top fit results



Bounds vary between operators
ttZ ones and 4-heavy ones loosely constrained

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006
Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965

Global nature of EFT



Adapted from K. Mimasu

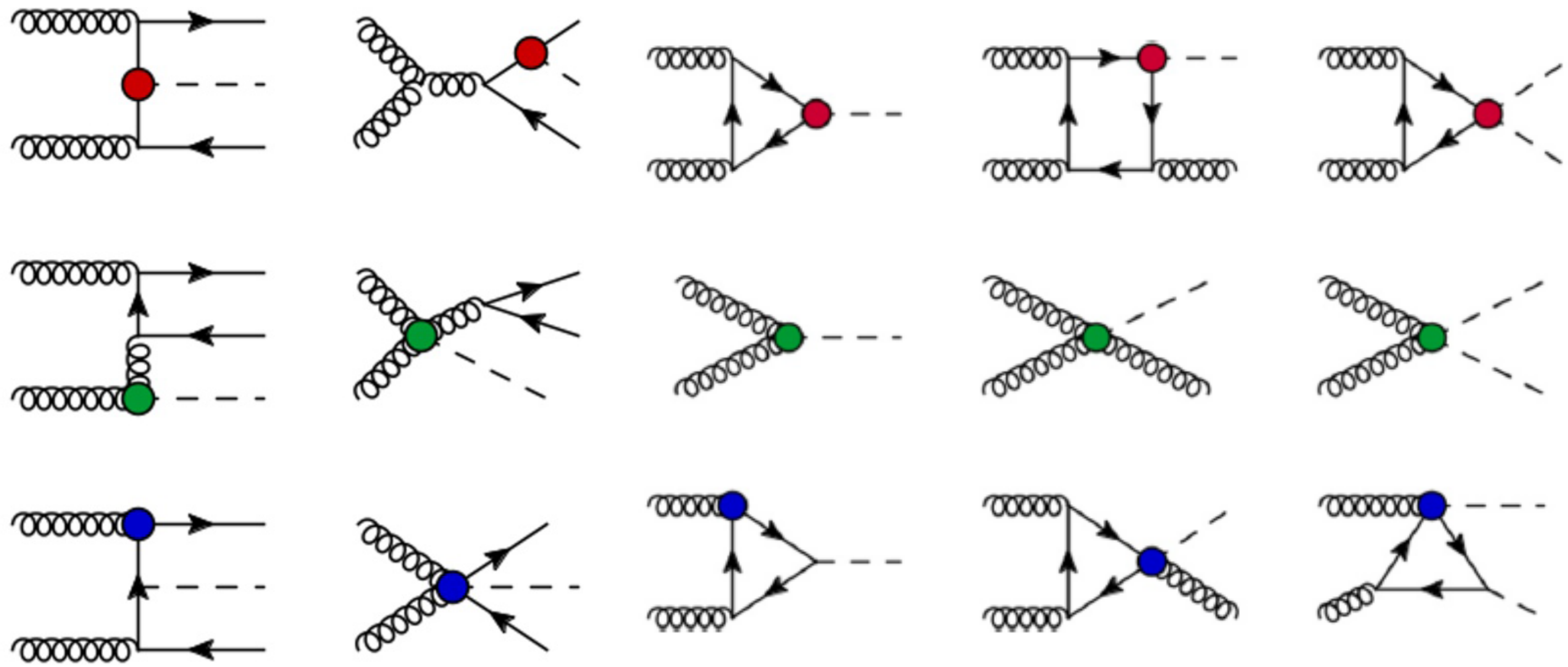
The top-Higgs interface

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi} \,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu} \,,$$

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

See also
Degrande et al. arXiv:1205.1065
Grojean et al. arXiv:1312.3317
Azatov et al arXiv:1608.00977



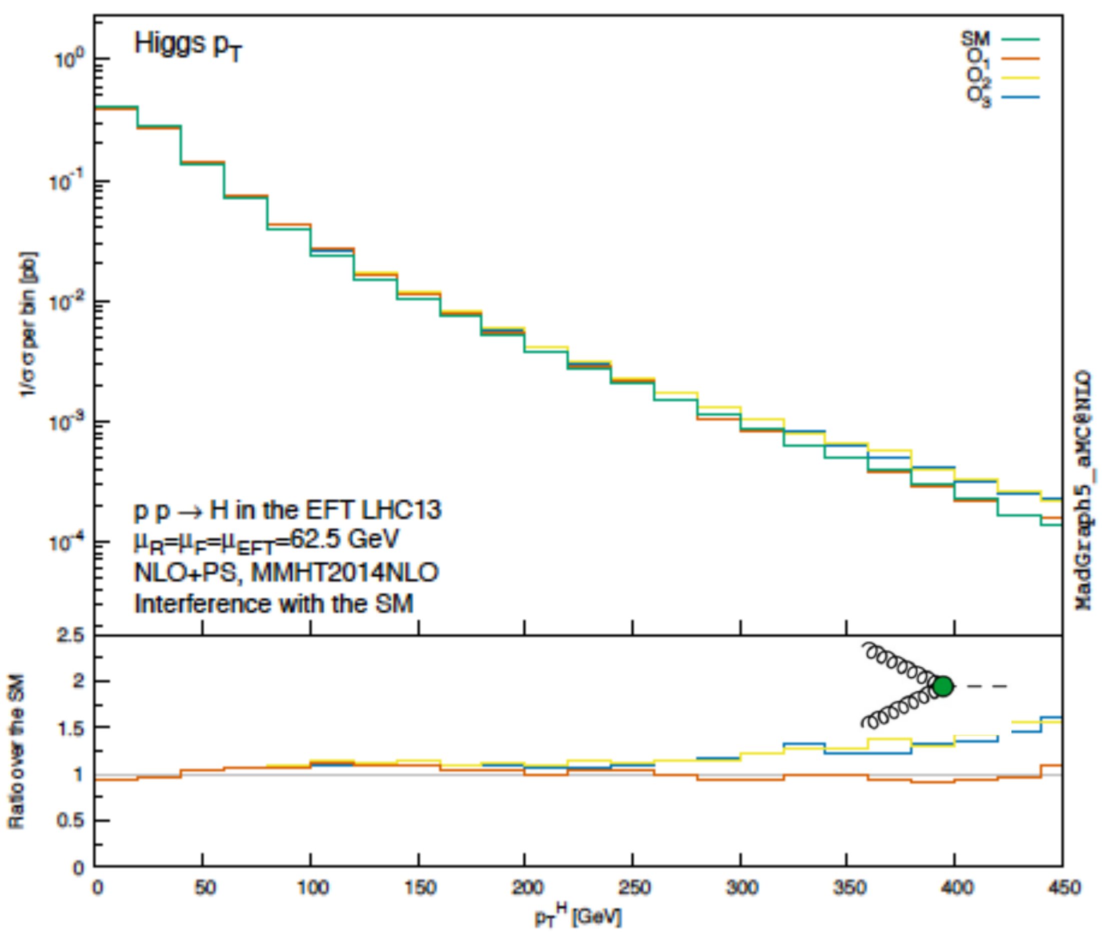
ttH

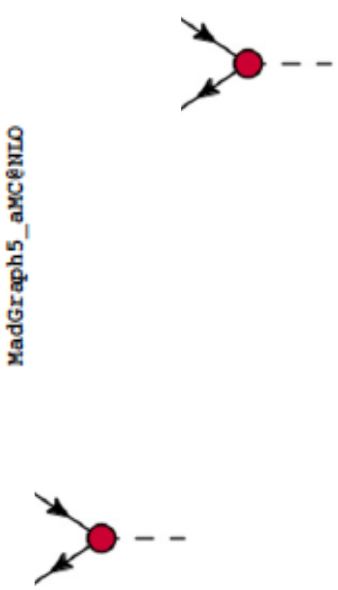
H, H+j, HH

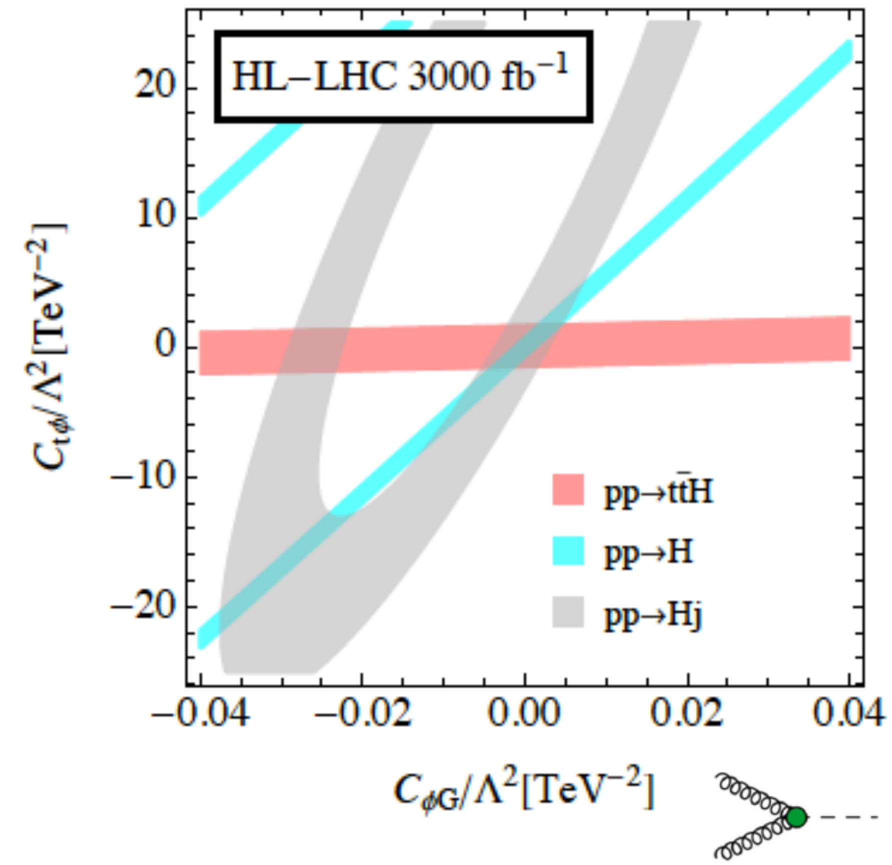
Use with 1) ttH and 2) H, H+j to break degeneracy between operators and extract maximal information on these operators

Maltoni, EV, Zhang: arXiv:1607.05330

SMEFT in Higgs production







Higgs p$_T$

14TeV projection
3000 fb^{-1}

Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

Grazzini et al 1612.00283

Extended top-Higgs interplay

Operators

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$

$$O_{\phi G} = y_t^2\left(\phi^\dagger\phi\right)G^A_{\mu\nu}G^{A\mu\nu}$$

Production process

$gg \rightarrow h$

$gg \rightarrow hj$

tth

$gg \rightarrow hh$

$gg \rightarrow hz$

thj

$gg \rightarrow ZZ$

Top-Higgs are deeply connected

Exploring the interplay further

Top EW couplings

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

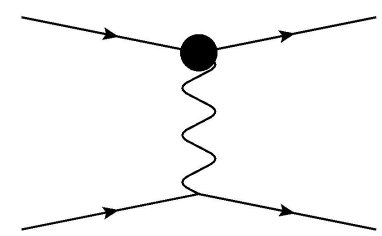
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

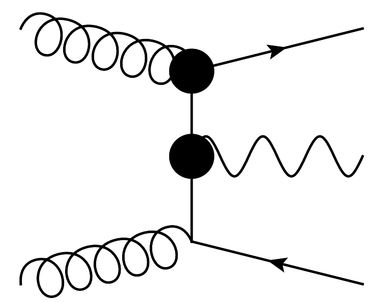
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

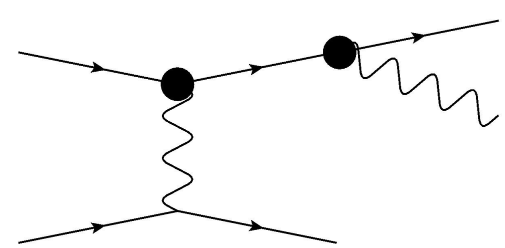
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

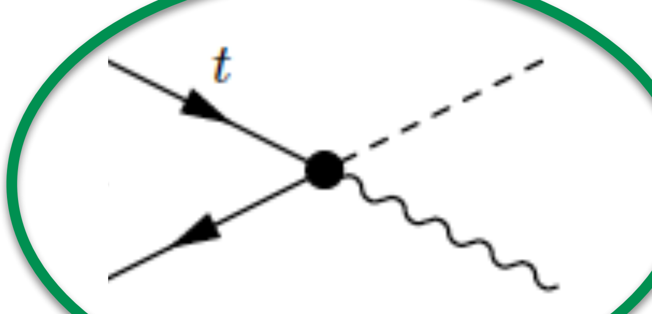
Typically searched for in







Also relevant for:



New Higgs interactions

relevant for tHj, gg>HZ gg>ZZ, H>Zγ

Aren't these unconstrained from top fits?

A clear motivation for top+Higgs fits

Adding Higgs data to a global fit

New data

Run I & 2 signal strengths (CMS+ATLAS):
gluon fusion
VH
VBF
ttH
H decays

New predictions

NLO QCD for all production
Full decay width computation
Including corrections to V widths

New operators

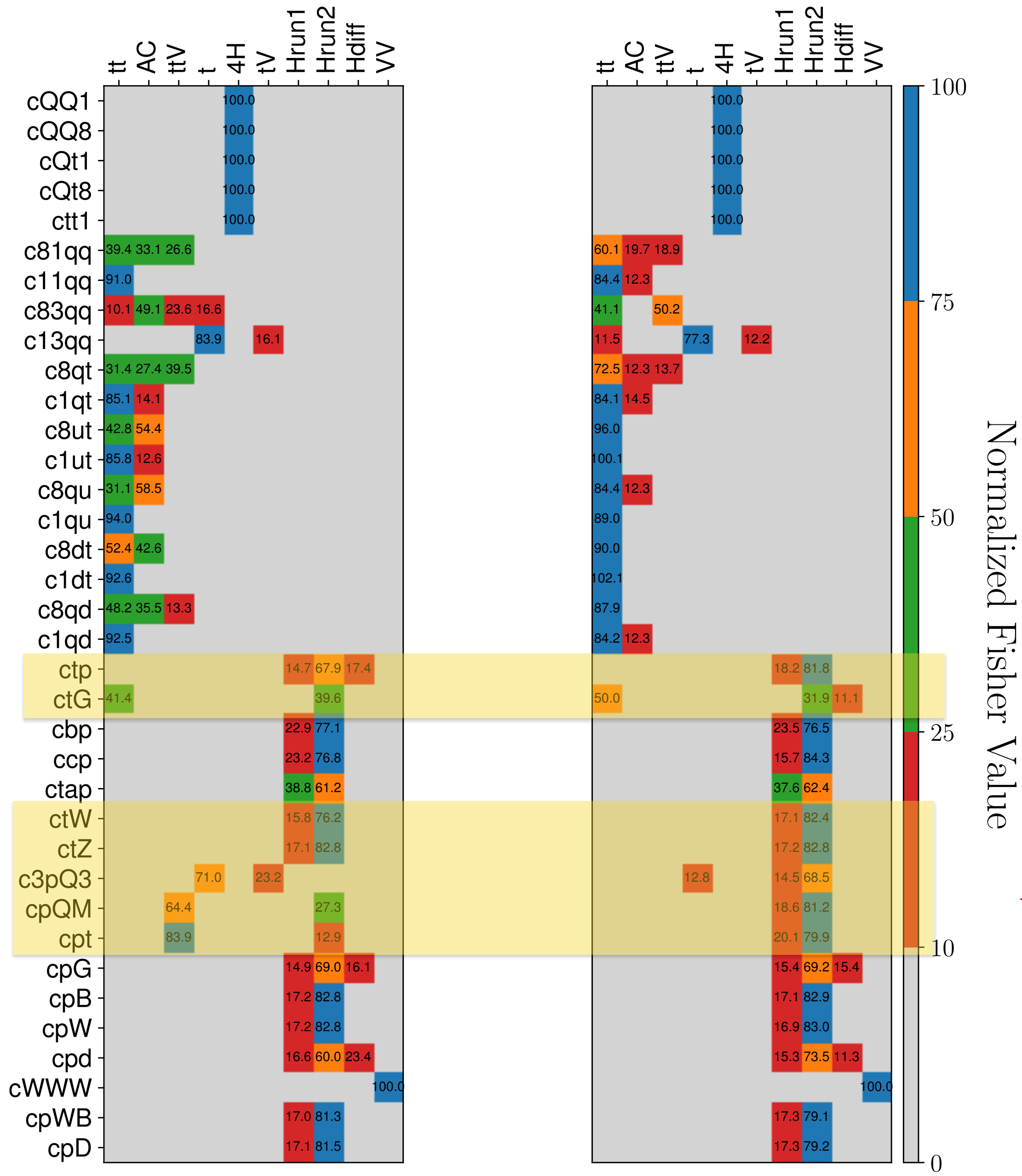
Bosonic					
$\mathcal{O}_{\phi G}$	OpG	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) G_A^{\mu\nu} G^A_{\mu\nu}$	$\mathcal{O}_{\phi B}$	OpB	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$
$\mathcal{O}_{\phi W}$	OpW	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}_{\phi WB}$	OpWB	$(\phi^\dagger\tau_I\phi)\, B^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{\phi d}$	Opd	$\partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$	$\mathcal{O}_{\phi D}$	OpD	$(\phi^\dagger D^\mu\phi)^\dagger(\phi^\dagger D_\mu\phi)$

2 Fermions					
$\mathcal{O}_{t\varphi}$	Otp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, t\, \tilde{\phi} + \text{h.c.}$	$\mathcal{O}_{tG}$	OtG	$ig_S\,(\bar{Q}\tau^{\mu\nu}\, T_A\, t)\, \tilde{\phi}\, G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{b\varphi}$	Obp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, b\, \phi + \text{h.c.}$	$\mathcal{O}_{c\varphi}$	Ocp	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, c\, \phi + \text{h.c.}$
$\mathcal{O}_{\tau\varphi}$	Otap	$\left(\phi^\dagger\phi - \frac{v^2}{2}\right)\bar{Q}\, \tau\, \tilde{\phi} + \text{h.c.}$	$\mathcal{O}_{tW}$	OtW	$i(\bar{Q}\tau^{\mu\nu}\, \tau_I\, t)\, \tilde{\phi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tB}$	-	$i(\bar{Q}\tau^{\mu\nu}\, t)\, \tilde{\phi}\, B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{tZ}$	OtZ	$-\sin\theta_W \mathcal{O}_{tB} + \cos\theta_W \mathcal{O}_{tW}$
$\mathcal{O}^{(1)}_{\varphi l_1}$	Opl1	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_1\, \gamma^\mu\, l_1)$	$\mathcal{O}^{(3)}_{\varphi l_1}$	O3pl1	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_1\, \gamma^\mu\, \tau^I l_1)$
$\mathcal{O}^{(1)}_{\varphi l_2}$	Opl2	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_2\, \gamma^\mu\, l_2)$	$\mathcal{O}^{(3)}_{\varphi l_2}$	O3pl2	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_2\, \gamma^\mu\, \tau^I l_2)$
$\mathcal{O}^{(1)}_{\varphi l_3}$	Opl3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{l}_3\, \gamma^\mu\, l_3)$	$\mathcal{O}^{(3)}_{\varphi l_3}$	O3pl3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{l}_3\, \gamma^\mu\, \tau^I l_3)$
$\mathcal{O}_{\varphi e}$	Ope	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{e}\, \gamma^\mu\, e)$	$\mathcal{O}_{\varphi\mu}$	Opmu	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{\mu}\, \gamma^\mu\, \mu)$
$\mathcal{O}_{\varphi\tau}$	Opta	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{\tau}\, \gamma^\mu\, \tau)$			
$\mathcal{O}^{(1)}_{\varphi q_i}$	-	$\sum\limits_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{q}_i\, \gamma^\mu\, q_i)$	$\mathcal{O}^{(3)}_{\varphi q_i}$	O3pq	$\sum\limits_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{q}_i\, \gamma^\mu\, \tau^I q_i)$
$\mathcal{O}^{(1)}_{\varphi Q}$	-	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{Q}\, \gamma^\mu\, Q)$	$\mathcal{O}^{(3)}_{\varphi Q}$	O3pQ3	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\phi)(\bar{Q}\, \gamma^\mu\, \tau^I Q)$
$\mathcal{O}^{(-)}_{\varphi q_i}$	OpqMi	$\mathcal{O}^{(1)}_{\varphi q_i} - \mathcal{O}^{(3)}_{\varphi q_i}$	$\mathcal{O}^{(-)}_{\varphi Q}$	OpQM	$\mathcal{O}^{(1)}_{\varphi Q} - \mathcal{O}^{(3)}_{\varphi Q}$
$\mathcal{O}_{\varphi u_i}$	Opui	$\sum\limits_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{u}_i\, \gamma^\mu\, u_i)$	$\mathcal{O}_{\varphi d_i}$	Opdi	$\sum\limits_{i=1,2} i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{d}_i\, \gamma^\mu\, d_i)$
$\mathcal{O}_{\phi t}$	Opt	$i(\phi^\dagger \overleftrightarrow{D}_\mu\, \phi)(\bar{t}\, \gamma^\mu\, t)$			
$\mathcal{O}_{ll}$	Oll	$(l\gamma_\mu l)(l\gamma^\mu l)$			

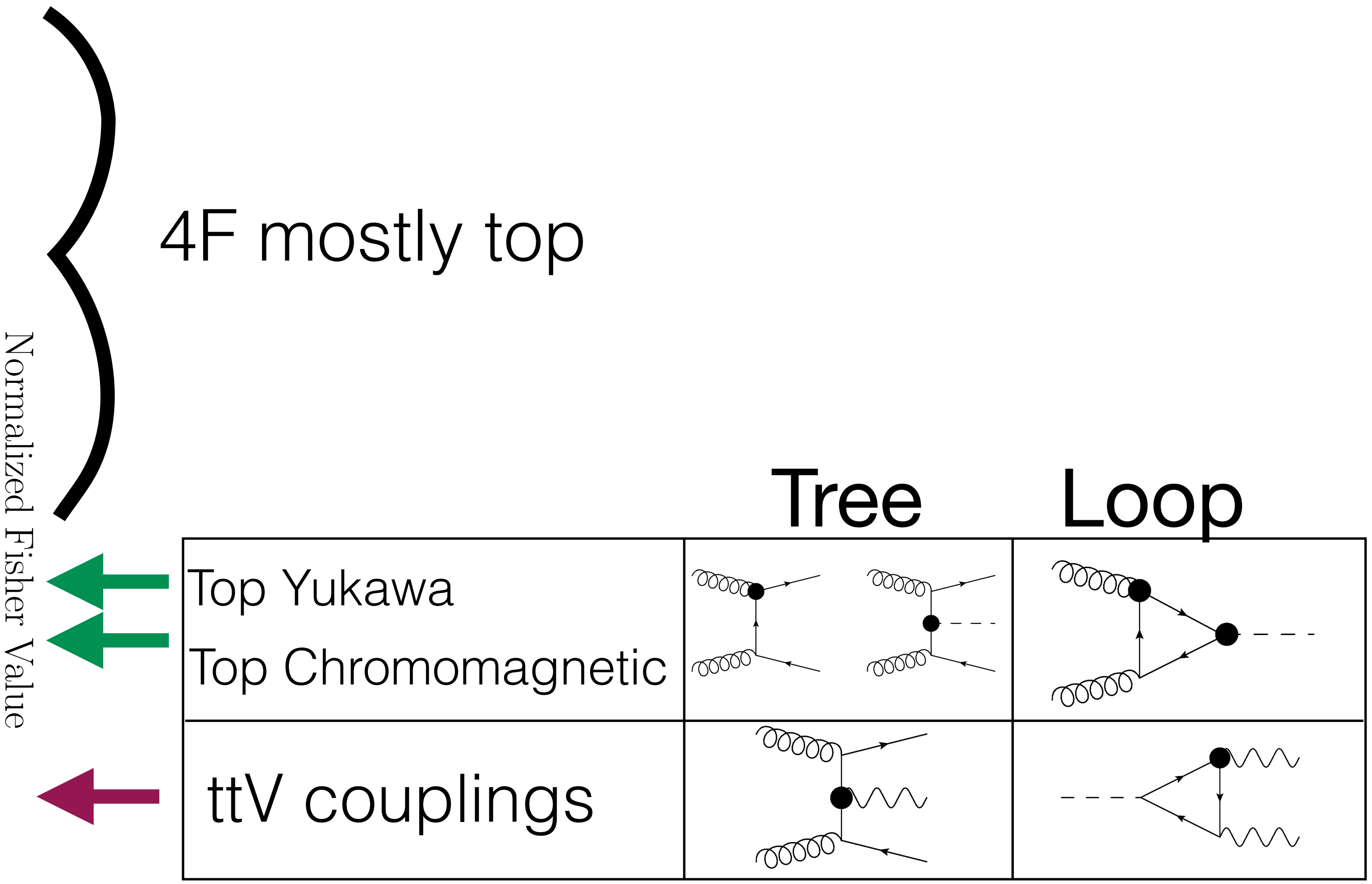
24 new d.o.f.s

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Where is most information from?



Fisher information table

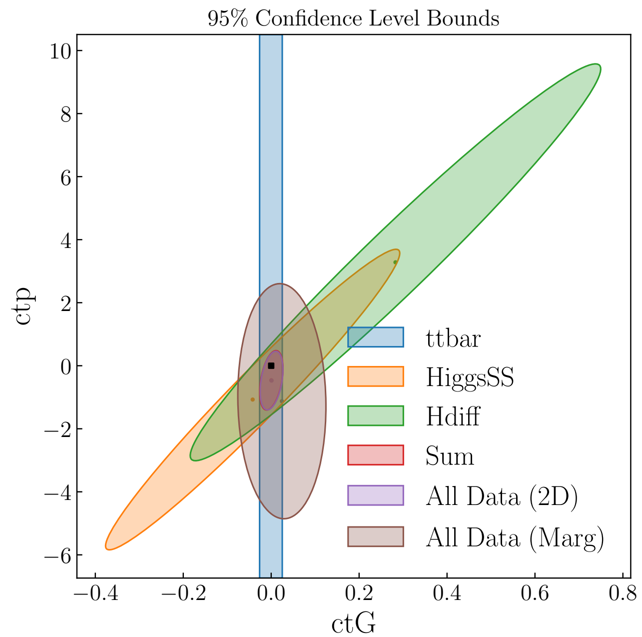


Tree-loop interface

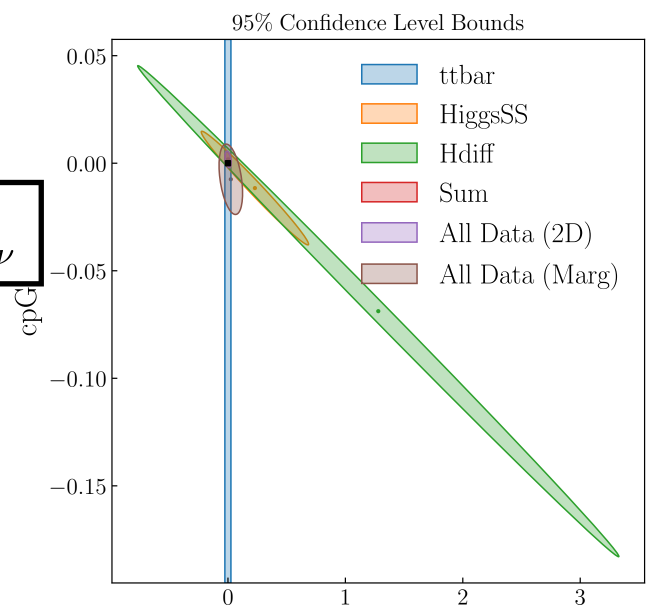
Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Higgs and top interplay

$$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$$



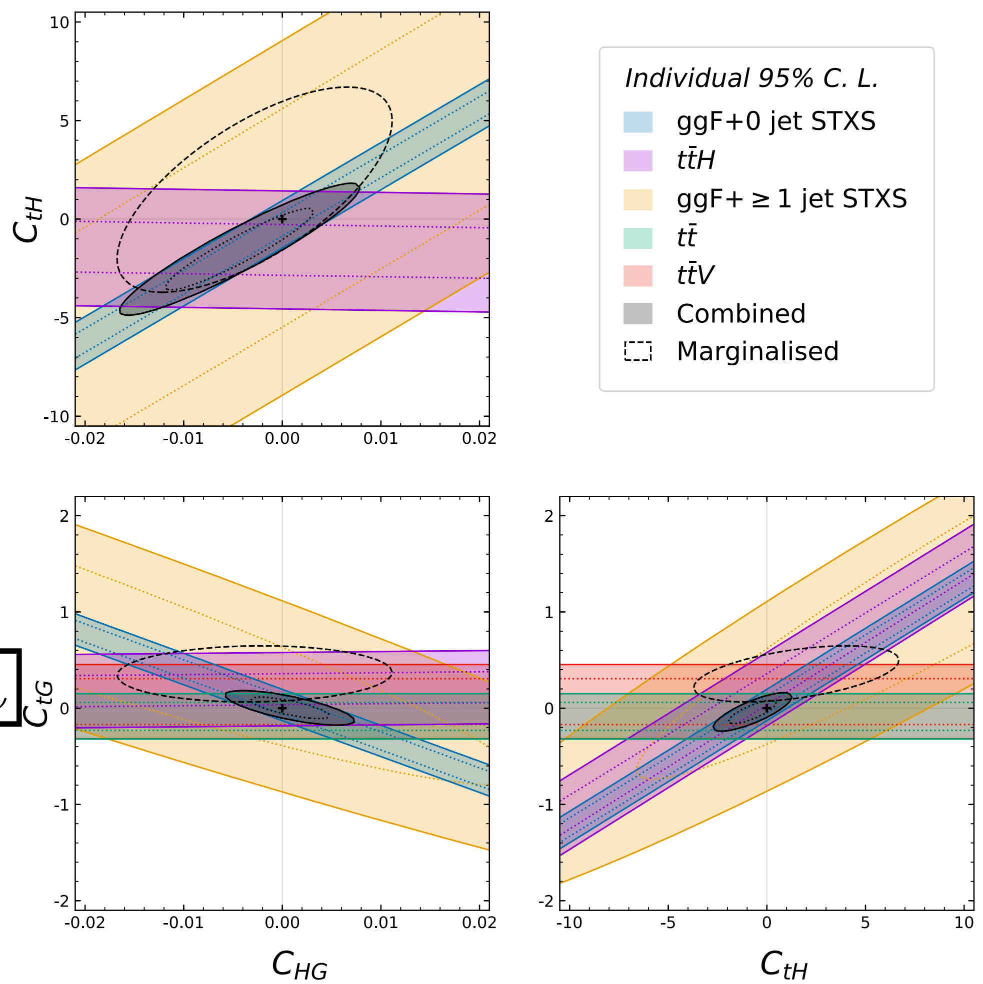
$$\left(\varphi^\dagger\varphi\right)G_A^{\mu\nu}\,G^A_{\mu\nu}$$



$$(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu}$$

$$\left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$$

$$(\bar{Q}\tau^{\mu\nu}\,T_A\,t)\,\tilde{\varphi}\,G^A_{\mu\nu}$$



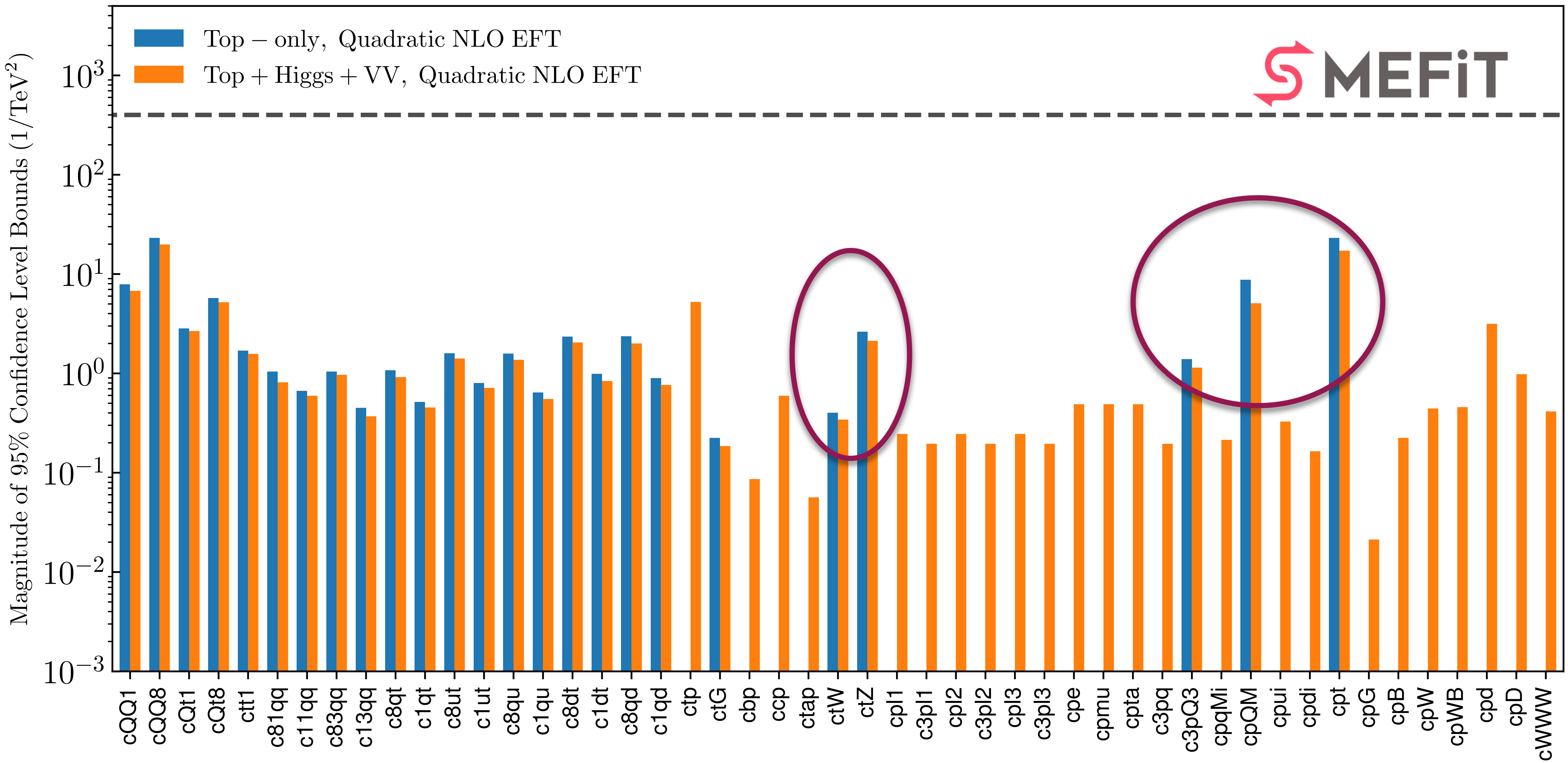
$$\left(\varphi^\dagger\varphi\right)G_A^{\mu\nu}\,G^A_{\mu\nu} \qquad \left(\varphi^\dagger\varphi\right)\bar{Q}\,t\,\tilde{\varphi}$$

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Top measurements break the degeneracy between Higgs operators

Global fit results



Higgs data improves certain top operator bounds

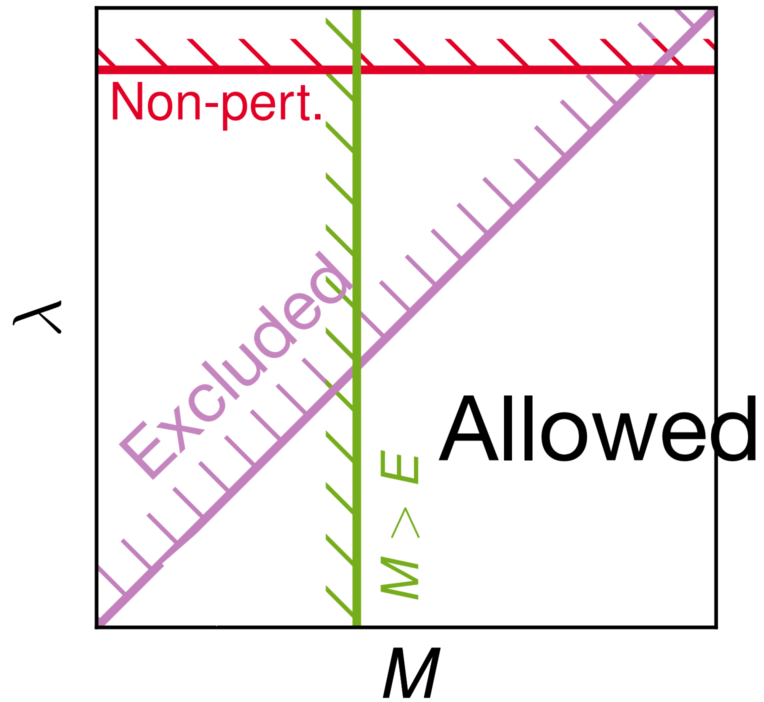
Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

What do we learn from global fits?

Bounds on new physics scale vary from 0.1 TeV (unconstrained) to 10s of TeV.
Bounds depend on:

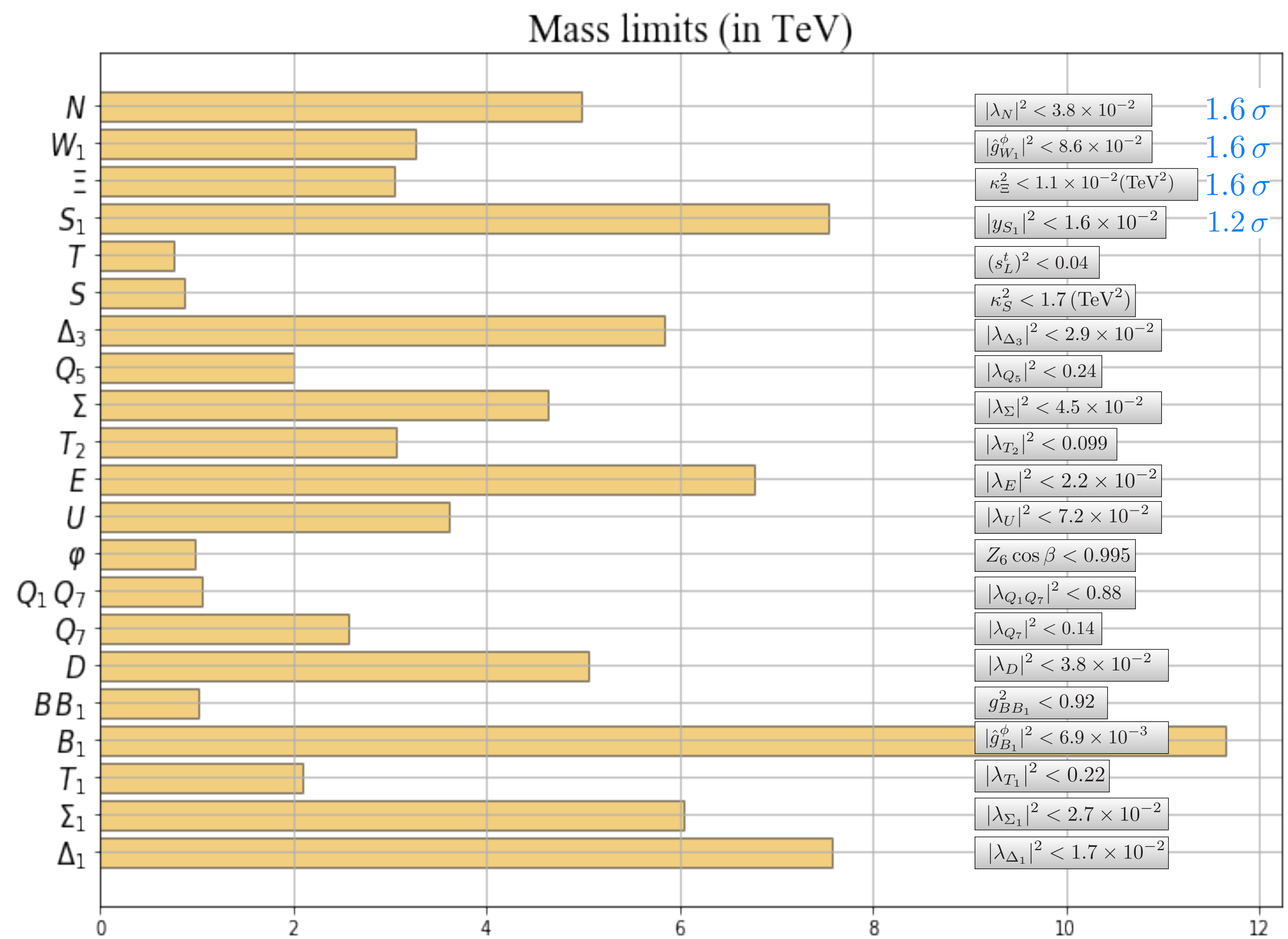
- the operator
- assumption of a strongly or weakly coupled theory
- individual or marginalised bounds (reality is somewhere in-between)
- linear or quadratic bounds

constraint: $\frac{c_i^6(\mu)}{\Lambda^2} = \frac{\lambda^2}{M^2} < X$



What can we learn from these fits?

- EFT bounds translate to constraints on parameters of UV models
- Simplest case: single-field extensions of the SM



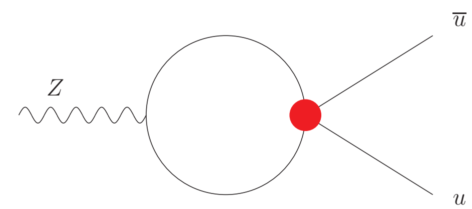
Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

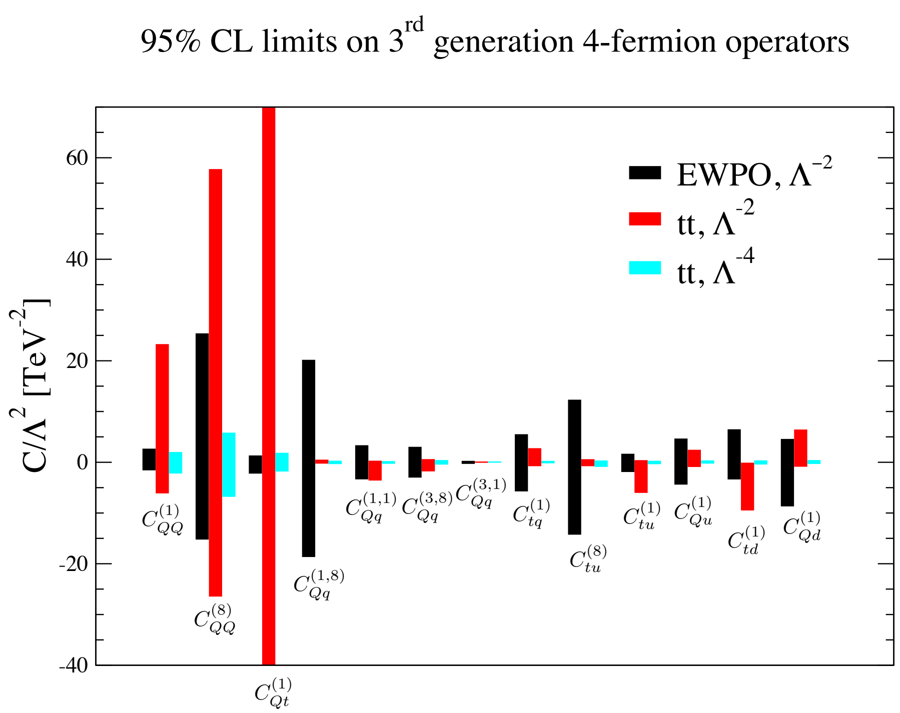
Future of EFT predictions

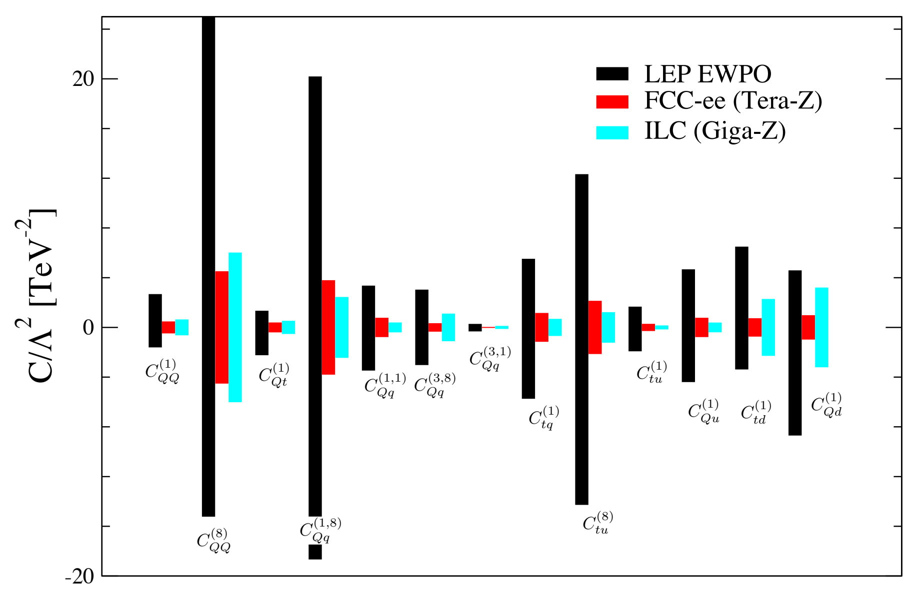
- Missing Higher Orders in $1/\Lambda^4$
  - squared dim-6 contributions
  - double insertions of dim-6 (e.g.arXiv: 2212.03258)
  - dim-8 contributions
- Missing Higher Orders in QCD and EW
  - EFT is a QFT, renormalisable order-by-order $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$

4-heavy operators in EWPO





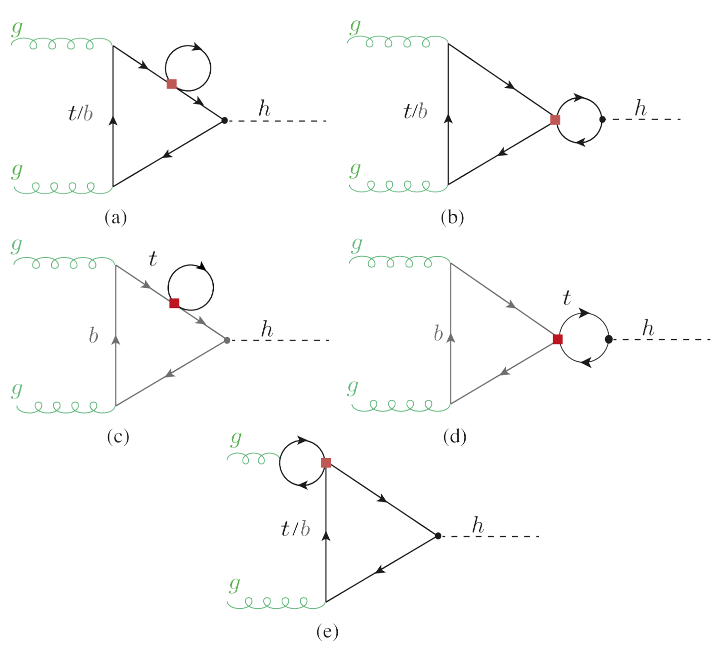


Dawson and Giardino arXiv: 2201.09887

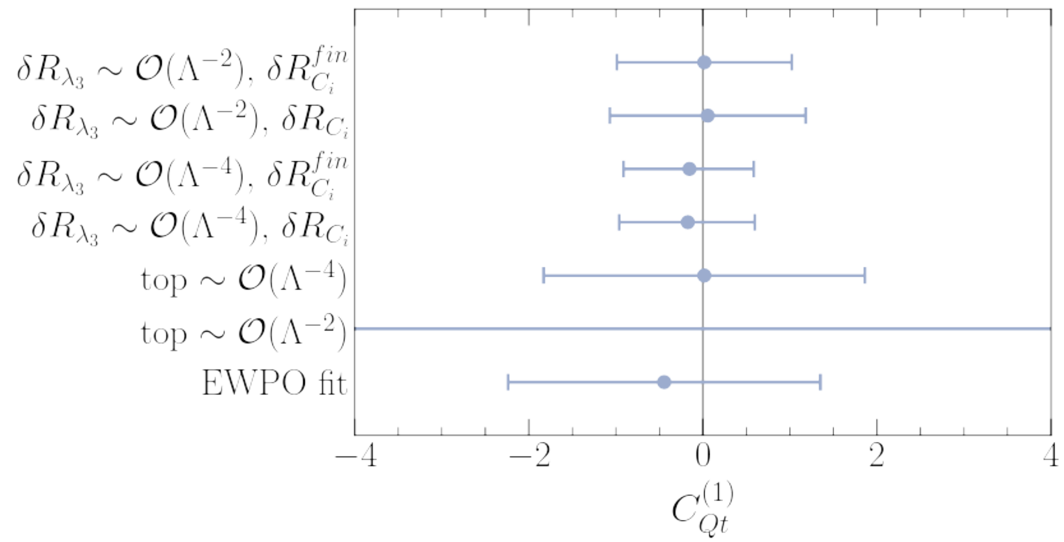
New loop-induced sensitivity
Competitive to 4top production

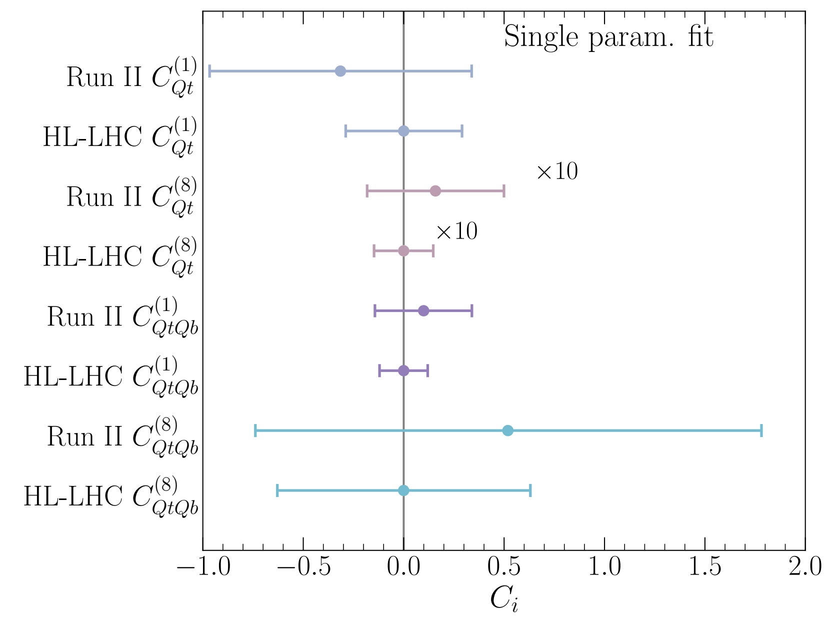
Improved sensitivity due to EW loops

4-heavy operators in Higgs production



Alasfar, de Blas, Gröber arXiv:2202.02333

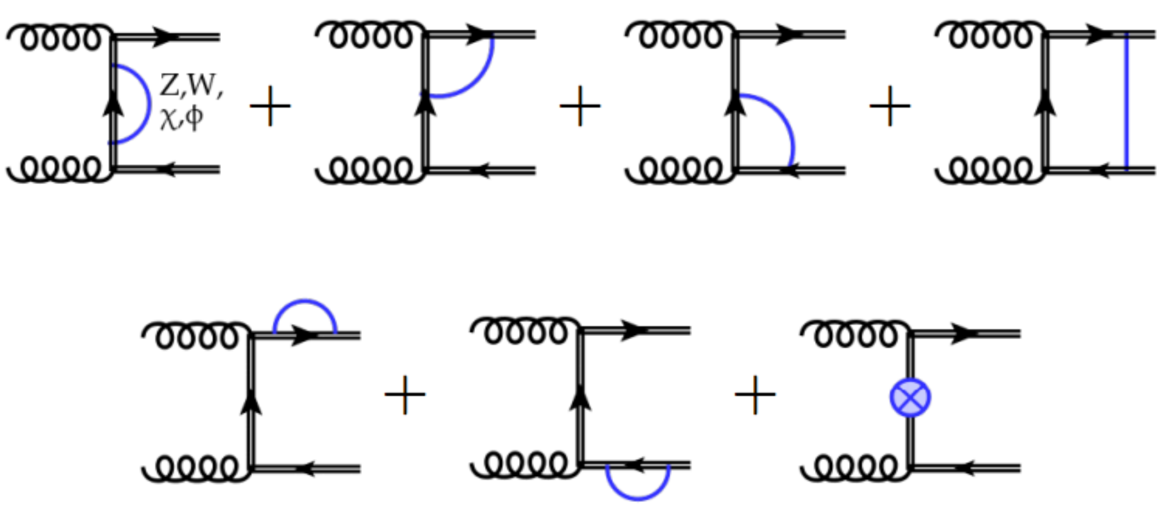




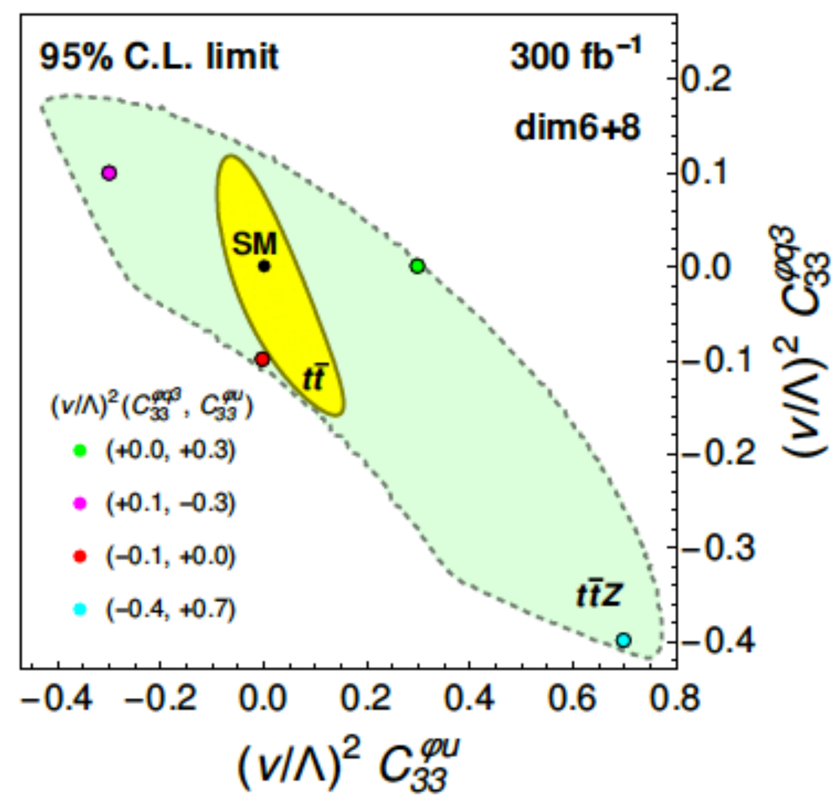
Again competitive with top fit bounds!

More loop-induced sensitivities

EW corrections to top pair production:



Top-Z couplings



Martini and Schulze arXiv:1911.11244

Ongoing and future developments

Status of SMEFT computations at dimension-6:

Tree level Monte Carlo: Done

NLO QCD: ~Done

NNLO QCD: A couple of examples

NLO EW: Some examples available, needed to probe unconstrained operators.

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2}\, a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

How about this μ?

RGE in MC

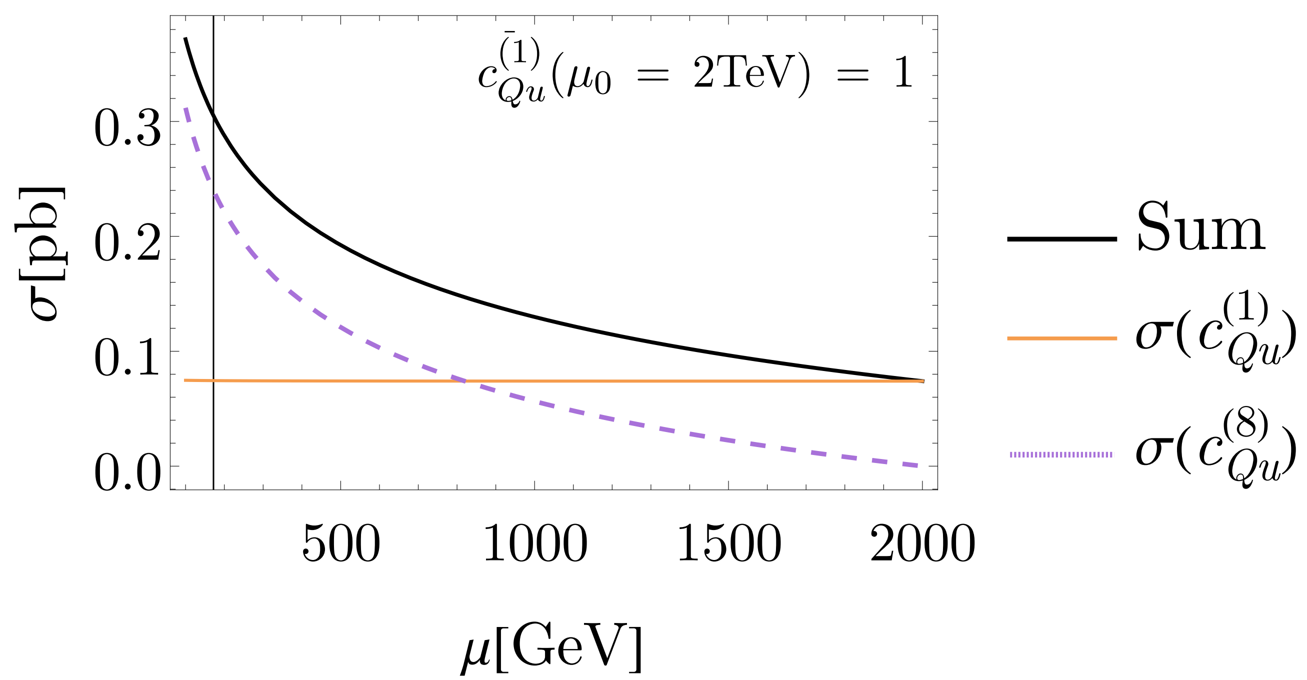
$$\frac{dc_i(\mu)}{d\log\mu} = \gamma_{ij}\, c_j(\mu)$$

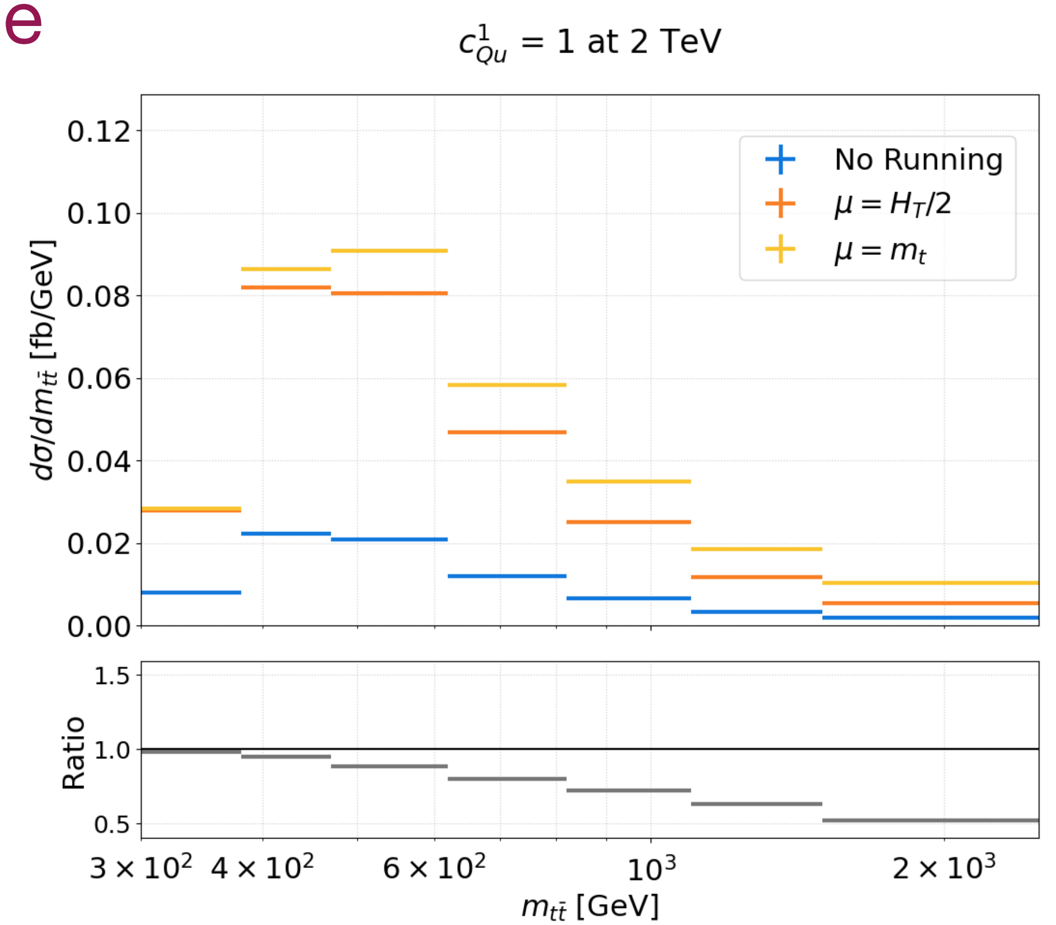
One loop known:

(Alonso) Jenkins et al arXiv:1308.2627, 1310.4838, 1312.2014

Example: Turn one 1 operator at high-scale

Compute effect on top pair cross-section

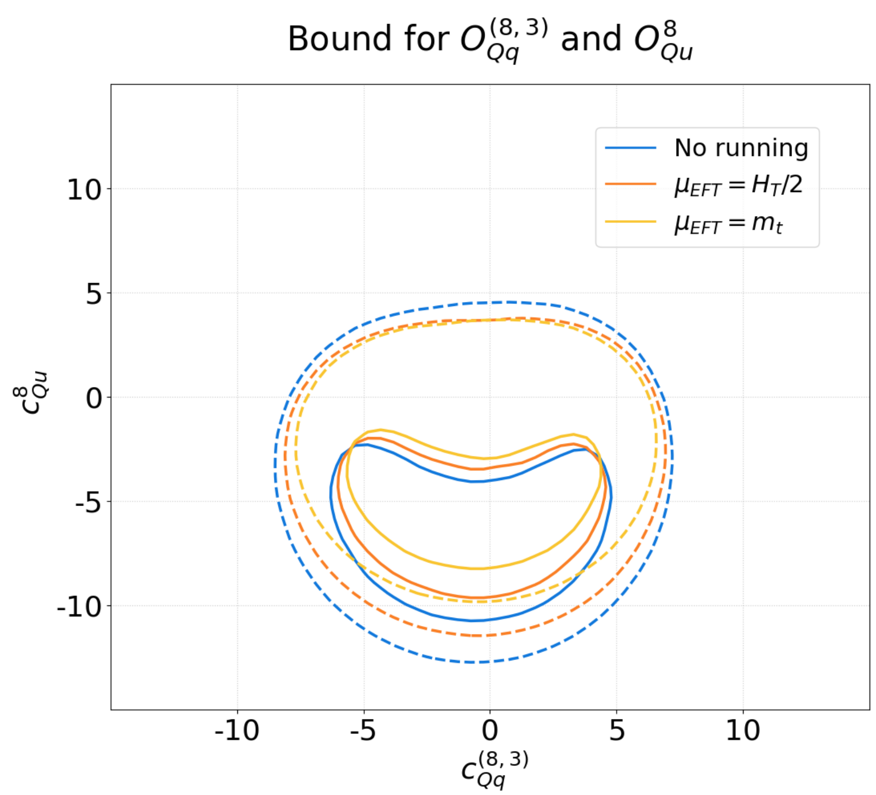


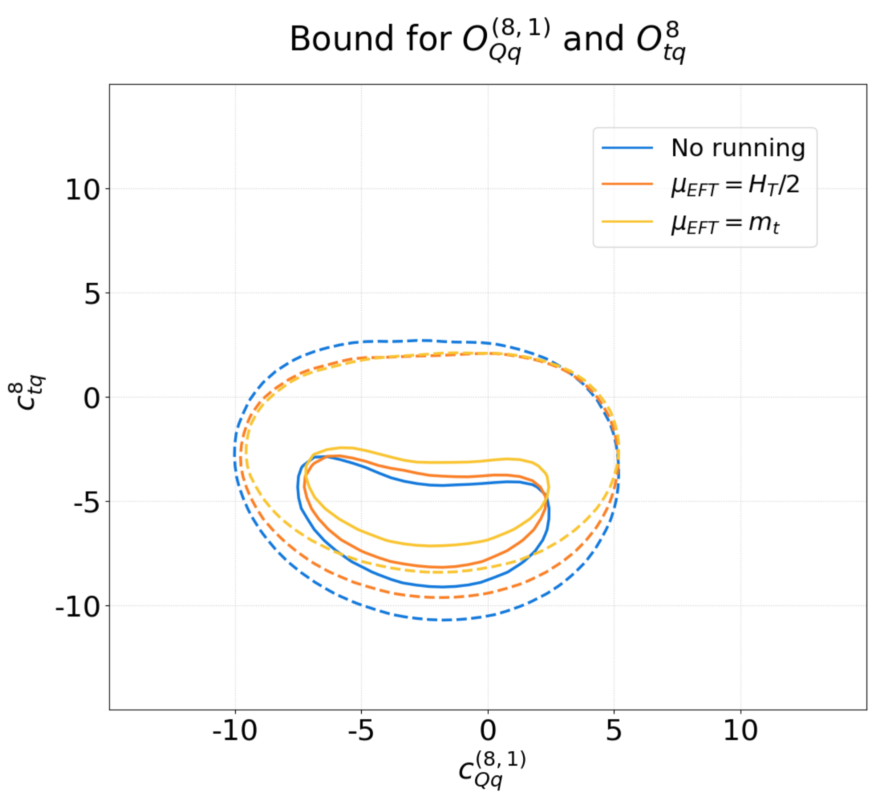


Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

Impact of RGE on constraints

Mini-fit in the top sector





Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

See also Battaglia, Grazzini, Spira, Wiesemann arXiv: 2109.02987

Outlook

- SMEFT is a consistent way to look for new interactions
- The LHC gives a lot of opportunities to explore top interactions through a lot of new top measurements

- First global fits results already available: important to combine as many processes as possible to extract maximal information
- Strong link between Higgs and top sectors
- Eventually global fit results give us a clear indication of the scale of potential new physics

Thank you for your attention