Joint Workshop of the CEPC Physics,
Software and New Detector Concept
May 24, 2022

Higgs probes of top-quark contact interactions at the LHC and interplay with the Higgs self-coupling

Jorge de Blas

University of Granada

Based on:

L. Alasfar, J.B. R. Gröber, arXiv: 2202.0233 [hep-ph]

(Accepted for publication in JHEP)

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Universidad de Granada

Transformación Económica, Industria, Conocimiento y Universidades

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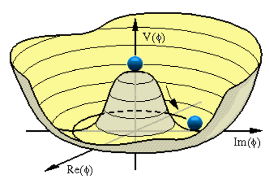
Introduction

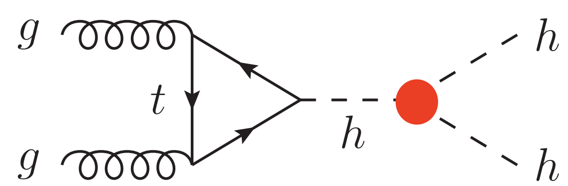
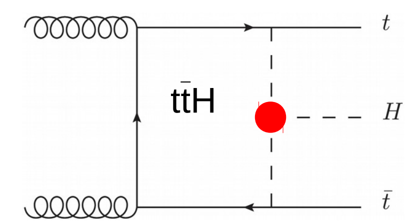
- Two main ways of extracting the **Higgs self-coupling, κ_λ, at the LHC**



$$V(\phi) = -\mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 \longrightarrow V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

$$\lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \lambda_\phi = \frac{G_\mu m_h^2}{\sqrt{2}} \approx 0.129$$

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$

	Higgs-pair production	Via loop effect in single Higgs
Hadron Collider		
Lepton Collider		

	di-Higgs	single-H
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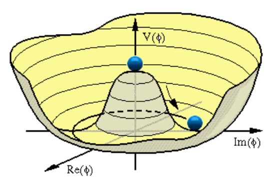

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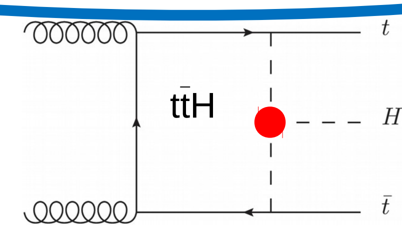
Hadron Collider		
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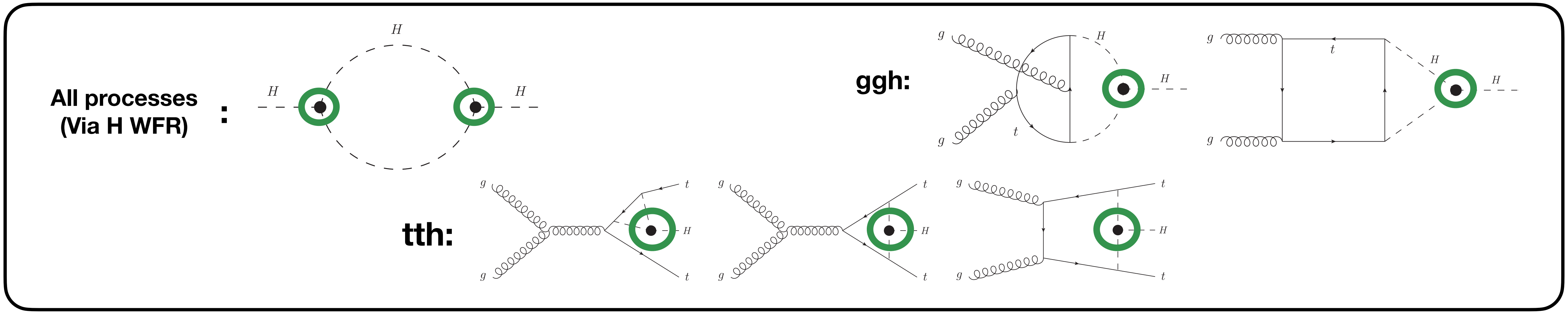
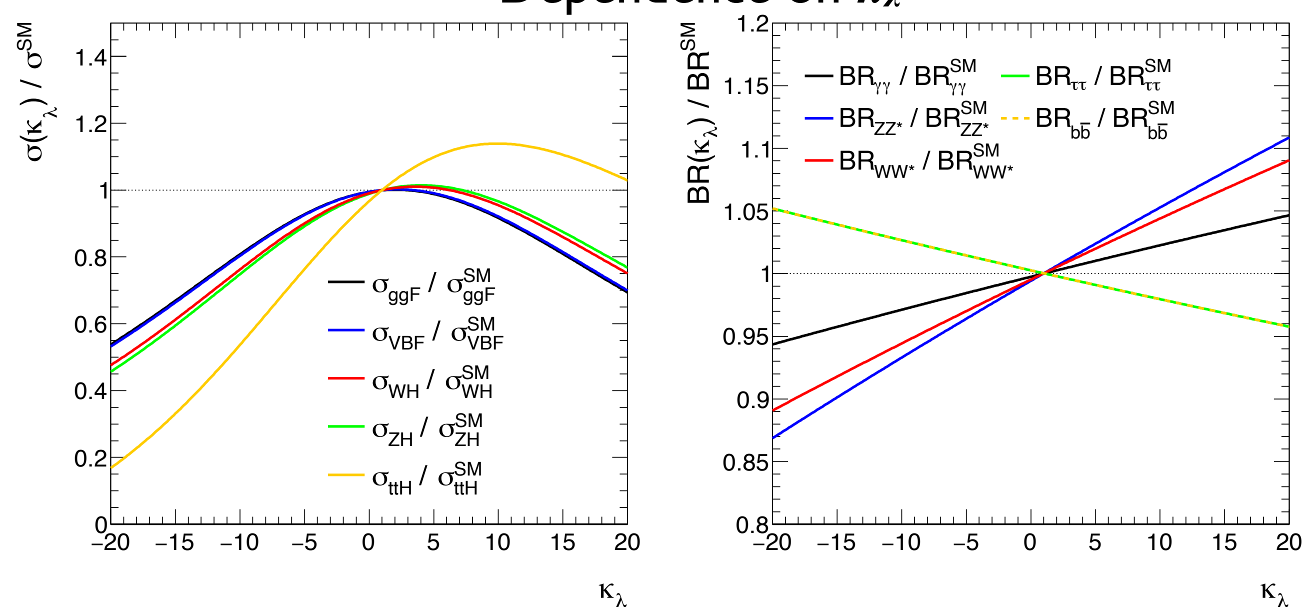
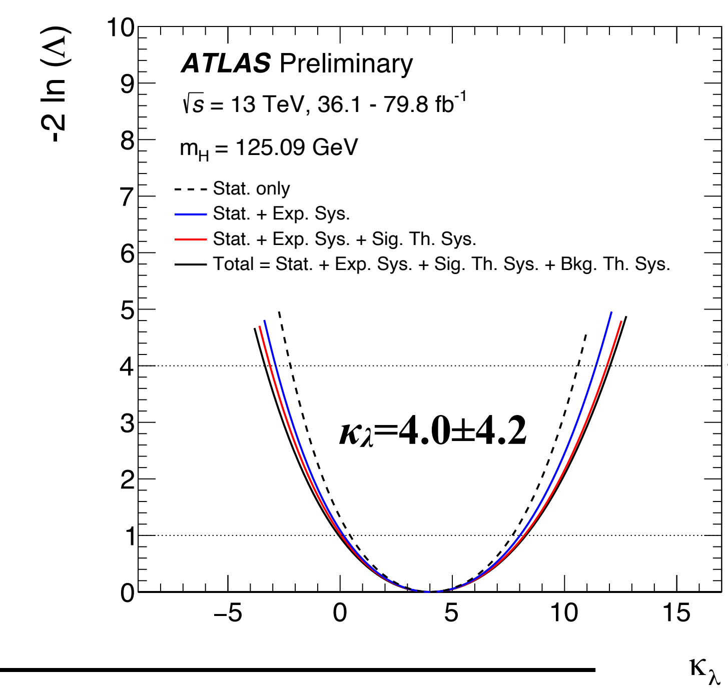


- ✓ Used already in EXP analyses/interpretations…

Dependence on κ_λ





ATL-PHYS-PUB-2019-009

*** First suggested in the context of future e+e- Higgs factories by:**
M. McCullough, PRD 90 (2014) 1, 015001 (PRD 92 (2015) 3, 039903 [erratum]), arXiv: 1312.3322 [hep-ph]

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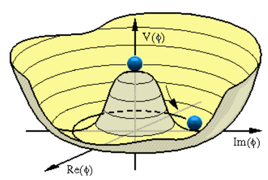

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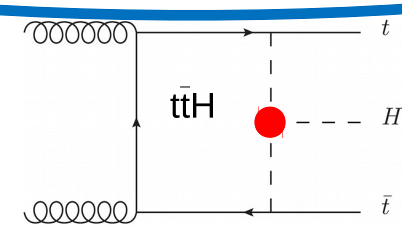
Hadron Collider		
Lepton Collider		

Already being implemented in EXP analyses (see e.g. ATLAS-CONF-2019-049) but…

…not enough for a model-independent determination

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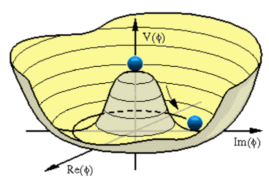

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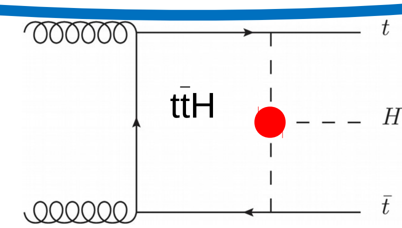
Hadron Collider		
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Not enough to add LO couplings (for the LHC)!… Why?

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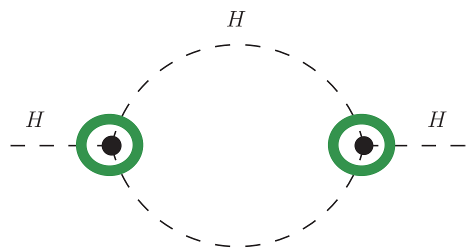
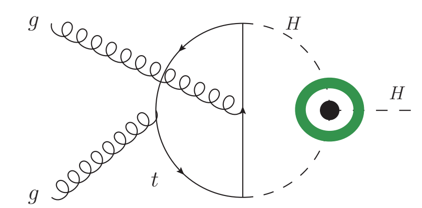
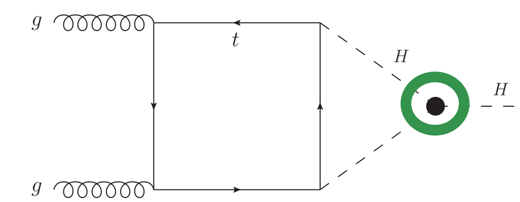
All processes (Via H WFR) :

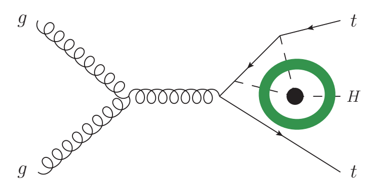


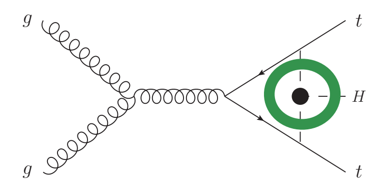
ggh:

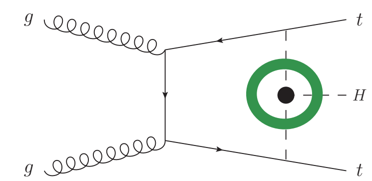




tth:

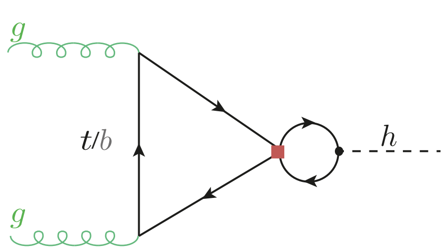






  - ✓ Other new physics effects can also modify single Higgs processes at the same order in perturbation theory! For instance,

ggh:



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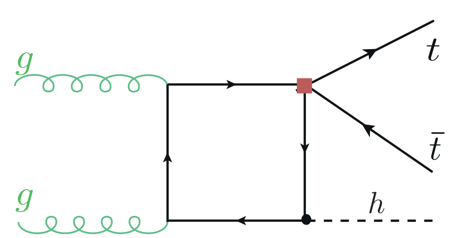
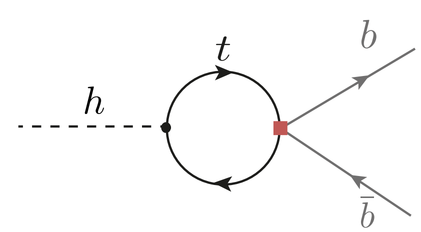


h→bb:



4-Top operators ALSO enter in ggF, *tth*, *h→bb* and *h→γγ* @ NLO and <u>experimental bounds are weak</u> ⇒ **Can difficult the interpretation of single-Higgs processes as probes of h³**

Conversely, one can use Higgs data to probe such interactions, similar to what was proposed in G. Durieux, J. Gu, E. Vryonidou, C. Zhang, Chin. Phys. C 42 (2018) 12, 123107 (at future Higgs factories)

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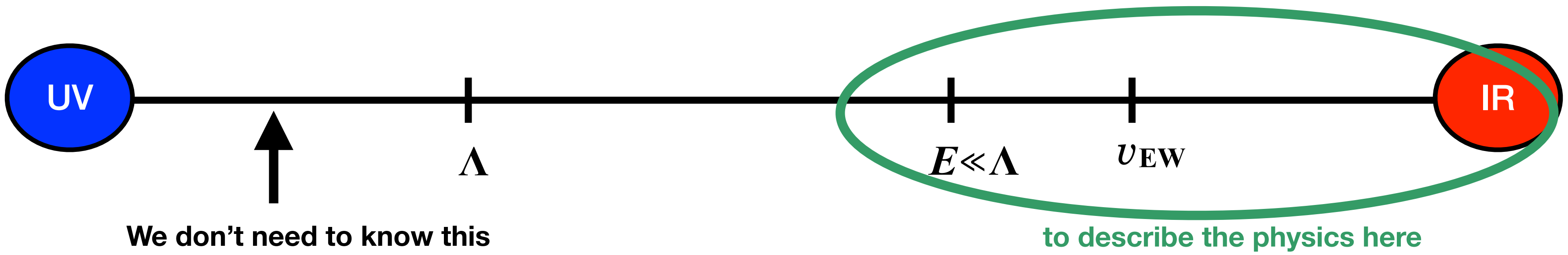
Extraction of the Higgs trilinear is only robust when interpreted within a consistent (preferably model-independent) theoretical framework

⇒ Effective Field Theories



Model-Independent interpretation requires to introduce <u>all</u> interactions entering at the same order in perturbation theory, <u>unless</u> experimentally very well constrained (again, in a model-independent way)

In this talk we focus on the case of 4-Top operators, which is another set of interactions that is currently weakly constrained and compute their NLO effects in single Higgs observables

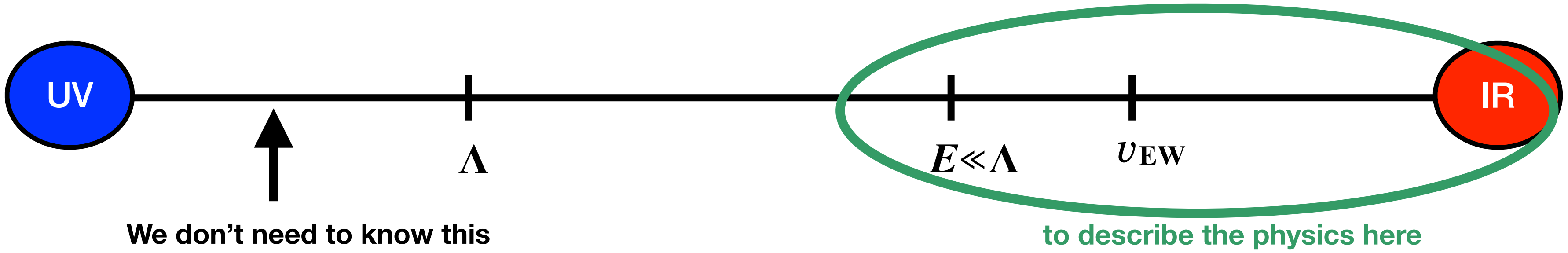
Conversely, one can use Higgs data to probe such interactions, similar to what was proposed in G. Durieux, J. Gu, E. Vryonidou, C. Zhang, Chin. Phys. C 42 (2018) 12, 123107 (at future Higgs factories)

Setup of the Calculation

The Standard Model Effective Field Theory

The dimension-six SMEFT

- We will work within the formalism of the EFTs…



- … and, in particular, in the **SMEFT:** SM particles and symmetries at low energies, with *the Higgs scalar in an $SU(2)_L$ doublet* + mass gap with new physics (entering at scale Λ)

$$\mathcal{L}_{\mathrm{UV}}(?) \xrightarrow[E \ll \Lambda]{} \quad \mathcal{L}_{\mathrm{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

- Leading Order (LO) Beyond the SM effects (assuming B & L)

$\Rightarrow$ Dim-6 SMEFT: 2499 operators

- In this talk, we will follow the conventions of the *Warsaw basis*

The dimension-six SMEFT: 4-quark operators

- We focus on the set of 4-fermion interactions between 3rd-family quarks:

$$\begin{aligned}\Delta\mathcal{L}^{d=6}_{\rm SMEFT} &= \frac{C_{tt}}{\Lambda^2}(\bar{t}_R\gamma_\mu t_R)(\bar{t}_R\gamma^\mu t_R) + \frac{C^{(1)}_{Qt}}{\Lambda^2}(\overline{Q}_L\gamma_\mu Q_L)(\bar{t}_R\gamma^\mu t_R) + \frac{C^{(8)}_{Qt}}{\Lambda^2}(\overline{Q}_L T^A\gamma_\mu Q_L)(\bar{t}_R T^A\gamma^\mu t_R)\\
&+ \frac{C^{(1)}_{QQ}}{\Lambda^2}(\overline{Q}_L\gamma_\mu Q_L)(\overline{Q}_L\gamma^\mu Q_L) + \frac{C^{(3)}_{QQ}}{\Lambda^2}(\overline{Q}_L\sigma_a\gamma_\mu Q_L)(\overline{Q}_L\sigma_a\gamma^\mu Q_L)\\
&+ \left[\frac{C^{(1)}_{QtQb}}{\Lambda^2}(\overline{Q}_L t_R)i\sigma_2(\overline{Q}^{\rm T}_L b_R) + \frac{C^{(8)}_{QtQb}}{\Lambda^2}(\overline{Q}_L T^A t_R)i\sigma_2(\overline{Q}^{\rm T}_L T^A b_R) + \text{h.c.}\right]\\
&+ \frac{C_{bb}}{\Lambda^2}(\bar{b}_R\gamma_\mu b_R)(\bar{b}_R\gamma^\mu b_R) + \frac{C^{(1)}_{tb}}{\Lambda^2}(\bar{t}_R\gamma_\mu t_R)(\bar{b}_R\gamma^\mu b_R) + \frac{C^{(8)}_{tb}}{\Lambda^2}(\bar{t}_R T^A\gamma_\mu t_R)(\bar{b}_R T^A\gamma^\mu b_R)\\
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- In particular, several of these mix under renormalisation with the operators modifying the Yukawas (enter at LO in the relevant single-Higgs processes):

$$\Delta\mathcal{L}^{d=6}_{\rm SMEFT} = \left(\frac{C_{t\phi}}{\Lambda^2}\phi^\dagger\phi\,\overline{Q}_L\tilde{\phi}\,t_R + \frac{C_{b\phi}}{\Lambda^2}\phi^\dagger\phi\,\overline{Q}_L\phi\,b_R + \text{h.c.}\right)$$

- We will discuss the interplay with the Higgs trilinear ⇒ consider the operator

$$\Delta\mathcal{L}^{d=6}_{\rm SMEFT} = \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3, \qquad \rightarrow \qquad \delta\kappa_\lambda = -2\frac{C_\phi v^4}{m_h^2\Lambda^2}$$

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Either because chirality or because they only enter in bottom loops, these will have very small effects in Higgs observables and can be neglected

- In pa... rs modifying the Yukawas (enter at LO in the relevant single-Higgs processes):

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\end{aligned}
$$

- Note that these interactions are also relevant from BSM point of view, e.g.
  - ✓ Composite Higgs : $C_i/\Lambda^2\sim 1/f^2$. (Similar to single h couplings though)
  - ✓ Can be generated in isolation, at tree level, by several SM extensions, e.g.
    - New Scalars: $\Omega_1 \quad (6,1)_{\frac{1}{3}} \longrightarrow \mathcal{O}^{(1)}_{qq},\, \mathcal{O}^{(3)}_{qq},\, \mathcal{O}^{(1)}_{ud},\, \mathcal{O}^{(8)}_{ud},\, \mathcal{O}^{(1)}_{quqd},\, \mathcal{O}^{(8)}_{quqd}$

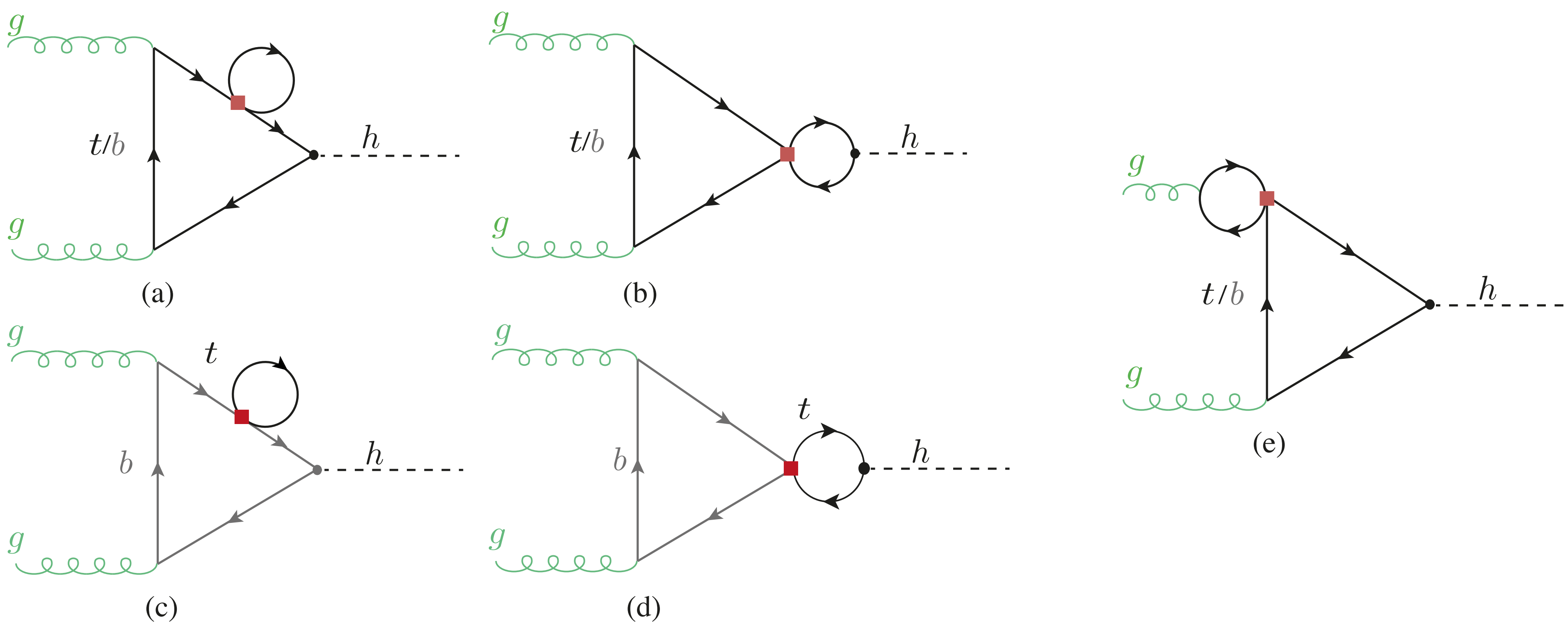
      $\Phi \quad (8,2)_{\frac{1}{2}} \longrightarrow \mathcal{O}^{(1)}_{qu},\, \mathcal{O}^{(8)}_{qu},\, \mathcal{O}^{(1)}_{qd},\, \mathcal{O}^{(8)}_{qd},\, \mathcal{O}^{(8)}_{quqd}$

Four-quark operators
in LHC Higgs observables

Effective Higgs couplings to gluons and photons

- Four-quark operators induce NLO 2-loop contributions to ggF, $h\to\gamma\gamma$, $h\to gg$

Example Feynman diagrams



Corrections to propagators

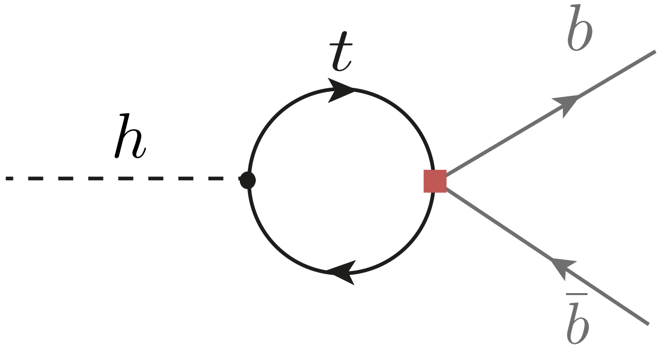
Corrections to Yukawa couplings

Corrections to ttg, $tt\gamma$ vertices (0 when on-shell)

- Results can be written as product of 1-loop integrals
- Relevant operators → $\mathcal{O}_{Qt}^{(1),(8)}$ $\mathcal{O}_{QtQb}^{(1),(8)}$ $\cancel{\mathcal{O}_{Qb}^{(1),(8)}}$ **Contrib. suppressed by m_b**
- Also contribute to $h\to Z\gamma$, but given the expected precision at (HL-)LHC and the small BR this mode is of little relevance and we ignore it

Higgs decays to bottom quarks

- 2-Top 2-Bottom operators also induce NLO 1-loop contributions to $h \to bb$



First computed in R. Gauld, B.D.Pecjack, D.J. Scott, JHEP 05 (2016) 080
Recomputed in our work and in agreement with their results

- Relevant operators: $\mathcal{O}_{QtQb}^{(1),(8)}$ $\cancel{\mathcal{O}_{Qb}^{(1),(8)}}$ **Contrib. suppressed by m_b**

$$\frac{\Gamma_{h\to b\bar{b}}}{\Gamma^{\rm SM}_{h\to b\bar{b}}} = 1 + \frac{1}{16\pi^2}\frac{m_t}{m_b}(m_h^2 - 4m_t^2)\frac{(2N_c+1)C^{(1)}_{QtQb} + c_F C^{(8)}_{QtQb}}{\Lambda^2}$$
$$\times\left[2 + \sqrt{1-\frac{4m_t^2}{m_h^2}}\log(x_t) - \log\left(\frac{m_t^2}{\mu_R^2}\right)\right],$$

- Note: similarly, decays $h \to \tau\tau$ would be affected by analogous (semi-leptonic) operators ($O_{L\tau Qt}$) that may not be strongly constrained

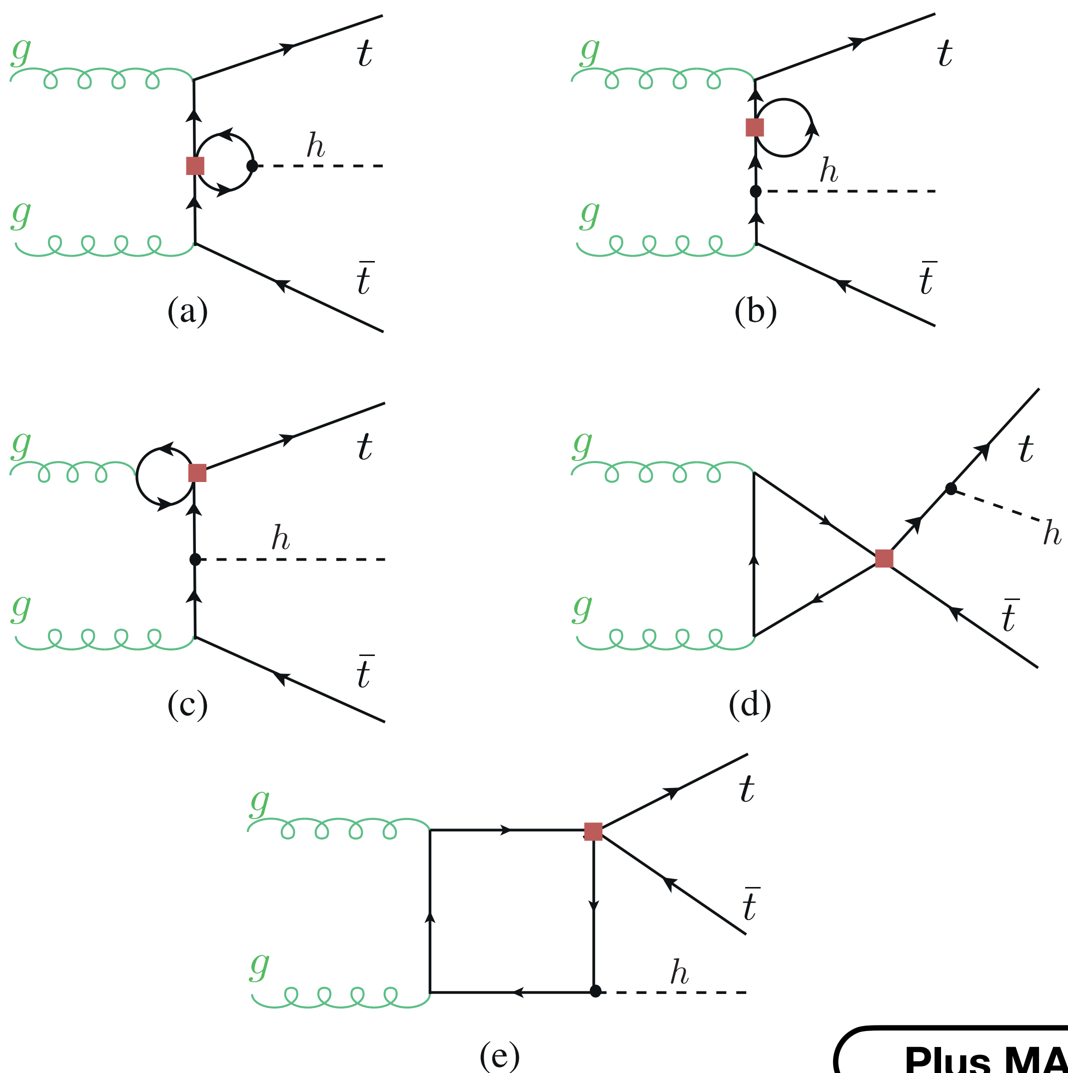
R. Gauld, B.D.Pecjack, D.J. Scott, JHEP 05 (2016) 080

Higgs production in association to Top quark pairs

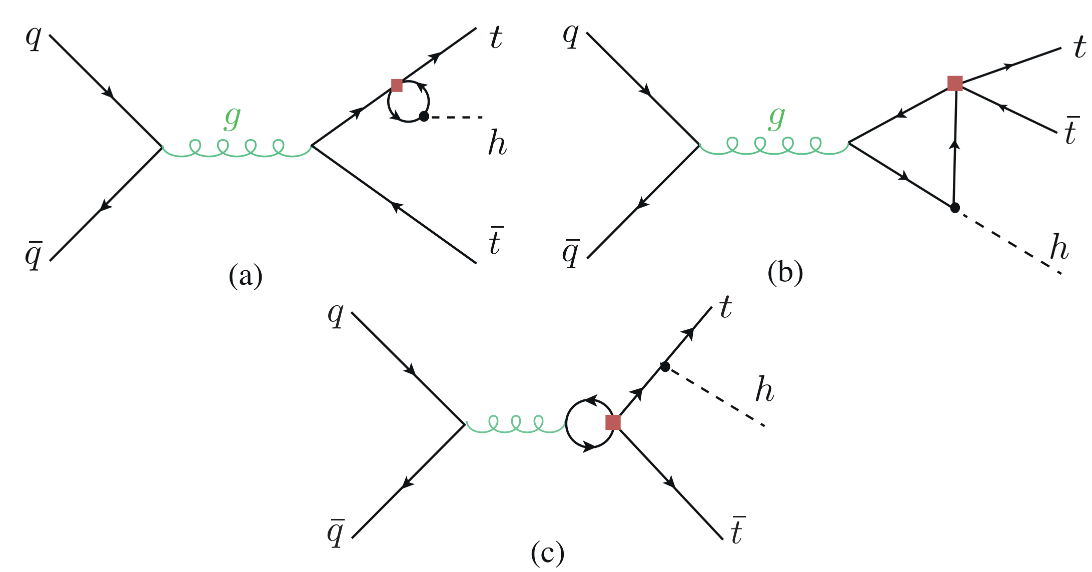
- tth can be initiated either via $gg\to tth$ or $qq\to tth$, both of which are corrected at 1-loop by 4-quark operators

Example Feynman diagrams

$gg\to tth$



$qq\to tth$



Plus MANY more diagrams

- Relevant operators: $\mathcal{O}_{Qt}^{(1)}$ $\mathcal{O}_{Qt}^{(8)}$ $\mathcal{O}_{QQ}^{(1)}$ $\mathcal{O}_{QQ}^{(3)}$ $\mathcal{O}_{tt}$

Other ops. contribute via b-loops and corrections are suppressed by m_b

NLO effects of 4 Top operators in Higgs production

Some (brief) details of the calculation

- Dimensional regularisation + Mixed On-Shell (OS)-$\overline{\text{MS}}$ renormalisation scheme:
  - ✓ Quark masses renorm. OS/dim-6 Wilson coefficients renorm. in $\overline{\text{MS}}$
- *ggF, h→γγ, h→gg, h→bb*: Computed analytically using algebra tools such as PackageX, Kira, Fire, FeynRules, FeynArts
  - ✓ Analytical expressions provided, e.g.

$$\frac{\sigma_{ggF}}{\sigma_{ggF}^{\rm SM}} = 1 + \frac{\sum_{i=t,b} 2\mathrm{Re}\left(F_{\rm LO}^i F_{\rm NLO}^*\right)}{\left|F_{\rm LO}^t + F_{\rm LO}^b\right|^2}$$

$$F_{\rm LO}^i = -\frac{8m_i^2}{m_h^2}\left[1 - \frac{1}{4}\log^2(x_i)\left(1 - \frac{4m_i^2}{m_h^2}\right)\right]$$

$$\begin{aligned} F_{\rm NLO} =& \frac{1}{4\pi^2\Lambda^2}(C_{Qt}^{(1)} + c_F C_{Qt}^{(8)}) F_{\rm LO}^t \left[2m_t^2 + \frac{1}{4}(m_h^2 - 4m_t^2)\left(3 + 2\sqrt{1 - \frac{4m_t^2}{m_h^2}}\log(x_t)\right)\right. \\ &\left. + \frac{1}{2}(m_h^2 - 4m_t^2)\log\left(\frac{\mu_R^2}{m_t^2}\right)\right] \\ &+ \frac{1}{32\pi^2\Lambda^2}((2N_c+1)C_{QtQb}^{(1)} + c_F C_{QtQb}^{(8)})\left[F_{\rm LO}^b \frac{m_t}{m_b}\left(4m_t^2 - 2m_h^2\right.\right. \\ &\left.\left. - (m_h^2 - 4m_t^2)\sqrt{1 - \frac{4m_t^2}{m_h^2}}\log(x_t) - (m_h^2 - 4m_t^2)\log\left(\frac{\mu_R^2}{m_t^2}\right)\right) + (t \leftrightarrow b)\right]. \end{aligned}$$

- *tth*: Analytical calculation, cross-checked using Madgraph_aMCNLO and SMEFTatNLO v1.0.2 model
  - ✓ We modified SMEFTatNLO to include operators not available in public version of the model, e.g. $\mathcal{O}_{QtQb}^{(1),(8)}$
  - ✓ Our analytical result available in FORTRAN code (on request)

Results

- We evaluate the size of these corrections and provide semi-analytical expressions (in the leading-log approx.) that can be used inside fitting tools:

Operator	Process	μ_R	$\delta R^{fin}_{C_i}$ [TeV^2]	$\delta R^{log}_{C_i}$ [TeV^2]
$\mathcal{O}^{(1)}_{Qt}$	ggF	$\frac{m_h}{2}$	$9.91 \cdot 10^{-3}$	$2.76 \cdot 10^{-3}$
	$h \to gg$	m_h	$6.08 \cdot 10^{-3}$	$2.76 \cdot 10^{-3}$
	$h \to \gamma\gamma$		$-1.76 \cdot 10^{-3}$	$-0.80 \cdot 10^{-3}$
	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$-4.20 \cdot 10^{-1}$	$-2.78 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$-4.30 \cdot 10^{-1}$	$-2.78 \cdot 10^{-3}$
$\mathcal{O}^{(8)}_{Qt}$	ggF	$\frac{m_h}{2}$	$1.32 \cdot 10^{-2}$	$3.68 \cdot 10^{-3}$
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	$t\bar{t}h$ 14 TeV		$7.29 \cdot 10^{-2}$	$-2.48 \cdot 10^{-3}$
$\mathcal{O}^{(1)}_{QtQb}$	ggF	$\frac{m_h}{2}$	$2.84 \cdot 10^{-2}$	$9.21 \cdot 10^{-3}$
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	$t\bar{t}h$ 14 TeV		$1.65 \cdot 10^{-3}$	$1.76 \cdot 10^{-3}$
$\mathcal{O}^{(3)}_{QQ}$	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$1.32 \cdot 10^{-2}$	$5.48 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$1.24 \cdot 10^{-2}$	$5.30 \cdot 10^{-3}$
$\mathcal{O}_{tt}$	$t\bar{t}h$ 13 TeV	$m_t + \frac{m_h}{2}$	$4.60 \cdot 10^{-3}$	$1.82 \cdot 10^{-3}$
	$t\bar{t}h$ 14 TeV		$4.57 \cdot 10^{-3}$	$1.74 \cdot 10^{-3}$

$$\delta R(C_i) = R/R^{\mathrm{SM}} - 1$$

$$\delta R(C_i) = \frac{C_i}{\Lambda^2}\left(\delta R^{fin}_{C_i} + \delta R^{log}_{C_i} \log\left(\frac{\mu_R^2}{\Lambda^2}\right)\right)$$

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$$R = \sigma,\, \Gamma$$

Comments:

For Λ=1 TeV, log effects usually ~ finite terms (with some exceptions)

O_{QtQb} operators only enter via the combination appearing in the RGEs of $C_{t\phi,b\phi}$

$$C^{+}_{QtQb} = (2N_c+1)C^{(1)}_{QtQb} + c_F C^{(8)}_{QtQb}.$$

O_{QQ} and O_{tt} operators only contribute to tth but, for Λ=1 TeV and O(1) coefficients their effects are typically below SM theory uncertainty ~10%

$\Rightarrow$ to good approx. tth only affected by $O_{Qt}^{(1),(8)}$

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$$R = \sigma,\ \Gamma$$

Contrib. from *h* self-coupling (C_ϕ)

Process	$\delta R^{fin}_{C_\phi}$
ggF/ $gg \to h$	$-3.10 \cdot 10^{-3}$
$t\bar{t}h$ 13 TeV	$-1.64 \cdot 10^{-2}$
$t\bar{t}h$ 14 TeV	$-1.62 \cdot 10^{-2}$
$h \to \gamma\gamma$	$-2.30 \cdot 10^{-3}$
$h \to b\bar{b}$	0.00
$h \to W^+W^-$	$-3.40 \cdot 10^{-3}$
$h \to ZZ$	$-3.90 \cdot 10^{-3}$
$pp \to Zh$ 13 TeV	$-5.60 \cdot 10^{-3}$
$pp \to Zh$ 14 TeV	$-5.50 \cdot 10^{-3}$
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G. Degrassi et al. , JHEP 12 (2016) 080

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G. Degrassi et al. , JHEP 12 (2016) 080

Sizable effects in ggF (dominant at LHC)…

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	$t\bar{t}h$ 14 TeV		$4.57 \cdot 10^{-3}$	$1.74 \cdot 10^{-3}$

$$\delta R(C_i) = R/R^{\rm SM} - 1$$

$$\delta R(C_i) = \frac{C_i}{\Lambda^2}\left(\delta R^{fin}_{C_i} + \delta R^{log}_{C_i} \log\left(\frac{\mu_R^2}{\Lambda^2}\right)\right)$$

$$R = \sigma,\ \Gamma$$

Contrib. from h self-coupling (C_ϕ)

Process	$\delta R^{fin}_{C_\phi}$
ggF/ $gg \to h$	$-3.10 \cdot 10^{-3}$
$t\bar{t}h$ 13 TeV	$-1.64 \cdot 10^{-2}$
$t\bar{t}h$ 14 TeV	$-1.62 \cdot 10^{-2}$
$h \to \gamma\gamma$	$-2.30 \cdot 10^{-3}$
$h \to b\bar{b}$	0.00
$h \to W^+W^-$	$-3.40 \cdot 10^{-3}$
$h \to ZZ$	$-3.90 \cdot 10^{-3}$
$pp \to Zh$ 13 TeV	$-5.60 \cdot 10^{-3}$
$pp \to Zh$ 14 TeV	$-5.50 \cdot 10^{-3}$
$pp \to W^\pm h$	$-4.80 \cdot 10^{-3}$
VBF	$-3.00 \cdot 10^{-3}$
$h \to 4\ell$	$-3.80 \cdot 10^{-3}$

G. Degrassi et al. , JHEP 12 (2016) 080

Sizable effects in ggF (dominant at LHC)…

… and *tth* (strongest dependence on C_ϕ)…

Interplay between 4 Top operators
and h^3 in LHC Higgs fits

(Toy) Fits to LHC Higgs observables

- Not attempting global fit. Only interested in studying effects of NLO corrections from 4-quark operators in Higgs data and their interplay with the h self-coupling
- Toy fits with few parameters to Run 2 data:
  - ✓ We evaluated linear vs. leading quadratic effects from 4-fermion contrib.
    - ~10% difference in the results → We keep only linear terms
  - ✓ We compare finite and log terms: "fin" (C_i renorm. at process scale) vs. full result (C_i renorm. at Λ)
  - ✓ **Interplay with h self-coupling:** linear vs. quad. effects in C_ϕ:

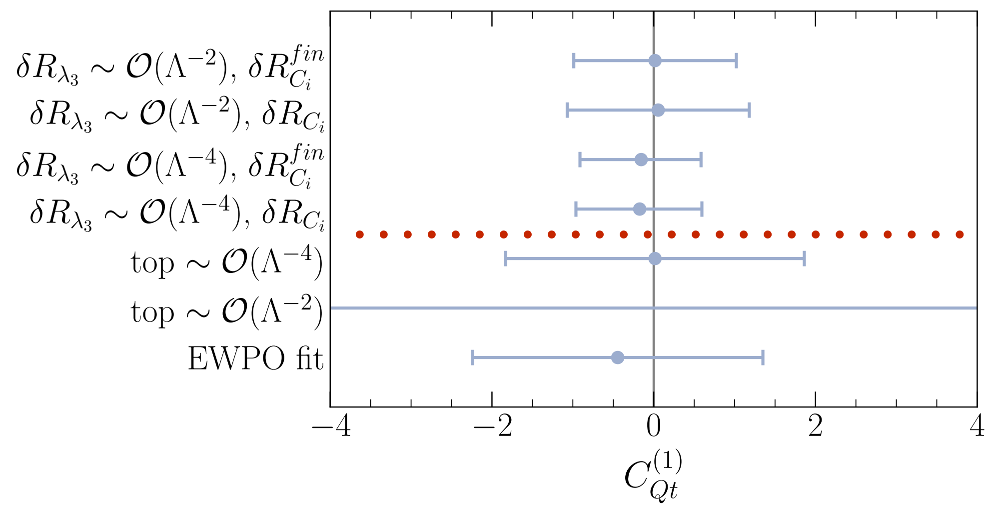
$$\delta R_{\lambda_3} \equiv \frac{R_{\rm NLO}(\lambda_3) - R_{\rm NLO}(\lambda_3^{\rm SM})}{R_{\rm LO}} = -2\frac{C_\phi v^4}{\Lambda^2 m_h^2} C_1 + \left(-4\frac{C_\phi v^4}{\Lambda^2 m_h^2} + 4\frac{C_\phi^2 v^8}{m_h^4 \Lambda^4}\right) C_2 \qquad C_2 = \frac{\delta Z_h}{1 - \left(1 - \frac{2C_\phi v^4}{\Lambda^2 m_h^2}\right)^2 \delta Z_h}$$

G. Degrassi et al. , JHEP 12 (2016) 080

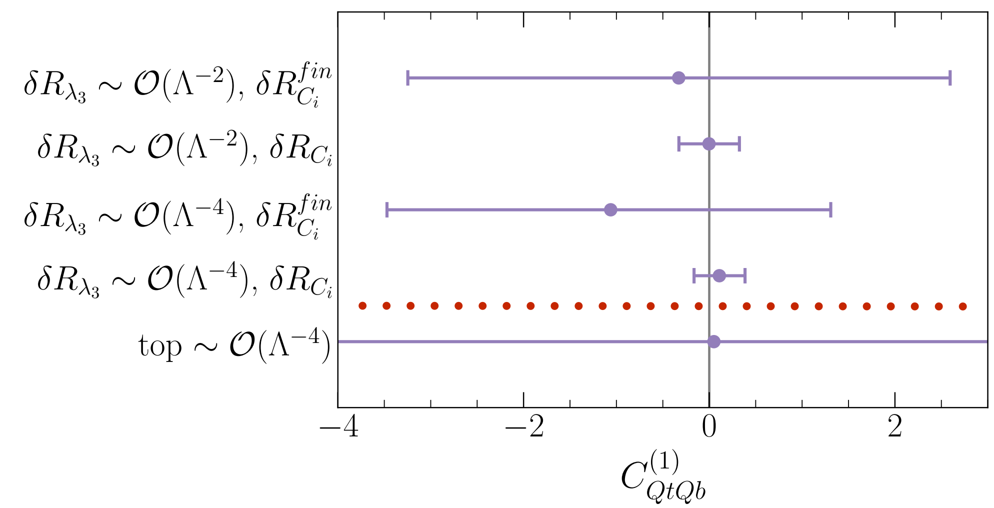
  - ✓ We also compare the bounds with those from other observables:
    - Top, EWPO, Flavour

(Toy) Fits to LHC Higgs observables

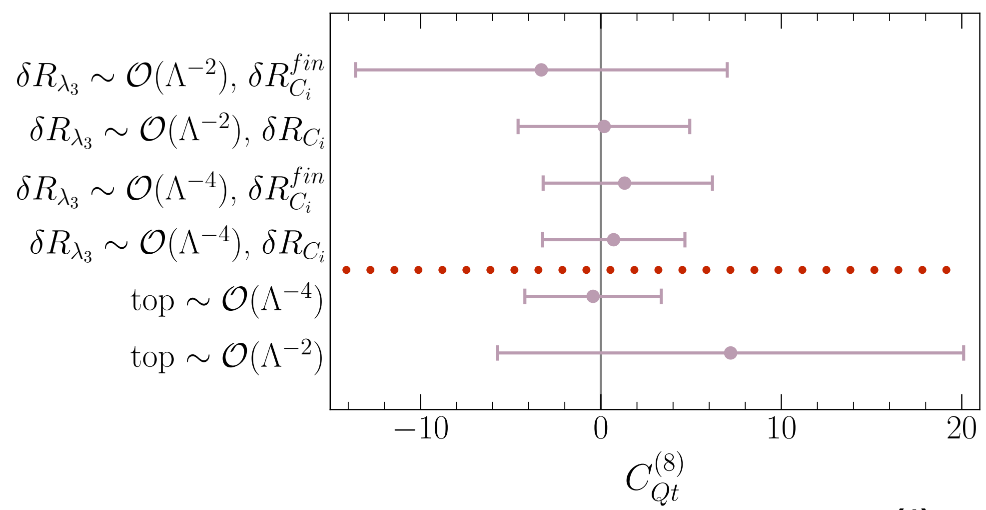
- Toy fits to each 4-Quark operator Wilson coefficient, together with C_ϕ
- Results marginalising over C_ϕ



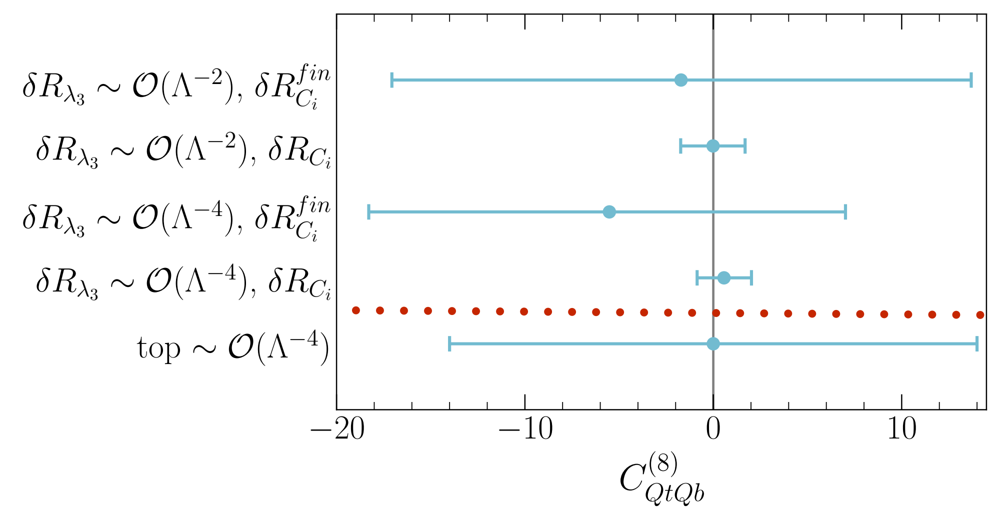
$\langle C_{Qt}^{(1)} \rangle$	95% CI
0.0	[-1.0, 1.0]
0.1	[-1.1, 1.2]
-0.2	[-0.9, 0.6]
-0.2	[-1.0, 0.6]
0.0	[-1.8, 1.9]
-18.0	[-195.0, 159.0]
-0.4	[-2.2, 1.4]



$\langle C_{QtQb}^{(1)} \rangle$	95% CI
-0.33	[-3.25, 2.59]
-0.0	[-0.33, 0.32]
-1.06	[-3.47, 1.31]
0.11	[-0.16, 0.39]
0.05	[-5.4, 5.5]



$\langle C_{Qt}^{(8)} \rangle$	95% CI
-3.3	[-13.6, 7.0]
0.2	[-4.6, 4.9]
1.3	[-3.2, 6.2]
0.7	[-3.2, 4.7]
-0.4	[-4.2, 3.3]
7.2	[-5.7, 20.1]



$\langle C_{QtQb}^{(8)} \rangle$	95% CI
-1.7	[-17.1, 13.7]
-0.0	[-1.7, 1.7]
-5.5	[-18.3, 7.0]
0.6	[-0.9, 2.0]
0.0	[-14.0, 14.0]

(RGE) Flavor bounds: $C_{Qt}^{(1)}$ **~±0.73,** $C_{Qt}^{(8)}$ **~±2.3**
$C_{QtQb}^{(1)}$ **~±2.4,** $C_{QtQb}^{(8)}$ **~±10**

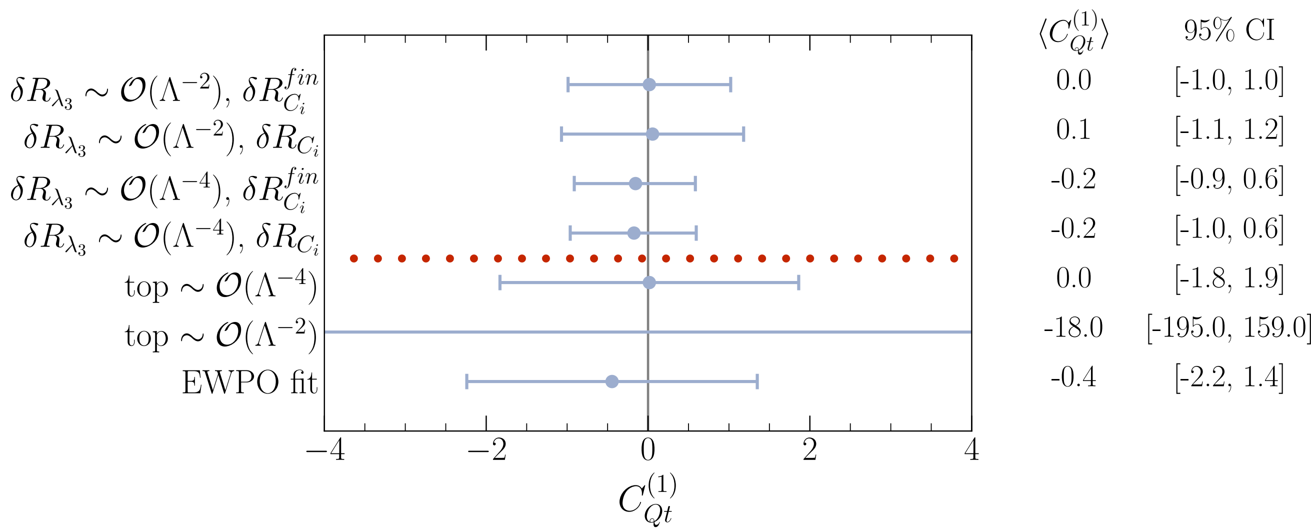
Y_U diag. (If Y_D diag → no bound)

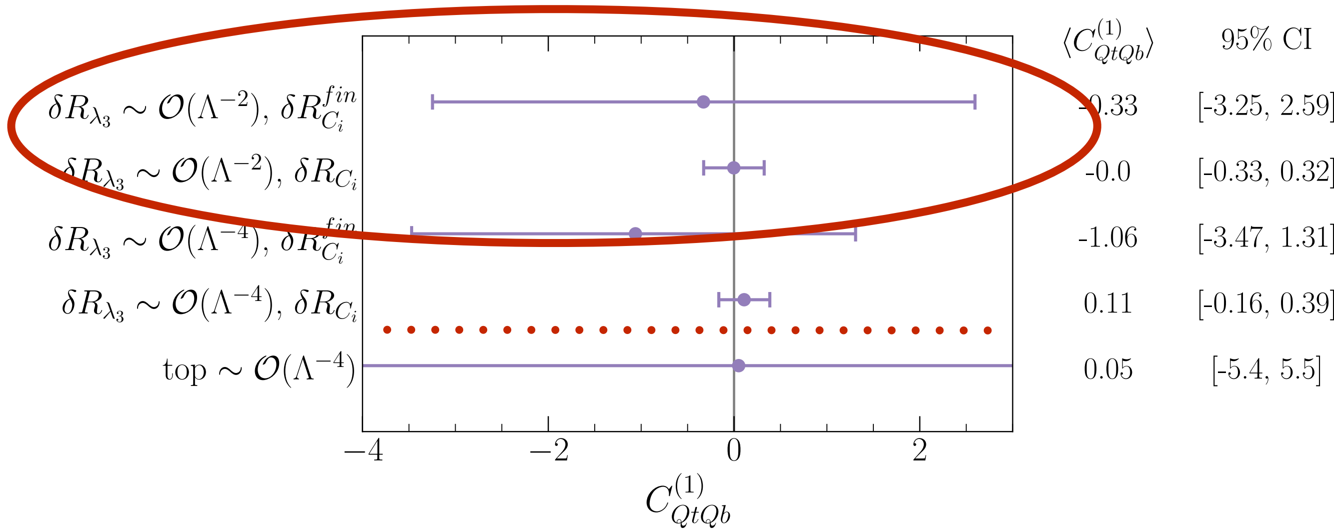
L. Silvestrini and M. Valli, Phys. Lett. B 799 (2019) 135062

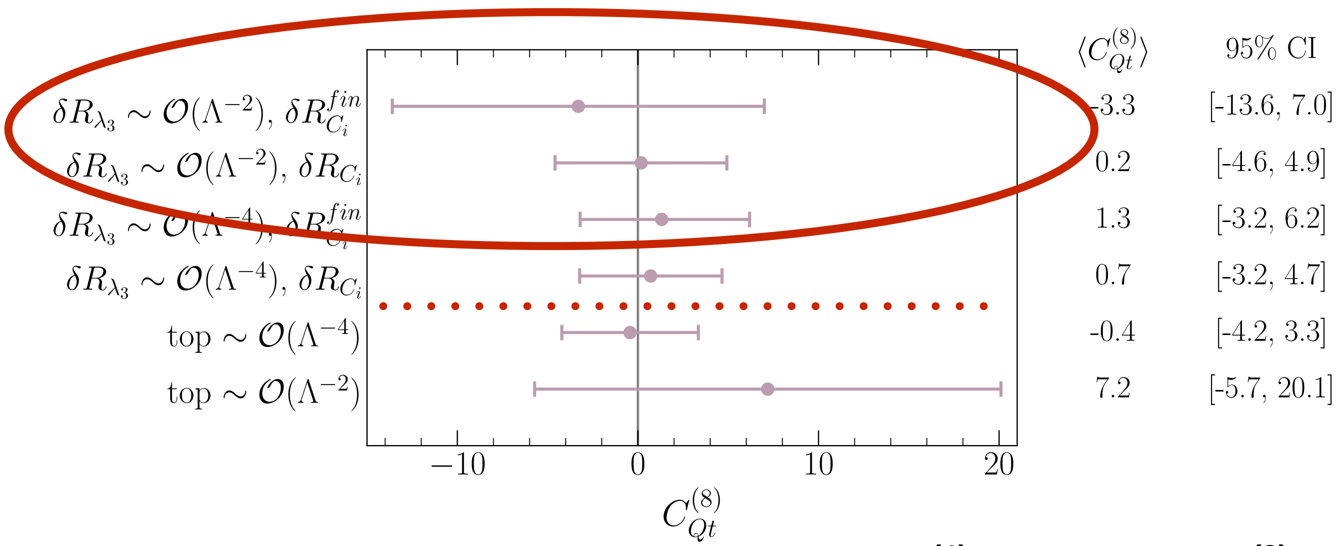
(Toy) Fits to LHC Higgs observables

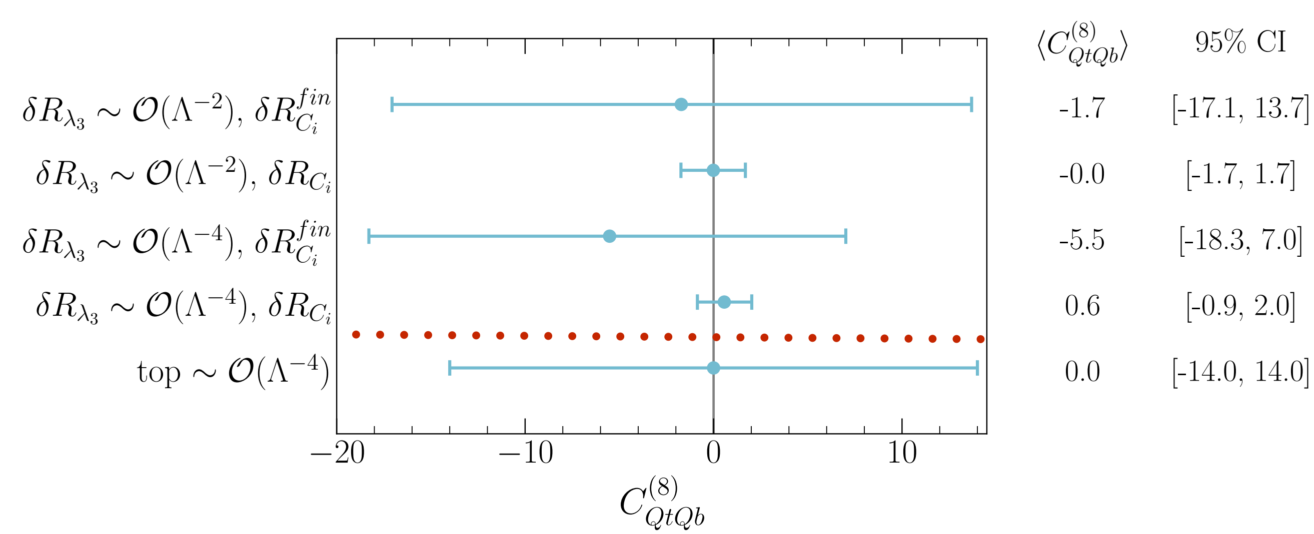
- Toy fits to each 4-Quark operator Wilson coefficient, together with C_ϕ
- Results marginalising over C_ϕ

Finite vs. Logs









(RGE) Flavor bounds: $C_{Qt}^{(1)} \sim \pm 0.73$, $C_{Qt}^{(8)} \sim \pm 2.3$, $C_{QtQb}^{(1)} \sim \pm 2.4$, $C_{QtQb}^{(8)} \sim \pm 10$

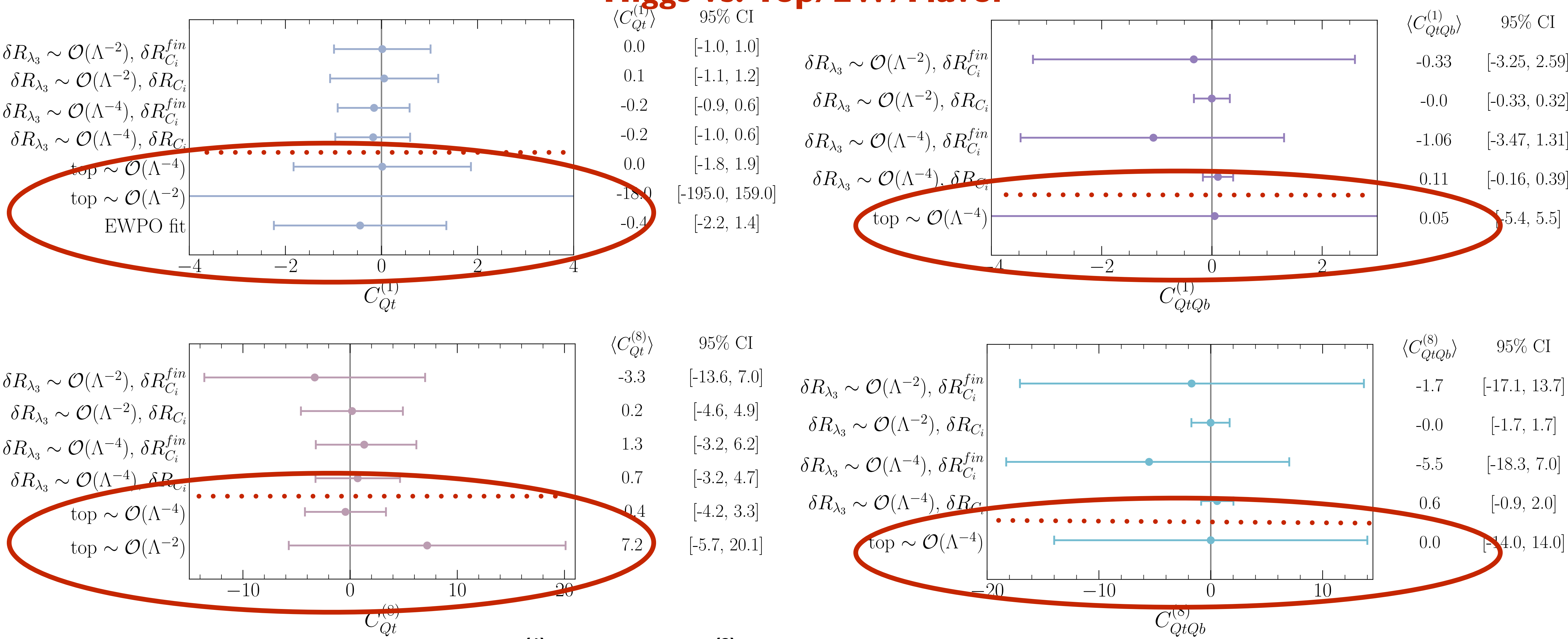
Y_U diag. (If Y_D diag → no bound)

L. Silvestrini and M. Valli, Phys. Lett. B 799 (2019) 135062

(Toy) Fits to LHC Higgs observables

- Toy fits to each 4-Quark operator Wilson coefficient, together with C_ϕ
- Results marginalising over C_ϕ

Higgs vs. Top/EW/Flavor



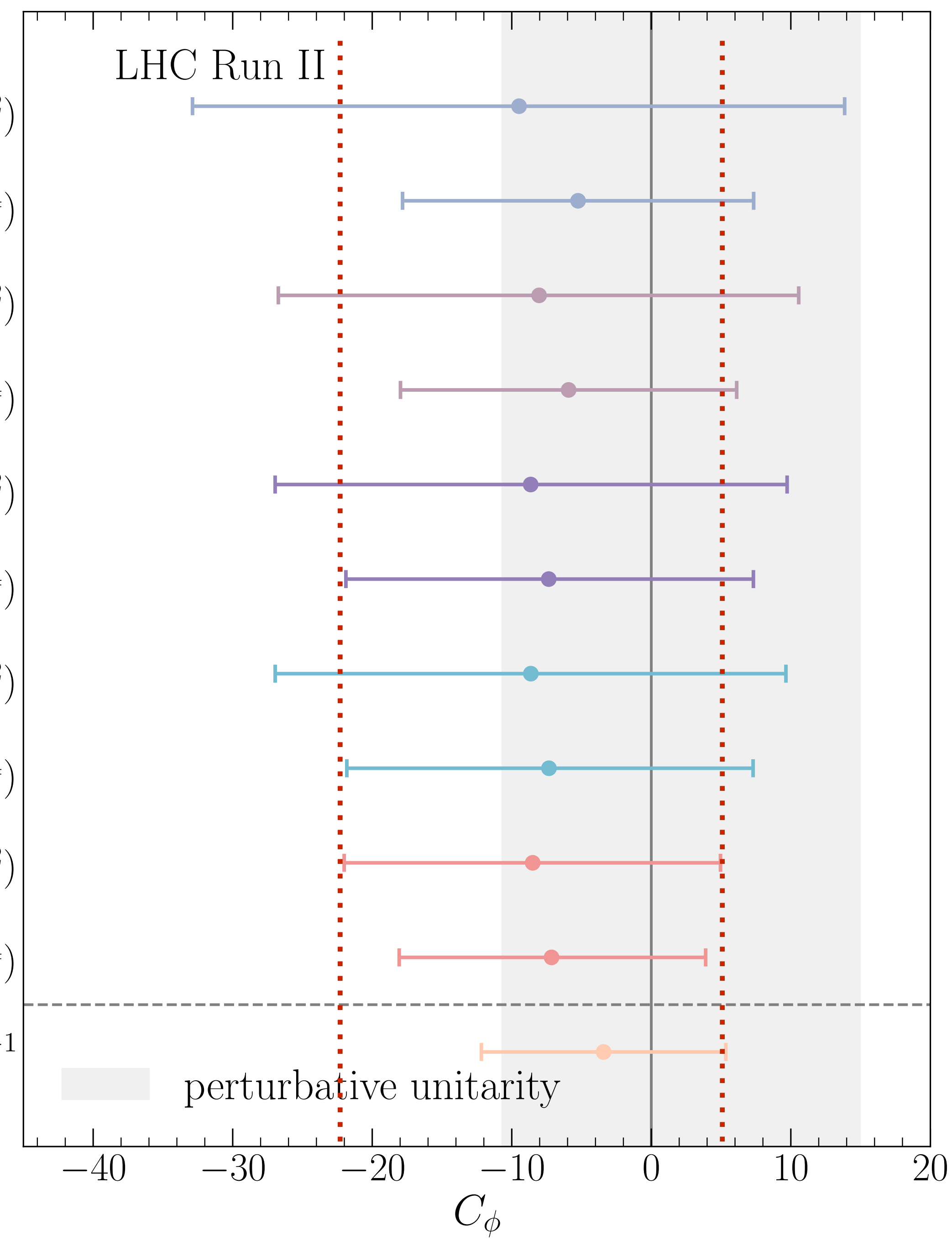
(RGE) Flavor bounds: $C_{Qt}^{(1)} \sim \pm 0.73$, $C_{Qt}^{(8)} \sim \pm 2.3$
$C_{QtQb}^{(1)} \sim \pm 2.4$, $C_{QtQb}^{(8)} \sim \pm 10$

Y_U diag. (If Y_D diag → no bound)

L. Silvestrini and M. Valli, Phys. Lett. B 799 (2019) 135062

(Toy) Fits to LHC Higgs observables

- Toy fits to each 4-Quark operator Wilson coefficient, together with C_ϕ
- Impact on extraction of C_ϕ : Results marginalising over 4-Quark operator

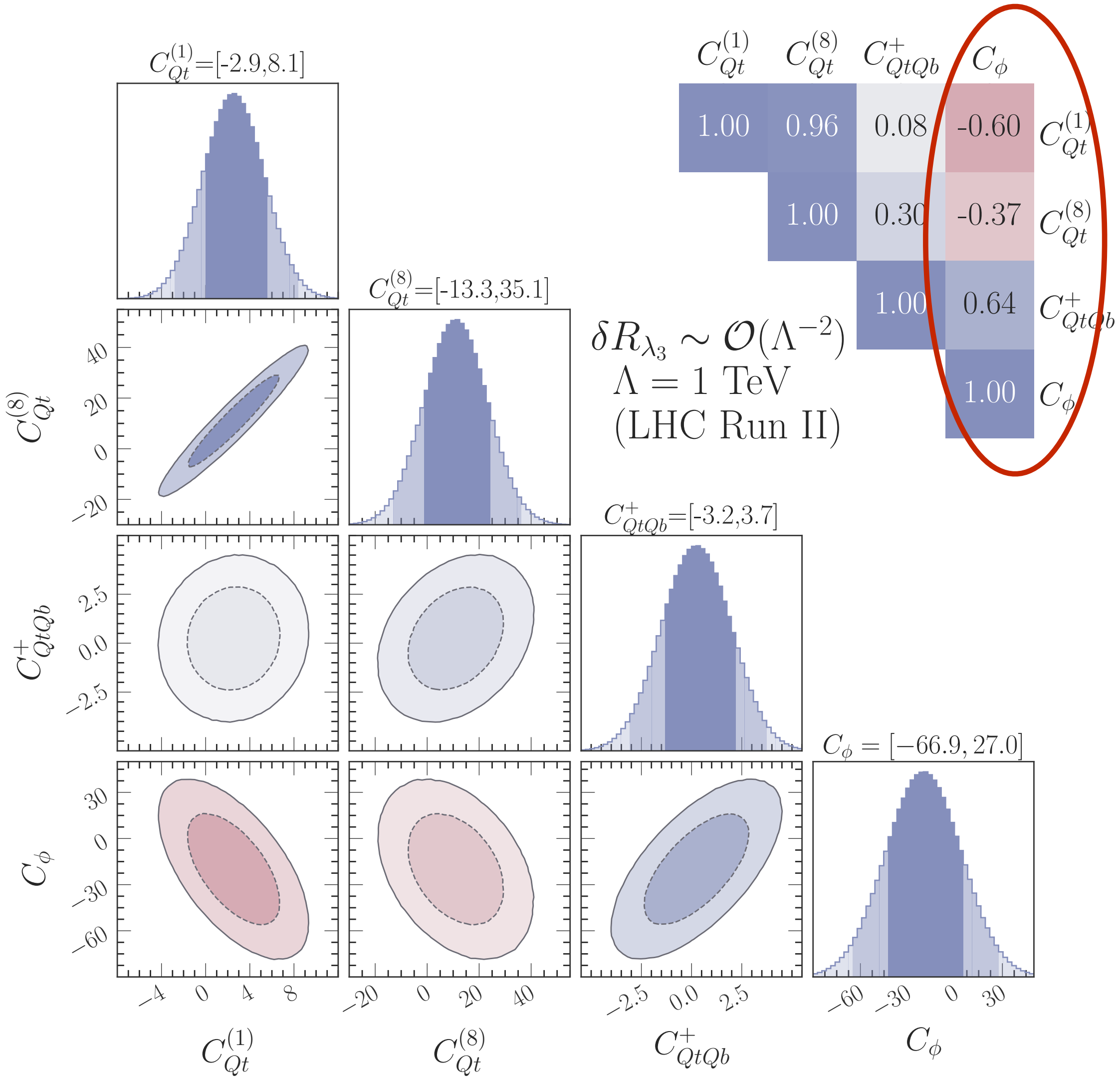


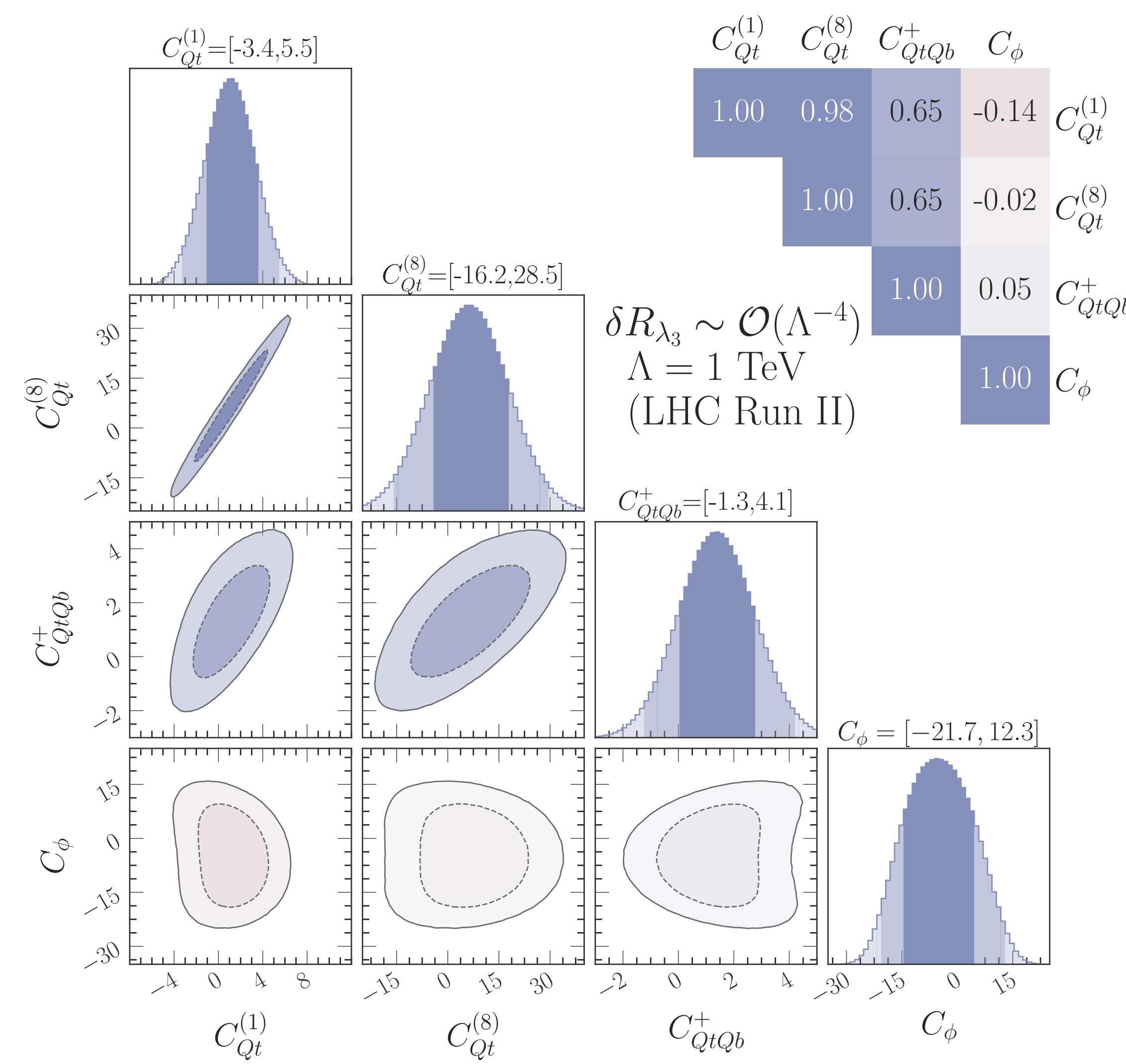
	$\langle C_\phi \rangle$	95% CI
$C_{Qt}^{(1)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-2})$	-9.5	[-32.9, 13.9]
$C_{Qt}^{(1)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-4})$	-5.2	[-17.8, 7.3]
$C_{Qt}^{(8)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-2})$	-8.0	[-26.7, 10.6]
$C_{Qt}^{(8)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-4})$	-5.9	[-18.0, 6.1]
$C_{QtQb}^{(1)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-2})$	-8.6	[-27.0, 9.7]
$C_{QtQb}^{(1)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-4})$	-7.4	[-21.9, 7.3]
$C_{QtQb}^{(8)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-2})$	-8.6	[-27.0, 9.6]
$C_{QtQb}^{(8)}$, $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-4})$	-7.3	[-21.8, 7.3]
single param. fit $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-2})$	-8.5	[-22.0, 5.0]
single param. fit $\delta R_{\lambda_3} \sim \mathcal{O}(\Lambda^{-4})$	-7.1	[-18.1, 3.9]
ATLAS hh 139 fb^{-1}	-3.4	[-12.2, 5.3]

Mild relaxation of bounds on C_ϕ
Somewhat more stable including quadratic corr.

(Toy) Fits to LHC Higgs observables

- Toy fits to 4-Quark operator Wilson coefficients together with C_ϕ
- Impact on extraction of C_ϕ : Correlations with 4-Quark operator





Single operator fit: $C_\phi \sim$ [-22.0, 5.0]

Impact ~3.5x

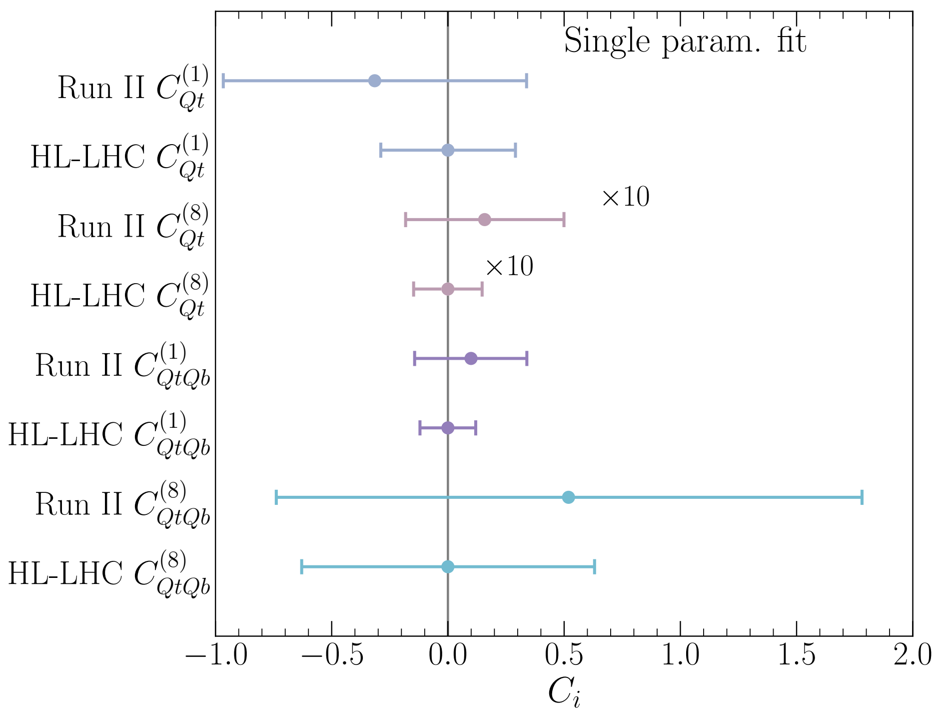
Single operator fit: $C_\phi \sim$ [-18.1, 3.9]

Impact ~1.5x

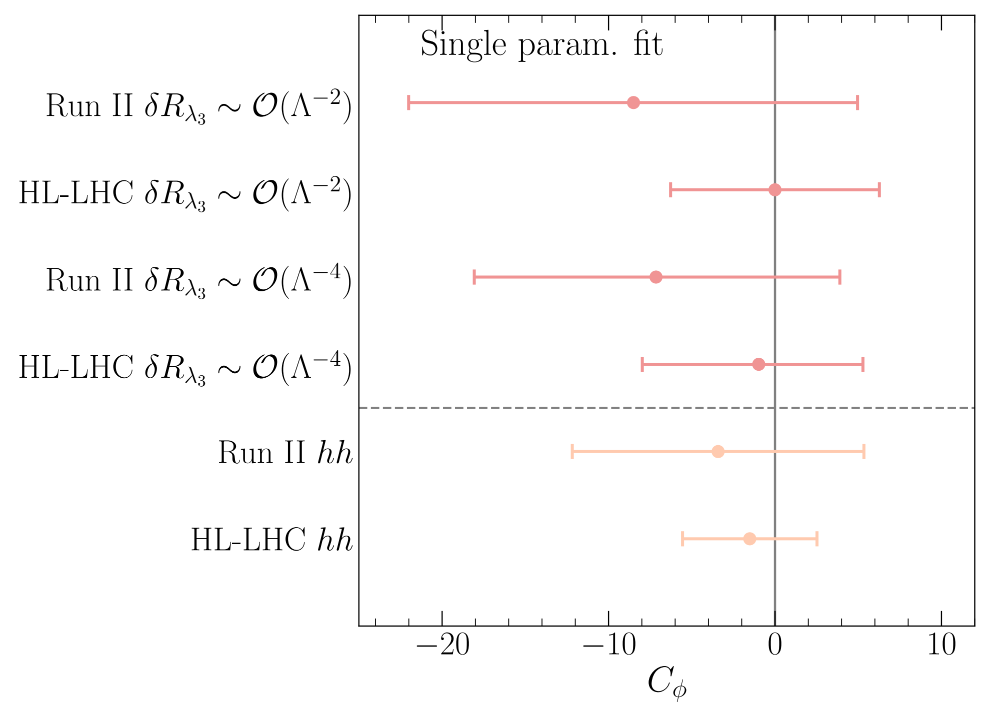
Beyond the LHC

(Toy) Fits to HL-LHC Higgs observables

- Projections at the HL-LHC:
  - ✓ Same considerations apply in terms of the interpretation of single Higgs measurements to obtain h^3
  - ✓ We illustrate the improved constraining power to bound 4-Top operators at HL-LHC, via single parameter fits:



$\langle C_i \rangle$	95% CI
-0.31	[-0.97, 0.34]
0.0	[-0.29, 0.29]
1.58	[-1.82, 4.99]
-0.0	[-1.48, 1.47]
0.1	[-0.14, 0.34]
0.0	[-0.12, 0.12]
0.52	[-0.74, 1.78]
-0.0	[-0.63, 0.63]



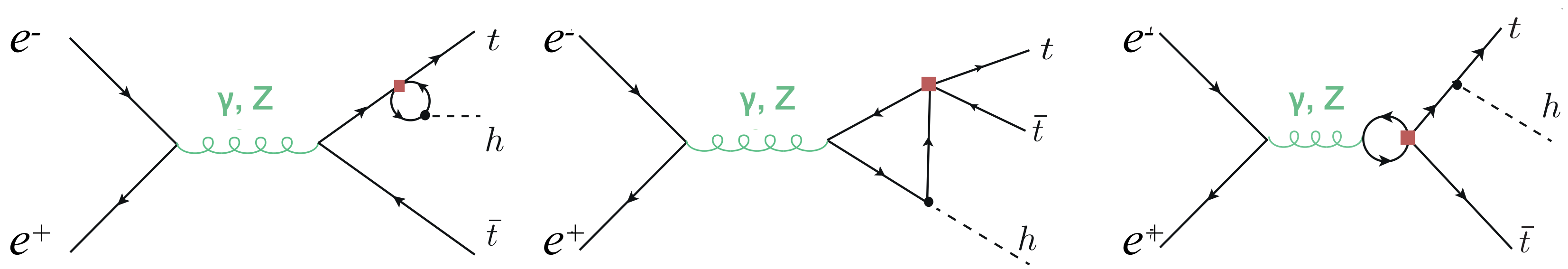
$\langle C_\phi \rangle$	95% CI
-8.5	[-22.0, 5.0]
-0.0	[-6.3, 6.3]
-7.1	[-18.1, 3.9]
-1.0	[-8.0, 5.3]
-3.4	[-12.2, 5.3]
-1.5	[-5.6, 2.5]

Roughly ~2x improvement

Warning: Remember, not a global fit! But can be relevant for BSM scenarios contributing dominantly through these operators

Comments on Future e^+e^- Higgs Factories

- Production at e^+e^- Higgs factories is via electroweak interactions:
  - ✓ Zh and WBF not corrected by 4-Top operators at NLO
  - ✓ Above the tth threshold, however, 4-Top interactions will enter at NLO (as in $qq \to tth$)



- Decay is however affected in the same way as in Hadron colliders…
- …but the possibility of an inclusive measurement of the Zh cross section facilitates the interpretation of Higgs measurements in terms of the h^3 coupling
  - ✓ Currently studying whether is possible to obtain a model independent determination in a global fit (LO + NLO from h^3 and 4-Top ops)
  - ✓ Still a partial result, since other interactions may "contaminate" the NLO determination of the h^3 coupling
    - e.g. 2-lepton 2-Top operators ⇒ Require tt production at lepton collider

Comments on Future e^+e^- Higgs Factories

- …but the possibility of an inclusive measurement of the Zh cross section facilitates the interpretation of Higgs measurements in terms of the h^3 coupling
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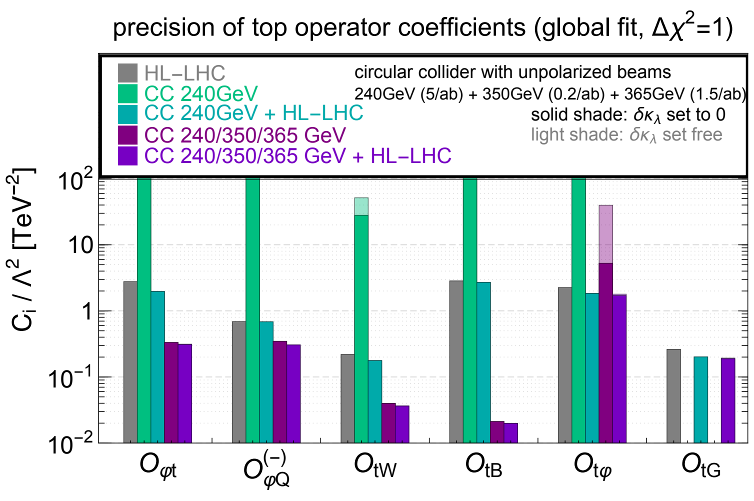
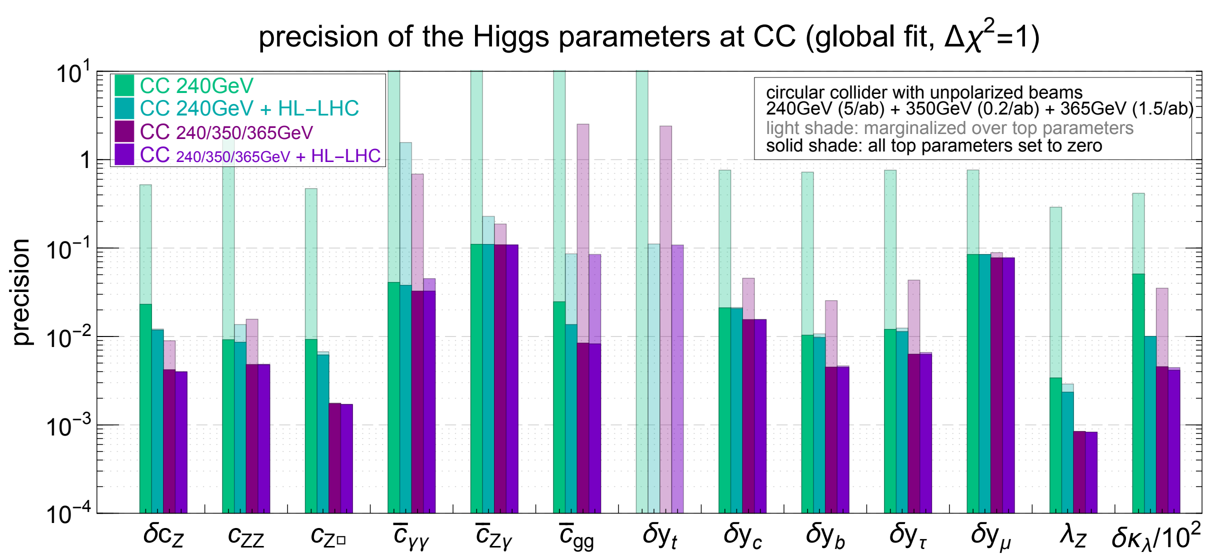
  - ✓ Still a partial result, since other interactions may "contaminate" the NLO determination of the h^3 coupling
    - e.g. 2-lepton 2-Top operators ⇒ Require tt production at lepton collider
    - Studied for (non-4 fermion) Top operators in

G. Durieux, J. Gu, E. Vryonidou, C. Zhang, Chin. Phys. C 42 (2018) 12, 123107

$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,$$
$$O^{(1)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$
$$O^{(3)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q),$$
$$O_{\varphi t} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t),$$
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$
$$O_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$
$$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\,\tilde{\varphi}G^A_{\mu\nu} + h.c..$$





Changes the interpretation of LO/NLO results!

Need more observables ⇒ Is it possible to close a GLOBAL fit in the d-6 SMEFT at NLO ?

Summary and Conclusions

Summary and Conclusions

- Precision measurements provide a powerful tool to test indirectly physics beyond the Standard Model in a Model-Independent (MI) way ⇒ SMEFT

- SMEFT LO → NLO: increase in complexity but may bring sensitivity to several interactions of physical interest, difficult to test directly:
  - ✓ Most famous example is Higgs self-coupling in single Higgs
  - ✓ Proliferation of SMEFT interactions at NLO difficults interpretation unless:
    - It's done within particular scenarios (e.g. only h^3 is generated) ← Not MI
    - All other operators are well constrained experimentally ← Not the case

- Towards SMEFT@NLO interpretation: We evaluated NLO effects of 4-quark operators in single Higgs observables (only another piece of the global picture!):
  - ✓ Sizable effect in LHC observables + poor bounds → Need to be taken into account in NLO SMEFT single-Higgs studies of h^3
  - ✓ Also relevant, via Higgs decays, for physics at future e^+e^- Higgs factories

- In general, many interactions (in particular involving e.g. Top) enter at NLO in single H (and EW) → Difficult to use, in isolation, as robust probes of a particular interaction entering only at NLO (plus can affect LO results!)

1st compute ⇒ Need to close the global fit ⇒ What observables are needed?