Four-fermion operators in Higgs production and decay

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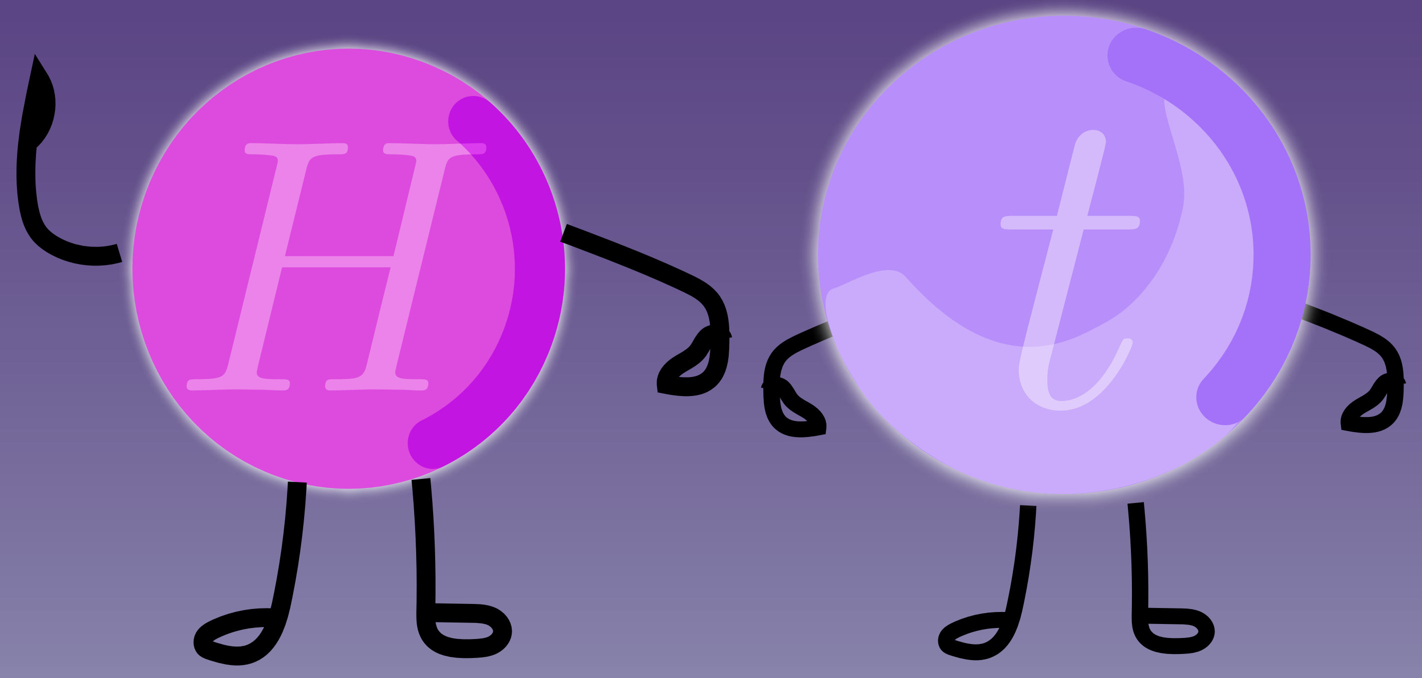
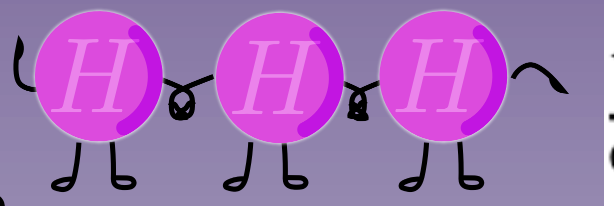


Introduction

There are several operators in the Standard Model effective field theory (SMEFT) that are weakly bounded, e.g.

The operator $\hat{O}_\phi = (\phi^\dagger \phi)^3$ which only modifies the Higgs self-couplings

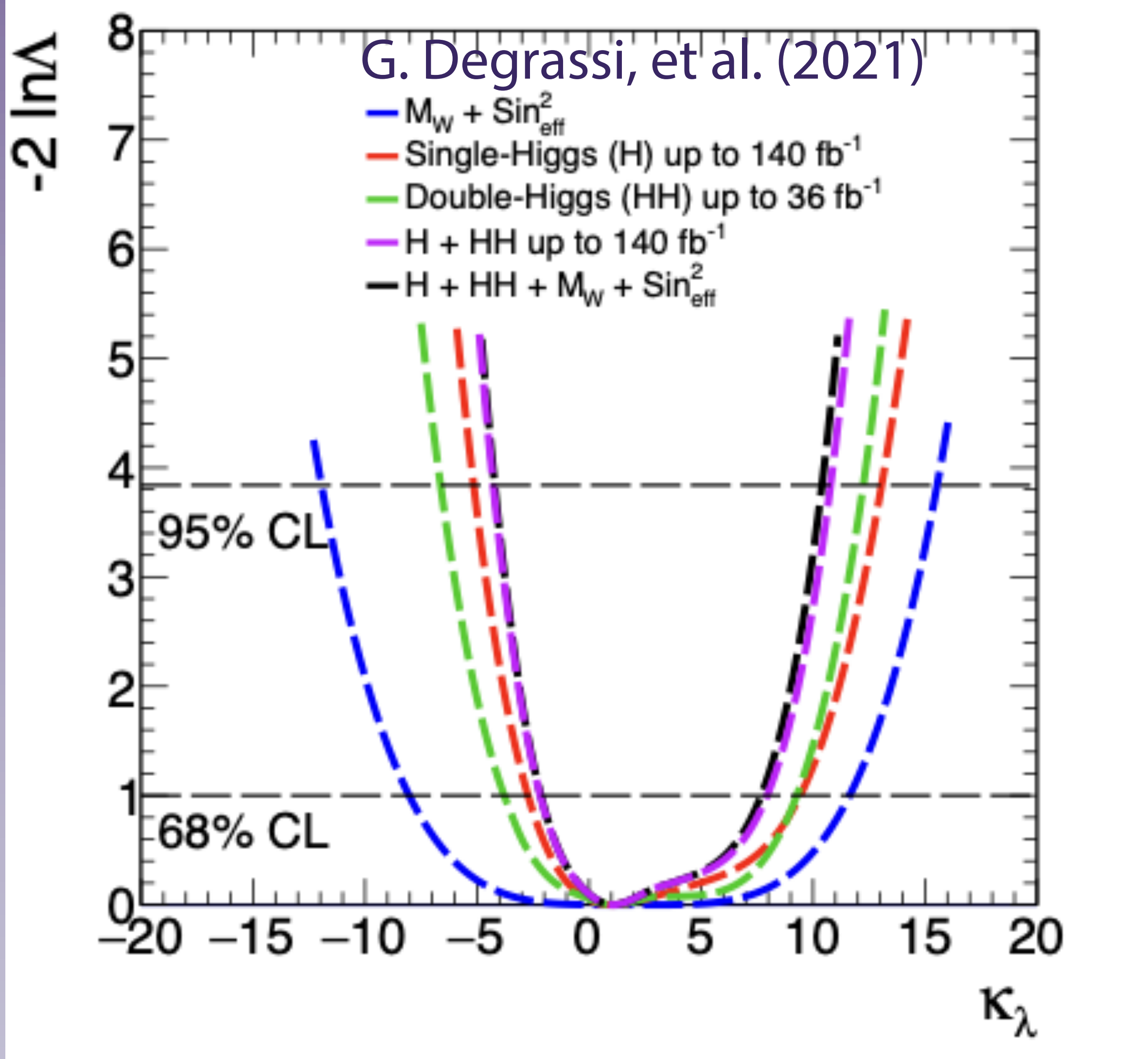


- It can be directly constrained by measuring the Higgs trilinear coupling via HH production.
- It is also possible to set bounds of this operator via loop corrections to single Higgs rates.

W. Bizon et al. (2016) M. Gorbahn and U. Haisch (2016) G. Degrassi et al. (2016)

A Global fit combining EW precision with the Higgs observables has been made to constrain the modification of the trilinear coupling

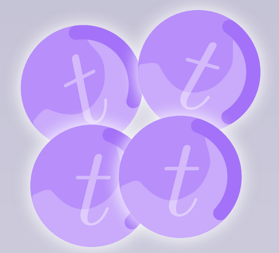
G. Degrassi, et al. (2017) S. Di Vita, et al (2017)
G. D. Kribs, et al. (2017) ATLAS collaboration (2020)
G. Degrassi, et al. (2021)



Four-heavy quarks operators

- These operators can be constrained from top data, e.g. 4 top, or 2 top + 2 jet production.

(ATLAS (2018)- arXiv:1811.12113, CMS (2020)- arXiv:2003.06467)



Global fit from top and EW data is used (usually in the framework of SMEFT) to set bounds on these operators.

See for example :
N. P. Hartland et al (2019),
C. Degrande et al (2020),
J. J. Ethier et al (2021)

What about combining these 2 classes in the same fit ?

Including 4 fermion operators in Higgs observables

Working in the SMEFT, Warsaw basis. We have the following dim-6 operators contributing to radiative Higgs processes (e.g. ggF, diphoton decays)

- For the Higgs

Modifies the trilinear coupling

$$\mathcal{L} = \frac{C_{\phi,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{\phi,D}}{\Lambda^2}(\phi^\dagger D^\mu\phi)^*(\phi^\dagger D_\mu\phi) + \frac{C_\phi}{\Lambda^2}(\phi^\dagger\phi)^3 + \frac{C_{\phi G}}{\Lambda^2}\phi^\dagger\phi G^A_{\mu\nu}G^{A,\mu\nu} + \frac{C_{\phi B}}{\Lambda^2}\phi^\dagger\phi B_{\mu\nu}B^{\mu\nu} + \frac{C_{\phi W}}{\Lambda^2}\phi^\dagger\phi W^a_{\mu\nu}W^{\mu\nu,a}$$
$$+ \left(\frac{C_{u\phi}}{\Lambda^2}\phi^\dagger\phi\,\bar{Q}_L\tilde{\phi}\,t_R + \frac{C_{d\phi}}{\Lambda^2}\phi^\dagger\phi\,\bar{Q}_L\phi\,b_R + h.c\right)$$

- In addition, the four fermion operators which we are considering for this work

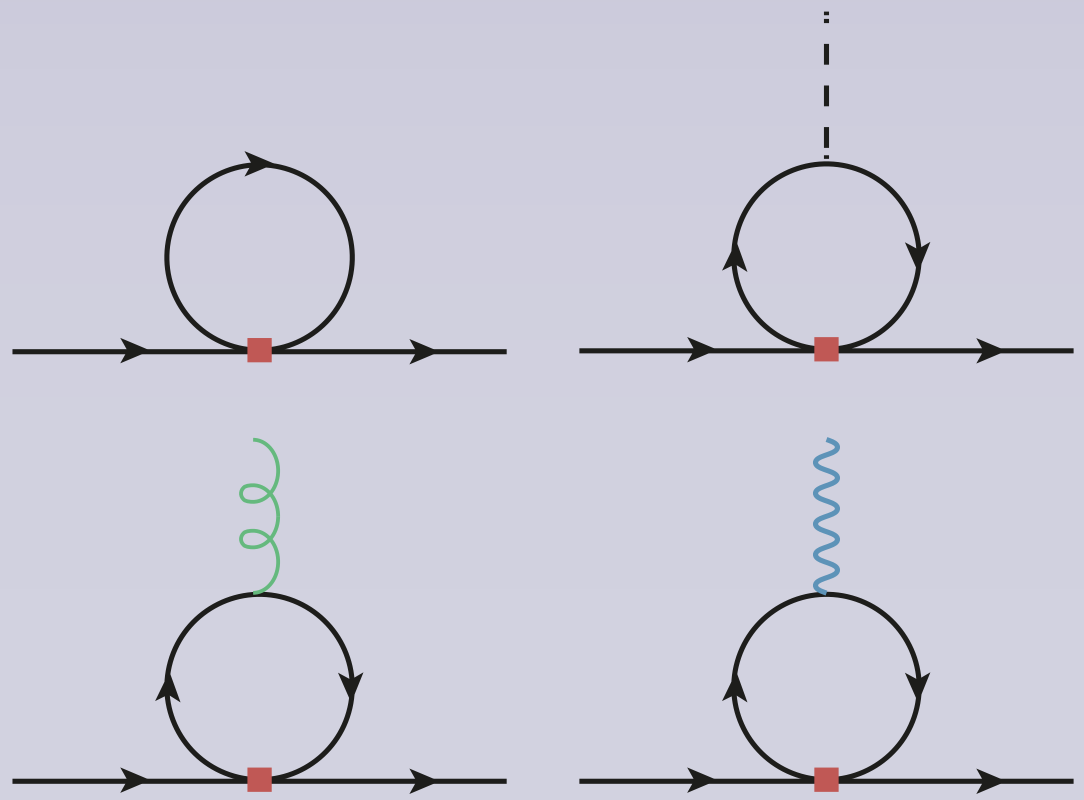
$$\hat{O}^{(1)}_{tt} := (\bar{t}_R\gamma_\mu t_R)(\bar{t}_R\gamma^\mu t_R)$$

$$\hat{O}^{(1)}_{QQ} := (\bar{Q}_L\gamma_\mu Q_L)(\bar{Q}_L\gamma^\mu Q_L)$$
$$\hat{O}^{(3)}_{QQ} := (\bar{Q}_L\sigma_a\gamma_\mu Q_L)(\bar{Q}_L\sigma_a\gamma^\mu Q_L)$$

$$\hat{O}^{(1)}_{Qt} := (\bar{Q}_L\gamma_\mu Q_L)(\bar{t}_R\gamma^\mu t_R)$$
$$\hat{O}^{(8)}_{Qt} := (\bar{Q}_L T^A\gamma_\mu Q_L)(\bar{t}_R T^A\gamma^\mu t_R)$$

$$\hat{O}^{(1)}_{QtQb} := (\bar{Q}_L t_R)i\sigma_2(\bar{Q}^{\mathrm{T}}_L b_R)$$
$$\hat{O}^{(8)}_{QtQb} := (\bar{Q}_L T^A t_R)i\sigma_2(\bar{Q}^{\mathrm{T}}_L T^A b_R)$$

Operators with opposite chirality enter in the NLO corrections of single Higgs rates via these diagrams



While operators with the same chirality enter in finite contributions, e.g. triangles and boxes.

RGE analysis

The top Yukawa gets modified by the SMEFT dim (6) Lagrangian

$$-\mathcal{L}_{\phi tt} = y_t\, \bar{t}_R \tilde{\phi} q_L + \frac{C_{t\phi}}{\Lambda^2} \phi\phi^\dagger\, \bar{t}_R \tilde{\phi} q_L \ \text{h.c.} \quad \longrightarrow \quad m_t = \frac{v}{\sqrt{2}} \left(y_t - \frac{v^2}{\sqrt{2}} \frac{C_{t\phi}}{\Lambda^2} \right). \qquad v = 246\,\text{GeV}$$

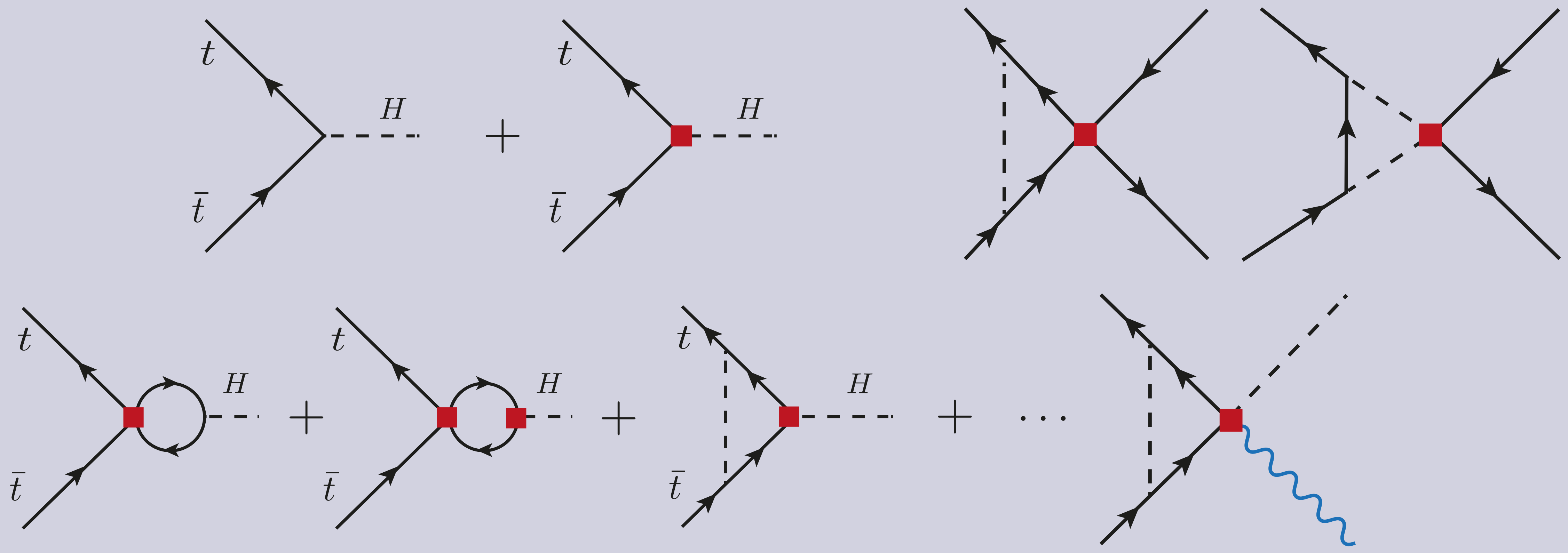
Now, consider NLO corrections to the top Yukawa, we get also contributions from other SMEFT operators E. Jenkins, A. Manohar & M. Trott (2013,2014)

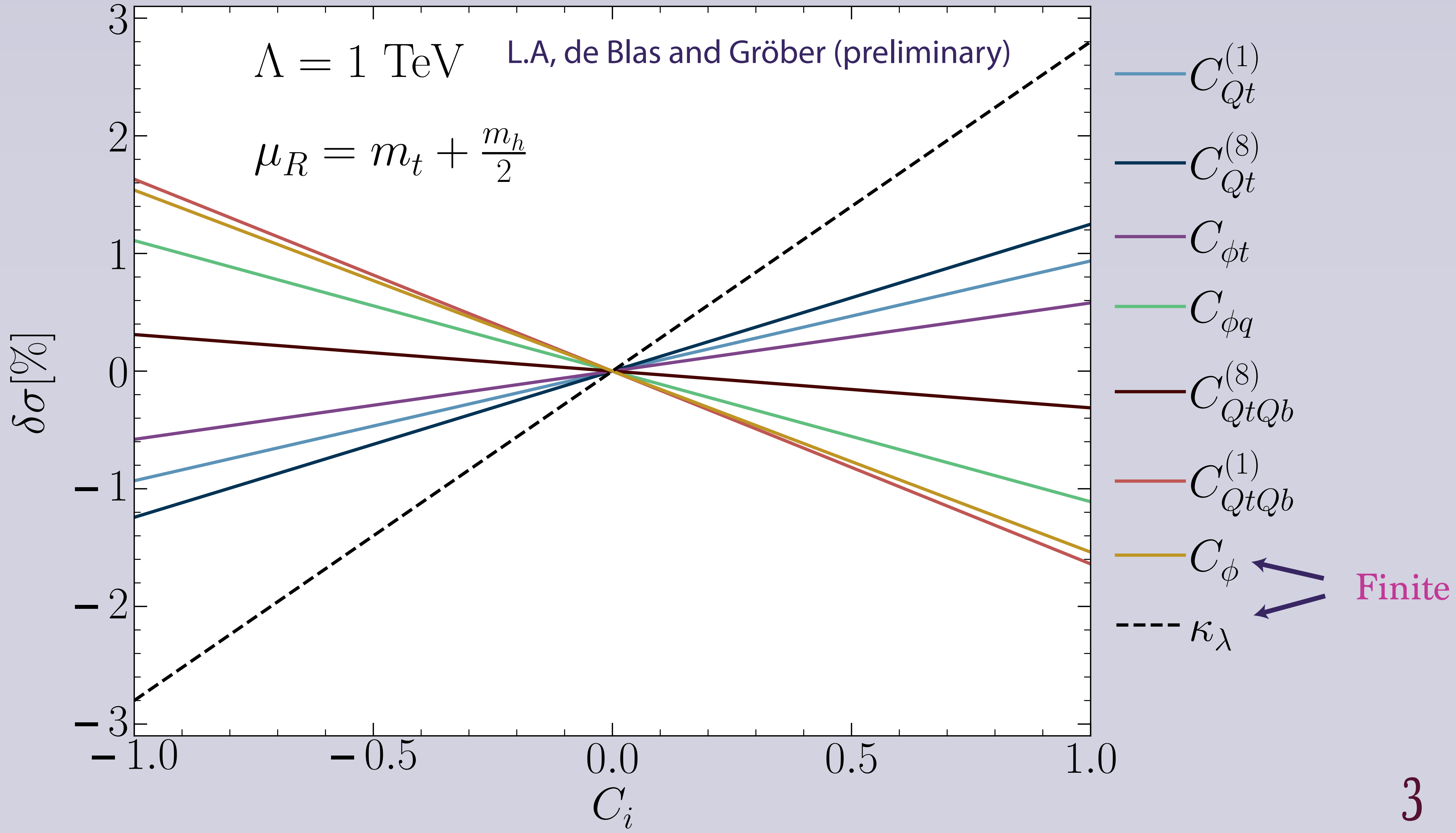
$$\mu \frac{dC_{t\phi}}{d\mu} = \frac{y_t^2}{16\pi^2} \left(2N_c C_{t\phi} - 2 \left(C^{(1)}_{\phi Q} + (3 - 4N_c) C^{(3)}_{\phi Q} \right) y_t + 2C_{\phi t}\, y_t + C_{\phi t}\, y_t \right.$$
$$\left. +8 \left(C^{(1)}_{Qt} + \langle C_F \rangle C^{(8)}_{Qt} \right) y_t \right)$$

Operators of same chirality only have finite contributions

Similar story for the beauty Yukawa,

$$\mu \frac{dC_{b\phi}}{d\mu} = \frac{y_t^2}{16\pi^2} \left(-2 \left((2N_c + 1)\, C^{(1)*}_{QtQb} + \langle C_F \rangle C^{(8)*}_{QtQb} \right) y_t \right)$$





Full NLO calculations

We define the percent change in the rates δR

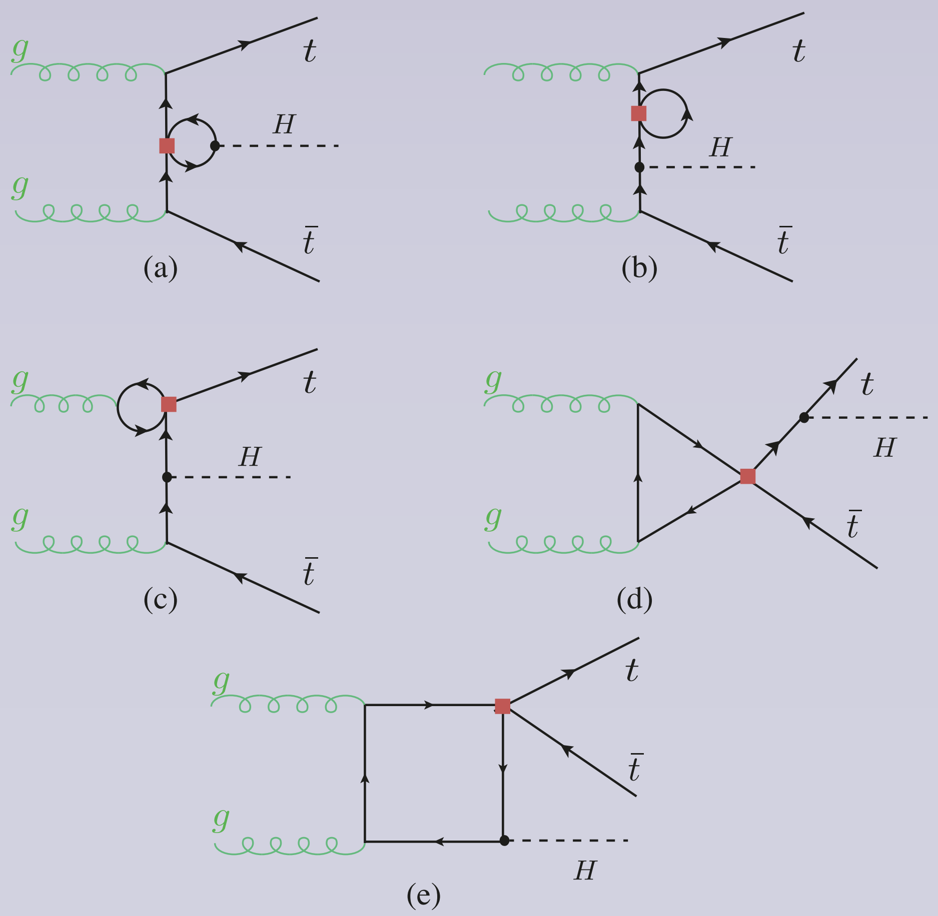
The leading log is not sufficient for accurate results, as the finite contributions are usually sizable. Moreover, operators having the same chirality have finite contributions only.

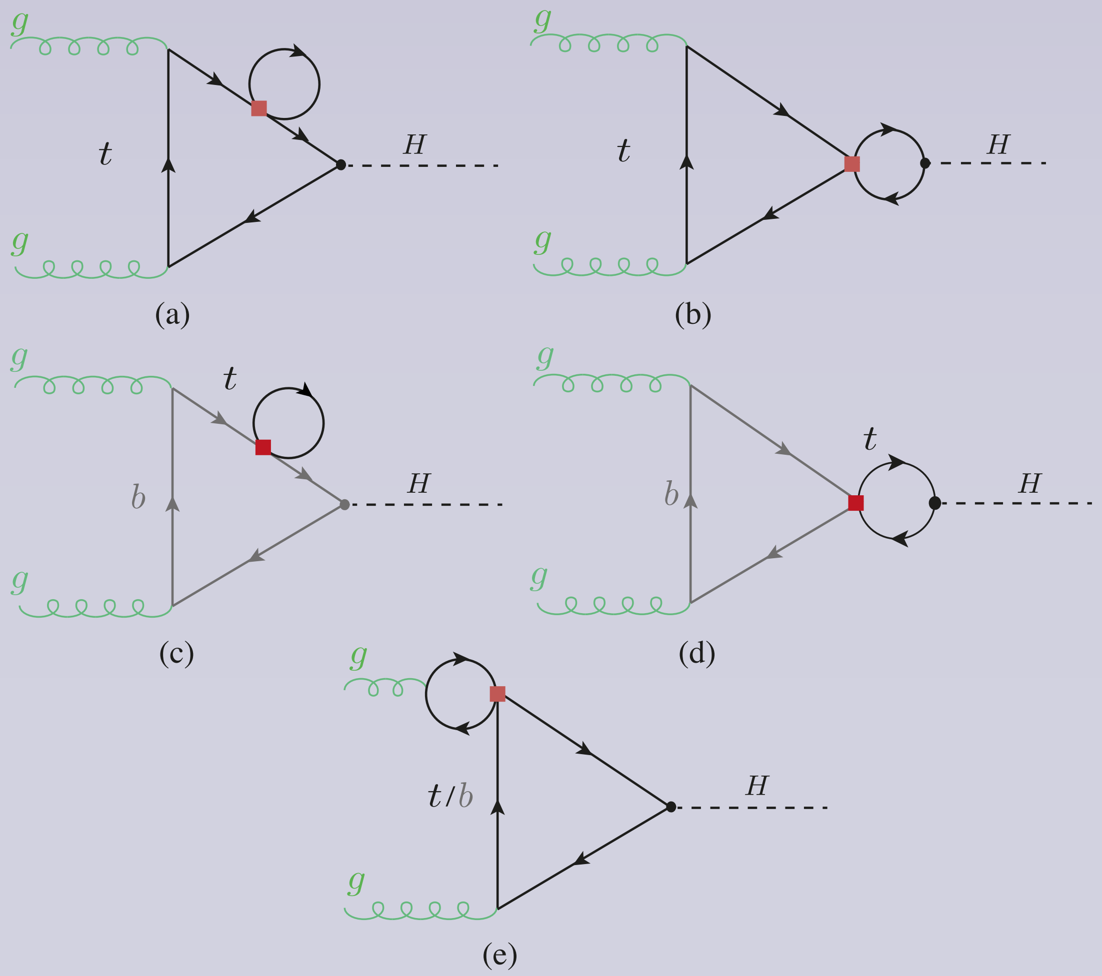
$$\delta\sigma = \frac{\sum_{ij}\int dx_1 dx_2 f_i(x_1) f_j(x_2) 2\Re(\mathcal{M}_{NLO}(C_i)\mathcal{M}_{LO})}{\sum_{ij}\int dx_1 dx_2 f_i(x_1) f_j(x_2) |\mathcal{M}_{LO}|^2},$$

$$\delta\Gamma = \frac{\int d\Phi 2\Re(\mathcal{M}_{NLO}(C_i)\mathcal{M}_{LO})}{\int d\Phi |\mathcal{M}_{LO}|^2}.$$

G. Degrassi et al. (2016)

The NLO matrix elements are calculated for ggF, ttH and Higgs decays to photons and b quarks



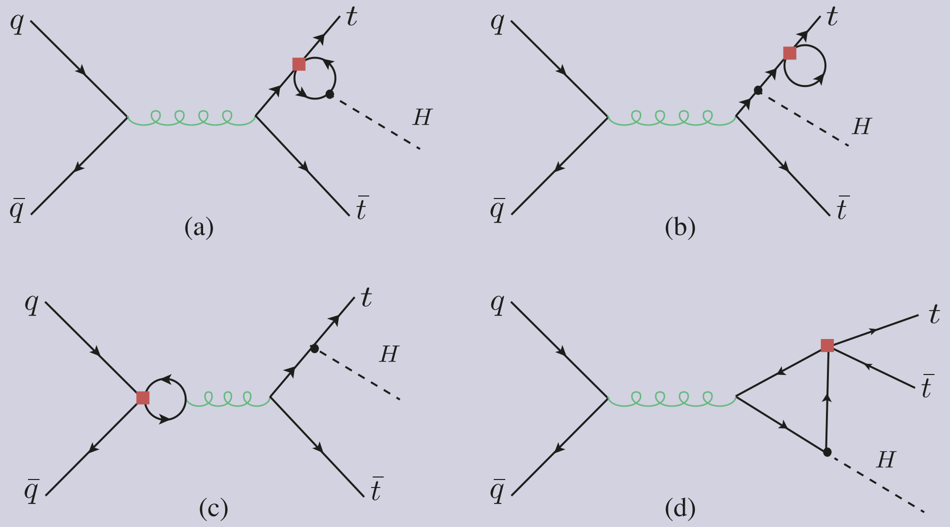


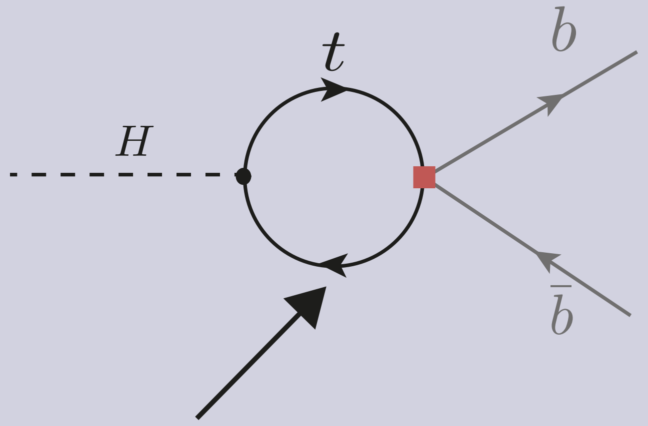
$\delta R(C_i)\cdot 10^{-2}$	$C_{Qt}^{(1)}$	$C_{Qt}^{(8)}$	$C_{QtQb}^{(1)}$	$C_{QtQb}^{(8)}$	$C_{tt}^{(1)}$	$C_{QQ}^{(1)}$	$C_{QQ}^{(8)}$
ggF/ $gg \to h$	0.950	1.267	-2.230	-0.425	0.000	0.000	0.000
$t\bar{t}h$	-1.000	0.243	Work in progress		0.266	0.169	0.259
$h \to \gamma\gamma$	-0.291	-0.388	0.173	0.033	0.000	0.000	0.000
$h \to b\bar{b}$	0.000	0.000	-59.035	-11.029	0.000	0.000	0.000

G. Degrassi et al. (2016)

$\delta R(C_i)\cdot 10^{-2}$	C_ϕ
ggF/ $gg \to h$	-0.31
$t\bar{t}h$	-1.64
$gg \to \gamma$	-0.23
$gg \to b\bar{b}$	0.00
$gg \to W^+W^-$	-0.34
$gg \to ZZ$	-0.39
$pp \to Zh$	-0.56
$pp \to W^\pm h$	-0.48
VBF	-0.30

For ttH, we used MadGraph SMEFT@NLO for cross checks C. Degrande et al (2020).





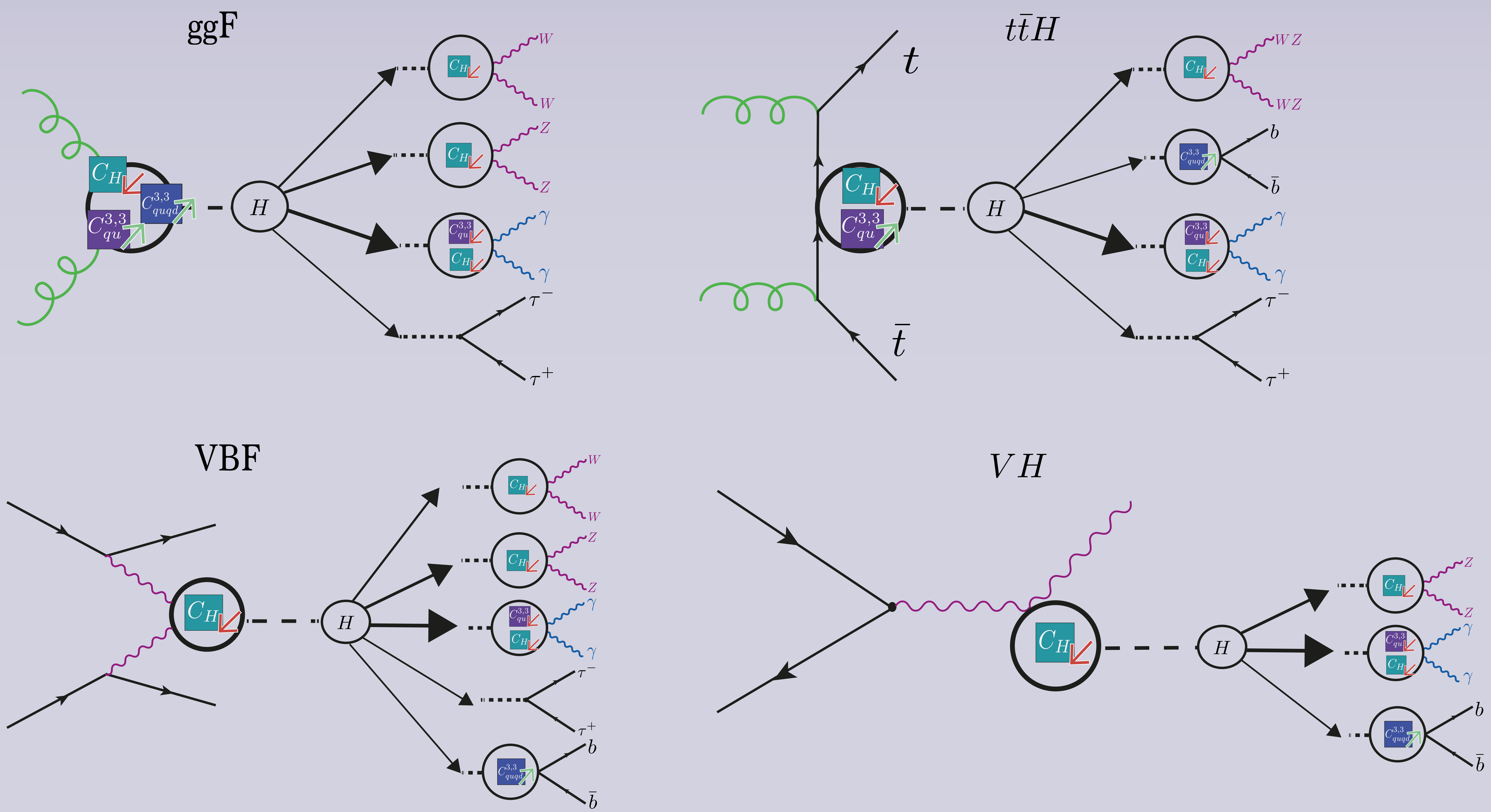
Cross checked with R.Gauld, B. Pecjak, and D. Scott (2016)

Fit to experimental results

Higgs data are from CMS and ATLAS $\sqrt{s} = 13\,\mathrm{TeV},\;\; 80\,\mathrm{fb}^{-1}$

CMS JHEP 11 (2019) 082 and ATLAS Phys. Rev. D 101 (2020) 012002

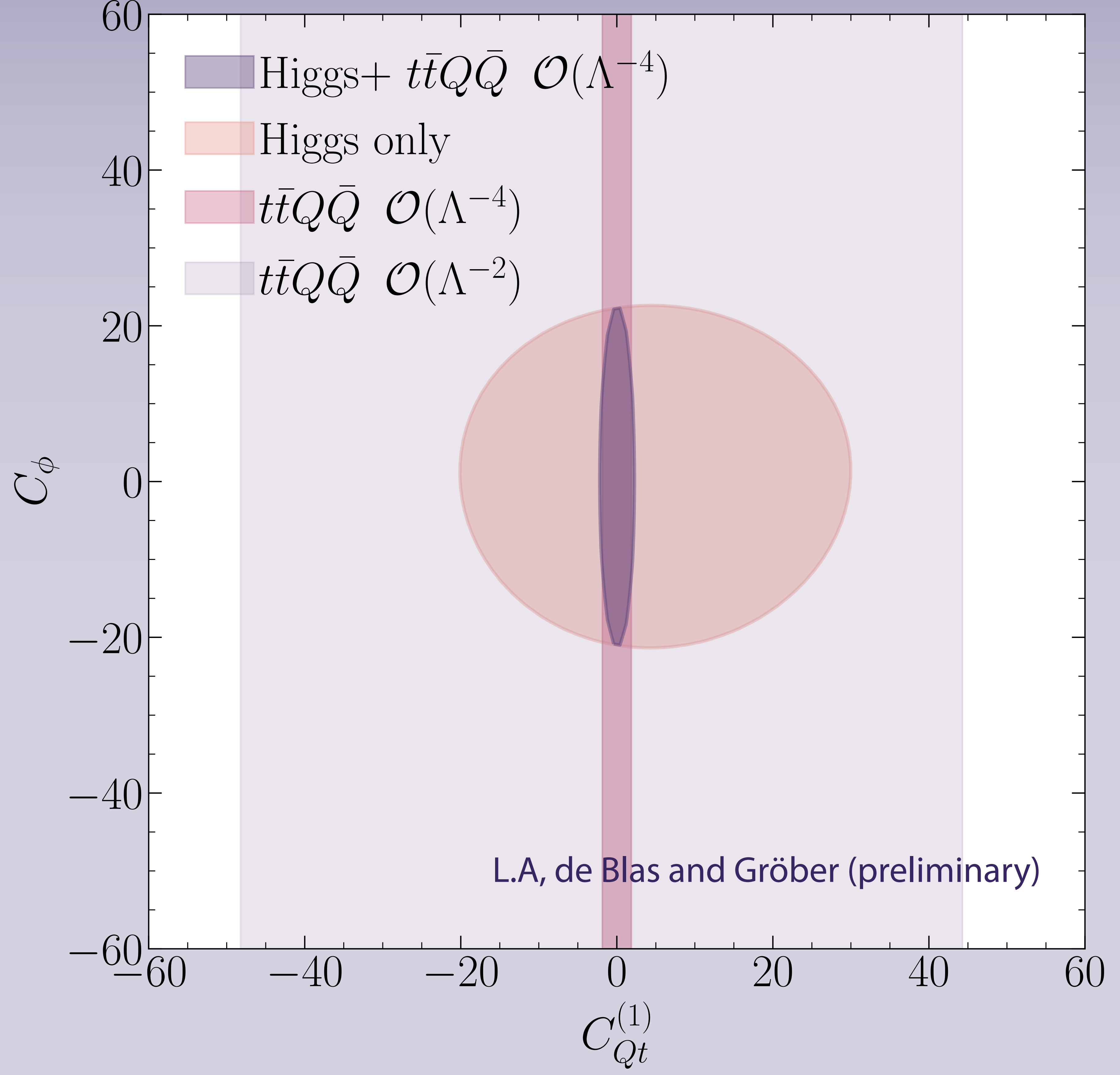
Top data, global fits taken from J. J. Ethier et al (2021)

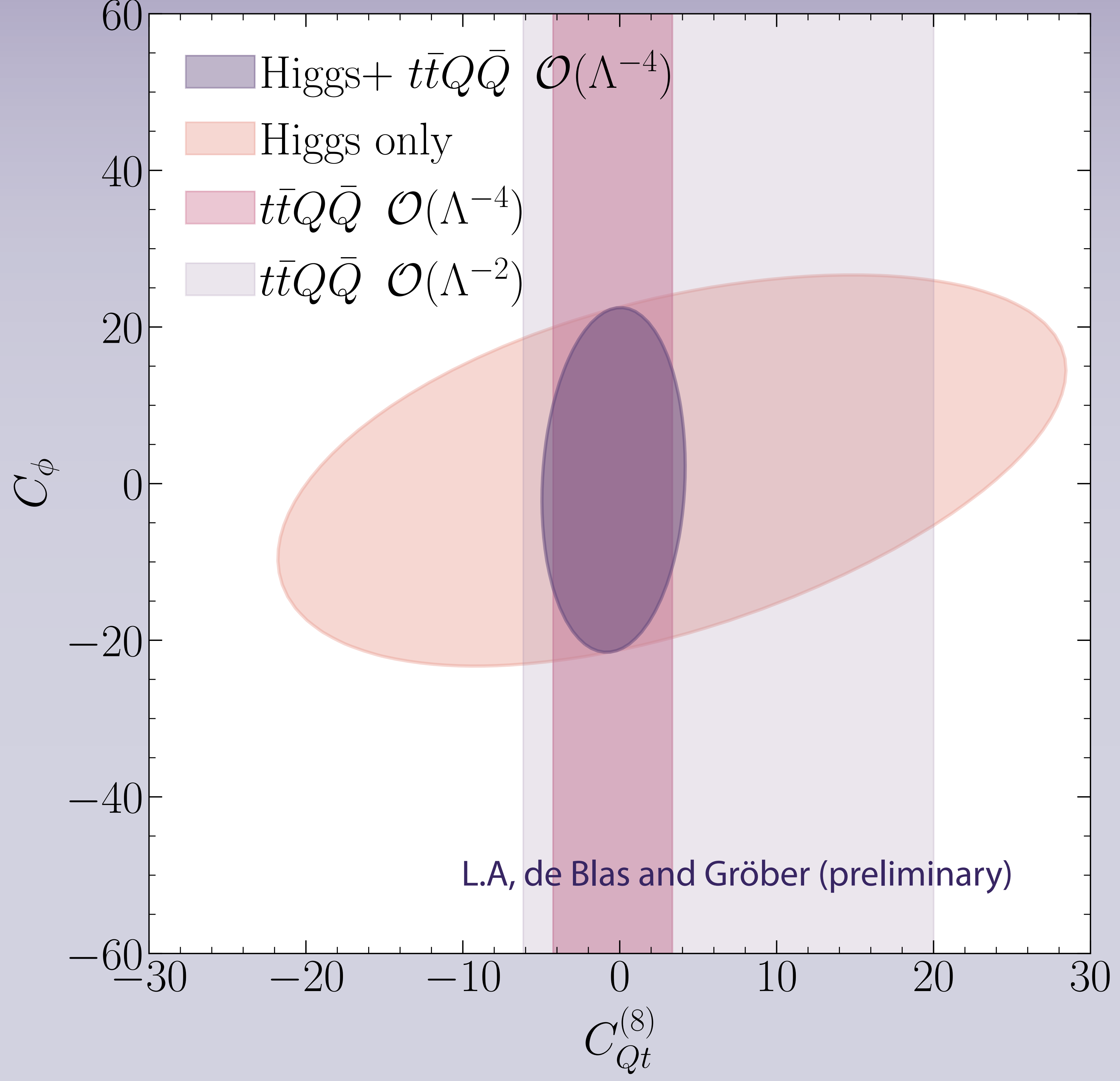


	Observable	value	uncertainty
ggF	$\mu(h \to \gamma\gamma)$	0.960	0.140
	$\mu(h \to ZZ)$	1.045	0.155
	$\mu(h \to W^+W^-)$	1.080	0.190
	$\mu(h \to \tau^+\tau^-)$	0.995	0.550
VBF	$\mu(h \to \gamma\gamma)$	1.390	0.375
	$\mu(h \to ZZ)$	2.680	0.970
	$\mu(h \to W^+W^-)$	0.595	0.357
	$\mu(h \to \tau^+\tau^-)$	1.181	0.591
	$\mu(h \to b\bar{b})$	2.990	1.667
$t\bar{t}h$	$\mu(h \to \gamma\gamma)$	1.100	0.410
	$\mu(h \to VV)$	1.492	0.590
	$\mu(h \to \tau^+\tau^-)$	1.389	1.117
	$\mu(h \to b\bar{b})$	0.792	0.586
Vh	$\mu(h \to \gamma\gamma)$	1.101	0.573
	$\mu(h \to ZZ)$	0.682	1.193
	$\mu(h \to b\bar{b})$	1.188	0.267

Fit Results (preliminary)

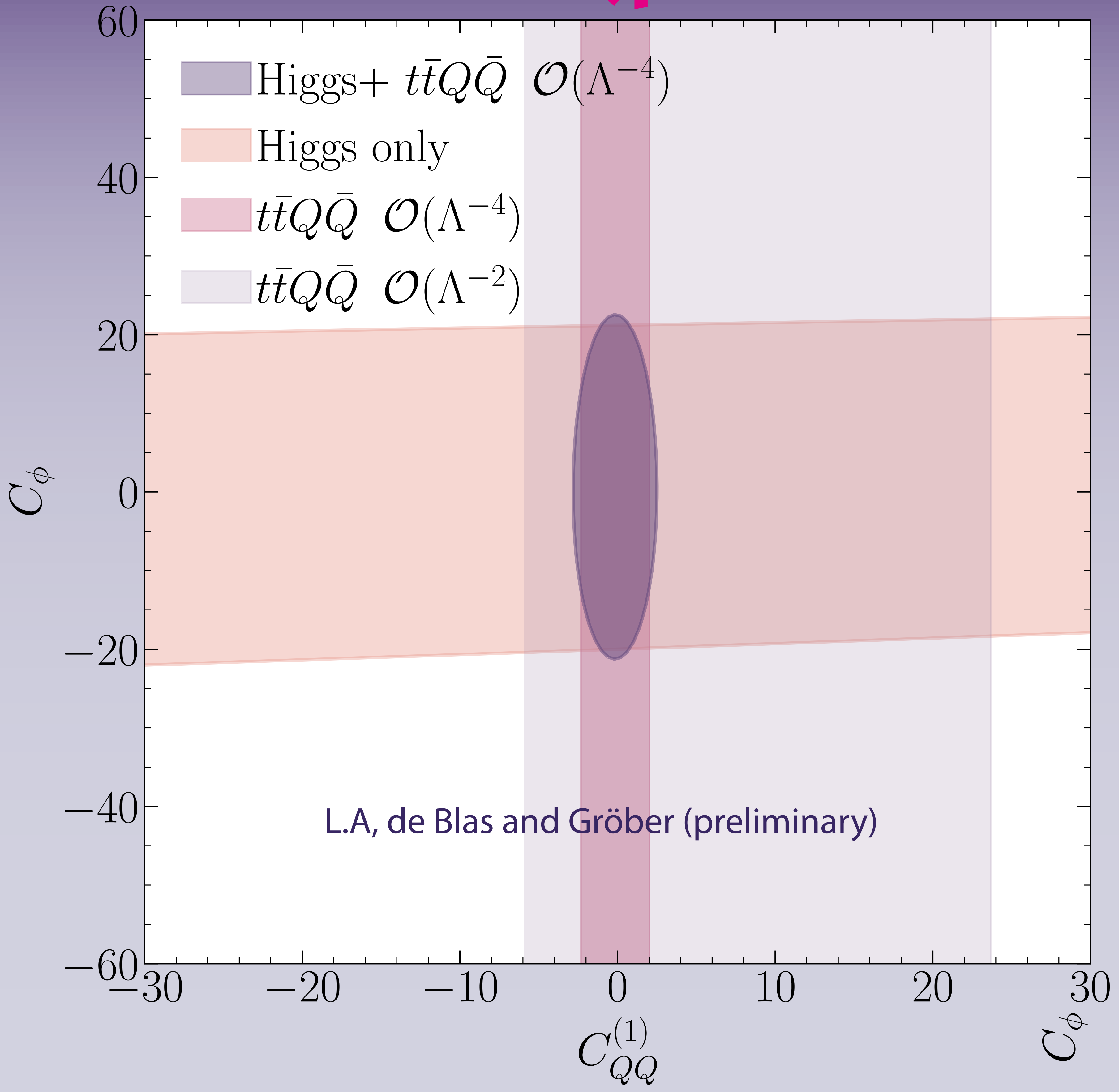
We use Pearson's Chi squared test statistics, to preform the 2D fit. $\chi^2 = \frac{1}{N_{d.o.f}} \sum_i \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$ $\quad \mu_i = 1 + \delta\sigma_i \times \delta\mathcal{B}_i$, $\quad \delta\mathcal{B}_i = \frac{\delta\Gamma_i}{\Gamma_h + \delta\Gamma_h}$

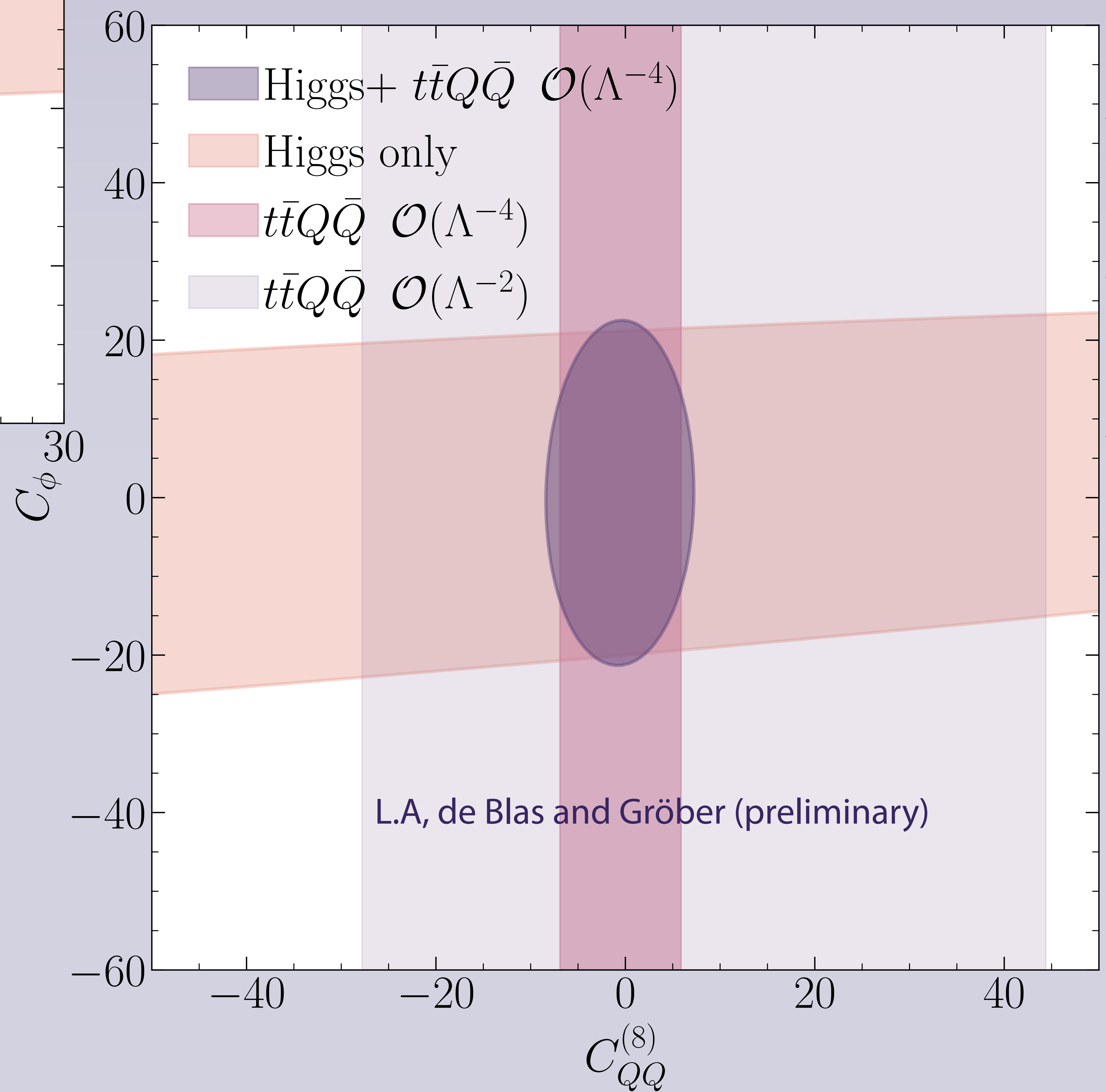


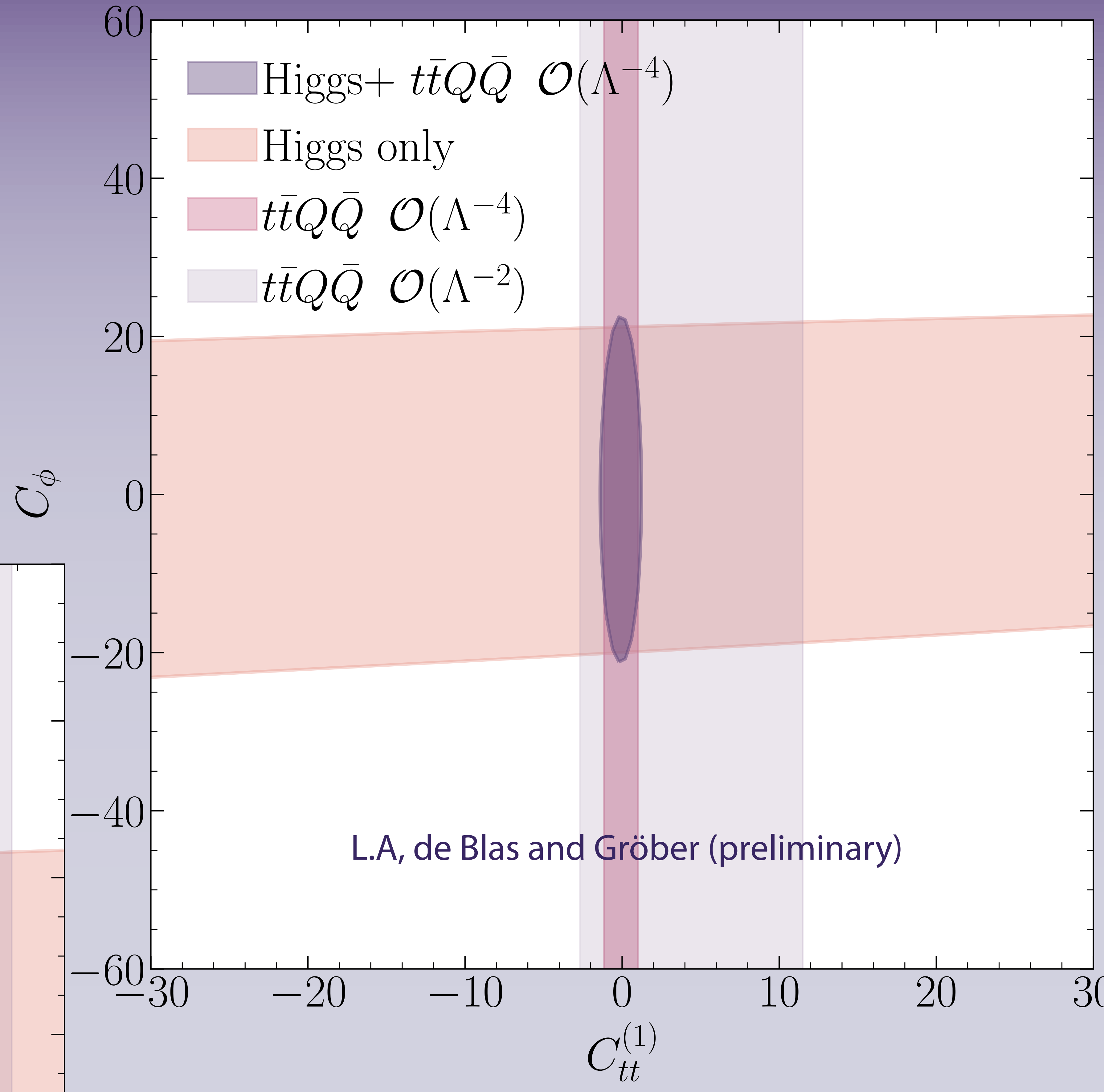


The Higgs data alone is better at constraining $C_{Qt}^{(1)}$ than the conservative (linear EFT) top data.

Fit Results (preliminary)





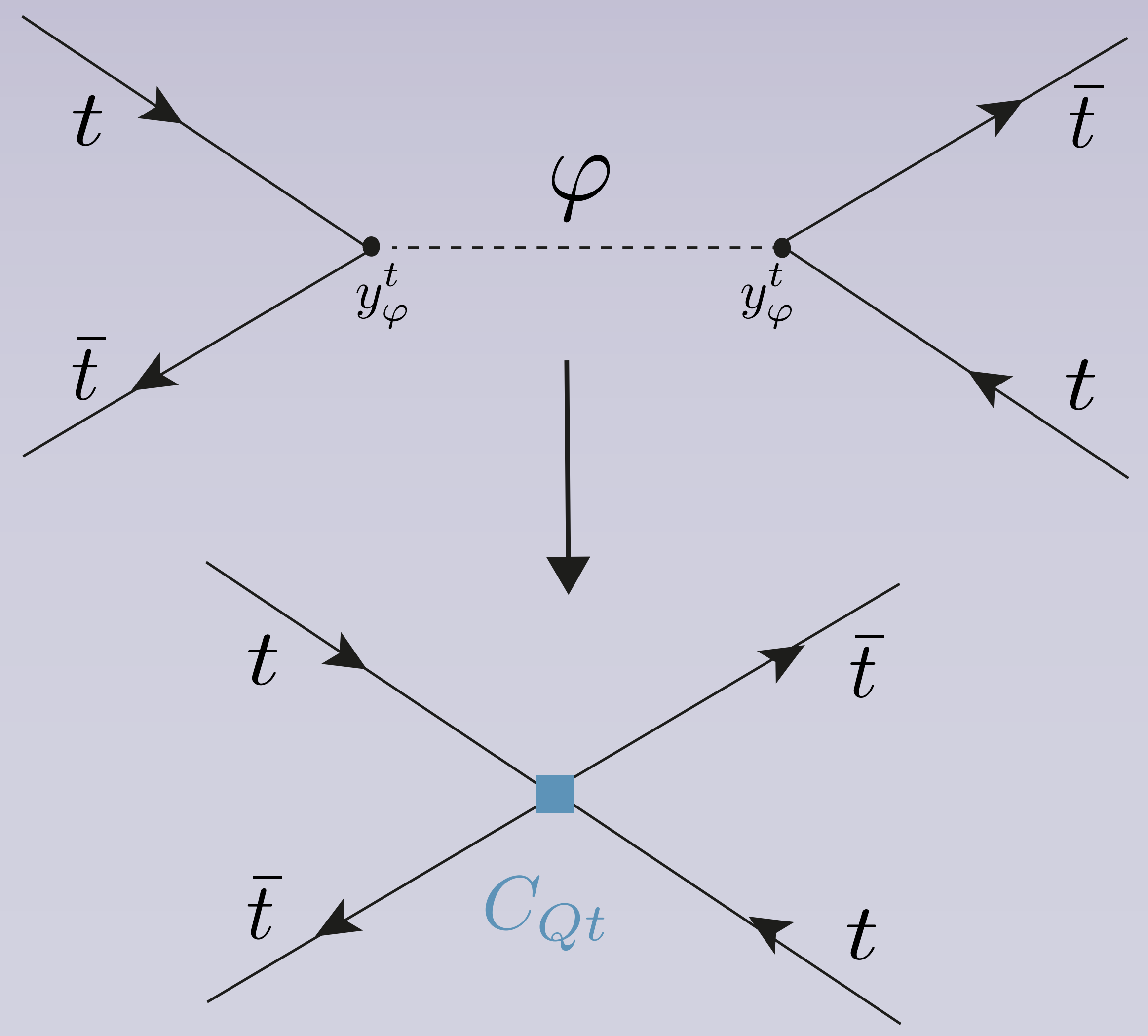


UV complete models

-New scalar or vector bosons are the possible candidates for introducing the 4 Fermion operators.

Name	φ	ω_1	ω_4	ζ	Ω_1	Ω_4	Υ	Φ
Irrep	$(1,2)_{\frac{1}{2}}$	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,3)_{-\frac{1}{3}}$	$(6,1)_{\frac{1}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$
4-top ops	$\mathcal{O}_{Qt}^{(1),(8)}$, $\mathcal{O}_{QtQb}^{(1)}$,	$\mathcal{O}_{QQ}^{(1),(3)}$, $\mathcal{O}_{QtQb}^{(1),(8)}$	$\mathcal{O}_{tt}$,	$\mathcal{O}_{QQ}^{(1),(3)}$,	$\mathcal{O}_{QQ}^{(1),(3)}$, $\mathcal{O}_{QtQb}^{(1),(8)}$	$\mathcal{O}_{tt}$	$\mathcal{O}_{QQ}^{(1),(3)}$	$\mathcal{O}_{Qt}^{(1),(8)}$, $\mathcal{O}_{QtQb}^{(8)}$

Name	$\mathcal{B}$	$\mathcal{W}$	$\mathcal{G}$	$\mathcal{H}$	$\mathcal{L}_1$	$\mathcal{Q}_5$	$\mathcal{Y}_5$
Irrep	$(1,1)_0$	$(1,3)_0$	$(8,1)_0$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$	$(3,2)_{-\frac{5}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$
4-top ops	$\mathcal{O}_{tt}$, $\mathcal{O}_{Qt}^{(1)}$, $\mathcal{O}_{QQ}^{(1)}$	$\mathcal{O}_{QQ}^{(3)}$	$\mathcal{O}_{Qt}^{(8)}$, $\mathcal{O}_{QQ}^{(1),(3)}$	$\mathcal{O}_{QQ}^{(1),(3)}$	$\mathcal{O}_{Qt}^{(1),(8)}$, $\mathcal{O}_{QtQb}^{(1)}$,	$\mathcal{O}_{Qt}^{(1),(8)}$,	$\mathcal{O}_{Qt}^{(1),(8)}$



-Some of the new scalars will also modify the Higgs self couplings, for example

$$C_\phi = \frac{|\lambda_\varphi|^2}{M_\varphi^2} \qquad C_{Qt}^{(1)} = -\frac{|y_\varphi^t|^2}{6M_\varphi^2} \qquad C_{QtQb}^{(1)} = -\frac{y_\varphi^t\, y_\varphi^{b,*}}{M_\varphi^2}$$

We use the same notation as J. de Blas et al (2017)

Conclusion and Outlook.

- NLO corrections with 4 Fermion operators were computed analytically for Higgs processes (and cross-checked via MadGraph for ttH) .

  Computing ttH with CQtQb operators is still in progress.

- 4 top operators bounds from single Higgs production comparable to bounds from top data.

  Both the 4 top and trilinear coupling bounds are affected in the combined fit
  The bounds from single Higgs data is generally better than the single operator fit with top data in the linear EFT.

- Some Higgs channels show strong correlation between the 2 operators.

- Operators having 2 top and 2 b quarks are weakly constrained in general, but precision Higgs observables provide another handle to constrain these interactions. (stay tuned !)

- We have investigated some simplified UV complete models that match to 4 fermion effective coupling.

  Constraints on these models will be obtained projecting the SMEFT bounds after matching.

Thank You !