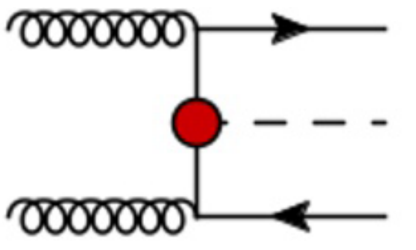
ttH in the SMEFT

Fabio Maltoni
Centre for Cosmology, Particle Physics and Phenomenology (CP3)
Université catholique de Louvain

In collaboration with Eleni Vryonidou and Cen Zhang, arXiv: 1607.05330

ttH: levels of analysis



The study of pp→ttH at the LHC can be performed at different levels of generality:

Level 0: kappa framework [LHCXSWG, 2012]

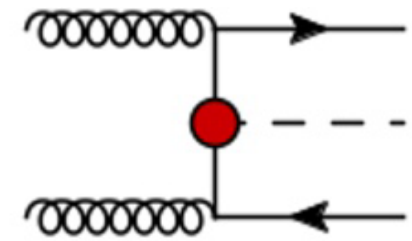
Rescaling of the cross section (LO or NLO) by a global factor k_t

Level 1: anomalous coupling including CP violation:

$$\mathcal{L}_0^t = -\bar{\psi}_t \big(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att} \, \gamma_5 \big) \psi_t \, X_0$$

Level 2: SMEFT

ttH: levels of analysis



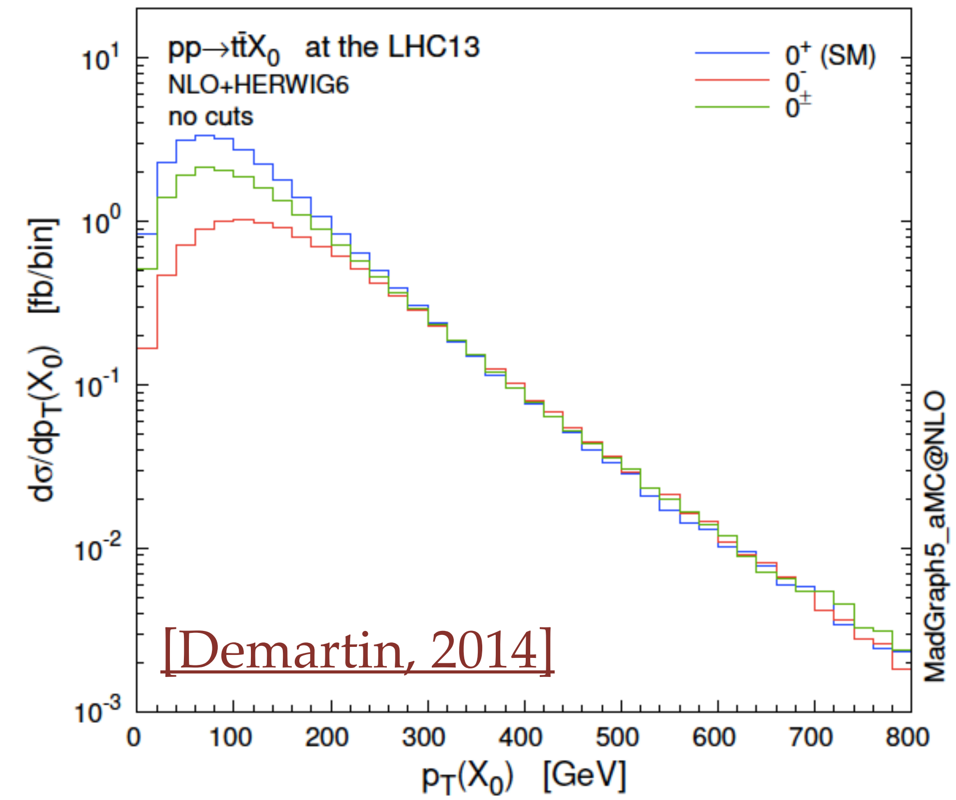
The study of pp→ttH at the LHC can be performed at different levels of generality:

Level 0: kappa framework [LHCXSWG, 2012]

Rescaling of the cross section (LO or NLO) by a global factor k_t

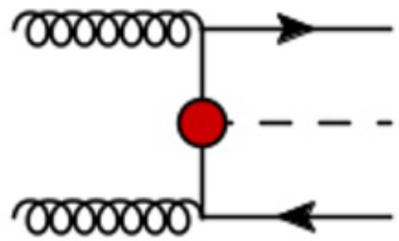
Level 1: anomalous coupling including CP violation:

$$\mathcal{L}_0^t = -\bar{\psi}_t \big(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\, \gamma_5 \big) \psi_t X_0$$



Level 2: SMEFT

ttH: levels of analysis



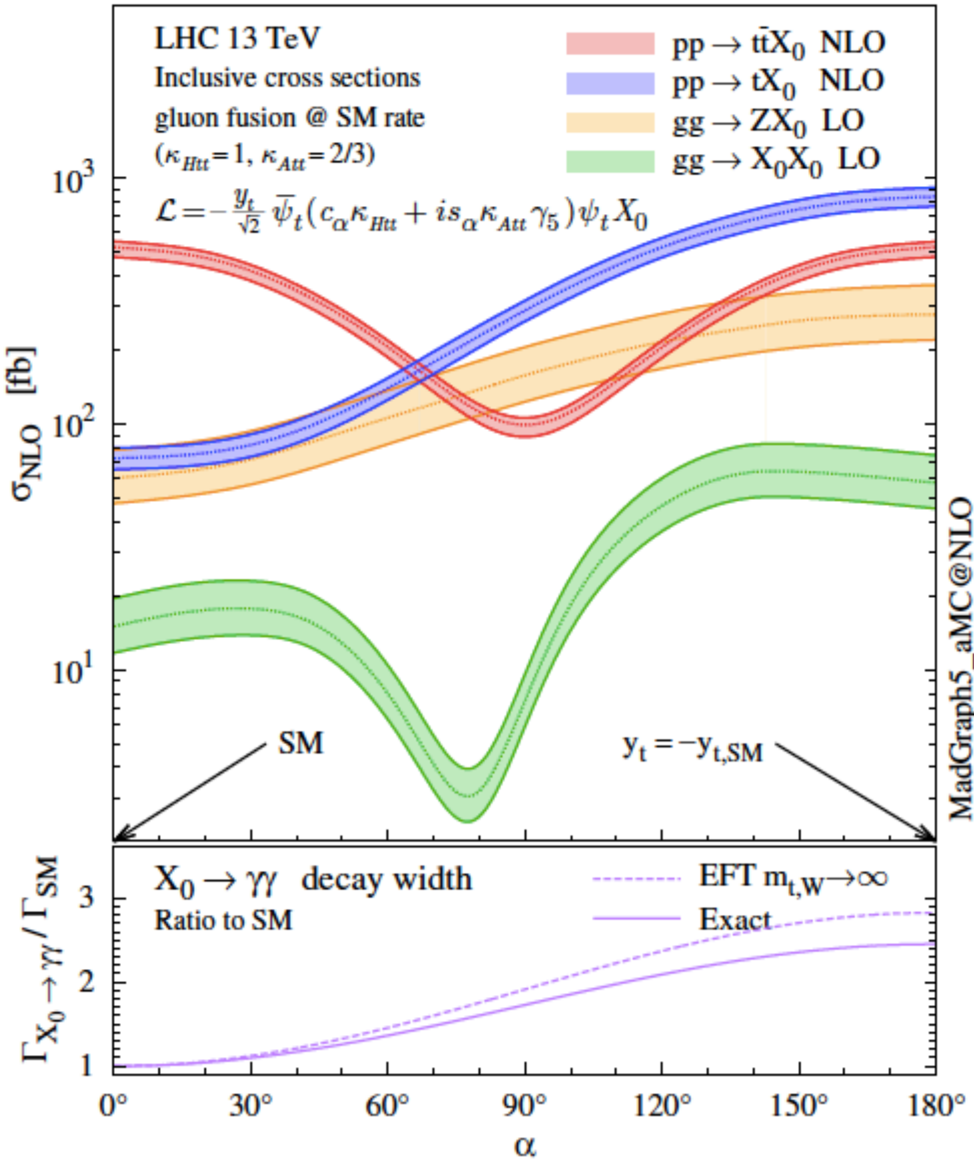
The study of pp→ttH at the LHC can be performed at different levels of generality:

Level 0: kappa framework [LHCXSWG, 2012]

Rescaling of the cross section (LO or NLO) by a global factor k_t

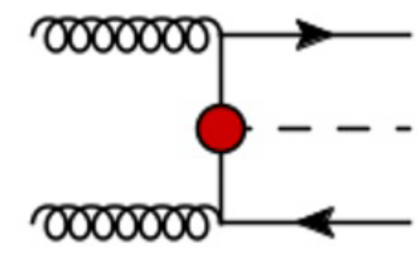
Level 1: anomalous coupling including CP violation:

$$\mathcal{L}_0^t = -\bar{\psi}_t\left(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\, \gamma_5\right)\psi_t\, X_0$$



Level 2: SMEFT

ttH: levels of analysis



The study of pp→ttH at the LHC can be performed at different levels of generality:

Level 0: kappa framework [LHCXSWG, 2012]

Rescaling of the cross section (LO or NLO) by a global factor k_t

Level 1: anomalous coupling including CP violation:

$$\mathcal{L}_0^t = -\bar{\psi}_t\big(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\, \gamma_5\big)\psi_t\, X_0$$

Level 2: SMEFT

SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

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

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r) \varepsilon_{jk} (\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r) \varepsilon_{jk} (\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \varepsilon_{mn} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r) \varepsilon_{jk} (\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} \left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} \left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)

- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

The EFT approach: managing unknown unknowns

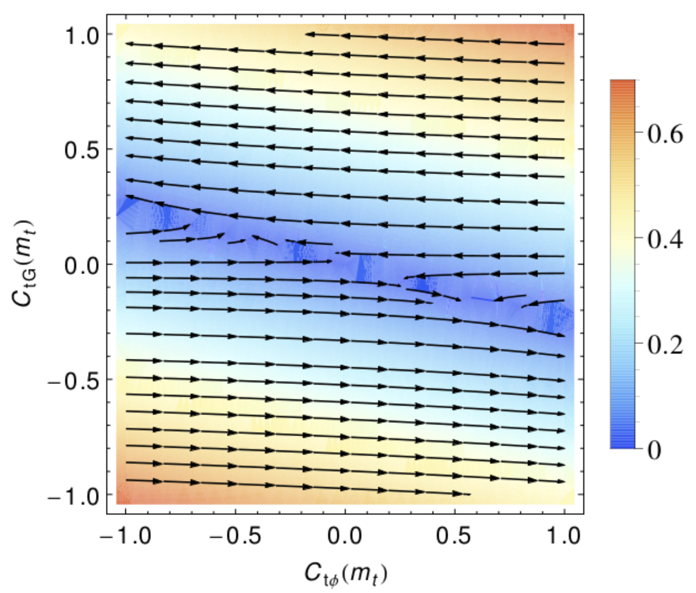
- Very powerful model-indepedent approach.
- A **global constraining strategy** needs to be employed:
  - assume all* couplings not be zero at the EW scale.
  - identify the operators entering predictions for each observable (LO, NLO,..)
  - find enough observables (cross sections, BR's, distributions,…) to constrain all operators.
  - solve the linear (+quadratic)* system.
- Use to constrain UV-complete* models.
- The final reach on the scale of New Physics crucially depends on the THU.

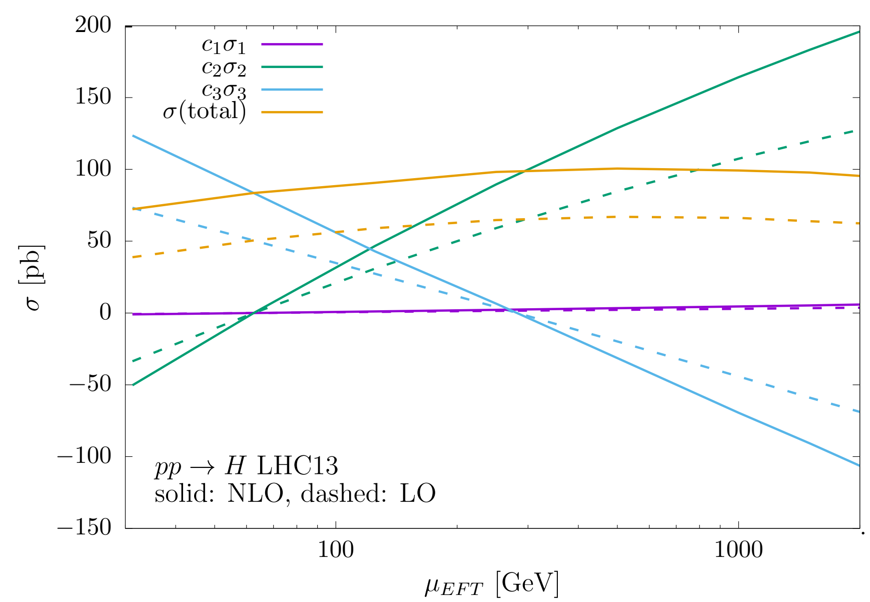
Going beyond LO

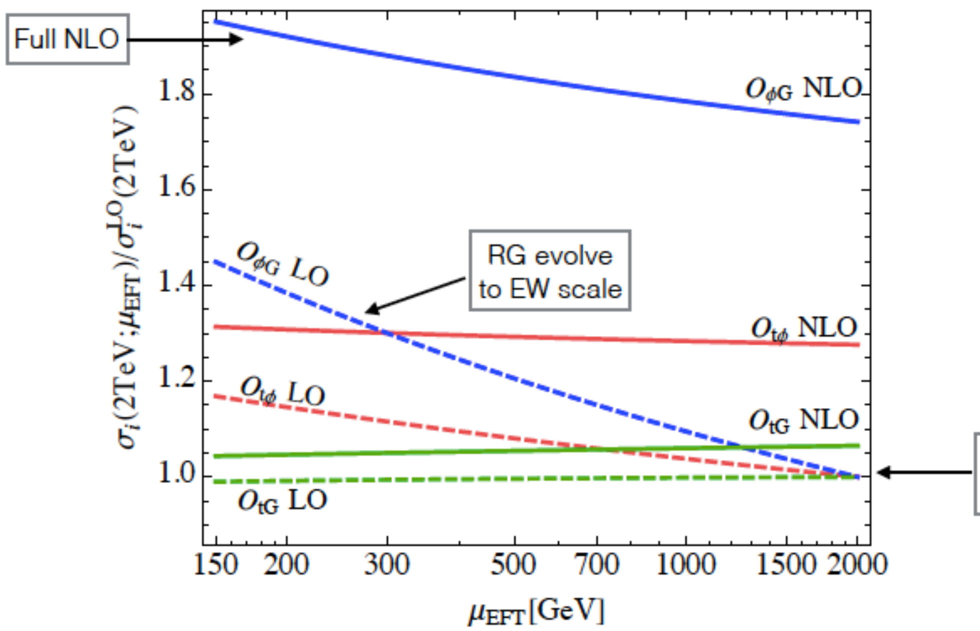
- SMEFT is a renormalizable theory order by order in $1/\Lambda$.
- We need higher-corrections to be included to control THU for two main class of reasons:
  - Same as for the SM@dim=4: QCD corrections are very important at the LHC for both accuracy and precision. EW corrections are mostly important for accucacy and in specific areas of phase space (which in the long term which can be important for the SMEFT) and observables (Ex: VBF). NLO corrections affect normalisation, shapes, scale (μR, μF) PDF dependences.
  - Specific issues of SM@dim>4: NLO is the first order where non-trivial EFT structure becomes manifest: Running, Mixing, μEFT dependence, new contributions can arise at NLO…

Why NLO?

1. Operators run and mix under RGE
2. Improve EFT scale dependence
3. Genuine NLO corrections (finite terms) are important
4. New operators arise







At = 1 TeV: CtG = 1, $C_{t\varphi}$ = 0;

At = 173 GeV: CtG = 0.98, $C_{t\varphi}$= 0.45

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}\,,$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu}G^{A\mu\nu}\,,$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}\,.$$

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu), \quad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

Status of the SMEFT at NLO: Higgs production

Channel	SM: QCD, EW	dim=6 : QCD	Comments
gg→H	N3LO,NLO	NLO: $C_{t\phi}$,$C_{\phi G}$ C_{tG}	—
gg→Hj	NNLO, LO	NLO: $C_{\phi G}$, LO: $C_{t\phi}$,C_{tG}	NLO QCD hard
ttH	NNLO, NLO	NLO	NLO EW hard
bbH	NNLO, LO	LO	—
gg→HH (LI)	NLO, LO	NLO: $C_{\phi G}$, LO: $C_{t\phi}$,C_{tG}	NLO QCD very hard
gg→HZ (LI)	LO, LO	LO	NLO QCD very hard
tHj	NLO, LO	LO	—
VBF	N3LO, NLO	(N)NLO	NLO EW welcome
VH	NNLO,NLO	(N)NLO	NLO EW welcome

more SU(3) ↑

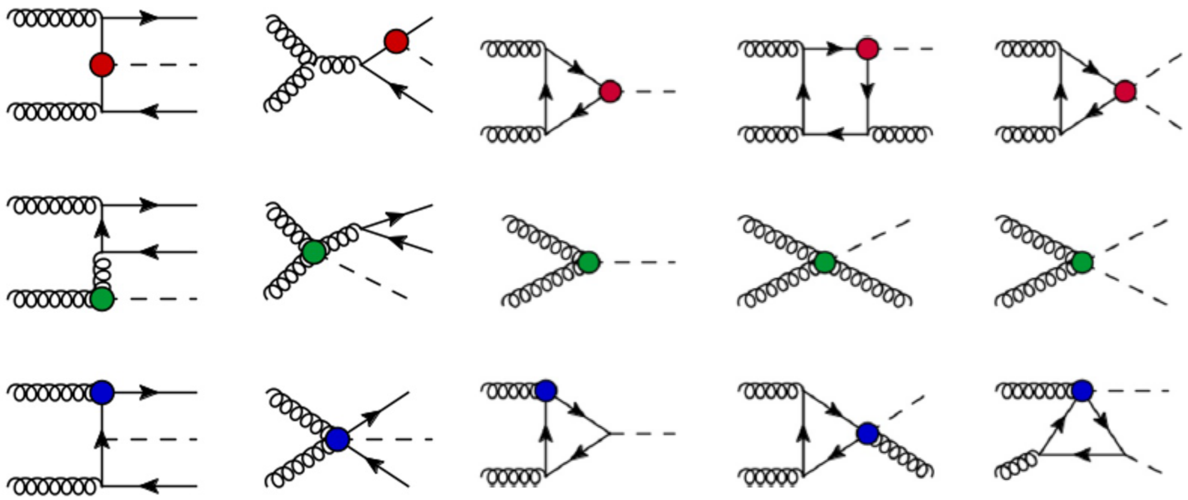
more SU(2)xU(1) ↓

Top/Higgs operators and processes

Several operators typically enter each process at LO (or at LO²) and

NLO (no 4f)	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L²	L²	1L²		
✓	$pp \to tj$	N		L	L				L²	L²	1L		
✓	$pp \to tW$	L		L	L				L²	L²	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L²	L²	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L²	L²	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L²	L²	1L		N
○ ✓	$gg \to H$	L						L				N	L
○ ✗	$gg \to Hj$	L						L				L	L
○ ✗	$gg \to HH$	L						L				N	L
○ ✗	$gg \to HZ$	L			L	L	L	L				N	L

Top/Higgs operators and processes

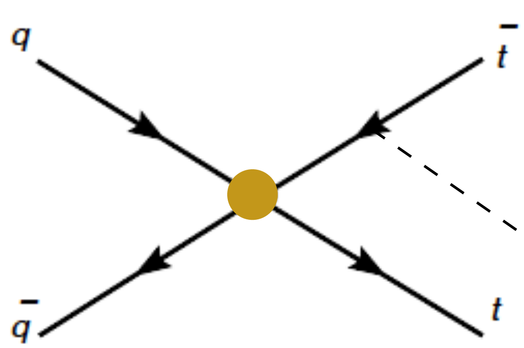


ttH H H+j HH

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

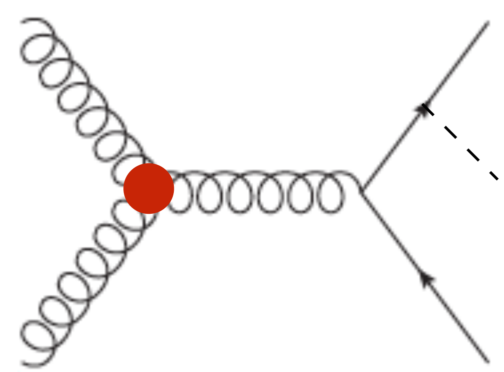
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

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



4-fermion operators

Exactly the same as in ttbar production



$$O_G = g_s f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$$

Multijet constraints: Krauss et al arXiv:1611.00767

Cross-section results

13 TeV	σ NLO	K
σ_{SM}	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	1.09
$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	1.13
$\sigma_{\phi G}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	1.39
σ_{tG}	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	1.58
$\sigma_{tG,tG}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	1.42
$\sigma_{t\phi,tG}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	1.37

$$\sigma = \sigma_{\mathrm{SM}} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

Different K-factors for different operators, different from the SM

Large $1/\Lambda^4$ contribution for the chromomagnetic operator

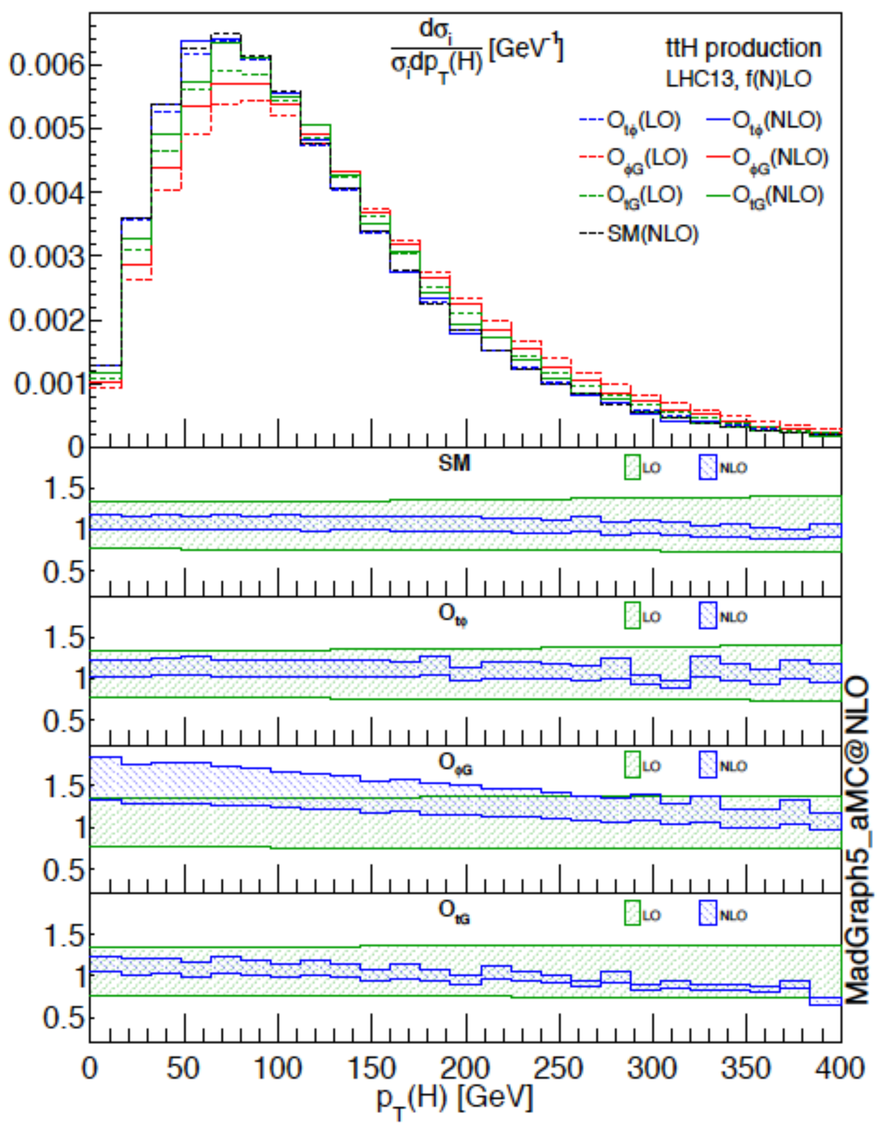
Constraints from top pair production: ctG=[-0.42,0.30] Franzosi and Zhang arxiv: 1503.08841

Global approach needed to consistently extract information on coefficients within the SMEFT framework

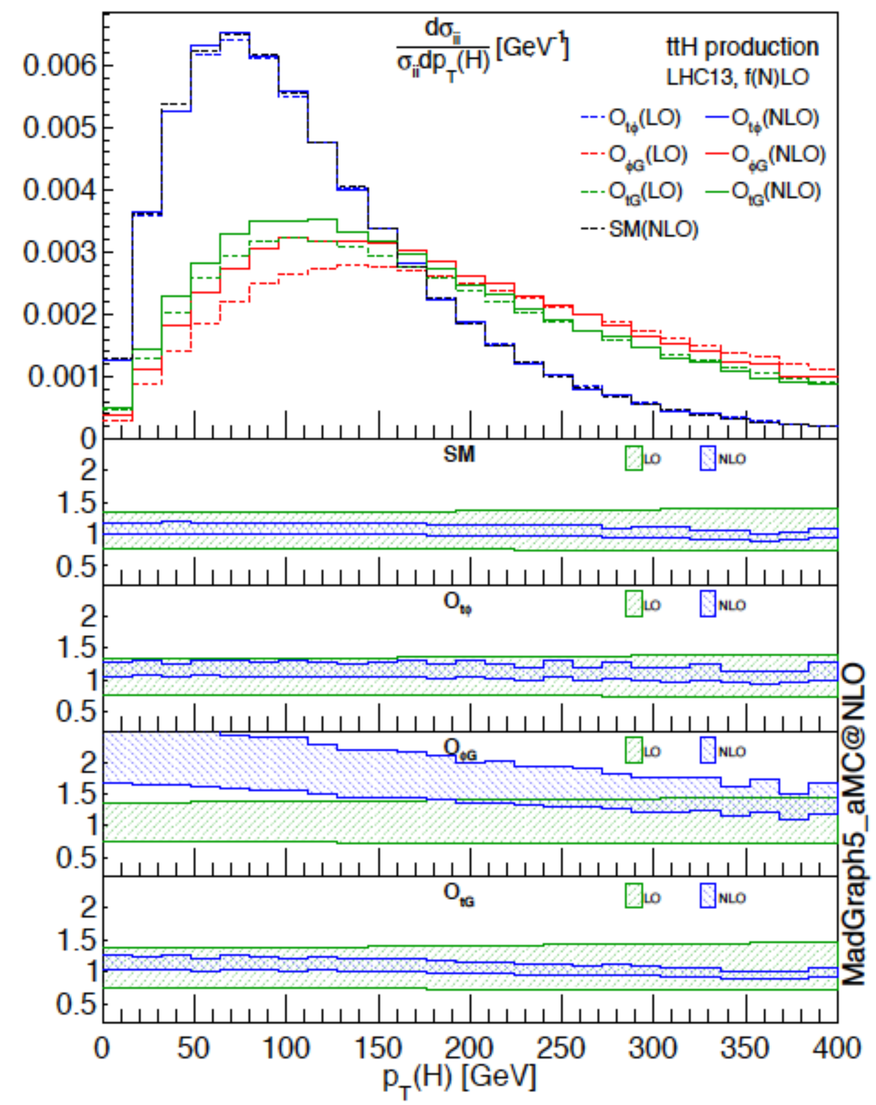
Differential information also important.

ttH in the SMEFT

[FM, Vryonidou, Zhang, 16]



NLO: smaller uncertainties, non-flat K-factors



Different shapes for different operators for the squared terms

Constraints on the Wilson coefficients

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

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

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

Toy χ2 fit for illustrative purposes using: single H, ttH Run I and Run II results. Impact of the 3 operators also included in Higgs decays

	Individual	Marginalised	C_{tG} fixed
$C_{t\phi}/\Lambda^2$ [TeV^{-2}]	[-3.9,4.0]	[-14,31]	[-12,20]
$C_{\phi G}/\Lambda^2$ [TeV^{-2}]	[-0.0072,-0.0063]	[-0.021,0.054]	[-0.022,0.031]
C_{tG}/Λ^2 [TeV^{-2}]	[-0.68,0.62]	[-1.8,1.6]	

95% c.l.

typically $C_{tG}=0$ in Higgs analyses

Individual limit on CtG comparable to the one from top pair production-room to improve with ttH measurement in run II.

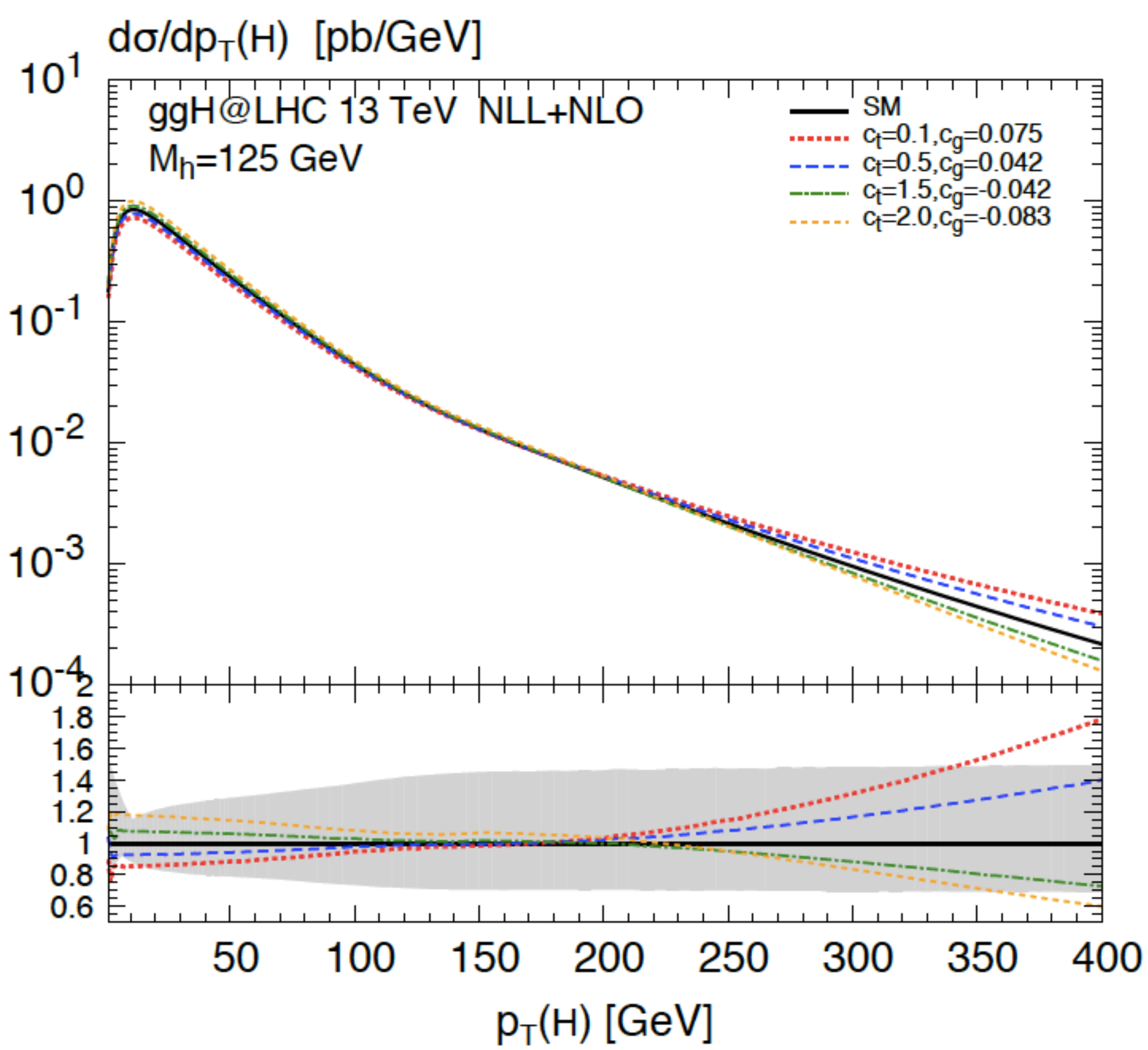
Including the chromomagnetic operator leaves much more space to the other two operators

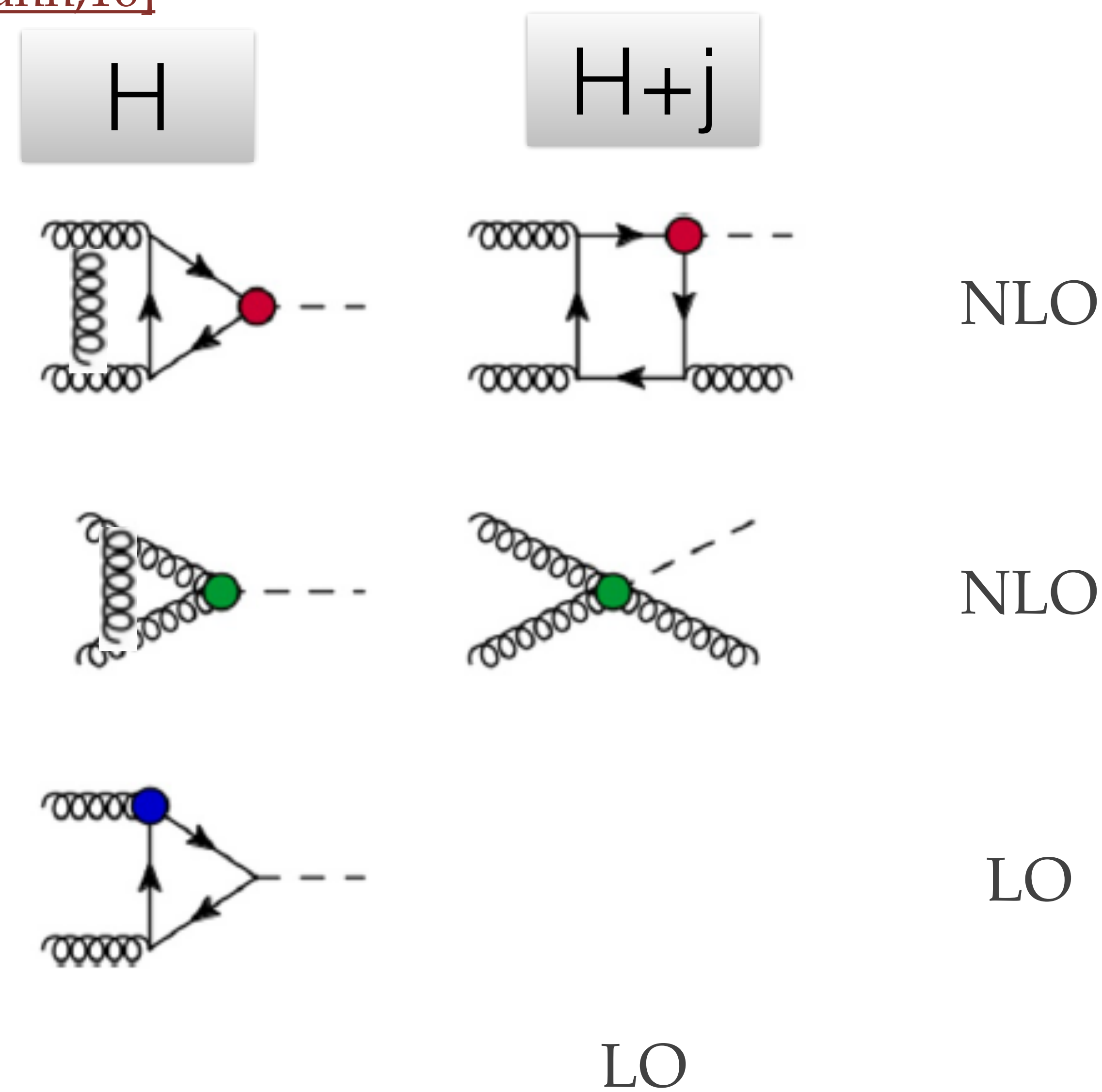
→ Need for global analysis

ggH in the SMEFT

Earlier studies of ggH in the SMEFT [Degrande et al. 12] [Grojean et al. 13]

More recently, [Grazzini, Ilnicka, Spira, Wiesemann,16]

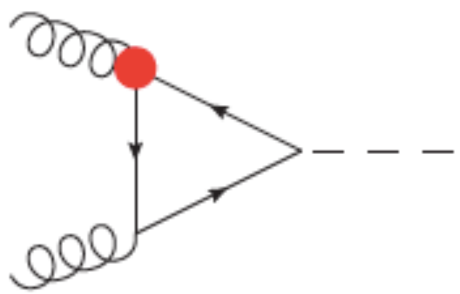




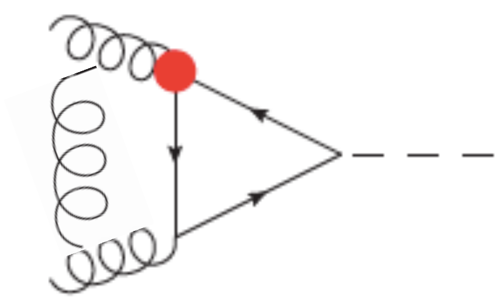
ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]

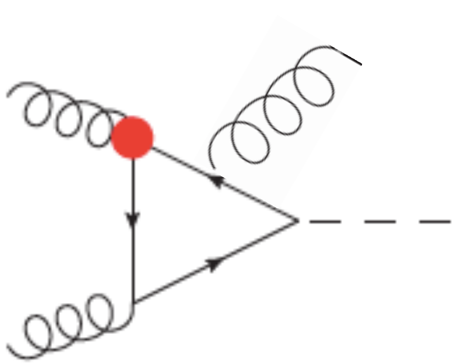
Now known at NLO (two-loop virtuals+1-loop real)



$\bar{Q}_L \Phi\, \sigma q_R G$



$\bar{Q}_L \Phi\, \sigma q_R G$



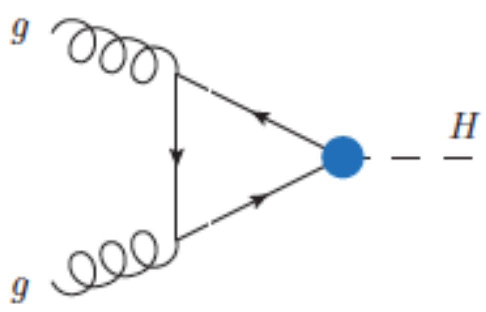
$\bar{Q}_L \Phi\, \sigma q_R G$

$$
\begin{aligned}
\mathcal{R}_3 = & -i\pi\, m_t\, \beta_0 \left(1 - \frac{\theta^2}{\tau} + 2\log\tau\right) + \frac{\theta^2\, m_t}{\tau^2}\,(16\log\tau + 35) \qquad (3.34)\\
& + \frac{m_t}{\tau}\Bigg[\theta\left(-48\,\mathrm{Cl}_{1,-2}(\theta) - \frac{8}{3}\,\mathrm{Cl}_{2,1}(\theta) + \frac{1}{3}\,\mathrm{Cl}_2(\theta)\,\log\tau - \frac{64}{3}\,\mathrm{Cl}_{-2}(\theta) - 74\,\mathrm{Cl}_2(\theta)\right)\\
& \quad - 96\,\mathrm{Cl}_{1,-3}(\theta) - 48\,\mathrm{Cl}_{2,-2}(\theta) - \frac{8}{3}\,\mathrm{Cl}_{3,1}(\theta) - \frac{4}{3}\,\mathrm{Cl}_3(\theta)\,\log\tau + \frac{5}{3}\,\mathrm{Cl}_2(\theta)^2\\
& \quad + \frac{61}{48}\,\theta^4 - \frac{2\pi}{9}\,\theta^3 + \theta^2\left(\frac{1}{4}\,\log^2\tau - \frac{92}{3}\,\log\tau + \frac{16}{3}\log(4-\tau) + 5\,\zeta_2 - \frac{100}{3}\right)\\
& \quad - \frac{64}{3}\,\mathrm{Cl}_{-3}(\theta) - 64\,\mathrm{Cl}_3(\theta) - 16\,\log\tau - \frac{104}{3}\,\zeta_3\,\log\tau + 80\,\zeta_3 - \frac{151}{3}\,\zeta_4 - \frac{71}{3}\Bigg]\\
& + m_t\Bigg[\frac{32\,\theta}{3}\,(2\,\mathrm{Cl}_{-2}(\theta) - \mathrm{Cl}_2(\theta)) + 32\,\mathrm{Cl}_{-3}(\theta) - 16\,\mathrm{Cl}_3(\theta) - 8\,\zeta_3 + \frac{5}{3}\,\log^2\tau + \frac{62}{3}\,\log\tau\\
& \quad - \theta^2\left(\frac{8}{3}\log(4-\tau) + \frac{4}{3}\,\log\tau + \frac{1}{4}\right) + \frac{238}{3}\Bigg]\\
& - \frac{i\pi\,\theta\,(4-\tau)\,m_t}{\sqrt{(4-\tau)\tau}}\,\beta_0 + \frac{64\,\theta^3\,m_t}{\tau^2\sqrt{(4-\tau)\tau}} - \frac{2\,m_t}{\sqrt{(4-\tau)\tau}}\left(1 - \frac{2}{\tau}\right) R(\theta)\\
& + \frac{\theta\, m_t}{6\sqrt{(4-\tau)\tau}}\left[13\,\theta^2 + 62 - \frac{4}{\tau}\,(63\,\theta^2 + 62)\right] - \frac{(4-\tau)\,m_t}{\sqrt{(4-\tau)\tau}}\Bigg[-\frac{32}{3}\mathrm{Cl}_{-2}(\theta) + 3\mathrm{Cl}_2(\theta)\\
& \quad + \theta\left(\frac{16}{3}\,\log(4-\tau) - \frac{1}{6}\,\log\tau - \frac{71}{2}\right)\Bigg].
\end{aligned}
$$

ggH in the SMEFT

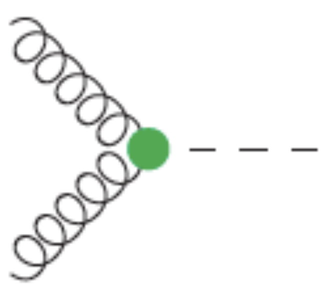
[Deutschmann, Duhr, FM, Vryonidou, 17]

σ1



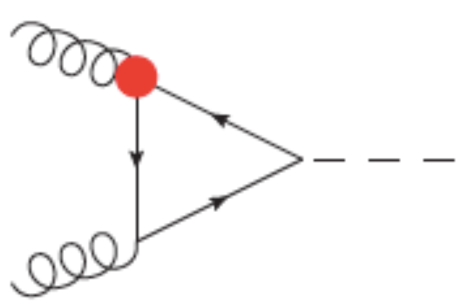
$(\Phi^\dagger\Phi)\,\bar{Q}_L \Phi\, q_R$

σ2



$(\Phi^\dagger\Phi)\, GG$

σ3



$\bar{Q}_L \Phi\, \sigma q_R G$

13 TeV	σ LO	σ/σ_{SM} LO	σ NLO	σ/σ_{SM} NLO	K
σ_{SM}	$21.3^{+34.0+1.5\%}_{-25.0-1.5\%}$	1.0	$36.6^{+26.4+1.9\%}_{-20.0-1.6\%}$	1.0	1.71
σ_1	$-2.93^{+34.0+1.5\%}_{-25.0-1.5\%}$	-0.138	$-4.70^{+24.8+1.9\%}_{-20.0-1.6\%}$	-0.127	1.61
σ_2	$2660^{+34.0+1.5\%}_{-25.0-1.5\%}$	125	$4130^{+23.9+1.9\%}_{-19.6-1.6\%}$	114	1.55
σ_3	$50.5^{+34.0+1.5\%}_{-25.0-1.5\%}$	2.38	$83.5^{+26.0+1.9\%}_{-20.6-1.6\%}$	2.28	1.65
σ_{11}	$0.0890^{+34.0+1.5\%}_{-25.0-1.5\%}$	0.0042	$0.141^{+24.8+1.9\%}_{-20.0-1.6\%}$	0.0038	1.59
σ_{22}	$74100^{+34.0+1.5\%}_{-25.0-1.5\%}$	3480	$109100^{+22.6+1.9\%}_{-18.9-1.6\%}$	3000	1.47
σ_{33}	$26.6^{+34.0+1.5\%}_{-25.0-1.5\%}$	1.25	$41.6^{+25.3+2.0\%}_{-20.4-1.7\%}$	1.13	1.56
σ_{12}	$-162^{+34.0+1.5\%}_{-25.0-1.5\%}$	-7.61	$-248^{+23.6+1.9\%}_{-19.5-1.6\%}$	-6.78	1.53
σ_{13}	$-3.08^{+34.0+1.5\%}_{-25.0-1.5\%}$	-0.145	$-5.04^{+25.4+1.9\%}_{-20.3-1.6\%}$	-0.138	1.64
σ_{23}	$2800^{+34.0+1.5\%}_{-25.0-1.5\%}$	131	$4460^{+24.6+1.9\%}_{-19.9-1.6\%}$	122	1.59

$$\mathcal{O}_1 = \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\overline{Q}_L\tilde{\Phi}\,t_R\,,$$

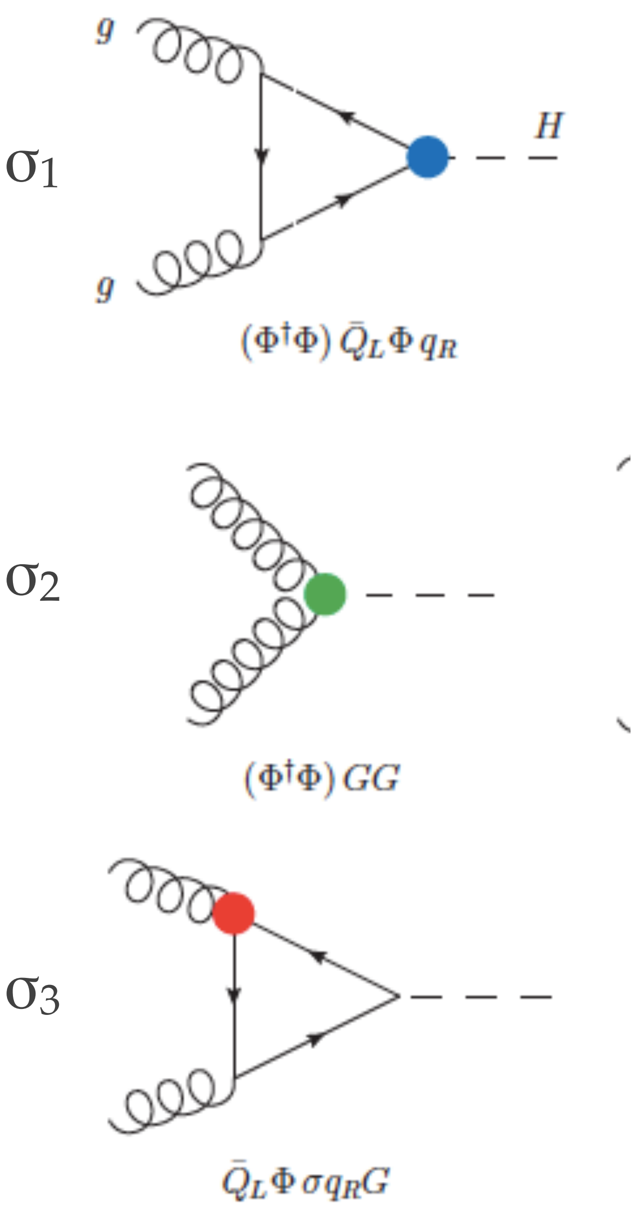
$$\mathcal{O}_2 = g_s^2\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)G^a_{\mu\nu}G^{\mu\nu}_a$$

$$\mathcal{O}_3 = g_s\,\overline{Q}_L\tilde{\Phi}\,T^a\,\sigma^{\mu\nu}t_R\,G^a_{\mu\nu}\,,$$

$$\sigma = \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2}C_i\sigma_i + \sum_{i\leq j}\frac{1\text{TeV}^4}{\Lambda^4}C_iC_j\sigma_{ij}$$

ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]



Only linear terms:

$$-0.28 < -0.128C_1 + 114C_2 + 2.28C_3 < 0.48.$$

One operator at the time:

$$-3.8 < C_1 < 2.2,\ -0.0025 < C_2 < 0.0043,\ -0.12 < C_3 < 0.21\,.$$

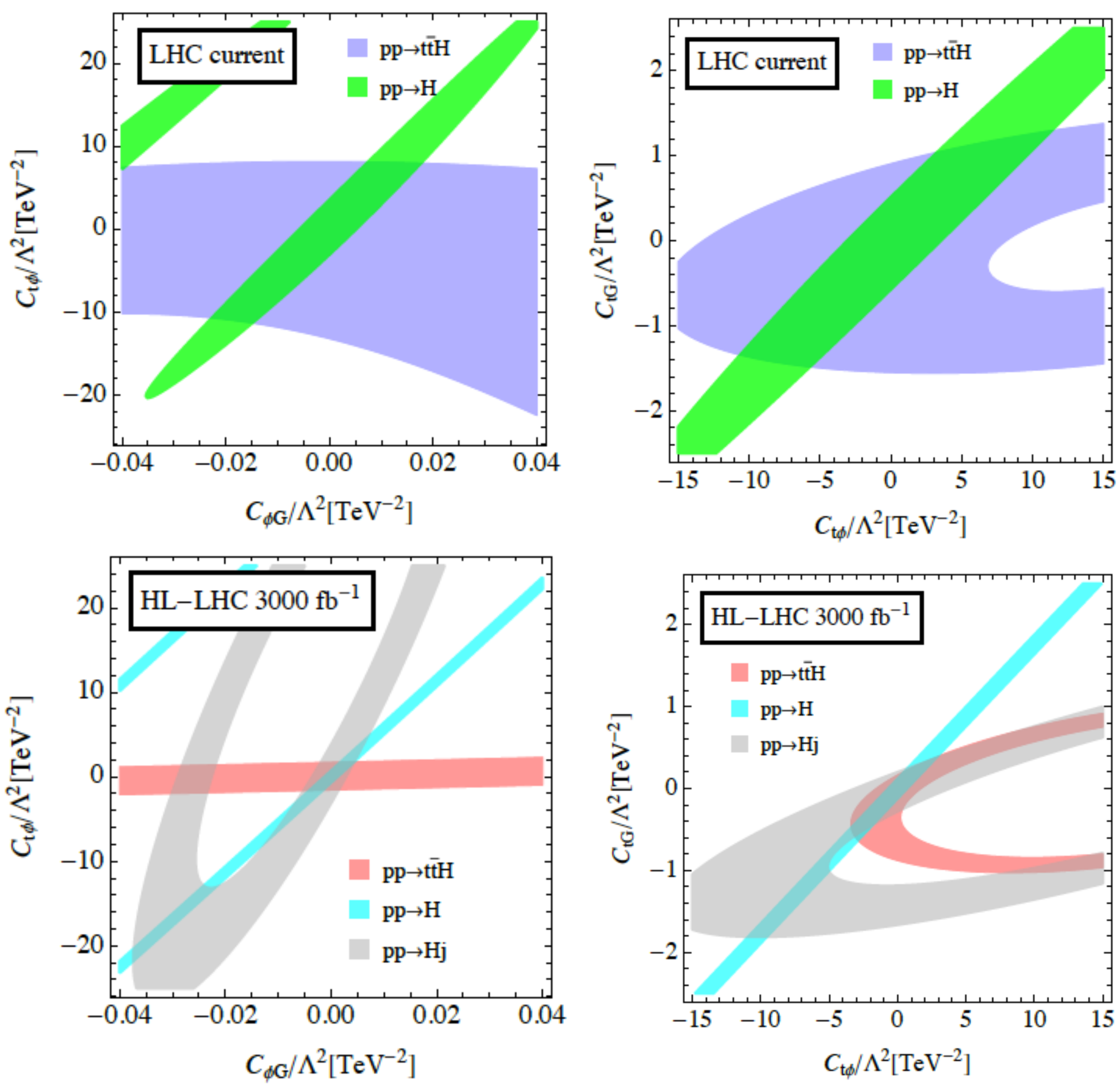
At one operator at the time, inclusion of the quadratic terms change the limits by only 10%.

$$-0.28 < -0.128C_1 + 114C_2 + 2.28C_3 + 0.0038C_1^2 + 3000C_2^2 + 1.13C_3^2 - 6.78C_1C_2 - 0.138C_1C_3 + 122C_2C_3 < 0.48\,.$$

$$\sigma = \sigma_{SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i\sigma_i + \sum_{i\leq j} \frac{1\mathrm{TeV}^4}{\Lambda^4} C_iC_j\sigma_{ij}$$

Constraints from ttH and Higgs production

[FM, Vryonidou, Zhang, 16]



Current limits using LHC measurements

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu}G^{A\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$$

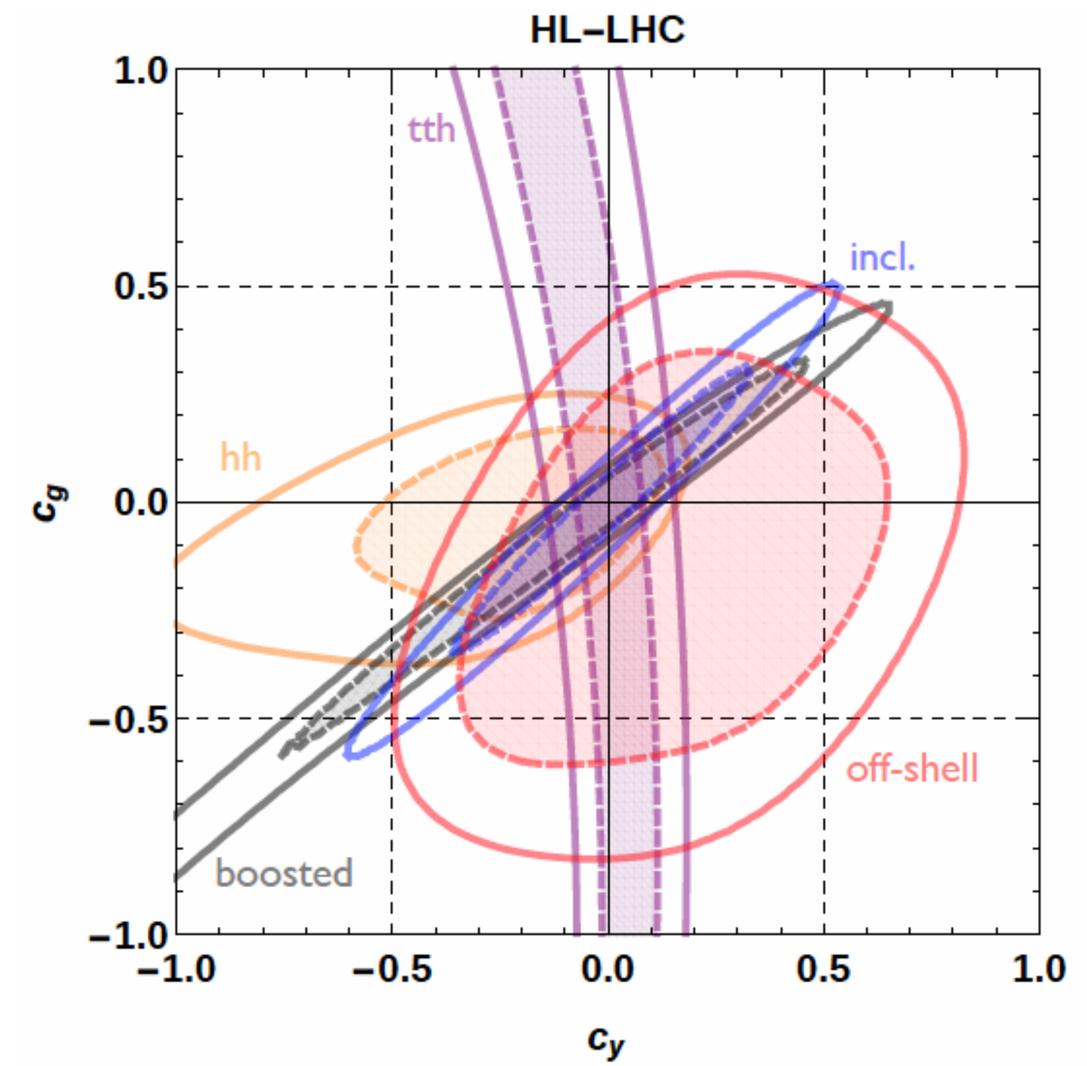
14TeV projection

3000 fb-1

Constraints from ttH and Higgs production

[Azatov et al, 16]

Combination:
- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs



A theorist's study. Future: More realistic experimental analyses needed.

Conclusions and Outlook

- NLO in the SMEFT is mandatory. Theoretical/MC effort to provide accurate/precise/usable predictions has started a few years ago.
- NLO-QCD predictions for LHC processes being made available in a MC form (4F still in the working).
- ttH at NLO in QCD in the SMEFT has become available last year in MG5aMC.

Additional information

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

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

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

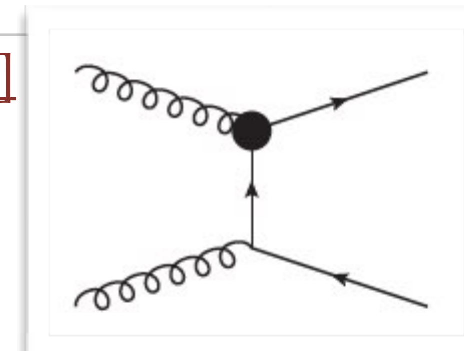
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

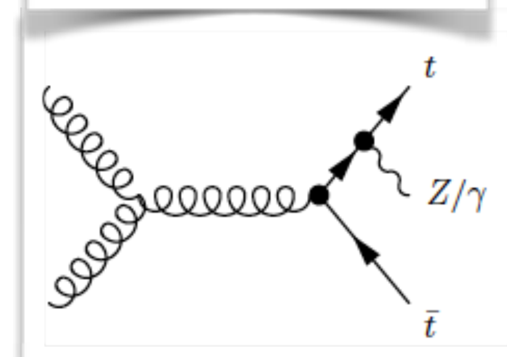
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu} \,,$$

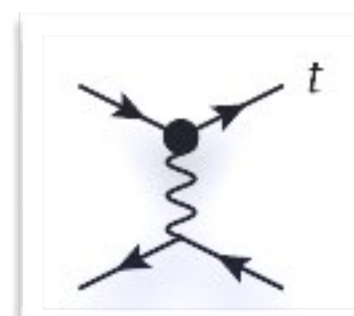
$$O_{t\varphi} = y_t^3 (\varphi^\dagger \varphi)\bar{Q}\tilde{\varphi} t$$

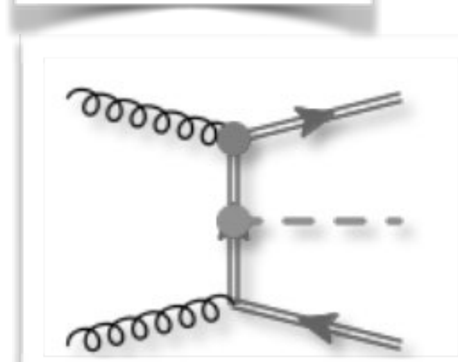
+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…









Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

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

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

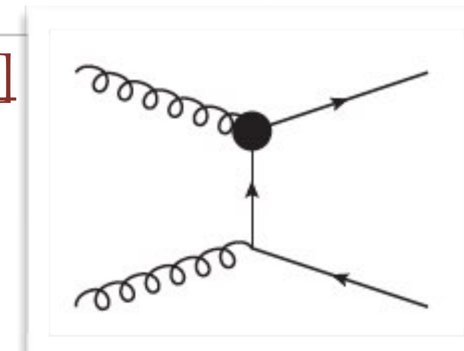
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

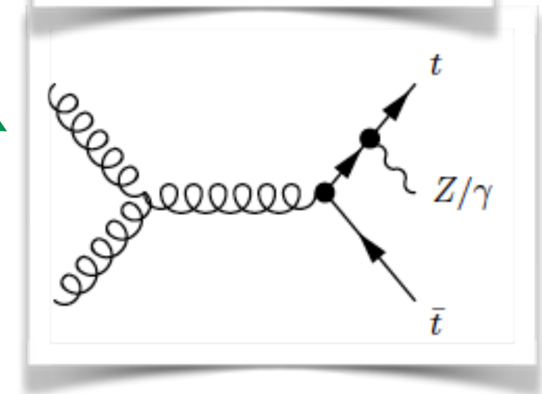
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

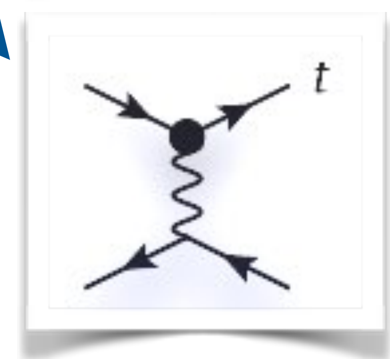
$$O_{t\varphi} = y_t^3 (\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$

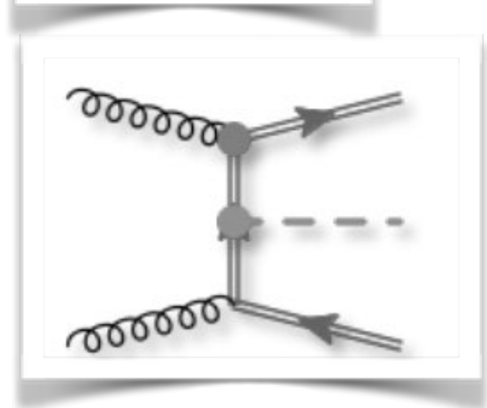
+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…









Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

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

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

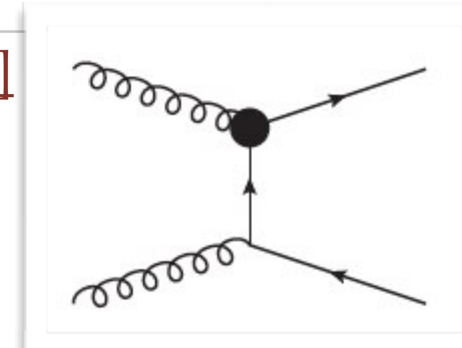
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

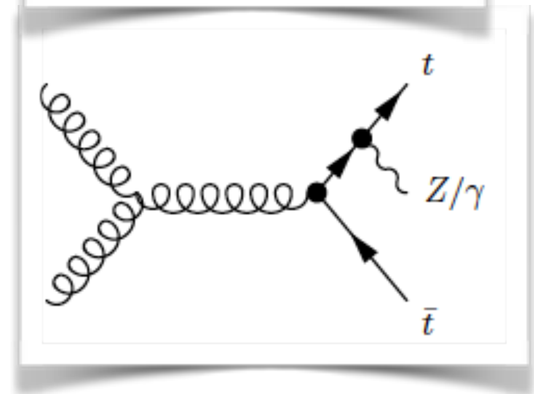
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

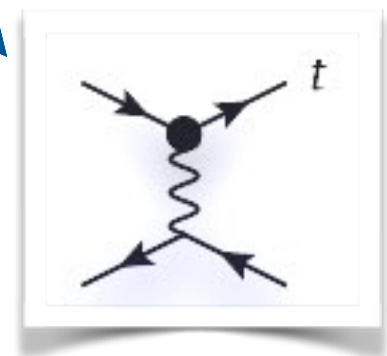
$$O_{t\varphi} = y_t^3(\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$

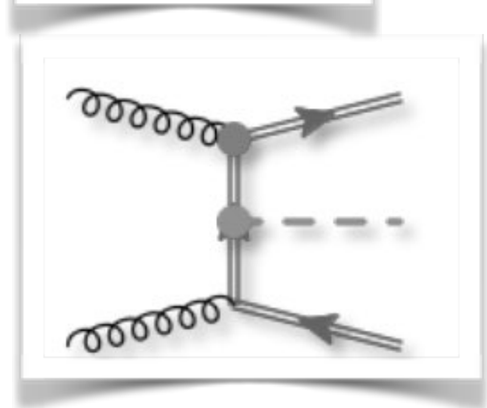
+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…









Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

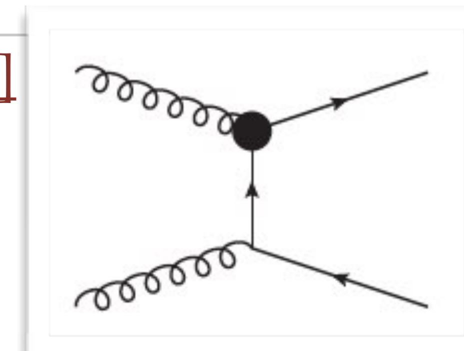
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

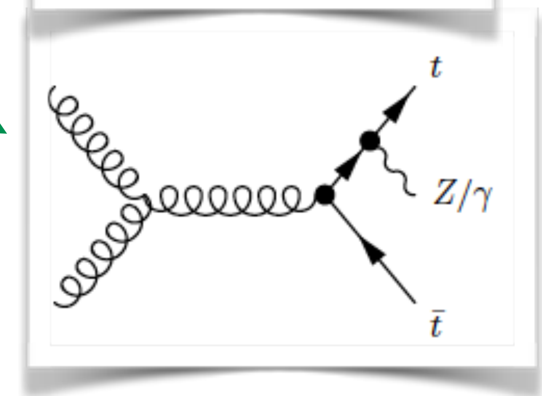
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

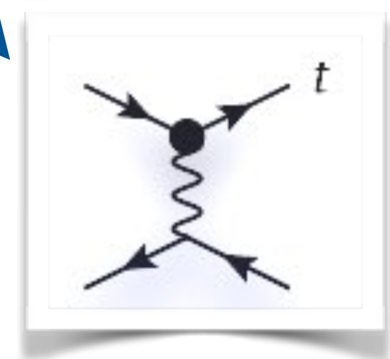
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

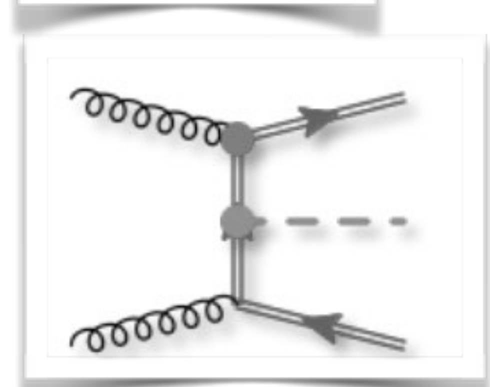
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu},$$

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









+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

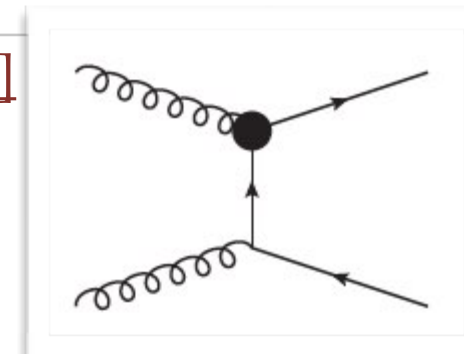
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

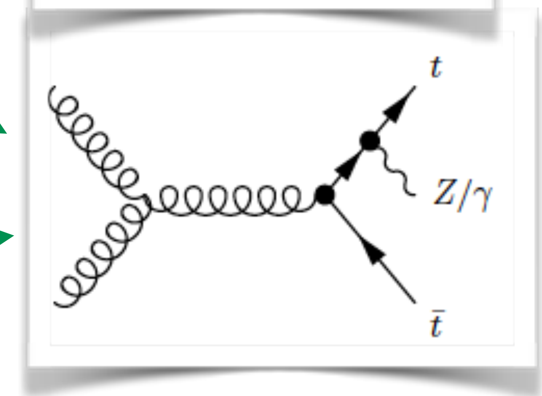
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

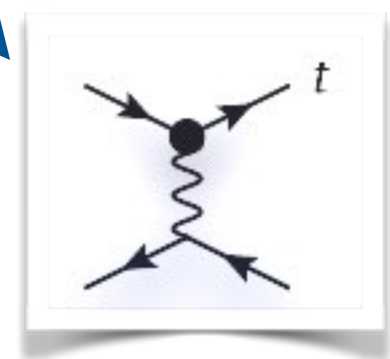
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

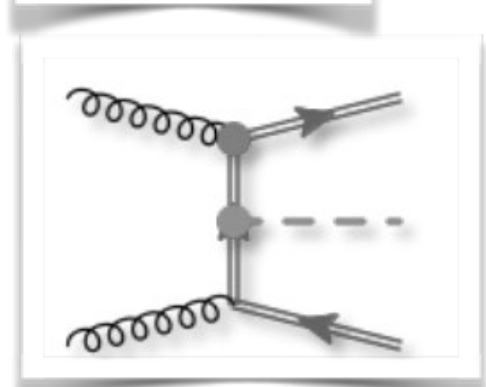
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

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









+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

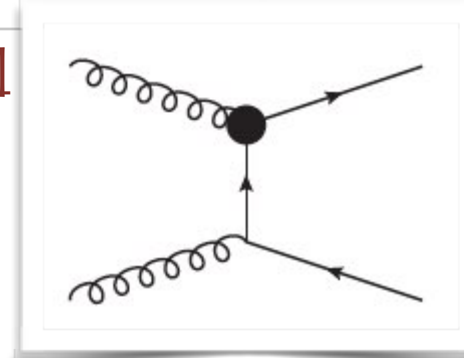
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

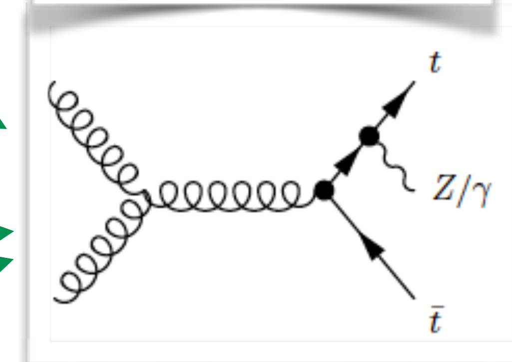
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W_{\mu\nu}^I$$

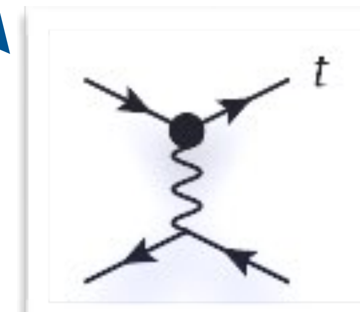
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

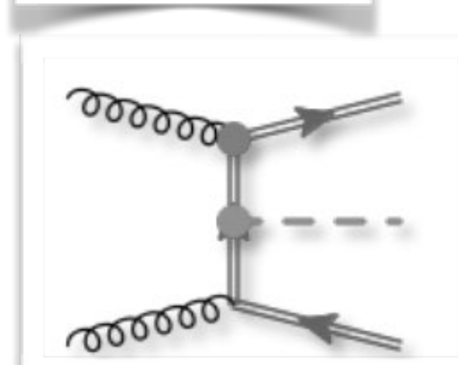
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G_{\mu\nu}^A \,,$$

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









+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

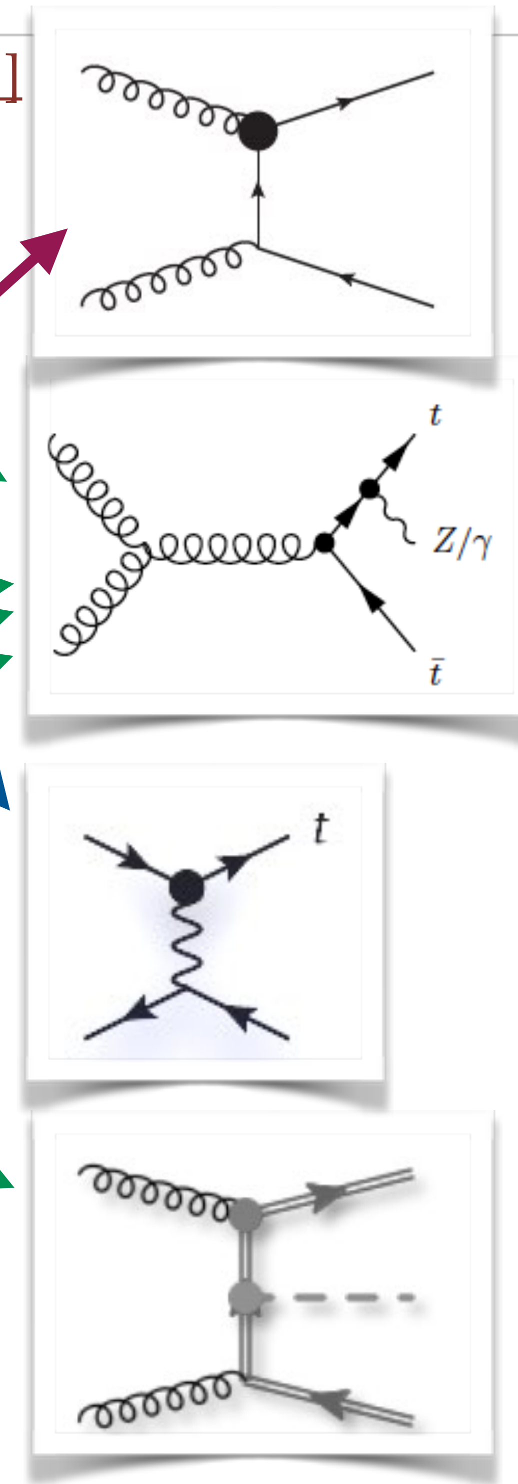
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

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

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

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

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



+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

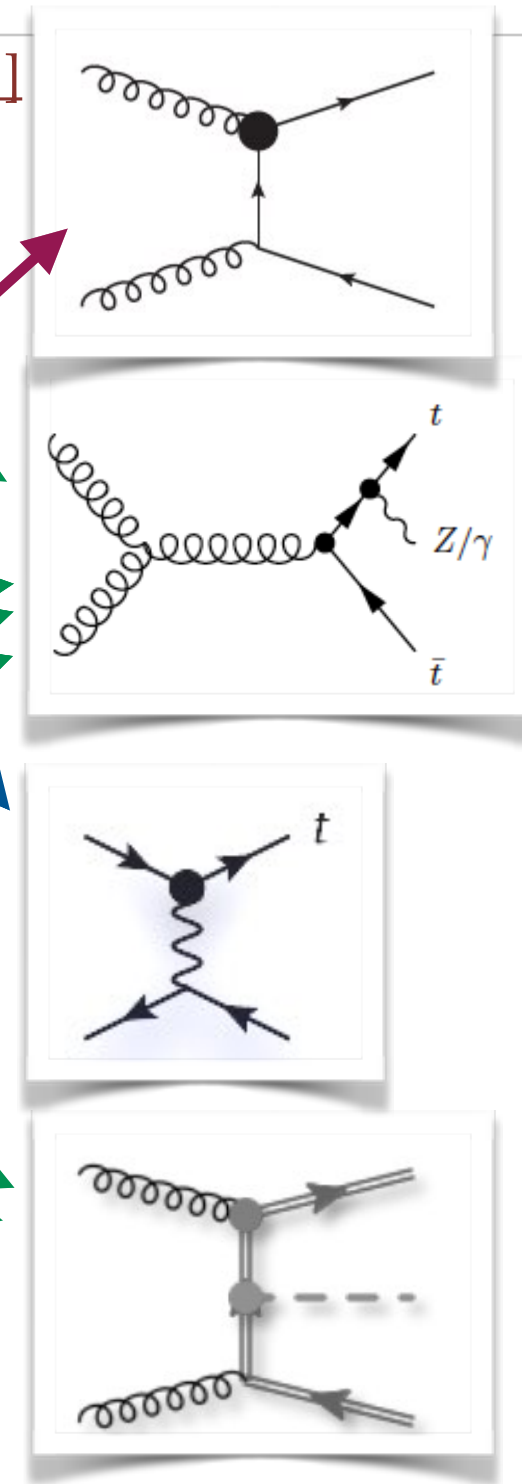
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right) (\bar{t}\gamma^\mu t)$$

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

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

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

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



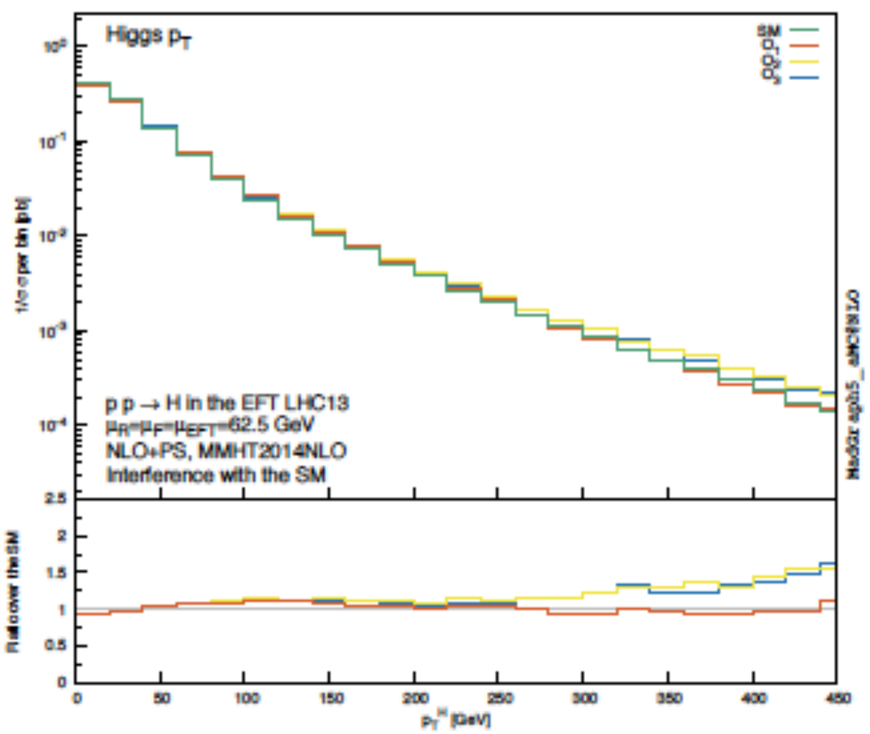
+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

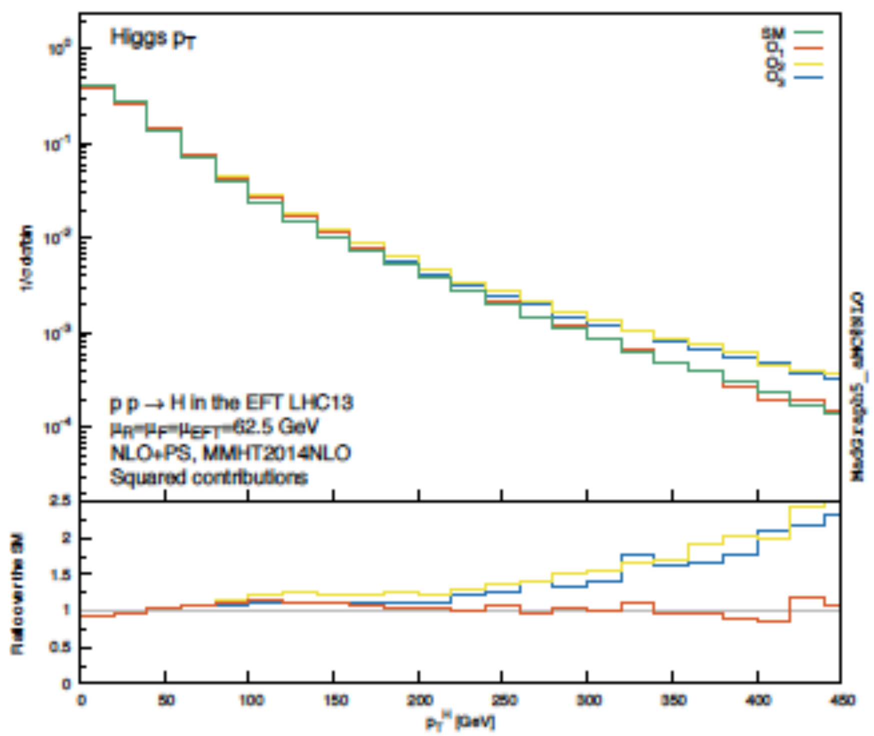
ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]

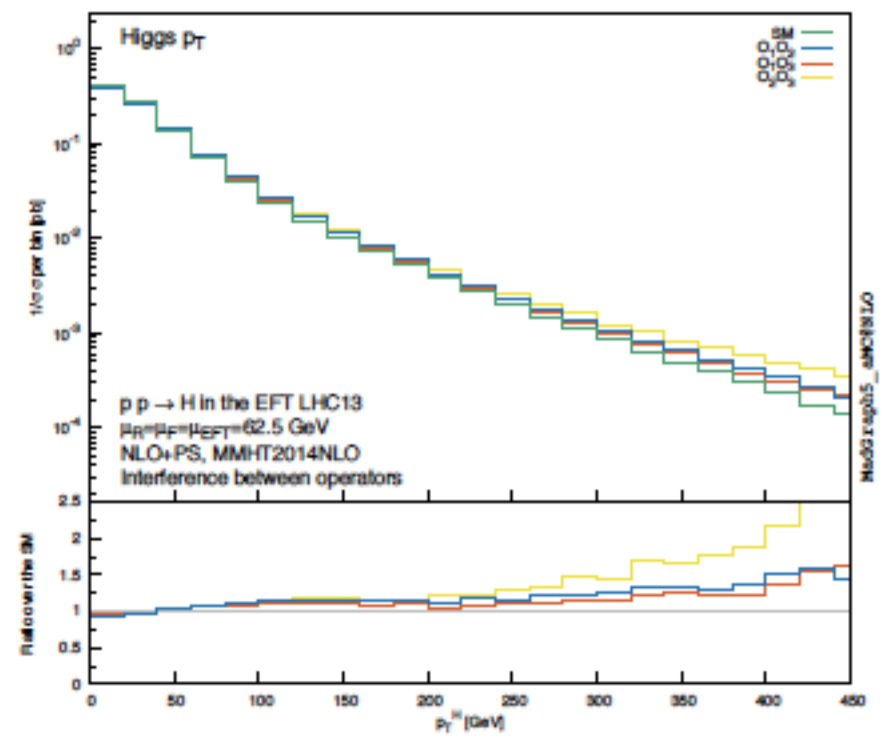
Interference w/ SM



Squared (diagonal)



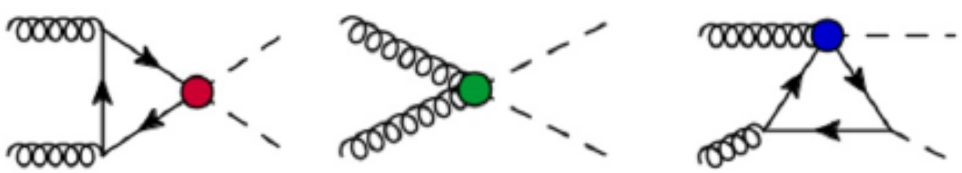
Squared (crossed)



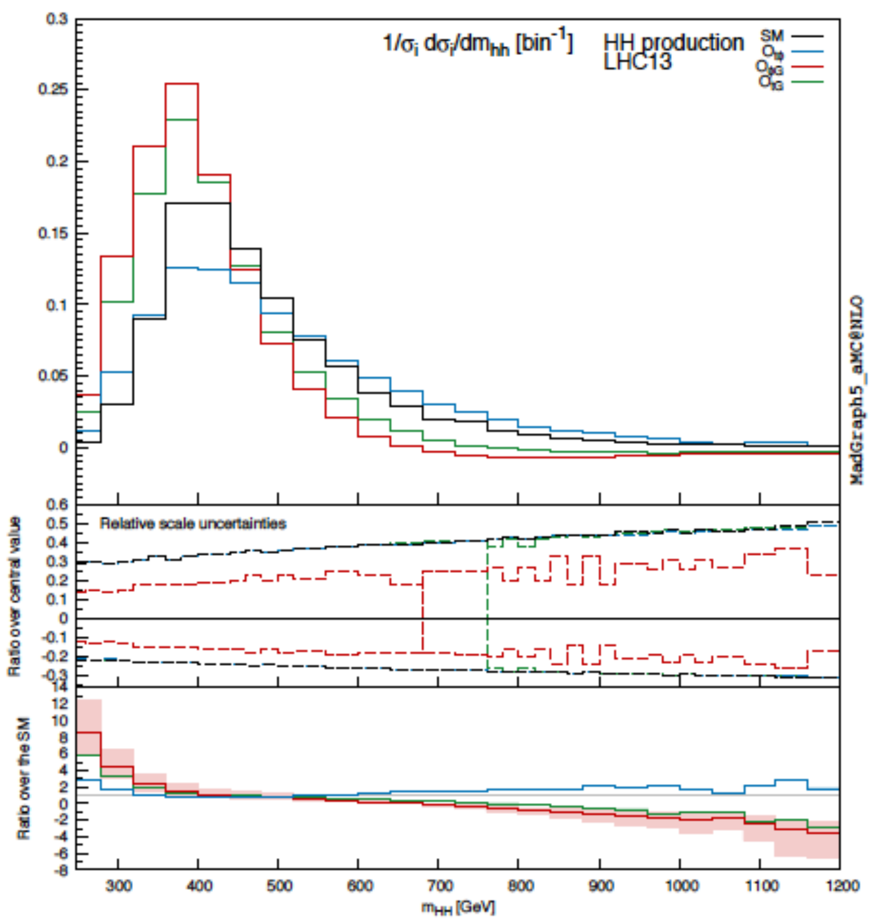
The effects of the chromo are "degenerate" with those of the $O_{\varphi G}$ operator in the interference and diagonal squared terms.

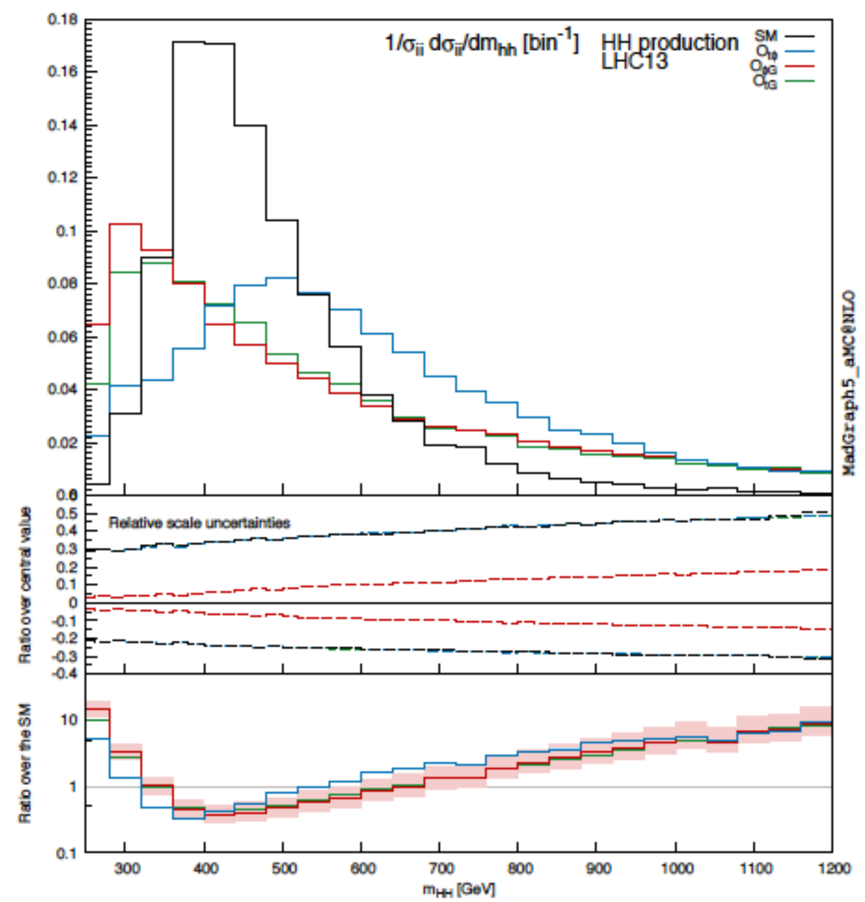
Note also the behaviour at small pT due to the bottom loop which has been only included in the SM part.

SMEFT in HH



Chromomagnetic operator computed for the first time



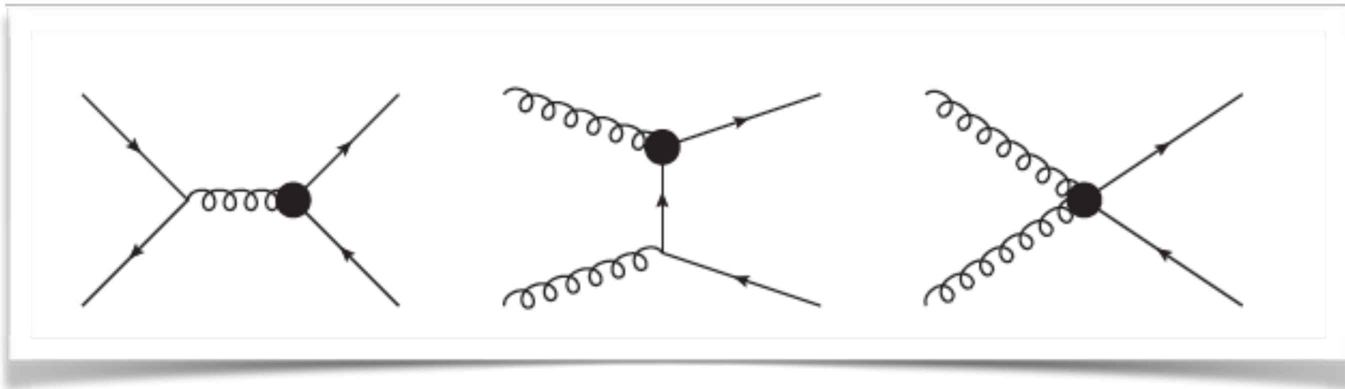


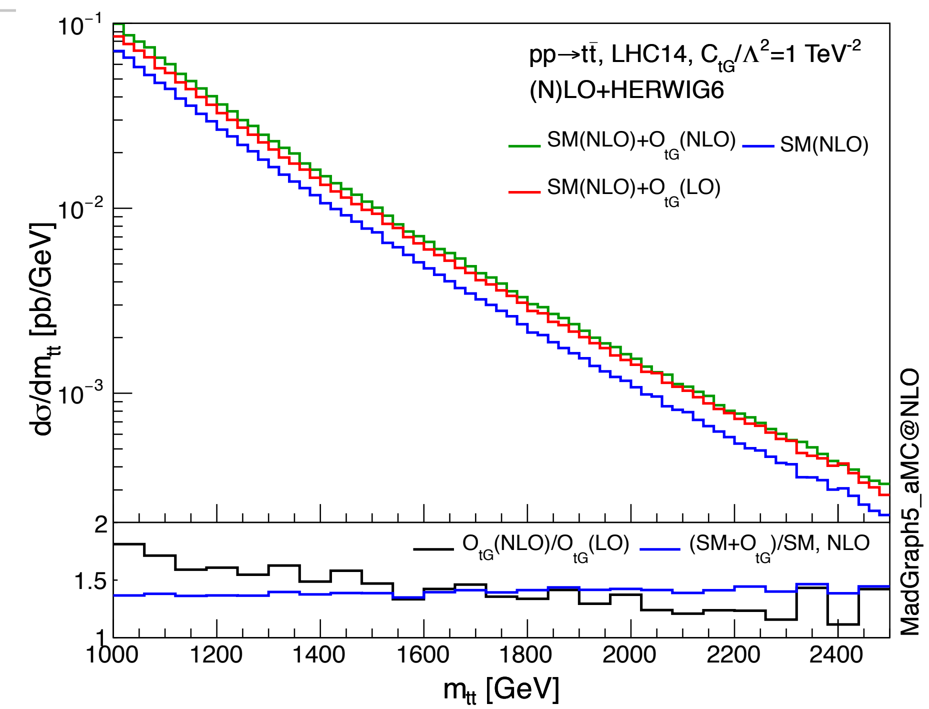
13 TeV	σ/σ_{SM} LO
σ_{SM}	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.227^{+0.00114+0.0116}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
σ_{tG}	$-1.356^{+0.0271+0.161}_{-0.0225-0.051}$
$\sigma_{t\phi,t\phi}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi G,\phi G}$	$2856.2^{+743.3+552}_{-628.5-425}$
$\sigma_{tG,tG}$	$1.940^{+0.0650+0.198}_{-0.0477-0.493}$
$\sigma_{t\phi,\phi G}$	$-11.83^{+1.39+1.42}_{-1.41-1.77}$
$\sigma_{t\phi,tG}$	$-0.340^{+0.000238+0.064}_{-0.000438-0.047}$
$\sigma_{\phi G,tG}$	$147.5^{+20.83+20.7}_{-18.86-31.4}$

To be investigated: the impact of the chromomagnetic operator in EFT analyses that focus on the extraction of the triple Higgs coupling λ (e.g. arXiv:1502.00539 and arXiv: 1410.3471)

Bounding OtG at NLO from ttbar

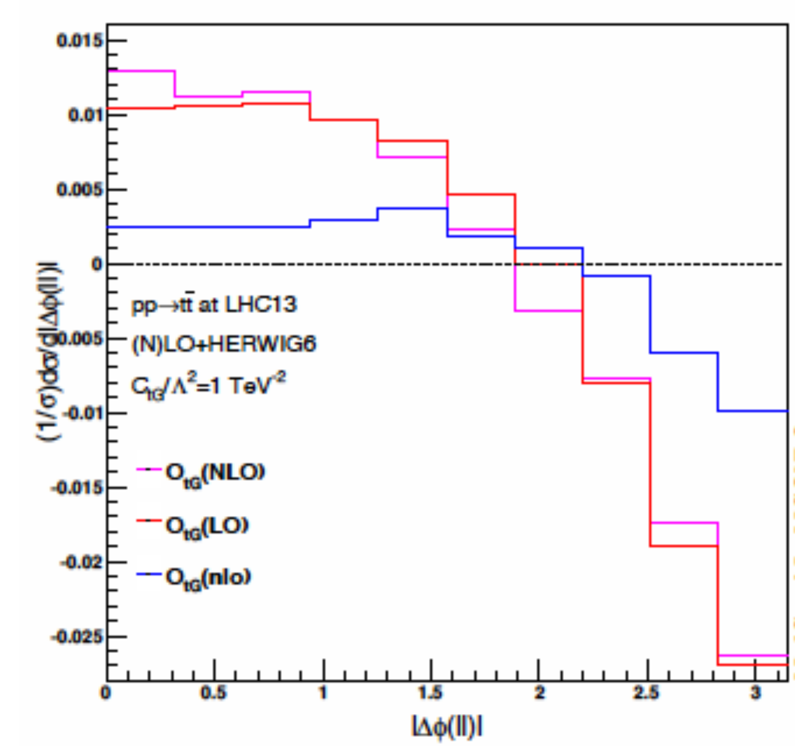
[Franzosi and Zhang, 2015]





Recent analysis at NLO in QCD

$$\sigma = \sigma_{\rm SM} + \frac{C_{tG}}{\Lambda^2}\beta_1 + \left(\frac{C_{tG}}{\Lambda^2}\right)^2 \beta_2$$

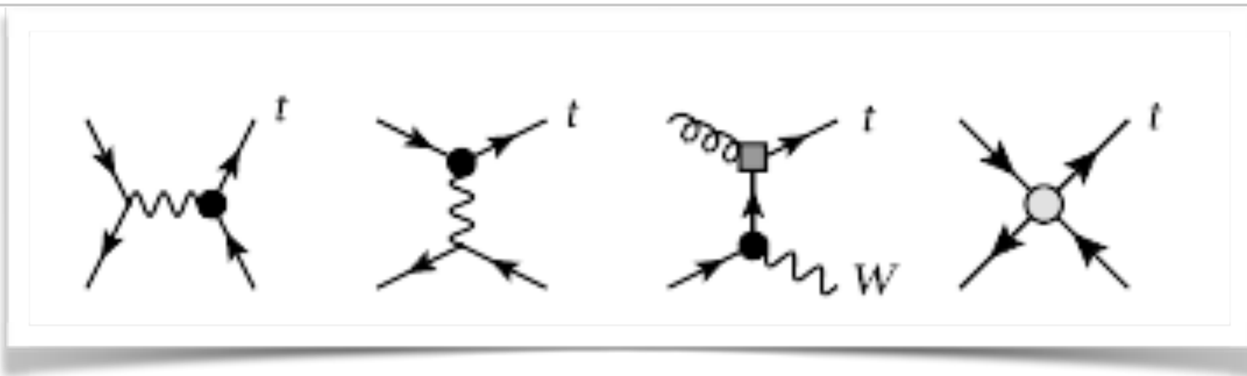


Limits on ctG from LHC8

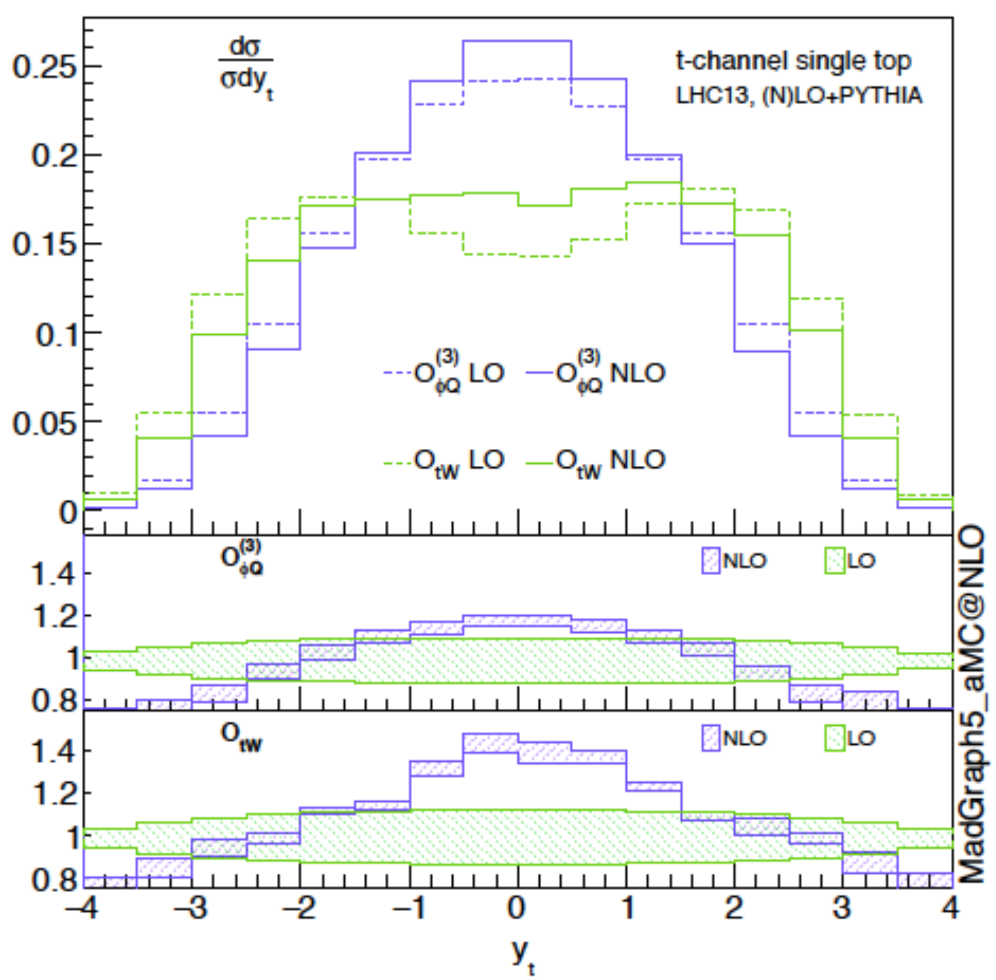
	LO [TeV^{-2}]	NLO [TeV^{-2}]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

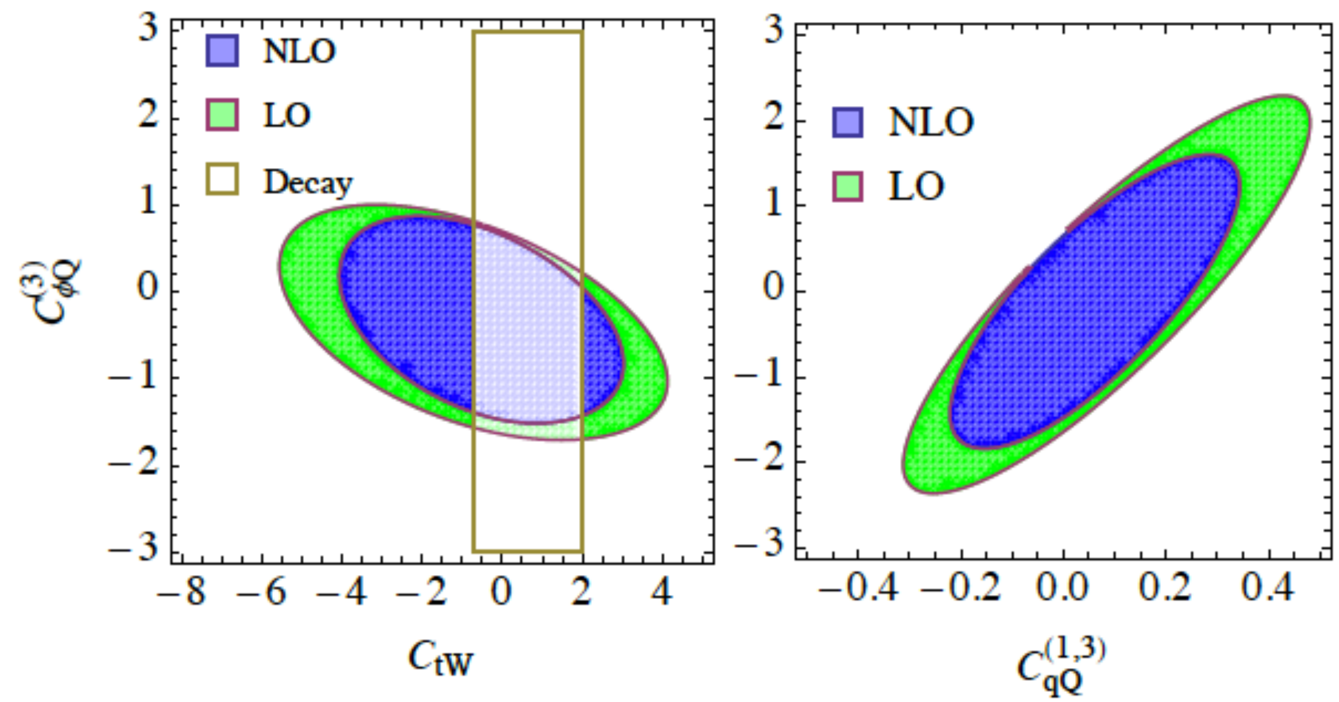
Single-top in the EFT at NLO

[Cen Zhang, 2016]



4F operator can also be included (on-going).





NLO corrections distort LO distributions, they impact the limits in accuracy and precision.

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma_i^{(1)} + \sum_{i<j} \frac{C_i C_j}{(\Lambda/1\mathrm{TeV})^4}\sigma_{ij}^{(2)}$$

13TeV	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$
$\sigma_{i,LO}^{(1)}$	$286.7^{+38.2\%}_{-25.5\%}$	$78.3^{+40.4\%}_{-26.6\%}$	$51.6^{+40.1\%}_{-26.4\%}$	$-0.20(3)^{+88.0\%}_{-230.0\%}$
$\sigma_{i,NLO}^{(1)}$	$310.5^{+5.4\%}_{-9.7\%}$	$90.6^{+7.1\%}_{-11.0\%}$	$57.5^{+5.8\%}_{-10.3\%}$	$-1.7(2)^{+31.3\%}_{-49.1\%}$
K-factor	1.08	1.16	1.11	8.5
$\sigma_{ii,LO}^{(2)}$	$258.5^{+49.7\%}_{-30.4\%}$	$2.8(1)^{+39.7\%}_{-26.9\%}$	$2.9(1)^{+39.7\%}_{-26.7\%}$	$20.9^{+44.3\%}_{-28.3\%}$
$\sigma_{ii,NLO}^{(2)}$	$244.5^{+4.2\%}_{-8.1\%}$	$3.8(3)^{+13.2\%}_{-14.4\%}$	$3.9(3)^{+13.8\%}_{-14.6\%}$	$24.2^{+6.2\%}_{-11.2\%}$

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

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

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

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

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

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

Small contribution from OtW and OtB at $O(1/\Lambda^2)$ but large at $O(1/\Lambda^4)$

How should we treat $O(1/\Lambda^4)$ terms?

$$C_i^2\frac{E^4}{\Lambda^4} > C_i\frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

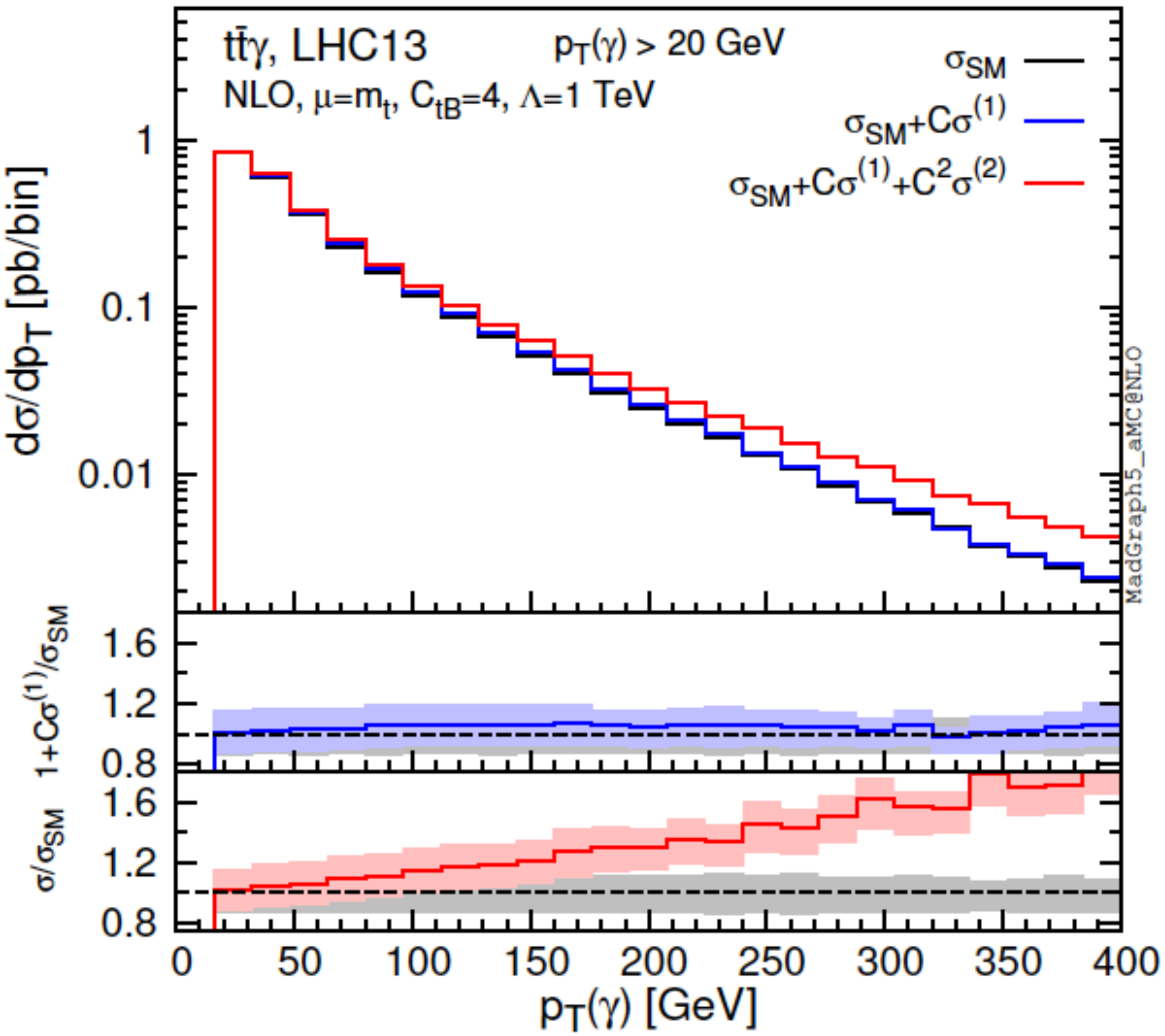
EFT condition satisfied. To be checked on a case-by-case basis

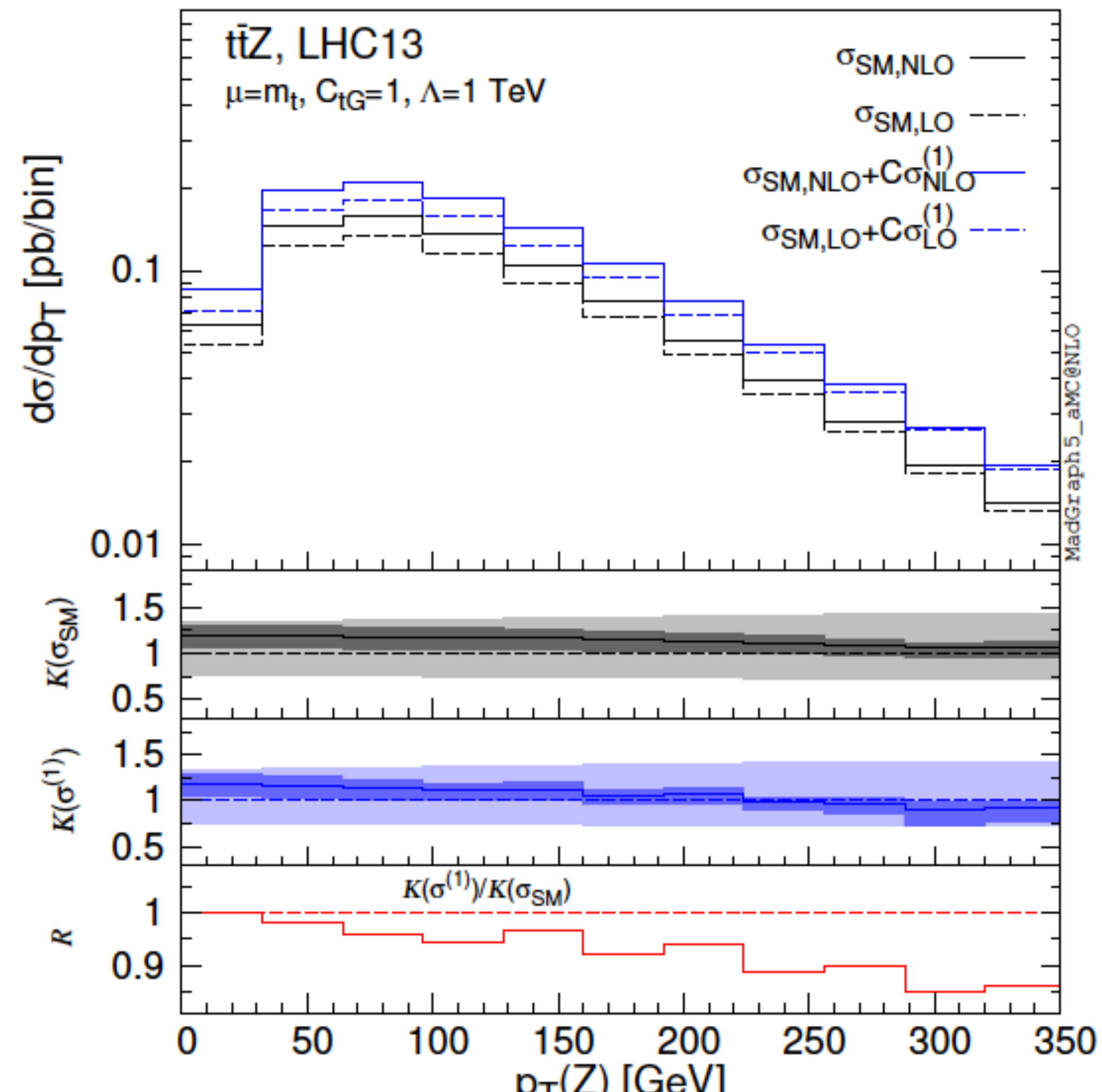
$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} \end{pmatrix}$$

Anom. dim. matrix: O_{tW}, O_{tB}, O_{tG}

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]



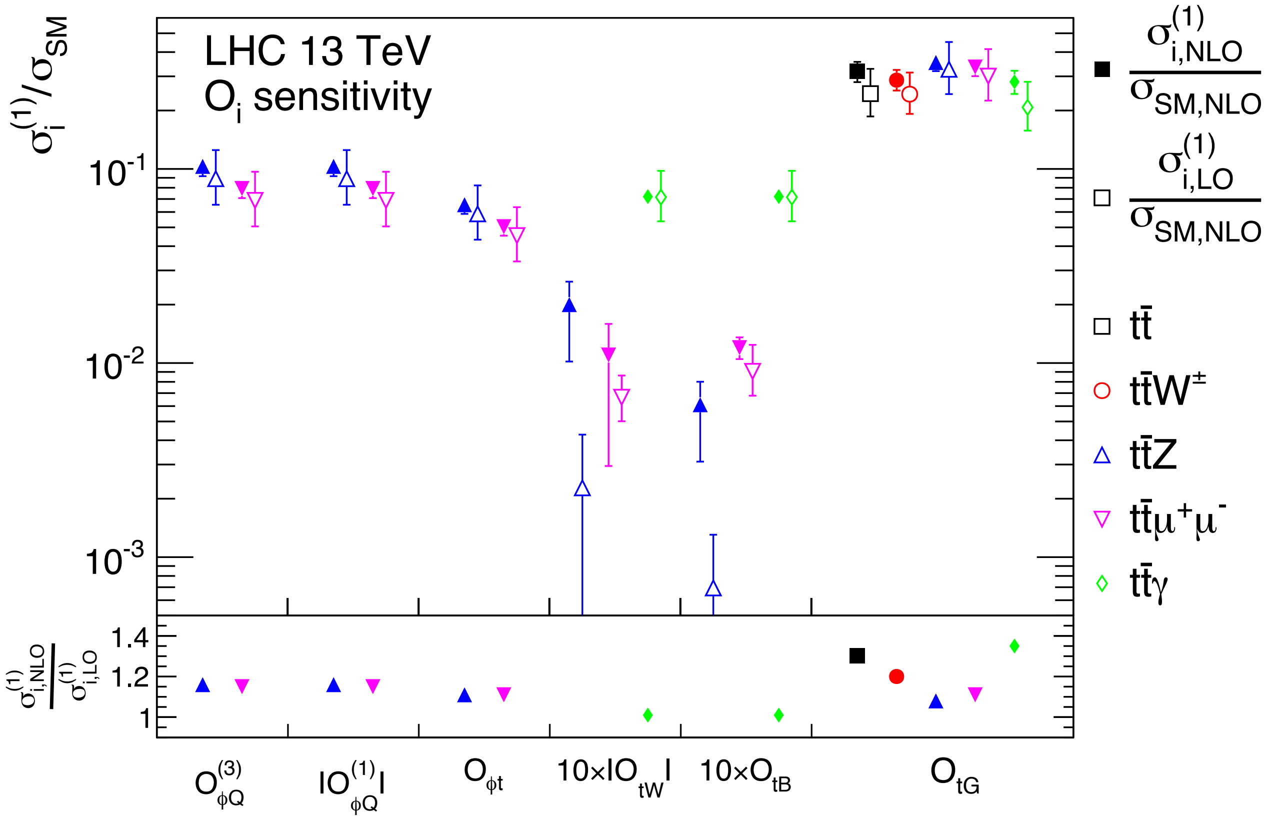


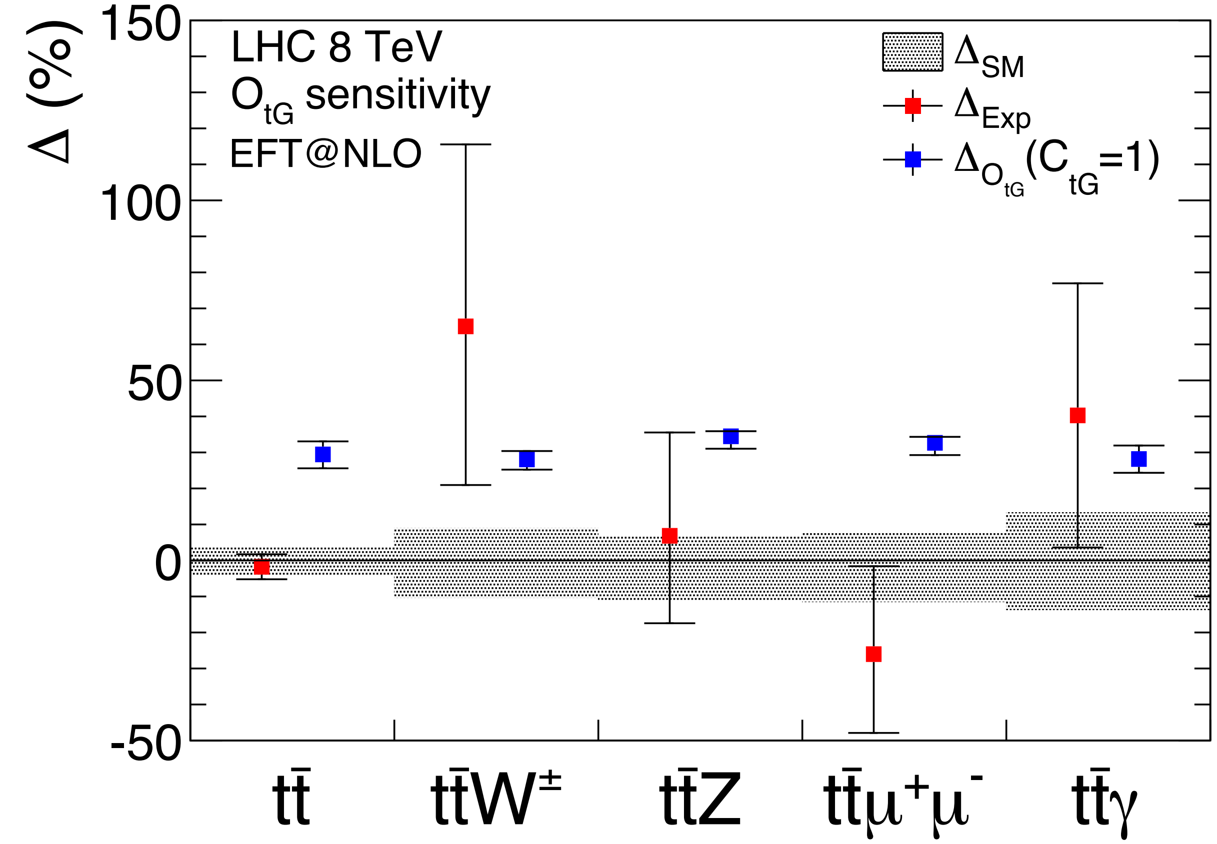
Large contribution at $O(1/\Lambda^4)$ rising with energy

Using SM k-factors is not enough

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]





Chromomagnetic operator affecting all processes in the same way.

LHC measurements of ttV processes can set constraints on the Wilson coefficients See also: [Rontsch and Schulze et al. 2014, 2015] and [Schulze 2016] in the anomalous coupling framework.

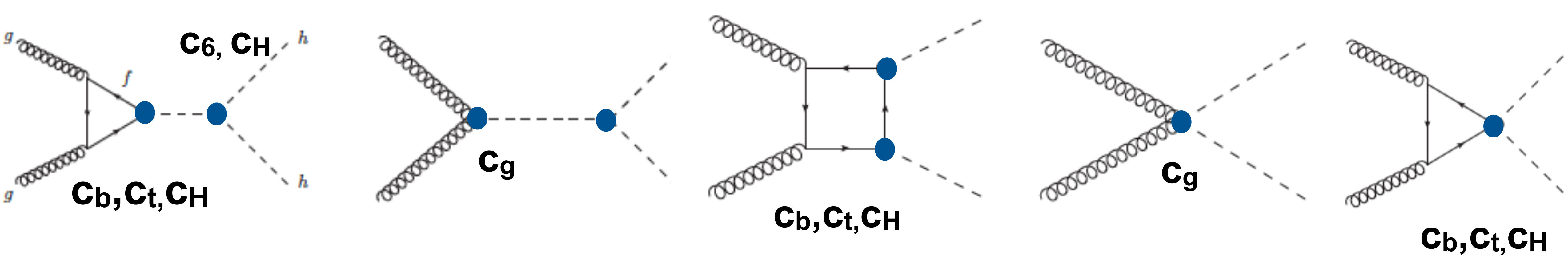
HH production in the SMEFT

$$\mathcal{L}_{h^n} = -\mu^2|H|^2 - \lambda|H|^4 - \left(y_t\bar{Q}_L H^c t_R + y_b\bar{Q}_L H b_R + \text{h.c.}\right)$$
$$+ \frac{c_H}{2\Lambda^2}(\partial^\mu|H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda|H|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu}G^{\mu\nu}_a$$
$$-\left(\frac{c_t}{\Lambda^2}y_t|H|^2\bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2}y_b|H|^2\bar{Q}_L H b_R + \text{h.c.}\right),$$

[Goertz et al. , arxiv:1410.3471]
[Contino et al. , arXiv:1502.00539]

EFT approach: No additional light states
Dimension-6 operators suppressed by scale Λ

$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1-\frac{3}{2}c_H + c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1-\frac{25}{3}c_H + 6c_6\right)h^4$$
$$+\frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a$$
$$-\left[\frac{m_t}{v}\left(1-\frac{c_H}{2}+c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1-\frac{c_H}{2}+c_b\right)\bar{b}_L b_R h + \text{h.c.}\right]$$
$$-\left[\frac{m_t}{v^2}\left(\frac{3c_t}{2}-\frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2}-\frac{c_H}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right],$$

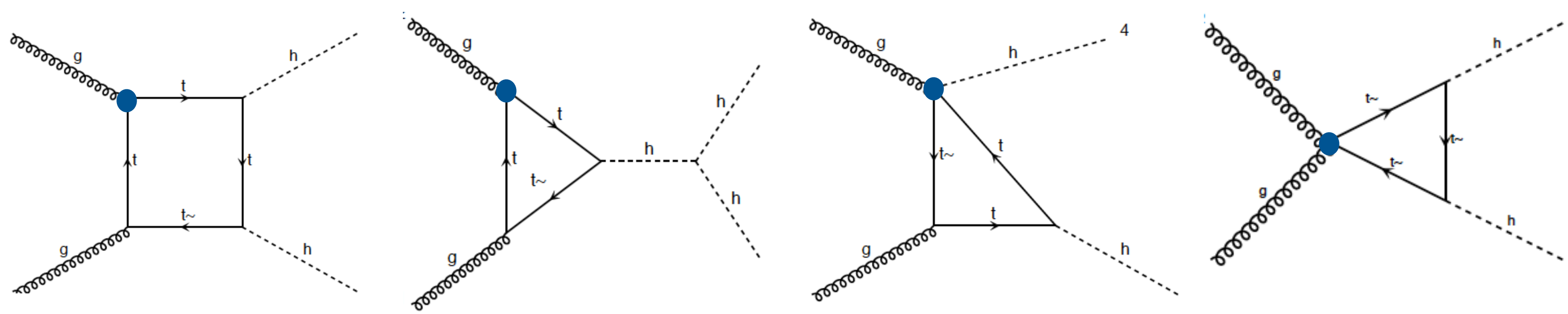


5 parameters:c6, cH, cb,ct,cg

HH production in the SMEFT

Chromomagnetic operator is also contributing [FM, Vryonidou, Zhang, 16]

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



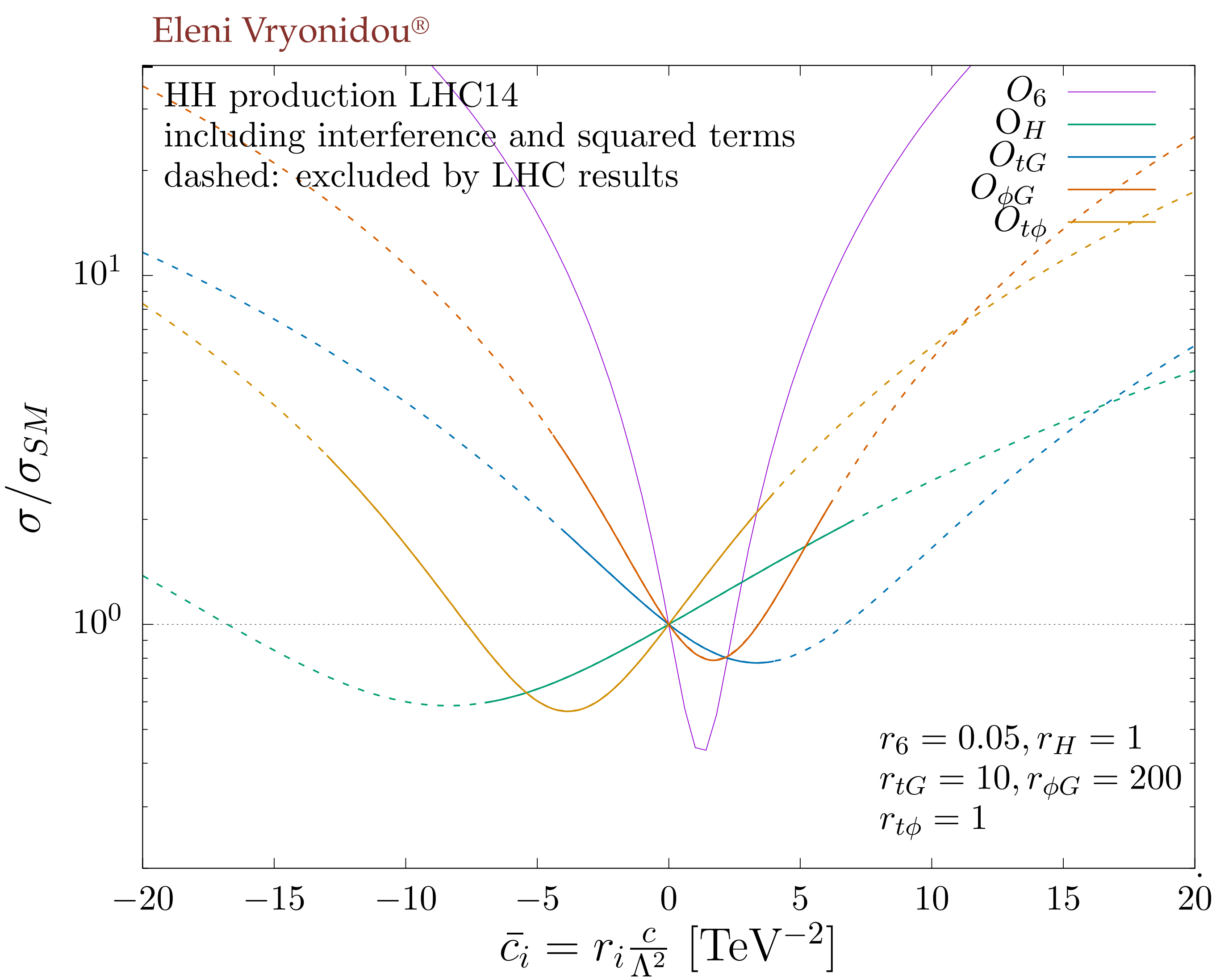
Needs to be taken into account in the context of a global EFT analysis for HH
Constraints from top pair production at NLO:

C_{tg}= [-0.42,0.30] [Zhang and Franzosi,15]

show that this operator contribution is important.

Note: now that NLO in the SM is known, one could have c_t,c_H,c_g contributions at NLO.
The c_g is known at NNLO [de Florian, Fabre, Mazzittelli, 17]

HH sensitivity in the SMEFT



Sensitivity plot of σ(HH) in terms of the five relevant operators. Coefficients are rescaled so that the ranges are comparable.

1. An accurate measurement of the Higgs self-couplings will depend on our ability to bound several (top-related) SMEFT operators: O_{tG},$O_{\varphi G}$,$O_{t\varphi}$.
2. Given the current constraints on σ(HH), the Higgs self-coupling can be constrained "ignoring" the other EFT couplings.
3. The current "EFT-relevant" range corresponds to values around -2 ≲ k_λ ≲ 4.