

EFT in the top-Higgs sector

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LHC HXSWG General Assembly

CERN

14/07/2017

SMEFT

- BSM? New Interactions of SM particles

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

- Operators at dim-6: [Buchmuller, Wyler Nucl.Phys. B268 \(1986\) 621-653](#)
[Grzadkowski et al arxiv:1008.4884](#)

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{Av} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p \gamma^\mu l_t)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{Av} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p \gamma^\mu u_r)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p \gamma^\mu d_r)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{WB}}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B -violating			
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s^k q_t^i)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{ijk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^\gamma)^T C l_t^k]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{ijk} [(q_p^\alpha)^T C q_r^\beta] [(u_s^\gamma)^T C e_t]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{ijk} \varepsilon_{mnn} [(q_p^\alpha)^T C q_r^\beta] [(q_s^\gamma)^T C l_t^n]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^\alpha)^T C q_r^\beta] [(q_s^\gamma)^T C l_t^n]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$		

Focussing on top-Higgs

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

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

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

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

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

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

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

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

Production process

gg → h

gg → hj

tth

gg → hh

gg → hz

thj

+4-fermion top operators

+Higgs decays

A messy picture

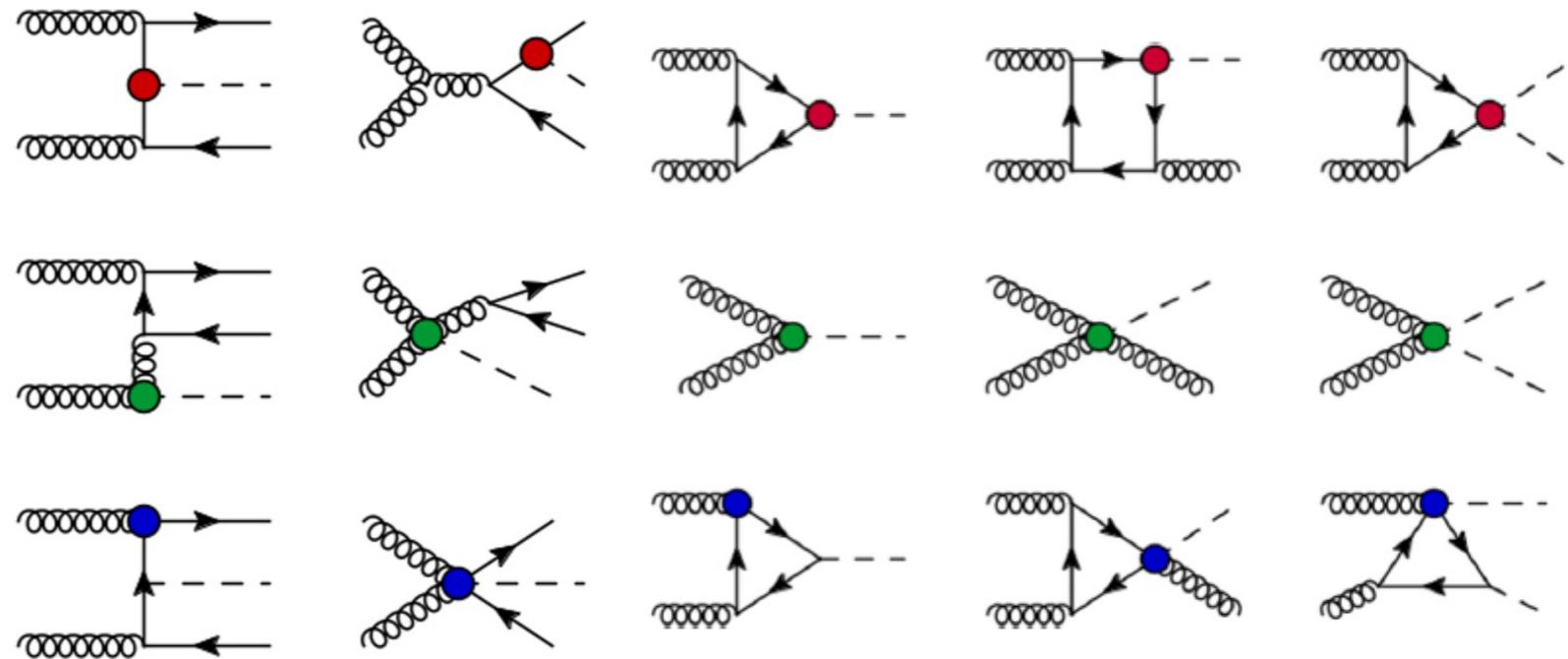
Top and Higgs

Starting from a subset:

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

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

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



ttH

H, H+j, HH

See also

Degrande et al. [arXiv:1205.1065](https://arxiv.org/abs/1205.1065)

Grojean et al. [arXiv:1312.3317](https://arxiv.org/abs/1312.3317)

Azatov et al [arXiv:1608.00977](https://arxiv.org/abs/1608.00977)

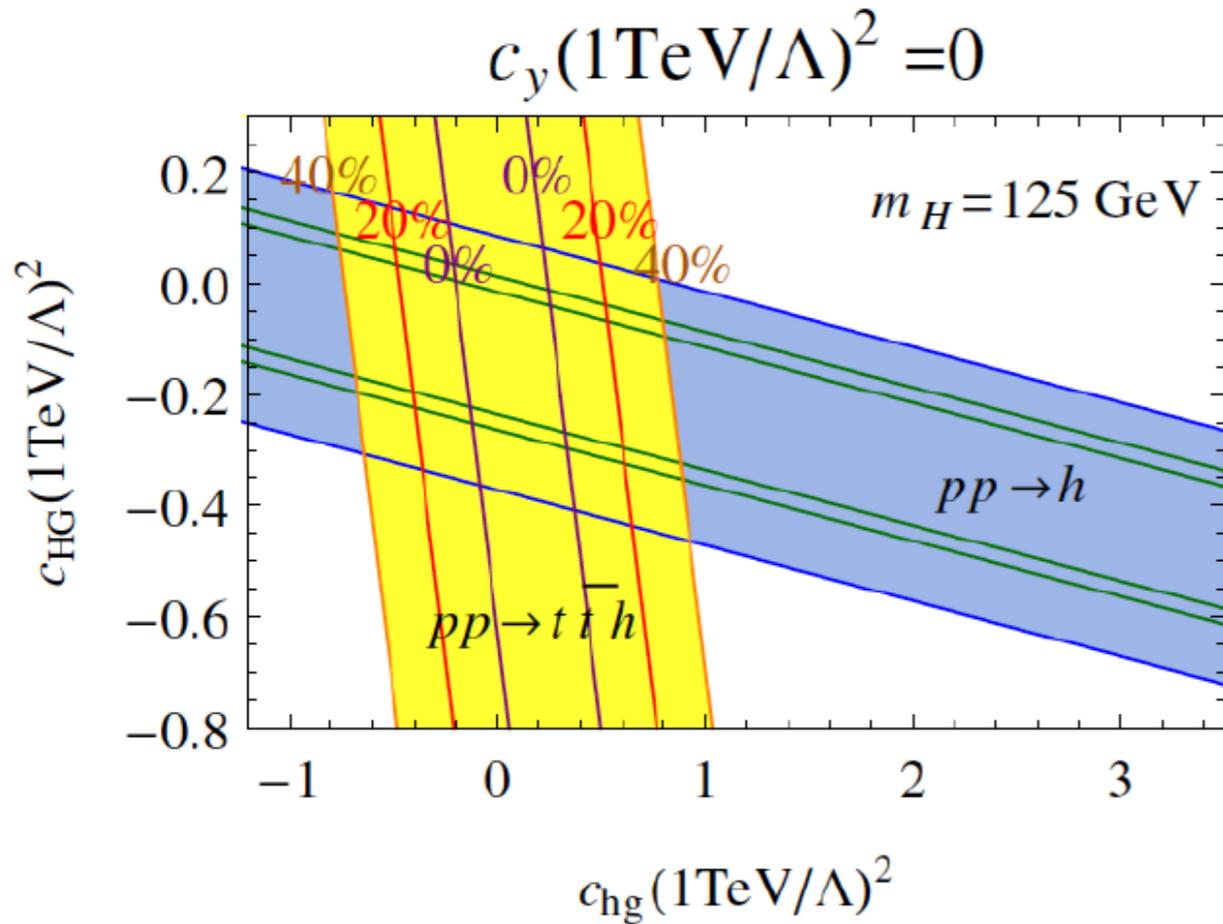
Use inclusive H with 1) ttH and/or 2) boosted H production to break degeneracy between $O_{t\phi}$ and $O_{\phi G}$ operators

Constraints from top pair production: $c_{tG} = [-0.42, 0.30]$

Why also O_{tG} ? [Franzosi and Zhang arxiv:1503.08841](https://arxiv.org/abs/1503.08841)

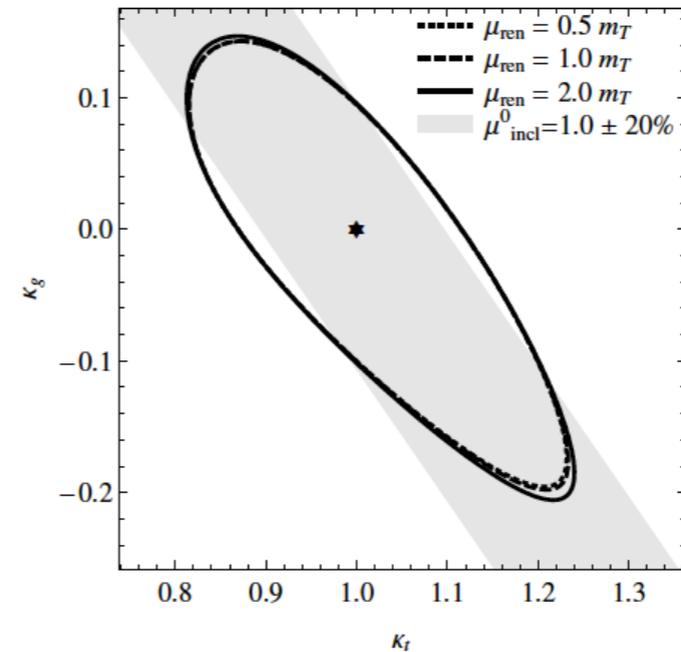
not sufficiently stringent

Breaking the degeneracy between $O_{\phi G}$ and $O_{t\phi}$

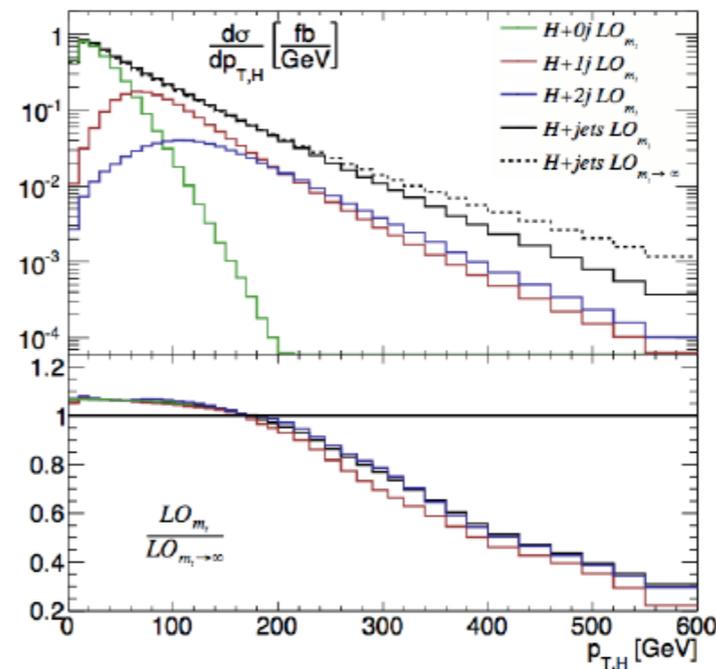


Degrande et al 1205.1065

Use ttH



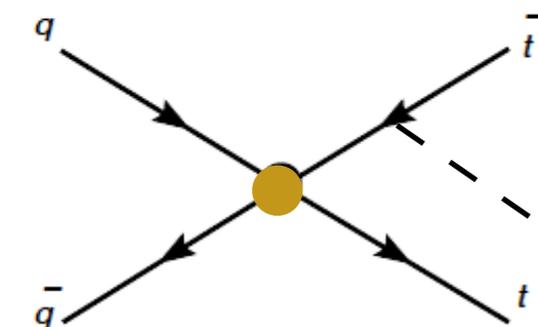
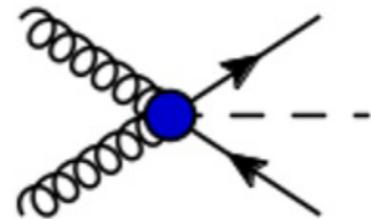
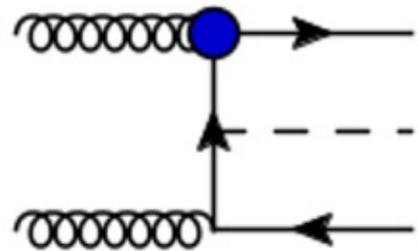
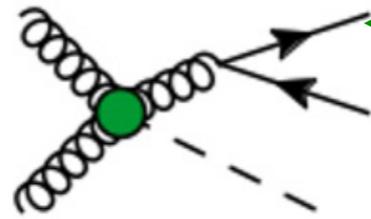
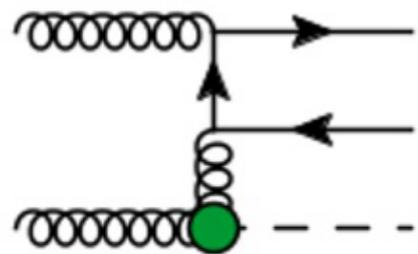
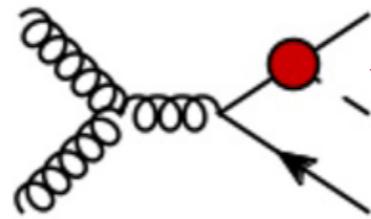
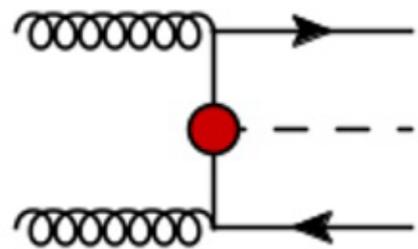
Grojean et al
1312.3317



Buschmann et al
arXiv:1410.5806

Use boosted Higgs

Progress in ttH in the EFT



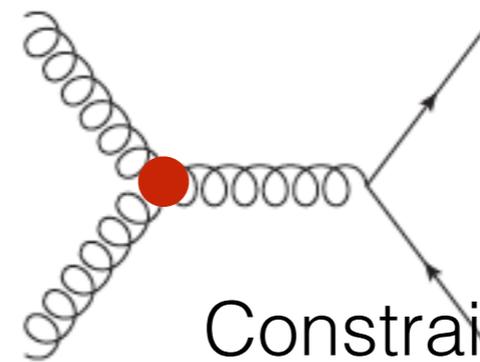
4-fermion operators

As in top pair: constraints

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

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

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



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

Constrained from multijets
Krauss et al arXiv:1611.00767

ttH@NLO in QCD

$(O_{t\phi}, O_{\phi G}, O_{tG})$

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

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

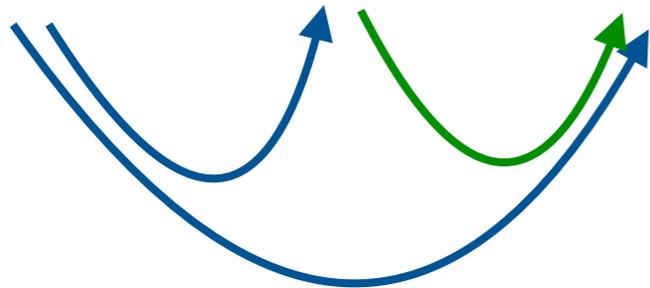
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$$

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

Alonso et al. arxiv:1312.2014

dim-6 dim-5 dim-4

O_{tG} $O_{\phi G}$ $O_{t\phi}$



Higher-dimension operators mix into lower-dimension ones

Setup in MG5_aMC allows computation of:

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

interference with SM

interference between operators, squared contributions

Cross-section results

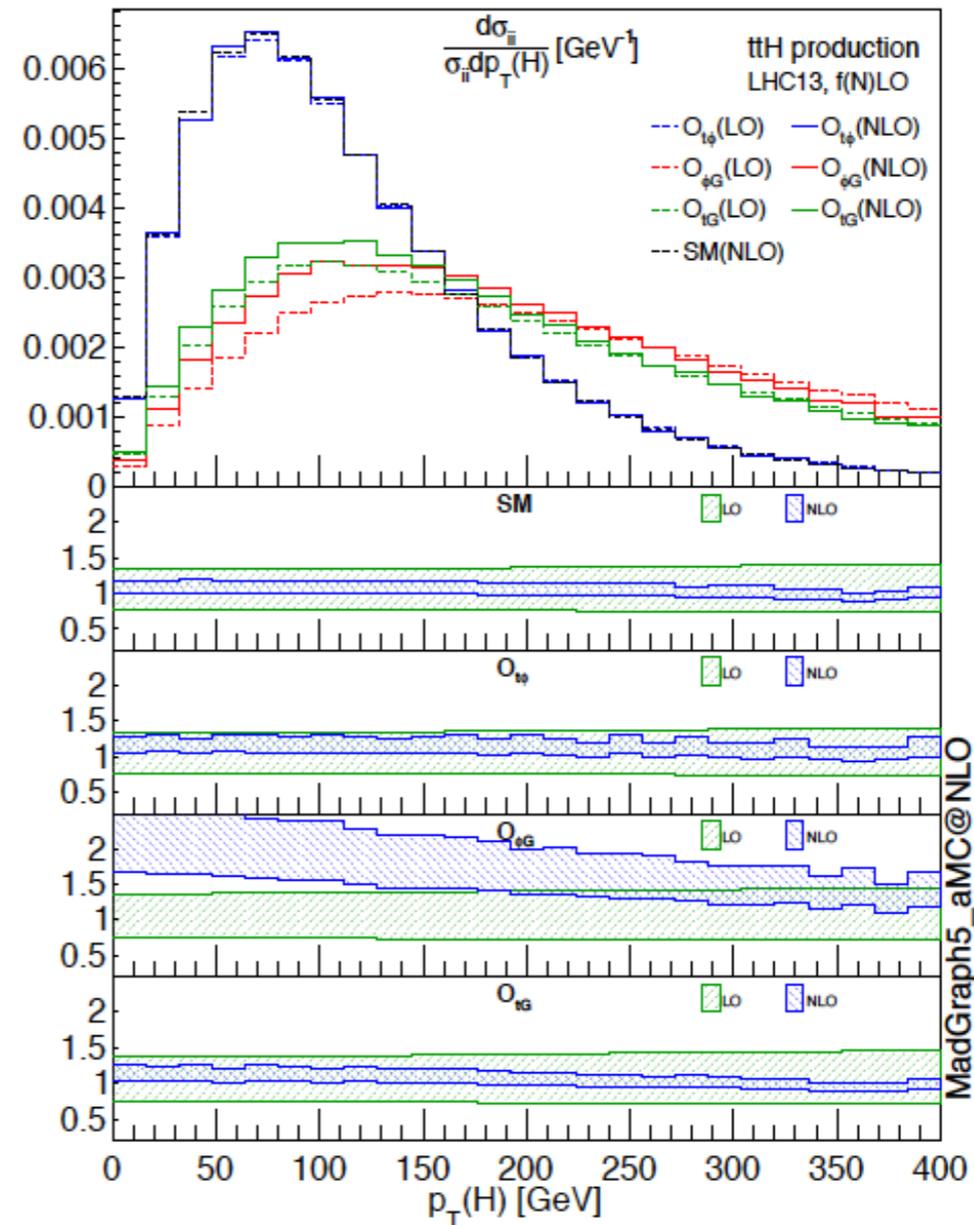
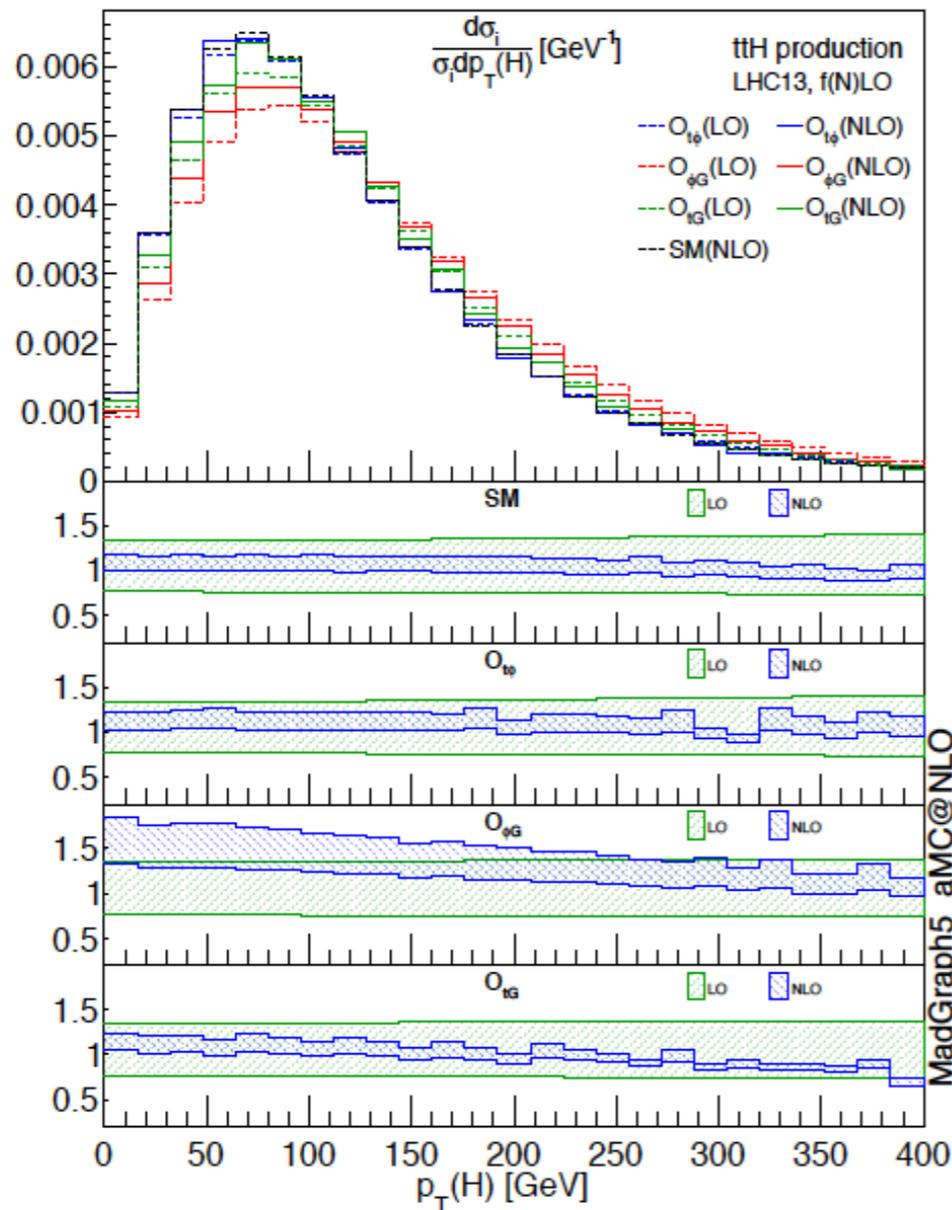
13 TeV	σ NLO	K
σ_{SM}	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	1.09
$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	1.13
$\sigma_{\phi G}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	1.39
σ_{tG}	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	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

- Different K-factors for different operators, different from the SM
- Large $1/\Lambda^4$ contribution for the chromomagnetic operator
- Constraints from one operator fit in top pair production: $c_{tG} = [-0.42, 0.30]$
[Franzosi and Zhang arxiv:1503.08841](#)
- Large contributions still allowed

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

Maltoni, EV, Zhang: arXiv:1607.05330

Differential distributions for ttH

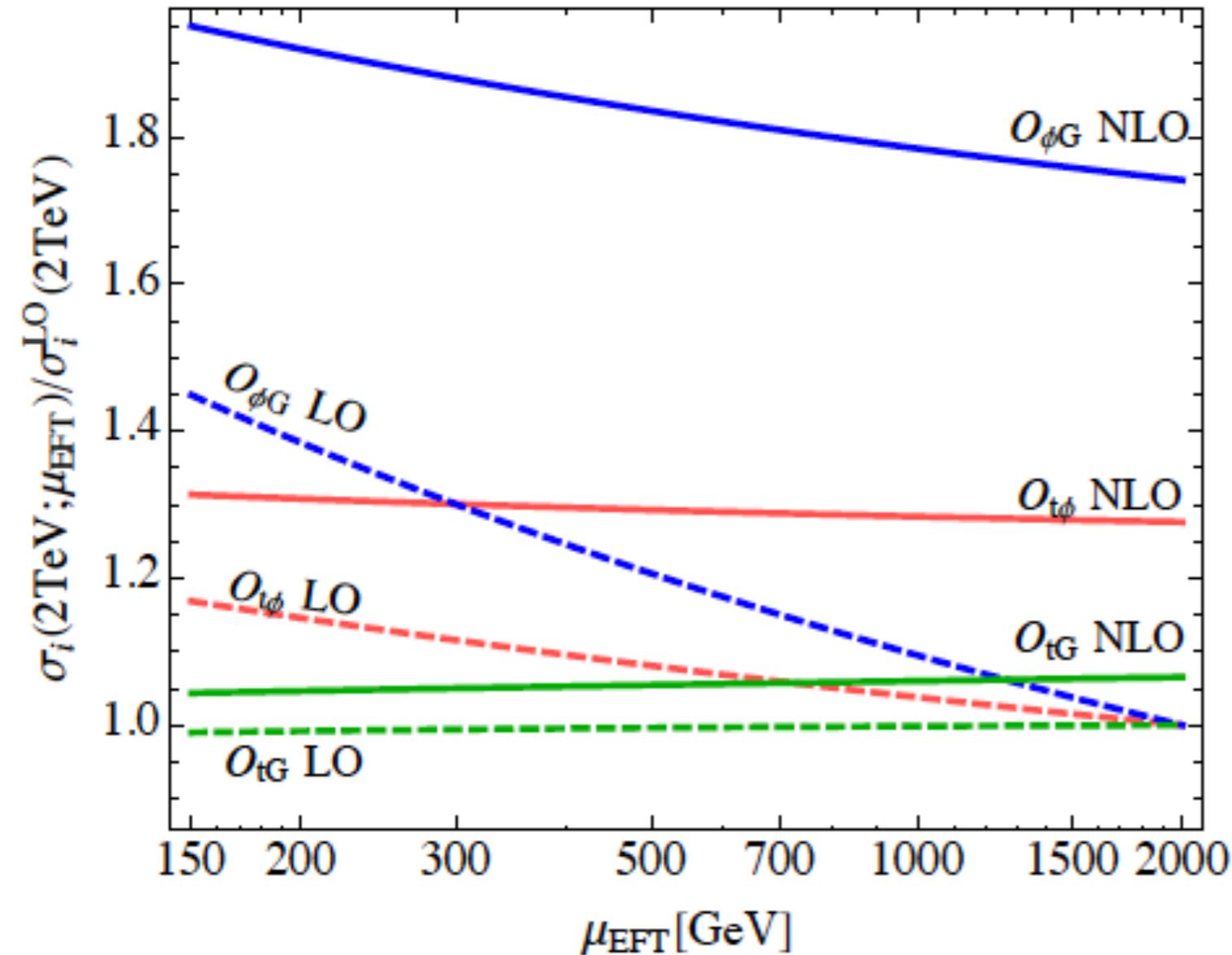


➔ NLO: smaller uncertainties,
non-flat K-factors

Different shapes for different
operators for the squared terms

Maltoni, EV, Zhang arXiv:1607.05330

A study of RG effects



RG corrections not a good approximation to the NLO result, underestimate the NLO corrections

Milder EFT scale dependence at NLO, when mixing effects also taken into account

Comparison of exact NLO with LO improved by 1-loop RG running

Some considerations

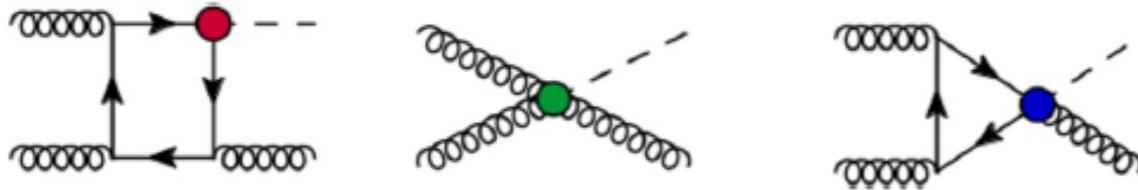
- Theory uncertainties:
 - SM: factorisation and renormalisation scale, PDF uncertainties
 - EFT: as in SM but also EFT scale $c(\mu)$, running and mixing
 - EFT expansion: dimension-8 operators
- Validity of the EFT expansion: $E < \Lambda$, report limits as a function of the max scale probed: Contino et al arXiv:1604.06444
- $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
 - $1/\Lambda^2$ suppressed due to helicity: Azatov et al arXiv:1607.05236
 - $1/\Lambda^4$ can be large for loosely constrained operator coefficients/strongly coupled theories

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

EFT condition satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

- Range of Wilson coefficients:
 - The theory: perturbativity, unitarity, linear or non-linear EFT, UV completion
 - The experimental limits: Think about and use as many processes as possible

Progress in H+jet in the EFT (1)

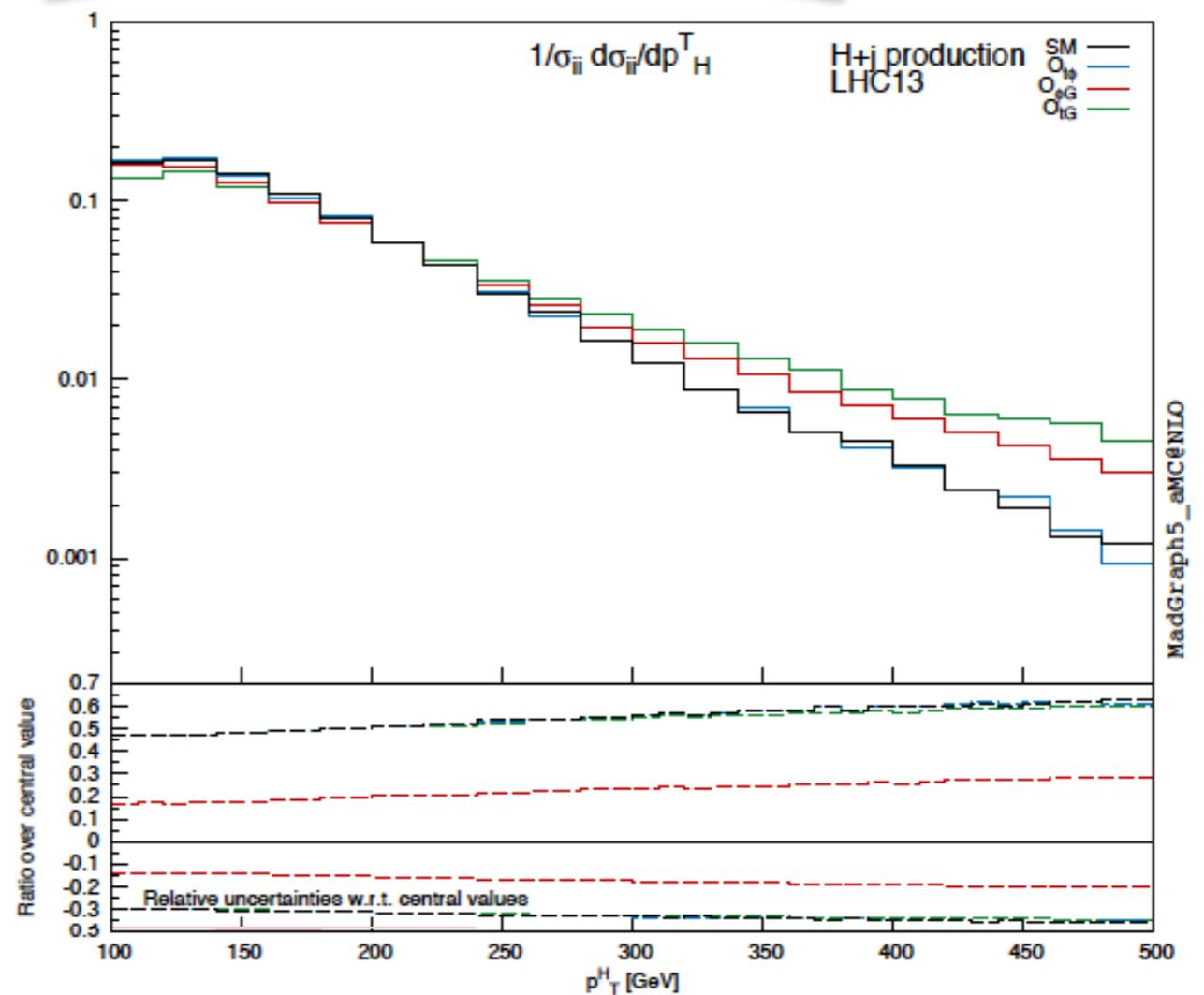
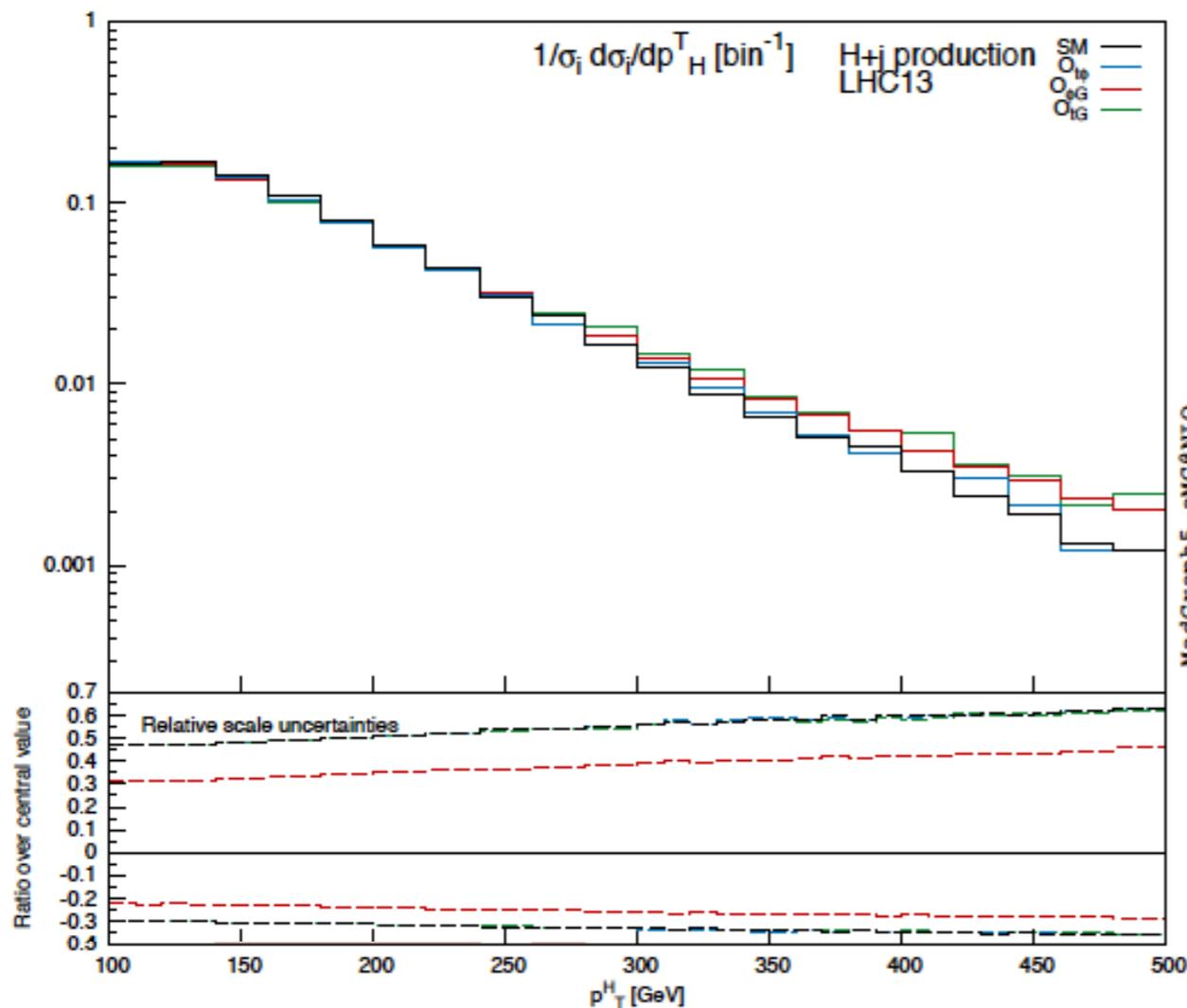


$$O_{t\phi} = y_t^3 (\phi^\dagger \phi) (\bar{Q}t) \tilde{\phi}$$

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

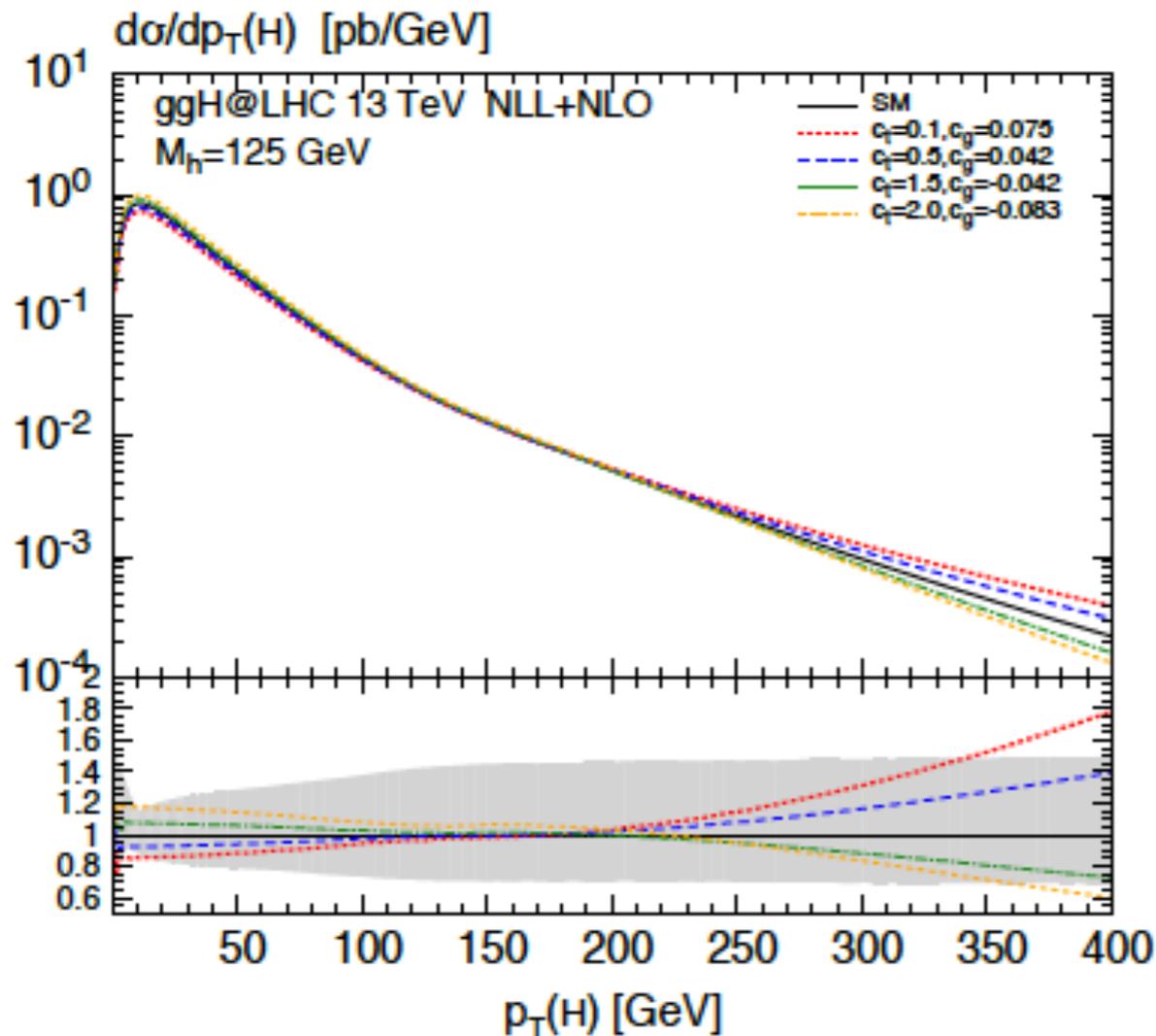
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$$

New



Harder tails from dim-6 operators: Boosted analysis

Progress in H+jet in the EFT (2)



Grazzini et al 1612.00283

NLO+NLL Higgs p_T spectrum

$$\mathcal{O}_1 = |H|^2 G_{\mu\nu}^a G^{a,\mu\nu}$$

$$\mathcal{O}_2 = |H|^2 \bar{Q}_L H^c u_R + h.c., \quad \text{Top Yukawa}$$

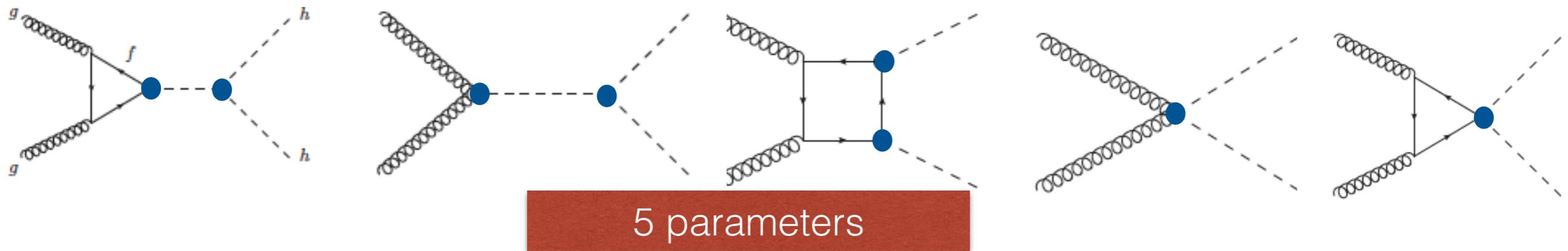
$$\mathcal{O}_3 = |H|^2 \bar{Q}_L H d_R + h.c. \quad \text{Bottom Yukawa}$$

Non-trivial EFT parameter combinations not changing the inclusive cross-section but changing the distributions: **impact of differential measurements**

Rarer processes: HH

Current HH EFT treatment:

$$\mathcal{L} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}$$



The full EFT picture:

$$\Delta\mathcal{L}_6 \supset \frac{\bar{c}_H}{2v^2} [\partial_\mu (H^\dagger H)]^2 + \frac{\bar{c}_u}{v^2} y_u H^\dagger H \bar{q}_L H^c u_R - \frac{\bar{c}_6}{v^2} \frac{m_h^2}{2v^2} (H^\dagger H)^3 + \frac{\bar{c}_g}{m_w^2} g_s^2 H^\dagger H G_{\mu\nu} G^{\mu\nu} + \frac{c_{tG}}{\Lambda^2} \bar{Q} \sigma^{\mu\nu} T^A t \tilde{\phi} G_{\mu\nu}^A$$

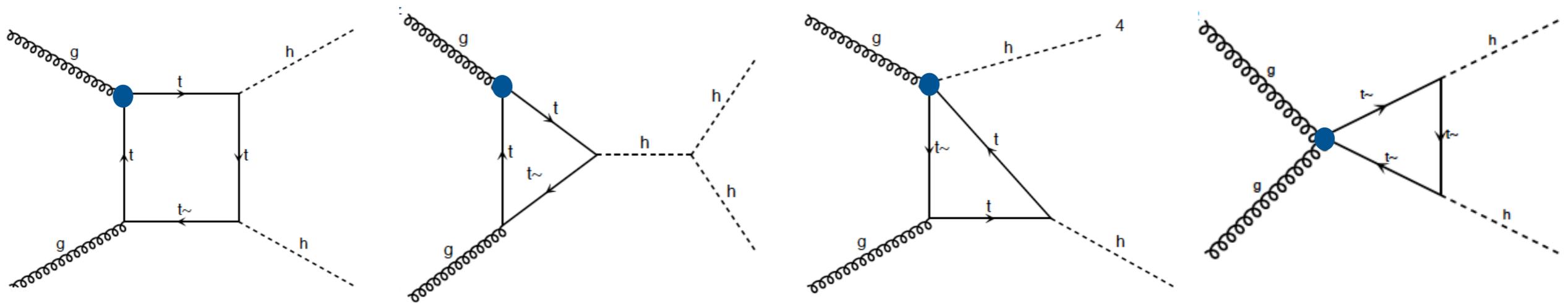
5 (different) parameters

c.f. Goertz et al. arxiv:1410.3471,
Contino et al. arXiv:1502.00539₁₄

The missing dimension-6 part

Chromomagnetic operator is also contributing

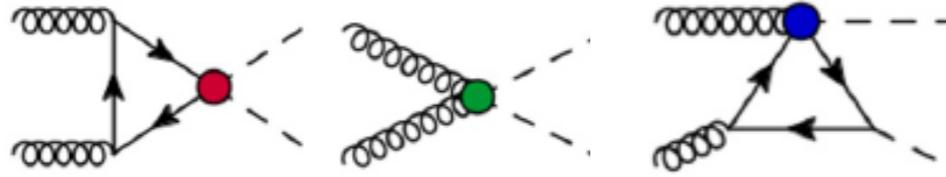
$$\frac{c_{tG}}{\Lambda^2} \bar{Q} \sigma^{\mu\nu} T^A t \tilde{\phi} G_{\mu\nu}^A$$



Needs to be taken into account in the context of a global EFT analysis for HH

How much does this operator contribute to HH?

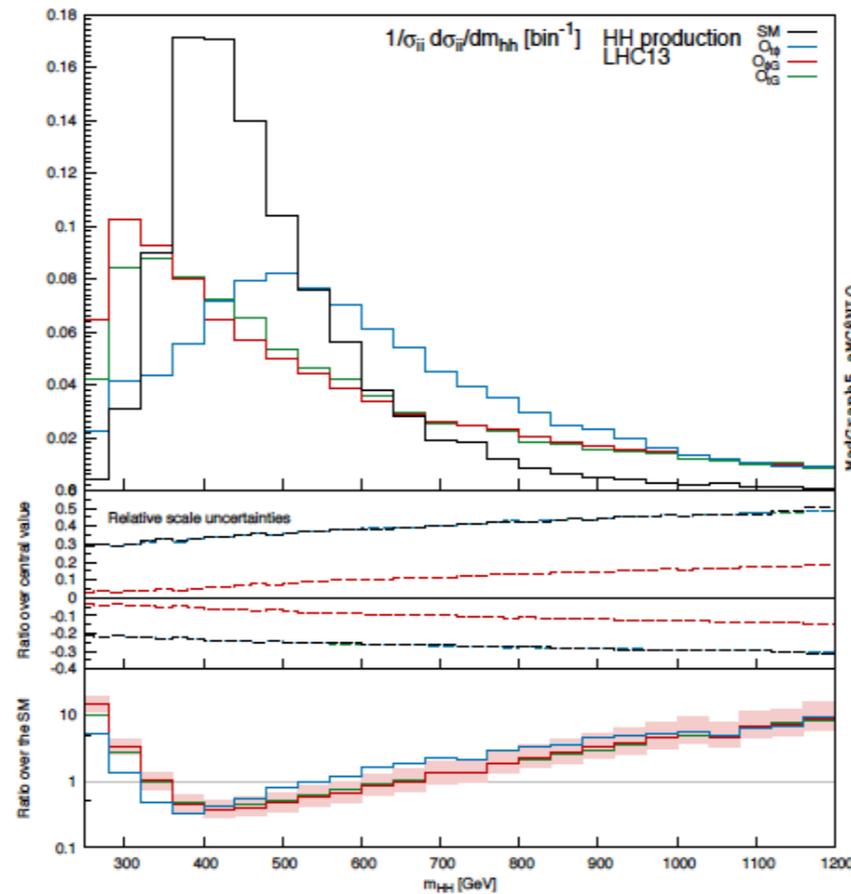
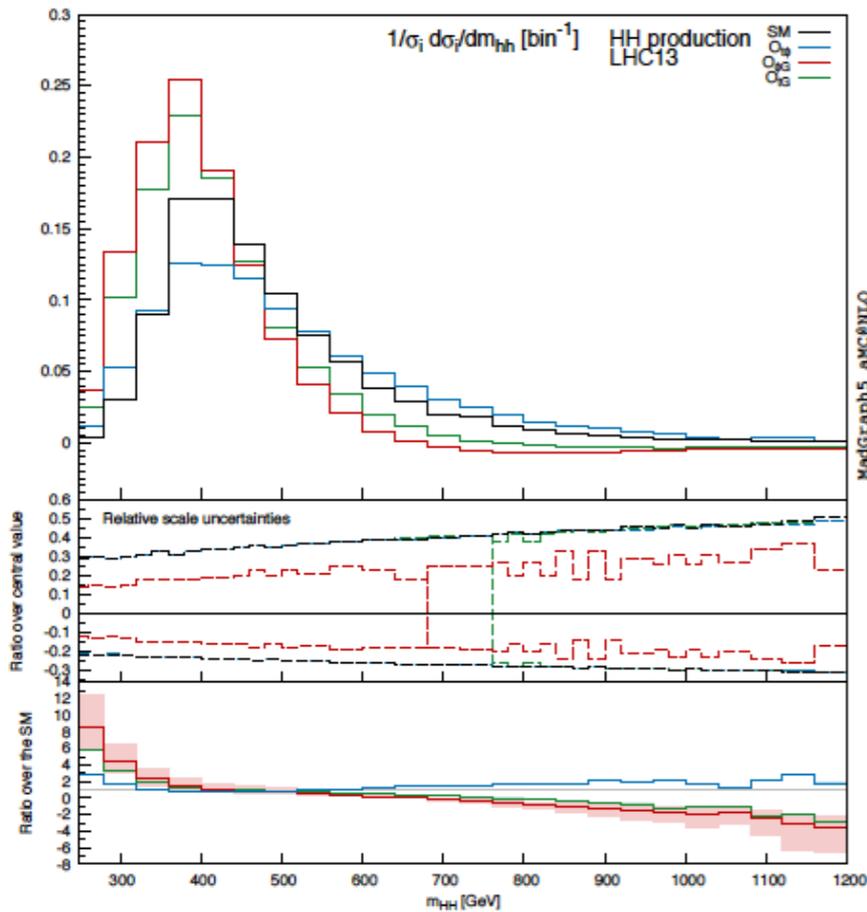
SMEFT in HH



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

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

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

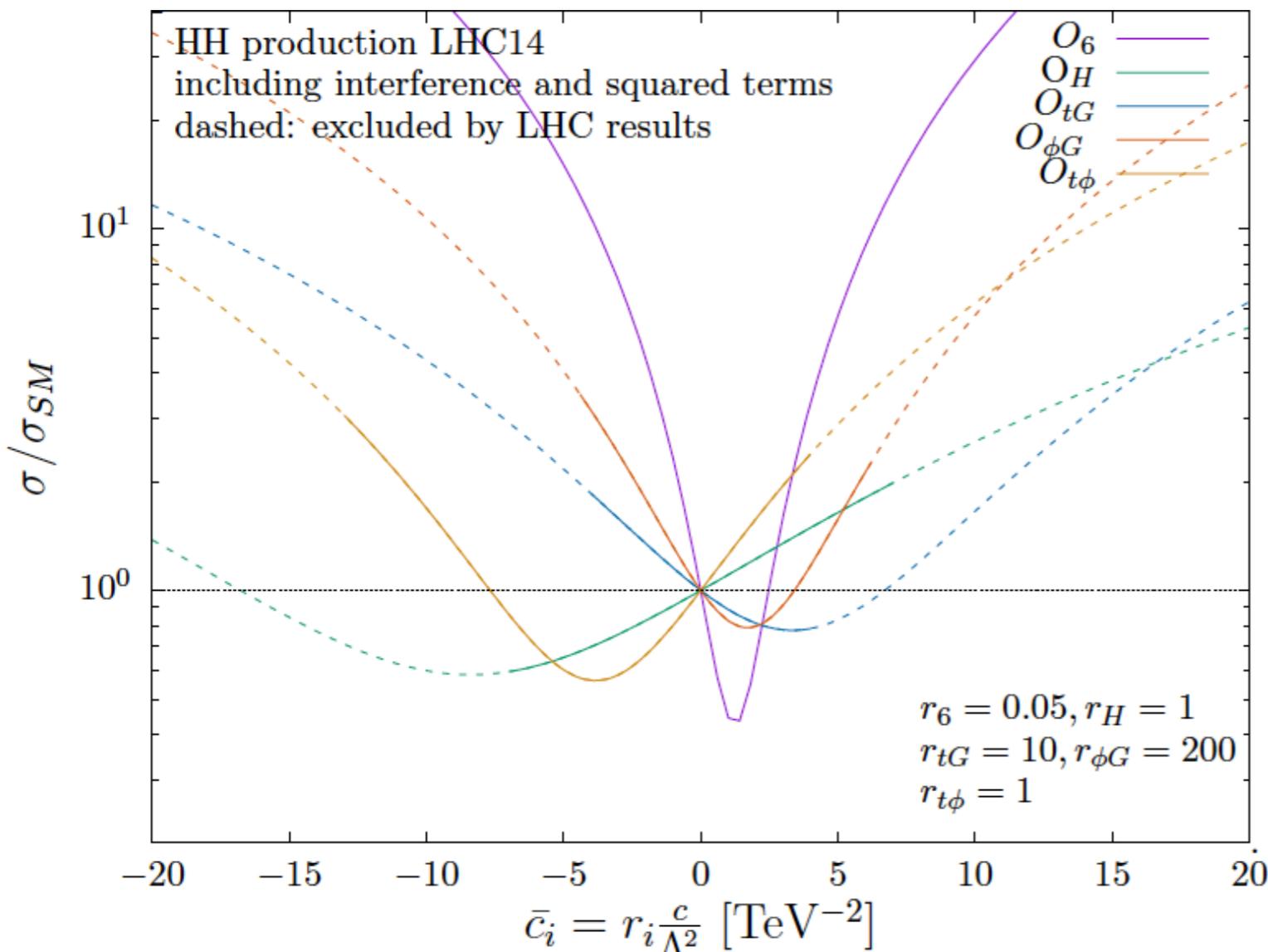


13 TeV	σ/σ_{SM} LO
σ_{SM}	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.227^{+0.00114+0.0118}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
σ_{tG}	$-1.356^{+0.0271+0.161}_{-0.0225-0.051}$
$\sigma_{t\phi,t\phi}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi G,\phi G}$	$2856.2^{+743.3+552}_{-628.5-425}$
$\sigma_{tG,tG}$	$1.940^{+0.0650+0.198}_{-0.0477-0.493}$
$\sigma_{t\phi,\phi G}$	$-11.83^{+1.39+1.42}_{-1.41-1.77}$
$\sigma_{t\phi,tG}$	$-0.340^{+0.000238+0.064}_{-0.000438-0.047}$
$\sigma_{\phi G,tG}$	$147.5^{+20.83+20.7}_{-18.86-31.4}$

Experimental HH analyses with EFT interpretation need to consider:

C_{tG} , $C_{\phi G}$, $C_{t\phi}$, C_H , C_6

How will O_{tG} affect the HH EFT analyses?



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

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

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

$$O_6 = -\lambda (\phi^\dagger \phi)^3 \quad \kappa_\lambda = 1 - c_H \frac{3v^2}{2\Lambda^2} + c_6 \frac{v^2}{\Lambda^2}$$

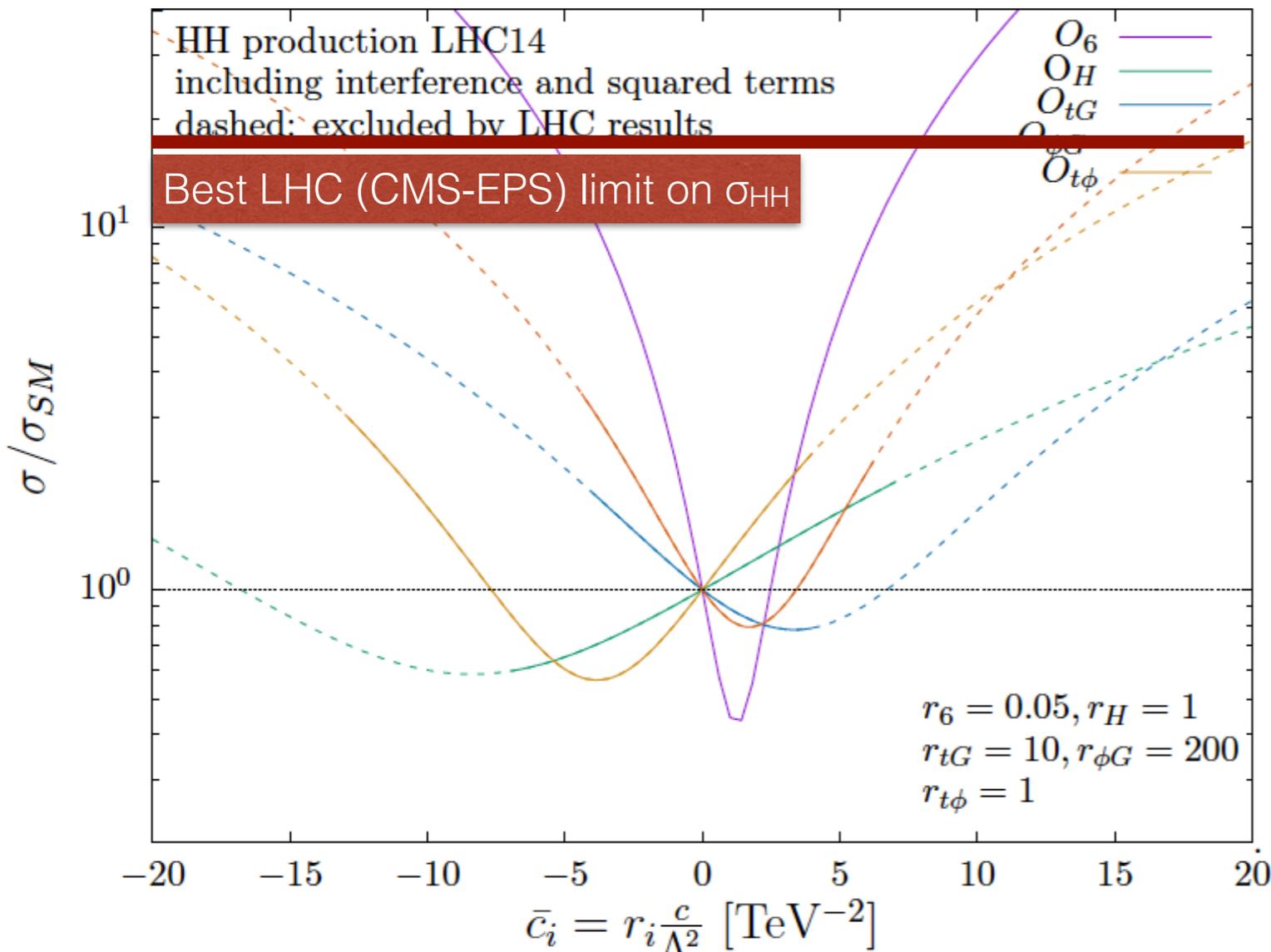
$$O_H = \frac{1}{2} (\partial_\mu (\phi^\dagger \phi))^2$$

5 parameters

Approximate constraints from single Higgs (e.g. Butter et al arxiv:1604.03105) and top pair production (Franzosi and Zhang arxiv:1503.08841)

- Precise knowledge of other Wilson coefficients will be needed to bound c_6 as the bound gets closer to SM
- Differential distributions will also be necessary

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- Differential distributions will also be necessary

Constraining our 3 operator subset

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

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

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

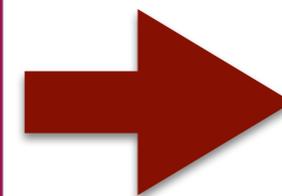
Toy χ^2 fit for illustrative purposes using:
 single H, ttH Run I and Run II results
 Impact of the 3 operators also included in
 Higgs decays

	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.

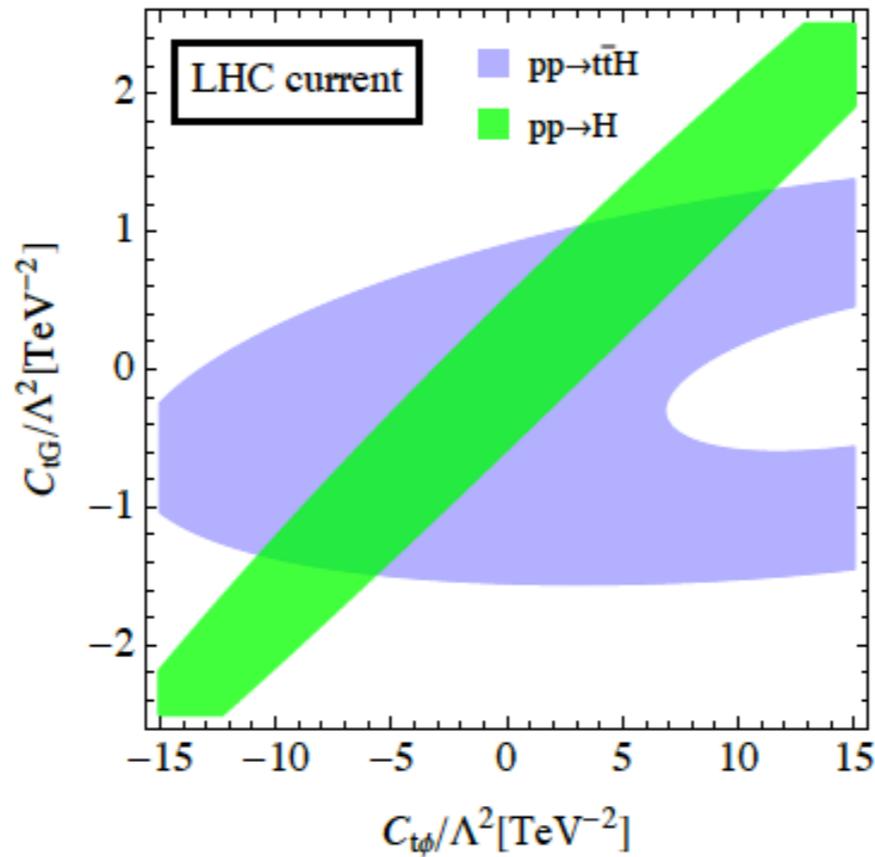
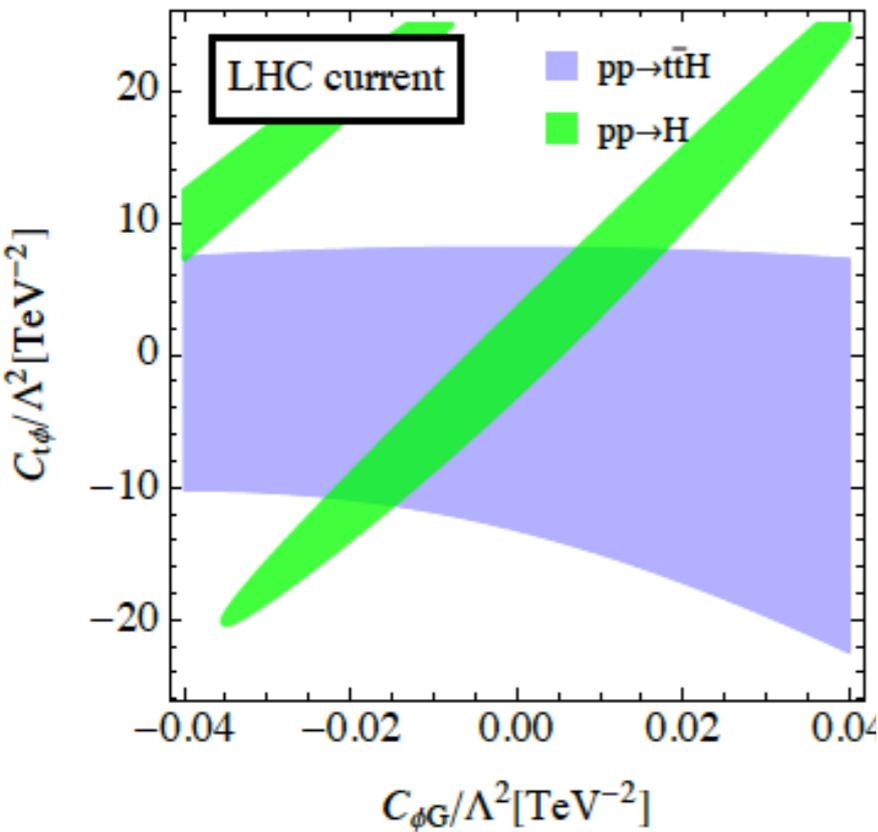
typically $C_{tG}=0$ in
 Higgs analyses

- Individual limit on C_{tG} 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

Two-operator fits using H, Hj, ttH

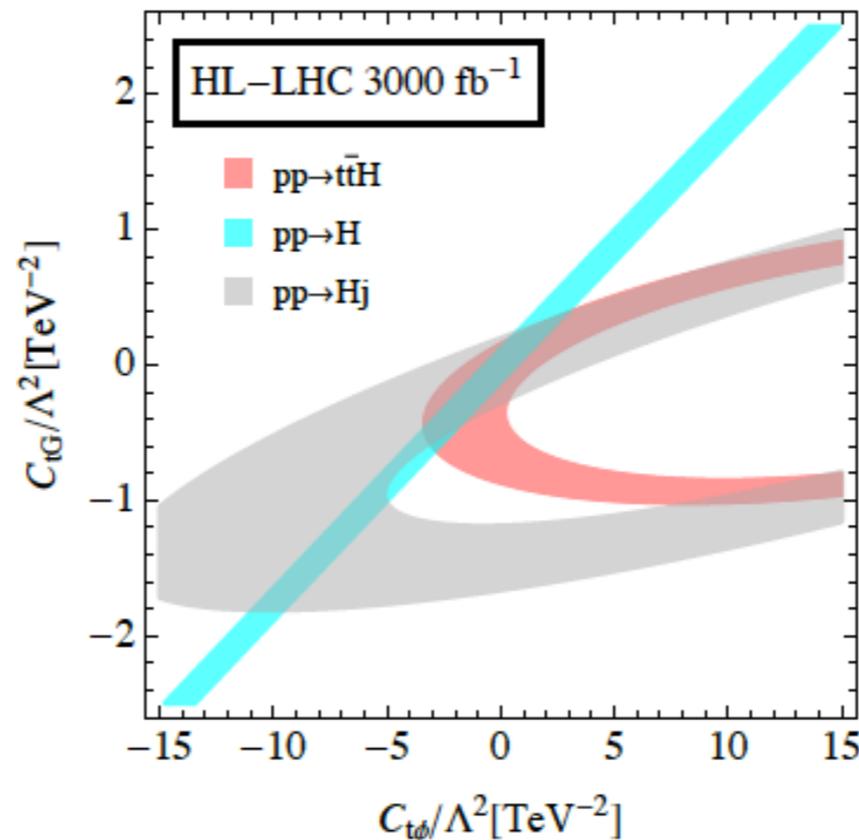
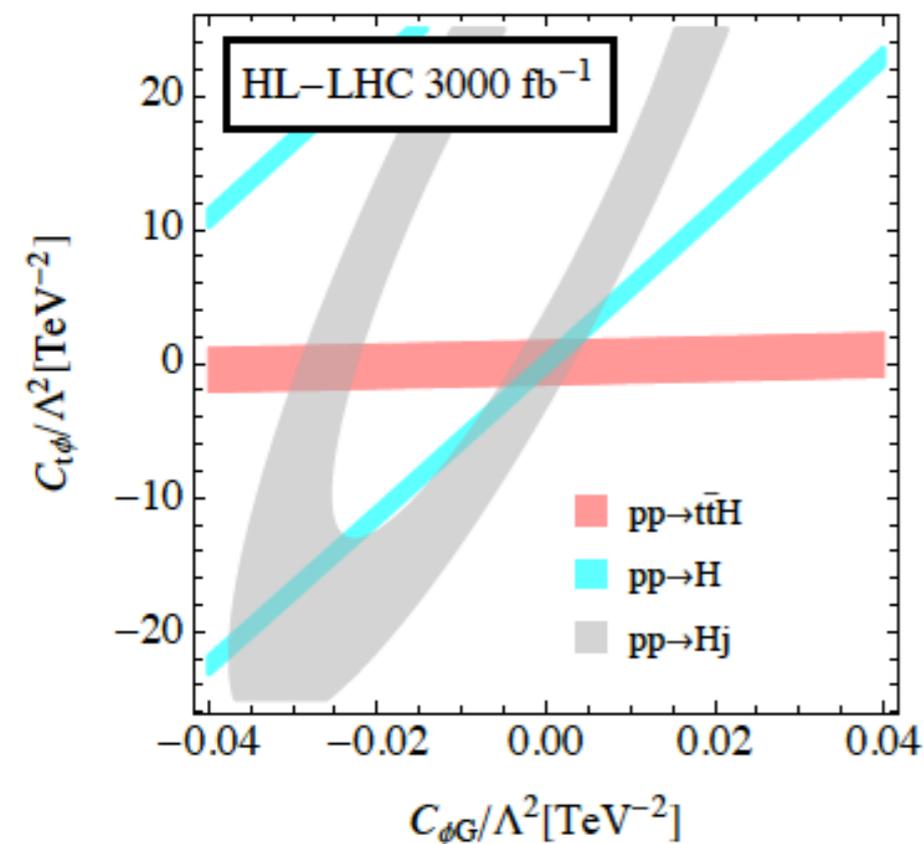


Current limits
using LHC
measurements

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

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

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



14TeV projection
3000 fb⁻¹

Maltoni, EV, Zhang
arXiv:1607.05330

How to extract maximal information?

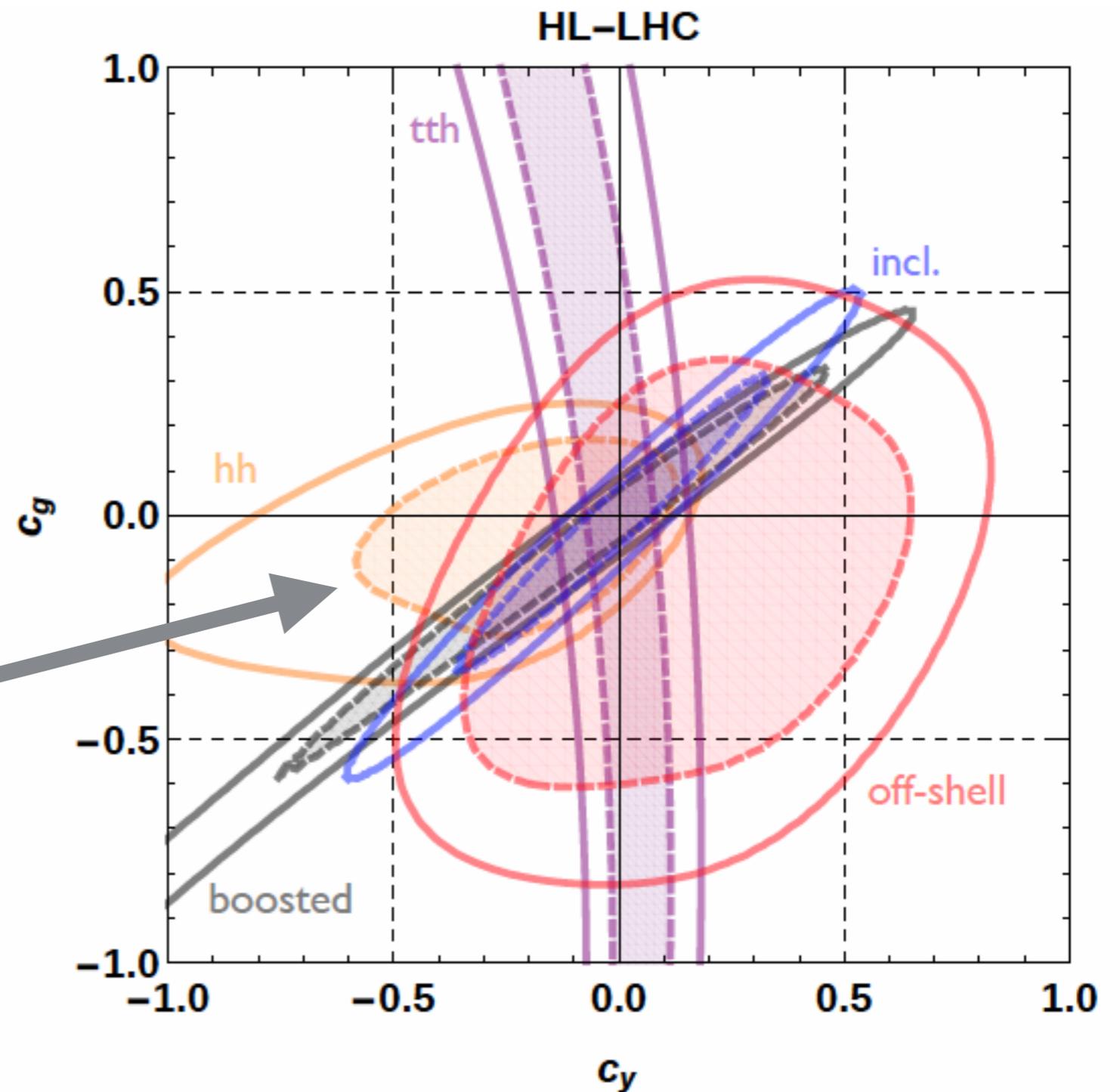
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$$O_{\phi G} = y_t^2 (\phi^\dagger \phi) G_{\mu\nu}^A G^{A\mu\nu}$$

Lots of processes

Combination:

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



Azatov et al arXiv:1608.00977

Adding more operators

Top EW couplings

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

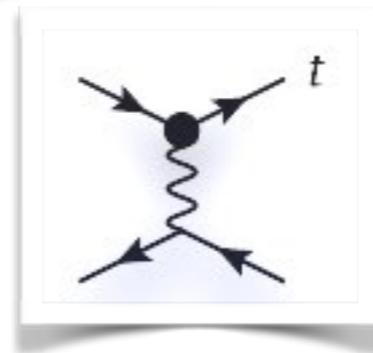
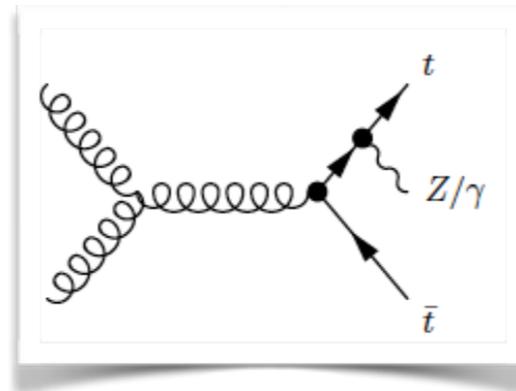
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi \right) (\bar{Q}\gamma^\mu Q)$$

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

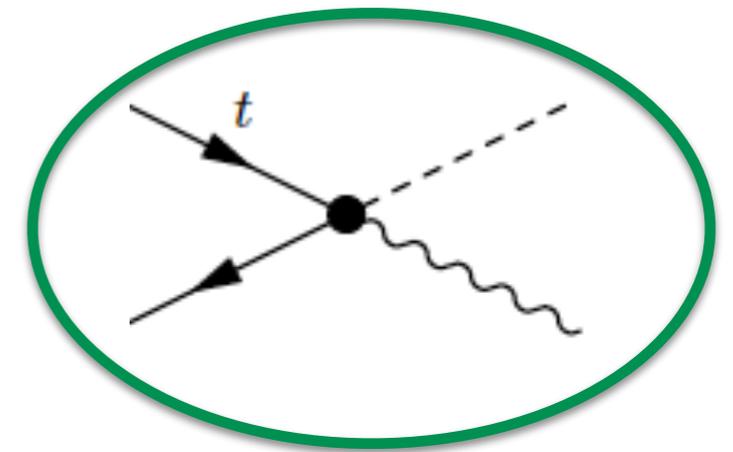
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I$$

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

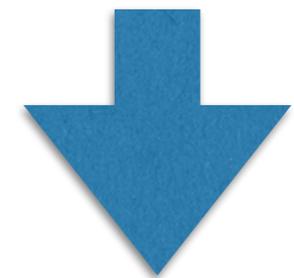
Typically searched for in



Also relevant for:



New Higgs interactions



relevant for tHj,
gg>HZ

EFT studies in the top sector: top+V

Bylund et al arXiv:1601.08193

Schulze et al. arXiv:1404.1005, 1501.05939,
1603.08911 (using ratios of cross-sections)

Dror et al. arXiv:1511.03674 for ttWj

single top:

Zhang arxiv:1601.06163

HZ in gluon fusion

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

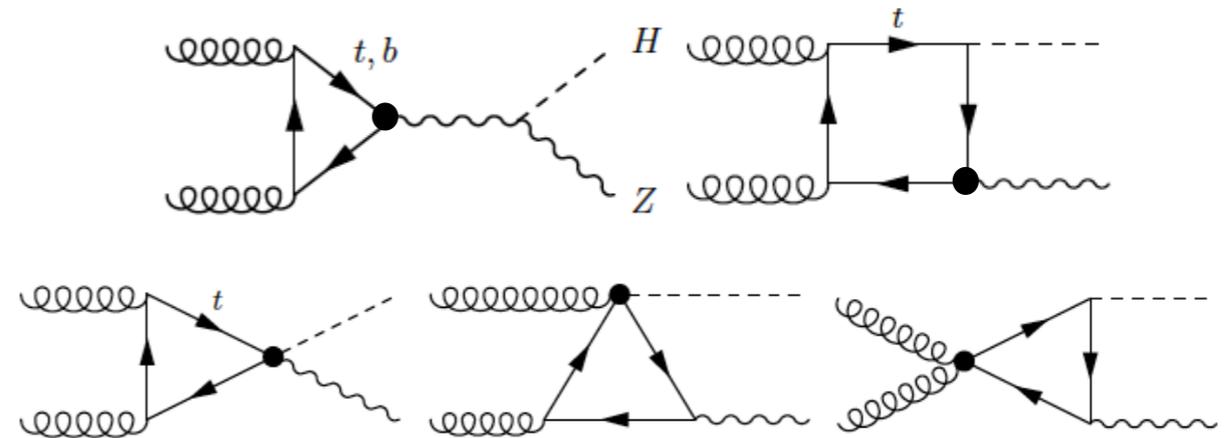
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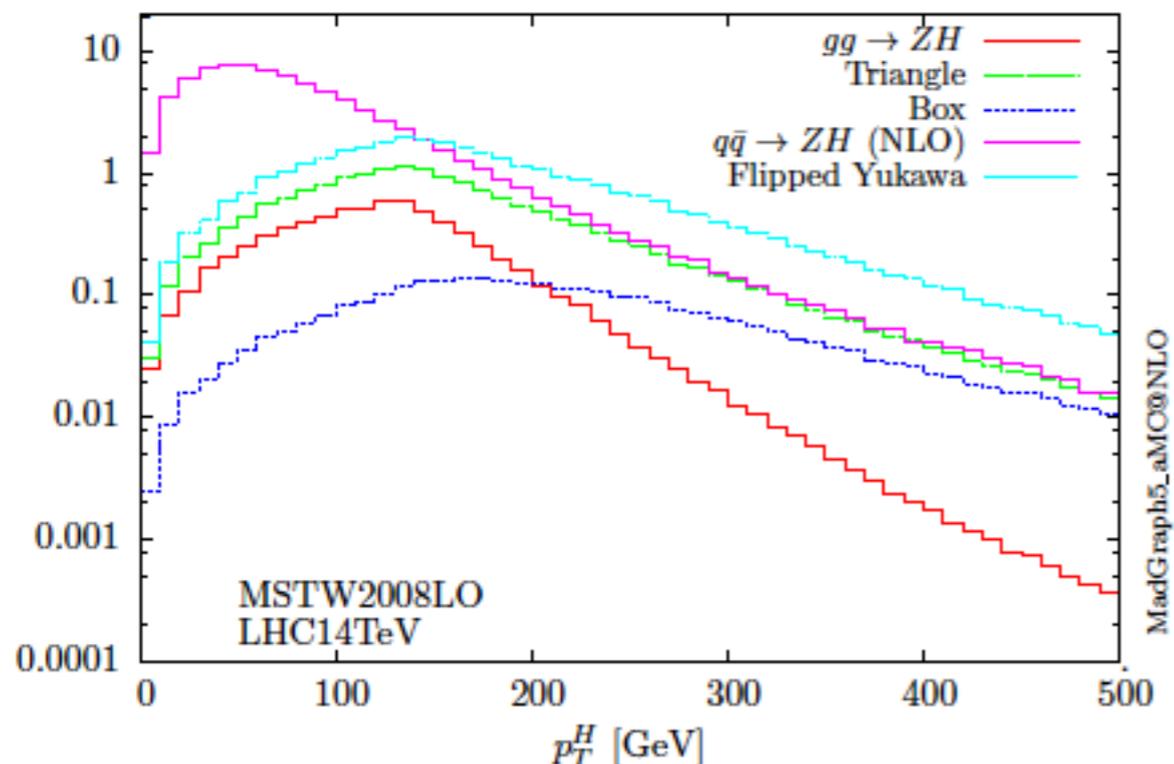
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t) \tilde{\varphi} G_{\mu\nu}^A,$$

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

+HZZ operators



Gluon-fusion contribution to HZ production affected by the operators changing g_{tt} , ttZ and ttH ➔ Additional information

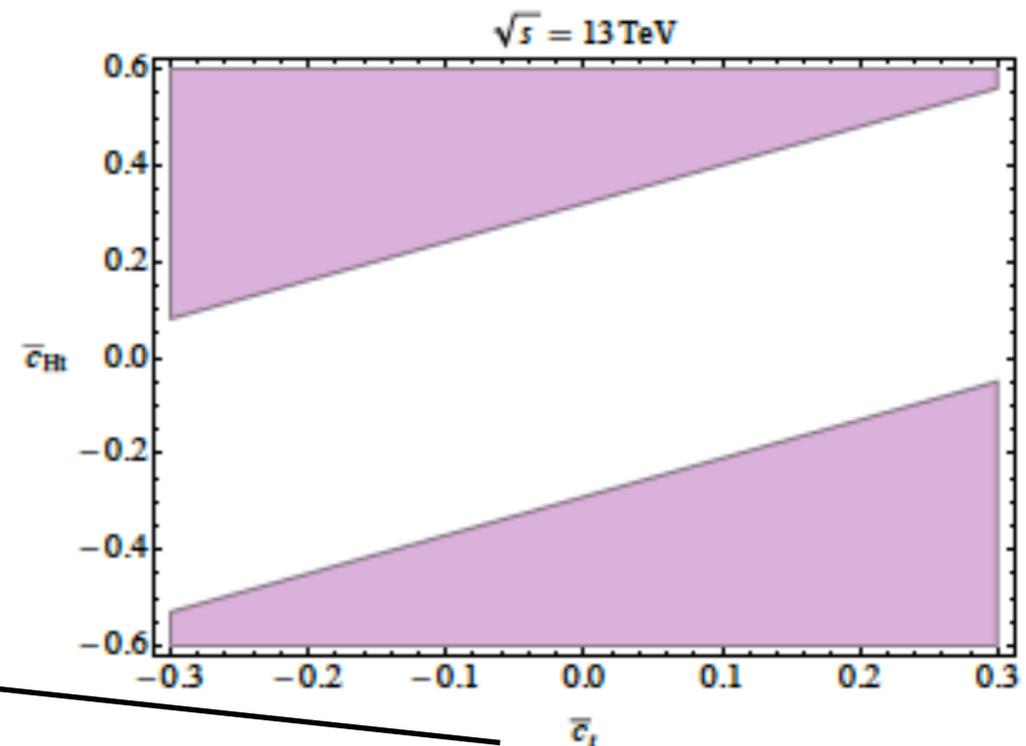
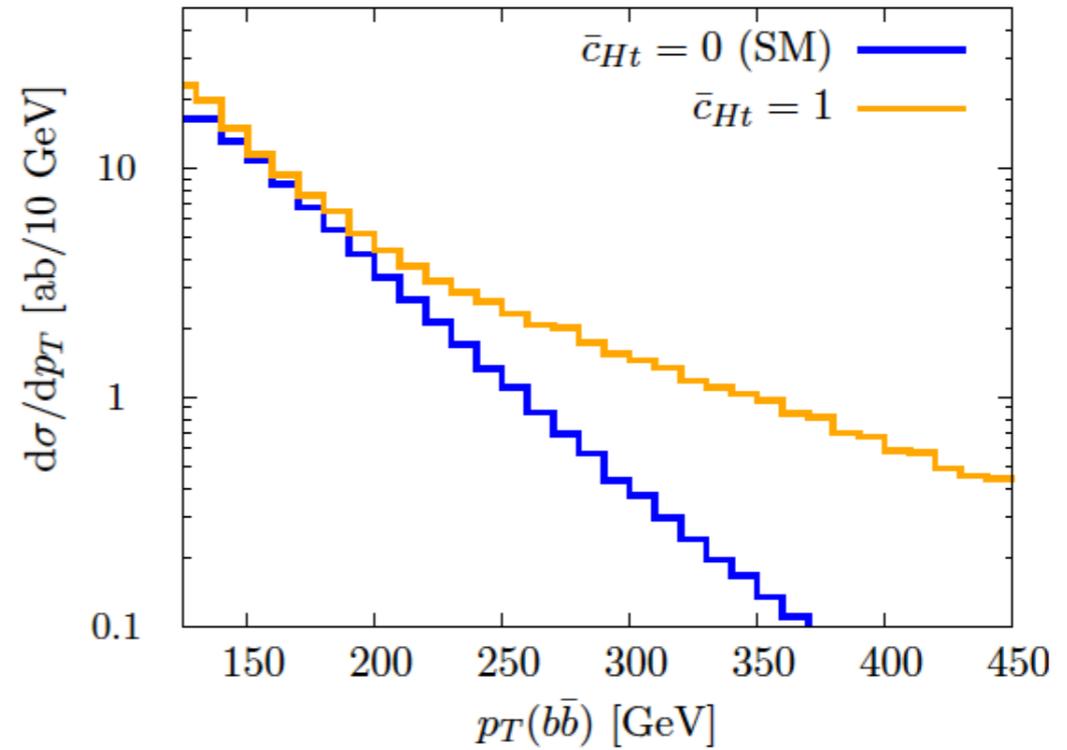
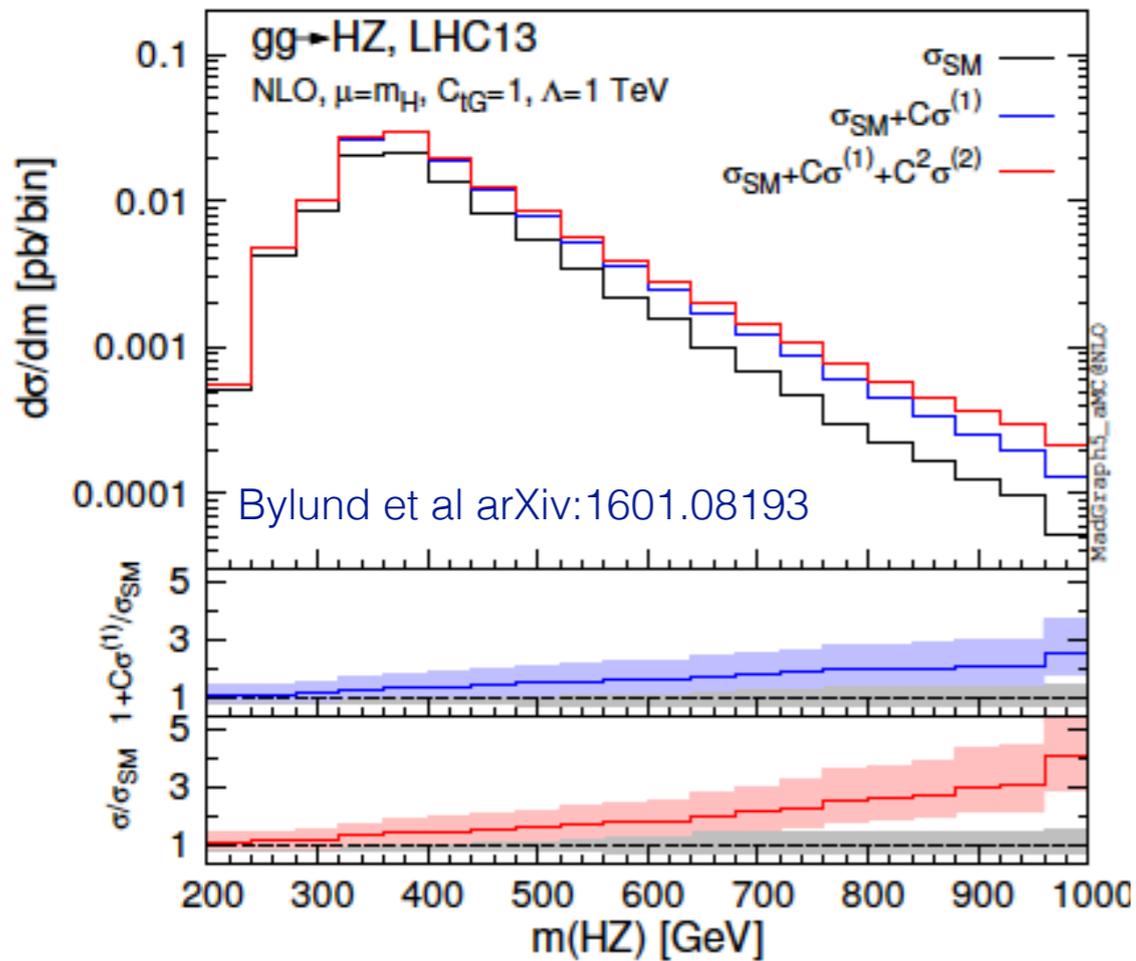


Sensitive to the relative phase of the top and Z Higgs couplings

[fb]	SM	O_{tG}	$O_{\varphi Q}^{(1)}$
13TeV	$93.6^{+34.3\%}_{-23.8\%}$	$\sigma_i^{(1)}$	$5.91^{+36.4\%}_{-24.9\%}$
		$\sigma_{ii}^{(2)}$	$0.182^{+40.2\%}_{-26.6\%}$
		$\sigma_i^{(1)} / \sigma_{SM}$	$0.0631^{+1.6\%}_{-1.5\%}$
		$\sigma_{ii}^{(2)} / \sigma_i^{(1)}$	$0.0309^{+2.8\%}_{-2.2\%}$

No contributions from the electroweak dipole operators due to charge conjugation invariance

HZ in gluon fusion

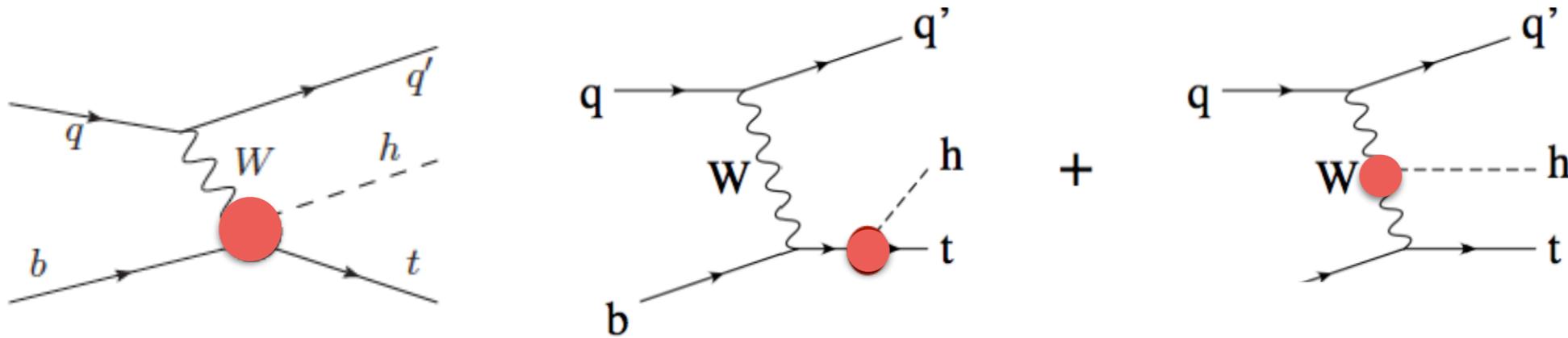


Differential information important

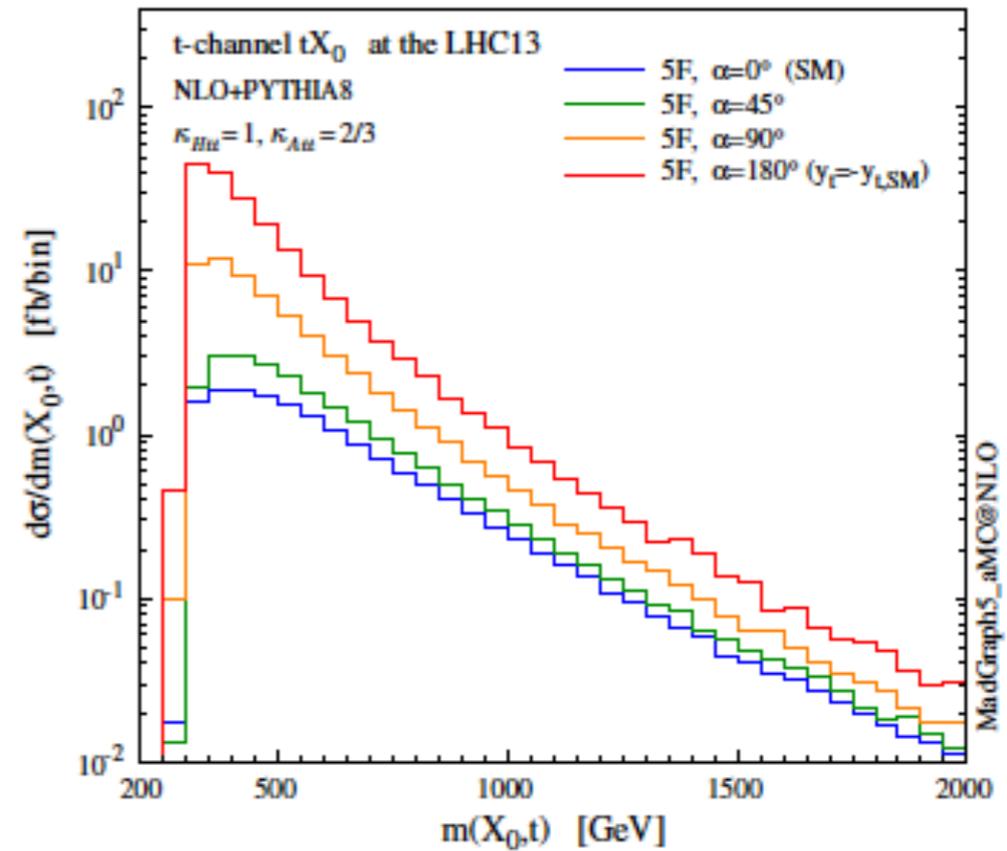
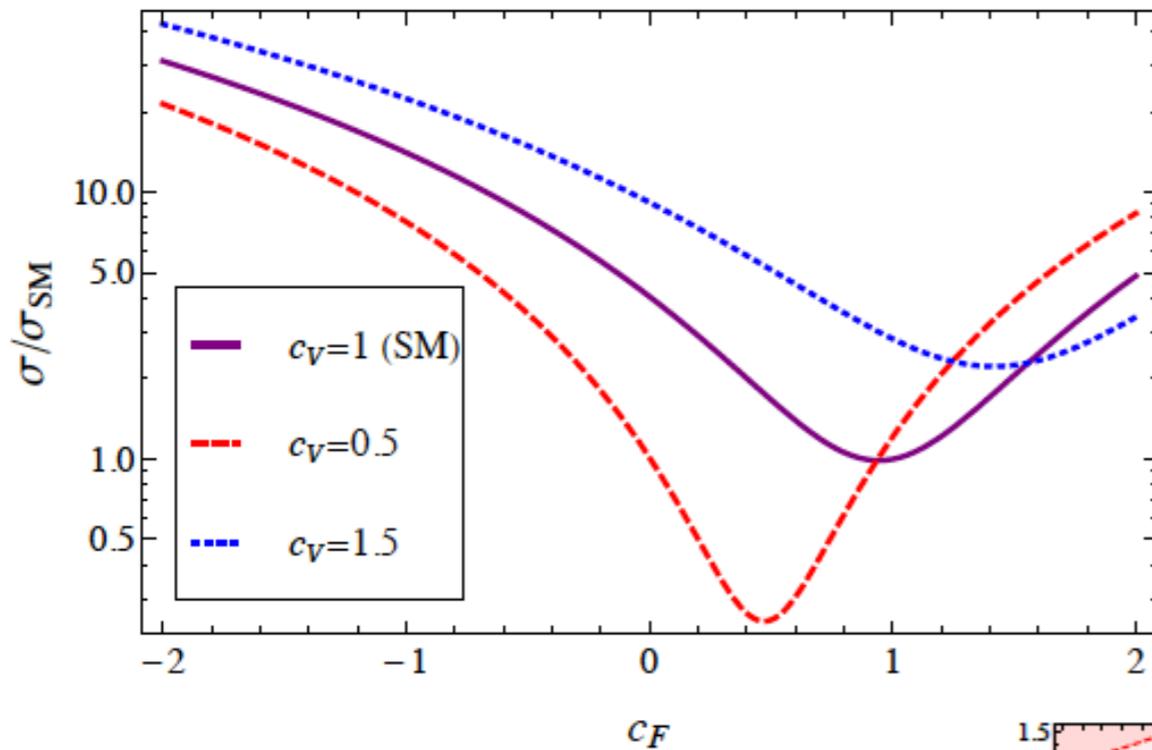
$$\mathcal{O}_{Ht} = \frac{i\bar{c}_{Ht}}{v^2} (\bar{t}_R \gamma^\mu t_R) (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi),$$

$$\mathcal{O}_t = -\frac{\bar{c}_t}{v^2} y_t \Phi^\dagger \Phi \Phi^\dagger \cdot \bar{Q}_L t_R + \text{h.c.}$$

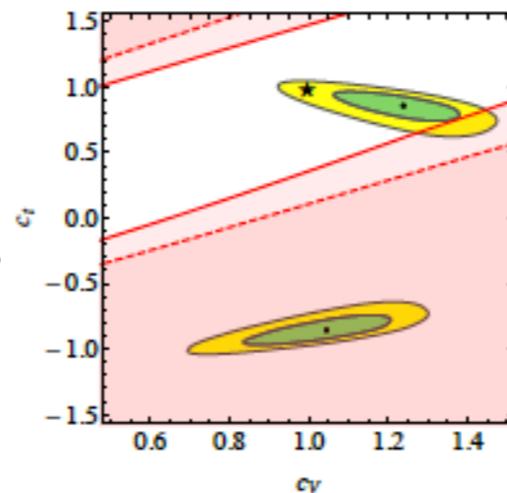
single top+Higgs



$pp \rightarrow thj$ (LHC 14 TeV)



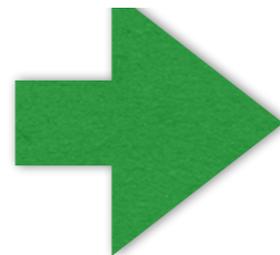
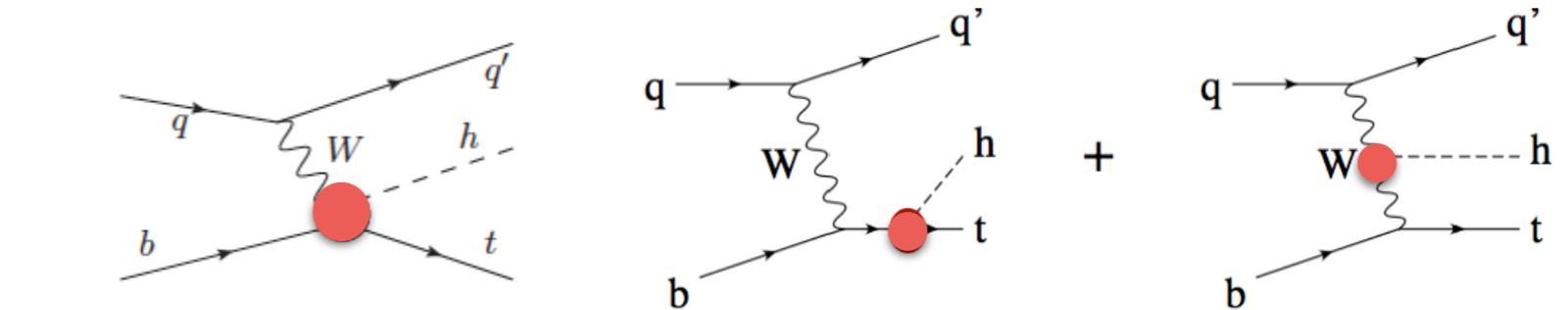
Farina et al 1211.3736
A probe of the relative sign
of the H_{tt} and H_{WW} couplings



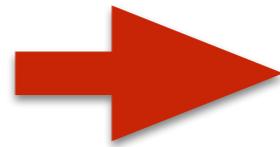
Higgs characterisation
Demartin et al. arXiv:1504.00611

single top+Higgs in the EFT

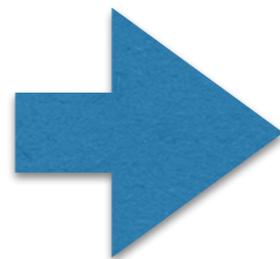
operator	tHj inter	tHj square
$\mathcal{O}_{\phi W}$	0.00693	0.00439
$\mathcal{O}_{\phi D}$	-0.0012	0.0000091
$\mathcal{O}_{\phi WB}$	0.00319	0.000150
$\mathcal{O}_{t\phi}$	-0.00105	0.000485
\mathcal{O}_{tW}	0.00872	0.0108
$\mathcal{O}_{\phi dQL}^{(3)}$	-0.000449	0.000552
$\mathcal{O}_{\phi dq}^{(3)}$	-0.00169	0.00233



Higgs weak boson couplings



Top Yukawa



Top weak couplings

$$\mathcal{O}_{\phi D} = (\phi^\dagger D_\mu \phi)^\dagger (\phi^\dagger D^\mu \phi)$$

$$\mathcal{O}_{\phi W} = \left(\phi^\dagger \phi - \frac{v^2}{2}\right) W_i^{\mu\nu} W_{\mu\nu}^i$$

$$\mathcal{O}_{\phi WB} = (\phi^\dagger W^{\mu\nu} \phi) B_{\mu\nu}$$

$$\mathcal{O}_{t\phi} = \left(\phi^\dagger \phi - \frac{v^2}{2}\right) \bar{Q}_L t_R \tilde{\phi}$$

$$\mathcal{O}_{tW} = Q_L \sigma_{\mu\nu} W^{\mu\nu} t_R \phi$$

$$\mathcal{O}_{\phi dq}^{(3)} = i \left(\phi^\dagger i \overleftrightarrow{D}_\mu^i \phi\right) \bar{q}_L \gamma^\mu \sigma^i q_L$$

$$\mathcal{O}_{\phi dQL}^{(3)} = i \left(\phi^\dagger i \overleftrightarrow{D}_\mu^i \phi\right) \bar{Q}_L \gamma^\mu \sigma^i Q_L$$

NLO QCD computation including all operators in progress

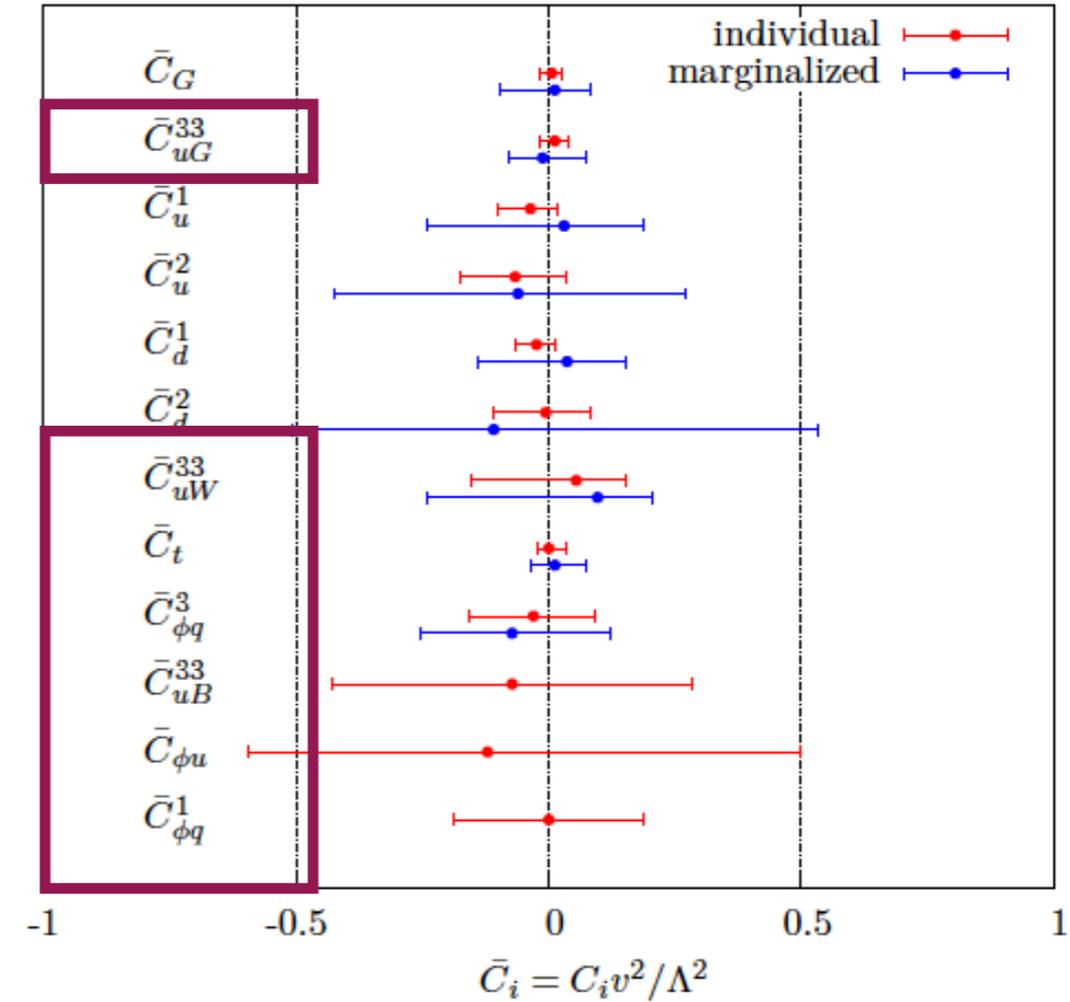
Input from top-EFT fits

Global EFT fit in the top sector can provide useful guidance:

Buckley et al arxiv:1506.08845 and 1512.03360

(N)NLO SM + LO EFT

Dataset	\sqrt{s} (TeV)	Measurements	arXiv ref.	Dataset	\sqrt{s} (TeV)	Measurements	arXiv ref.
<i>Top pair production</i>				<i>Differential cross-sections:</i>			
Total cross-sections:				Charge asymmetries:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t), M_{t\bar{t}}, y_{t\bar{t}} $	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar{t}}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
ATLAS	7	lepton w/ b jets	1406.5375	D ϕ	1.96	$M_{t\bar{t}}, p_T(t), y_t $	1401.5785
ATLAS	7	tau+jets	1211.7205	<i>Top widths:</i>			
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573	D ϕ	1.96	Γ_{top}	1308.4050
ATLAS	8	dilepton	1202.4892	CDF	1.96	Γ_{top}	1201.4156
CMS	7	all hadronic	1302.0508	<i>W-boson helicity fractions:</i>			
CMS	7	dilepton	1208.2761	ATLAS	7		1205.2484
CMS	7	lepton+jets	1212.6682	CDF	1.96		1211.4523
CMS	7	lepton+tau	1203.6810	CMS	7		1308.3879
CMS	7	tau+jets	1301.5755	D ϕ	1.96		1011.6549
CMS	8	dilepton	1312.7582	<i>Run II data</i>			
CDF + D ϕ	1.96	Combined world average	1309.7570	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
<i>Single top production</i>				<i>Associated production</i>			
ATLAS	7	t -channel (differential)	1406.7844	ATLAS	7	$t\bar{t}\gamma$	1502.00586
CDF	1.96	s -channel (total)	1402.0484	ATLAS	8	$t\bar{t}Z$	1509.05276
CMS	7	t -channel (total)	1406.7844	CMS	8	$t\bar{t}Z$	1406.7830
CMS	8	t -channel (total)	1406.7844				
D ϕ	1.96	s -channel (total)	0907.4259				
D ϕ	1.96	t -channel (total)	1105.2788				



Tevatron and LHC data

Cross-sections and distributions

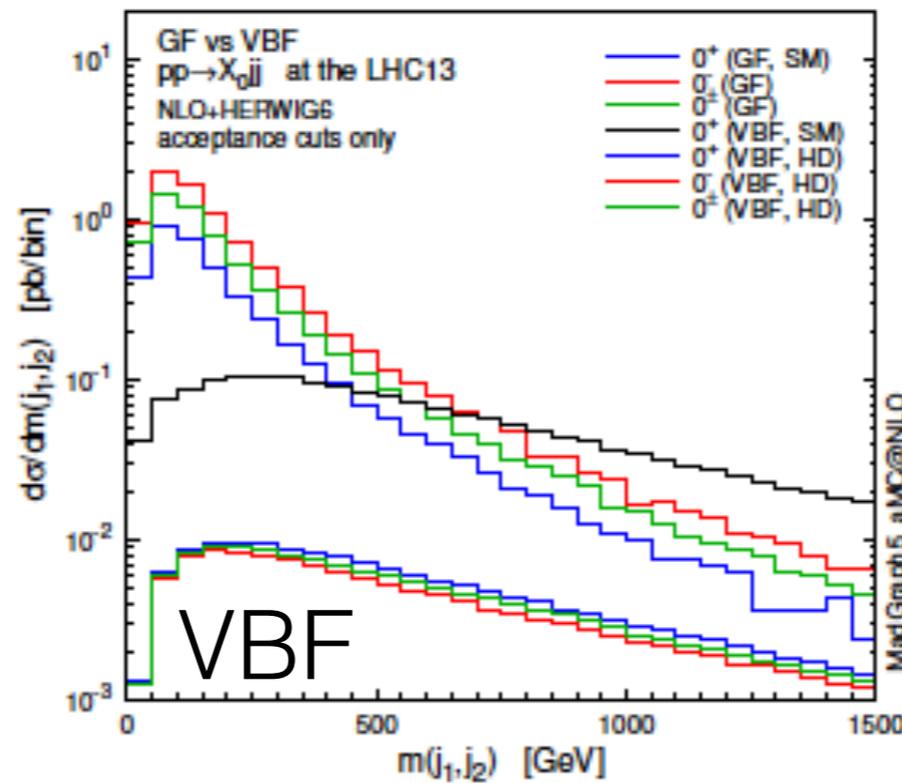
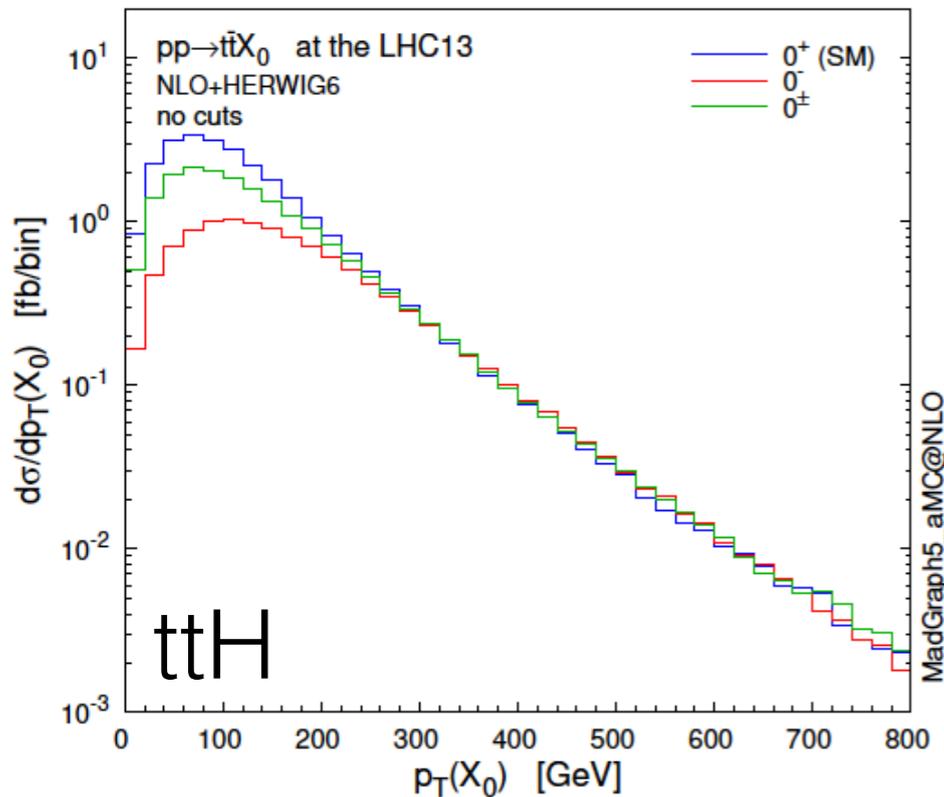
CP-violation in the top-Higgs sector

Yukawa

$$-\bar{\psi}_t \left(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att} \gamma_5 \right) \psi_t X_0$$

ggH

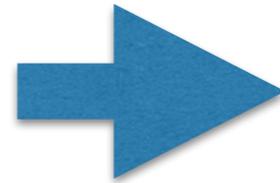
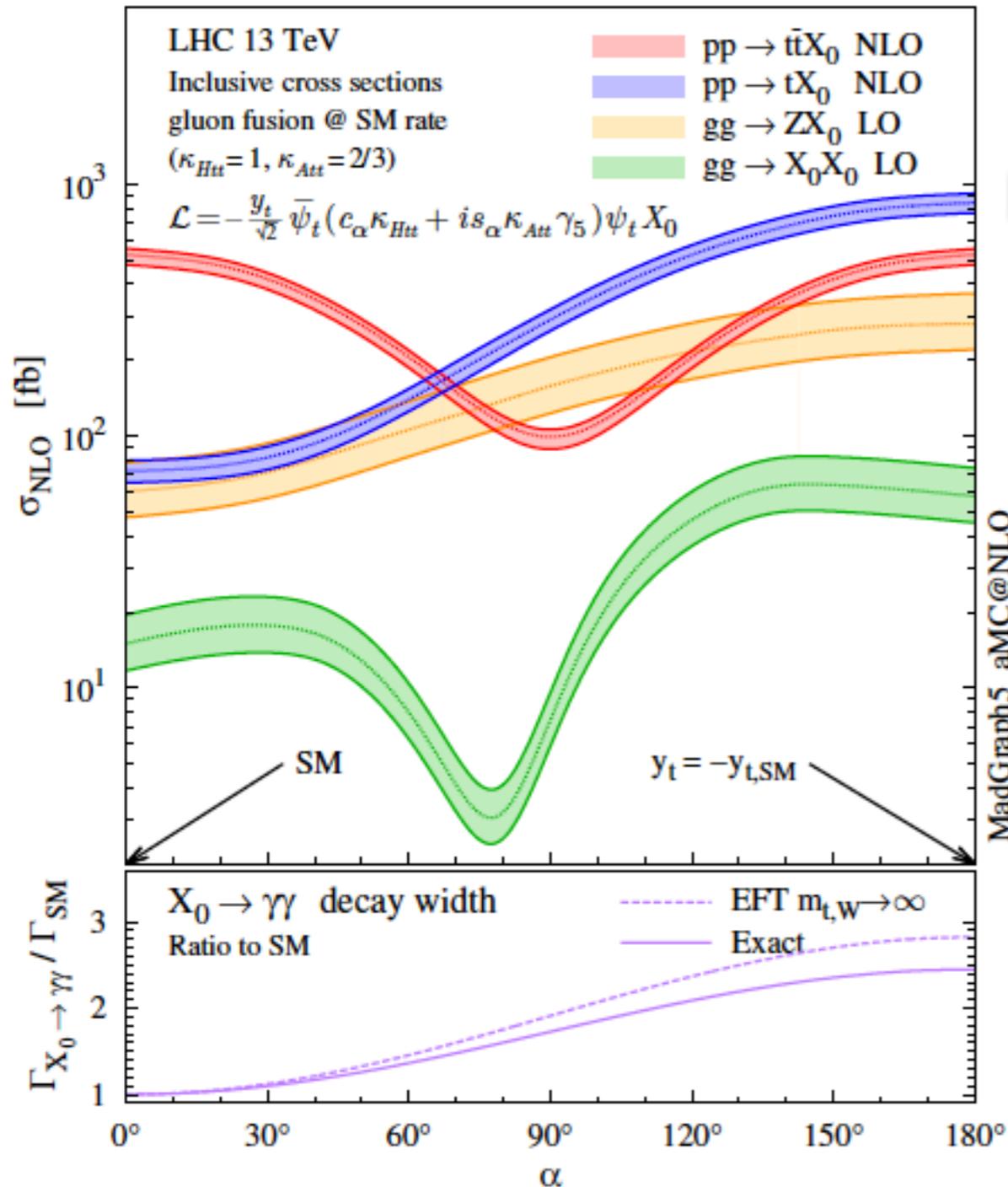
$$-\frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right] X_0$$



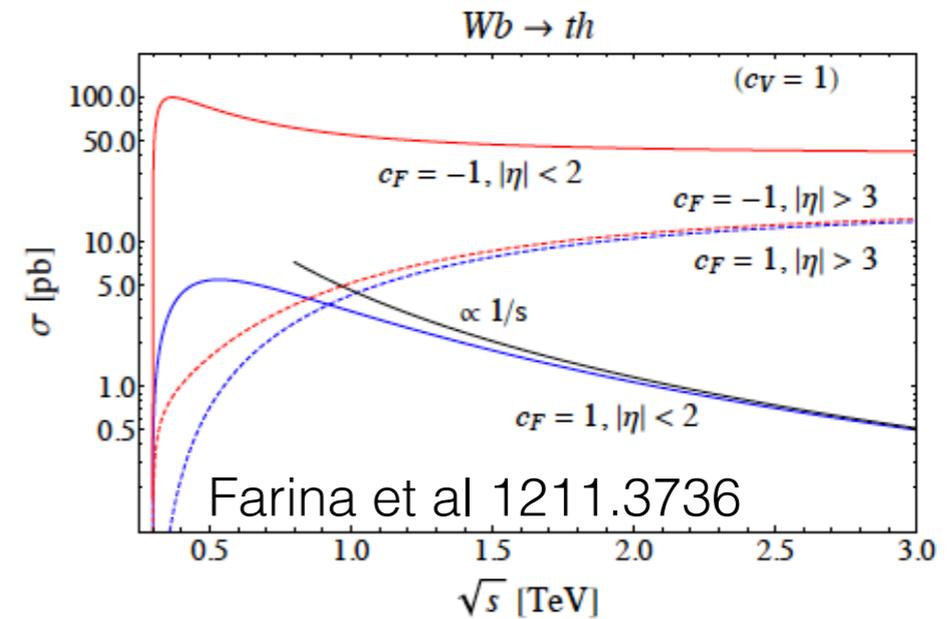
Studies within the HC model at NLO

Demartin et al. arXiv:
1504.00611,
1407.5089, 1306.6464

CP-violation in the top-Higgs sector



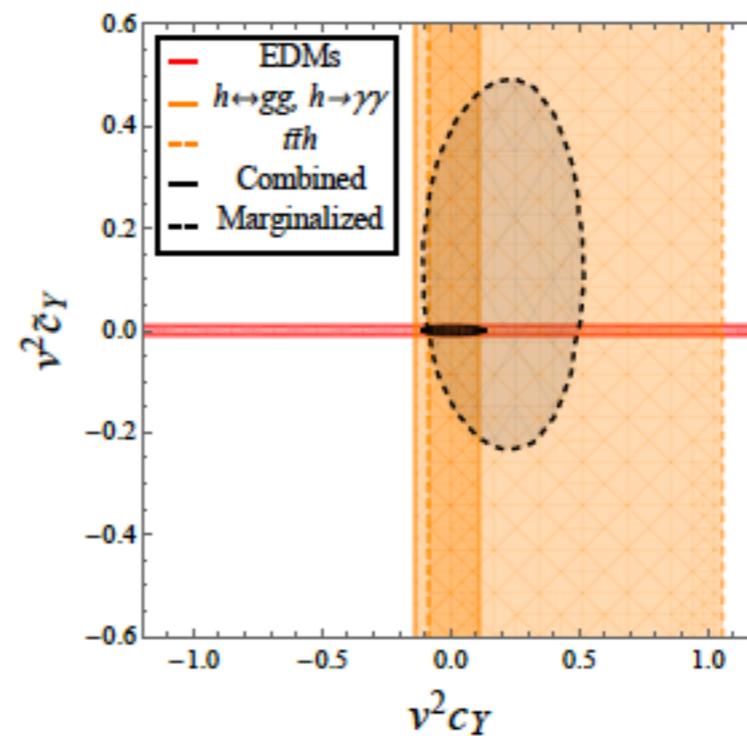
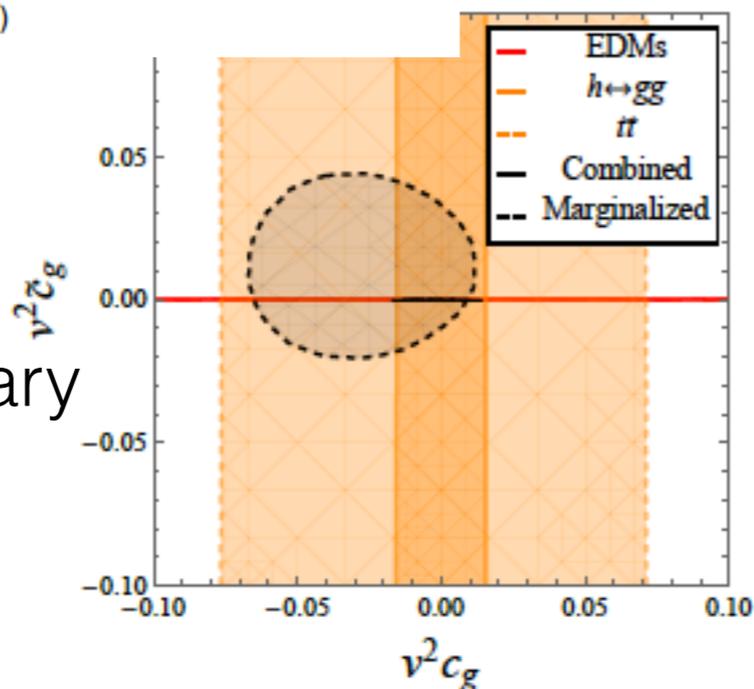
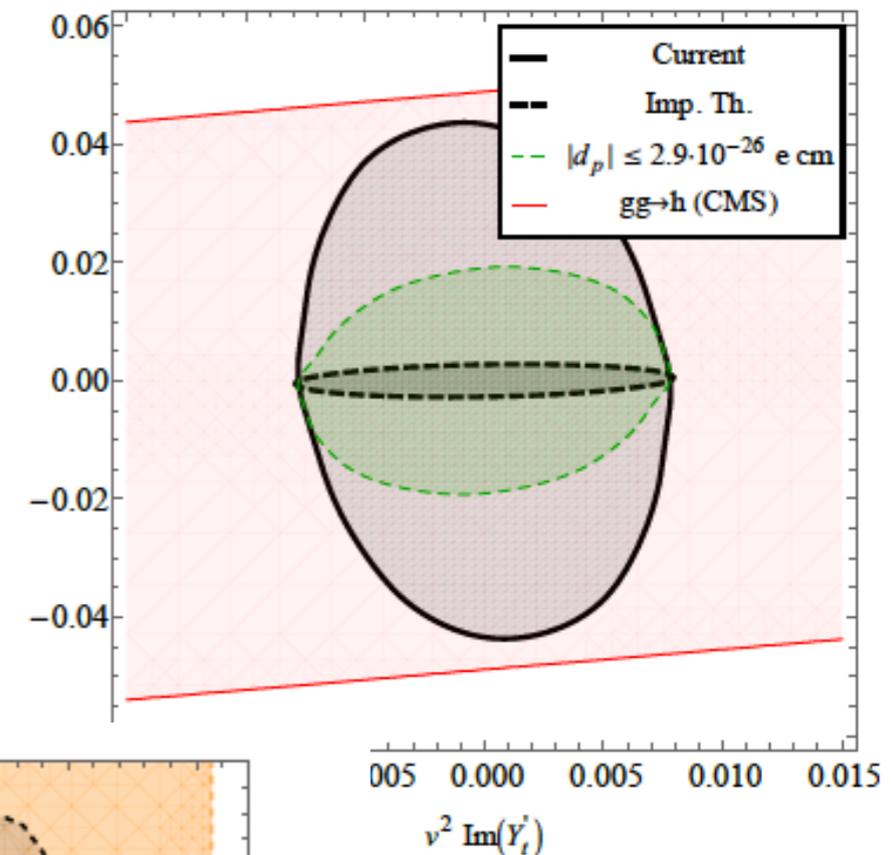
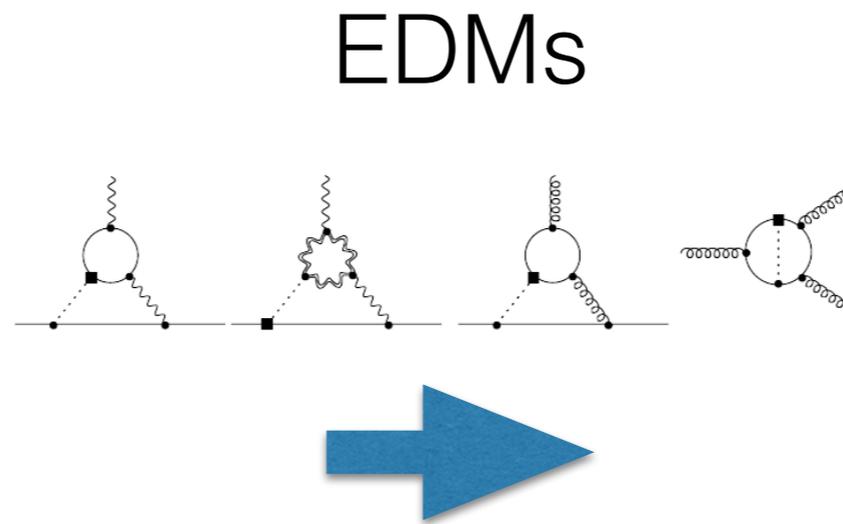
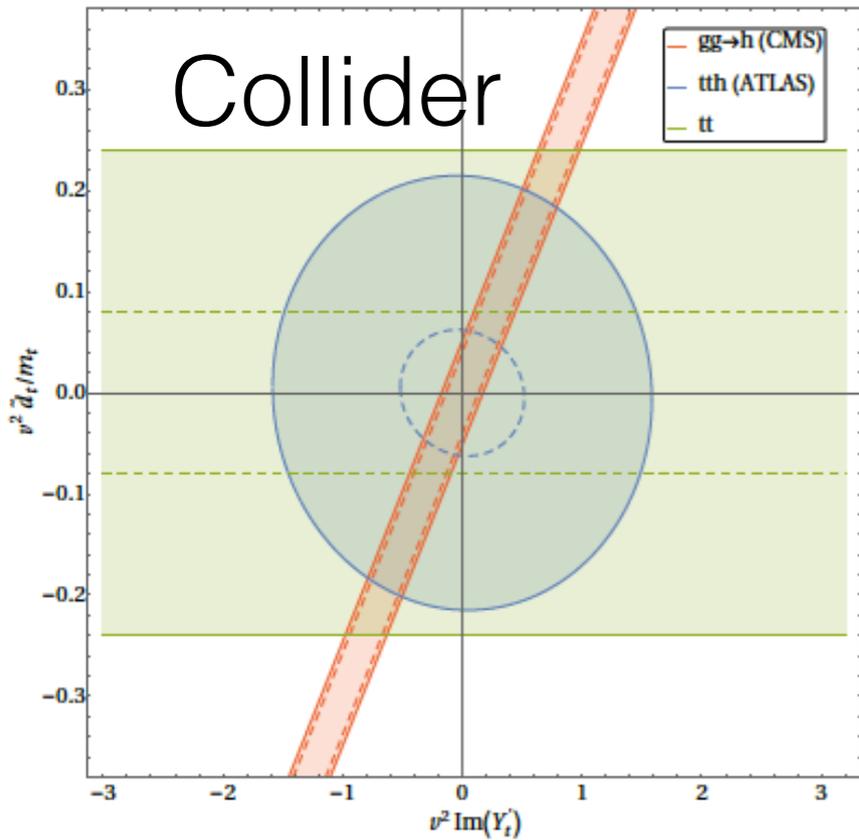
Single top Higgs:
Unitarity violation in
 $Wb \rightarrow th$ scattering



CP-odd operators in HH?

CP-violation

$$\mathcal{L}_6^{CPV} = -\theta' \frac{\alpha_s}{8\pi} h v \frac{1}{2} \varepsilon^{\mu\nu\alpha\beta} G_{\mu\nu}^a G_{\alpha\beta}^a + \sum_{q=u,d,c,s,t,b} v^2 \text{Im} Y'_q \bar{q} i \gamma_5 q h - \frac{i}{2} \tilde{d}_t g_s \bar{t} \sigma \cdot G \gamma_5 t \left(1 + \frac{h}{v} \right) + \dots$$



Cirigliano et al arXiv:
1510.00725, 1603.03
049, 1605.04311

real and imaginary

Outlook

- A large number of theory EFT studies on the top-Higgs
 - Improvement in precision
 - Improvement in availability of results
- Room for improvement:
 - Theory:
 - complete EFT studies of rarer processes e.g. tHj
 - go beyond LO/tree-level e.g. O_6 in single Higgs
 - go beyond 2 operator fits (see Gauge-Higgs sector)
 - Experimental:
 - introduce EFT interpretations of the relevant measurements, in particular in differential measurements
 - coordination between top/Higgs/EW groups: EFT is a global affair

Thank you for your attention

Backup

SMEFT in Higgs processes

Extensive work for Monte Carlo implementation and automation e.g. [Alloul, Fuks, Sanz arXiv:1310.5150](#)

- Higher-order corrections: SMEFT renormalisable order by order in $1/\Lambda$

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

Need for precision in EFT predictions has led to a lot of work towards NLO QCD predictions

- Higgs characterisation in MG5_aMC@NLO [Demartin et al.: ggH arXiv:1306.6464](#), [VH+VBF arXiv:1311.1829](#), [ttH arXiv:1407.5089](#), [tHj arXiv:1504.00611](#)
- MCFM+POWHEG box: VH [Mimasu et al arXiv:1512.02572](#)

Electroweak Higgs production
HEL@NLO: HV and VBF

The need for NLO

Impact of NLO corrections

- Accuracy and precision: NLO corrections modify the central value and come with reduced theoretical uncertainties compared to LO
- Impact on the distributions - non-flat K-factors different between operators and different from the SM
- Better control on RG and operator mixing effects - new operators entering at NLO
- Effort to match SM precision in the light of more sensitive measurements and in the context of global EFT fits where precision is needed to extract maximal information on the coefficients

SMEFT@NLO

- SMEFT@NLO ingredients:
 - Mixing between operators: anomalous dimension matrix: [Alonso et al. arxiv:1312.2014](#)
 - Additional operators at NLO

Automation within MadGraph5_aMC@NLO

R2+UV counterterms for the NLO computation:

NLOCT [Degrande \(arxiv:1406.3030\)](#)

Parallel progress in top quark processes in the same framework:

- top pair production: [Franzosi and Zhang \(arxiv:1503.08841\)](#)
- single top production: [C. Zhang \(arxiv:1601.06163\)](#)
- ttZ/ γ : [O. Bylund, F. Maltoni, I. Tsinikos, EV, C. Zhang \(arXiv:1601.08193\)](#)