

Top EFT at NLO in QCD Progress within MG5_aMC

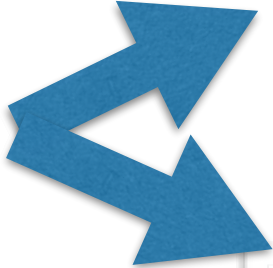
Eleni Vryonidou
Nikhef

based on arXiv: 1601.08193 and 1607.05330



MCNet Meeting
CERN
24/11/16

SMEFT

- BSM? 
 - New particles
 - New Interactions of SM particles

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

- 59 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	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p \gamma^\mu l_t)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_\mu^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_\mu^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_\mu^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_\mu^I W^{I\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_\mu^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{WB}}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_\mu^I B^{\mu\nu}$	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}	$(\bar{l}_p e_r)(\bar{d}_s q_t^k)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^\gamma)^T C l_t^k]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	Q_{ququ}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_t]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jkmn} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^m)^T C l_t^n]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^m)^T C l_t^n]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$		

SMEFT for top quark physics

SMEFT

vs

Anomalous couplings

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

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

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

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

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

$$\mathcal{L}_{ttZ} = e\bar{u}(p_t) \left[\gamma^\mu (C_{1,V}^Z + \gamma_5 C_{1,A}^Z) + \frac{i\sigma^{\mu\nu} q_\nu}{m_Z} (C_{2,V}^Z + i\gamma_5 C_{2,A}^Z) \right] v(p_{\bar{t}}) Z_\mu$$

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

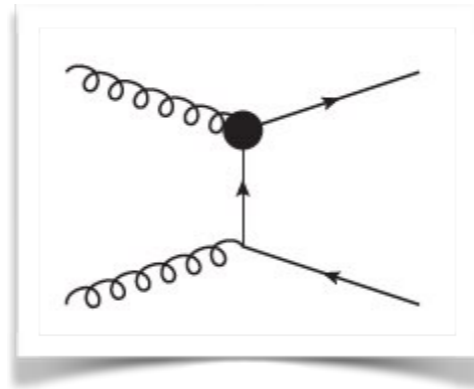
$$\mathcal{O}(\alpha_s) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \dots$$

- Complete description-respecting SM symmetries ✓
- Model Independent ✓

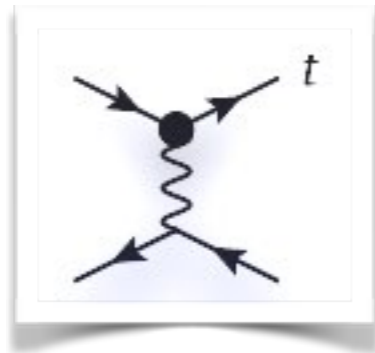
SMEFT in processes with tops

Rich phenomenology:

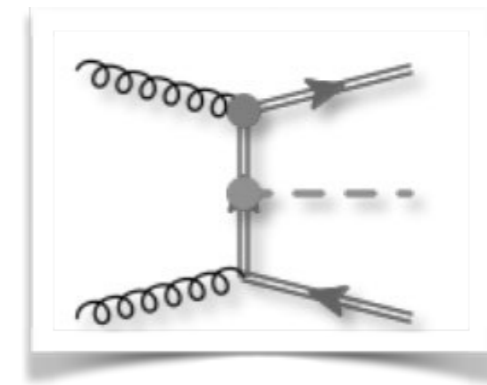
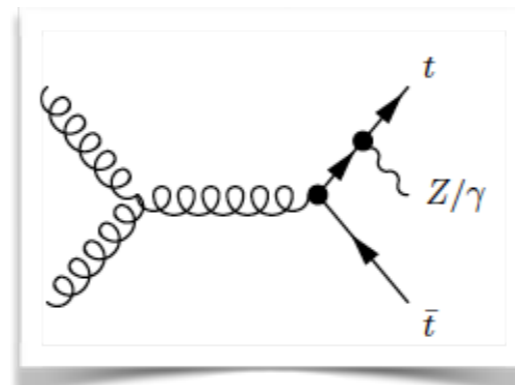
pair production



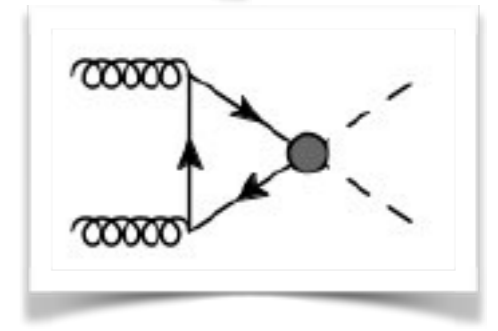
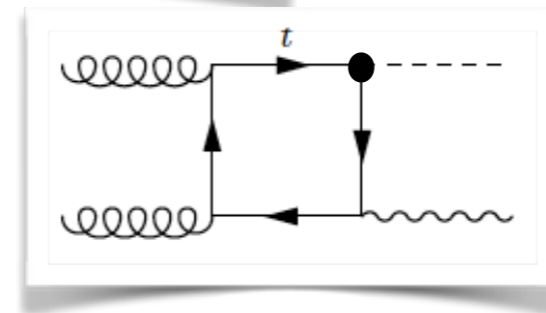
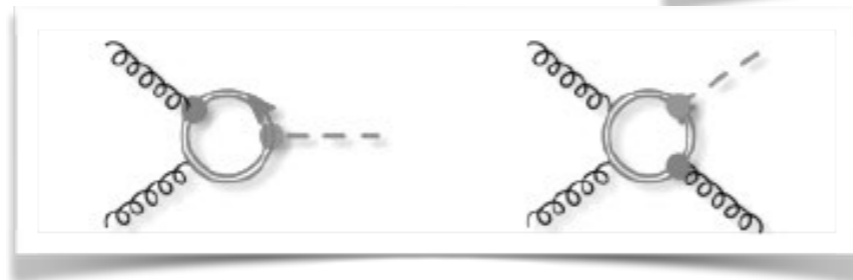
single



associated production



top loops



Top-quark operators and how to look for them

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

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

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

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

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

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

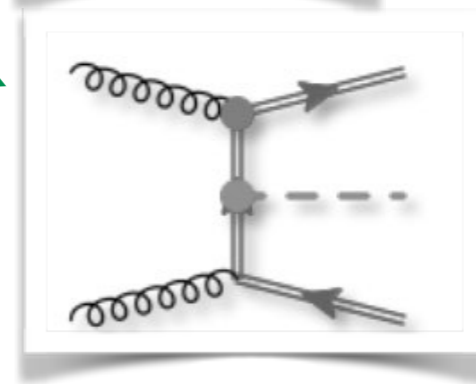
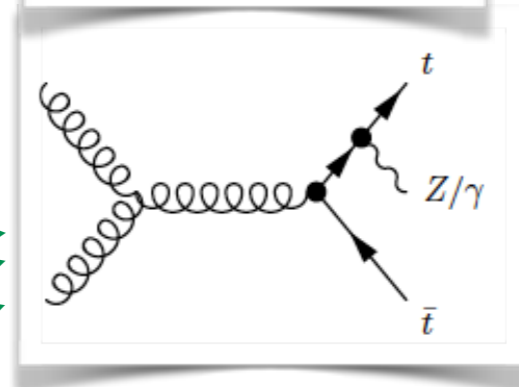
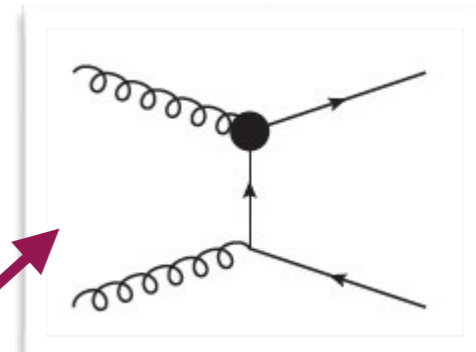
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi \right) (\bar{Q} t) \tilde{\phi}$$

see for example: Aguilar-Saavedra (arXiv:0811.3842)

Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+non-top operators (mixing)



Operators entering various processes: Global approach needed

Towards global fits

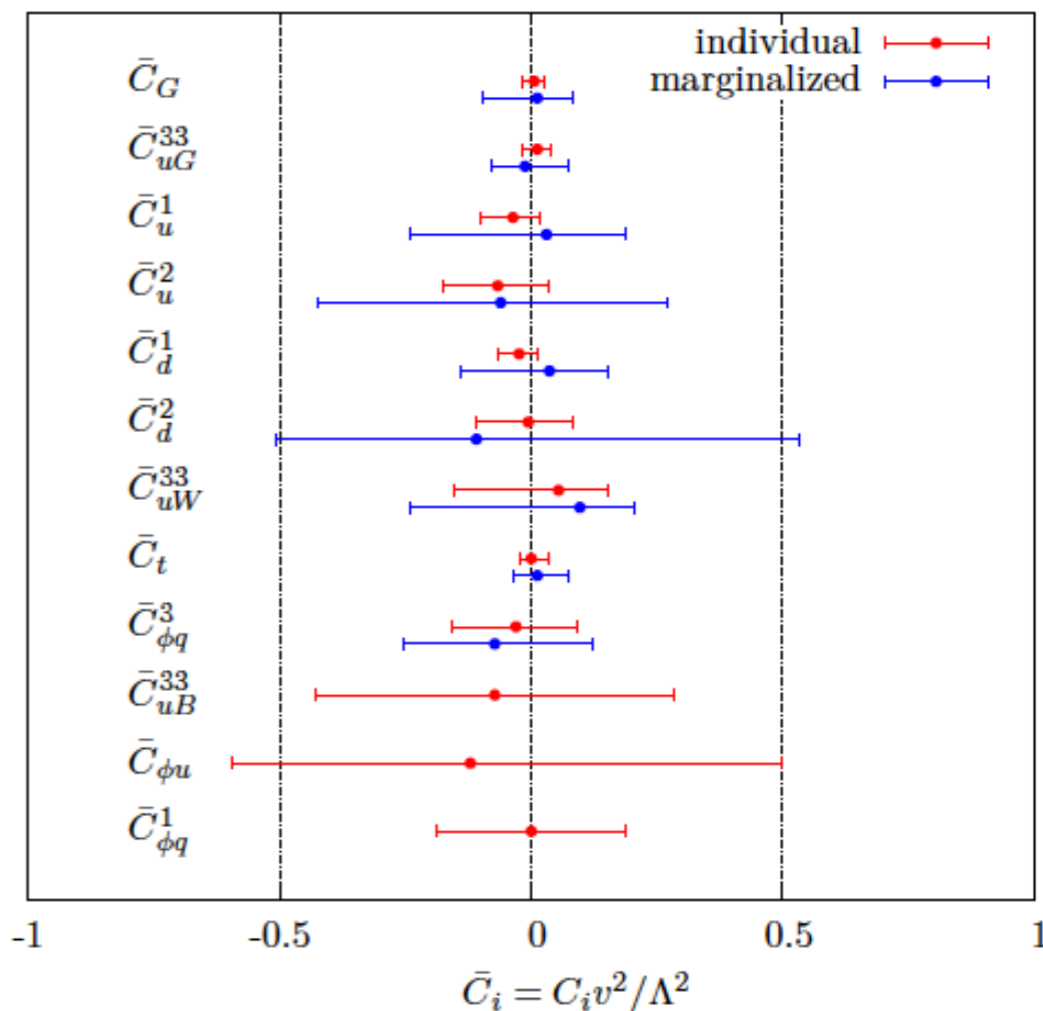
EFT only makes sense if we follow a global approach

First work towards global fits:

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	DØ	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	DØ	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	DØ	1.96		1011.6549
CMS	8	dilepton	1312.7582	<i>Run II data</i>			
CDF + DØ	1.96	Combined world average	1309.7570	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
<i>Single top production</i>							
ATLAS	7	t -channel (differential)	1406.7844				
CDF	1.96	s -channel (total)	1402.0484				
CMS	7	t -channel (total)	1406.7844				
CMS	8	t -channel (total)	1406.7844				
DØ	1.96	s -channel (total)	0907.4259				
DØ	1.96	t -channel (total)	1105.2788				
<i>Associated production</i>							
ATLAS	7	$t\bar{t}\gamma$	1502.00586				
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				



Tevatron and LHC data

Cross-sections and distributions

The need for NLO

Impact of NLO corrections in the light of global fits:

- 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 \(arxiv:1406.3030\)](#)

Progress in top quark processes in this 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 \(arXiv:1601.08193\)](#)
- ttH: [F. Maltoni, EV, C. Zhang \(arXiv:1607.05330\)](#)
- FCNC [Degrande et al \(arXiv:1412.5594\)](#), [Durieux et al \(arXiv:1412.7166\)](#)

In practice

FeynRules+NLOCT

➔ NLO UFO model including UV and R2 counterterms

```
MG5_DIR>./bin/mg5_aMC
```

```
MG5_aMC>import model TEFT
```

```
MG5_aMC>generate p p > t t~ Z EFT=1 [QCD]
```

```
MG5_aMC>output some_DIR
```

```
MG5_aMC>launch
```

NLO code:

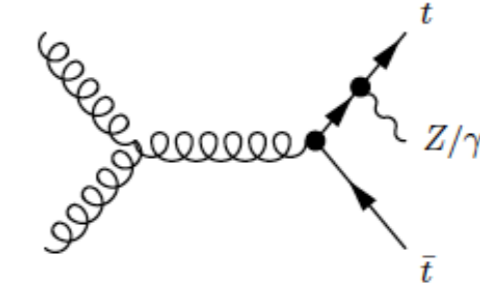
- Fixed-Order NLO
- NLO+PS with aMC@NLO

Results:

- SM
- Interference of dim-6 with SM
- Squared terms-Interference between operators

Top-pair + Z/γ

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%}
<i>K</i> -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%}



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

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

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

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

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

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

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

interference
with SM

squared contributions

$$\mathcal{L}_{ttZ} = e \bar{u}(p_t) \left[\gamma^\mu (C_{1,V}^Z + \gamma_5 C_{1,A}^Z) + \frac{i \sigma^{\mu\nu} q_\nu}{m_Z} (C_{2,V}^Z + i \gamma_5 C_{2,A}^Z) \right] v(p_{\bar{t}}) Z_\mu$$

$$C_{1,V}^Z = \frac{1}{2} \left(C_{\phi Q}^{(3)} - C_{\phi Q}^{(1)} - C_{\phi t} \right) \frac{m_t^2}{\Lambda^2 s_W c_W}$$

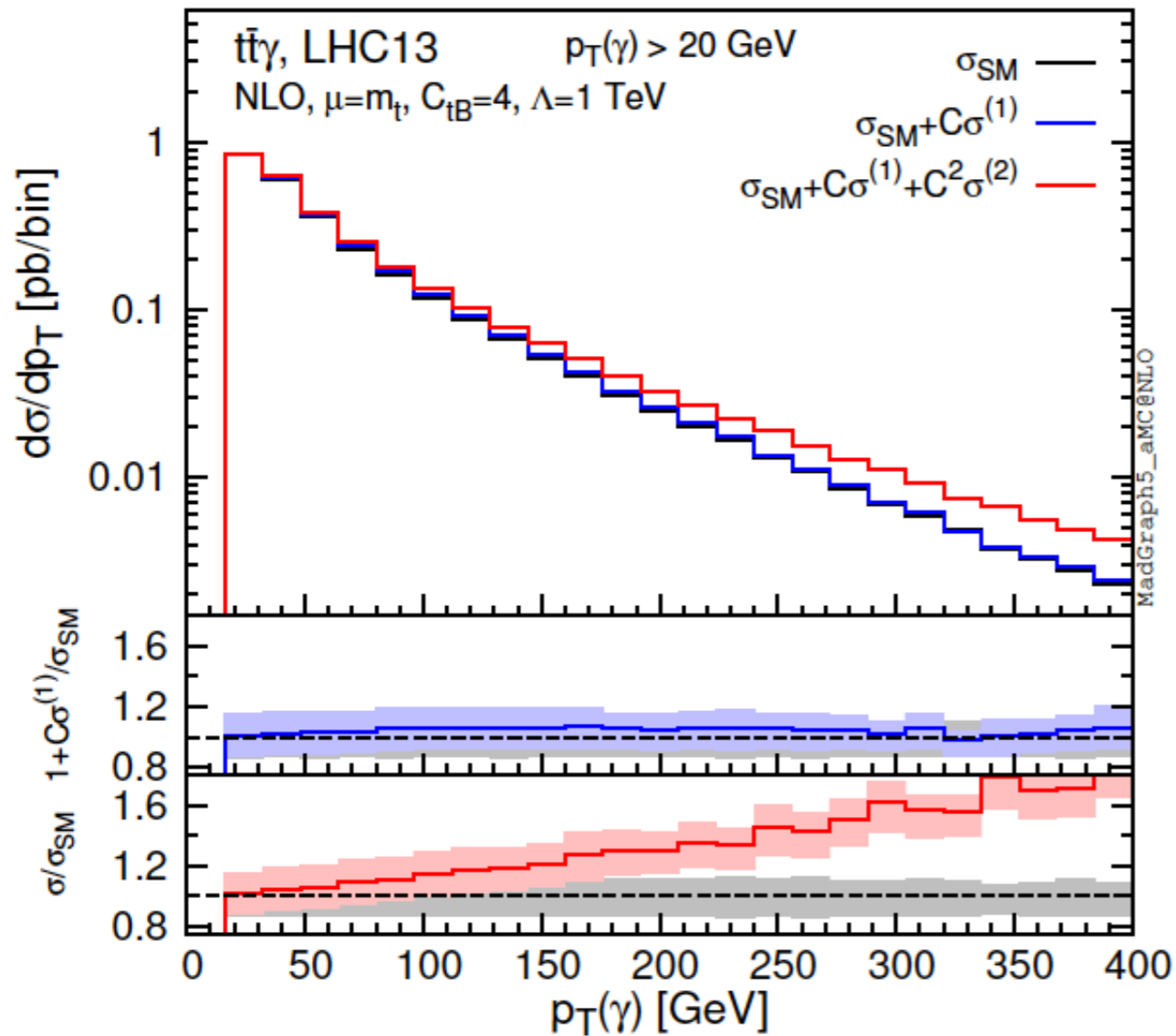
$$C_{1,A}^Z = \frac{1}{2} \left(-C_{\phi Q}^{(3)} + C_{\phi Q}^{(1)} - C_{\phi t} \right) \frac{m_t^2}{\Lambda^2 s_W c_W}$$

$$C_{2,V}^Z = (C_{tW} c_W^2 - C_{tB} s_W^2) \frac{2 m_t m_Z}{\Lambda^2 s_W c_W}$$

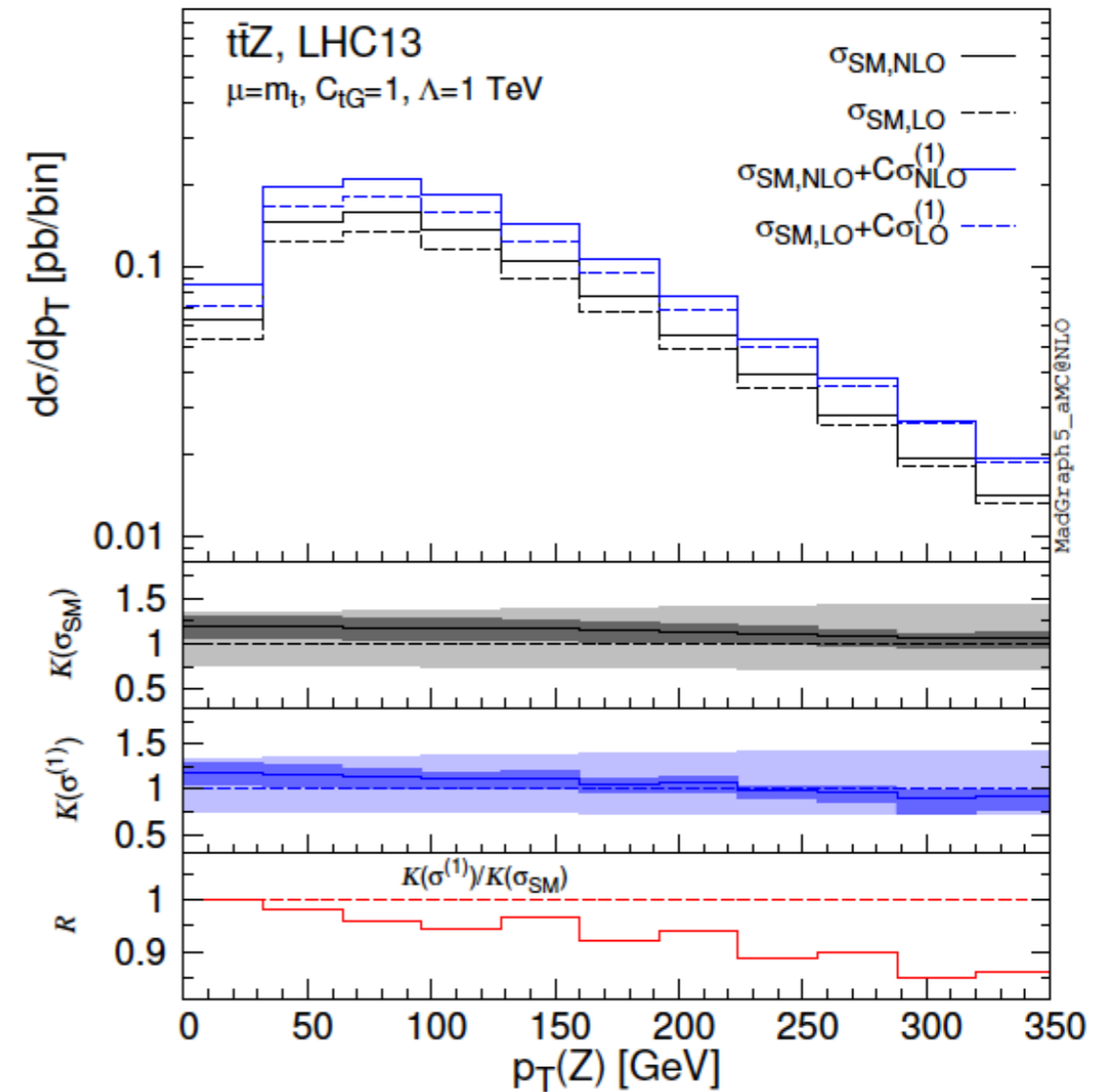
$$C_{2,A}^Z = 0$$

Anomalous
coupling approach

Differential distributions for $tt+V$



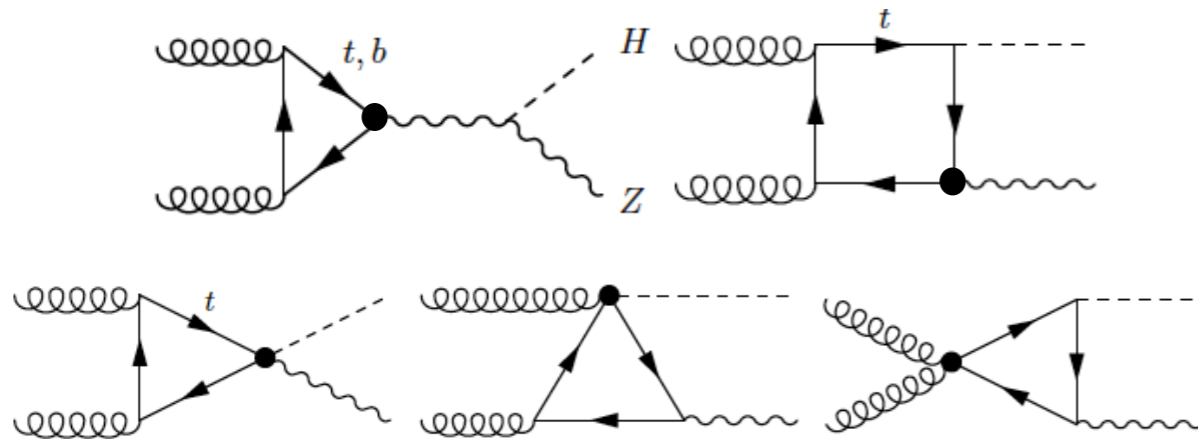
Large contribution at $O(1/\Lambda^4)$
 rising with energy



Using SM k-factors is not enough

arXiv:1601.08193

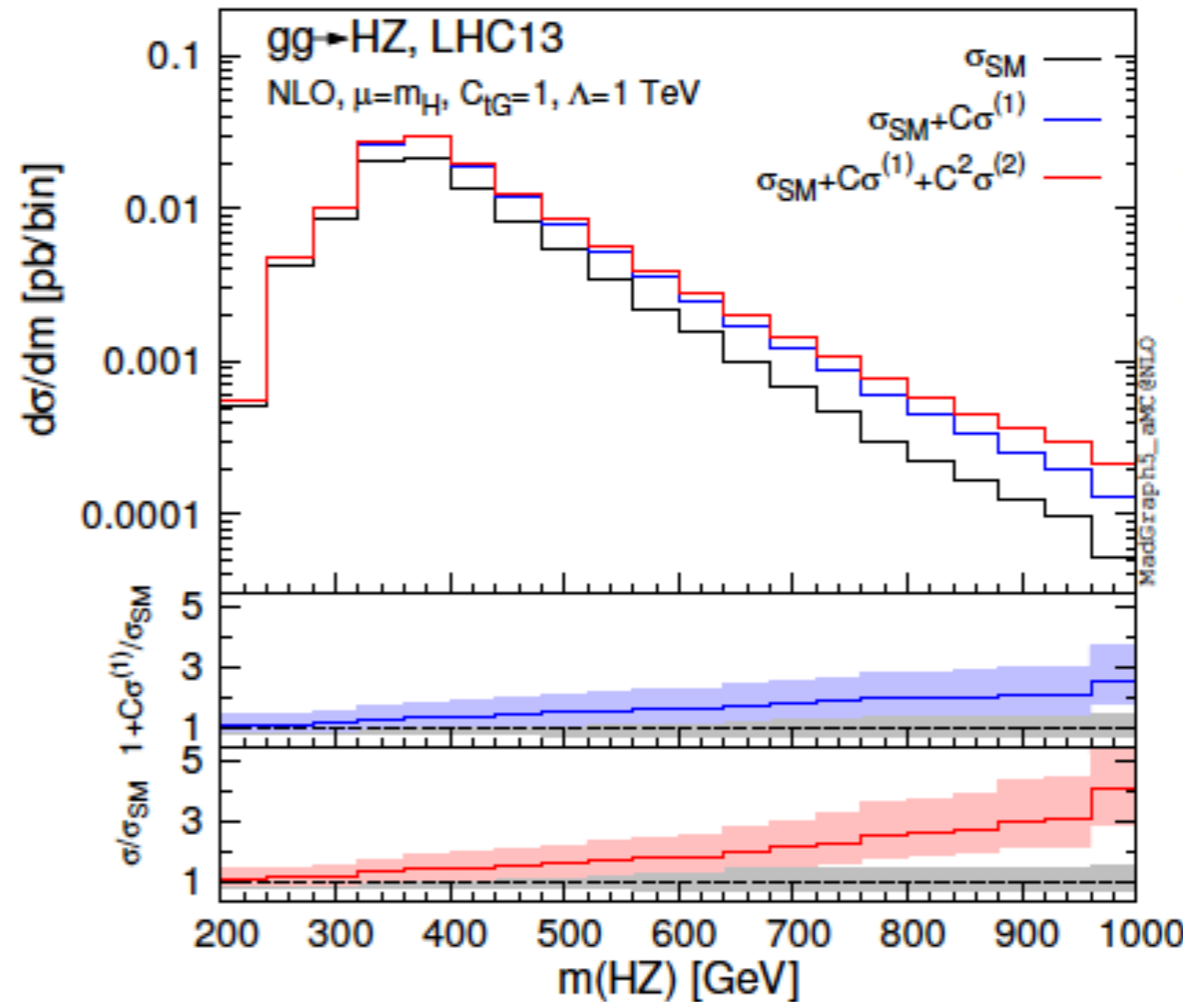
Top-operators in non-top final states



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

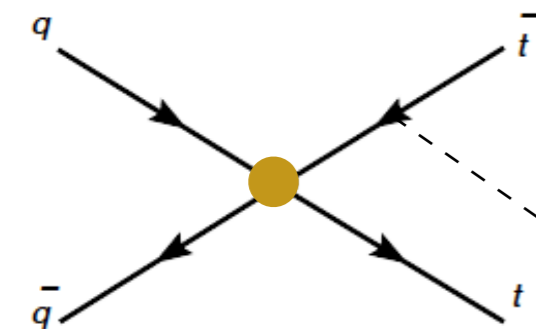
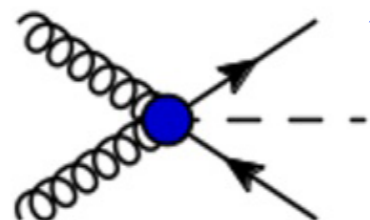
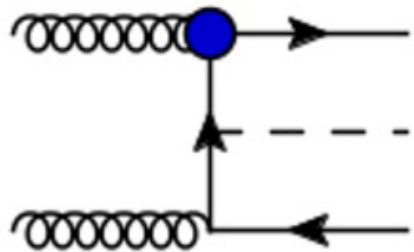
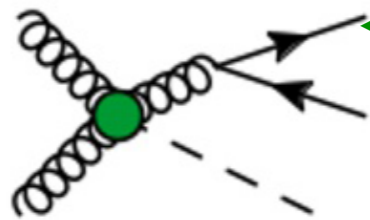
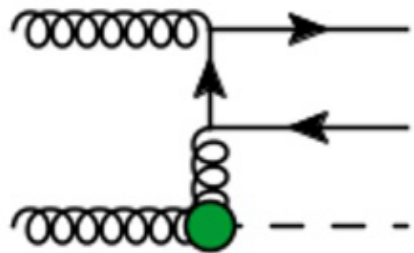
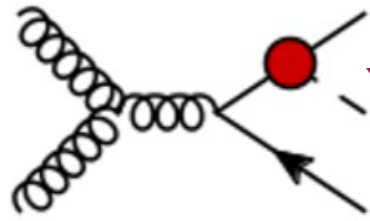
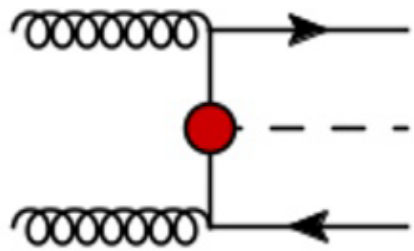
[fb]	SM		O_{tG}	$O_{tQ}^{(1)}$
13TeV	$93.6^{+34.3\%}_{-23.8\%}$	$\sigma_i^{(1)}$	$34.6^{+35.2\%}_{-24.5\%}$	$5.91^{+36.4\%}_{-24.9\%}$
		$\sigma_{ii}^{(2)}$	$6.09^{+39.2\%}_{-26.1\%}$	$0.182^{+40.2\%}_{-26.6\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.370^{+0.7\%}_{-0.9\%}$	$0.0631^{+1.6\%}_{-1.5\%}$
		$\sigma_{ii}^{(2)}/\sigma_i^{(1)}$	$0.176^{+2.9\%}_{-2.1\%}$	$0.0309^{+2.8\%}_{-2.2\%}$

Uses loop-induced event generation
Hirschi and Mattelaer
arXiv:1507.00020

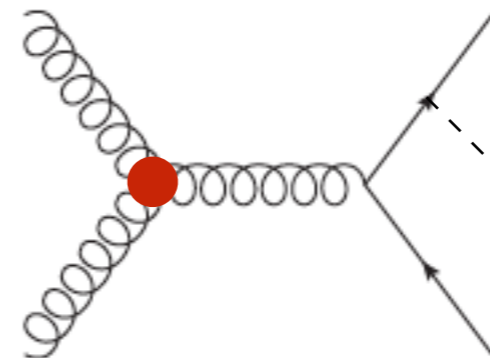


See also:
Englert et al arXiv:1603.05304

ttH in the EFT



4-fermion operators



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

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

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

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

At NLO in this talk

Not in this talk, NLO implementation: work in progress

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

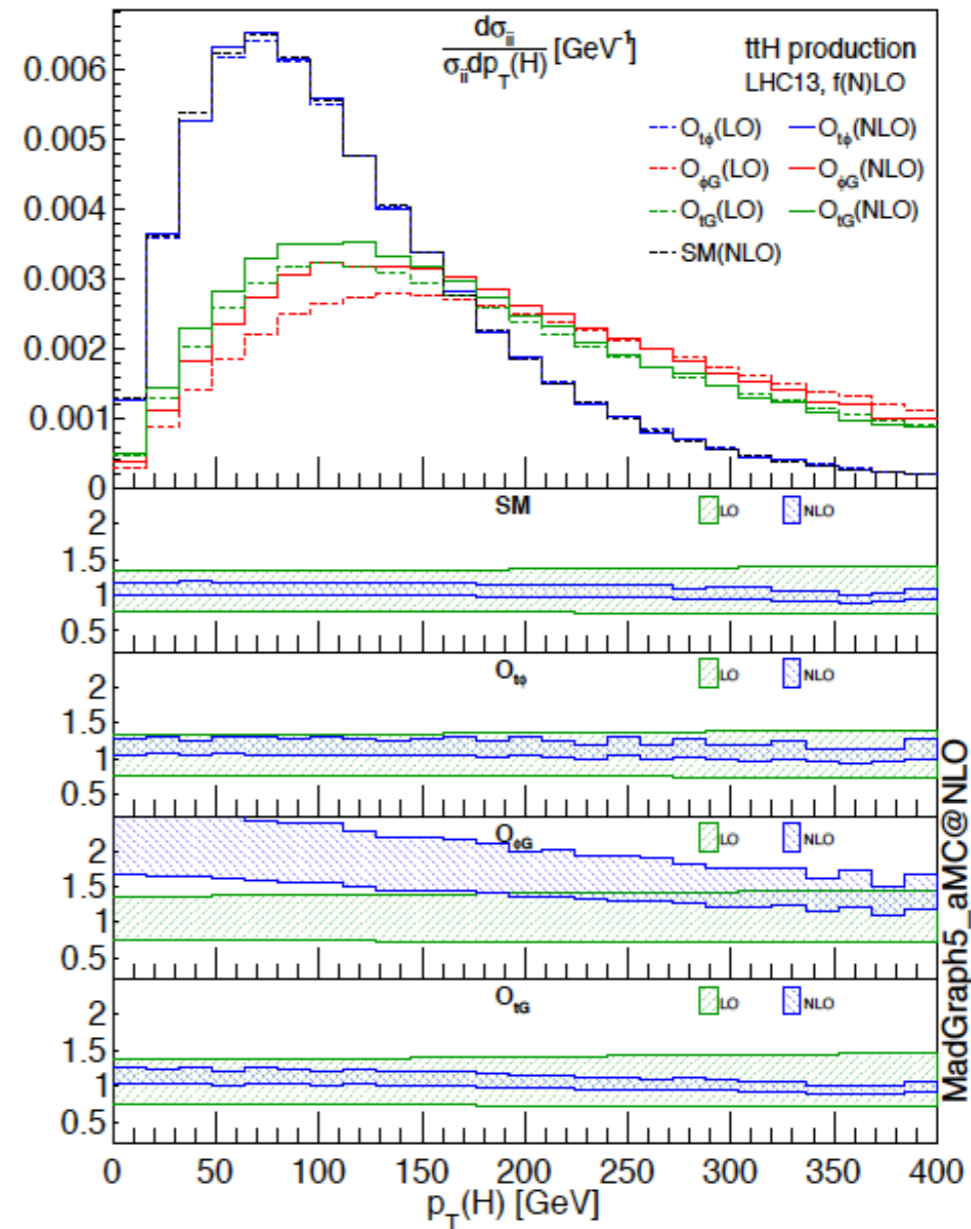
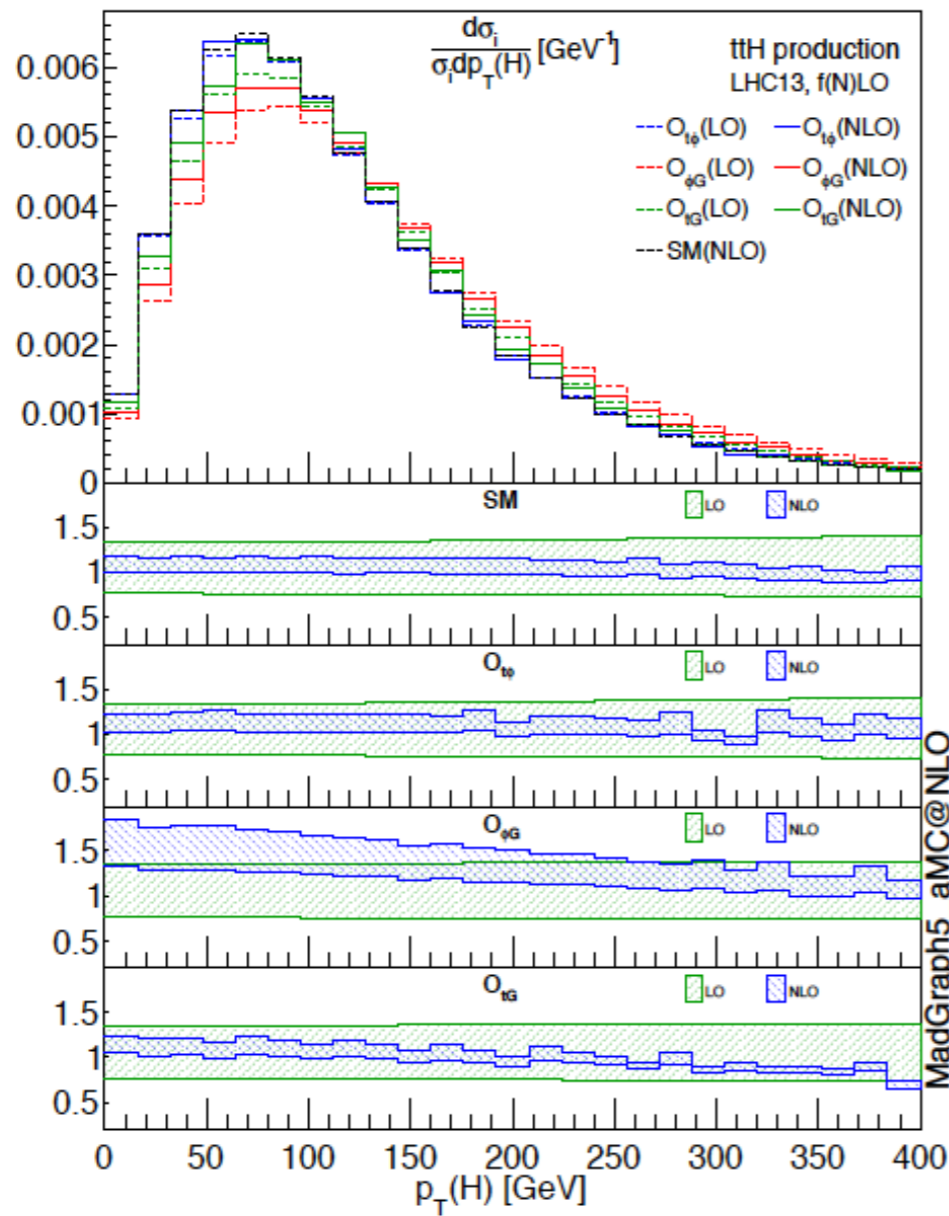
- Different K-factors for different operators, different from the SM
- Large $1/\Lambda^4$ contribution for the chromomagnetic operator
- Constraints from top pair production: $c_{tG} = [-0.42, 0.30]$ [Franzosi and Zhang arxiv:1503.08841](#)
- Systematic study of theoretical uncertainties: scale, PDF, EFT scale

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

interference
with SM

interference between
operators, squared
contributions

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

Top and Higgs

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

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

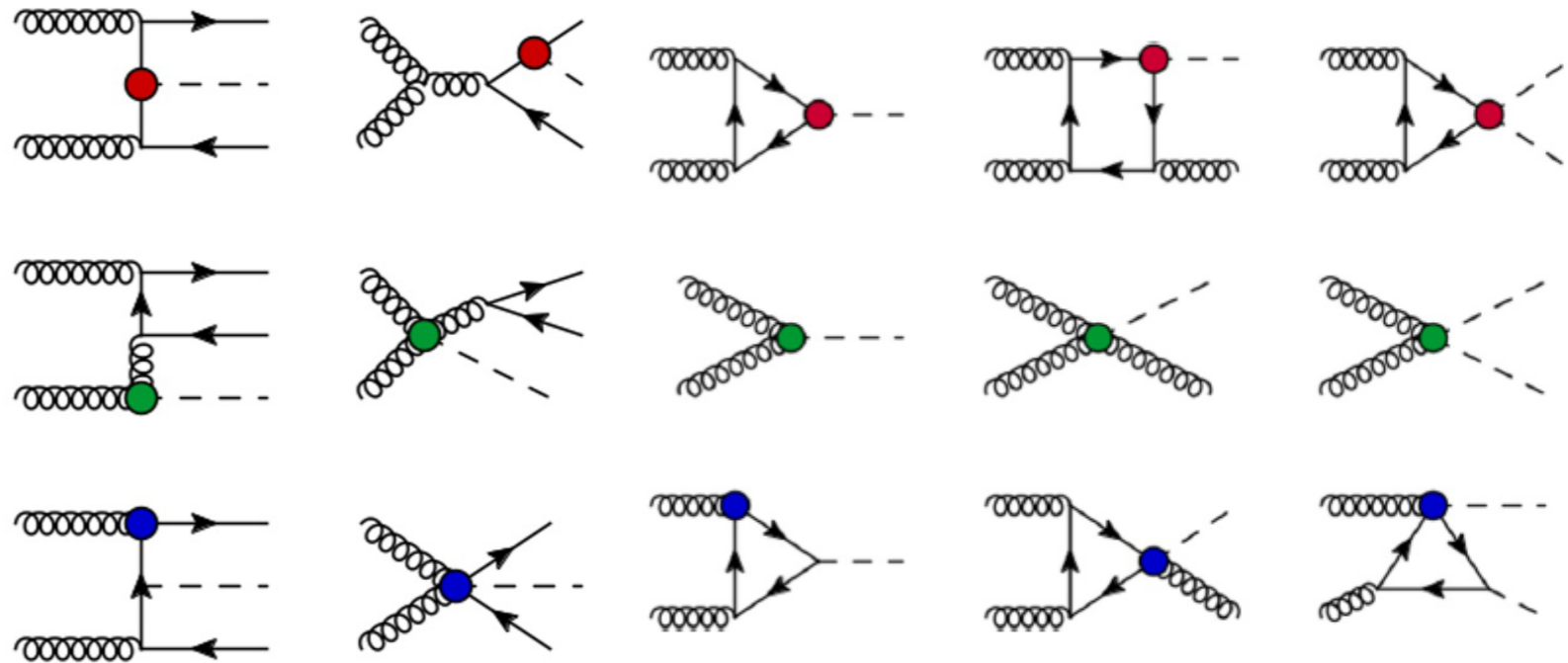
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$$

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)

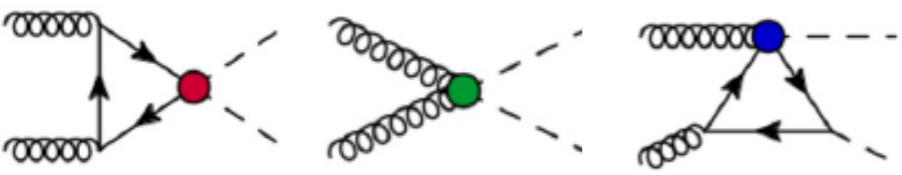


ttH

H, H+j, HH

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

SMEFT in HH

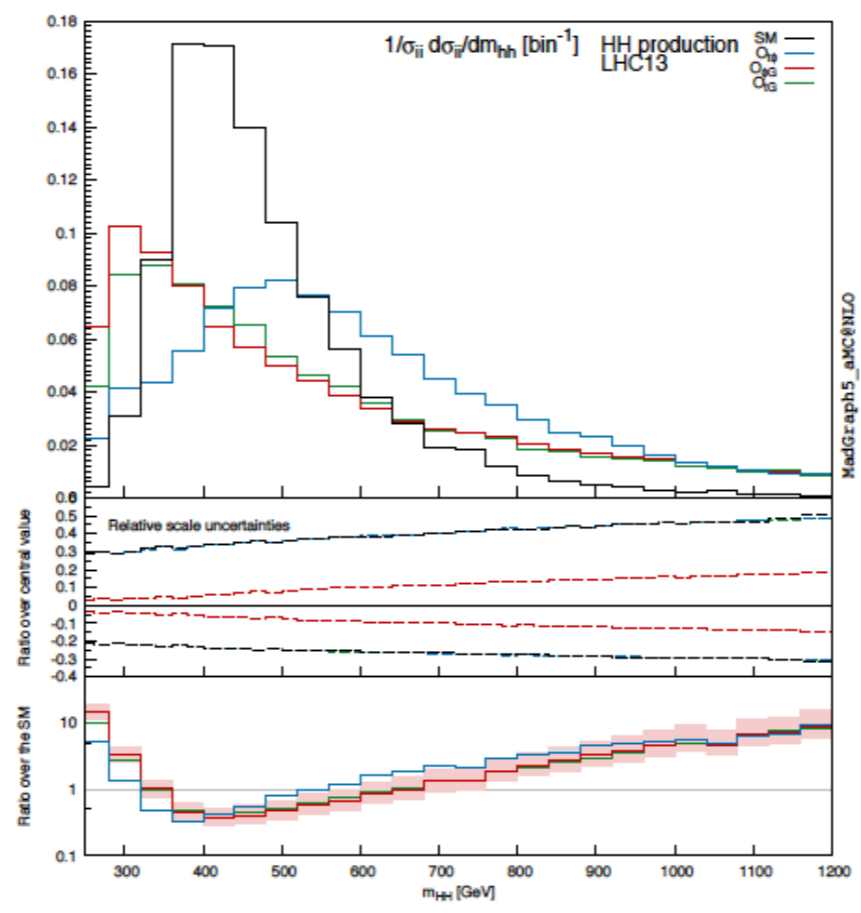
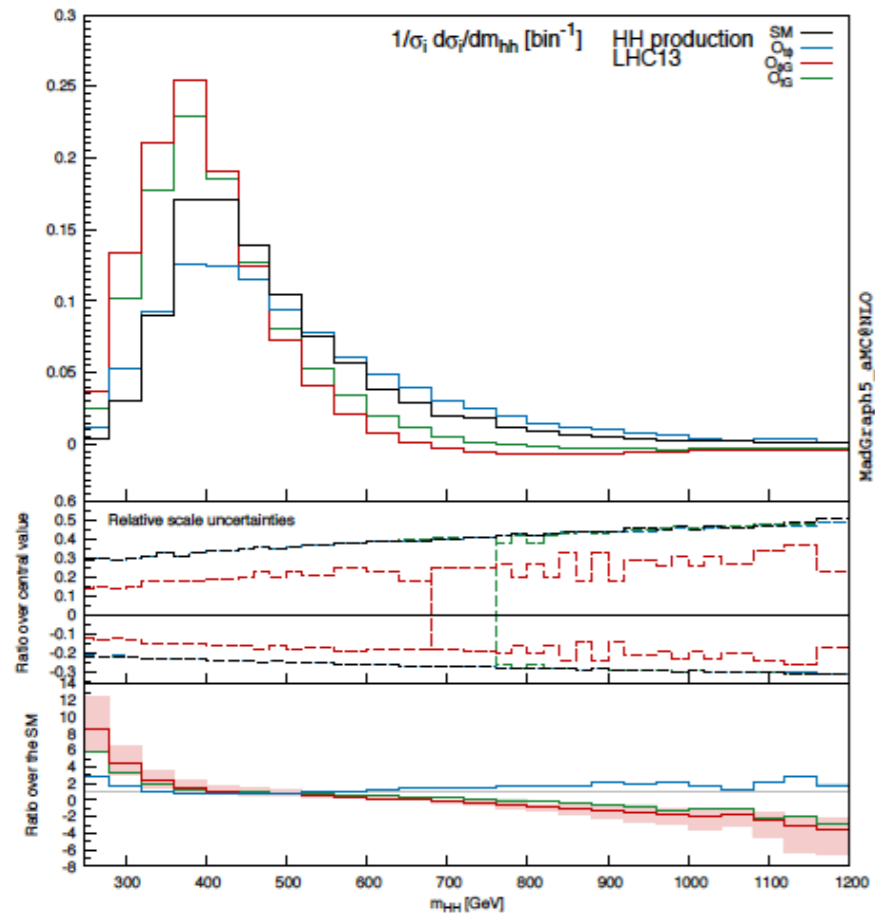


$$O_{t\phi} = y_t^3 (\phi^\dagger \phi) (\bar{Q}t) \tilde{\phi}$$

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

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

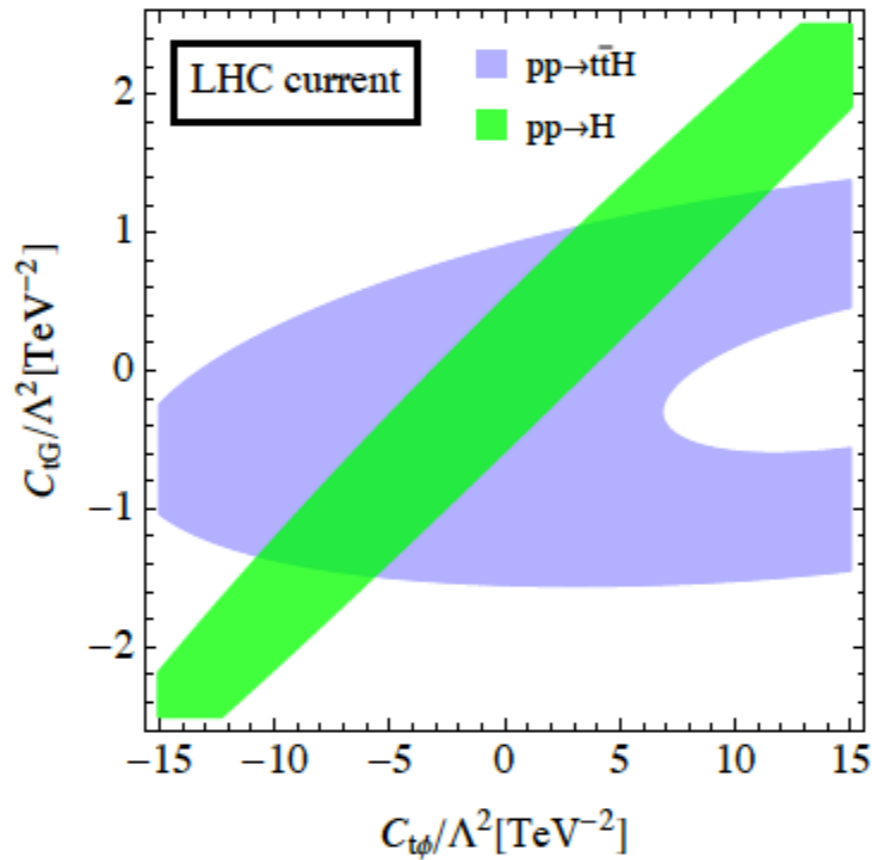
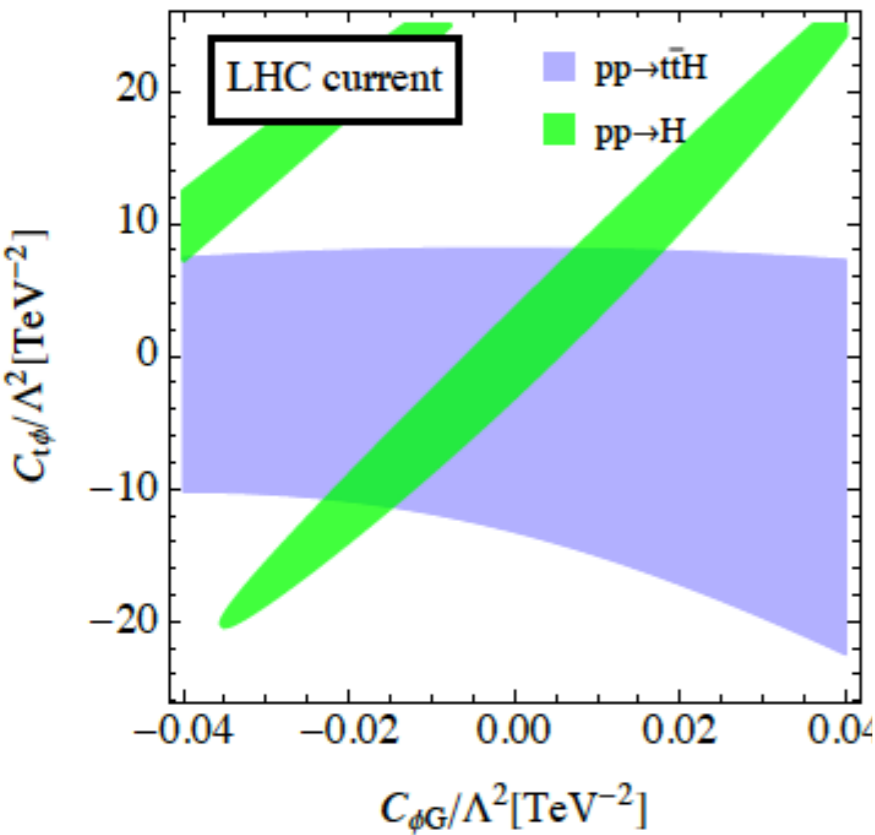
Chromomagnetic operator computed for the first time



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

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)

Constraints using two-operator fits

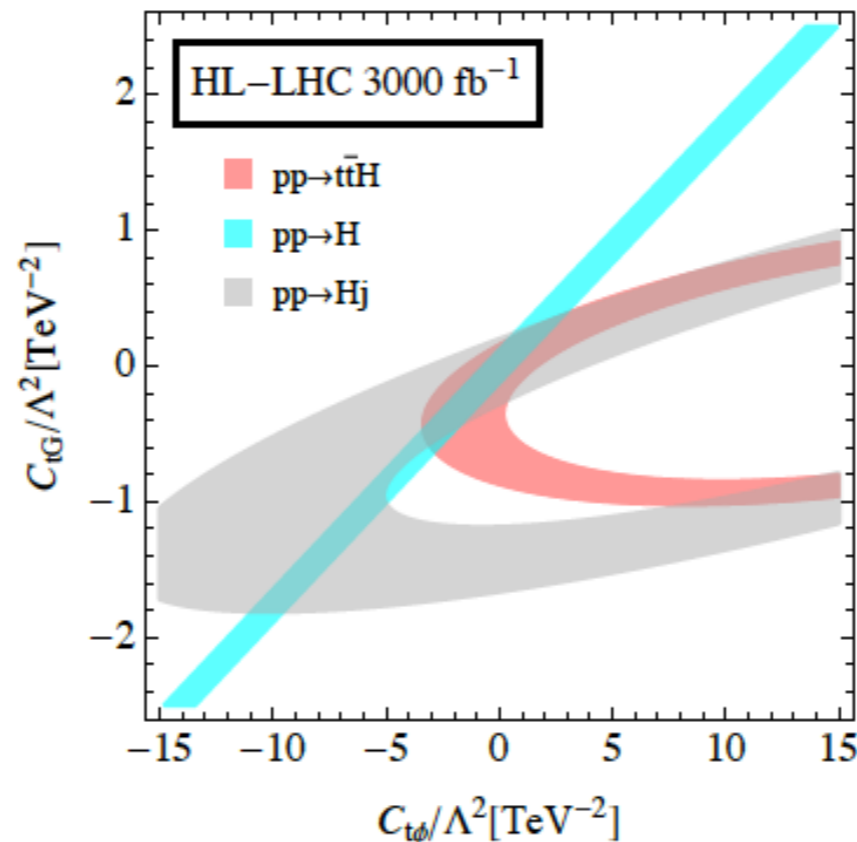
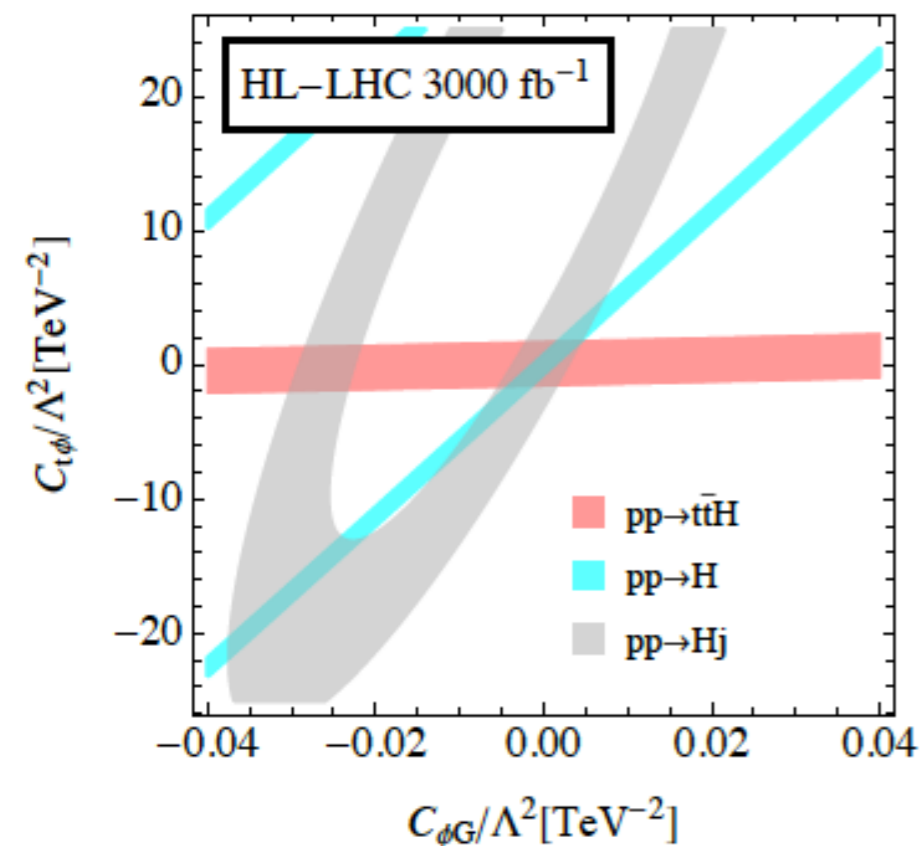


Current limits
using LHC
measurements

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

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

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



14TeV projection
3000 fb^{-1}

Maltoni, EV, Zhang
arXiv:1607.05330

Outlook

- SMEFT a consistent way to look for new interactions
- Higher-order corrections needed to match SM precision and experimental accuracy
- Progress in top-quark processes: pair production, single top, $tt+V$, $tt+H$ as well as loop-induced processes
- QCD corrections important both for total cross-sections and distributions: SM k-factors are not enough
- Global fits results already available: important to include NLO predictions where available to extract maximal and more reliable information
- Combination of Higgs and top results is crucial for a global EFT fit

Thank you for your attention