Top quark physics at NLO in the SMEFT

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based on arXiv:1607.05330 and 1601.08193

HEFT2017
Lumley Castle
23/5/17

Tops in SMEFT

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

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

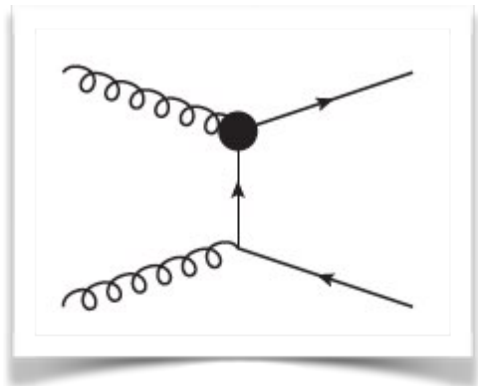
Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arxiv:1008.4884

SMEFT in processes with tops

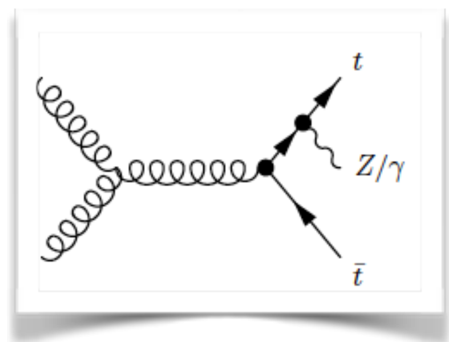
Rich phenomenology:

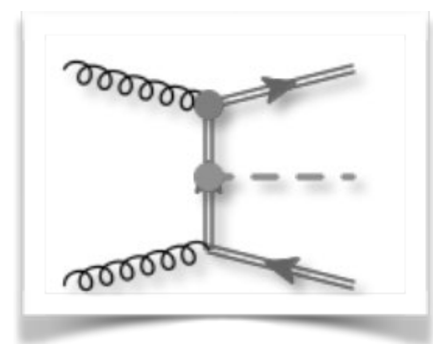
pair production



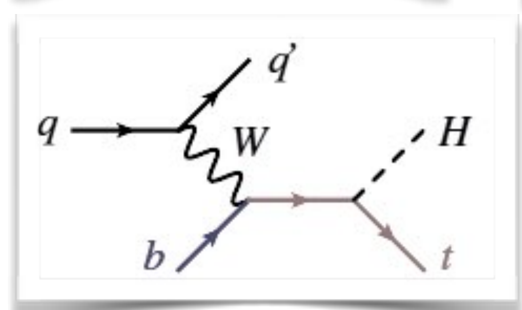
single

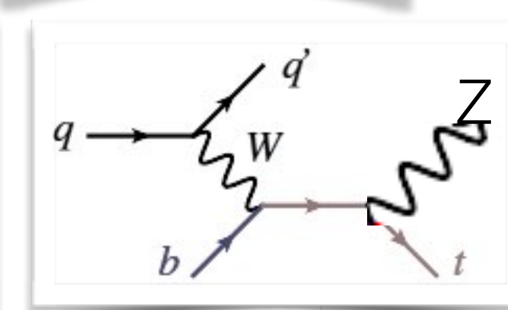
associated production





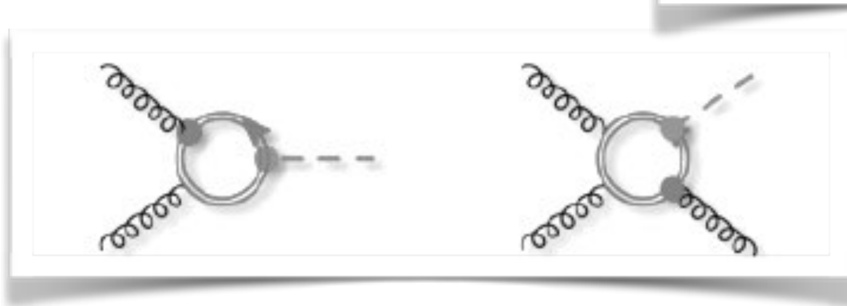
pair

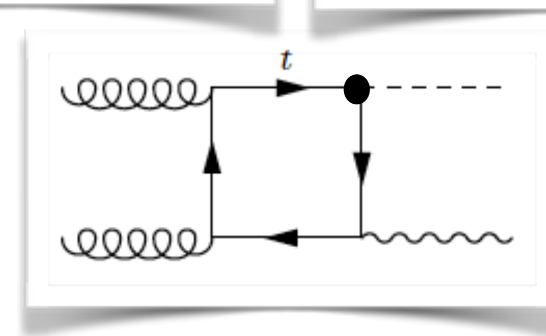


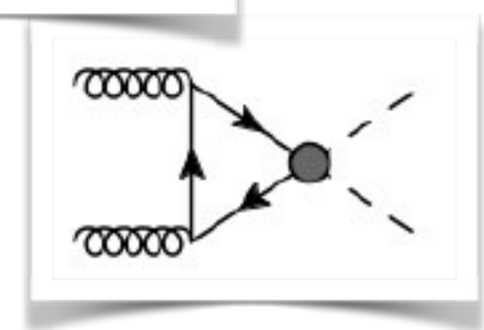


single

top loops







Top-quark operators and how to look for them

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

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

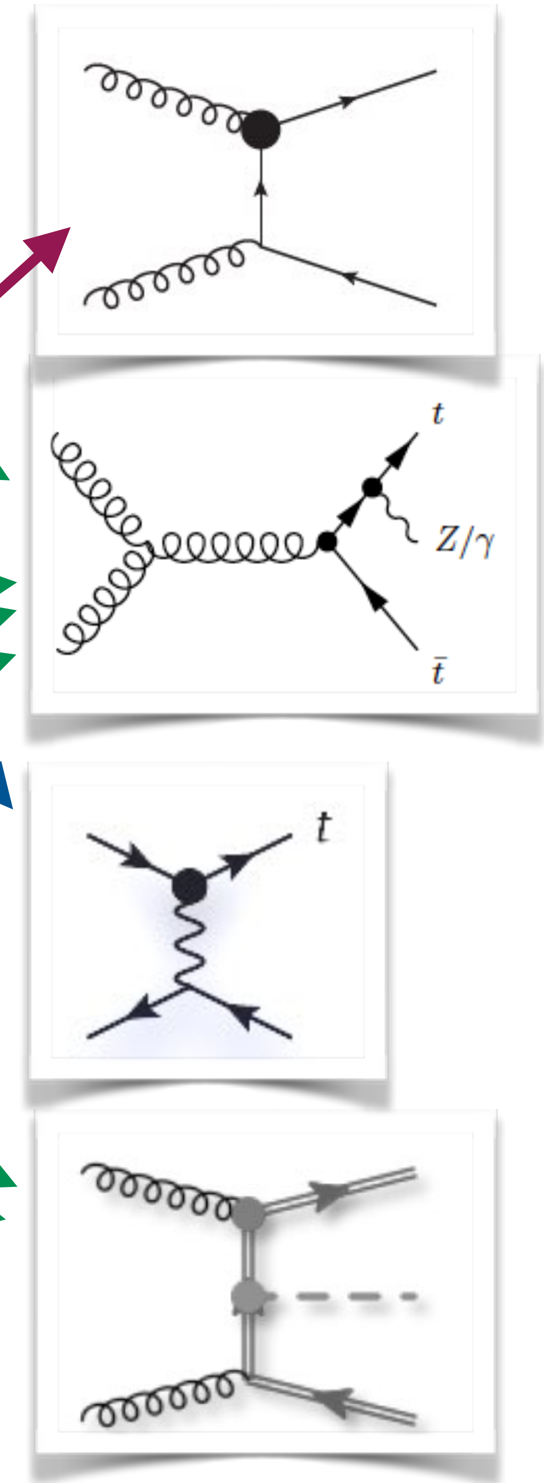
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

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

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

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

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



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

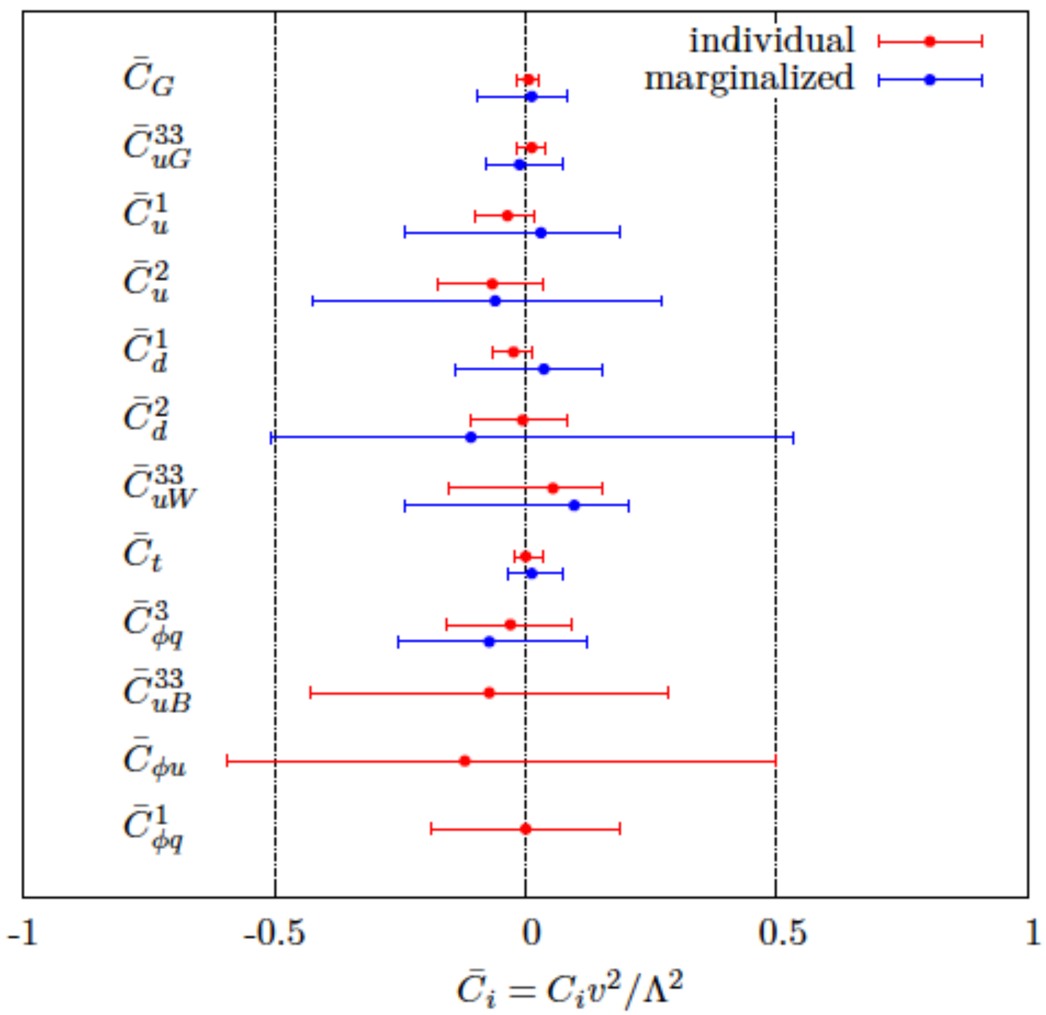
First work towards global fits (Christoph's talk):

Buckley et al arxiv:1506.08845 and 1512.03360

(N)NLO SM + LO EFT

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production			
Total cross-sections:			
ATLAS	7	lepton+jets	1406.5375
ATLAS	7	dilepton	1202.4892
ATLAS	7	lepton+tau	1205.3067
ATLAS	7	lepton w/o b jets	1201.1889
ATLAS	7	lepton w/ b jets	1406.5375
ATLAS	7	tau+jets	1211.7205
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573
ATLAS	8	dilepton	1202.4892
CMS	7	all hadronic	1302.0508
CMS	7	dilepton	1208.2761
CMS	7	lepton+jets	1212.6682
CMS	7	lepton+tau	1203.6810
CMS	7	tau+jets	1301.5755
CMS	8	dilepton	1312.7582
CDF + DØ	1.96	Combined world average	1309.7570
Single top production			
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
Associated production			
ATLAS	7	$t\bar{t}\gamma$	1502.00586
ATLAS	8	$t\bar{t}Z$	1509.05276
CMS	8	$t\bar{t}Z$	1406.7830

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Differential cross-sections:			
ATLAS	7	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.0371
CDF	1.96	$M_{t\bar{t}}$	0903.2850
CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
DØ	1.96	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.5785
Charge asymmetries:			
ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
Top widths:			
DØ	1.96	Γ_{top}	1308.4050
CDF	1.96	Γ_{top}	1201.4156
W-boson helicity fractions:			
ATLAS	7		1205.2484
CDF	1.96		1211.4523
CMS	7		1308.3879
DØ	1.96		1011.6549
Run II data			
CMS	13	$t\bar{t}$ (dilepton)	1510.05302



Tevatron and LHC data

Cross-sections and distributions

For a global fit in the FCNC sector: Durieux et al arXiv:1412.7166

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Fits: Some considerations

- Theory uncertainties (see also Roman's talk):
  - SM: factorisation and renormalisation scale, PDF uncertainties
  - EFT: as in SM but also EFT scale, dimension-8 operators
- Simplifying assumptions: flavour, CP violation, FCNC
- $1/\Lambda^2$ vs $1/\Lambda^4$ contributions
  - $1/\Lambda^2$ suppressed due to helicity: Azatov et al arXiv:1607.05236
  - Vanishing SM amplitude: FCNC
- Validity of the EFT expansion: $E<\Lambda$, report limits as a function of the max scale probed: Contino et al arXiv: 1604.06444

Use rich top phenomenology

- Measure and include as many observables as possible:
  - cross-sections
  - distributions of the top and decay products and associated V,H etc
  - spin correlations, polarisation: Bernreuther et al arXiv: 1508.05271, Aguilar et al arXiv:1508.04592, 1701.05900
  - asymmetries: Aguilar et al arXiv:1406.1798 and 1702.03297
  - W-helicities

To keep in mind: connection to Higgs, flavour, EWPO

The need for NLO predictions in the SMEFT

SMEFT is systematically improvable:

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

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

SMEFT@NLO

- SMEFT@NLO ingredients:
  - Mixing between operators: anomalous dimension matrix: Jenkins et al arXiv:1308.2627,1310.4838, Alonso et al. 1312.2014
  - Check for additional operators at NLO

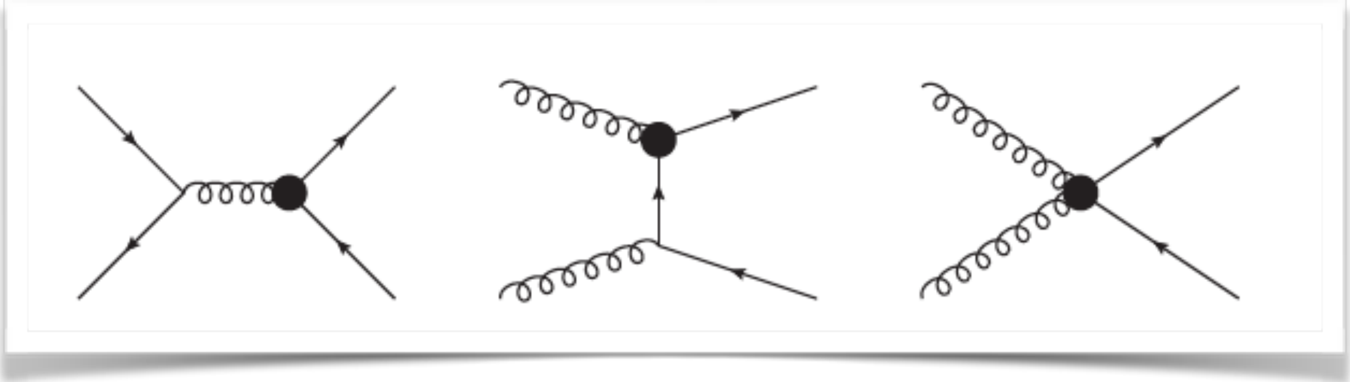
Automation within MadGraph5_aMC@NLO
R2+UV counterterms for the NLO computation:
NLOCT Degrande (arxiv:1406.3030)

Progress in **top** quark processes in this framework:

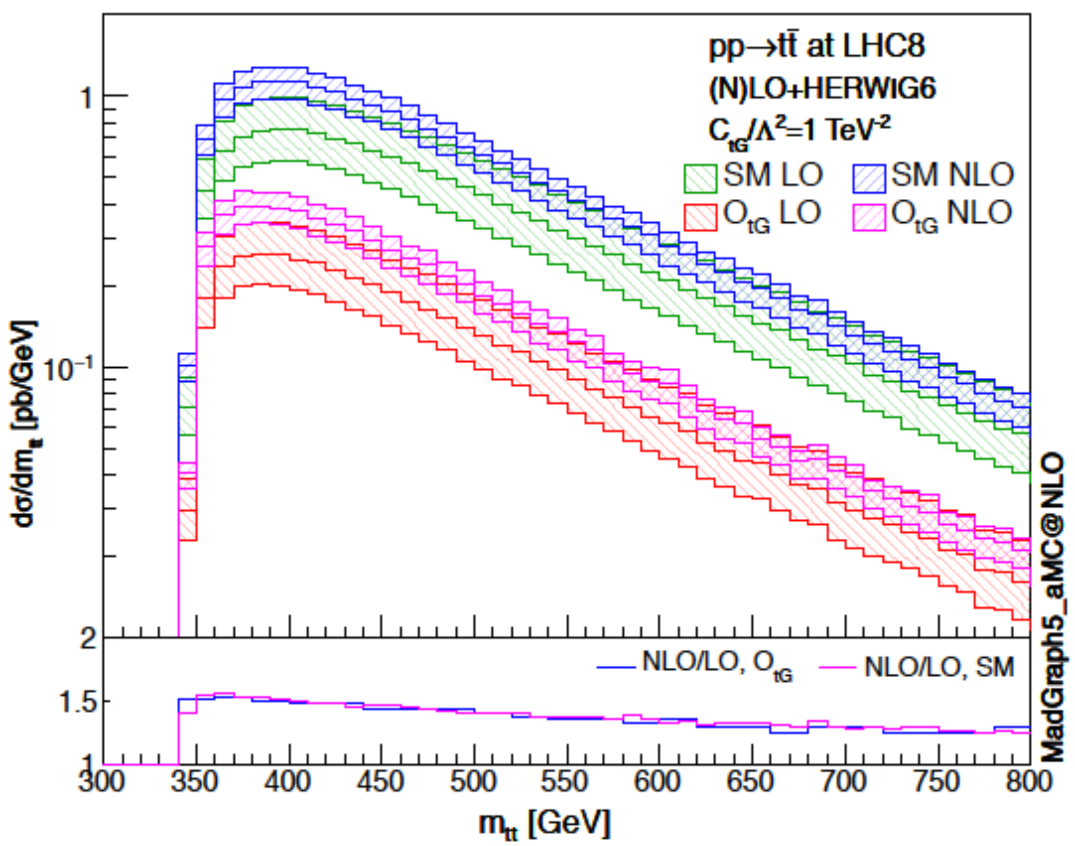
- top pair production: Franzosi and Zhang (arxiv:1503.08841)
- single top production: C. Zhang (arxiv:1601.06163)
- ttZ/γ: O. Bylund, F. Maltoni, I. Tsinikos, EV, C. Zhang (arXiv:1601.08193)
- ttH: F. Maltoni, EV, C. Zhang (arXiv:1607.05330)
- FCNC: Degrande et al(arXiv:1412.5594), Durieux et al(arXiv:1412.7166)

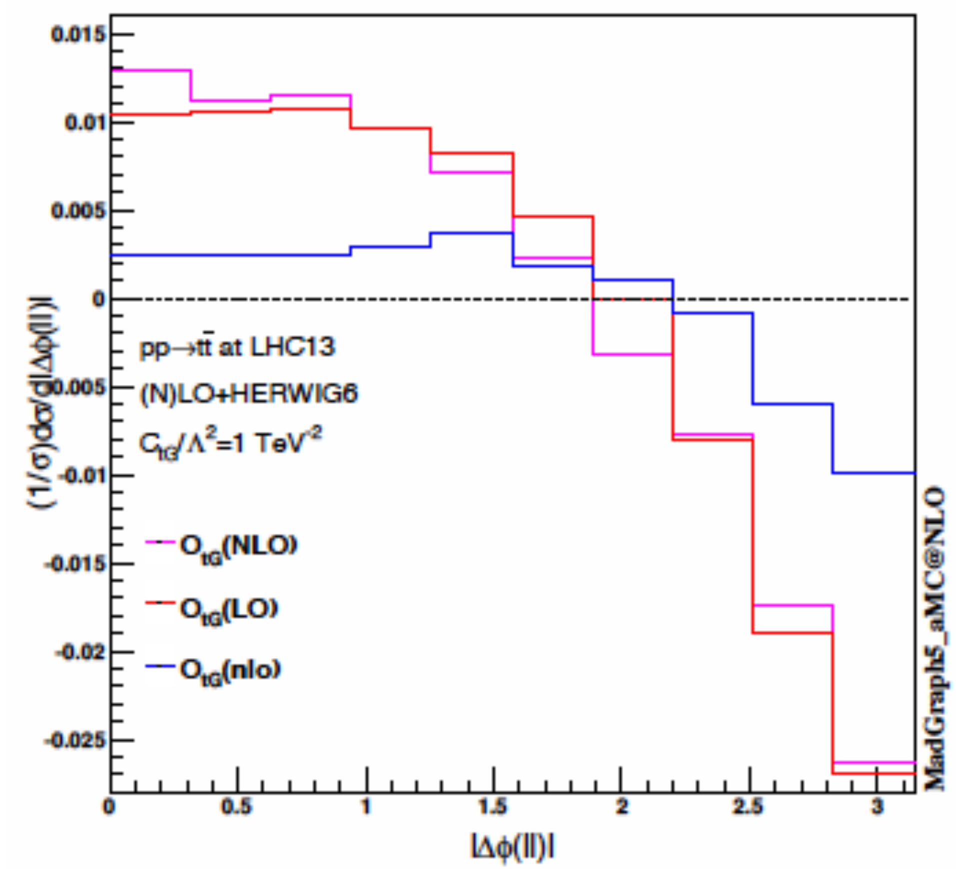
See B. Fuks talk for results in EW Higgs

First example: top-pair production



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





Zhang and Franzosi arXiv:1503.08841

Limits on c_{tG}/Λ^2 using total cross section

	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]

4-fermion NLO implementation: in progress Degrande et al

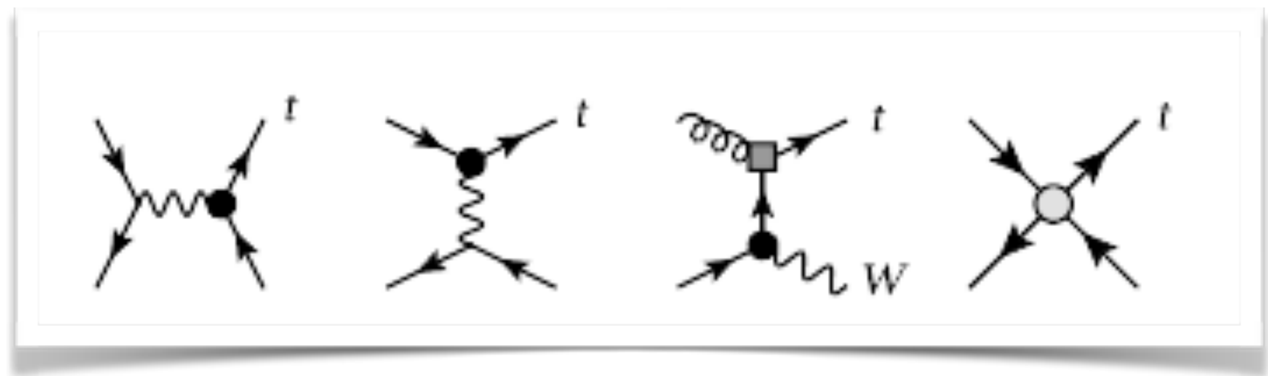
single top production

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

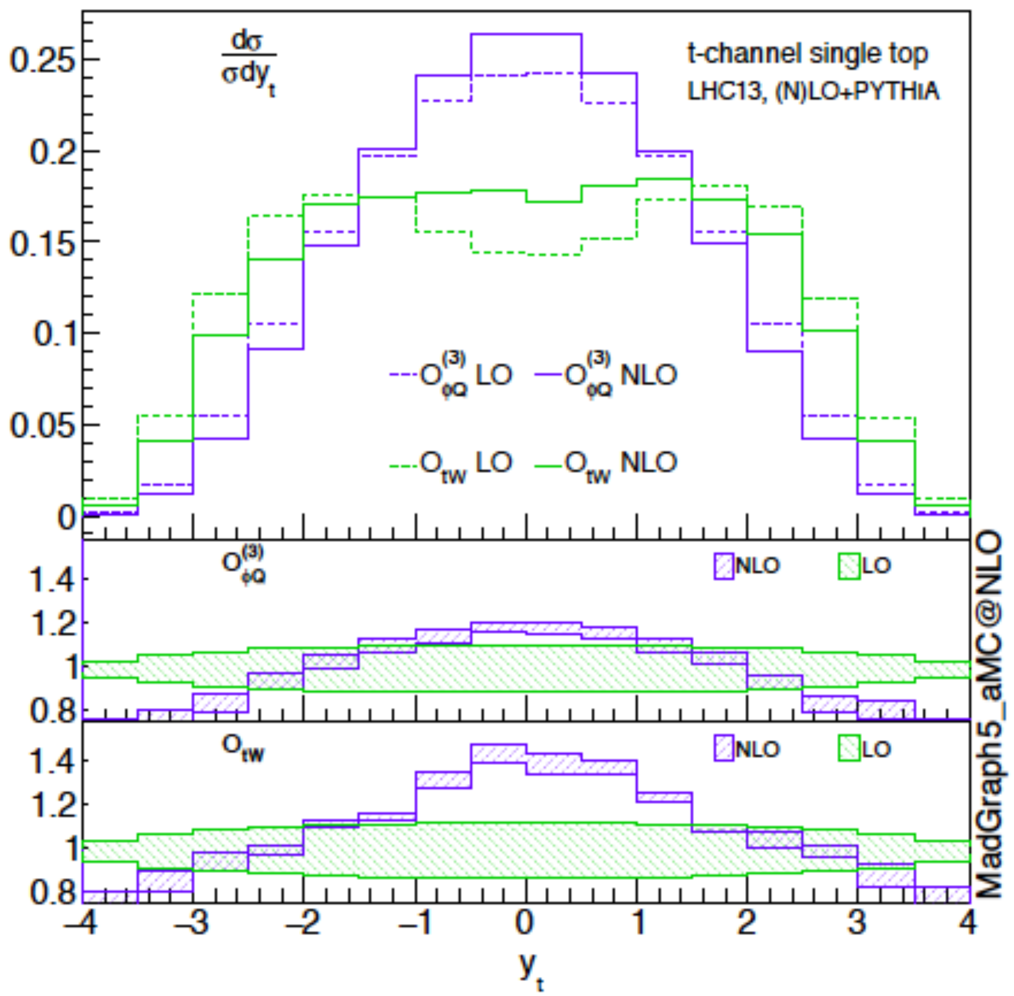
$$O_{tW} = y_t g_W (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

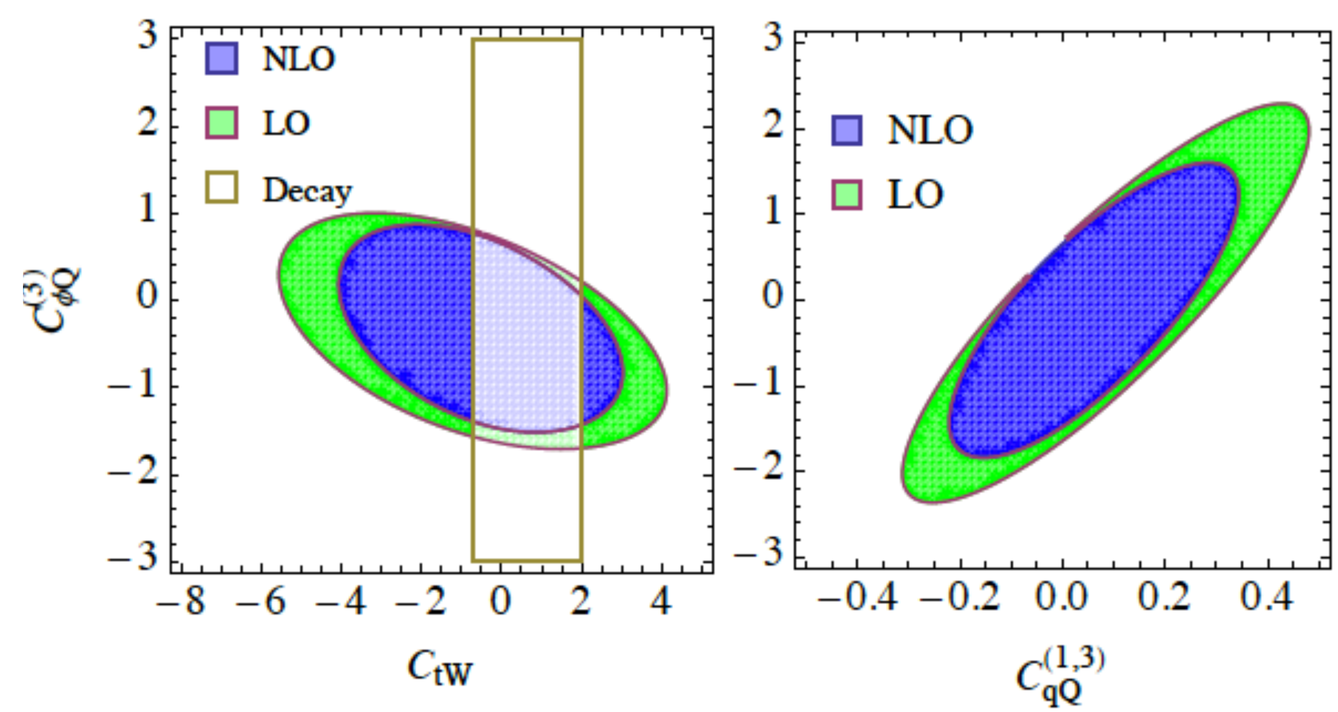
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

$$O_{qQ,rs}^{(3)} = (\bar{q}_r \gamma_\mu \tau^I q_s)(\bar{Q}\gamma^\mu \tau^I Q)$$



Only one four-fermion contributing at $1/\Lambda^2$



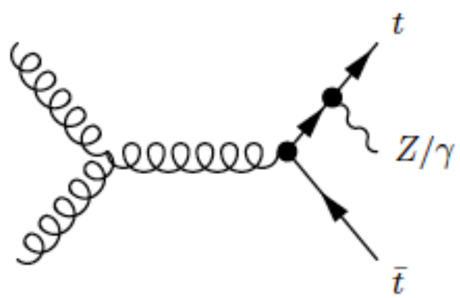


C. Zhang (arxiv:1601.06163)

NLO corrections:

- Impact on distributions
- Impact on limits
  - Accuracy+precision

Top pair + Z/γ



probe of top neutral couplings: ttZ,ttγ,ttg

SM σ(ttZ)=0.88 pb at 13TeV
LHC: ATLAS, CMS measurements

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

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
$\sigma_{ii,LO}^{(2)}$	$258.5^{+49.7\%}_{-30.4\%}$	$2.8(1)^{+39.7\%}_{-26.9\%}$	$2.9(1)^{+39.7\%}_{-26.7\%}$	$20.9^{+44.3\%}_{-28.3\%}$
$\sigma_{ii,NLO}^{(2)}$	$244.5^{+4.2\%}_{-8.1\%}$	$3.8(3)^{+13.2\%}_{-14.4\%}$	$3.9(3)^{+13.8\%}_{-14.6\%}$	$24.2^{+6.2\%}_{-11.2\%}$

Bylund et al arXiv:1601.08193

operators

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu},$$

Small contribution from O_{tW} and O_{tB} at $O(1/\Lambda^2)$ but large at $O(1/\Lambda^4)$

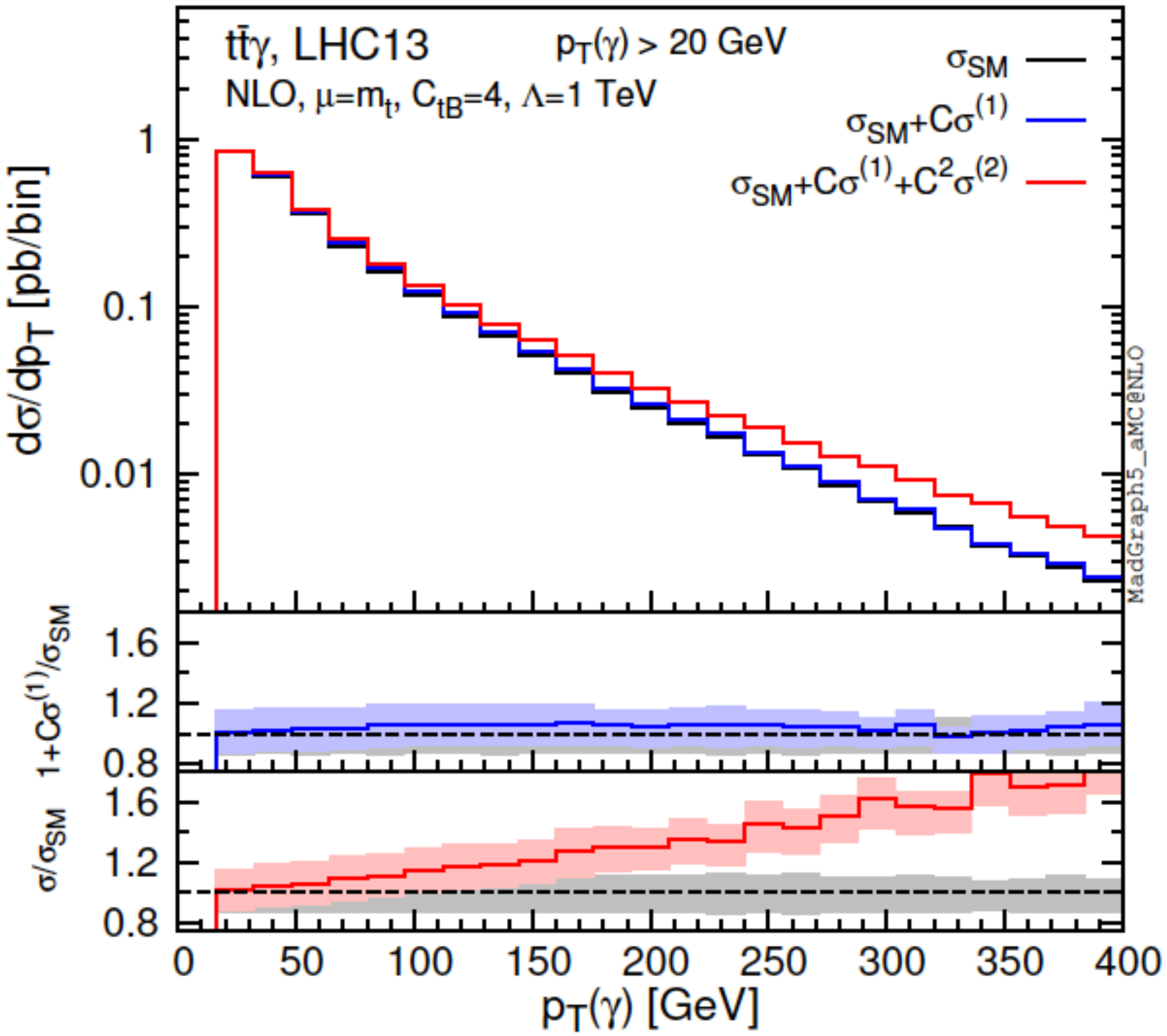
How should we treat $O(1/\Lambda^4)$ terms?

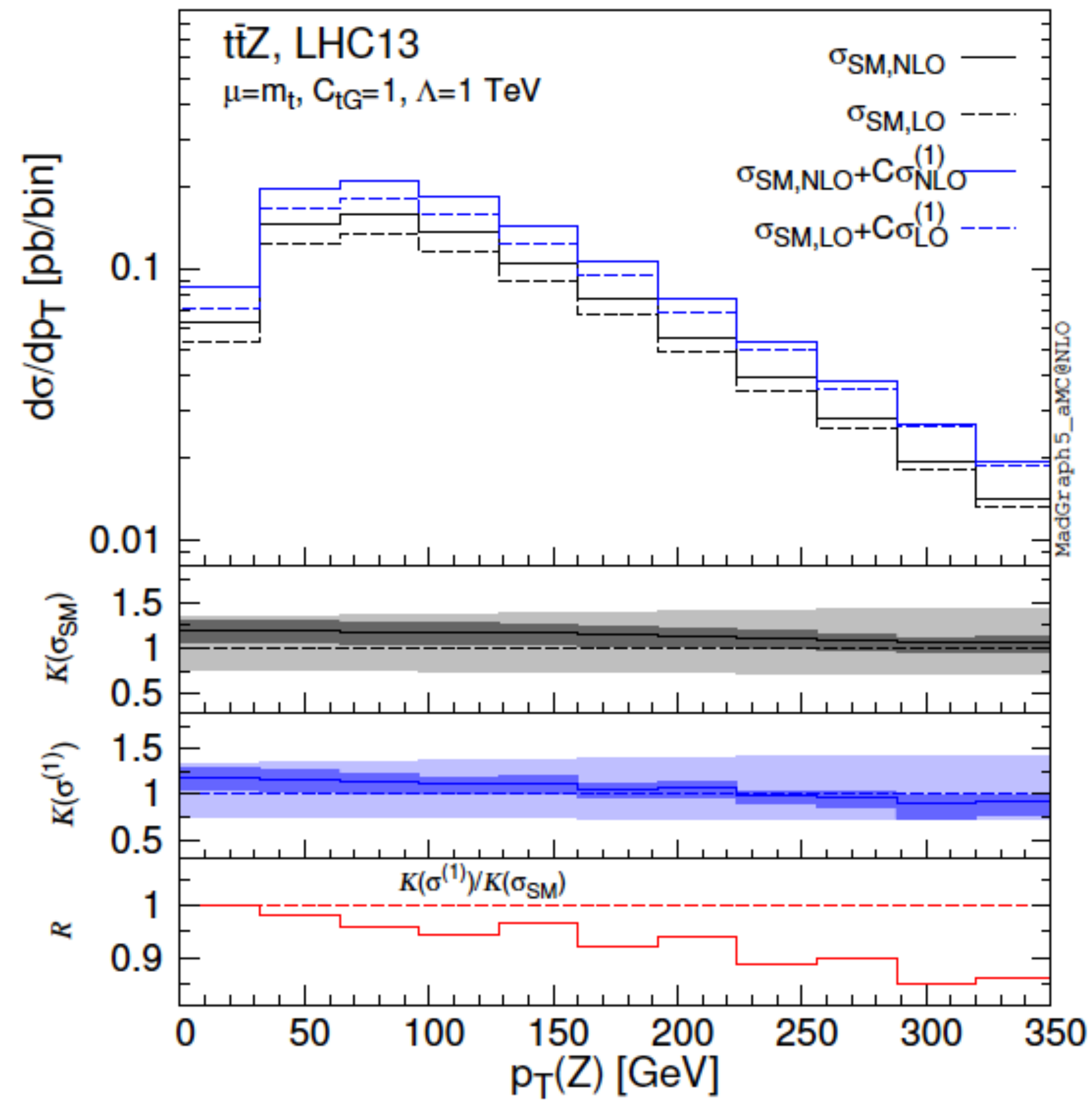
$$C_i^2\frac{E^4}{\Lambda^4} > C_i\frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

Check if EFT condition is satisfied

E.Vryonidou

Differential distributions for tt+V



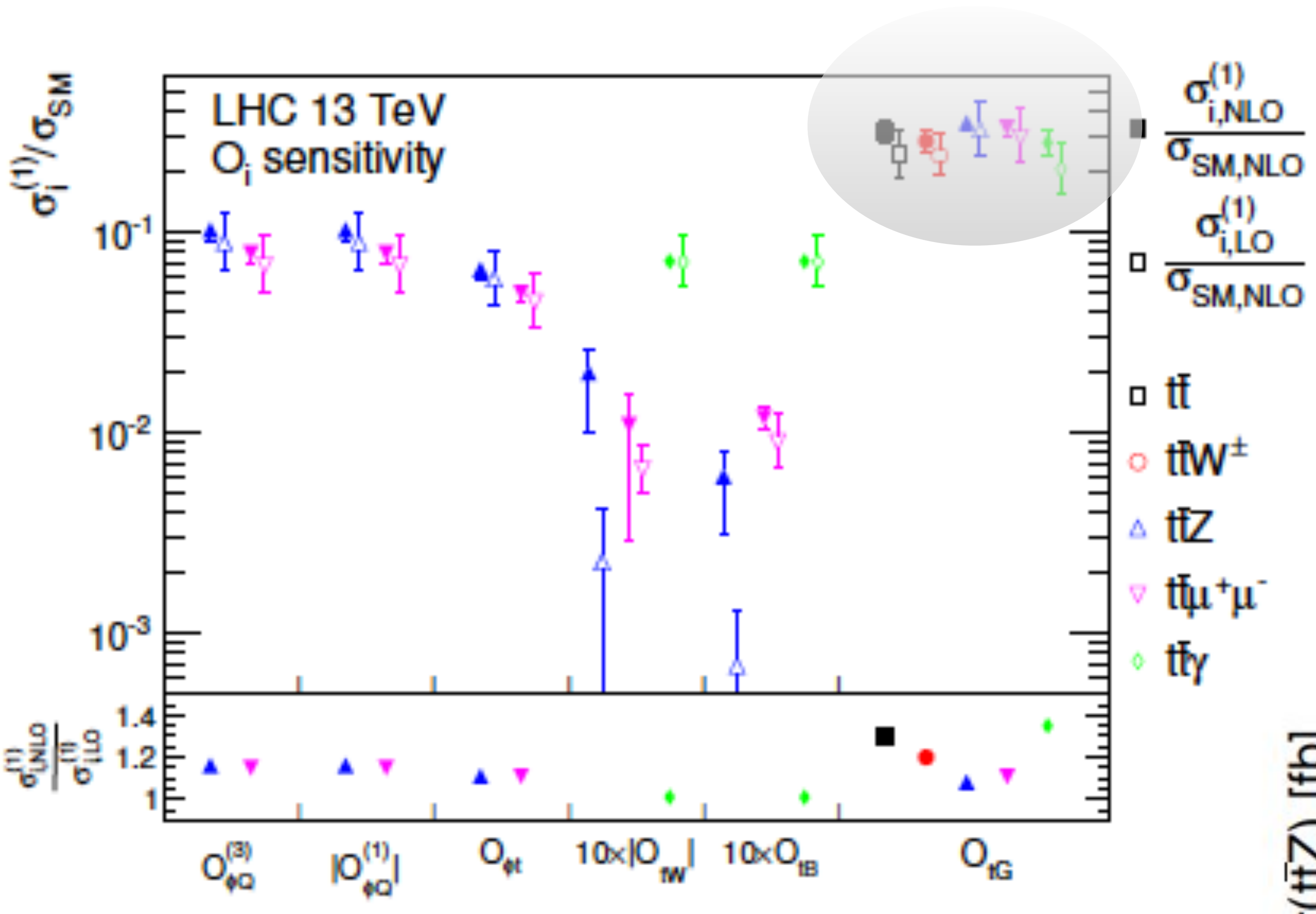


Large contribution at $O(1/\Lambda^4)$ rising with energy

Using SM k-factors is not enough

O. Bylund, F. Maltoni, I. Tsinikos, EV, C. Zhang (arXiv:1601.08193)

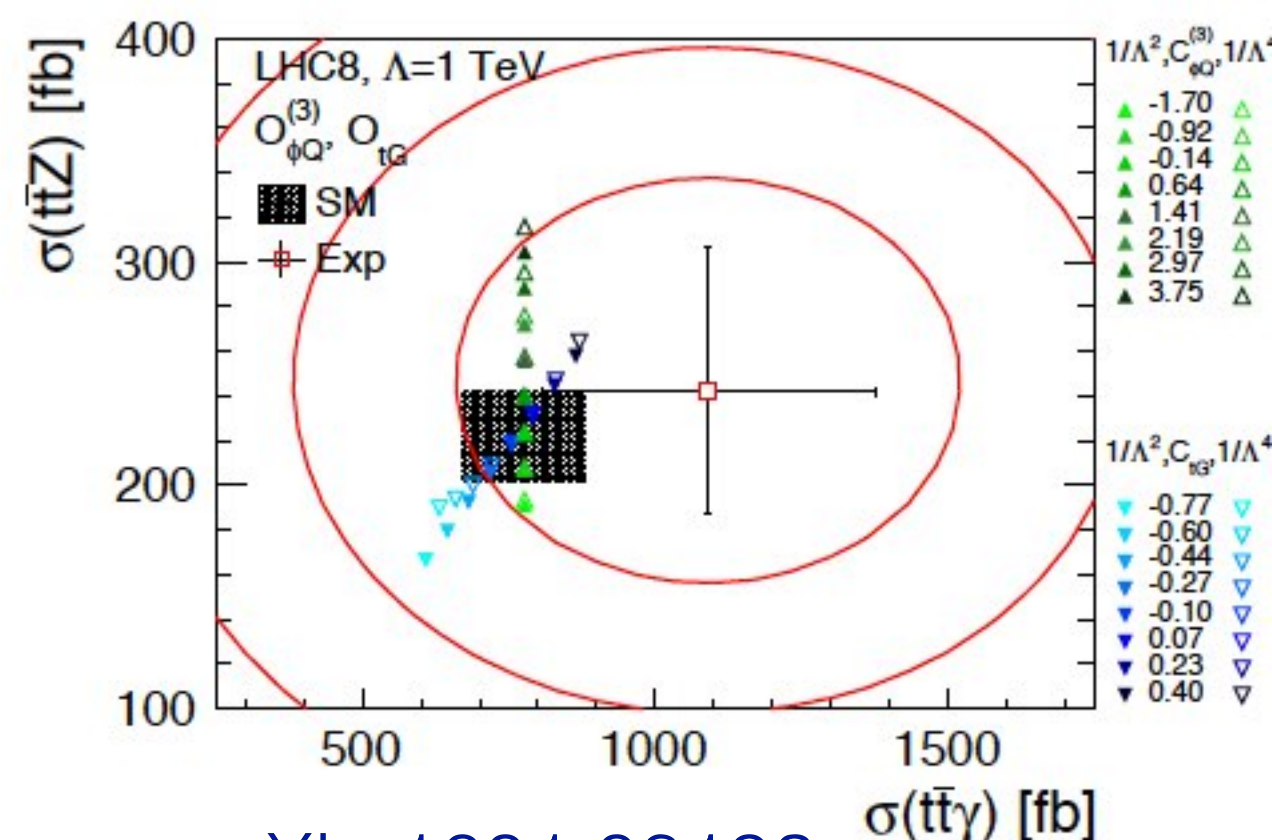
A sensitivity study



For a given (c,Λ) impact of operators varies
Chromomagnetic operator affecting all processes in the same way

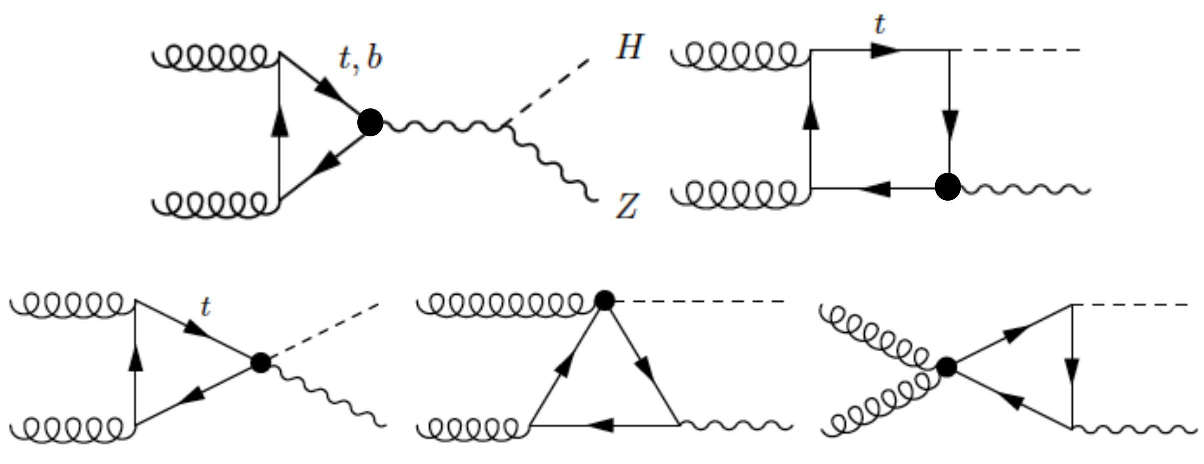
LHC measurements of ttV processes can set constraints on the Wilson coefficients as they become more precise at Run II

See also:
Schulze et al. arXiv:1404.1005,1501.05939, 1603.08911 (using ratios of cross-sections)
Dror et al. arXiv:1511.03674 for ttWj



arXiv:1601.08193

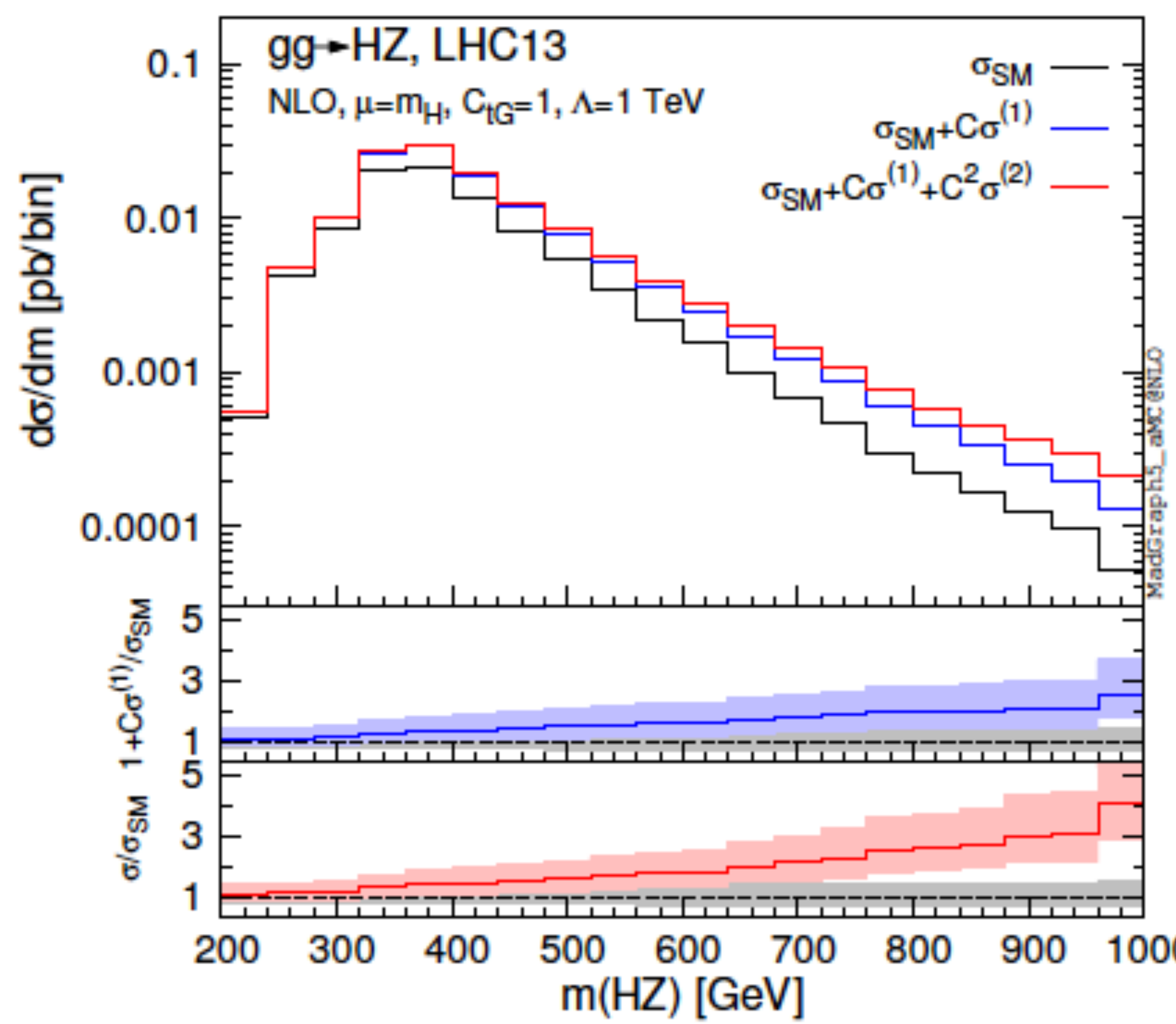
Top-operators in non-top final states



Gluon-fusion contribution to HZ production affected by the operators changing gtt, ttZ and ttH → Additional information

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

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

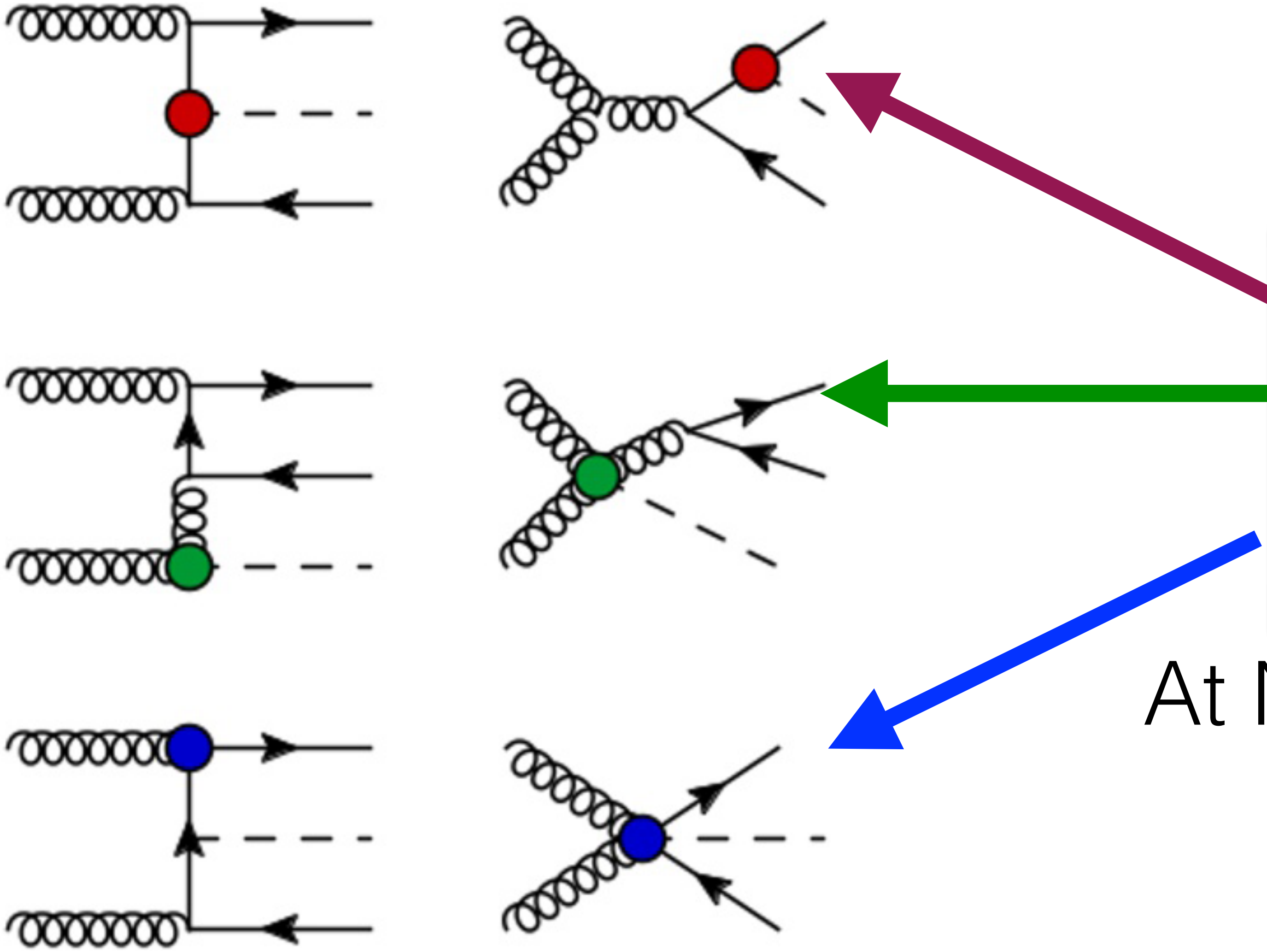


See also:
Englert et al arXiv:1603.05304

Combination with weak Higgs operators: in progress (also relevant for tH)

E.Vryonidou

ttH in the EFT

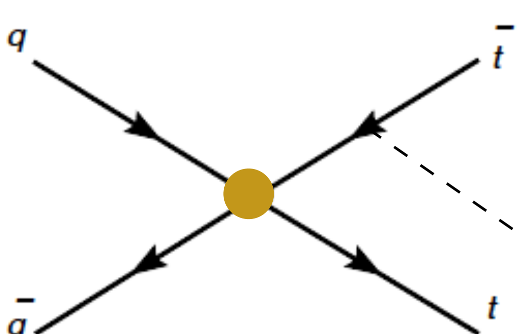


$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q} t)\, \tilde{\phi}$$

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

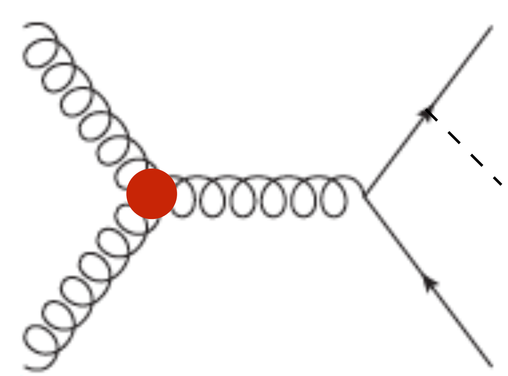
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

At NLO in QCD in this talk



4-fermion operators

Not in this talk, work in progress



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

Multijet constraints:
Krauss et al arXiv:1611.00767

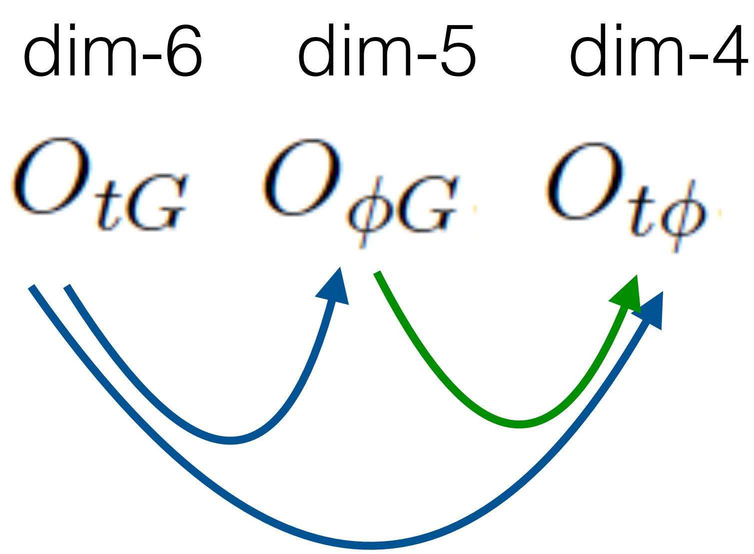
ttH@NLO

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

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

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

Jenkins et al. arXiv:1308.2627,1310.4838
Alonso et al arXiv:1312.2014



Higher-dimension operators mix into lower-dimension ones

Setup allows computation of:

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

interference with SM

interference between operators, squared contributions

E.Vryonidou

Cross-section results (1)

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

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

- 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
- Global approach needed to consistently extract information on coefficients within the SMEFT framework
- Differential information also important

Cross-section results (2)

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
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$\sigma_{\phi G,tG}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	1.37

First systematic study of uncertainties:

- 1) Scale and PDF uncertainties:

Similar to SM

- Reduced scale and PDF uncertainties in the ratio over the SM
- 2) EFT scale uncertainties

$$\sigma_i(\mu_0;\mu) = \Gamma_{ji}(\mu,\mu_0)\sigma_j(\mu)\,.$$

$$\sigma_{ij}(\mu_0;\mu) = \Gamma_{ki}(\mu,\mu_0)\Gamma_{lj}(\mu,\mu_0)\sigma_{kl}(\mu)$$

$$\Gamma_{ij}(\mu,\mu_0) = \exp\left(\frac{-2}{\beta_0}\log\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\gamma_{ij}\right)$$

Cross-sections evaluated at a different scale ($\mu_0/2$, $2\mu_0$) evolved back to μ_0 taking into account operator mixing and running

3) C/Λ^2 expansion

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{C_i^{\rm dim6}}{(\Lambda/1{\rm TeV})^2}\sigma_i^{\rm (dim6)} + \sum_{i<j}\frac{C_i^{\rm dim6}C_j^{\rm dim6}}{(\Lambda/1{\rm TeV})^4}\sigma_{ij}^{\rm (dim6)}$$

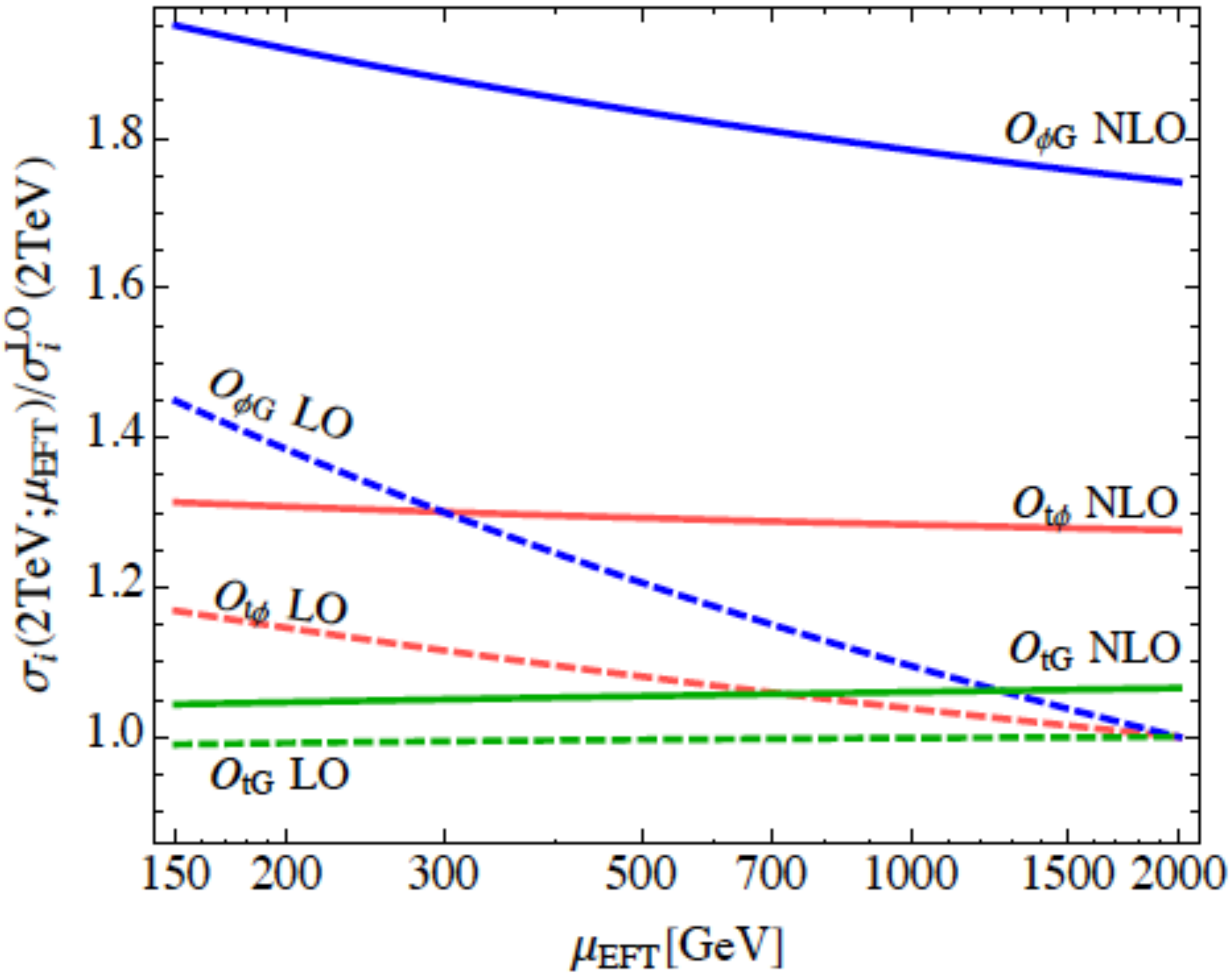
← Included

$$+ \sum_i \frac{C_i^{\rm dim8}}{(\Lambda/1{\rm TeV})^4}\sigma_i^{\rm (dim8)} + \mathcal{O}(\Lambda^{-6})\,.$$

← Needs dim-8 operators (Not included here)
But it can be estimated using a cut-off
Contino et al arXiv:1604.0644

E.Vryonidou

A study of RG effects



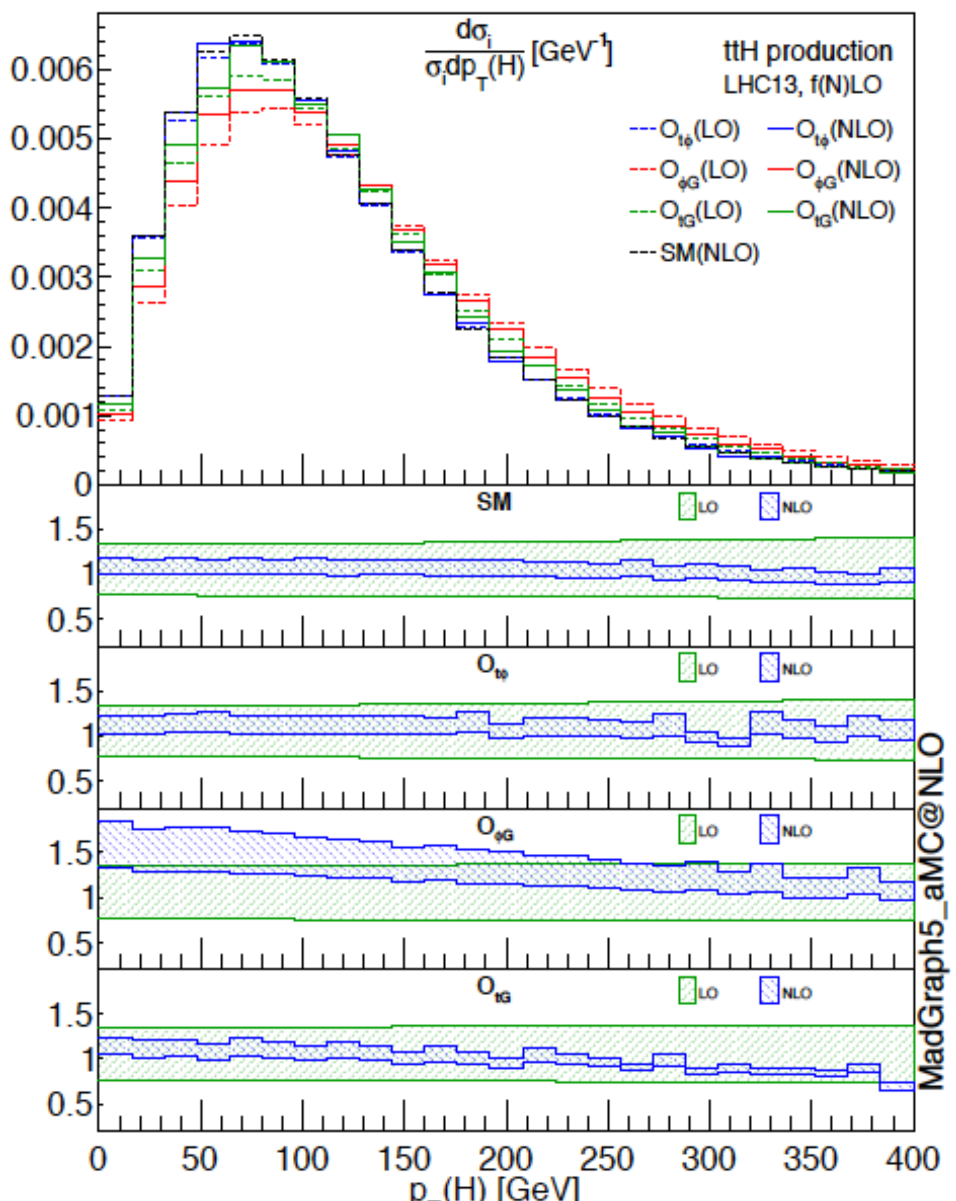
RG corrections not a good approximation to the NLO result, underestimate the NLO corrections

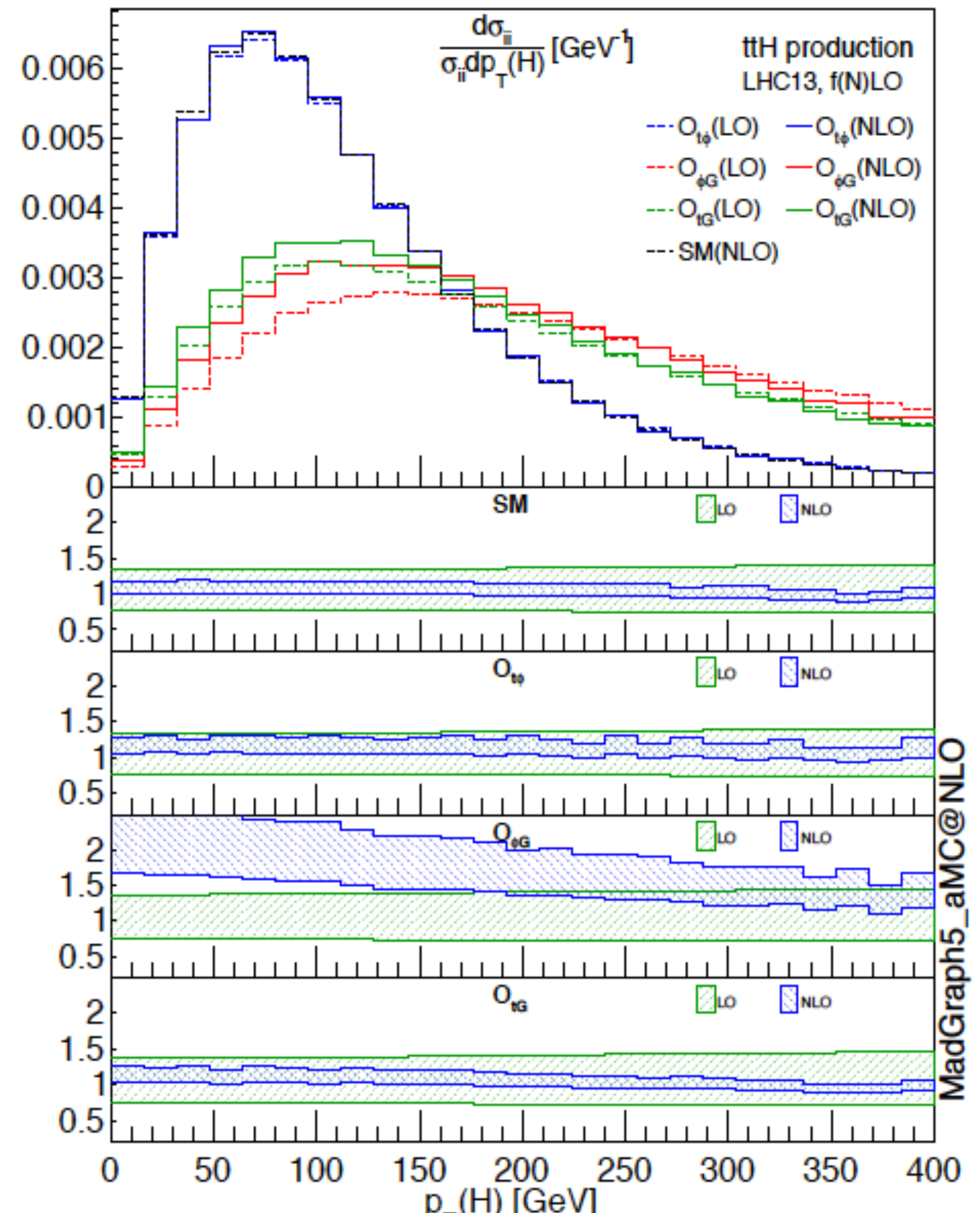
Milder EFT scale dependence at NLO, when mixing effects also taken into account

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

See also: Hartmann et al arXiv: 1505.02646,1611.09879

Differential distributions for ttH





NLO: smaller uncertainties, non-flat K-factors

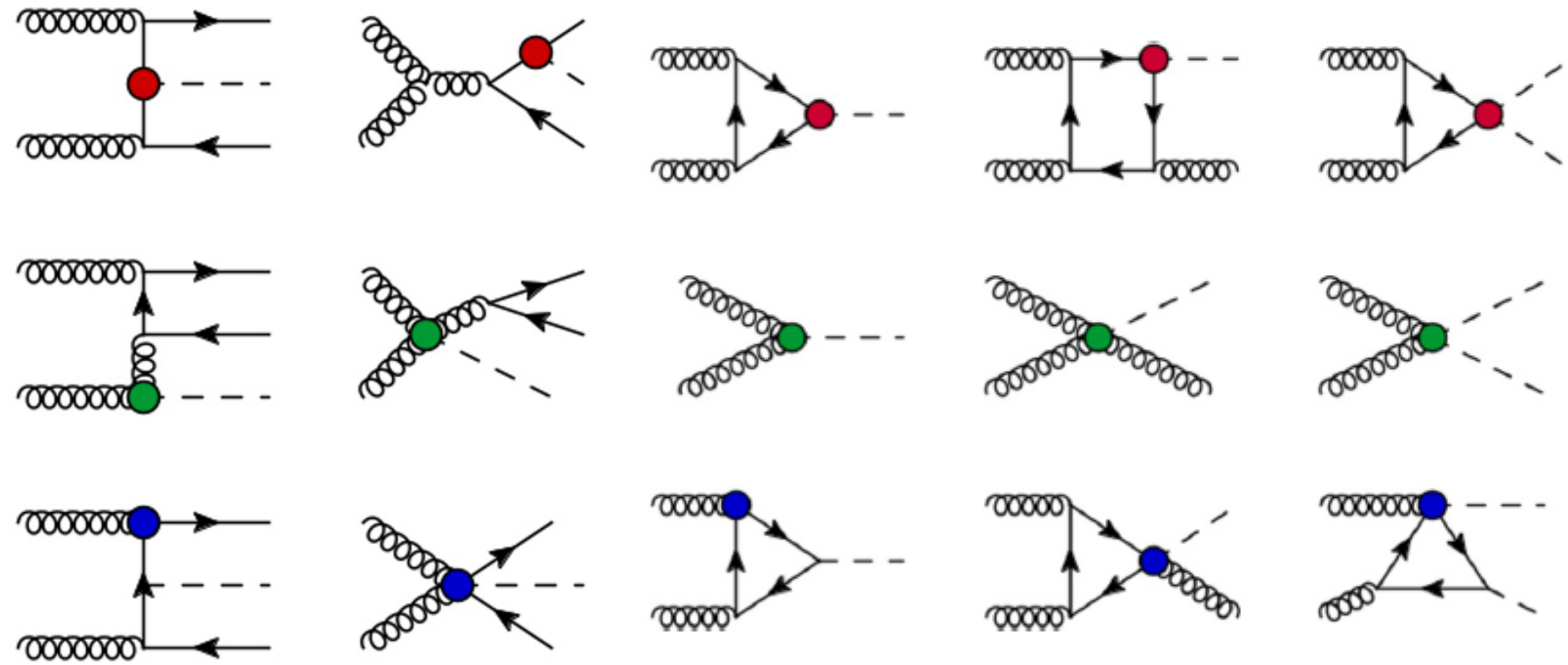
Different shapes for different operators for the squared terms

Maltoni, EV, Zhang arXiv:1607.05330

E.Vryonidou

Top and Higgs

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



ttH

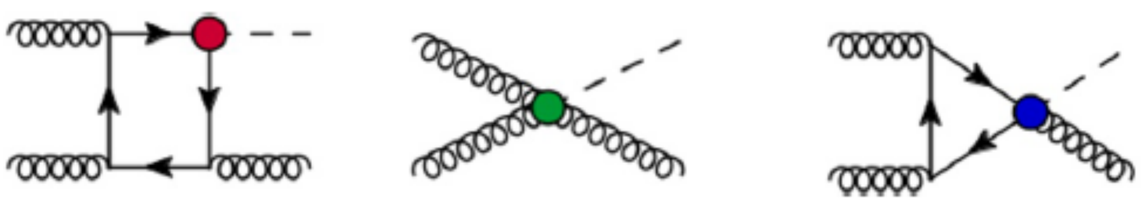
H, H+j, HH

See also
Degrande et al. arXiv:1205.1065
Grojean et al. arXiv:1312.3317
Azatov et al arXiv:1608.00977
Cirigliano et al arXiv: 1510.00725,1603.03049,1605.04311 (including CP-violation)

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

Maltoni, EV, Zhang: arXiv:1607.05330

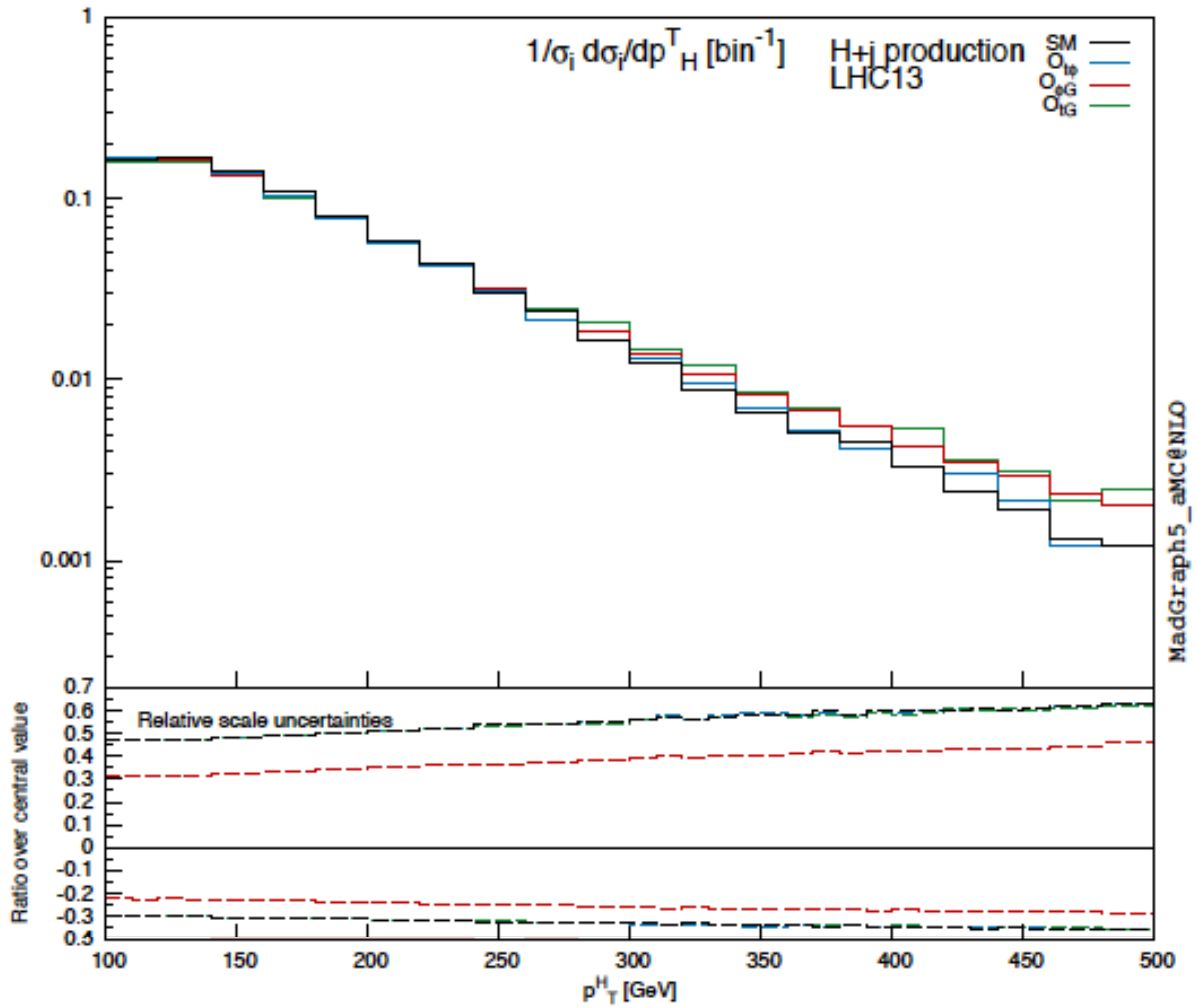
SMEFT in H+j

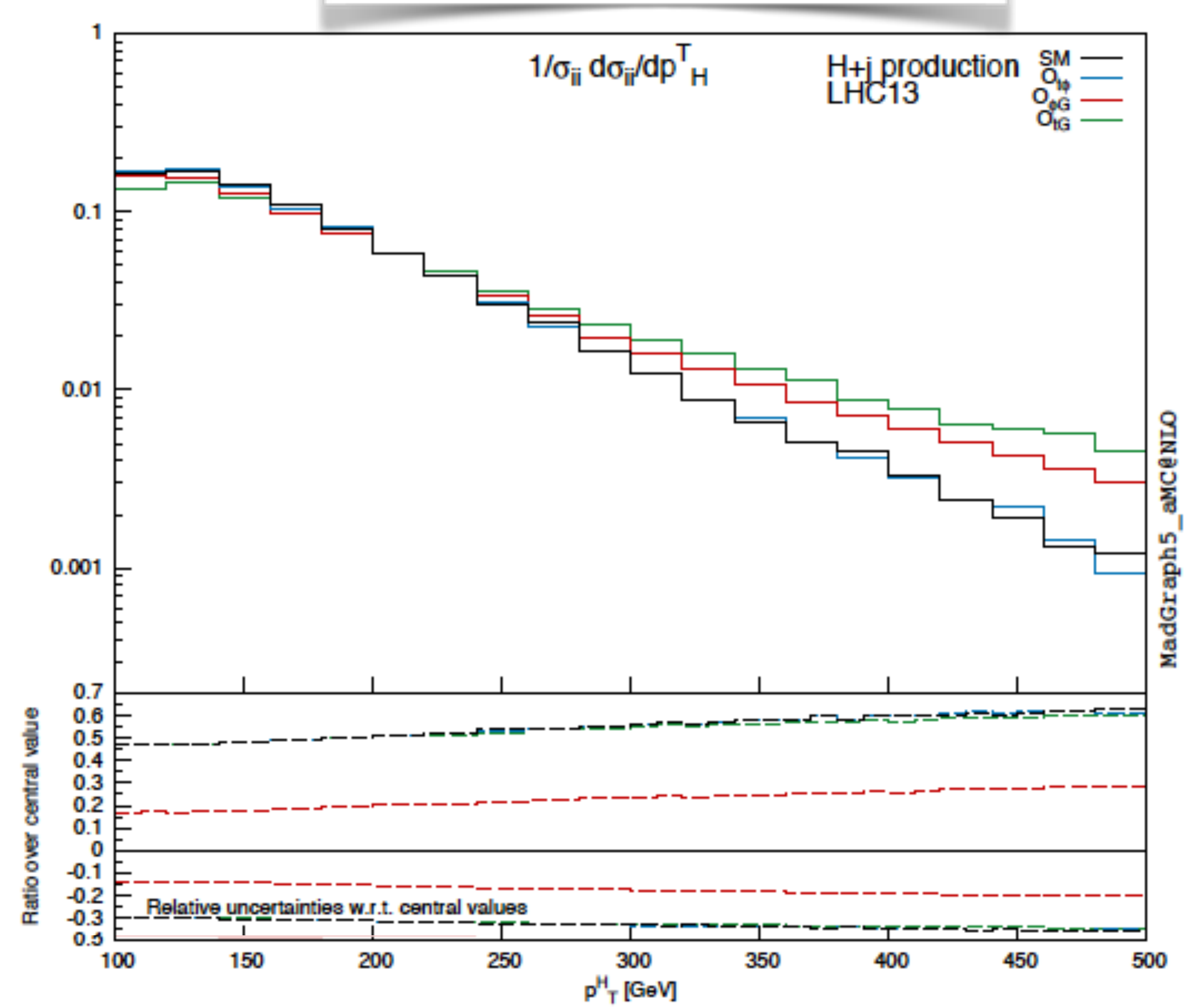


$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

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

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





Harder tails from dim-6 operators: Boosted analysis

Maltoni, EV, Zhang: arXiv:1607.05330

See also Grazzini et al arXiv:1612.00283
and Agnieszka's talk yesterday

E.Vryonidou

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 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]	

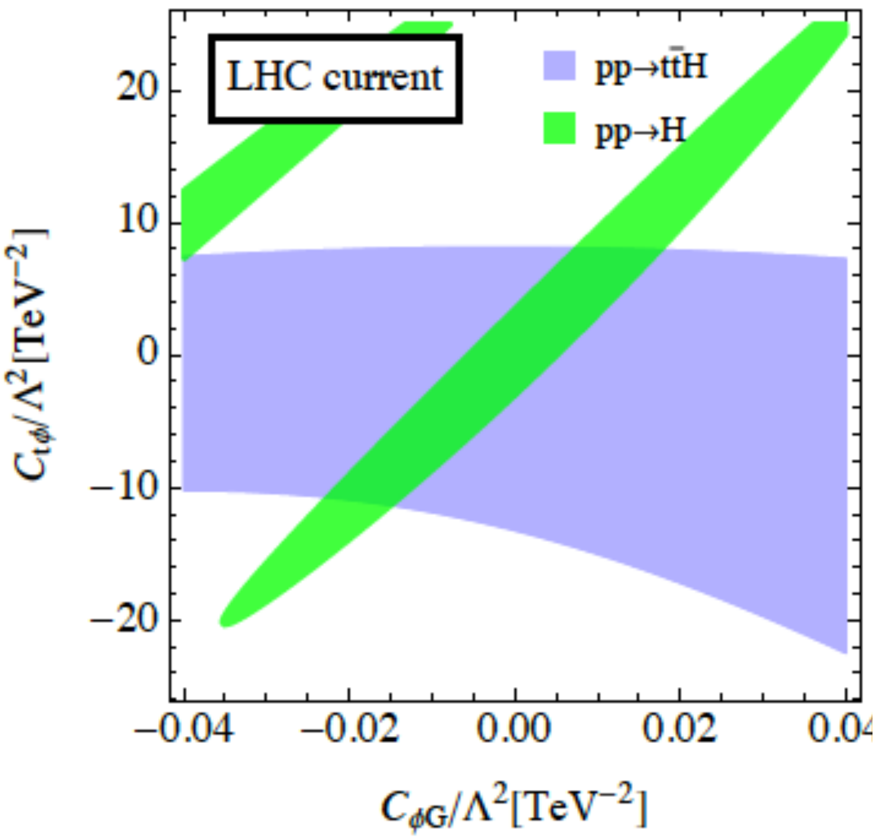
95% c.l.

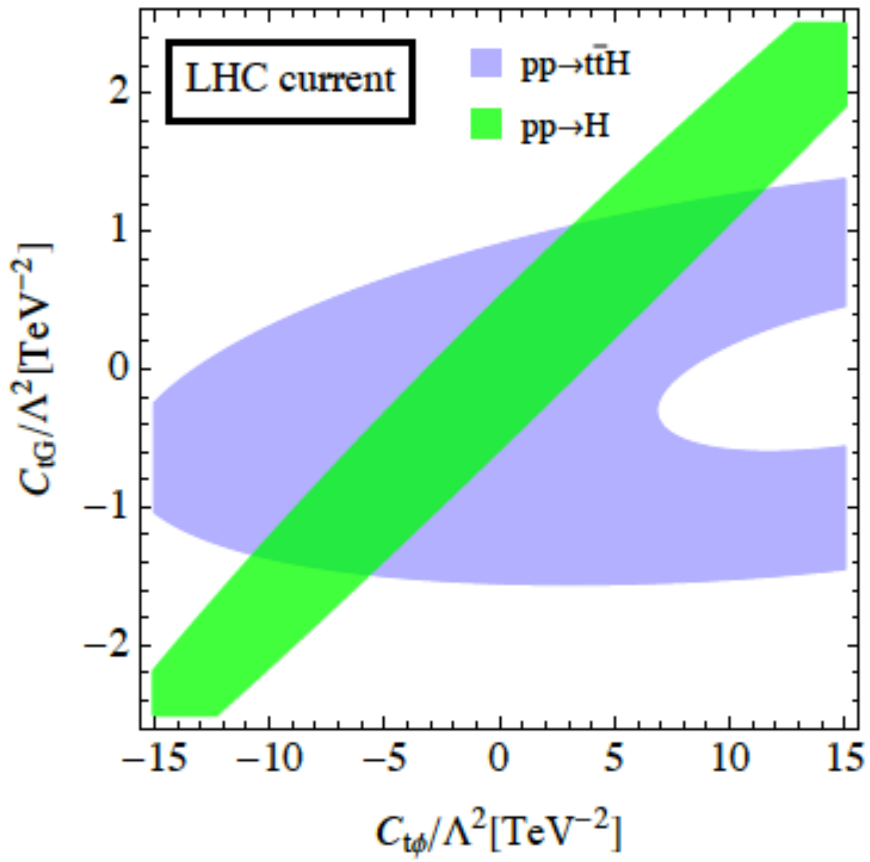
typically C_{tG}=0 in Higgs analyses

- 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

Constraints using two-operator fits



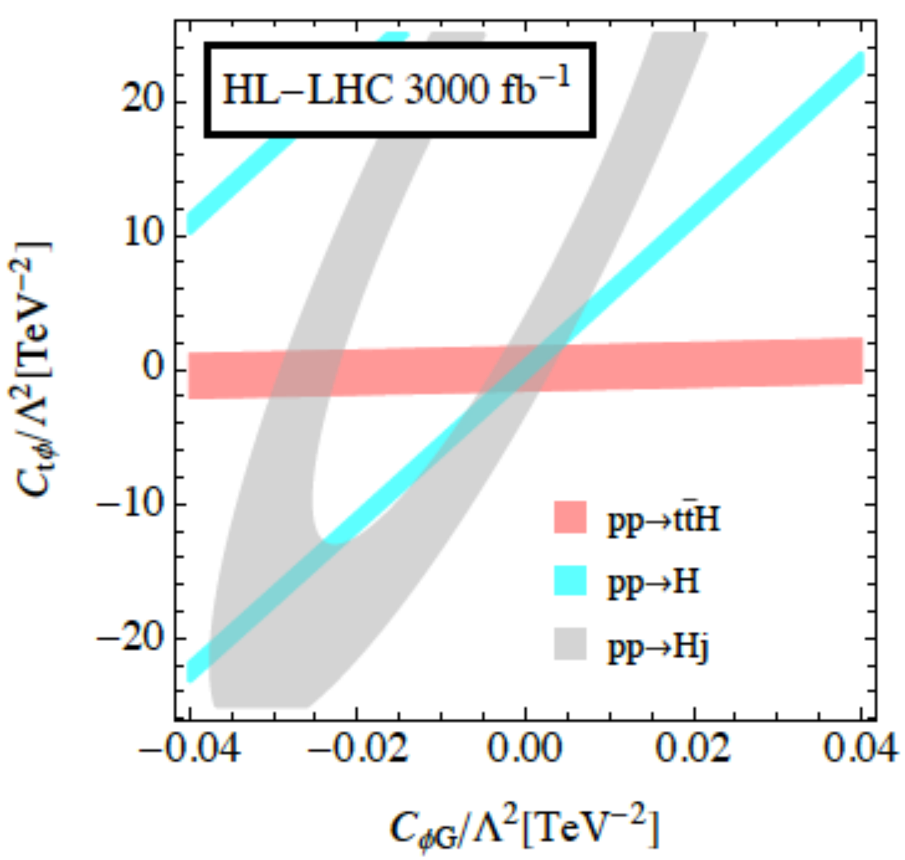


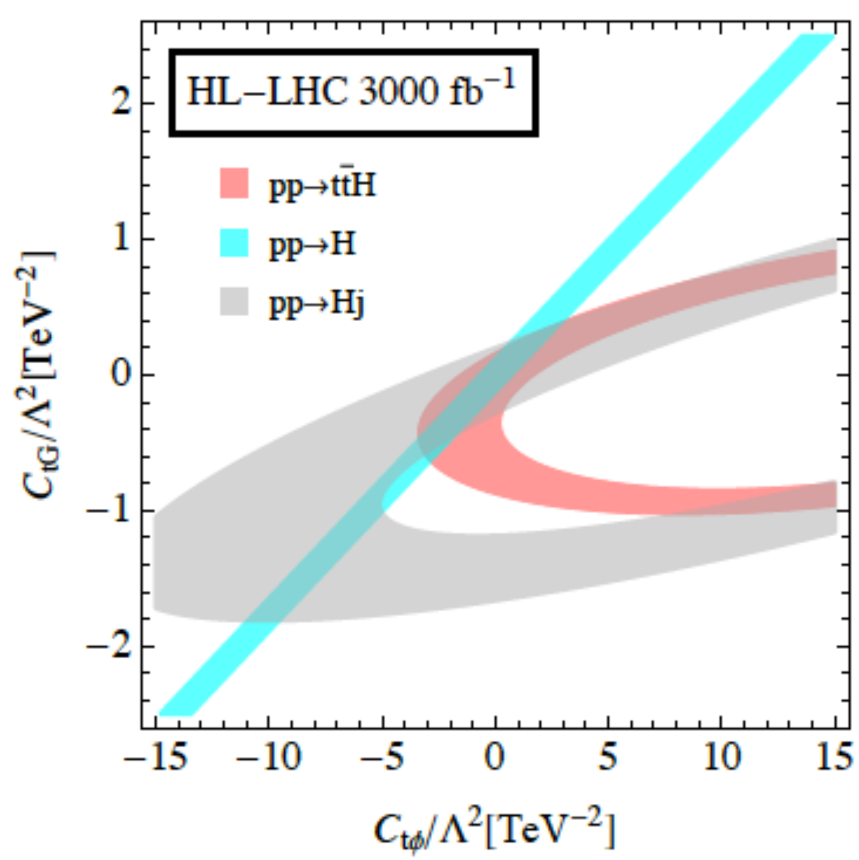
Current limits using LHC measurements

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

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

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

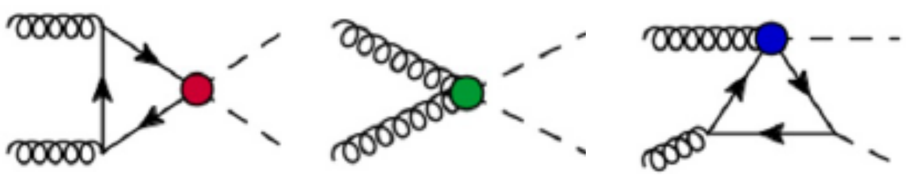




14TeV projection 3000 fb^{-1}

Maltoni, EV, Zhang
arXiv:1607.05330

SMEFT in HH

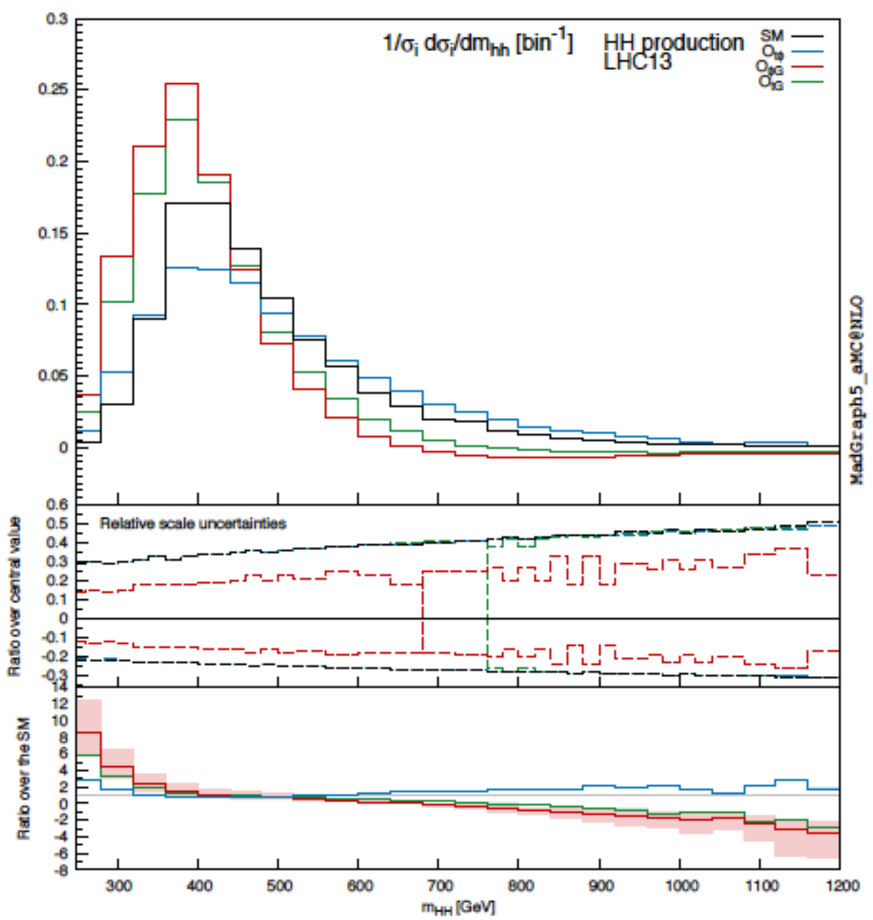


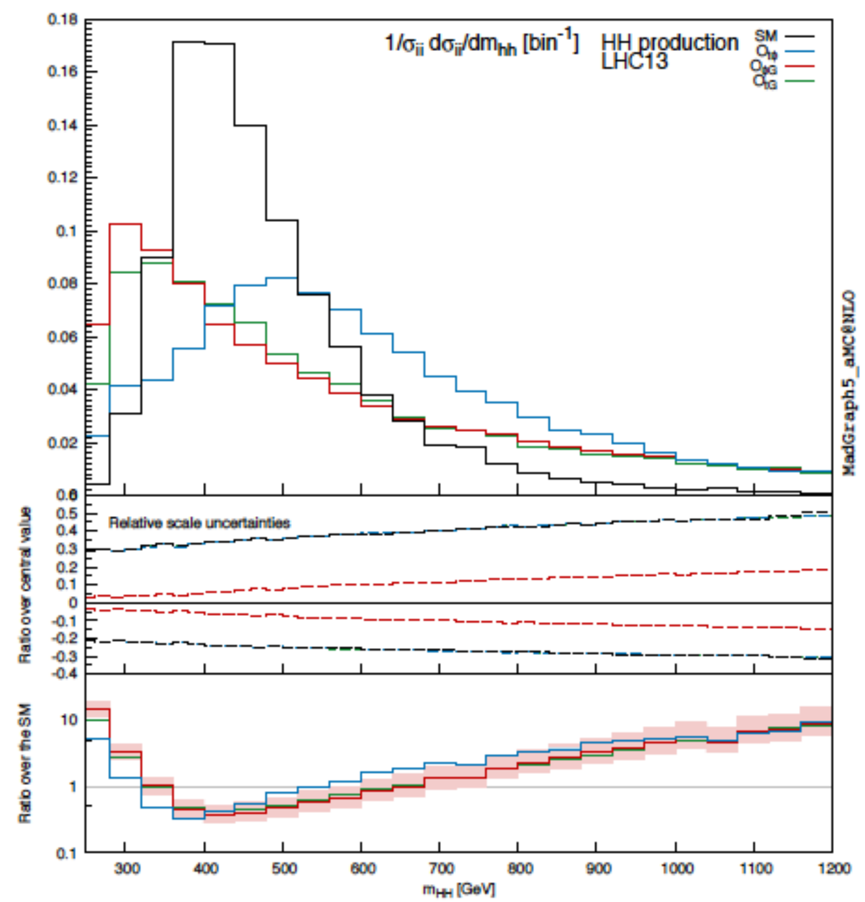
$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$

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

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

Chromomagnetic operator computed for the first time



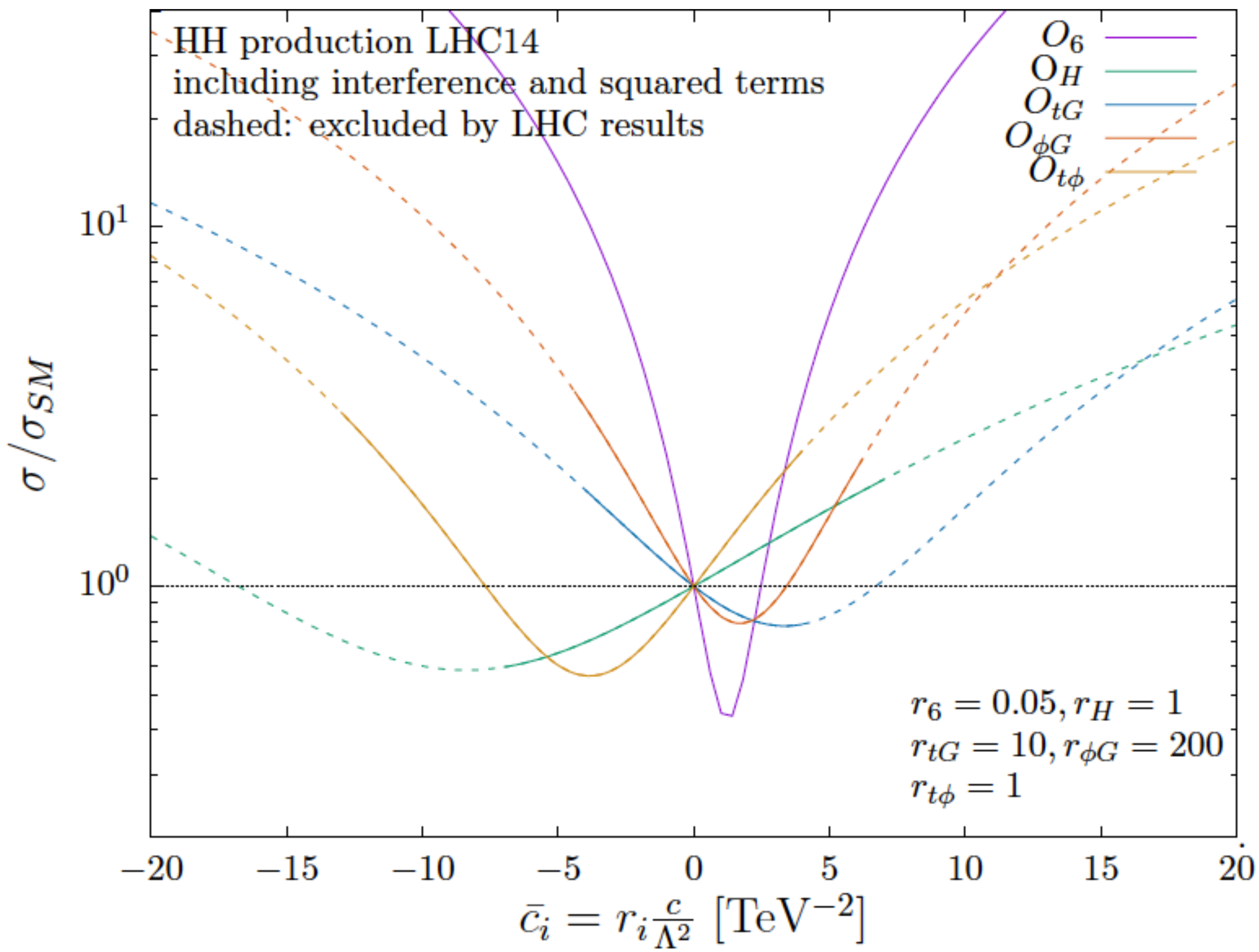


13 TeV	σ/σ_{SM} LO
σ_{SM}	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.227^{+0.00114+0.0116}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
σ_{tG}	$-1.356^{+0.0271+0.161}_{-0.0225-0.051}$
$\sigma_{t\phi,t\phi}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi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

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)

E.Vryonidou

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



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

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

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

$$O_6 = -\lambda(\phi^\dagger \phi)^3$$

$$\kappa_\lambda = 1 - c_H \frac{3v^2}{2\Lambda^2} + c_6 \frac{v^2}{\Lambda^2}$$

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

5 parameters

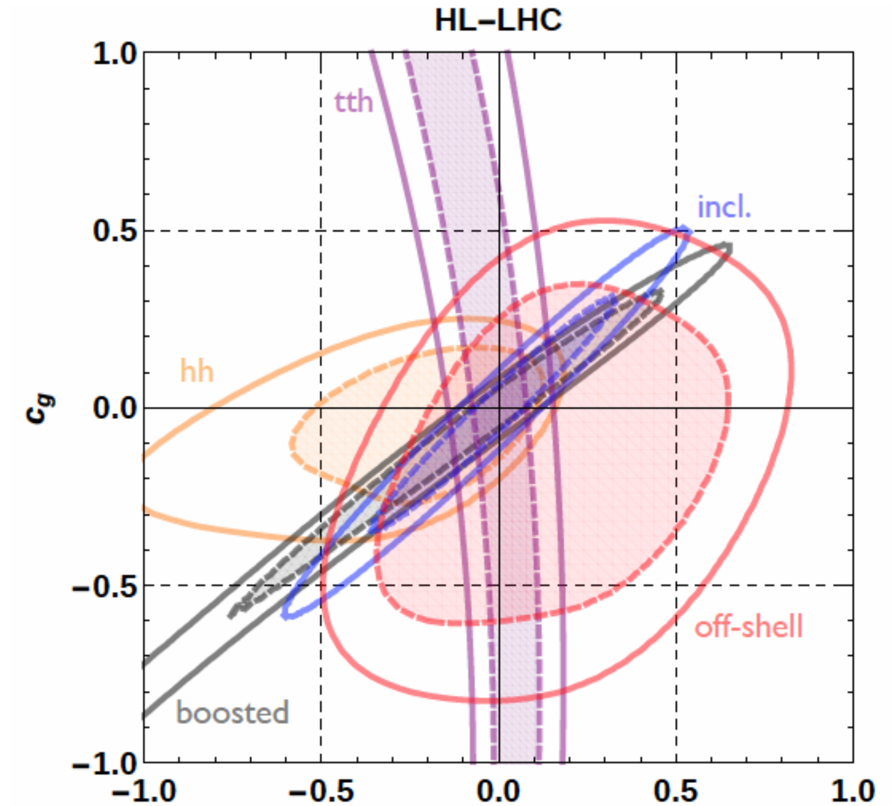
- Very mild dependence on c_6
- Precise knowledge of other Wilson coefficients needed to bound c_6
- Differential distributions will also be necessary

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

How to extract maximal information?

Go Global:

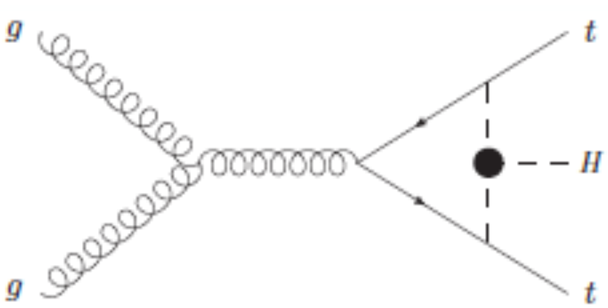
- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs

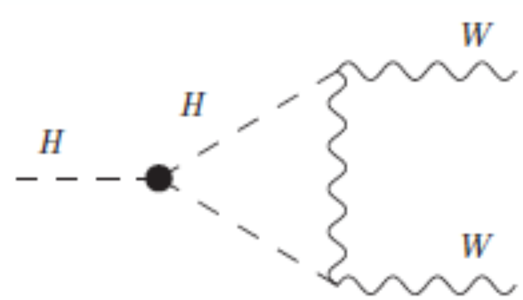


$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

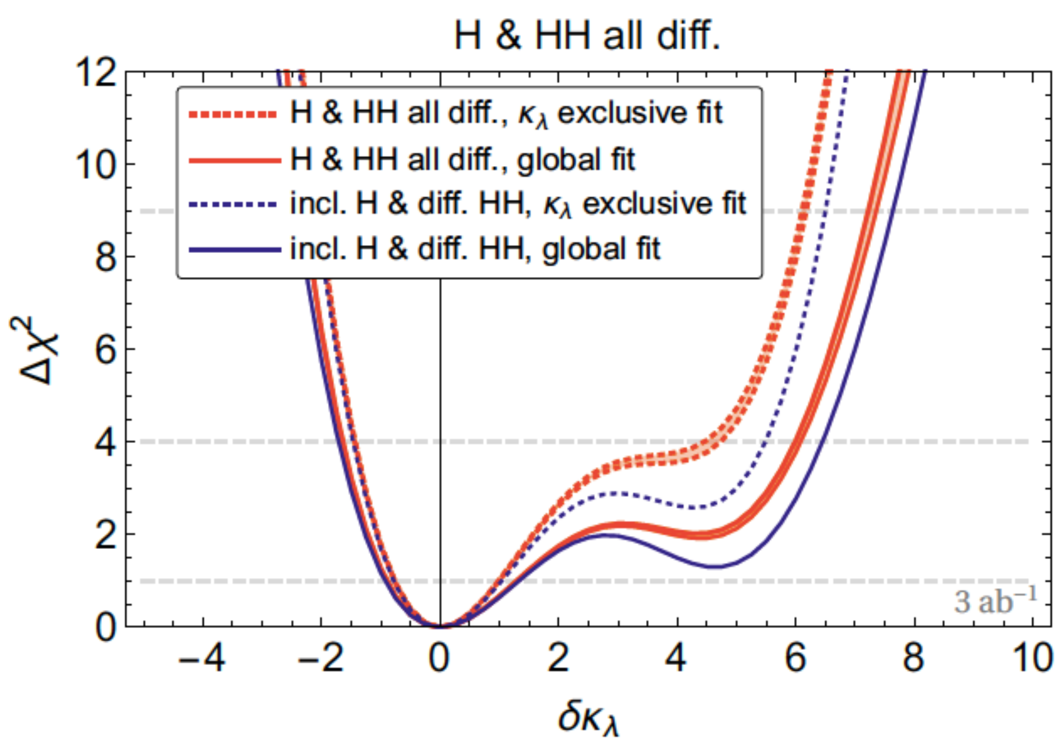
Azatov et al arXiv:1608.00977

Go beyond LO:





Gorbahn and Haisch 1607.03773
Degrassi et al 1607.04251



E.Vryonidou
see Martin's and Stefano's talks
Di Vita et al 1704.01953

Conclusions

- 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