Top + Electroweak bosons + Higgs

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Olomouc
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Why top+V/H?

- $t(\bar{t})V$: Direct probe of top couplings to the EW gauge bosons
- $t(\bar{t})H$: Probe of top Yukawa coupling
- tops+V(s): Important as a signal as well as a background for BSM scenarios with high multiplicity signatures
- $t\bar{t}V(V)$: main background for $t\bar{t}H$ searches
- High threshold processes: important for LHC13
- Experimental results are being collected: see following ATLAS and CMS talks
- Precision needed:
  - EW+QCD corrections
  - New physics?

Outline

- Overview of tops+V/H in the SM
  - higher order predictions
- Tops+V/H in the SMEFT
  - probe top couplings using precise predictions

Status of precision studies

tH QCD: NLO+PS MG5_aMC@NLO: Demartin et al. arXiv:1504.00611	tZ QCD: NLO+PS MG5_aMC@NLO:arXiv:1405.0301 MCFM: arXiv:1302.3856	tWH QCD: NLO+PS MG5_aMC@NLO: Demartin et al arXiv:1607.05862
$t\bar{t}H$ QCD: NLO+PS aMC@NLO: arXiv:1104.5613 PowHel: arXiv:1108.0387 Powheg Box: arXiv:1501.04498 Soft gluon resummation-beyond NLO: Kulesza et al. arXiv:1509.02780 Broggio et al. arXiv:1510.01914 Off-shell: Denner et al. arXiv:1506.07448 NLO EW: Frixione et al. arXiv:1407.0823 & arXiv:1504.03446 Zhang et al. arXiv:1407.1110	$t\bar{t}Z/W$ QCD: NLO+PS aMC@NLO: arXiv:1103.0621 PowHel: arXiv:1111.1444, 1208.2665 Soft gluon resummation for ttW: Broggio et al. arXiv:1607.05303 NLO EW: Frixione et al. arXiv:1504.03446	$t\bar{t}ZZ$, $t\bar{t}WW$, $t\bar{t}WZ$ $t\bar{t}Z\gamma$, $t\bar{t}W\gamma$ QCD: NLO+PS MG5_aMC@NLO: Maltoni et al. arXiv:1507.05640
	$t\bar{t}\gamma$ QCD: NLO+PS aMC@NLO: arXiv:1103.0621 PowHel: arXiv:1406.2324	$t\bar{t}\gamma\gamma$ NLO+PS PowHel: Kardos et al. arXiv: 1408.0278 aMC@NLO: Maltoni et al. arXiv: 1507.05640 van Deurzen et al. arXiv: 1509.02077

Precision for tops+V(V)/H

QCD corrections

Mature field: NLO QCD available for all processes
NLO+PS using automated tools such as:
MG5_aMC, PowHel, Powheg Box
Detailed phenomenological investigation $t\bar{t}V/t\bar{t}VV$:
Maltoni, Pagani, Tsinikos arXiv:1507.05640

EW corrections: Recent progress

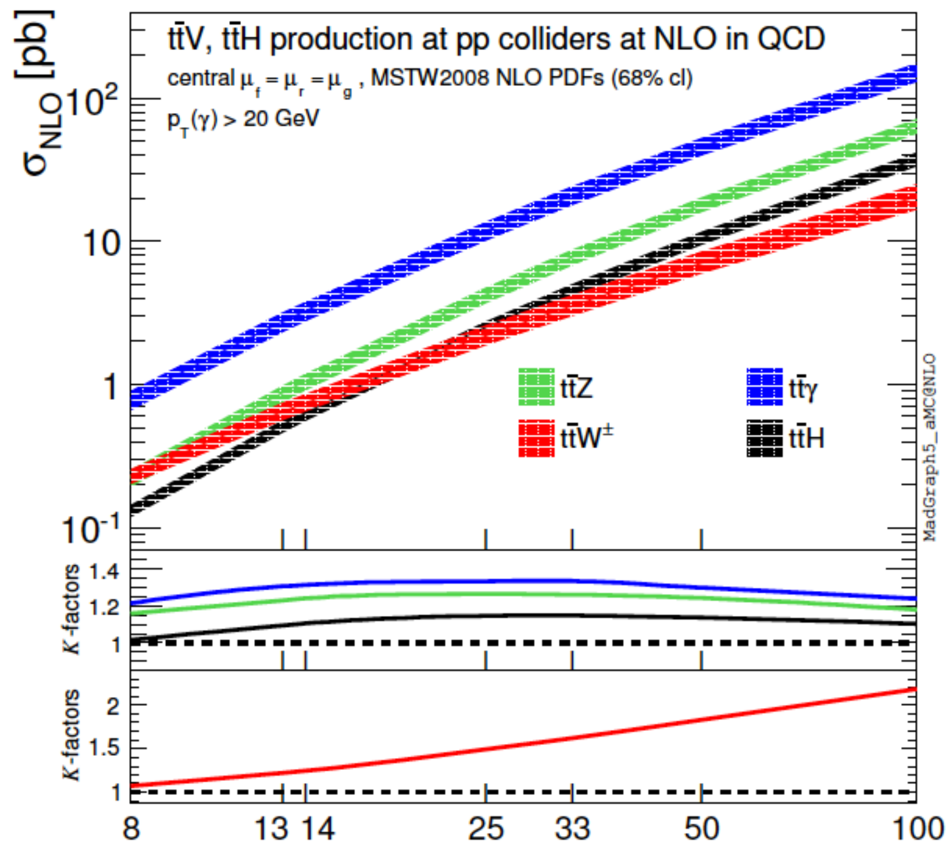
- $t\bar{t}V/H$
  - Frixione et al arXiv:1407.0823, arXiv:1504.03446
  - Zhang et al arXiv:1407.1110

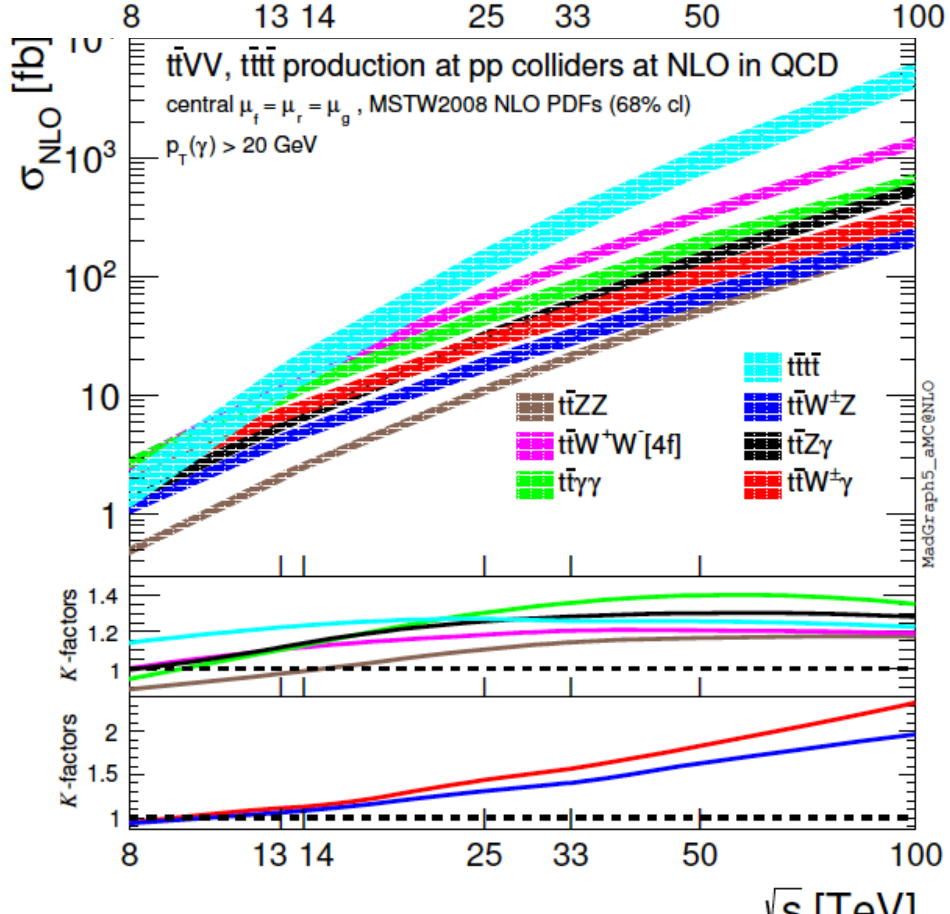
Towards the automation of EW corrections

Features of NLO QCD corrections(1)

13 TeV σ[fb]	$t\bar{t}H$	$t\bar{t}Z$
NLO	$522.2^{+6.0\%}_{-9.4\%}\ ^{+2.1\%}_{-2.6\%}$	$873.6^{+10.3\%}_{-11.7\%}\ ^{+2.0\%}_{-2.5\%}$
LO	$476.6^{+35.5\%}_{-24.2\%}\ ^{+2.0\%}_{-2.1\%}$	$710.3^{+36.1\%}_{-24.5\%}\ ^{+2.0\%}_{-2.1\%}$
K-factor	1.10	1.23
13 TeV σ[fb]	$t\bar{t}W^{\pm}$	$t\bar{t}\gamma$
NLO	$644.8^{+13.0\%}_{-11.6\%}\ ^{+1.7\%}_{-1.3\%}$	$2746^{+14.2\%}_{-13.5\%}\ ^{+1.6\%}_{-1.9\%}$
LO	$526.9^{+28.1\%}_{-20.4\%}\ ^{+1.7\%}_{-1.8\%}$	$2100^{+36.2\%}_{-24.5\%}\ ^{+1.8\%}_{-1.9\%}$
K-factor	1.22	1.31

$t\bar{t}ZZ$	$t\bar{t}W^+W^-$[4f]	$t\bar{t}\gamma\gamma$
$2.117^{+3.8\%}_{-8.6\%}\ ^{+1.9\%}_{-1.8\%}$	$11.84^{+8.3\%}_{-11.2\%}\ ^{+2.3\%}_{-2.4\%}$	$10.26^{+13.9\%}_{-13.3\%}\ ^{+1.3\%}_{-1.3\%}$
$2.137^{+36.1\%}_{-24.4\%}\ ^{+1.9\%}_{-1.9\%}$	$10.78^{+38.3\%}_{-25.4\%}\ ^{+2.2\%}_{-2.2\%}$	$8.838^{+36.5\%}_{-24.5\%}\ ^{+1.5\%}_{-1.6\%}$
0.99	1.10	1.16
$t\bar{t}W^{\pm}Z$	$t\bar{t}Z\gamma$	$t\bar{t}W^{\pm}\gamma$
$4.157^{+9.8\%}_{-10.7\%}\ ^{+2.2\%}_{-1.6\%}$	$5.771^{+10.5\%}_{-12.1\%}\ ^{+1.8\%}_{-1.9\%}$	$6.734^{+12.0\%}_{-11.6\%}\ ^{+1.8\%}_{-1.4\%}$
$3.921^{+32.6\%}_{-22.8\%}\ ^{+2.3\%}_{-2.2\%}$	$5.080^{+38.0\%}_{-25.3\%}\ ^{+1.9\%}_{-1.9\%}$	$6.145^{+32.4\%}_{-22.6\%}\ ^{+2.1\%}_{-2.0\%}$
1.06	1.14	1.10





Maltoni, Pagani, Tsinikos arXiv:1507.05640

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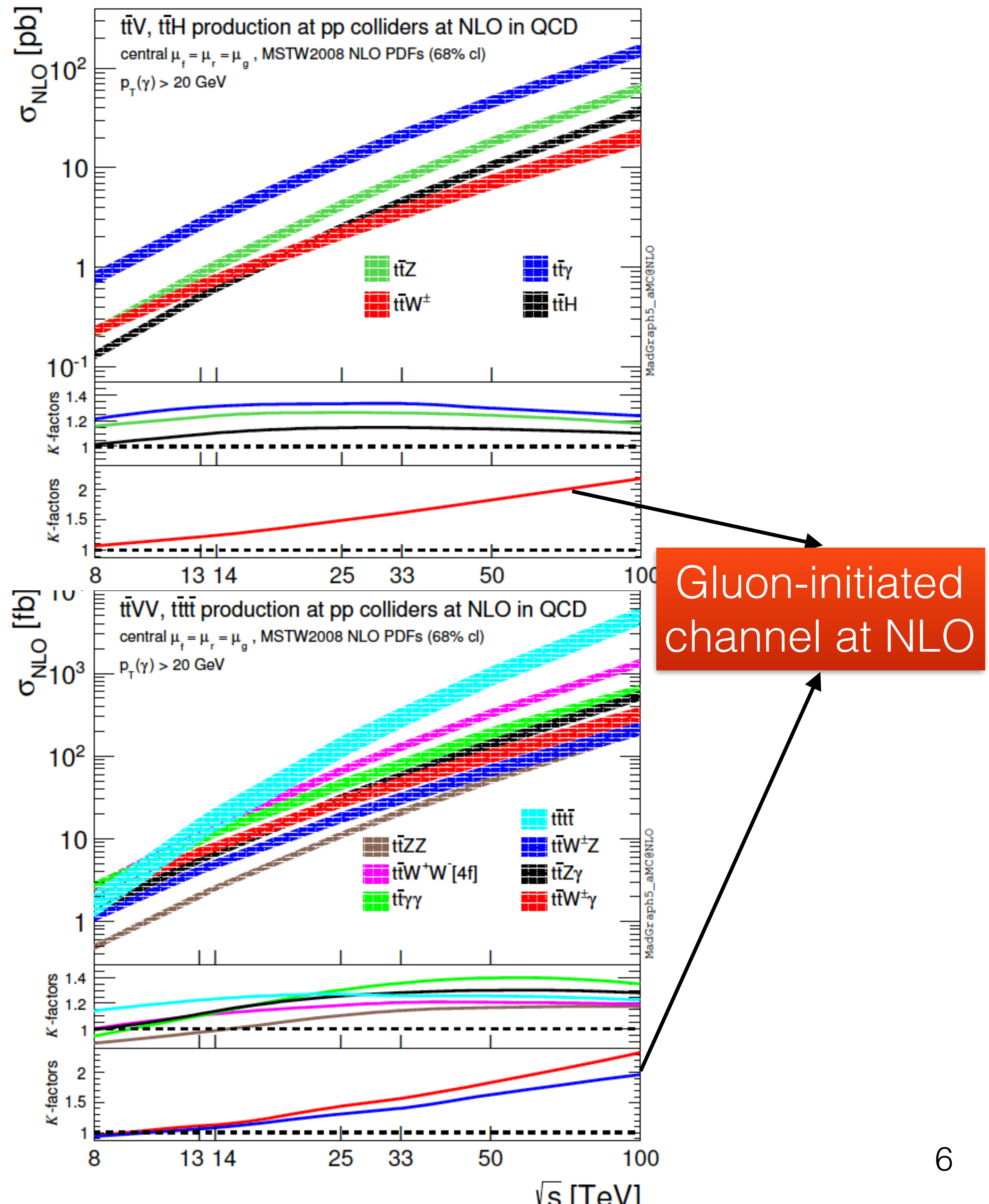
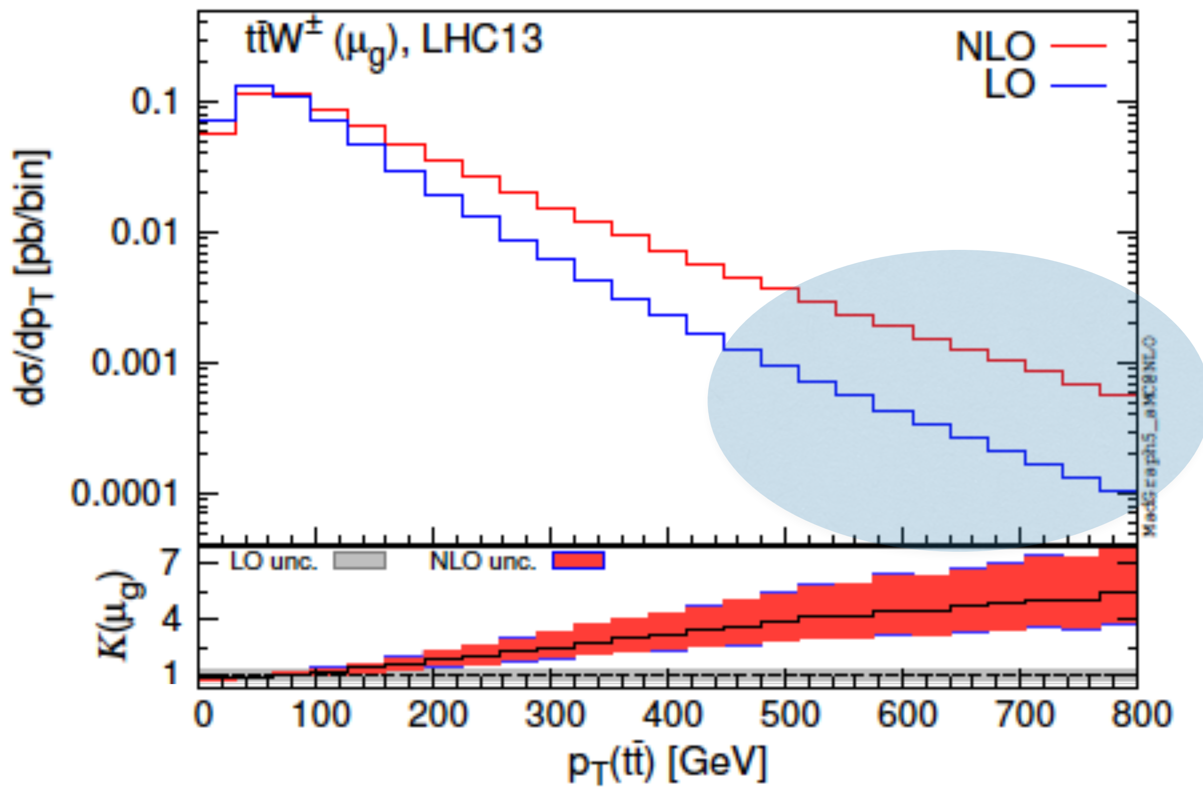
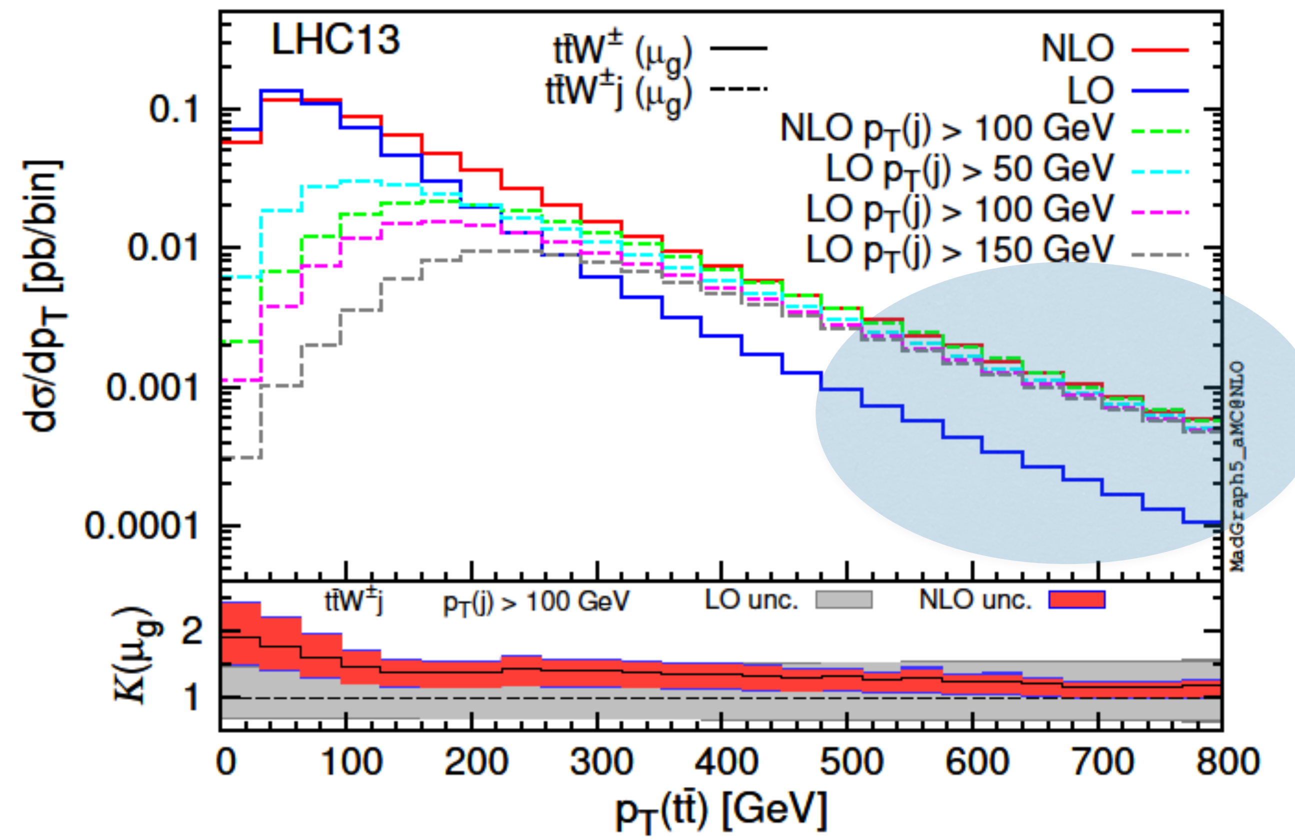
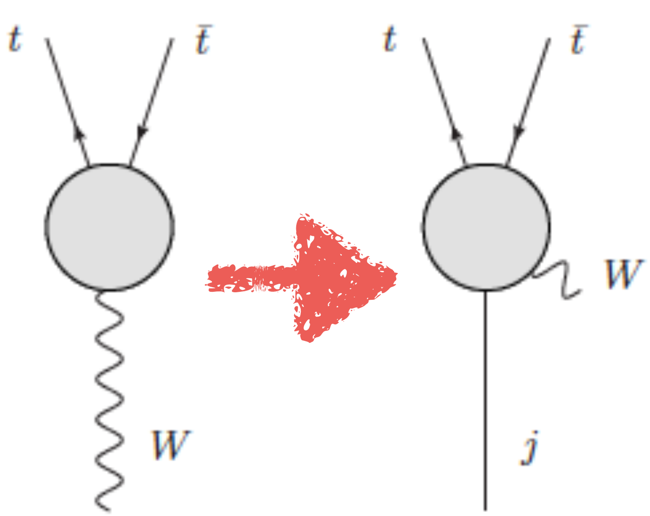


Features of NLO QCD corrections(2)





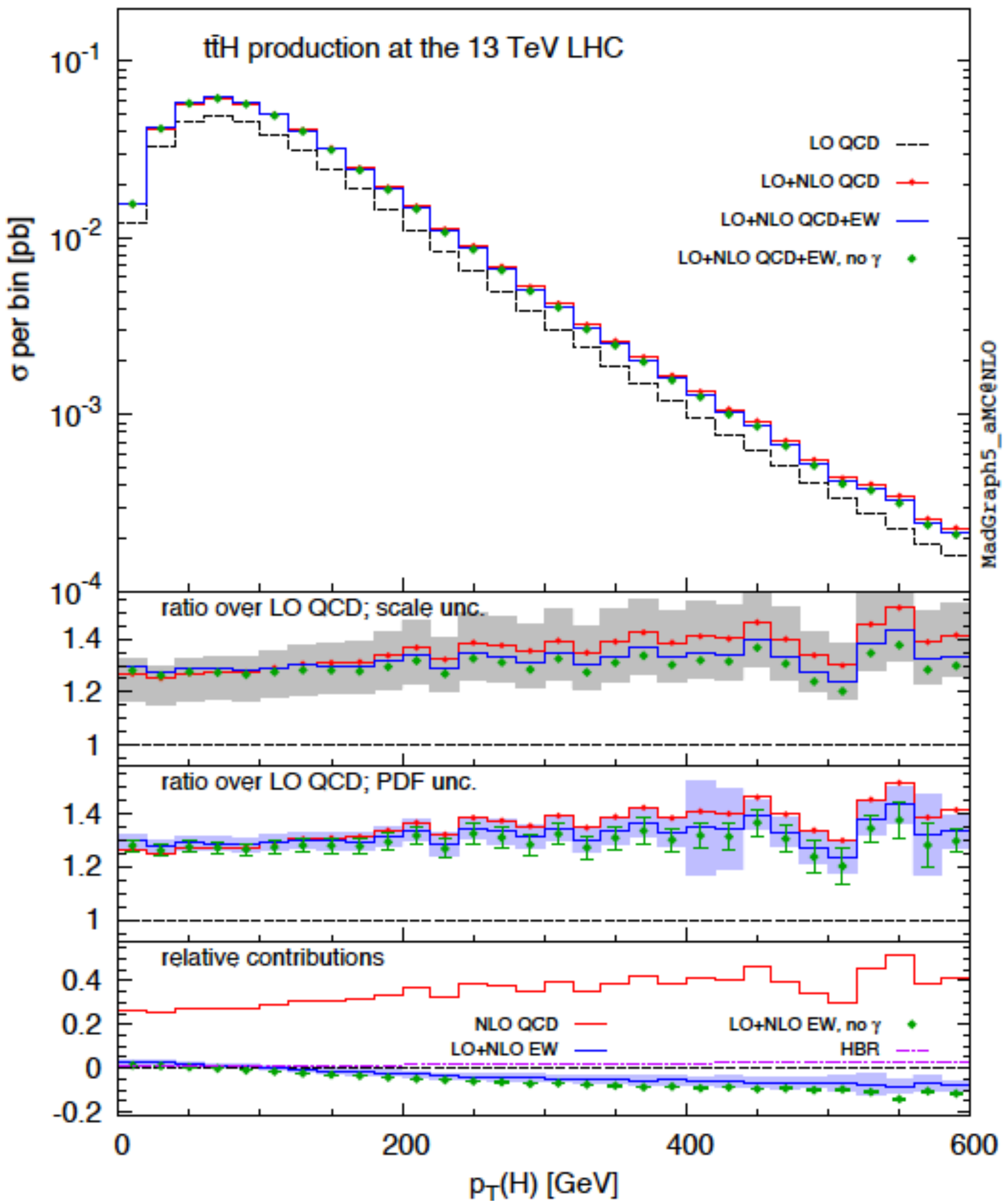


giant k-factors

Impact of extra jet independent of jet pT cut
Higher-order corrections (ttVj at NLO) not changing the results

Maltoni, Pagani, Tsinikos arXiv:1507.05640

Features of NLO EW corrections



Frixione et al arXiv:1504.03446

$t\bar{t}H$: $\delta(\%)$	8 TeV	13 TeV	
NLO QCD	$25.9^{+5.4}_{-11.1} \pm 3.5$	$29.7^{+6.8}_{-11.1} \pm 2.8$	$(24.2^{+4.8}_{-10.6} \pm 4.5)$
LO EW	1.8 ± 1.3	1.2 ± 0.9	(2.8 ± 2.0)
LO EW no γ	-0.3 ± 0.0	-0.4 ± 0.0	(-0.2 ± 0.0)
NLO EW	-0.6 ± 0.1	-1.2 ± 0.1	(-8.2 ± 0.3)
NLO EW no γ	-0.7 ± 0.0	-1.4 ± 0.0	(-8.5 ± 0.2)
HBR	0.88	0.89	(1.87)

- Small corrections at the total cross-section level
- Important and negative for high p_T tails
- Vector boson radiation only partially cancelling Sudakov logs
- Similar conclusions for $t\bar{t}W$ and $t\bar{t}Z$

What's next?

SM: precision for t(t)+V(V)/H
QCD corrections
Progress in EW
Needed to realistically describe the distributions

Precision calculations
Automated tools

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Top(s)+V(V)/H as a probe of new physics

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Use SMEFT to parametrise and look for deviations from SM predictions

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Need for precision also in SMEFT

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Top(s)+V(V)/H as a probe of new physics

Use SMEFT to parametrise and look for deviations from SM predictions

Need for precision also in SMEFT

New physics in ttV/ttH?

- BSM?
  - New particles (see talks tomorrow)
  - New Interactions of SM particles

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

- 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	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

SMEFT for top quark physics

SMEFT vs Anomalous couplings

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

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

dictionary

$$C^Z_{1,V} = \frac{1}{2}\left(C^{(3)}_{\varphi Q}-C^{(1)}_{\varphi Q}-C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W}$$
$$C^Z_{1,A} = \frac{1}{2}\left(-C^{(3)}_{\varphi Q}+C^{(1)}_{\varphi Q}-C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W}$$
$$C^Z_{2,V} = \left(C_{tW}c_W^2 - C_{tB}s_W^2\right)\frac{2m_t m_Z}{\Lambda^2 s_W c_W}$$

- SMEFT:
  - Gauge invariant ✔
  - Higher-order corrections: renormalisable order by order in 1/Λ ✔

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

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

Top-quark operators and how to look for them

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

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

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

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

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

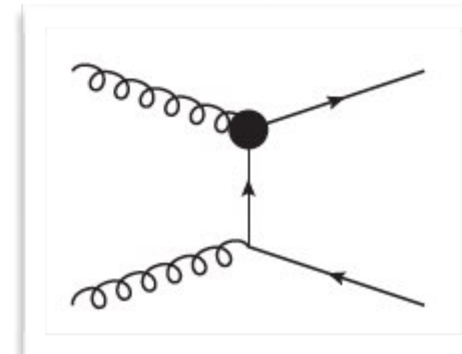
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

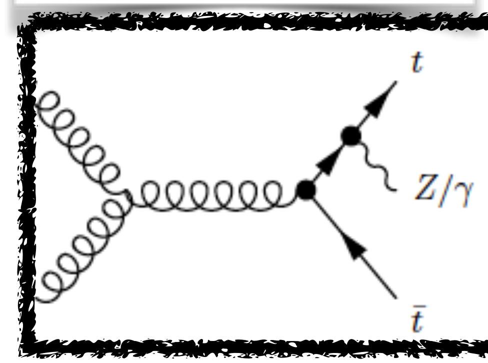
$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$

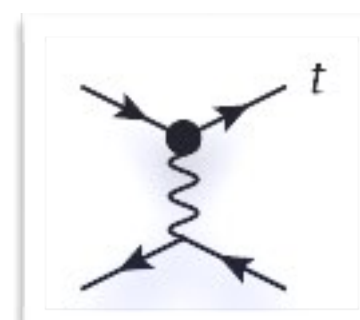
see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

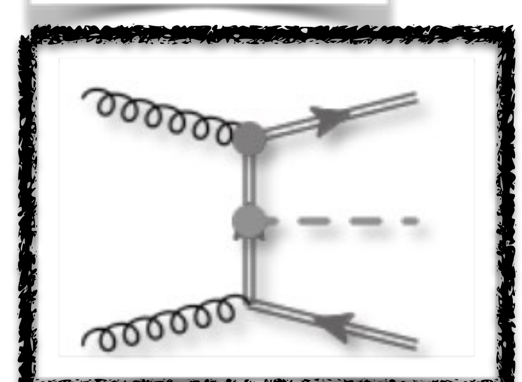
+four-fermion operators

+FCNC (see talk by G. Durieux)









Top-quark operators and how to look for them

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

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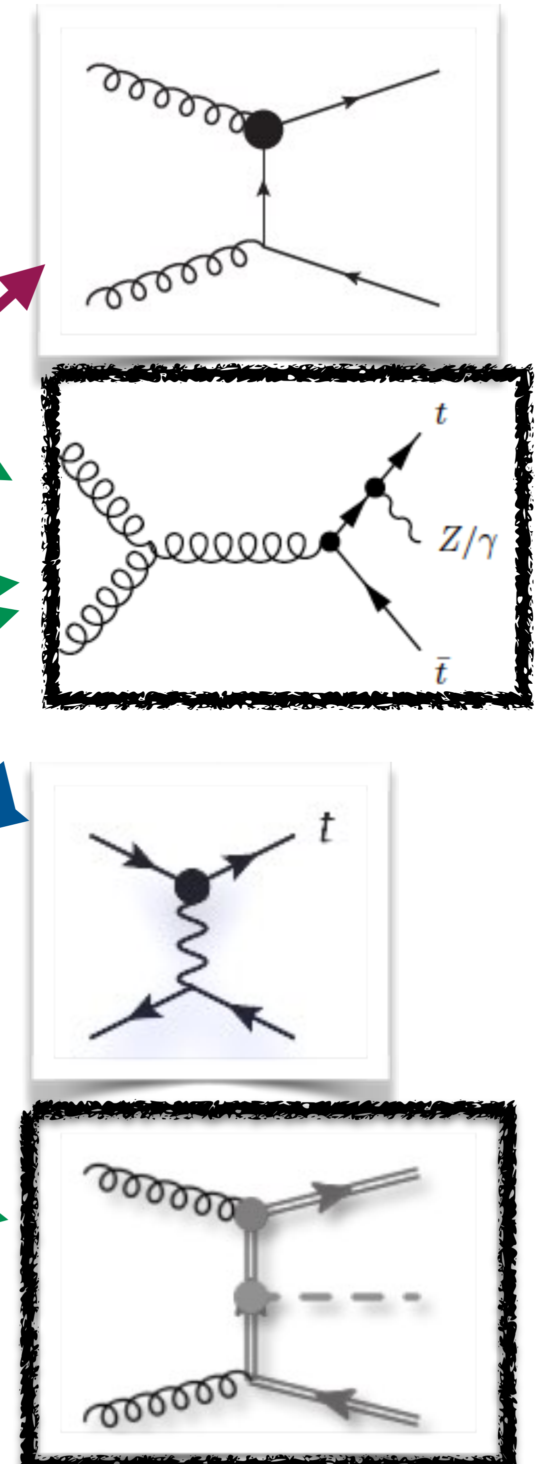

see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

+FCNC (see talk by G. Durieux)

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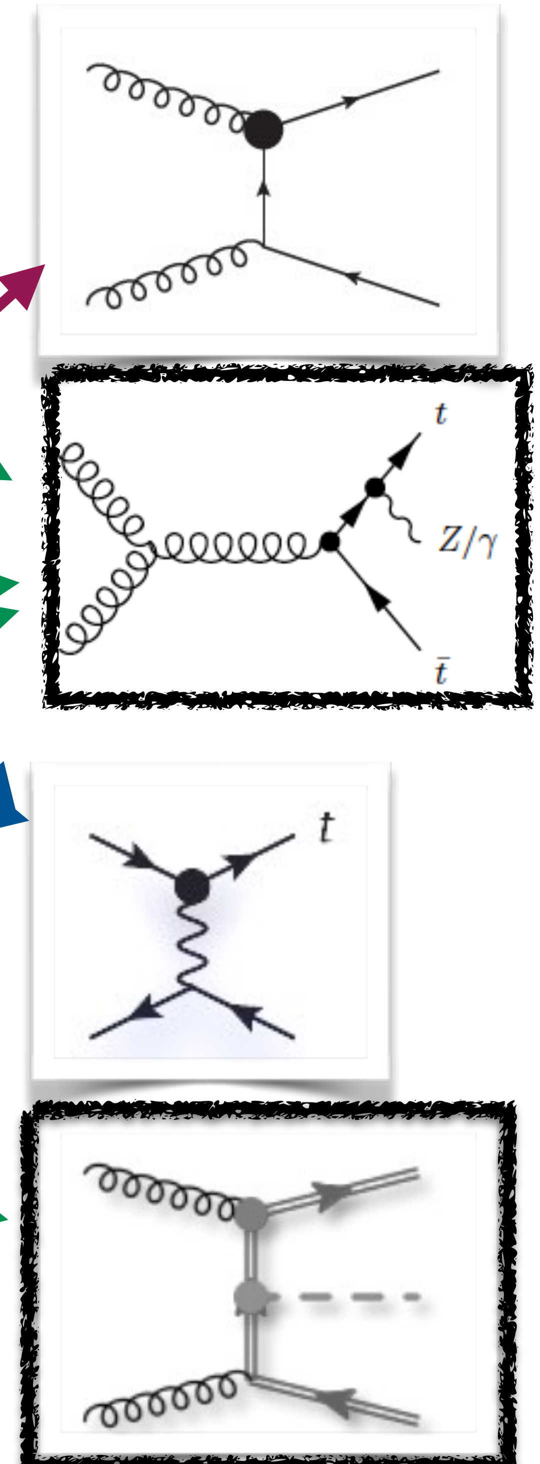

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Operators entering various processes: Global approach needed

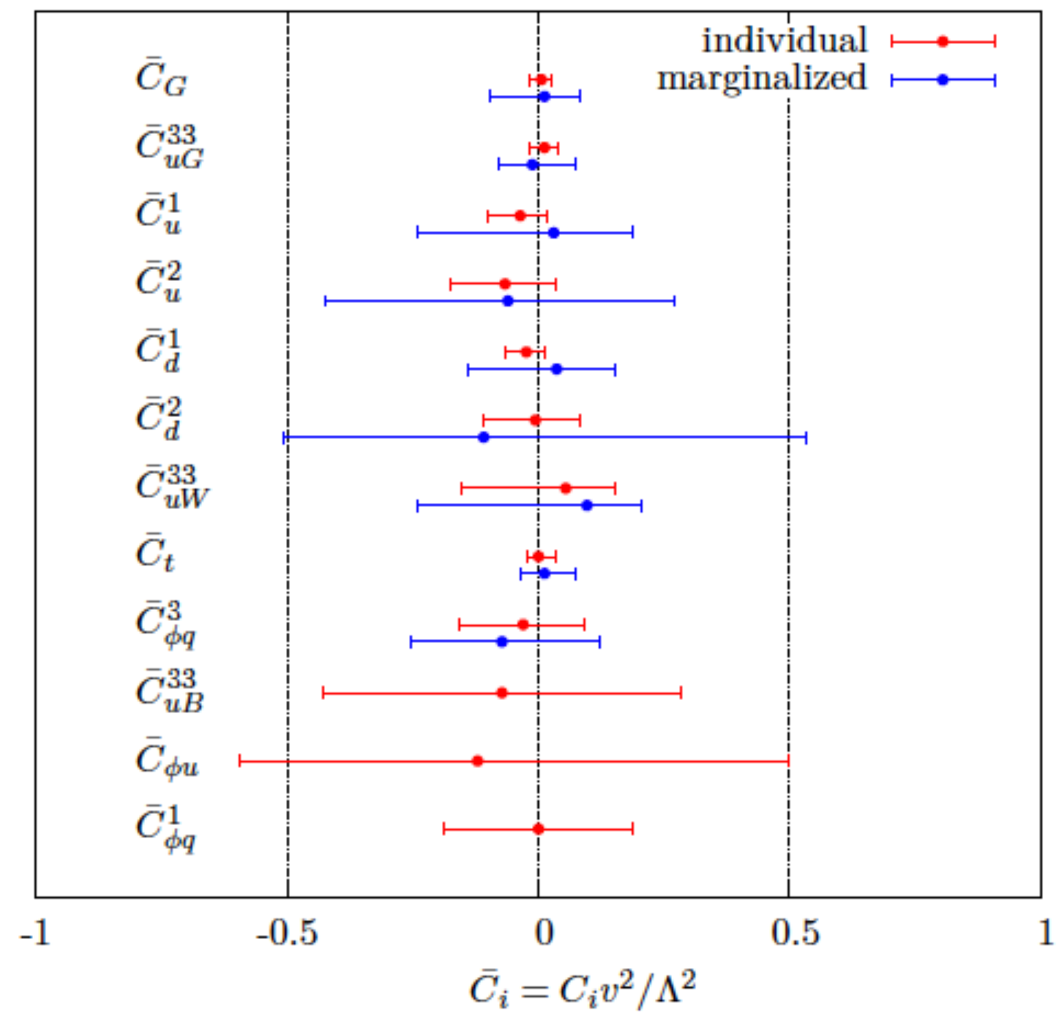
Towards global fits

EFT only makes sense if we follow a global approach

First work towards global fits:

TopFitter: Buckley et al arxiv:1506.08845 and 1512.03360

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
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				
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.4156
Single top production				*W*-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				



Tevatron and LHC data

Cross-sections and distributions

E.Vryonidou

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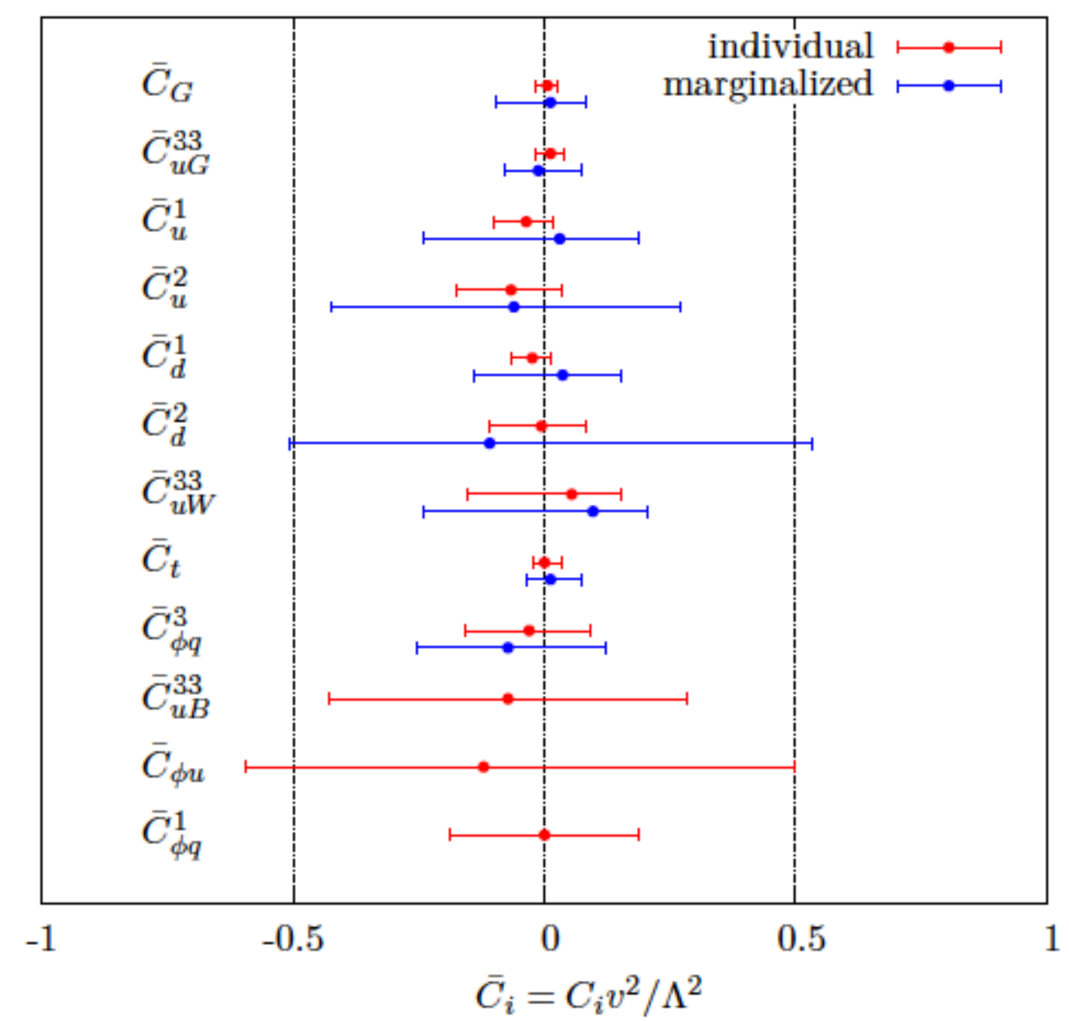


Tevatron and LHC data

Cross-sections and distributions

E.Vryonidou

How can we improve the fits?

- Need NLO in QCD to match the SM precision and experimental accuracy: SMEFT@NLO
  - Mixing between operators: anomalous dimension matrix: Alonso et al. arxiv:1312.2014

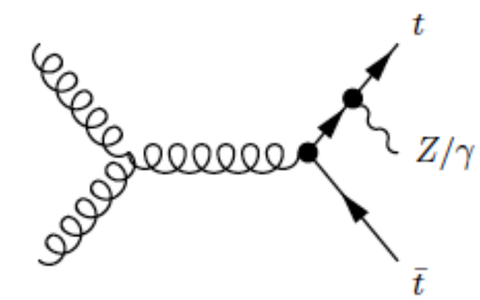
Recent progress:

- 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)

All automated within MadGraph5_aMC@NLO
R2+UV counterterms: NLOCT Degrande (arxiv:1406.3030)

Top pair + Z/γ

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



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

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

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?

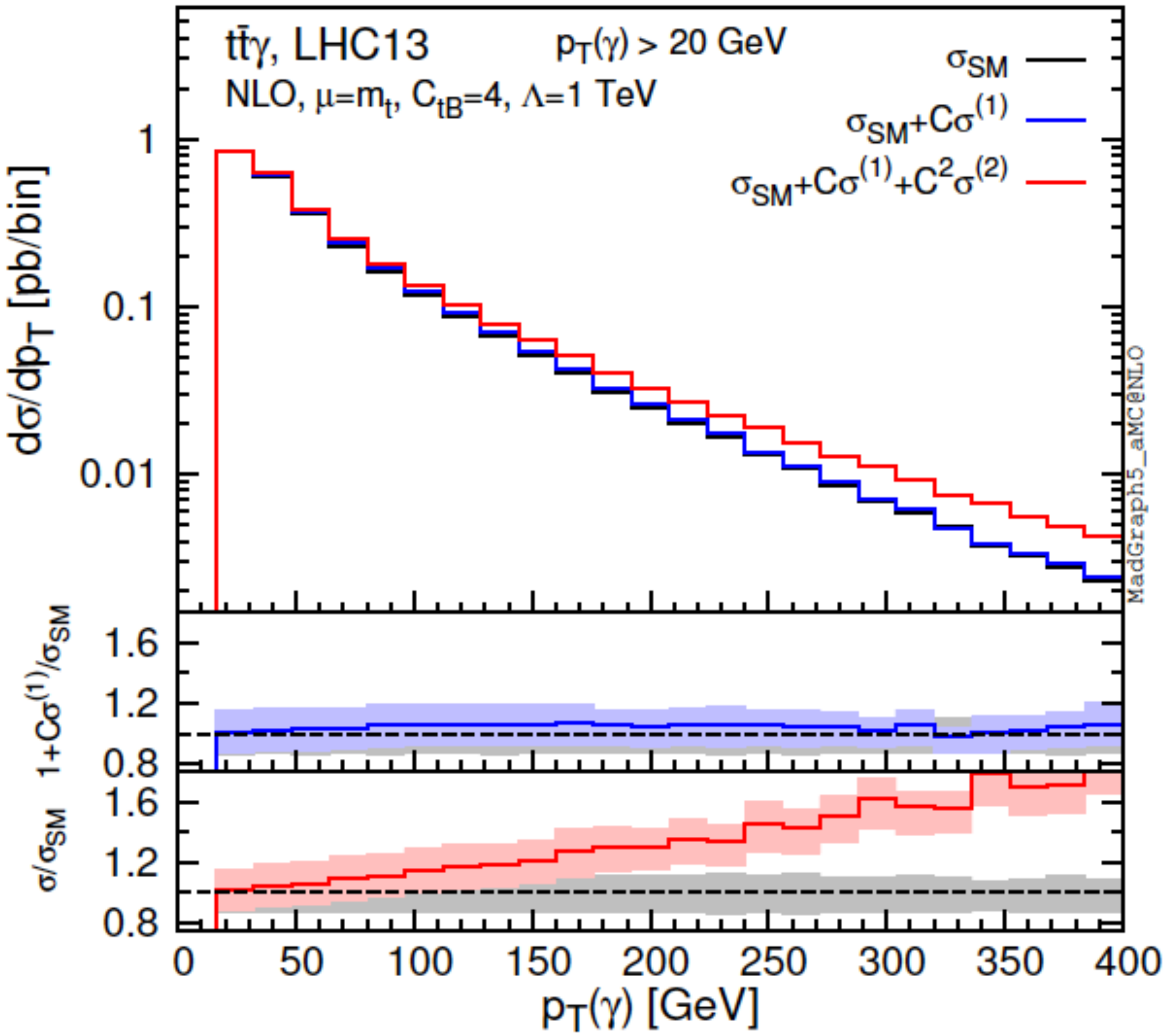
$$C_i^2\frac{E^4}{\Lambda^4} > C_i\frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

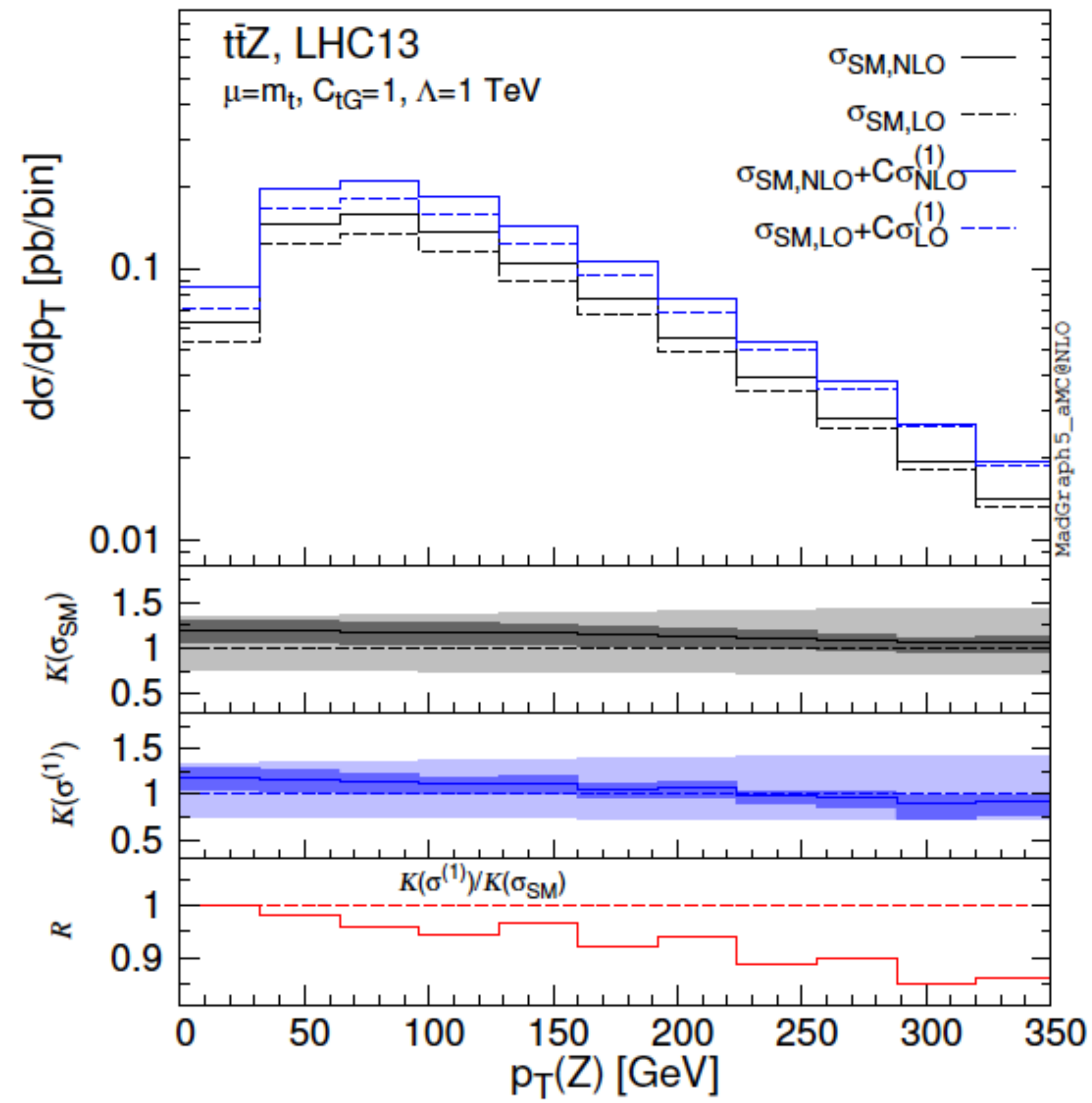
EFT condition satisfied but $O(1/\Lambda^4)$ large

To be checked on a case-by-case basis

Bylund et al arXiv:1601.08193

Differential distributions for tt+V



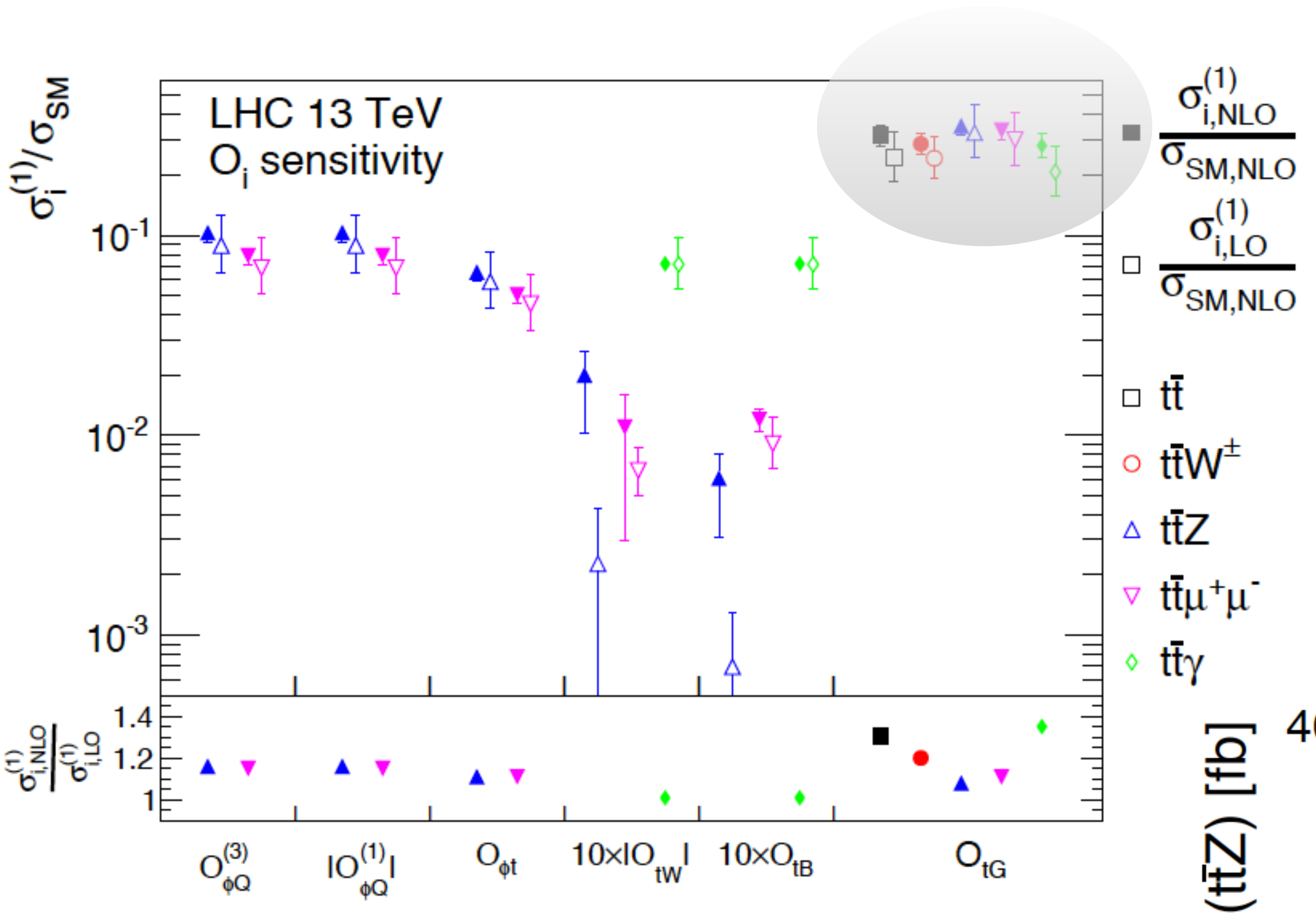


Large contribution at $O(1/\Lambda^4)$ rising with energy

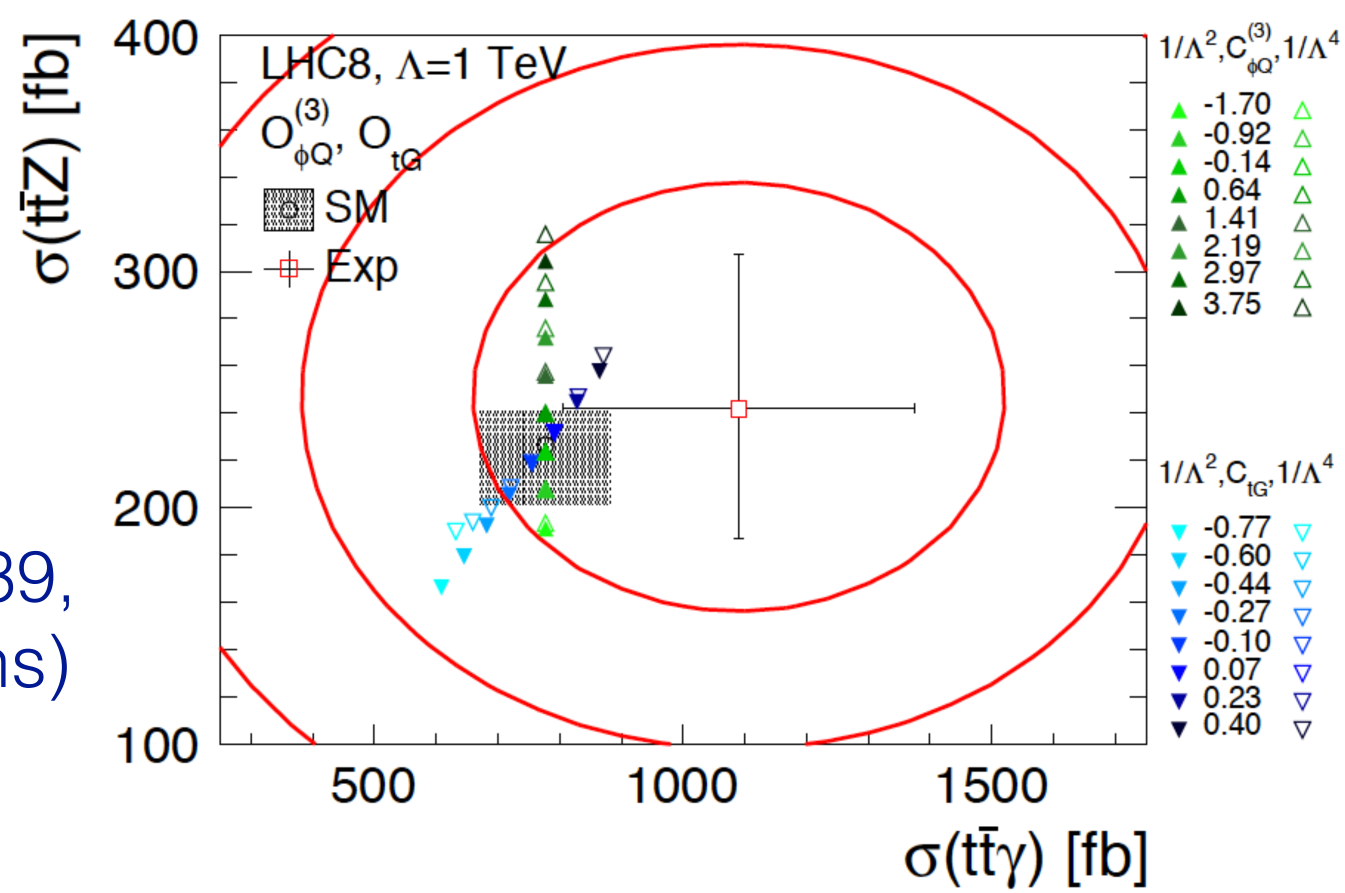
Using SM k-factors is not enough

arXiv:1601.08193

A sensitivity study



Chromomagnetic operator affecting all processes in the same way



LHC measurements of ttV processes can set constraints on the Wilson coefficients

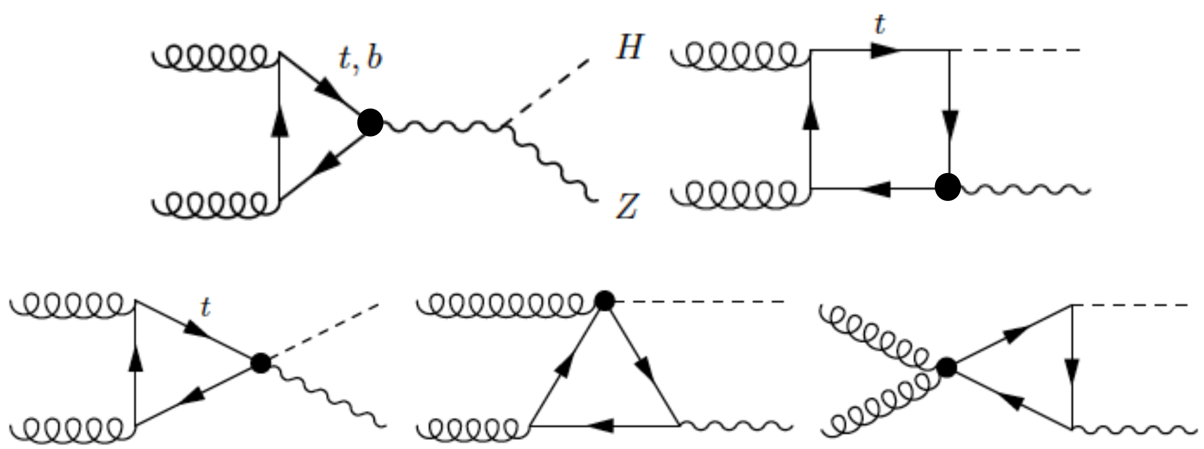
See also:

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

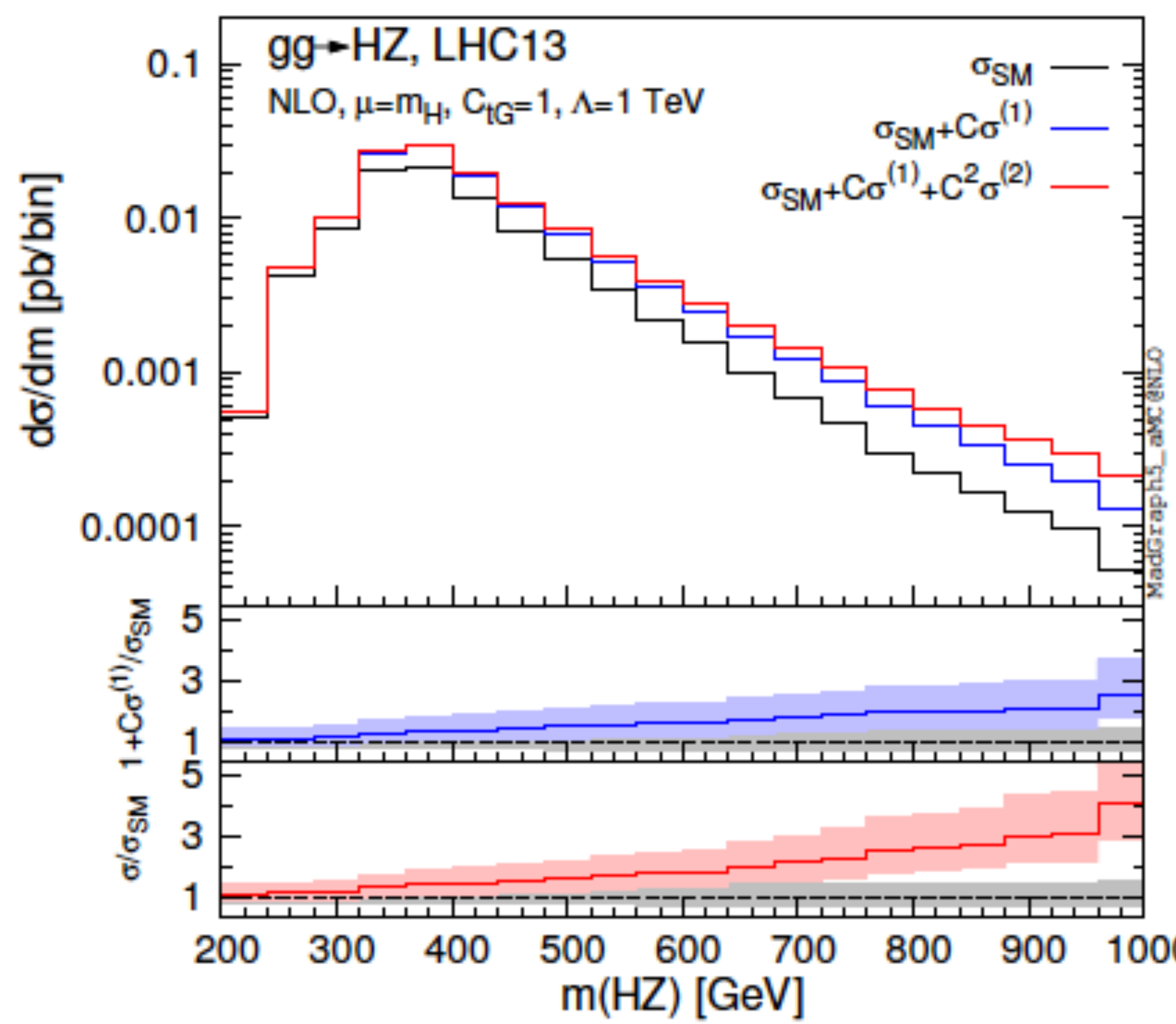
Top-V interactions in non-top final states



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

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

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



See also:
Englert et al arXiv:1603.05304

Top and Higgs

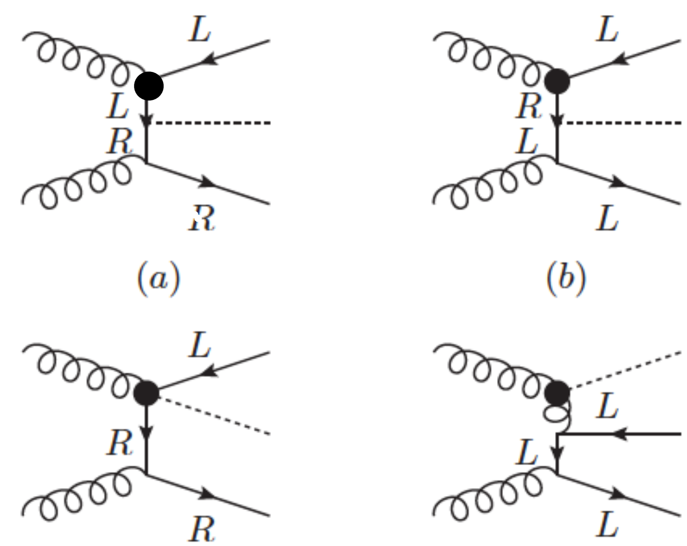
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

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

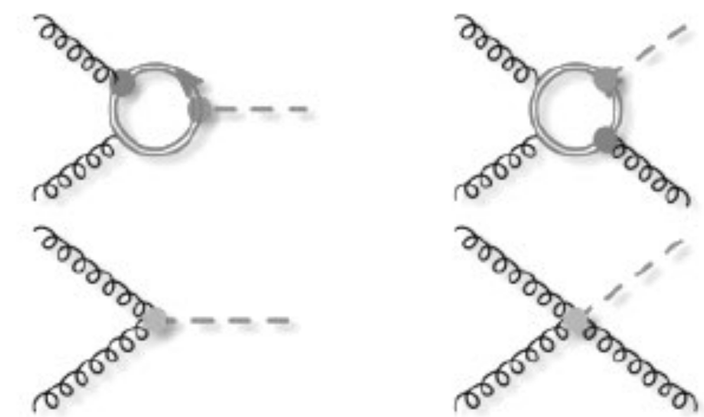
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A$$

needed due to mixing:

$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} \frac{1}{6} & 0 & 0 \\ 4 & -1 & 4 \\ \frac{1}{4} & 0 & -\frac{7}{4} \end{pmatrix}$$



ttH



H, H+j

See also
Degrande et al. arXiv:1205.1065
Grojean et al. arXiv:1312.3317
Azatov et al arXiv:1608.00977

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

Maltoni, EV, Zhang: arXiv:1607.05330

ttH@NLO in the EFT

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

First systematic study of uncertainties:

- Scale and PDF uncertainties: Similar to SM
- EFT scale uncertainties

- Missing higher order terms in 1/Λ expansion: squared terms computed

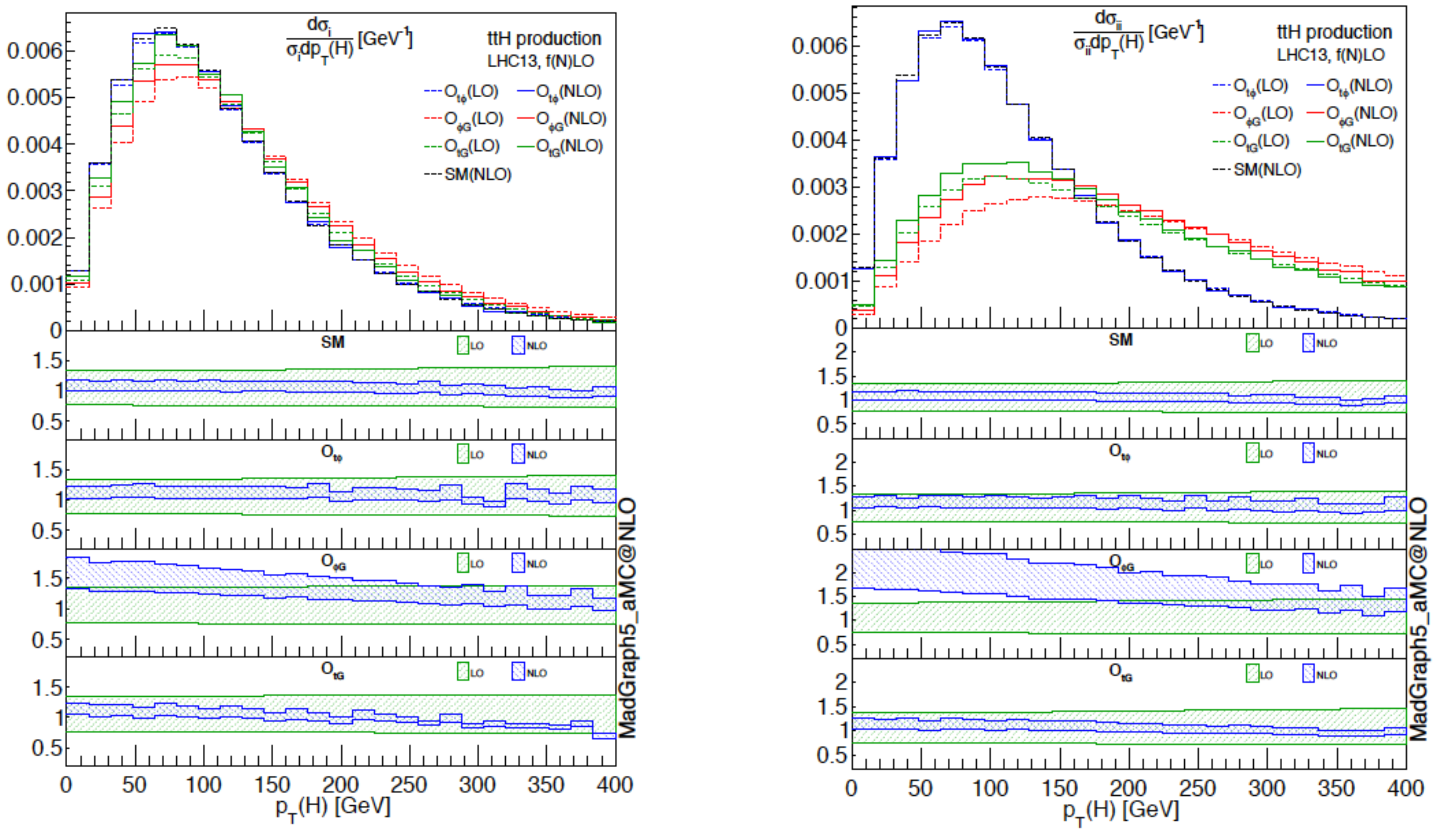
$$\sigma = \sigma_{SM} + \sum_i \frac{C_i^{\text{dim6}}}{(\Lambda/1\text{TeV})^2}\sigma_i^{(\text{dim6})} + \sum_{i\le j} \frac{C_i^{\text{dim6}} C_j^{\text{dim6}}}{(\Lambda/1\text{TeV})^4}\sigma_{ij}^{(\text{dim6})} + \sum_i \frac{C_i^{\text{dim8}}}{(\Lambda/1\text{TeV})^4}\sigma_i^{(\text{dim8})} + \mathcal{O}(\Lambda^{-6})\ .$$

Different k-factors for the SM and dimension-6 contributions
Different k-factors for different operators

→ NLO is important

Maltoni, EV, Zhang: arXiv:1607.05330

Differential distributions for ttH

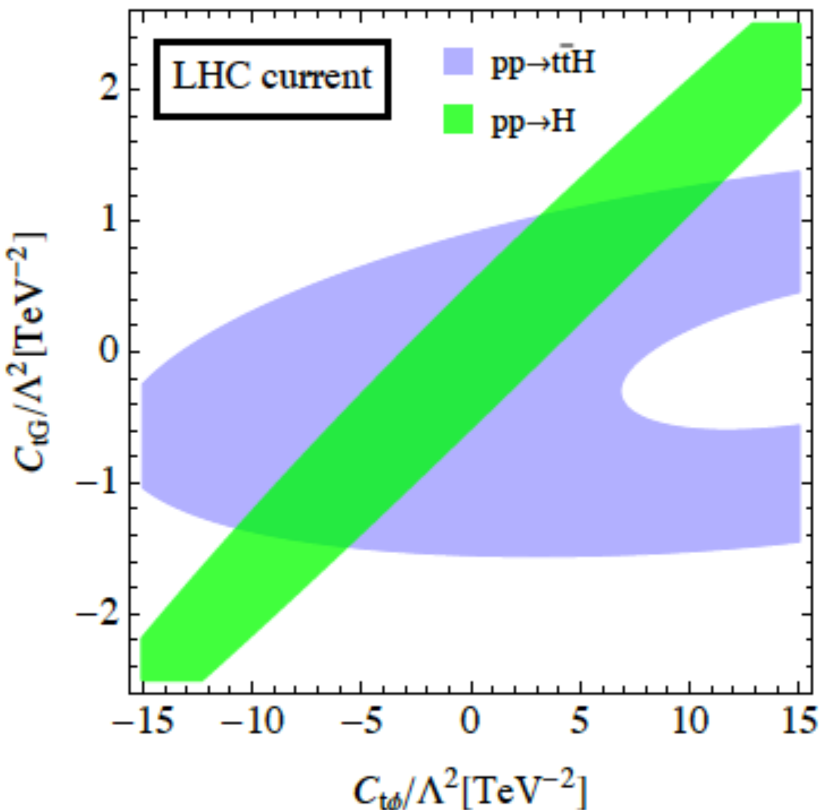


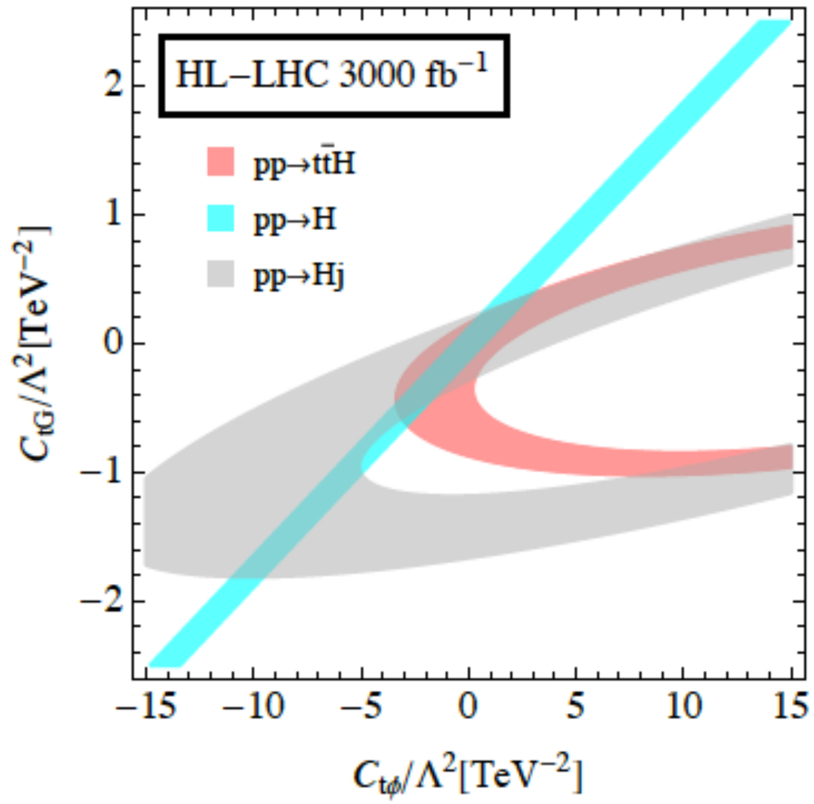
NLO: smaller uncertainties, non-flat K-factors

Different shapes for different operators for the squared terms

Maltoni, EV, Zhang arXiv:1607.05330

Constraints from ttH and Higgs production





Current limits using LHC measurements

HL-LHC 14TeV projection 3000 fb^{-1}

$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) \left(\bar{Q}t\right) \tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$
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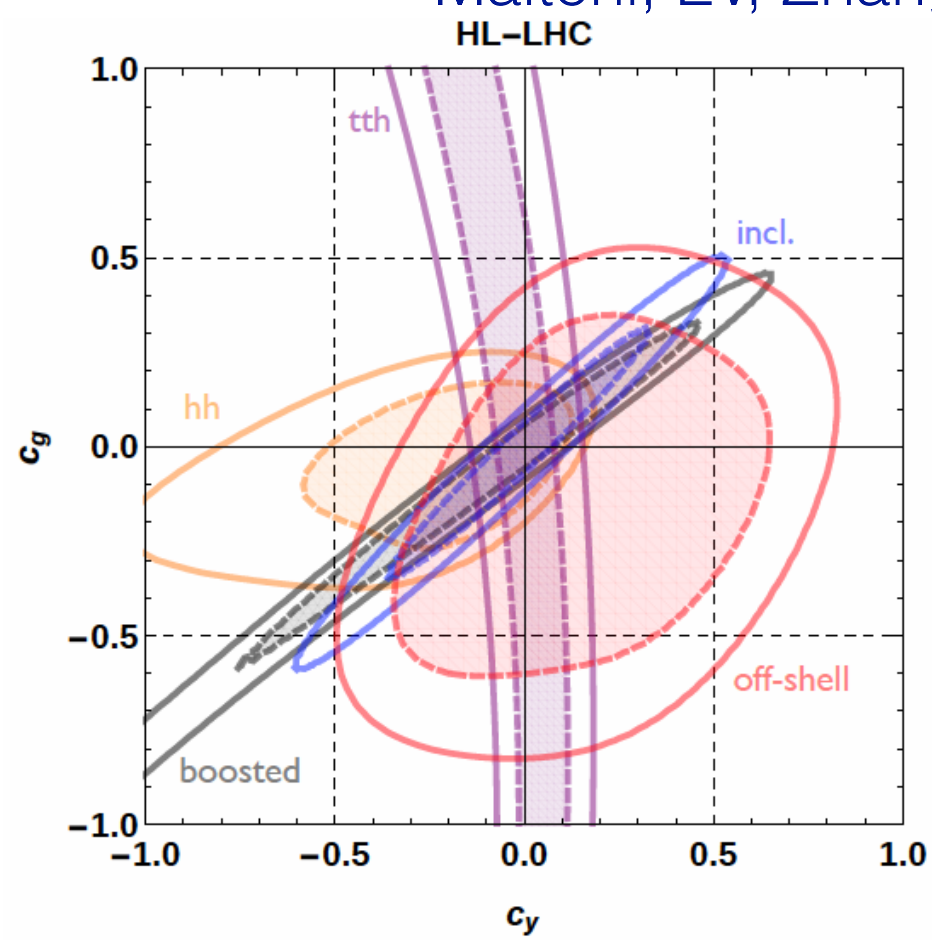
Maltoni, EV, Zhang arXiv:1607.05330



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

gives maximal information

Azatov et al arXiv:1608.00977

Summary

- Significant progress for precise predictions for top production with EW bosons and Higgs in the SM: QCD and EW corrections
- Higher-order corrections needed to match improving experimental accuracy
- Top+V/H processes a playground for new top interactions
- Precision needed also for EFT predictions: ttV, ttH 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
- Input from Higgs and loop-processes is important

Thank you for your attention