# EFT approach to New Physics searches at the LHC

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# Dimension-6 Lagrangian

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

| | $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2 \varphi^3$ |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger \varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$ |
| $Q_{\widetilde{G}}$ | $f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\square}$ | $(\varphi^\dagger \varphi)\square(\varphi^\dagger \varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger \varphi)(\bar{q}_p u_r \widetilde{\varphi})$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$ | $Q_{d\varphi}$ | $(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$ |
| $Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |

| | $X^2\varphi^2$ | | $\psi^2 X \varphi$ | | $\psi^2 \varphi^2 D$ |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger \varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$ |
| $Q_{\varphi \widetilde{G}}$ | $\varphi^\dagger \varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger \varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$ |
| $Q_{\varphi \widetilde{W}}$ | $\varphi^\dagger \varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi \widetilde{B}}$ | $\varphi^\dagger \varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$ |
| $Q_{\varphi W B}$ | $\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$ |
| $Q_{\varphi \widetilde{W} B}$ | $\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$ |

| | $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$ |

| | $(\bar{L}R)(\bar{R}L)$ 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

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# SMEFT framework

- SMEFT:
  - Complete description-respecting SM symmetries ✔
  - Valid up to scale Λ
  - Gauge invariant ✔
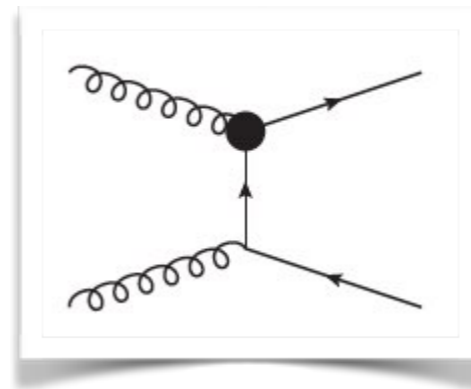  - Higher-order corrections: renormalisable order by order in 1/Λ ✔

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

  - Model Independent ✔
- Goal: Extract information for coefficients from data
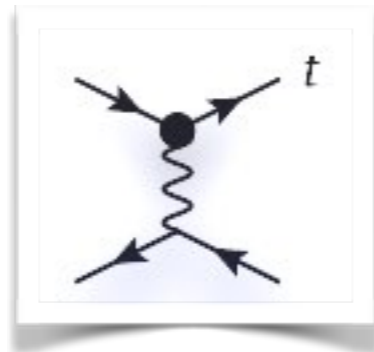  - Identify operators entering each observable
  - Collect enough observables
  - Fit all coefficients

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# SMEFT: a top application

Rich phenomenology:

**pair production**

**single**

**associated production**
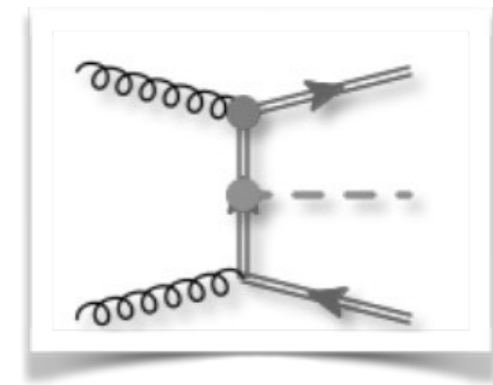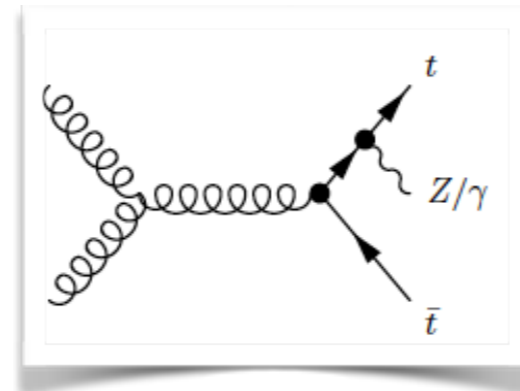
# Top-quark operators and how to look for them

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

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

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

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

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

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

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

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

+four-fermion operators
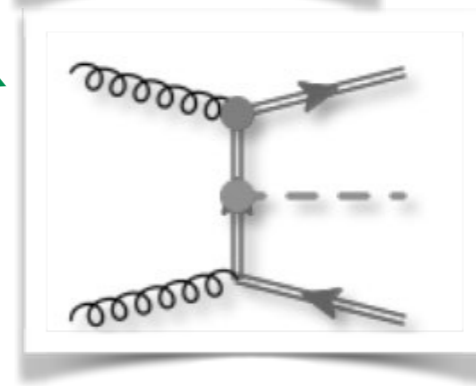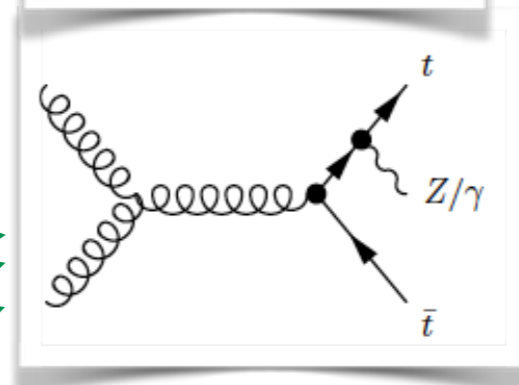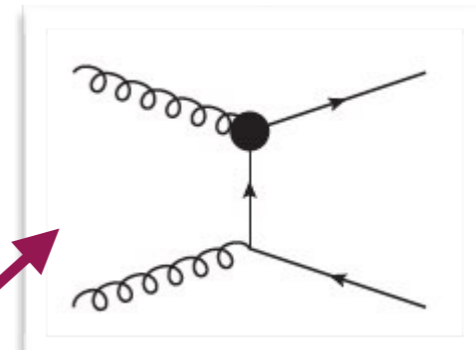


Operators entering various processes: Global approach needed

# 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. |
|---|---|---|---|---|---|---|---|
| **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 | $\Gamma_{top}$ | 1308.4050 |
| CDF + DØ | 1.96 | Combined world average | 1309.7570 | CDF | 1.96 | $\Gamma_{top}$ | 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 | | | | |



$$\bar{C}_i = C_i v^2/\Lambda^2$$
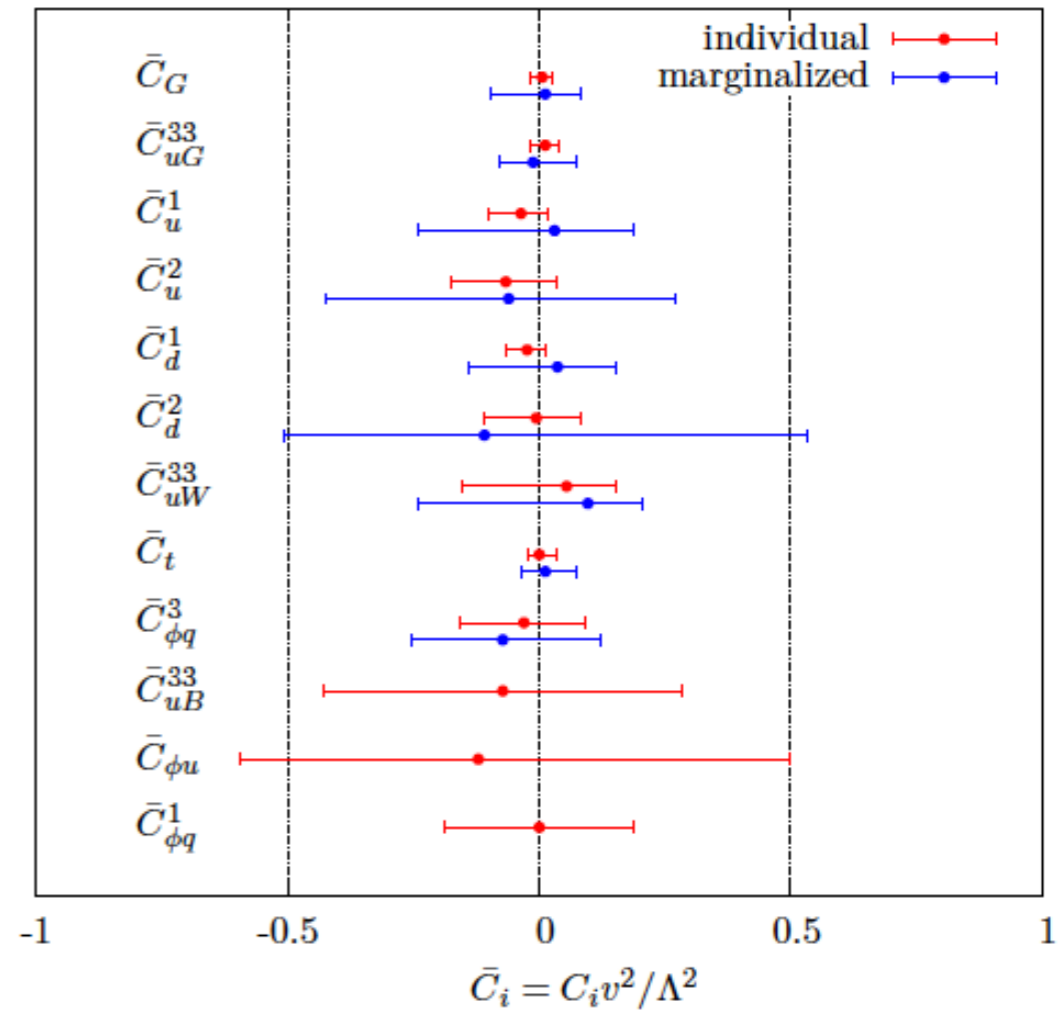
Tevatron and LHC data
Cross-sections and distributions

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# How can we improve the fits?

- Need NLO predictions to match the SM precision and experimental accuracy: SMEFT@NLO
  - Mixing between operators: anomalous dimension matrix: Alonso et al. arxiv:1312.2014
  - Additional operators at NLO: e.g. chromomagnetic dipole in single top

Recent progress:
- top pair production: Franzosi and Zhang (arxiv:1503.08841)
- single top production: Zhang (arxiv:1601.06163)
- ttZ/γ: Bylund, Maltoni, Tsinikos, EV, Zhang (arXiv:1601.08193)
- ttH: Maltoni, EV, Zhang work in progress

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

# First example: top-pair production
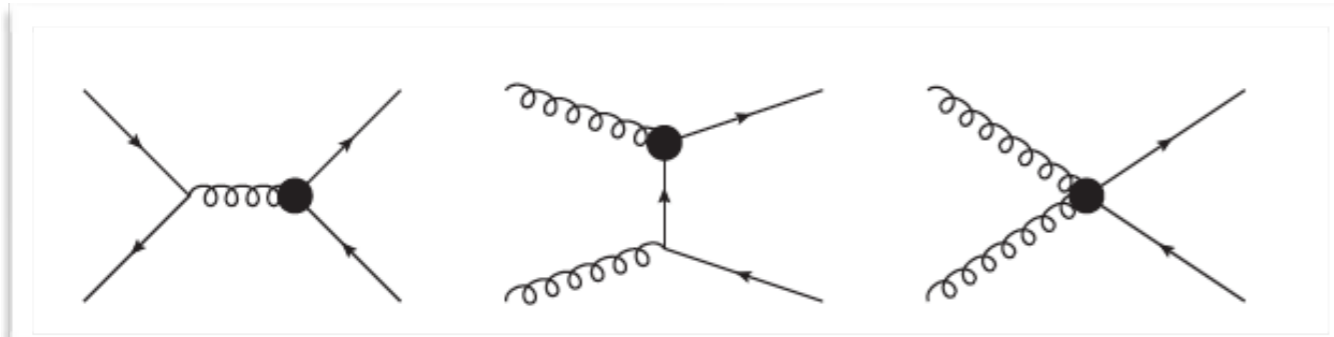


$$O_{tG} = y_t g_s \left( \bar{Q} \sigma^{\mu\nu} T^A t \right) \tilde{\phi} G^A_{\mu\nu}$$

NLO:
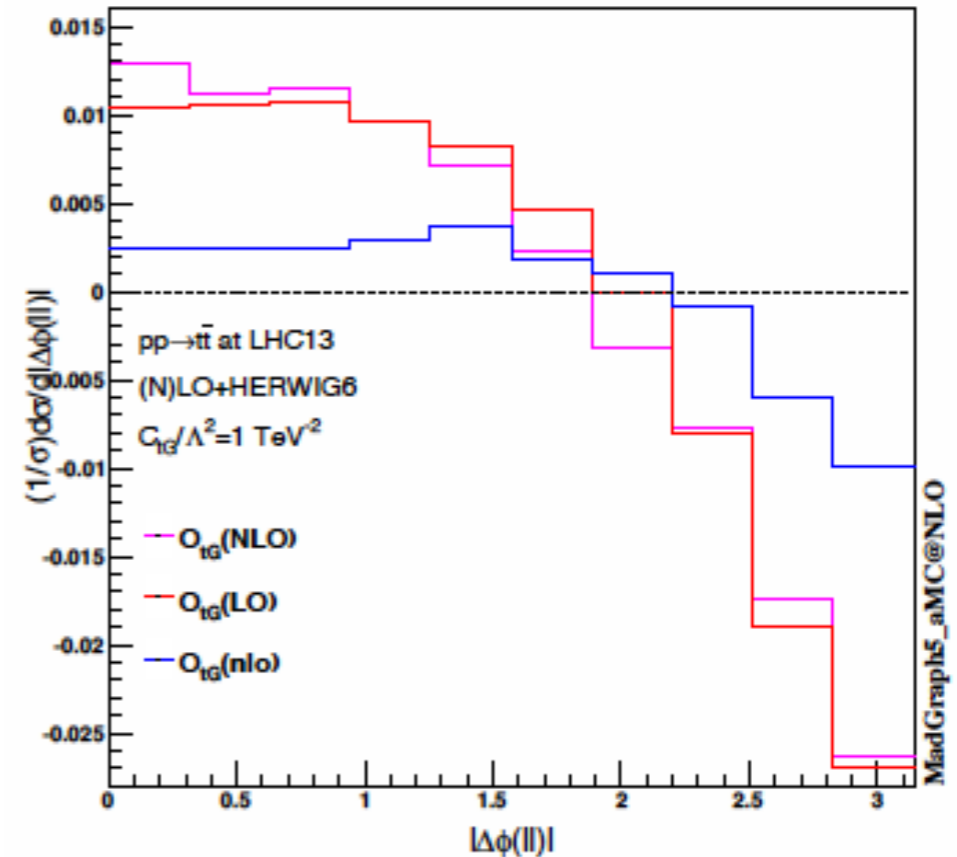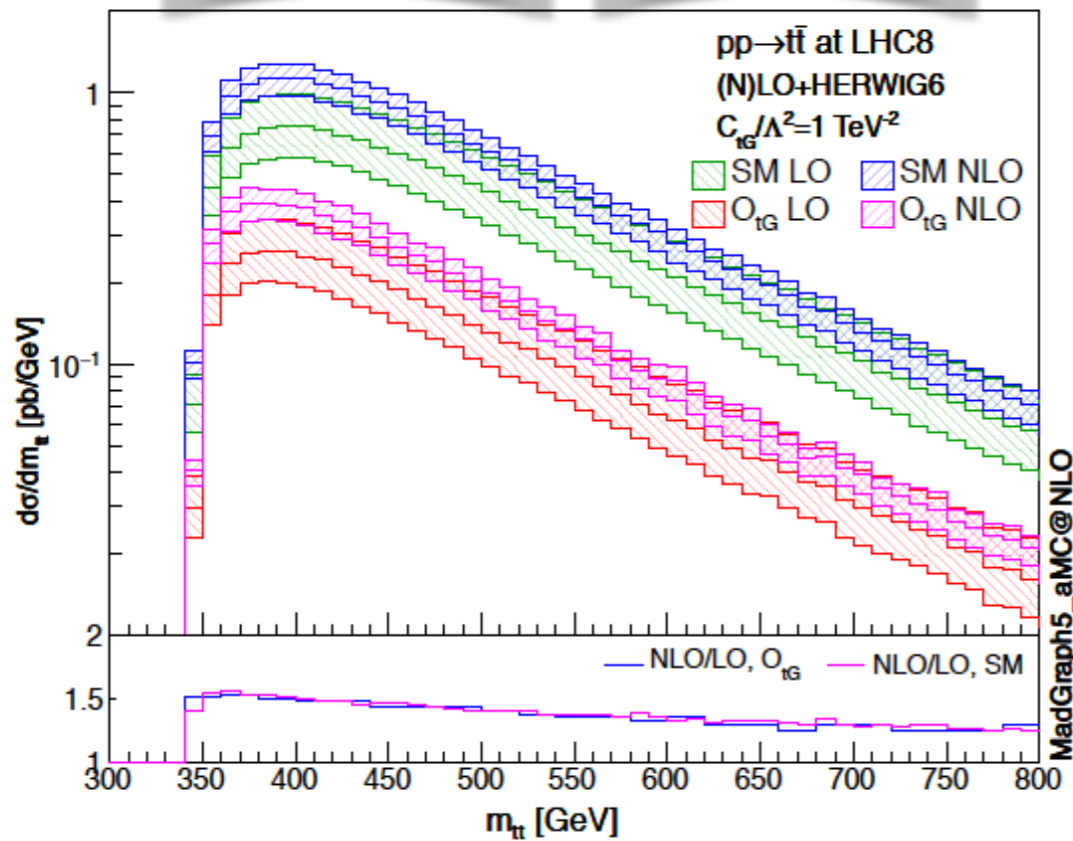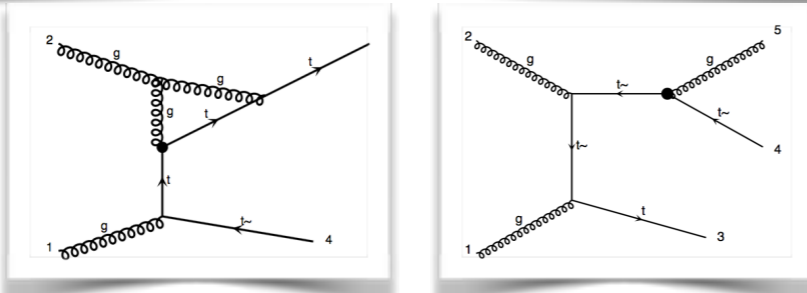




Limits on $c_{tG}/\Lambda^2$ using total cross section

Zhang and Franzosi
arXiv:1503.08841

| | 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] |

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# single top production

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

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

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

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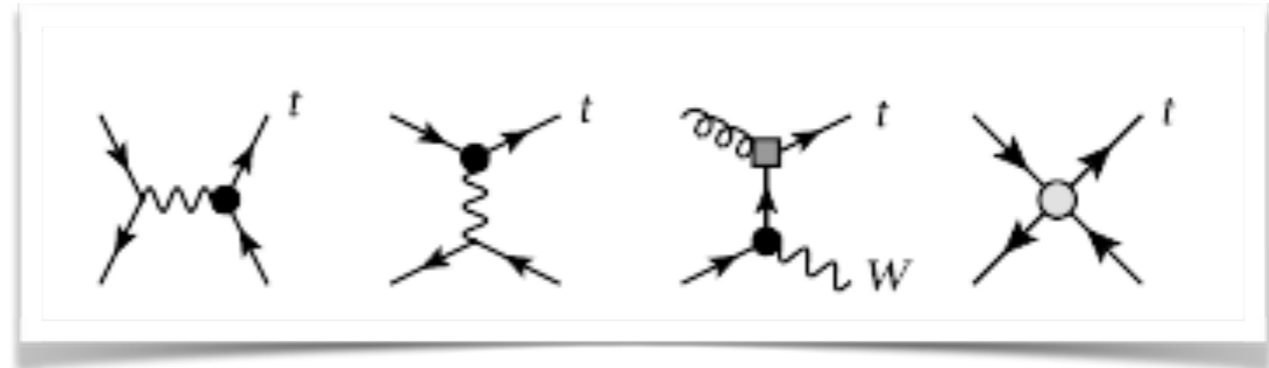


Only one four-fermion contributing
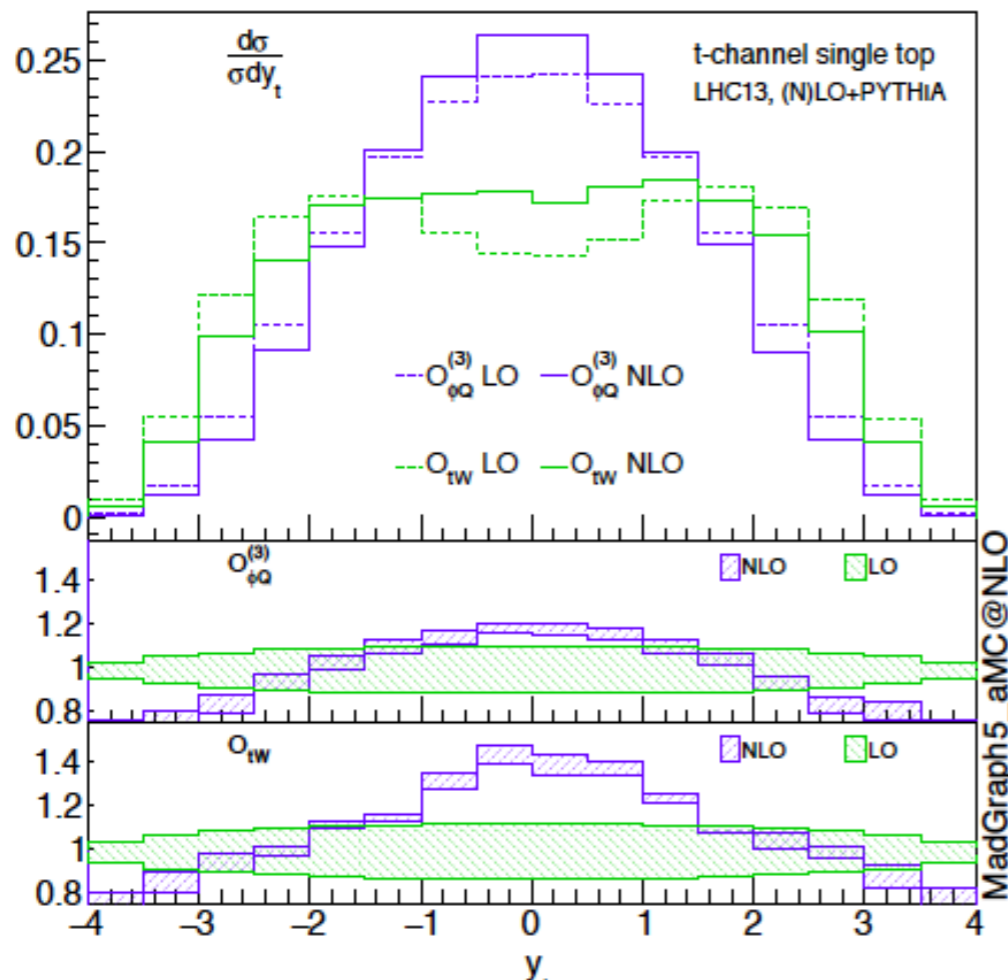


Zhang (arxiv:1601.06163)
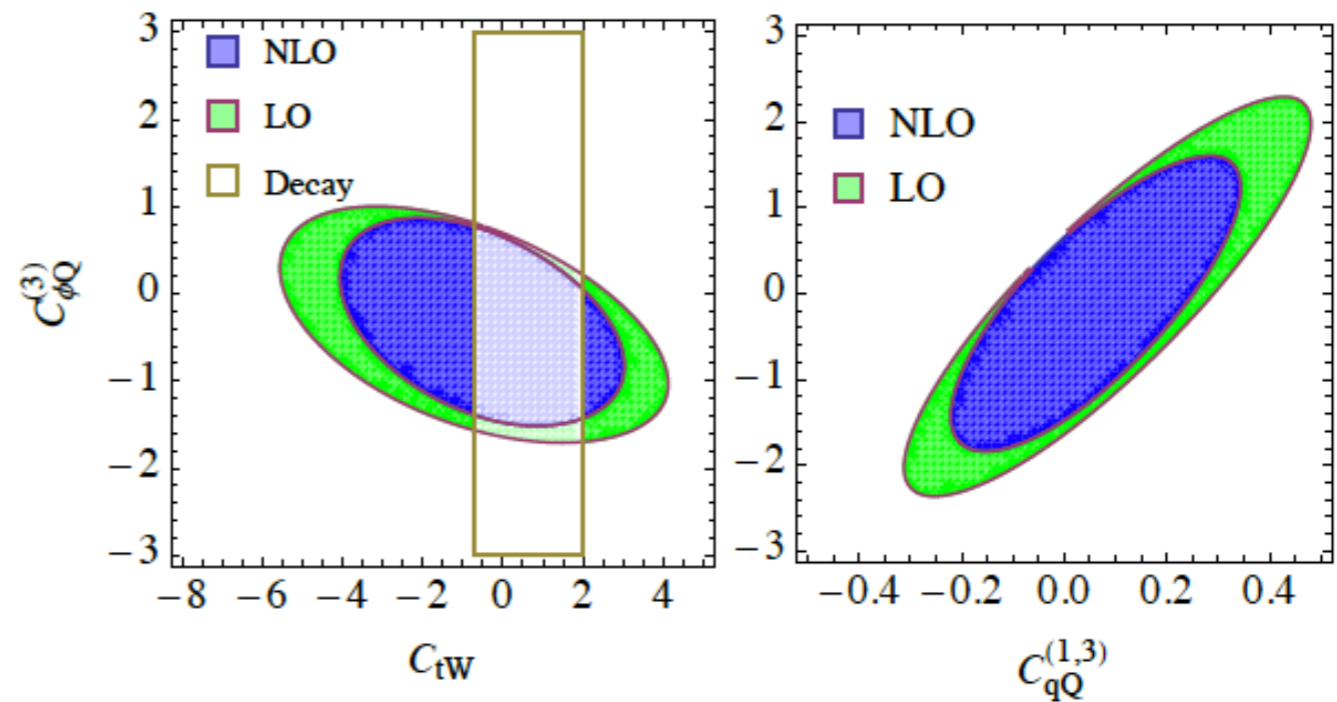


NLO corrections:
- Impact on distributions
- Impact on limits

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# 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 | $1.08$ | $1.16$ | $1.11$ | $8.5$ |
| $\sigma_{ii,LO}^{(2)}$ | $258.5^{+49.7\%}_{-30.4\%}$ | $2.8(1)^{+39.7\%}_{-26.9\%}$ | $2.9(1)^{+39.7\%}_{-26.7\%}$ | $20.9^{+44.3\%}_{-28.3\%}$ |
| $\sigma_{ii,NLO}^{(2)}$ | $244.5^{+4.2\%}_{-8.1\%}$ | $3.8(3)^{+13.2\%}_{-14.4\%}$ | $3.9(3)^{+13.8\%}_{-14.6\%}$ | $24.2^{+6.2\%}_{-11.2\%}$ |

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

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

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

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

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

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

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

**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?

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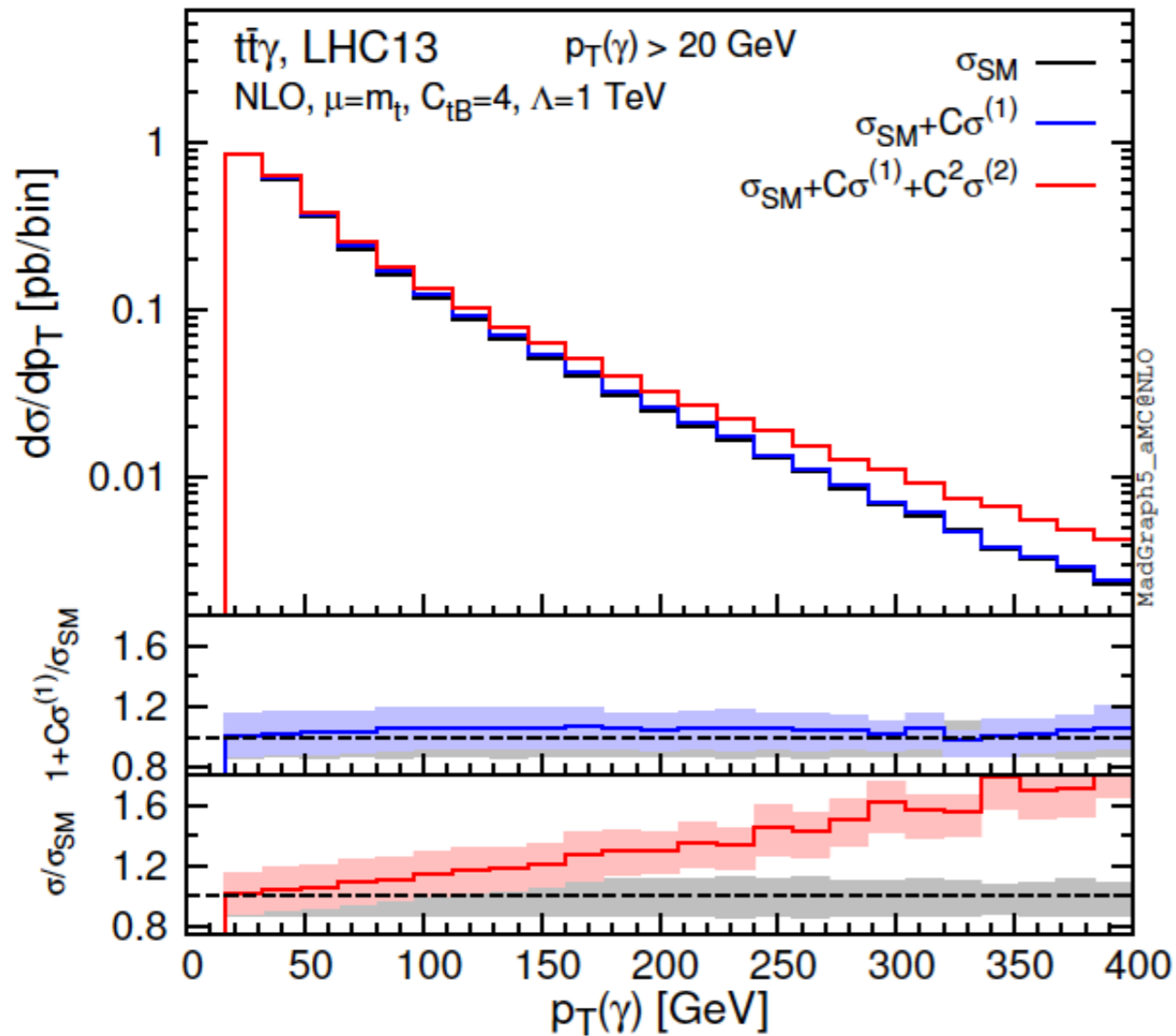
EFT condition satisfied

To be checked on a case-by-case basis
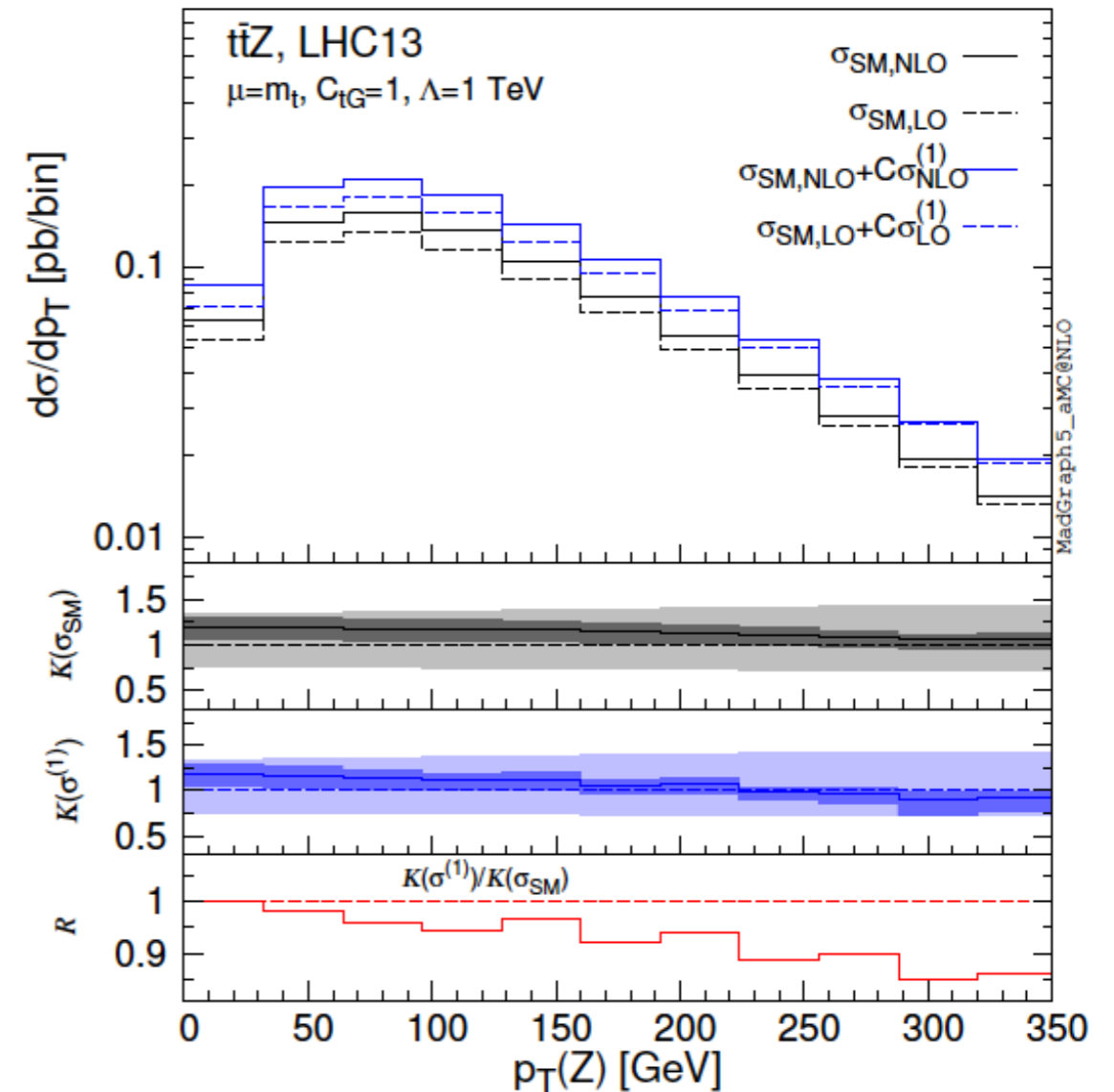
Anomalous dimension matrix: $O_{tW}$, $O_{tB}$, $O_{tG}$

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

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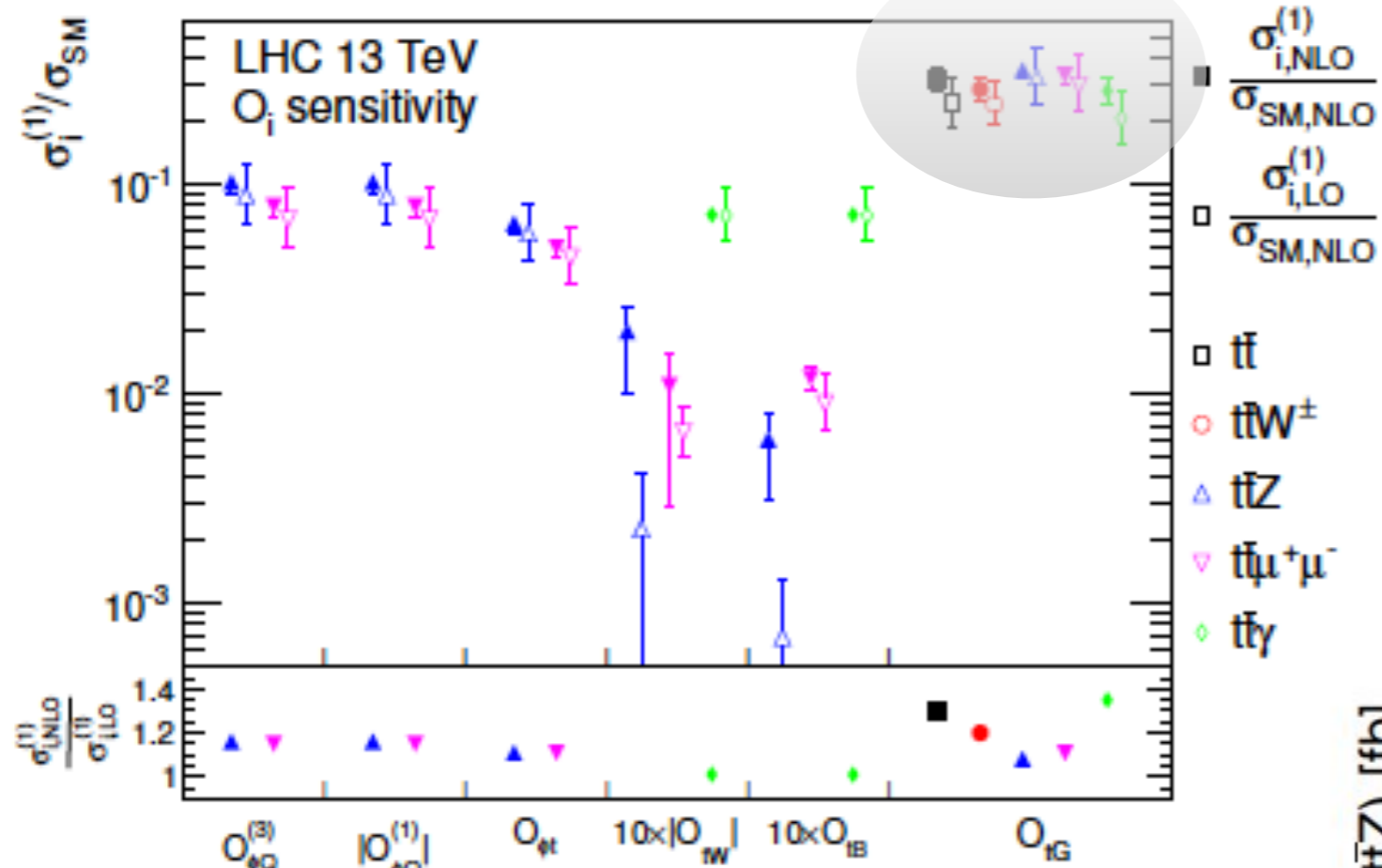# Differential distributions for tt+V



Large contribution at $O(1/\Lambda^4)$
rising with energy
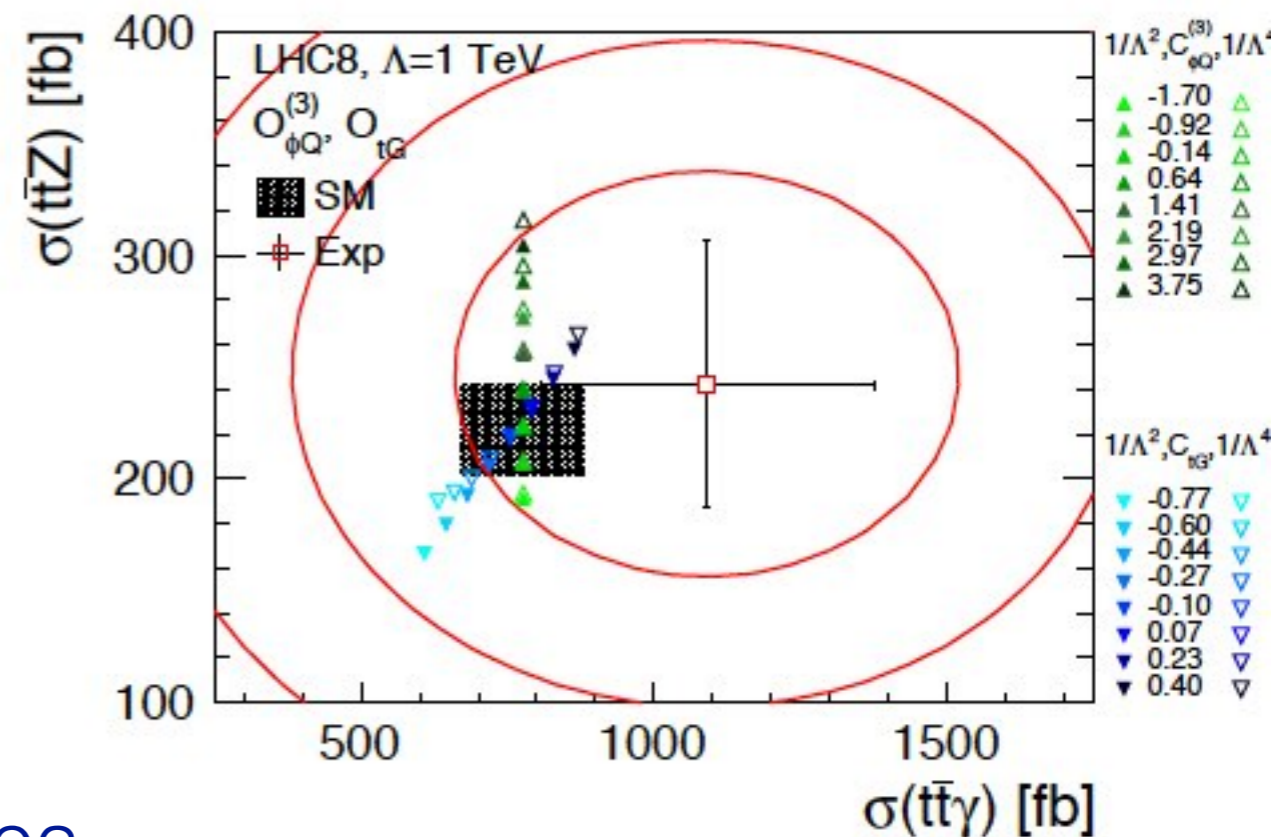
Using SM k-factors is not enough

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 in the anomalous coupling framework

arXiv:1601.08193

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# Top-operators in non-top final states
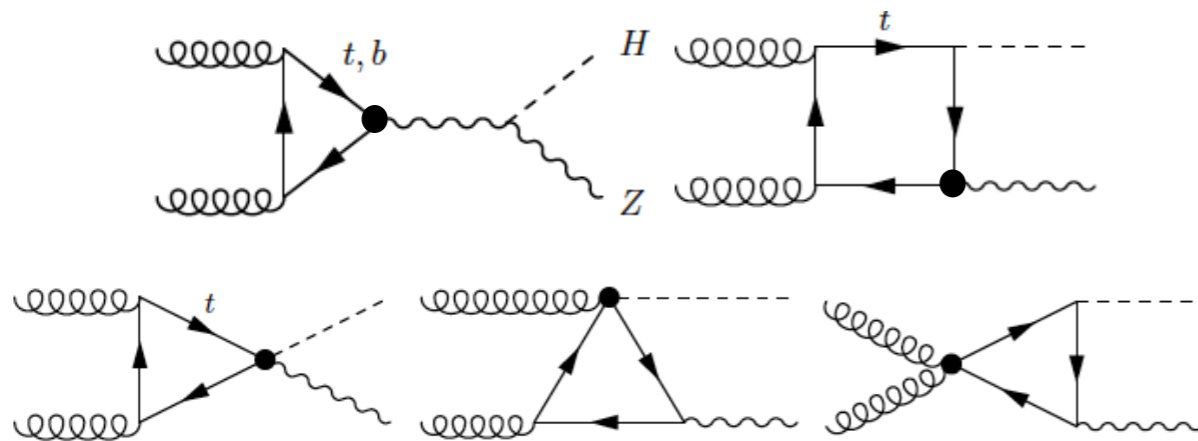


Gluon-fusion contribution to HZ production
affiliated by the operators changing gtt, ttZ
and ttH ➡ Additional information

| [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
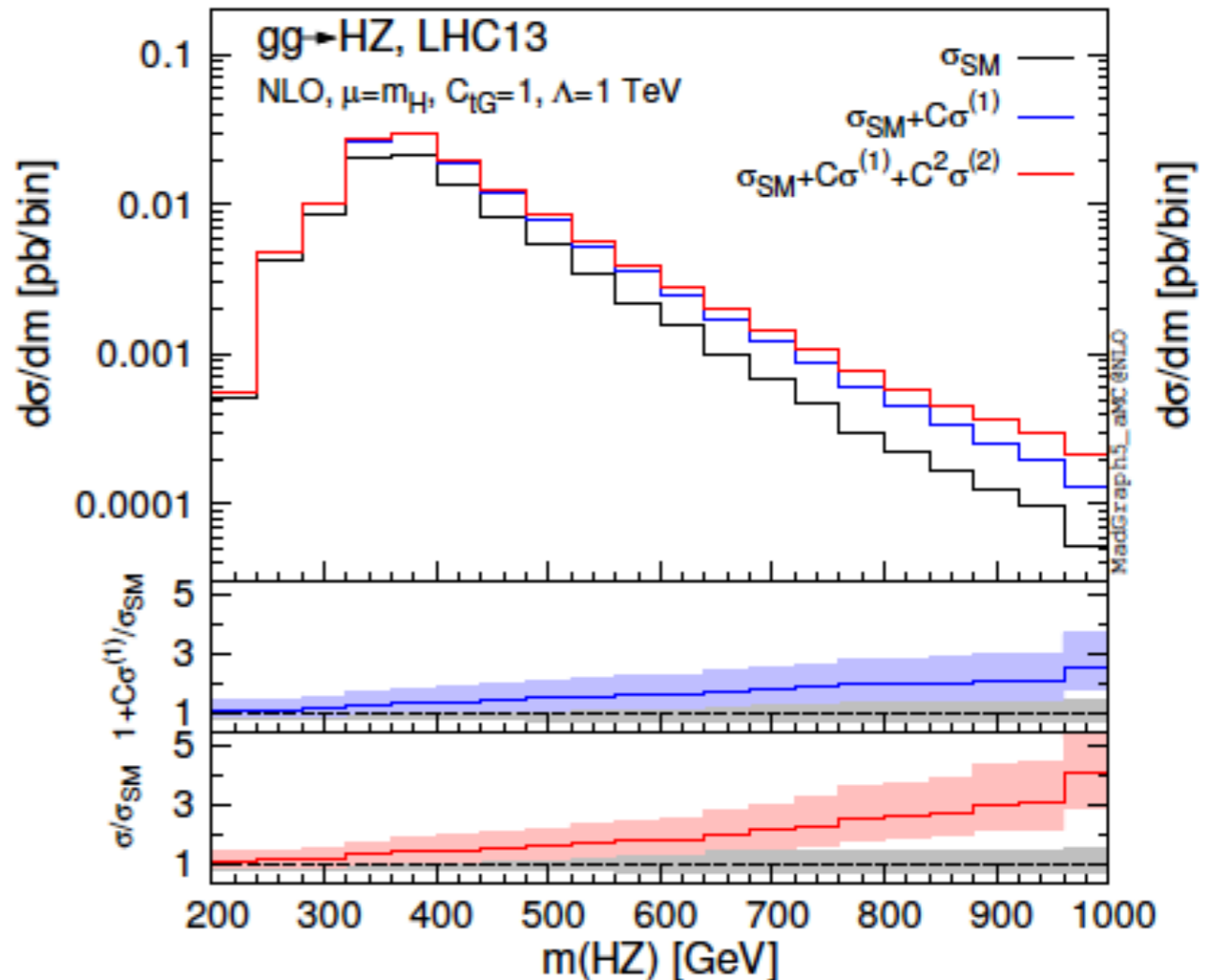
LO but loop-induced
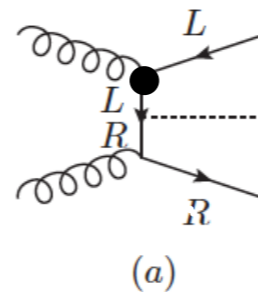Event generation possible in
MG5_aMC@NLO
Hirschi and Mattelaer (arxiv:
1507.00020)

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# Top and Higgs

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

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

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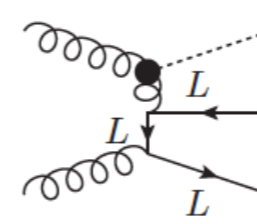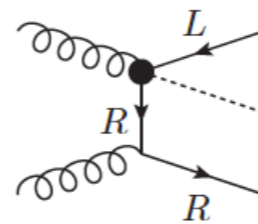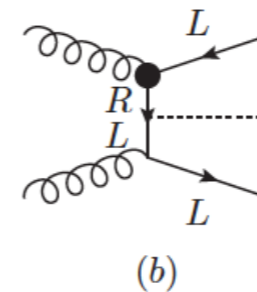
ttH

H, H+j

+four fermion operators

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

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

Use with 1) ttH and 2) H+j to break degeneracy between operators

Maltoni, EV, Zhang in preparation

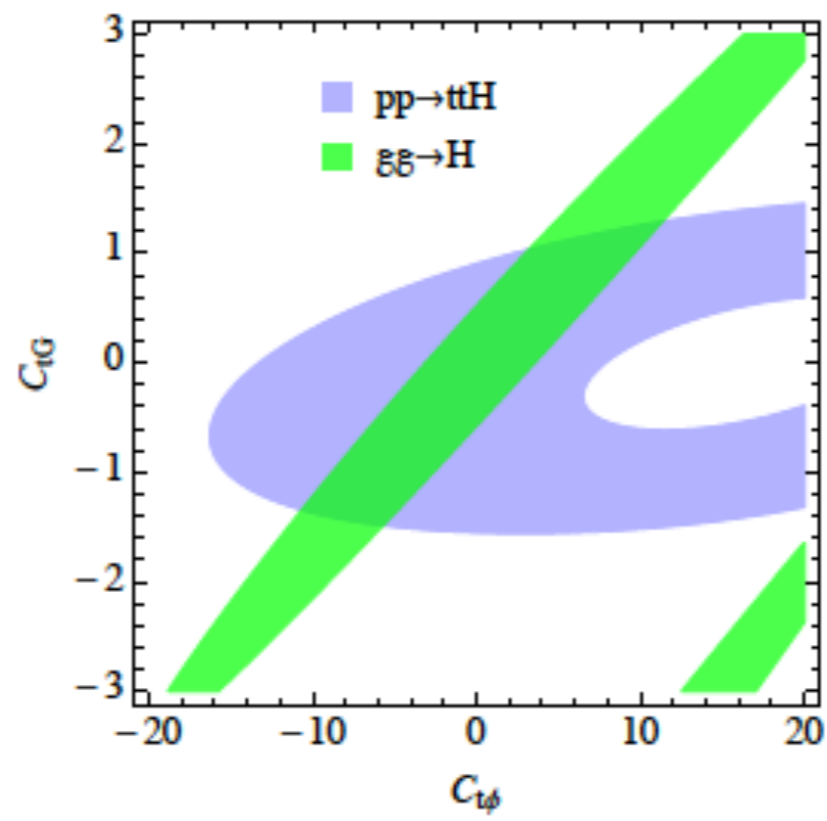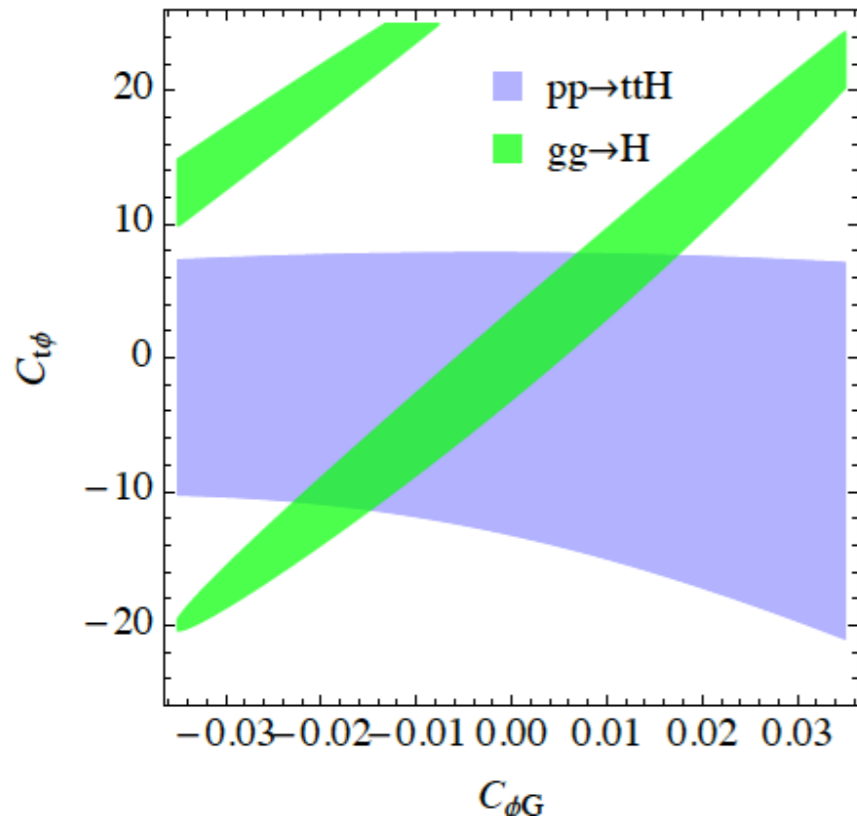E.Vryonidou

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# Top operators in ttH and H+j

ttH

H+j
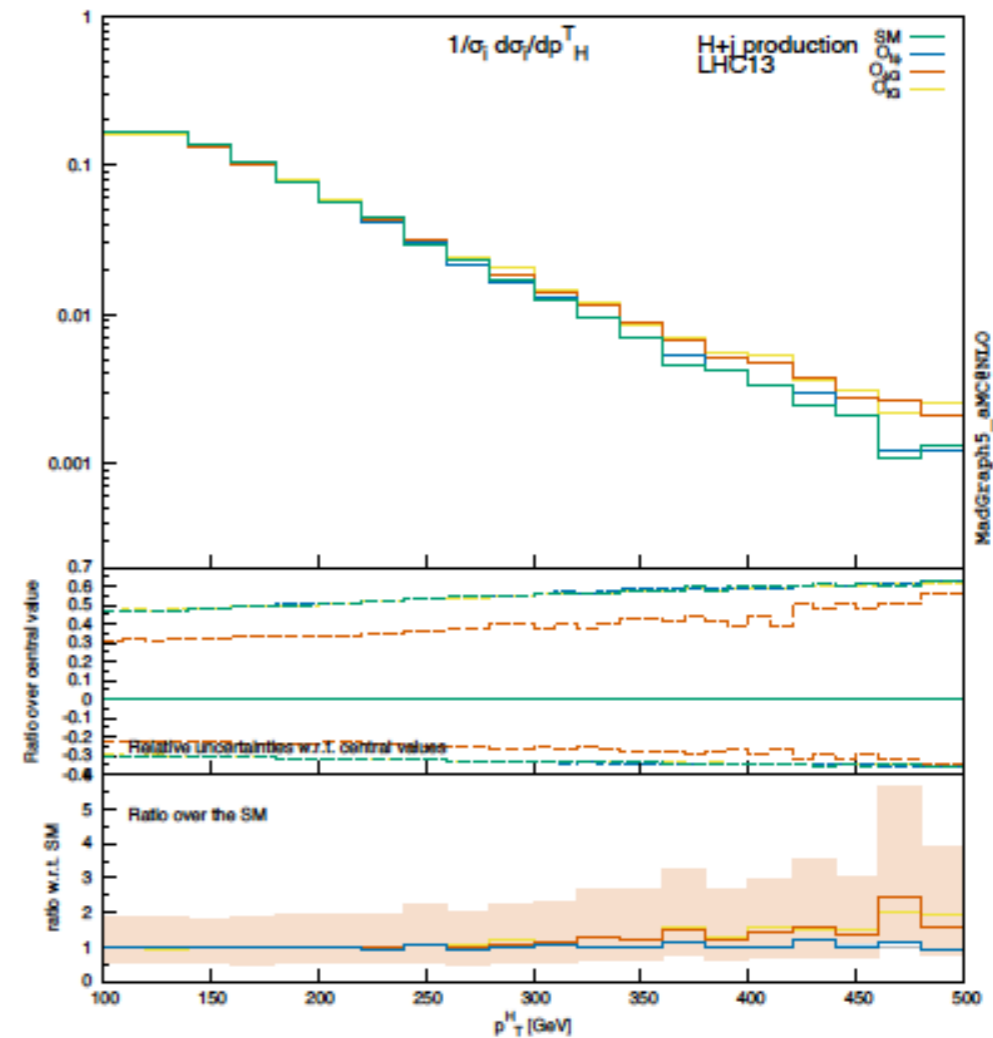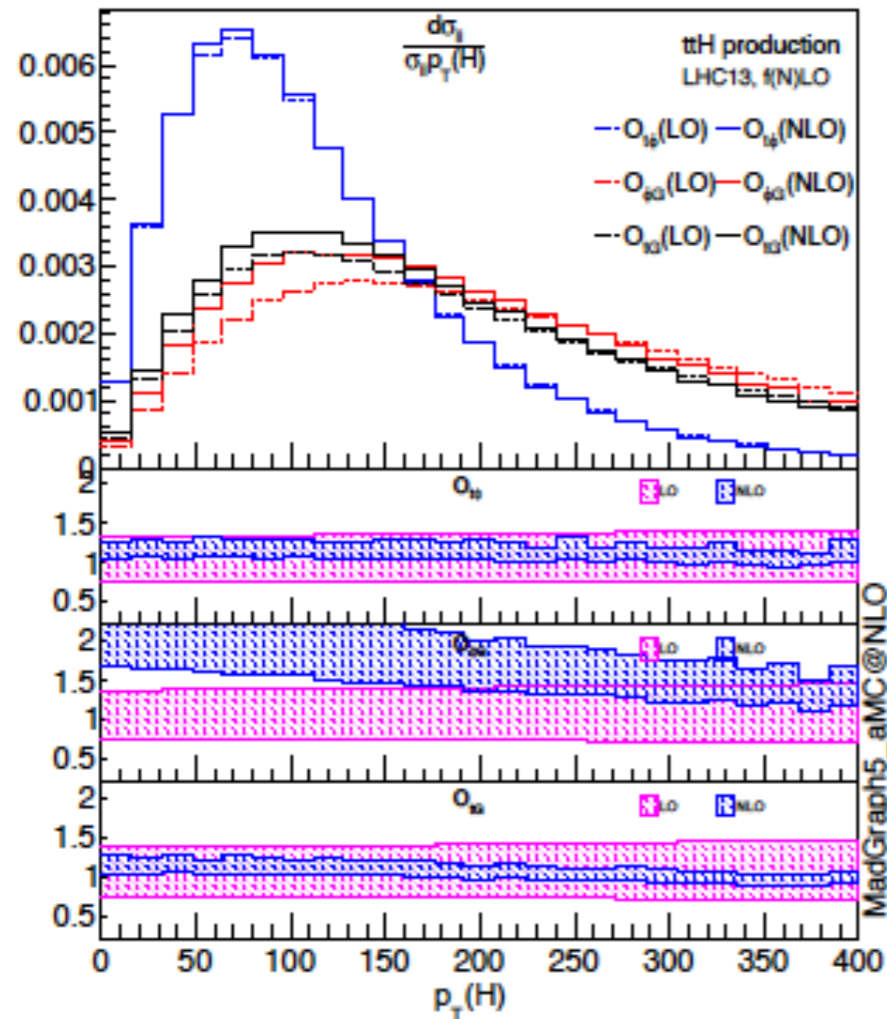


Different operators
different shapes

NLO smaller uncertainties,
non-flat K-factors

Harder tails from dim-6 operators
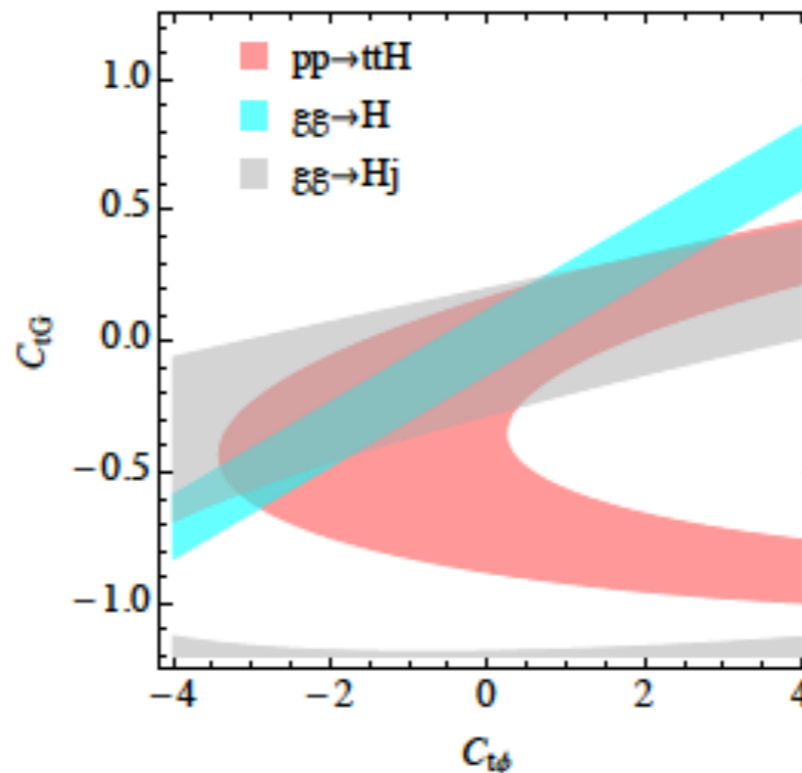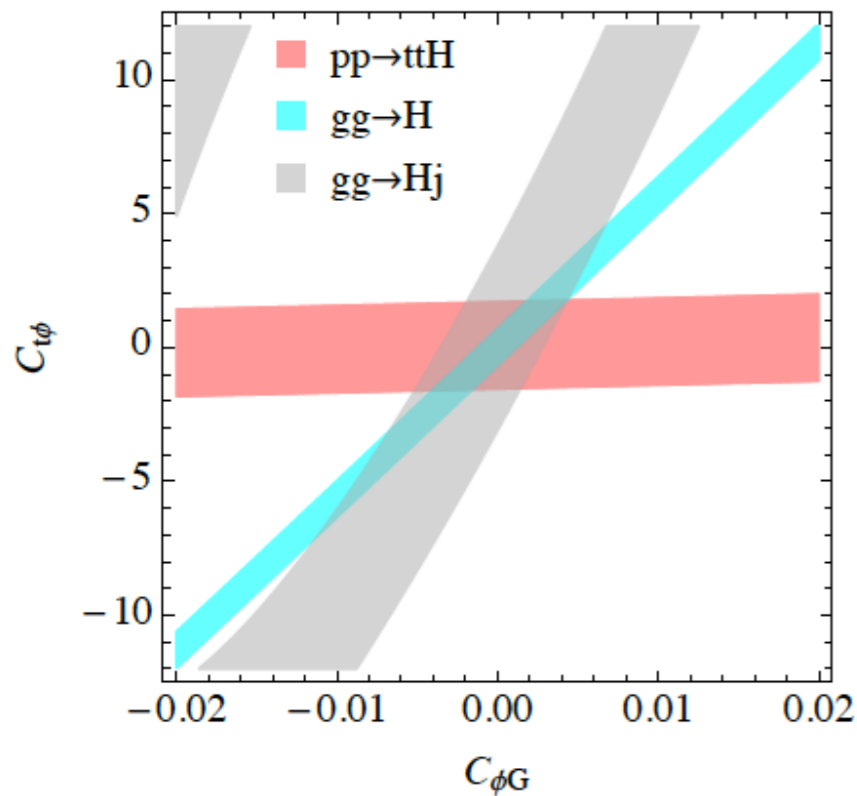
Maltoni, EV, Zhang in preparation

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# Constraints from ttH and Higgs production



Current limits using LHC measurements

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

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

14TeV projection 3000 fb⁻¹

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# EFT in HH

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

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

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

Chromomagnetic operator computed for the first time



E.Vryonidou
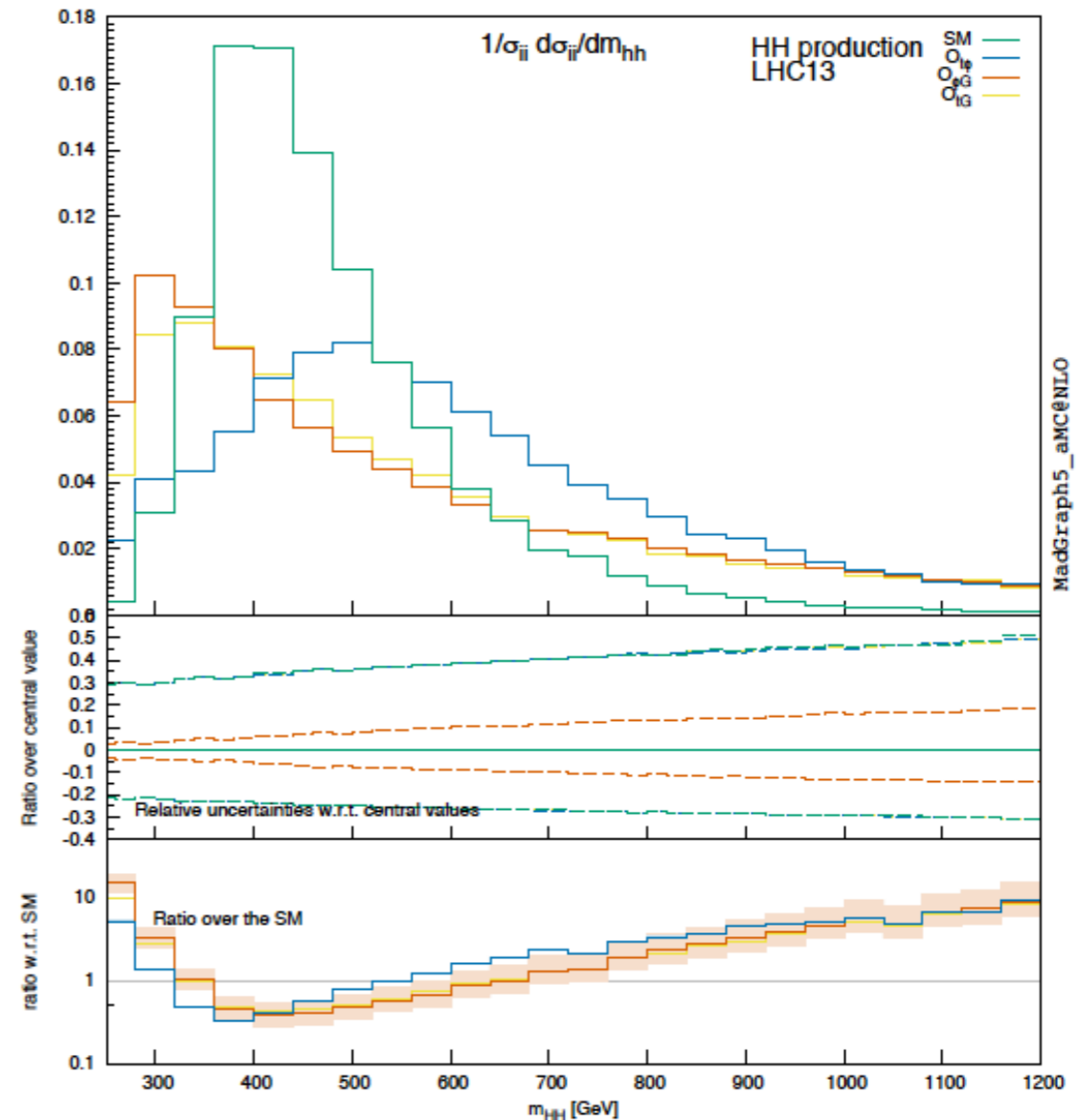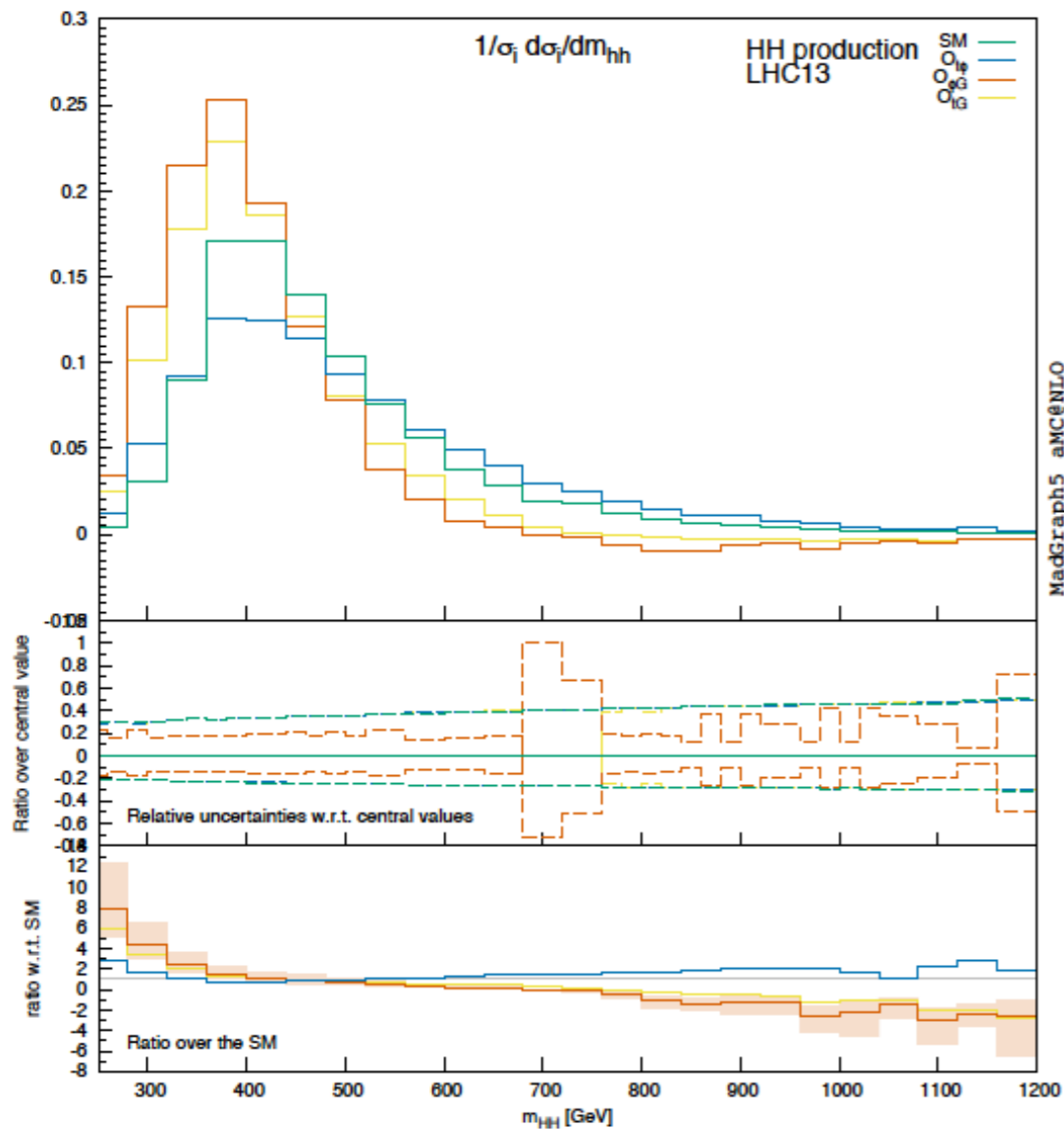
# Outlook

- SMEFT a consistent way to look for new interactions
- Higher-order corrections needed to match SM precision and experimental accuracy
- Progress in computing top-quark processes at NLO: pair production, single top, tt+V, tt+H
- 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 to extract maximum information (ongoing work with the Heidelberg group)

# Thank you for your attention