# Status of NLO EFT implementation in MG5_aMC

Eleni Vryonidou
CERN TH

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# SMEFT

New Interactions of SM particles

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

- Operators at dim-6:

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

Grzadkowski et al arxiv:1008.4884

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

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

# Towards NLO+PS for SMEFT

Recent progress in automated NLO+PS:

**Higgs:**

- Higgs characterisation arXiv:1306.6464
  - VBF, VH Maltoni et al arXiv:1311.1829
  - ttH Demartin et al arXiv:1407.5089, tH Demartin et al arXiv:1504.00611, tWH Demartin et al arXiv:1607.05862
- HELatNLO Degrande et al: arXiv:1609.04833
  - EW Higgs production
- Higgs production in gluon fusion Deutschmann, Duhr, Maltoni, EV (arXiv: 1708.00460)

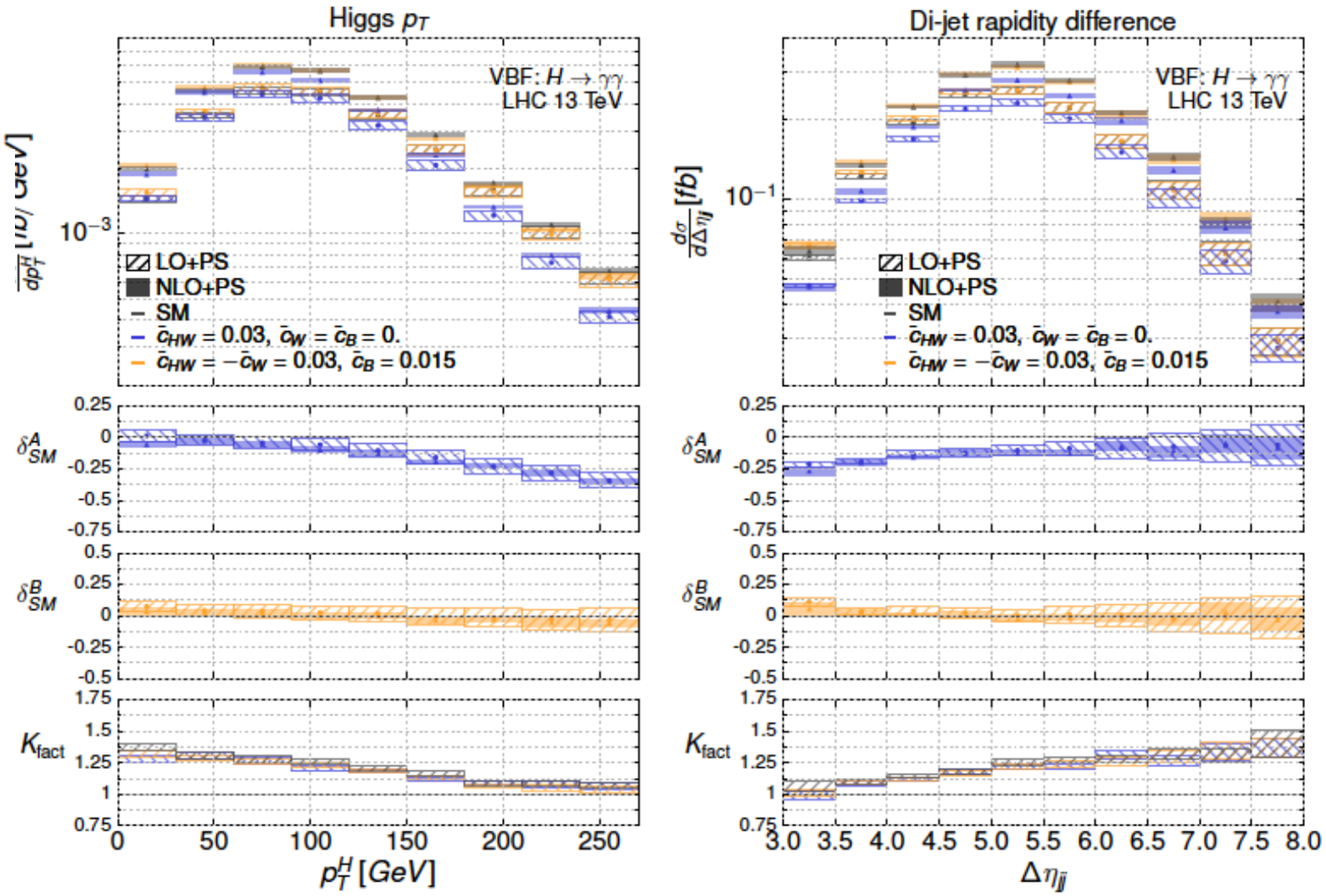
**Top:**

- 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)
- top FCNC: Degrande et al (arxiv:1412.5594), Durieux et al (arXiv:1412.7166)

# EW Higgs production

SILH operators:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{g'^2}{4\Lambda^2}\bar{c}_{BB}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}$$
$$+ \frac{ig}{2\Lambda^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$
$$+ \frac{ig'}{2\Lambda^2}\bar{c}_B\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\partial_\nu B^{\mu\nu}$$
$$+ \frac{ig}{\Lambda^2}\bar{c}_{HW}\left[D_\mu\Phi^\dagger T_{2k}D_\nu\Phi\right]W^{k,\mu\nu}$$
$$+ \frac{ig'}{\Lambda^2}\bar{c}_{HB}\left[D_\mu\Phi^\dagger D_\nu\Phi\right]B^{\mu\nu}\ .$$




Degrande et al: arXiv:1609.04833

http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

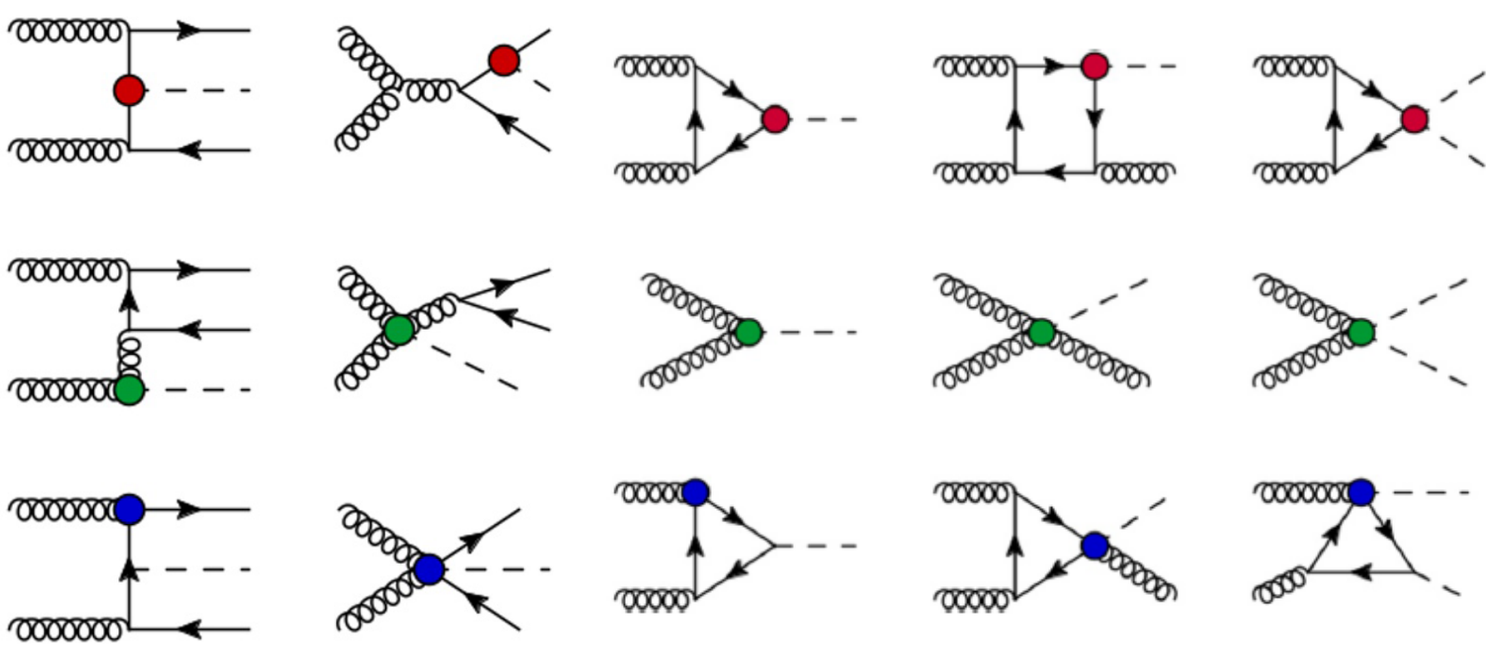
```
./bin/mg5_aMC
import model HELatNLO
generate p p > h j j $$ w+ w- z a  QCD=0 [QCD]
output VBFEFT
```

← NLO

# Top and Higgs in the EFT

## Top-Higgs operators

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



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

ttH

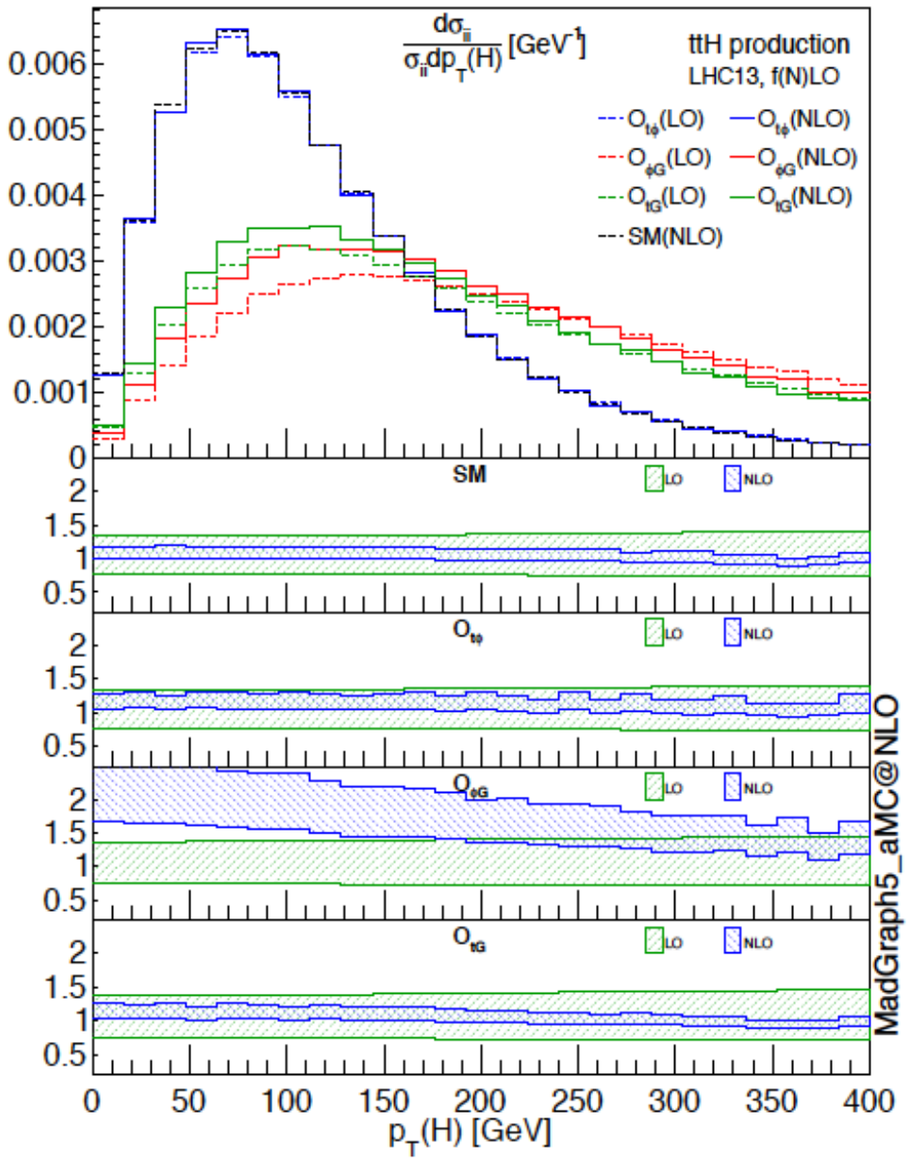
H, H+j, HH

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

# ttH@NLO in the EFT

| 13 TeV | $\sigma$ NLO | K |
|---|---|---|
| $\sigma_{SM}$ | $0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$ | 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 |
| $\sigma_{tG}$ | $0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$ | 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 |

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




Maltoni, EV, Zhang: arXiv:1607.05330

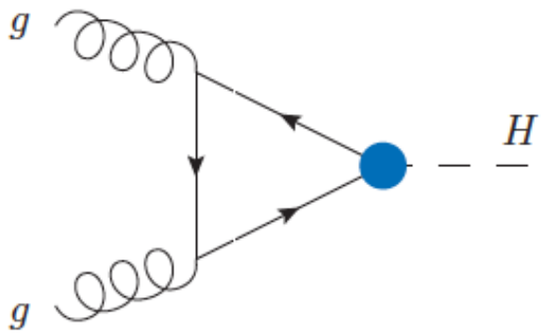
UFO available from authors

```
MG5_aMC>import model TEFT
MG5_aMC>generate p p > t t~ H EFT=1 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

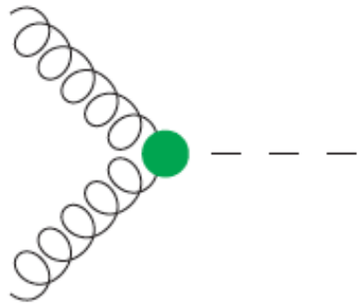
- Different K-factors for different operators, different from the SM
- NLO: smaller uncertainties, non-flat K-factors
- Different shapes for different operators for the squared terms

# SMEFT in single Higgs production

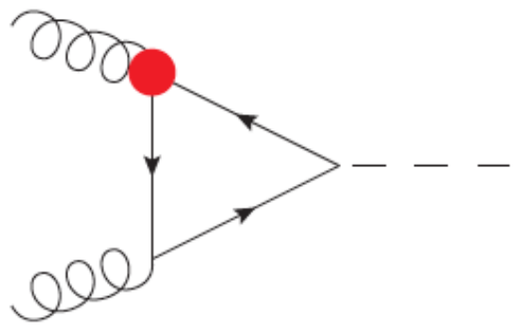
LO:




$(\Phi^\dagger\Phi)\,\bar{Q}_L\Phi\,q_R$



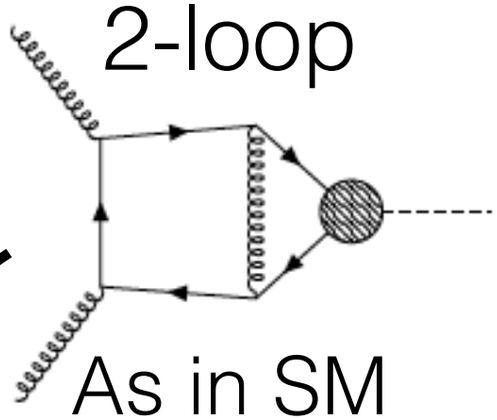
$(\Phi^\dagger\Phi)\,GG$



$\bar{Q}_L\Phi\,\sigma q_R G$

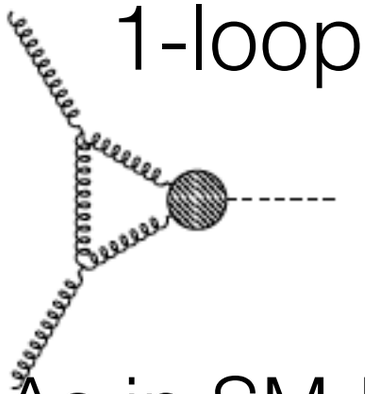
NLO:

2-loop



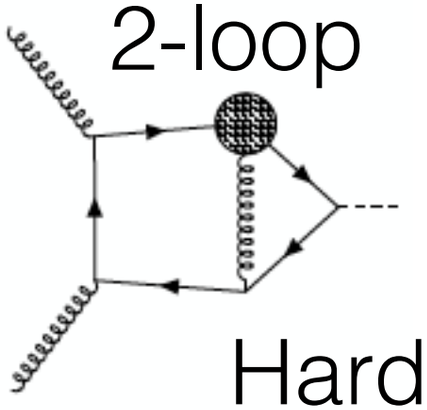
As in SM

1-loop



As in SM-HEFT

2-loop



Harder

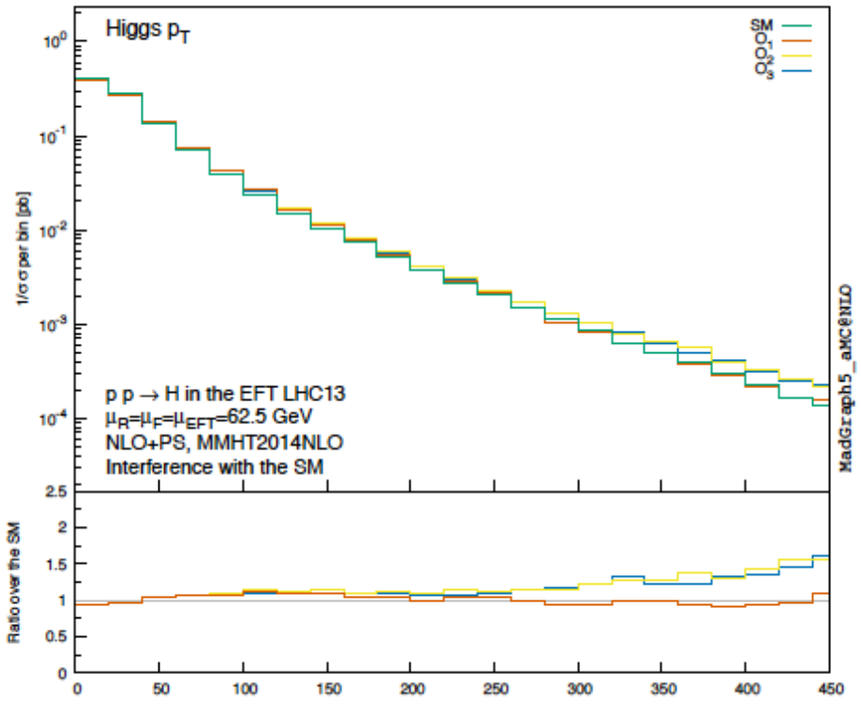
but master integrals known

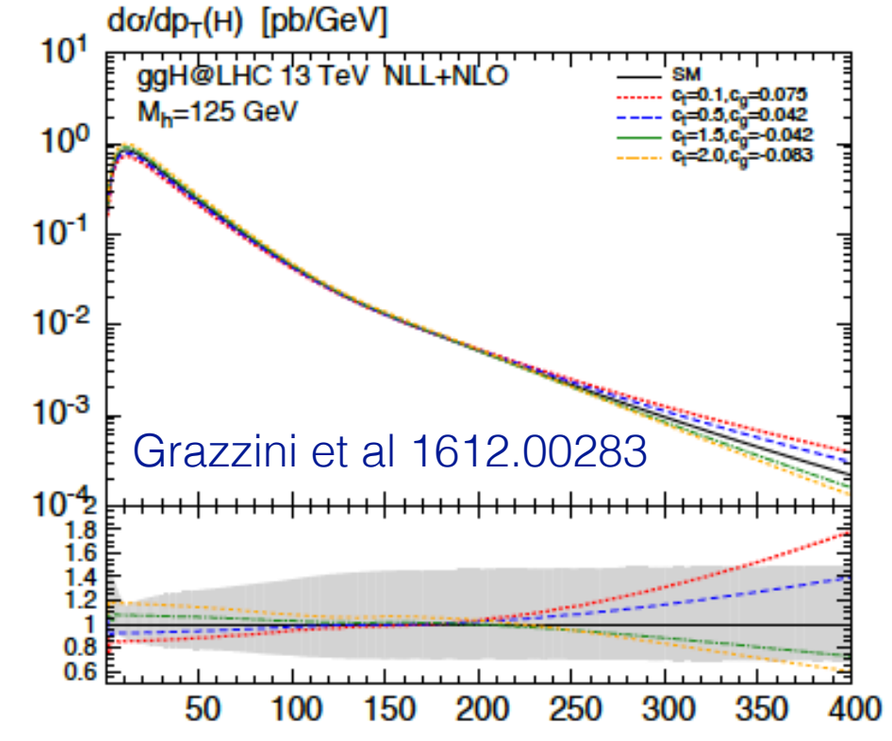
| 13 TeV | $\sigma$ LO | $\sigma/\sigma_{SM}$ LO | $\sigma$ NLO | $\sigma/\sigma_{SM}$ NLO | $K$ |
|---|---|---|---|---|---|
| $\sigma_{SM}$ | $21.3^{+34.0+1.5\%}_{-25.0-1.5\%}$ | 1.0 | $36.6^{+26.4+1.9\%}_{-20.0-1.6\%}$ | 1.0 | 1.71 |
| $\sigma_1$ | $-2.93^{+34.0+1.5\%}_{-25.0-1.5\%}$ | -0.138 | $-4.70^{+24.8+1.9\%}_{-20.0-1.6\%}$ | -0.127 | 1.61 |
| $\sigma_2$ | $2660^{+34.0+1.5\%}_{-25.0-1.5\%}$ | 125 | $4130^{+23.9+1.9\%}_{-19.6-1.6\%}$ | 114 | 1.55 |
| $\sigma_3$ | $50.5^{+34.0+1.5\%}_{-25.0-1.5\%}$ | 2.38 | $83.5^{+26.0+1.9\%}_{-20.6-1.6\%}$ | 2.28 | 1.65 |

Deutschmann, Duhr, Maltoni, EV arXiv: 1708.00460

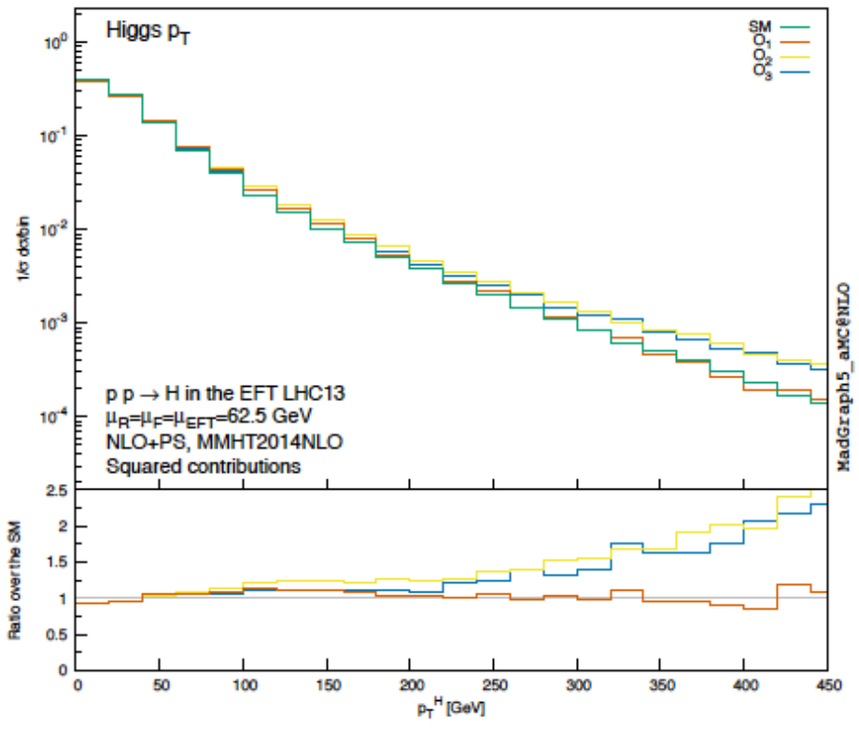
Cross-sections and samples can be provided by the authors

# SMEFT in Higgs production

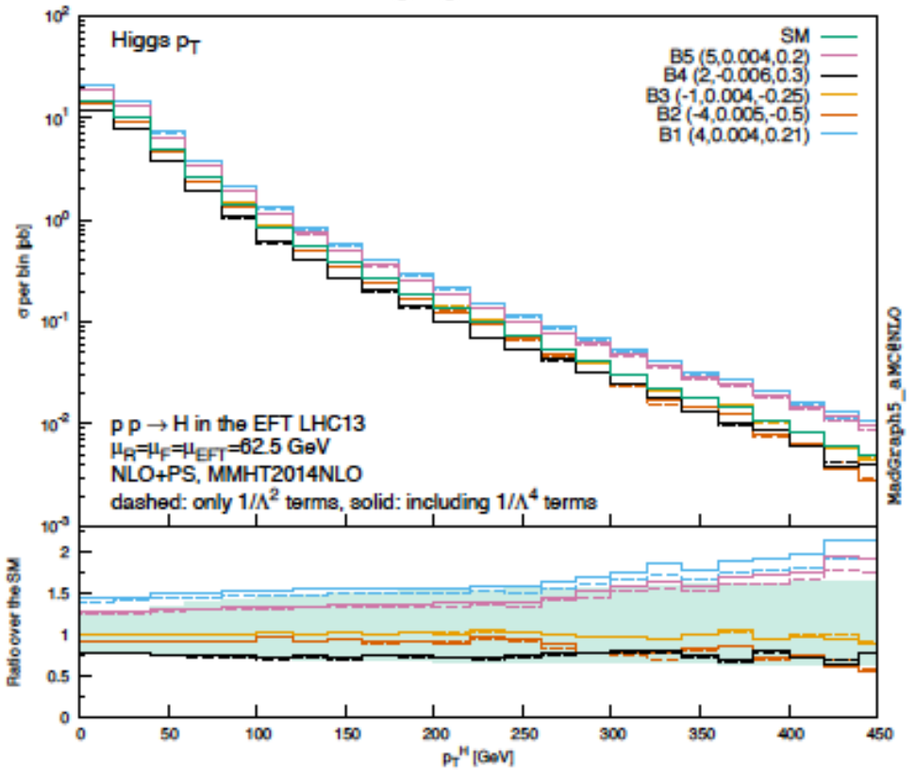



## Higgs $p_T$



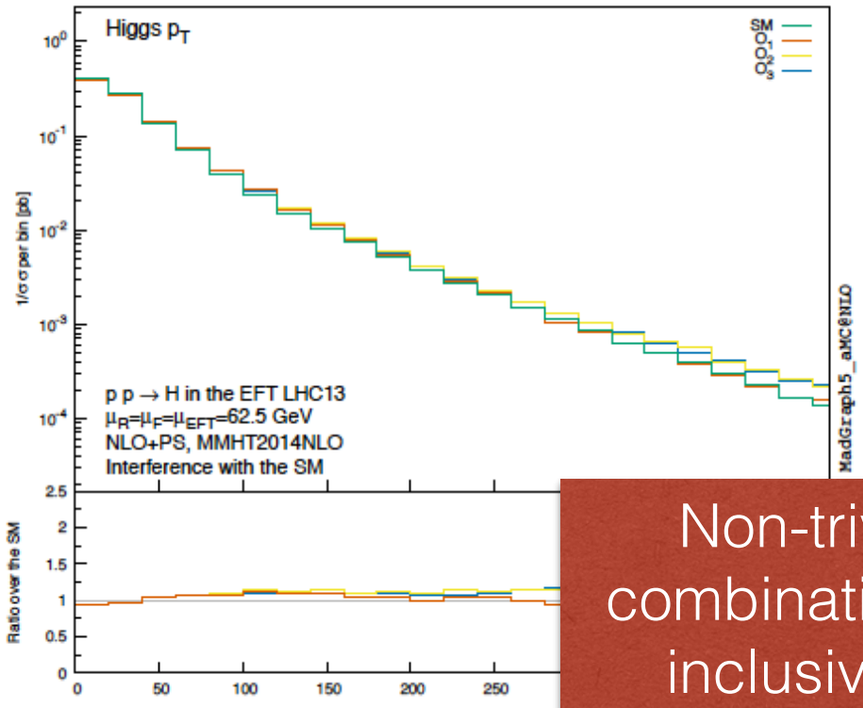

## Higgs $p_T$

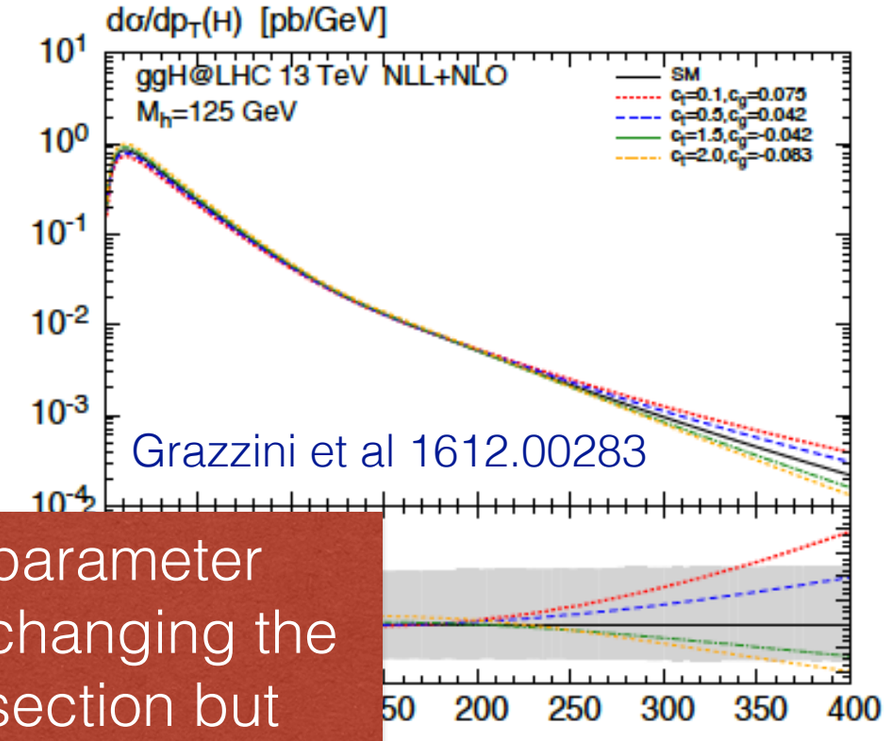





Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

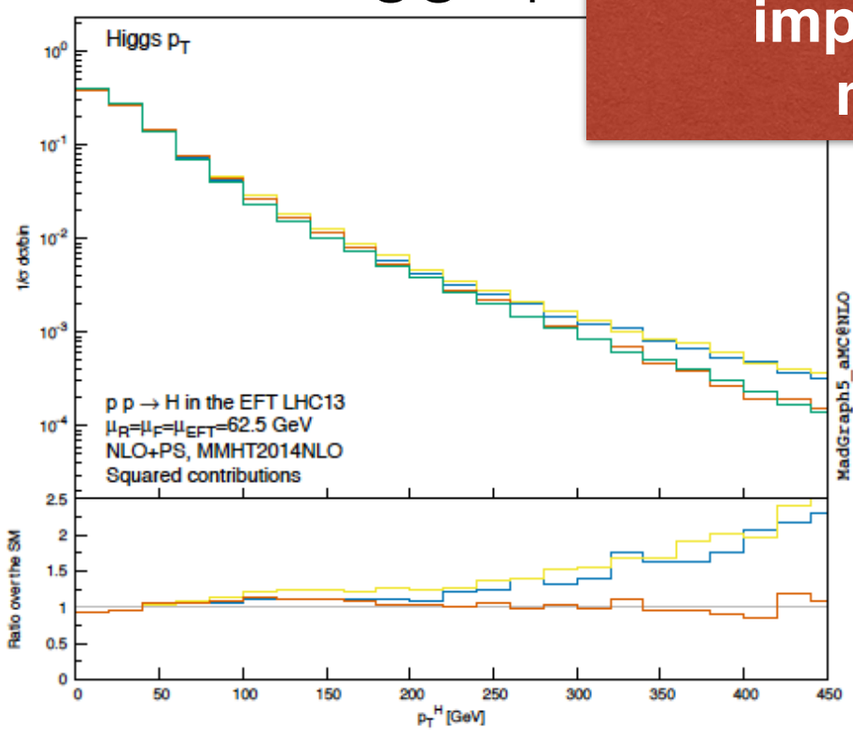
# SMEFT in Higgs production



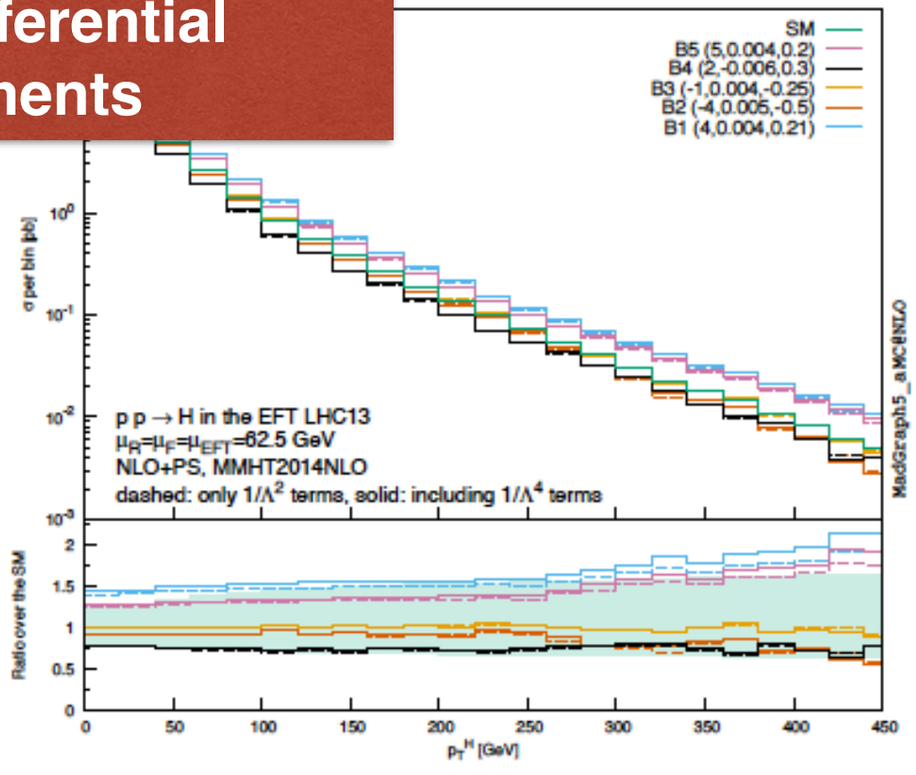




Non-trivial EFT parameter combinations not changing the inclusive cross-section but changing the distributions: **impact of differential measurements**

Higgs $p_T$




ggs $p_T$






Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

# Towards a more complete implementation

| | | |
|---|---|---|
| $\mathcal{O}_W$ | aW | $\varepsilon_{IJK} W^{I}_{\mu\nu} W^{J,\nu\rho} W^{K,\mu}_{\rho}$ |
| $\mathcal{O}_{\varphi G}$ | aphiG | $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G^{\mu\nu}_{A} G^{A}_{\mu\nu}$ |
| $\mathcal{O}_{\varphi B}$ | aphiB | $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$ |
| $\mathcal{O}_{\varphi W}$ | aphiW | $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_{I} W^{I}_{\mu\nu}$ |
| $\mathcal{O}_{\varphi WB}$ | aphiWB | $(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W^{I}_{\mu\nu}$ |
| $\mathcal{O}_{\varphi}$ | aphi | $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$ |
| $\mathcal{O}_{\varphi d}$ | aphid | $\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$ |
| $\mathcal{O}_{\varphi D}$ | aphiDC | $(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$ |
| $\mathcal{O}_{t\varphi}$ | aphit | $\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$ |
| $\mathcal{O}_{tG}$ | atG | $igs\left(\bar{Q}\sigma^{\mu\nu} T_A\, t\right)\tilde{\varphi}\, G^{A}_{\mu\nu} + \text{h.c.}$ |
| $\mathcal{O}_{tB}$ | atB | $i\left(\bar{Q}\sigma^{\mu\nu}\, t\right)\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$ |
| $\mathcal{O}_{tW}$ | atW | $i\left(\bar{Q}\sigma^{\mu\nu}\,\tau_I\, t\right)\tilde{\varphi}\, W^{I}_{\mu\nu} + \text{h.c.}$ |
| $\mathcal{O}^{(1)}_{\varphi l}$ | aphidl | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{l}\gamma^\mu l\right) + \text{h.c.}$ |
| $\mathcal{O}_{\varphi e}$ | aphide | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{e}\gamma^\mu e\right) + \text{h.c.}$ |
| $\mathcal{O}^{(1)}_{\varphi q}$ | aphidq | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{q}\gamma^\mu q\right) + \text{h.c.}$ |
| $\mathcal{O}^{(1)}_{\varphi Q}$ | aphidQL | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right) + \text{h.c.}$ |
| $\mathcal{O}_{\varphi u}$ | aphidu | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}\gamma^\mu u\right) + \text{h.c.}$ |
| $\mathcal{O}_{\varphi t}$ | aphidtR | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right) + \text{h.c.}$ |
| $\mathcal{O}_{\varphi d}$ | aphidd | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{d}\gamma^\mu d\right) + \text{h.c.}$ |
| $\mathcal{O}^{(3)}_{\varphi l}$ | a3phidl | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I\varphi\right)\left(\bar{l}\gamma^\mu \tau^I l\right) + \text{h.c.}$ |
| $\mathcal{O}^{(3)}_{\varphi q}$ | a3phidq | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I\varphi\right)\left(\bar{q}\gamma^\mu \tau^I q\right) + \text{h.c.}$ |
| $\mathcal{O}^{(3)}_{\varphi Q}$ | a3phidQL | $i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I\varphi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right) + \text{h.c.}$ |
| $\mathcal{O}_{\varphi ud}$ | aphiud | $i\left(\tilde{\varphi}\, D_\mu \varphi\right)\left(\bar{u}\gamma^\mu d\right) + \text{h.c.}$ |
| $\mathcal{O}_{\varphi tb}$ | aphitb | $i\left(\tilde{\varphi}\, D_\mu \varphi\right)\left(\bar{t}\gamma^\mu b\right) + \text{h.c.}$ |

A first combination of CP-even top, Higgs and gauge operators
Aim to have complete NLO-ready UFO with Warsaw basis operators soon

Degrande,Maltoni,Mimasu,EV,Zhang in preparation

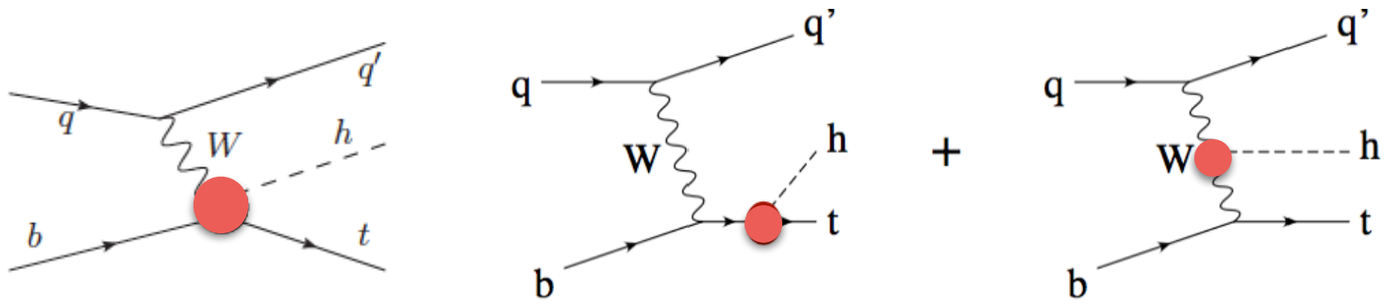
4-fermion operators@NLO also in progress: Degrande, Durieux, Zhang

Based on NLOCT (Degrande, arXiv:1406.3030)

# Application: tHj in the EFT

tHj@LO

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




Higgs weak boson couplings

Top Yukawa

Top weak couplings

$$\mathcal{O}_{\phi D} = \left(\phi^\dagger D_\mu \phi\right)^\dagger \left(\phi^\dagger D^\mu \phi\right)$$
$$\mathcal{O}_{\phi W} = \left(\phi^\dagger \phi - \tfrac{v^2}{2}\right) W_i^{\mu\nu} W^i_{\mu\nu}$$
$$\mathcal{O}_{\phi WB} = \left(\phi^\dagger W^{\mu\nu} \phi\right) B_{\mu\nu}$$

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

$$\mathcal{O}_{tW} = Q_L \sigma_{\mu\nu} W^{\mu\nu} t_R \phi$$
$$\mathcal{O}^{(3)}_{\phi dq} = i\left(\phi^\dagger i \overleftrightarrow{D}^i_\mu \phi\right) \bar{q}_L \gamma^\mu \sigma^i q_L$$
$$\mathcal{O}^{(3)}_{\phi dQ_L} = i\left(\phi^\dagger i \overleftrightarrow{D}^i_\mu \phi\right) \bar{Q}_L \gamma^\mu \sigma^i Q_L$$

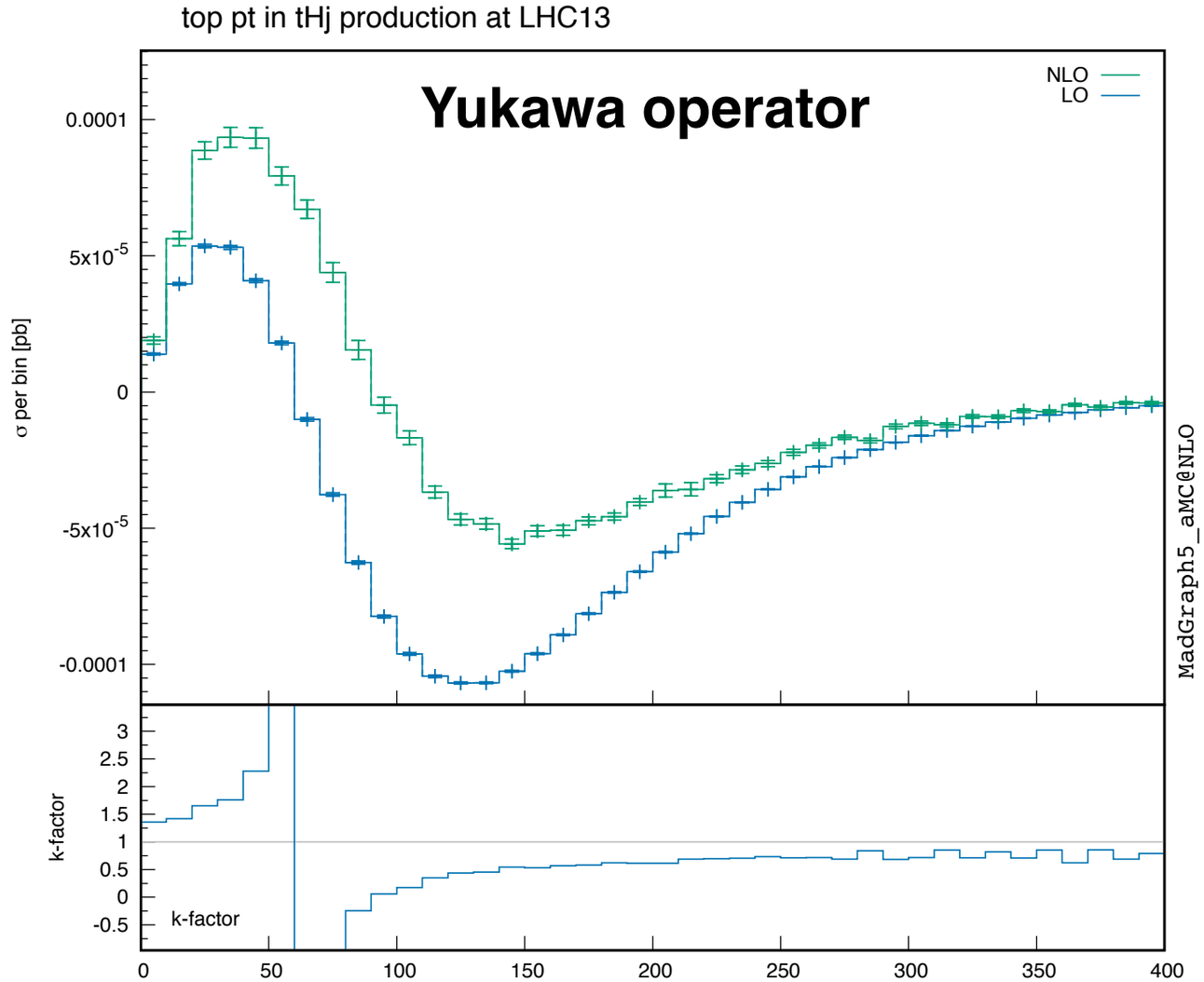
NLO QCD computation including all operators in progress: Degrande,Maltoni,Mimasu,EV,Zhang
Complete UFO model combining top and Higgs operators under construction

# single top+Higgs in the EFT

| $\sigma$ [fb] | LO | NLO |
|---|---|---|
| $\sigma_{SM}$ | $57.56(4)^{+11.2\%}_{-7.4\%} \pm 10.2\%$ | $75.87(4)^{+2.2\%}_{-6.4\%} \pm 1.2\%$ |
| $\sigma_{\varphi W}$ | $8.12(2)^{+13.1\%}_{-9.3\%} \pm 9.3\%$ | $7.76(2)^{+7.0\%}_{-6.3\%} \pm 1.0\%$ |
| $\sigma_{\varphi W,\varphi W}$ | $5.212(7)^{+10.6\%}_{-6.8\%} \pm 10.2\%$ | $6.263(7)^{+2.6\%}_{-7.8\%} \pm 1.3\%$ |
| $\sigma_{t\varphi}$ | $-1.203(6)^{+12.0\%}_{-15.6\%} \pm 8.9\%$ | $-0.246(6)^{+144.5\%}_{-157.8\%} \pm 2.1\%$ |
| $\sigma_{t\varphi,t\varphi}$ | $0.6682(9)^{+12.7\%}_{-8.9\%} \pm 9.6\%$ | $0.7306(8)^{+4.6\%}_{-7.3\%} \pm 1.0\%$ |
| $\sigma_{tW}$ | $9.69(3)^{+13.0\%}_{-9.3\%} \pm 9.4\%$ | $11.09(3)^{+3.8\%}_{-6.8\%} \pm 1.0\%$ |
| $\sigma_{tW,tW}$ | $11.60(2)^{+9.3\%}_{-5.5\%} \pm 11.1\%$ | $17.81(2)^{+7.4\%}_{-14.0\%} \pm 1.9\%$ |
| $\sigma_{\varphi Q^{(3)}}$ | $-0.757(8)^{+0.0\%}_{-2.2\%} \pm 15.4\%$ | $-2.51(1)^{+11.1\%}_{-8.9\%} \pm 1.8\%$ |
| $\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$ | $0.702(1)^{+9.4\%}_{-5.6\%} \pm 11.2\%$ | $0.955(1)^{+5.0\%}_{-10.9\%} \pm 1.8\%$ |
| $\sigma_{\varphi tb}$ | 0 | 0 |
| $\sigma_{\varphi tb,\varphi tb}$ | $2.752(4)^{+9.4\%}_{-5.5\%} \pm 11.3\%$ | $3.768(4)^{+5.0\%}_{-10.9\%} \pm 1.8\%$ |

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

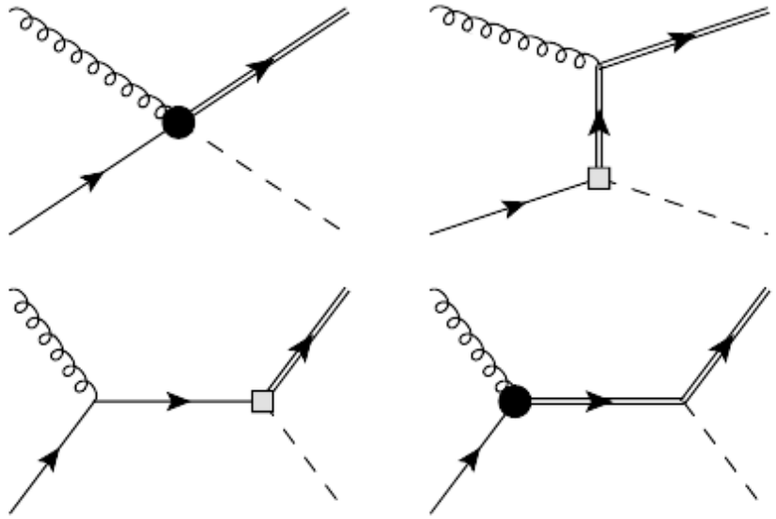
Preliminary

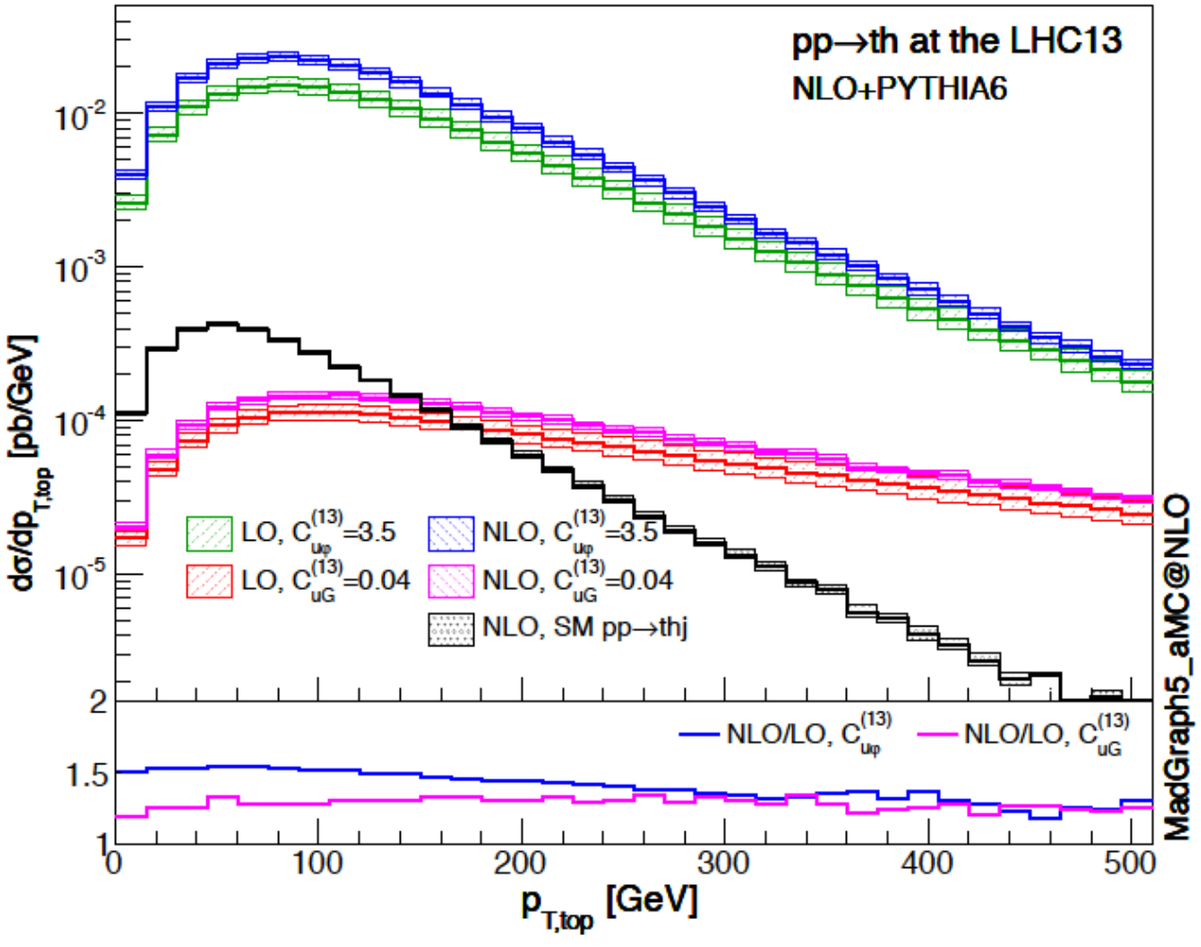



Potentially interesting shapes
Non-flat k-factors

# FCNC for tH

$$O_{\varphi q}^{(3,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{q}_i \gamma^\mu \tau^I Q)$$
$$O_{\varphi q}^{(1,i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_i \gamma^\mu Q)$$
$$O_{\varphi u}^{(i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{u}_i \gamma^\mu t)$$
$$O_{uB}^{(i3)} = g_Y(\bar{q}_i \sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}, \quad O_{uW}^{(i3)} = g_W(\bar{q}_i \sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
$$O_{uG}^{(i3)} = g_s(\bar{q}_i \sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}, \quad O_{u\varphi}^{(i3)} = (\varphi^\dagger\varphi)(\bar{q}_i t)\tilde{\varphi},$$






| | LO | | NLO | |
|---|---|---|---|---|
| Coefficient | $\sigma$[fb] | Scale uncertainty | $\sigma$[fb] | Scale uncertainty |
| $C_{u\varphi}^{(13)} = 3.5$ | 2603 | +13.0% -11.0% | 3858 | +7.4% -6.7% |
| $C_{uG}^{(13)} = 0.04$ | 40.1 | +16.5% -13.2% | 50.7 | +4.0% -5.2% |
| $C_{u\varphi}^{(23)} = 3.5$ | 171 | +9.7% -8.7% | 310 | +7.3% -6.3% |
| $C_{uG}^{(23)} = 0.09$ | 9.53 | +11.0% -9.7% | 16.6 | +5.5% -5.1% |

http://feynrules.irmp.ucl.ac.be/wiki/TopFCNC

>import model TopFCNC
>generate p p > t h [QCD]
>output some_DIR
>launch

Degrande et al (arxiv:1412.5594)

# Summary

- Improved Monte Carlo tools: towards reaching SM precision and automation for the EFT
- Better description of QCD effects for EFT in Higgs physics, through public and user-friendly tools
- Complete dim-6 EFT implementation at NLO QCD: in progress