SMEFT@NLO

Automated one-loop computations in the SMEFT

arXiv:2008.11743

Ken Mimasu

King's College London

LHC EW WG general meeting, 7th October 2020

on behalf of: Gauthier Durieux, Céline Degrande, Fabio Maltoni, KM, Cen Zhang & Eleni Vryonidou

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

SMEFT is…

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-4})$$

Model independent

- Underlying assumptions

Heavy new physics: $M > E_{exp}$

SM field content & gauge symmetries

Linear EWSB: Higgs = doublet

Systematically improvable

- Double expansion *higher dim.* $\frac{E^2}{\Lambda^2}$ & $\{g_S,\, g,\, g'\}$ *more loops*

Global

- Model independence: we don't know what operators NP will generate
- Patterns & correlations among observables are key
- Ultimate goal: complete likelihood for SMEFT confronted with HEP data

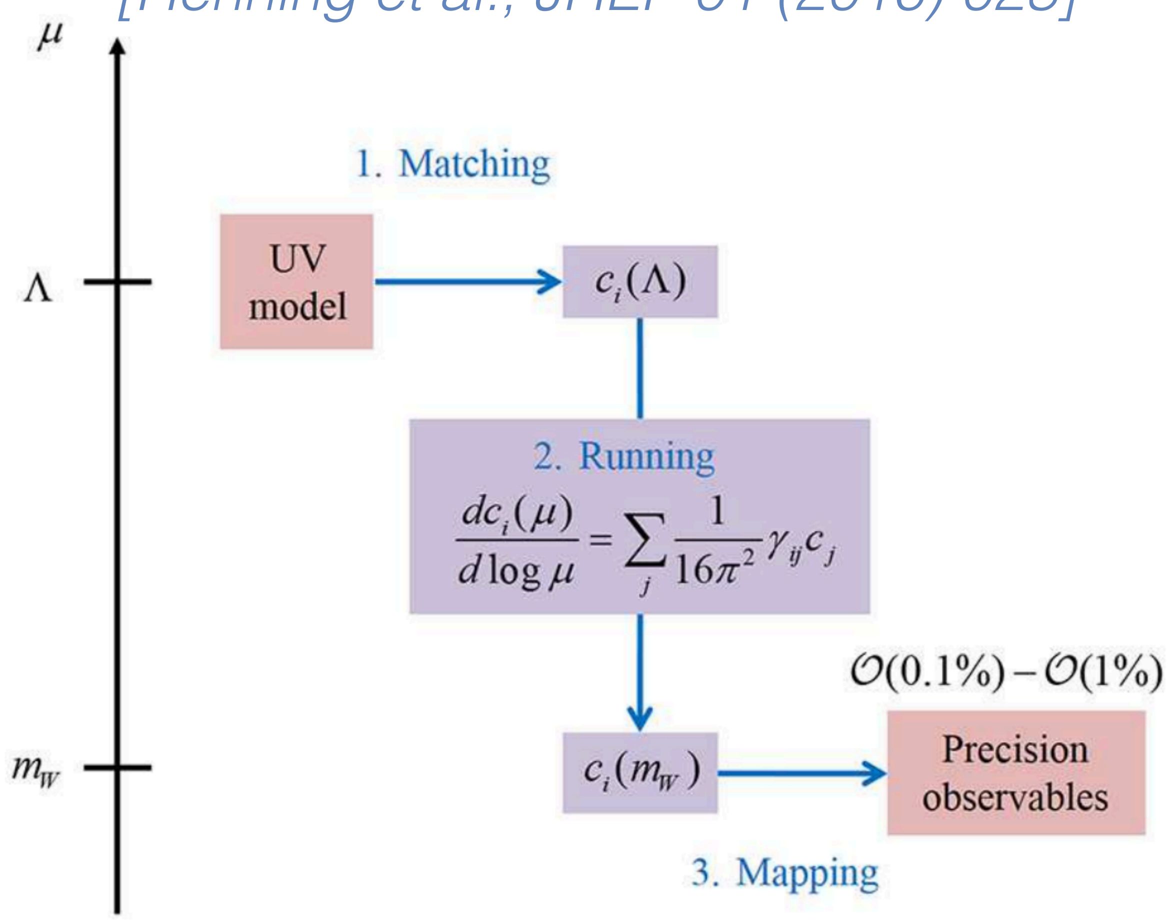
EWPO, Higgs, multiboson, top, DY, flavor,…

Established part of LHC programme

Higher orders

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-4})$$

[Henning et al.; JHEP 01 (2016) 023]



Dimension 7,8,9,…

[Lehman; PRD 90 (2014) 12, 125023]
[Lehman & Martin; JHEP 02 (2016) 081]
[Henning et al.; JHEP 08 (2017) 016]
[Liao, Ma & Wang; JHEP 08 (2020) 162]
[Li et al.; 2005.00008]
[Murphy; arXiv: 2005.00059]
[Liao & Ma.; 2007.08125]
[Li et al.; 2007.07899]
Increasing # of explicit studies

One-loop (QCD, EW)
Too many works to cite…

We can improve in Λ & g for all stages 1-3

- Bottom-up: mapping Wilson coefficients to observables (stage 3.)
- LHC priority: dimension-6 & QCD loops

Precision interpretations

Want to improve…

$$\Delta o_n = o_n^{\mathrm{EXP}} - o_n^{\mathrm{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Precision interpretations

Want to improve…

$$\boxed{\Delta o_n} = o_n^{\mathrm{EXP}} - o_n^{\mathrm{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Precision interpretations

Want to improve…

$$\Delta o_n = o_n^{\text{EXP}} - o_n^{\text{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity

Experiment:
Best measurements & understanding of uncertainties and correlations

Theory:
Best available predictions for observables (NLO, NNLO, N3LO,…)

Precision interpretations

Want to improve…

$$\Delta o_n = o_n^{\mathrm{EXP}} - o_n^{\mathrm{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity

Experiment:
Best measurements & understanding of uncertainties and correlations

Theory:
Best available predictions for observables (NLO, NNLO, N3LO,…)

Interpretation

Relies on accurate knowledge of the size & correlation among a_i

Determining $c_i^{(6)}$ requires most precise available SMEFT predictions

Why higher orders

Higher orders in SMEFT improve…

Accuracy (better central value)

- No deviation: better representation of new physics reach
- Yes deviation: better pinpointing of new physics origin

Precision (better error bars)

- Control over scale uncertainty (must include running & mixing)

Sensitivity

- Knowledge of the patterns & correlations
- Differential predictions - key for, *e.g.*, multivariate & ME based analyses
- New loop-induced sensitivity (*e.g.*, top loop in ggF)

SMEFT@NLO

NLO computations for SMEFT: very active field

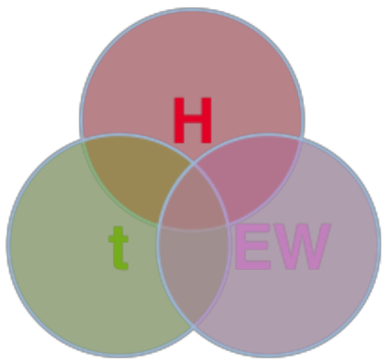
- Many results & analyses have appeared in the last few years
- Non-universal K-factors in EFT space → new information at NLO
- Experimental interest in including one-loop for SMEFT analyses/interpretations

Many processes x many operators

- NLO generally complicates picture: more cross-talk, more operators
- Automated tools for Fixed Order/NLO+PS are essential

SMEFT@NLO *[Degrande et al.; arXiv:2008.11743]*
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- NLO UFO model for MadGraph5_aMC@NLO
- Process independent SMEFT implementation: top-specific flavor limit
- Suitable for LO/NLO computations of EW/Higgs/Top processes



Standard Model Effective Theory at One-Loop in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang, arXiv:2008.11743

The implementation is based on the Warsaw basis of dimension-six SMEFT operators, after canonical normalization. Electroweak input parameters are taken to be G_F, M_Z, M_W. The CKM matrix is approximated as a unit matrix, and a $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$ flavor symmetry is enforced. It forbids all fermion masses and Yukawa couplings except that only of the top quark. The model therefore implements the five-flavor scheme for PDFs.

A new coupling order, `NP=2`, is assigned to SMEFT interactions. The cutoff scale `Lambda` takes a default value of 1 TeV^{-2} and can be modified along with the Wilson coefficients in the `param_card`. Operators definitions, normalisations and coefficient names in the UFO model are specified in definitions.pdf. The notations and normalizations of top-quark operator coefficients comply with the LHC TOP WG standards of 1802.07237. Note however that the flavor symmetry enforced here is slightly more restrictive than the baseline assumption there (see the dim6top page for more information). This model has been validated at tree level against the `dim6top` implementation (see 1906.12310 and the comparison details).

Current implementation

UFO model: SMEFTatNLO_v1.0.tar.gz

The current implementation imposes CP conservation. In the quark sector, it focuses primarily on top-quark interactions. The light-quark current operator, qqHDH, uuHDH, ddHDH, with coefficients `cpq3i`, `cpqMi`, `cpu`, `cpd` are however included. The triple-gluon operator, with coefficient `cG`, is currently not available (see the loop-capable GGG implementation). Vertices including more than four scalars or four leptons are not included. Scalar and tensor `QQll` operators, with coefficients `ctlS3`, `ctlT3`, and `cblS3`, break our flavor symmetry assumption and are not available for one-loop computations. Top-quark flavor-changing interactions, not compatible with the imposed flavor symmetry, are not included (see the loop-capable TopFCNC implementation).

Unlike prescribed by the LHC TOP WG, the top quark chromomagnetic-dipole operator coefficient `ctG` is normalized with a factor of the strong coupling, g_S. This normalization factor temporarily ensures compatibility with the 2.X.X series of MadGraph5_aMC@NLO but may be dropped in the future. As with every other appearance of this coupling in MadGraph5_aMC@NLO, its value is renormalisation-group evolved to the QCD renormalization scale (set in the run_card).

```
MG5_aMC>import model SMEFTatNLO
MG5_aMC>generate p p > t t~ NP=2 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

What's in there?

'Warsaw' basis

not 2499 operators!

[Grzadkowski et al.; JHEP 1010 (2010) 085]

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
~~$Q_{\varphi\widetilde WB}$~~	~~$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$~~	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		~~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}~~	~~$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$~~

Some symmetries imposed to control parameter space

- CP, B and flavor conservation
- Top-specific flavour structure of 2 & 4 fermion operators

Flavor symmetry

Approximate flavor symmetry in the SM

- Broken by Yukawa interactions
- In the SMEFT, broken by: $\psi^2 X\varphi,\ \psi^2\varphi^3, (\bar{L}R)(\bar{L}R), (\bar{L}R)(\bar{R}L)\ \&\ \mathcal{O}_{\varphi ud}$
- Any off-diagonal or non-universal entries of other 2F operators

SMEFTatNLO: minimal extension to single out top quark

universal	$U(3)_L \times U(3)_e \times U(3)_Q \times U(3)_u \times U(3)_d$
top	$U(3)_L \times U(3)_e \times U(2)_Q \times U(2)_u \times U(3)_d$

cf. Minimal flavor violation

Yukawa	$\psi^2 H^3 : (\varphi^\dagger\varphi)^2(\bar{Q}\, t\, \tilde{\varphi})$
Dipoles	$\psi^2 X H : (\bar{Q}\,\sigma^{\mu\nu}\, t\,\tilde{\varphi})B_{\mu\nu}\ [W^I_{\mu\nu}, G^a_{\mu\nu}]$
3rd gen. currents	$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\,\gamma^\mu\, Q)\ [(\bar{Q}\,\gamma^\mu\tau^I\, Q), (\bar{t}\,\gamma^\mu\, t), ...]$
3rd gen. 4F	$\psi^4 : (\bar{Q}\,\gamma^\mu\, Q)(\bar{q}\,\gamma_\mu\, q), (\bar{Q}\,\gamma^\mu\, Q)(\bar{Q}\,\gamma_\mu\, Q), ...$

See Dim6top

[Aguilar-Saavedra et al.; arXiv:1802.07237]

What's in there?

Bosonic operators of the Warsaw basis

Top-specific flavour structures

- Chirality-flipping interactions involving Q_3 & t_R
- Bottom quark chirality-flipping interactions not present (b_R)
- Chirality-conserving interactions: universal gen. 1 & 2 + 3rd gen

$$[\mathcal{O}^{(3)}_{\varphi q}] \to [\mathcal{O}^{(3)}_{\varphi q}]^{j,j} \text{ and } [\mathcal{O}^{(3)}_{\varphi q}]^{3,3} = \{\mathcal{O}^{(3)}_{\varphi q_i}, \mathcal{O}^{(3)}_{\varphi Q}\}$$
$$[\mathcal{O}_{\varphi u}] \to [\mathcal{O}_{\varphi u}]^{j,j} \text{ and } [\mathcal{O}_{\varphi u}]^{3,3} = \{\mathcal{O}_{\varphi u_i}, \mathcal{O}_{\varphi t}\}$$

- four-fermions: 2-heavy-2-light & 4-heavy (no 4-light)

Lepton sector: $[U(1)_L \times U(1)_e]^3$, flavor diagonal (e,μ,τ)

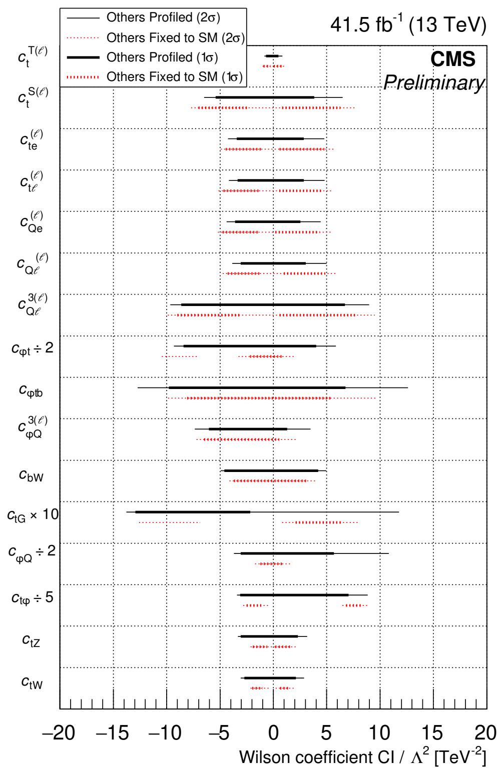
Conventions match dim6top, where relevant

See definitions.pdf on webpage for more details

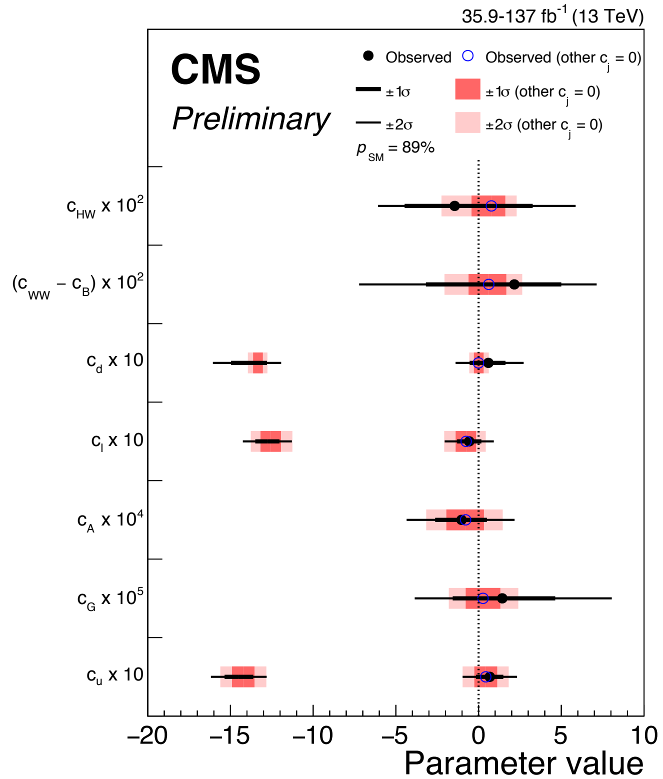
[CMS-PAS-TOP-001] [CMS-PAS-HIG-19-005] [CERN-EP-2020-034]

NLO QCD OK ✓

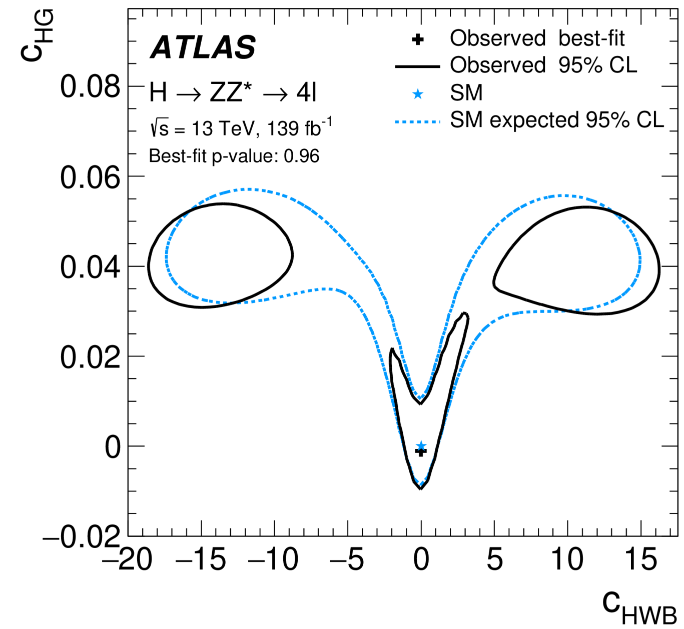
ttH, ttZ, ttW, tW, tZ, tH



Higgs combination

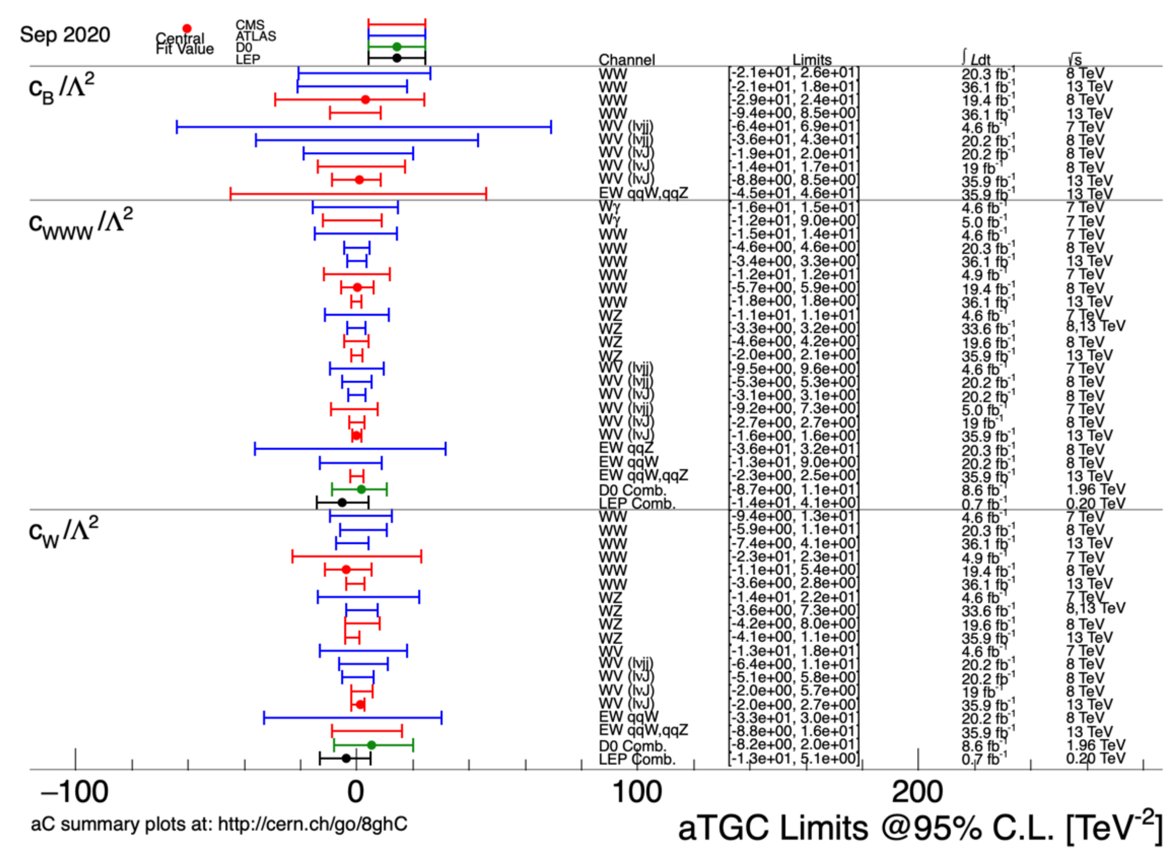


H → 4l



hh (LO),
VVV,
VBS,
tt,
4top,
. . .

WW & WZ



[ATLAS; PRD 99 (2017) 072009]

ttV

Coefficients	$\mathcal{C}^{(3)}_{\phi Q}/\Lambda^2$	$\mathcal{C}_{\phi t}/\Lambda^2$	$\mathcal{C}_{tB}/\Lambda^2$	$\mathcal{C}_{tW}/\Lambda^2$
Previous indirect constraints at 68% CL	[−4.7, 0.7]	[−0.1, 3.7]	[−0.5, 10]	[−1.6, 0.8]
Previous direct constraints at 95% CL	[−1.3, 1.3]	[−9.7, 8.3]	[−6.9, 4.6]	[−0.2, 0.7]
Expected limit at 68% CL	[−2.1, 1.9]	[−3.8, 2.7]	[−2.9, 3.0]	[−1.8, 1.9]
Expected limit at 95% CL	[−4.5, 3.6]	[−23, 4.9]	[−4.2, 4.3]	[−2.6, 2.6]
Observed limit at 68% CL	[−1.0, 2.7]	[−2.0, 3.5]	[−3.7, 3.5]	[−2.2, 2.1]
Observed limit at 95% CL	[−3.3, 4.2]	[−25, 5.5]	[−5.0, 5.0]	[−2.9, 2.9]
Expected limit at 68% CL (linear)	[−1.9, 2.0]	[−3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[−3.7, 4.0]	[−5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[−1.0, 2.9]	[−1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[−2.9, 4.9]	[−4.8, 7.5]	–	–

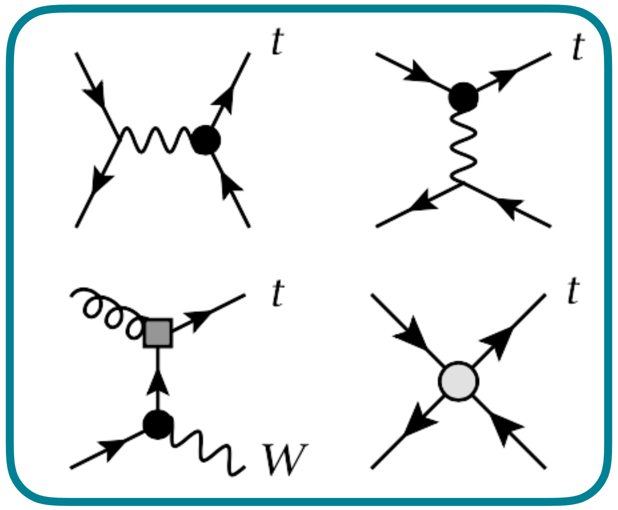
Selected results

Some from previous works, superseded by SMEFT@NLO

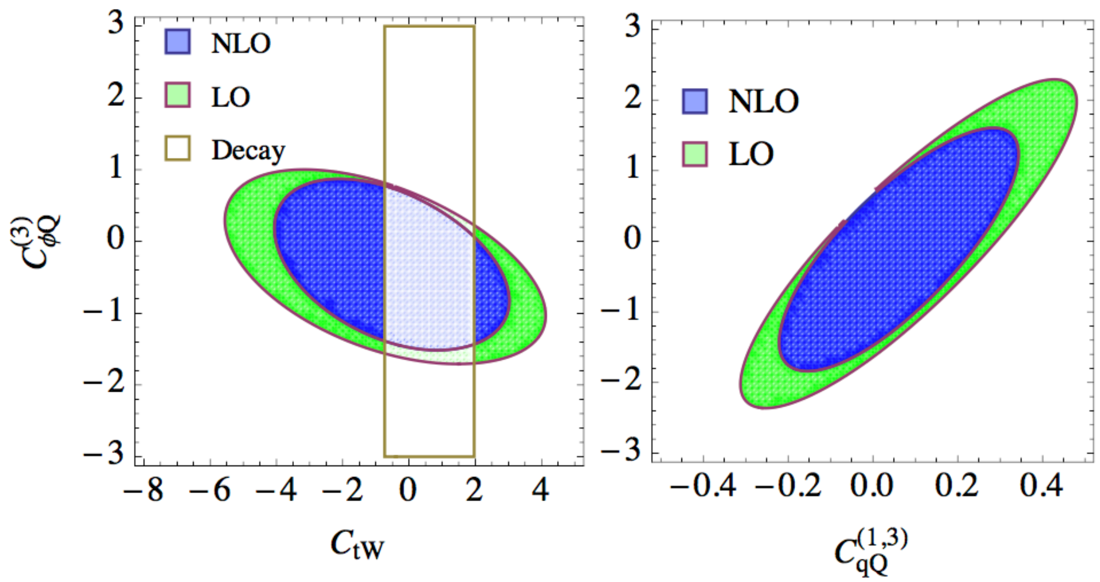
A few, simple new results presented in 2008.11743

Single top

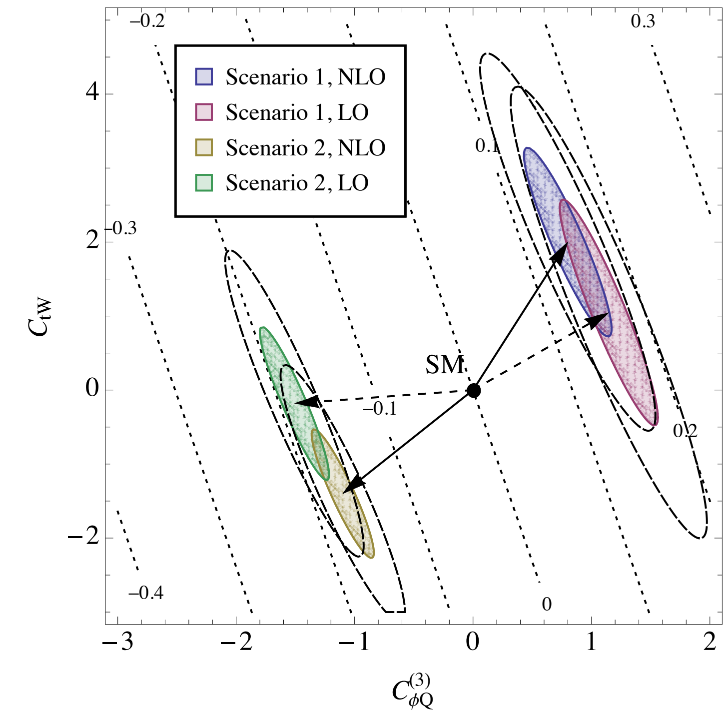
[Zhang; PRL 116 (2016) 162002]



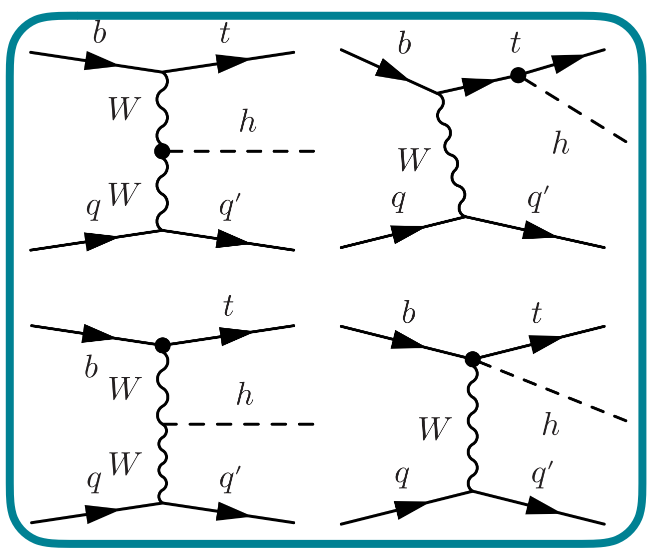
Fit without deviation



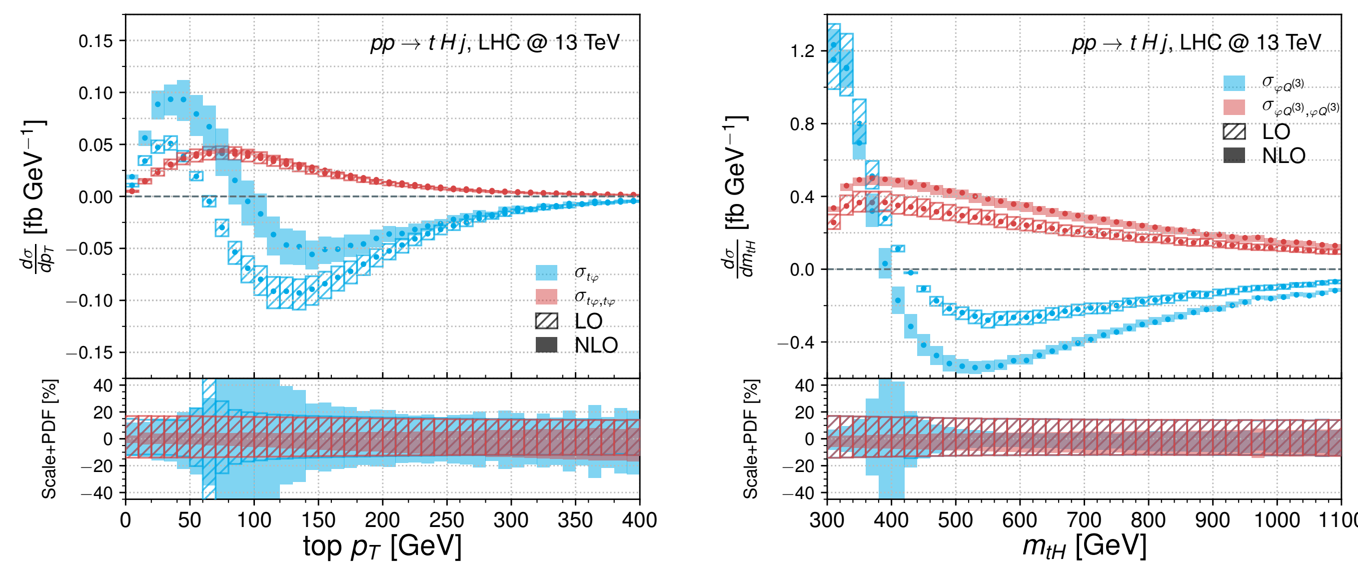
Fit with a (hypothetical) deviation



[Degrande et al.; JHEP 10 (2018) 005]



t Z j & t H j

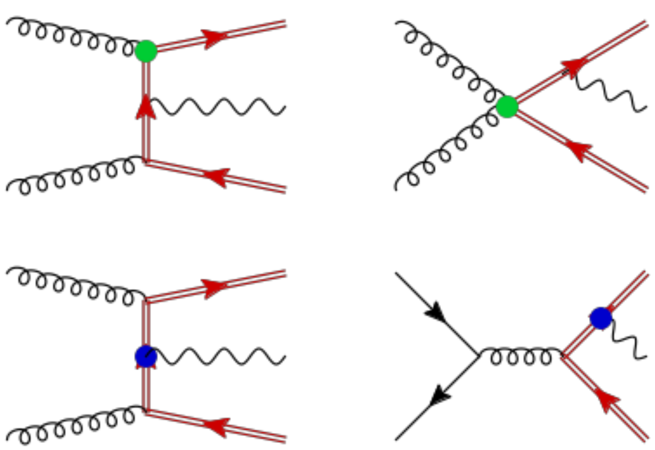


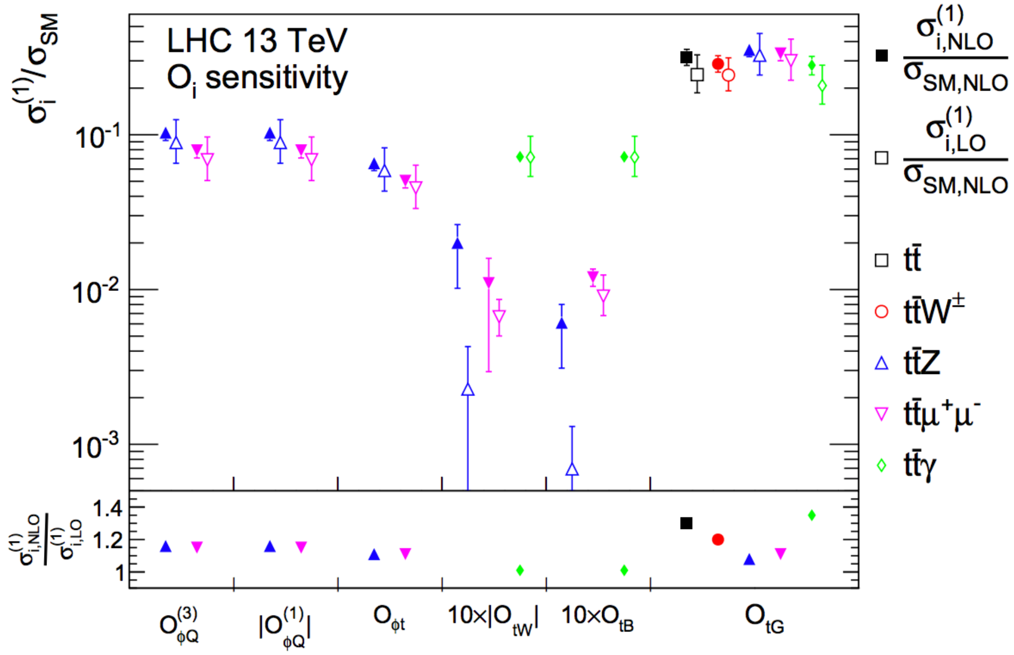
σ [fb]	K-factor
σ_{SM}	1.32
$\sigma_{\varphi W}$	0.96
$\sigma_{\varphi W,\varphi W}$	1.20
$\sigma_{t\varphi}$	0.20
$\sigma_{t\varphi,t\varphi}$	1.09
σ_{tW}	1.14
$\sigma_{tW,tW}$	1.54
$\sigma_{\varphi Q^{(3)}}$	3.31
$\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$	1.36

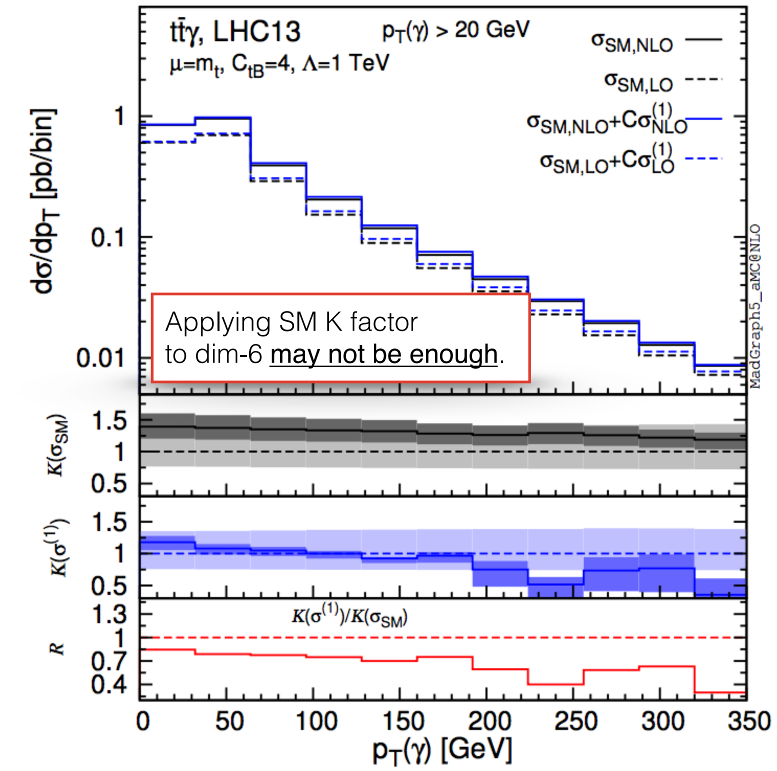
Different patterns of phase-space cancellations at LO/NLO lead to non-trivial & strange K factors

[Bylund et al.; JHEP 1605 (2016) 052]

$t\bar{t}\gamma / t\bar{t}Z$

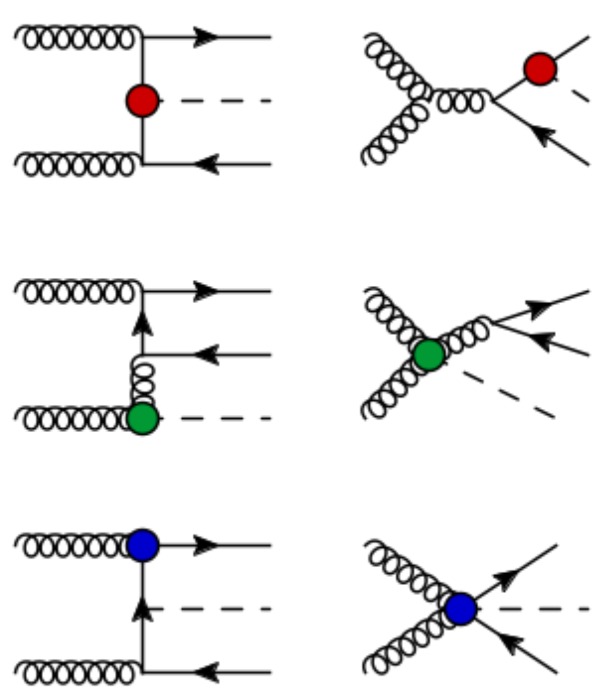


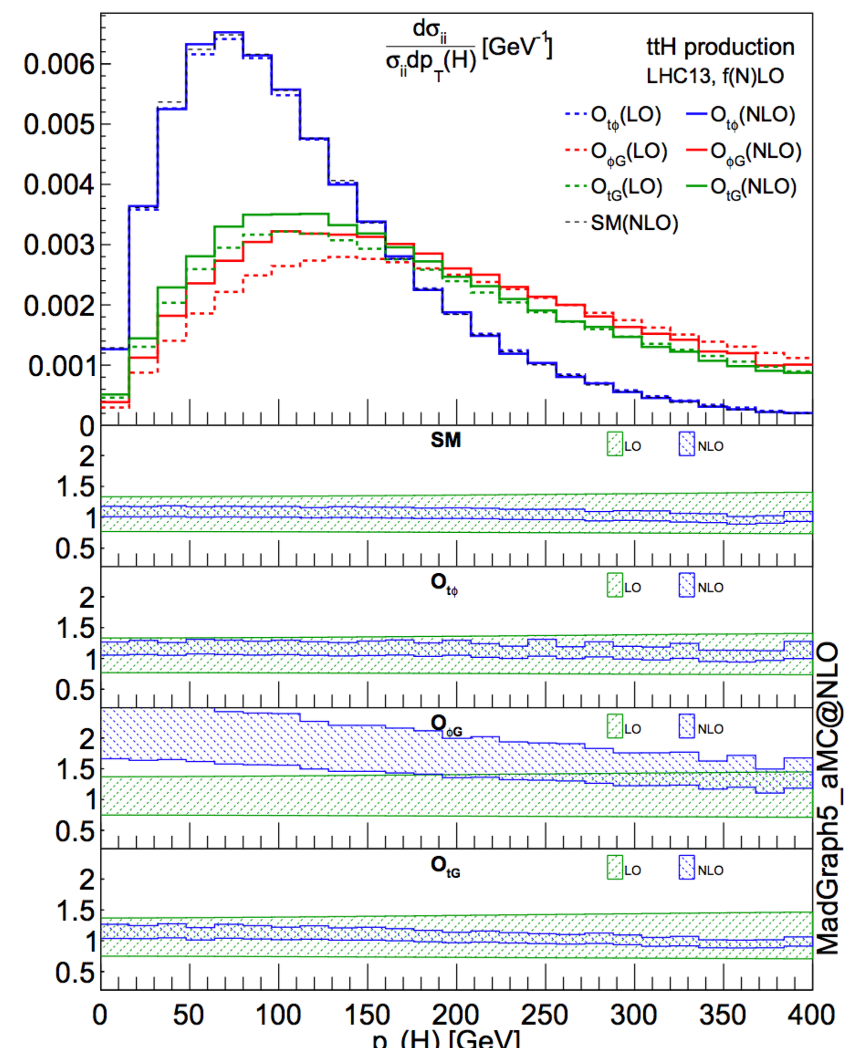




[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

$t\bar{t}H$





13 TeV	σ LO	σ NLO	K
σ_{SM}	$0.464^{+0.161}_{-0.111}$	$0.507^{+0.03}_{-0.04}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.0}_{-0.0}$	$-0.062^{+0.}_{-0.}$	1.13
$\sigma_{\phi G}$	$0.627^{+0.225}_{-0.153}$	$0.872^{+0.13}_{-0.12}$	1.39
σ_{tG}	$0.470^{+0.167}_{-0.114}$	$0.503^{+0.02}_{-0.04}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.00}_{-0.00}$	$0.0019^{+0.0}_{-0.0}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.274}_{-0.178}$	$1.021^{+0.20}_{-0.17}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.276}_{-0.178}$	$0.674^{+0.03}_{-0.06}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.037^{+0.0}_{-0.0}$	$-0.053^{+0.}_{-0.}$	1.42
$\sigma_{t\phi,tG}$	$-0.028^{+0.0}_{-0.0}$	$-0.031^{+0.}_{-0.}$	1.10
$\sigma_{\phi G,tG}$	$0.627^{+0.252}_{-0.166}$	$0.859^{+0.12}_{-0.12}$	1.37

Non-universal K-factors
in rates & distributions

[SMEFT@NLO; arXiv:2008.11743]

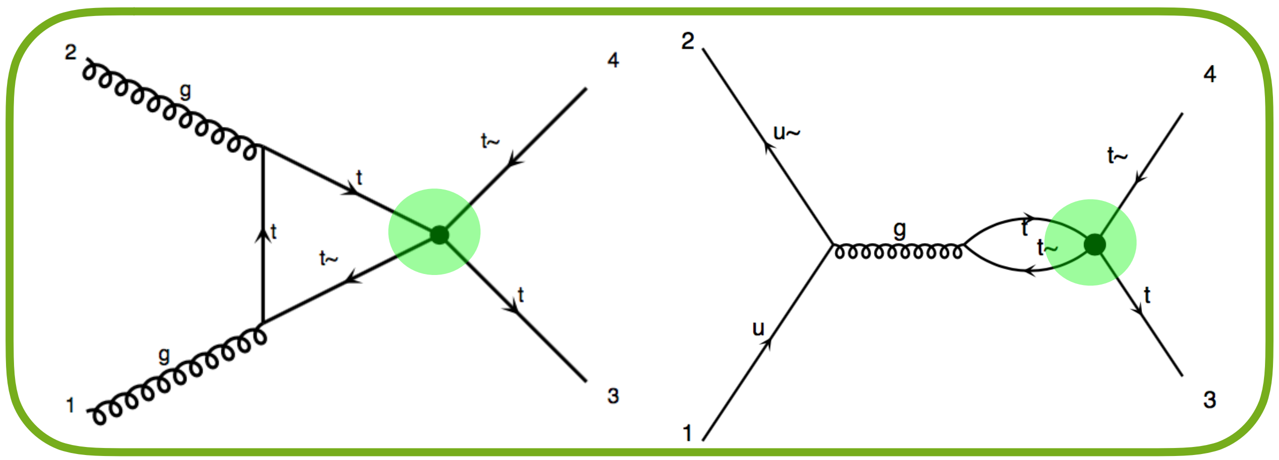
4F in top pair

LHC 13 TeV, SM = 744 pb, K-factor = 1.46

color-octet qqtt:
dominant operators in ttbar
NLO corrections can break degeneracies

color-singlet qqtt:
interference with QCD ttbar at NLO
[x] interference with EW ttbar

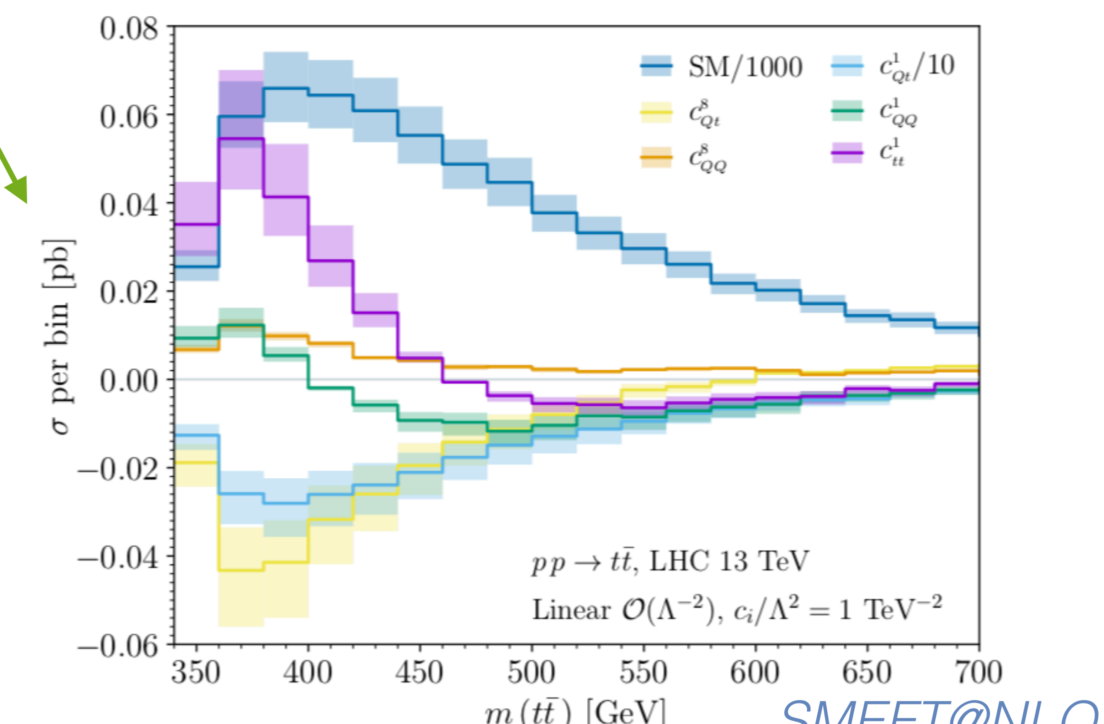
4-top operators: loop-induced sensitivity



some operators (Q) have a bb-initiated contribution

4-top interference in ttbar:
pattern of cancellations at differential level
competition between phase space & gg, bb

c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO		$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO
c^{8}_{tu}	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$		$1.04^{+6\%}_{-5\%}$	$1.03^{+2\%}_{-2\%}$
c^{8}_{td}	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$		$0.577^{+6\%}_{-5\%}$	$0.611^{+3\%}_{-2\%}$
c^{8}_{tq}	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.29^{+3\%}_{-2\%}$
c^{8}_{Qu}	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$		$1.04^{+6\%}_{-5\%}$	$0.798^{+3\%}_{-3\%}$
c^{8}_{Qd}	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$		$0.58^{+6\%}_{-5\%}$	$0.485^{+2\%}_{-2\%}$
$c^{8,1}_{Qq}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.69^{+3\%}_{-3\%}$
$c^{8,3}_{Qq}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.57^{+2\%}_{-2\%}$
c^{1}_{tu}	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$	$[0.41^{+13\%}_{-17\%}]$	$4.66^{+6\%}_{-5\%}$	$5.92^{+6\%}_{-5\%}$
c^{1}_{td}	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$	$[-0.15^{+10\%}_{-13\%}]$	$2.62^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
c^{1}_{tq}	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$	$[0.50^{+3\%}_{-2\%}]$	$7.25^{+6\%}_{-5\%}$	$9.36^{+6\%}_{-5\%}$
c^{1}_{Qu}	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$	$[0.57^{+6\%}_{-5\%}]$	$4.68^{+6\%}_{-5\%}$	$5.96^{+6\%}_{-5\%}$
c^{1}_{Qd}	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$	$[-0.19^{+6\%}_{-5\%}]$	$2.61^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
$c^{1,1}_{Qq}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$	$[0.39^{+9\%}_{-12\%}]$	$7.25^{+6\%}_{-5\%}$	$9.34^{+5\%}_{-5\%}$
$c^{1,3}_{Qq}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$	$[1.05^{+17\%}_{-22\%}]$	$7.25^{+6\%}_{-5\%}$	$9.32^{+5\%}_{-5\%}$
c^{8}_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^{8}_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^{1}_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c^{1}_{Qt}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c^{1}_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×

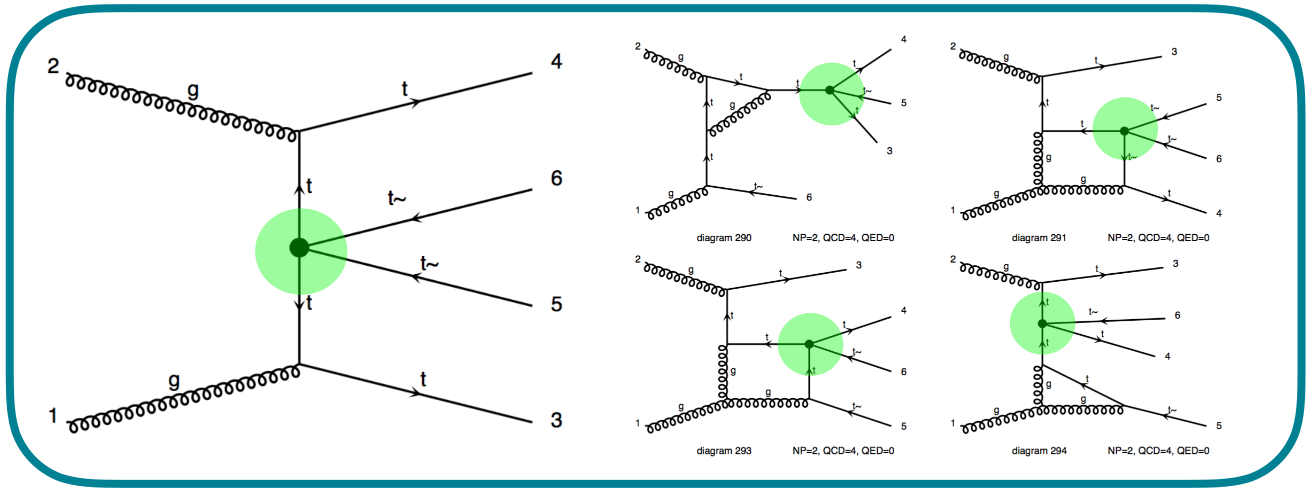


SMEFT@NLO

4-top

[SMEFT@NLO; arXiv:2008.11743]

! computation time warning !



c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO	K	$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO	K
c^8_{QQ}	$0.126^{+61\%}_{-35\%}$	$0.089^{+8\%}_{-66\%}$	0.71	$0.170^{+53\%}_{-32\%}$	$0.165^{+3\%}_{-26\%}$	0.97
c^8_{Qt}	$0.421^{+63\%}_{-35\%}$	$0.295^{+9\%}_{-69\%}$	0.70	$0.498^{+52\%}_{-32\%}$	$0.333^{+15\%}_{-75\%}$	0.67
c^1_{QQ}	$0.373^{+62\%}_{-35\%}$	$0.20(1)^{+23\%}_{-115\%}$	0.53	$1.513^{+53\%}_{-32\%}$	$1.40^{+3\%}_{-32\%}$	0.93
c^1_{Qt}	$-0.007(1)^{+88\%}_{-84\%}$	$-0.14(3)^{+83\%}_{-40\%}$	21	$2.061^{+53\%}_{-32\%}$	$1.89^{+3\%}_{-33\%}$	0.92
c^1_{tt}	$0.741^{+61\%}_{-35\%}$	$0.42(3)^{+18\%}_{-101\%}$	0.57	$6.08^{+53\%}_{-32\%}$	$5.65^{+3\%}_{-30\%}$	0.93

LHC 13 TeV, SM = 13.9 pb, K-factor = 1.37

All K-factors very different from SM

Interference K-factors mainly ≪ 1

Quadratic < 1

Recent 4.3(2.6) sigma evidence reported by ATLAS(CMS)

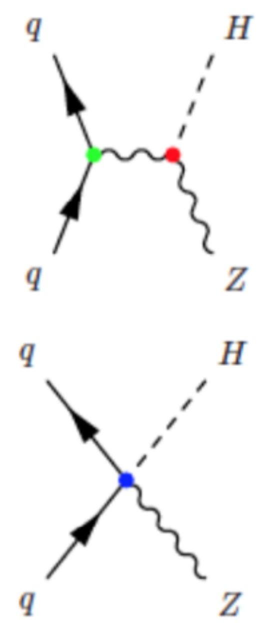
- Actually an excess, μ ~ 2 [ATLAS-CONF-2020-013] [CMS; EPJC 80 (2020) 2, 75]
- Current limits on 4-top operators ~ |C| < 2-5 (1 TeV)^2/Λ^2 [CMS; JHEP 11 (2019) 082]
- Dominated by EFT^2 quadratic term
- Room for complementarity from loop-induced top pair effects

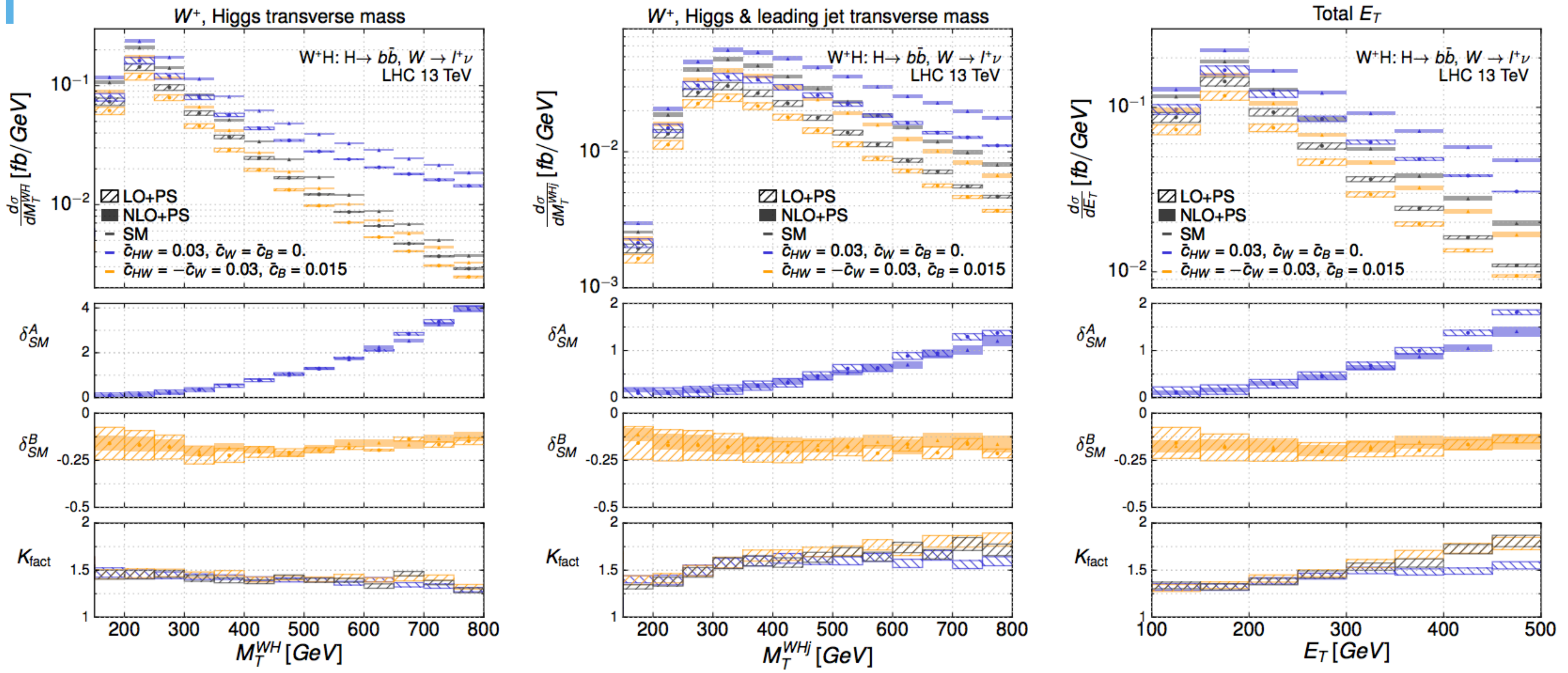
Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{QQ}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{Qt}$	[−7.4, 6.3]	[−8.0, 6.8]

pp →ZH

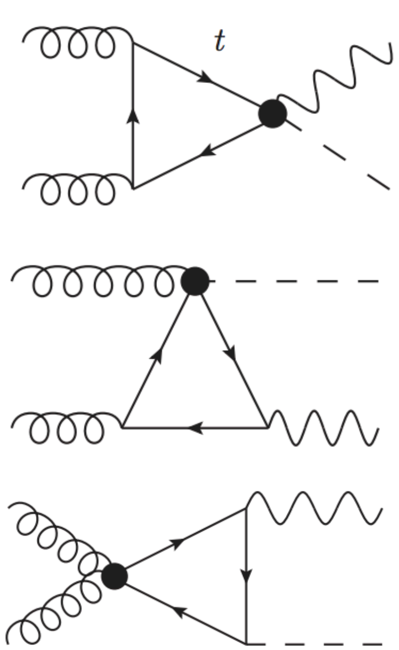
[Degrande, et al.; EPJC 77 (2017) 4, 262]

Quark-initiated



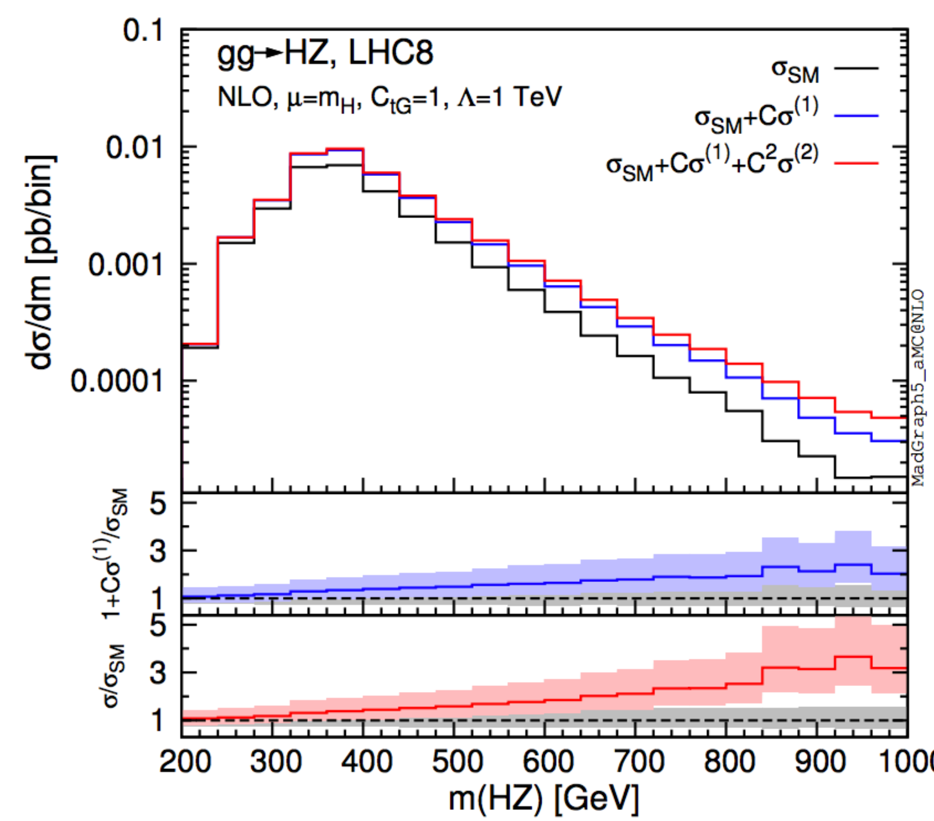


gg, loop-induced

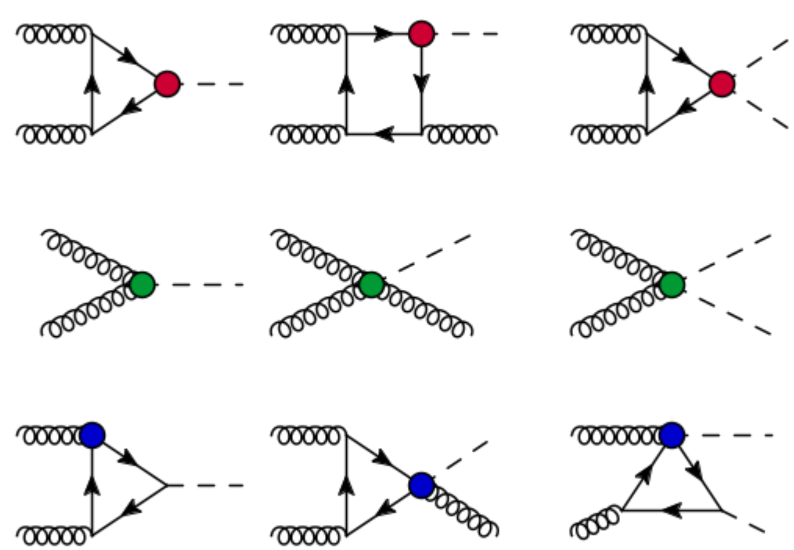


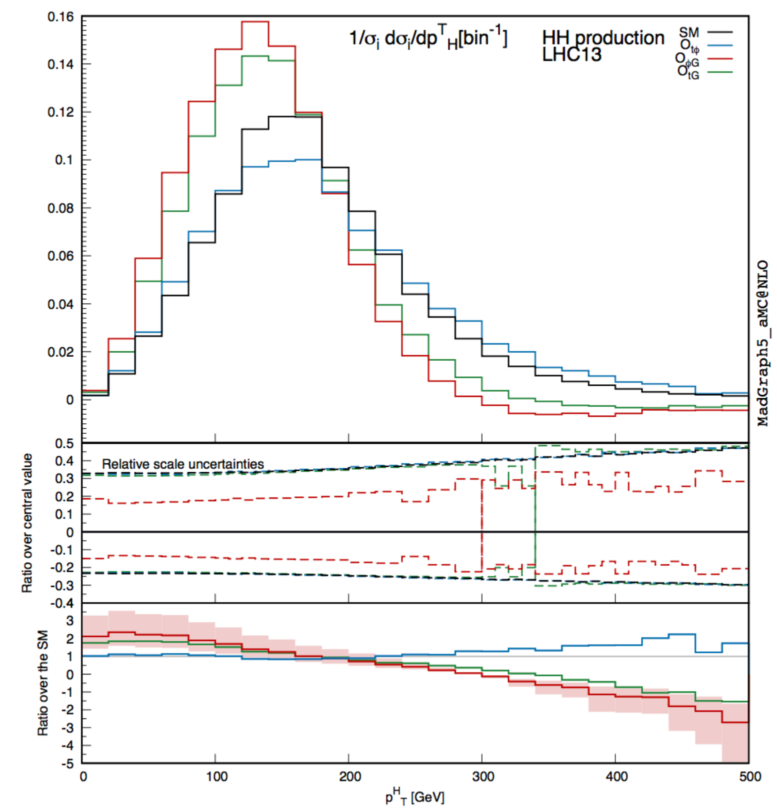
[Bylund et al.; JHEP 1605 (2016) 052]

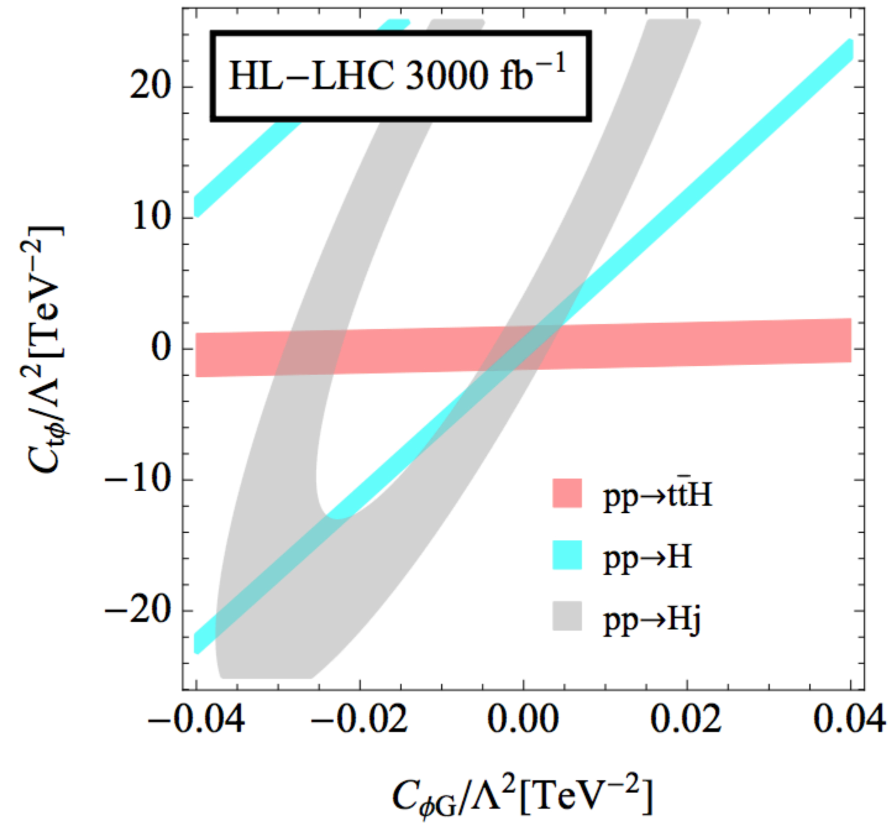
[fb]	SM		$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(1)}$
8TeV	$29.15^{+40.0\%}_{-26.6\%}$	$\sigma_i^{(1)}$	$10.37^{+41.3\%}_{-27.2\%}$	$1.719^{+42.5\%}_{-27.6\%}$
		$\sigma_i^{(2)}$	$1.621^{+45.1\%}_{-28.7\%}$	$0.0469^{+46.5\%}_{-29.2\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.356^{+0.9\%}_{-0.8\%}$	$0.0590^{+1.8\%}_{-1.4\%}$
		$\sigma_i^{(2)}/\sigma_i^{(1)}$	$0.156^{+2.6\%}_{-2.0\%}$	$0.0273^{+2.8\%}_{-2.3\%}$
13TeV	$93.6^{+34.3\%}_{-23.8\%}$	$\sigma_i^{(1)}$	$34.6^{+35.2\%}_{-24.5\%}$	$5.91^{+36.4\%}_{-24.9\%}$
		$\sigma_i^{(2)}$	$6.09^{+39.2\%}_{-26.1\%}$	$0.182^{+40.2\%}_{-26.6\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.370^{+0.7\%}_{-0.9\%}$	$0.0631^{+1.6\%}_{-1.5\%}$
		$\sigma_i^{(2)}/\sigma_i^{(1)}$	$0.176^{+2.9\%}_{-2.1\%}$	$0.0309^{+2.8\%}_{-2.2\%}$



loop-sensitivity, gg -> H/Hj/HH

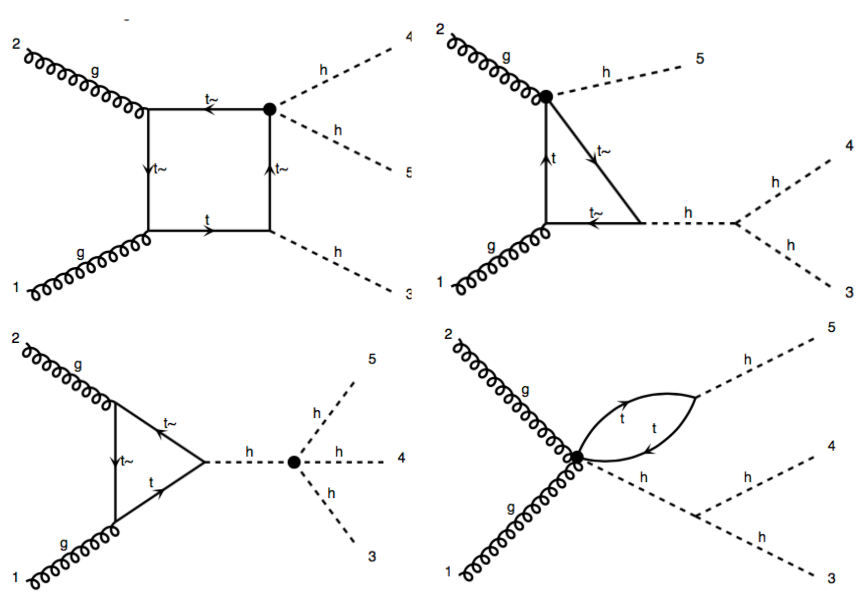




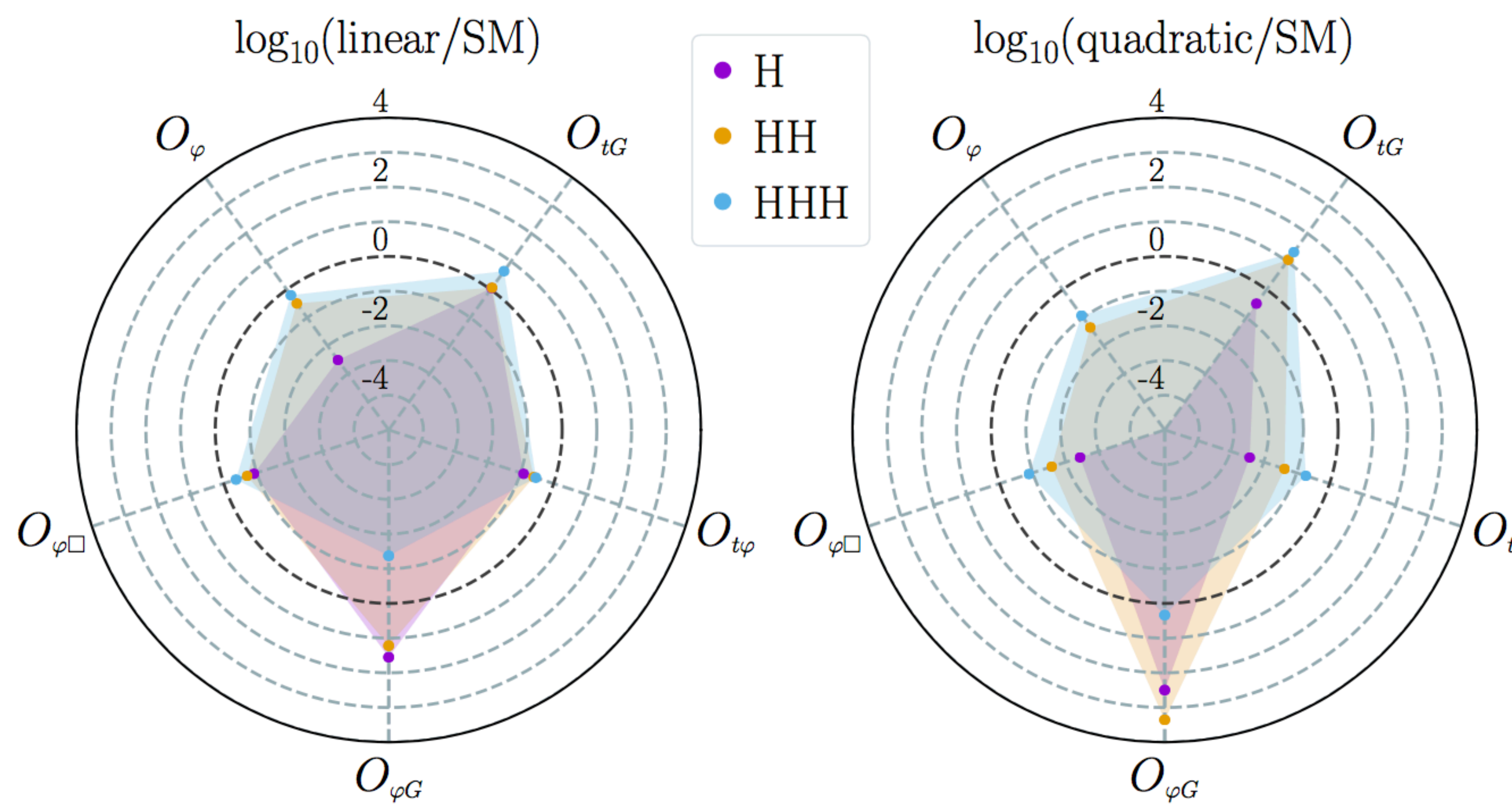


[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

gg -> H/HH/HHH (100 TeV)

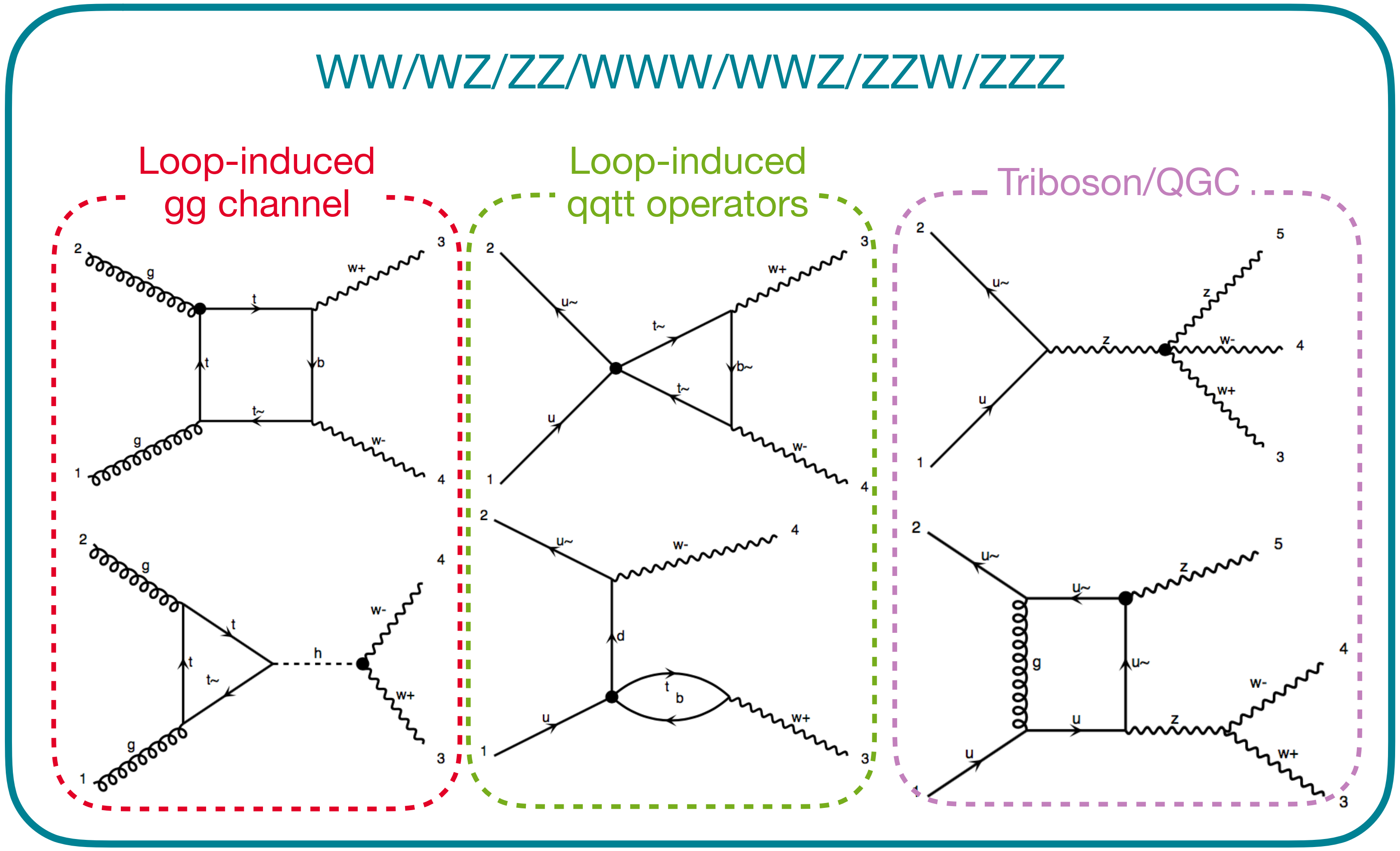


[SMEFT@NLO; arXiv:2008.11743]

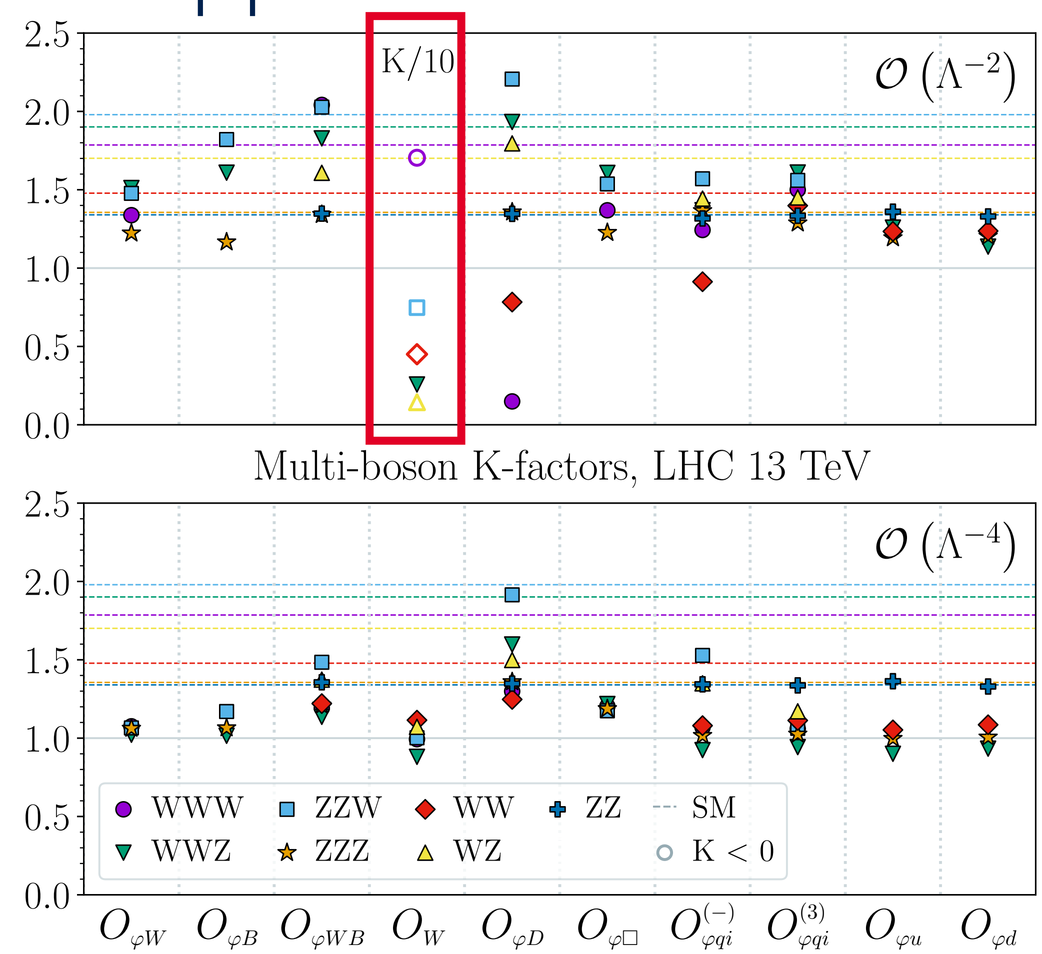


Projected FCC-hh reach: 1%, 5% and 50% on H, HH and HHH

Multiboson *[SMEFT@NLO; arXiv:2008.11743]*



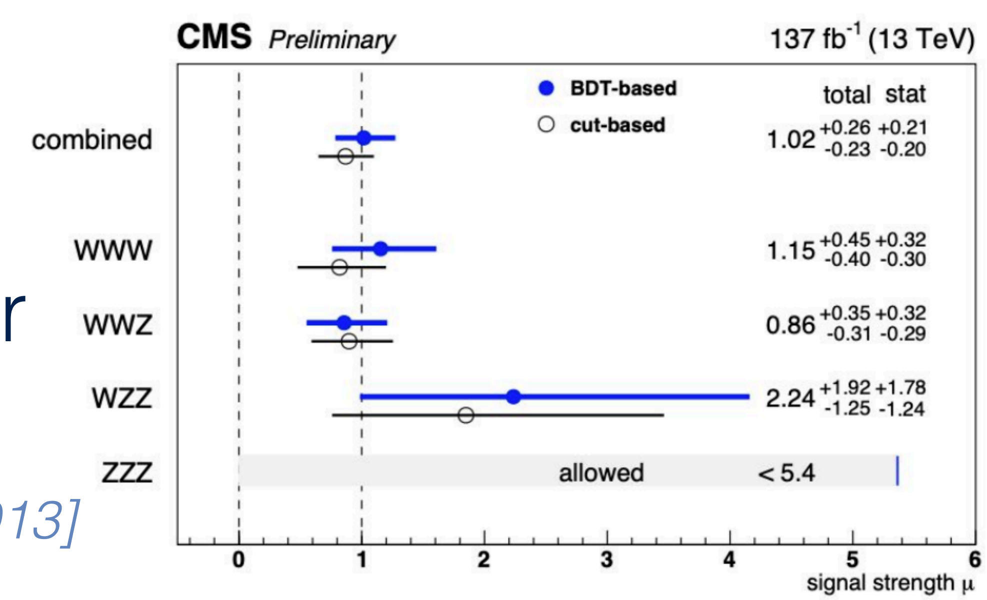
qq-initiated K-factors



Non-universal NLO corrections, different from SM

Large, negative K-factors for triple gauge operator, c_W
Non-interference/cancellation at LO broken at NLO

[CMS; arXiv:2006.11191]



First triboson observation by CMS this year

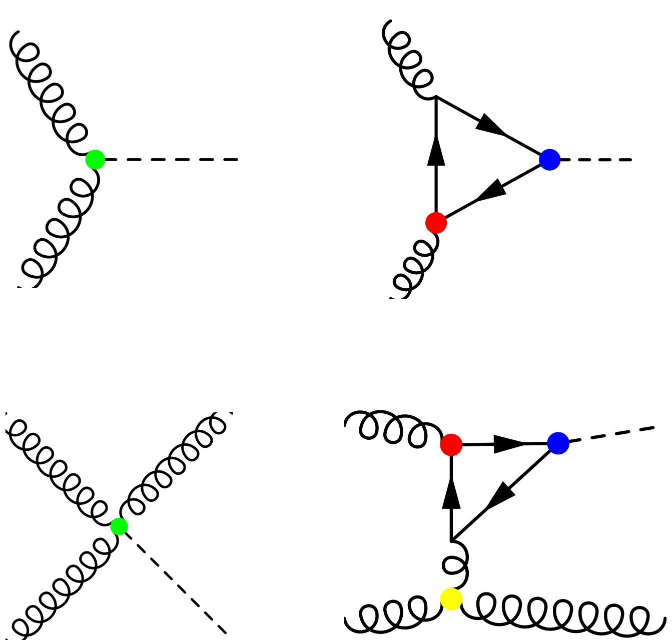
- Also strong evidence from ATLAS
- New window into SMEFT? *[ATLAS; PLB 798 (2019) 134913]*

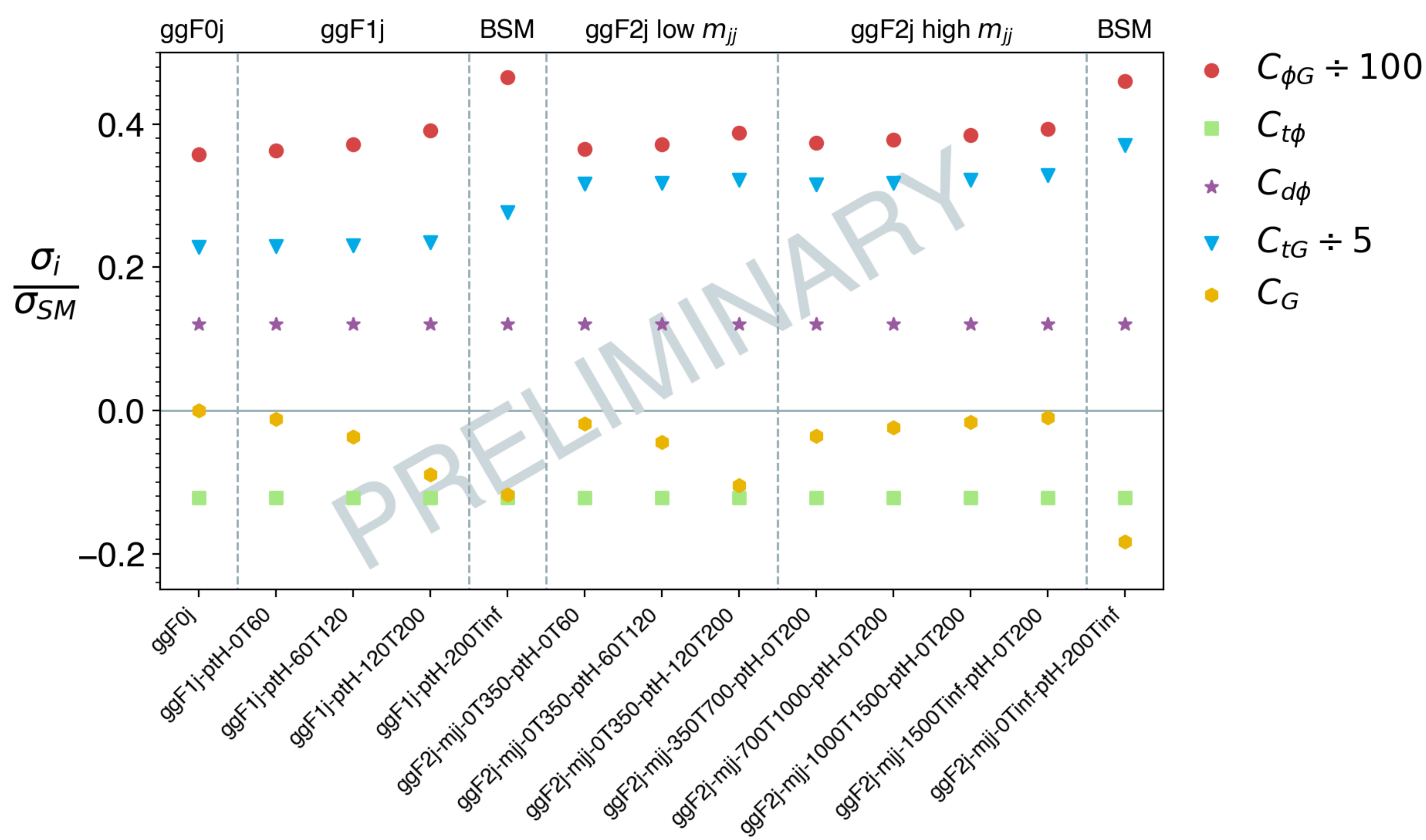
Improving fits

[Ellis, Madigan, KM, Sanz, You; in preparation]

STXS for ggF: one-loop is LO for the SM

- Tree-EFT x loop-SM and loop-EFT x loop-SM interference terms
- Heavy top limit OK for 0-jet, breaks down for high-p_T

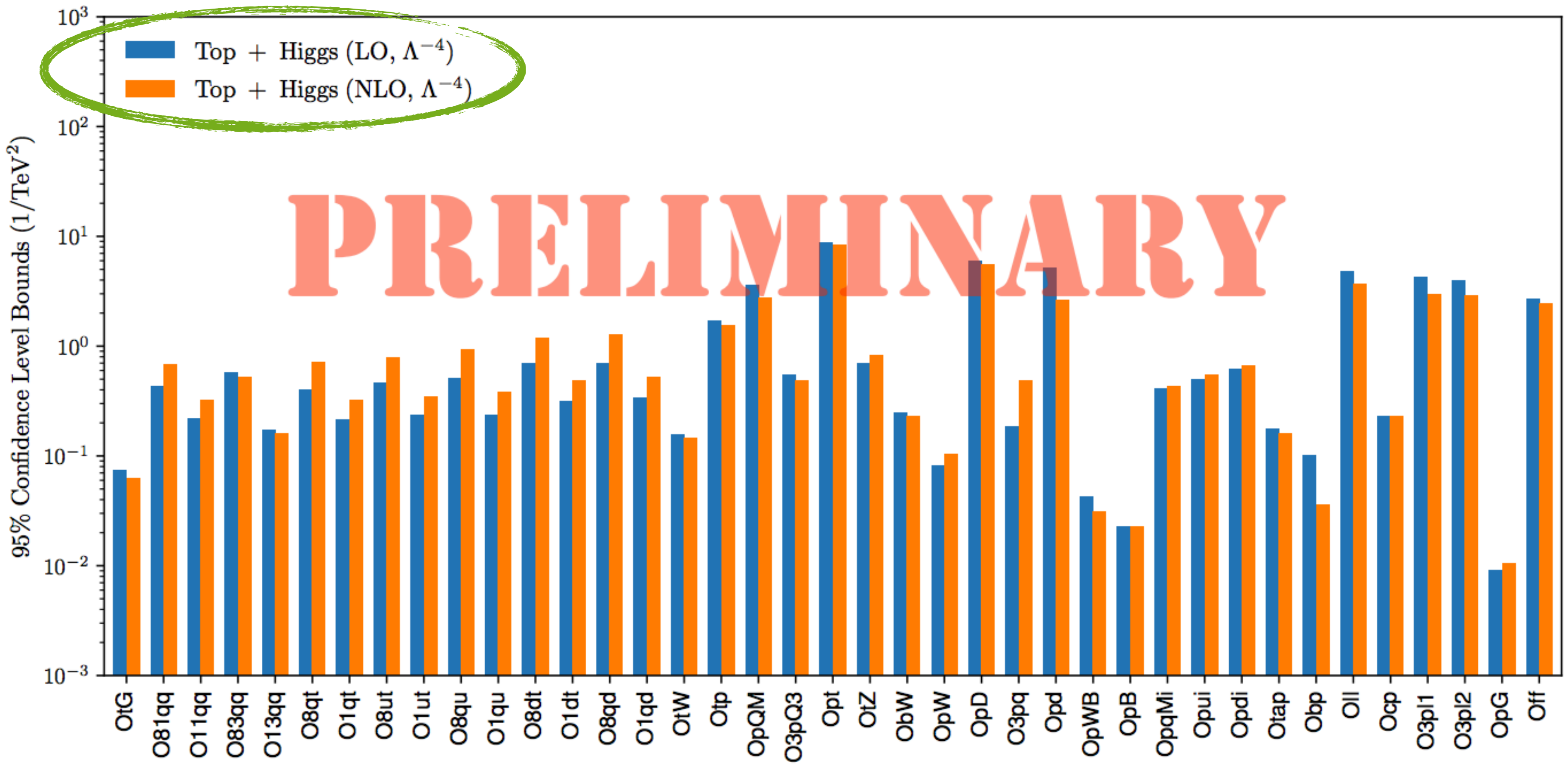




Improving fits

Impact of NLO corrections in combined Top + Higgs fit

- Update from SMEFiT collaboration adding diboson & Higgs



[Ethier et al.; in preparation]

Conclusion & future plans

SMEFT@NLO is a milestone in tools for SMEFT predictions

- Automated, fully differential computations up to one-loop
- NLO+PS, loop-induced, tree-loop interference (see backup)
- Visit & contact us for more info *http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO*

Many extensions planned

- CP-violation
- Extended flavor structure: $U(2)^5$ (b chirality-flipping ops)
- c_G @ NLO
- 4 light fermions operators (qqqq & qqll)
- Open to suggestions!

'add-on' for b-Yukawa operator at LO (see website)

Work in progress for running of Wilson coefficients in MG5

Long term: EW loops, already possible for the SM in MG5

Backup

Technical details

5-flavor scheme (massless b) & CKM=𝟙

EW input scheme: $\{G_F, M_Z, M_W\}$

- Relevant field redefinitions & EW parameter shifts performed

EFT renormalisation scale **mueft**

- Separate, fixed scale for the running of the Wilson coefficients
- MG5 does not run the Wilson coefficients (yet)
- Usual **muR** & **muF** are kept for α_s & PDFs

Everything available for NLO/loop calculations, except…

- Triple gluon operator, **cG** http://feynrules.irmp.ucl.ac.be/wiki/GGG *Dedicated model*
- Scalar & tensor 2-quark-2-lepton operators: **ctlS3, ctlT3, cblS3**

Validated at LO against dim6top & SMEFTsim

v2 or v3

MG5 uses coupling orders for command → diagrams

- `QCD`, `QED` & `NP` : NP(1/`Lambda`)=1
- v2: cannot mix QCD orders among diagrams in NLO computations
- 4F operators have only NP=2, cannot interfere with SM QCD using v2

Reason for g_S normalisation of top chromo-dipole operator `ctG`

Recommend v3 for full access to SMEFT@NLO features

https://code.launchpad.net/~maddevelopers/mg5amcnlo/3.0.3-neworders

- Dev. branch that works with SMEFT@NLO, merged to trunk soon
- ! Fixed Order only ! NLO+PS in preparation (out by end of the year)

v2.X.Y	v3.0.3-neworders
coupling order matters	*split interference & square*
no SM x four-fermion	*no events (yet)*

Always specify QCD,QED & NP orders when generating

Tree-loop interference

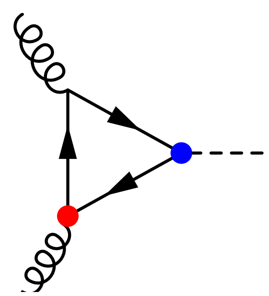
MG5 supports LO, NLO & loop-induced modes

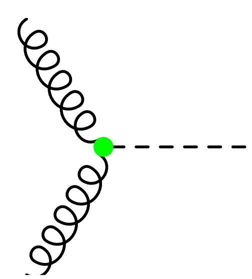
- Loop-induced is a relatively new feature
- Directly computing interference of tree & loop diagrams not implemented

Example: g g → H (+ X) in SMEFT

- SM is loop-induced but SMEFT has a tree-level contribution:

$\text{SM},\ C_{t\varphi}\,|\varphi|^2(\bar{Q}\,t)\,\tilde{\varphi},$
$\&\ \ C_{tG}\,(\bar{Q}\sigma_{\mu\nu}\,T^A\,t)\,\tilde{\varphi}\,G^{\mu\nu}_A$





$C_{\varphi G}\,|\varphi|^2 G^{\mu\nu}_A G^A_{\mu\nu}$

- Relevant for g g → H j, H j j, H H, H H H

Can be obtained using reweighting feature of MG5

- Alternative method at FO NLO in v3
- See backup for H+j reweighting recipe

Dedicated recipes on the webpage soon

Example commands

QCD

```
> p p > j j          QED=0 QCD=2 NP=2 [QCD]
```

Drell Yan

```
> p p > mu+ mu-      QCD=0 QED=2 NP=2 [QCD]
> p p > mu+ vm       QCD=0 QED=2 NP=2 [QCD]
> p p > W+  j  $$ t  QCD=1 QED=1 NP=2 [QCD]
> p p > W-  j  $$ t~ QCD=1 QED=1 NP=2 [QCD]
> p p > Z   j        QCD=1 QED=1 NP=2 [QCD]
```

Multi-boson production

quark-initiated

```
> p p > W+ W-    QED=2 QCD=0 NP=2 [QCD]
> p p > W+ Z     QED=2 QCD=0 NP=2 [QCD]
> p p > Z  Z     QED=2 QCD=0 NP=2 [QCD]
```

loop-induced

```
> g g > W+ W-    QED=2 QCD=2 NP=2 [QCD]
> g g > Z  Z     QED=2 QCD=2 NP=2 [QCD]
> g g > W+ W- Z  QED=3 QCD=2 NP=2 [QCD]
> g g > Z  Z  Z  QED=3 QCD=2 NP=2 [QCD]
```

Higgs production

loop-induced

```
> g g > H        QED=1 QCD=2 NP=2 [QCD]
> g g > H H      QED=2 QCD=2 NP=2 [QCD]
> g g > H H H    QED=3 QCD=2 NP=2 [QCD]
> g g > H j      QED=1 QCD=3 NP=2 [QCD]
```

Top quark production

```
> e+ e- > t t~           QED=2 QCD=0 NP=2 [QCD]
> p p > t t~             QED=0 QCD=2 NP=2 [QCD]
> p p > t t~ h           QED=1 QCD=2 NP=2 [QCD]
> p p > t t~ Z           QED=1 QCD=2 NP=2 [QCD]
> p p > t t~ W+          QED=1 QCD=2 NP=2 [QCD]
> p p > t W-     $$ t~   QED=1 QCD=1 NP=2 [QCD]
> p p > t W- j   $$ t~   QED=1 QCD=2 NP=2 [QCD]
> p p > t j      $$ W-   QED=2 QCD=0 NP=2 [QCD]
> p p > t h j    $$ W-   QED=3 QCD=0 NP=2 [QCD]
> p p > t Z j    $$ W-   QED=3 QCD=0 NP=2 [QCD]
> p p > t a j    $$ W-   QED=3 QCD=0 NP=2 [QCD]
```

**set widths to zero to ensure gauge invariance*

Supported processes passing gauge & pole checks

- Some amplitudes have been cross-checked analytically
- NLO can be costly, we are available to contact about ‘feasibility’ of processes

g g > h j in SMEFT@NLO

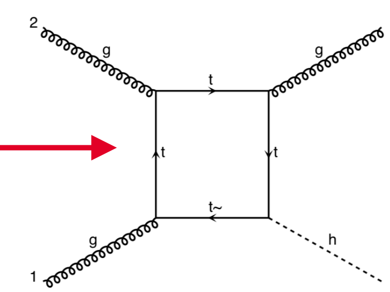
MG5_aMC draw diagrams based on coupling orders

- Loop-induced mode is triggered when no born diagrams are found
- Technical issue when you want to compute EFT-tree x SM-loop interference

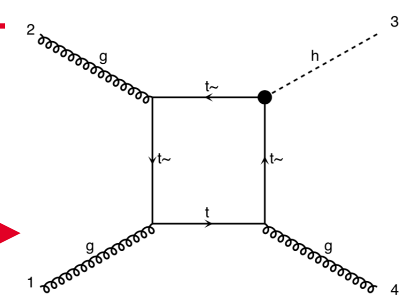
Ingredients: 2 restriction cards, one with **cpG=0** (restrict_opt.dat), one with **cpG≠0** (restrict_opG.dat)

1)
```
MG5_aMC>import model ./SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-opt
```
switch off cpG

```
MG5_aMC>generate g g > h j QCD=1 NP=0 QED=1 [QCD]
MG5_aMC>output ...
```
SM only

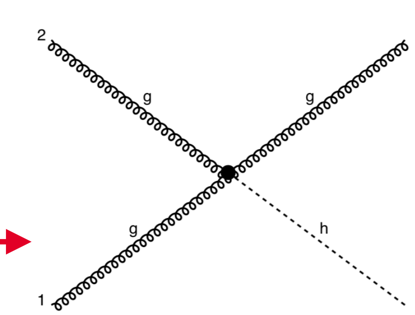


2)
```
MG5_aMC>generate g g > h j QCD=1 NP=2 NP^2==2 QED=1 [QCD]
MG5_aMC>output ...
```
Yukawa interference



3a)
```
MG5_aMC>import model ./SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-opG
MG5_aMC>generate g g  > h j NP=2 QCD=1 QED=1 NP^2==4
MG5_aMC>output gg_hg
```
switch on cpG

Tree-level



3b) Create & modify reweight_card.dat
```
change process g g  > h j NP=2 QCD=1 QED=1 NP^2==2 [QCD]
change output 2.0
launch
```