SMEFT @ NLO

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Going beyond LO

SMEFT is a renormalizable theory order by order in $1/\Lambda$

We need higher-corrections to be included to control THU for two main class of reasons:

I. Same as for the SM@dim=4: QCD corrections are very important at the LHC for both accuracy and precision. EW corrections are mostly important for accucacy and in specific areas of phase space (which in the long term which can be important for the SMEFT) and observables (Ex: VBF). NLO corrections affect normalisation, shapes, scale (μ_R, μ_F) PDF dependences.

II. Specific issues of SM@dim>4: NLO is the first order where non-trivial EFT structure becomes manifest: Running, Mixing, μ_{EFT} dependence, new contributions can arise at NLO…

Why NLO?

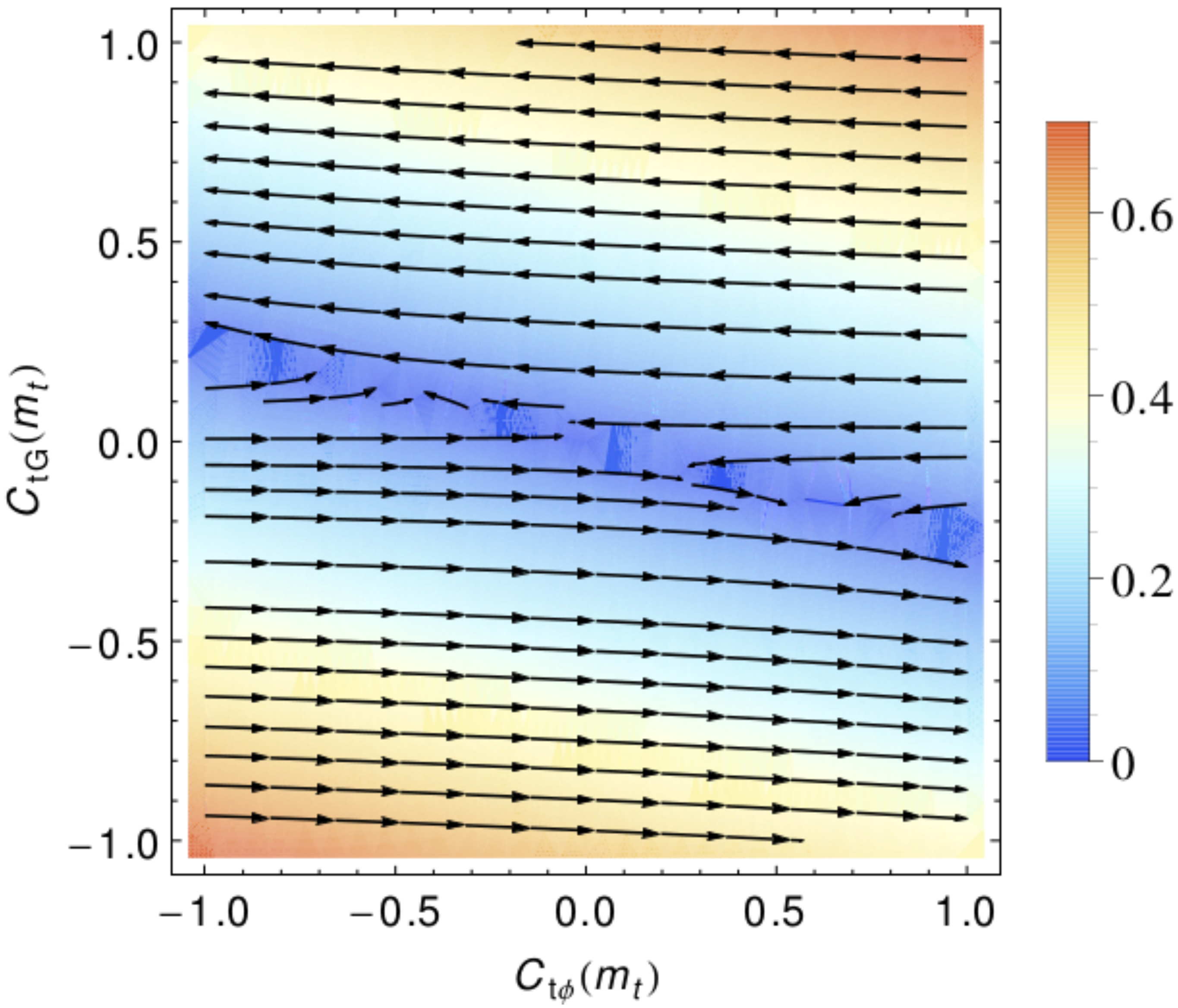
1. Operators run and mix under RGE

Running means that the Wilson coefficients depend on the scale where they are measured (as the couplings in the SM). Note that this introduces also an additional uncertainty in the perturbative computations.

Mixing means that in general the Wilson coefficients at low scale (=where the measurements happen) are related. One immediate consequence is that assumptions about some coefficients being zero at low scales are in general not valid (and in any case have to be consistent with the RGEs). Note also that operator mixing is not symmetric: Op1 can mix into Op2, but not viceversa.

Why NLO?

1. Operators run and mix under RGE



Scale corresponds to the change from mt to 2 TeV.

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

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

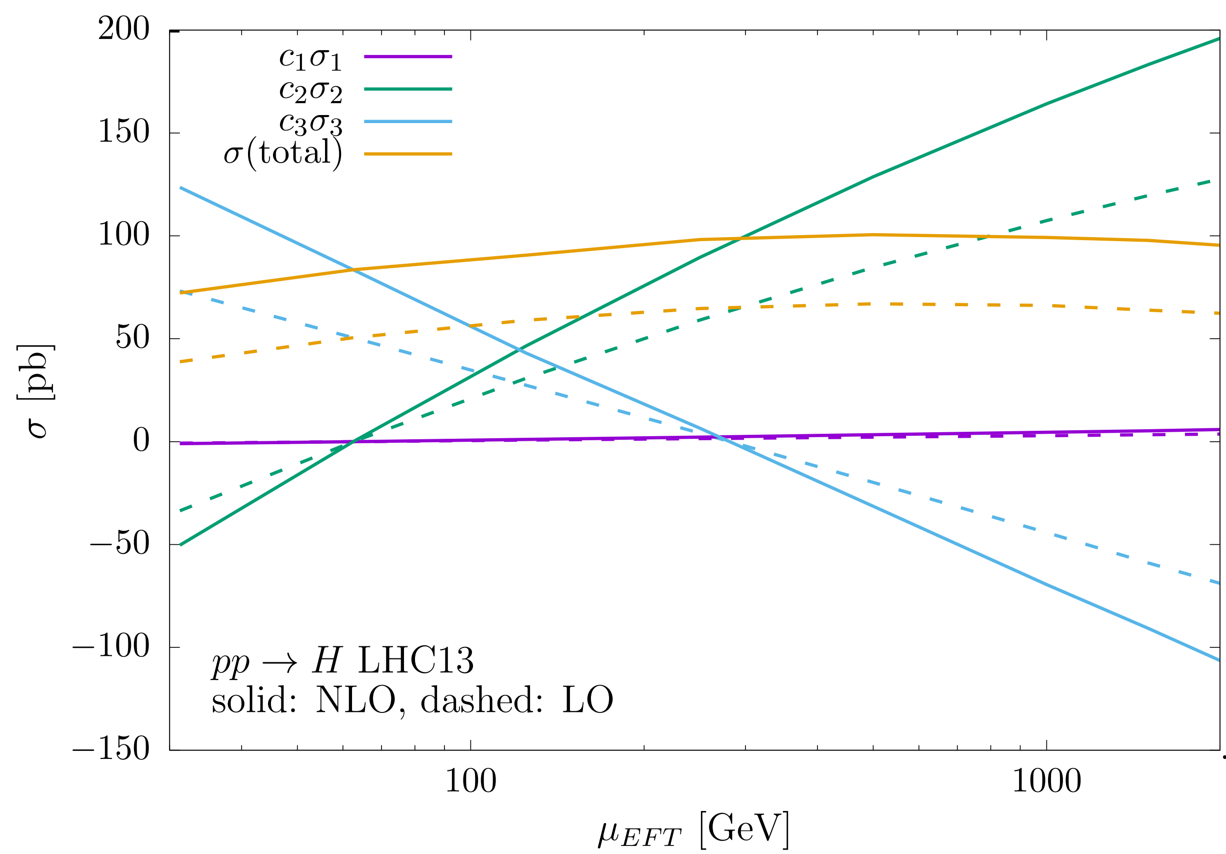
At = 1 TeV: $C_{tG} = 1$, $C_{t\varphi} = 0$;

At = 173 GeV: $C_{tG} = 0.98$, $C_{t\varphi} = 0.45$

Why NLO?

2. EFT scale dependence

[Deutschmann, Duhr, FM, Vryonidou, 17]



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$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij} C_j(\mu),$$

$$\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

By including the mixing, the overall scale dependence at LO, is very much reduced with respect to the single ones. A global point of view is required: contribution from each coupling may not make sense; only their sum is meaningful.

Why NLO?

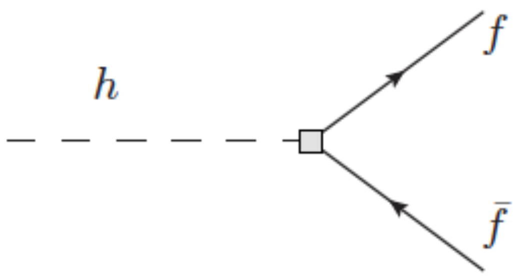
3. Genuine NLO corrections (finite terms) are important

The cancellation of UV divergences from more than 20 dim-6 operators in the full result gives a highly non-trivial check on the calculation. The logarithmic corrections could have been deduced from a Leading Log analysis:

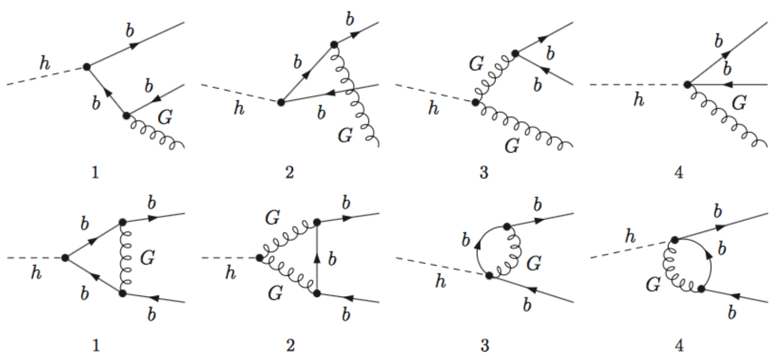
[Gauld, Pecjak, Scott, 15]

[Gauld, Pecjak, Scott, 16]

$$C_i(\mu_t) = C_i(\Lambda_{\rm NP}) + \frac{1}{2}\frac{1}{16\pi^2}\dot{C}_i(\Lambda_{\rm NP}) \ln\left(\frac{\mu_t^2}{\Lambda_{\rm NP}^2}\right)$$



However, calculation of the full NLO calculation illuminates term which would be missed in an RG analysis



$$\overline{\Gamma}^{(6,1)}_{\beta\to 1} = \left(2C_{H,\rm kin} - \frac{\sqrt{2}v_T^3}{\overline{m}_b} C_{bH}\right)\overline{\Gamma}^{(4,1)}_{\beta\to 1} + \frac{\alpha_s C_F}{\pi}\frac{N_c m_h^3 \overline{m}_b}{8\sqrt{2}\pi v_T} C_{bG} + \frac{\alpha_s C_F}{\pi}\frac{N_c m_h \overline{m}_b^2}{8\pi} C_{HG} \times \left(19 - \pi^2 + \ln^2\left[\frac{\overline{m}_b^2}{m_h^2}\right] + 6\ln\left[\frac{\mu^2}{m_h^2}\right]\right)$$

See also Z→ff at NLO:

[Hartmann, Shepherd, Trott, 16]

Why NLO?

3. Genuine NLO corrections (finite terms) are important

Let us consider the uncertainties associated to changes of μ_{EFT} .
The result at μ_0 can be expressed as:

$$\sigma(\mu_0) = \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i(\mu_0)\sigma_i(\mu_0) + \sum_{i,j} \frac{1\text{TeV}^4}{\Lambda^4} C_i(\mu_0)C_j(\mu_0)\sigma_{ij}(\mu_0) \,,$$

While the same result at a different scale μ can be expressed as:

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

$$= \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i(\mu_0)\sigma_i(\mu_0;\mu) + \sum_{i,j} \frac{1\text{TeV}^4}{\Lambda^4} C_i(\mu_0)C_j(\mu_0)\sigma_{ij}(\mu_0;\mu)$$

with:

$$C_i(\mu) = \Gamma_{ij}(\mu,\mu_0)C_j(\mu_0)$$

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

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

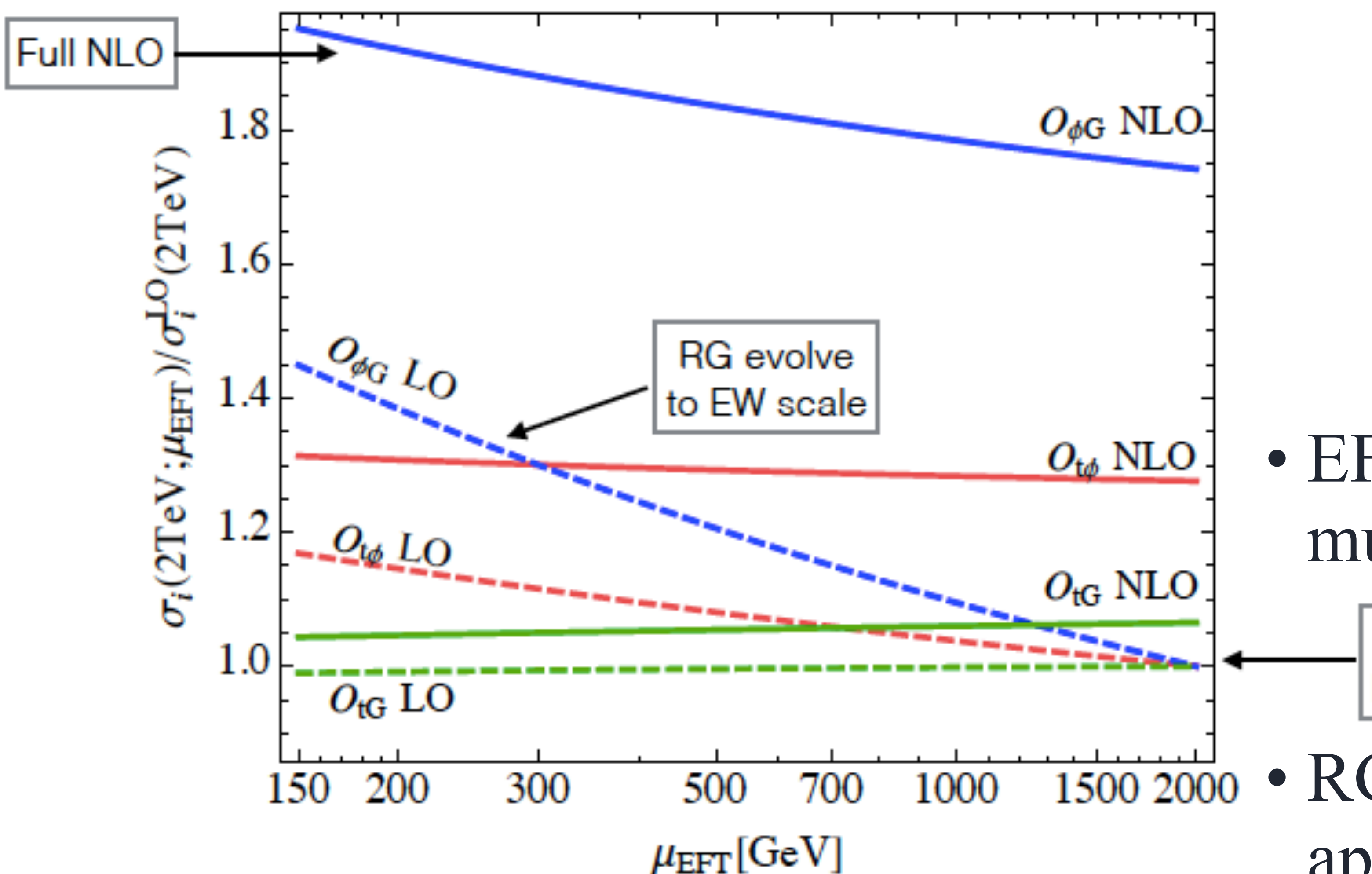
$$\Gamma_{ij}(\mu,\mu_0) = \exp\left(\frac{-2}{\beta_0}\log\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\gamma_{ij}\right)$$

$$\beta_0 = 11 - 2/3 n_f \,,$$

Why NLO?

3. Genuine NLO corrections (finite terms) are important

[FM, Vryonidou, Zhang, 16]



- pp → ttH

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

- EFT scale uncertainties are very much reduced at NLO.
- RG are sometimes thought to be an approximation for full NLO, but it is often not the case.

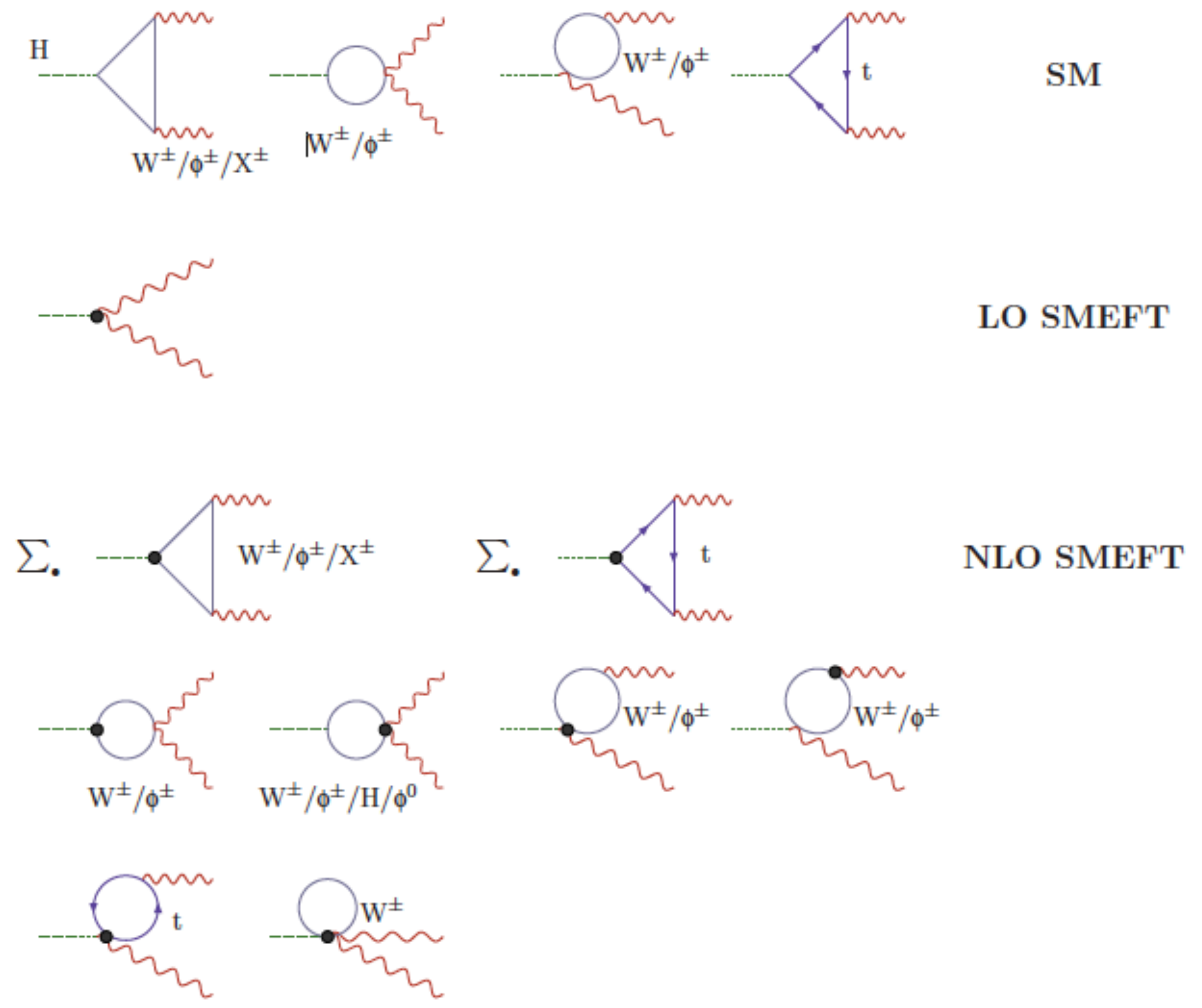
Why NLO?

4. New operators arise

New operators can arise at one-loop or via real corrections.

- At variance with the SM, loop-induced processes might not be finite.
- Including the full set of operators at a given order implies that no extra UV divergences appear (closure check).
- Choice of the normalisation of operators matters for LO, NLO nomenclature…

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a]
[Hartmann and Trott, 15]
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b]



Status of the SMEFT at NLO: Decays

- H decays:

Channel	SM: QCD, EW	dim=6 : QCD,EW	Comments
H→gg	N3LO,NLO	NLO: $C_{t\phi}$,$C_{\phi G}$ LO:	C_{tG} feasible
H→ff	NNLO, NLO	NLO,NLO	—-
H→γγ	NLO, NLO	one-loop	two-loop?
H→4l	NLO, NLO	LO	NLO EW welcome

  - Part of the NLO effects available in eHDECAY [Contino et al. 14]
  - Event generation for H→4l available from Prophecy4f and Hto4l including dim=6 at LO. [Bredenstein, 07] [Boselli et al. 17]

- Z→ff at NLO: [Hartmann, Shepherd, Trott, 16]
- t decays at NLO: [Zhang, 14]

Status of the SMEFT at NLO: Higgs production

Channel	SM: QCD, EW	dim=6 : QCD	Comments
gg→H	N3LO,NLO	NLO: $C_{t\phi}$,$C_{\phi G}$ C_{tG}	Now complete
gg→Hj	NNLO, LO	NLO: $C_{\phi G}$, LO: $C_{t\phi}$,C_{tG}	NLO hard to complete
ttH	NNLO, NLO	NLO	NLO EW hard
bbH	NNLO, LO	LO	NLO to do
gg→HH (LI)	NLO, LO	LO (apart $C_{\phi G}$)	NLO very hard
gg→HZ (LI)	LO, LO	LO	NLO very hard
tHj	NLO, LO	LO	NLO to do
VBF	N3LO, NLO	(N)NLO	NLO EW welcome
VH	NNLO,NLO	(N)NLO	NLO EW welcome

more SU(3)

more SU(2)xU(1)

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

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

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

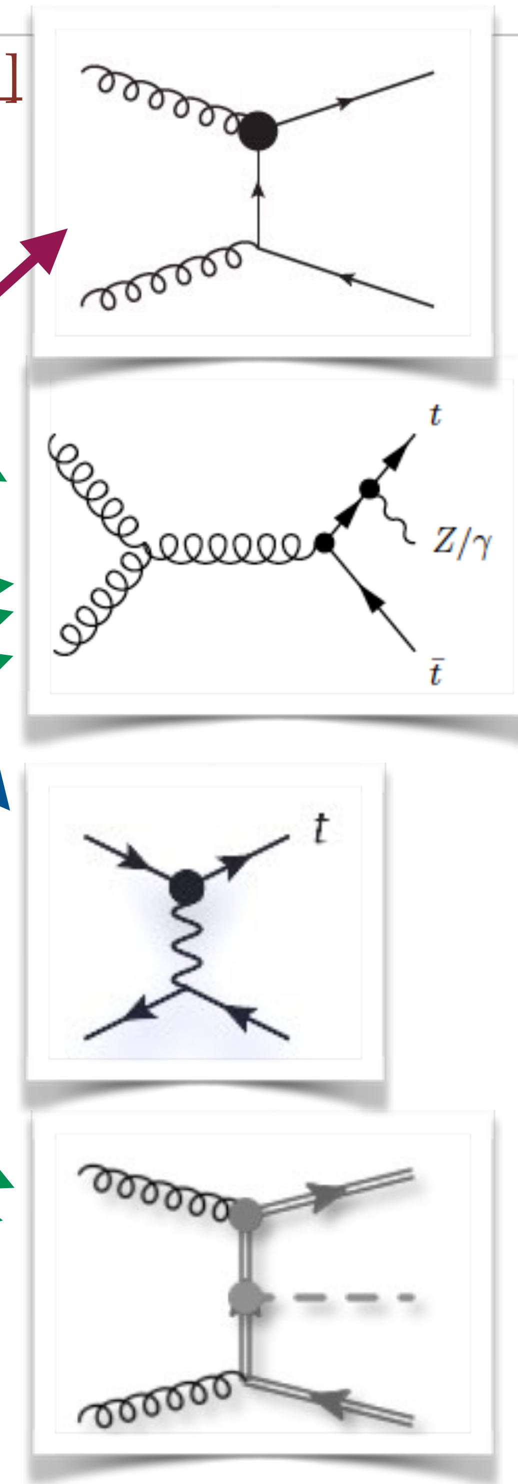
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

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

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

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

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



+four-fermion operators

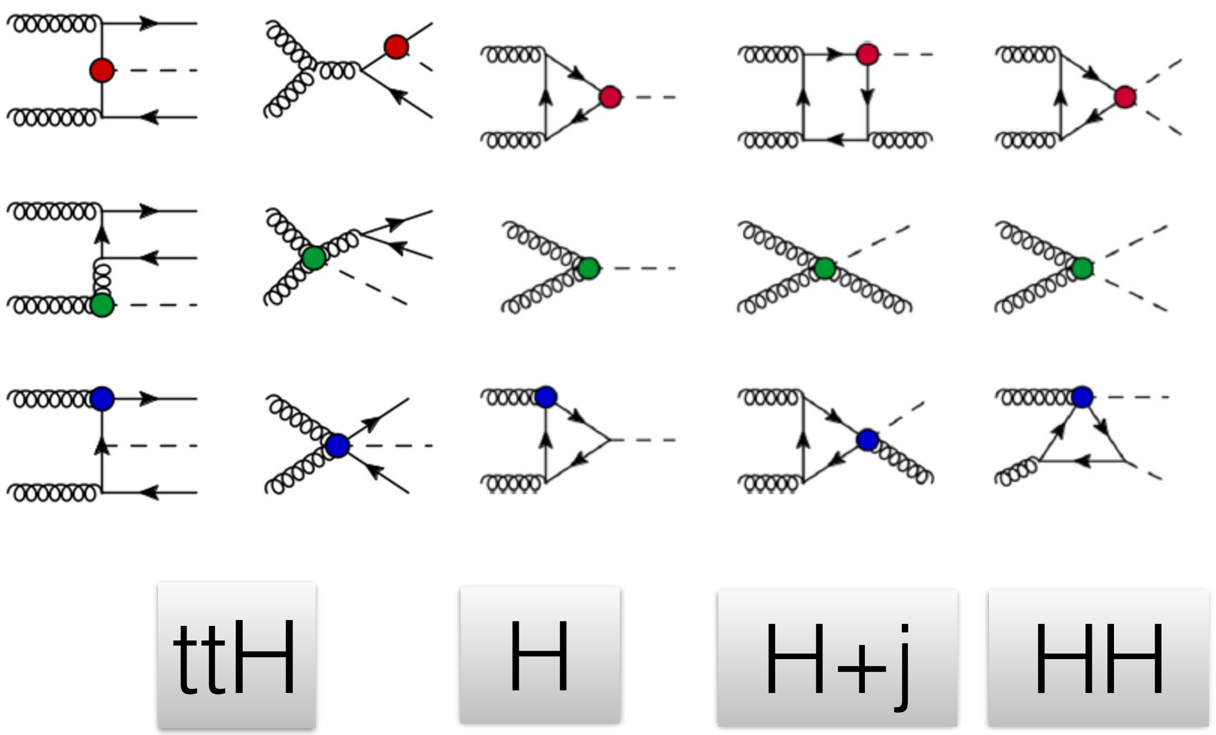
+ operators that do not feature a top, but contribute to the procs…

Top/Higgs operators and processes

Several operators typically enter each process at LO (or at LO^2) and

NLO (no	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	1L^2		
✓	$pp \to tj$	N		L	L				L^2	L^2	1L		
✓	$pp \to tW$	L		L	L				L^2	L^2	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
O ✓	$gg \to H$	L						L				N	L
O ✗	$gg \to Hj$	L						L				L	L
O ✗	$gg \to HH$	L						L				N	L
O ✗	$gg \to HZ$	L			L	L	L	L				N	L

Top/Higgs operators and processes



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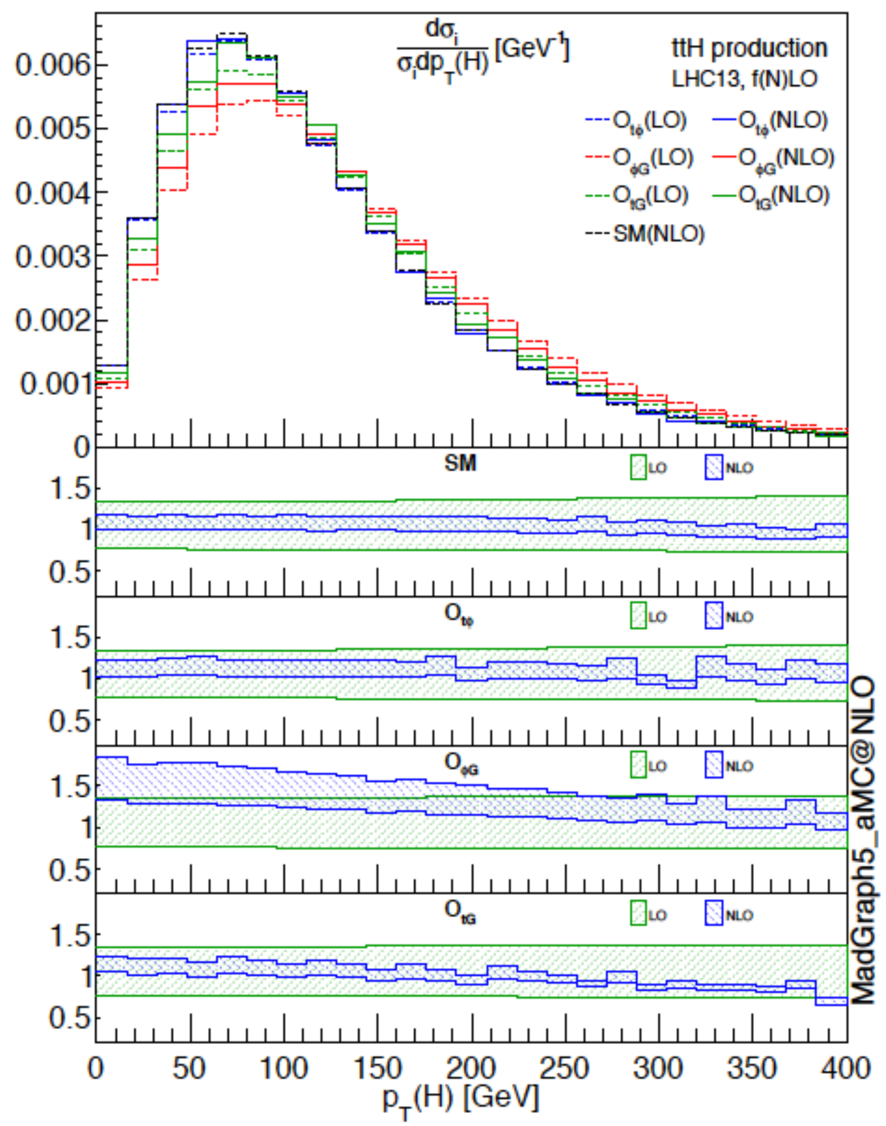
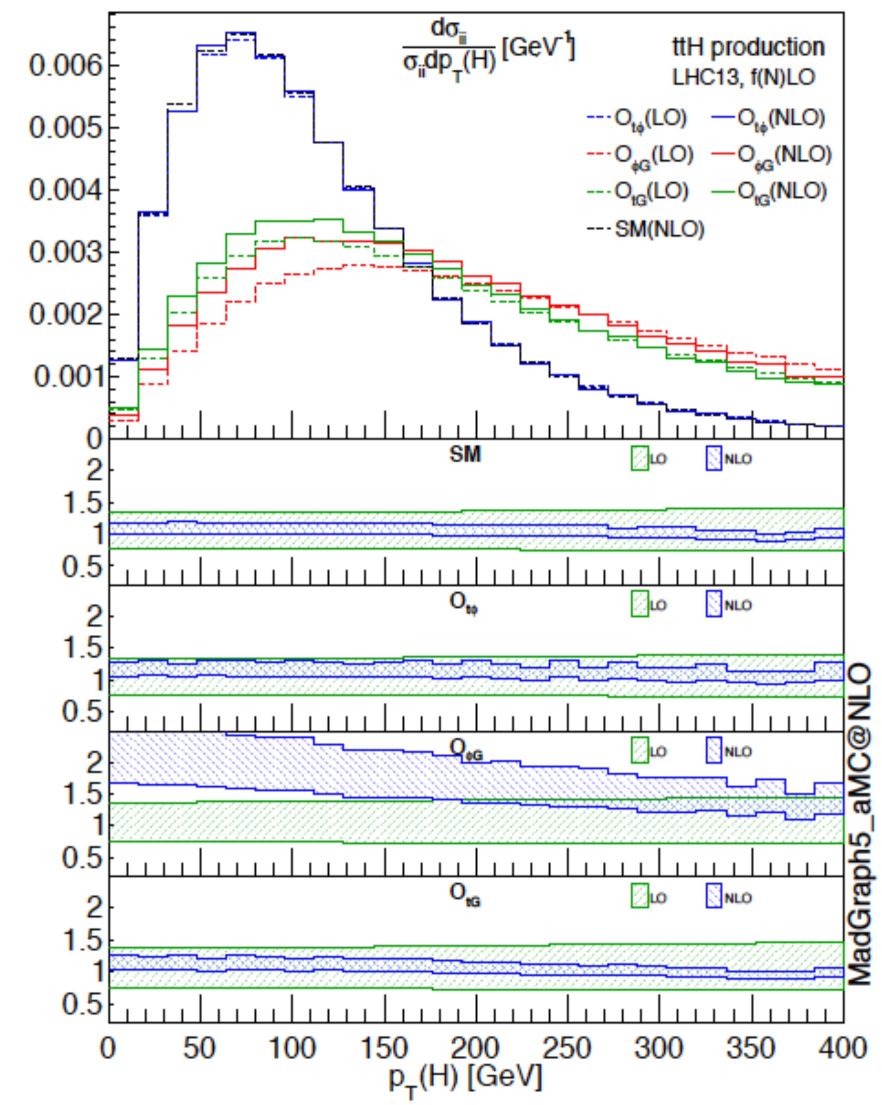
ttH in the SMEFT

[FM, Vryonidou, Zhang, 16]



NLO: smaller uncertainties, non-flat K-factors

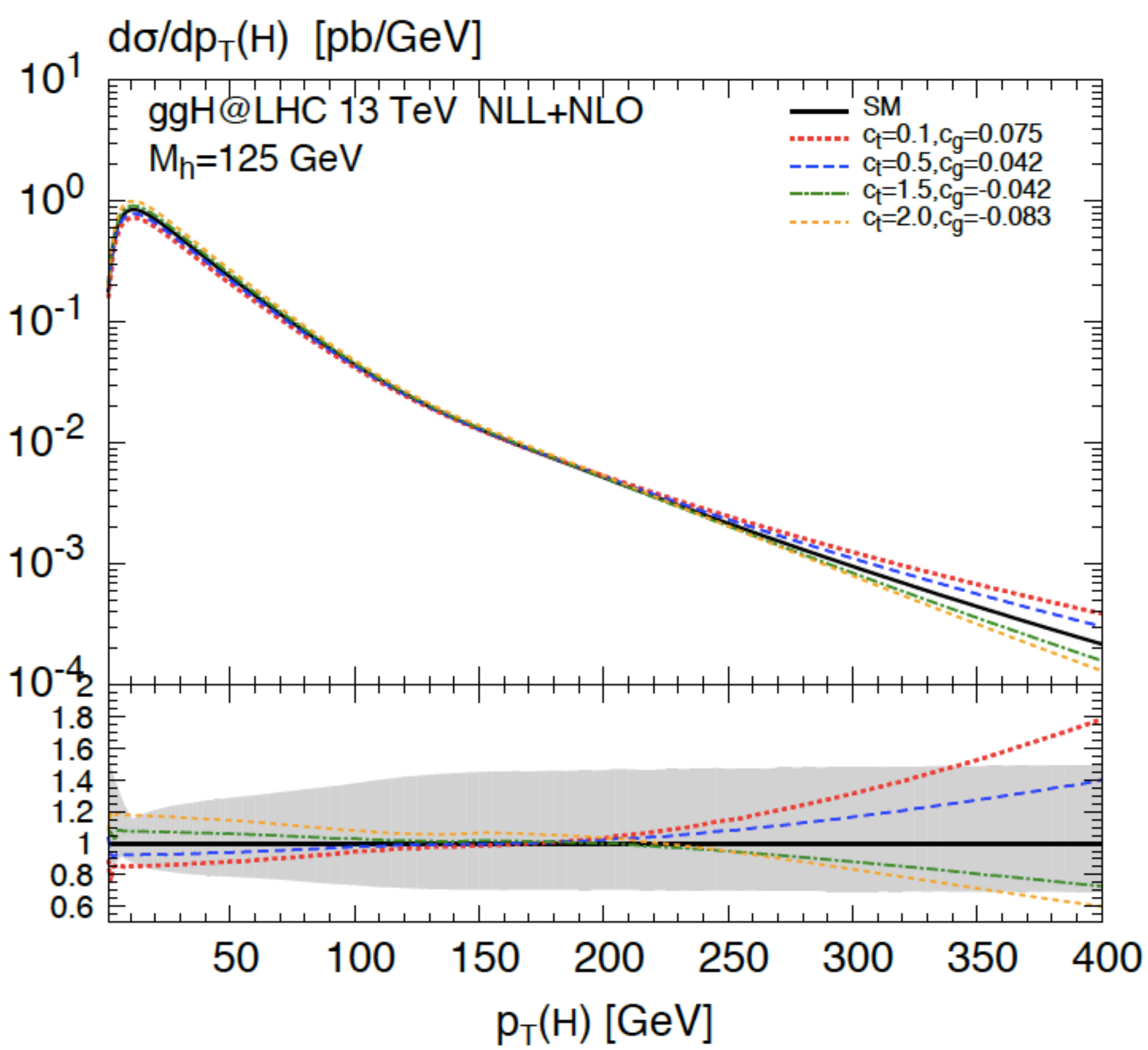


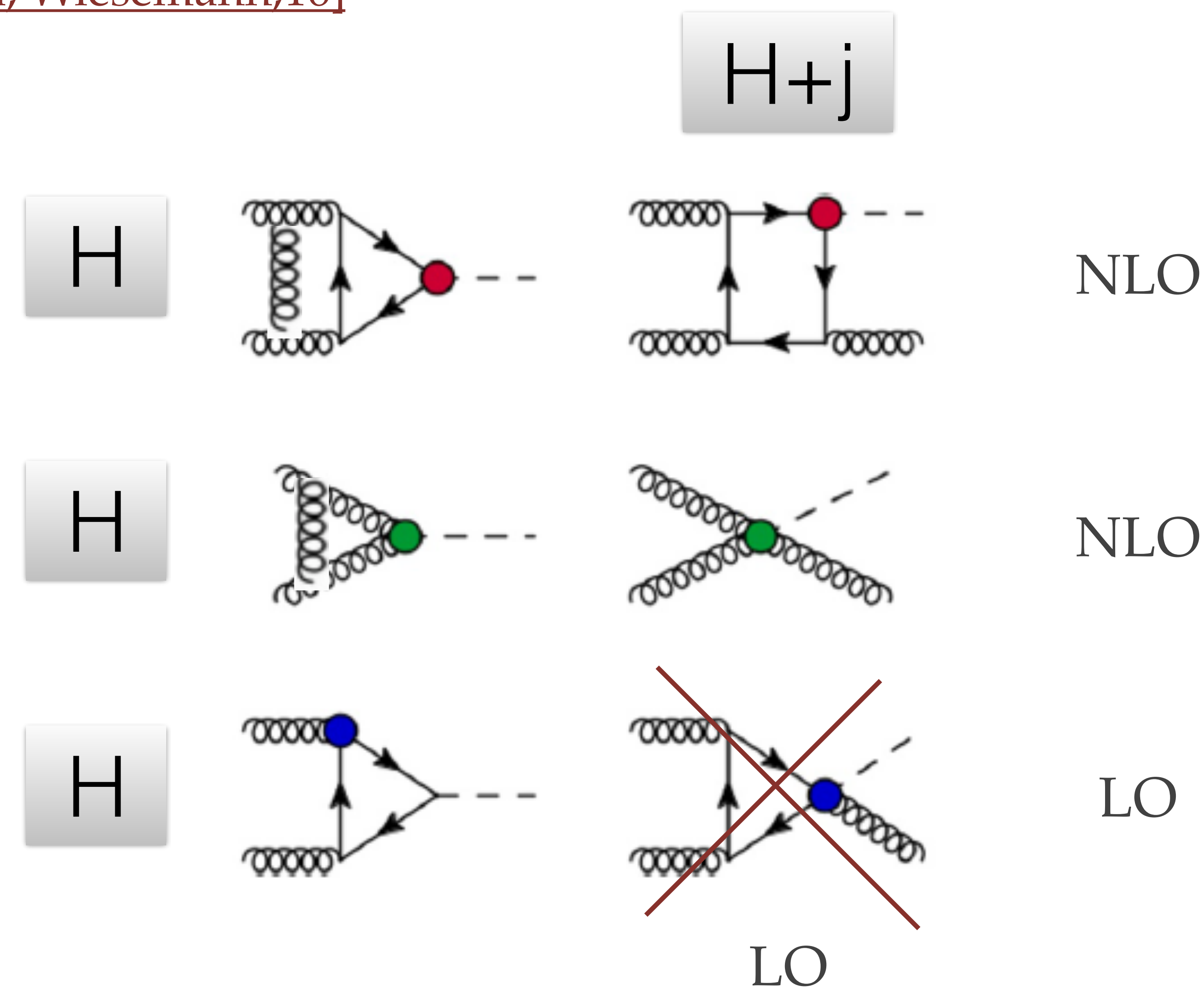
Different shapes for different operators for the squared terms

ggH in the SMEFT

Earlier studies of ggH in the SMEFT [Degrande et al. 12] [Grojean et al. 13]

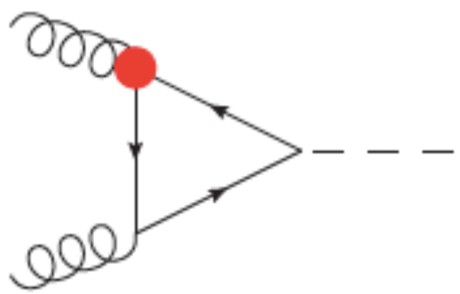
More recently, [Grazzini, Ilnicka, Spira, Wiesemann,16]





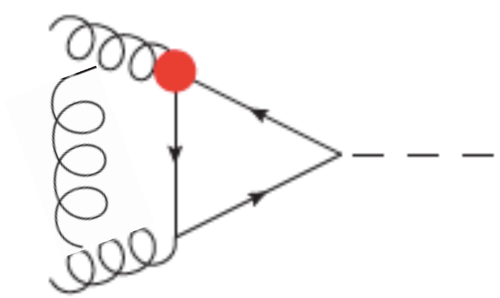
ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]

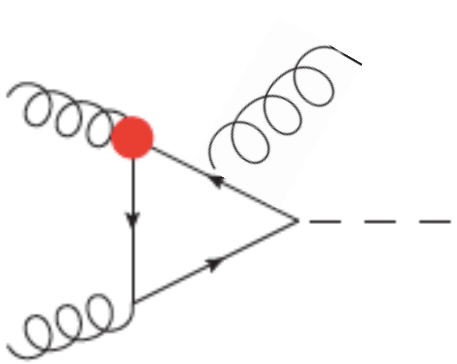


$\bar{Q}_L \Phi \sigma q_R G$

Now known at NLO (two-loop virtuals+1-loop real)



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

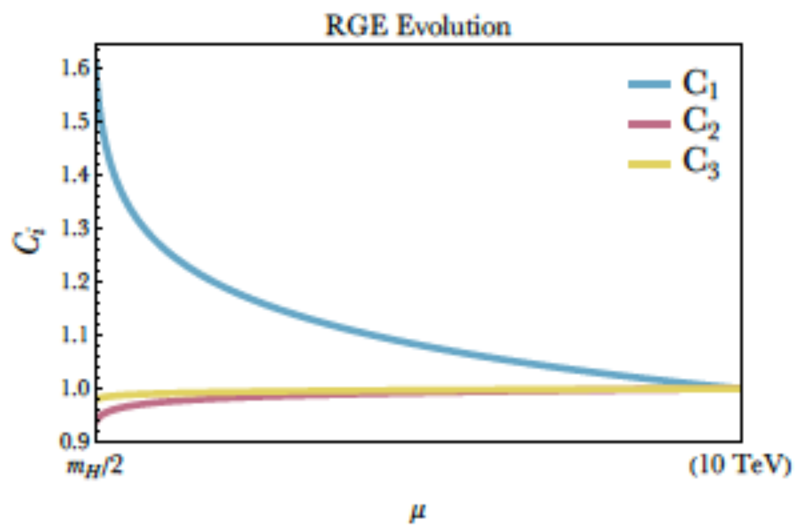


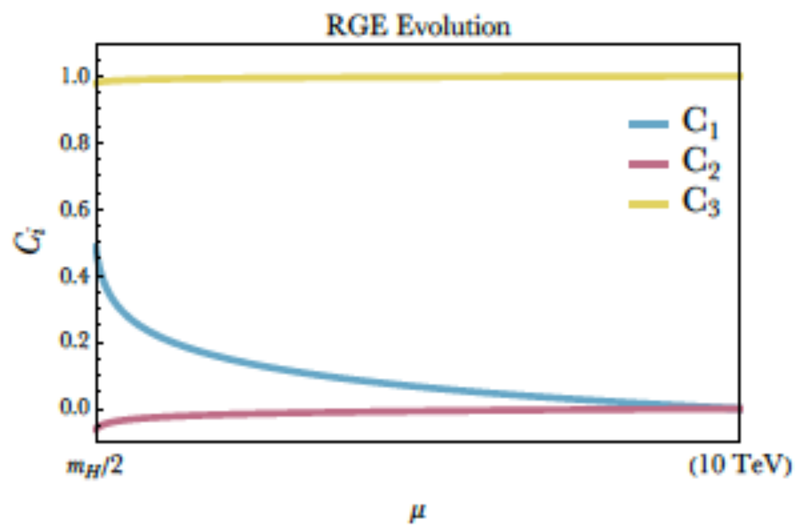
$\bar{Q}_L \Phi \sigma q_R G$

$$\begin{aligned}
\mathcal{R}_3 =& -i\pi\, m_t\, \beta_0 \left(1 - \frac{\theta^2}{\tau} + 2\log\tau\right) + \frac{\theta^2\, m_t}{\tau^2}\,(16\log\tau + 35) \qquad (3.34)\\
&+ \frac{m_t}{\tau}\Bigg[\theta\left(-48\,\mathrm{Cl}_{1,-2}(\theta) - \frac{8}{3}\,\mathrm{Cl}_{2,1}(\theta) + \frac{1}{3}\,\mathrm{Cl}_2(\theta)\,\log\tau - \frac{64}{3}\,\mathrm{Cl}_{-2}(\theta) - 74\,\mathrm{Cl}_2(\theta)\right)\\
&\quad - 96\,\mathrm{Cl}_{1,-3}(\theta) - 48\,\mathrm{Cl}_{2,-2}(\theta) - \frac{8}{3}\,\mathrm{Cl}_{3,1}(\theta) - \frac{4}{3}\,\mathrm{Cl}_3(\theta)\,\log\tau + \frac{5}{3}\,\mathrm{Cl}_2(\theta)^2\\
&\quad + \frac{61}{48}\,\theta^4 - \frac{2\pi}{9}\,\theta^3 + \theta^2\left(\frac{1}{4}\,\log^2\tau - \frac{92}{3}\,\log\tau + \frac{16}{3}\,\log(4-\tau) + 5\,\zeta_2 - \frac{100}{3}\right)\\
&\quad - \frac{64}{3}\,\mathrm{Cl}_{-3}(\theta) - 64\,\mathrm{Cl}_3(\theta) - 16\,\log\tau - \frac{104}{3}\,\zeta_3\,\log\tau + 80\,\zeta_3 - \frac{151}{3}\,\zeta_4 - \frac{71}{3}\Bigg]\\
&+ m_t\Bigg[\frac{32\,\theta}{3}\,(2\,\mathrm{Cl}_{-2}(\theta) - \mathrm{Cl}_2(\theta)) + 32\,\mathrm{Cl}_{-3}(\theta) - 16\,\mathrm{Cl}_3(\theta) - 8\,\zeta_3 + \frac{5}{3}\,\log^2\tau + \frac{62}{3}\,\log\tau\\
&\quad - \theta^2\left(\frac{8}{3}\log(4-\tau) + \frac{4}{3}\,\log\tau + \frac{1}{4}\right) + \frac{238}{3}\Bigg]\\
&- \frac{i\pi\,\theta\,(4-\tau)\,m_t}{\sqrt{(4-\tau)\tau}}\,\beta_0 + \frac{64\,\theta^3\,m_t}{\tau^2\sqrt{(4-\tau)\tau}} - \frac{2\,m_t}{\sqrt{(4-\tau)\tau}}\left(1 - \frac{2}{\tau}\right)R(\theta)\\
&+ \frac{\theta\,m_t}{6\sqrt{(4-\tau)\tau}}\left[13\,\theta^2 + 62 - \frac{4}{\tau}\,(63\,\theta^2 + 62)\right] - \frac{(4-\tau)\,m_t}{\sqrt{(4-\tau)\tau}}\Bigg[-\frac{32}{3}\mathrm{Cl}_{-2}(\theta) + 3\mathrm{Cl}_2(\theta)\\
&\quad + \theta\left(\frac{16}{3}\,\log(4-\tau) - \frac{1}{6}\,\log\tau - \frac{71}{2}\right)\Bigg].
\end{aligned}$$

ggH in the SMEFT

$$
\begin{aligned}
C_1(\mu^2) &= C_1(Q^2) - \frac{\alpha_s(Q^2)}{\pi}\log\frac{\mu^2}{Q^2}\left(C_1(Q^2) + 8\,C_3(Q^2)\,\frac{m_t^2(Q^2)}{v^2}\right) + \mathcal{O}(\alpha_s(Q^2)^2)\,,\\
C_2(\mu^2) &= C_2(Q^2) + \sqrt{2}\,\frac{C_3(Q^2)}{16\,\pi^2}\,\log\frac{\mu^2}{Q^2}\,\frac{m_t(Q^2)}{v}\\
&\quad - \sqrt{2}\,\frac{\alpha_s(Q^2)}{192\,\pi^3}\,C_3(Q^2)\,\log\frac{\mu^2}{Q^2}\,\frac{m_t(Q^2)}{v}\left(5\,\log\frac{\mu^2}{Q^2} - 69\right) + \mathcal{O}(\alpha_s(Q^2)^2)\,,\\
C_3(\mu^2) &= C_3(Q^2) + C_3(Q^2)\,\frac{\alpha_s(Q^2)}{6\pi}\,\log\frac{\mu^2}{Q^2} + \mathcal{O}(\alpha_s(Q^2)^2)\,.
\end{aligned}
$$

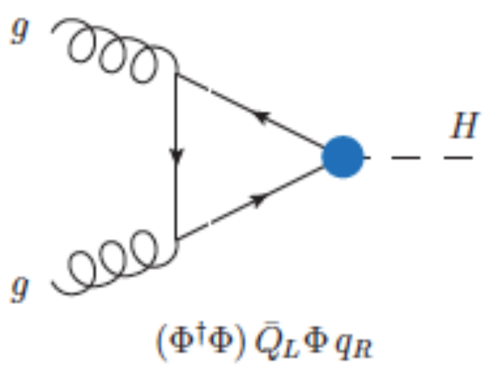




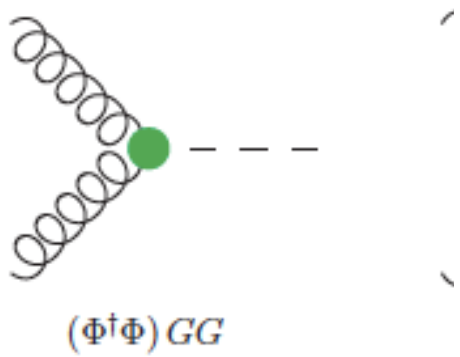
ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]

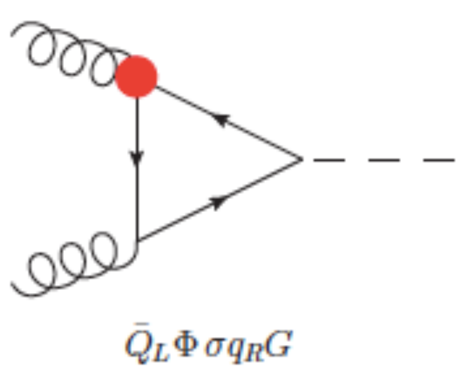
σ_1



σ_2



σ_3



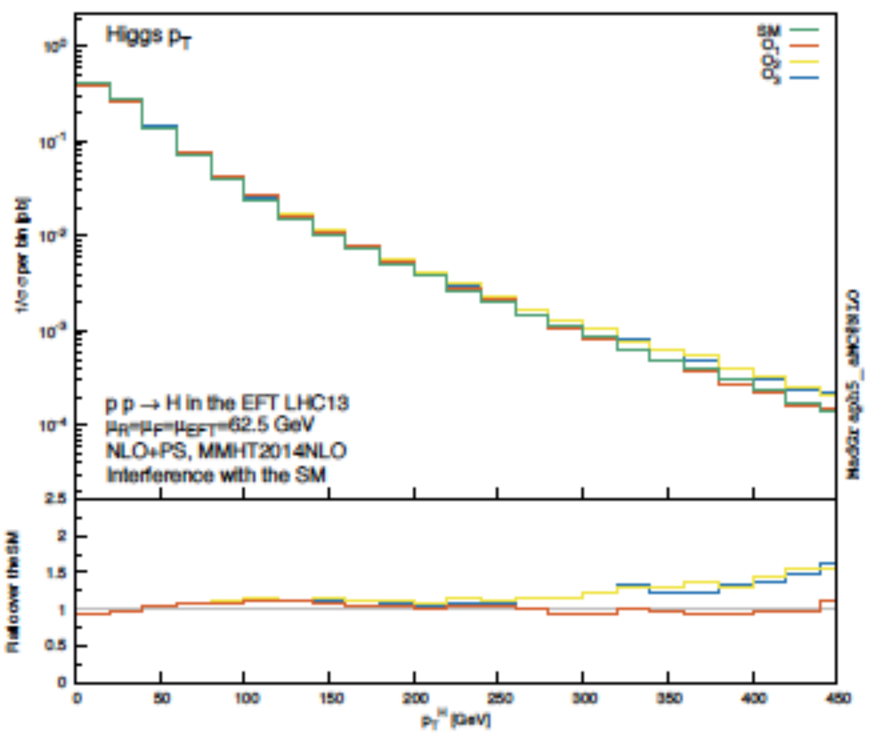
13 TeV	σ LO	σ/σ_{SM} LO	σ NLO	σ/σ_{SM} NLO	K
σ_{SM}	$21.3^{+34.0+1.5\%}_{-25.0-1.5\%}$	1.0	$36.6^{+26.4+1.9\%}_{-20.0-1.6\%}$	1.0	1.71
σ_1	$-2.93^{+34.0+1.5\%}_{-25.0-1.5\%}$	-0.138	$-4.70^{+24.8+1.9\%}_{-20.0-1.6\%}$	-0.127	1.61
σ_2	$2660^{+34.0+1.5\%}_{-25.0-1.5\%}$	125	$4130^{+23.9+1.9\%}_{-19.6-1.6\%}$	114	1.55
σ_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
σ_{11}	$0.0890^{+34.0+1.5\%}_{-25.0-1.5\%}$	0.0042	$0.141^{+24.8+1.9\%}_{-20.0-1.6\%}$	0.0038	1.59
σ_{22}	$74100^{+34.0+1.5\%}_{-25.0-1.5\%}$	3480	$109100^{+22.6+1.9\%}_{-18.9-1.6\%}$	3000	1.47
σ_{33}	$26.6^{+34.0+1.5\%}_{-25.0-1.5\%}$	1.25	$41.6^{+25.3+2.0\%}_{-20.4-1.7\%}$	1.13	1.56
σ_{12}	$-162^{+34.0+1.5\%}_{-25.0-1.5\%}$	-7.61	$-248^{+23.6+1.9\%}_{-19.5-1.6\%}$	-6.78	1.53
σ_{13}	$-3.08^{+34.0+1.5\%}_{-25.0-1.5\%}$	-0.145	$-5.04^{+25.4+1.9\%}_{-20.3-1.6\%}$	-0.138	1.64
σ_{23}	$2800^{+34.0+1.5\%}_{-25.0-1.5\%}$	131	$4460^{+24.6+1.9\%}_{-19.9-1.6\%}$	122	1.59

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

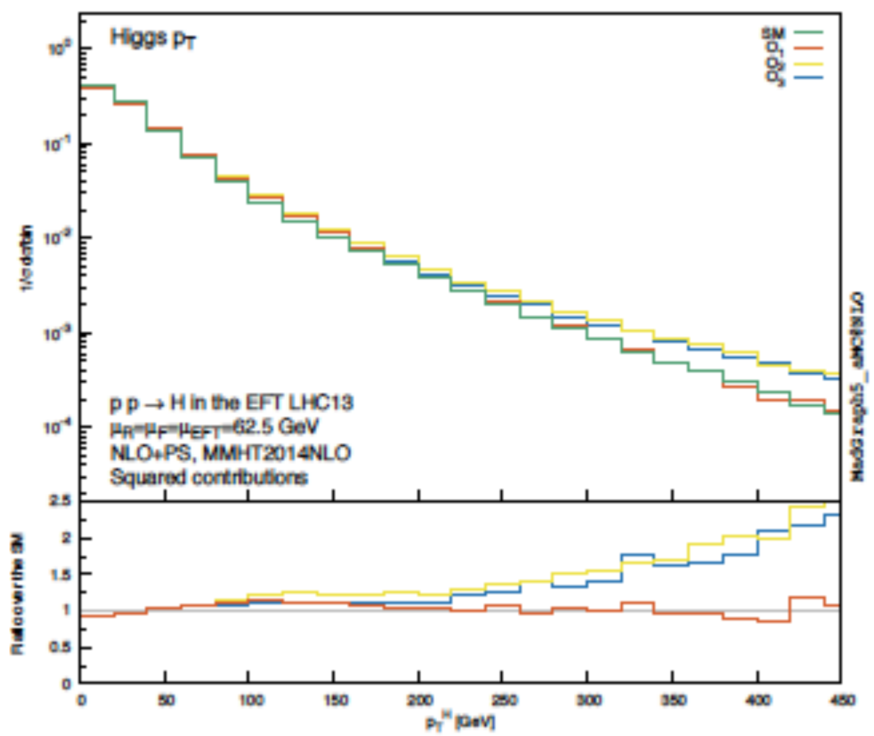
ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]

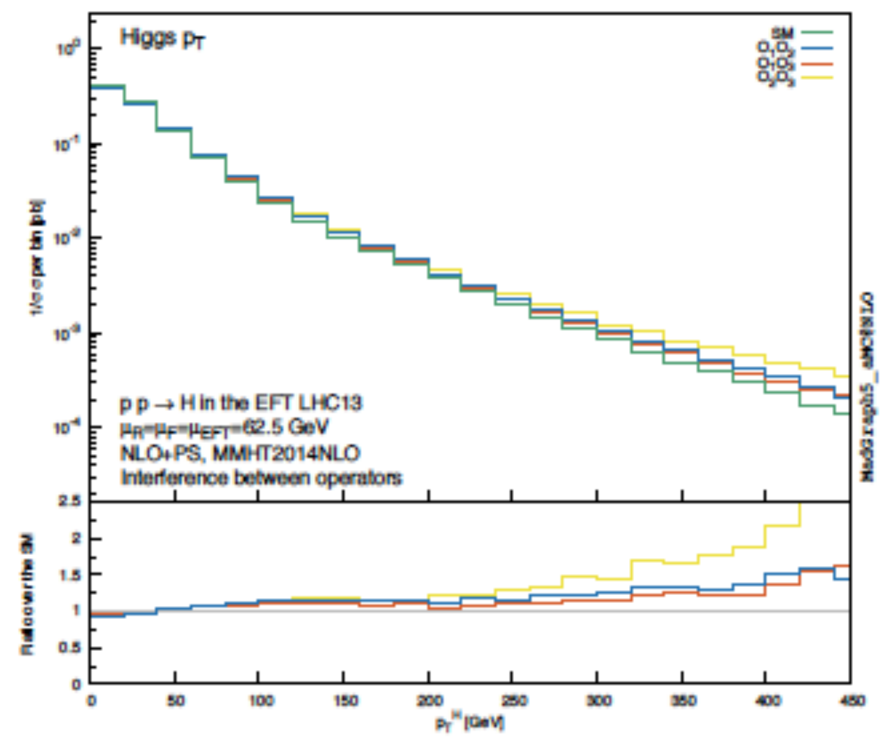
Interference w/ SM



Squared (diagonal)



Squared (crossed)



The effects of the chromo are "degenerate" with those of the $O_{\varphi G}$ operator in the interference and diagonal squared terms.

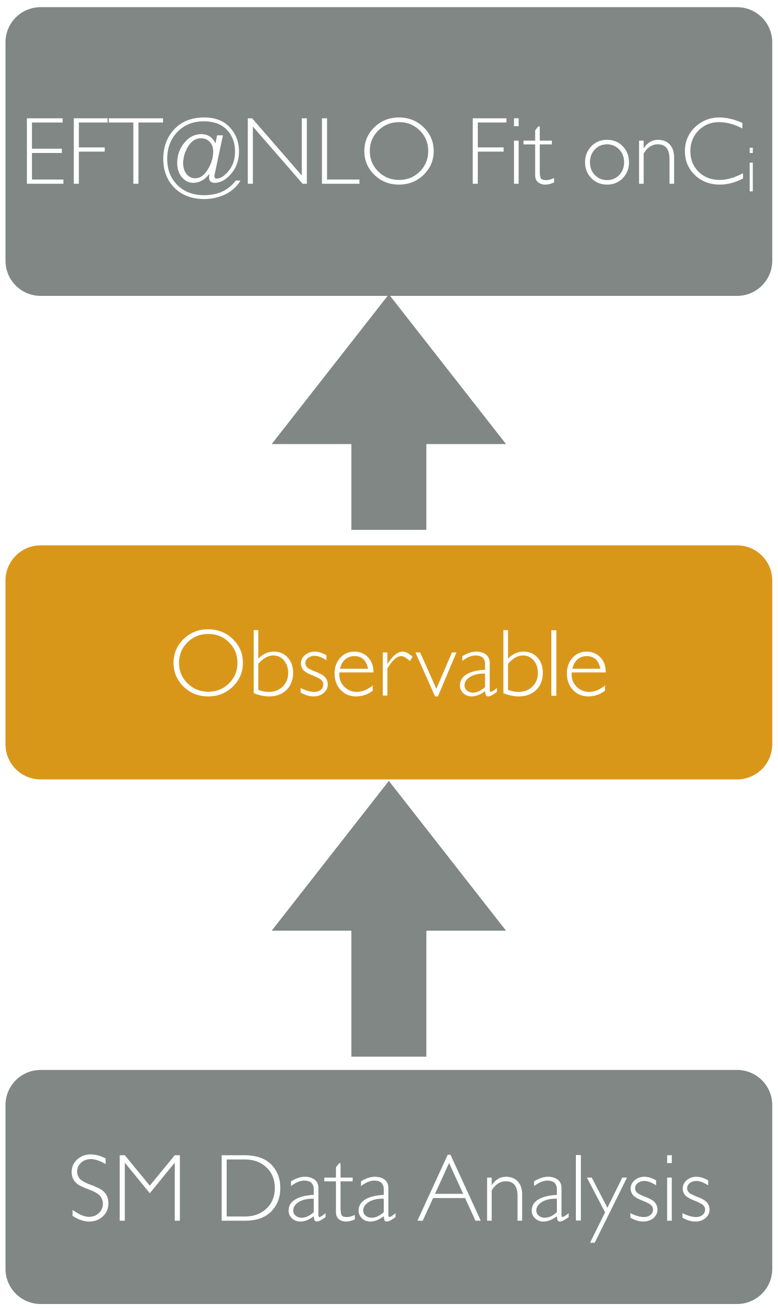
Note also the behaviour at small pT due to the bottom loop which has been only included in the SM part.

Approaches

OPTION top-down

- This is the ideal way as it would maximise the sensitivity (in analogy to any BSM top-down search) and it does not need providing information back at the particle level.
- However, it assumes several important conditions:
  - The analyses at the experimental level are fully coordinated and can be combined.
  - The theoretical setup is final and the dependence on additional theoretical assumptions is minimal.
- While globally this might not be a realistic option, feasibility studies could start for specific subsets.

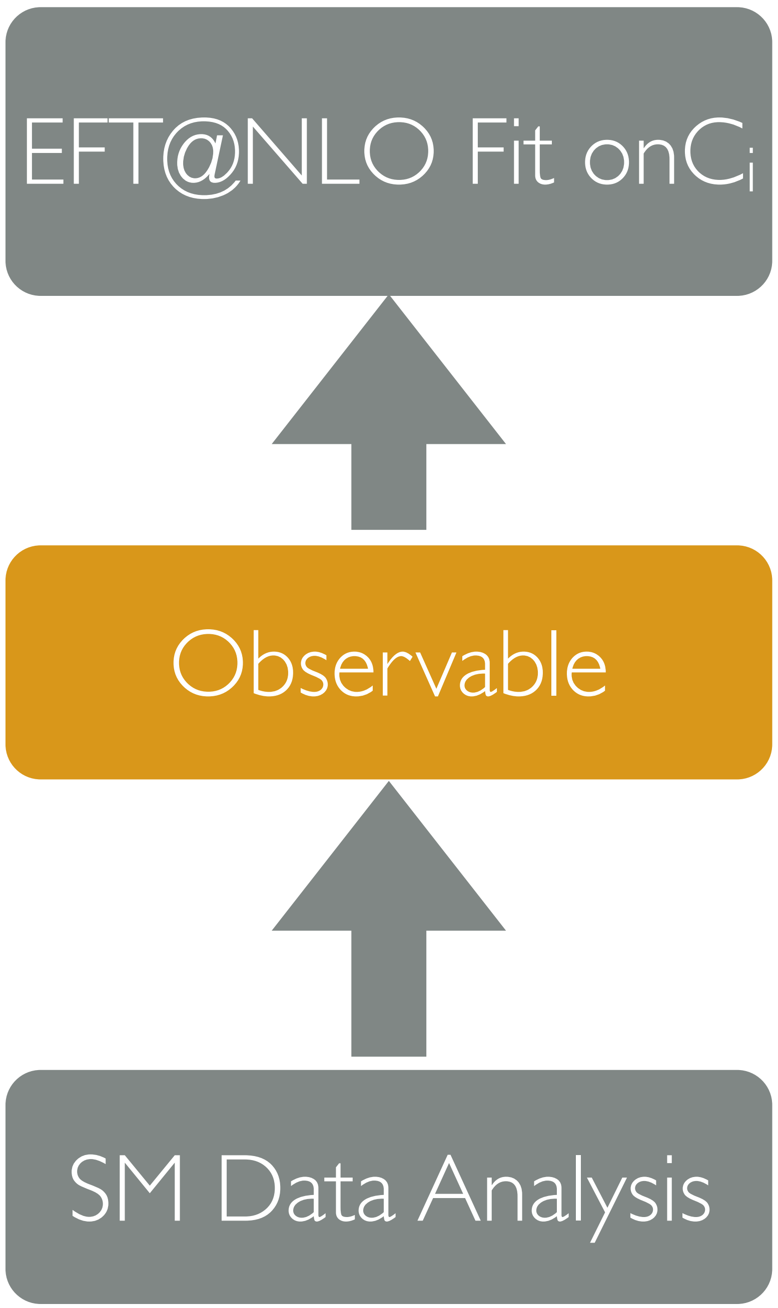
Approaches



OPTION bottom-up

- A (continuously extendable) set of observables is identified and measured.
- Such observables can be of various types, from “total cross section” to differential distributions, typically at the particle level or parton level.
- Ex: total cross sections, (pt, eta) distributions, correlations.
- Results are provided with the minimal systematic uncertainty breakdown so that they can be combined with other measurements.
- One dimensional differential distributions should be provided with the bin-by-bin correlation matrix.

Approaches



OPTION bottom-up

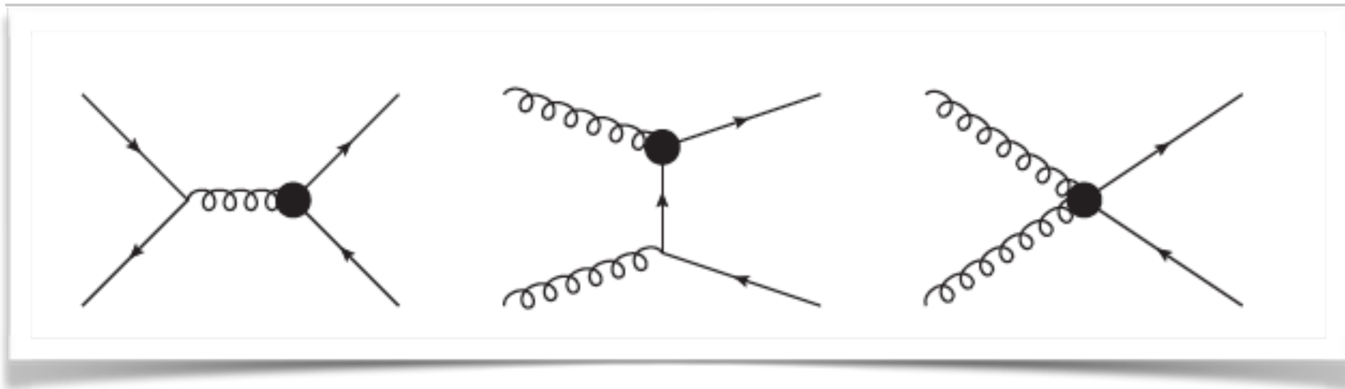
- This approach has the advantage that TH predictions, evaluations of the uncertainties, constraints coming from other studies, can be constantly and continuously included.
- It could be used to prepare a top-down and global approach.
- It might motivate and pave the way to the more sensitive EXP fits.

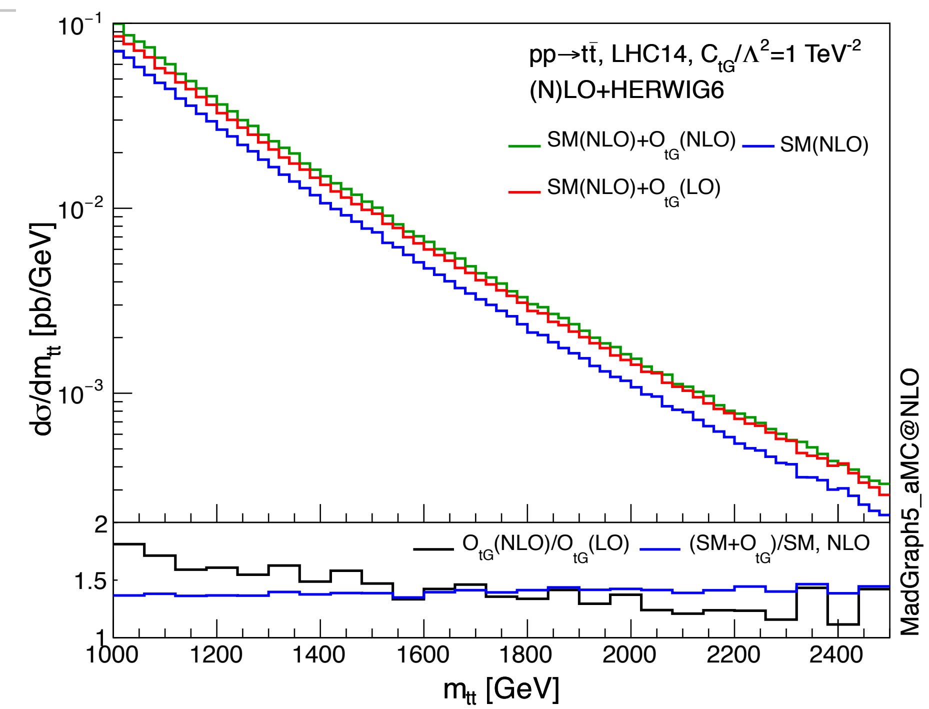
Conclusions and Outlook

- NLO in the SMEFT is imho mandatory. Theoretical/MC effort to provide accurate/precise/usable predictions has started a few years ago.
- NLO-QCD predictions being made available in a MC form (4F still in the working). NLO-EW will be welcome at least for EW Higgs prod. and 4l decays.
- Reliable evaluation of the THU is a key aspect of the data intepretation in the SMEFT approch.
- Top-down and bottom-up approaches possible in principle.

Bounding OtG at NLO from ttbar

[Franzosi and Zhang, 2015]



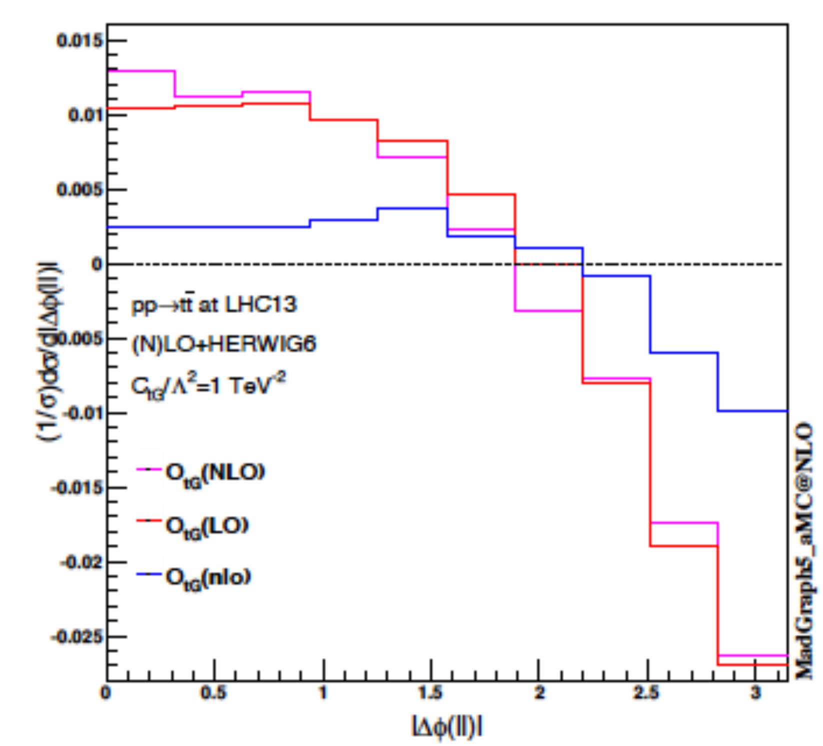


Recent analysis at NLO in QCD

$$\sigma = \sigma_{\rm SM} + \frac{C_{tG}}{\Lambda^2}\beta_1 + \left(\frac{C_{tG}}{\Lambda^2}\right)^2 \beta_2$$

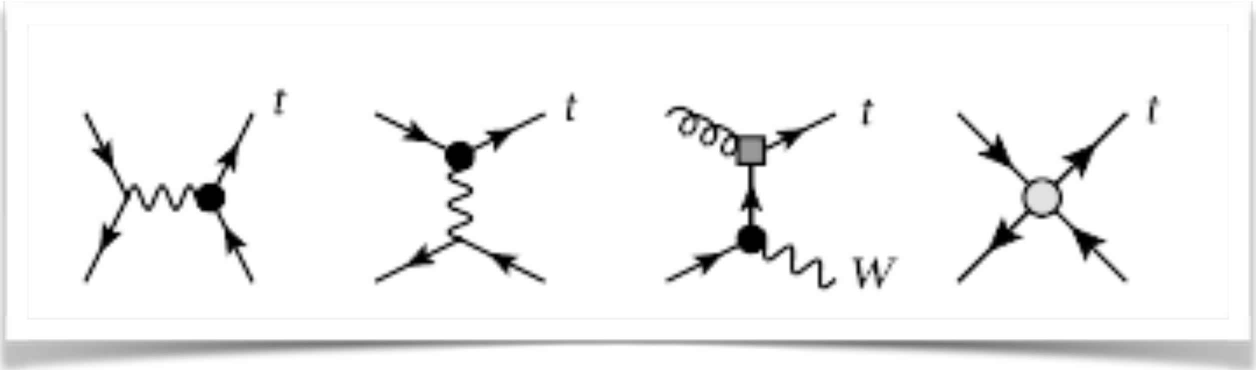
Limits on ctG from LHC8

	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]

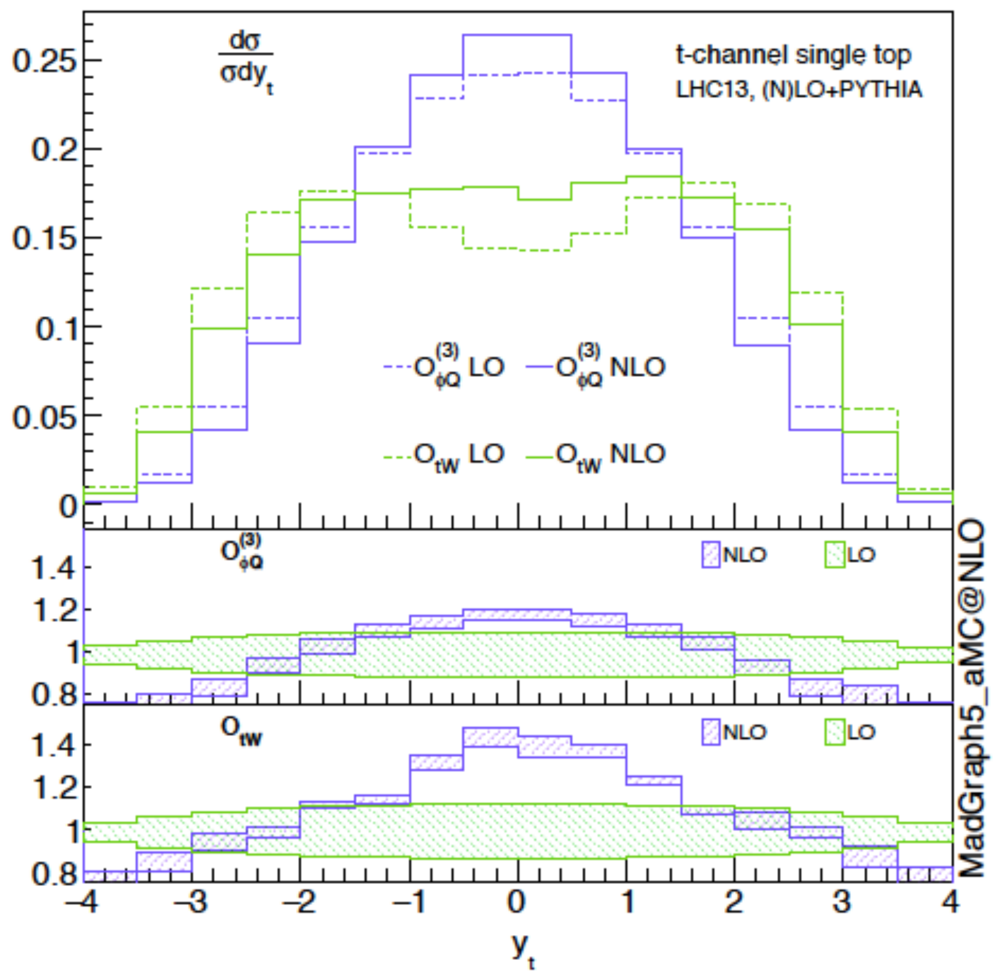


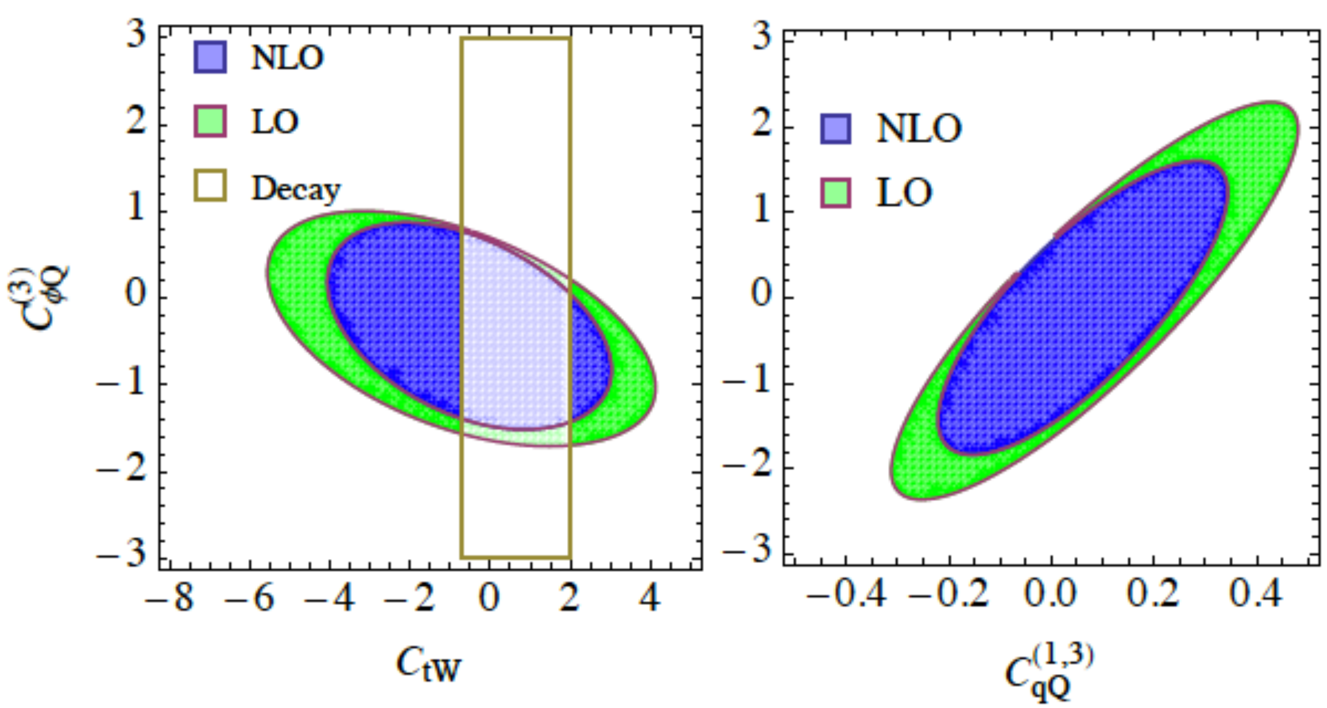
Single-top in the EFT at NLO

[Cen Zhang, 2016]



4F operator can also be included (on-going).





NLO corrections distort LO distributions, they impact the limits in accuracy and precision.

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]

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

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

Small contribution from OtW and OtB 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

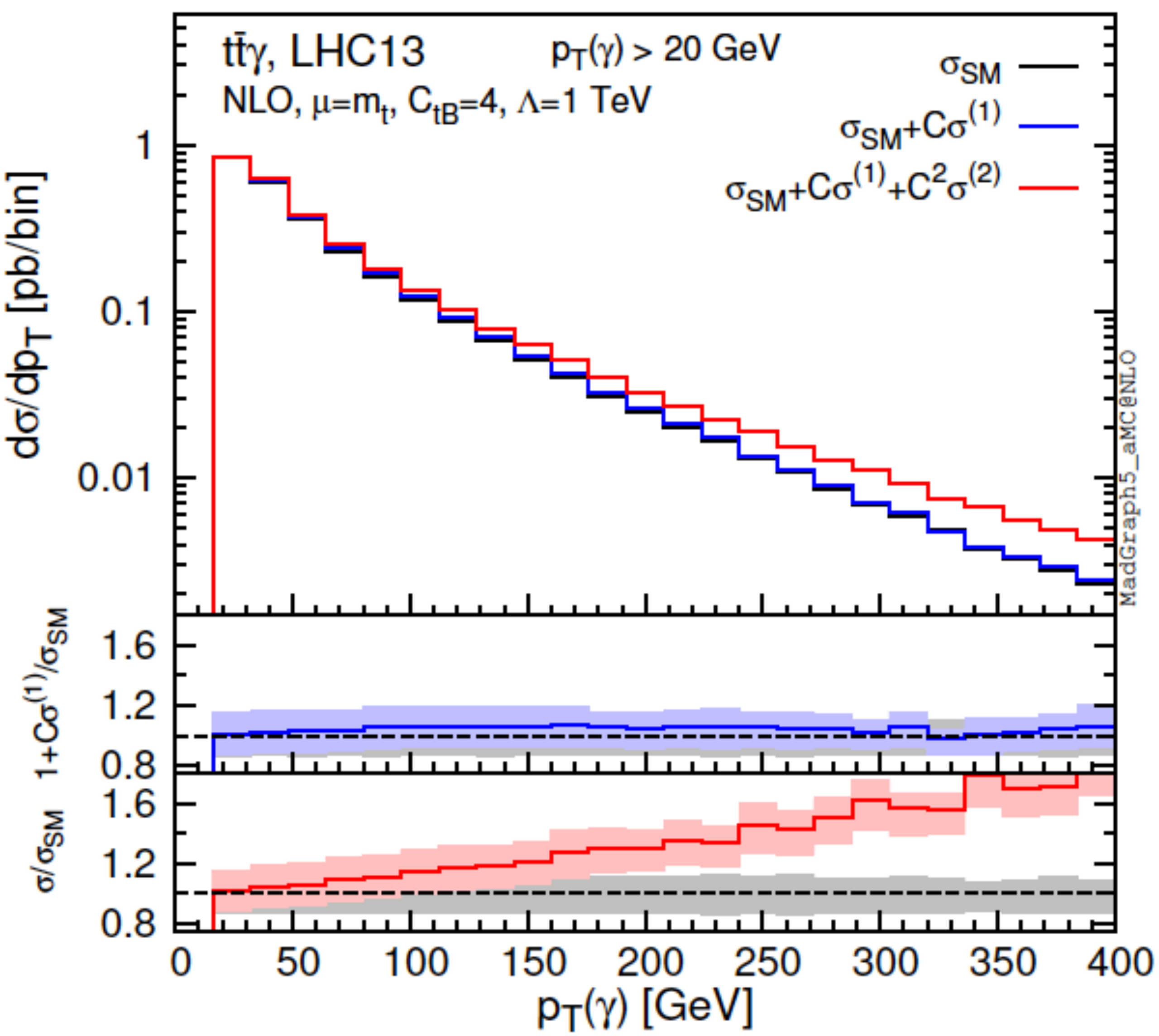
$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\frac{1}{2}y_t^2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

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

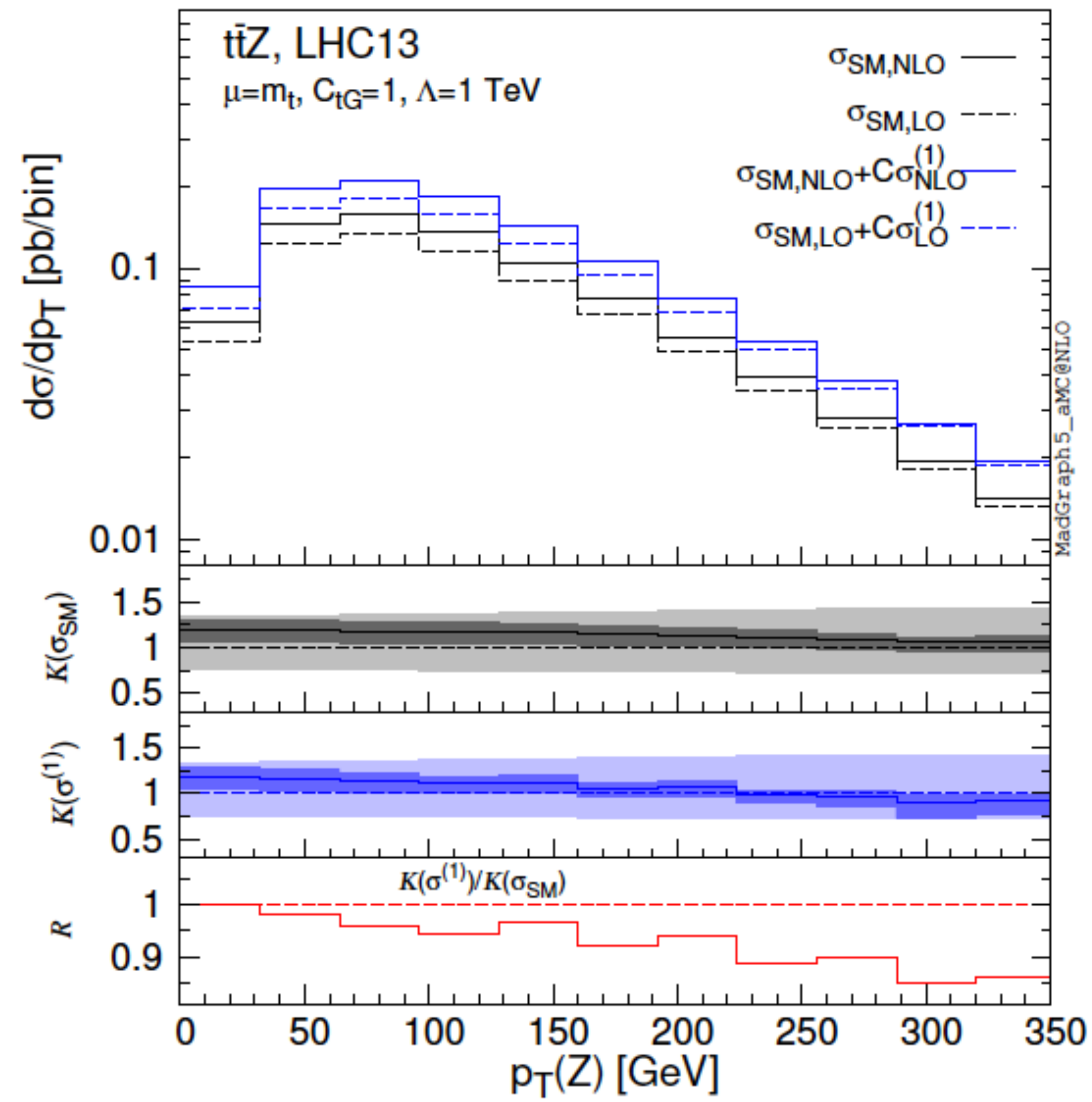
Anom. dim. matrix: O_{tW}, O_{tB}, O_{tG}

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]



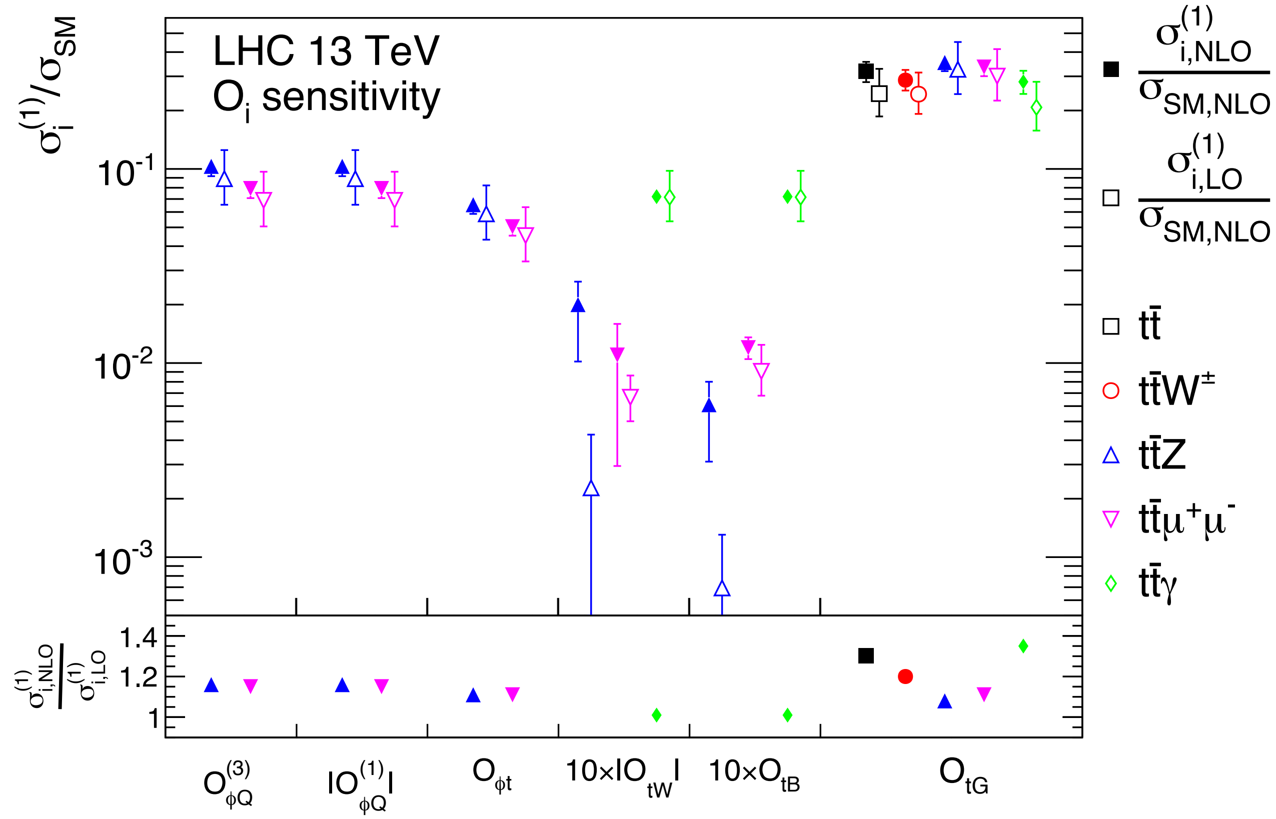
Large contribution at $O(1/\Lambda^4)$ rising with energy

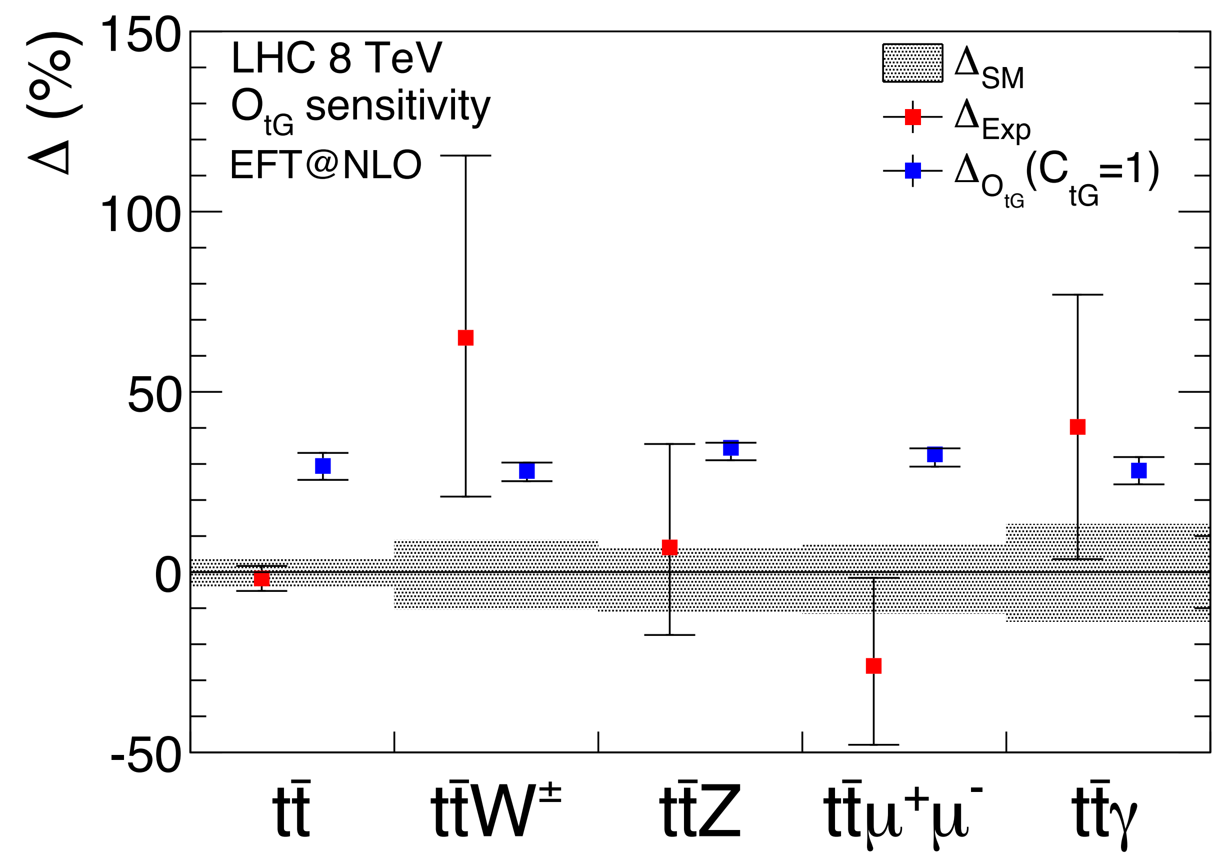


Using SM k-factors is not enough

ttV in the EFT at NLO

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]





Chromomagnetic operator affecting all processes in the same way.

LHC measurements of ttV processes can set constraints on the Wilson coefficients See also: [Rontsch and Schulze et al. 2014, 2015] and [Schulze 2016] in the anomalous coupling framework.

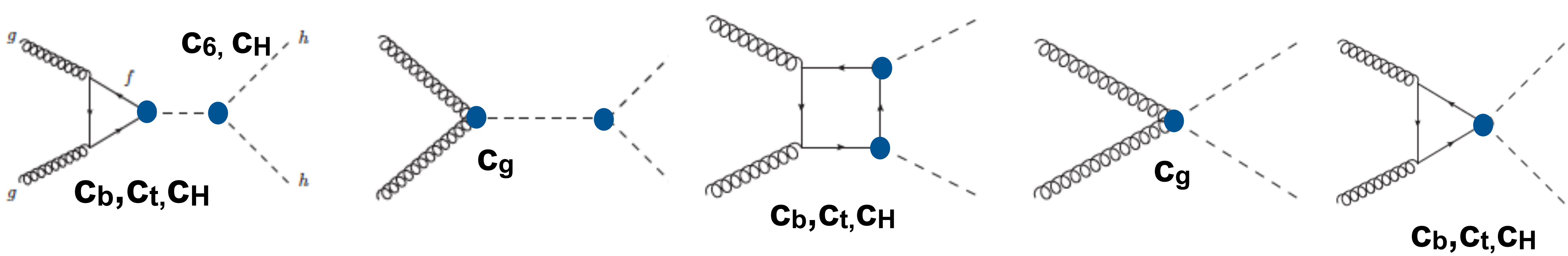
HH production in the SMEFT

$$
\begin{aligned}
\mathcal{L}_{h^n} = & -\mu^2|H|^2 - \lambda|H|^4 - \left(y_t\bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R + \text{h.c.}\right) \\
& + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda|H|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu}G^{\mu\nu}_a \\
& - \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \text{h.c.}\right),
\end{aligned}
$$

[Goertz et al. , arxiv:1410.3471]
[Contino et al. , arXiv:1502.00539]

EFT approach: No additional light states
Dimension-6 operators suppressed by scale Λ

$$
\begin{aligned}
\mathcal{L}_{hh} = & -\frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1 - \frac{25}{3}c_H + 6c_6\right)h^4 \\
& + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a \\
& - \left[\frac{m_t}{v}\left(1 - \frac{c_H}{2} + c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1 - \frac{c_H}{2} + c_b\right)\bar{b}_L b_R h + \text{h.c.}\right] \\
& - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2} - \frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2} - \frac{c_H}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right],
\end{aligned}
$$

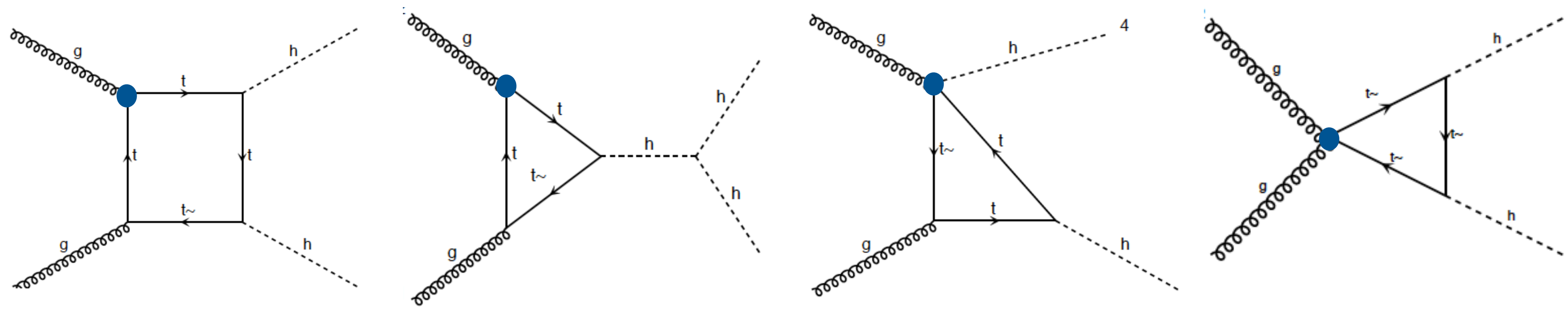


5 parameters:c6, cH, cb,ct,cg

HH production in the SMEFT

Chromomagnetic operator is also contributing [FM, Vryonidou, Zhang, 16]

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



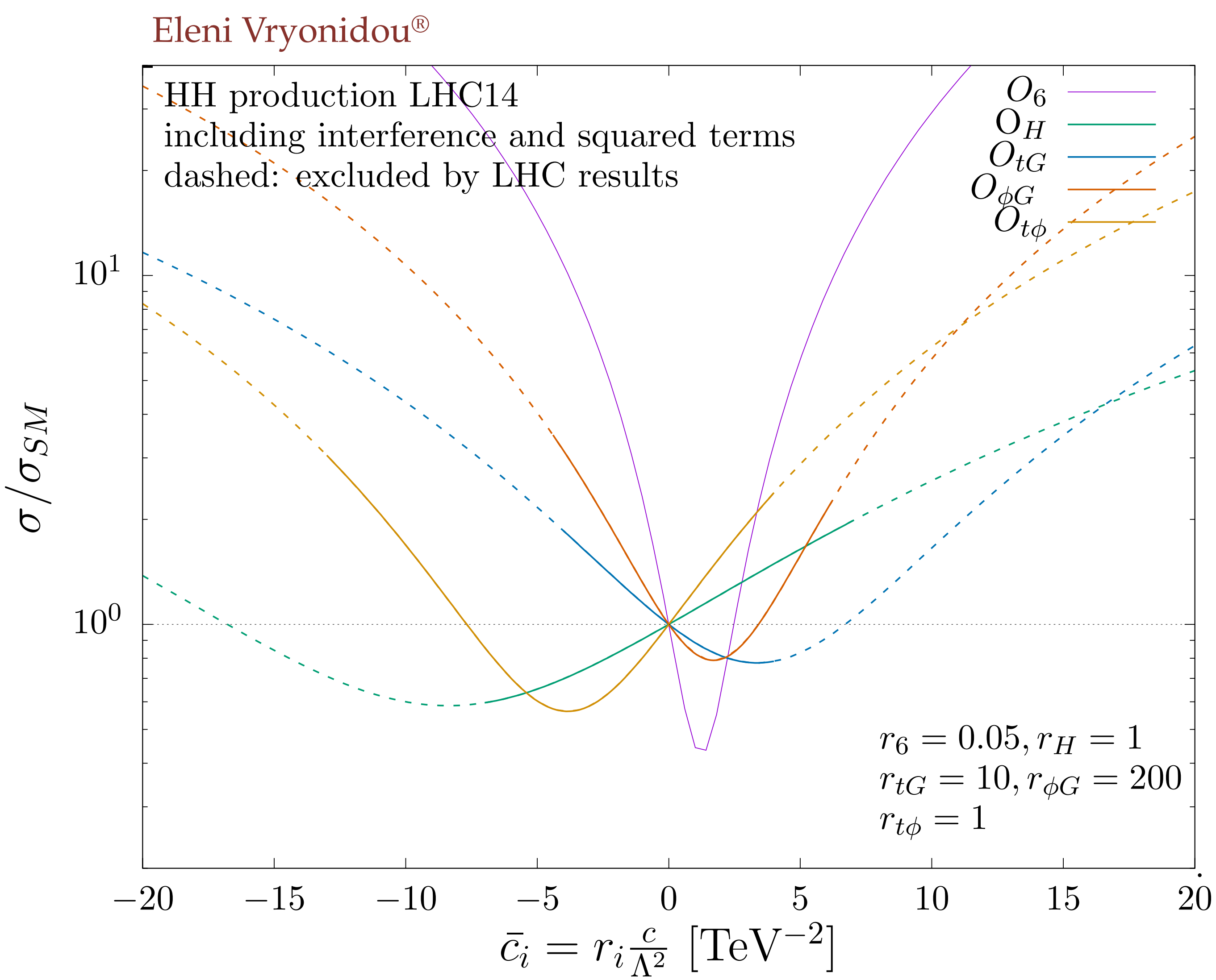
Needs to be taken into account in the context of a global EFT analysis for HH
Constraints from top pair production at NLO:

C_{tg}= [-0.42,0.30] [Zhang and Franzosi,15]

show that this operator contribution is important.

Note: now that NLO in the SM is known, one could have c_t,c_H,c_g contributions at NLO.
The c_g is known at NNLO [de Florian, Fabre, Mazzittelli, 17]

HH sensitivity in the SMEFT

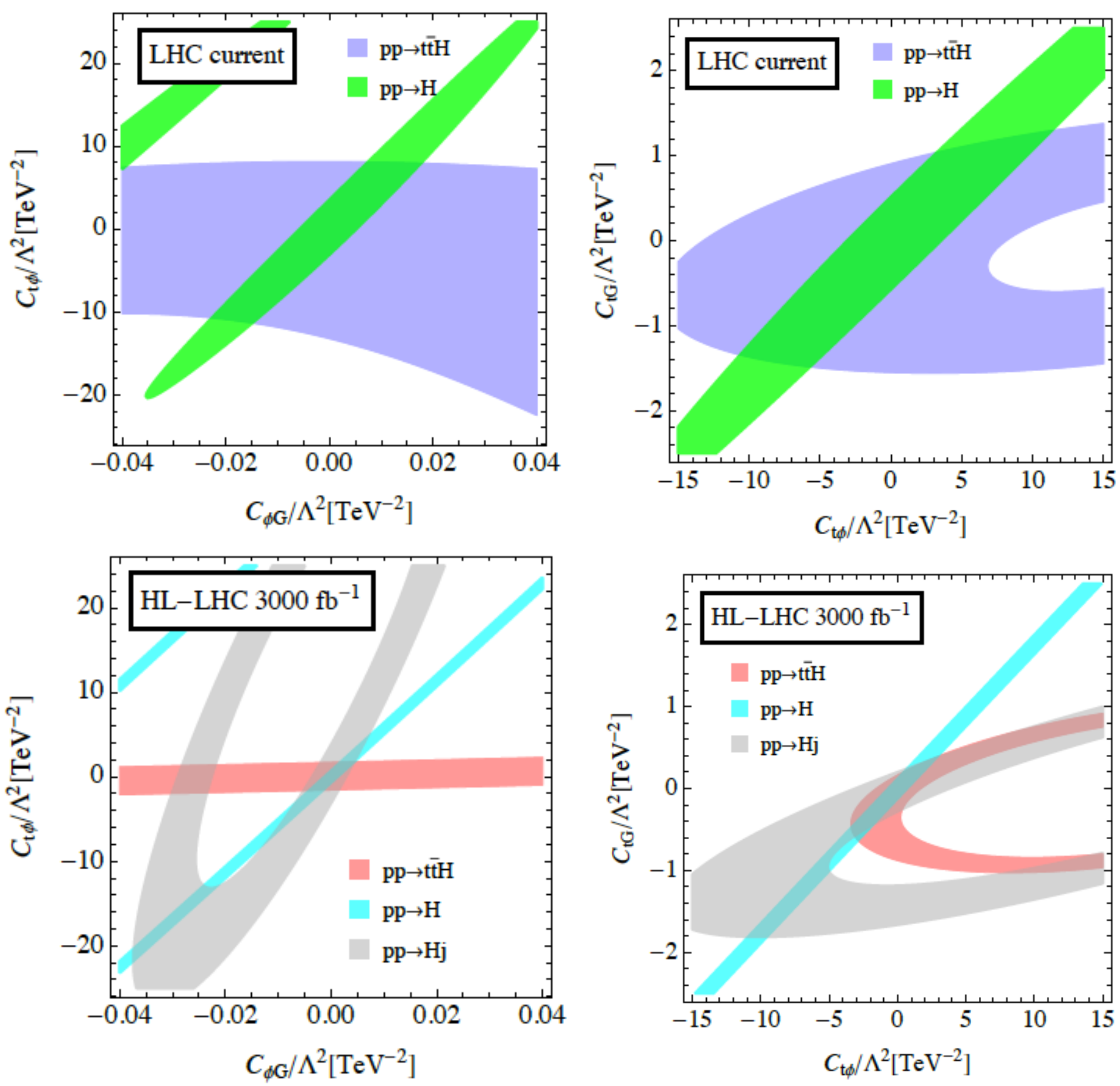


Sensitivity plot of σ(HH) in terms of the five relevant operators. Coefficients are rescaled so that the ranges are comparable.

1. An accurate measurement of the Higgs self-couplings will depend on our ability to bound several (top-related) SMEFT operators: O_{tG}, $O_{\varphi G}$, $O_{t\varphi}$.
2. Given the current constraints on σ(HH), the Higgs self-coupling can be constrained "ignoring" the other EFT couplings.
3. The current "EFT-relevant" range corresponds to values around $-2 \lesssim k_\lambda \lesssim 4$.

Constraints from ttH and Higgs production

[FM, Vryonidou, Zhang, 16]



Current limits using LHC measurements

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

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

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

14TeV projection

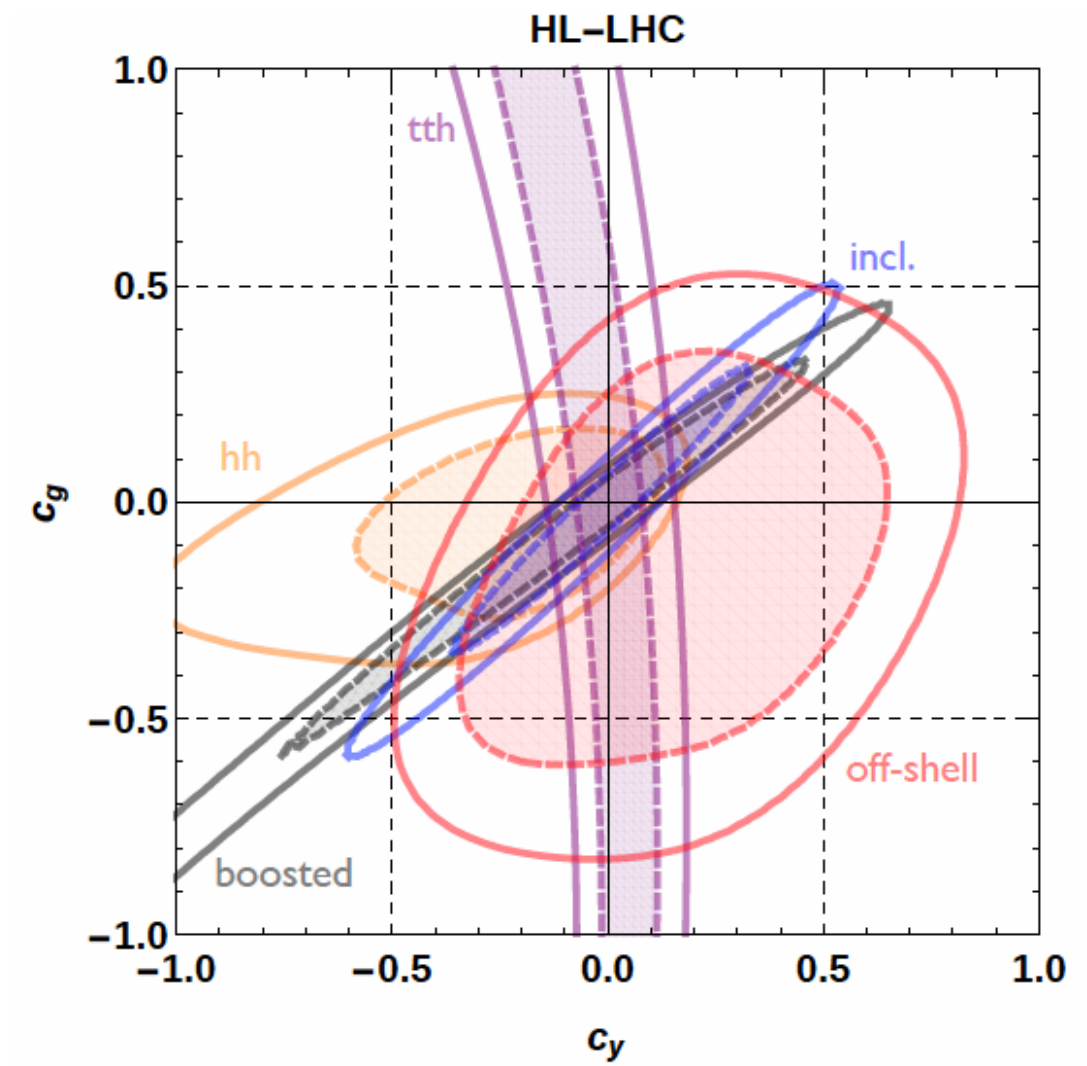
3000 fb-1

Constraints from ttH and Higgs production

Combination:

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

[Azatov et al, 16]



A theorist's study. Future: More realistic experimental analyses needed.

EW production at NLO(+PS) in QCD

Higgs production

[FM, Mawatari, Zaro, 13] MG5_aMC@NLO in the HC basis

[Mimasu, Sanz, Williams, 15] MCFM + POWHEG

[Greljo, Isidori, Lindert, Marzocca, 15] Sherpa+OpenLoops in the PO's + UFO

[Degrande, Fuks, Mawatari, Mimasu, Sanz, 16] MG5_aMC@NLO in SILH

+JHUGen, VBF@NLO, WHIZARD

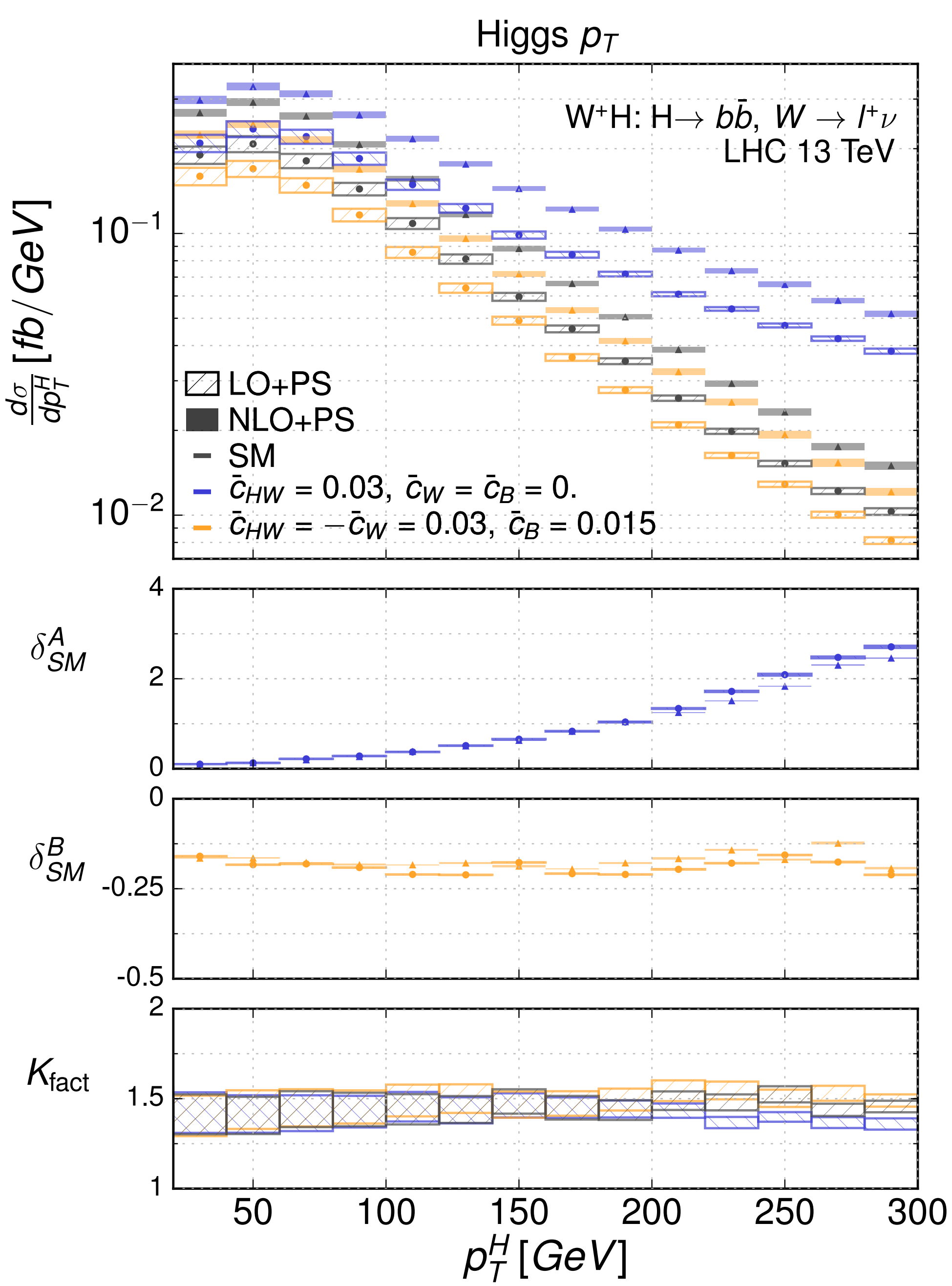
Multi-boson production

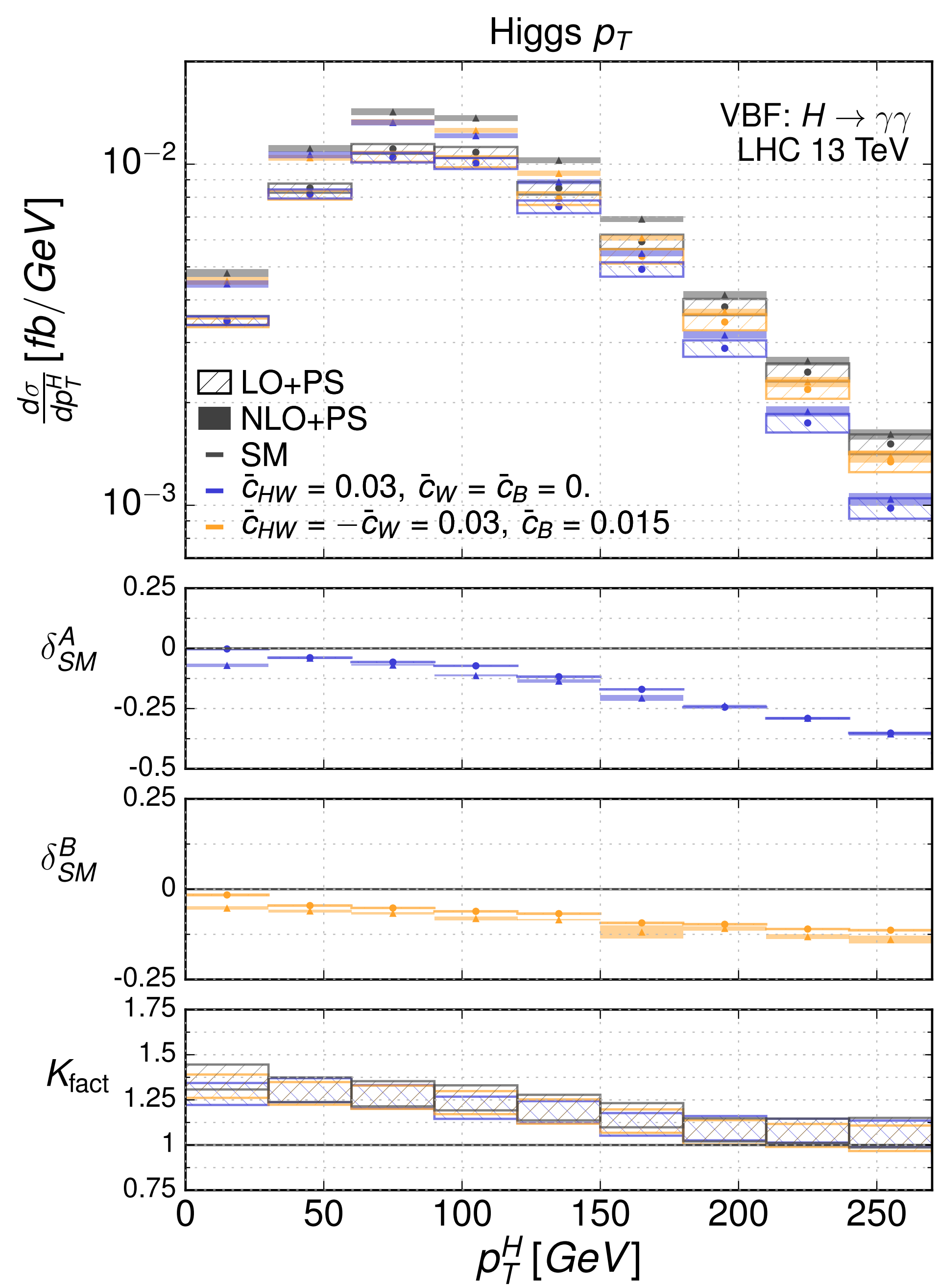
[Degrande, 13] (dim=8) FeynRules model (can be upgraded to NLO)

[Degrande, Fuks, Mawatari, Mimasu, Sanz, 16] FR+MG5_aMC@NLO in SILH

+VBF@NLO, WHIZARD

Higgs EW production at NLO+PS in QCD





[Degrande, Fuks, Mawatari, Mimasu, Sanz, 16]

List of tools relevant for the HEFT

Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector

SMEFT FeynRules implementations

[Artoisenet et al. 13] [FM, Mawatari, Zaro, 13] [Demartin, FM, Mawatari, Zaro, 14] [Demartin, FM, Mawatari, Zaro, 15] [Demartin, FM, Mawatari, Zaro, 16]	All production/decay: MG5_aMC@NLO in the HC basis at NLO in QCD.
[Alloul, Fuks, Sanz 13] [Degrande, Fuks, Mawatari, Mimasu, Sanz, 16]	HELatNLO : SILH at NLO in QCD
[Greljo, Isidori, Lindert,	
[FM, Vryonidou, Zhang, [Bylund et al., 16] [Zhang, 16]	
[Dedes et al. 17]	

- No restriction is made for the structure of flavor violating terms and for CP-, lepton- or baryon-number conservation,
- SMEFT is quantized in R_ξ-gauges written with four different arbitrary gauge parameters, $\xi_\gamma, \xi_Z, \xi_W, \xi_G$ for better cross checks of physical amplitudes.
- Gauge fixing and ghost part of the Lagrangian is chosen to be SM-like and preserve Becchi, Rouet, Stora [18], and Tyutin [19] (BRST) invariance.
- All bilinear terms in the Lagrangian have canonical form, both for physical and unphysical Goldstone and ghost fields; all propagators are diagonal and SM-like.
- Feynman rules for interactions are expressed in terms of physical SM fields and canonical Goldstone and ghost fields.