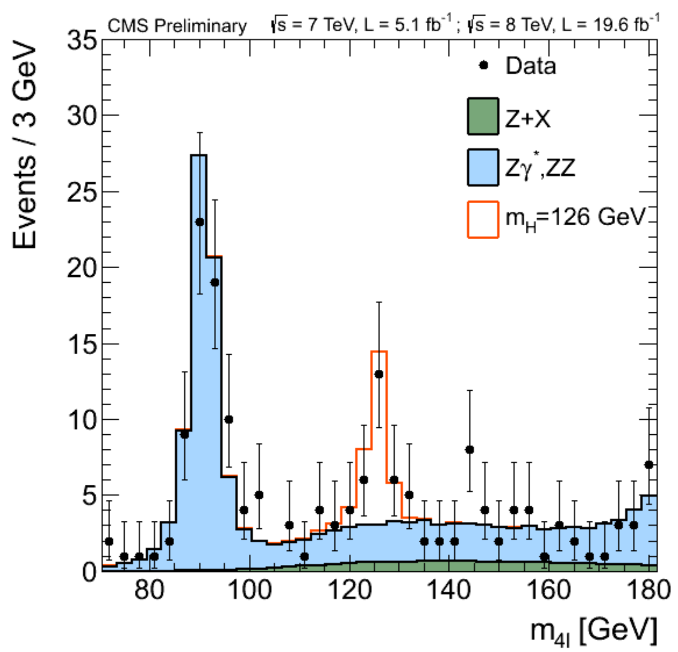
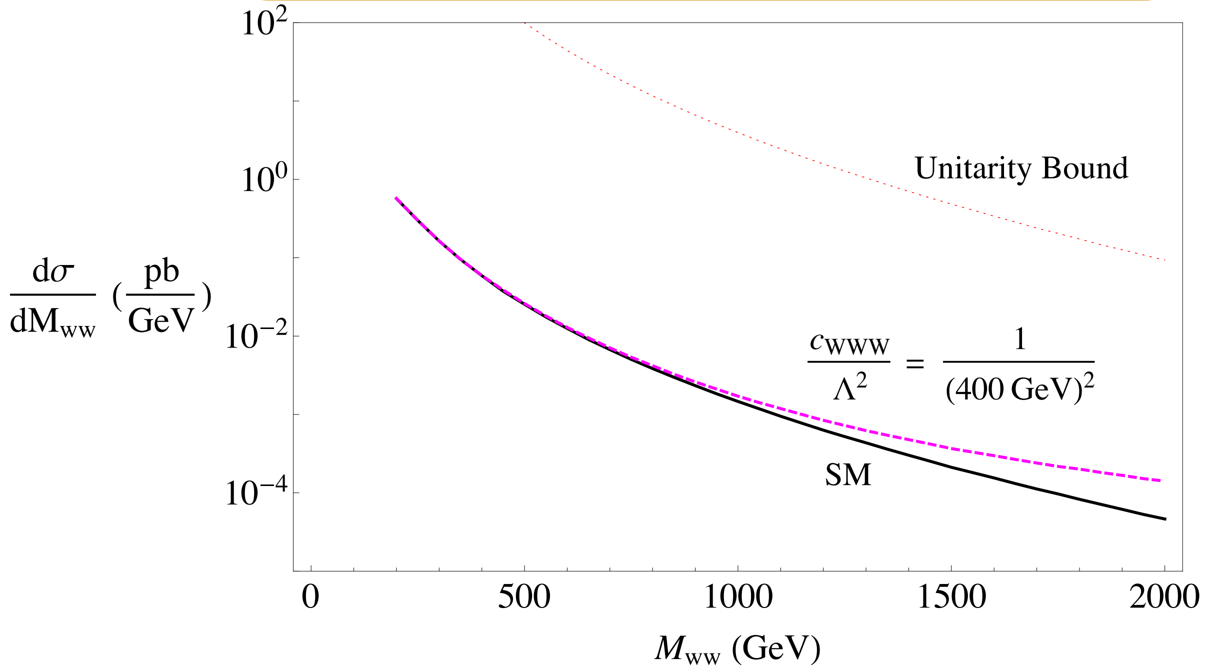
SMEFT: Tools and predictions

Fabio Maltoni
Centre for Cosmology, Particle Physics and Phenomenology (CP3)
Université catholique de Louvain

Search for New Physics at the LHC

Search for new states ⟷ **Search for new interactions**





"Peak" or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

Search for New Physics at the LHC

Search for new states ⟷ Search for new interactions

The matter content of SM has been experimentally verified and evidence for light states is not present. SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions.

$$\mathcal{L}_{SM}^{EFT} = \mathcal{L}_{SM}^{(4)} + \sum_{n=3} \sum_{i} c_i \frac{\mathcal{O}_i^{(2n)}}{\Lambda^{2n-4}}$$

BSM goal of the SM LHC program:

determination of the couplings of the SMEFT Lagrangian

SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)

- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

SMEFT Lagrangian: theoretical progress

- Full RGE at 1-loop mixing matrix known:
  [Jenkins, Manohar and Trott, 13] [Jenkins, Manohar and Trott, 13]
  [Alonso, Jenkins, Manohar and Trott, 13]
- Extension to dim=7,8,….:
  [Lehman, 14] [Kobach, 16] [Lehman and Martin, 15][Henning et al., 14, 15,15,16][Liao et al. 16]
- Matching to UV:
  [Passarino, 12][Henning et al., 14] [Brehmer et al., 15][Freytas et al., 16] [Biekotter et al., 16]
- Reparametrisation invariance:
  [Passarino, 16] [Brivio and Trott, 17]
- HEFT topics
  [LHCXSWG 4]

The EFT approach: managing unknown unknowns

- Very powerful model-indepedent approach.
- A **global constraining strategy** needs to be employed:
  - assume all* couplings not be zero at the EW scale.
  - identify the operators entering predictions for each observable (LO, NLO,..)
  - find enough observables (cross sections, BR's, distributions,…) to constrain all operators.
  - solve the linear (+quadratic)* system.
- Use to constrain UV-complete* models.
- The final reach on the scale of New Physics crucially depends on the THU.

List of tools relevant for the HEFT

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

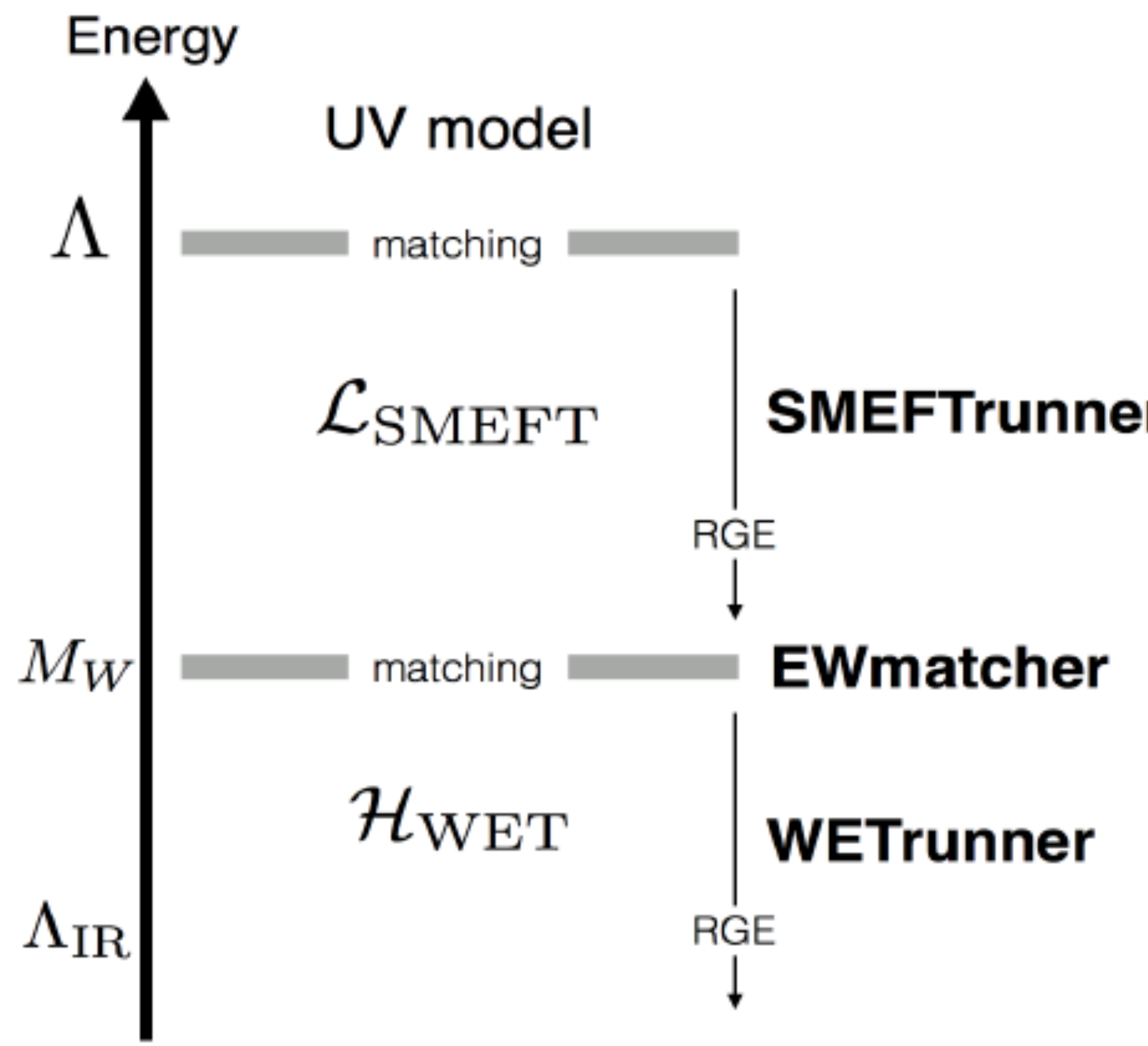
List of tools relevant for the HEFT

- New tools being released quite often

[Celis et al. 17]

Abstract

We present DsixTools, a Mathematica package for the Model Effective Field Theory. Among other features, the full one-loop Renormalization Group Evolution of basis. This is achieved thanks to the SMEFTrunner modu anomalous dimension matrix previously derived in the contains modules devoted to the matching to the $\Delta B = \Delta$ the Weak Effective Theory at the electroweak scale, anc Group Evolution below the electroweak scale.



https://dsixtools.github.io

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, Marzocca, 15]	EW interactions PO's
[FM, Vryonidou, Zhang, 16] [Bylund et al., 16] [Zhang, 16]	Top/Higgs sector in the Warsaw basis at NLO in QCD
[Dedes et al. 17]	Complete Warsaw basis in Rxi gauge BFA at LO (http://www.fuw.edu.pl/smeft/)

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.

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?

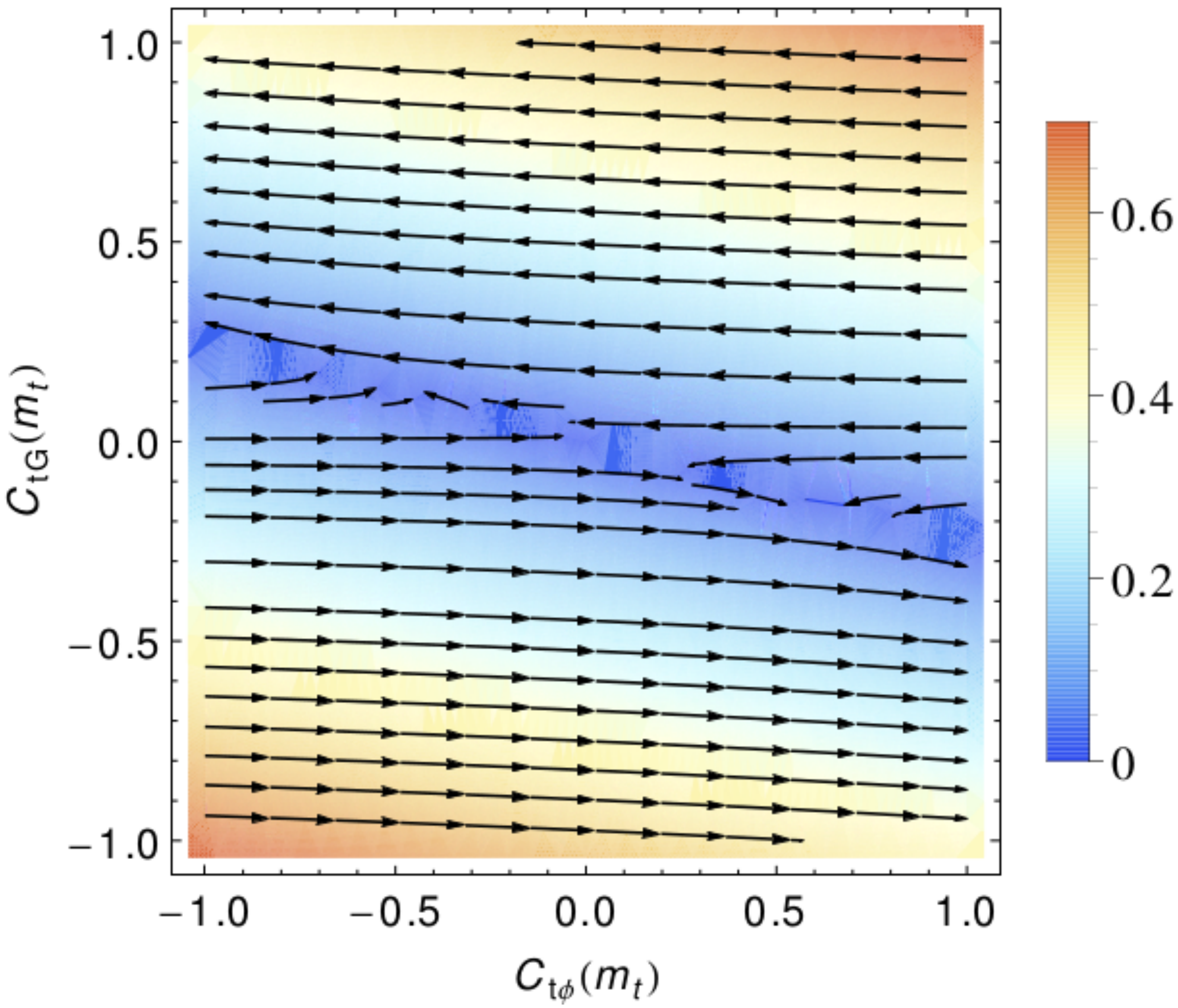
1. Operators run and mix under RGE

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.

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

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

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

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

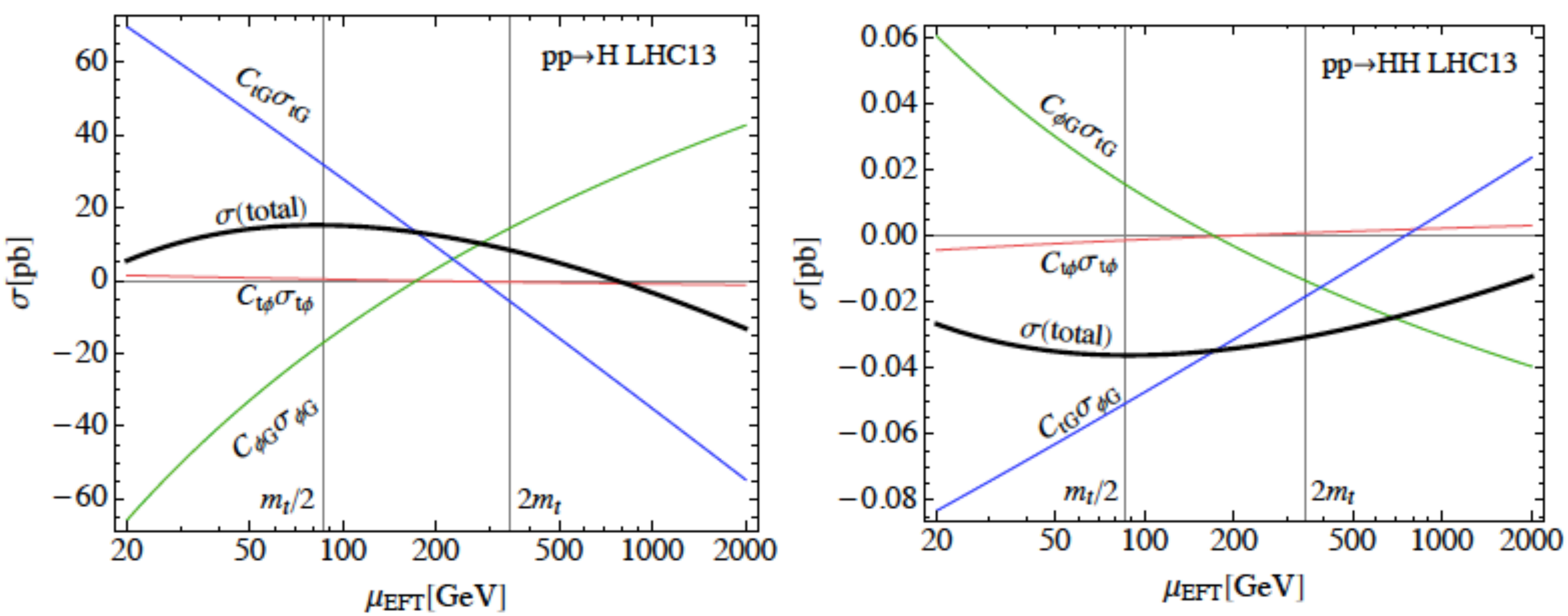
At = 1 TeV: $C_{tG} = 1$, $C_{t\varphi} = 0$;

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

Why NLO?

2. EFT scale dependence

[FM, Vryonidou, Zhang, 16]



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

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

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

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

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

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.

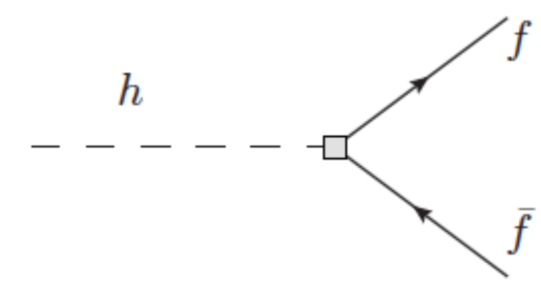
Why NLO?

3. Genuine NLO corrections (finite terms) are be important

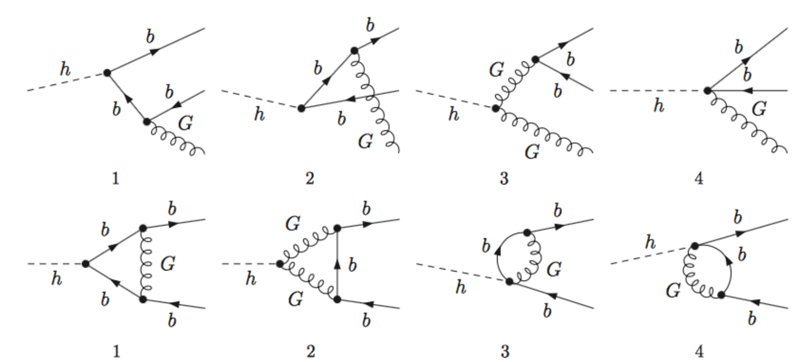
The cancellation of UV divergences from more than 20 dim-6 operators in the full result gives a highly non-trivial check on the calculation. The logarithmic corrections could have been deduced from a Leading Log analysis:

[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 be 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:

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

with:

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

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

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

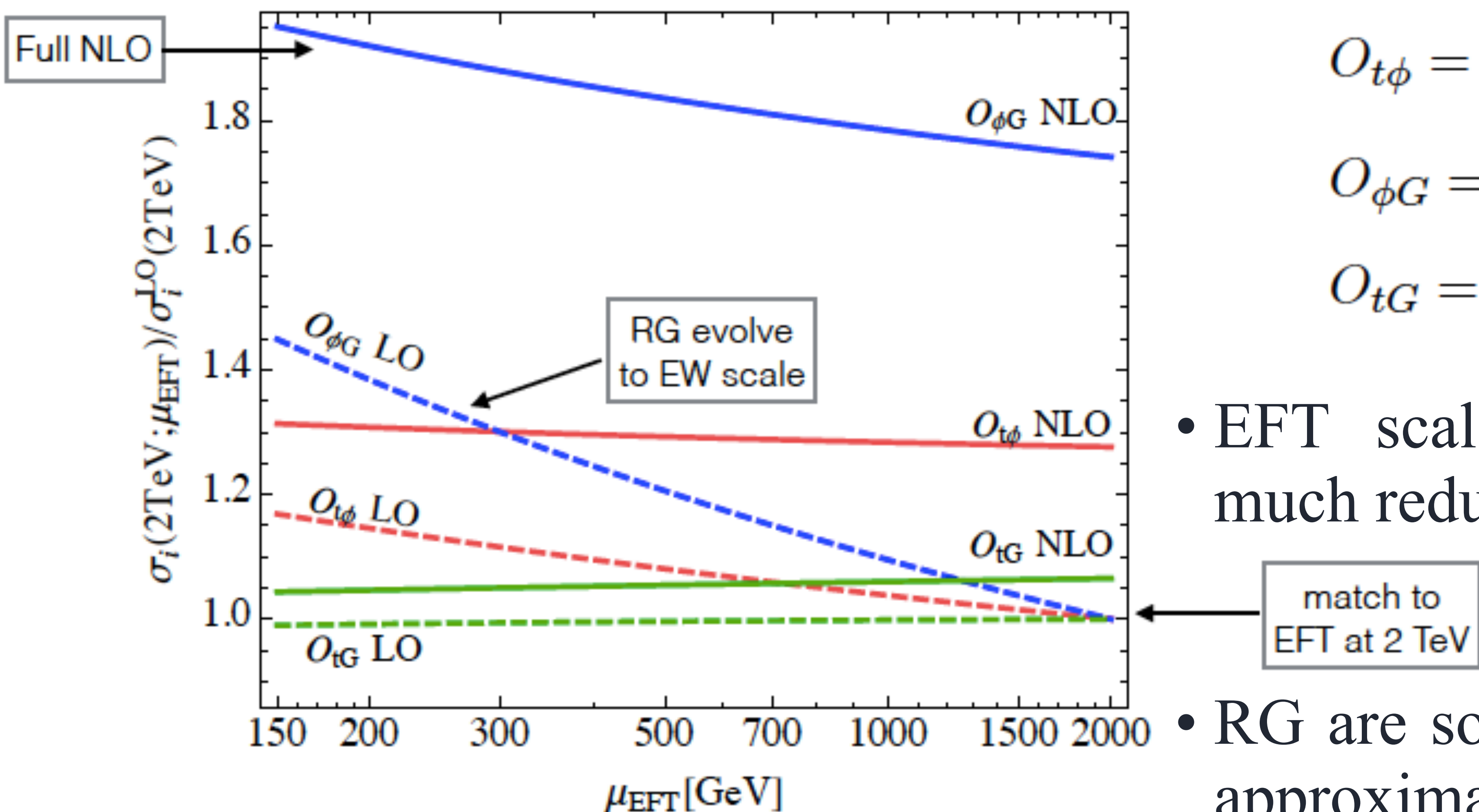
$$\Gamma_{ij}(\mu,\mu_0) = \exp\left(\frac{-2}{\beta_0}\log\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\gamma_{ij}\right)$$

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

Why NLO?

3. Genuine NLO corrections (finite terms) are be important

[FM, Vryonidou, Zhang, 16]



- pp → ttH

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

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

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

- 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.

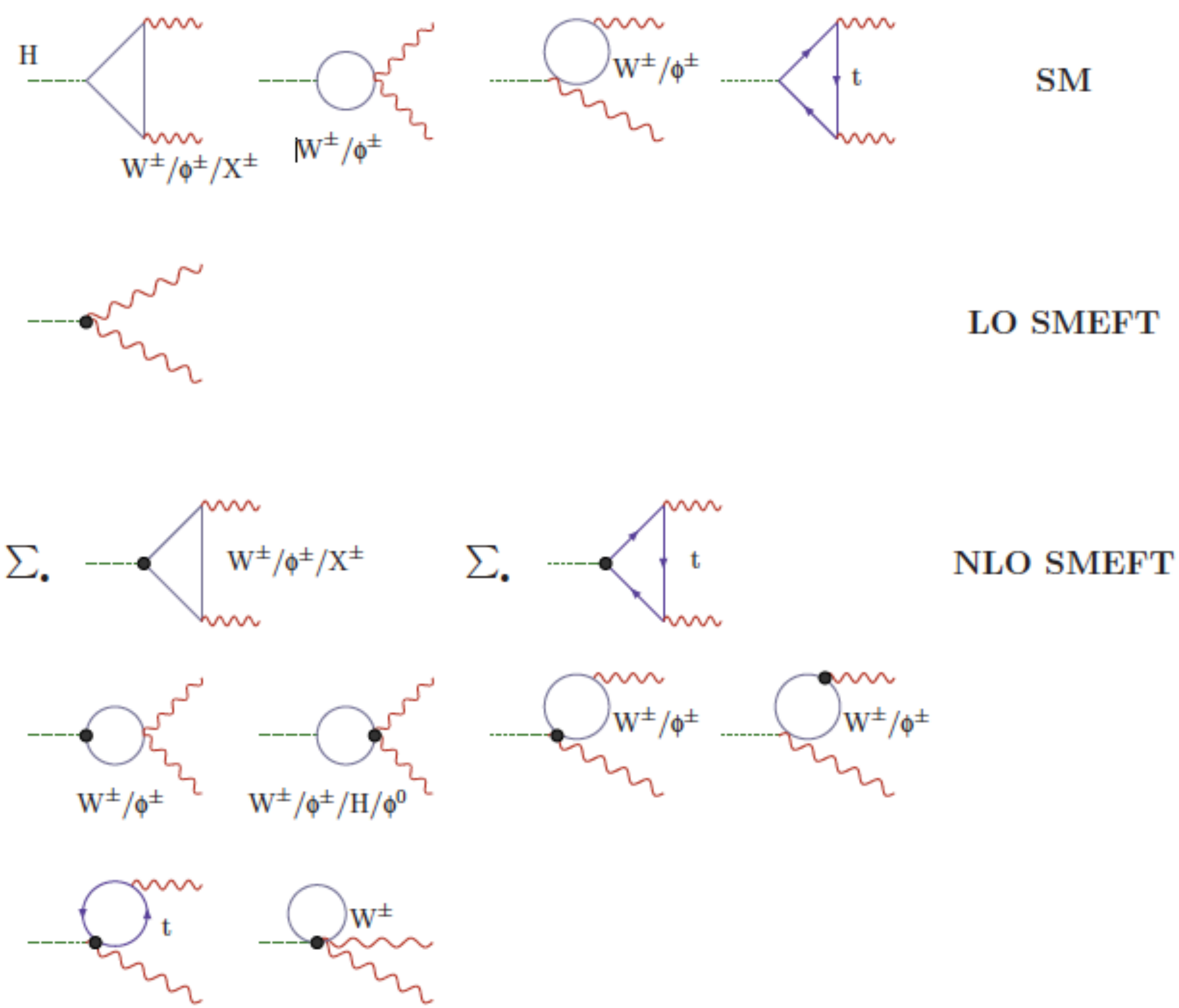
Why NLO?

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…

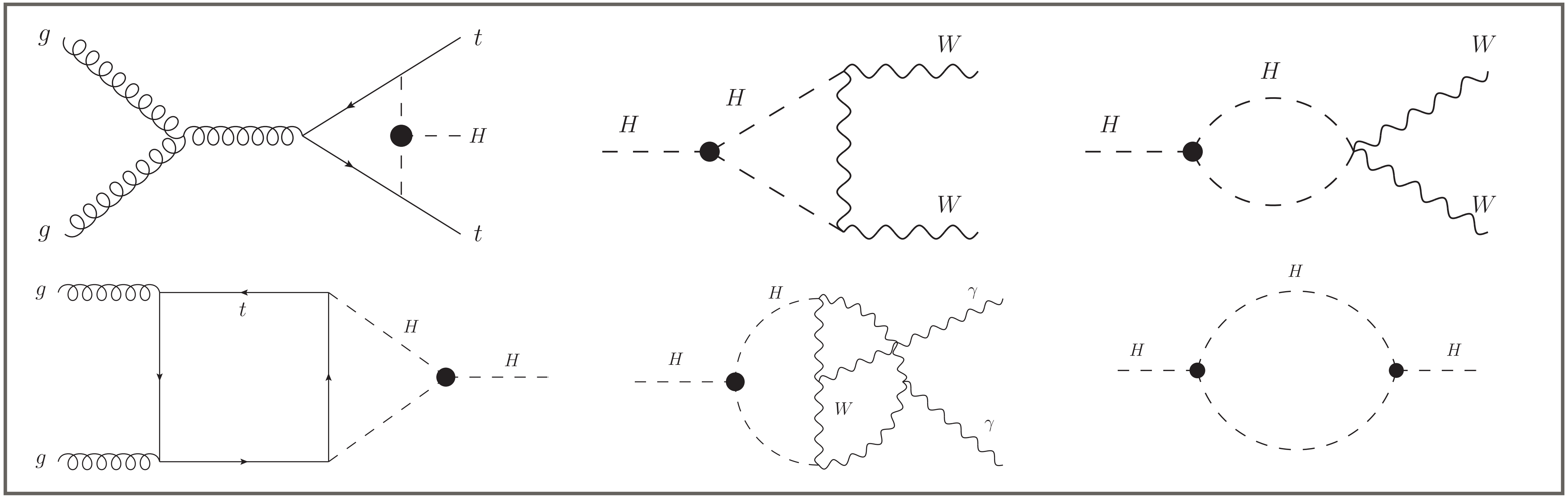
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a]
[Hartmann and Trott, 15]
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b]



Why NLO?

4. New operators arise ⇒ new sensitiviness. Example: O_6

1) Exploit the dependence of single-Higgs (total and differential) cross sections and decay rates on the self couplings at NLO (EW) level:



2) Combine all the information (rates and distributions) coming from the relevant single Higgs channels in a global way.

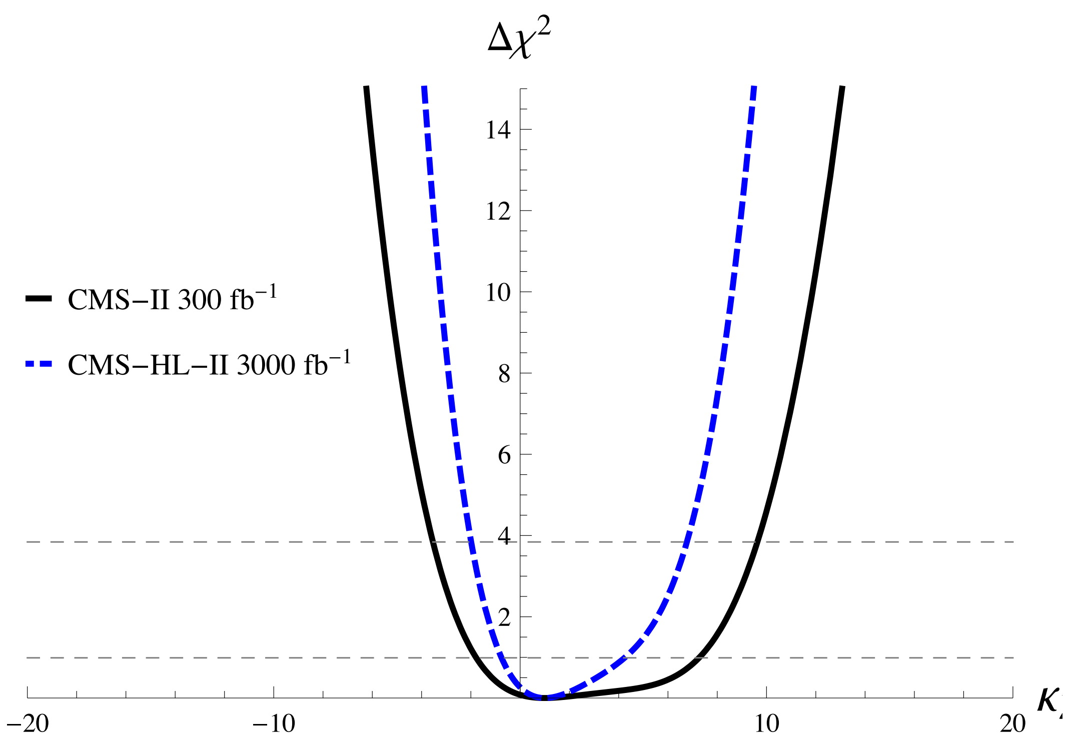
Why NLO?

4. New operators arise ⇒ new sensitiviness. Example: O_6

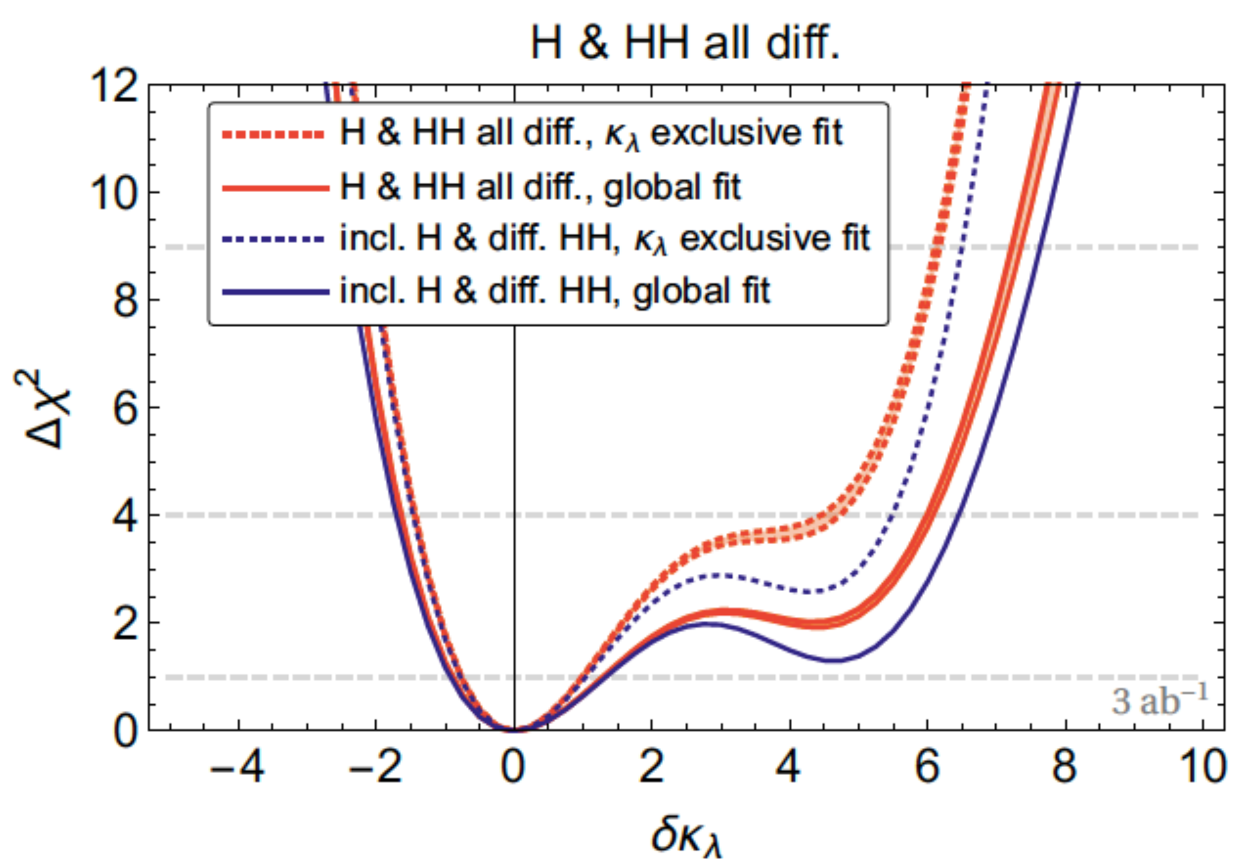
Ref	Authors	Processes	Comments
1312.3322	M.McCullough	e+e- → ZH	applications at future colliders
1607.03773	M.Gorbahn, U.Haisch	gg→H, H→γγ	approx. two-loop results mh →0
1607.04251	G.Degrassi, P.P. Giardino, F.M., D.Pagani	gg→H,WH,ZH,VBF, ttH H→γγ,WW*/ZZ*→4l, gg	total and diff.
1610.05771	W.Bizon, M.Gorbahn, U.Haisch, G.Zanderighi	WH,ZH,VBF	total and diff. + effects of QCD corrections
1702.01737	G. Degrassi, M. Fedele, PP. Giardino.	MW, sin(theta)	EW precision observables
1702.07678	G. Kribs et al.	S,T	EW precision observables
1704.01953	S. de Vita et al.	all (from 1607.04251)	Global approach

Why NLO?

4. New operators arise ⇒ new sensitiviness. Example: O_6



[G.Degrassi, P.P. Giardino, F.M., D.Pagani, 16]



[S. de Vita et al. 17]

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: $C_{t\phi}$,$C_{\phi G}$ LO: C_{tG}	NLO C_{tG} feasible
gg→Hj	NNLO, LO	NLO: $C_{\phi G}$, LO: $C_{t\phi}$,C_{tG}	NLO very hard
ttH	NNLO, NLO	NLO	NLO EW
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) ↓

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

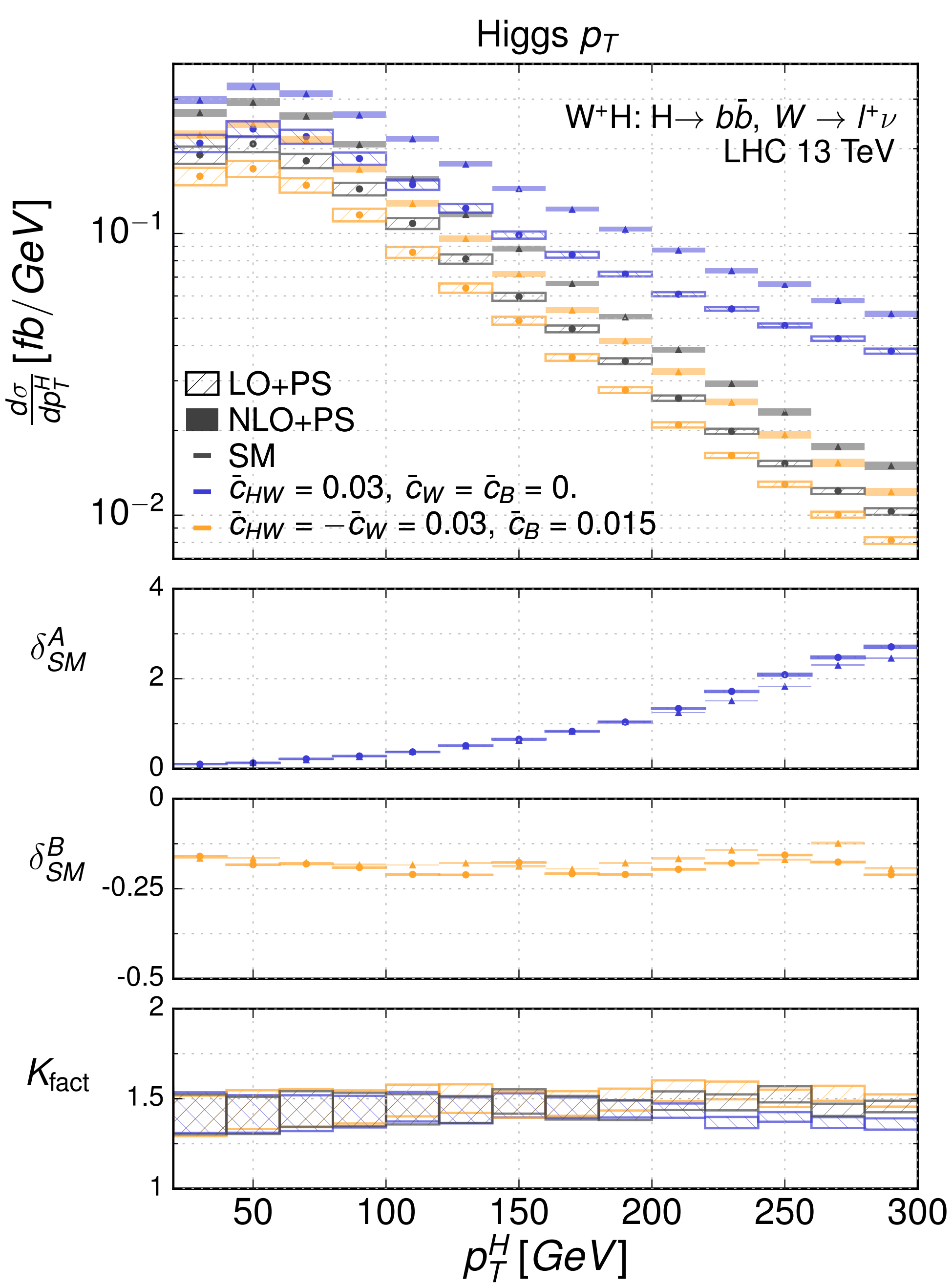
+JHUGen, VBF@NLO, WHIZARD

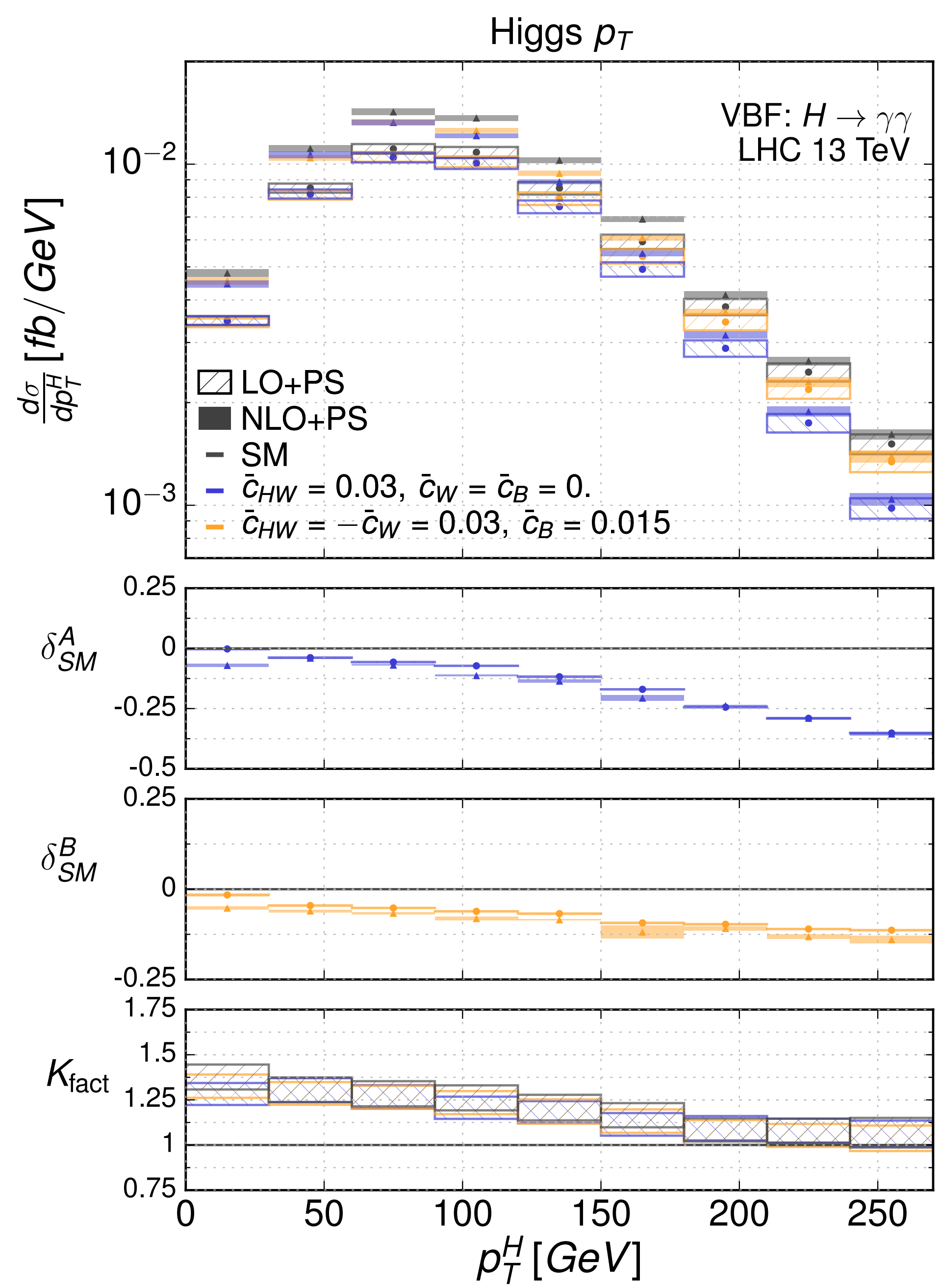
Multi-boson production

[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





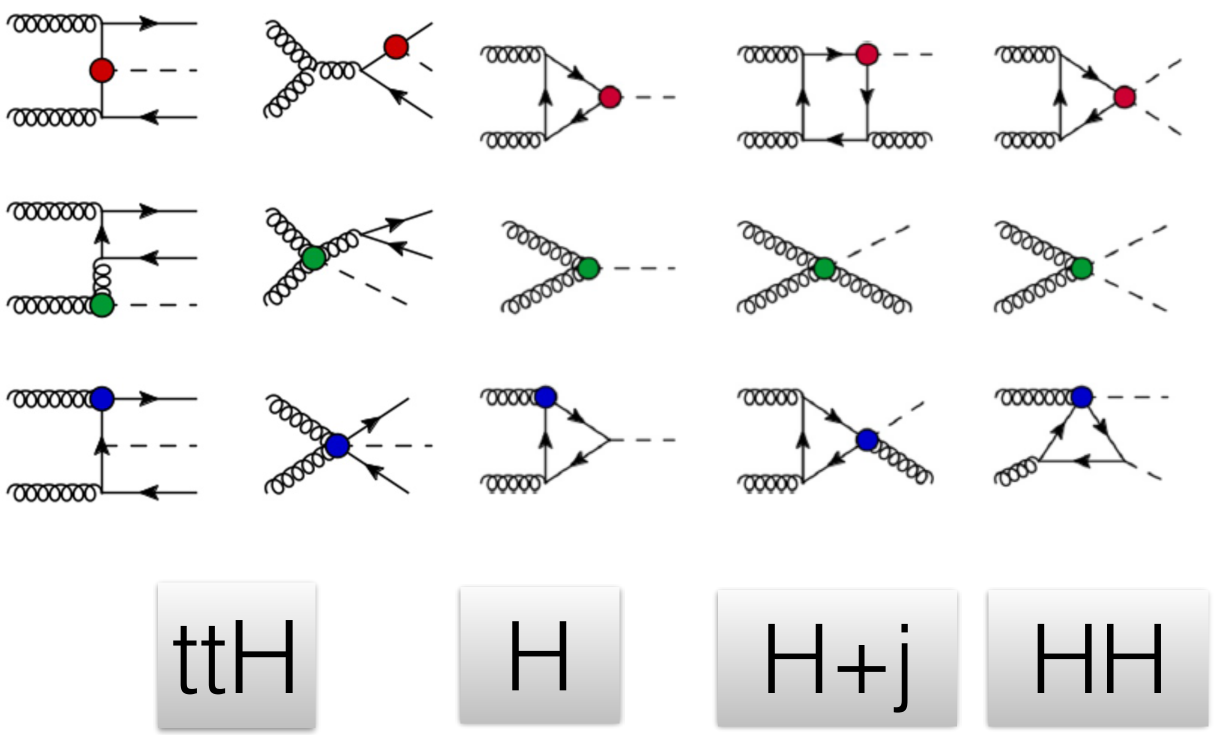
[Degrande, Fuks, Mawatari, Mimasu, Sanz, 16]

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



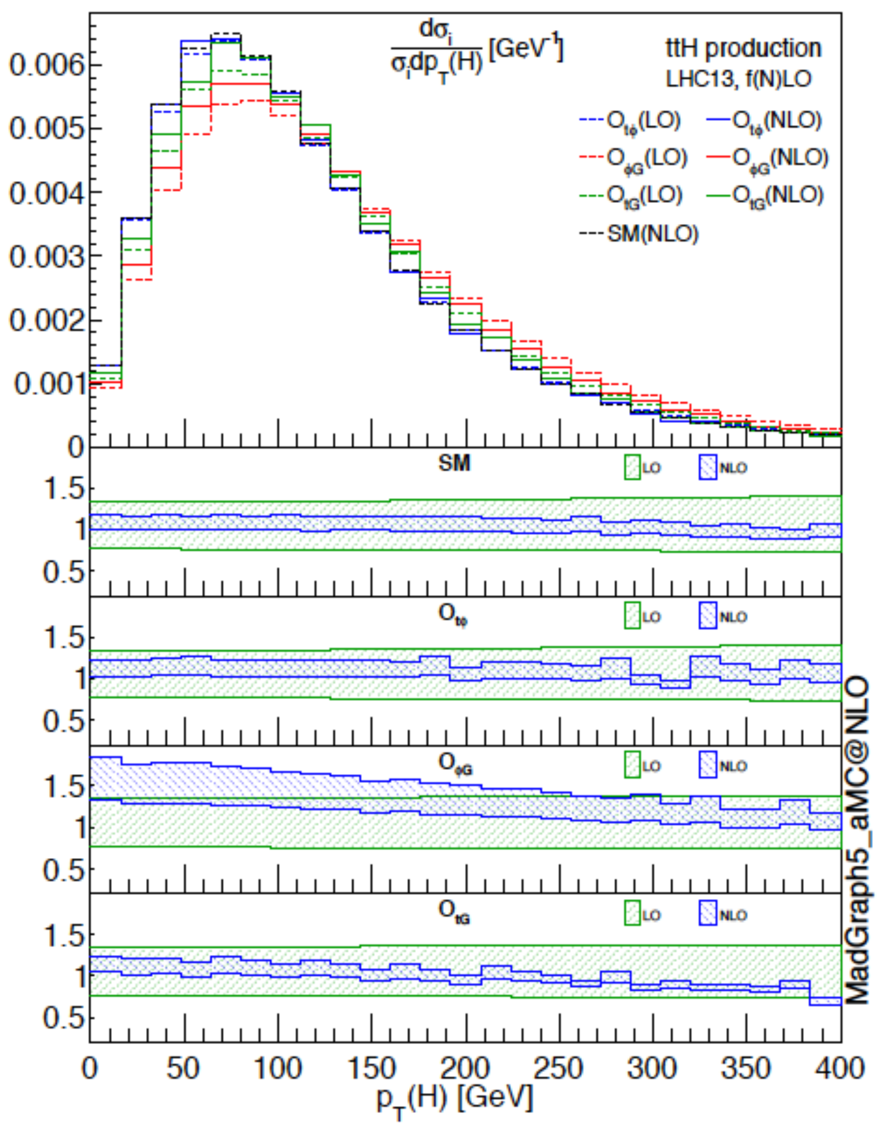
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

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

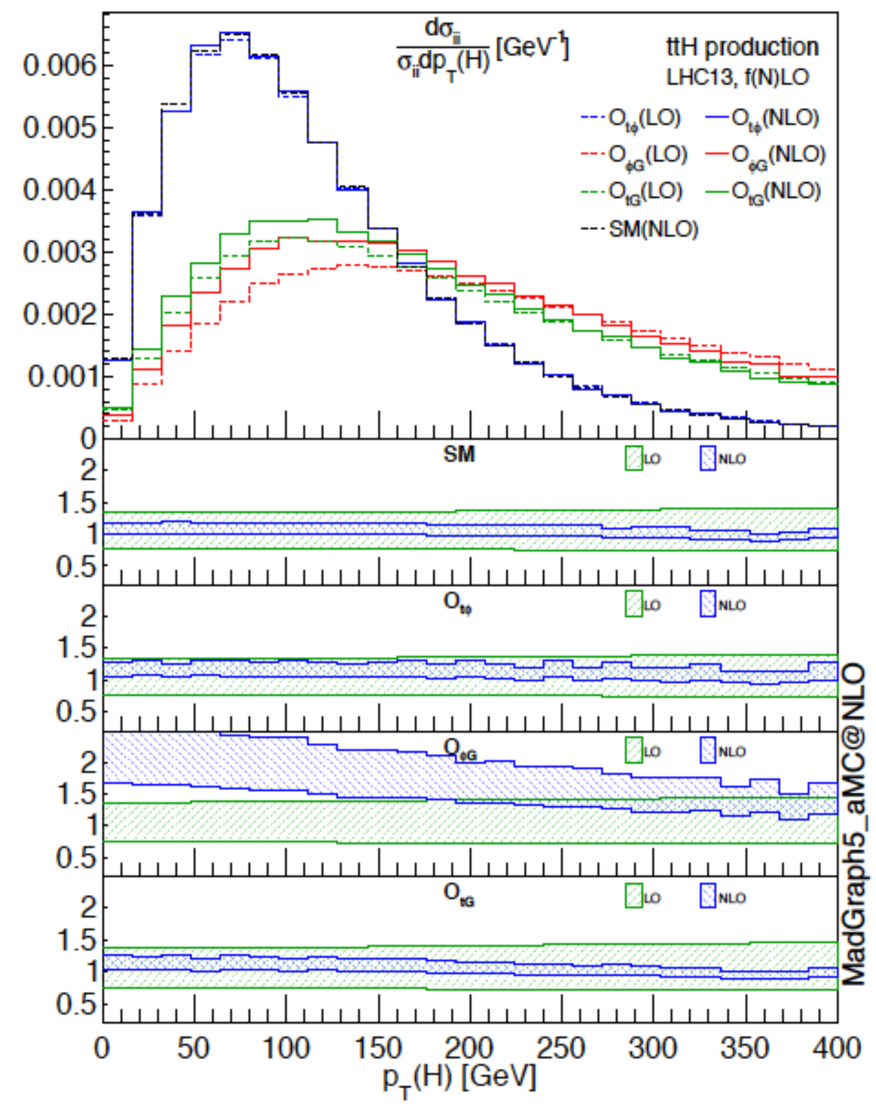
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

ttH in the SMEFT

[FM, Vryonidou, Zhang, 16]



NLO: smaller uncertainties, non-flat K-factors

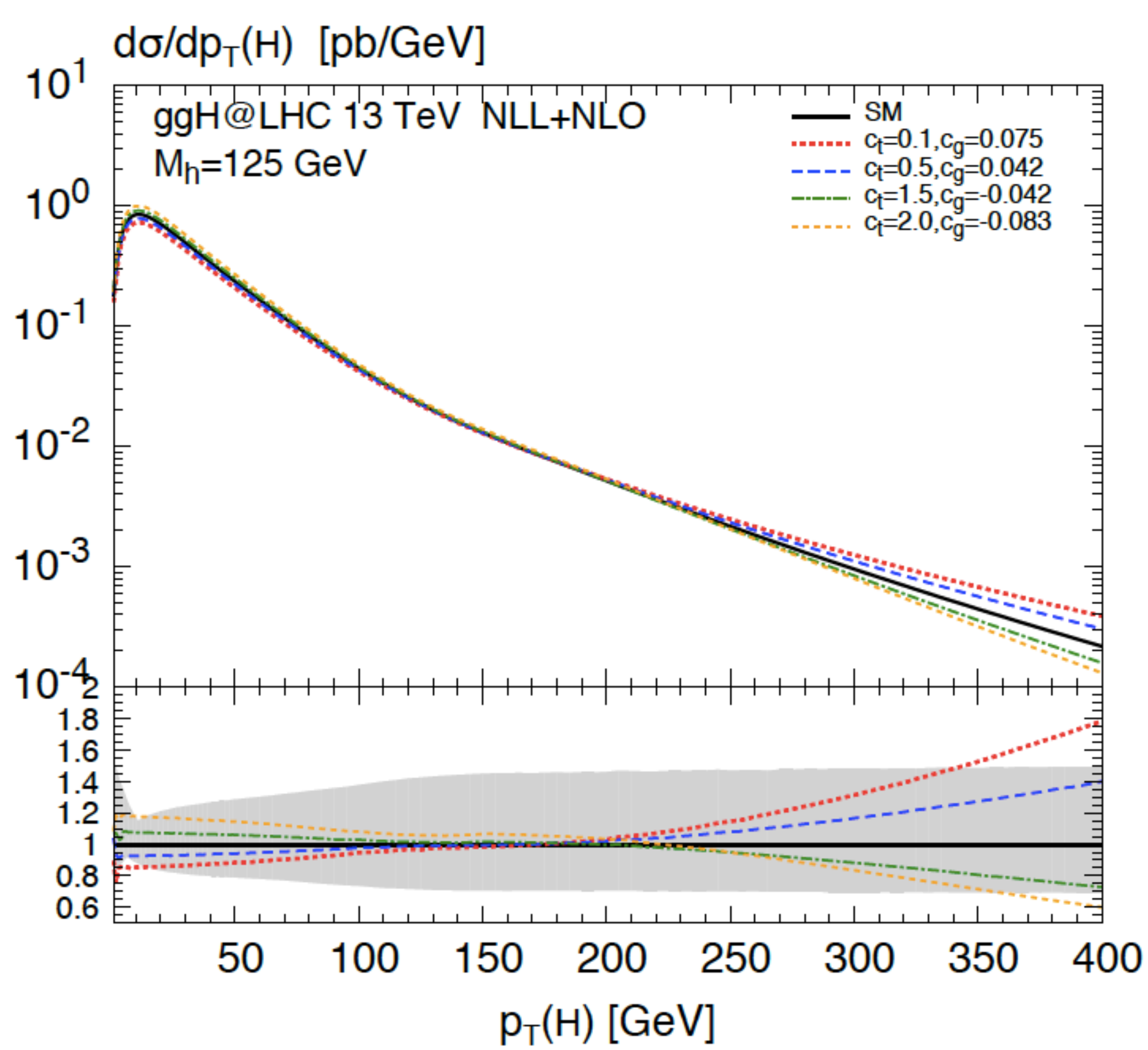


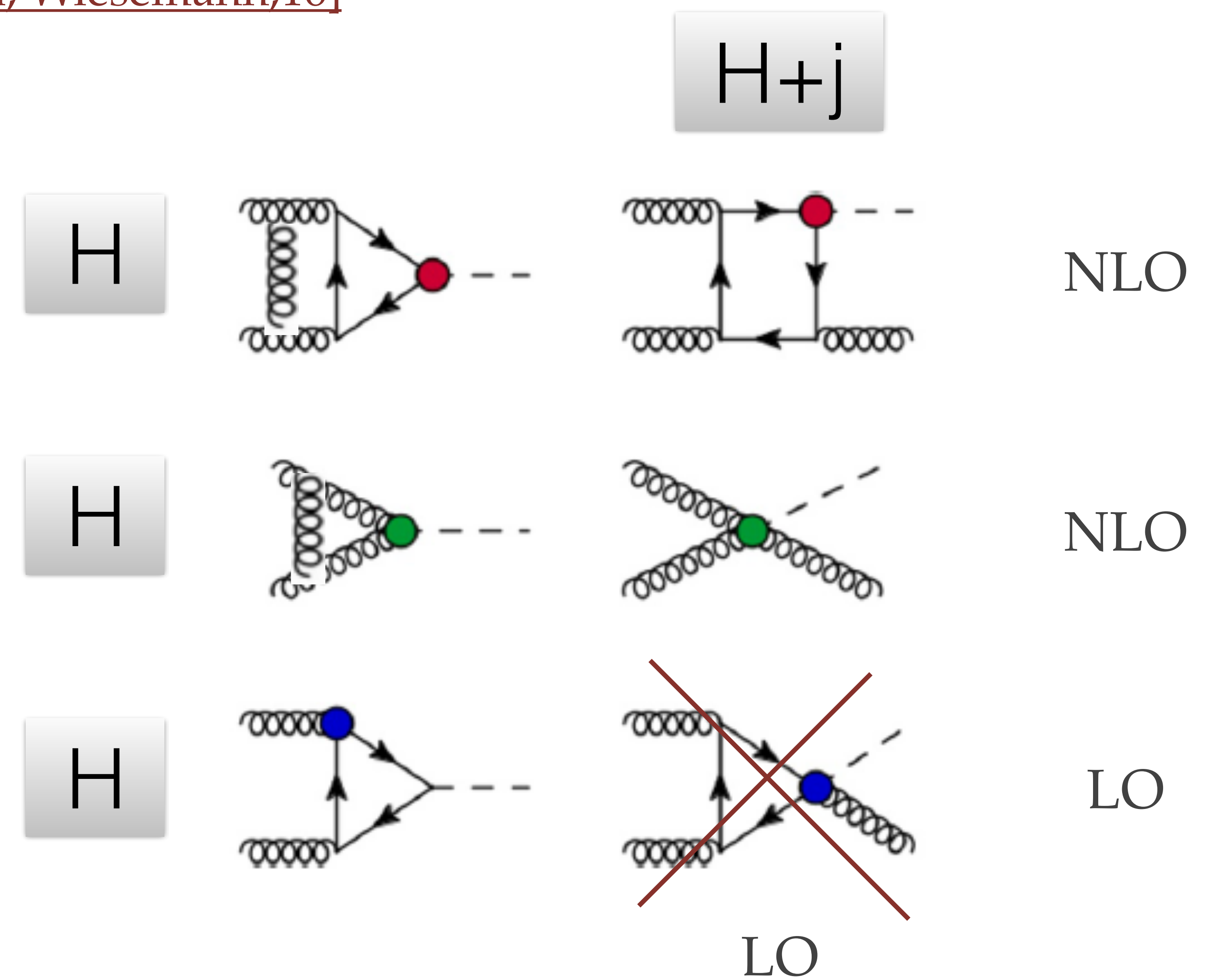
Different shapes for different operators for the squared terms

ttH 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]





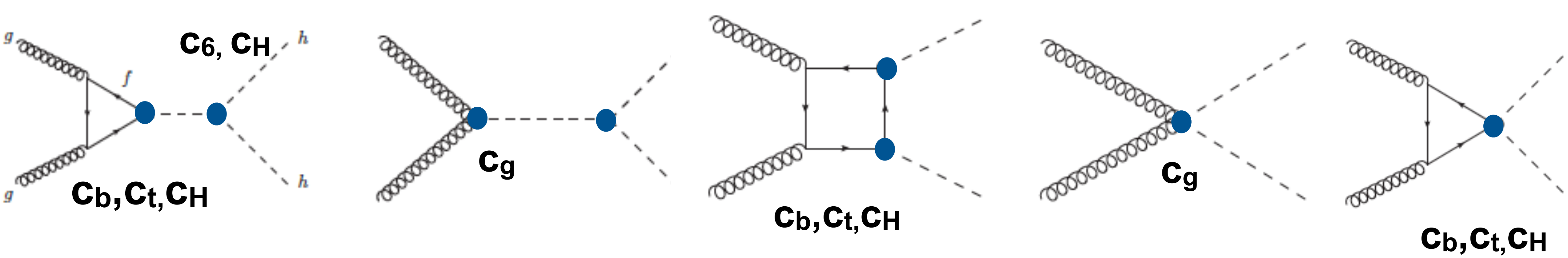
HH production in the SMEFT

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

[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

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

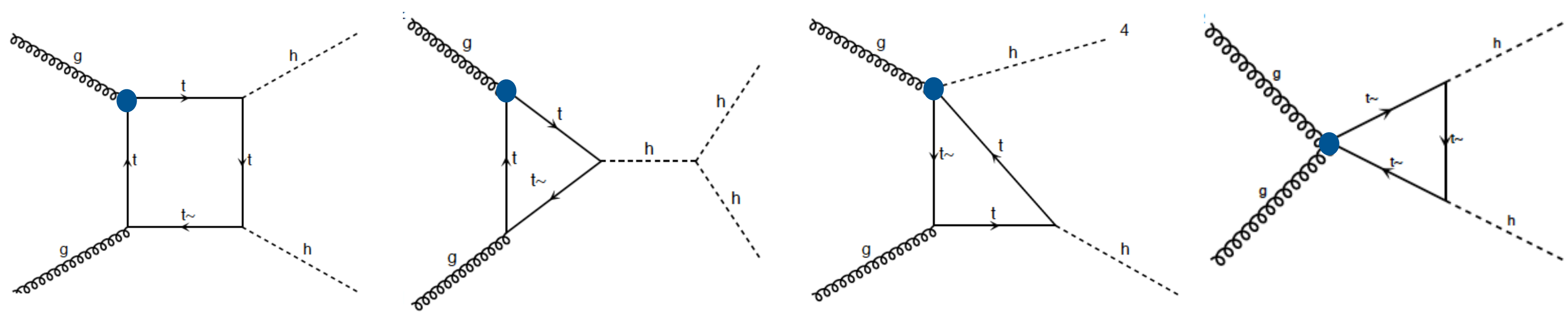


5 parameters:c6, cH, cb,ct,cg

HH production in the SMEFT

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

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



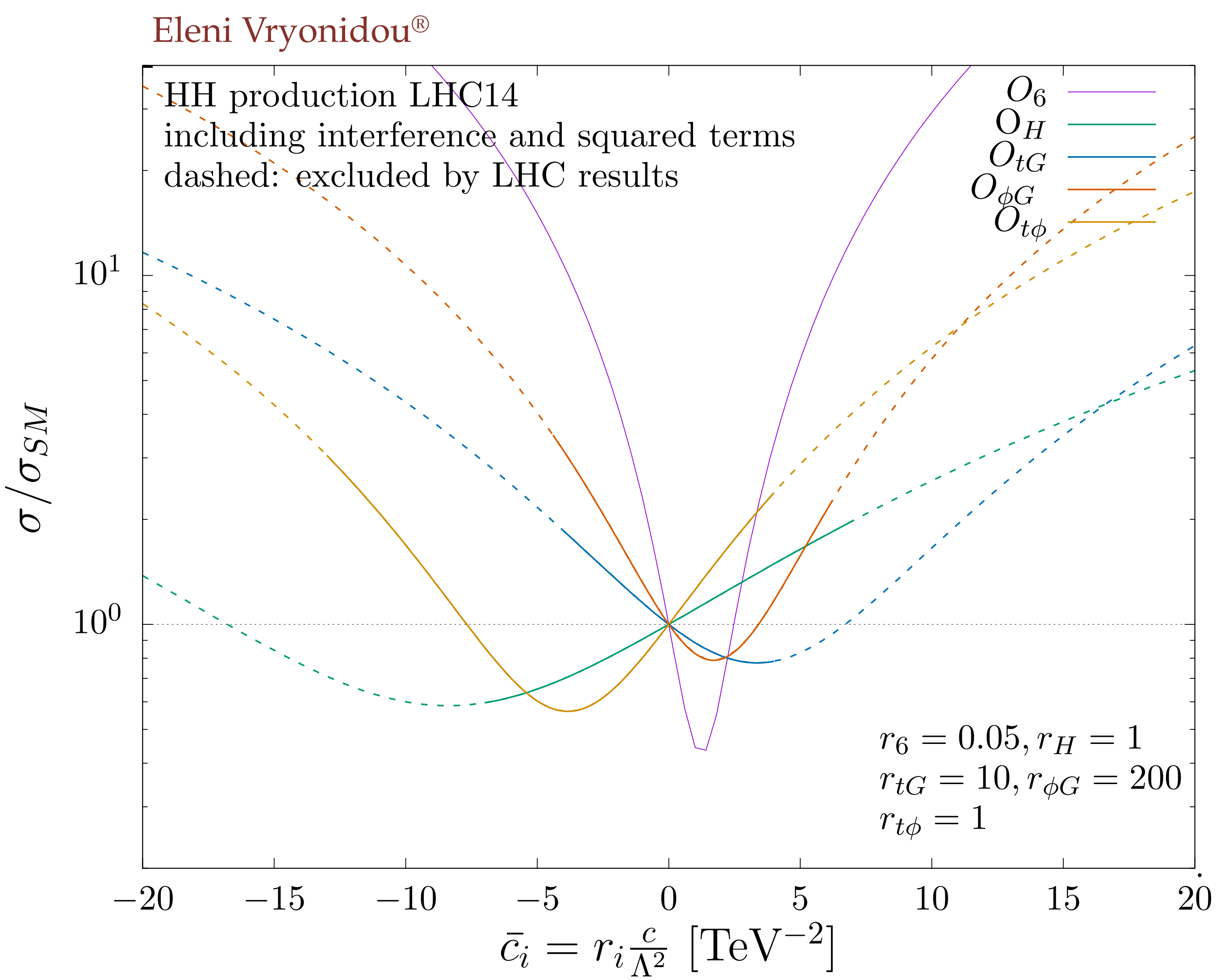
Needs to be taken into account in the context of a global EFT analysis for HH
Constraints from top pair production at NLO:

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

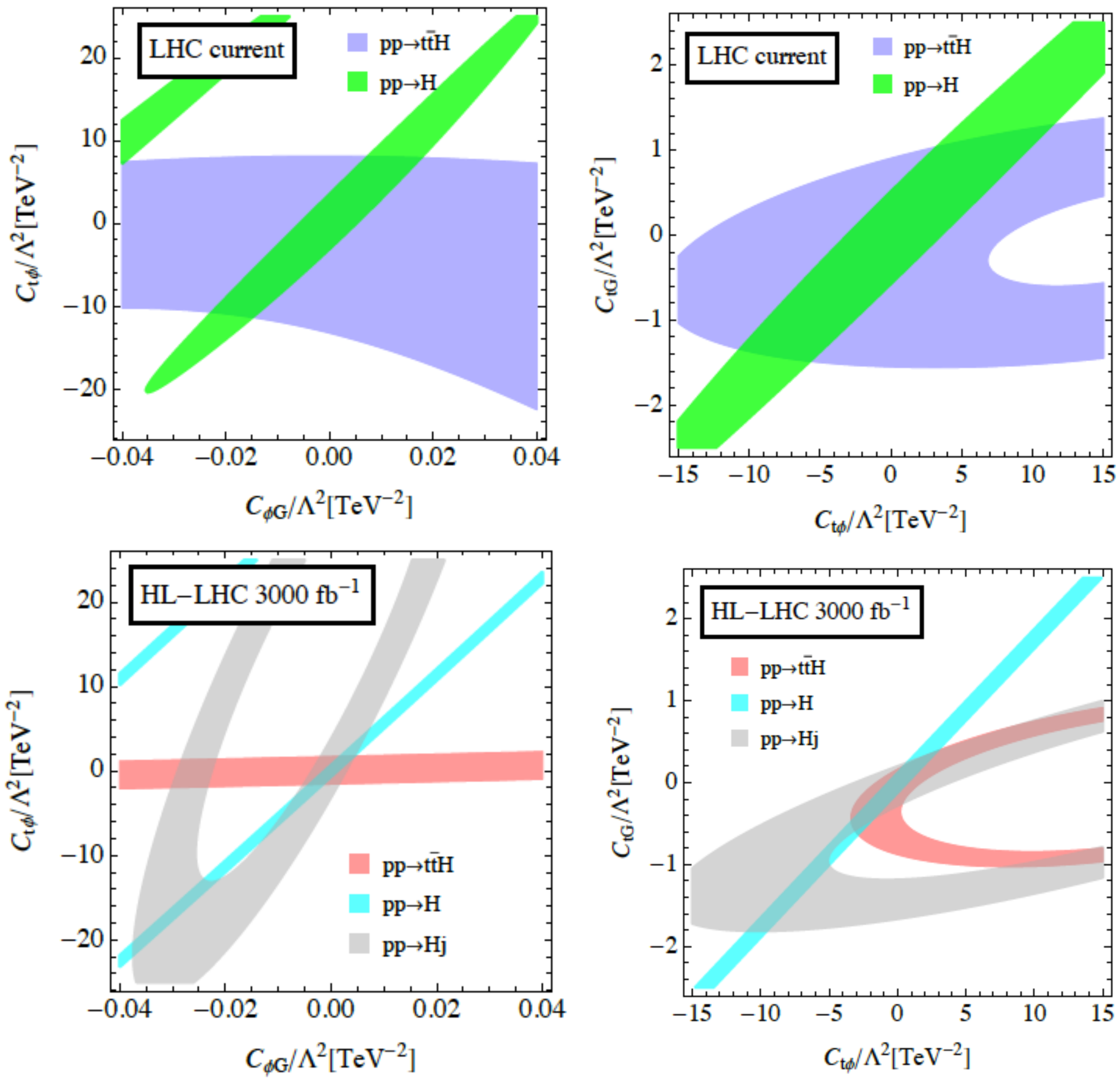


Sensitivity plot of σ(HH) in terms of the five relevant operators. Coefficients are rescaled so that the ranges are comparable.

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

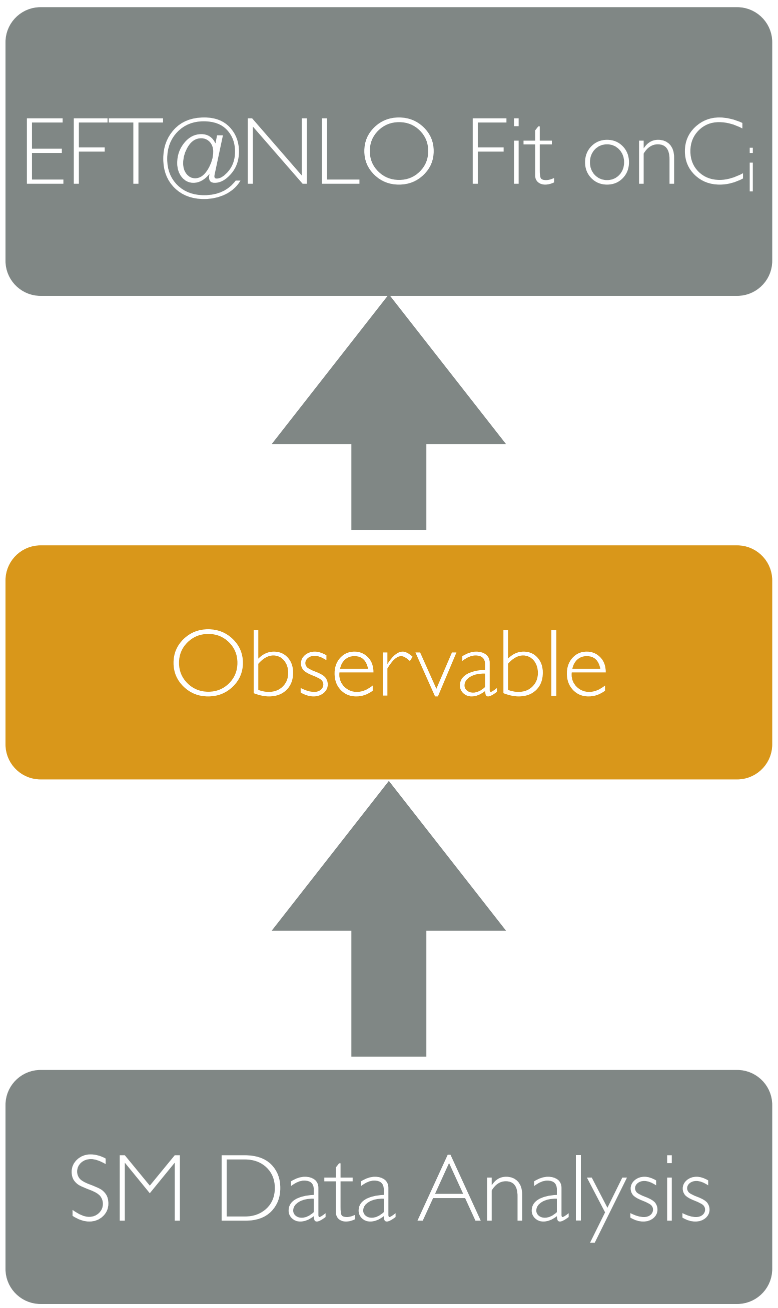
3000 fb-1

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.

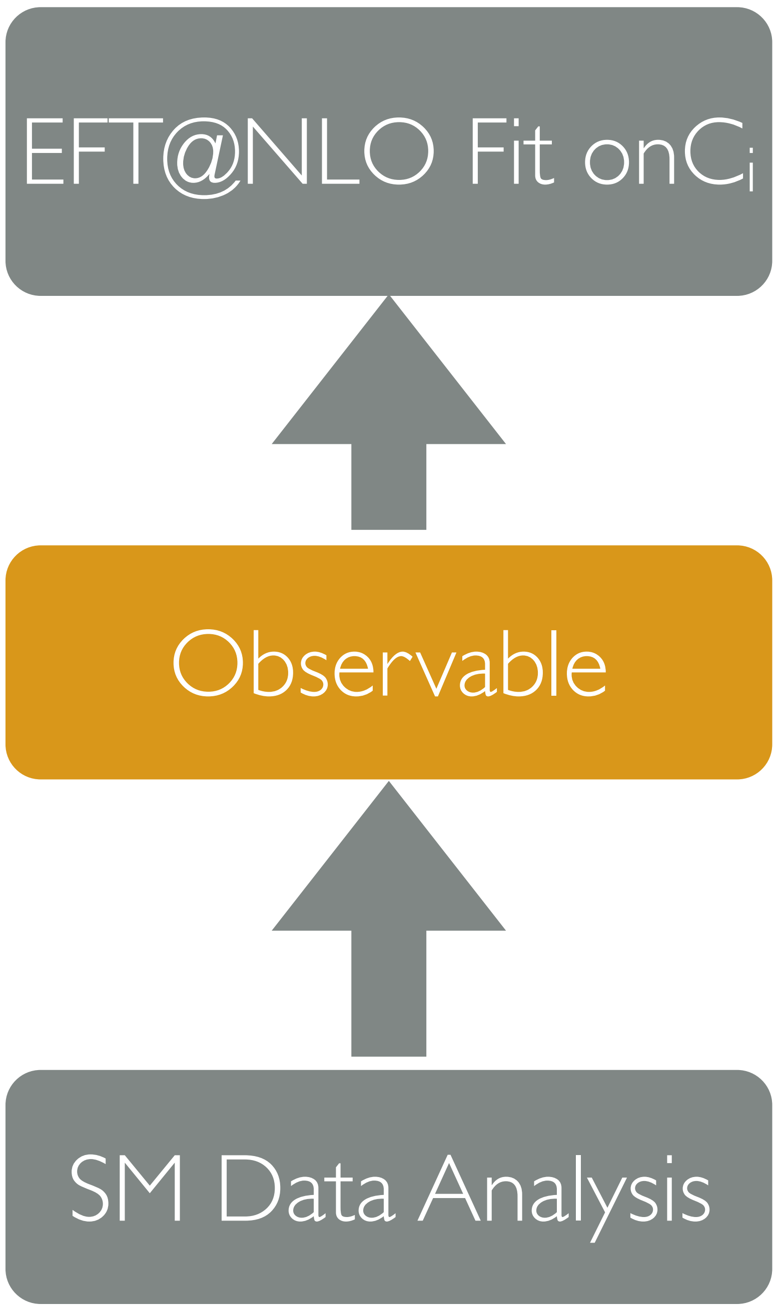
Approaches



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

- The importance of the SMEFT as THE model-independent interpretational framework for SM LHC interpretations is widely recognised.
- Strategies to make a global approach possible are needed.
- At least NLO in the SMEFT is mandatory. Theoretical/MC effort to provide accurate/precise/usable predictions has started ~5 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.

Topics for discussion

- What global really mean? Some kind of assumptions are always (implictily or explicitly) made. A hierchical approach should be employed.
- Is a top-down approach feasible? At least in some cases it could be tried (top FCNC).
- EW, top, Higgs (and others!) measurements are all different ways of accessing the SAME operators. Coordination among the LHC groups on conventions (for example to estimate validity of the EFT and basis/normalisation) should be established.
- The method used to evaluate the THU should be always clearly stated and at least cover both "SM" like uncertainties and specific SMEFT ones (μ_{EFT}, higher order EFT terms,…)

Thanks to

- The members of the LHCHXSWG
- The members to the LHCTOPWG
- Thanks to all enthusiastic collaborators on SMEFT for keeping my mind alive with their dreams.