Top quark physics and the EFT

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

The top is special

The top is special

1. It is rich

It is the elementary particle with the largest mass so far.

The top is special

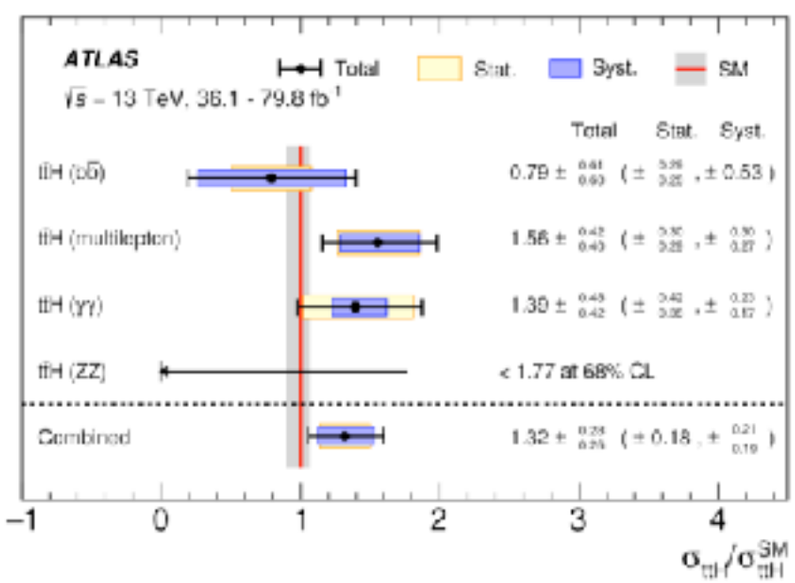
1. It is rich

It is the elementary particle with the largest mass so far.

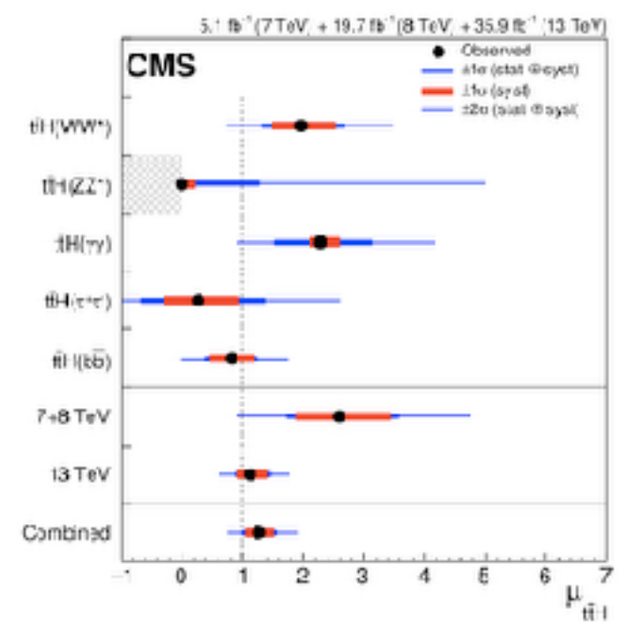
2. It is strong

$m_{top} = y_t\, v/\sqrt{2} \approx 174$ GeV $\Rightarrow y_t \approx 1$

Since last Monday we know that it “strongly" interacts with the Higgs sector.



Exciting results!
A new chapter in Higgs and top physics is now open



The top is special

1. It is rich

It is the elementary particle with the largest mass so far.

2. It is strong

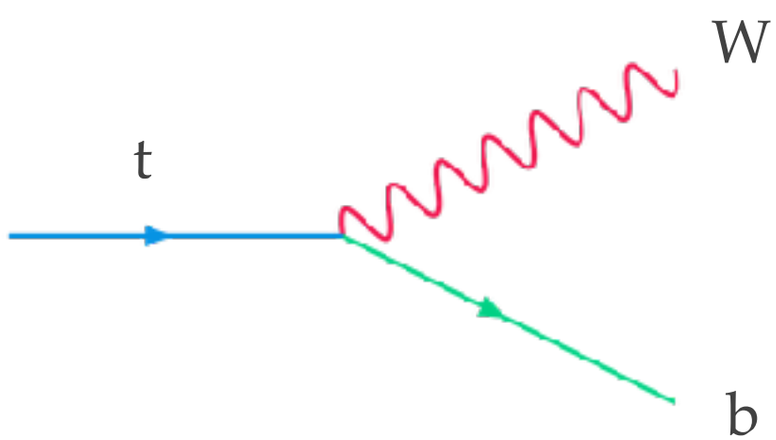
$m_{top} = y_t\, v/\sqrt{2} \approx 174$ GeV$\Rightarrow y_t \approx 1$

Since last Monday we know that it “strongly" interacts with the Higgs sector.

3. It is naked

$\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \cdot 10^{-24}$ s
$\tau_{top} \approx h/\,\Gamma_{top} = 1/(G_F\, m_t^3\, |V_{tb}|^2/8\pi\sqrt{2}) \approx 5 \cdot 10^{-25}$ s
(with $h = 6.6\ 10^{-25}$ GeV s)

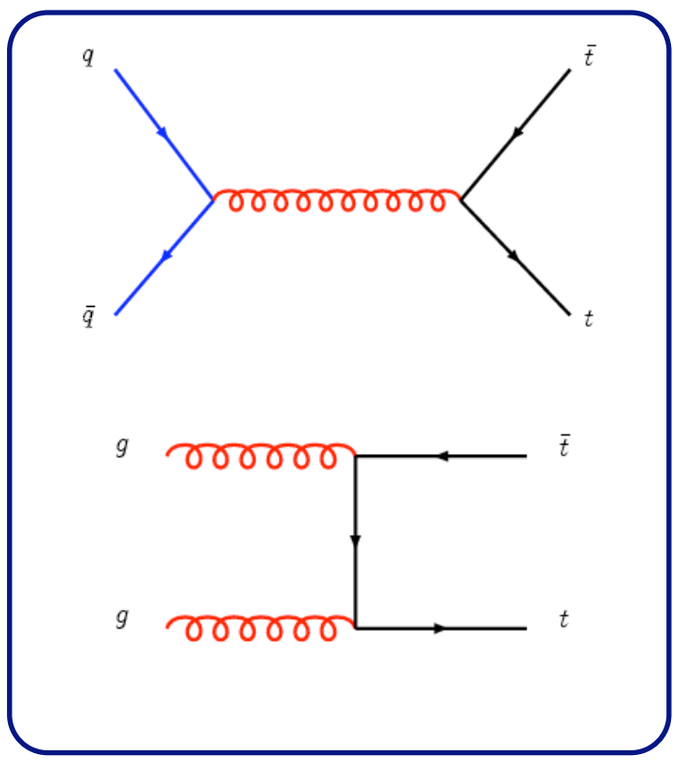
(Compare with $\tau_b \approx (G_F^2\, m_b^5\, |V_{bc}|^2)^{-1} \approx 10^{-12}$ s)



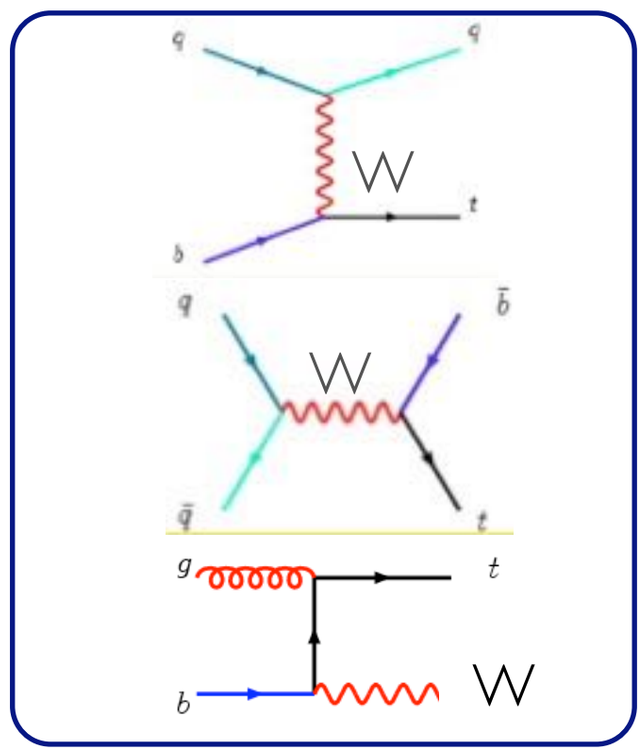
The top is special

4. It is popular

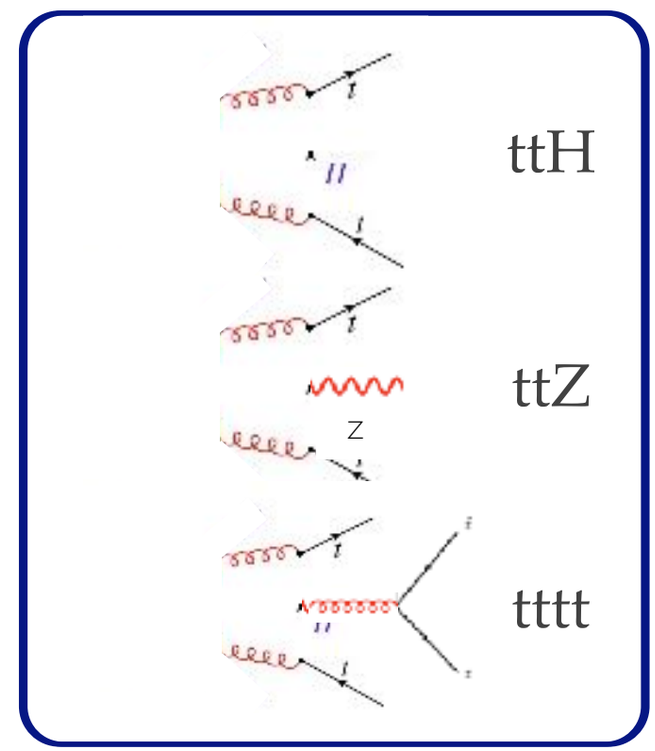
Strong



Weak



Associated

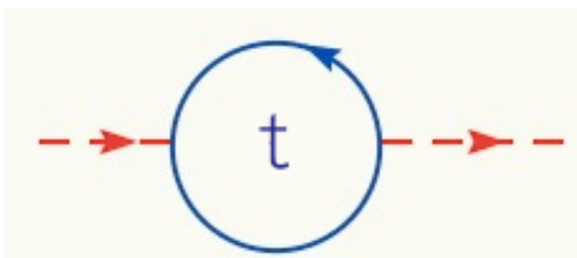


10^6 $250 \cdot 10^3$ $< (2-3) \cdot 10^3$

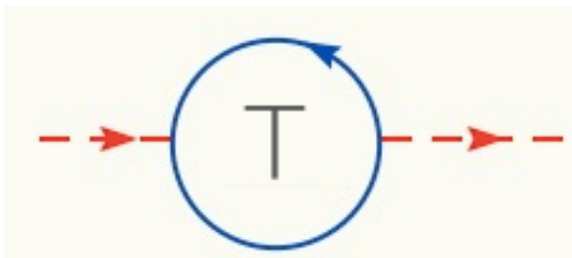
number of events @13TeV 1 fb^{-1}

The top is special

5. It goes beyond (the SM)

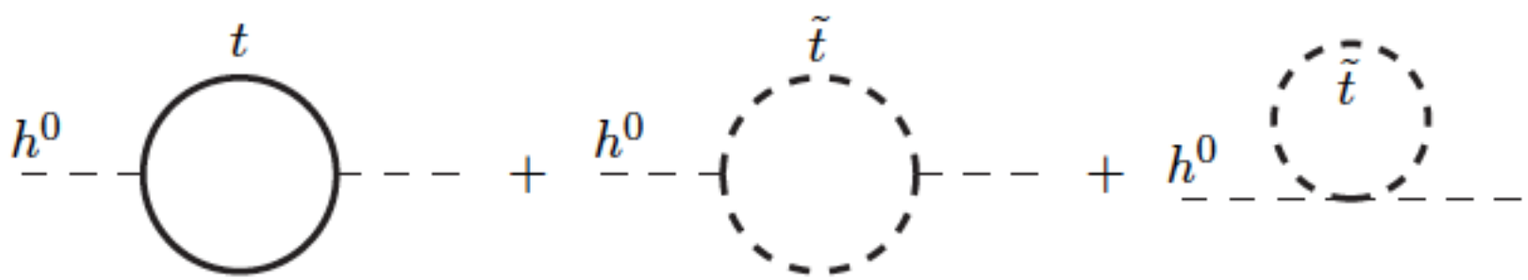


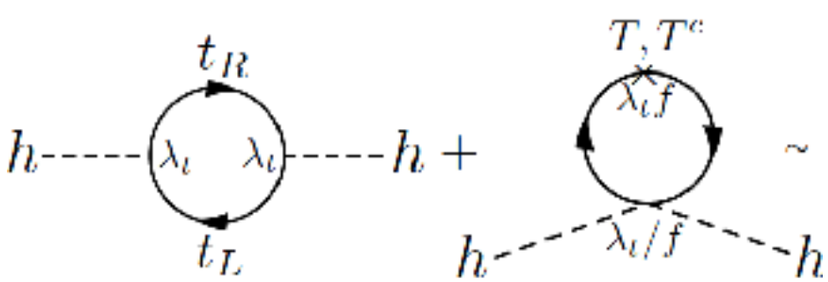
$+$



$$= \frac{8}{3\pi^2} m_T^2 \log \Lambda$$

$\Delta(m_{h^0}^2) =$





$$\mathcal{L} = y_t \left[iqht^c + f \left((1 - \frac{h^\dagger h}{2f^2} \right) TT^c + \ldots \right] + h.c.$$

The top is special

1. **It is rich**
2. **It is strong**
3. **It is naked**
4. **It is popular**
5. **It goes beyond**

The top is special

1. **It is rich**
2. **It is strong**
3. **It is naked**
4. **It is popular**
5. **It goes beyond**

The top quark is the Ronaldo of elementary particles

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.

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

BSM goal of the SM LHC program:

determination of the couplings of the SM lagrangian at DIM=6

SMEFT

[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
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ
- 59 operators (when flavour universal)

SMEFT

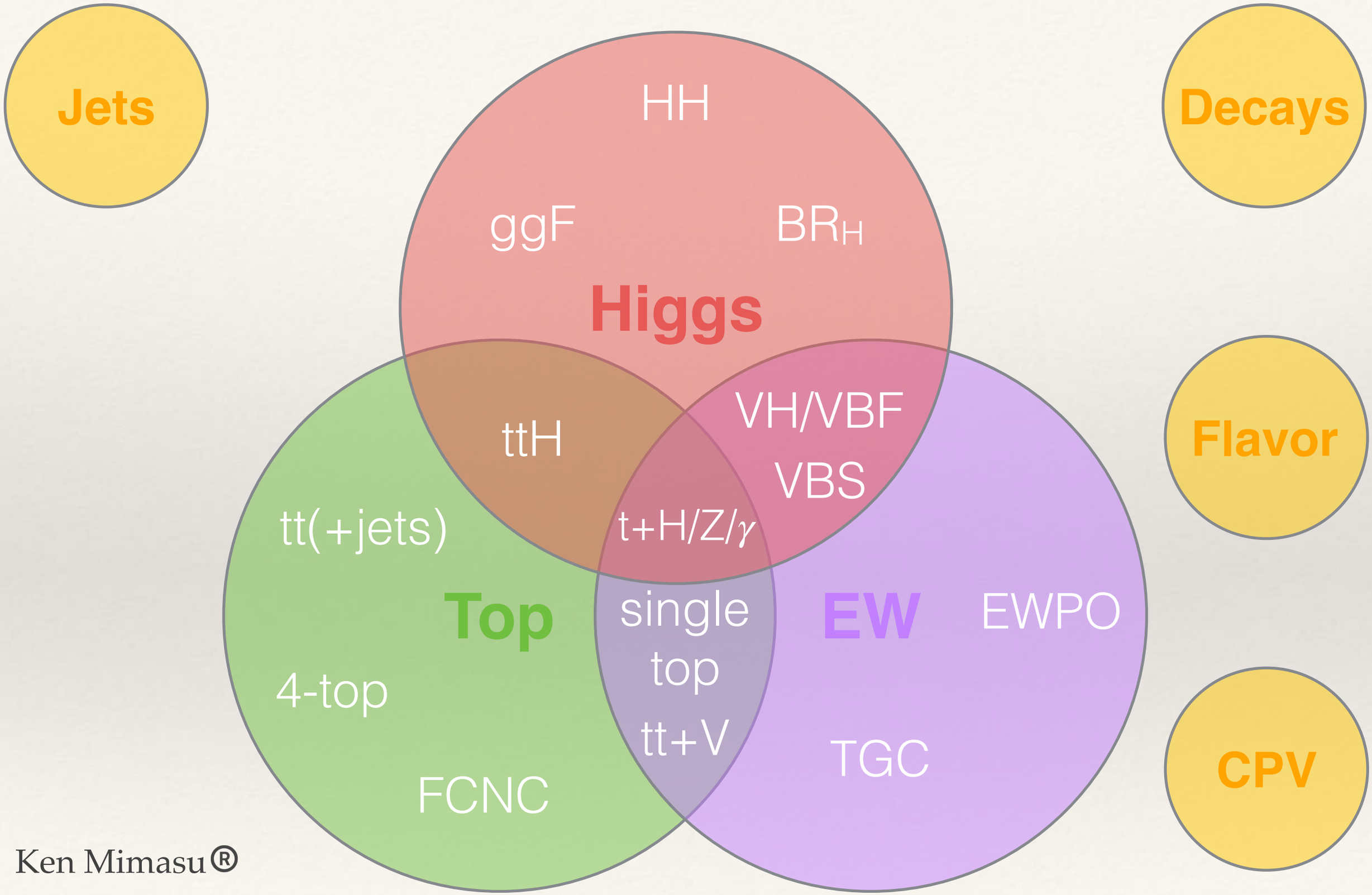
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

Three important observations:

1. The SMEFT is **not** stress-testing the SM, it is measuring the parameters of the SM Lagrangian…at dim=6. In other words it is a consistent QFT, i.e. it is renormalisable in QCD and EW (order by order in $1/\Lambda$) interactions. Loops can be consistently included.

2. Without UV model/bias, all operators enter on the same footing. In particular the c_i cannot be ordered a priori. The SM (and anomalous coupling) naive classification in terms of strong and EW top couplings does not hold.

3. A global fitting strategy at the EW scale needs to be set in place to extract information from the LHC data. In particular, one has to assume all couplings might not be zero at the EW scale.


Jets
Decays
Flavor
CPV
HH
ggF
BR$_H$
Higgs
ttH
VH/VBF
VBS
t+H/Z/γ
tt(+jets)
Top
single top
tt+V
4-top
FCNC
EW
EWPO
TGC

Ken Mimasu®

Top operators and processes

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

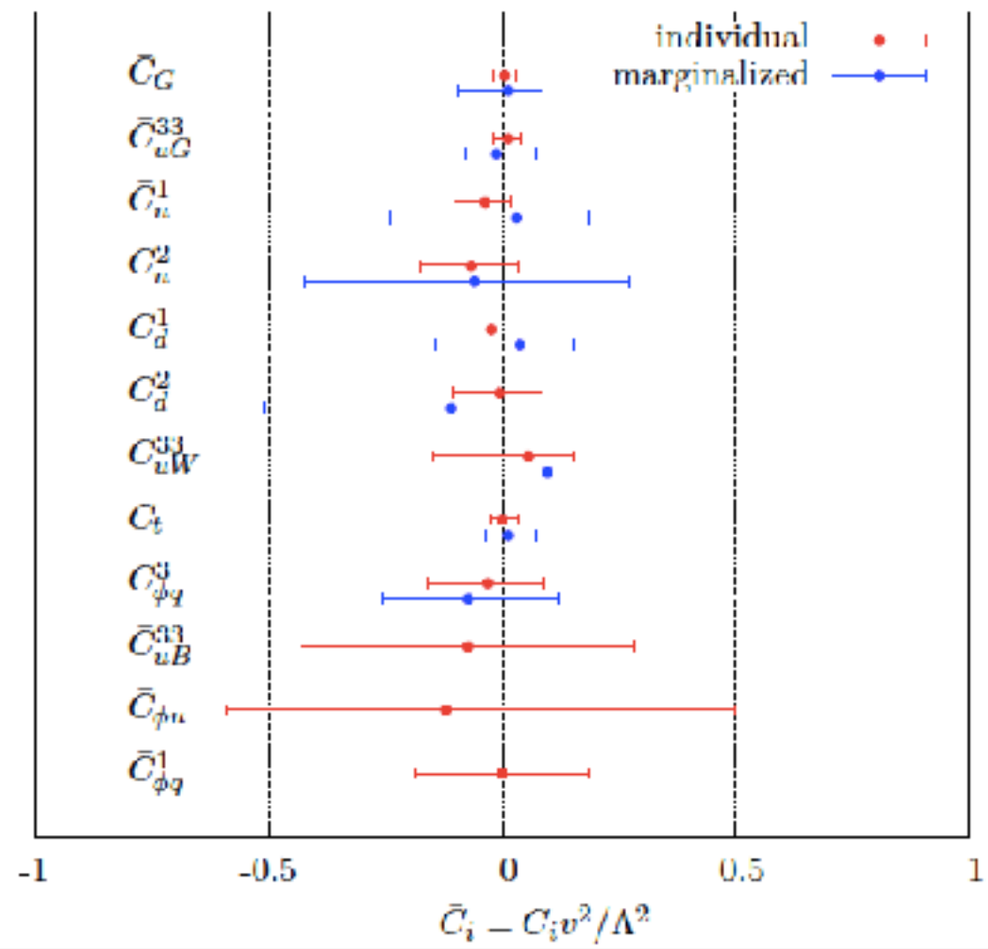
NLO	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	$1L^2$		
✓	$pp \to tj$	N		L	L				L^2	L^2	1L		
✓	$pp \to tW$	L		L	L				L^2	L^2	1N	N	
✓	$pp \to t\bar{t}$	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
✓	$gg \to H$	L						L				N	L
✗	$gg \to Hj$	L						L				L	L
✗	$gg \to HH$	L						L				N	L
✗	$gg \to HZ$	L			L	L	L	L				N	L

LO fit at the LHC

[Buckley et al.,2015]

4-fermion operators		Non 4-fermion operators	
O^1_{qq}	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$	$O^3_{\phi q}$	$i(\phi^\dagger \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$
O^3_{qq}	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$	O_{tW}	$(\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W^I_{\mu\nu}$
O_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	O_{tG}	$(\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G^A_{\mu\nu}$
O^8_{qu}	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$	O_G	$f_{ABC} G^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda$
O^8_{qd}	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$	$O_{\tilde{G}}$	$f_{ABC} \tilde{G}^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda$
O^8_{ud}	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$	$O_{\phi G}$	$(\phi^\dagger \phi) G^A_{\mu\nu} G^{A\mu\nu}$
		$O_{\phi \tilde{G}}$	$(\phi^\dagger \phi) \tilde{G}^A_{\mu\nu} G^{A\mu\nu}$

TABLE I: All dimension-six operators relevant to top quark production, in the notation of Ref. [12]. Details of each are included in the text. We do not include explicit flavor indices here. 13 operators are shown, but O_{tW} and O_{tG} have both real and imaginary parts which should be considered as independent operators; the latter produce $\mathcal{CP}$-violating effects.



- EFT based, fit on Tevatron and LHC data: total as well as differential information from ttbar and t-channel single-top.
- SM at NLO (or NNLO) and EFT at LO in QCD (Feynrules+MadGraph).

Need for NLO

1. Operators run and mix under RGE

2. EFT scale dependence

3. Genuine NLO corrections (finite terms) are important

4. New operators arise

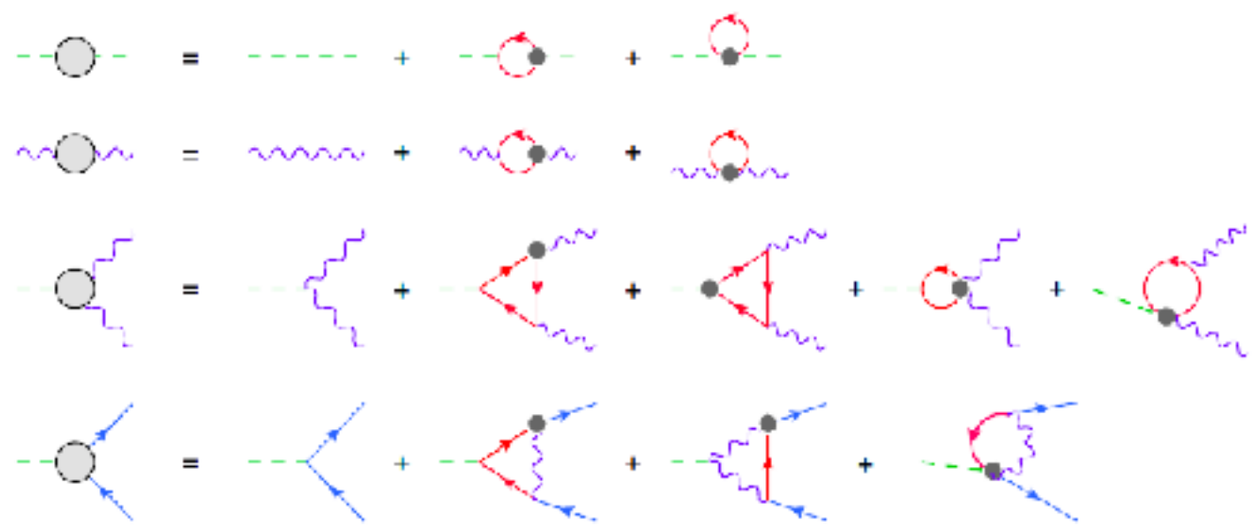
Need for NLO

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).
- Use tree-level, loop-level, hierarchy but not gauge couplings.

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a]
[Hartmann and Trott, 15]
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b]
[Dawson, Giardino, 2018]
[Dedes et al, 2018]
[Vryonidou and Zhang, 2018]



SMEFT for top physics

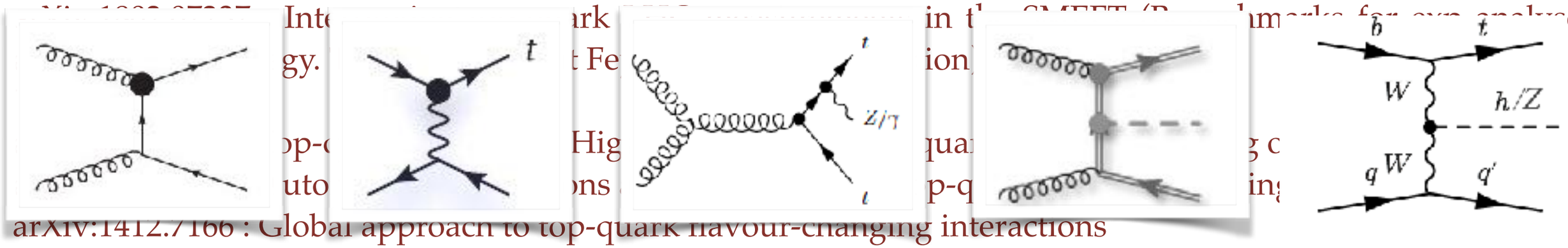
Implementations and results in FeynRules + MG5aMC

Top SMEFT : Implementation
arXiv:1802:07237 : Interpreting top-quark LHC measurements in the SMEFT (Bennchmarks for exp analyses and minimal strategy. Two independent FeynRules implementation)
Top FCNC @NLO
arXiv:1305.7386 : Top-quark decay into Higgs boson and a light quark at next-to-leading order in QCD
arXiv:1412.5594 : Automatic computations at NLO in QCD for top-quark flavour-changing neutral processes
arXiv:1412.7166 : Global approach to top-quark flavour-changing interactions
Top SMEFT @NLO
arXiv:1404.1264 : Top decays at NLO in QCD in the SMEFT
arXiv:1503.08841 : Probing the top-quark chromo-magnetic dipole moment at next-to-leading order in QCD
arXiv:1601.06163: Single Top Production at NLO in the Standard Model Effective Field Theory
arXiv:1601.08193 : Probing top quark neutral couplings in the SMEFT at NLO in QCD
arXiv:1607.05330 : Higgs production in association with a top-anti-top pair in the SMEFT at NLO in QCD
arXiv:1708.00460 : Gluon-fusion Higgs production in the SMEFT
arXiv:1804.07773 : Single-top associated production with a Z or H at the LHC: the SMEFT interpretation
arXiv:1804:09766 : Dim 6 electroweak top loop effects in Higgs production and decay.

SMEFT for top physics

Implementations and results in FeynRules + MG5aMC

Top SMEFT : Implementation



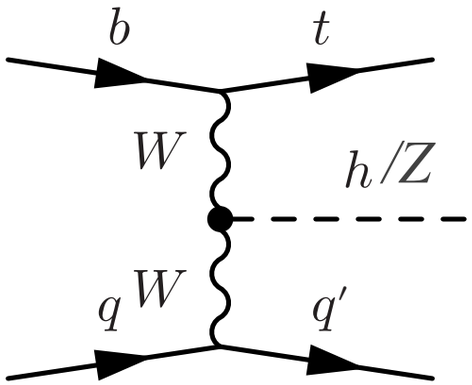
arXiv:1412.7166 : Global approach to top-quark flavour-changing interactions

Top SMEFT @NLO

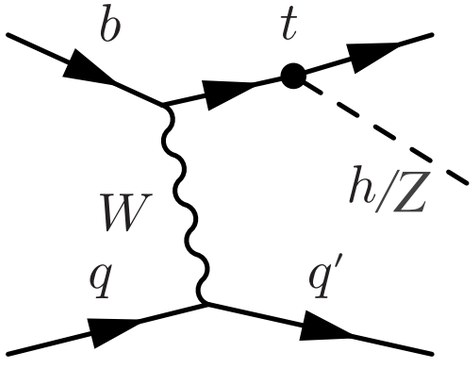
arXiv:1404.1264 : Top decays at NLO in QCD in the SMEFT
arXiv:1503.08841 : Probing the top-quark chromo-magnetic dipole moment at next-to-leading order in QCD
arXiv:1601.06163: Single Top Production at NLO in the Standard Model Effective Field Theory
arXiv:1601.08193 : Probing top quark neutral couplings in the SMEFT at NLO in QCD
arXiv:1607.05330 : Higgs production in association with a top-anti-top pair in the SMEFT at NLO in QCD
arXiv:1708.00460 : Gluon-fusion Higgs production in the SMEFT
arXiv:1804.07773 : Single-top associated production with a Z or H at the LHC: the SMEFT interpretation
arXiv:1804:09766 : Dim 6 electroweak top loop effects in Higgs production and decay.

Case study: tZj/tHj

- Single top rate about 1/4 of QCD tt
- Purely EW processes => no QCD contribution
- Sensitive to 2 four-fermion and 3 top/EW operators that modify tbW vertex



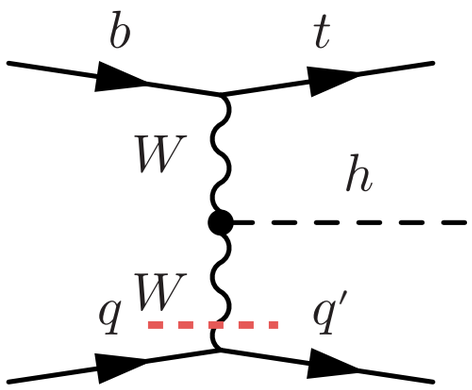
- Requiring the presence of an additional Z or Higgs
  - Unique possibility of probing full set of top/Higgs/EW operators at once
  - Higher thresholds may enhance EFT effects
  - Recent LHC measurement of tZj cross section at 4.2σ



[ATLAS; arXiv:1710.03659], [CMS-PAS-TOP-16-020 & arXiv:1712.02825]

SMEFT in tHj/tZj

tHj (tZj = h→Z) : classes of operators

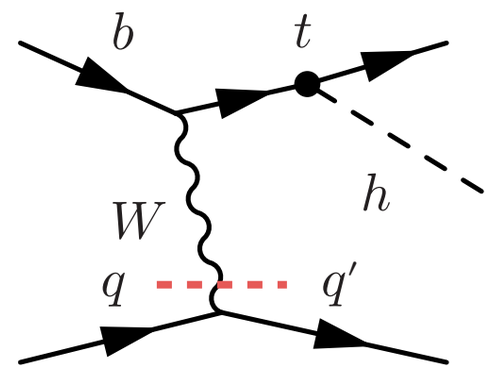


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi\, W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

$\mathcal{O}_W : \epsilon^{ijk} W_{i,\mu\nu} W_j^{\nu\rho} W^\mu_{k,\rho}$

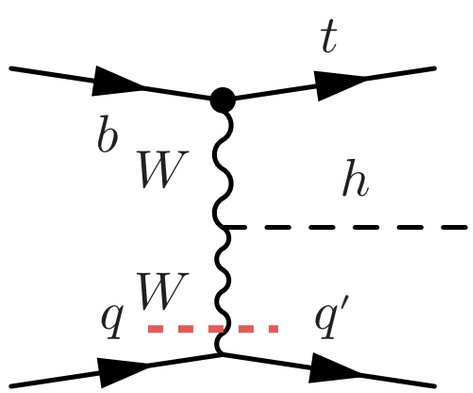


$\mathcal{O}_{t\varphi} : (\varphi^\dagger \varphi)\,(\bar{Q}\, t)\,\tilde{\varphi}$

top Yukawa

ttZ coupling

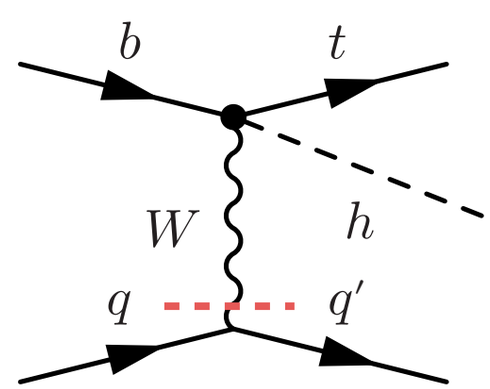
$\mathcal{O}_{\varphi t} : i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$



$\mathcal{O}^{(3)}_{\varphi Q} : i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

Wtb vertex

$\mathcal{O}_{\varphi tb} : i(\tilde{\varphi}\, D_\mu \varphi)(\bar{b}\gamma^\mu t)$

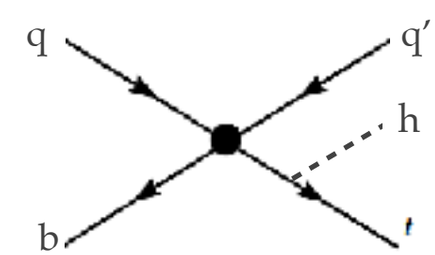


$\mathcal{O}^{(3)}_{\varphi Q} : i(\varphi^\dagger \overleftrightarrow{D}^i_\mu \varphi)(\bar{Q}\gamma^\mu \sigma_i Q)$

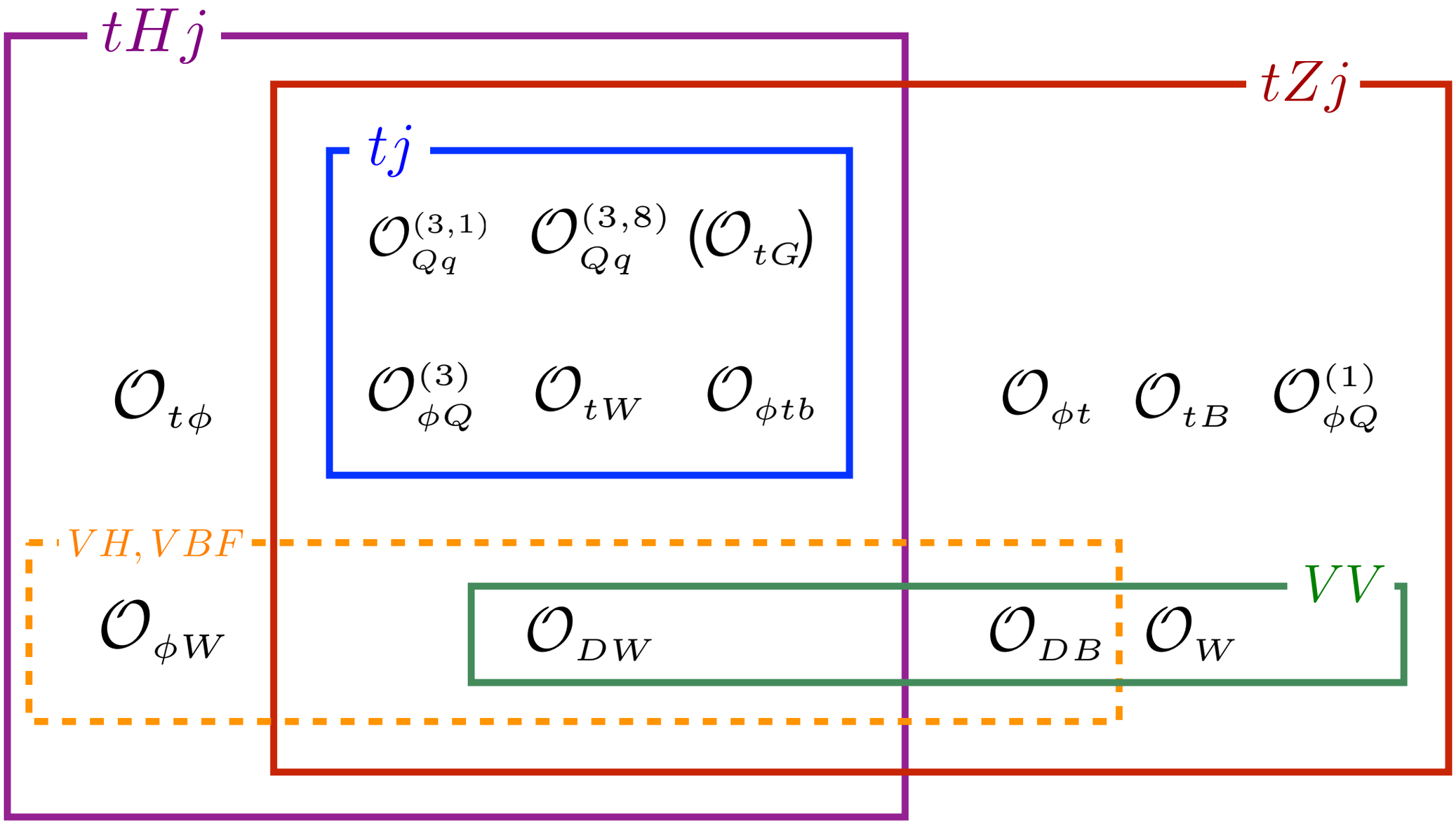
Contact terms

$\mathcal{O}_{tB} : (\bar{Q}\, \sigma_{\mu\nu}\, t)\, \tilde{\varphi}\, B^{\mu\nu}$

- Accessing the bW→tH & bW→tZ sub-amplitudes
  - Rich interplay between EFT operators from different sectors
  - Different energy growth and interference with the SM
  - Four fermion interactions also present



SMEFT in tHj/tZj



Existing limits

[Buckley et al.; JHEP 1604 (2016) 015]
[Alioli et al.; JHEP 1705 (2017) 086]
[Butter et al.; JHEP 1607 (2016) 152]
[Zhang et al.; PRD 86 (2012) 014024]

Combination of LHC single-top

$$c_{Qq}^{(3,8)} \subset [-1.40, 1.20]$$

[CMS; JHEP 12 (2012) 035]
[ATLAS; PRD 90 (2014) 11, 112006]
[CMS; JHEP 09 (2016) 027]
[ATLAS; JHEP 04 (2017) 086]
[ATLAS; EPJC 77 (2017) 8, 531]
[ATLAS; PLB 756 (2016) 228-246]

Combination of ttH @ 13 TeV

$$c_{t\varphi} \subset [-6.5, 1.3]$$

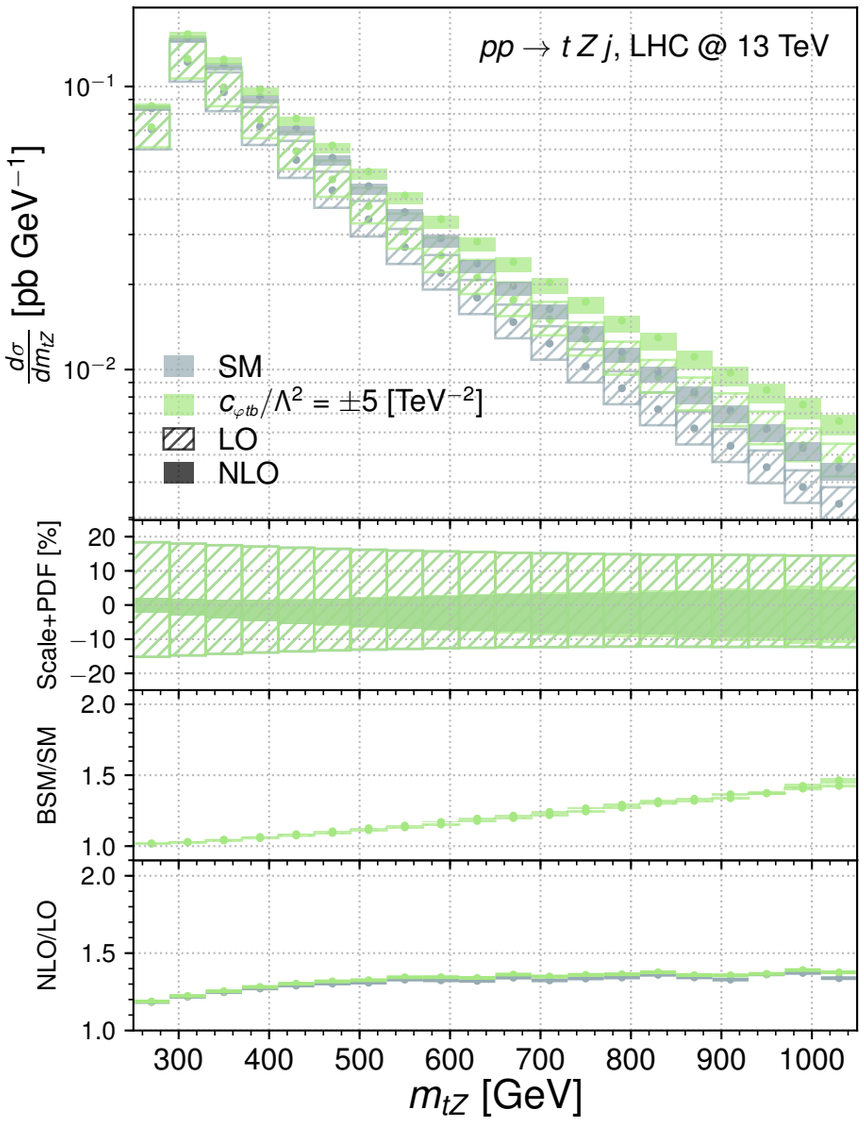
[CMS; CMS-PAS-HIG-17-003]
[CMS; CMS-PAS-HIG-17-004]
[ATLAS; CERN-EP-2017-281]

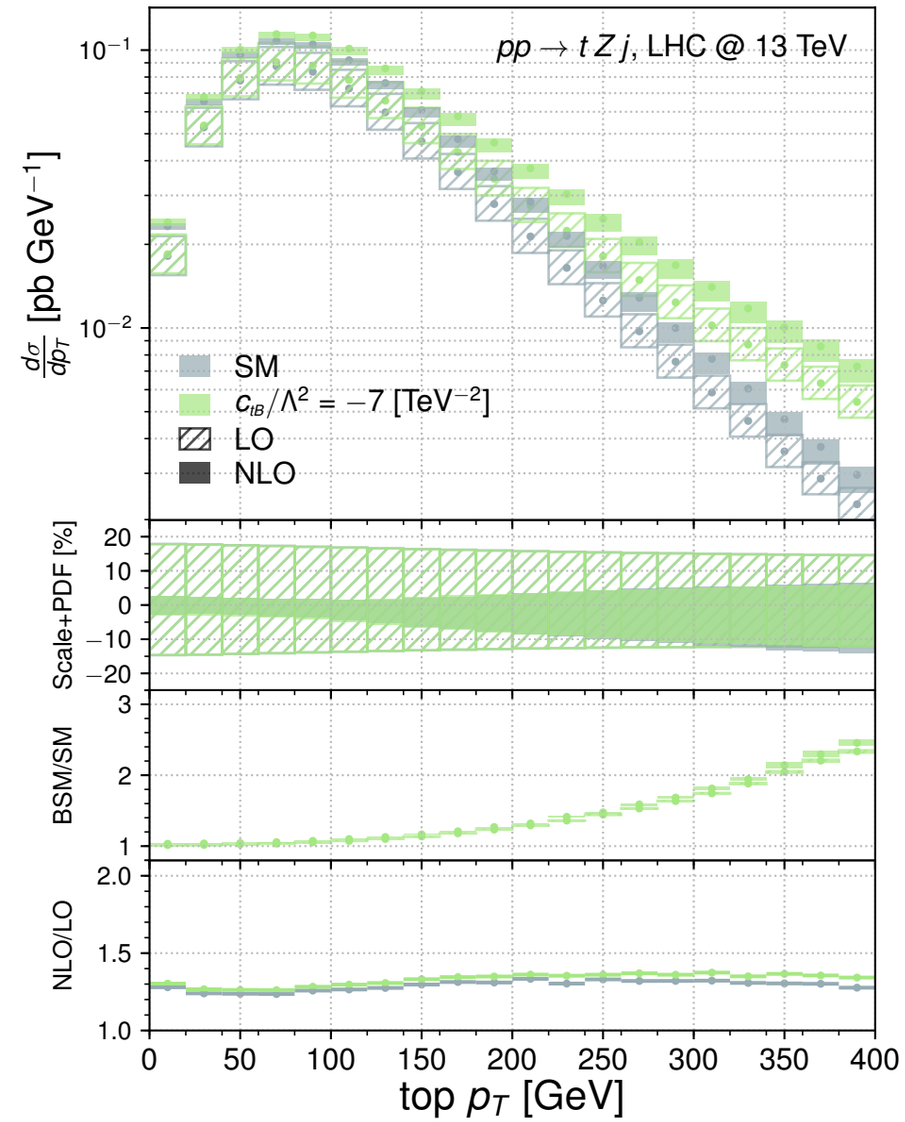
Op.	TF (I)	TF (M)	RHCC (I) tree/loop	SFitter (I)	PEWM[2]
$\mathcal{O}_W$				[-0.18,0.18]	
$\mathcal{O}_{HW}$				[-0.32,1.62]	
$\mathcal{O}_{HB}$				[-2.11,1.57]	
$\mathcal{O}_{\varphi W}$				[-0.39,0.33]	
$\mathcal{O}_{\varphi tb}$			[-5.28,5.28]/[-0.046,0.040]		
$\mathcal{O}_{\varphi Q}^{(3)}$	[-2.59,1.50]	[-4.19,2.00]			-1.0 ± 2.7 [3]
$\mathcal{O}_{\varphi Q}^{(1)}$	[-3.10,3.10]				1.0 ± 2.7
$\mathcal{O}_{\varphi t}$	[-9.78,8.18]				1.8 ± 3.8
$\mathcal{O}_{tW}$	[-2.49,2.49]	[-3.99,3.40]			-0.4 ± 2.4
$\mathcal{O}_{tB}$	[-7.09,4.68]				4.8 ± 10.6
$\mathcal{O}_{tG}$	[-0.24,0.53]	[-1.07,0.99]			
$\mathcal{O}_{t\varphi}$				[-18.2,6.30]	
$\mathcal{O}_{Qq}^{(3,1)}$	[-0.40,0.60]	[0.66,1.24]			
$\mathcal{O}_{Qq}^{(3,8)}$	[-4.90,3.70]	[6.06,6.73]			

(I) : Individual
(M) : Marginalised

[TeV^{-2}]

LHC sensitivity





Effects of operators with coefficientes set at the boundaries of current exclusions

LHC sensitivity

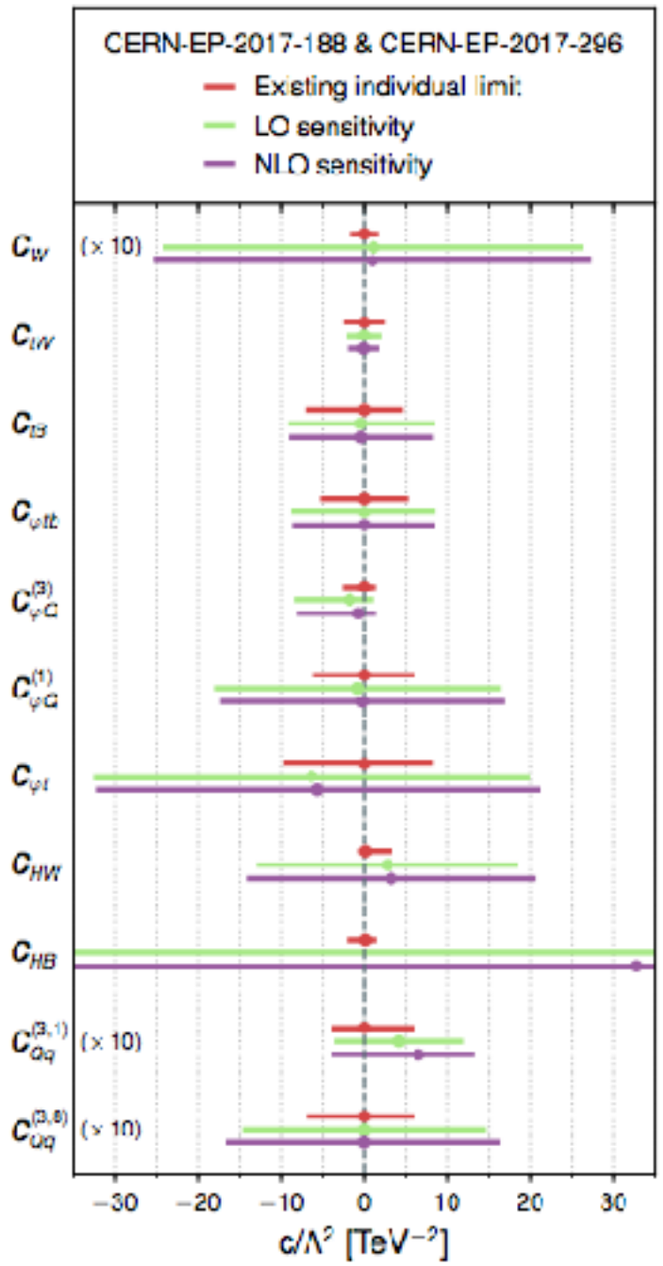
Usual EFT story: looking at high energy tails increases sensitivity

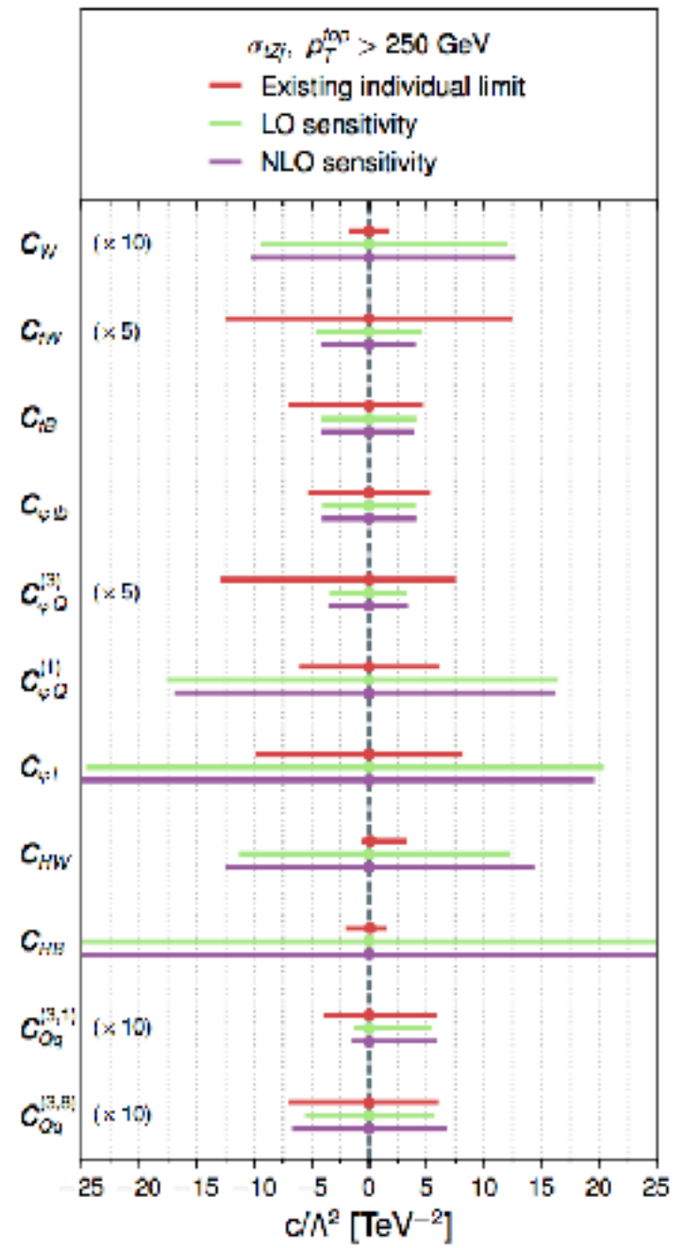
Important to put into context w.r.t single top which has a much larger rate

$r=\sigma_i/\sigma_{SM}$	tj	tj ($p_T^t > 350$ GeV)	tZj	tZj ($p_T^t > 250$ GeV)	$ttlj$
σ_{SM}	224 pb	880 fb	839 fb	69 fb	75.9 fb
r_{tW}	0.0275	0.024	0.016	0.010	0.292
$r_{tW,tW}$	0.0162	0.35	0.095	0.67	0.940
$r_{\varphi Q^{(3)}}$	0.121	0.121	0.192	0.172	-0.132
$r_{\varphi Q^{(3)},\varphi Q^{(3)}}$	0.0037	0.0037	0.029	0.114	0.21
$r_{\varphi tb,\varphi tb}$	0.00090	0.0008	0.0050	0.027	0.050
r_{tG}	0.0003	-0.01	0.00053	-0.0048	-0.0055
$r_{tG,tG}$	0.00062	0.045	0.0027	0.022	0.025
$r_{Qq^{(3,1)}}$	-0.353	-4.4	-0.59	-2.22	-0.39
$r_{Qq^{(3,1)},Qq^{(3,1)}}$	0.126	11.5	0.65	5.1	1.21
$r_{Qq^{(3,8)},Qq^{(3,8)}}$	0.0308	2.73	0.133	1.01	1.08

- Increased sensitivity for dipoles, RHCC
- Consistent with 2→2 subamplitude analysis
- Single top should eventually outperform tHj/tZj for four fermion operators

Current/Future sensitivity in tZj





Conclusions and Outlook

- The top quark is special (i.e. is the only normal) quark in the SM. It plays an important role and its electroweak behaviour could be a gateway to new physics.
- The most beaten path for searching new physics at the LHC so far it has involved top-down (or simplified models) approach to detecting new resonances.

A far reaching approach to new physics is that of searching for new interactions employing an EFT.

- The EFT approach provides a consistent QFT to work with. Predictions can be obtained and systematically improved. To be fully meaningful and useful, predictions have to be available at NLO accuracy in QCD (and EW) and constraints need to be obtained in a global way.
- TH results and MC tools to put in action this strategy have become available.
- New joint theoretical/experimental effort

Back-up slides

Need for NLO

1. Operators run and mix under RGE

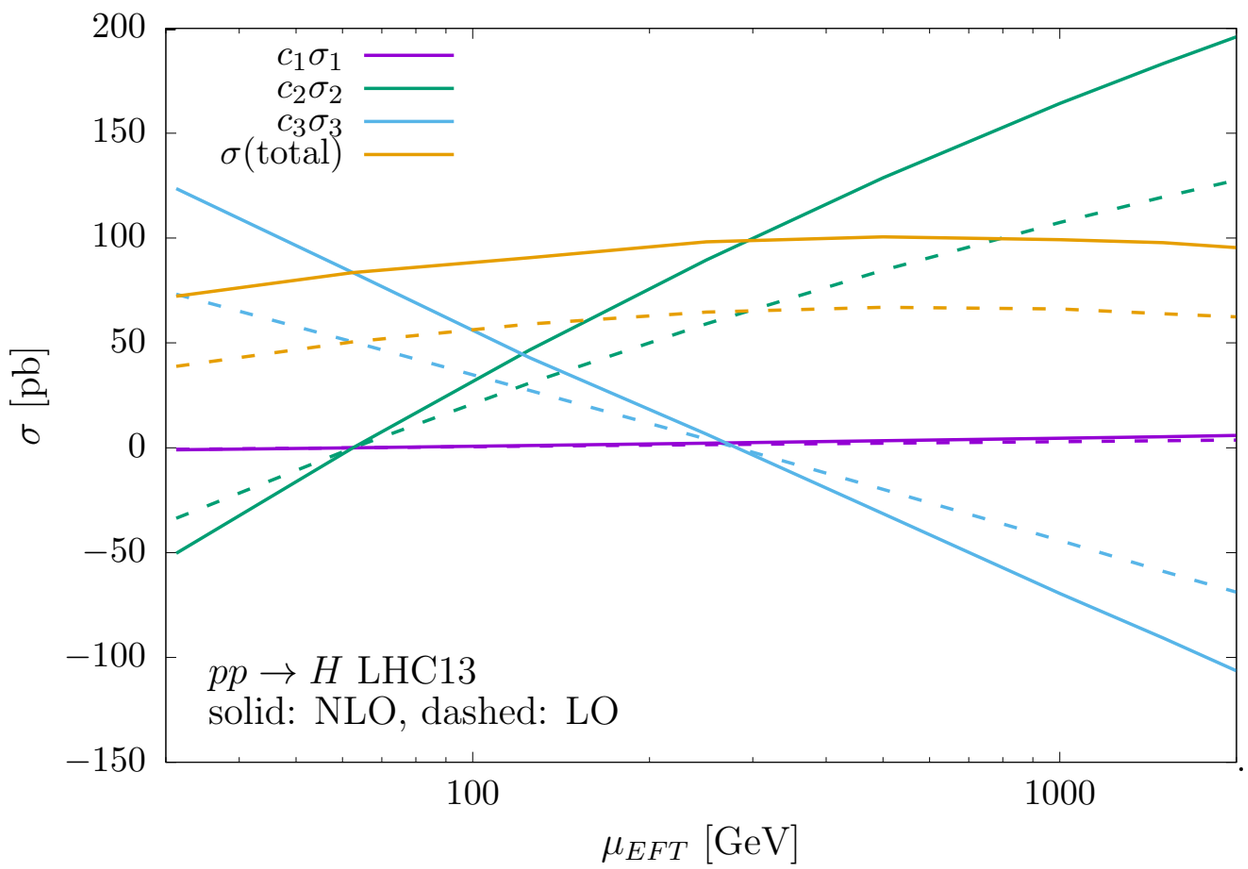
Running means that the Wilson coefficients depend on the scale where they are measured (as the couplings in the SM). Note that this introduces also an additional uncertainty in the perturbative computations.

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.

Need for NLO

2. EFT scale dependence

[Deutschmann, Duhr, FM, Vryonidou, 17]



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

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

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

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

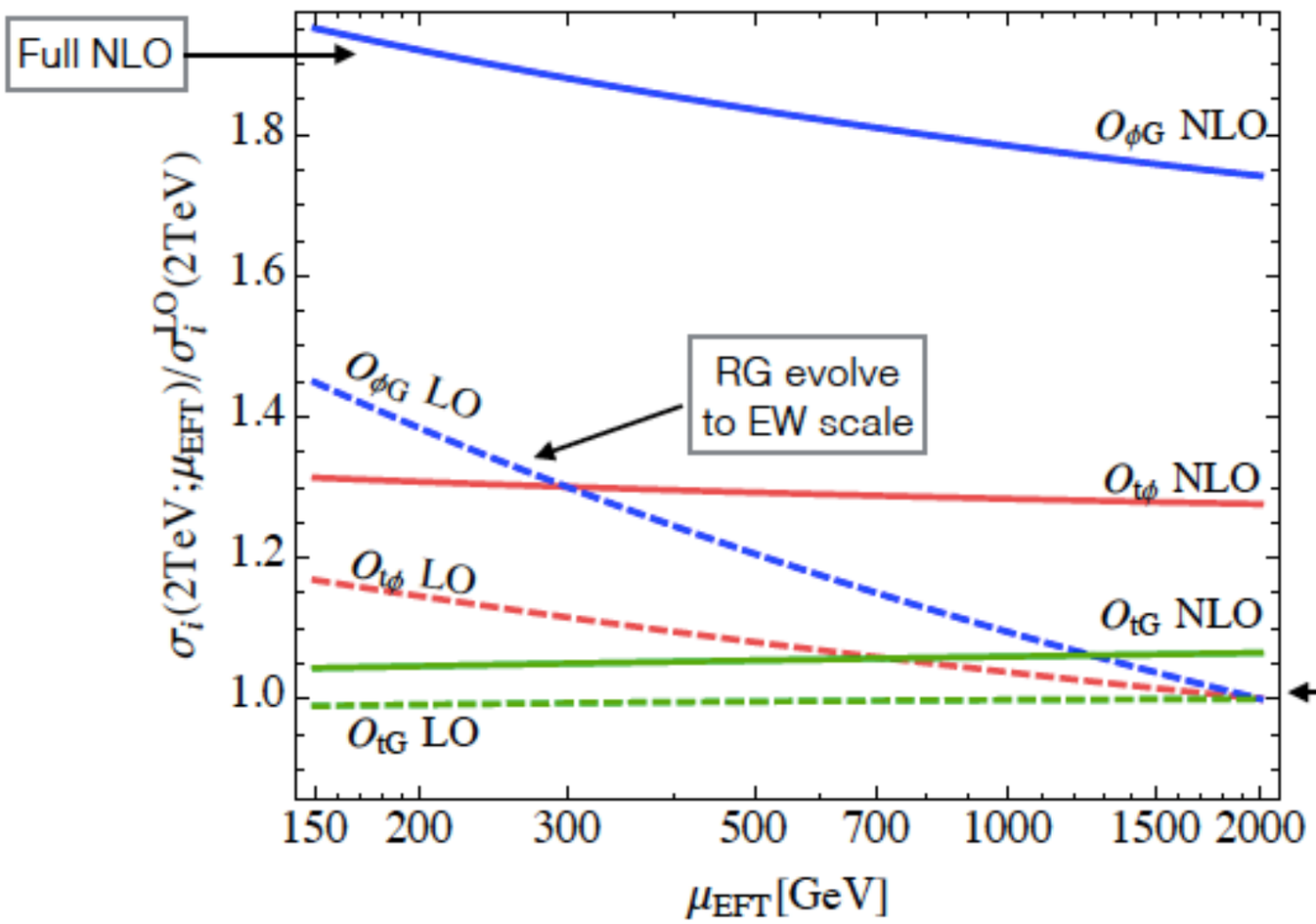
$$\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

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.

Need for NLO

3. Genuine NLO corrections (finite terms) are important

[FM, Vryonidou, Zhang, 16]



- pp → ttH

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

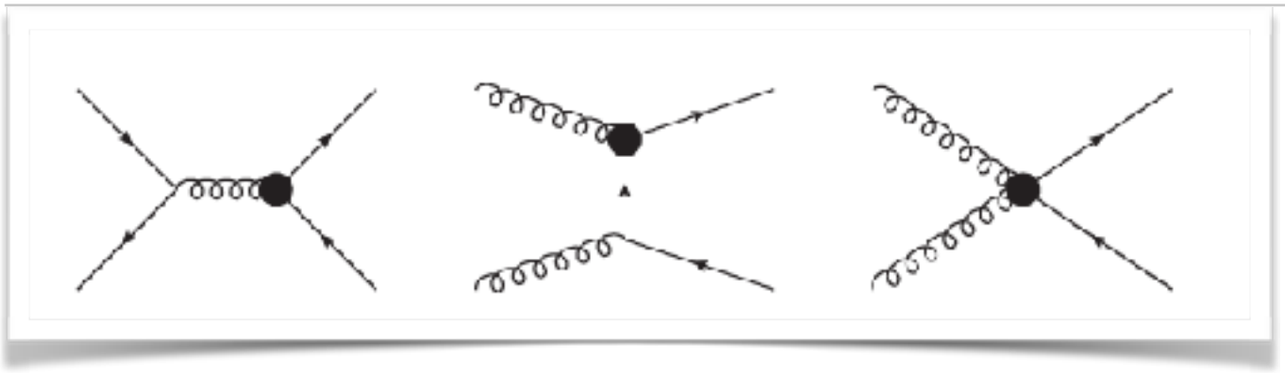
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

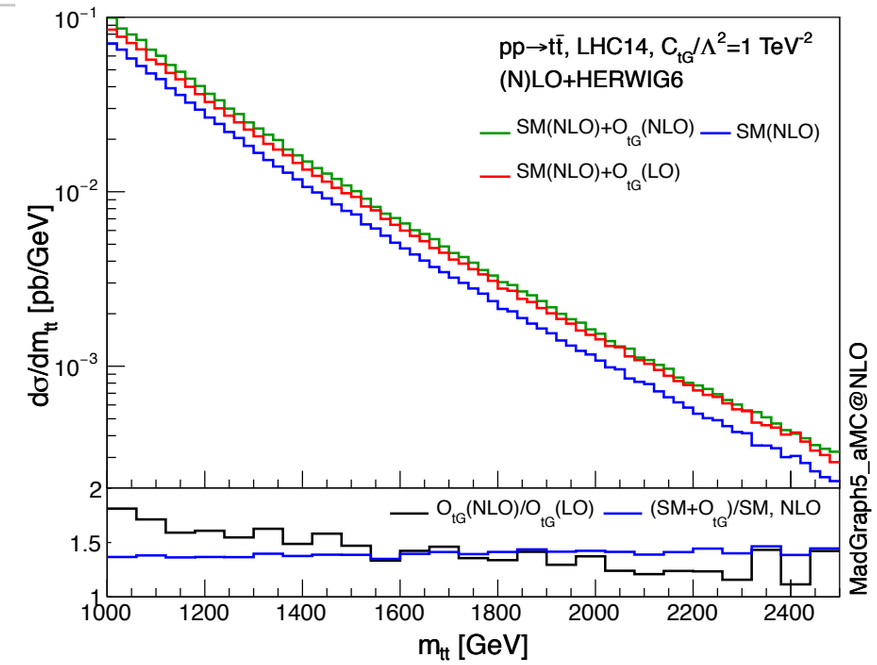
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

- 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.

Bounding OtG at NLO from ttbar

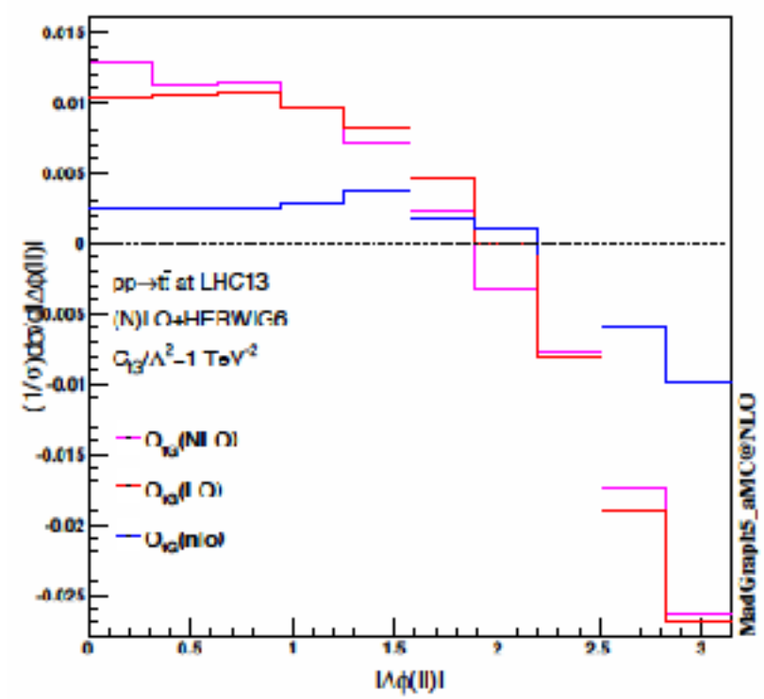
[Franzosi and Zhang, 2015]





Recent analysis at NLO in QCD

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

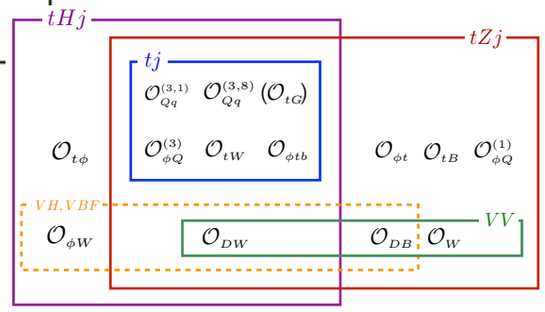


Limits on ctG from LHC8

	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]

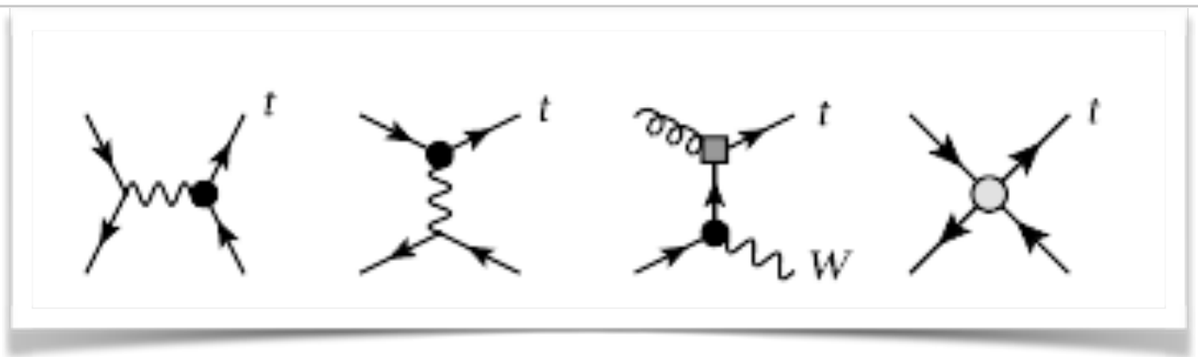
SMEFT in tHj/tZj

$\mathcal{O}_W$	$\varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\ \rho}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{Q}\,\gamma^\mu\,\tau^I Q\right) + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_I\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\,\gamma^\mu\, Q\right) + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi)\, B^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}_{\varphi t}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\,\gamma^\mu\, t\right) + \text{h.c.}$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{\varphi tb}$	$i\left(\tilde{\varphi}\, D_\mu\, \varphi\right)\left(\bar{t}\,\gamma^\mu\, b\right) + \text{h.c.}$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}^{(1)}_{\varphi q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{q}_i\,\gamma^\mu\, q_i\right) + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}^{(3)}_{\varphi q}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi\right)\left(\bar{q}_i\,\gamma^\mu\,\tau^I q_i\right) + \text{h.c.}$
$\mathcal{O}_{tW}$	$i\left(\bar{Q}\sigma^{\mu\nu}\,\tau_I\, t\right)\tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{\varphi u}$	$i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}_i\,\gamma^\mu\, u_i\right) + \text{h.c.}$
$\mathcal{O}_{tB}$	$i\left(\bar{Q}\sigma^{\mu\nu}\, t\right)\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,1)}_{Qq}$	$\left(\bar{q}_i\,\gamma_\mu\,\tau_I q_i\right)\left(\bar{Q}\,\gamma^\mu\,\tau^I Q\right)$
$\mathcal{O}_{tG}$	$i\left(\bar{Q}\sigma^{\mu\nu}\, T_A\, t\right)\tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,8)}_{Qq}$	$\left(\bar{q}_i\,\gamma_\mu\,\tau_I T_A q_i\right)\left(\bar{Q}\,\gamma^\mu\,\tau^I T^A Q\right)$

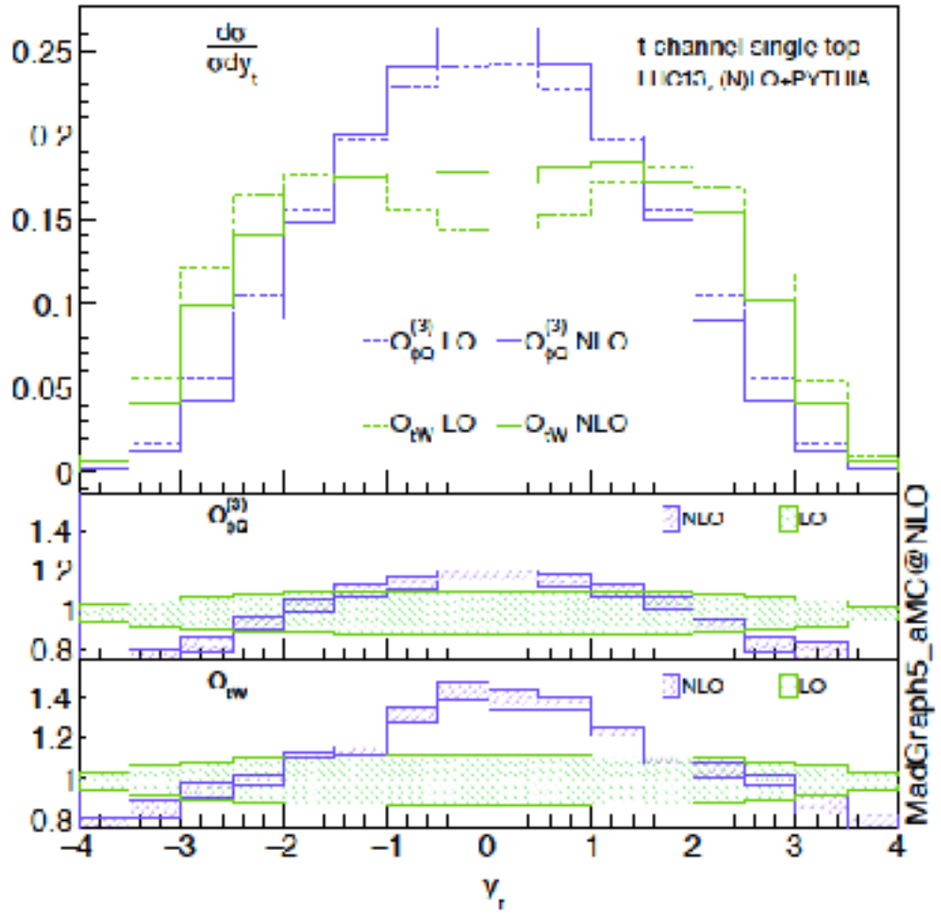


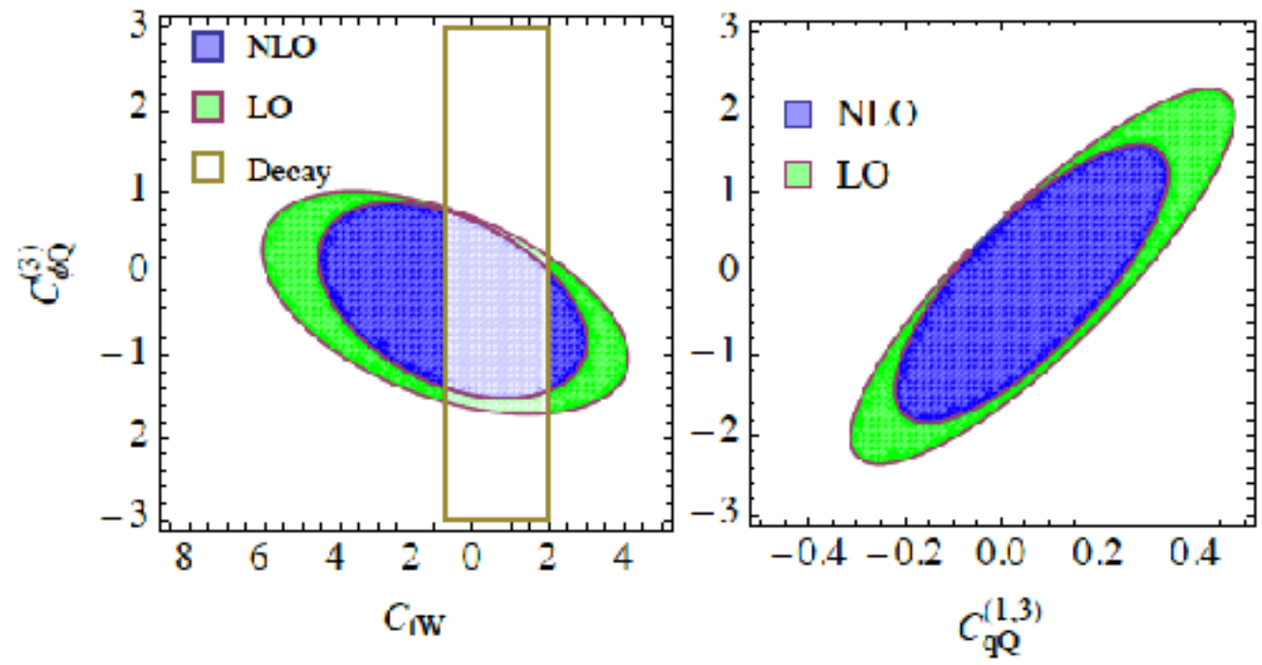
Single-top in the EFT at NLO

[Cen Zhang, 2016]



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





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

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

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

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

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

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

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

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

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?

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

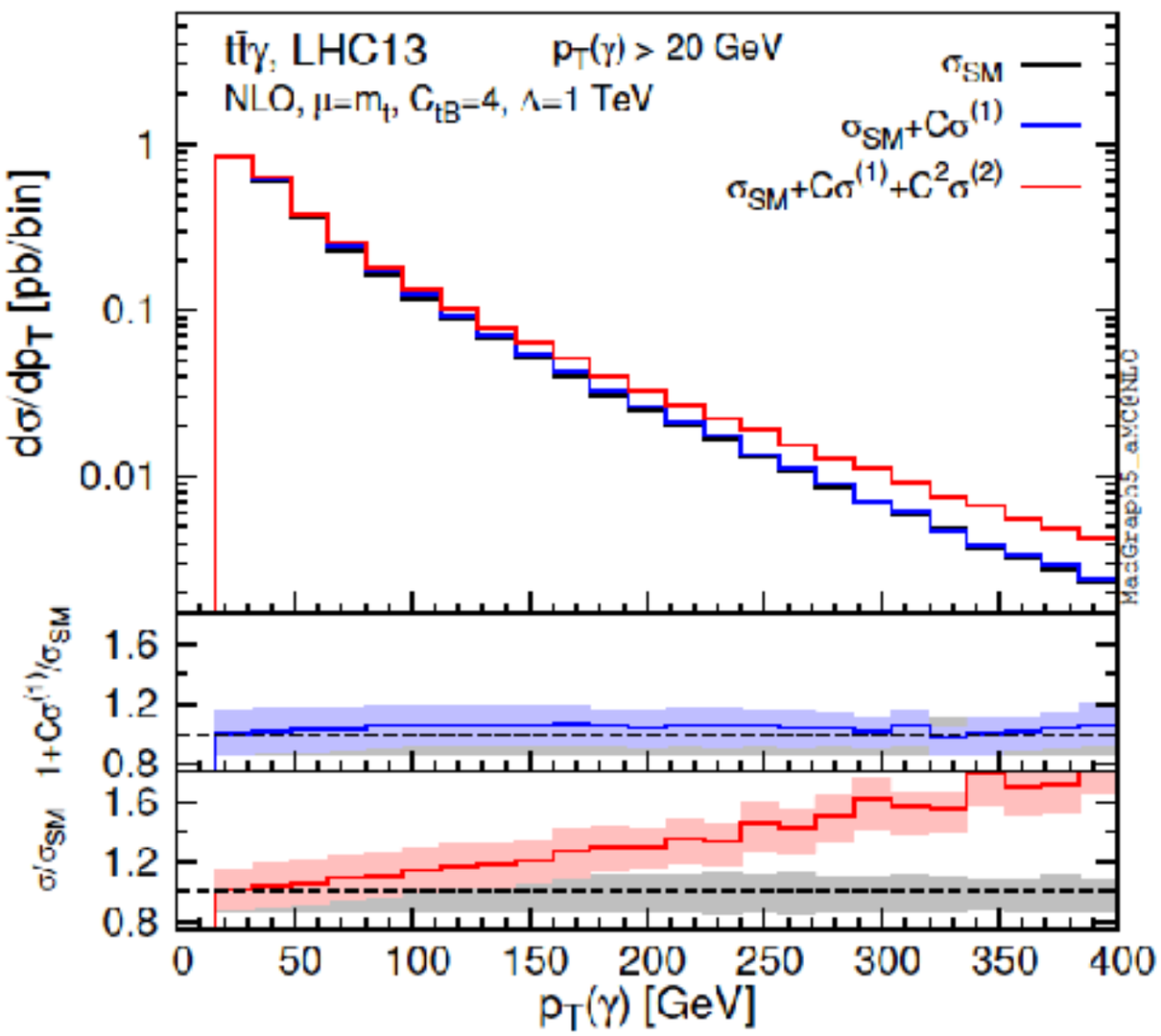
EFT condition satisfied. To be checked on a case-by-case basis

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

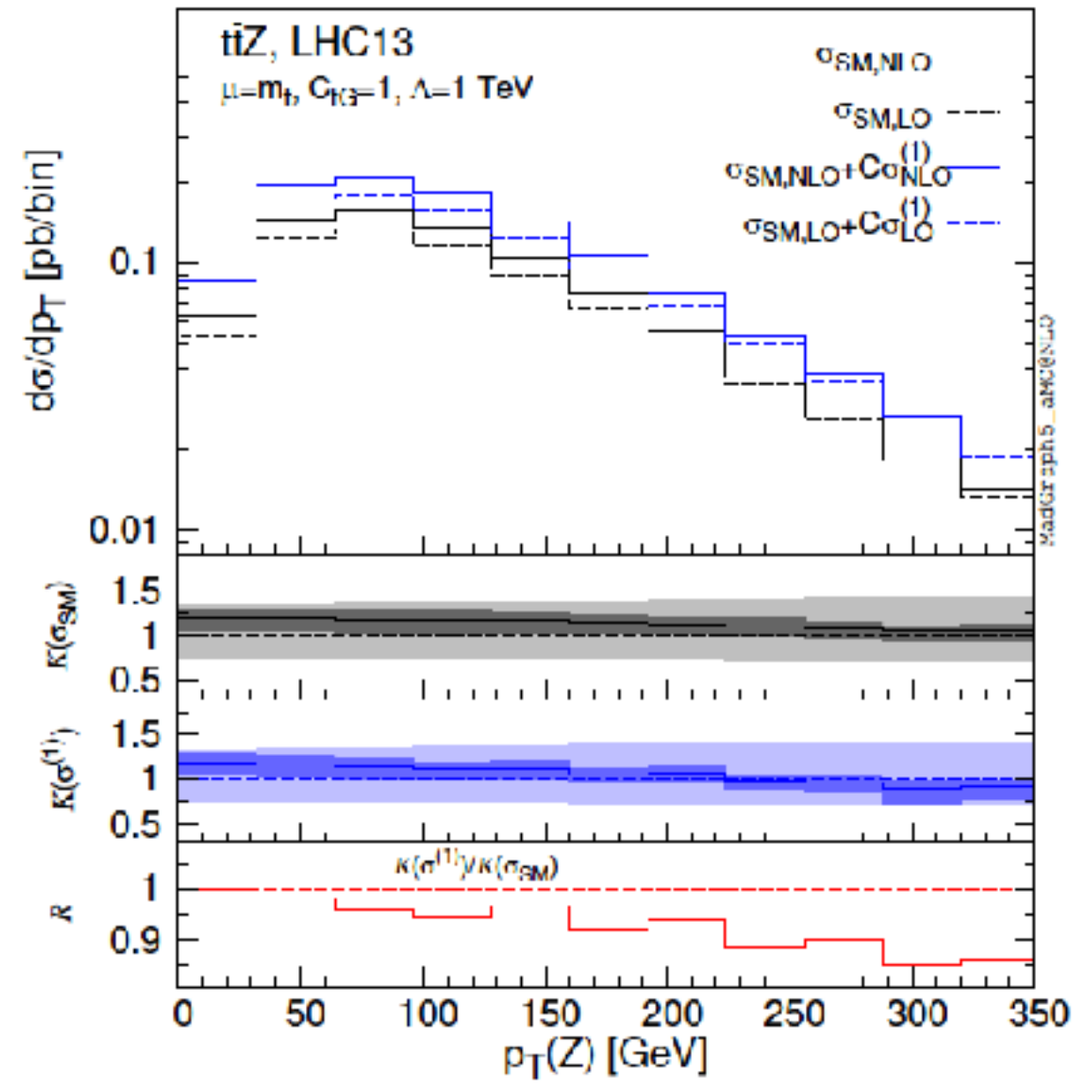
Anom. dim. matrix:
O_{tW}, O_{tB}, O_{tG}

ttZ and tty in the EFT at NLO

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



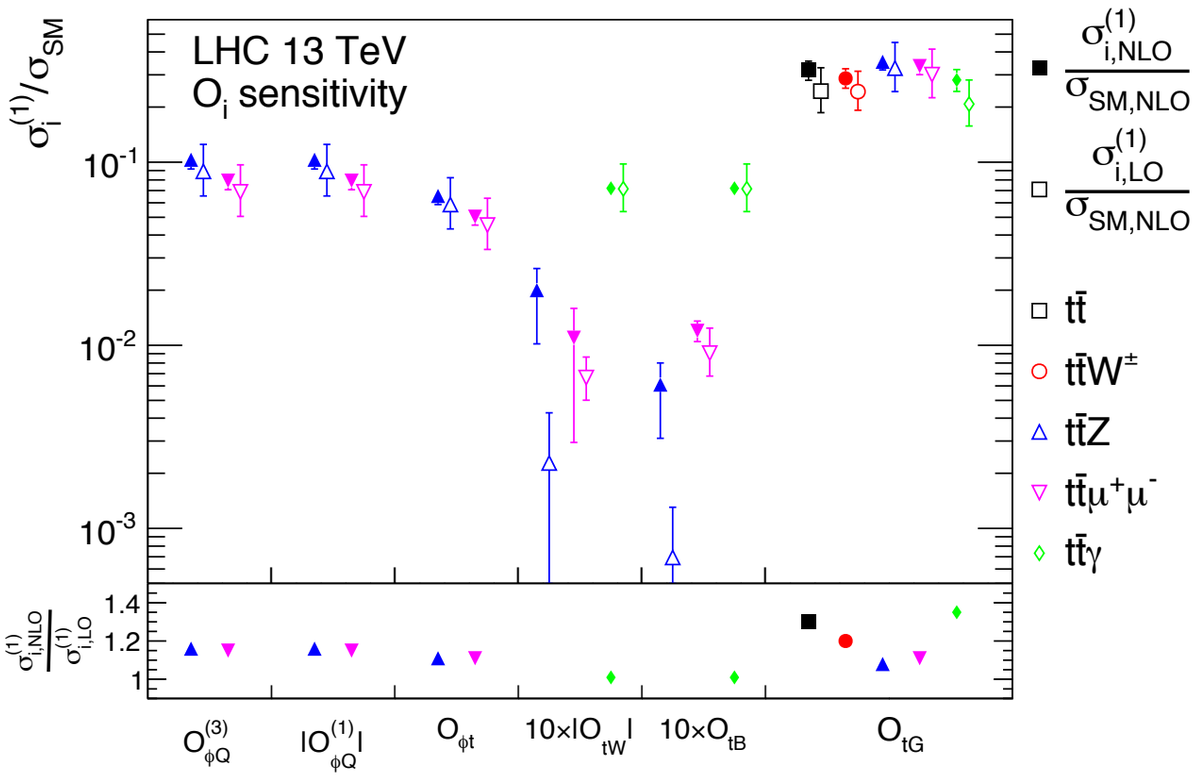
Large contribution at $O(1/\Lambda^4)$ rising with energy

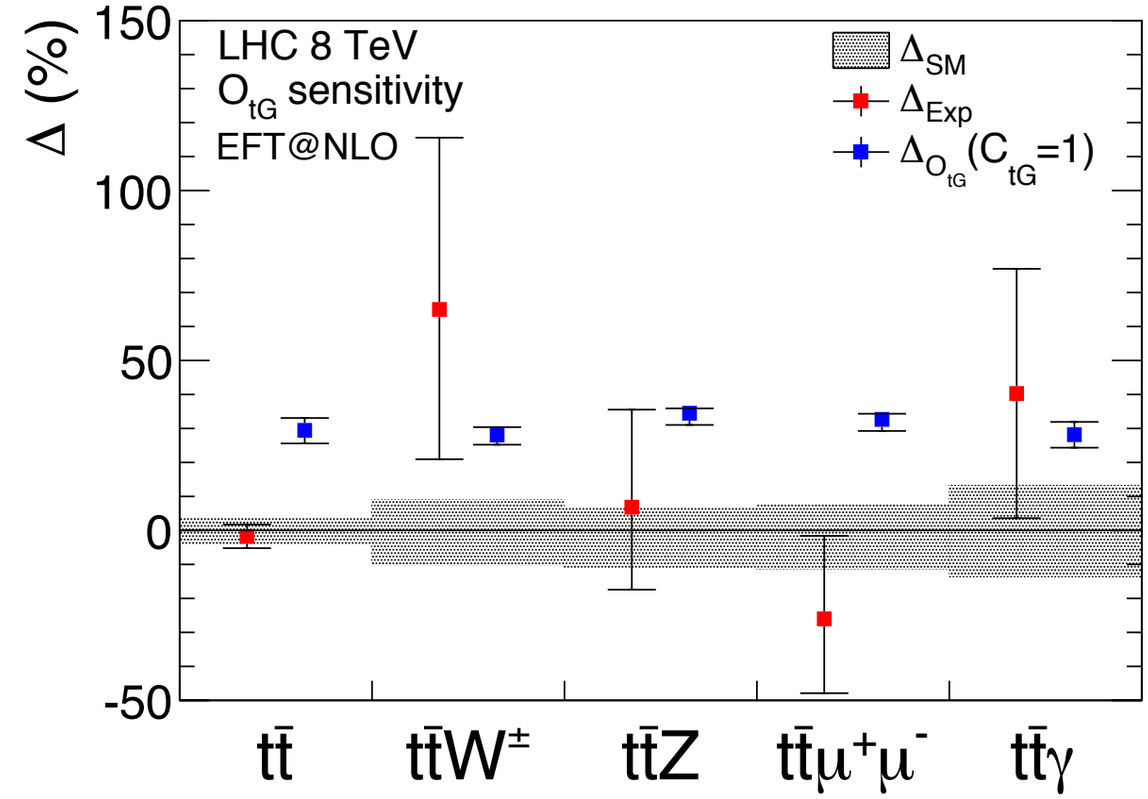


Using SM k-factors is not enough

ttZ and tty 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.

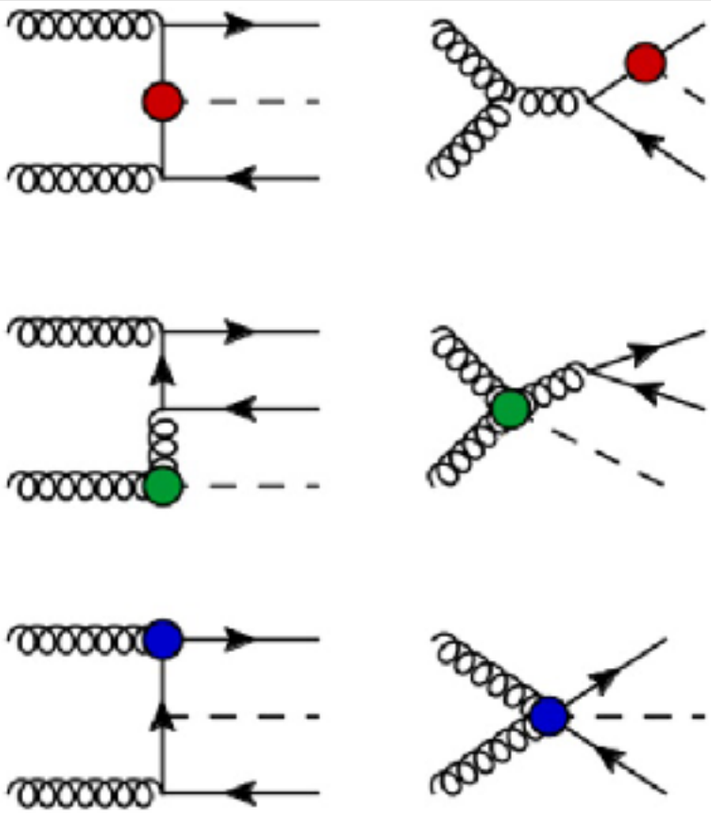
Status of the SMEFT at NLO: Higgs production

Channel	SM: QCD, EW	dim=6 : QCD	Comments
gg→H	N3LO,NLO	NLO: $C_{t\phi}$,$C_{\phi G}$ C_{tG}	—-
gg→Hj	NNLO, LO	NLO: $C_{\phi G}$, LO: $C_{t\phi}$,C_{tG}	NLO hard to complete
ttH	NNLO, NLO	NLO	—-
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	NLO	—-
VBF	N3LO, NLO	(N)NLO	NLO EW welcome
VH	NNLO,NLO	(N)NLO	NLO EW welcome

more SU(3)

more SU(2)xU(1)

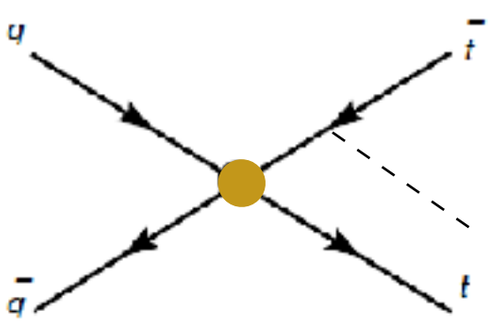
ttH in the EFT



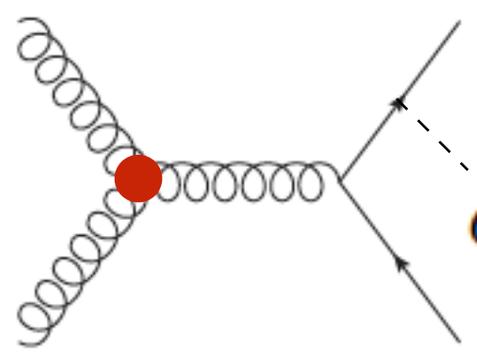
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

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

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



4 - f e r m i o n operators



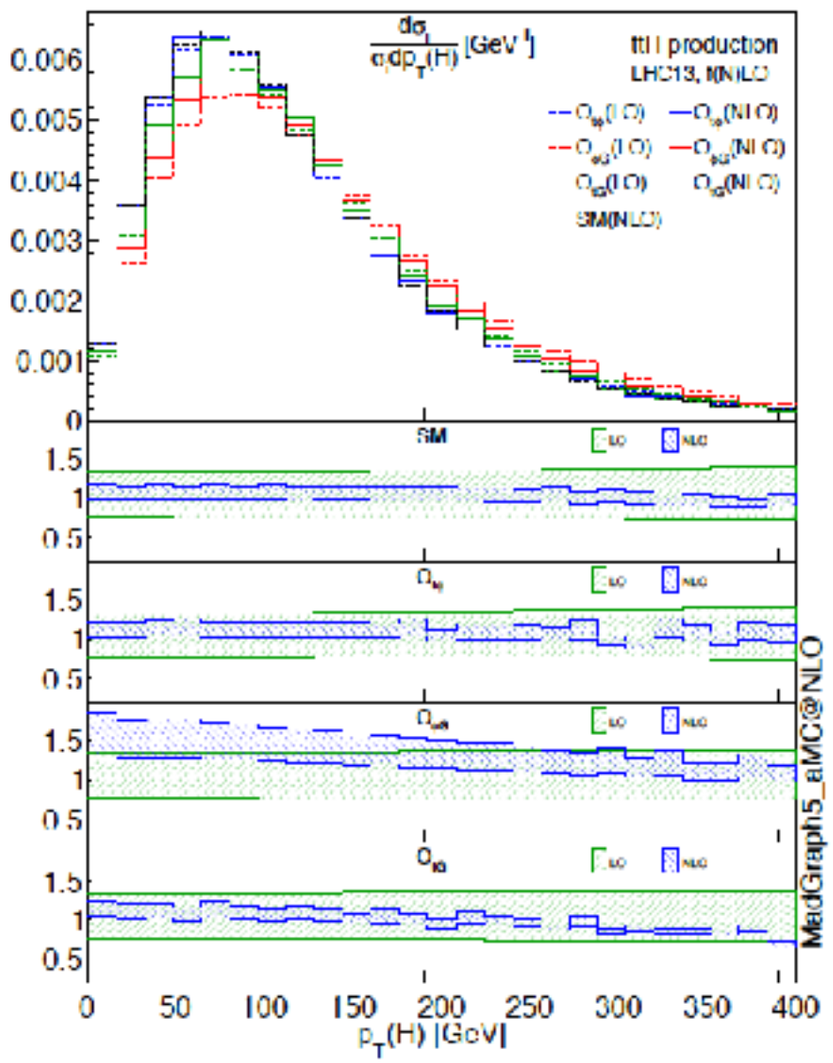
$$O_G = g_s f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$$

[In progress]

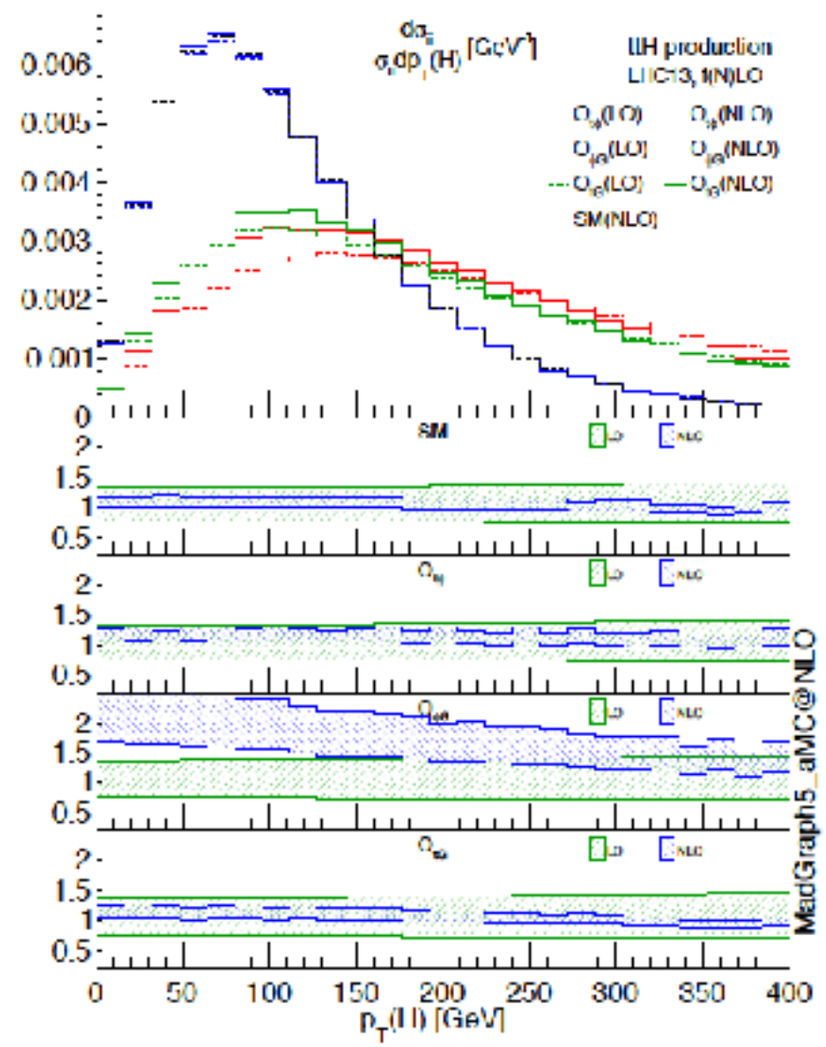
[Multijet constraints: Krauss et al arXiv:1611.00767]

ttH in the SMEFT

[FM, Vryonidou, Zhang, 16]

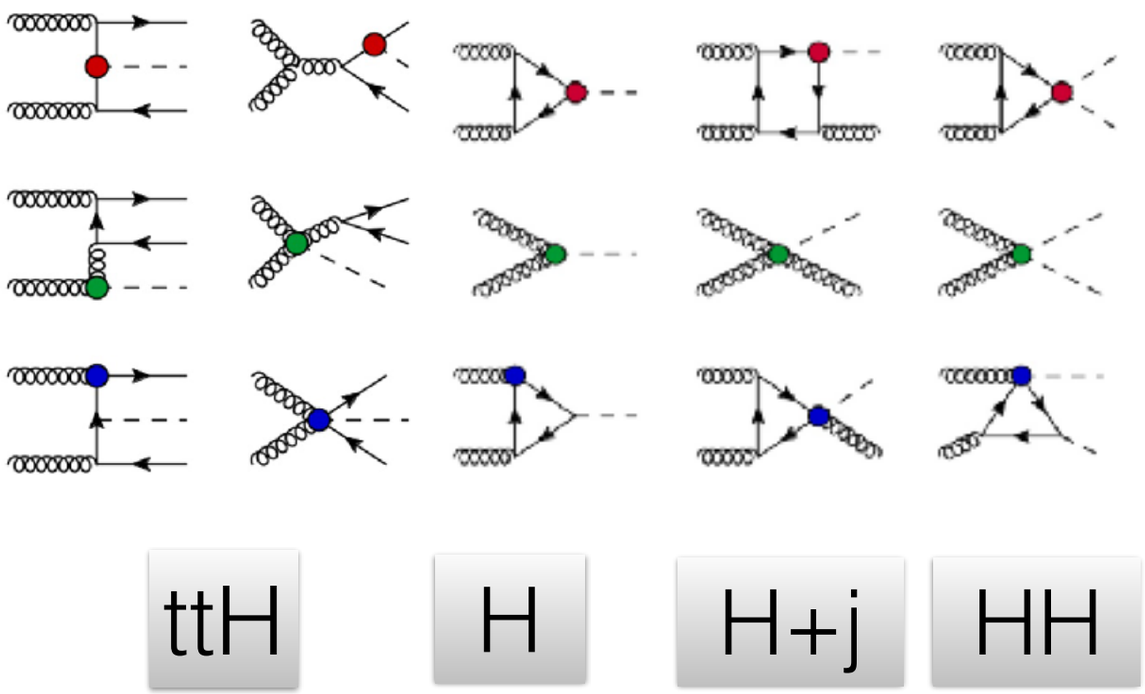


NLO: smaller uncertainties, non-flat K-factors



Different shapes for different operators for the squared terms

A global approach on top/Higgs on a subset of ops



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

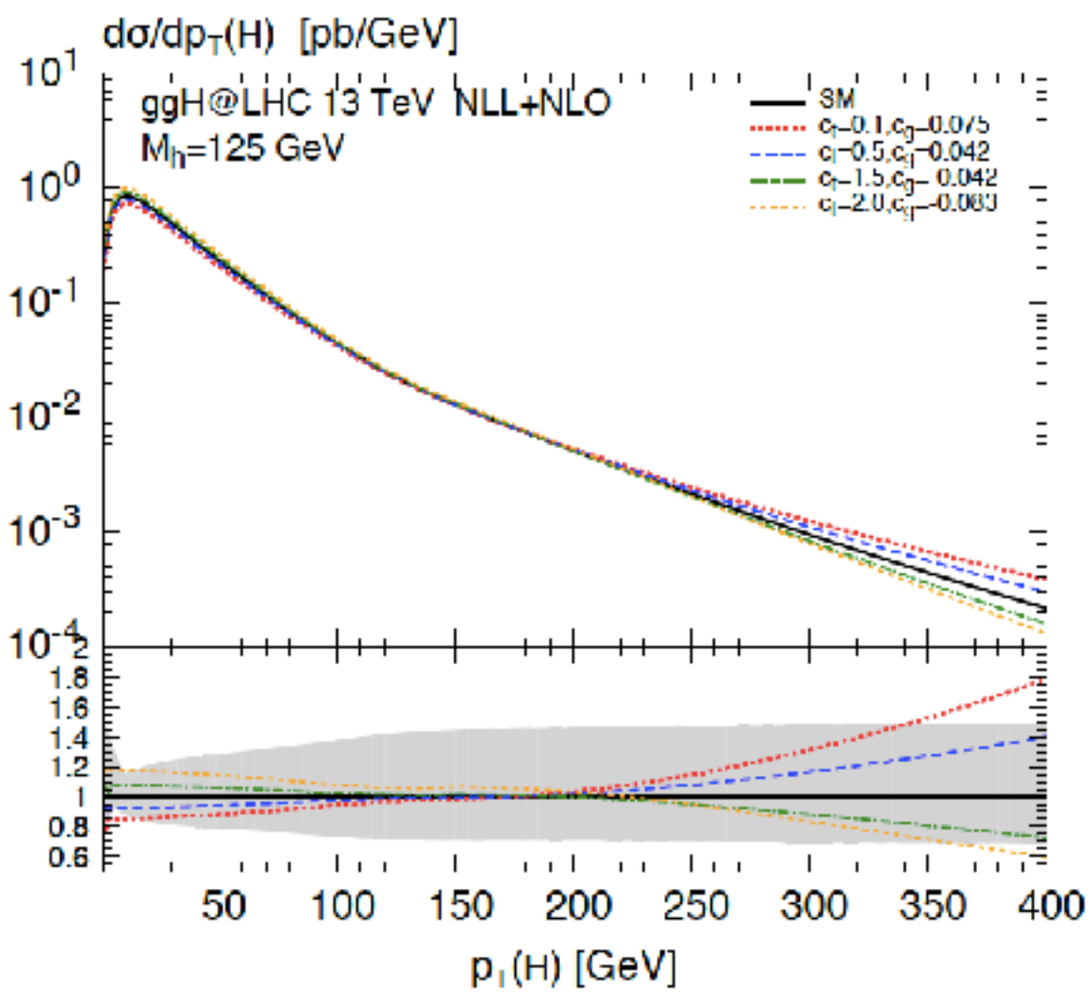
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

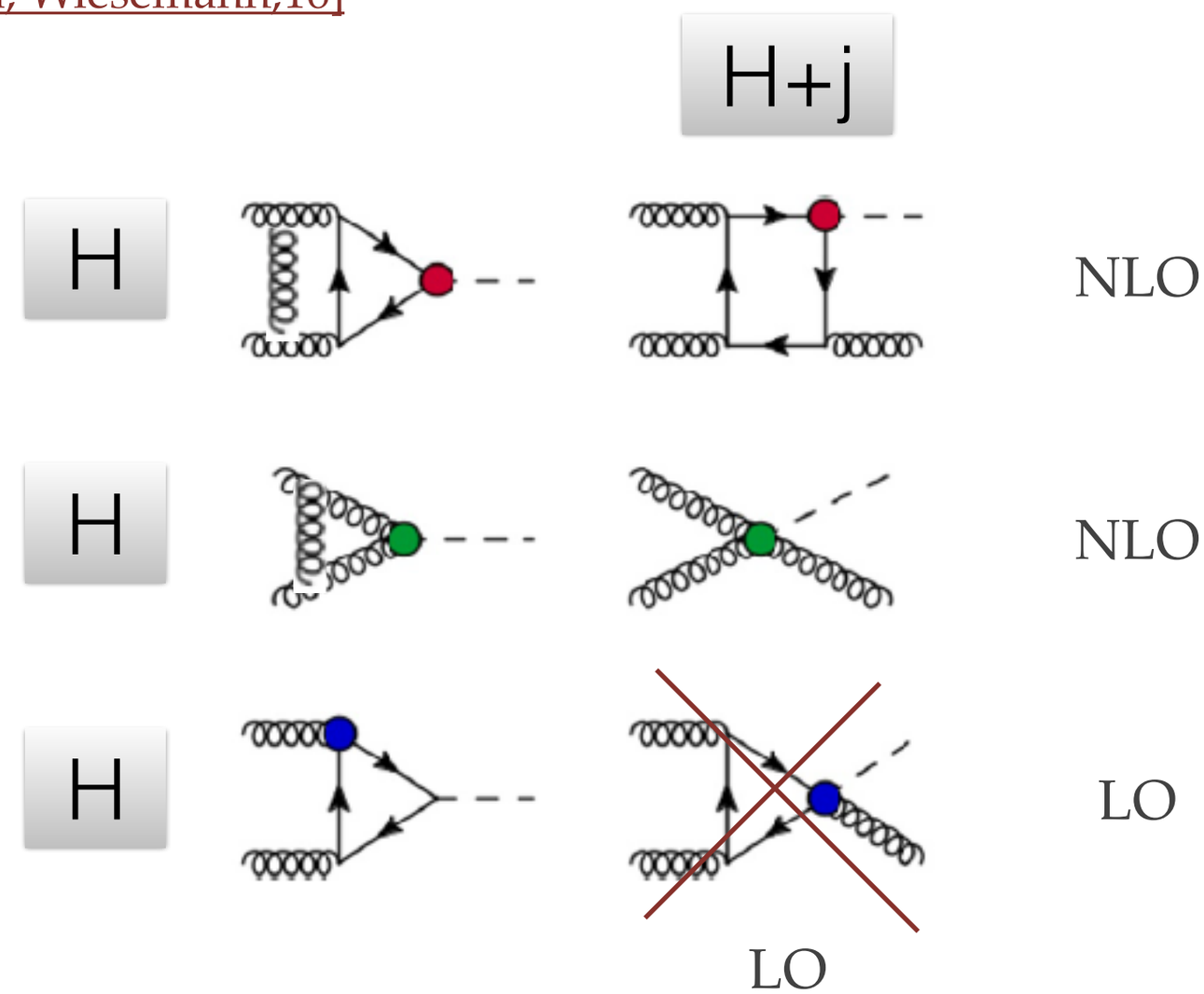
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

ggH in the SMEFT

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

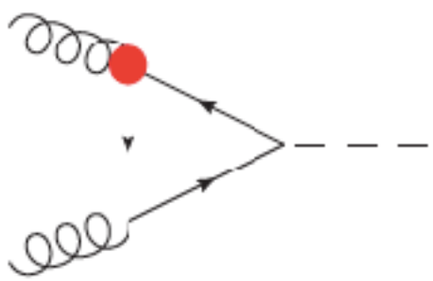
More recently, [Grazzini, Ilnicka, Spira, Wiesemann,16]





ggH in the SMEFT

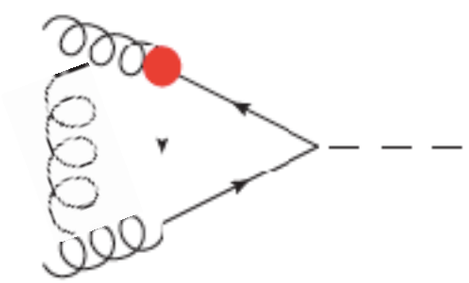
[Deutschmann, Duhr, FM, Vryonidou, 17]



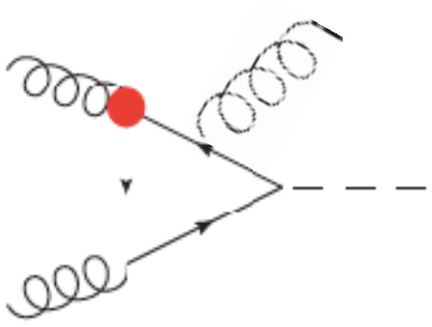
$\bar{Q}_L \Phi \sigma q_R G$

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

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



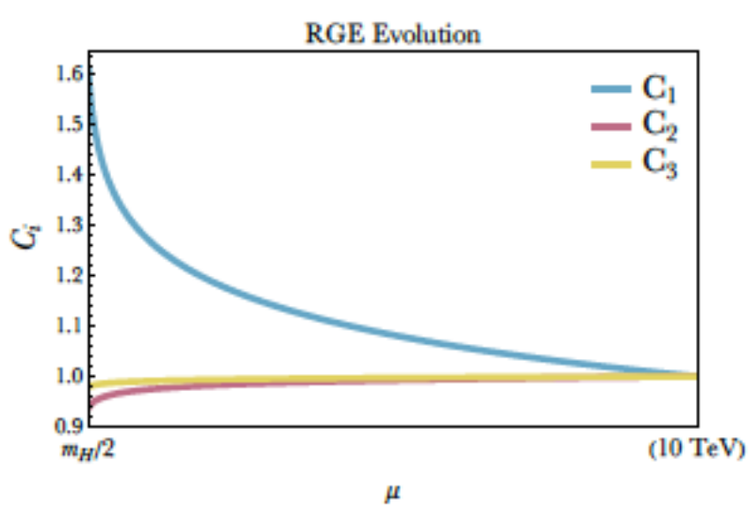
$\bar{Q}_L \Phi \sigma q_R G$

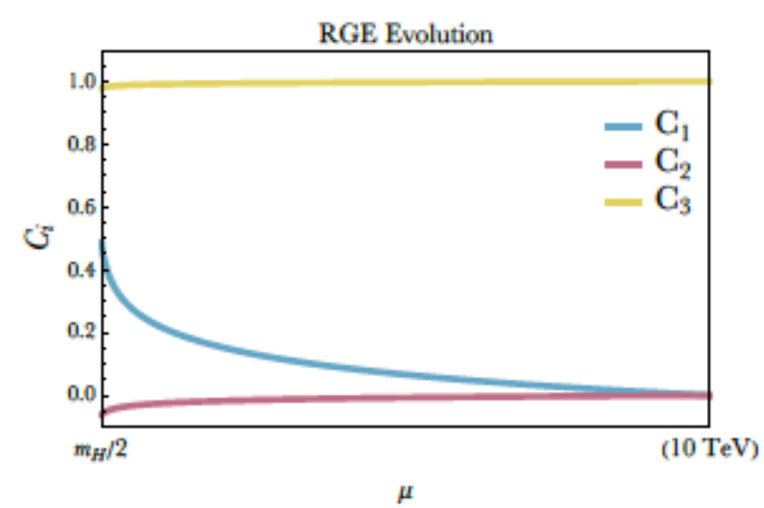


$\bar{Q}_L \Phi \sigma q_R G$

ggH in the SMEFT

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

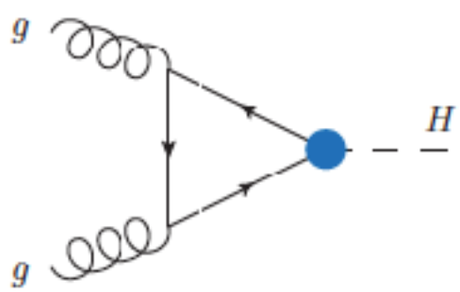




ggH in the SMEFT

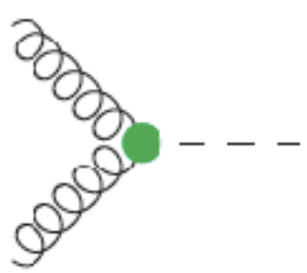
[Deutschmann, Duhr, FM, Vryonidou, 17]

σ_1



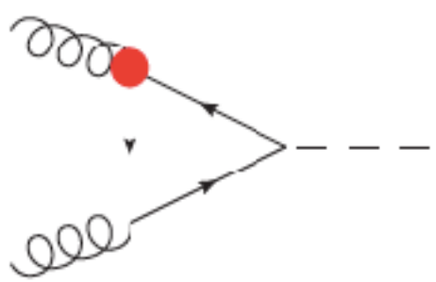
$(\Phi^\dagger\Phi)\,\bar{Q}_L\Phi\, q_R$

σ_2



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

σ_3



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

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	$36.6^{+25.4+1.9\%}_{-20.0-1.6\%}$	1.0	1.71
σ_1	$2.03^{+34.0+1.5\%}_{25.0\ \ 1.5\%}$	-0.138	$4.70^{+24.8+1.9\%}_{20.0\ \ 1.5\%}$	-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

$$\mathcal{O}_1 \quad \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right) Q_L\tilde{\Phi}\, t_R\,,$$

$$\mathcal{O}_2 = g_s^2\left(\Phi^\dagger\Phi \quad \frac{v^2}{2}\right) G^a_{\mu\nu}G^{\mu\nu}_a$$

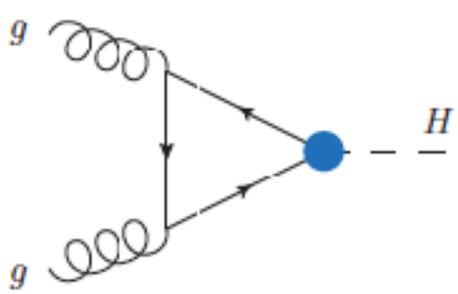
$$\mathcal{O}_3 = y_s\,\overline{Q}_L\tilde{\Phi}\,T^a\,\sigma^{\mu\nu}\,t_R\,G^a_{\mu\nu}\,;$$

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

ggH in the SMEFT

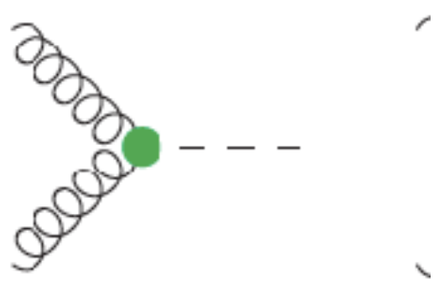
[Deutschmann, Duhr, FM, Vryonidou, 17]

σ_1



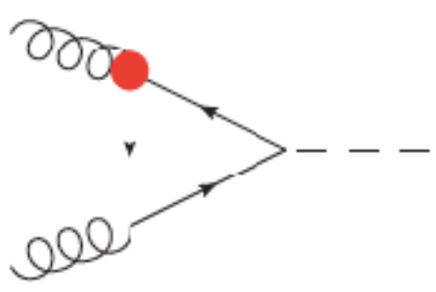
$(\Phi^\dagger\Phi)\,\bar{Q}_L\Phi\, q_R$

σ_2



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

σ_3



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

Only linear terms:

$$-0.28 < -0.128C_1 + 114C_2 + 2.28C_3 < 0.48.$$

One operator at the time:

$$-3.8 < C_1 < 2.2,\ -0.0025 < C_2 < 0.0043,\ -0.12 < C_3 < 0.21\,.$$

At one operator at the time, inclusion of the quadratic terms change the limits by only 10%.

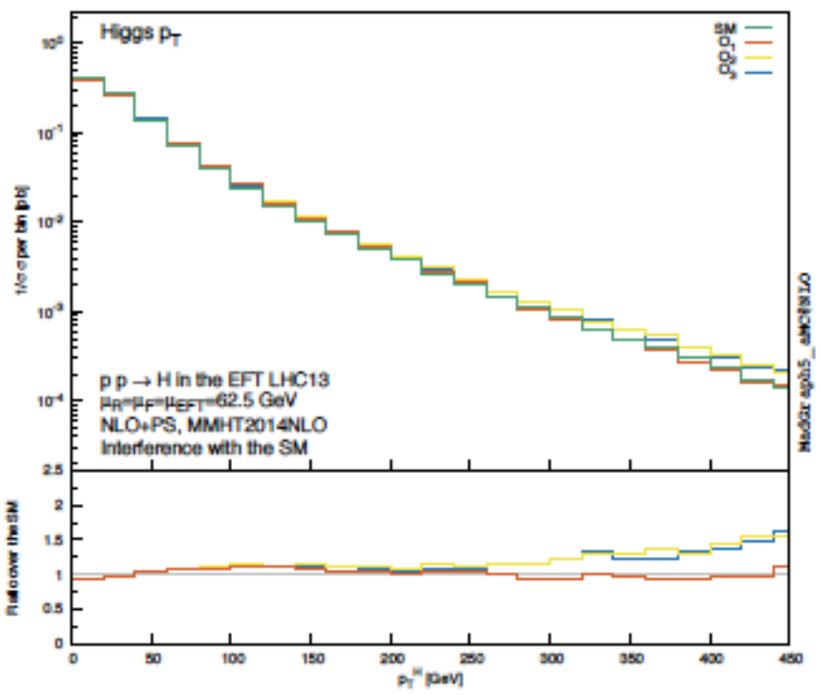
$$\begin{aligned}-0.28 < & -0.128C_1 + 114C_2 + 2.28C_3 + 0.0038C_1^2 + 3000C_2^2 \\ & +1.13C_3^2 - 6.78C_1C_2 - 0.138C_1C_3 + 122C_2C_3 < 0.48\,.\end{aligned}$$

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

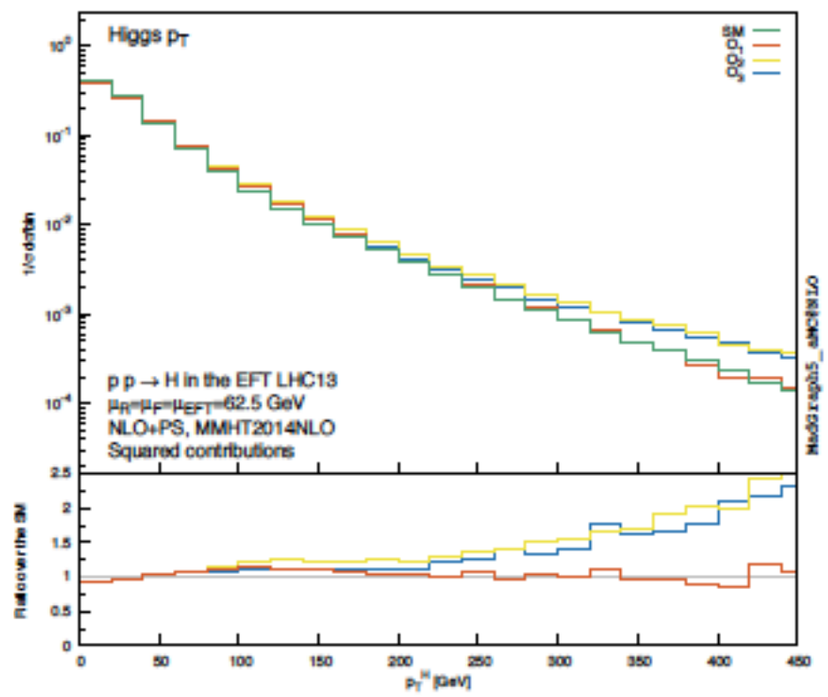
ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]

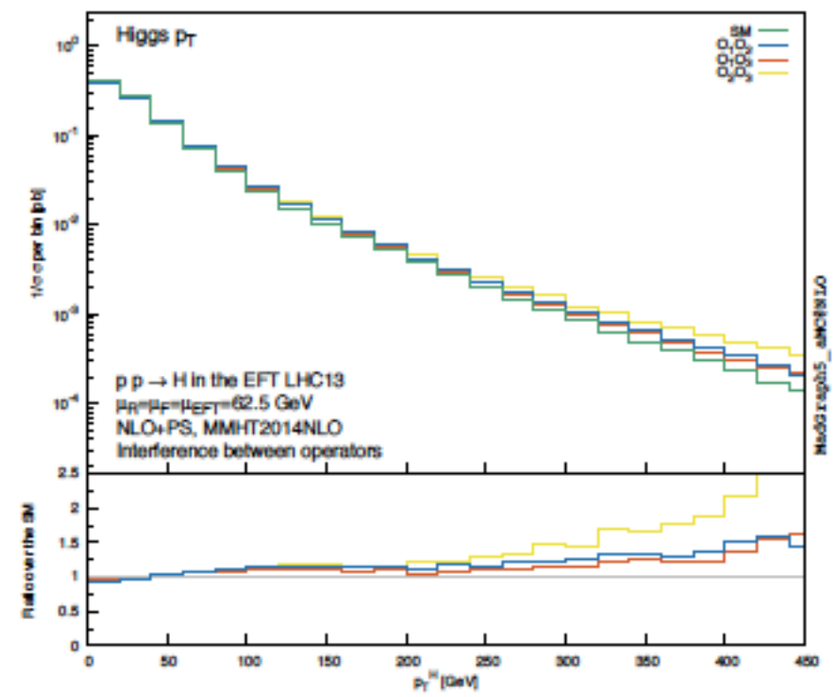
Interference w / SM



Squared (diagonal)



Squared (crossed)



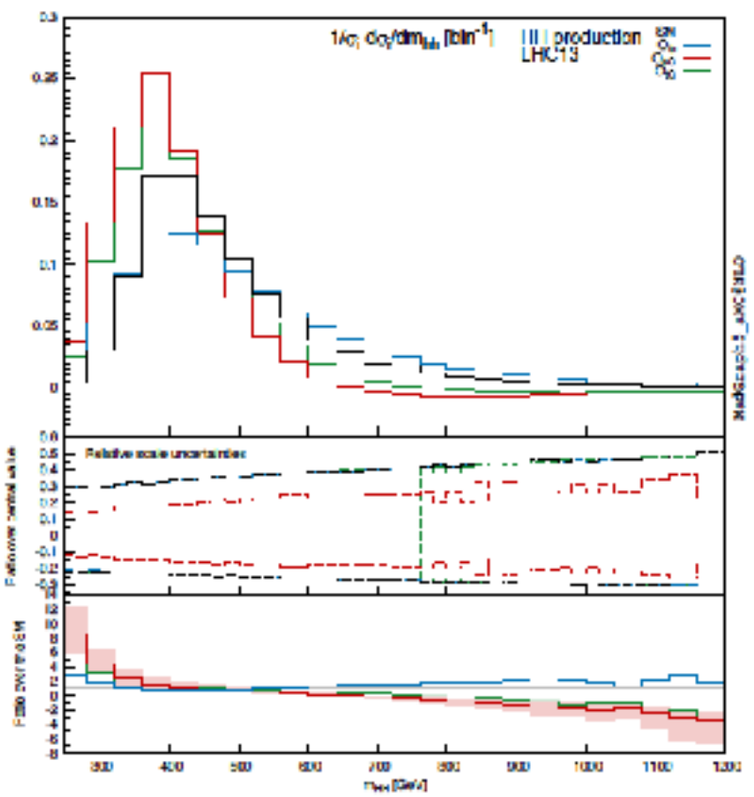
The effects of the chromo are "degenerate" with those of the $O_{\varphi G}$ operator in the interference and diagonal squared terms.

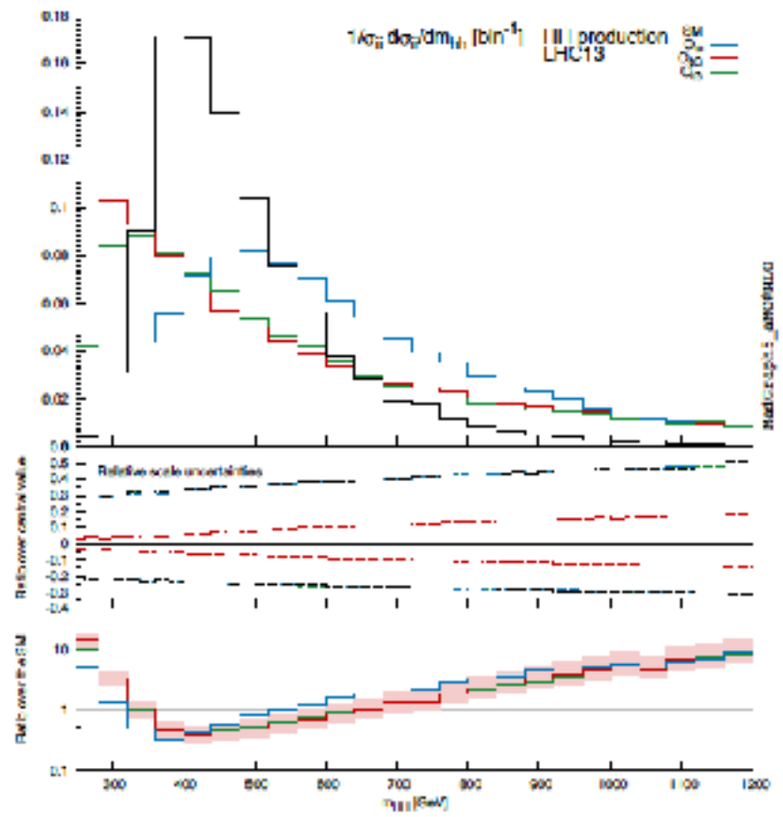
Note also the behaviour at small pT due to the bottom loop which has been only included in the SM part.

HH in the EFT

[FM, Vryonidou, Zhang, 2016]

Contribution of the chromomagnetic operator to HH computed for the first time



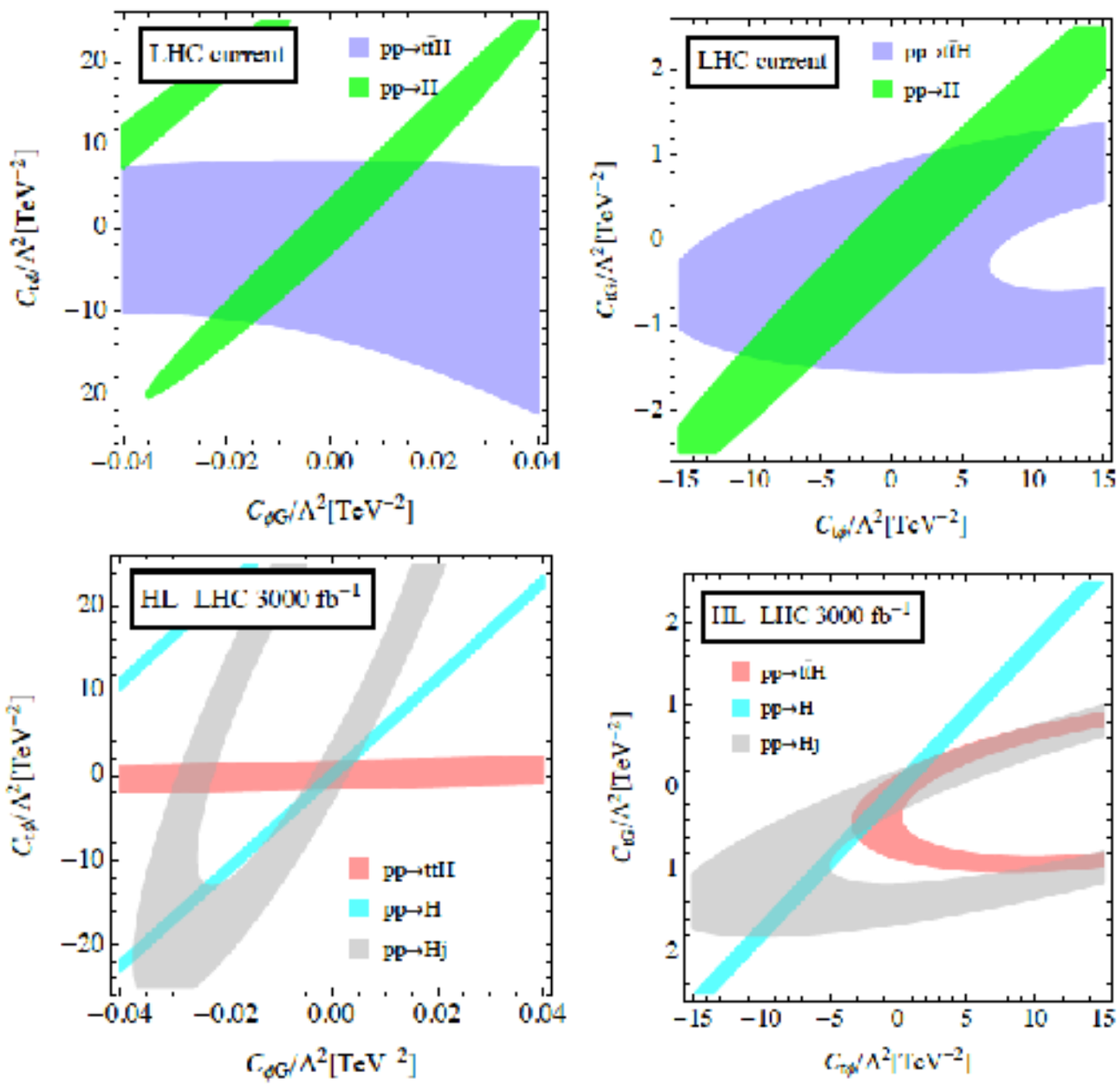


13 TeV	σ/σ_{SM} LO
σ_{SM}	$1.000^{+0.000+0.000}_{-0.000-0.000}$
$\sigma_{t\phi}$	$0.227^{+0.00114+0.0116}_{-0.000918-0.0101}$
$\sigma_{\phi G}$	$-47.3^{+6.18+3.707}_{-6.14-4.42}$
σ_{tG}	$-1.356^{+0.0271+0.161}_{-0.0225-0.051}$
$\sigma_{t\phi,t\phi}$	$0.0293^{+0.000727+0.0031}_{-0.000584-0.0026}$
$\sigma_{\phi G,\phi G}$	$2856.2^{+743.3+552}_{-628.5-425}$
$\sigma_{tG,tG}$	$1.940^{+0.0650+0.198}_{-0.0477-0.493}$
$\sigma_{t\phi,\phi G}$	$-11.83^{+1.39+1.42}_{-1.41-1.77}$
$\sigma_{t\phi,tG}$	$-0.340^{+0.000238+0.064}_{-0.000438-0.047}$
$\sigma_{\phi G,tG}$	$147.5^{+20.83+20.7}_{-18.86-31.4}$

To be investigated: the impact of the chromomagnetic operator in EFT analyses that focus on the extraction of the triple Higgs coupling λ (e.g. arXiv:1502.00539 and arXiv:1410.3471)

Constraints from ttH and Higgs production

[FM, Vryonidou, Zhang, 16]



Current limits using LHC measurements

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

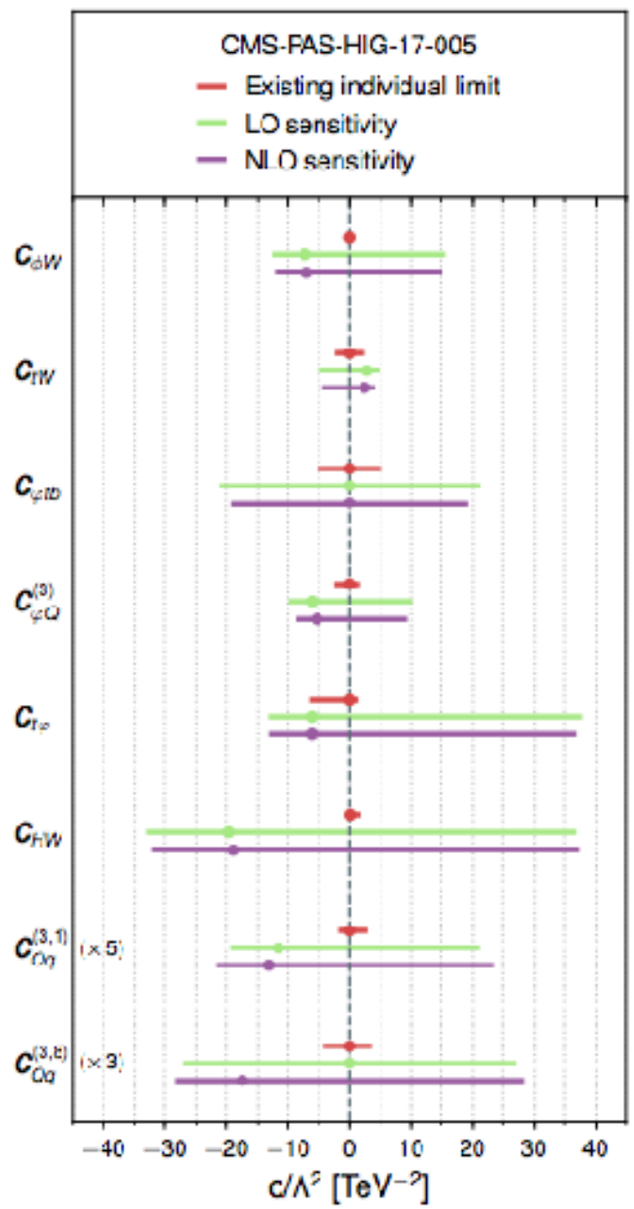
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

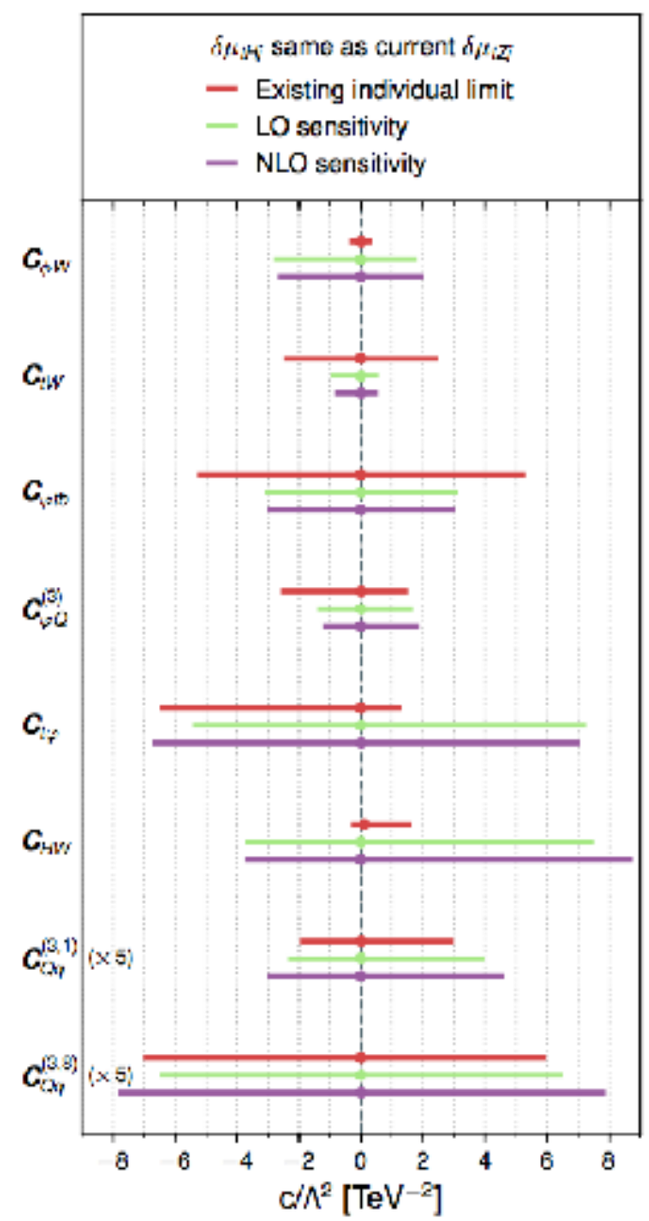
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

14TeV projection

3000 fb-1

Current/Future sensitivity in tHj





Approaches

EFT@NLO+PS

↓

Data Analysis

↓

Exp fit on C_i

Approaches