Top/Higgs/EW processes in the SMEFT at NLO in QCD

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JHEP 1608 (2016) 039, EPJC 77 (2017) 4, 262 & JHEP 1810 (2018) 005

Higgs Couplings 2018, Tokyo

29th November 2018

Introduction

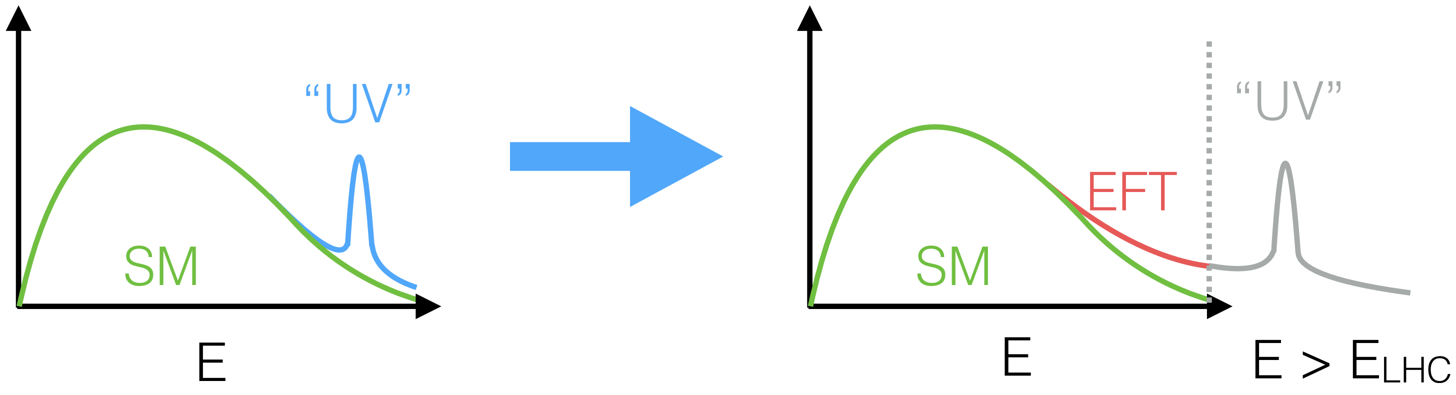
The LHC is entering a "precision era"

- No clear evidence for new physics from direct searches
- We are approaching the limits of the 'energy frontier'
- Higgs boson discovery has completed the picture of the Standard Model (SM) Electroweak (EW) sector
- Properties consistent with SM expectations (so far)
- Complementary: Standard Model Effective Field Theory

Many channels are becoming systematics dominated

- Requires high precision theory input: higher order predictions
- Fixed order & interfaced with parton shower (PS)
- NLOQCD+PS standard for SM, also useful for BSM effects

SMEFT



Parametrise new physics effects at experimental energy E

- BSM states are 'decoupled' *i.e.* live at an energy $\Lambda >> E$
- Generalised, gauge/Lorentz-invariant interactions between SM d.o.f

Operator expansion:

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

more: fields
derivatives

- Higher-derivative/contact operators: sensitive via large momentum flows through vertices (tails of energy distributions)

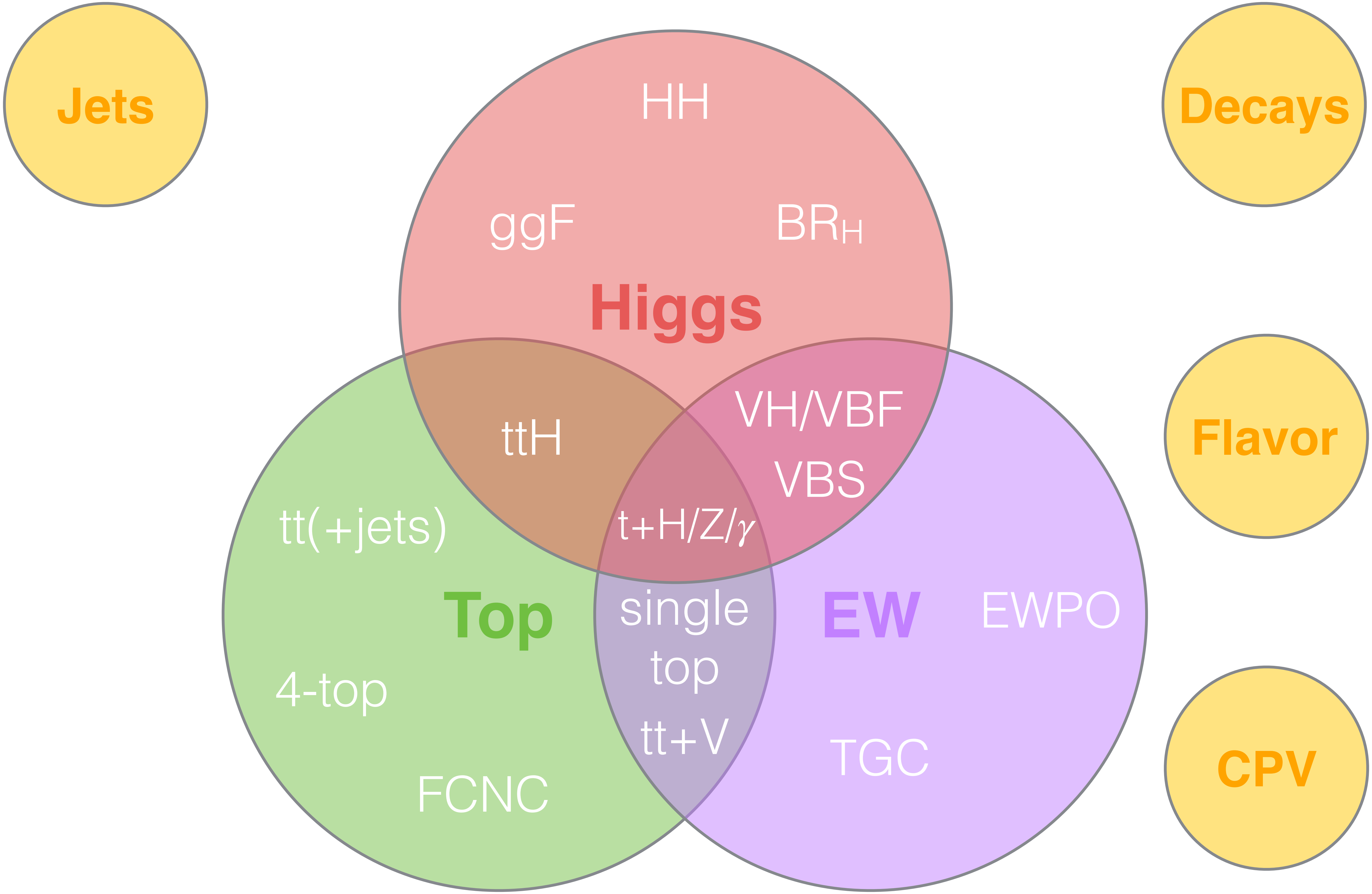
Dimension 6: 59 (76 real) - 2499 operators, depends on CP, flavor assumptions

[Buchmuller & Wyler; Nucl.Phys. B268 (1986) 621]
[Grzadkowski et al.; JHEP 1010 (2010) 085]

Order-by-order, self-consistent, renormalisable QFT

- Unlike 'Anomalous Couplings' approach
- Consistent matching to new physics models → patterns/correlations

SMEFT at the LHC: testing the EWSB sector



Status: LO

Increasing number of EFT interpretations in experimental analyses

Several MC implementations of SMEFT at LO

- HEL, SMEFTsim, dim6top,…
- Higgs Characterisation, BSMC, HiggsPO,…

[Alloul et al.; JHEP 1404 (2014) 110]
[Brivio et al.; JHEP 1712 (2017) 070]
[Aguilar Saavedra et al.; arXiv:1802.07237]
[Artoisenet et al.; JHEP 1311 (2013) 043]
[Falkowski et al.; EPJC 75 (2015) 12, 583]
[Greljo et al,; EPJC 77 (2017) 12, 838]

Many phenomenological analyses and global fits performed for SMEFT at LHC+…

- Separate Higgs/Gauge and top sector
- LO accuracy

[Falkowksi & Riva; JHEP 1502 (2015) 039]
[Berthier & Trott; JHEP 1505 (2015) 024]
[Corbett et al.; JHEP 1508 (2015) 156]
[Buckley et al.; JHEP 1604 (2016) 015]
[Englert et al.; EPJC 76 (2016) 7, 393]
[Butter et al.; JHEP 1607 (2016) 152]
[Ellis et al.; arXiv:JHEP 1806 (2018) 146]

Going NLO

Ultimate goal: a precision global fit of full SMEFT including LHC observables at HL-LHC

NLO QCD(+PS) predictions

- K-factors/shapes & control over PDF + scale uncertainties

NLO EW corrections

- Potentially important but much harder
- Automation on the way with SHERPA, Madgraph5_aMC@NLO

RG-improved predictions & operator mixing

- Very helpful for cross checking NLO implementations
- Compare to full NLO calculations, assess the importance of finite terms

[Alonso, Jenkins, Manohar & Trott; JHEP 1310 (2013) 087, JHEP 1401 (2014) 035 & JHEP 1404 (2014) 159*]*

[Degrande, Durieux, Maltoni, KM, Vryonidou, Zhang; in preparation]

SMEFT@NLO in QCD

Motivation

- Bring SMEFT predictions to the required precision level for the LHC lifetime
- Include operators describing EWSB (top/Higgs/EW) sector interactions

Today's results: part of ongoing efforts in developing MC tool for SMEFT in top/Higgs/EW sector

- General FeynRules/NLOCT UFO implementation of 'Warsaw' basis

[Alloul et al.; Comp. Phys. Comm. 185 (2014) 2250] & [Degrande; Comp. Phys. Comm. 197 (2015) 239]

- NLOQCD + PS events in general purpose MC generators
- Generate any process including SMEFT

Model validated against existing implementations

- EW Higgs production, single-top, ttH, ttZ/γ

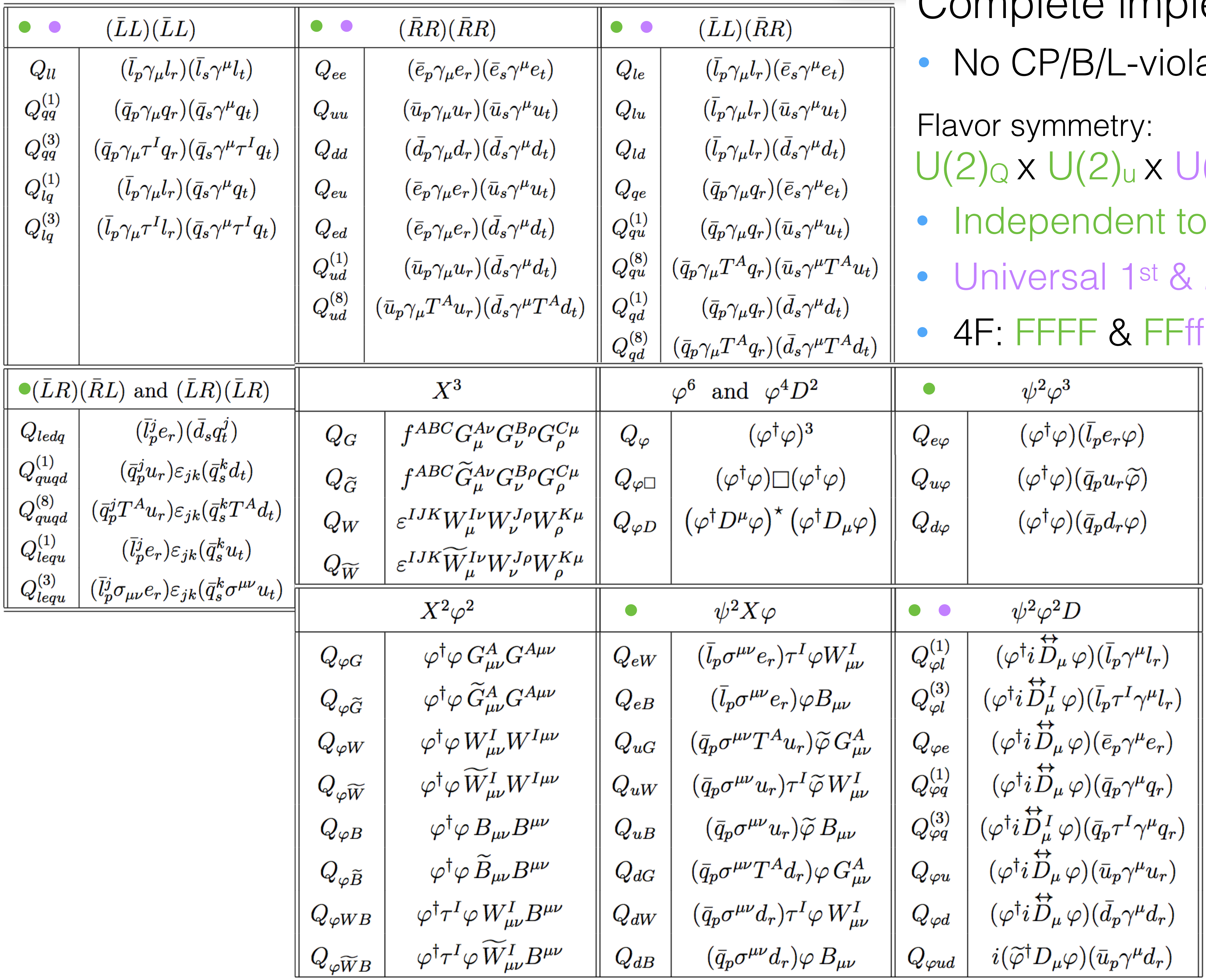
[Degrande et al; EPJC 77 (2017) 4, 262]
[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]
[Bylund et al.; JHEP 1605 (2016) 052]

[Zhang; PRL 116 (2016) 162002]
[Degrande et al.; PRD 91 (2015) 034024]
[Durieux, Maltoni & Zhang; PRD 91 (2015) 074017]

Operators

‘Warsaw’ basis

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



	● ● $(\bar{L}L)(\bar{L}L)$		● ● $(\bar{R}R)(\bar{R}R)$		● ● $(\bar{L}L)(\bar{R}R)$
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

	●$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

	X^3		φ^6 and $\varphi^4 D^2$		● $\psi^2\varphi^3$
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

	$X^2\varphi^2$		● $\psi^2 X\varphi$		● ● $\psi^2\varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Complete implementation

- No CP/B/L-violation

Flavor symmetry:

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

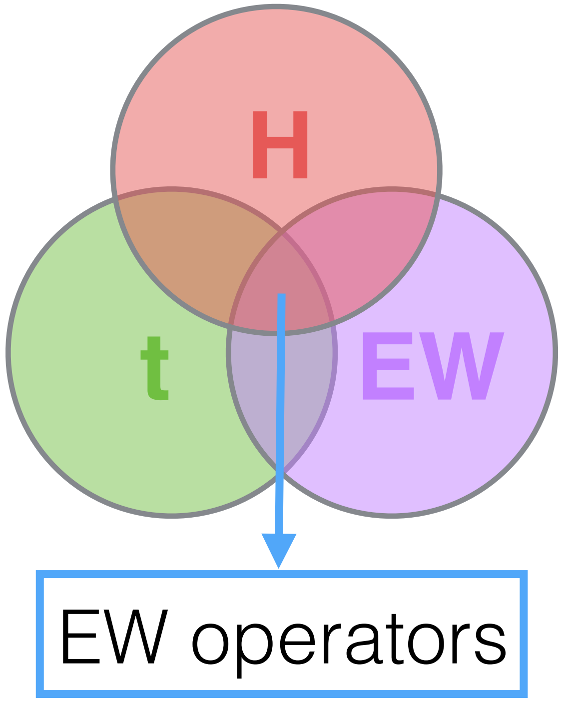
- Independent top operators
- Universal 1st & 2nd generations
- 4F: FFFF & FFff (ffff omitted)

+ bosonic ops.

≈ 75 parameters

Case study: tZj/tHj

[Degrande, Maltoni, KM, Vryonidou, Zhang; JHEP 1810 (2018) 005]



EW top interactions: single top production

- No QCD contribution
- Single top rate at 13 TeV LHC ~ 200 pb (1/4 of QCD tt)
- Sensitive to 2 four-fermion and 3 top/EW operators that modify tbW vertex
- Limited energy dependence

Require the presence of an additional Z or Higgs

- Unique possibility of probing large set of top/Higgs/EW operators at once
- New energy growth from unitarity violating/EFT effects
- Higher thresholds may enhance EFT effects

Recent LHC measurement of tZj cross section at 4.2σ

[ATLAS; PLB 780 (2018) 557-577], [CMS-PAS-TOP-16-020 & PLB 779 (2018) 358-384]

- Timely moment to perform EFT sensitivity study in this pair of challenging processes & showcase model implementation

Operators

tHj

tZj

both

NLO

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

Constrained by electroweak precision tests (LEP)

Two blind directions in Warsaw basis:

$$\mathcal{O}_{HW} = (D^\mu\varphi)^\dagger \tau_I (D^\nu\varphi) W^I_{\mu\nu}$$

$$\mathcal{O}_{HB} = (D^\mu\varphi)^\dagger (D^\nu\varphi) B_{\mu\nu}.$$

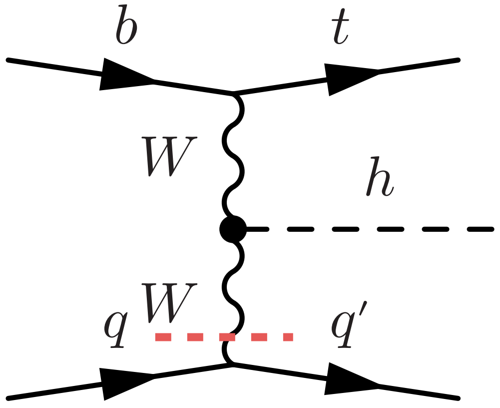
RGE

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

Consider these two instead to assess orthogonal sensitivity of tZj/tHj

SMEFT in tHj/tZj

tHj (tZj = h→Z)

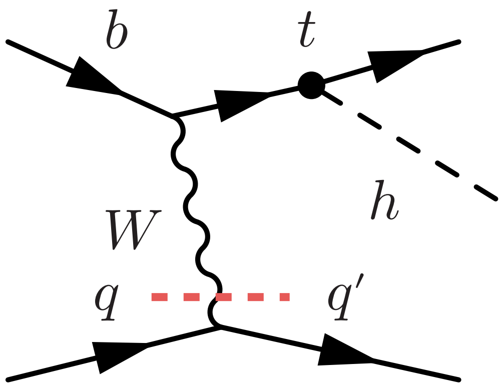


$\mathcal{O}_{\varphi W} : \varphi^{\dagger}\varphi\, W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

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

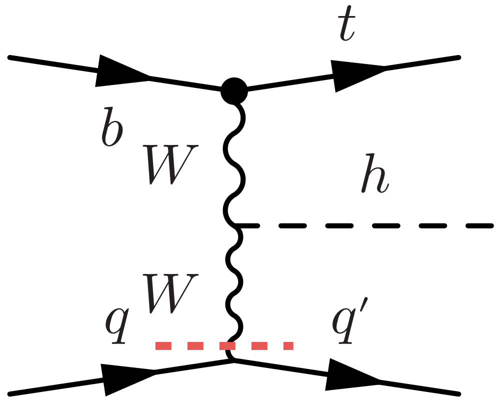


$\mathcal{O}_{t\varphi} \;:\; (\varphi^{\dagger}\varphi)\,(\bar{Q}\,t)\,\tilde{\varphi}$

top Yukawa

ttZ coupling

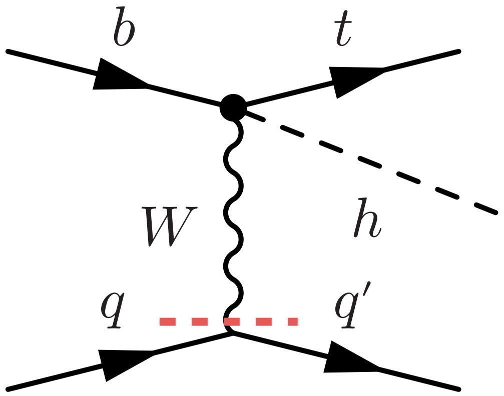
$\mathcal{O}_{\varphi t} : i(\varphi^{\dagger} \overleftrightarrow{D}_{\mu} \varphi)(\bar{t}\gamma^{\mu} t)$



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

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

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

Access the bW→tH & bW→tZ sub-amplitudes

- Rich interplay between EFT operators from different sectors
- Different energy growth and interference with the SM
- Potentially bring new information at high p_T

Λ= 1 TeV everywhere

Results

- Fixed order using Madgraph5_aMC@NLO
  - NNPDF3.0 LO/NLO PDF sets
  - 5-flavor scheme

$$m_t = 172.5 \text{ GeV}\,, \quad m_H = 125 \text{ GeV}\,, \quad m_Z = 91.1876 \text{ GeV}\,,$$
$$\alpha_{EW}^{-1} = 127.9\,, \quad G_F = 1.16637 \times 10^{-5} \text{ GeV}^{-2}\,.$$

- Scale choice
  - t H j: $\mu_0=(m_H+m_t)/4$
  - t Z j: $\mu_0=(m_Z+m_t)/4$

[Demartin, Maltoni & Mawatari; EPJC 75 (2015) 267]

- Uncertainties:

$$\sigma^{+\delta\mu_0\,[\delta\mu_{EFT}]}_{-\delta\mu_0\,[\delta\mu_{EFT}]} \pm \delta_{PDF}$$

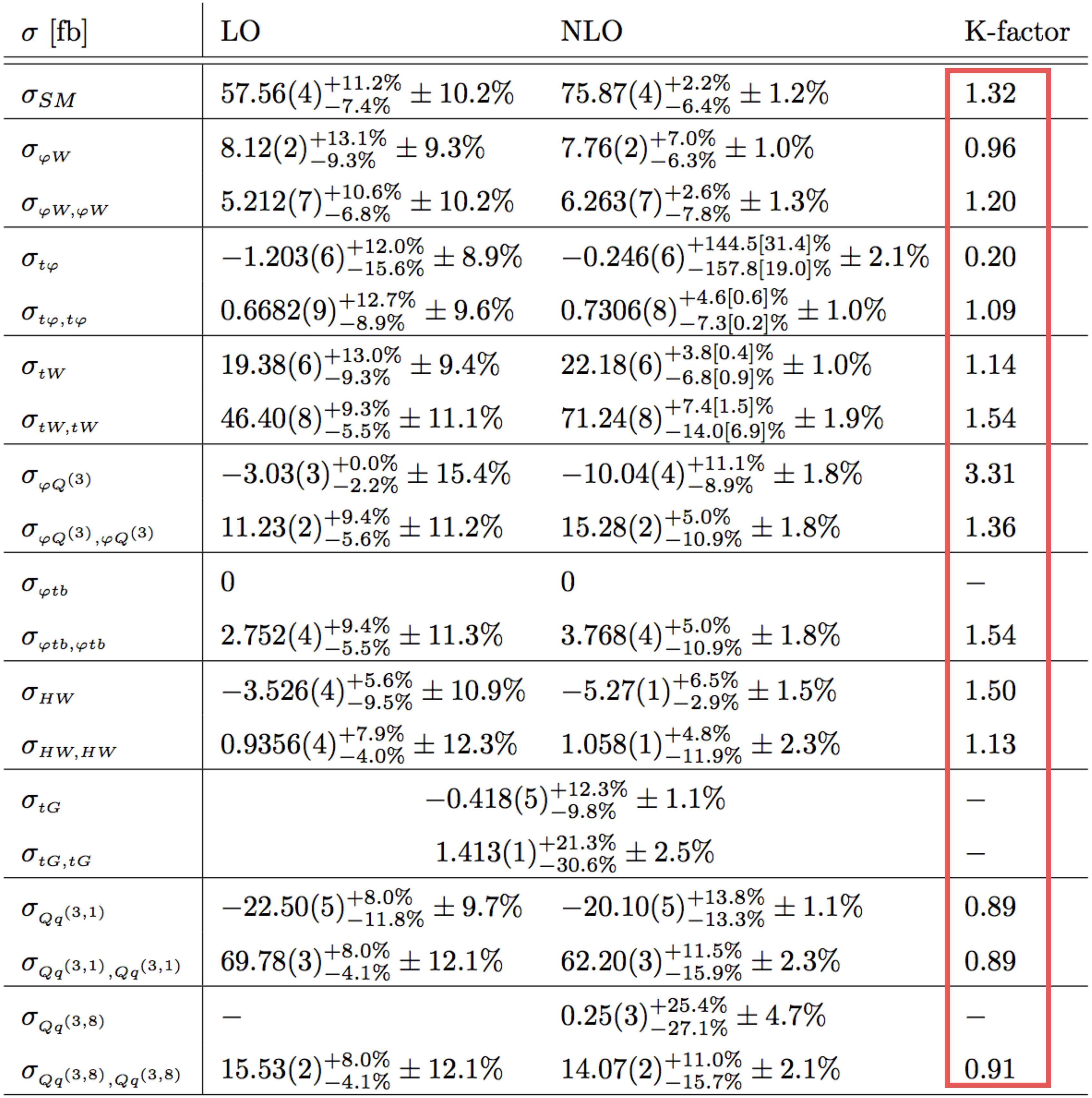
  - 9 point variation of factorisation and renormalisation scale ($\mu_0/2$, μ_0 , $2\mu_0$)
  - PDF uncertainties
  - EFT scale variation from QCD running of operators (where relevant)

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

Inclusive results: tHj

$pp \to t(\bar{t})\,H\,j$ LHC@13 TeV

c/Λ = 1 [TeV^{-2}]



σ [fb]	LO	NLO	K-factor
σ_{SM}	$57.56(4)^{+11.2\%}_{-7.4\%} \pm 10.2\%$	$75.87(4)^{+2.2\%}_{-6.4\%} \pm 1.2\%$	1.32
$\sigma_{\varphi W}$	$8.12(2)^{+13.1\%}_{-9.3\%} \pm 9.3\%$	$7.76(2)^{+7.0\%}_{-6.3\%} \pm 1.0\%$	0.96
$\sigma_{\varphi W,\varphi W}$	$5.212(7)^{+10.6\%}_{-6.8\%} \pm 10.2\%$	$6.263(7)^{+2.6\%}_{-7.8\%} \pm 1.3\%$	1.20
$\sigma_{t\varphi}$	$-1.203(6)^{+12.0\%}_{-15.6\%} \pm 8.9\%$	$-0.246(6)^{+144.5[31.4]\%}_{-157.8[19.0]\%} \pm 2.1\%$	0.20
$\sigma_{t\varphi,t\varphi}$	$0.6682(9)^{+12.7\%}_{-8.9\%} \pm 9.6\%$	$0.7306(8)^{+4.6[0.6]\%}_{-7.3[0.2]\%} \pm 1.0\%$	1.09
σ_{tW}	$19.38(6)^{+13.0\%}_{-9.3\%} \pm 9.4\%$	$22.18(6)^{+3.8[0.4]\%}_{-6.8[0.9]\%} \pm 1.0\%$	1.14
$\sigma_{tW,tW}$	$46.40(8)^{+9.3\%}_{-5.5\%} \pm 11.1\%$	$71.24(8)^{+7.4[1.5]\%}_{-14.0[6.9]\%} \pm 1.9\%$	1.54
$\sigma_{\varphi Q^{(3)}}$	$-3.03(3)^{+0.0\%}_{-2.2\%} \pm 15.4\%$	$-10.04(4)^{+11.1\%}_{-8.9\%} \pm 1.8\%$	3.31
$\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$	$11.23(2)^{+9.4\%}_{-5.6\%} \pm 11.2\%$	$15.28(2)^{+5.0\%}_{-10.9\%} \pm 1.8\%$	1.36
$\sigma_{\varphi tb}$	0	0	–
$\sigma_{\varphi tb,\varphi tb}$	$2.752(4)^{+9.4\%}_{-5.5\%} \pm 11.3\%$	$3.768(4)^{+5.0\%}_{-10.9\%} \pm 1.8\%$	1.54
σ_{HW}	$-3.526(4)^{+5.6\%}_{-9.5\%} \pm 10.9\%$	$-5.27(1)^{+6.5\%}_{-2.9\%} \pm 1.5\%$	1.50
$\sigma_{HW,HW}$	$0.9356(4)^{+7.9\%}_{-4.0\%} \pm 12.3\%$	$1.058(1)^{+4.8\%}_{-11.9\%} \pm 2.3\%$	1.13
σ_{tG}	$-0.418(5)^{+12.3\%}_{-9.8\%} \pm 1.1\%$		–
$\sigma_{tG,tG}$	$1.413(1)^{+21.3\%}_{-30.6\%} \pm 2.5\%$		–
$\sigma_{Qq^{(3,1)}}$	$-22.50(5)^{+8.0\%}_{-11.8\%} \pm 9.7\%$	$-20.10(5)^{+13.8\%}_{-13.3\%} \pm 1.1\%$	0.89
$\sigma_{Qq^{(3,1)},Qq^{(3,1)}}$	$69.78(3)^{+8.0\%}_{-4.1\%} \pm 12.1\%$	$62.20(3)^{+11.5\%}_{-15.9\%} \pm 2.3\%$	0.89
$\sigma_{Qq^{(3,8)}}$	–	$0.25(3)^{+25.4\%}_{-27.1\%} \pm 4.7\%$	–
$\sigma_{Qq^{(3,8)},Qq^{(3,8)}}$	$15.53(2)^{+8.0\%}_{-4.1\%} \pm 12.1\%$	$14.07(2)^{+11.0\%}_{-15.7\%} \pm 2.1\%$	0.91

K-factors not universal

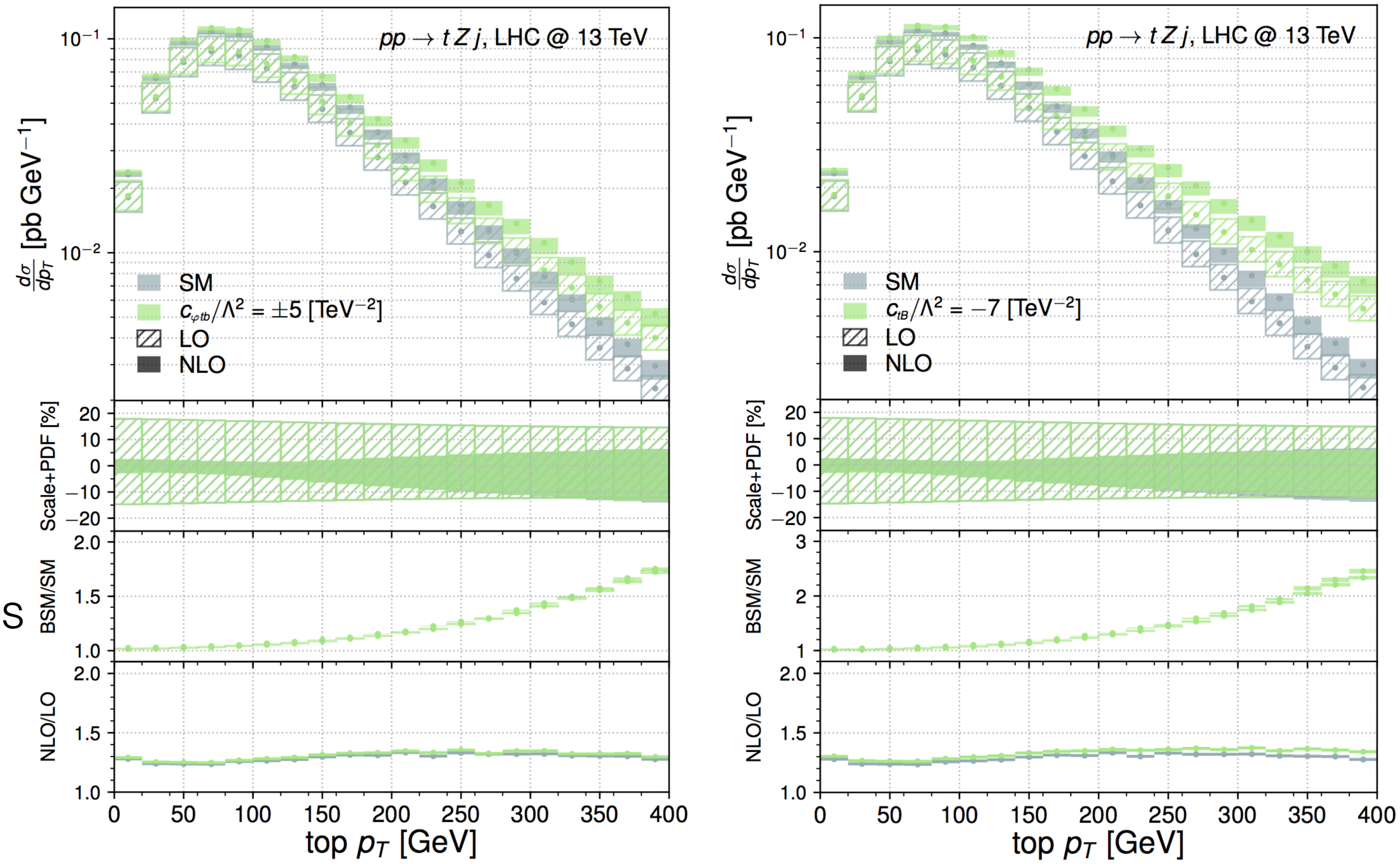
Reduction of QCD scale/PDF uncertainties

EFT scale uncertainty subdominant

Some very strong dependence on EFT operators

O(>1) deviations within current bounds

Differential results in tZj



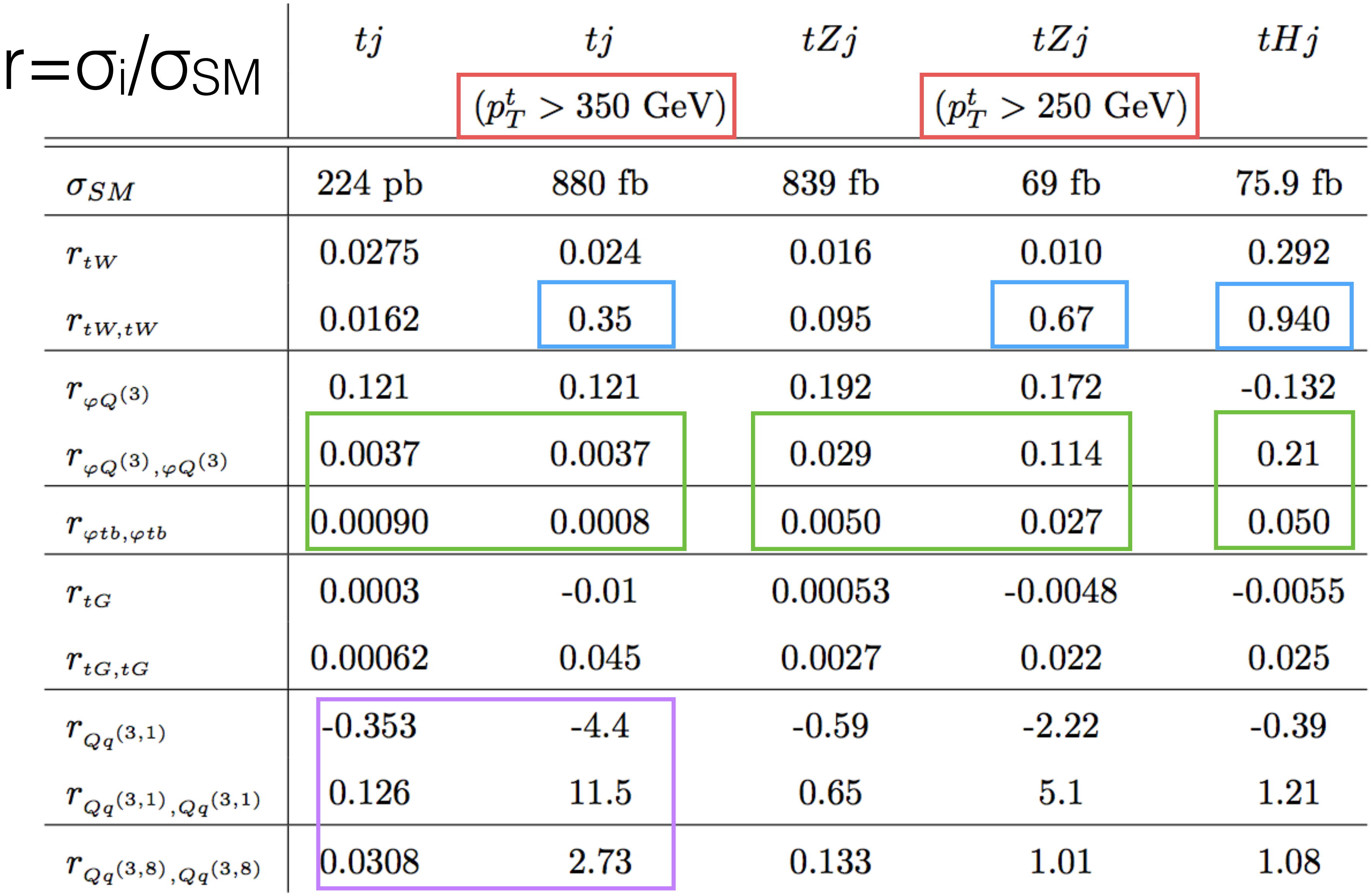
Reduced uncert.

Large effects

Potentially large deviations in the tails (saturating current limits)
tHj process is very rare, differential results not likely at LHC

LHC sensitivity

Usual EFT story: looking at high energy tails increases sensitivity
Compare to single top which has a much larger rate



$r=\sigma_i/\sigma_{SM}$	tj	tj $(p_T^t > 350\text{ GeV})$	tZj	tZj $(p_T^t > 250\text{ GeV})$	tHj
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 weak dipoles

Consistent with 2→2 subamplitude analysis

New energy growths w.r.t single top

Single top should eventually outperform tHj/tZj for four fermion operators

Current sensitivity

Gauge sensitivity of these processes at LHC

Recent measurements of tZj at CMS & ATLAS

[CMS; PLB 779 (2018) 358-384]
[ATLAS; CERN-EP-2017-188]

- Signal strengths 0.75 ± 0.27 & 1.31 ± 0.47
- Cast into naive 'confidence intervals'
- Ignore acceptance effects & contribution of operators to bkg processes
- Which include tW, ttV, ttH, tWZ, tHW

CMS analysis of tHj + tHW + ttH

[CMS-PAS-HIG-17-005]

- Combined signal strength 1.8 ± 0.67
- Take into account only modifications to tHj
- Except top Yukawa operator contribution to ttH

σ [fb]	LO	NLO
$t\,H\,j$	57.5	75.9
$t\,\bar{t}\,H$	464	507
$t\,H\,W$	14.5	15.9

Current sensitivity

tZj

TGC

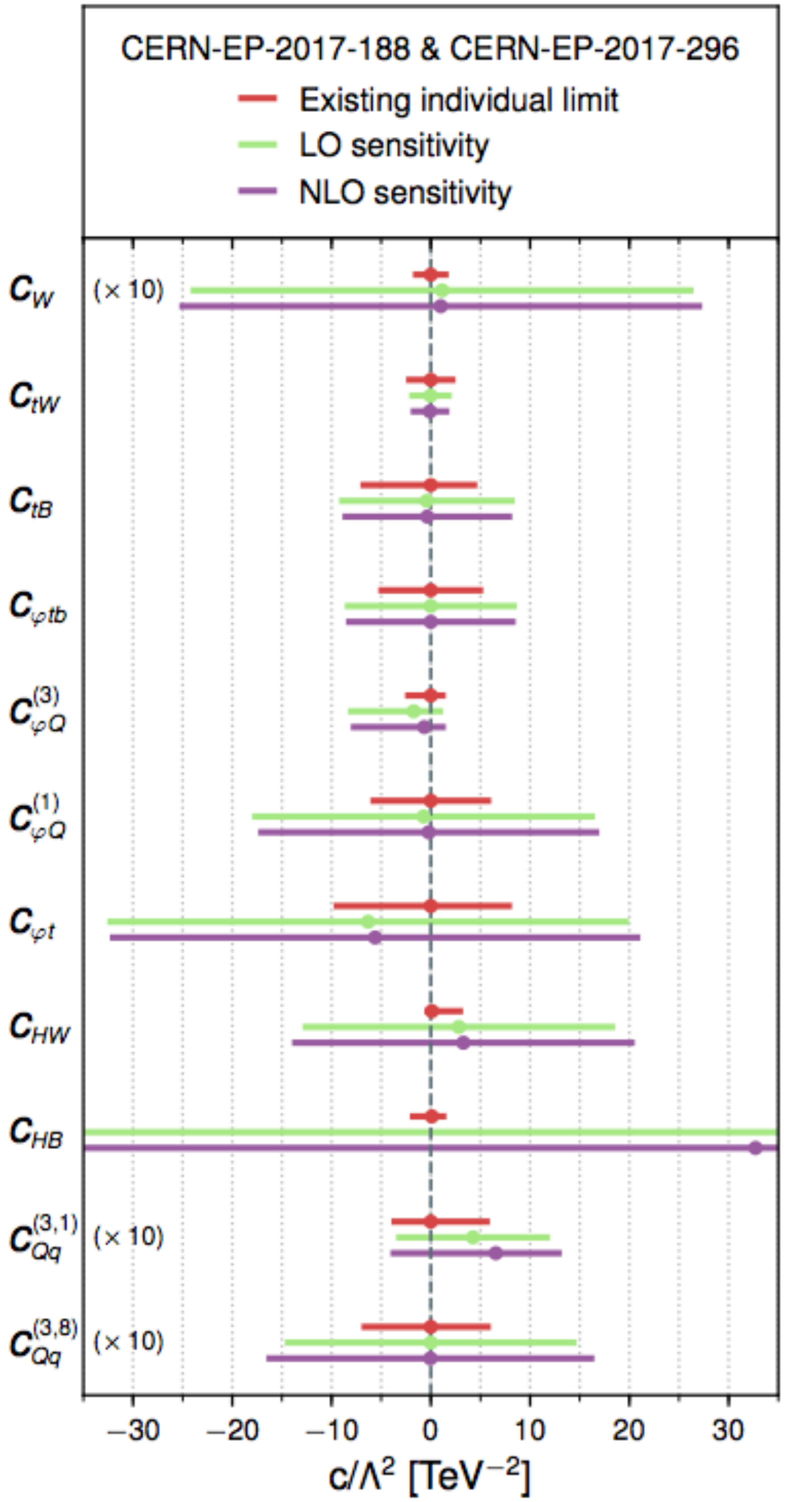
Dipoles

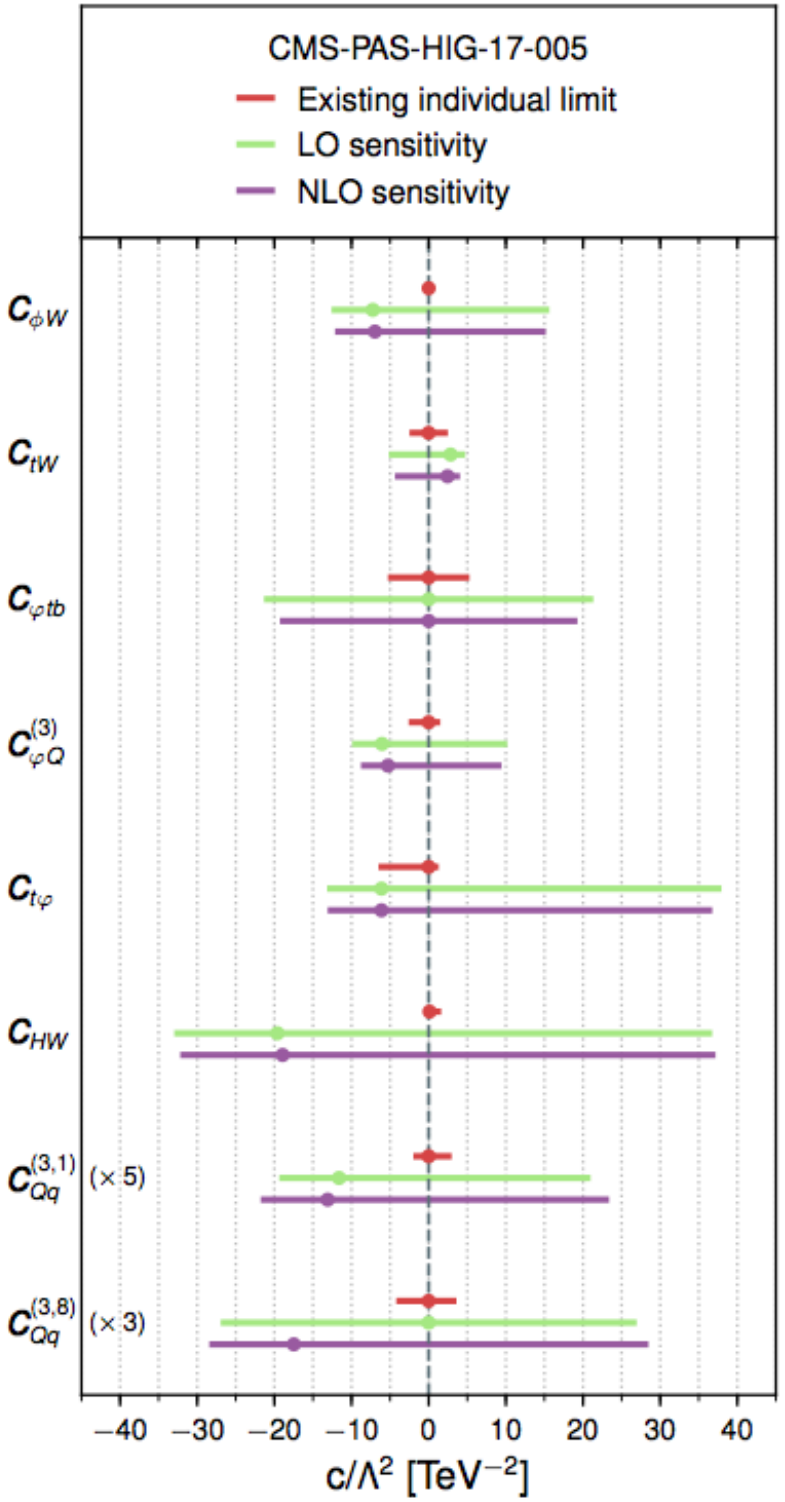
RHCC

Currents

LEP
orthogonal

4-fermion





tHj

Gauge-Higgs

Dipole

RHCC

Currents

LEP
orthogonal

4-fermion

Future sensitivity

tZj: take high top p_T region > 250 GeV

- 10x smaller cross section → end of Run II or HL-LHC

tHj: assume it is measured with the current tZj precision

- tHj inclusive cross section is similar to the high p_T tZj cross section
- target for HL-LHC

Start to improve on existing limits for certain operators

- Dipoles, RHCC, (top Yukawa)

NLO predictions increase sensitivity

- Bring theory uncertainties down below experimental stat. and syst.

Future sensitivity

tZj

TGC

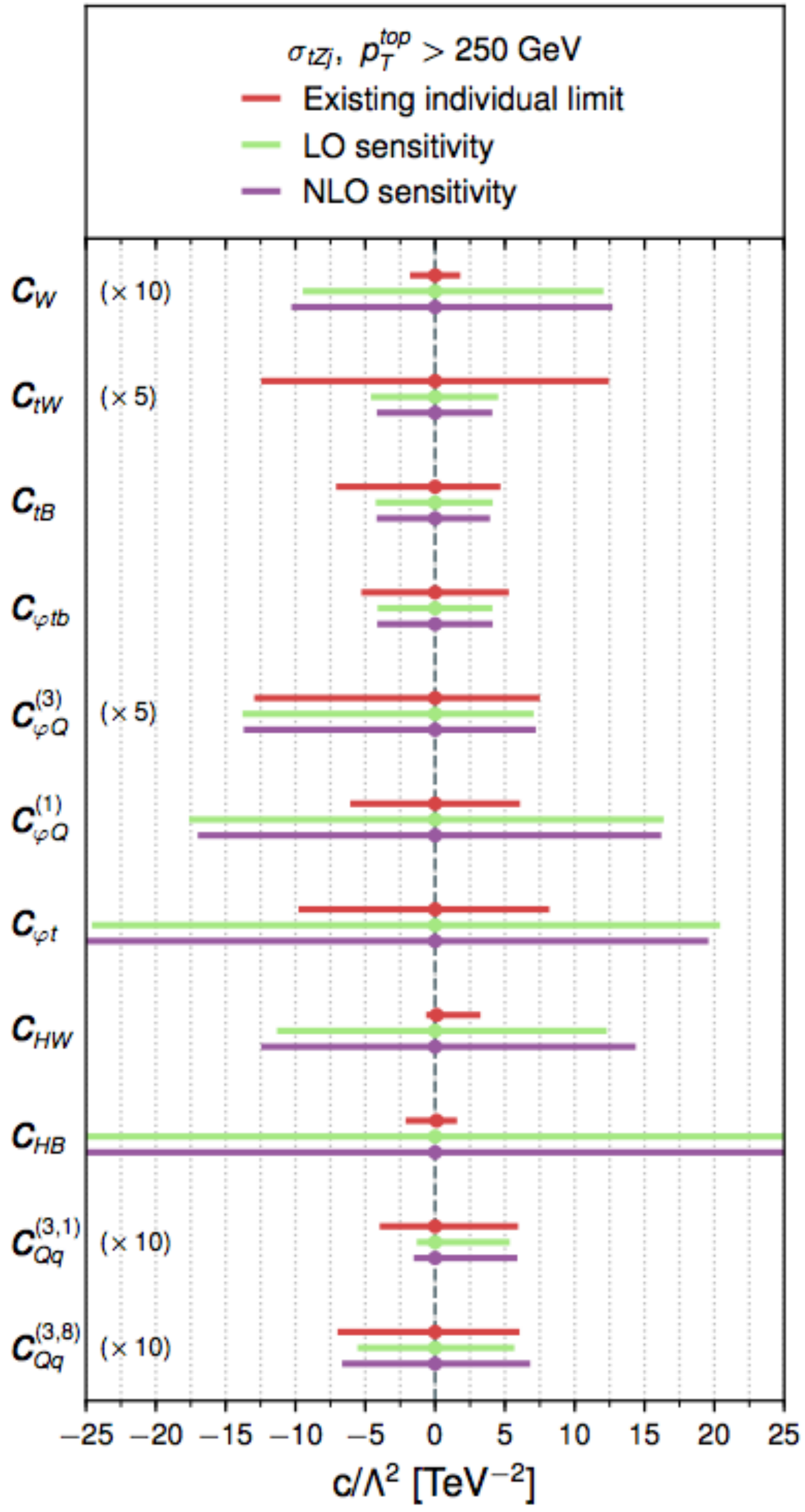
Dipoles

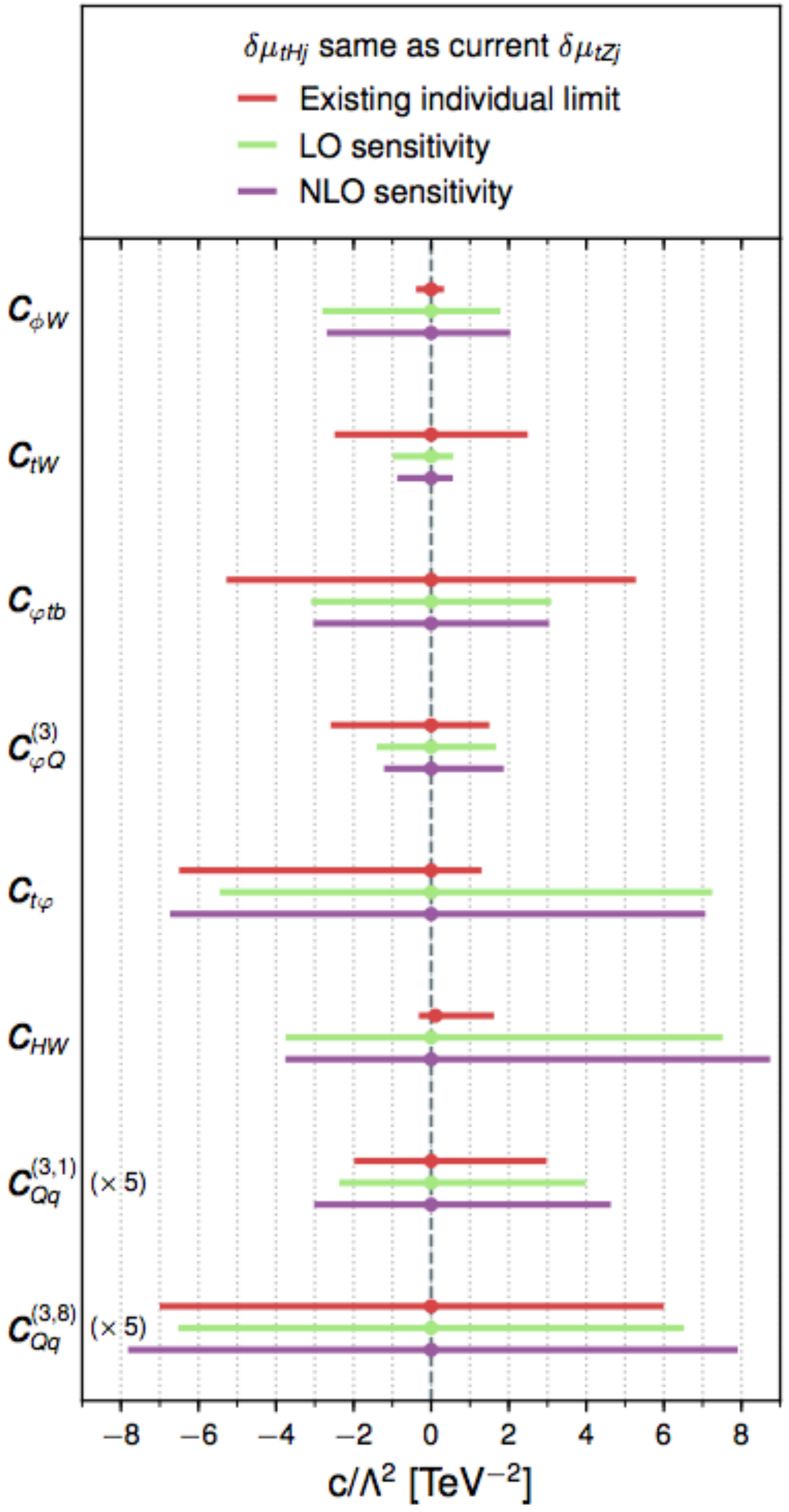
RHCC

Currents

LEP
orthogonal

4-fermion





tHj

Gauge-Higgs

Dipole

RHCC

Currents

LEP
orthogonal

4-fermion

Conclusion

Presented a FeynRules/NLOCT UFO implementation of top/EW/Higgs sector in SMEFT

- $U(3)^3$ x $U(2)^2$ flavor symmetry to select top quark operators
- Allows for NLOQCD+PS predictions for any relevant process in, *e.g.*, MG5

Fixed order NLO predictions for tZj & tHj in SMEFT at LHC

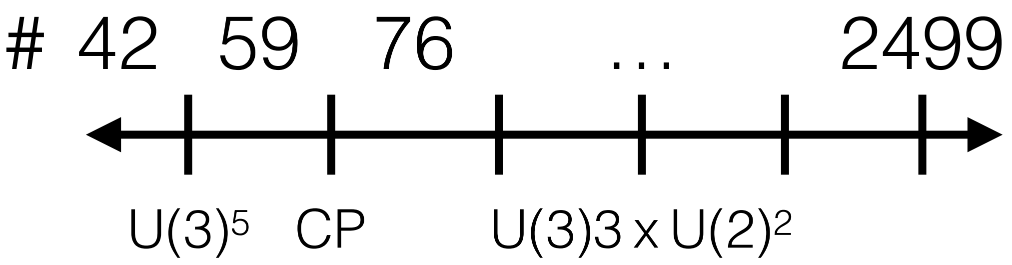
- Challenging process that showcases implementation
- Related to mass generation/unitarity cancellations in SM
- Complete predictions for large operator set → can be used in fits

Current & future LHC sensitivity study

- New energy growth with respect to single top for SU(2) current and RHCC
- Interesting future sensitivity at high energy to dipoles, 4F ops.

Thank you

Flavor symmetry


42 59 76 … 2499

$U(3)^5$ CP $U(3)3 \times U(2)^2$

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

SM fermion sector: $q^i,\, u^i,\, d^i,\, l^i,\, e^i$

- 5 SU(3) x SU(2) x U(1) representations → $U(3)^5$ flavor symmetry
- Only broken by Yukawa interactions

Some SMEFT operators also break it

- Chirality flipping $F_L f_R$ structures (Yukawa-like)
- Flavor-violating (off diagonal/non-universal) entries

Staring point: flavor symmetric

- No chirality flipping & diagonal, universal structure

Controlled departures

- Minimal for top physics: U(3)3 x U(2)2, single out q_3, u_3
- Similar to MFV: expansion in Yukawa couplings with only y_t non-zero

[D'Ambrosio et al.; Nucl. Phys. B645 (2002) 155]

[Mantani, Maltoni, KM; in preparation] [Dror et al.; JHEP 01 (2016) 071]

Anatomy of tHj

bW → tH Helicity amplitudes: s ~ -t ≫ v^2

$\mathcal{O}_{\varphi tb}$, $\lambda_b = +$

λ_t \ λ_W	0	$+$	$-$
$+$	$\boxed{\sqrt{s(s+t)}}$	$m_W\sqrt{-t}$	$\frac{1}{\sqrt{s}}$
$-$	$m_t\sqrt{-t}$	s^0	s^0

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{HW}$
$-,0,-$	$\boxed{s^0}$	s^0	$\boxed{\sqrt{s(s+t)}}$	s^0	s^0	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W s}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$\frac{m_W s}{\sqrt{-t}}$	$m_t\sqrt{-t}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,-,+$	$\frac{1}{s}$	s^0	s^0	$-$	$\boxed{\sqrt{s(s+t)}}$	$\frac{1}{s}$
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,+,+$	s^0	$-$	s^0	s^0	s^0	$\frac{1}{s}$

Consistent with non-interference theorem in 2 → 2

[Cheung & Shen; PRL 115 (2015) 071601]
[Azatov, Contino & Riva; PRD 95 (2017) 065014]

Maximum energy growth: E^2

- SU(2) current in (-,0,-) configuration → Interference growth!
- RH Charged Current (bR), Weak dipole (transverse) → no interference growth
- Subleading growth ∝ m_t E, SM decreases with energy → no intereference growth

FeynRules/NLOCT/UFO

FeynRules

[Christensen & Duhr; Comp. Phys. Comm. 180 (2009) 1614]
[Alloul et al.; Comp. Phys. Comm. 185 (2014) 2250]

- Framework: Lagrangian → Feynman rules → UFO model → MC events

Universal FeynRules Output (UFO)

[Degrande et al.; Comp. Phys. Comm. 183 (2012) 1201]

- Model file with particle content, internal/external parameters, Feynman rules, Lorentz structures, counter-terms,…
- Compatible with many MC event generators (MG5, Sherpa, Whizard,…)

NLOCT

[Degrande; Comp. Phys. Comm. 197 (2015) 239]
[Hahn; Comp. Phys. Comm. 140 (2001) 415]

- Automatic calculation of UV and R_2 counter-terms from FeynRules model
- Implemented as additional Feynman rules in the UFO format
- UV: on-shell renormalisation procedure for masses/wavefunction, MSbar for higher point functions
- R_2: numerical artefacts of dimensional regularisation

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

ttH in SMEFT

$$\mathcal{O}_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}_L\,\tilde{\varphi}\,t_R)$$
$$\mathcal{O}_{\varphi G} = (\varphi^\dagger\varphi)\,G^A_{\mu\nu}G^{\mu\nu}_A$$
$$\mathcal{O}_{tG} = (\bar{Q}_L\sigma_{\mu\nu}\,T^A\;t_R)\,\tilde{\varphi}\,G^{\mu\nu}_A$$

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

$$(O_{t\phi}, O_{\phi G}, O_{tG})$$
$$\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

Operators involving the top/Higgs/gluon

- ttH is the only direct probe of the Top-Higgs interaction
- gg→H & tt production partly constrain the Wilson coefficient space
- 3-gluon O_G and 4 fermion operators also contribute but are better constrained by tt and multi-jet measurements

Different K-factors among SM/dim-6 operators

Large Λ^{-4} effects in both shape & normalisation

- Scenarios where “EFT-squared” terms are large but energy is below cutoff

$$\frac{E^2}{\Lambda^2} < 1 < c_i^{(6)}\frac{E^2}{\Lambda^2} < c_i^{(6)}c_j^{(6)}\frac{E^4}{\Lambda^4}$$

EFT scale dependence

Set of running/mixing EFT couplings

- Additional source of theoretical uncertainty
- Like with α_S, can be estimated by scale variation

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

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

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

$\mu_0 \rightarrow \mu$

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

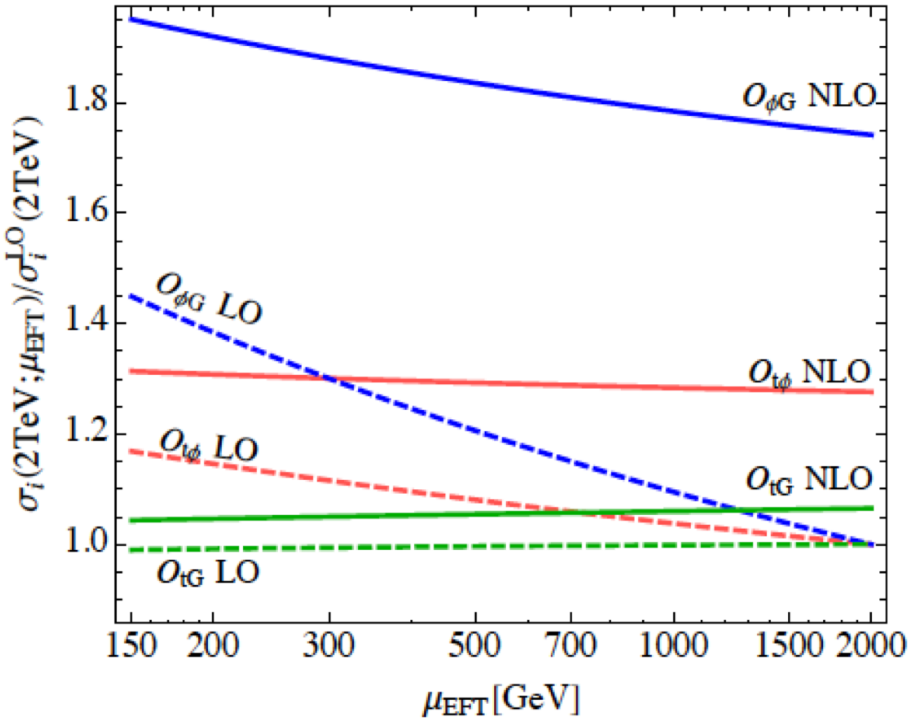
$$\sigma_i(\mu_0;\mu) = \Gamma_{ji}(\mu,\mu_0)\sigma_j(\mu)\ ,$$

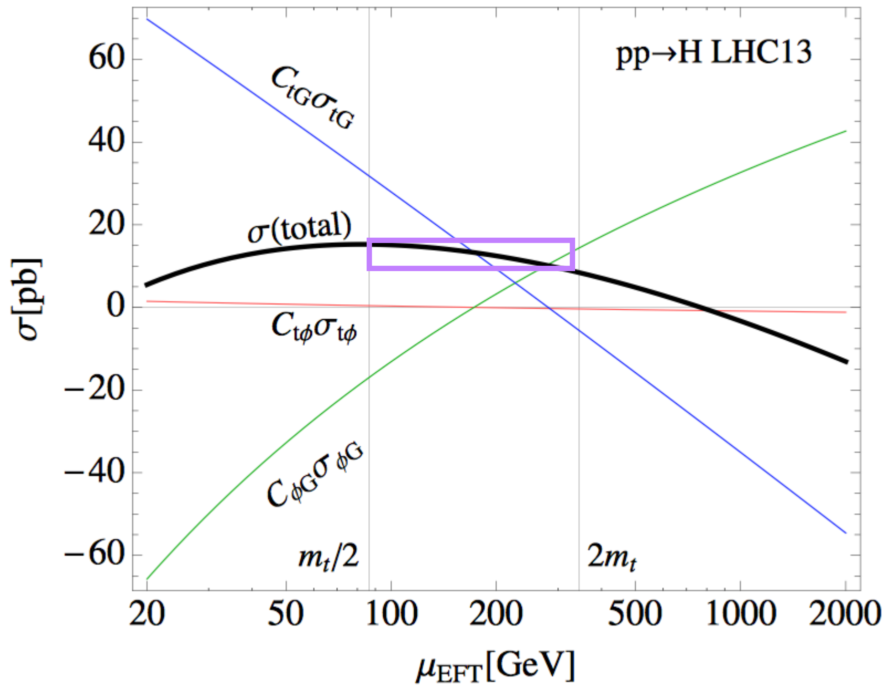
$$\sigma_{ij}(\mu_0;\mu) = \Gamma_{ki}(\mu,\mu_0)\Gamma_{lj}(\mu,\mu_0)\sigma_{kl}(\mu)$$

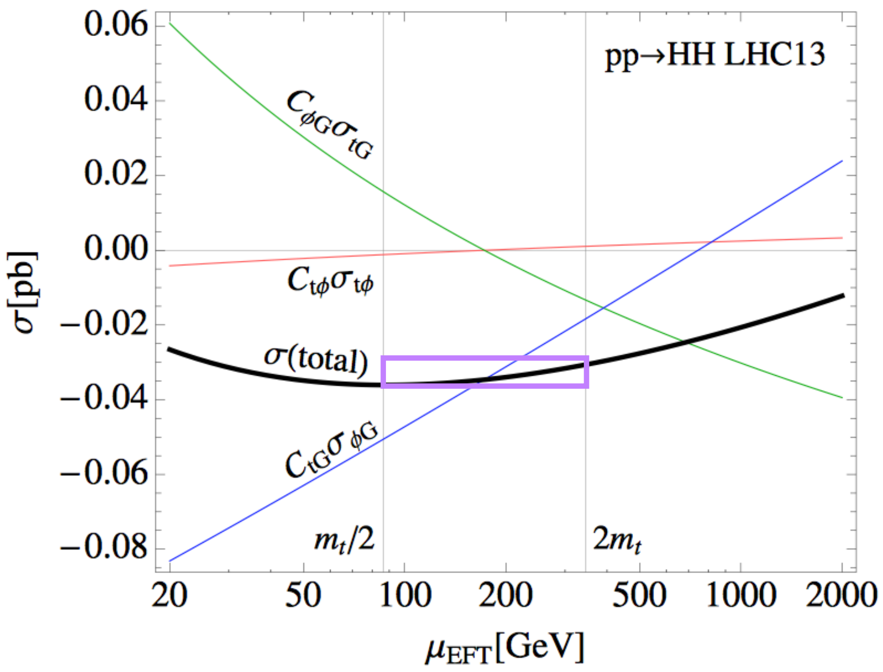
EFT scale dependence

Full NLO stable under scale variation

- Large finite effects: RG improved underestimates NLO
- Scale uncertainty estimate
- Take c_i defined at scales $2\mu_0$ & $\mu_0/2$ and run back to the central scale







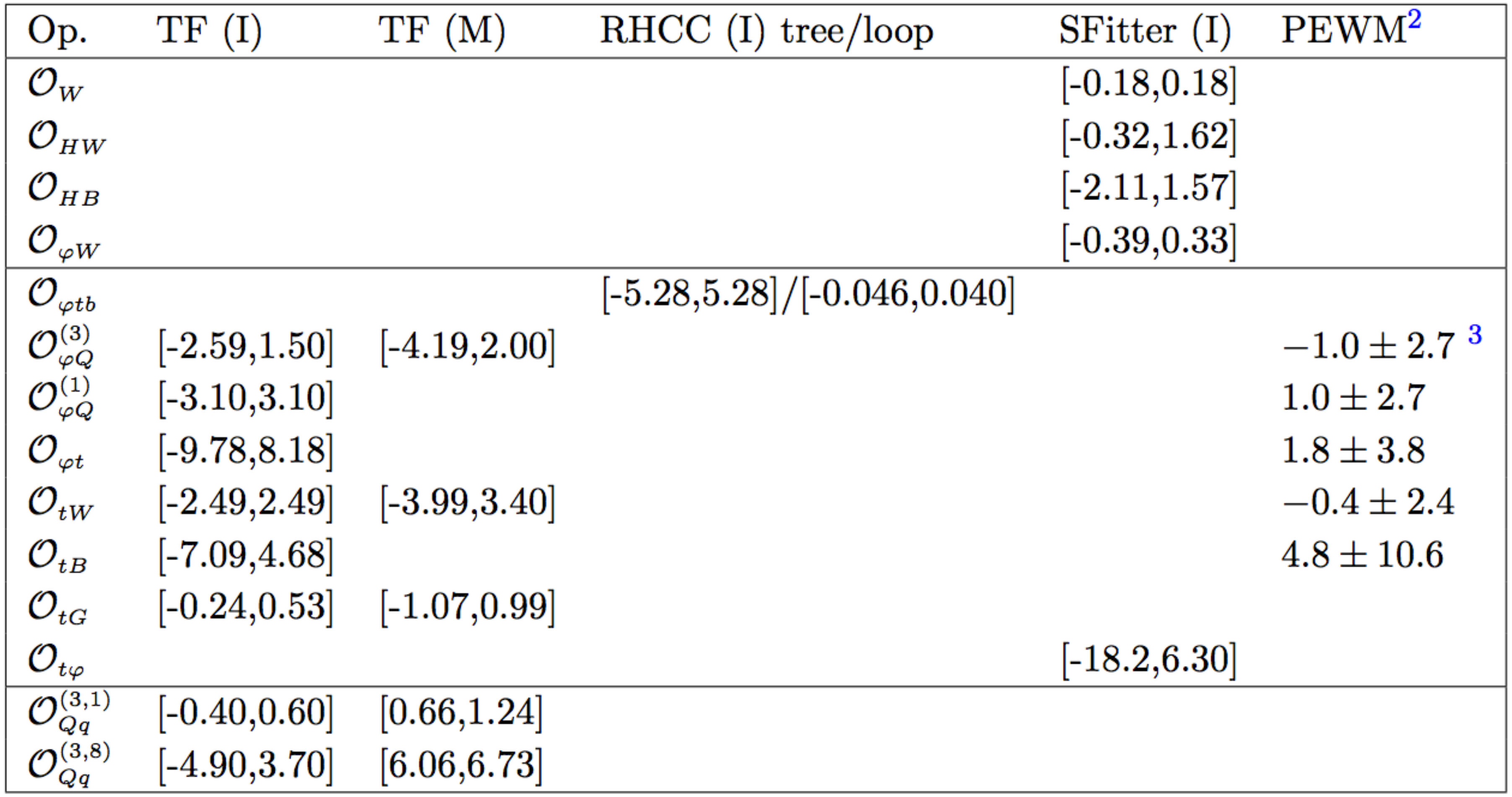
$\delta\mu_{\mathrm{EFT}}$:

Does not cancel in e.g. cross section ratios

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

Existing limits

(I) : Individual
(M) : Marginalised



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]			

[TeV^{-2}]

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

Combination of ttH @ 13 TeV

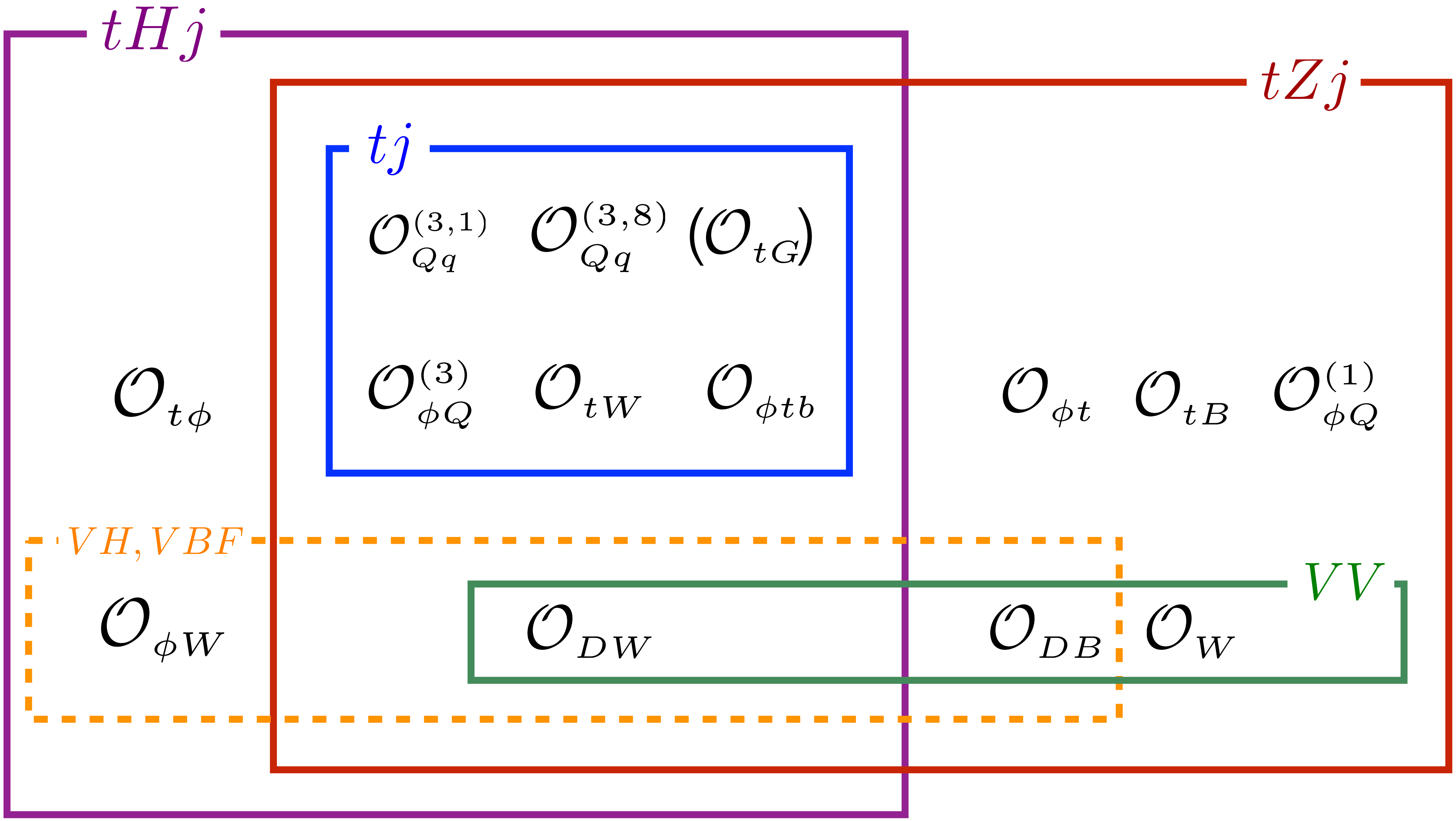
[CMS; CMS-PAS-HIG-17-003]
[CMS; CMS-PAS-HIG-17-004]
[ATLAS; CERN-EP-2017-281]

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

Combination of LHC single-top

[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]

Interplay



tHj

tZj

tj

$\mathcal{O}_{Qq}^{(3,1)}$ $\mathcal{O}_{Qq}^{(3,8)}$ $(\mathcal{O}_{tG})$

$\mathcal{O}_{t\phi}$

$\mathcal{O}_{\phi Q}^{(3)}$ $\mathcal{O}_{tW}$ $\mathcal{O}_{\phi tb}$

$\mathcal{O}_{\phi t}$ $\mathcal{O}_{tB}$ $\mathcal{O}_{\phi Q}^{(1)}$

VH, VBF

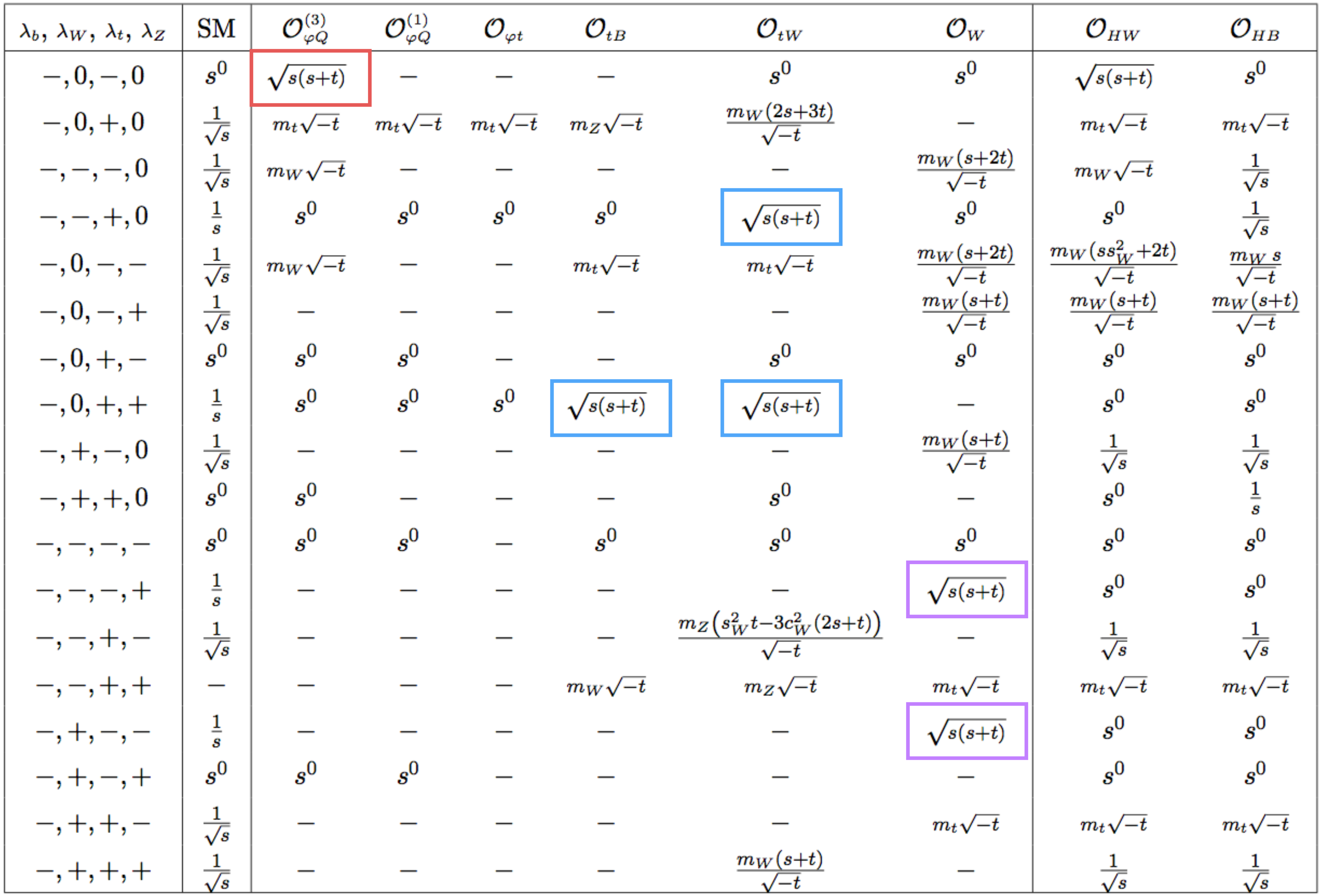
VV

$\mathcal{O}_{\phi W}$ $\mathcal{O}_{DW}$ $\mathcal{O}_{DB}$ $\mathcal{O}_{W}$

[Mantani, Maltoni, KM; in preparation] [Dror et al.; JHEP 01 (2016) 071]

Anatomy of tZj

bW → tZ



$\lambda_b,\ \lambda_W,\ \lambda_t,\ \lambda_Z$	SM	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$
$-,0,-,0$	s^0	$\boxed{\sqrt{s(s+t)}}$	$-$	$-$	$-$	s^0	s^0	$\sqrt{s(s+t)}$	s^0
$-,0,+,0$	$\frac{1}{\sqrt{s}}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_Z\sqrt{-t}$	$\frac{m_W(2s+3t)}{\sqrt{-t}}$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,-,-,0$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$m_W\sqrt{-t}$	$\frac{1}{\sqrt{s}}$
$-,-,+,0$	$\frac{1}{s}$	s^0	s^0	s^0	s^0	$\boxed{\sqrt{s(s+t)}}$	s^0	s^0	$\frac{1}{\sqrt{s}}$
$-,0,-,-$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$\frac{m_W(ss_W^2+2t)}{\sqrt{-t}}$	$\frac{m_W s}{\sqrt{-t}}$
$-,0,-,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,0,+,-$	s^0	s^0	s^0	$-$	$-$	s^0	s^0	s^0	s^0
$-,0,+,+$	$\frac{1}{s}$	s^0	s^0	s^0	$\boxed{\sqrt{s(s+t)}}$	$\boxed{\sqrt{s(s+t)}}$	$-$	s^0	s^0
$-,+,-,0$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,+,+,0$	s^0	s^0	$-$	$-$	$-$	s^0	$-$	s^0	$\frac{1}{s}$
$-,-,-,-$	s^0	s^0	s^0	$-$	s^0	s^0	s^0	s^0	s^0
$-,-,-,+$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\boxed{\sqrt{s(s+t)}}$	s^0	s^0
$-,-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_Z\left(s_W^2t-3c_W^2(2s+t)\right)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,-,+,+$	$-$	$-$	$-$	$-$	$m_W\sqrt{-t}$	$m_Z\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,-,-$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\boxed{\sqrt{s(s+t)}}$	s^0	s^0
$-,+,-,+$	s^0	s^0	s^0	$-$	$-$	$-$	$-$	s^0	s^0
$-,+,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,+,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$

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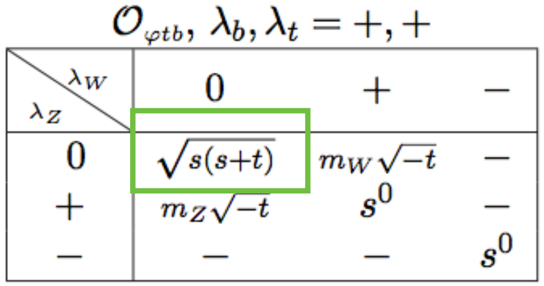
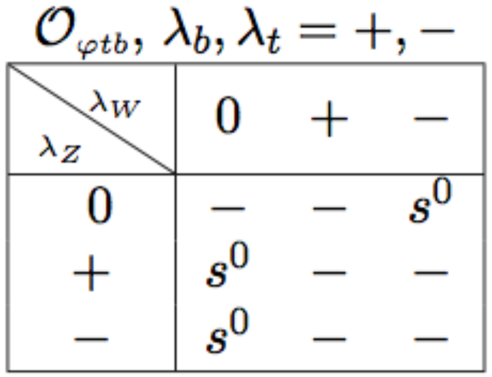


$\mathcal{O}_{\varphi tb},\ \lambda_b, \lambda_t = +, +$

$\lambda_Z \backslash \lambda_W$	0	+	$-$
0	$\boxed{\sqrt{s(s+t)}}$	$m_W\sqrt{-t}$	$-$
+	$m_Z\sqrt{-t}$	s^0	$-$
$-$	$-$	$-$	s^0



$\mathcal{O}_{\varphi tb},\ \lambda_b, \lambda_t = +, -$

$\lambda_Z \backslash \lambda_W$	0	+	$-$
0	$-$	$-$	s^0
+	s^0	$-$	$-$
$-$	s^0	$-$	$-$

Consistent with non-interference theorem in 2 → 2

[Cheung & Shen; PRL 115 (2015) 071601]
[Azatov, Contino & Riva; PRD 95 (2017) 065014]

Non-interference

Sometimes, accidentally have $\sigma^{(6)}_{INT} < \sigma^{(6)}_{SQ}$

- Non-interference by *e.g.* helicity selection rules in the high energy limit

High energy theorem

[Cheung & Shen; PRL 115 (2015) 071601]
[Azatov, Contino & Riva; PRD 95 (2017) 065014]

- Many 2 → 2 amplitudes involving at least one transverse gauge boson mediated by D=6 operators do not interfere with the SM

Total Helicity

Interference?	A_4	$\lvert h(A_4^{\text{SM}})\rvert$	$\lvert h(A_4^{\text{BSM}})\rvert$
✗	$VVVV$	0	4,2
	$VV\phi\phi$	0	2
	$VV\psi\psi$	0	2
	$V\psi\psi\phi$	0	2
✓	$\psi\psi\psi\psi$	2,0	2,0
	$\psi\psi\phi\phi$	0	0
	$\phi\phi\phi\phi$	0	0

V = Transverse vector
ϕ = Longitudinal vector or Higgs
Ψ = Fermion

p p → ZH, WH, WW, WZ

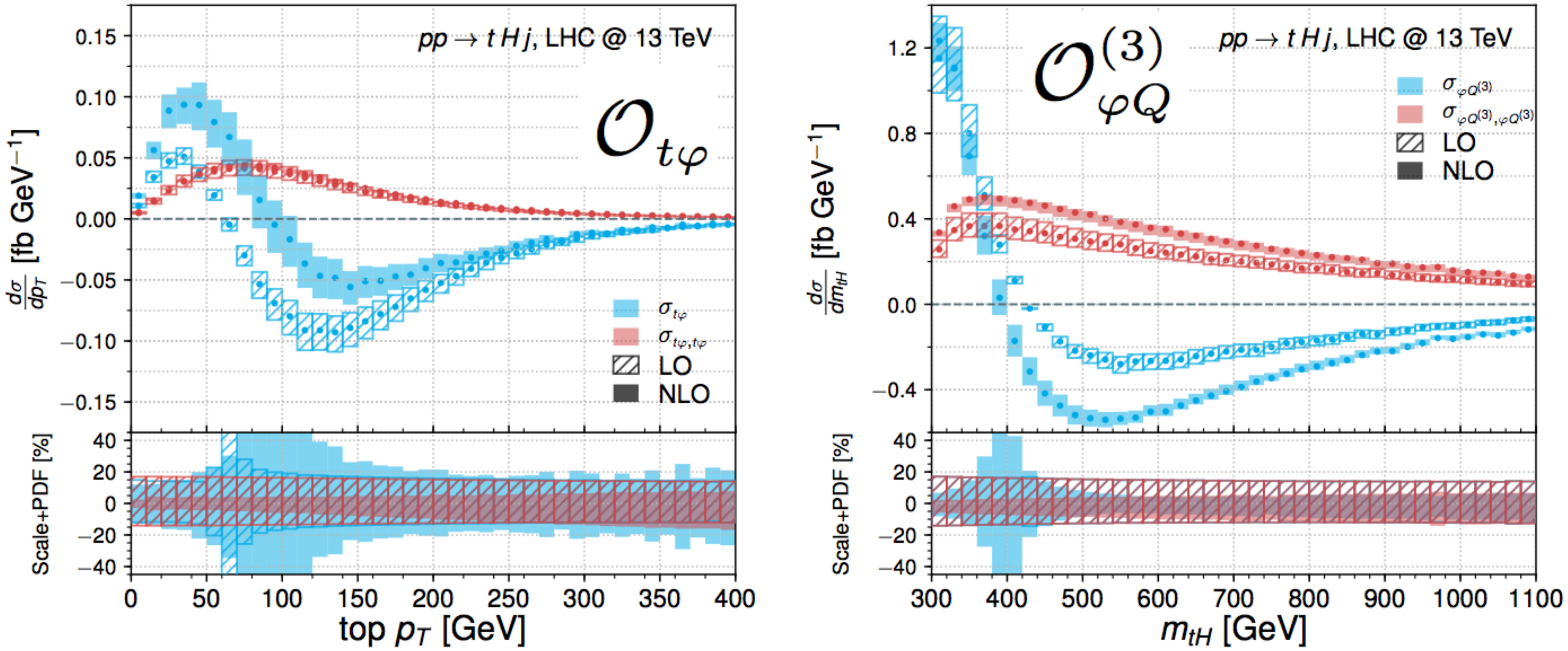
Interference can be recovered:
finite mass effects
higher order corrections
higher multiplicity (2→3,4,…)

[Panico, Riva & Wulzer; CERN-TH-2017-85]
[Azatov, et al. LHEP 1710 (2017) 027]

$pp \to t(\bar{t})\,H\,j$

LHC@13 TeV

Inclusive results: tHj

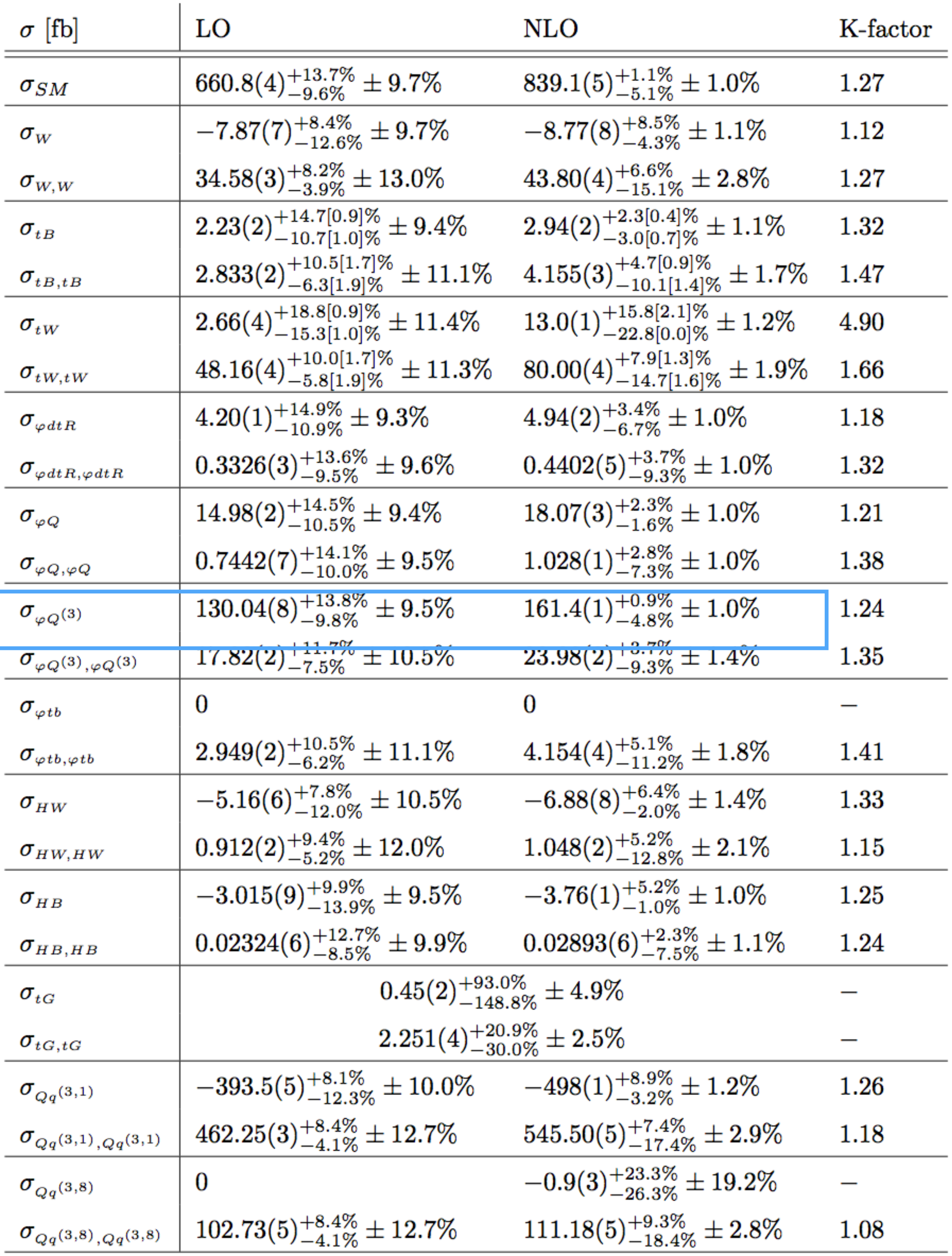


Cancellations over the PS appear/disappear for the interference contributions.
→Between top and antitop
→Strange *K*-factors
→Large scale uncert.

σ_{ij}	$c_{\varphi W}$	$c_{t\varphi}$	c_{tW}	$c^{(3)}_{\varphi Q}$	c_{HW}	c_{u31}	c_{u38}
$c_{\varphi W}$	—	2.752 (1.29)	12.88 (0.61)	6.384 (0.65)	-0.43 (-0.17)	—	—
$c_{t\varphi}$	2.514 (1.35)	—	-1.912 (-0.27)	-4.168 (-1.25)	-0.699 (-0.80)	—	—
c_{tW}	10.54 (0.68)	-1.772 (-0.32)	—	-26.24 (-0.79)	3.988 (0.46)	—	—
$c^{(3)}_{\varphi Q}$	5.12 (0.67)	-3.584 (-1.31)	-11.2 (-0.49)	—	4.864 (1.21)	—	—
c_{HW}	-0.402 (-0.18)	-0.6138 (-0.78)	3.124 (0.47)	3.5784 (1.10)	—	—	—
c_{u31}	-13.475 (-0.71)	5.16 (0.76)	-19.1 (-0.34)	-15.44 (-0.55)	-6.96 (-0.86)	—	4.525 (0.15)
c_{u38}	—	—	—	—	—	—	—

Inclusive results: tZj

$pp \to t(\bar{t})\,Z\,j$ LHC@13 TeV



σ [fb]	LO	NLO	K-factor
σ_{SM}	$660.8(4)^{+13.7\%}_{-9.6\%} \pm 9.7\%$	$839.1(5)^{+1.1\%}_{-5.1\%} \pm 1.0\%$	1.27
σ_{W}	$-7.87(7)^{+8.4\%}_{-12.6\%} \pm 9.7\%$	$-8.77(8)^{+8.5\%}_{-4.3\%} \pm 1.1\%$	1.12
$\sigma_{W,W}$	$34.58(3)^{+8.2\%}_{-3.9\%} \pm 13.0\%$	$43.80(4)^{+6.6\%}_{-15.1\%} \pm 2.8\%$	1.27
σ_{tB}	$2.23(2)^{+14.7[0.9]\%}_{-10.7[1.0]\%} \pm 9.4\%$	$2.94(2)^{+2.3[0.4]\%}_{-3.0[0.7]\%} \pm 1.1\%$	1.32
$\sigma_{tB,tB}$	$2.833(2)^{+10.5[1.7]\%}_{-6.3[1.9]\%} \pm 11.1\%$	$4.155(3)^{+4.7[0.9]\%}_{-10.1[1.4]\%} \pm 1.7\%$	1.47
σ_{tW}	$2.66(4)^{+18.8[0.9]\%}_{-15.3[1.0]\%} \pm 11.4\%$	$13.0(1)^{+15.8[2.1]\%}_{-22.8[0.0]\%} \pm 1.2\%$	4.90
$\sigma_{tW,tW}$	$48.16(4)^{+10.0[1.7]\%}_{-5.8[1.9]\%} \pm 11.3\%$	$80.00(4)^{+7.9[1.3]\%}_{-14.7[1.6]\%} \pm 1.9\%$	1.66
$\sigma_{\varphi dtR}$	$4.20(1)^{+14.9\%}_{-10.9\%} \pm 9.3\%$	$4.94(2)^{+3.4\%}_{-6.7\%} \pm 1.0\%$	1.18
$\sigma_{\varphi dtR,\varphi dtR}$	$0.3326(3)^{+13.6\%}_{-9.5\%} \pm 9.6\%$	$0.4402(5)^{+3.7\%}_{-9.3\%} \pm 1.0\%$	1.32
$\sigma_{\varphi Q}$	$14.98(2)^{+14.5\%}_{-10.5\%} \pm 9.4\%$	$18.07(3)^{+2.3\%}_{-1.6\%} \pm 1.0\%$	1.21
$\sigma_{\varphi Q,\varphi Q}$	$0.7442(7)^{+14.1\%}_{-10.0\%} \pm 9.5\%$	$1.028(1)^{+2.8\%}_{-7.3\%} \pm 1.0\%$	1.38
$\sigma_{\varphi Q^{(3)}}$	$130.04(8)^{+13.8\%}_{-9.8\%} \pm 9.5\%$	$161.4(1)^{+0.9\%}_{-4.8\%} \pm 1.0\%$	1.24
$\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$	$17.82(2)^{+11.7\%}_{-7.5\%} \pm 10.5\%$	$23.98(2)^{+3.7\%}_{-9.3\%} \pm 1.4\%$	1.35
$\sigma_{\varphi tb}$	0	0	–
$\sigma_{\varphi tb,\varphi tb}$	$2.949(2)^{+10.5\%}_{-6.2\%} \pm 11.1\%$	$4.154(4)^{+5.1\%}_{-11.2\%} \pm 1.8\%$	1.41
σ_{HW}	$-5.16(6)^{+7.8\%}_{-12.0\%} \pm 10.5\%$	$-6.88(8)^{+6.4\%}_{-2.0\%} \pm 1.4\%$	1.33
$\sigma_{HW,HW}$	$0.912(2)^{+9.4\%}_{-5.2\%} \pm 12.0\%$	$1.048(2)^{+5.2\%}_{-12.8\%} \pm 2.1\%$	1.15
σ_{HB}	$-3.015(9)^{+9.9\%}_{-13.9\%} \pm 9.5\%$	$-3.76(1)^{+5.2\%}_{-1.0\%} \pm 1.0\%$	1.25
$\sigma_{HB,HB}$	$0.02324(6)^{+12.7\%}_{-8.5\%} \pm 9.9\%$	$0.02893(6)^{+2.3\%}_{-7.5\%} \pm 1.1\%$	1.24
σ_{tG}	$0.45(2)^{+93.0\%}_{-148.8\%} \pm 4.9\%$		–
$\sigma_{tG,tG}$	$2.251(4)^{+20.9\%}_{-30.0\%} \pm 2.5\%$		–
$\sigma_{Qq^{(3,1)}}$	$-393.5(5)^{+8.1\%}_{-12.3\%} \pm 10.0\%$	$-498(1)^{+8.9\%}_{-3.2\%} \pm 1.2\%$	1.26
$\sigma_{Qq^{(3,1)},Qq^{(3,1)}}$	$462.25(3)^{+8.4\%}_{-4.1\%} \pm 12.7\%$	$545.50(5)^{+7.4\%}_{-17.4\%} \pm 2.9\%$	1.18
$\sigma_{Qq^{(3,8)}}$	0	$-0.9(3)^{+23.3\%}_{-26.3\%} \pm 19.2\%$	–
$\sigma_{Qq^{(3,8)},Qq^{(3,8)}}$	$102.73(5)^{+8.4\%}_{-4.1\%} \pm 12.7\%$	$111.18(5)^{+9.3\%}_{-18.4\%} \pm 2.8\%$	1.08

tZj ~ 10 times bigger than tHj

NLO corrections: similar features to tHj

EFT contributions smaller relative to SM

Higgs always radiated from top/EW gauge boson

Z boson can also come from light quark leg