SMEFT@NLO in QCD: Top/Higgs/EW sector

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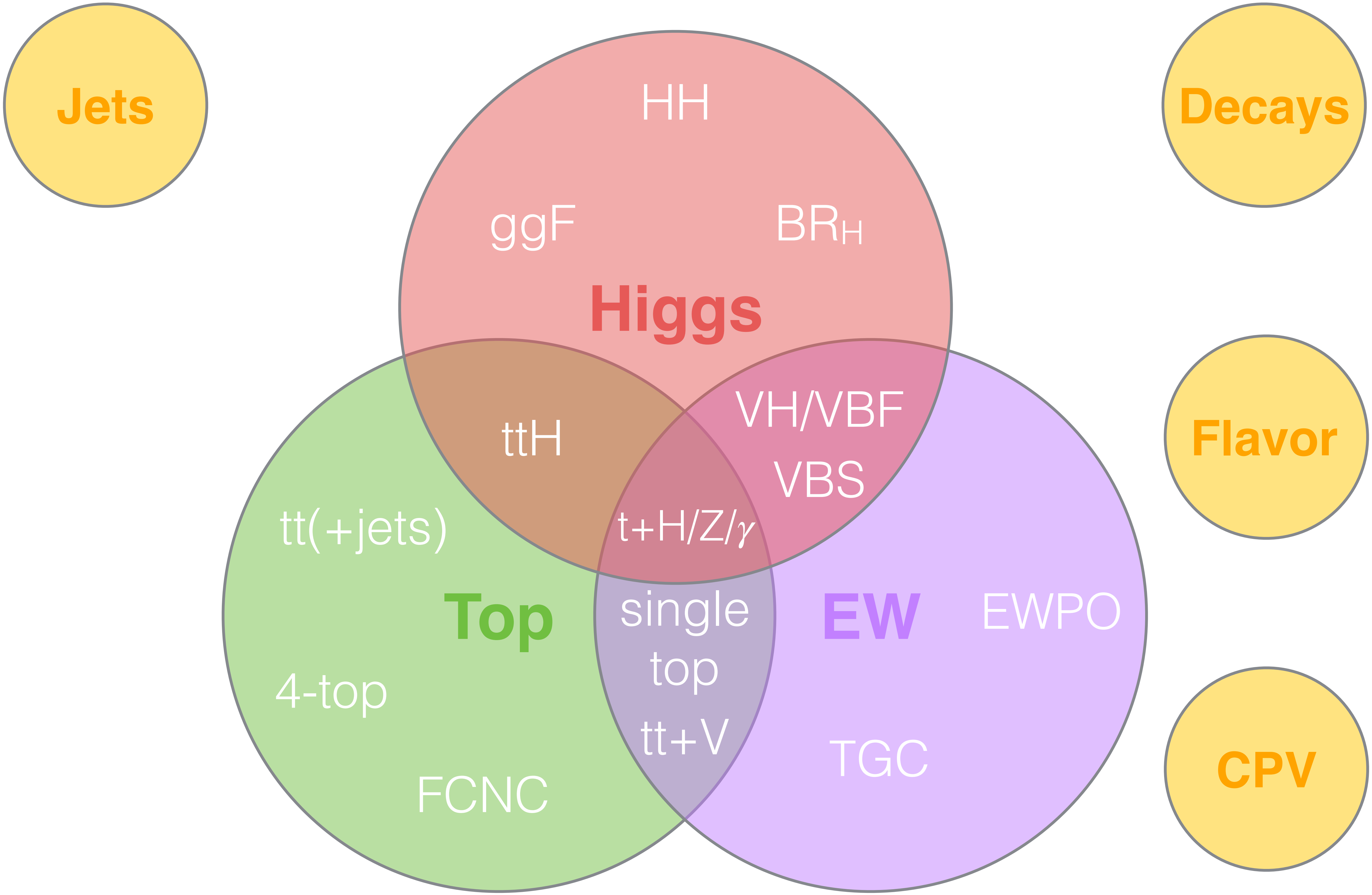
Outline

- Update on status & progress in SMEFT at NLO in QCD
    - Towards complete public Monte Carlo tool
- Top/Higgs/EW SMEFT @ the LHC
    - Interactions with Higgs, gauge bosons & top quark
    - Model implementation in leading MFV expansion
- Showcase study
    - Single top production in association with a Z or Higgs at the LHC
    - Investigate energy growth in helicity sub amplitudes
    - Current & future LHC sensitivity study vs. existing constraints
- Motivate & facilitate global LHC analyses of top/Higgs/EW sector at NLO in QCD

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
  - Complementary approach: SMEFT
- Many channels are becoming systematics dominated
  - Requires high precision theory input: higher order predictions
  - Fixed order (FO) & interfaced with parton shower (PS)
  - Standard for SM, also useful for BSM effects

SMEFT at the LHC: 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:1803.03252]

Going NLO

- Ultimate goal: a precision global fit of full SMEFT including LHC observables at HL-LHC
- Step 1: 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*]*

Status: Higgs

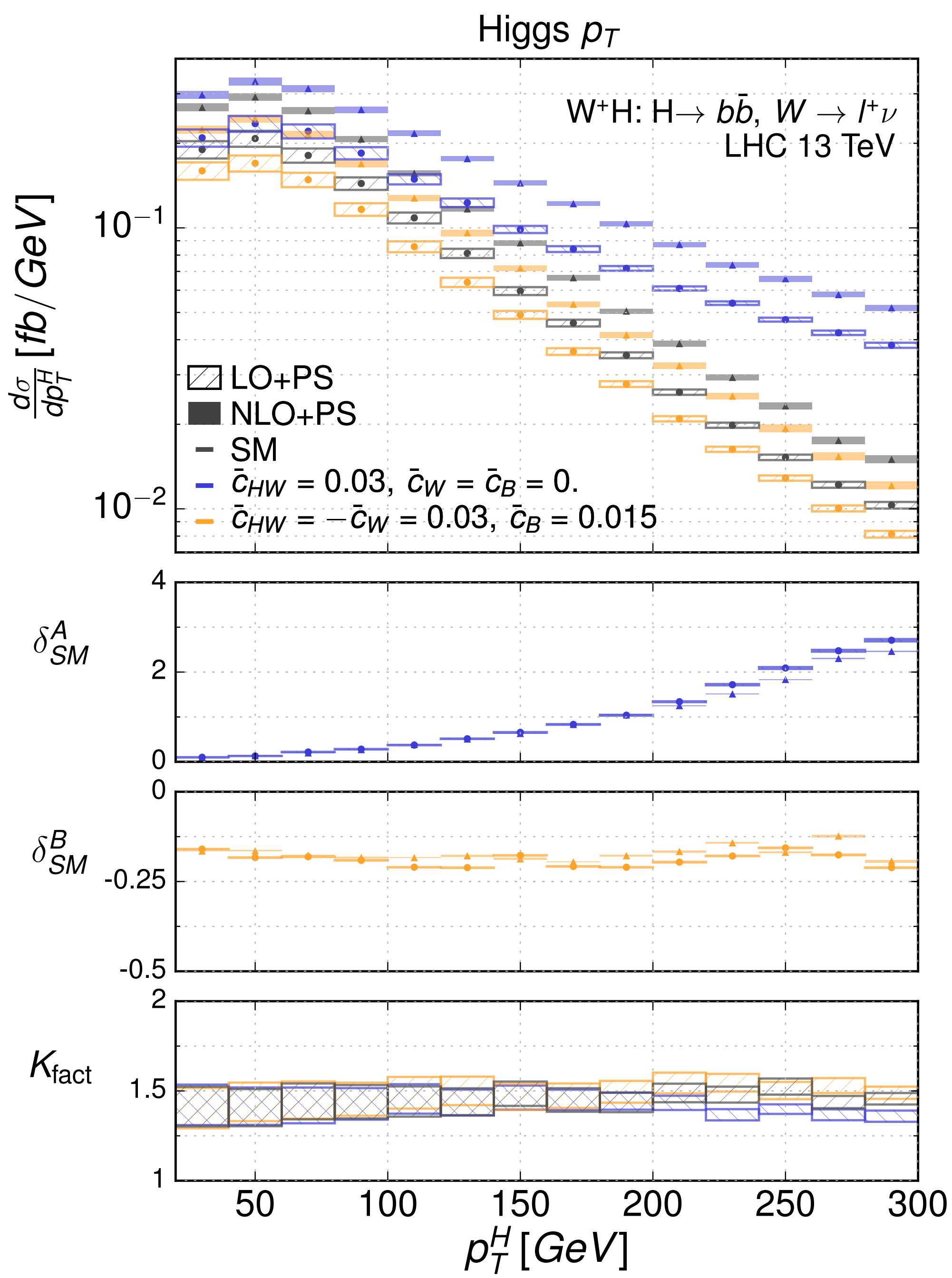
- Single Higgs state of the art @ fixed order:
  - Yukawa & HGG ops. (NNLO+NNLL) *[Grazzini et al.; arXiv:1705.05143]*
  - Top chromomagnetic op. (NLO) *[Deutschmann et al.; JHEP 1712 (2017) 063]*
- Public codes with partial SMEFT contributions @ NLO
  - HiGlu *[Spira; arXiv:hep-ph/9510347]*
  - SusHi (aMC-SusHi) *[Harlander, Liebler & Mantler; arXiv:1605.03190]*
- Double Higgs
  - HPAIR *[Dawson, Dittmaier & Spira; Phys. Rev. D58:115012]*
  - HiggsPair (HERWIG++) *[Goertz et al.; JHEP 1504 (2015) 167]*
- eHDECAY for BR *[Contino et al.; Comp. Phys. Comm. 185 (2014) 3412-3423]*
- Full 1-loop H→$\gamma\gamma$ and H→bb *[Hartmann & Trott; PRL115 (2015) 191801]* *[Gauld, Scott & Pecjak; PRD94 (2016) 074045]*

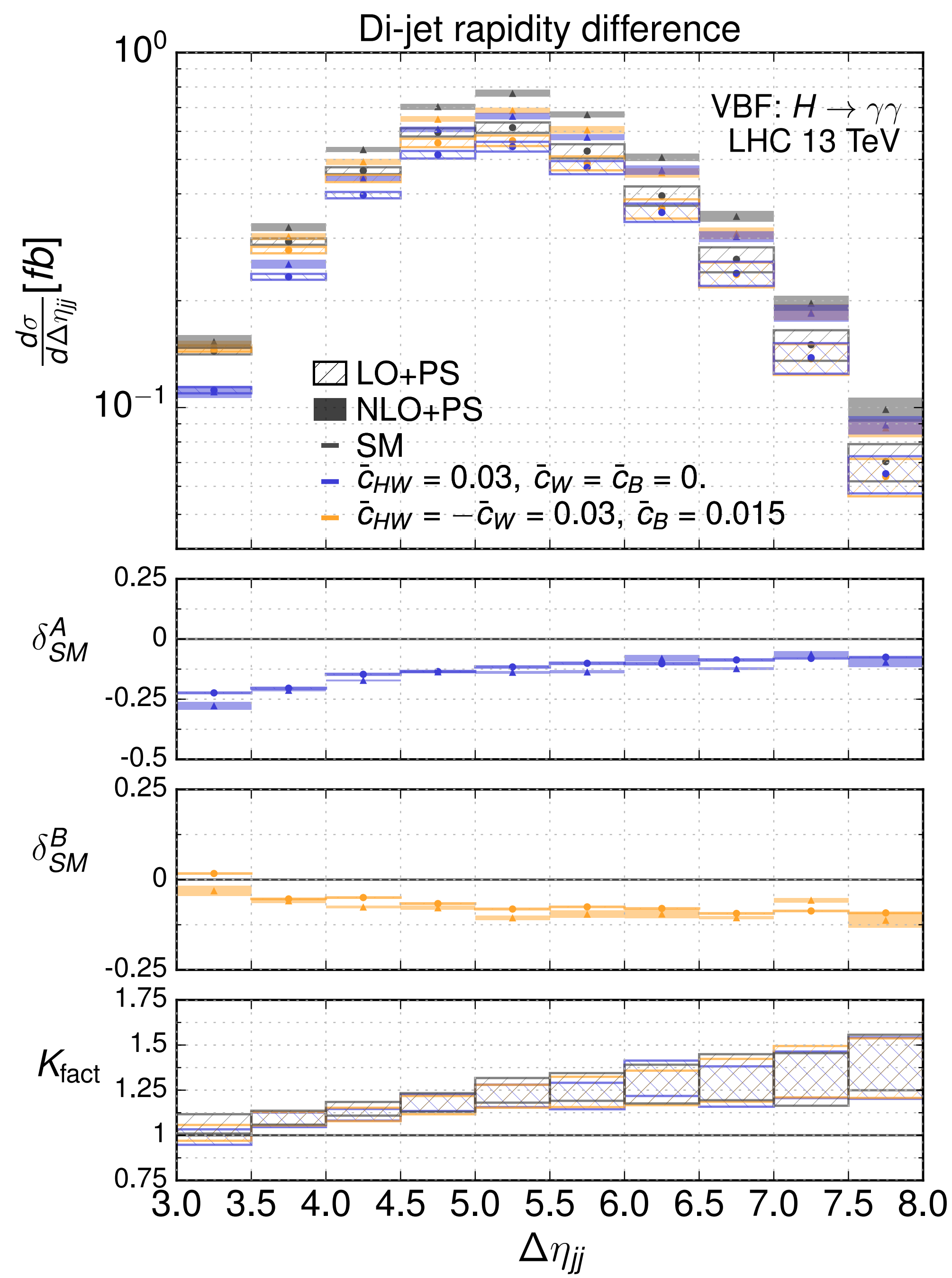
Status: Higgs & EW

- HAWK
  [Denner et al.; JHEP 1203 (2012) 075]
  http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk
  - VBF and VH @ NLO in QCD & EW for SM
  - 2 anomalous couplings parameters at NLO in QCD
- VBFNLO
  [Baglio et al.; arXiv:1404.3940]
  https://www.itp.kit.edu/vbfnlo
  - General tool for Higgs/weak boson production @ NLO in QCD
  - LO event generation & general L3 anomalous coupling parametrisation
- WH & ZH via POWHEG-BOX/MCFM
  [KM, Sanz & Williams.; JHEP 1608 (2016) 039]
  http://powhegbox.mib.infn.it
  - NLO QCD +PS event generation for Higgs/EW operators (SILH)
- HELatNLO
  [Degrande, et al.; EPJC 77 (2017) 4, 262]
  http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO
  - FeynRules/NLOCT/UFO implementation of Higgs/EW operators
  - VH, VBF & any other process of interest (CPV operators also on the way)

SMEFT@NLO QCD+PS

WH





VBF

Status: Top

- Currently no public SMEFT tool for top sector at NLO
- Several works on specific processes based on private implementations
- Single top *[Zhang; PRL 116 (2016) 162002]*
- ttH *[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]*
- tt+Z/γ *[Bylund et al.; JHEP 1605 (2016) 052]*
- top FCNC *[Degrande et al.; PRD 91 (2015) 034024]* *[Durieux, Maltoni & Zhang; PRD 91 (2015) 074017]*
- Our work: bring all previous implementations together into a public model for top/Higgs/EW SMEFT at NLO in QCD

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

Top/Higgs/EW SMEFT

- Top quark is a crucial ingredient of the EW sector
  - Top-Higgs-W/Z couplings/masses are related in SM: unitarity cancellations
  - May reveal hints about the underlying nature of EWSB
- Coloured sector, strongly coupled to the Higgs
  - Large corrections to inclusive rates (~1 K-factors)
  - Non-trivial shape corrections at differential level
  - Non-trivial renormalisation/operator mixing from QCD
- Active research topic in SMEFT at NLO in QCD
- Many measurements at the LHC
  - Total, differential & boosted
  - Access rare processes *e.g.* tt+Z/W/γ, tZj

Minimal Flavor Violation

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

- Building SMEFT for top/Higgs/EW sector:
  - Fermion operators singling out top/3rd generation fermion fields
  - Go beyond flavor universal scenario in a controlled way

$$q^i \to U_q^{ij} q^j,\; u^i \to U_u^{ij} u^j,\; d^i \to U_d^{ij} d^j,\; l^i \to U_l^{ij} l^j,\; e^i \to U_e^{ij} e^j$$

- SM possesses a large U(1)^5 flavor symmetry
  - Only broken by Yukawa couplings
  - Restore symmetry by promoting Yukawa matrices to spurions
  - Apply principle to higher dim. operators

$$Y_u \to U_q Y_u U_u^\dagger,\; Y_d \to U_q Y_d U_d^\dagger,\; Y_e \to U_L Y_e U_e^\dagger$$

$$\mathcal{L}_{\text{Yuk.}} = Y_d^{ij}(\bar{q}_i\,\varphi)d_j + Y_u^{ij}(\bar{q}_i\,\tilde{\varphi})u_j + Y_e^{ij}(\bar{l}_i\,\varphi)e_j + \text{h.c.}$$

$$\langle Y_d\rangle^{ij} = y_d^{ij} \propto m_d^{ij},\; \langle Y_e\rangle^{ij} = y_e^{ij} \propto m_e^{ij},\; \langle Y_u\rangle^{ij} = (V^\dagger y_u)^{ij} \propto (V^\dagger)^{ik} m_u^{kj}$$

Classification in SMEFT

- Operators that break U(1)^5: spurion insertion
  - Yukawa $\quad a_{u\varphi}\,[V^\dagger\, y_u]^{ij}\,(\varphi^\dagger\varphi)(\bar{q}_i\,\tilde{\varphi})u_j$
  - Dipoles $\quad a_{uW}\,[V^\dagger\, y_u]^{ij}(\bar{q}_i\,\tilde{\varphi})\sigma^{\mu\nu}\tau_I\,u_j\,W^I_{\mu\nu}$
  - Right handed charged current $\quad i\,a_{\varphi ud}\,[y_u\,V\,y_d]^{ij}(\tilde{\varphi}^\dagger\,D_\mu\,\varphi)(\bar{u}_i\gamma^\mu d_j)$
- Operators that preserve U(1)^5: spurions parametrise departures from symmetric limit
  - All other fermion currents
  - 3rd generation quarks preferentially selected due to large Yukawas
  - SMEFT → Flavor symmetric + 3rd generation only operators

$$(\bar{q}^i\,q^j)[\mathbb{I}+Y_uY_u^\dagger+Y_dY_d^\dagger+\ldots]^{ij}\to(\bar{q}^i\,q^j)[\mathbb{I}+V^\dagger(y_u)^2V+(y_d)^2+\ldots]^{ij}$$

$$(\bar{u}^i\,u^j)[\mathbb{I}+Y_u^\dagger Y_u+\ldots]^{ij}\to(\bar{u}^i\,u^j)[\mathbb{I}+(y_u)^2+\ldots]^{ij},$$

$$(\bar{d}^i\,d^j)[\mathbb{I}+Y_d^\dagger Y_d+\ldots]^{ij}\to(\bar{d}^i\,d^j)[\mathbb{I}+(y_d)^2+\ldots]^{ij},$$

SMEFT@NLO in QCD

- MC tool for all top/EW/Higgs operators
- Use Warsaw basis for definiteness
  - Tools for translation between bases [Falkowski et al.; EPJC 75 (12) 1-14] rosetta.hepforge.org

Gauge/Higgs

Higgs vev & kinetic term	$\mathcal{O}_{\varphi}$	$(\varphi^\dagger\varphi)^3$	–	–
	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	–	–
m_Z (cust. sym.)	$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D_\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	–	–
Gauge/Higgs & gauge kinetic terms/mixing	$\mathcal{O}_{\varphi G}$	$\varphi^\dagger\varphi\, G^{\mu\nu}_A G^A_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{G}}$	$\varphi^\dagger\varphi\, G^{\mu\nu}_A \tilde{G}^A_{\mu\nu}$
	$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi\, W^{\mu\nu}_i W^i_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{W}}$	$\varphi^\dagger\varphi\, W^{\mu\nu}_i \tilde{W}^i_{\mu\nu}$
	$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi\, B^{\mu\nu} B_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{B}}$	$\varphi^\dagger\varphi\, B^{\mu\nu} \tilde{B}_{\mu\nu}$
	$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger\sigma^i\varphi\, W^{\mu\nu}_i B_{\mu\nu}$	$\mathcal{O}_{\varphi W\tilde{B}}$	$\varphi^\dagger\sigma^i\varphi\, W^{\mu\nu}_i \tilde{B}_{\mu\nu}$
Triple gauge,…	$\mathcal{O}_{3W}$	$\epsilon^{ijk} W_{i,\,\mu\nu} W^{\nu\rho}_j W^{\mu}_{k,\,\rho}$	$\mathcal{O}_{3\tilde{W}}$	$\epsilon^{ijk} \tilde{W}_{i,\,\mu\nu} W^{\nu\rho}_j W^{\mu}_{k,\,\rho}$

CP violation in v2

SMEFT@NLO in QCD

- Work in MFV hypothesis, keeping only y_t non-zero
- Validate with existing implementations where available

3rd generation

	Top	
Yukawa	$\mathcal{O}_{t\varphi}$	$(\varphi^\dagger\varphi)\,(\bar{Q}\,t)\,\tilde{\varphi}$
Dipole	$\mathcal{O}_{tG}$	$(\bar{Q}\,\sigma_{\mu\nu}T^A\,t)\,\tilde{\varphi}\,G_A^{\mu\nu}$
	$\mathcal{O}_{tW}$	$(\bar{Q}\,\sigma_{\mu\nu}\tau^i\,t)\,\tilde{\varphi}\,W_i^{\mu\nu}$
	$\mathcal{O}_{tB}$	$(\bar{Q}\,\sigma_{\mu\nu}\,t)\,\tilde{\varphi}\,B^{\mu\nu}$
Currents	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu^i\varphi)(\bar{Q}\gamma^\mu\sigma_i Q)$
	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$
	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t)$
RHCC	$\mathcal{O}_{\varphi b}$	$i(\tilde{\varphi}D_\mu\varphi)(\bar{b}\gamma^\mu t)$

Flavor universal

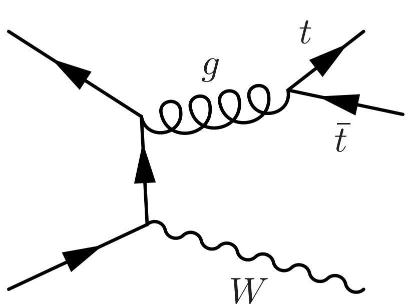
Light	
$\mathcal{O}_{\varphi l}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu^i\varphi)(\bar{l}\gamma^\mu\sigma_i\,l)$
$\mathcal{O}_{\varphi l}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{l}\gamma^\mu l)$
$\mathcal{O}_{\varphi u}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{\varphi q}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu^i\varphi)(\bar{q}\gamma^\mu\sigma_i\,q)$
$\mathcal{O}_{\varphi q}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{q}\gamma^\mu q)$
$\mathcal{O}_{\varphi u}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{\varphi d}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{d}\gamma^\mu d)$

The model

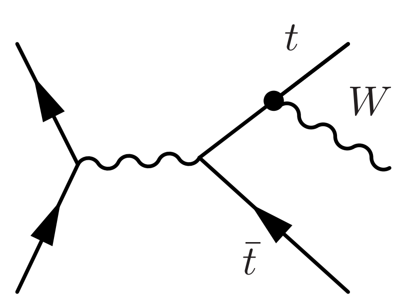
- FeynRules/NLOCT UFO implementation of above operators from Warsaw basis
- Leading MFV expansion *[Aguilar-Saavedra et al.; arXiv:1802.07237]*
  - U(2) flavor symmetry in the light quarks
  - Flavor universal 1st and 2nd gen. & no chirality flipping or RHCC bilinears
  - 3rd generation bilinears associated to the Top Yukawa
  - No CPV operators
- Omit gauge/Yukawa coupling normalisations
- Include field redefinitions needed for canonical EW sector
- 4-fermion operators: in progress

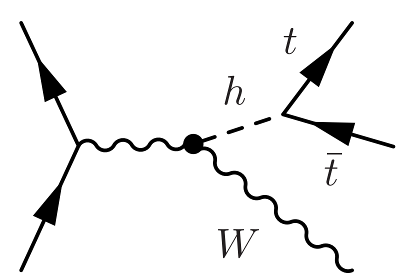
Case study

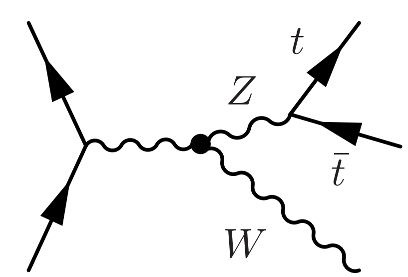
- Processes involving top/Higgs/W/Z
  - Unitarity cancellations ↔ top mass generation mechanism
- Previous tt+(W/Z/H/γ) EFT studies
  - Considered effects on dominant QCD-induced production
  - In the SM, pure EW contributions 2 orders of magnitude smaller
  - EFT effects can enhance these due to strong energy growth



vs.







- Challenging to access top/EW operators in top processes with a QCD counterpart

[Degrande, Maltoni, KM, Vryonidou, Zhang; arXiv 1804.xxxxx]

Case study: tZj/tHj

- Alternative: require presence of a single top quark
  - Eliminates 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
- Require the presence of an additional Z or Higgs
  - Unique possibility of probing full set of top/Higgs/EW operators at once
  - Processes at the heart of EWSB sector
  - 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]
- Timely moment to perform EFT sensitivity study in this pair of challenging processes & showcase model implementation

Operators

tHj

tZj

both

Rescaling of h couplings

NLO

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

Constrained by electroweak precision tests (LEP)

RGE

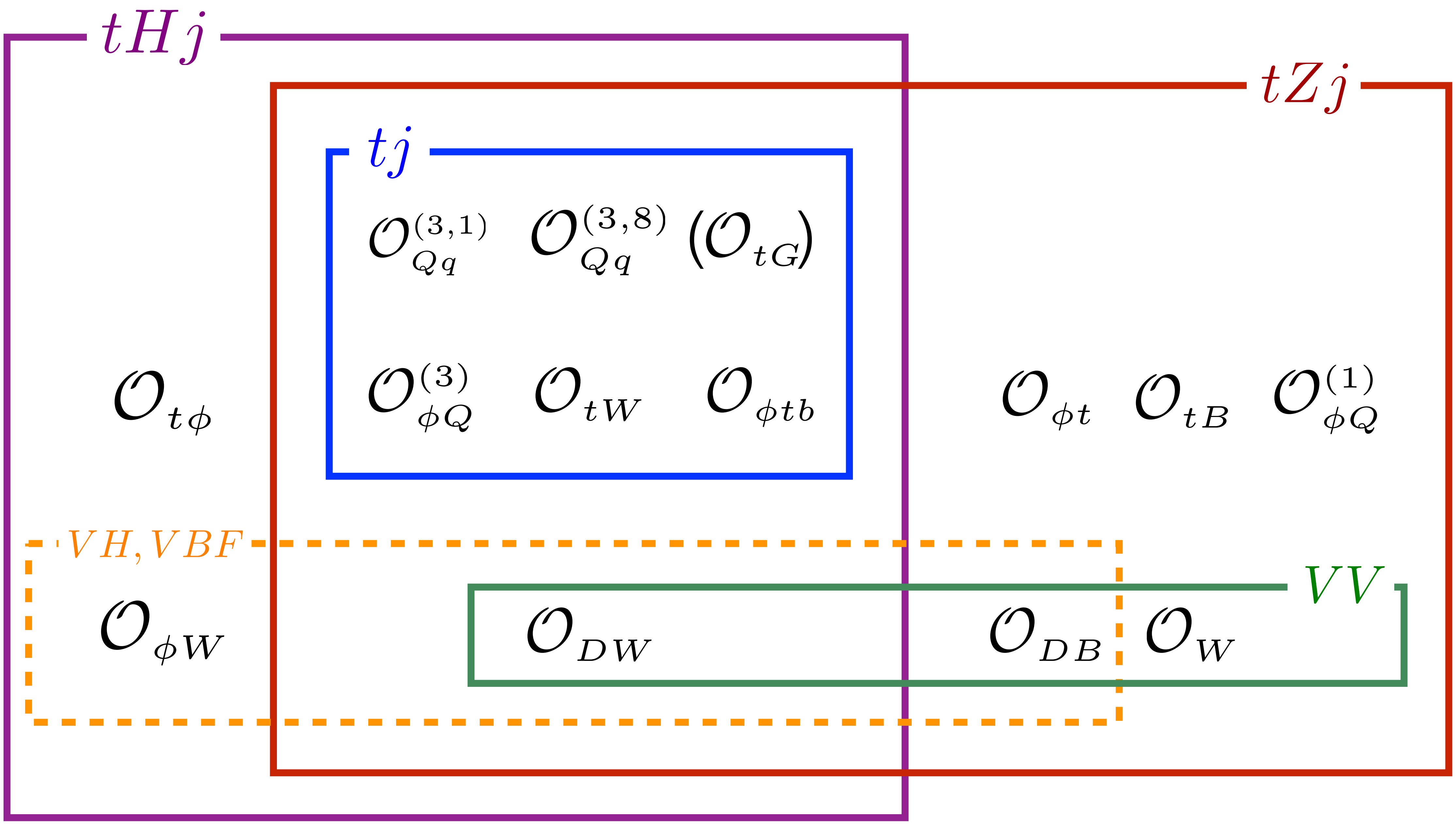
Two blind directions in Warsaw basis:

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

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

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

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

(I) : Individual
(M) : Marginalised
[TeV^{-2}]

[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

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]		
$\mathcal{O}^{(3)}_{\varphi Q}$	[-2.59,1.50]	[-4.19,2.00]			-1.0 ± 2.7 [3]
$\mathcal{O}^{(1)}_{\varphi Q}$	[-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]	
$\mathcal{O}^{(3,1)}_{Qq}$	[-0.40,0.60]	[0.66,1.24]			
$\mathcal{O}^{(3,8)}_{Qq}$	[-4.90,3.70]	[6.06,6.73]			

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

Combination of ttH @ 13 TeV

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

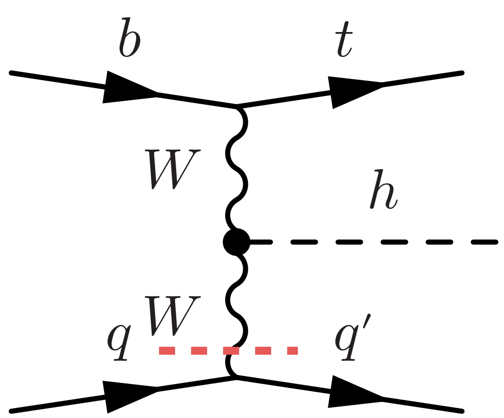
$$c^{(3,8)}_{Qq} \subset [-1.40, 1.20]$$

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]

SMEFT in tHj/tZj

tHj (tZj = h→Z)

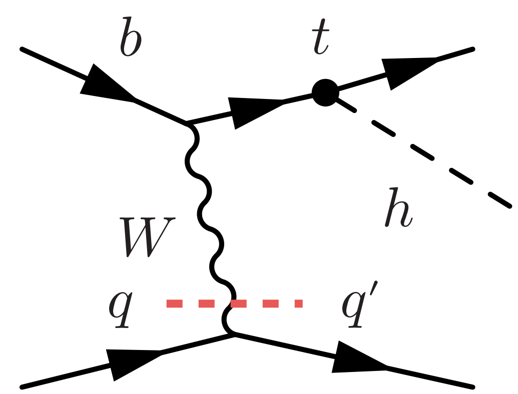


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

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

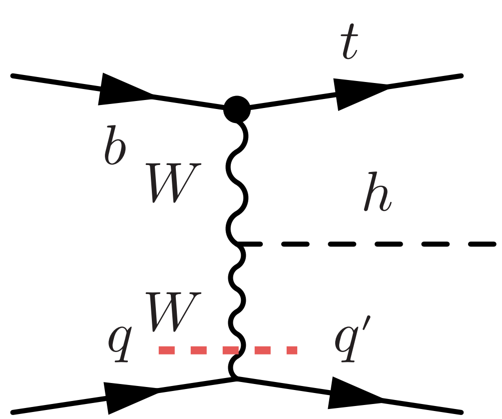


$\mathcal{O}_{t\varphi} \ : \ (\varphi^\dagger\varphi)\,(\bar{Q}\,t)\,\tilde{\varphi}$

top Yukawa

ttZ coupling

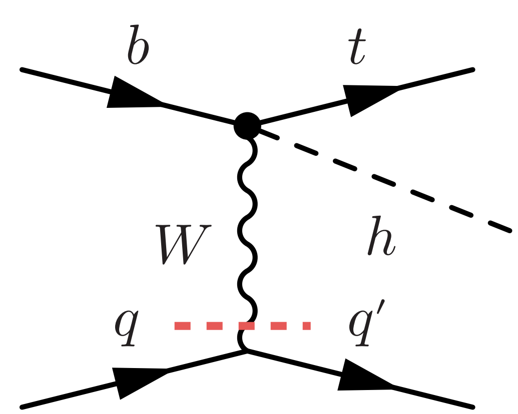
$\mathcal{O}_{\varphi t} : i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$



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

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

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

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

Anatomy of tHj

bW → tH

- LO helicity amplitudes
  - High energy limit: $s \sim -t \gg v^2$
- Maximum energy growth
  - SU(2) triplet current
  - Interferes with leading SM
  - RHCC
  - Weak dipole
  - Fields strengths source transverse gauge bosons
  - Not captured by Goldstone equiv.

$\lambda_b, \lambda_W, \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{HW}$
$-,0,-$	s^0	s^0	$\frac{\sqrt{s(s+t)}}{\sqrt{2}}$	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	$-$	$\sqrt{s(s+t)}$	$\frac{1}{s}$
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,+,+$	s^0	$-$	s^0	s^0	s^0	$\frac{1}{s}$

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

$\lambda_t \backslash \lambda_W$	0	+	−
+	$\sqrt{s(s+t)}$	$m_W\sqrt{-t}$	$\frac{1}{\sqrt{s}}$
−	$m_t\sqrt{-t}$	s^0	s^0

- Subleading energy growth
  - $\propto$ m_t & interferes with sub-leading SM amplitude → no growth

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	$\sqrt{s(s+t)}$	$-$	$-$	$-$	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	$\sqrt{s(s+t)}$	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	$\sqrt{s(s+t)}$	$\sqrt{s(s+t)}$	$-$	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
$-,-,-,+$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$	s^0	s^0
$-,-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_Z\left(s_W^2 t-3c_W^2(2s+t)\right)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
$-,-,+,+$	$-$	$-$	$-$	$-$	$m_W\sqrt{-t}$	$m_Z\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,-,-$	$\frac{1}{s}$	$-$	$-$	$-$	$-$	$-$	$\sqrt{s(s+t)}$	s^0	s^0
$-,+,-,+$	s^0	s^0	s^0	$-$	$-$	$-$	$-$	s^0	s^0
$-,+,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,+,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$

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

λ_Z \ λ_W	0	+	−
0	$\sqrt{s(s+t)}$	$m_W\sqrt{-t}$	$-$
+	$m_Z\sqrt{-t}$	s^0	$-$
−	$-$	$-$	s^0

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

λ_Z \ λ_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]

Λ= 1 TeV

Results

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

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

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

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

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

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

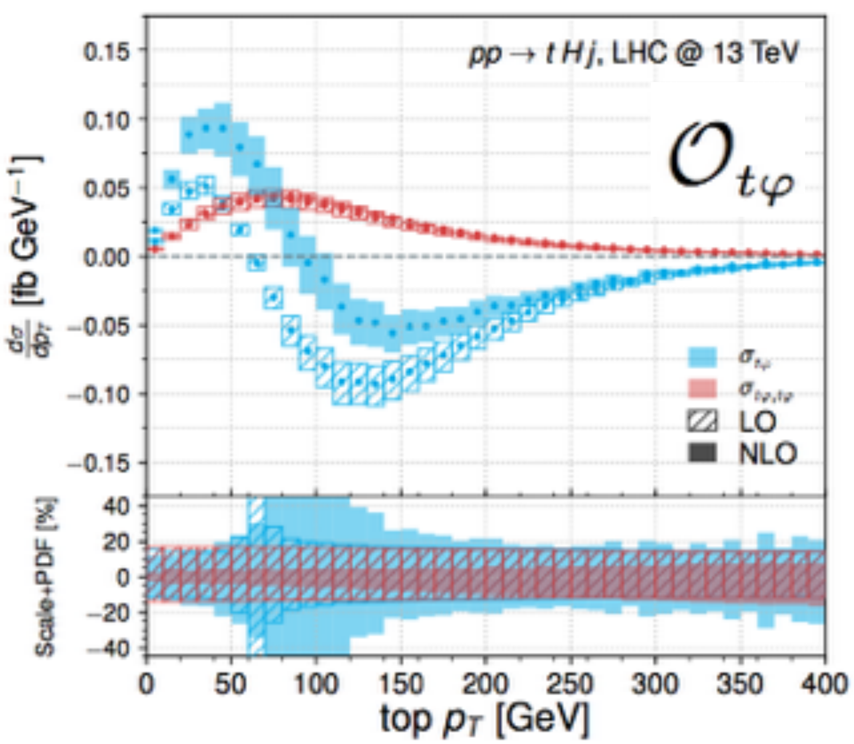
Reduction of QCD scale/PDF uncertainties

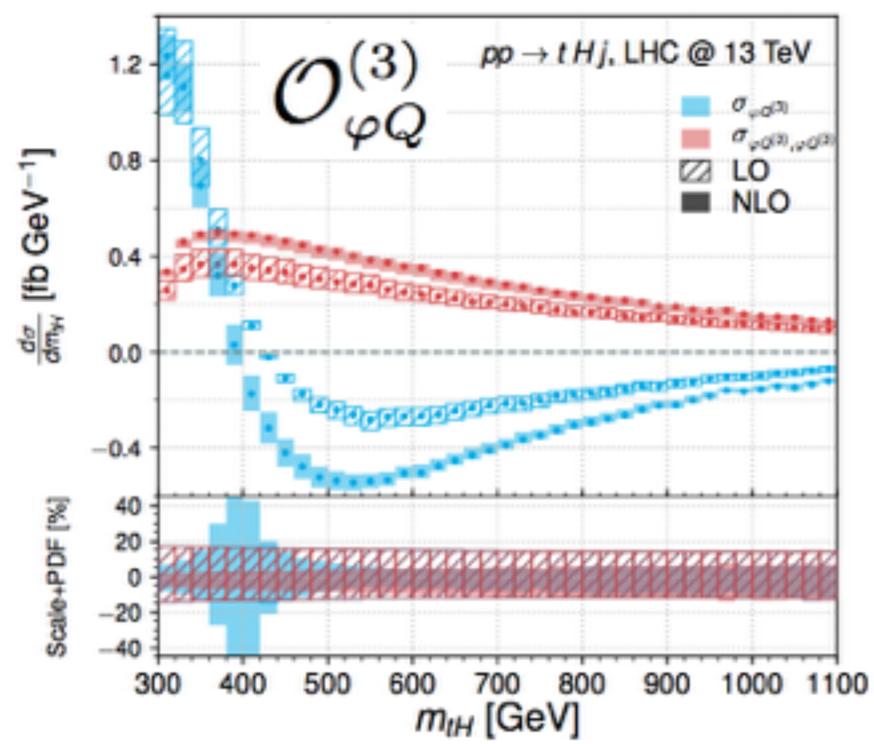
EFT scale uncertainty subdominant

Some very strong dependence on EFT operators

O(>1) deviations within current direct bounds

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}	—	—	—	—	—	—	—

$pp \to t(\bar{t})\, Z\, j$ — Inclusive results: tZj — 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

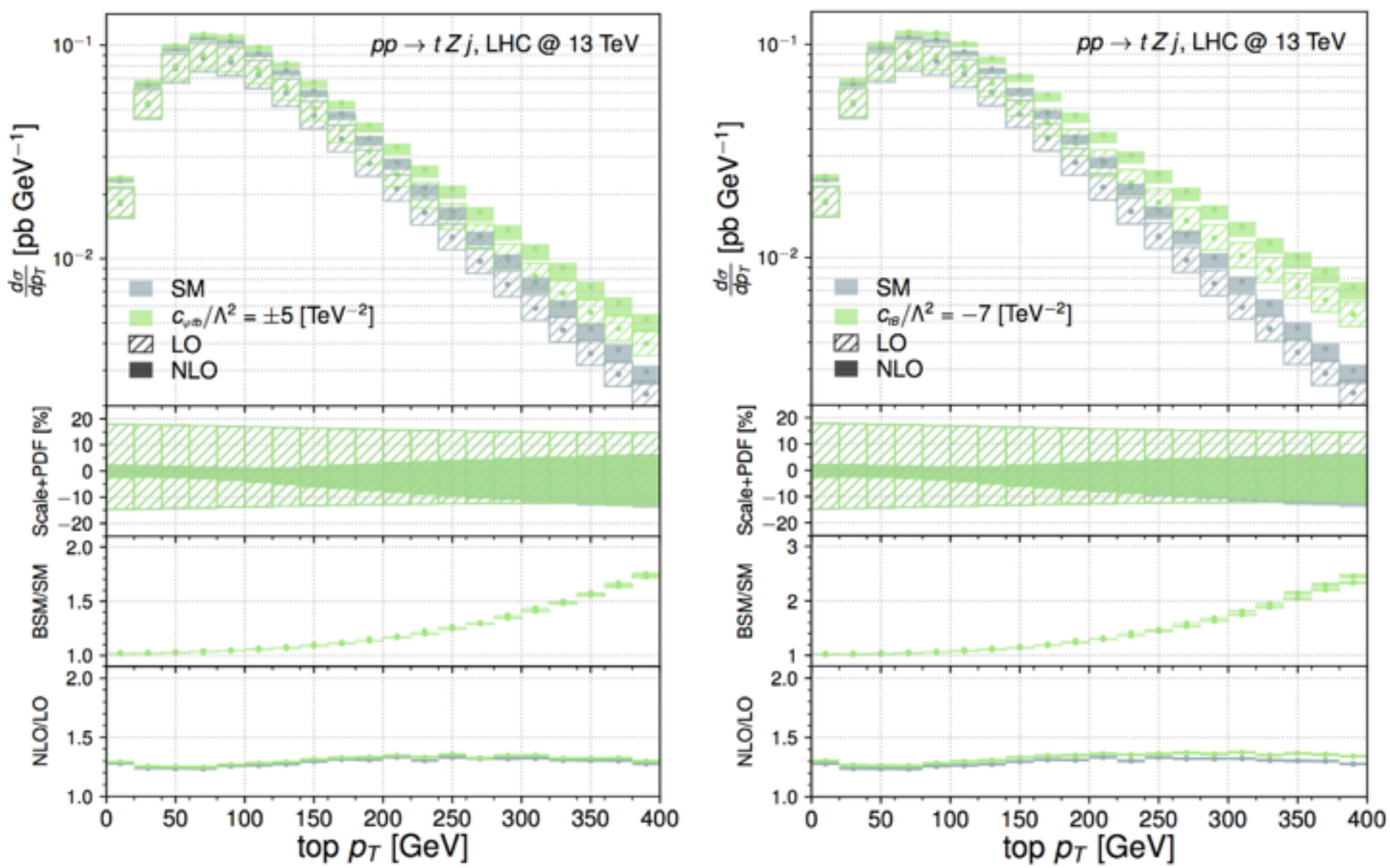
tZj ~ 10 times bigger than tHj

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

Differential results in tZj



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
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)	tHj
σ_{SM}	224 pb	880 fb	839 fb	69 fb	75.9 fb
r_{tW}	0.028	0.024	0.0156	0.0104	0.292
$r_{tW,tW}$	0.016	0.356	0.096	0.672	0.940
$r_{\varphi Q^{(3)}}$	0.120	0.120	0.192	0.686	-0.132
$r_{\varphi Q^{(3)},\varphi Q^{(3)}}$	0.0037	0.0037	0.023	0.28	0.21
$r_{\varphi tb,\varphi tb}$	0.00090	0.0008	0.0050	0.00052	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	-0.595	-2.22	-0.39
$r_{Qq^{(3,1)},Qq^{(3,1)}}$	0.126	11.5	0.70	5.08	1.21
$r_{Qq^{(3,8)},Qq^{(3,8)}}$	0.0308	2.73	0.16	1.01	1.08

Increased sensitivity for dipoles, RHCC

Consistent with 2→2 subamplitude analysis

New energy growth in tZj for SU(2) current 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
  - 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; PLB 779 (2018) 358-384]
[ATLAS; CERN-EP-2017-188]

- CMS analysis of tHj + tHW + ttH

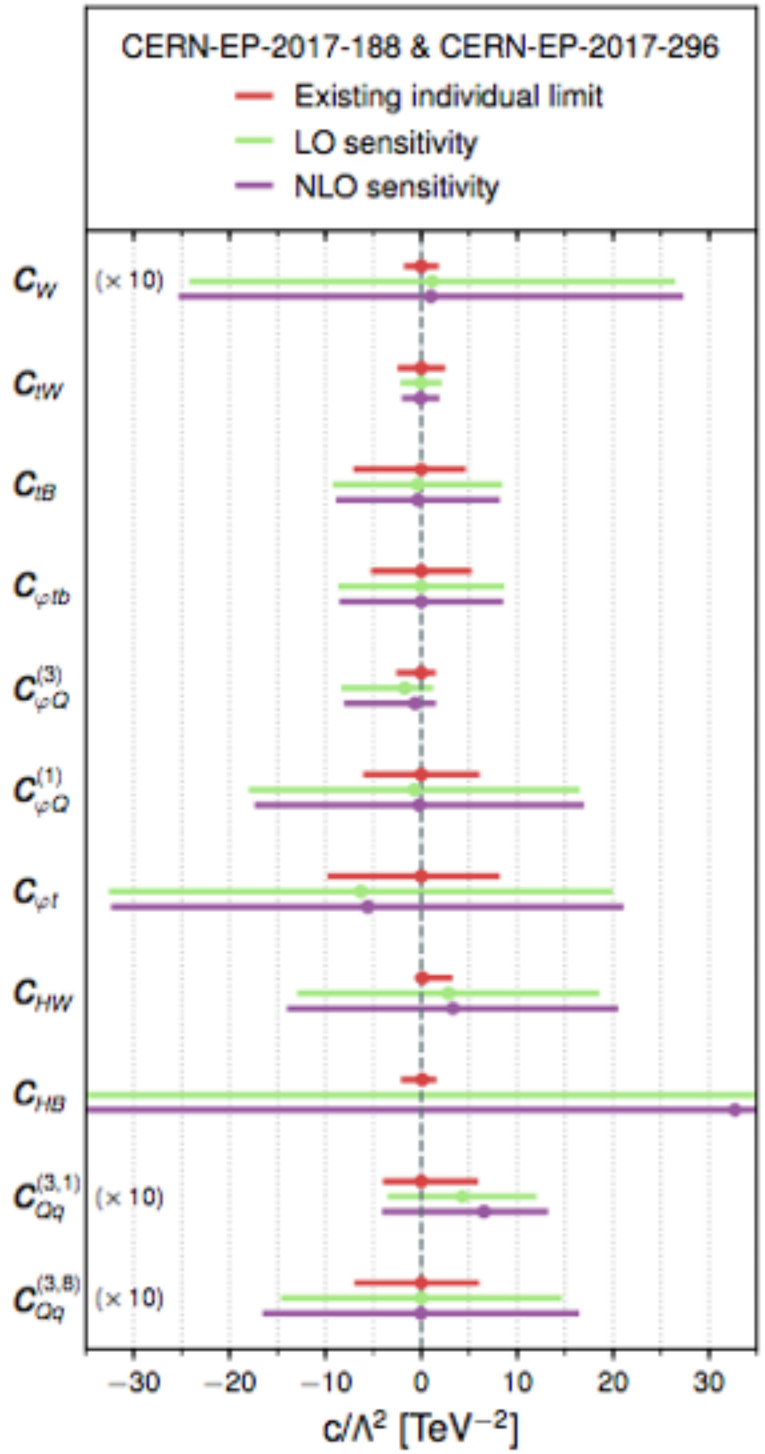
[CMS-PAS-HIG-17-005]

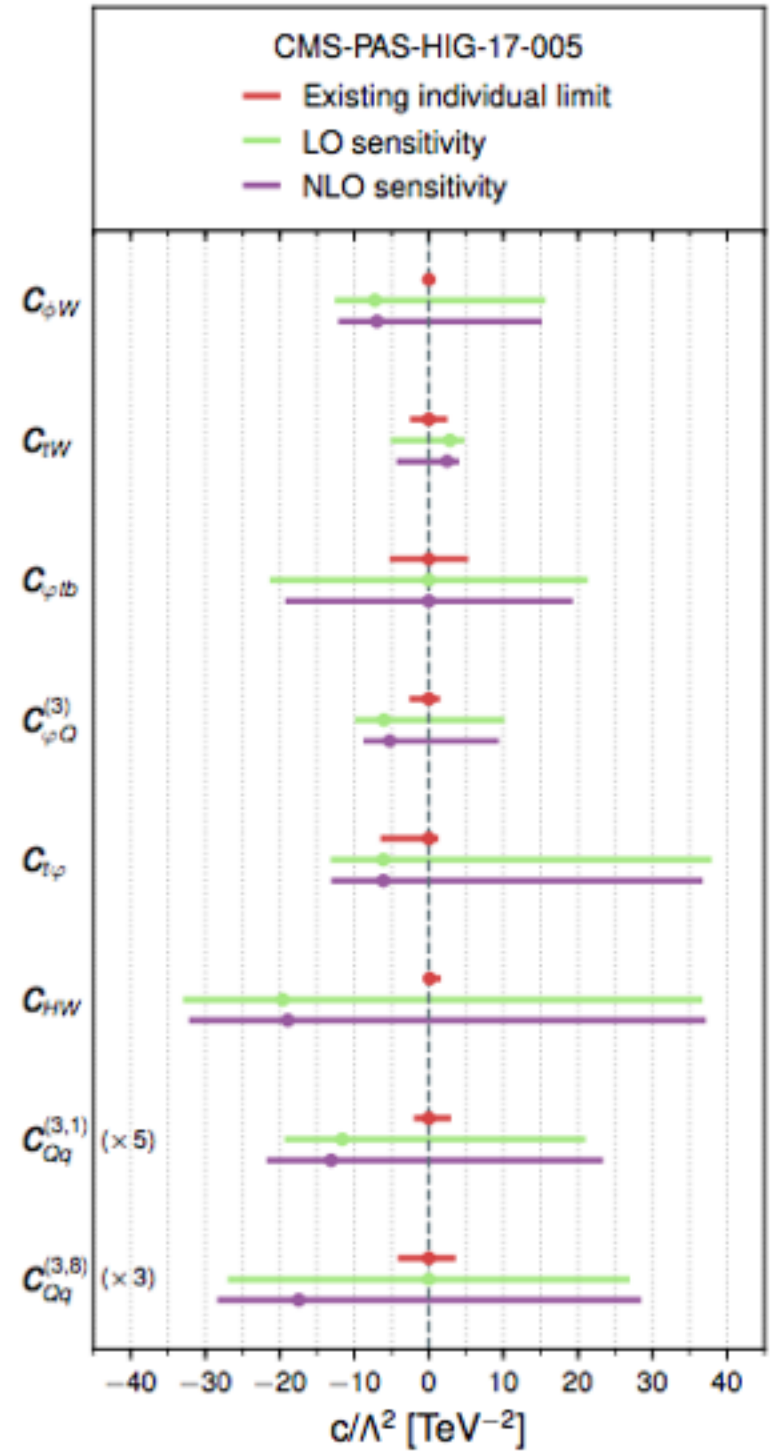
  - Combined signal strength 1.8 ± 0.67
  - Take into account only modifications to tZj
  - Except top Yukawa operator contribution to ttH

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





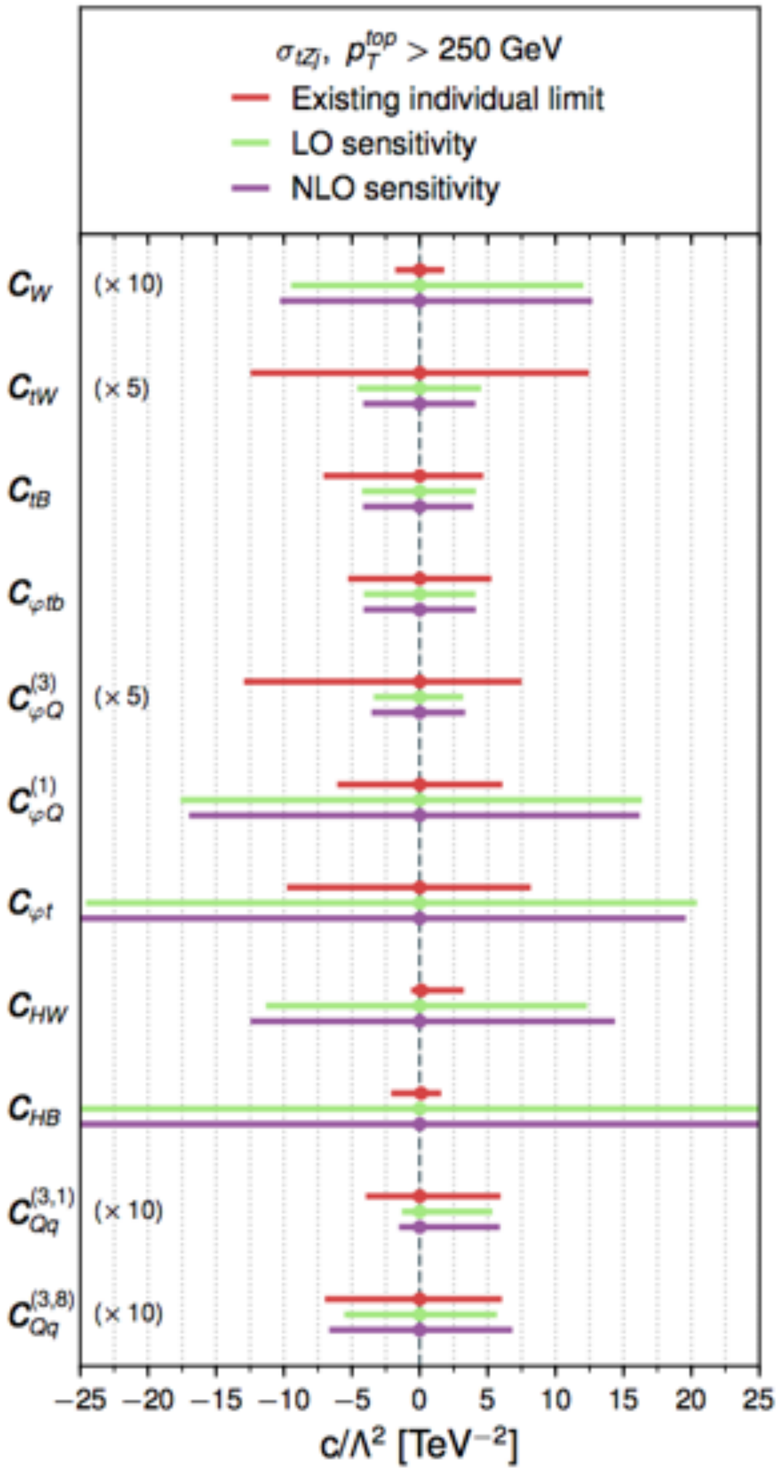
tHj

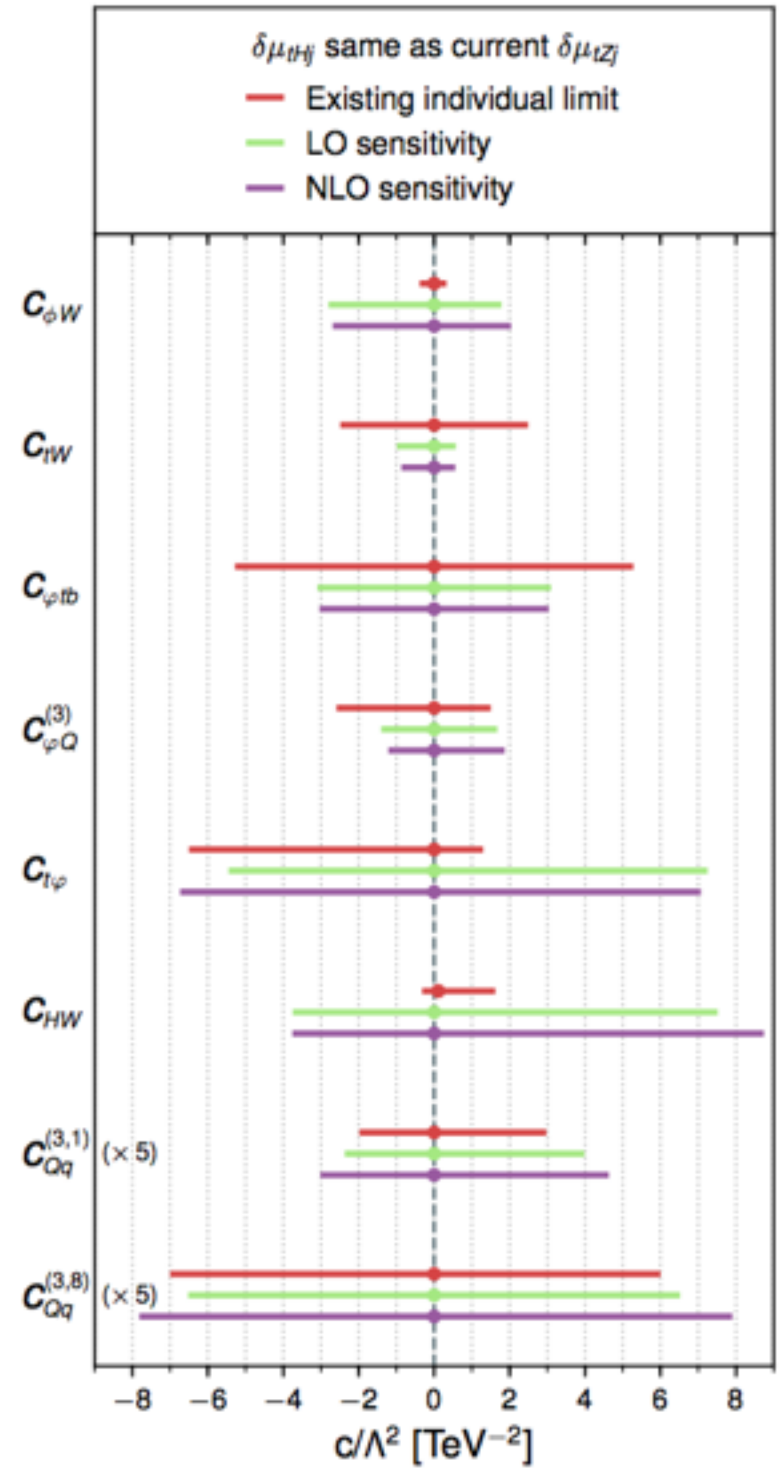
Future sensitivity

- 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





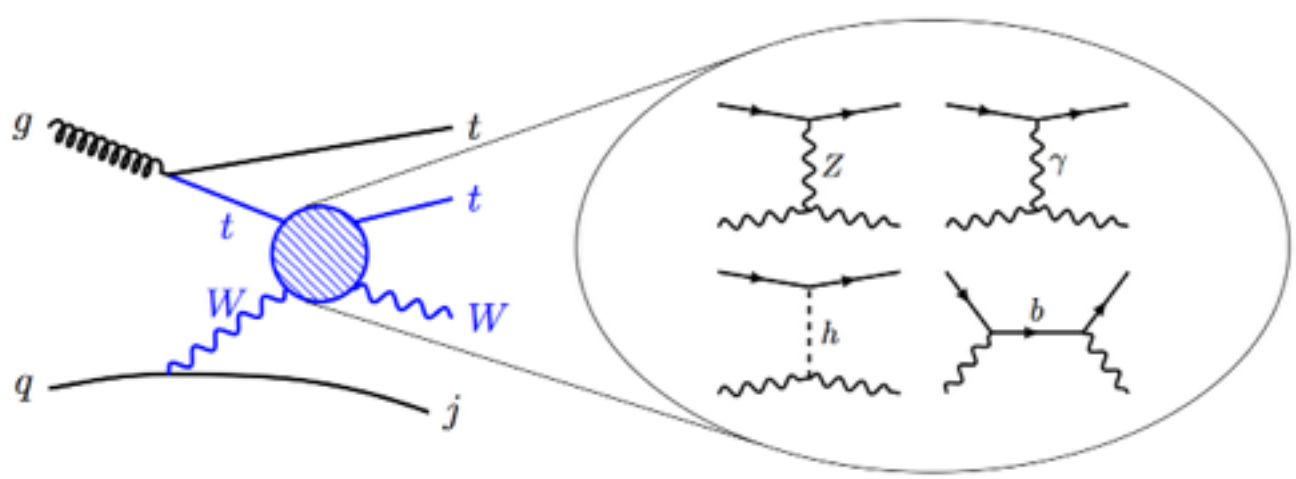
tHj

Global top/Higgs/EW

- Several interesting 2 → 2 sub-amplitudes & processes

bW → tH : tHj	bW → tZ : tZj
tW → tW : ttW (EW)	tZ → tH : ttH (EW)
tZ → tZ : ttZ	tH → tH : ?

- Possibly access higher energies by *e.g.* ttW+j



[Dror et al.; JHEP 01 (2016) 071]

Similar operators contribute to all of these

Top/Higgs/EW EFT @ LHC

- Clear that a global effort must be undertaken
- Individual measurements of these processes may not easily lend themselves to EFT interpretation
- *e.g.* CMS measurement of ttW/ttZ cross section ratio

  [CMS-PAS-TOP-17-005]
  - "Backgrounds": ttH, tqZ, tHq,…
- Global fits to LHC top quark observables *[Buckley et al.; PRD 92 (2016) 9 091501]*
  - top pair, single top (s+t channel), ttZ, ttγ
  - Extension to top/Higg/EW sector will be a valuable exercise
  - SMEFTatNLO model implementation a necessary ingredient
- Model public soon

Conclusion

- Presented a FeynRules/NLOCT UFO implementation of top/EW/Higgs sector in SMEFT
  - Leading MFV expansion 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 in SU(2) current op.
  - Interesting future sensitivity at high energy to dipoles, RHCC, 4F ops.

Thank you

ttH in SMEFT

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

$(O_{t\phi}, O_{\phi G}, O_{tG})$

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

- Operators involving the top/Higgs/gluon
  - gg→H & tt production partly constrain the Wilson coefficient space
  - ttH is the only direct probe of the Top-Higgs interaction
  - In principle 3-gluon O_G and 4 fermion operators also contribute but turn out to be 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

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

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

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

$\mu_0 \rightarrow \mu$

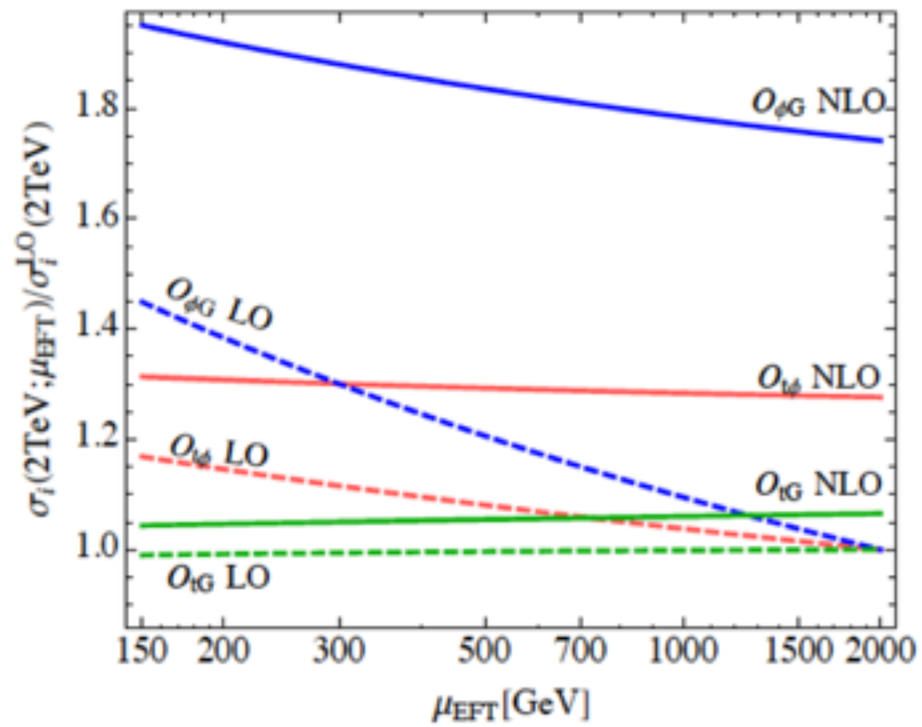
$$\begin{aligned} \sigma(\mu) =& \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i(\mu)\sigma_i(\mu) + \sum_{i,j} \frac{1\text{TeV}^4}{\Lambda^4} C_i(\mu) C_j(\mu) \sigma_{ij}(\mu) \\ =& \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i(\mu_0)\sigma_i(\mu_0;\mu) + \sum_{i,j} \frac{1\text{TeV}^4}{\Lambda^4}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

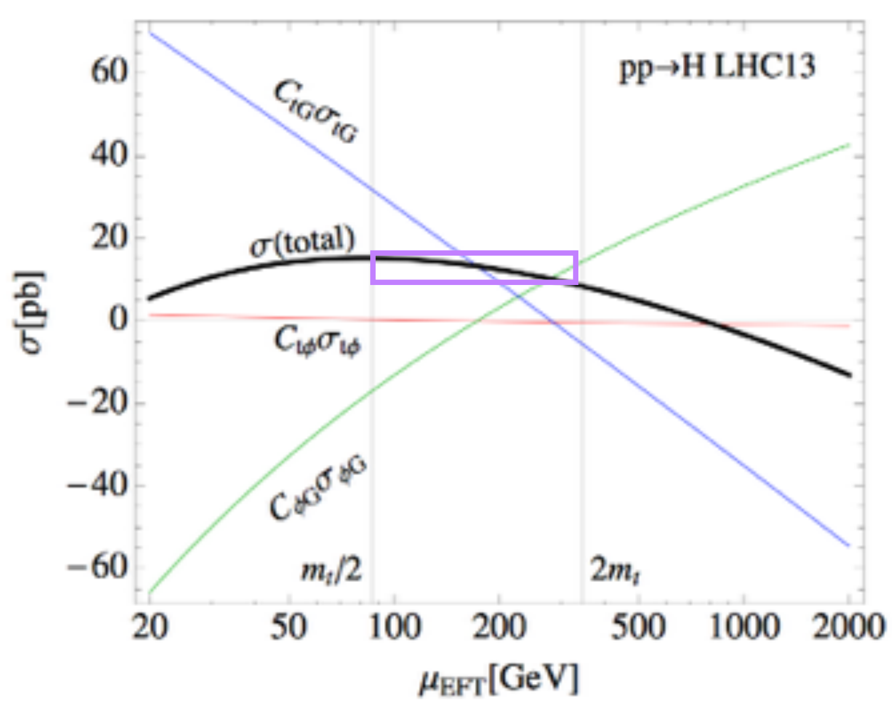
$$\sigma_i(\mu_0;\mu) = \Gamma_{ji}(\mu,\mu_0)\sigma_j(\mu) \ ,$$

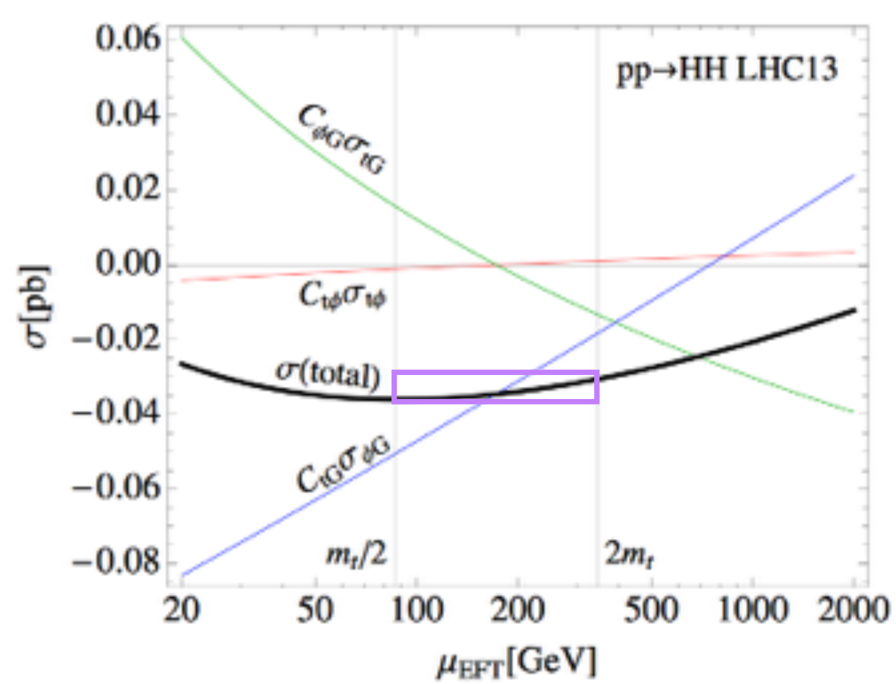
$$\sigma_{ij}(\mu_0;\mu) = \Gamma_{ki}(\mu,\mu_0)\Gamma_{lj}(\mu,\mu_0)\sigma_{kl}(\mu)$$

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







$\delta\mu_{EFT}$:
Does not cancel in e.g. cross section ratios

SMEFT - ‘EW’ sector

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

‘Warsaw’ basis *[Grzadkowski et al.; JHEP 1010 (2010) 085]*

SMEFT - 4 fermions

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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 $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Flavour indices = most of the 2499!

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

Non-interference

- Alternatively, one may have $\sigma^{(6)}_i < \sigma^{(6)}_{ij}$
  - 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	$\|h(A_4^{\rm SM})\|$	$\|h(A_4^{\rm BSM})\|$
✗	$VVVV$	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]