EFT approach to searches for new physics at the LHC

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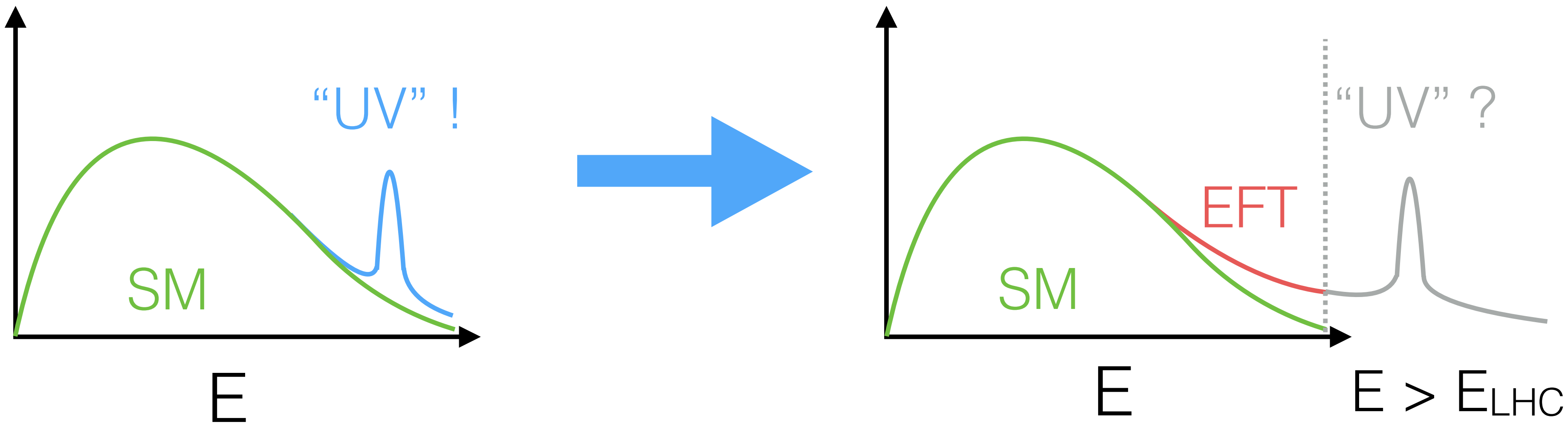
Introduction

- 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 all but completed the picture of the Standard Model (SM) Electroweak (EW) sector
  - Properties consistent with SM expectations
  - Complementary approach: searches for deviations in SM processes
- Many channels are becoming systematics dominated
  - Requires high precision theory input including higher order corrections
  - Fixed order (FO) & interfaced with parton shower (PS)
  - Both for SM and BSM effects

From bumps to tails

direct searches

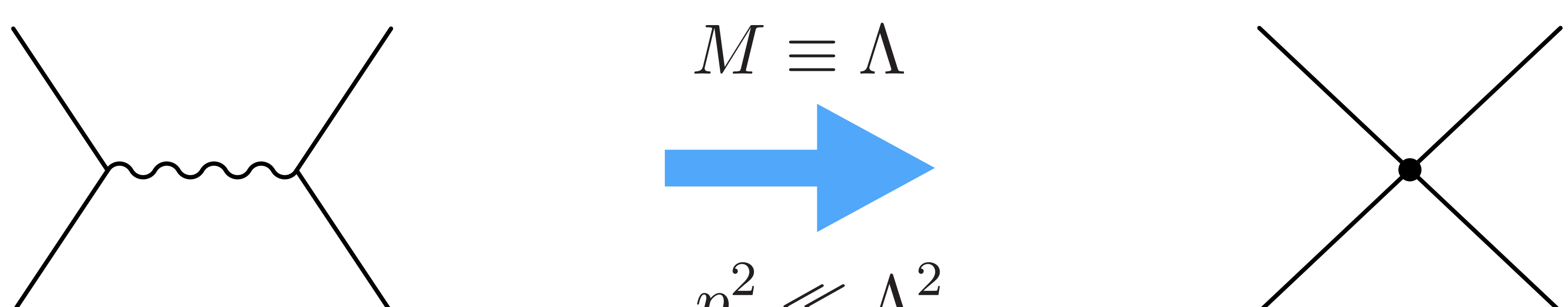


global fits

- Possibility that new states exist (just) beyond the energy reach of the LHC
  - We may still observe indirect effects of such particles in the kinematic tails of distributions, e.g., LEP limits on ~ TeV Z'
  - Intrinsically small effects that require precise theoretical control on signal and background predictions
- Framework: SM effective field theory (SMEFT)
  - Theoretically consistent, 'model independent' approach to deviations of interactions between SM fields

SMEFT

- Operator expansion: $\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$ more: fields derivatives
- Heavy states are integrated out
  - Leaving only local operators built from SM fields
  - We are sensitive to these via large momentum flows through effective vertices (i.e. tails of energy distributions)
  - Truncated at dimension 6 (leading B & L preserving interactions)



cf. Fermi Theory

$$\frac{g^2}{p^2 - M^2}$$

'Matching'

$$-\frac{g^2}{\Lambda^2}\left[1 + \frac{p^2}{\Lambda^2} + \frac{p^4}{\Lambda^4} + \cdots\right]$$

D=6

SMEFT: the new SM

- Wilsonian approach: our world is a low energy EFT
  - SM: all possible relevant & marginal operators
  - SMEFT: tower of irrelevant operators
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge invariant operator set
  - Linear realisation of EW symmetry breaking: Higgs field is an SU(2) doublet
- Order-by-order: self-consistent, renormalisable QFT
  - Unlike an 'Anomalous Couplings' approach
  - It is a theory, applicable within a finite energy range $< \Lambda$
- Can be matched to UV theories of new physics
  - Each theory predicts specific Wilson coefficients
  - Patterns/correlations among them

SMEFT operators

'Warsaw' basis

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

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

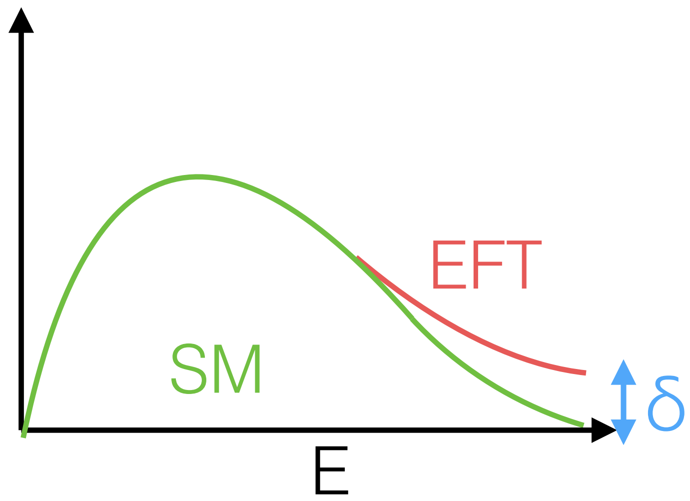
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Complete, non-redundant set of operators: Basis
- Dimension 6: 59 (76 real) - 2499 operators
  - Depends on CP/flavour assumptions
  - New parameters to be measured at the LHC & beyond

SILH
HISZ
Higgs
…

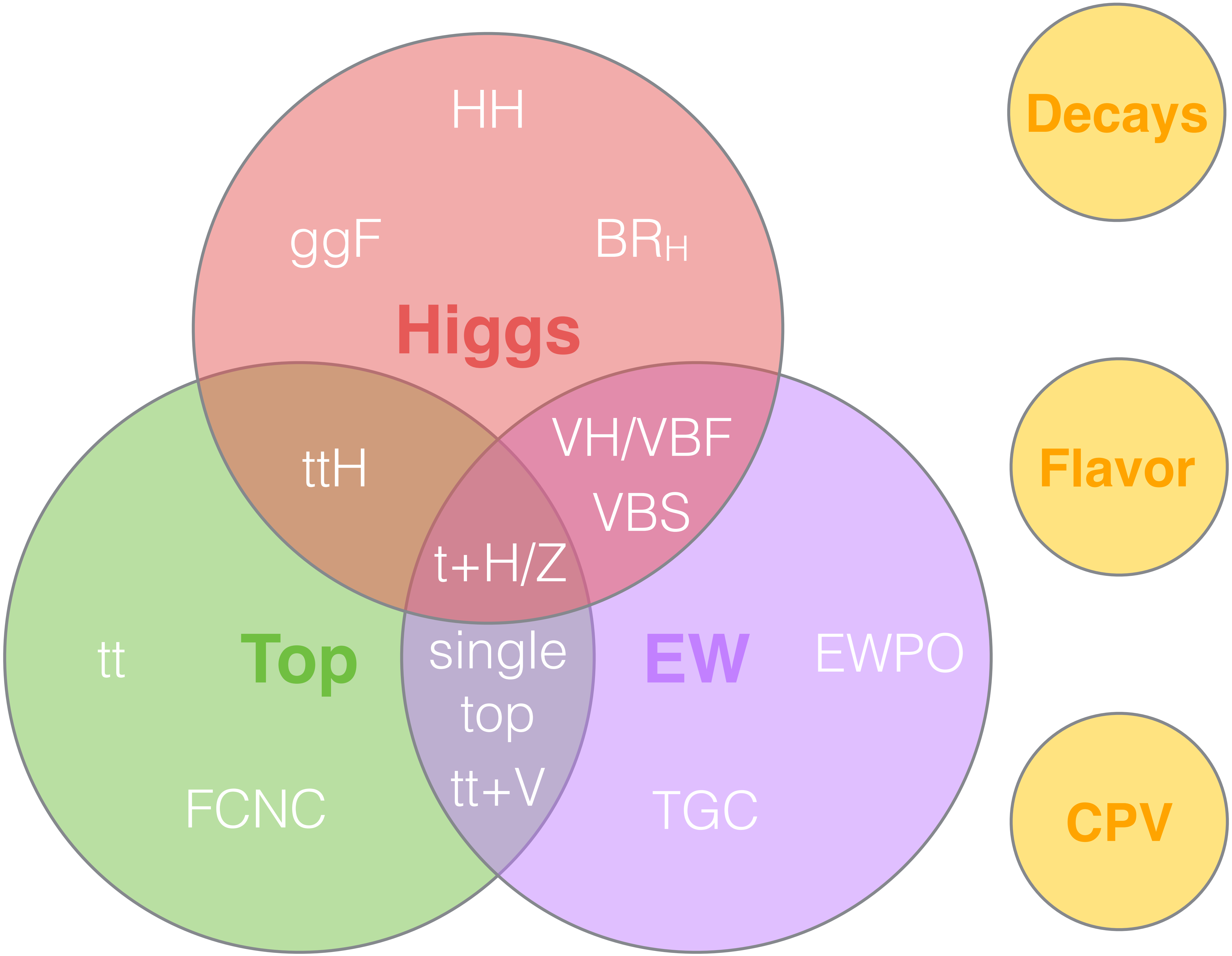
SMEFT at the LHC



Higgs/gauge interactions
Precision top physics
EW production processes
Blind directions from low energy experiments (LEP,...)

- We have a great theory, lets test it!
  - How? by measuring SM processes at inclusive & differential level
  - And then? like for the SM at LEP, perform a global fit
- The LHC is a great high-energy machine to do this
  - Countless SM measurements & even a few dedicated EFT interpretations
- What do we need?
  - Precise MC tools for signal generation
  - Well designed analyses/measurements with control over energy scale

SMEFT at the LHC: key players



General strategy

- Process that gets contributions from SMEFT operator(s)
- Step 1: sensitivity
  - Process → sensitive observable(s)
  - Determine functional dependence of observable on Wilson coefficients

MC implementations ↓

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

  - One at a time → all together
- Step 2: LHC study
  - Observable in fiducial detector volume
  - Unfolded detector effects but not to full phase space (model dependent)
  - Never sensitive to deviations outside the fiducial region

General strategy

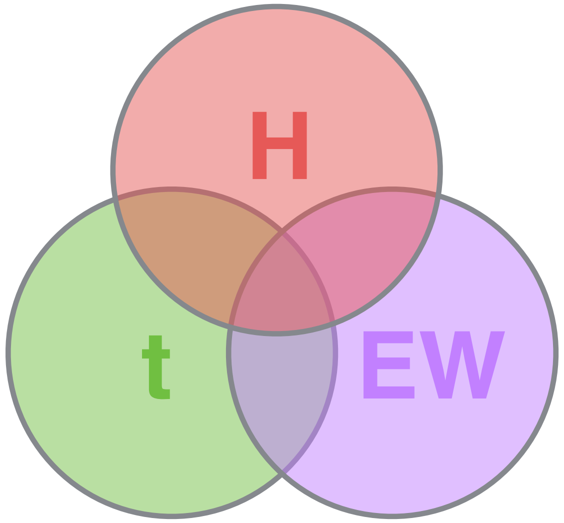
- Step 3: LHC measurement
  - If unfolded to particle level ➝ reinterpretation without full/fast-sim
  - If MVA used: more complicated but not a showstopper
  - Reproducible event selection & background rejection
  - Easy to include in global fit
  - Dedicated EFT interpretation possible here
  - Control energy scale, binned observables or variable upper cuts
- Step 4: Input to global fit
  - Combine many such observables & perform statistical interpretation
  - Validity (energy scale vs cut-off) assessment a posteriori
  - Compare to UV models

Tools for SMEFT

- Ultimate goal: a precision global fit to all available data including LHC measurements
  - Need precise theoretical predictions for the full SMEFT
- Higher order (NLO) predictions
  - Control over scale and PDF uncertainties
  - Also scale uncertainty due to running of Wilson coefficients
  - Operators mix under renormalisation group running
  - New operators can enter at loop-level
- So far, existing global fits are performed
  - At leading order in perturbation theory
  - Separately for the Higgs/EW and top quark sectors

Need for a public, comprehensive implementation of SMEFT at NLO in QCD for the LHC

Top/Higgs/EW SMEFT



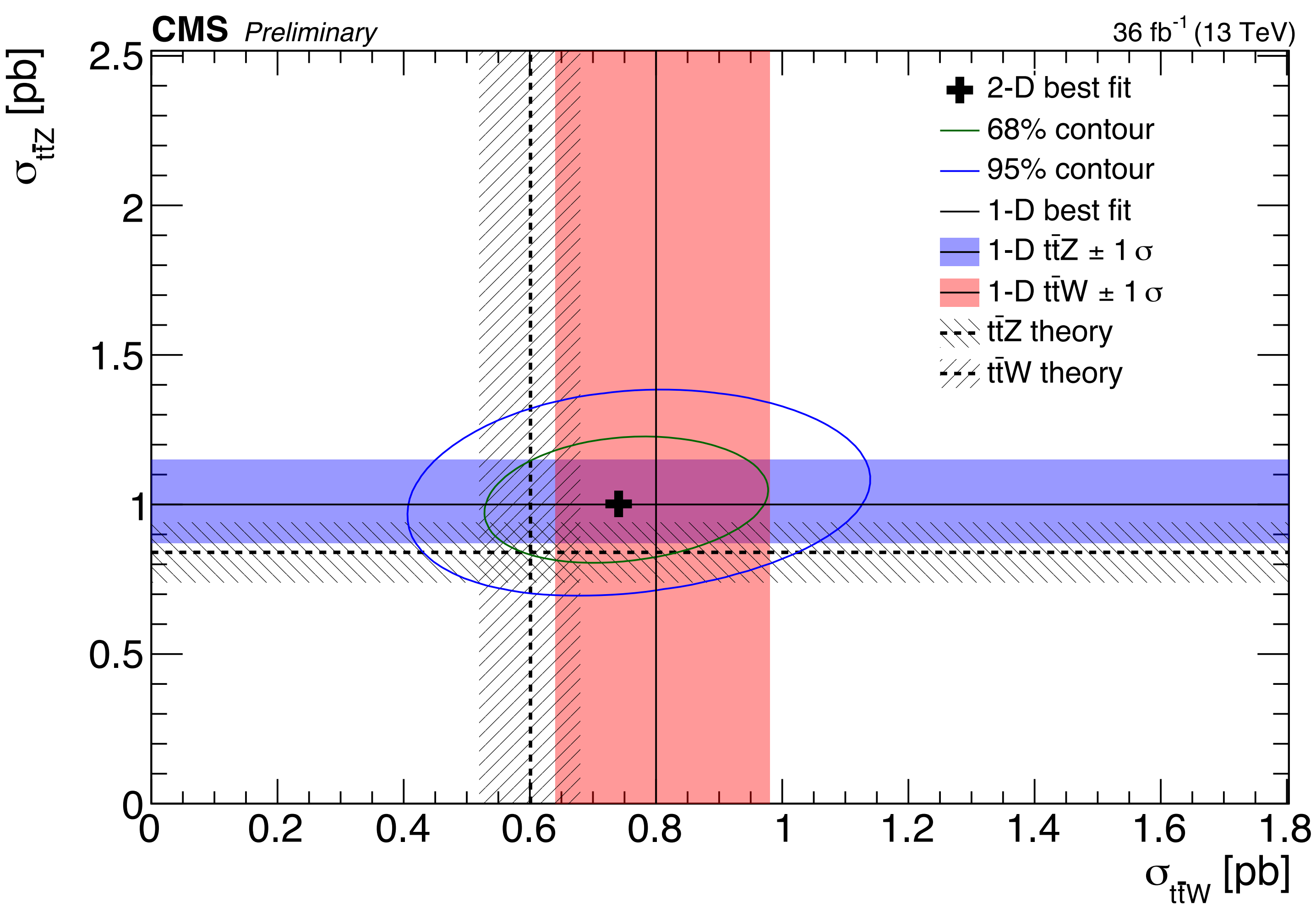
- Explore the origin of EW symmetry breaking
  - Precisely measure the interactions of the Higgs boson
  - Continue to probe EW gauge boson sector post-LEP
- Top quark is also a crucial ingredient in the story
  - Top-Higgs-W/Z couplings/masses are related in SM: unitarity cancellations
  - May reveal hints about the underlying nature of EWSB
  - Coloured particle, strongly coupled to the Higgs
  - QCD corrections relevant & interesting
- Many measurements at the LHC (total/differential/boosted)
  - Also rare processes *e.g.* tt+Z/W/γ, ttH (NEW!), tZj (NEW!)
  - Possibility to simultaneously probe all three sectors

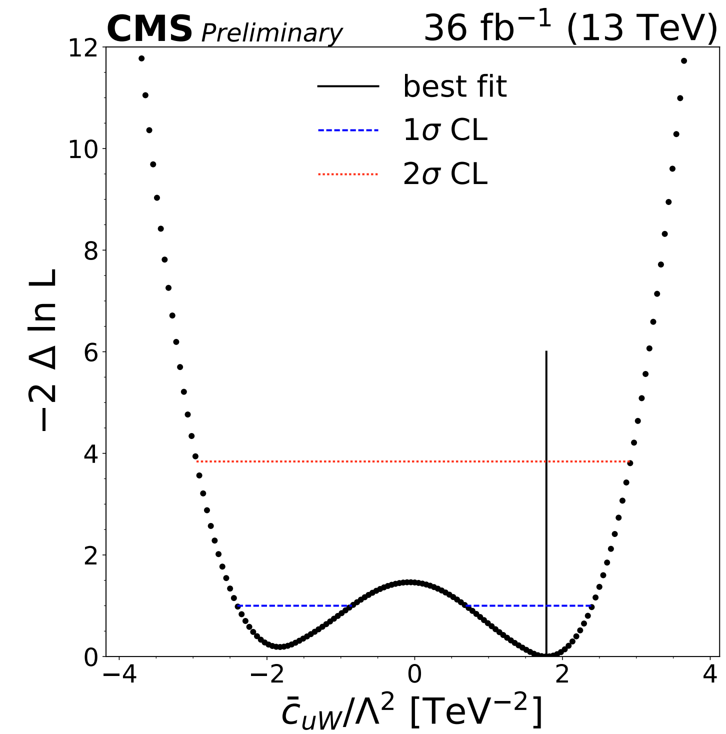
[CMS-PAS-TOP-17-005]

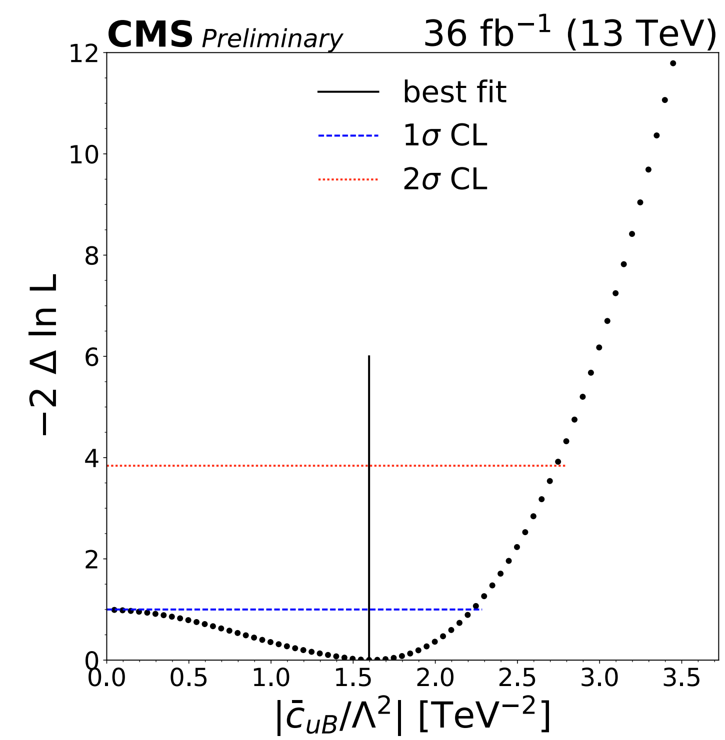
Top/Higgs/EW EFT @ LHC

- CMS ttW & ttZ cross section measurement with EFT interpretation
- Backgrounds: ttH, tZj, tHj,…

Are also modified by EFT!







SMEFT@NLO

- Unified MC implementation for top/Higgs/EW sector
  - All processes at NLO QCD accuracy with, e.g. MadGraph5_aMC@NLO
  - Flavour symmetry assumptions to reduce 2499-dim. parameter space
  - Single out top interactions in a controlled way
- Based on a body of previous work concerning NLO SMEFT predictions for top processes and EW Higgs production

VH & VBF

ttH, ttZ, ttγ

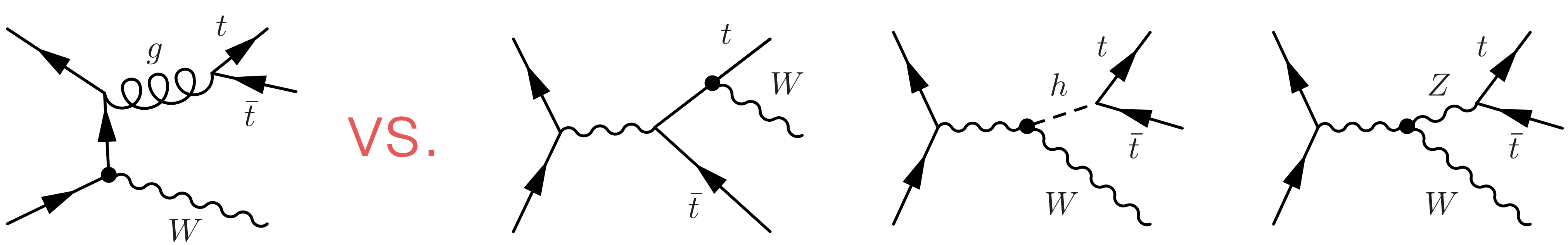
tt & Single top

top FCNC

[KM, Sanz & Williams.; JHEP 1608 (2016) 039]
[Degrande, Fuks, Mawatari, KM & Sanz; 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]

Case study: tZj/tHj

- Processes involving top+Higgs/W/Z
  - Interesting set of LHC-accessible processes to study EW sector + top
  - Unitarity cancellations ↔ top mass generation mechanism
- Previous tt+X EFT studies considered QCD contributions
  - In the SM, pure EW contributions 2 orders of magnitude smaller
  - EFT effects can strongly enhance these due to unitarity-violating behaviour



- SMEFT interpretation different from anomalous couplings
  - Quantitative power counting/expansion for high energy behaviour

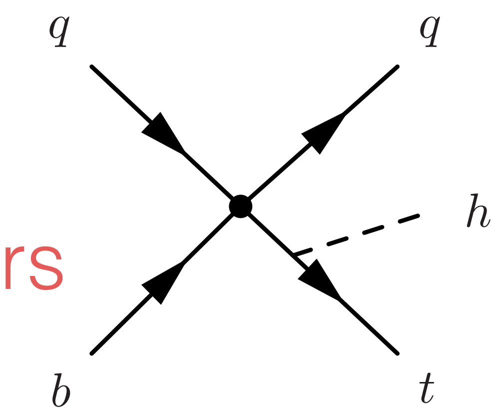
Case study: tZj/tHj

- Alternative to tt+X: require a single top quark
  - Eliminates dominant 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
  - Possibility of probing large 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

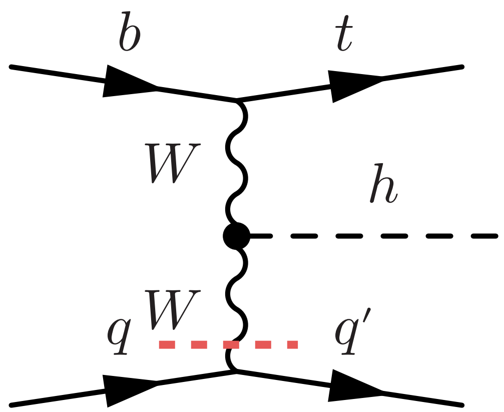
  [ATLAS; arXiv:1710.03659], [CMS-PAS-TOP-16-020 & arXiv:1712.02825]
- Timely moment to perform EFT sensitivity study in this pair of challenging processes & showcase model implementation

Anatomy of tHj/tZj

Single-top 4f operators



tHj (tZj = h→Z)

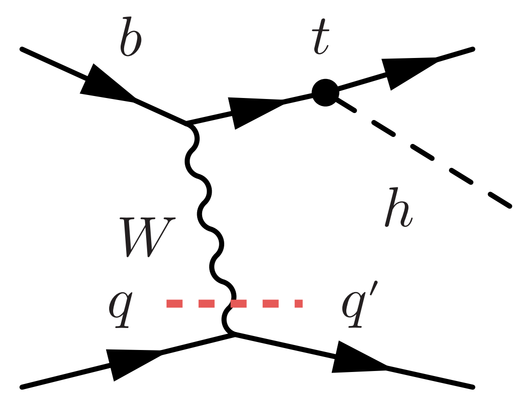


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

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

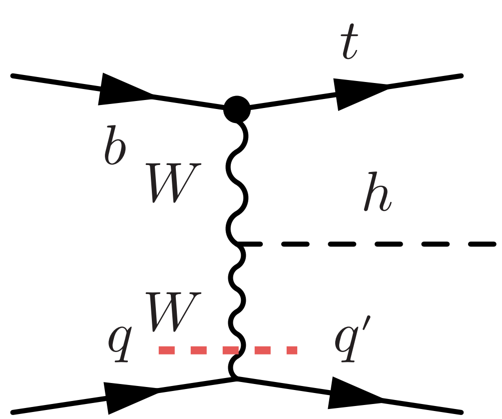


$\mathcal{O}_{t\varphi}$

top Yukawa

ttZ coupling

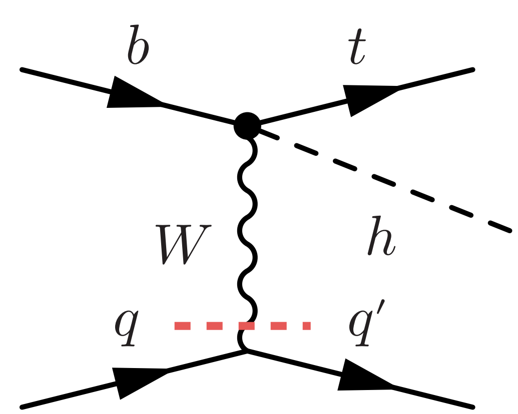
$\mathcal{O}_{\varphi t}$



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

Wtb vertex

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



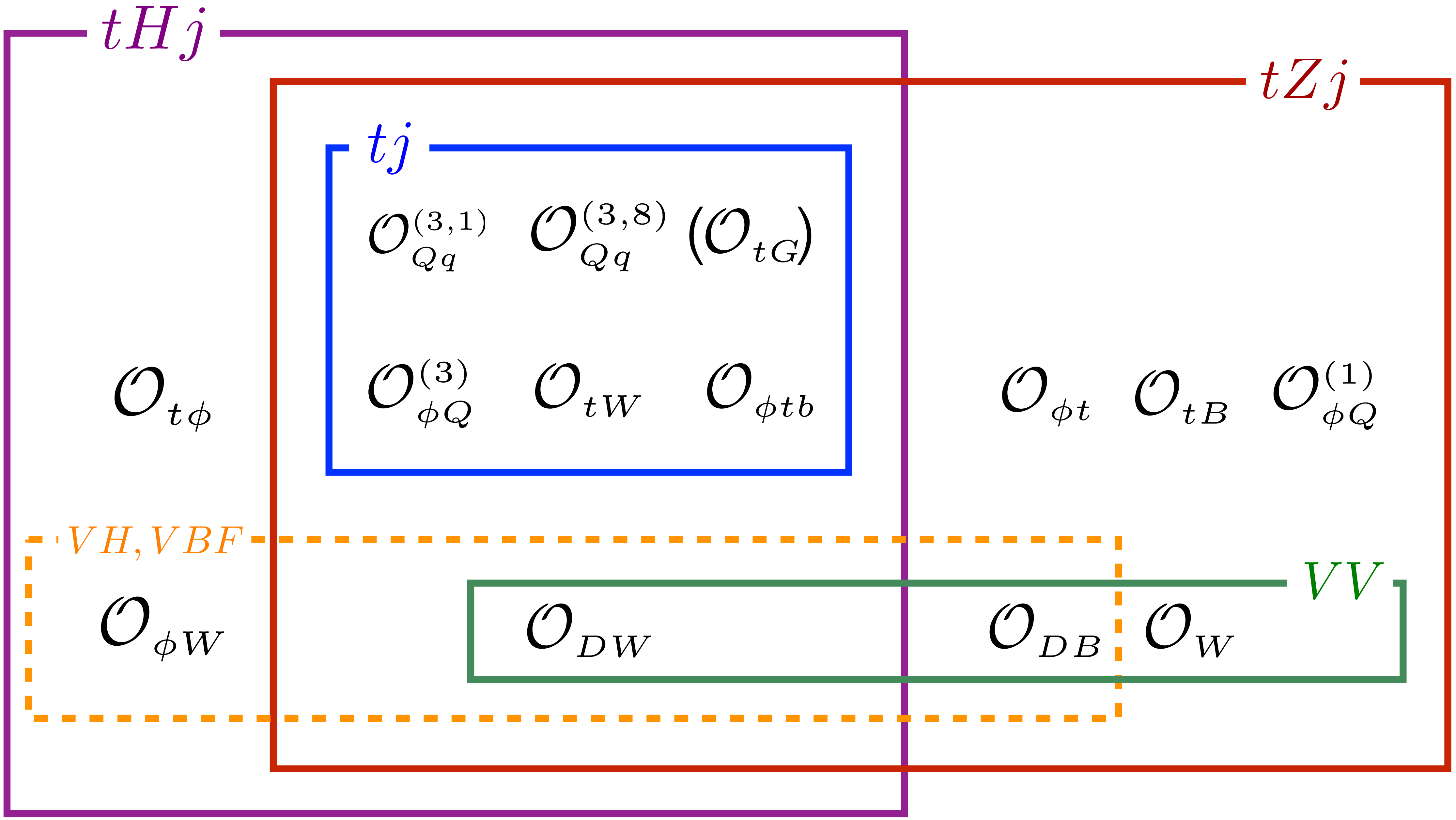
$\mathcal{O}^{(3)}_{\varphi Q}$

Contact terms

$\mathcal{O}_{tB}$

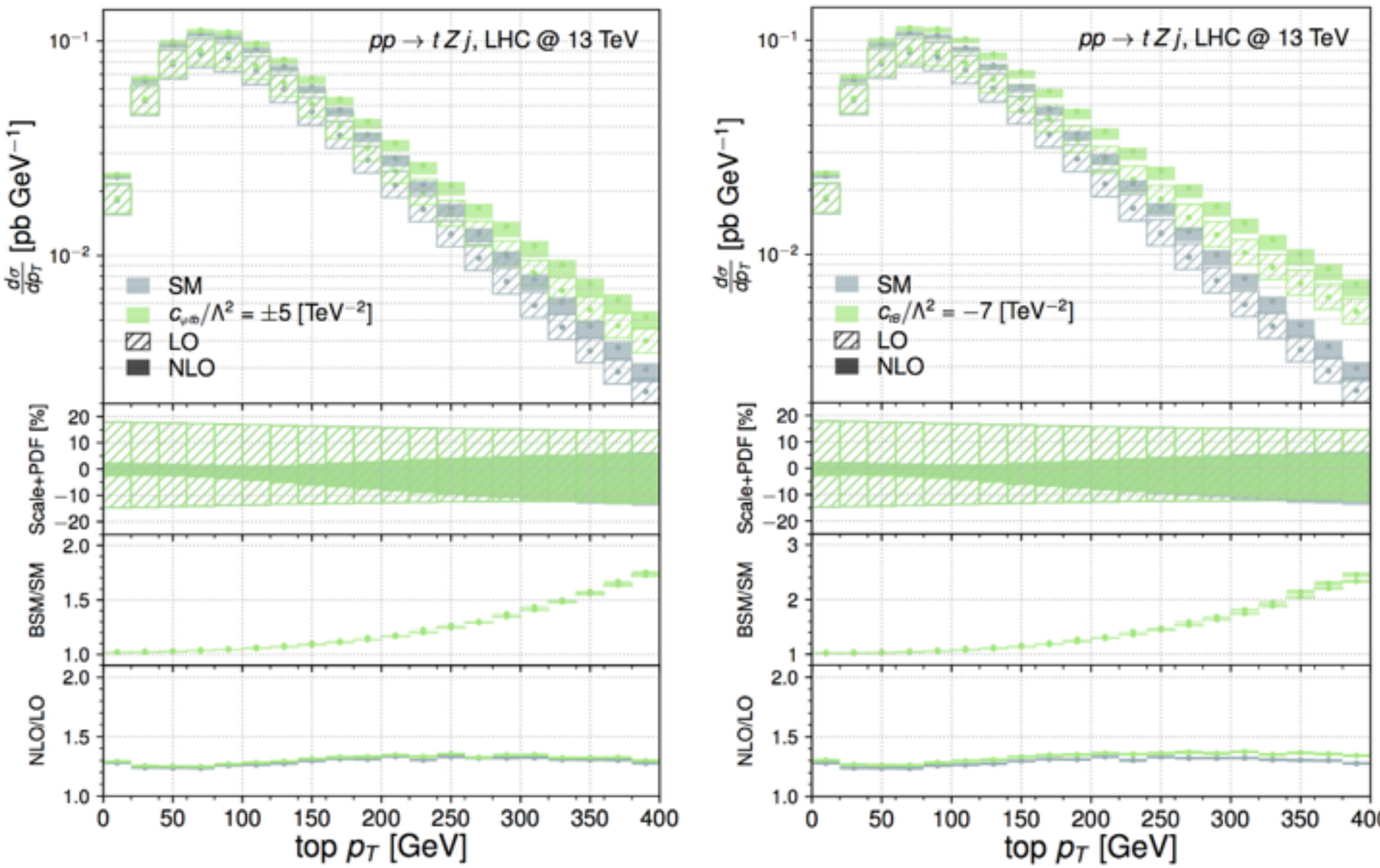
- Accessing the bW→tH & bW→tZ sub-amplitudes
  - Rich interplay between EFT operators from different sectors
  - Different energy growth and interference patterns with the SM

Interplay



+ ttW/Z/H/γ

LHC sensitivity



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}	0.0275	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 certain operators

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

High p_T tZj: end of run II/HL-LHC
tHj: HL-LHC ?

Future sensitivity

tZj

TGC

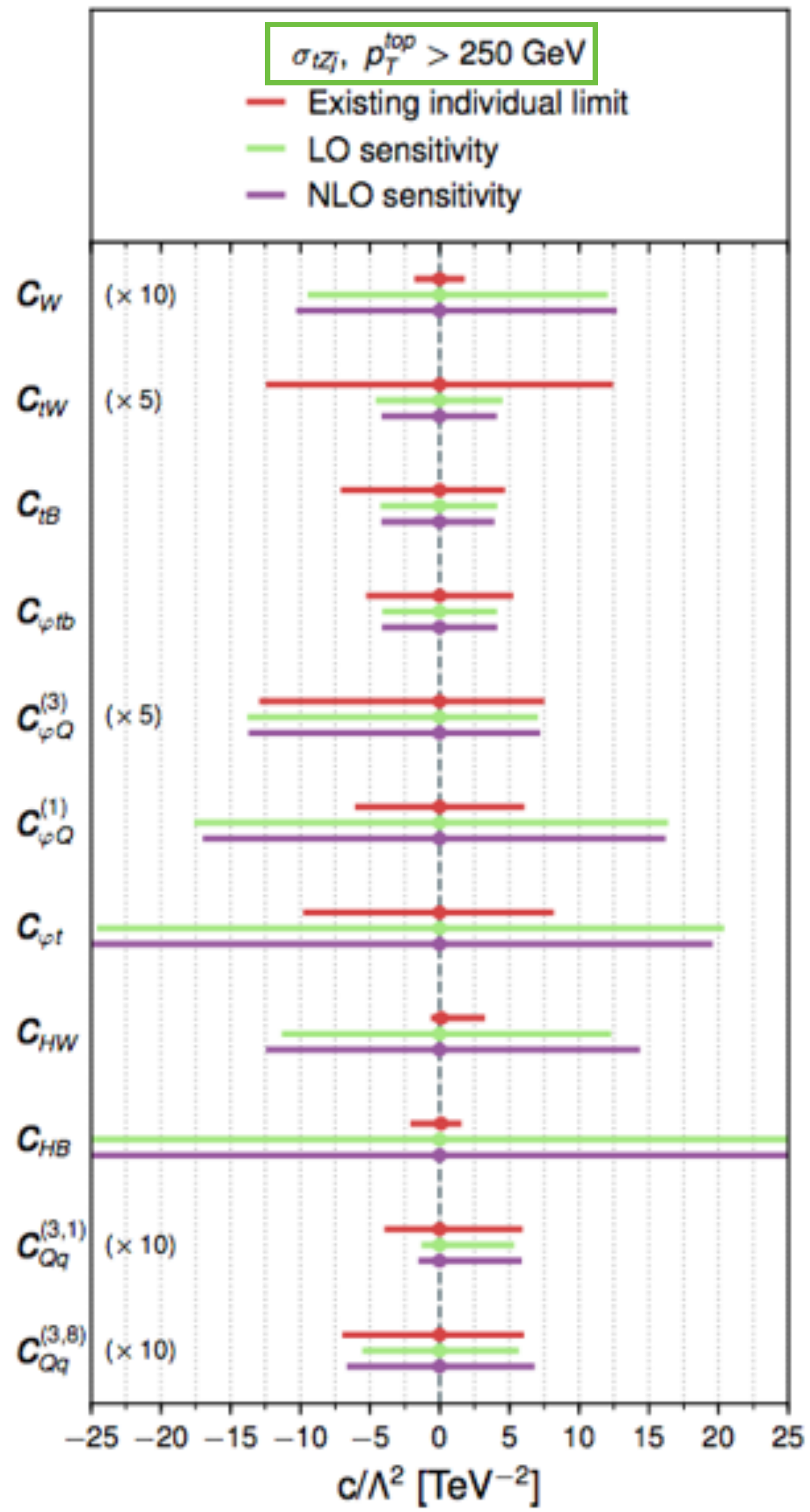
Dipoles

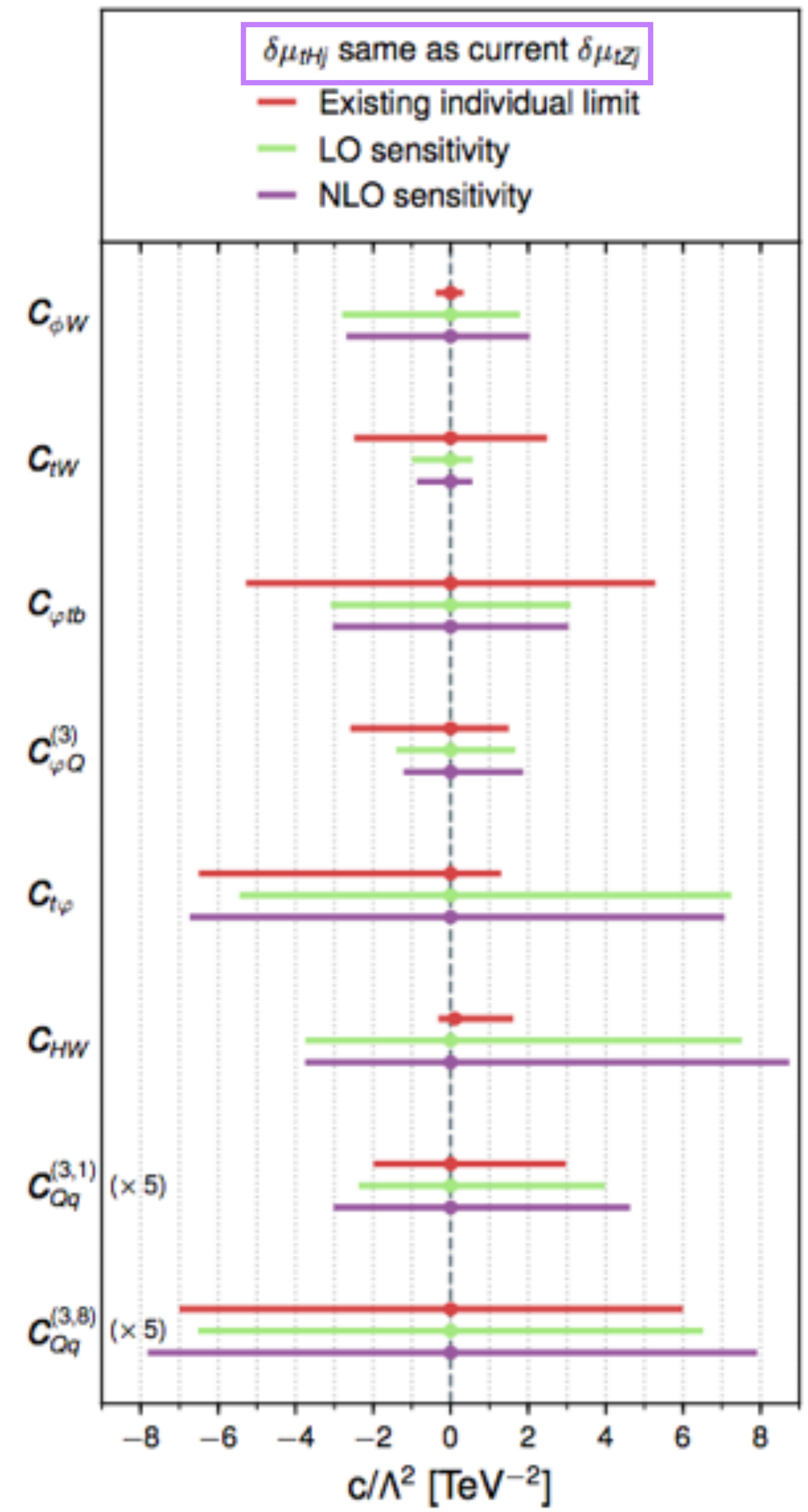
RHCC

Currents

LEP orthogonal

4-fermion





tHj

Gauge-Higgs

Dipole

RHCC

Currents

LEP orthogonal

4-fermion

Top 4F operators @ LHC

- Generated by heavy, new physics coupling to 3rd generation
  - Top mass generation
  - Z'/Composite dynamics?
- Contain tttt, ttbb and bbbb interactions
  - Colour singlet & triplet
  - Vector & scalar currents
- One way to constrain them is by measuring four top production
  - Only a subset of operators

$$O^1_{QQ} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{Q}\,\gamma^\mu\,Q)\,,$$

- $$O^8_{QQ} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{Q}\,\gamma^\mu\,T^A\,Q)\,,$$
- $$O^1_{tt} = (\bar{t}\,\gamma_\mu\,t)\,(\bar{t}\,\gamma_\mu\,t)\,,$$

$$O^1_{tb} = (\bar{t}\,\gamma_\mu\,t)\,(\bar{b}\,\gamma_\mu\,b)\,,$$

$$O^8_{tb} = (\bar{t}\,\gamma_\mu T^A\,t)\,(\bar{b}\,\gamma_\mu\,T^A\,b)\,,$$

- $$O^1_{Qt} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{t}\,\gamma^\mu\,t)\,,$$
- $$O^8_{Qt} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{t}\,\gamma^\mu\,T^A\,t)\,,$$

$$O^1_{Qb} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{b}\,\gamma^\mu\,b)\,,$$

$$O^8_{Qb} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{b}\,\gamma^\mu\,T^A\,b)\,,$$

$$O^1_{QtQb} = (\bar{Q}\,t)\,\varepsilon\,(\bar{Q}\,b)\,,$$

$$O^8_{QtQb} = (\bar{Q}\,T^A\,t)\,\varepsilon\,(\bar{Q}\,T^A\,b)$$

Four top production

- Very rare process at the LHC ~ 9 fb
  - Best effort at the LHC about 4.6 times the SM

[ATLAS-EXOT-2016-13]
[CMS; EPJC 78 (2018) 2, 140]
[Zhang; Chin. Phys. C42 (2018) 023104]

- Not a precision measurement
  - Sensitive to four heavy quark & 2 heavy + 2 light quark operators
  - High threshold ~ 700 GeV

[TeV^{-2}]

$$
\begin{array}{lll}
c^1_{Qt} & [-4.97, 4.90] & (E_{cut} = 3\,\mathrm{TeV}) \\
c^8_{Qt} & [-10.3, 9.33] & (E_{cut} = 3\,\mathrm{TeV}) \\
c^1_{tt} & [-2.92, 2.80] & (E_{cut} = 3\,\mathrm{TeV})
\end{array}
$$

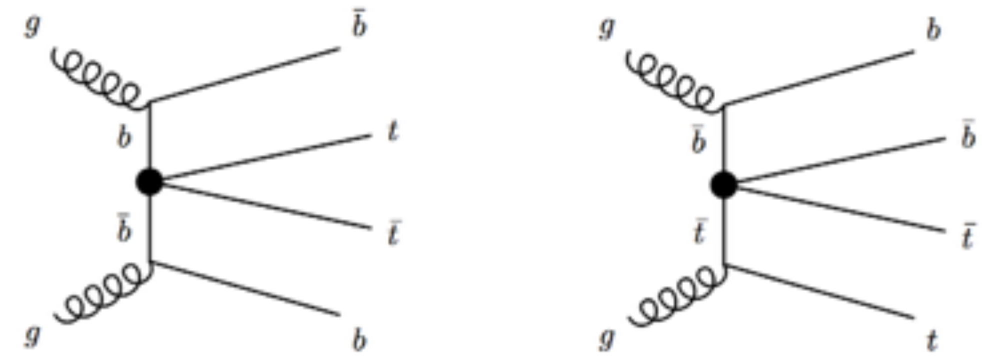
3 out of 14 relevant degrees of freedom

Best limit: dedicated ATLAS EFT interpretation!

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

[D'Hondt, Mariotti, KM, Moortgat, Zhang; in preparation]

ttbb production



- Less rare process at the LHC ~ 3 pb
  - Measured at the LHC with ~ 30% accuracy *[CMS; PLB 776 (2018) 355-378]*
  - Major background for ttH(bb) search
  - Turn it around into a new physics signature!
- Affected by all but one of the14 operators *[Degrande et al.; JHEP 03 (2011) 125]*
  - Some of which have never been bounded before
- Sensitivity study of ttbb to four heavy operators
  - New limits on 3rd generations four-quark operators
  - Future projections of dedicated analyses optimised to EFT kinematics
  - Experimented with multivariate classification techniques
  - Sensitivity may exceed that of 4 top for operators common to both

General strategy

ttbb

- Process that gets contributions from SMEFT operator(s)
- Step 1: sensitivity

  M_{4b} & NN discriminant

  - Process → sensitive observable(s)
  - Determine functional dependence of observable on Wilson coefficients

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

  - One at a time → all together
- Step 2: LHC study

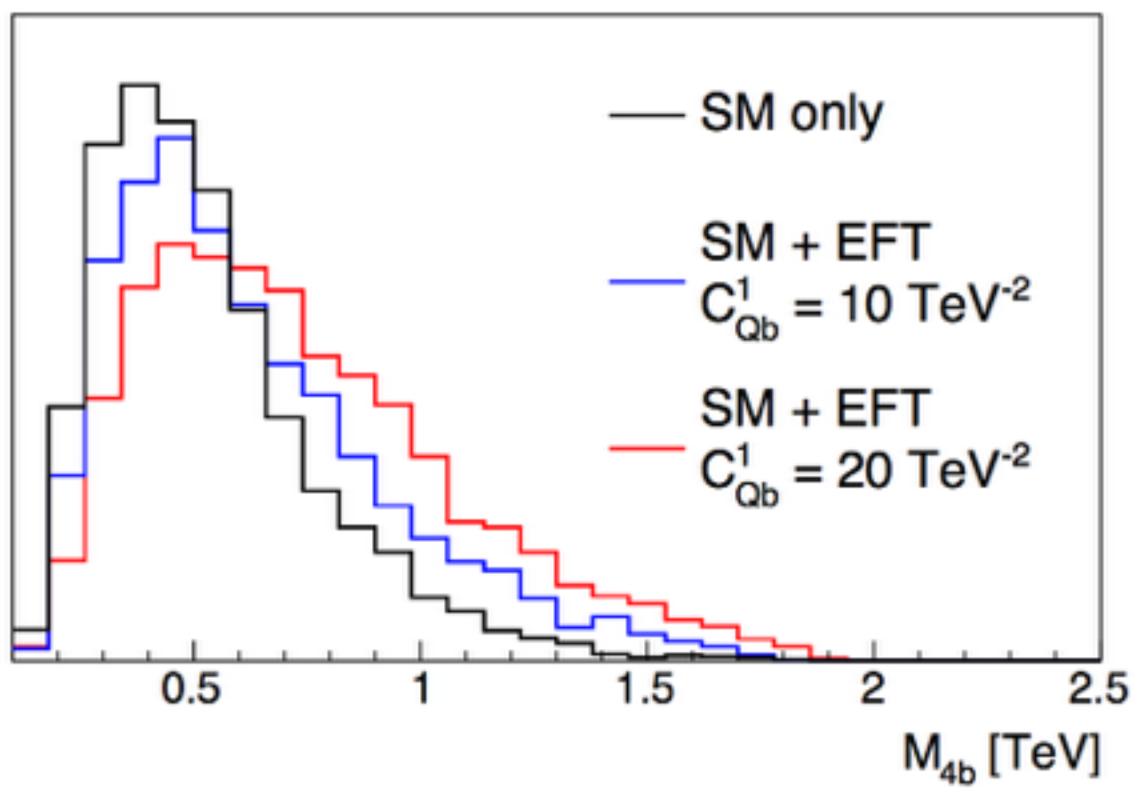
  MG5_aMC@NLO + Pythia8 + Delphes

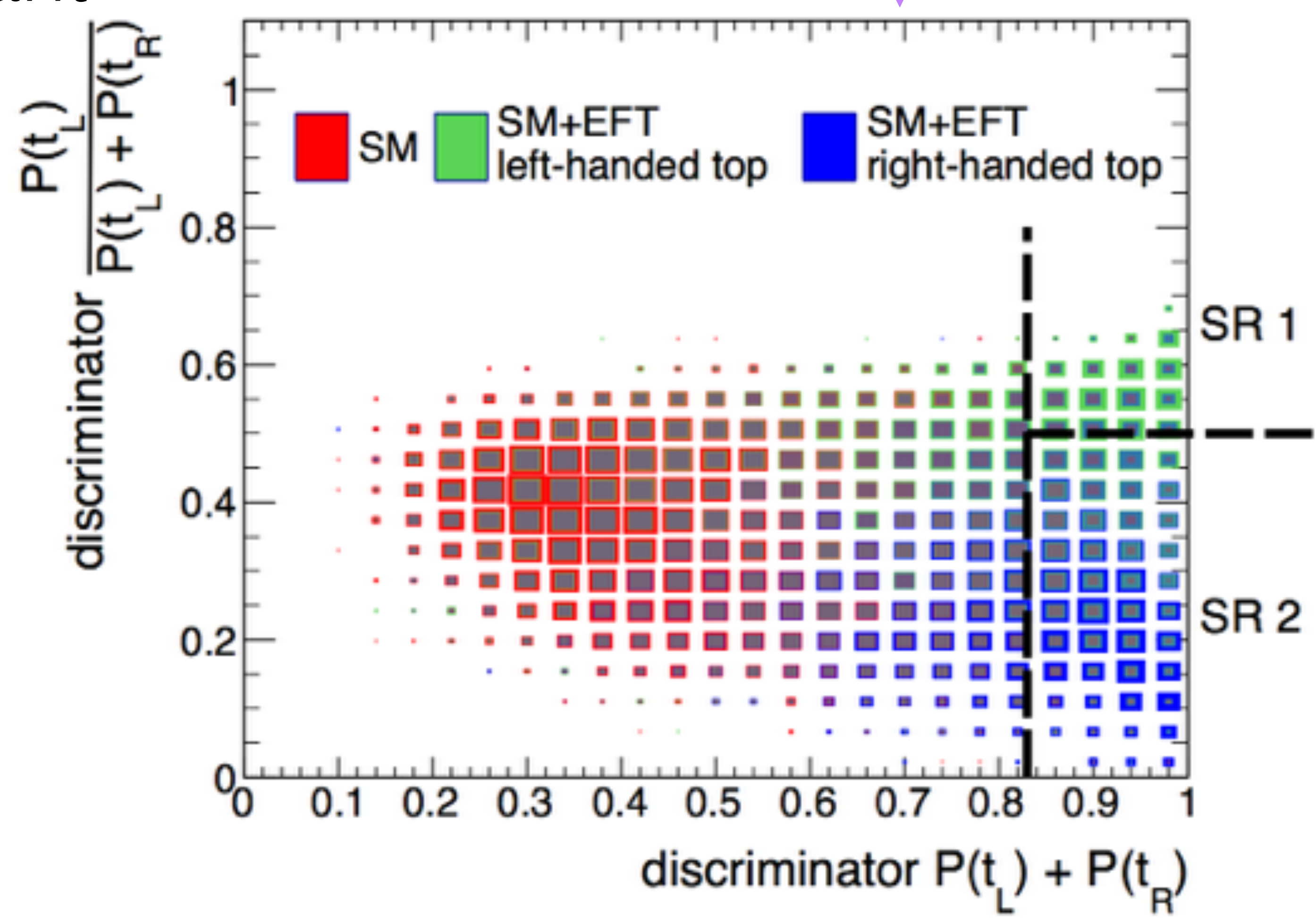
  - Observable in fiducial detector volume
  - Unfolded detector effects but not to full phase space (model dependent)
  - Never sensitive to deviations outside the fiducial region

Observables

- "High energy" kinematic variable M_{4b}
  - Bulk of sensitivity to 4F operators
  - Sensitivity comes from events below 1.5 TeV → M_{cut} = 2 TeV
- Multi(3) class NN discriminant
  - SM vs t_L operators vs t_R operators

Cut on discriminant
vs.
template fit





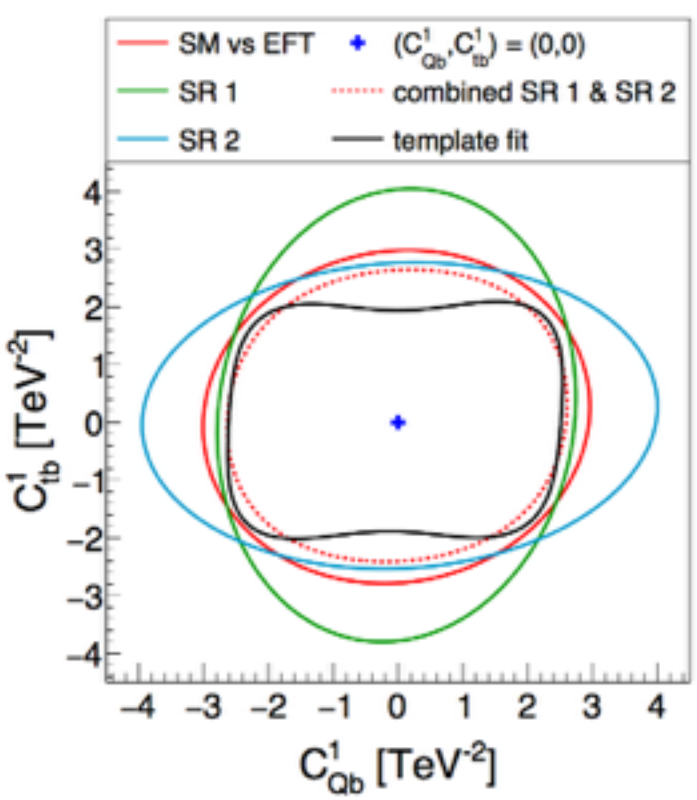
LHC sensitivity

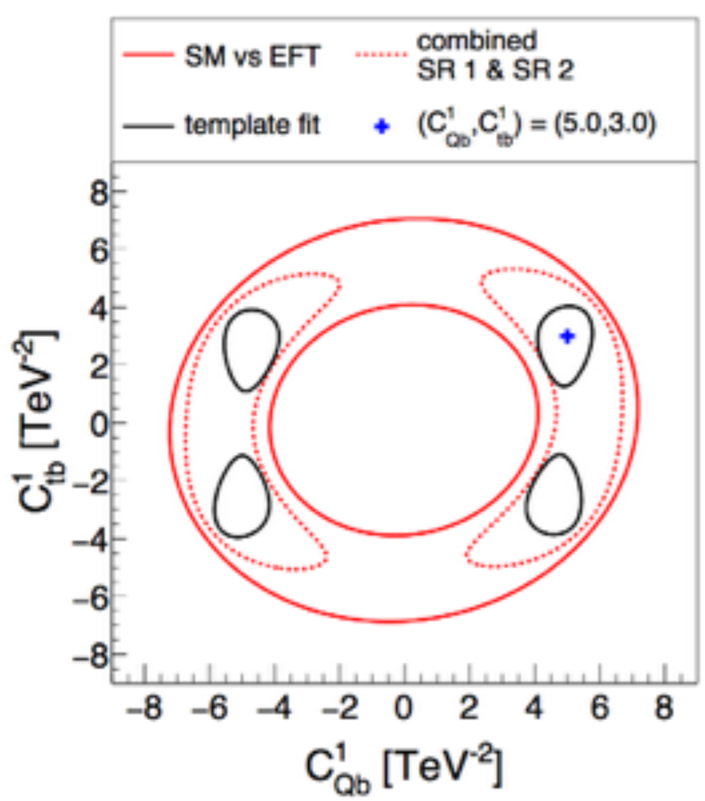
1) Assuming SM observation

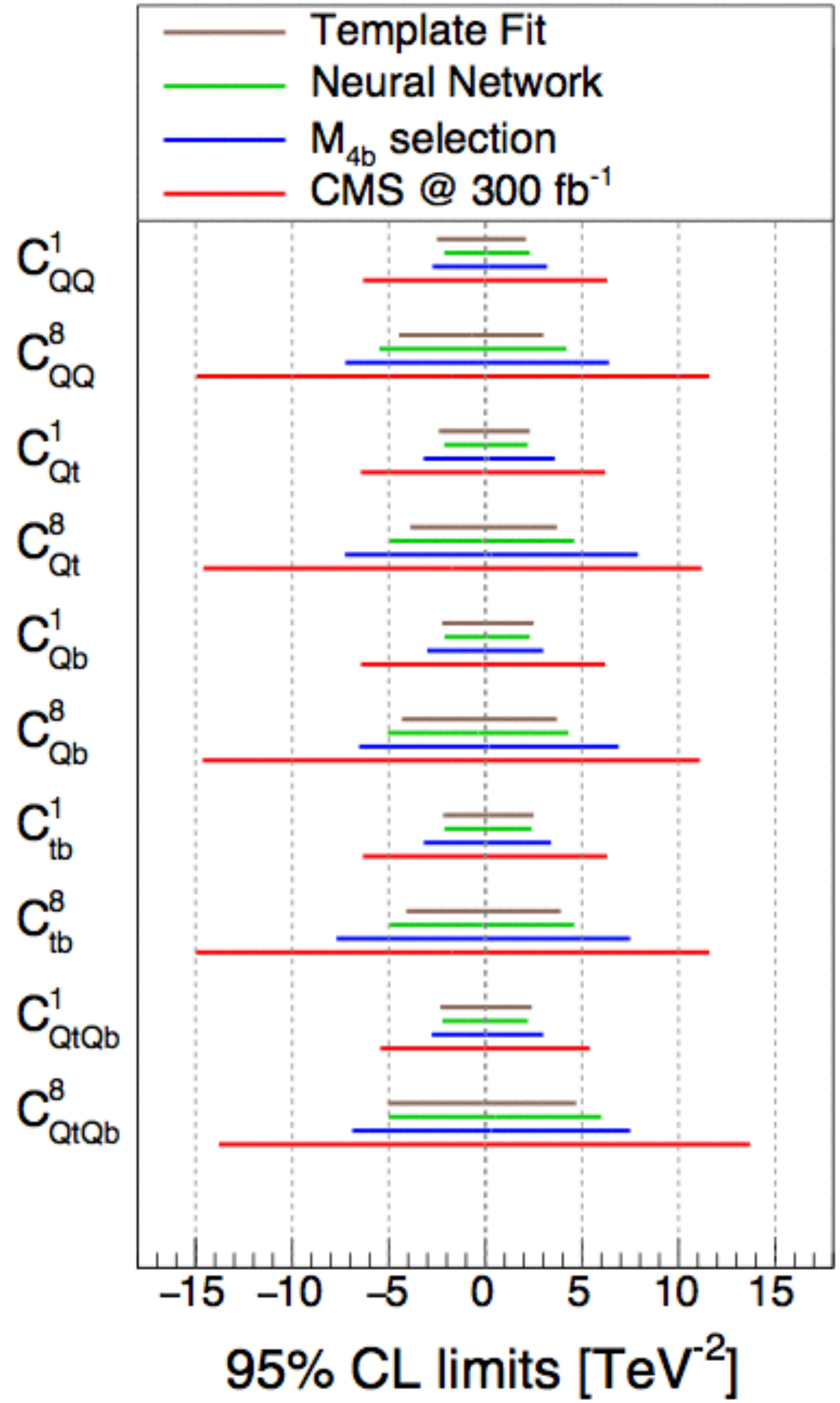
- Improve on inclusive measurement
- Template fit to NN similar to M_{4b}

2) EFT signal injection

- NN focuses in on preferred parameters







Conclusion

- The LHC has entered an EFT era
- SMEFT: consistent framework to go beyond the SM
  - Theory consensus for global description & MC implementation
  - Extended to top/Higgs/EW sector & NLO in QCD
- Global view of top/Higgs/EW measurements
  - Blurring the line between signal & background
  - Different approach needed?
  - Ensure measurements can be interpreted by a global SMEFT fit
- Many unexplored processes
  - New sensitivity studies ripe for the picking!
  - Single MC tool for all top/Higgs/EW processes at the LHC

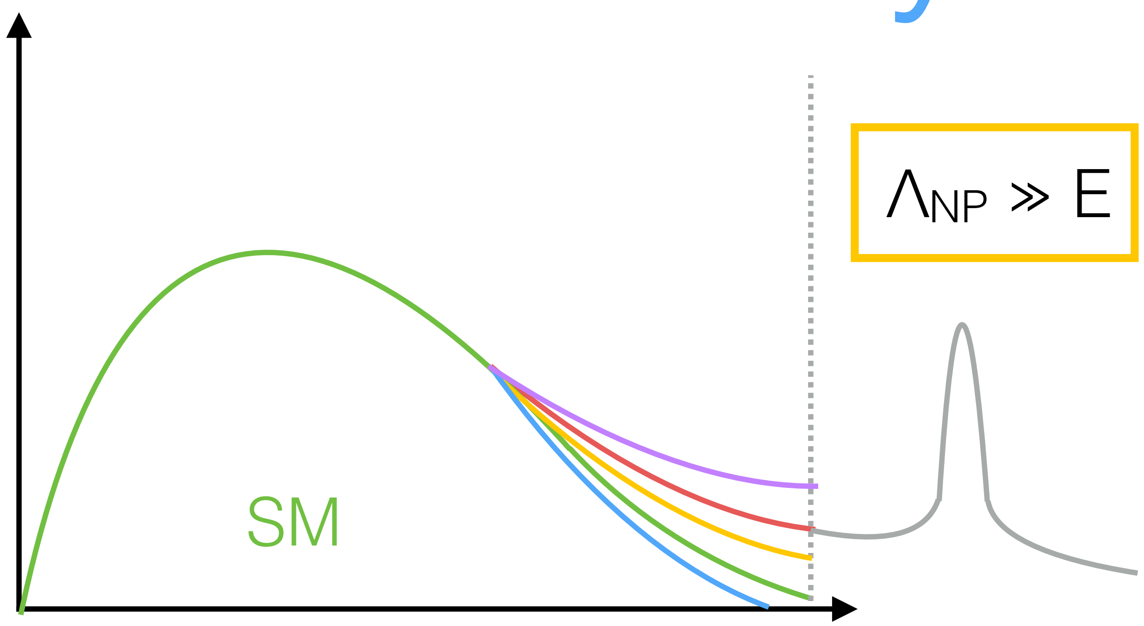
Université catholique de Louvain

Thank you

Interpretation

- Global likelihood in SMEFT parameter space
- Individual & marginalised confidence intervals
  - Individual limits are useful to quantify degree of sensitivity to given coeff.
  - Marginalised intervals reveal degeneracies/blind directions
- Impact of including or not squared EFT terms
- Constraints as a function of cuts
  - Allow a wider range of model interpretations (different NP mass scales)
  - Perturbativity in Wilson coefficients
- Matching to UV models
  - Correlated Wilson coefficients → better limits
  - Validity & perturbativity in NP couplings

EFT validity



Q: How well does my EFT approximate full theory?
A: Depends on the theory!
Q: But I thought EFT was model independent….

- Two "expansions" occur
- Lagrangian level, (E/Λ_{NP}), truncated at operator dimension
  - Golden rule: cannot probe energies beyond Λ_{NP}

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

- Observable level, (c_i E/Λ_{NP}) truncated at… ?

$$\sigma = \sigma_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\sigma_i^{(6)} + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4}\sigma_{ij}^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\sigma_i^{(8)} + \cdots$$

EFT expansion

- Practically: $$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$
- Observable: $$\sigma = \sigma_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\sigma_i^{(6)} + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4}\sigma_{ij}^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\sigma_i^{(8)} + \cdots$$
- To square or not to square…
  - Formally, D=6 squared part is of the same order as D=8 interference
  - D=8 part, in general, is unknown and/or not feasible
- Is the EFT invalid if (D=6 squared) > (D=6 interference)?
  - Depends on $c^{(6)}_i$, $c^{(6)}_{ij}$, $c^{(8)}_i$ and $\sigma^{(6)}_i$, $\sigma^{(6)}_{ij}$, $\sigma^{(8)}_i$ → model dependence
  - At most, the σ scale with energy as: $\sigma^{(6)}_i \sim E^2$, $\sigma^{(6)}_{ij} \sim E^4$, $\sigma^{(8)}_i \sim E^4$

Large coefficients

- If c is large *e.g.* Wilson coefficient is poorly constrained
- $(D=6)^2$ terms could be important without invalidating EFT

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

- Truncating L at D=6, σ is not really a series expansion

$$\sigma = \sigma_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \sigma_i^{(6)} + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} \sigma_{ij}^{(6)} \text{ + nothing}$$

- Dropping the squared terms → σ not positive-definite
- If $(D=6)^2$ are relevant, UV interpretations lean towards strongly coupled models (large c's)
    - Most model independent approach: assume nothing about the size of c's

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	$\lvert h(A_4^{\rm SM})\rvert$	$\lvert h(A_4^{\rm BSM})\rvert$
✗	$VVVV$	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 considering finite mass effects or higher order corrections (2 → 3,4)

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

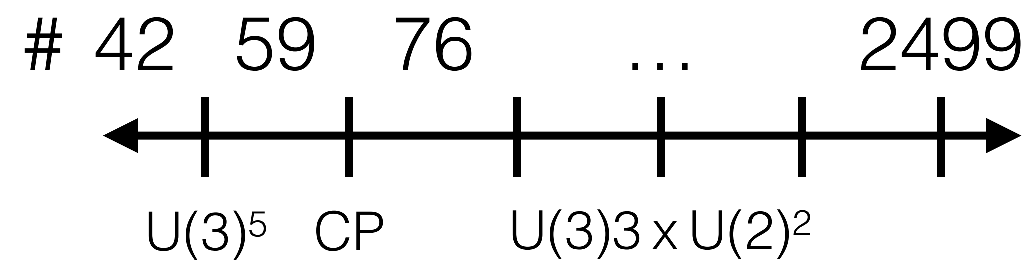
EFT "expansion"

- To square or not to square…
  - Model & process dependent
  - Better calculate both and check the effect of including or not the square
- Relation to the validity question
  - Depends on the sensitivity of each measurement/process
  - We can only constrain (c/Λ) & Λ an arbitrary scale w.r.t to unknown Λ_{NP}
- Validity assessment is an *a posteriori* check at interpretation stage on a process-by-process basis
  - Publish limits as a function of experimental energy

[Contino et al.; JHEP 1607 (2016) 144]

- Realistically can't include D=8 without sufficient motivation
  - If $c^{(6)}_i=0$ e.g. for neutral triple gauge boson couplings

Flavor symmetry



- 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: $U(3)^3 \times U(2)^2$, single out q^3, u^3
  - Similarly MFV: expansion in Yukawa couplings

Going NLO

- Ultimate goal: a precision global fit of SMEFT to 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*]*

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

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

ttH in SMEFT

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

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

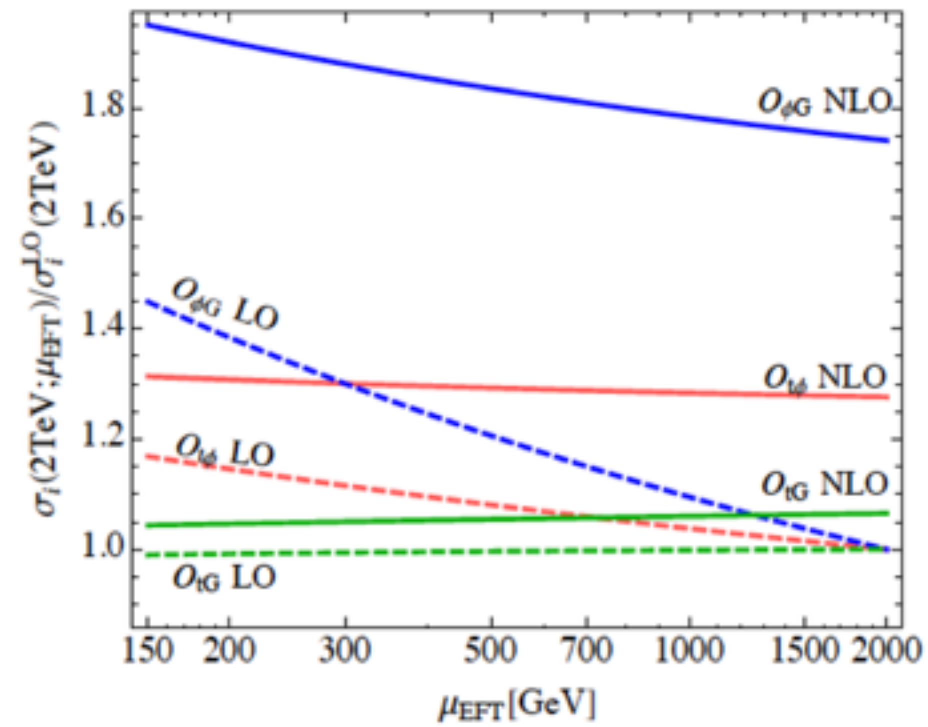
- Operators involving the top/Higgs/gluon
    - gg→H & tt production partly constrain the Wilson coefficient space
    - ttH is the only direct probe of the Top-Higgs interaction
    - In principle 3-gluon O_G and 4 fermion operators also contribute but turn out to be better constrained by tt and multi-jet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

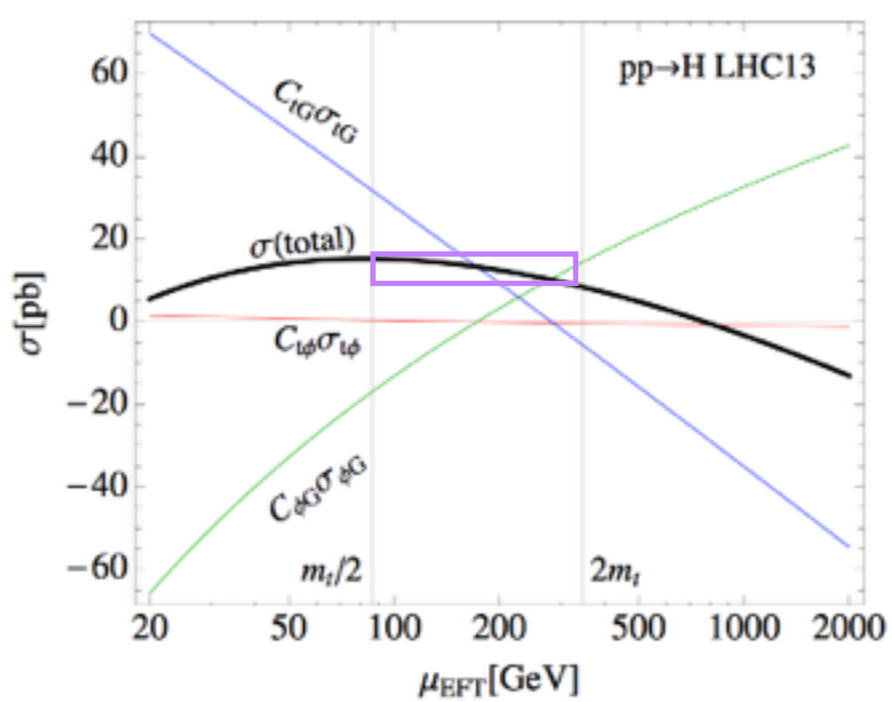
$$\frac{E^2}{\Lambda^2} < 1 < c_i^{(6)}\frac{E^2}{\Lambda^2} < c_i^{(6)}c_j^{(6)}\frac{E^4}{\Lambda^4}$$

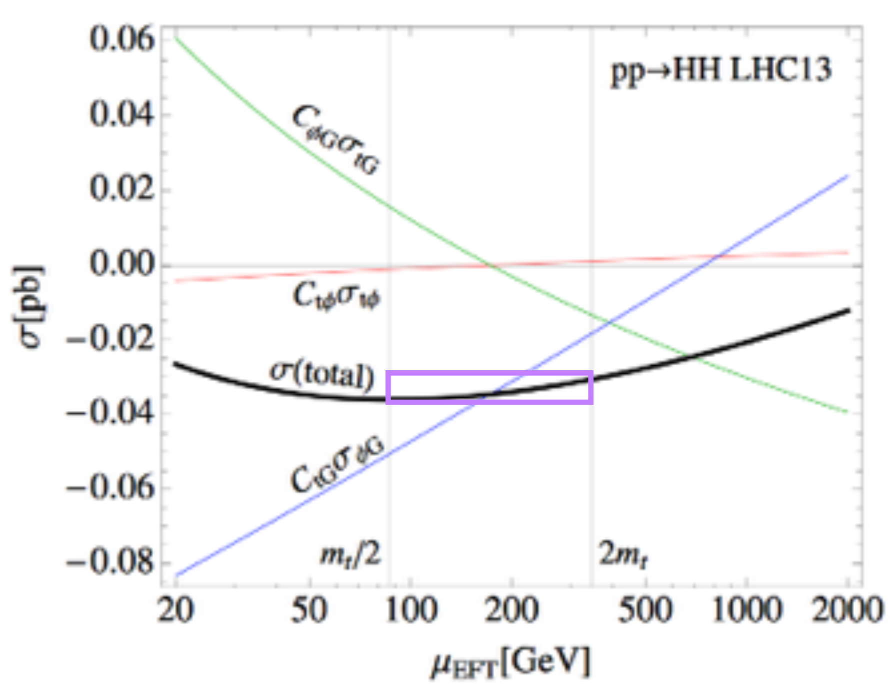
ttH in SMEFT

Update from ttH signal strengths $c_{t\varphi} \subset [-6.5, 1.3]$ TeV^{-2}

- Full NLO stable under scale variation
- Large finite terms: RG improved underestimates NLO
- EFT scale uncertainty estimate
    - Take c_i defined at scales $2\mu_0$ & $\mu_0/2$ and run back to the central scale

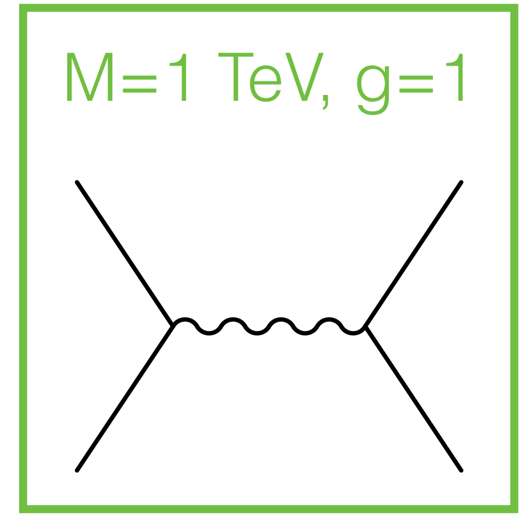




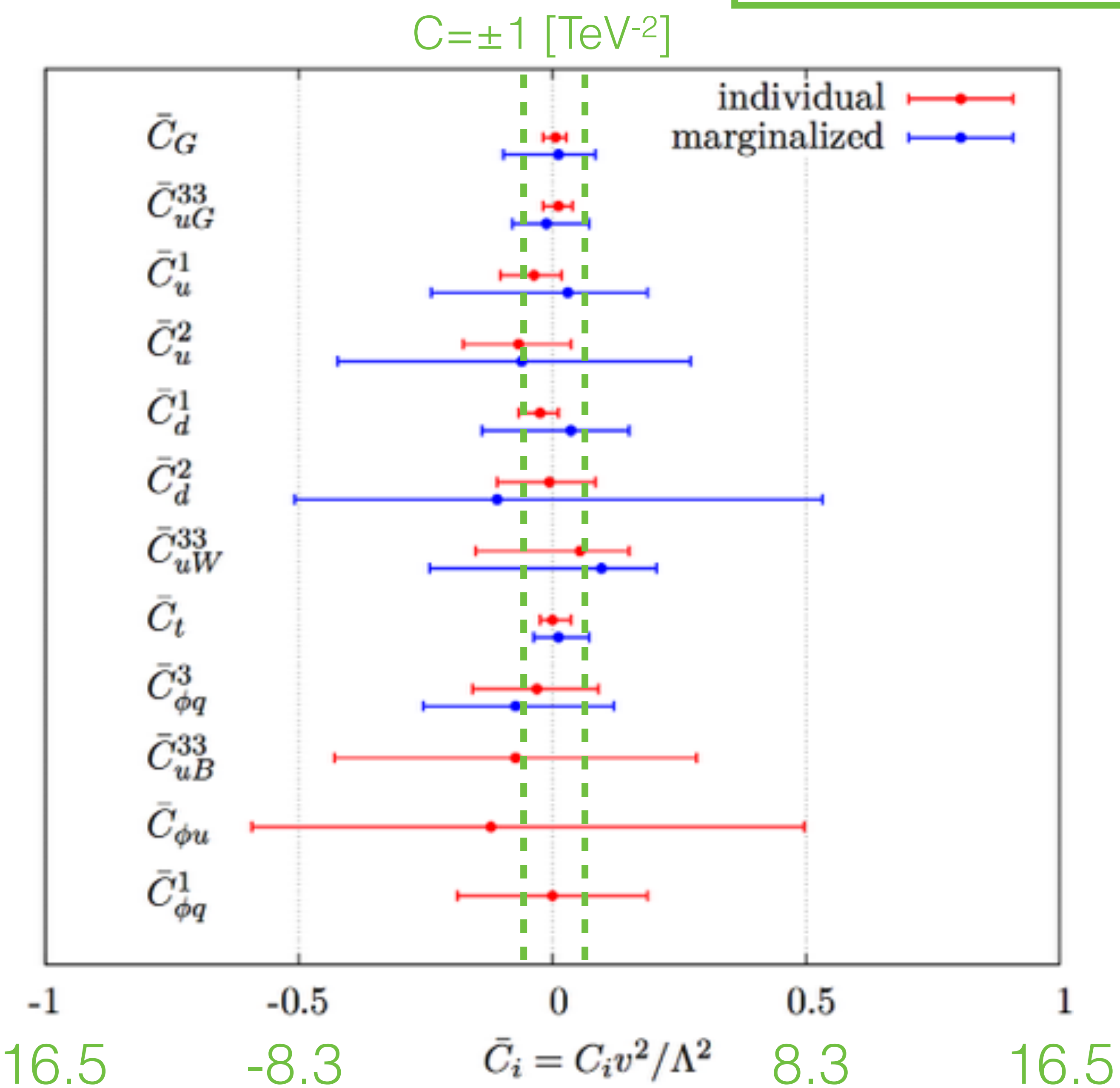


$\delta\mu_{EFT}$: Does not cancel in e.g. cross section ratios

TopFitter



- Constrained a set of 12 operators at LO
  - tt, single-top & tt+Z/γ
  - Helicity fractions, A_{FB} & A_C
- Selected operators that interfere with SM
  - ttg, tbW, ttZ, ggg + linear combinations of 4F operators
  - EFT^2 dependence included in observables
  - Impact is significant
  - Validity assessment necessary



dim6top

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

Interpreting top-quark LHC measurements in the standard-model effective field theory

J. A. Aguilar Saavedra,[1] C. Degrande,[2] G. Durieux,[3] F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors), D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11] M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16] M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17] T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20] A. Tonero,[21] M. Trott,[7] S. Westhoff,[18] C. White,[22] A. Wulzer,[2,23,24] J. Zupan.[25]

- Consensus from the LHC top WG on SMEFT description for top physics
  - Classification of the relevant degrees of freedom (independent operators)
  - Prescription for staged implementation of flavor assumptions
  - Very nice overview & bigger picture discussion
- dim6top: FeynRules/UFO model provided
  - Useful to have a 'unified' & community validated tool
  - Avoid confusion of results presented in different bases, normalisations etc.
  - LO predictions only

All operators previously described (including 4F)

http://feynrules.irmp.ucl.ac.be/wiki/dim6top

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

Anatomy of tHj

- LO helicity amplitudes
  - High energy limit: $s \sim -t \gg v^2$
- Maximum energy growth
  - SU(2) triplet current
  - Interferes with leading SM
  - RH Charged Current
  - Weak dipole
  - Fields strengths source transverse gauge bosons
  - Not captured by Goldstone equiv.
- Subleading energy growth
  - $\propto m_t$ & interferes with sub-leading SM amplitude → no growth

bW → tH (bW → tZ in backup)

$\lambda_b, \lambda_W, \lambda_t$	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	$\sqrt{s(s+t)}$	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	$-$	$\sqrt{s(s+t)}$	$\frac{1}{s}$
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,+,+$	s^0	$-$	s^0	s^0	s^0	$\frac{1}{s}$

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

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

Anatomy of tZj

$bW \to tZ$

$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	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
$-,+,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$
$-,+,+,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$

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

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

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

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

Consistent with non-interference theorem in $2 \to 2$

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

[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]

(I) : Individual
(M) : Marginalised

Existing limits

[TeV^{-2}]

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]			

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

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]

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

c/Λ = 1 [TeV^{-2}]

Inclusive results: tHj

LHC@13 TeV

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

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

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

Dimension 8 in ttbb

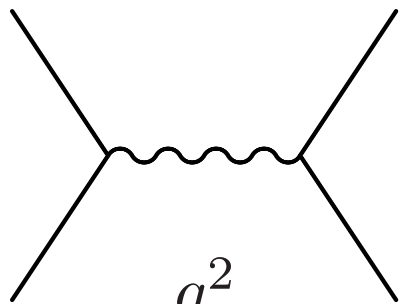
- Sensitivity dominated by EFT squared ($1/\Lambda^4$) terms
  - Non-interference due to colour
  - Large Wilson coefficients ~ strong coupling regime $\frac{C^{(6)}E^2}{\Lambda^2} \gtrsim 1$
- Are higher dimension operators relevant?
- As long as E < Λ
  - 6 fermion operators: at least dim-10 ~ $(E/\Lambda)^6$
  - Dim-8 four fermion operators ~ $(E/\Lambda)^4$

schematically: $ffffD_\mu D_\nu$ & $ffffG_{\mu\nu}$

one coupling & one scale power counting:

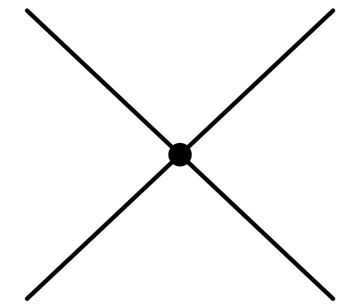
$$\mathcal{L}_{\text{EFT}} = \frac{\Lambda_{NP}^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda_{NP}}, \frac{g_* H}{\Lambda_{NP}}, \frac{g_* f_{L,R}}{\Lambda_{NP}^{3/2}}, \frac{gF_{\mu\nu}}{\Lambda_{NP}^2}\right)$$

Power counting



$$\frac{g^2}{p^2 - M^2}$$

$p^2 \ll \Lambda^2$



$$-\frac{g^2}{\Lambda^2}\left[1 + \frac{p^2}{\Lambda^2} + \frac{p^4}{\Lambda^4} + \cdots\right]$$

D=6 D=8

$$\frac{C^{(6)}_{4F}}{\Lambda^2} \sim \frac{C^{(8)}_{4F}}{\Lambda^2} \sim \frac{g_*^2}{M^2}$$

dim-6 interference: $\frac{g_s^6 g_*^2 E^2}{\Lambda_{NP}^2}$

dim-6 quadratic term: $\frac{g_s^4 g_*^4 E^4}{\Lambda_{NP}^4}$

$(g_*/g_s)^2 E^2/\Lambda_{NP}^2 \approx 1.$ → SQ ~ INT

$ffffD_\mu D_\nu$ $\quad \frac{C_i^{(8)}}{\Lambda^2} \sim \frac{g_*^2}{M^2}$

ttbb operator + 2 derivatives

gttbb contact term

ggttbb contact term

$ffffG_{\mu\nu}$ $\quad \frac{C_i^{(8)}}{\Lambda^2} \sim \frac{g_*^2 g_s}{M^2}$

dim-8 interference: $\frac{g_s^6 g_*^2 E^4}{\Lambda_{NP}^4}$

no g* enhancement