EFT aspects in top physics

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Higgs Toppings Workshop
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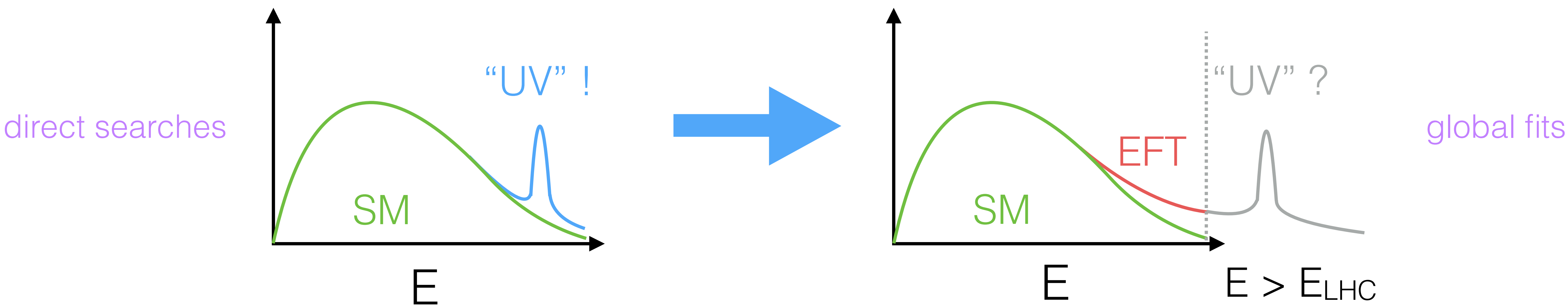
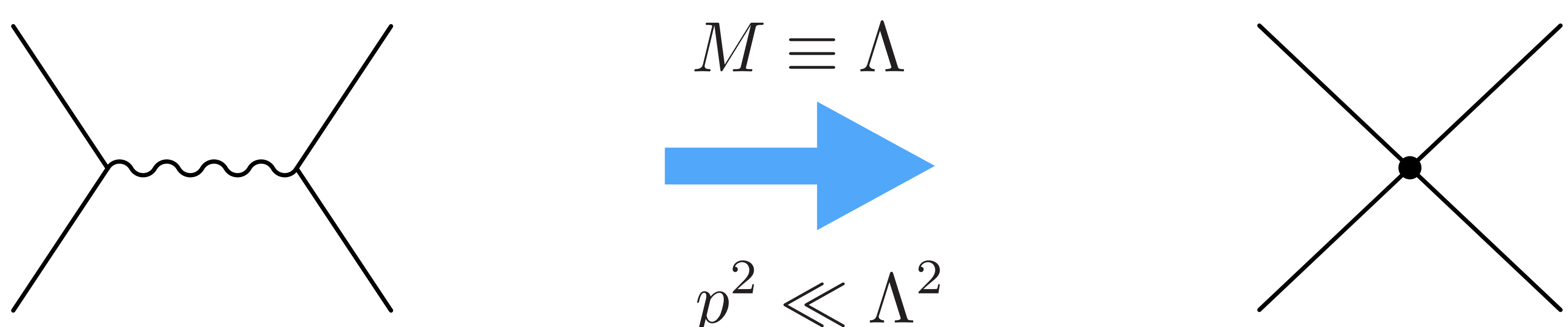
From bumps to tails



- 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 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)



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

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

D=6

cf. Fermi Theory

SMEFT

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge invariant operator set
- Linear realisation of EW symmetry breaking
  - Higgs field is an $SU(2)_L$ doublet
  - Non-linear realisations also possible → different EFT
- Complete, non-redundant set of operators: Basis
  - Relations via SM EoM, field redefinitions, Fierz identities,…
- Dimension 6: 59 (76 real) - 2499 operators
  - Depends on CP/flavour assumptions

SILH
Warsaw
HISZ
Higgs

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

- Dimension 8 now known ~ 895 - 36971 operators…

[Lehman et al.; PRD 91 (2015) 105014]
[Henning et al.; Commun.Math.Phys. 347 (2016) no.2, 363-388 & arXiv:1512.03433]

SMEFT - 0/2 fermions

'Warsaw' basis

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

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

SMEFT - 4 fermions

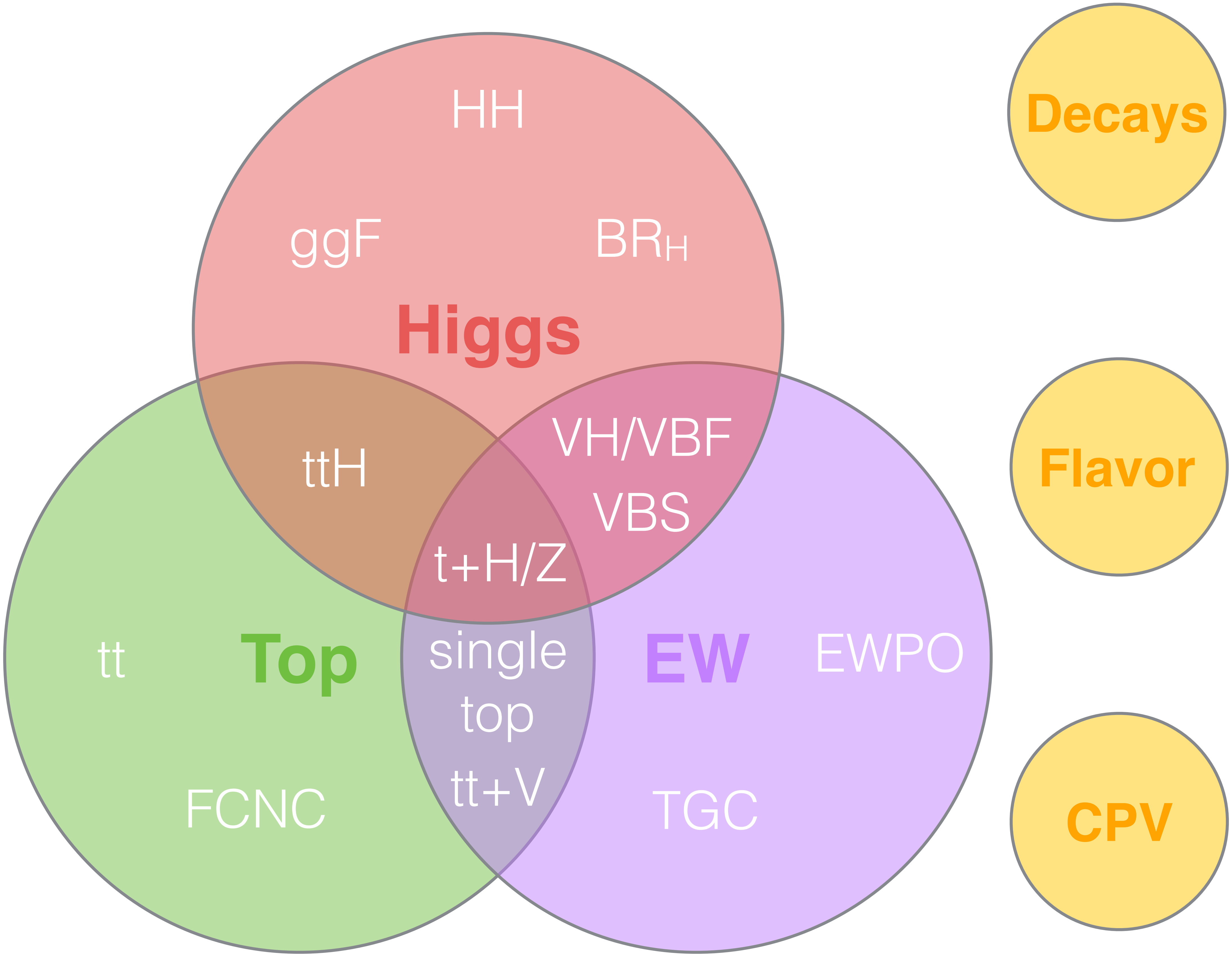
Flavor indices = Most of the 2499

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	• $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	• $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	• $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	• $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	• $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	• $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

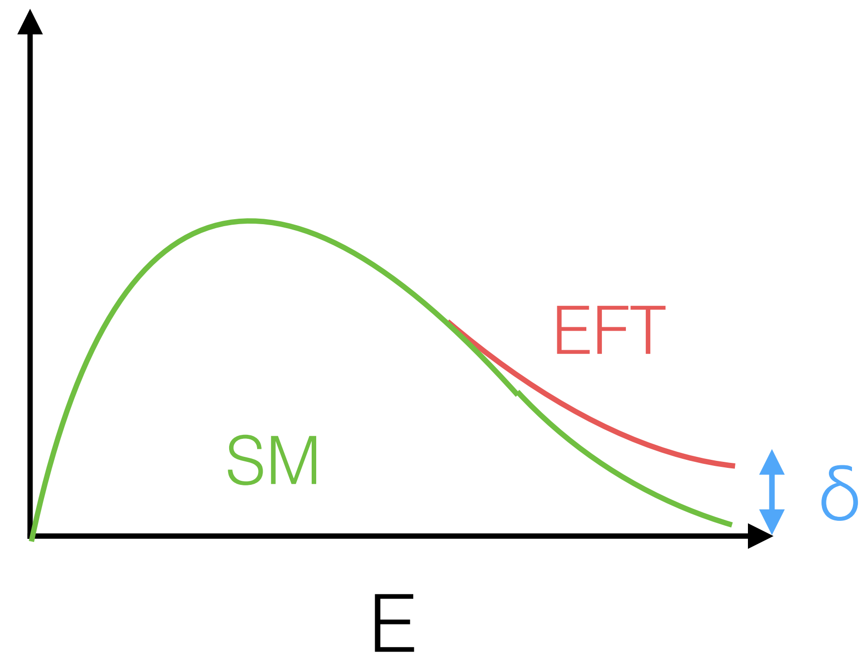
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	• $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	• $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	• $(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	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}	• $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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

SMEFT at the LHC: key players



SMEFT at the LHC



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

- LHC has much to contribute towards global picture of SMEFT constraints
  - Many SM measurements & a few dedicated EFT interpretations
  - Important to ensure the EFT interpretation is possible
  - Precise MC tools for signal generation
  - Well designed analyses/measurements with control over energy scale
  - Awareness of correlations between different processes in SMEFT picture

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

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

  - 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

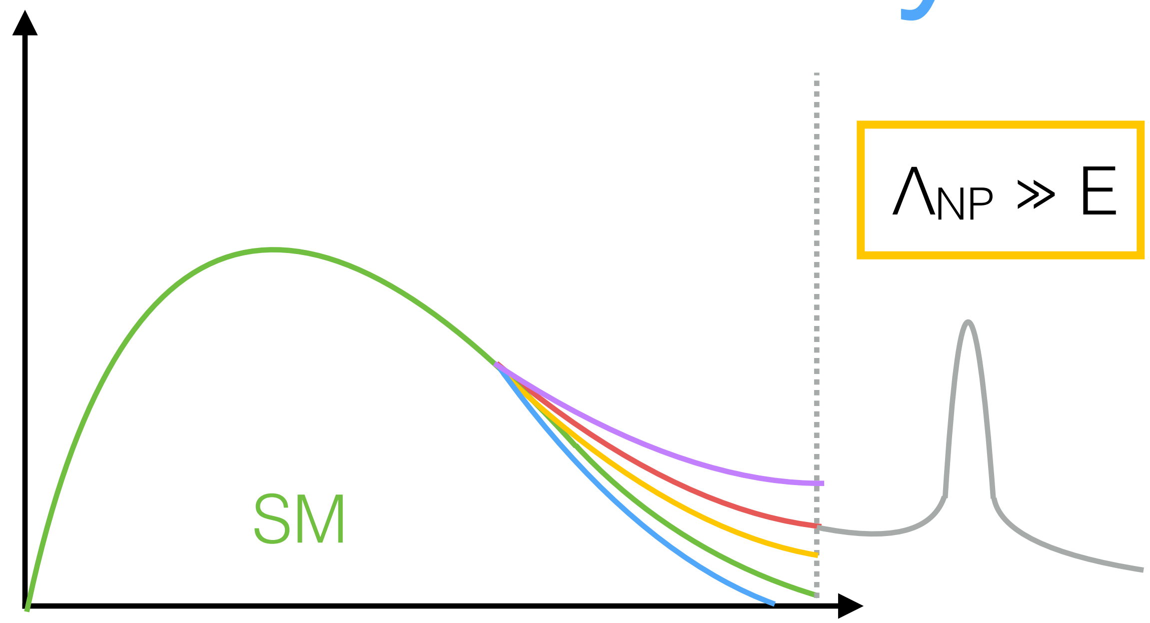
General strategy

- Step 3: LHC measurement
  - Unfolded to fiducial volume = reinterpretation without full/fast-sim
  - Reproducible event selection & background rejection
  - If MVA used: more complicated but not a showstopper
  - 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

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, ($c_i\, E/\Lambda_{NP}$) 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	$\lvert h(A_4^{\mathrm{SM}})\rvert$	$\lvert h(A_4^{\mathrm{BSM}})\rvert$
	$VVVV$	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)

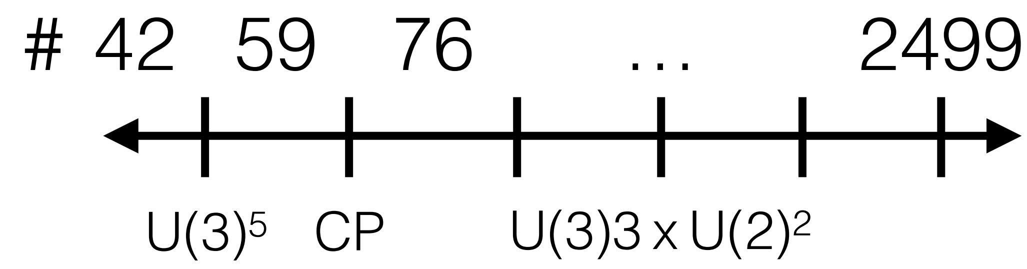
[Panico, Riva & Wulzer; CERN-TH-2017-85]
[Azatov, et al. LHEP 1710 (2017) 027]

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

SMEFT for top physics

- 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
    - Global fits, higher order corrections
- Many measurements at the LHC
    - Total, differential, boosted & rare processes *e.g.* tt+Z/W/γ, tZj

Anomalous top interactions

- EFT interpretation of top quark data
  - Measurement of deviations from SM interactions of the top
  - = anomalous couplings (?)
- SMEFT
  - SU(3) x SU(2) x U(1) gauge invariant construction
  - Correlations between interactions
  - SU(2) multiplets: $t_L \leftrightarrow b_L$
  - Non Abelian gauge field strengths: V ↔ VV ↔ VVV
  - Higgs field insertions: ffV ↔ ffVh
- Important to exploit this
  - Global approach

Gluon interactions

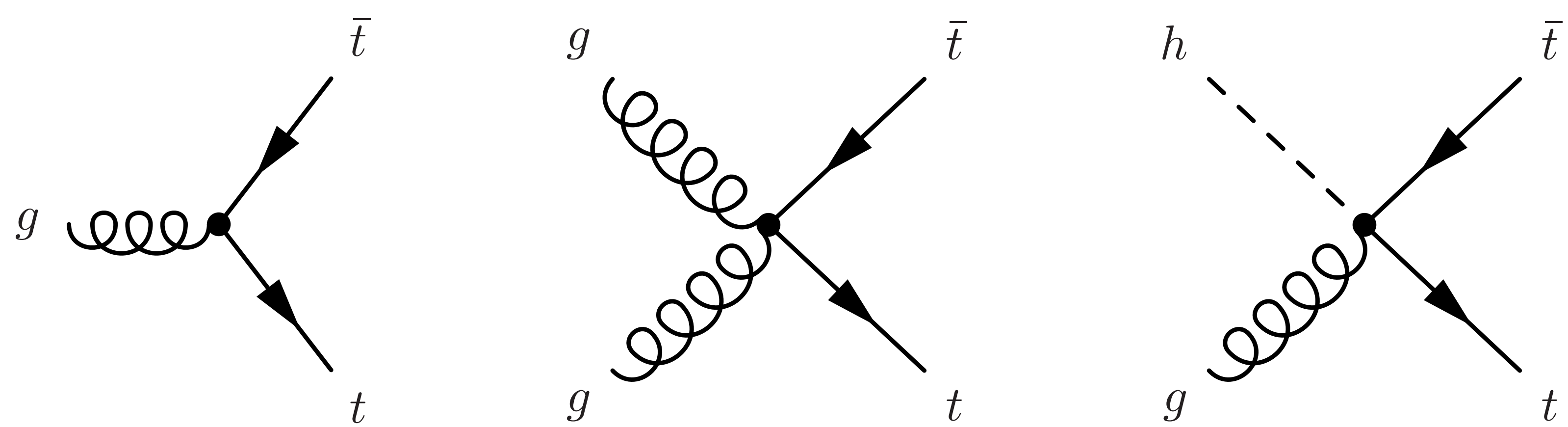
$$\mathcal{L}_{gtt} = -g_s \bar{t}\,\frac{\lambda^a}{2}\gamma^\mu t\, G^a_\mu - g_s \bar{t}\,\lambda^a \frac{i\sigma^{\mu\nu} q_\nu}{m_t}\,(d^g_V + i d^g_A \gamma_5)\, t\, G^a_\mu$$

SM

Dipole

Fixed by SU(3) gauge symmetry

$$\mathcal{O}_{tG} = i\left(\bar{Q}\,\sigma^{\mu\nu}\,T_A t\right)\tilde{\varphi}\,G^A_{\mu\nu} + \text{h.c}$$



tt, ttH, H, HH,…

W interactions

SM · RHCC · Dipole

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^\mu\,(V_L P_L + V_R P_R)\,t\,W^-_\mu - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\,(g_L P_L + g_R P_R)\,t\,W^-_\mu + \text{H.c.}$$

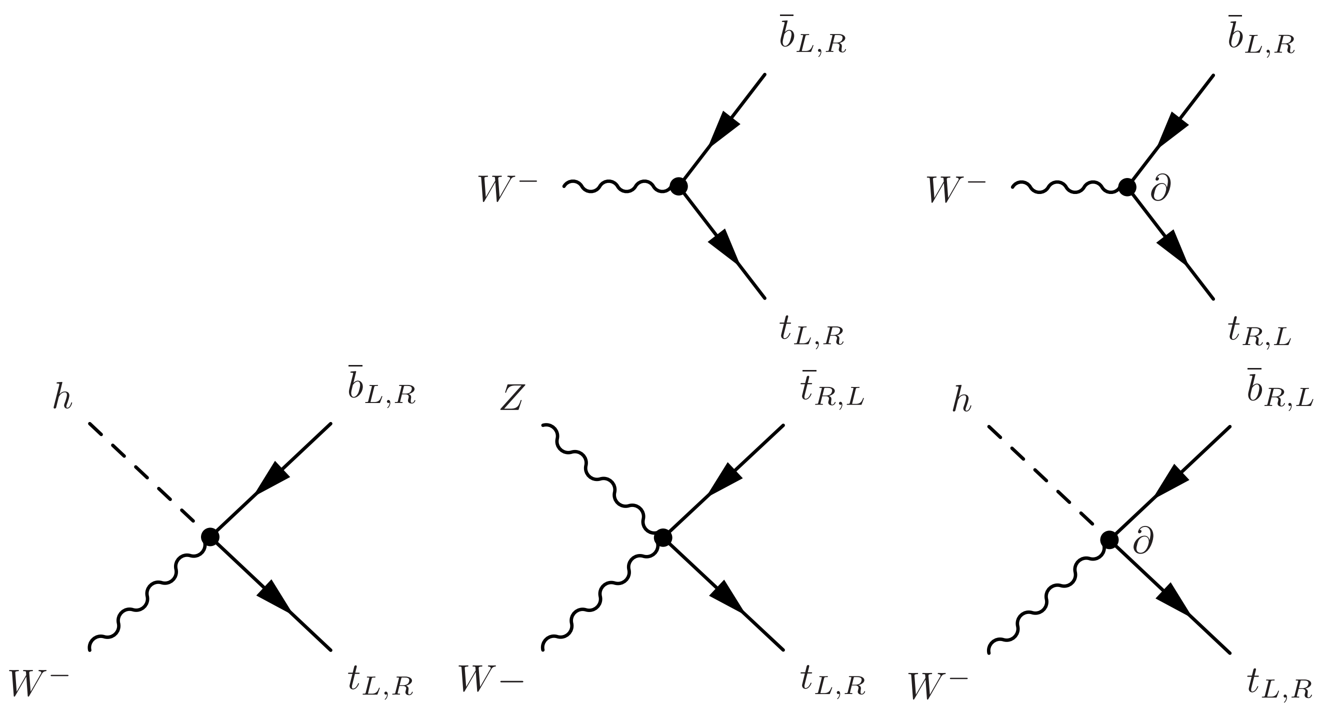
No gauge symmetry, deviations after EWSB

$$\mathcal{O}^{(3)}_{\varphi Q} = i(\varphi^\dagger \overleftrightarrow{D}_\mu\,\sigma^I\varphi)(\bar{Q}\,\gamma^\mu\,\sigma_I\,Q)$$

$$\mathcal{O}_{\varphi tb} = i(\tilde{\varphi}\,D_\mu\varphi)(\bar{t}\,\gamma^\mu\,b) + \text{h.c.}$$

$$\mathcal{O}_{tW} = i\left(\bar{Q}\,\sigma^{\mu\nu}\,\sigma_I t\right)\tilde{\varphi}\,W^I_{\mu\nu} + \text{h.c}$$

$$\mathcal{O}_{bW} = i\left(\bar{Q}\,\sigma^{\mu\nu}\,\sigma_I b\right)\varphi\,W^I_{\mu\nu} + \text{h.c}$$



t-decay, single-t, tZj, tHj,…

Z interactions

$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\,\gamma^\mu\left(X^L_{tt}P_L + X^R_{tt}P_R - 2s^2_W Q_t\right)t\,Z_\mu$$

SM

$$-\frac{g}{2c_W}\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(d^Z_V + id^Z_A\gamma_5\right)t\,Z_\mu\,,$$

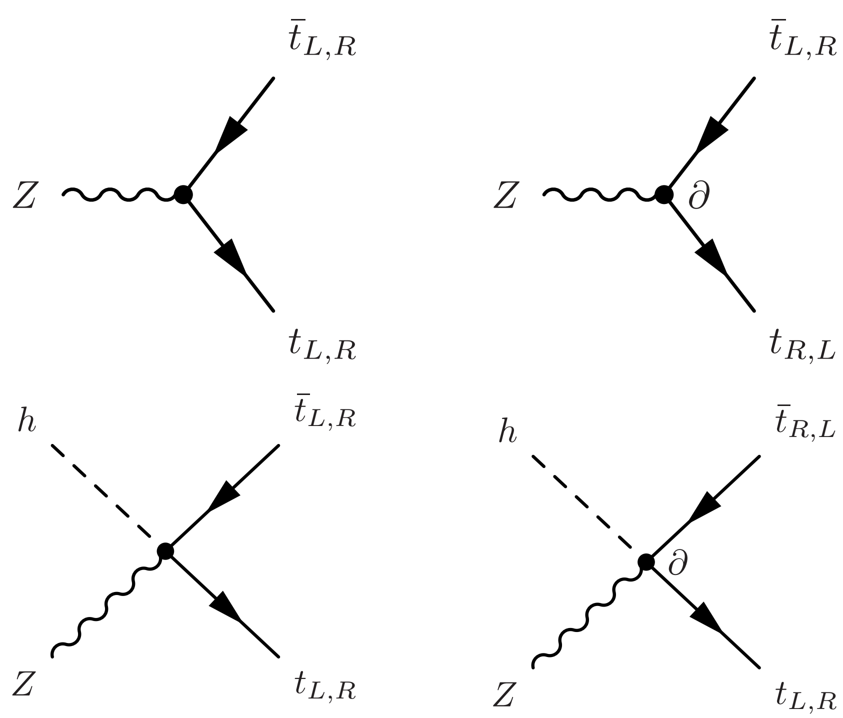
Dipole

No gauge symmetry, deviations after EWSB

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

$$\mathcal{O}^{(1)}_{\varphi Q} = i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\,\gamma^\mu\,Q)$$

$$\mathcal{O}^{(3)}_{\varphi Q} = i(\varphi^\dagger \overleftrightarrow{D}_\mu\,\sigma^I \varphi)(\bar{Q}\,\gamma^\mu\,\sigma_I\,Q)$$



ttZ, ttW, tZj,…

Photon interactions

$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\,\gamma^\mu t\,A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\,(d_V^\gamma + i d_A^\gamma\gamma_5)\,t\,A_\mu$$

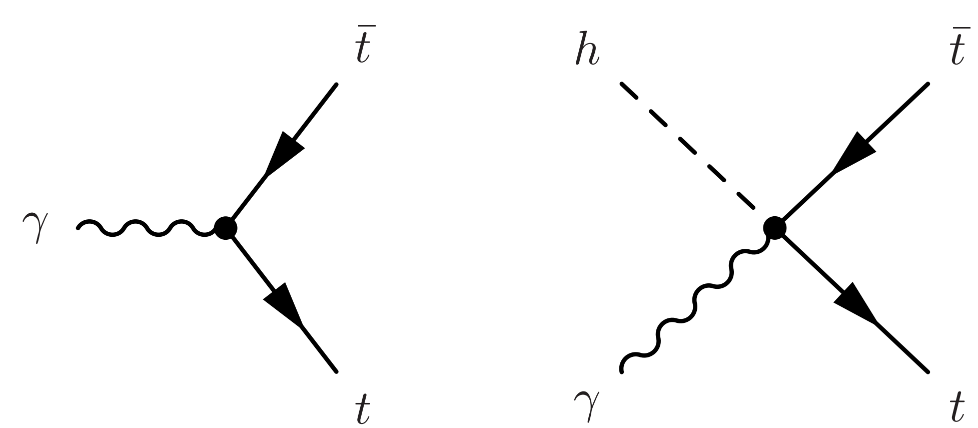
SM

Dipole

Fixed by QED gauge symmetry

$$\mathcal{O}_{tW} = i\left(\bar{Q}\,\sigma^{\mu\nu}\,\sigma_I t\right)\tilde{\varphi}\,W^I_{\mu\nu} + \text{h.c}$$

$$\mathcal{O}_{tB} = i\left(\bar{Q}\,\sigma^{\mu\nu}\,t\right)\tilde{\varphi}\,B_{\mu\nu} + \text{h.c}$$



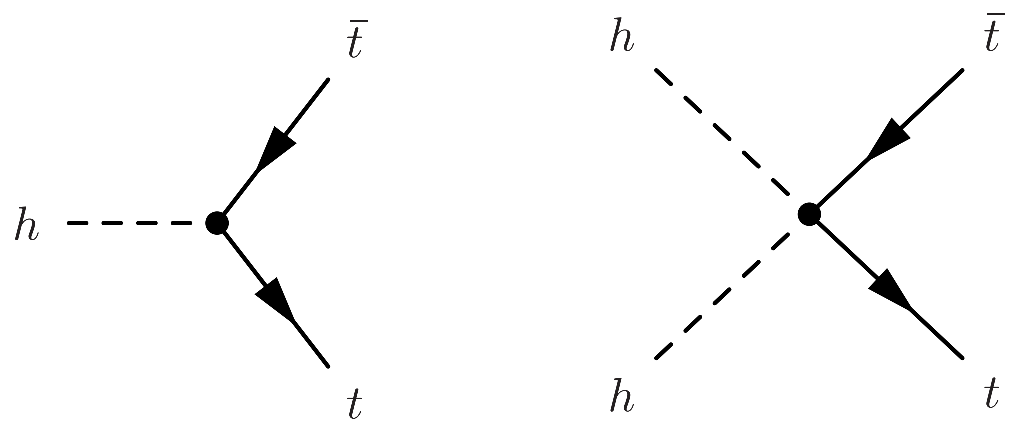
ttγ, tγj,…

Higgs interaction

$$\mathcal{L}_{tth} = -\frac{m_t}{v}(\kappa_t h + \frac{c_2}{v} hh)(t_L\, \bar{t}_R + \mathrm{h.c})$$

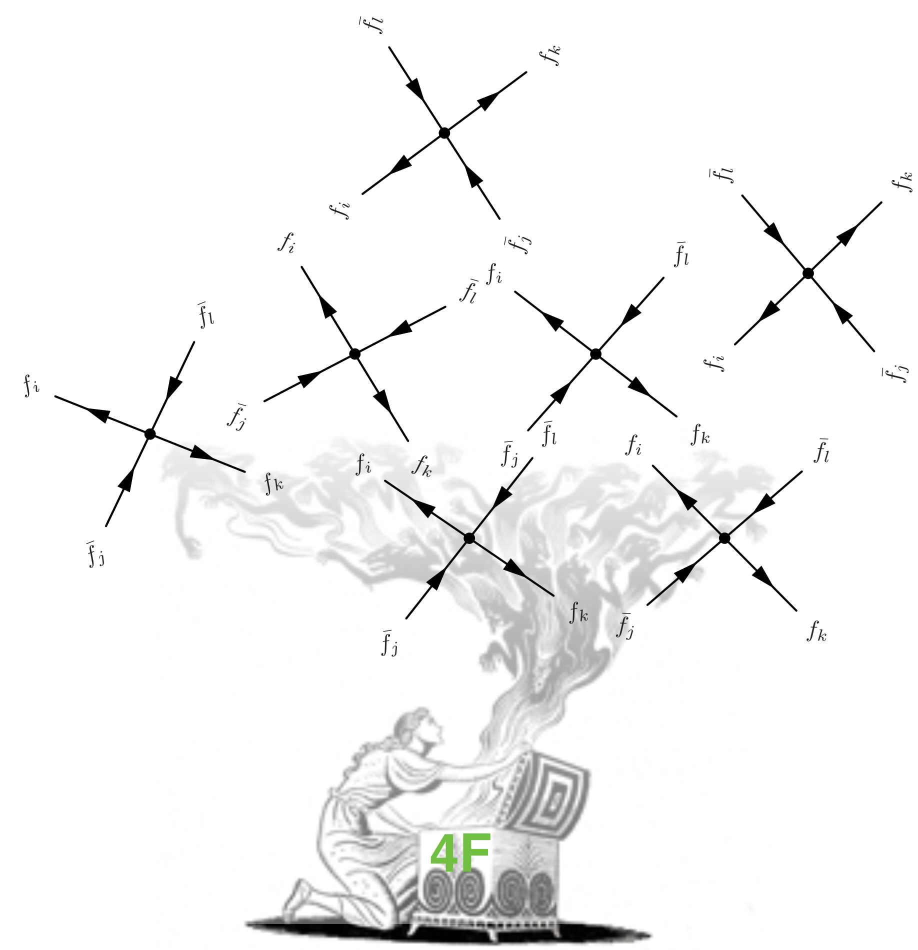
SM

$$\mathcal{O}_{t\varphi} = i\,(\varphi^\dagger \varphi)\,(\bar{Q}\, t\, \tilde{\varphi}) + \mathrm{h.c}$$



ttH, tHj, H, HH…

Four fermion



- Pandora's box of SMEFT
  - Huge number of flavor indices
  - Mostly flavor violating
- ~30 operators in minimal flavor symmetry assumption
  - Decompose into QQQQ, QQqq & QQll

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

tt, tt+W/Z/H/γ, single-t, t+X, 4t, ttbb, ttjj,…

Status: global fits

- TopFitter collaboration: global SMEFT analysis of Top data
  - 195 measurements (of which 174 differential)

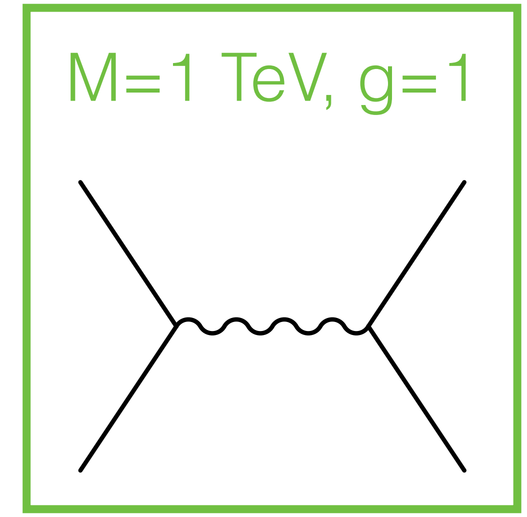
Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production			
Total cross-sections:			
ATLAS	7	lepton+jets	1406.5375
ATLAS	7	dilepton	1202.4892
ATLAS	7	lepton+tau	1205.3067
ATLAS	7	lepton w/o b jets	1201.1889
ATLAS	7	lepton w/ b jets	1406.5375
ATLAS	7	tau+jets	1211.7205
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573
ATLAS	8	dilepton	1202.4892
CMS	7	all hadronic	1302.0508
CMS	7	dilepton	1208.2761
CMS	7	lepton+jets	1212.6682
CMS	7	lepton+tau	1203.6810
CMS	7	tau+jets	1301.5755
CMS	8	dilepton	1312.7582
CDF + DØ	1.96	Combined world average	1309.7570
Single top production			
ATLAS	7	t-channel (differential)	1406.7844
CDF	1.96	s-channel (total)	1402.0484
CMS	7	t-channel (total)	1406.7844
CMS	8	t-channel (total)	1406.7844
DØ	1.96	s-channel (total)	0907.4259
DØ	1.96	t-channel (total)	1105.2788
Associated production			
ATLAS	7	$t\bar{t}\gamma$	1502.00586
ATLAS	8	$t\bar{t}Z$	1509.05276
CMS	8	$t\bar{t}Z$	1406.7830

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Differential cross-sections:			
ATLAS	7	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.0371
CDF	1.96	$M_{t\bar{t}}$	0903.2850
CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
DØ	1.96	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.5785
Charge asymmetries:			
ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
Top widths:			
DØ	1.96	Γ_{top}	1308.4050
CDF	1.96	Γ_{top}	1201.4156
W-boson helicity fractions:			
ATLAS	7		1205.2484
CDF	1.96		1211.4523
CMS	7		1308.3879
DØ	1.96		1011.6549
Run II data			
CMS	13	$t\bar{t}$ (dilepton)	1510.05302

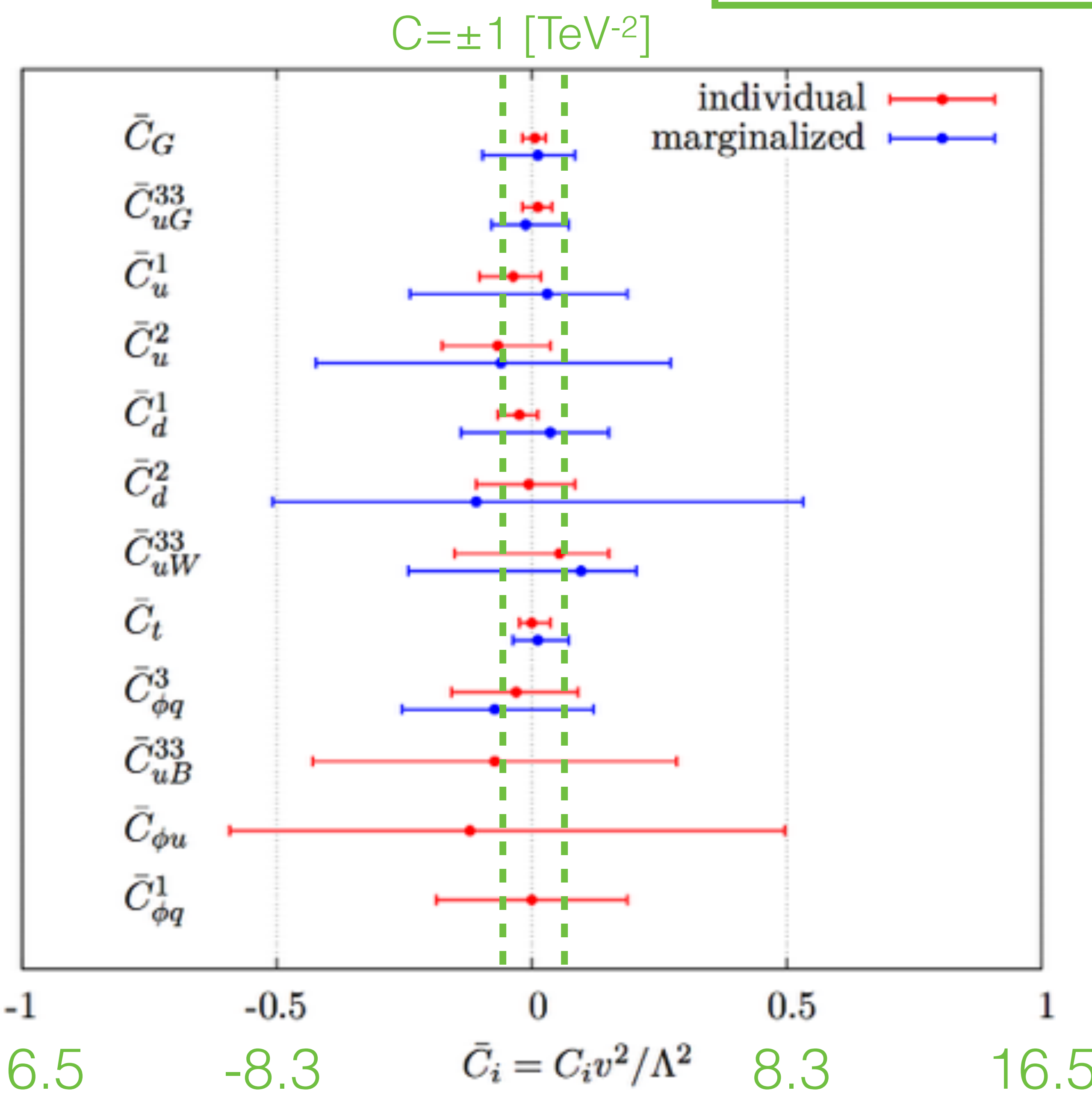
LHC 7 & 8 TeV

Tevatron

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



Status: MC

- SM
  - NLO+PS predictions standard
  - FO EW corrections available
  - Automated tools abound
- SMEFT interpretations
  - Require their own MC tools
  - ‘Global’ implementation including all operators
  - EFT effects on signal & background
  - Higher order QCD predictions (see Marco’s talk on Monday)
  - Useful for sensitivity studies & experimental interpretations

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

Going beyond

- State-of-the-art in MC event generation is well beyond LO
  - Software like FeynRules+NLOCT+MG5_aMC@NLO provides automated event generation at NLO in QCD from Lagrangian
- Some codes permit the inclusion of anomalous couplings
- SMEFT implementation is well motivated and a valuable addition to the NLO toolbox
- Great performance of the LHC for top processes
  - Complex/rare processes: differential tt, 4top, ttbb
  - EW induced: single-top, tt+Z/W/γ/H, t+Z/H, tHW,…
- Starting to probe full top/Higgs/EW sector

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

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

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

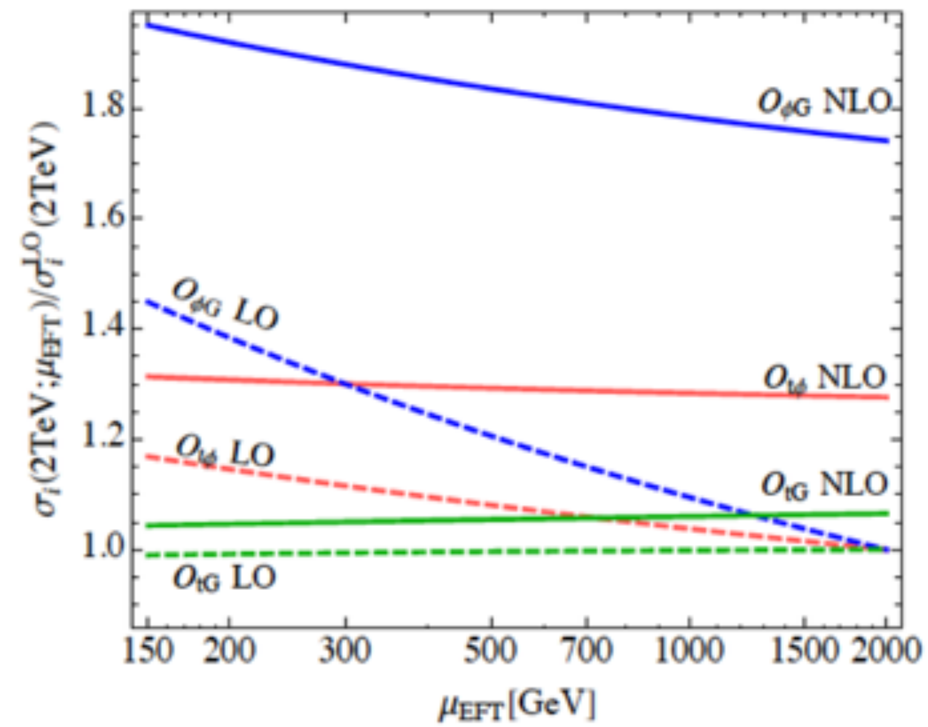
- Operators involving the top/Higgs/gluon
  - gg→H & tt production partly constrain the Wilson coefficient space
  - ttH is the only direct probe of the Top-Higgs interaction
  - In principle 3-gluon O_G and 4 fermion operators also contribute but turn out to be better constrained by tt and multi-jet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

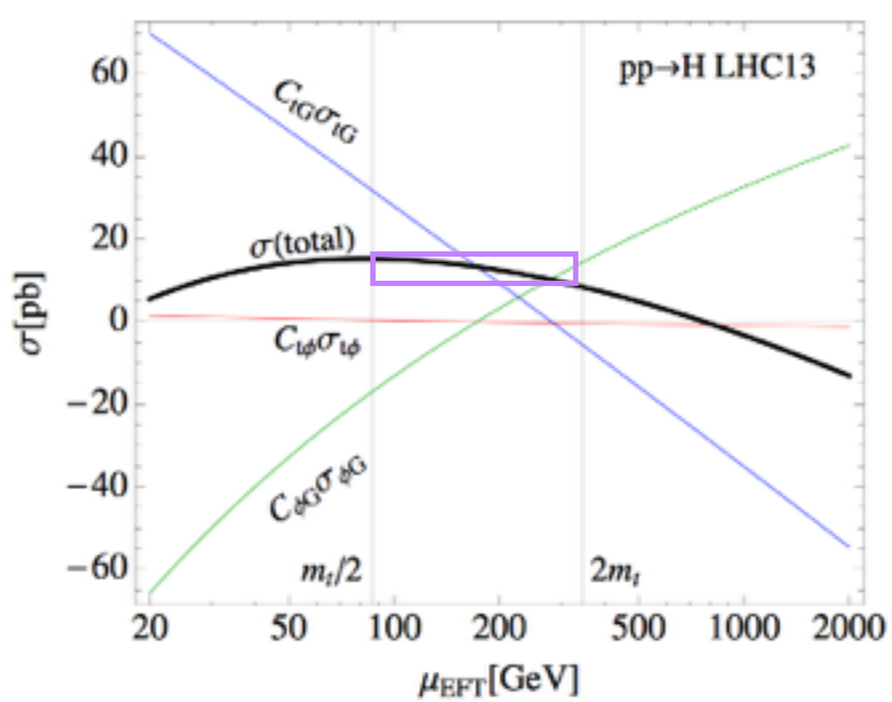
$$\frac{E^2}{\Lambda^2} < 1 < c_i^{(6)}\frac{E^2}{\Lambda^2} < c_i^{(6)}c_j^{(6)}\frac{E^4}{\Lambda^4}$$

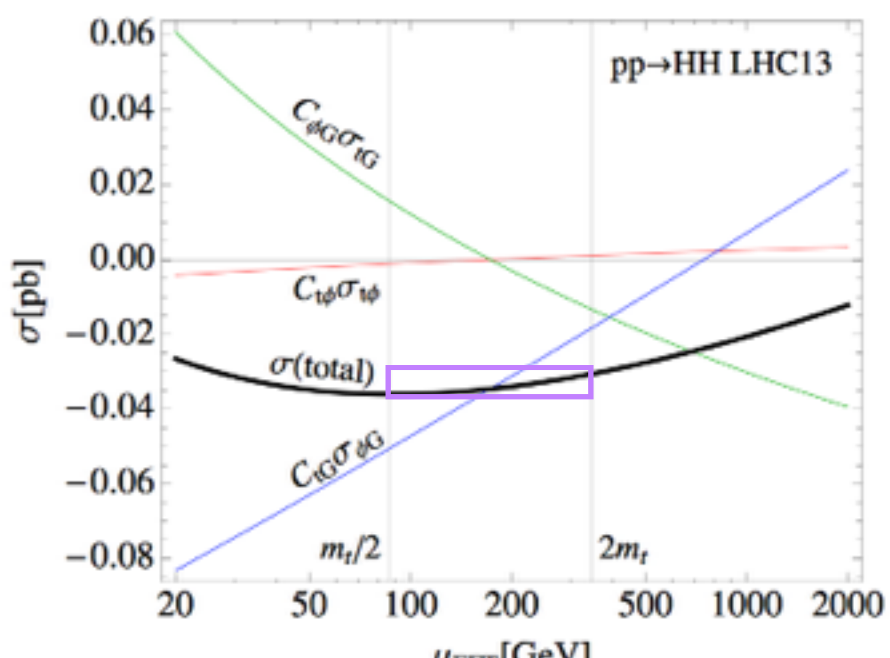
ttH in SMEFT

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

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

SMEFT@NLO

- MC tool for top/EW/Higgs sector of SMEFT
- 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	$\mathcal{O}_{\varphi G}$	$\varphi^\dagger\varphi\, G_A^{\mu\nu} G_{\mu\nu}^A$	$\mathcal{O}_{\varphi\tilde{G}}$	$\varphi^\dagger\varphi\, G_A^{\mu\nu}\tilde{G}_{\mu\nu}^A$
	$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi\, W_i^{\mu\nu} W_{\mu\nu}^i$	$\mathcal{O}_{\varphi\tilde{W}}$	$\varphi^\dagger\varphi\, W_i^{\mu\nu}\tilde{W}_{\mu\nu}^i$
	$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi\, B^{\mu\nu} B_{\mu\nu}$	$\mathcal{O}_{\varphi\tilde{B}}$	$\varphi^\dagger\varphi\, B^{\mu\nu}\tilde{B}_{\mu\nu}$
	$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger\sigma^i\varphi\, W_i^{\mu\nu} B_{\mu\nu}$	$\mathcal{O}_{\varphi W\tilde{B}}$	$\varphi^\dagger\sigma^i\varphi\, W_i^{\mu\nu}\tilde{B}_{\mu\nu}$
Triple gauge,…	$\mathcal{O}_{3W}$	$\epsilon^{ijk} W_{i,\,\mu\nu} W_j^{\nu\rho} W_{k,\,\rho}^{\mu}$	$\mathcal{O}_{3\tilde{W}}$	$\epsilon^{ijk} \tilde{W}_{i,\,\mu\nu} W_j^{\nu\rho} W_{k,\,\rho}^{\mu}$

CP violation in v2

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

Based on:
[Degrande et al; EPJC 77 (2017) 4, 262]
[Maltoni et al; JHEP 1610 (2016) 123]
[Bylund et al.; JHEP 1605 (2016) 052]
[Zhang; PRL 116 (2016) 162002]

SMEFT@NLO

- Work in $U(3)^3 \times U(2)^2$ 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	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}^i_\mu\varphi)(\bar{Q}\gamma^\mu\sigma_i Q)$
	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$
	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t)$
RHCC	$\mathcal{O}_{\varphi b}$	$i(\tilde{\varphi}D_\mu\varphi)(\bar{b}\gamma^\mu t)$

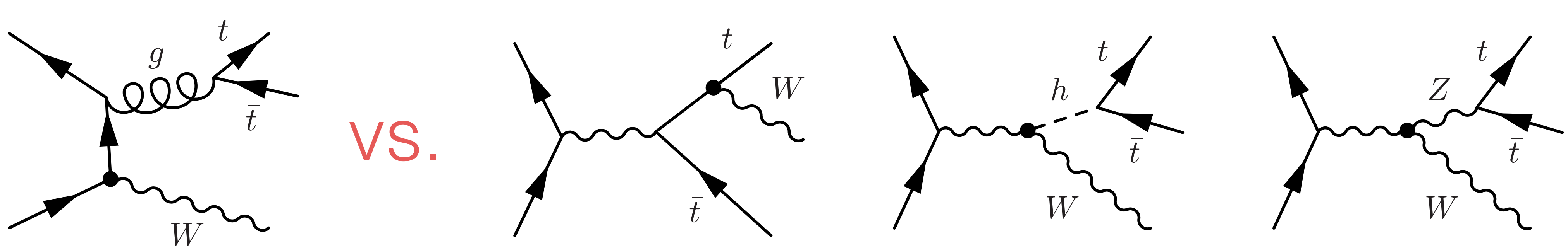
Flavor universal 1st & 2nd

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

+ 4F operators from dim6top

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

Operators

tHj

tZj

both

NLO

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

Constrained by electroweak precision tests (LEP)

Two blind directions in Warsaw basis:

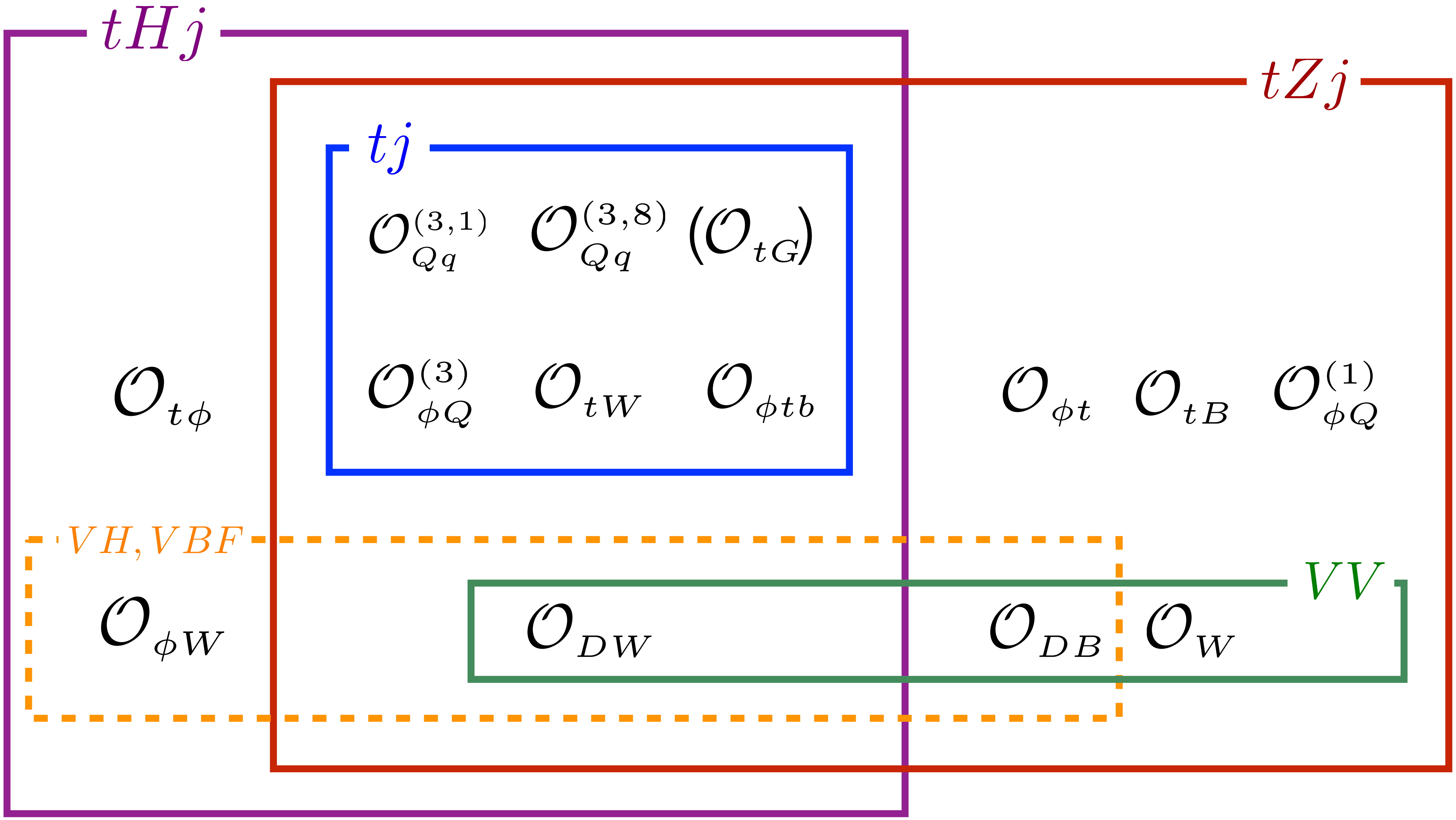
$$\mathcal{O}_{HW} = (D^\mu\varphi)^\dagger \tau_I (D^\nu\varphi) W^I_{\mu\nu}$$
$$\mathcal{O}_{HB} = (D^\mu\varphi)^\dagger (D^\nu\varphi) B_{\mu\nu}.$$

RGE

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

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

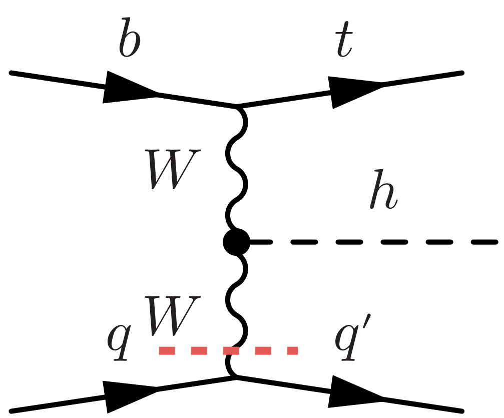
Interplay



+ ttW/Z/H/γ

Anatomy of tHj/tZj

tHj (tZj = h→Z)

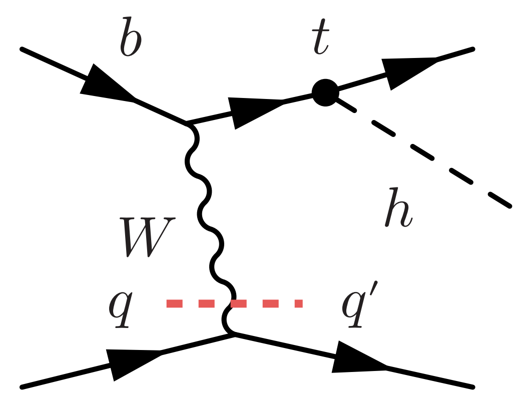


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

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

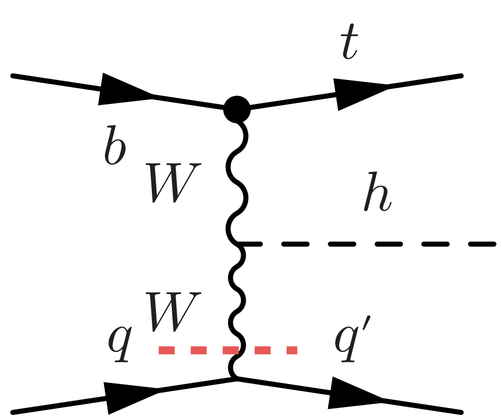


$\mathcal{O}_{t\varphi}$

top Yukawa

ttZ coupling

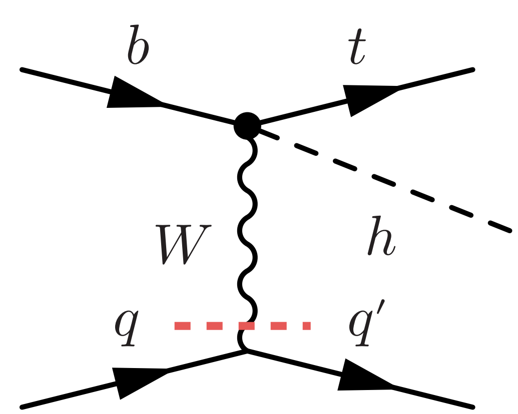
$\mathcal{O}_{\varphi t}$



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

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 with the SM

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	$\mathcal{O}_{t\varphi}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{HW}$
$-,0,-$	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]

LHC sensitivity

Compare to 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 weak dipoles

Consistent with 2→2 subamplitude analysis

New energy growths w.r.t single top

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

Results

- Non-universal K-factors
- Reduction in scale+PDF uncertainties
  - EFT scale uncertainty subdominant
- Room for O(1) deviations within existing limits
  - Relative impact of EFT contributions larger in tHj than tZj
  - tZj has much larger rate: differential measurements possible
- Future projections: high p_T tZj vs inclusive tHj
  - Competitive/improved sensitivity w.r.t existing limits (e.g. helicity fractions)
  - Weak dipole operators, RHCC, SU(2) triplet current
- High p_T single top measurements best for 4F operators

Global top/Higgs/EW

- Several interesting 2 → 2 sub-amplitudes

bW → tH : tHj

bW → tZ : tZj

tW → tW : ttW (EW)

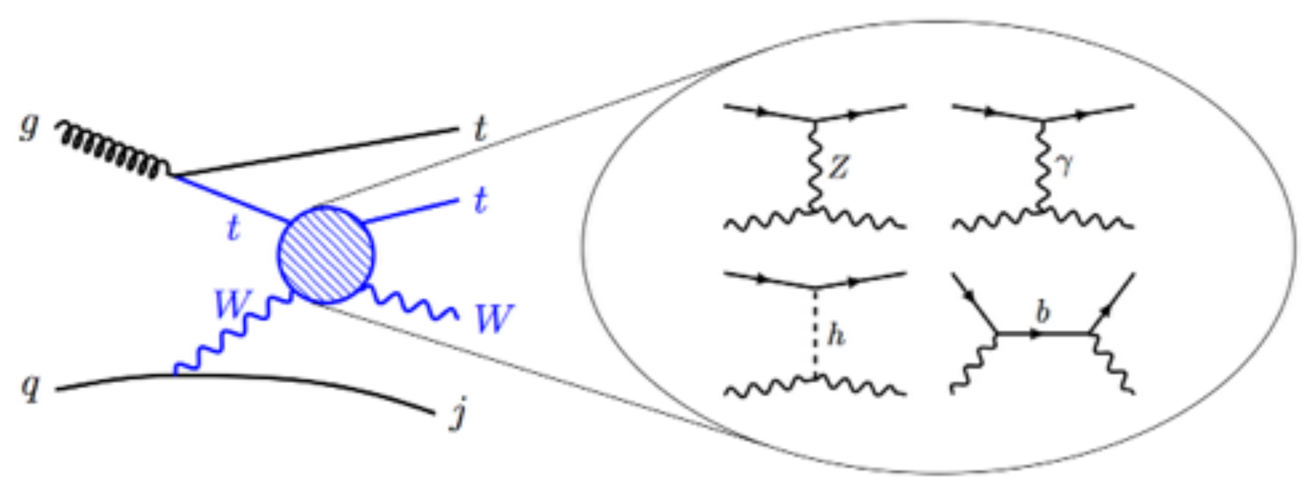
tZ → tH : ttH (EW)

tZ → tZ : ttZ

tH → tH : ttHH?

photon final states: tγj,…

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



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

Even more rare: ttWW, ttZZ, ttZH, ttHH,…

Global top/Higgs/EW

- 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
  - "Backgrounds": ttH, tqZ, tHq,…
  - Considerable statistical overlap between different top+EW measurements
  - Abundant use of multivariate methods
- SMEFT interpretation = going beyond individual processes
- Global fits to top & EW observables exist separately
  - Unifying top/Higgs/EW sector a valuable exercise
  - SMEFTatNLO model implementation a necessary ingredient

Top 4F operators

- Generated by heavy, new physics coupling to 3rd generation
  - Top mass generation
- Manageable set of operators
- Contain tttt, ttbb and bbbb interactions
  - Colour singlet & triplet
  - Vector & scalar currents

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

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

$$O^1_{Qb} = (\bar{Q}\,\gamma_\mu\,Q)\,(\bar{b}\,\gamma^\mu\,b)\,,$$
$$O^8_{Qb} = (\bar{Q}\,\gamma_\mu\,T^A\,Q)\,(\bar{b}\,\gamma^\mu\,T^A\,b)\,,$$
$$O^1_{QtQb} = (\bar{Q}\,t)\,\varepsilon\,(\bar{Q}\,b)\,,$$
$$O^8_{QtQb} = (\bar{Q}\,T^A\,t)\,\varepsilon\,(\bar{Q}\,T^A\,b)$$

- four top

Four top production

- Very rare process at the LHC ~ 9 fb
  - Best effort at the LHC about 4.6 times the SM *[ATLAS-CONF-2016-104]*

[Zhang; Chin. Phys. C42 (2018) 023104]

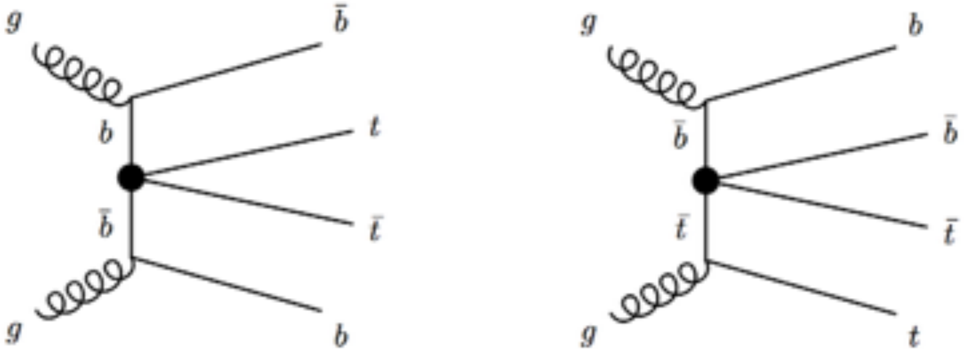
- Not a precision measurement
  - Sensitive to four heavy quark & 2 heavy + 2 light quark operators
  - High threshold ~ 700 GeV
  - Sensitivity dominated by quadratic terms & beyond = validity issue?

[TeV^{-2}]

$$c^1_{Qt} \quad [-4.97, 4.90] \; (E_{cut} = 3\,\text{TeV})$$
$$c^8_{Qt} \quad [-10.3, 9.33] \; (E_{cut} = 3\,\text{TeV})$$
$$c^1_{tt} \quad [-2.92, 2.80] \; (E_{cut} = 3\,\text{TeV})$$

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

ttbb production



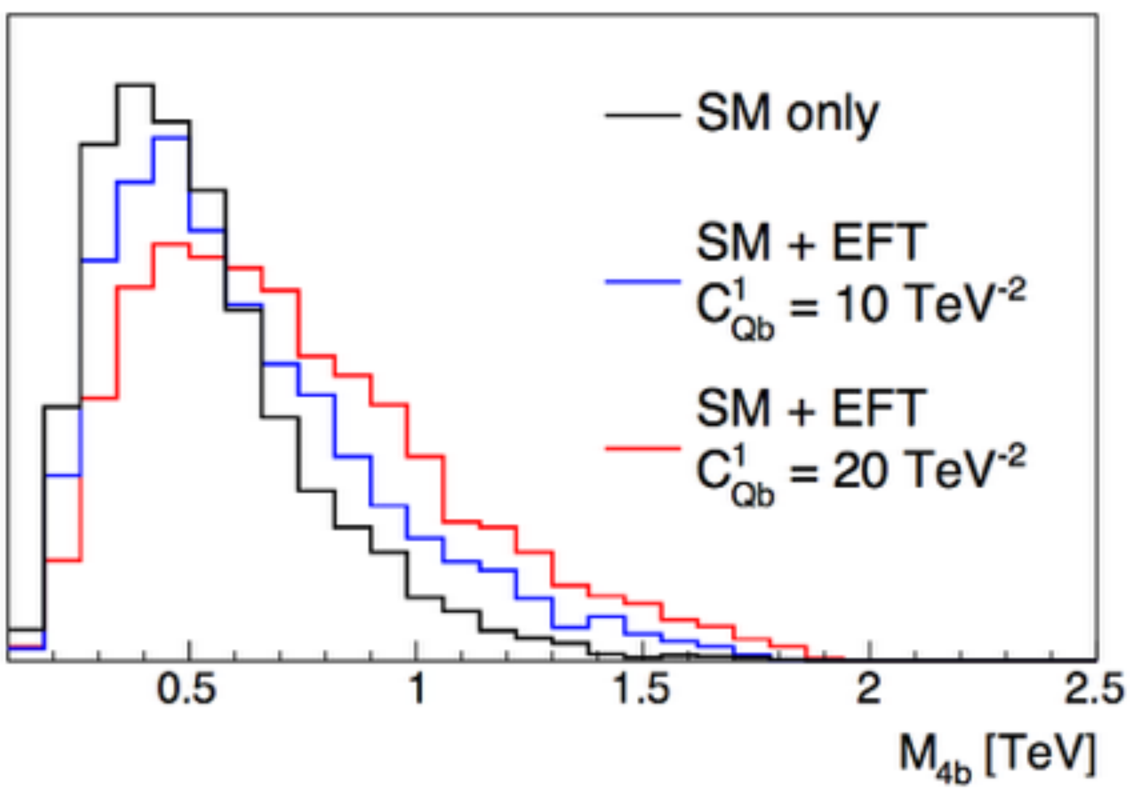
- Less rare process at the LHC ~ 3 pb
  - Measured at the LHC with ~ 30% accuracy *[CMS; PLB 776 (2018) 355-378]*
  - Background for ttH(bb)
- Affected by all but one of the previous list of operators
  - Some of which have never been bounded before *[Degrande et al.; JHEP 03 (2011) 125]*
- Sensitivity of ttbb to four heavy operators
  - Future projections of dedicated analyses optimised to EFT kinematics
  - Sensitivity may exceed that of 4 top for common operators
  - Modulo a resolution of the large theory uncertainties in the SM
  - Once again, dominated by quadratic terms

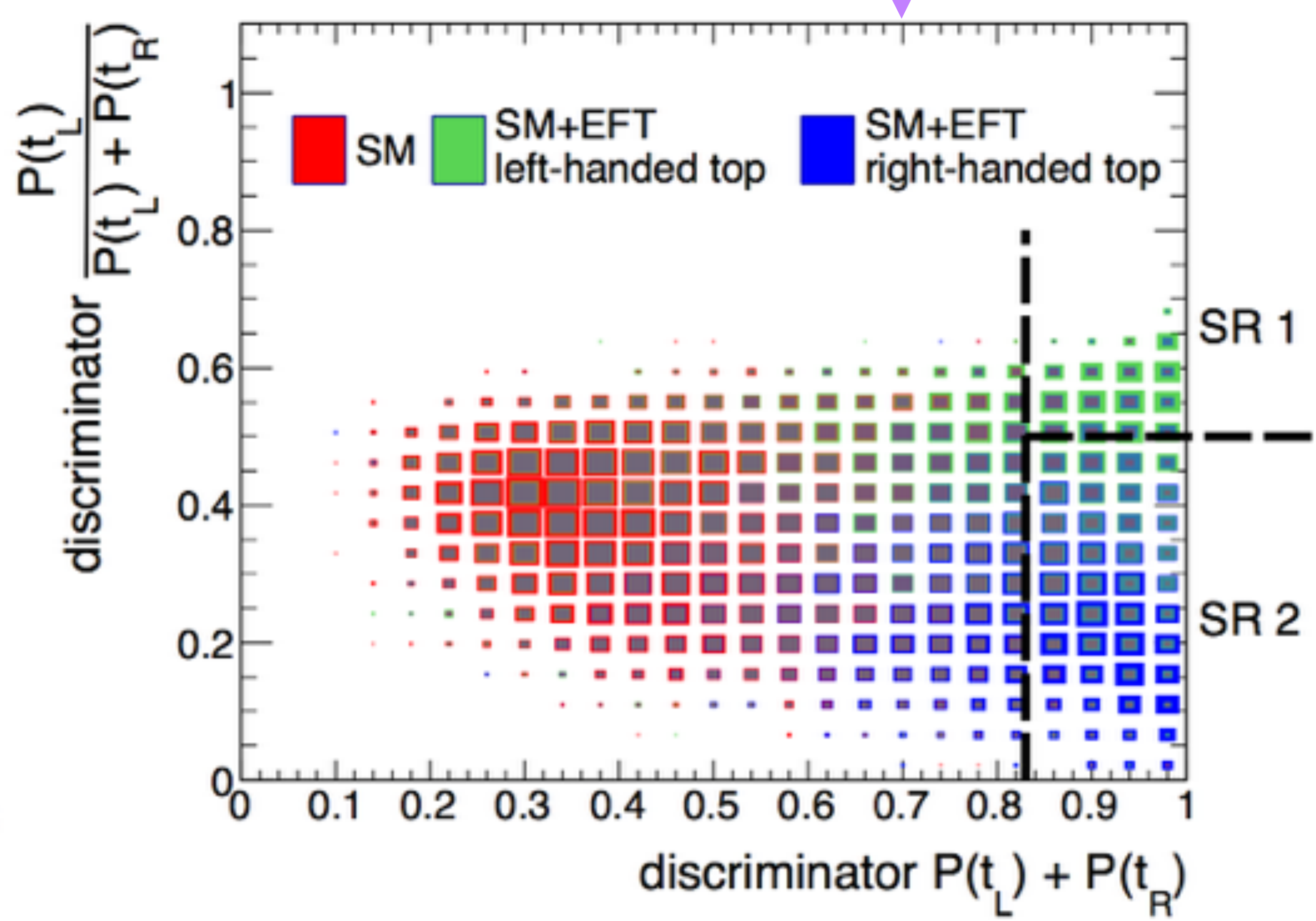
Preliminary

ttbb production

- "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 class NN discriminant
  - SM vs t_L operators vs t_R operators

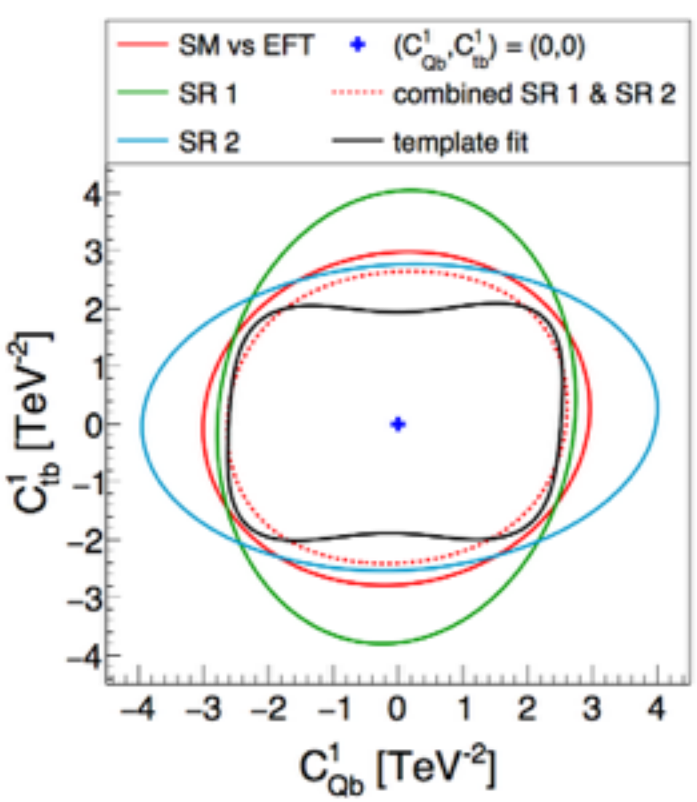
Cut on discriminant
vs.
template fit

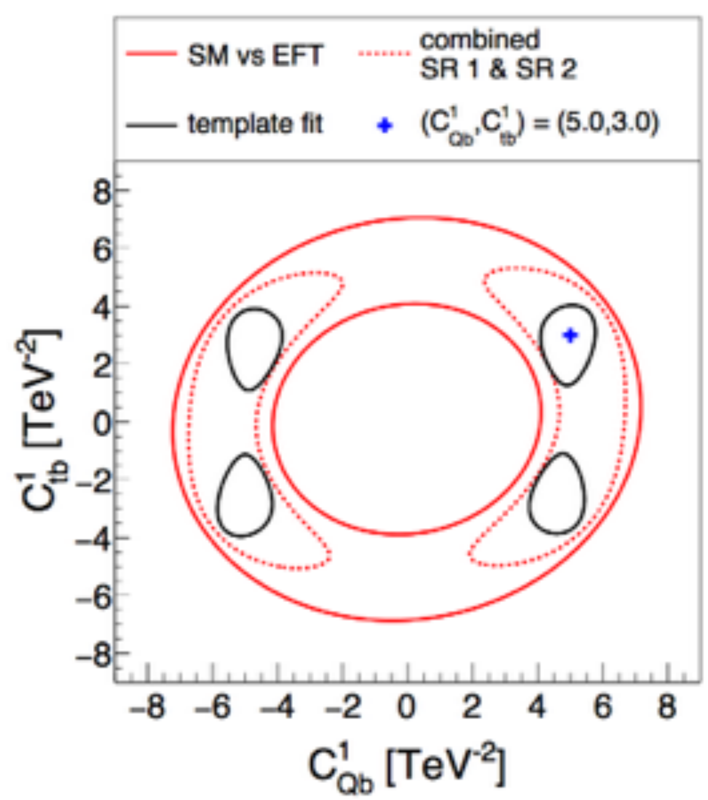


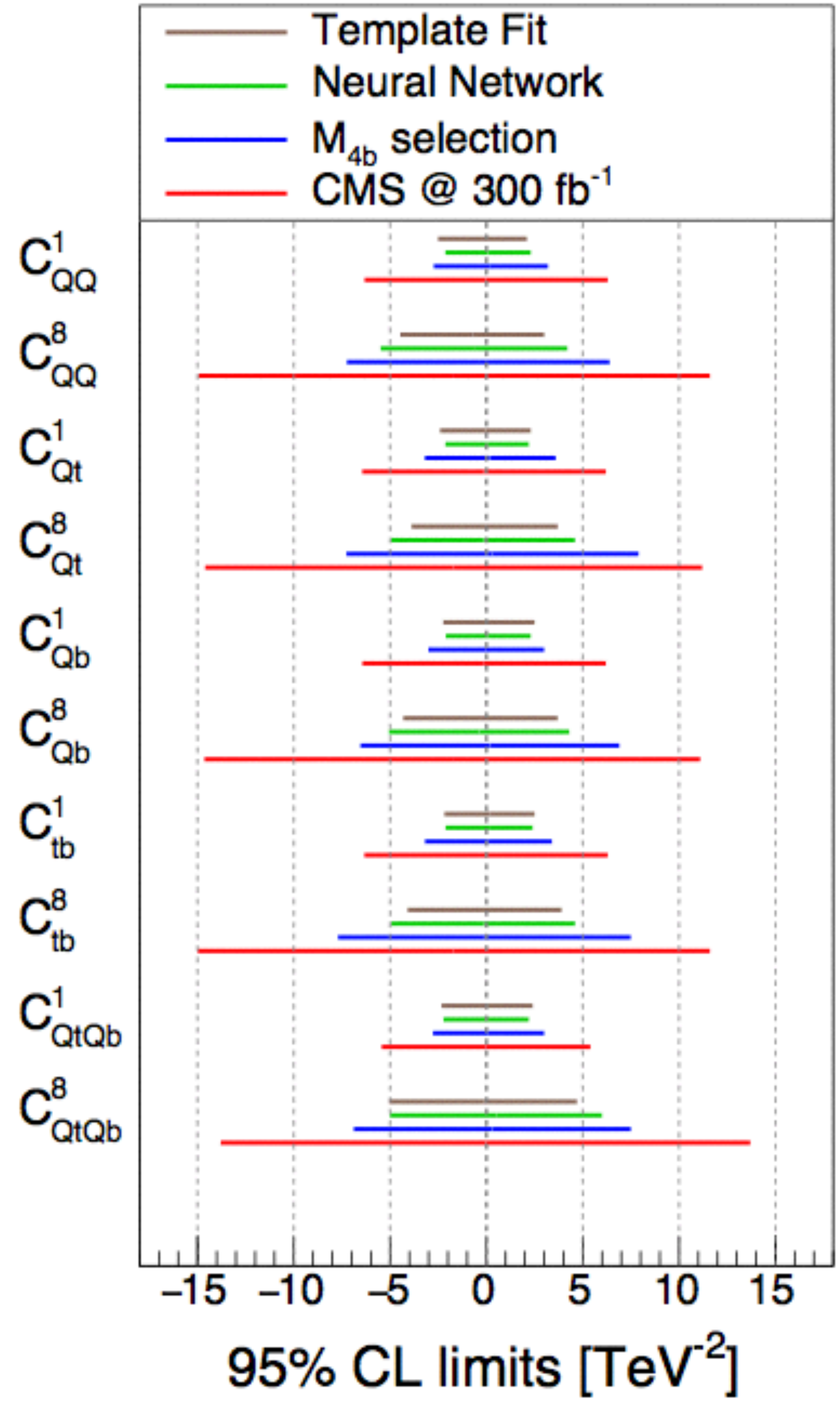


ttbb production

- SM observation
  - Template fit to NN similar to M_{4b}
- EFT signal injection
  - NN focuses in on preferred parameters







Conclusion

- SMEFT: consistent framework to stress-test the SM
  - Theory consensus for global description & MC implementation
  - Extended to top/Higgs/EW sector & NLO in QCD
  - Towards a global likelihood
- 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 available for all top/Higgs/EW processes at the LHC

Thank you

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

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

$\lambda_Z \backslash \lambda_W$	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 → 2

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

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

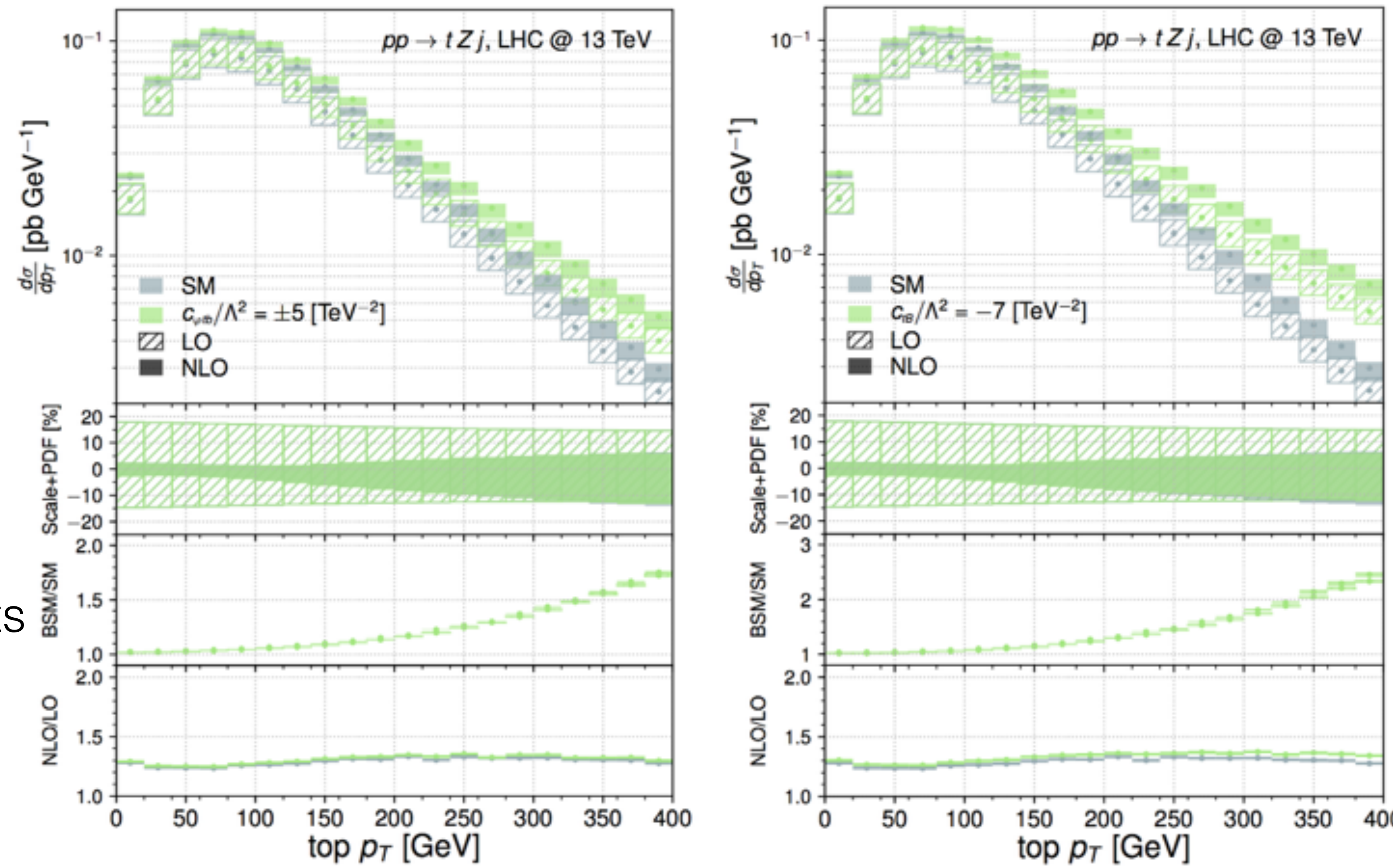
Higgs always radiated from top/EW gauge boson

Z boson can also come from light quark leg

Differential tZj

Reduced uncert.

Large effects



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

Current sensitivity

tZj

TGC

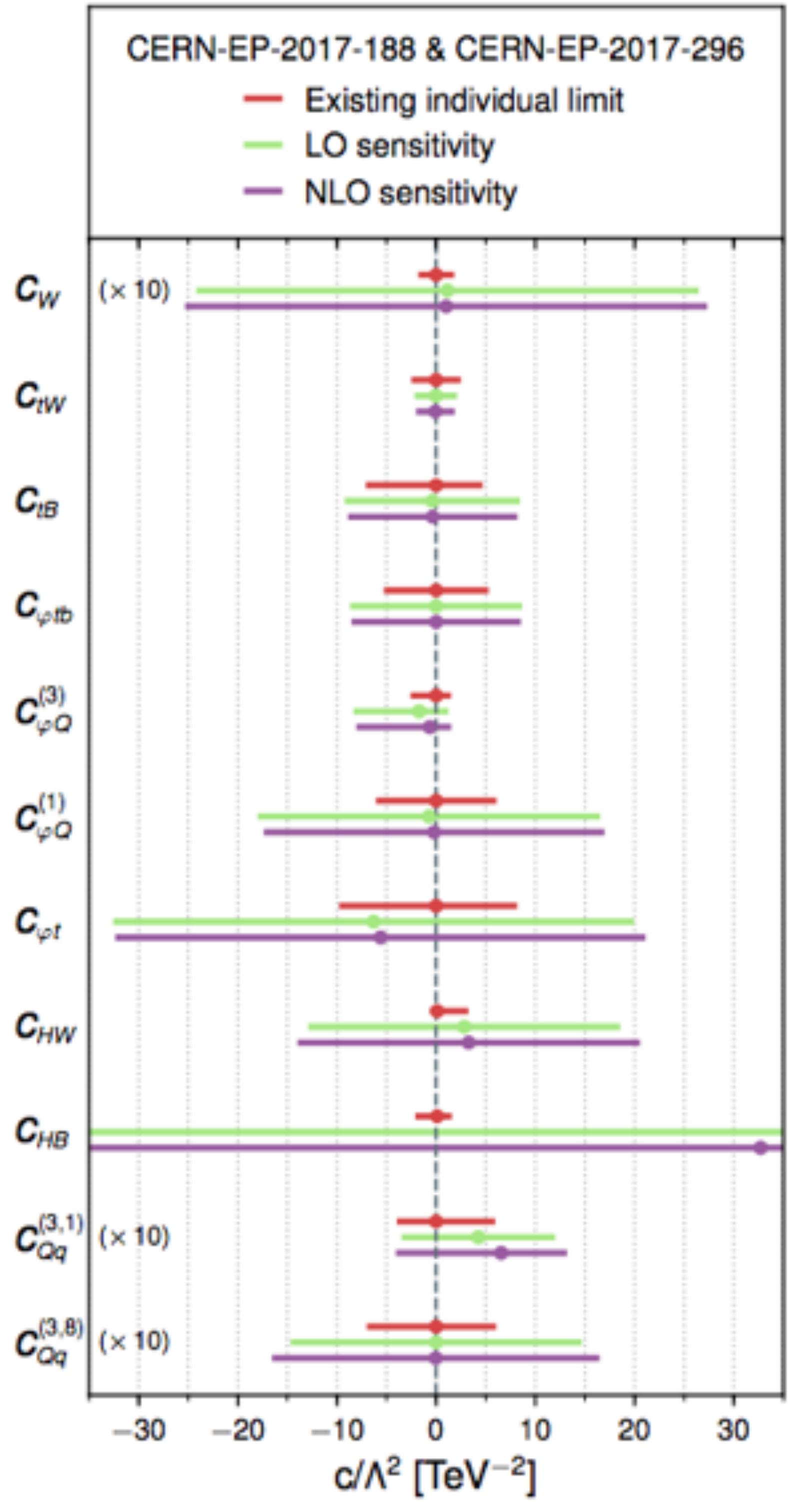
Dipoles

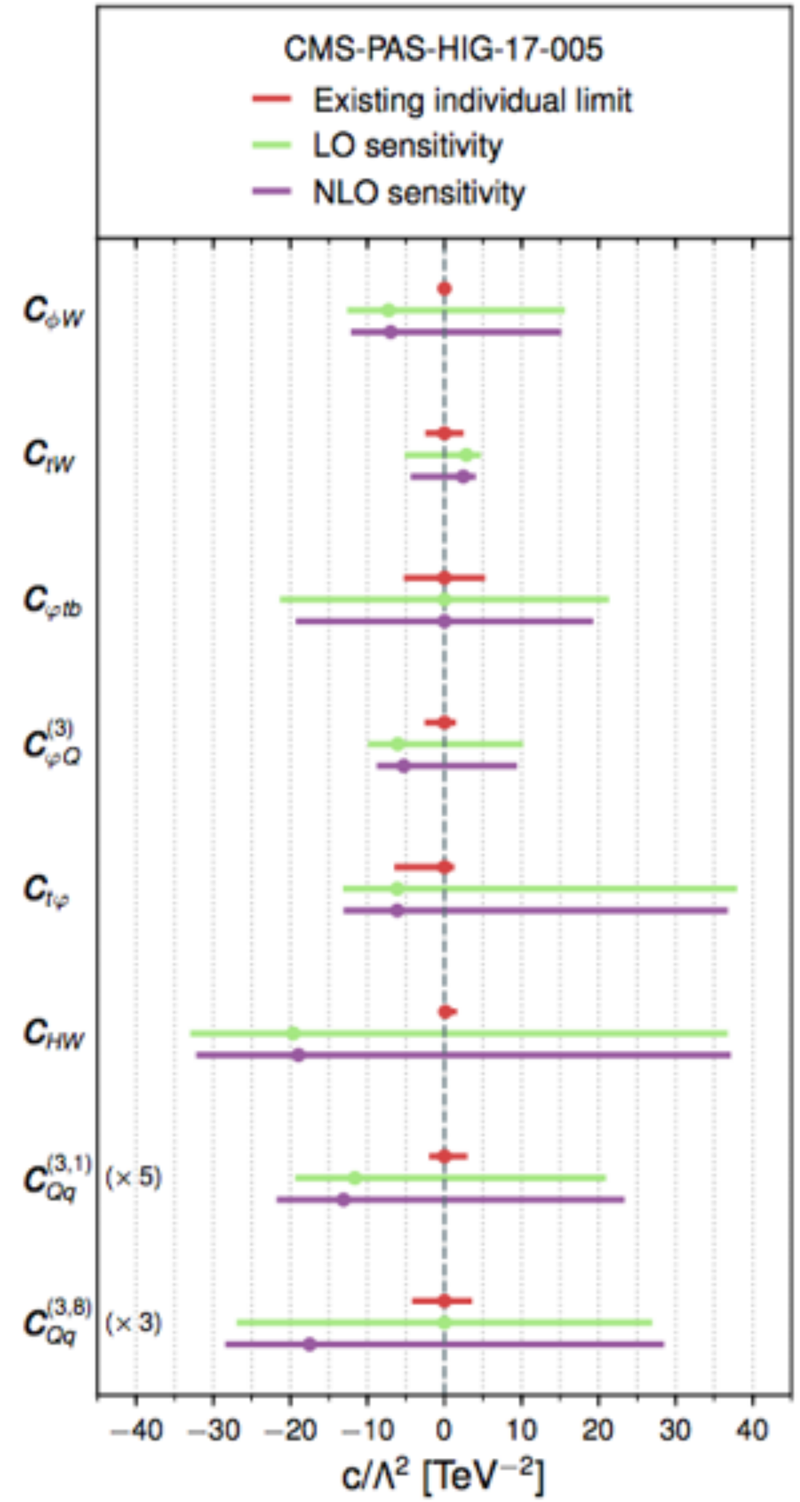
RHCC

Currents

LEP
orthogonal

4-fermion





tHj

Gauge-Higgs

Dipole

RHCC

Currents

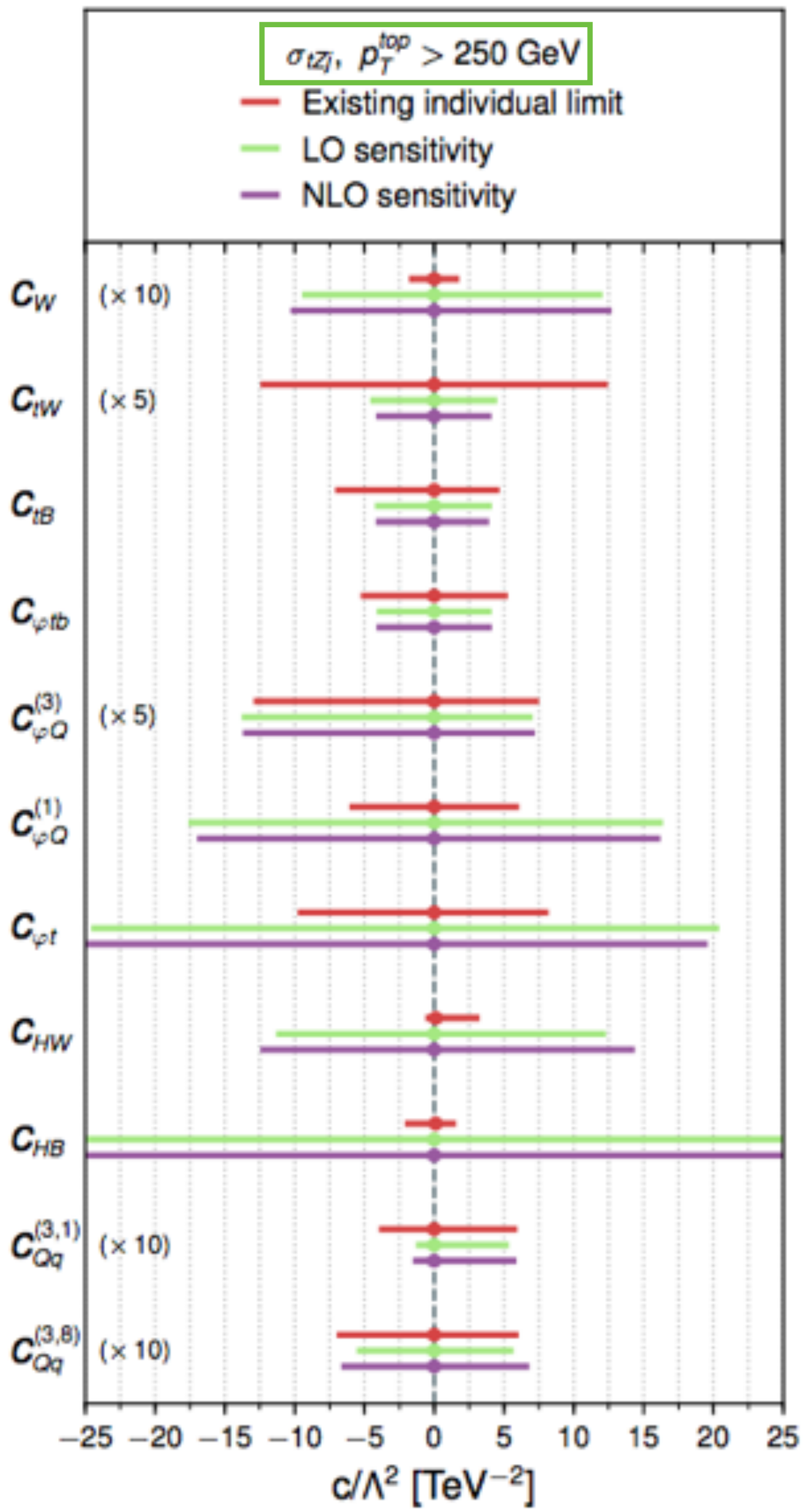
LEP
orthogonal

4-fermion

Future sensitivity

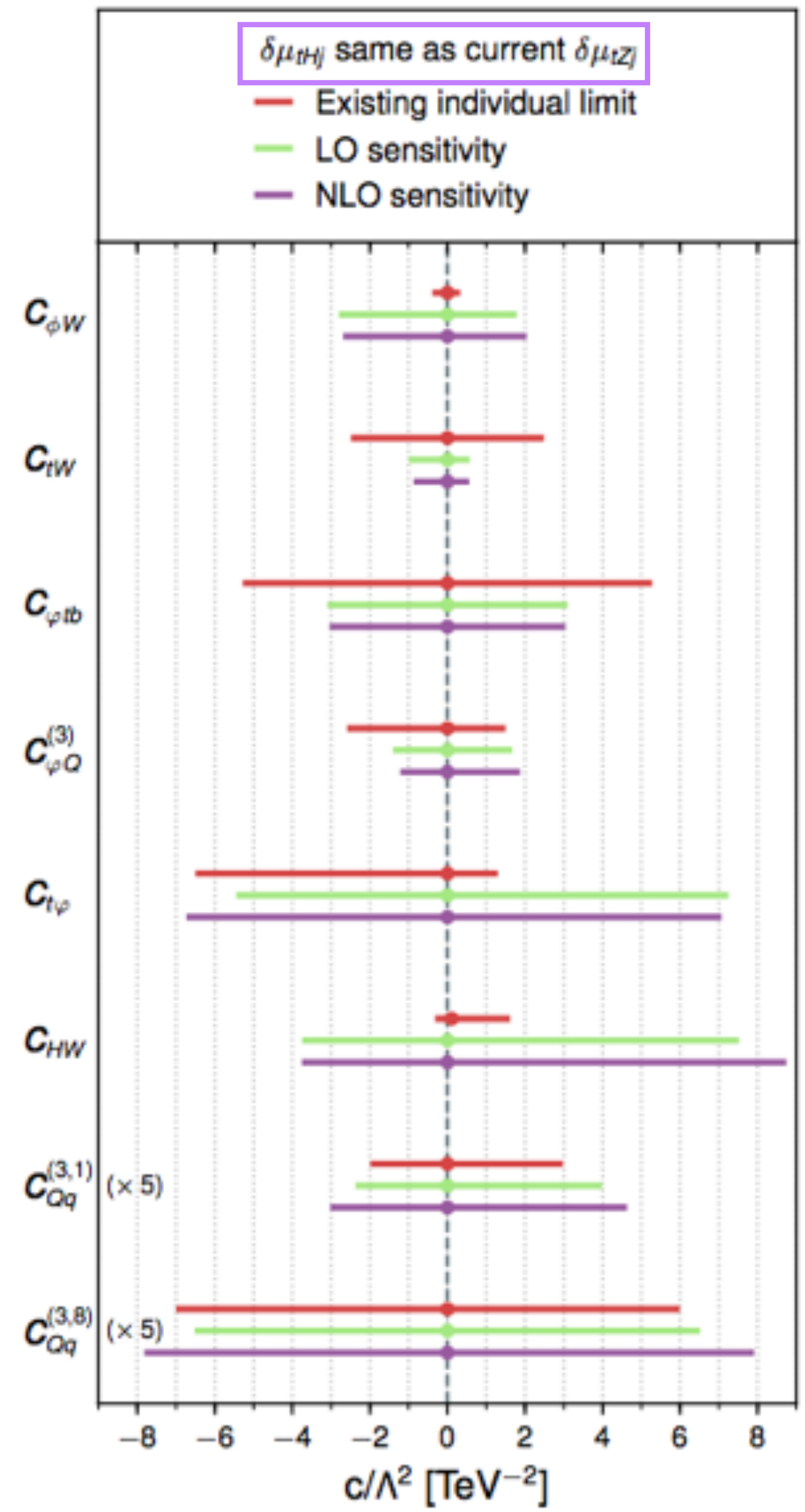
High p_T tZj: end of run II/HL-LHC
tHj: HL-LHC ?

tZj



TGC
Dipoles
RHCC
Currents
LEP orthogonal
4-fermion

tHj



Gauge-Higgs
Dipole
RHCC
Currents
LEP orthogonal
4-fermion

Dimension 8 in ttbb

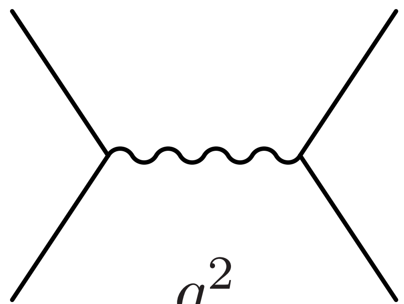
- Sensitivity dominated by EFT squared ($1/\Lambda^4$) terms
  - Non-interference due to colour
  - Large Wilson coefficients ~ strong coupling regime $\frac{C^{(6)}E^2}{\Lambda^2} \gtrsim 1$
- Are higher dimension operators relevant?
- As long as $E < \Lambda$
  - 6 fermion operators: at least dim-10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

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

one coupling & one scale power counting:

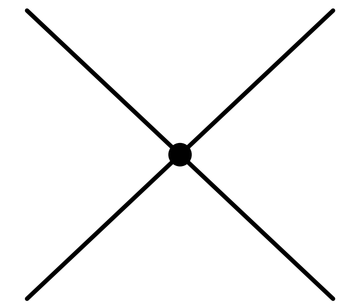
$$\mathcal{L}_{\text{EFT}} = \frac{\Lambda_{NP}^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda_{NP}}, \frac{g_* H}{\Lambda_{NP}}, \frac{g_* f_{L,R}}{\Lambda_{NP}^{3/2}}, \frac{gF_{\mu\nu}}{\Lambda_{NP}^2}\right)$$

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

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

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

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