EW interactions in high-energy top quark final states

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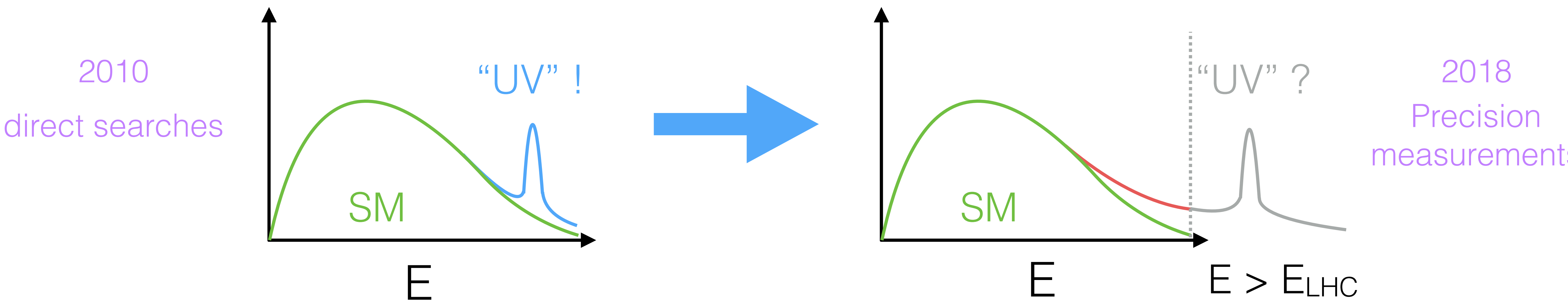
Outline

1. Energy growth/unitarity violating behaviour in EW top scattering
   - Helicity amplitude study
   - Anomalous couplings vs SMEFT interpretation
2. Connect to high energy collider processes
   - Case study: single top in association with a Z or Higgs
   - High energy behaviour from 2 → 2 to 2 → 3/4
   - Survey of interesting processes and SMEFT sensitivity

From bumps to tails

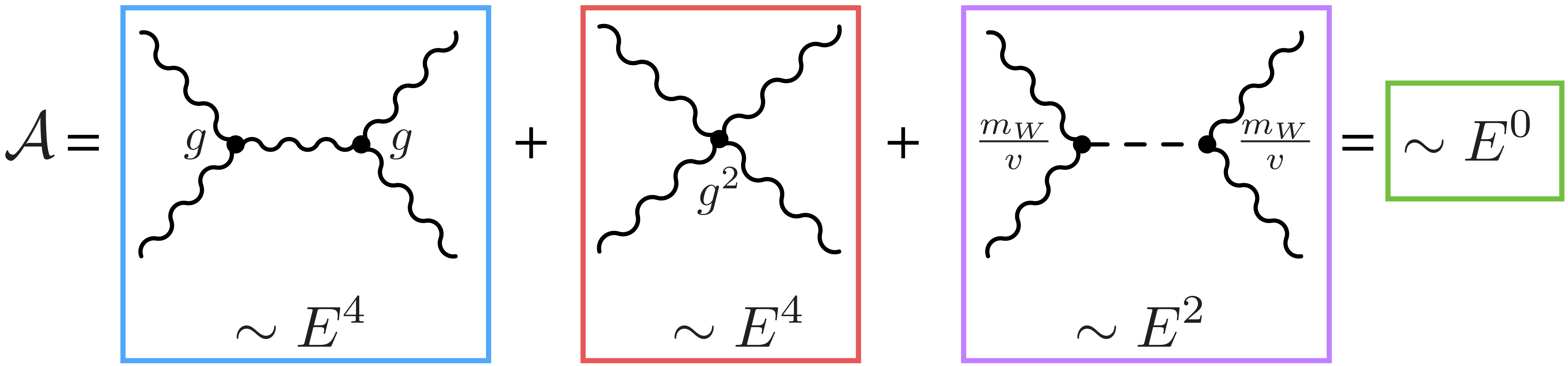


- Possibility that new states exist (just) beyond the energy reach of the LHC
  - We may still observe indirect effects of such particles in the kinematic tails of distributions, e.g., LEP limits on ~ TeV Z'
  - Deviations from SM-like interactions & new Lorentz structures

Unitarity-violating behaviour ⟷ Energy growth

Scattering unitarity

- $W_L W_L \to W_L W_L$: SM unitarity cancellations

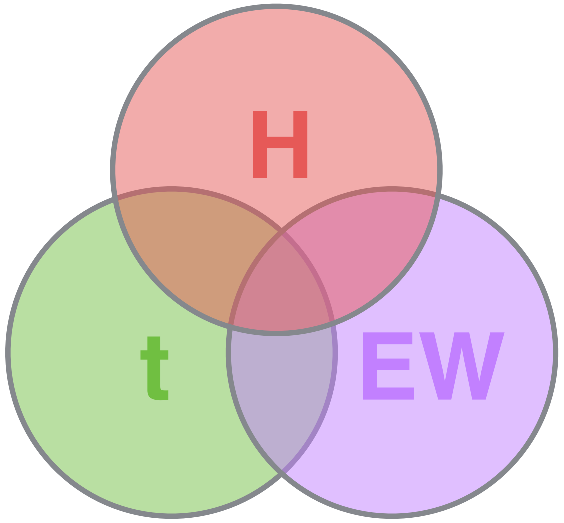


gauge EWSB

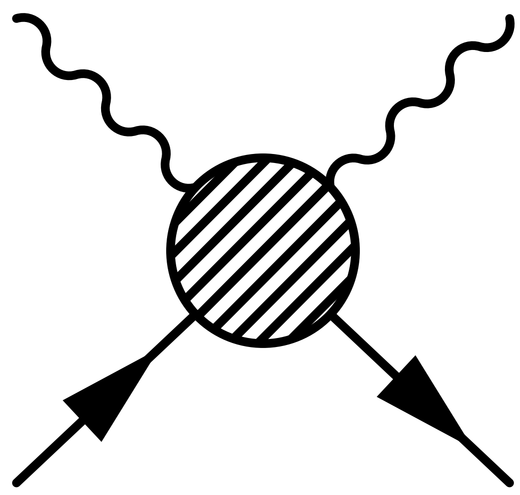
- Deviations from SM interactions = energy growth
  - Theory has limited validity range → heavy new physics
  - Cancellations a feature of gauge invariance & SM EWSB mechanism

Diboson (TGC) VBS (TGC, QGC) EW Higgs prod./decay

Unitarity and tops



- Top quark: other key player in EWSB
  - One of the great hopes is that it may give us hints on the nature of EWSB
  - Coloured & strongly coupled to the Higgs
  - Relatively poorly measured, especially its EW interactions



$$\mathcal{A} \sim E^2 \to E^0 \quad \text{gauge}$$

$$\mathcal{A} \sim m_t E \to E^{-1} \quad \text{EWSB}$$

Modified SM couplings in EWSB generically lead to energy growth

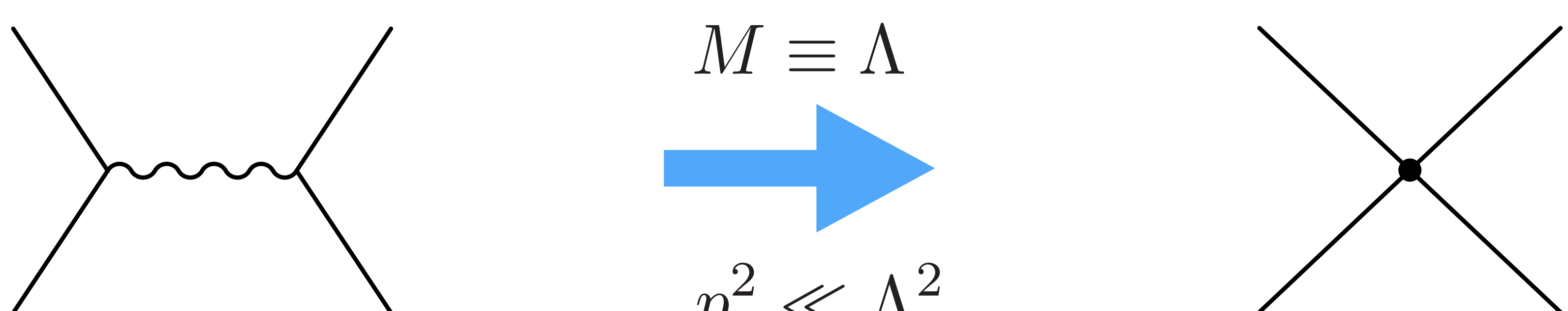
Limited validity range

Heavy new physics

→ Effective Field Theory

SMEFT

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



cf. Fermi Theory

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

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

D=6

Energy growth & precision

- SMEFT is a natural framework to extend the LHC reach
  - Parametrises modified SM interactions & new Lorentz structures
  - Dim-6 fully captures energy growth up to E^2

$$\mathcal{A} \sim \mathcal{A}_{SM}\left(\boxed{1 + c_i \frac{v^2}{\Lambda^2}} + \boxed{c_j \frac{v\,E}{\Lambda^2} + c_k \frac{E^2}{\Lambda^2}}\right)$$

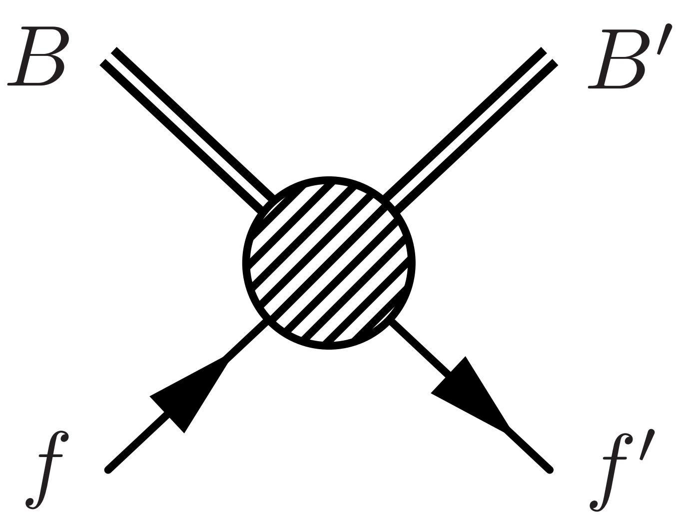
Inclusive measurements	High-energy measurements
Signal-strength modifiers	Differential distributions
κ-framework	SMEFT

'Energy helps accuracy'

$$c = 1,\ \Lambda = 1\,\mathrm{TeV},\ E \sim 500\,\mathrm{GeV} \to \delta_i \sim 0.06,\ \delta_j \sim 0.12,\ \delta_k \sim 0.25$$

EW-top scatterings

- Probe for new interactions (SMEFT) in EWSB sector
- Top quark 2→2 scattering amplitudes with energy growth
  - High-energy limit: $s \sim |t| \gg v^2$
  - Unitarity non-cancellations incl. mass effects? SMEFT interpretation
  - Interfering with the SM or not? Compute helicity amplitudes
  - What collider processes can be sensitive?



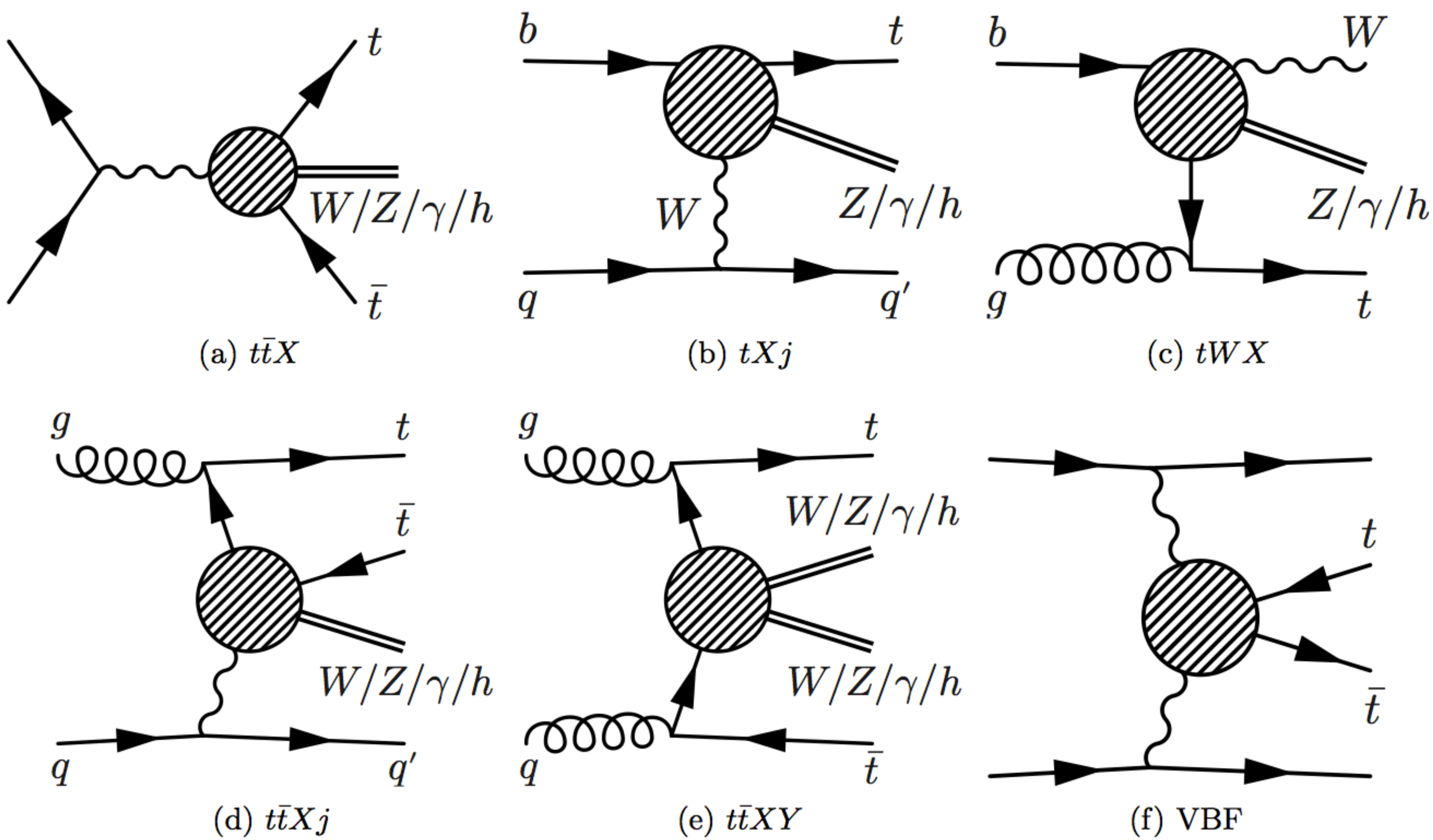
$$f = t, b \quad \& \quad B = W, Z, h, \gamma$$

*at least one top quark

$$\begin{array}{llll} b\,W \to t\,h & b\,W \to t\,Z & b\,W \to t\,\gamma & t\,W \to t\,W \\ t\,Z \to t\,h & t\,Z \to t\,Z & t\,Z \to t\,\gamma & \\ t\,h \to t\,h & t\,h \to t\,Z & t\,h \to t\,\gamma & \end{array}$$

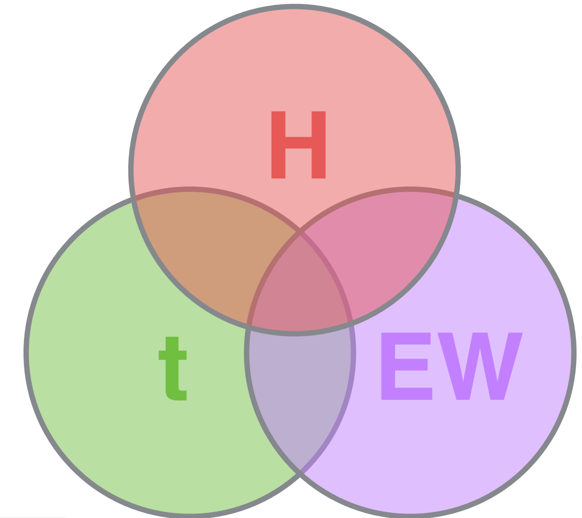
High energy EW top prod.

- Collider processes embedding 2→2 EW-top scattering



[Grzadkowski et al.; JHEP 1010 (2010) 085]
[Aguilar-Saavedra et al.; arXiv:1802.07237]

SMEFT for EWSB



	↓more constrained↓		↓less constrained↓		
Bosonic	$\mathcal{O}_{W}$	$\varepsilon_{IJK}\, W^{I}_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	Yukawa
	$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}_{tW}$	$i(\bar{Q}\sigma^{\mu\nu}\,\tau_I\, t)\,\tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$	weak dipoles
	$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$	$\mathcal{O}_{tB}$	$i(\bar{Q}\sigma^{\mu\nu}\, t)\,\tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$	
	$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi)\, B^{\mu\nu}W^I_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\varphi)(\bar{Q}\,\gamma^\mu\,\tau^I Q)$	
	$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{Q}\,\gamma^\mu\, Q)$	currents
	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{t}\,\gamma^\mu\, t)$	
		(Λ = 1 TeV)	$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi}\, D_\mu\, \varphi)(\bar{t}\,\gamma^\mu\, b) + \text{h.c.}$	RHCC

- Relevant dim-6 SMEFT d.o.f. for EW-top scattering
  - Warsaw basis with $U(2)_Q$ x $U(2)_u$ x $U(3)_d$ x $U(3)_L$ x $U(3)_e$ flavor symmetry
  - Bosonic + top operators

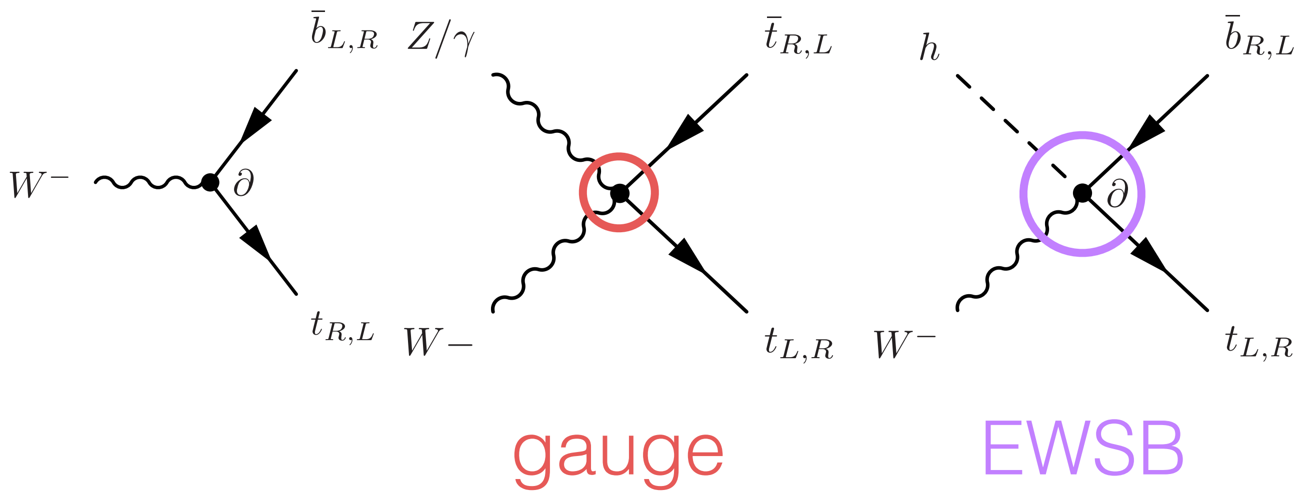
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

EFT vs. AC

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

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

$$c_{tW} \to 2g_R$$



- SMEFT construction predicts additional interactions
  - EFT → AC map is one-way
  - Potentially different from anomalous couplings
  - AC generally violate SU(2)
  - May have different high energy behaviour
- Contact interactions responsible for energy growth

Max growth?

- 2 → 2 amplitude is dimensionless
  - Guess E-growth ↔ canonical dimension of contact interaction
  - In unitary gauge: $[\mathcal{L}_{\text{contact}}] = N \to \mathcal{A} \propto E^{N-4}$
- Goldstone equivalence: $V_L \leftrightarrow \partial_\mu \phi / M$
  - Longitudinal modes ↔ additional powers of growth
- Naive formula:

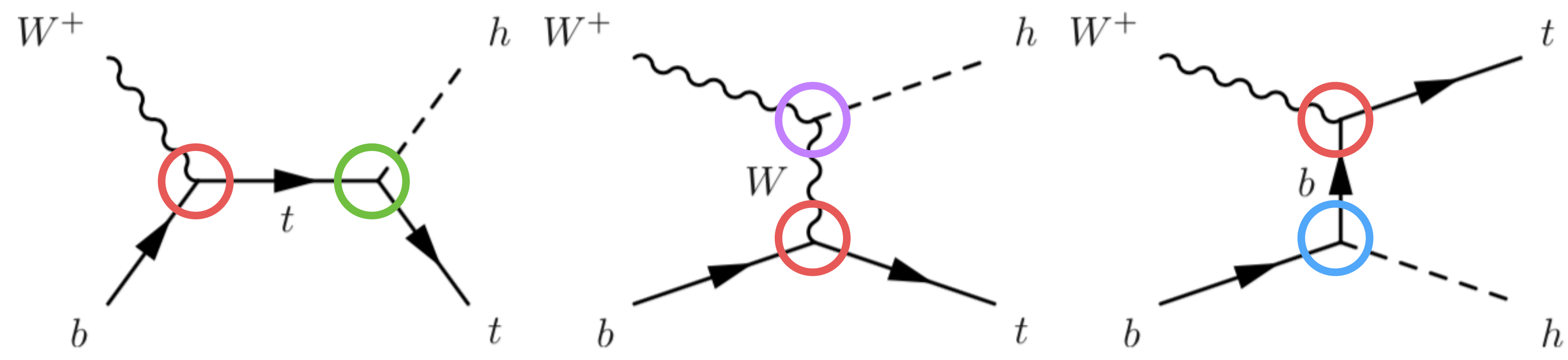
$$\mathcal{A}_{\text{dim-6}} \propto \frac{v^m}{\Lambda^2} \frac{E^{2+n-m}}{M}$$

n: # of V_L

m: # of vev insertions

Dim-6 expectation: $A_{max} \sim E^2$

b W → t h



- In the SM, fully left-handed & longitudinal configuration ~ E^0
- Energy growth from anomalous SM interactions
  - tbW vertex present in all diagrams → overall rescaling
  - bbH interaction ∝ mb ~ 0
  - hWW and ttH interaction participate in unitarity cancellation

$$\mathcal{A}(b_L, W_L, t_R) \propto \sqrt{-t}(2m_W^2 g_{th} - g_{Wh} m_t)$$

  - Setting SM values sends it to ~1/E

b W → t h

SMEFT: many more sources of energy growth

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

b W → t h

Helicity configurations

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

b W → t h

Helicity configurations

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

W_L (rows with $\lambda_W = 0$)

W_T (rows with $\lambda_W = \pm$)

b W → t h

Schematic SM E-dependence down to E^{-2}

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

$b\,W \to t\,h$

All operators with some degree of growth

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

$b\,W \to t\,h$

Max growth

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

b W → t h

Interfering E-growth: SU(2) current operator

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

b W → t h

Non-interfering / no E growth in interference

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

$\propto m_b$

W_T

b W → t h

Sub-leading growth ∝ EW scale (m_t, m_W, v)

g_{th}

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

b W → t h

No E-growing interference

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

$b\, W \rightarrow t\, h$

- Only one source of energy growth from modified SM-like interactions
  - All other sources in the SMEFT are from contact terms
  - E.g. max growths in (-,0,-) & (+,0,+)

$$\mathcal{O}^{(3)}_{\varphi Q} = i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I \varphi\big)\big(\bar{Q}\,\gamma^\mu\, \tau^I Q\big) \quad \rightarrow \quad h\,\boxed{\partial_\mu G_+}\,\bar{t}_L \gamma^\mu b_L \;+ \text{h.c.}$$

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

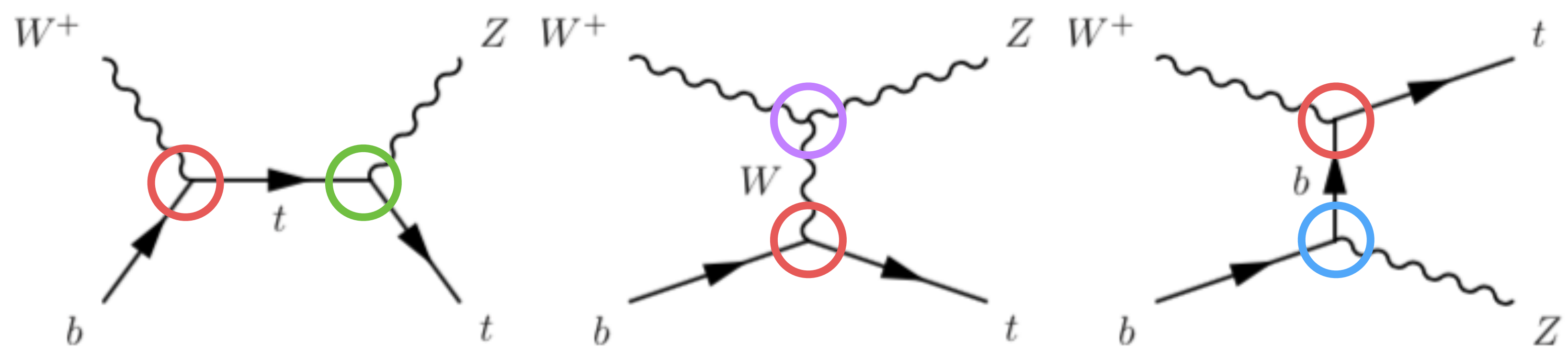
dim-6 contact interaction w/ Goldstone ↔ W_L

- Lower energy dependences
  - 'Pay' a mass factor (E → m) to flip fermion helicity/gauge boson polarisation

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

m_W m_t

b W → t Z



- Similar to b W → t h: longitudinal & left-handed ~ E^0
  - tbW → overall rescaling
  - ZWW and ttZ, bbZ interaction → more unitarity cancellations

$$\mathcal{A}(b_L, W_0, t_L, Z_0) \propto \sqrt{s(s+t)}\,(g^Z_{b_L} - g^Z_{t_L} + g_{WZ})$$
$$\mathcal{A}(b_L, W_0, t_R, Z_0) \propto \sqrt{-t}\,(2m^2_W(g^Z_{b_L} - g^Z_{t_R} + g_{WZ}) - g_{WZ}m^2_Z)\,.$$

  - Gauge boson self interactions ↔ fermion interactions
  - Doublet nature of (b, t), EWSB (m_W & m_Z), gauge structure

b W → t Z

Max growth

$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	SM	$\mathcal{O}_{\phi D}$	$\mathcal{O}_{\phi tb}$	$\mathcal{O}_{\phi WB}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{\phi Q}^{(1)}$
$-,0,-,0$	s^0	s^0	–	s^0	–	s^0	s^0	$\sqrt{s(s+t)}$	–	–
$-,0,+,0$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}m_t$	–	–	$\sqrt{-t}m_W$	$\frac{m_W(s+t)}{\sqrt{-t}}$	–	$\sqrt{-t}m_t$	$\sqrt{-t}m_t$	$\sqrt{-t}m_t$
$+,0,-,0$	–	–	–	–	–	–	–	–	–	–
$+,0,+,0$	–	–	$\sqrt{s(s+t)}$	–	–	–	–	–	–	–
$-,-,-,0$	$\frac{1}{\sqrt{s}}$	–	–	–	–	–	$\frac{m_W^2(s+t)}{\sqrt{-t}v}$	$\sqrt{-t}m_W$	–	–
$-,-,+,0$	$\frac{1}{s}$	s^0	–	s^0	s^0	$\sqrt{s(s+t)}$	s^0	s^0	s^0	s^0
$-,0,-,-$	$\frac{1}{\sqrt{s}}$	–	–	$\frac{s m_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_t$	$\frac{m_W^2(s+t)}{\sqrt{-t}v}$	$\sqrt{-t}m_W$	–	–
$-,0,-,+$	$\frac{1}{\sqrt{s}}$	–	–	$\frac{m_W(s+t)}{\sqrt{-t}}$	–	–	$\frac{m_W^2(s+t)}{\sqrt{-t}v}$	–	–	–
$-,0,+,-$	s^0	s^0	–	s^0	–	s^0	s^0	s^0	–	s^0
$-,0,+,+$	$\frac{1}{s}$	s^0	–	–	$\sqrt{s(s+t)}$	$\sqrt{s(s+t)}$	–	s^0	s^0	s^0
$-,+,-,0$	$\frac{1}{\sqrt{s}}$	–	–	–	–	–	$\frac{m_W^2(s+t)}{\sqrt{-t}v}$	–	–	–
⋮					⋮					
$+,0,+,+$	–	–	$\sqrt{-t}m_W$	–	–	–	–	–	–	–
$+,+,-,0$	–	–	–	–	–	–	–	–	–	–
$+,+,+,0$	–	–	$\sqrt{-t}m_W$	–	–	–	–	–	–	–
$-,-,-,-$	s^0	s^0	–	s^0	s^0	s^0	s^0	s^0	–	s^0
$-,-,-,+$	$\frac{1}{s}$	–	–	s^0	–	–	$\frac{m_W\sqrt{s(s+t)}}{v}$	–	–	–
$-,-,+,-$	$\frac{1}{\sqrt{s}}$	–	–	–	–	$\frac{m_W(s+t)}{\sqrt{-t}}$	–	–	–	–
$-,-,+,+$	–	–	–	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$	$\sqrt{-t}m_W$	$\frac{\sqrt{-t}m_t m_W}{v}$	–	–	–
$-,+,-,-$	$\frac{1}{s}$	–	–	s^0	–	–	$\frac{m_W\sqrt{s(s+t)}}{v}$	–	–	–
$-,+,-,+$	s^0	s^0	–	s^0	–	–	–	s^0	–	s^0
$-,+,+,-$	$\frac{1}{\sqrt{s}}$	–	–	$\sqrt{-t}m_t$	–	–	$\frac{\sqrt{-t}m_t m_W}{v}$	–	–	–
$-,+,+,+$	$\frac{1}{\sqrt{s}}$	–	–	–	–	$\frac{m_W(s+t)}{\sqrt{-t}}$	–	–	–	–
⋮					⋮					

$b\,W \to t\,Z$ Many subleading growths (non-interfering)

$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	SM	$\mathcal{O}_{\phi D}$	$\mathcal{O}_{\phi tb}$	$\mathcal{O}_{\phi WB}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{\phi Q}^{(1)}$
$-,0,-,0$	s^0	s^0	$-$	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$	$-$	$-$
$-,0,+,0$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}m_t$	$-$	$-$	$\sqrt{-t}m_W$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$\sqrt{-t}m_t$	$\sqrt{-t}m_t$	$\sqrt{-t}m_t$
$+,0,-,0$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
$+,0,+,0$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
$-,-,-,0$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W^2(s+t)}{\sqrt{-t}v}$	$\sqrt{-t}m_W$	$-$	$-$
$-,-,+,0$	$\frac{1}{s}$	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$	s^0	s^0	s^0	s^0
$-,0,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_t$	$\frac{m_W^2(s+t)}{\sqrt{-t}v}$	$\sqrt{-t}m_W$	$-$	$-$
$-,0,-,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$	$\frac{m_W^2(s+t)}{\sqrt{-t}v}$	$-$	$-$	$-$
$-,0,+,-$	s^0	s^0	$-$	s^0	$-$	s^0	s^0	s^0	$-$	s^0
$-,0,+,+$	$\frac{1}{s}$	s^0	$-$	$-$	$\sqrt{s(s+t)}$	$\sqrt{s(s+t)}$	$-$	s^0	s^0	s^0
$-,+,-,0$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$-$	$\frac{m_W^2(s+t)}{\sqrt{-t}v}$	$-$	$-$	$-$
$\vdots$					$\vdots$					
$+,0,+,+$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,-,0$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
$+,+,+,0$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$	$-$	$-$	$-$	$-$
$-,-,-,-$	s^0	s^0	$-$	s^0	s^0	s^0	s^0	s^0	$-$	s^0
$-,-,-,+$	$\frac{1}{s}$	$-$	$-$	s^0	$-$	$-$	$\frac{m_W\sqrt{s(s+t)}}{v}$	$-$	$-$	$-$
$-,-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$	$-$	$-$
$-,-,+,+$	$-$	$-$	$-$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$	$\sqrt{-t}m_W$	$\frac{\sqrt{-t}m_t m_W}{v}$	$-$	$-$	$-$
$-,+,-,-$	$\frac{1}{s}$	$-$	$-$	s^0	$-$	$-$	$\frac{m_W\sqrt{s(s+t)}}{v}$	$-$	$-$	$-$
$-,+,-,+$	s^0	s^0	$-$	s^0	$-$	$-$	$-$	s^0	$-$	s^0
$-,+,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$\frac{\sqrt{-t}m_t m_W}{v}$	$-$	$-$	$-$
$-,+,+,+$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$-$	$-$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$-$	$-$	$-$	$-$
$\vdots$					$\vdots$					

Gauge invariance & AC

- Naive E formula for dipole contact term

$$\mathcal{O}_{tW} = i(\bar{Q}\sigma^{\mu\nu}\tau_I t)\,\tilde{\varphi}\,W^I_{\mu\nu} + \text{h.c.} \quad \rightarrow \quad gv\,\bar{t}_L\sigma^{\mu\nu}t_R W^+_\mu W^-_\nu\,,\; gv\,\bar{b}_L\sigma^{\mu\nu}t_R Z_\mu W^-_\nu$$

  - Longitudinal configuration: n=2 & m=1 → E^3!
  - Larger than dim-6 expectations…

$\lambda_b,\,\lambda_W,\,\lambda_t,\,\lambda_Z$	SM	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$
$-,0,-,0$	s^0	$-$	s^0
$-,0,+,0$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}m_W$	$\frac{m_W(s+t)}{\sqrt{-t}}$

  - Not present in SMEFT prediction, cancelled by gauge invariance ~ E
  - Not the case for general (AC) dipole modification of tbW vertex ~ E^3!

- Different high energy behaviour for AC vs. SMEFT
  - Cannot naively map constraints on e.g. g_R from single-top production/decay to predictions for e.g high-p_T tZj in SMEFT

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

Top/EW scattering

Max. energy growth of SMEFT amplitude (s ~ -t ≫ v)

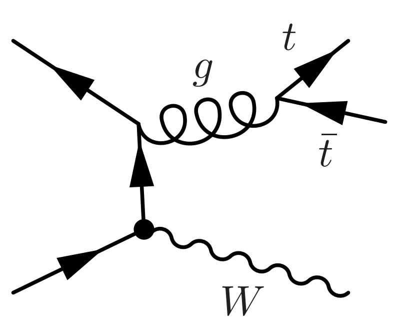
	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$bW \to th$	–	–	–	E	–	–	E	–	E^2	–	E^2	–	E^2
$bW \to tZ$	E	–	–	–	E	E^2	–	E^2	E^2	E	E^2	E	E^2
$bW \to t\gamma$	–	–	–	–	E	E^2	–	E^2	E^2	–	–	–	–
$tW \to tW$	E	E	–	E	E	E^2	E	E	E^2	E^2	E^2	E^2	–
$tZ \to th$	E	–	E	E	E	–	E	E^2	E^2	E^2	E^2	E^2	–
$tZ \to tZ$	E	E	E	E	E	–	E	E^2	E^2	E	E	E	–
$tZ \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	E	–	–
$th \to th$	E	E	–	–	–	–	E	–	–	–	–	–	–
$th \to t\gamma$	–	–	E	E	E	–	–	E^2	E^2	–	–	–	–
$t\gamma \to t\gamma$	–	–	E	E	E	–	–	E	E	–	–	–	–

photon interactions protected by U(1)Q
Only dipole & TGC operators

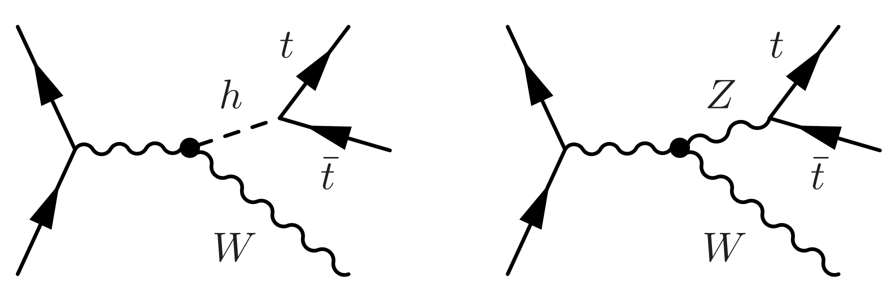
*Interferes with SM
In longitudinal config.

Case study

- Interesting processes to study top/Higgs/EW sector
  - LHC-accessible processes that contain top-EW 2→2 sub amplitudes
  - How much does unitarity violating behaviour translate to collider process?
- Candidate: tt + (W/H/Z)
  - Large QCD-induced contribution, less sensitive to EW operators
  - In the SM, pure EW contributions ~100 times smaller
  - Involve highly off-shell, s-channel gauge bosons



vs.



- Difficult to see SMEFT effects in EW interactions in tt+X

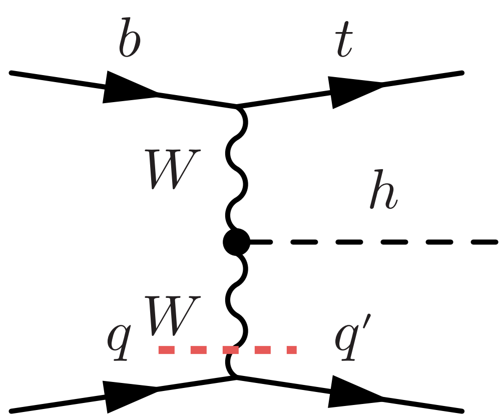
Case study: tZj/tHj

- 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
  - Contain top-EW 2→2
  - Higher kinematic 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 study energy growth & EFT sensitivity of these challenging processes

Anatomy of tHj/tZj

tHj (tZj = h→Z)

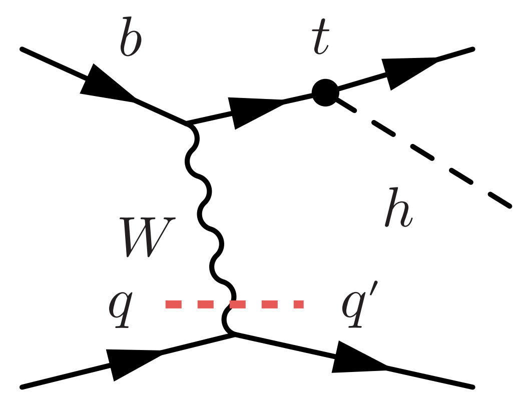


$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi W_i^{\mu\nu} W^i_{\mu\nu}$

HWW

TGC

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

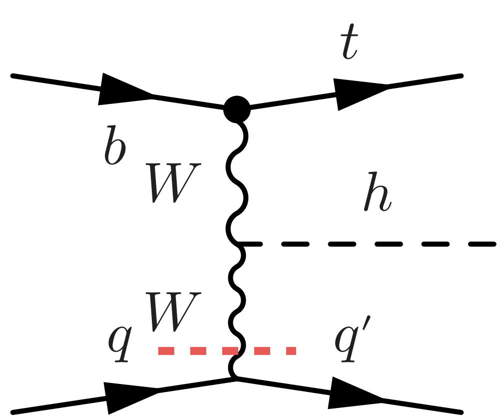


$\mathcal{O}_{t\varphi}$

top Yukawa

ttZ coupling

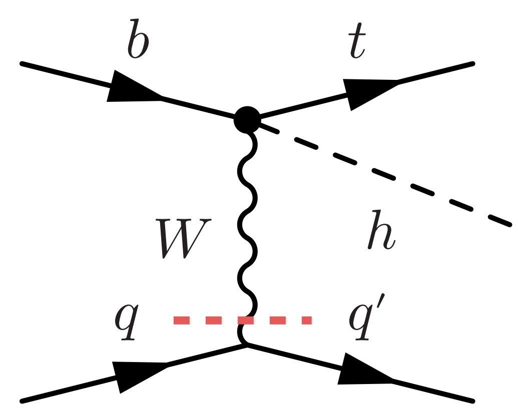
$\mathcal{O}_{\varphi t}$



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

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
  - VBF meets single-top
  - Different energy growth and interference with the SM

LHC sensitivity

Energy growth: looking at tails to increase 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

Increased sensitivity for certain operators

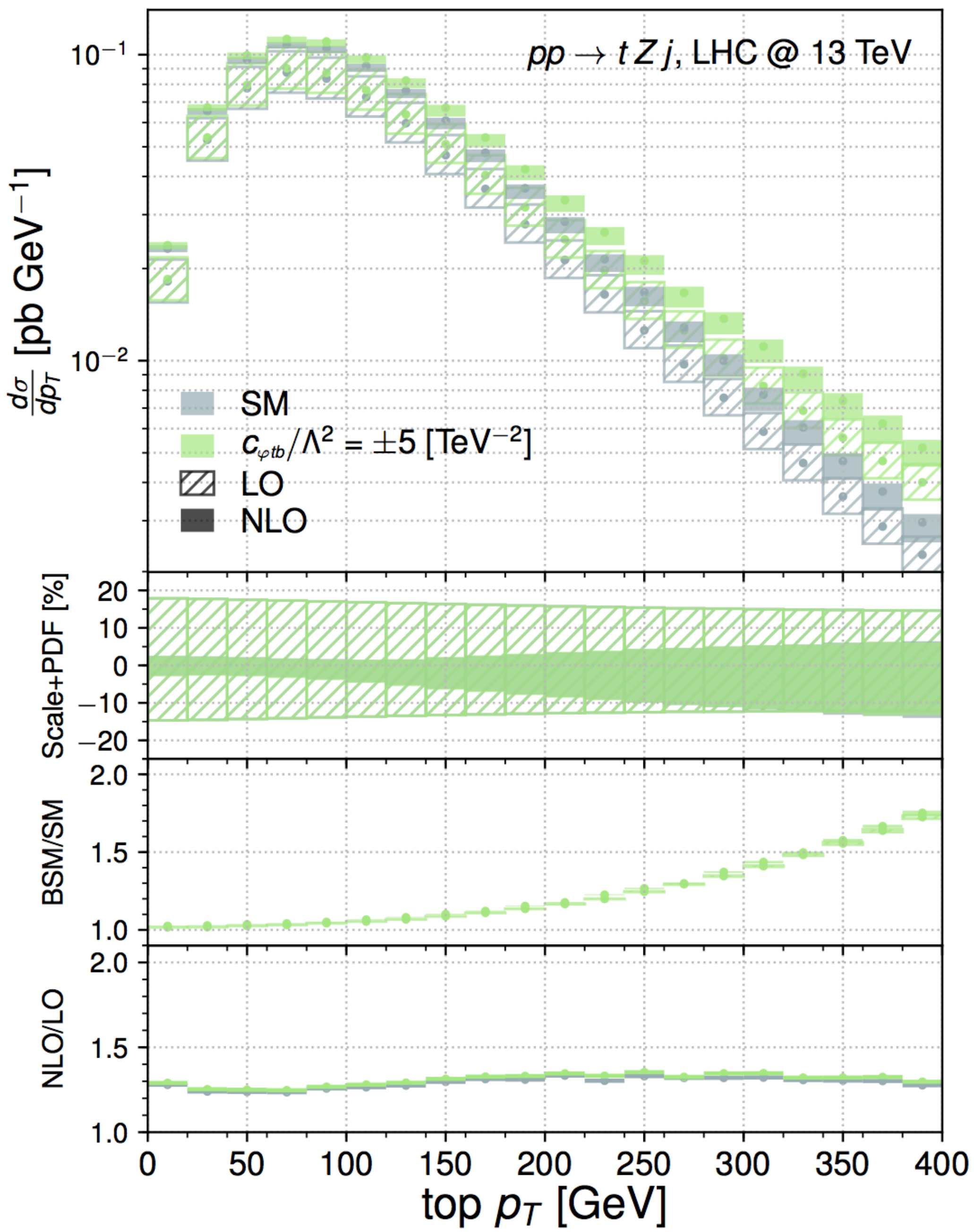
New energy growths w.r.t single top

Consistent with 2→2 subamplitude analysis

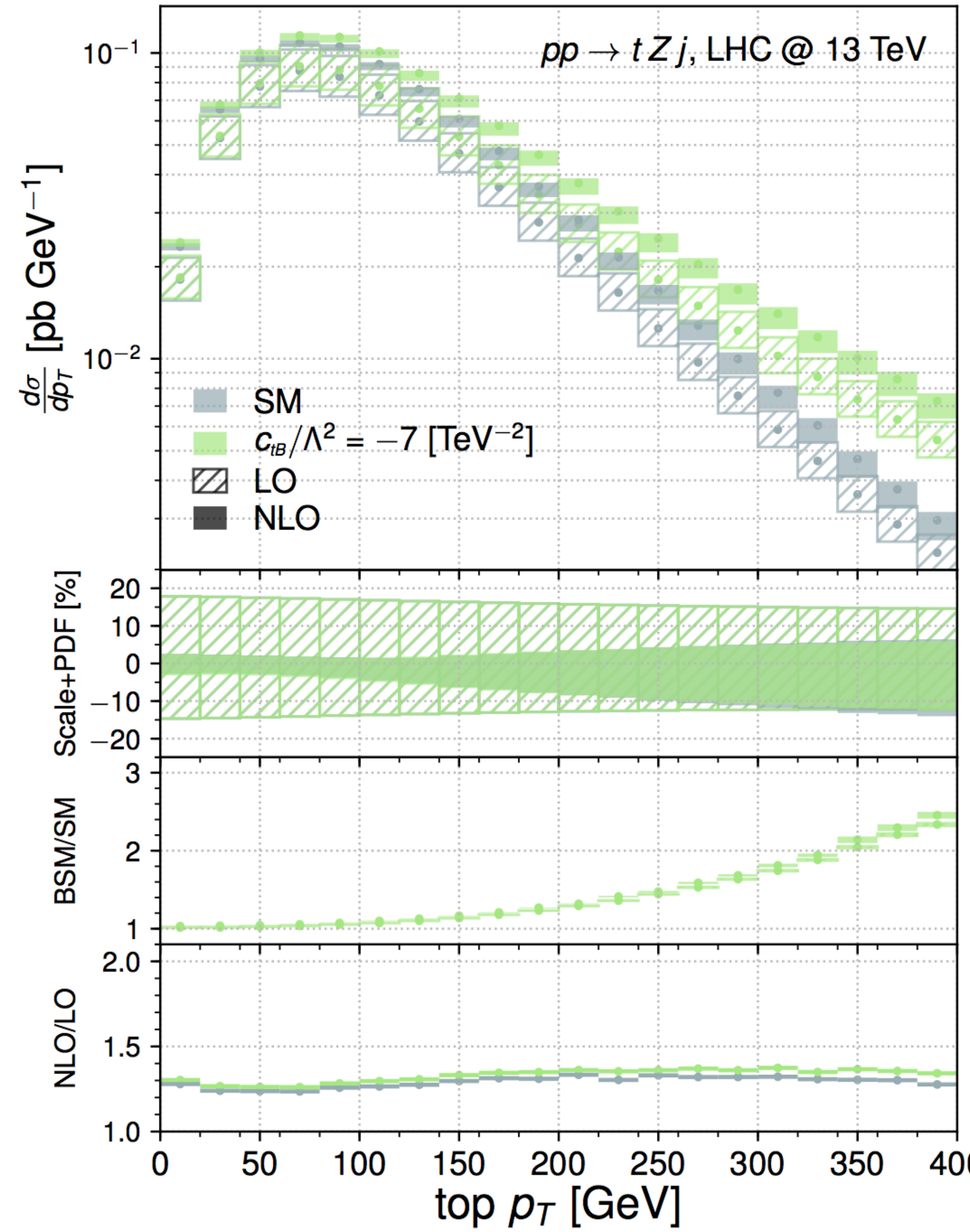
- Except SU(2) current operator
  - Expected energy-growing interference absent
  - Confirmed presence in tHj (not shown)
  - Energy growing Z_L swamped by energy constant Z_T at high p_T

Differential sensitivity

Fixed NLOQCD (mg5_aMC)



Saturating existing limits

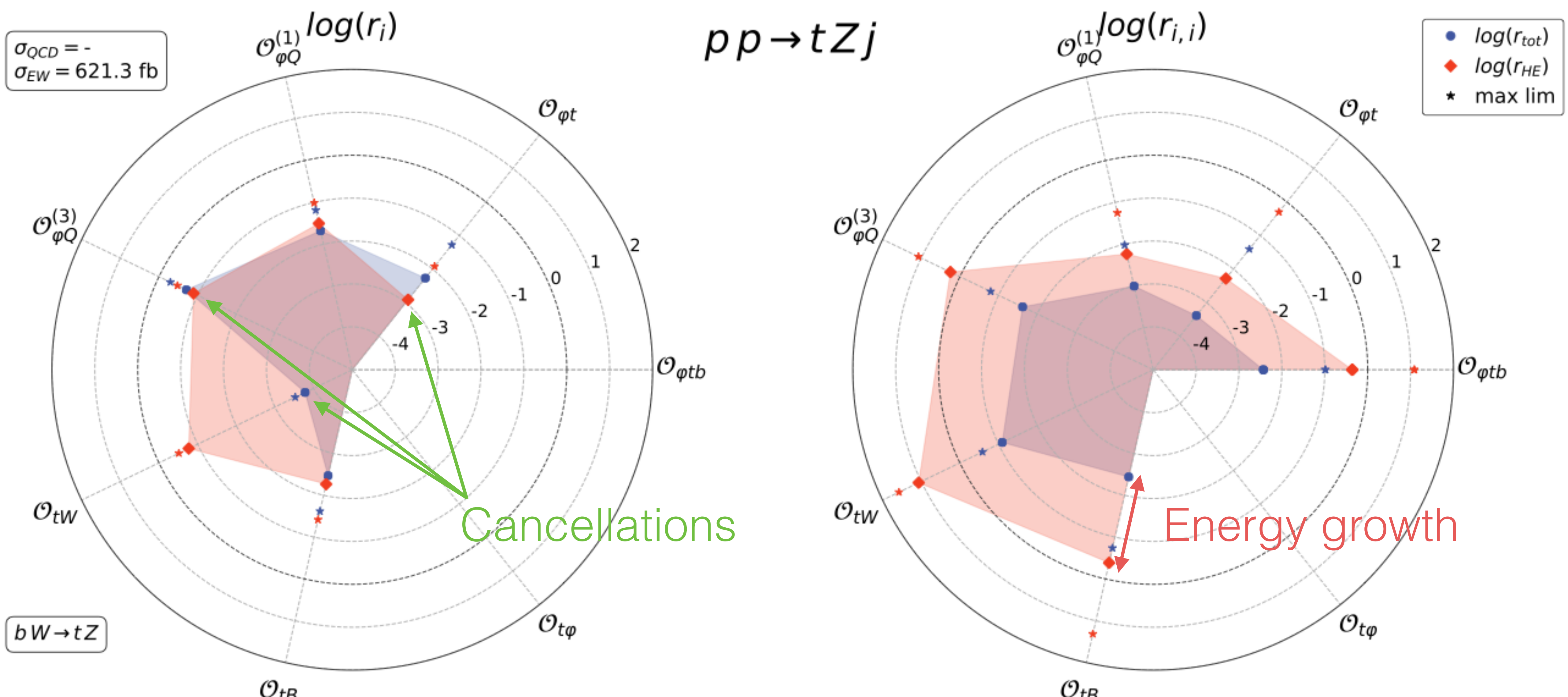


bW → tZ : tZj vs tZW

[Mantani, Maltoni, KM; arXiv:1901.XXXXX]

XS ratio:

interference/SM | square/SM



Expected growth in $O^{(3)}_{\phi Q}$ interference term absent ($b\ W_L \to t\ Z_L$)

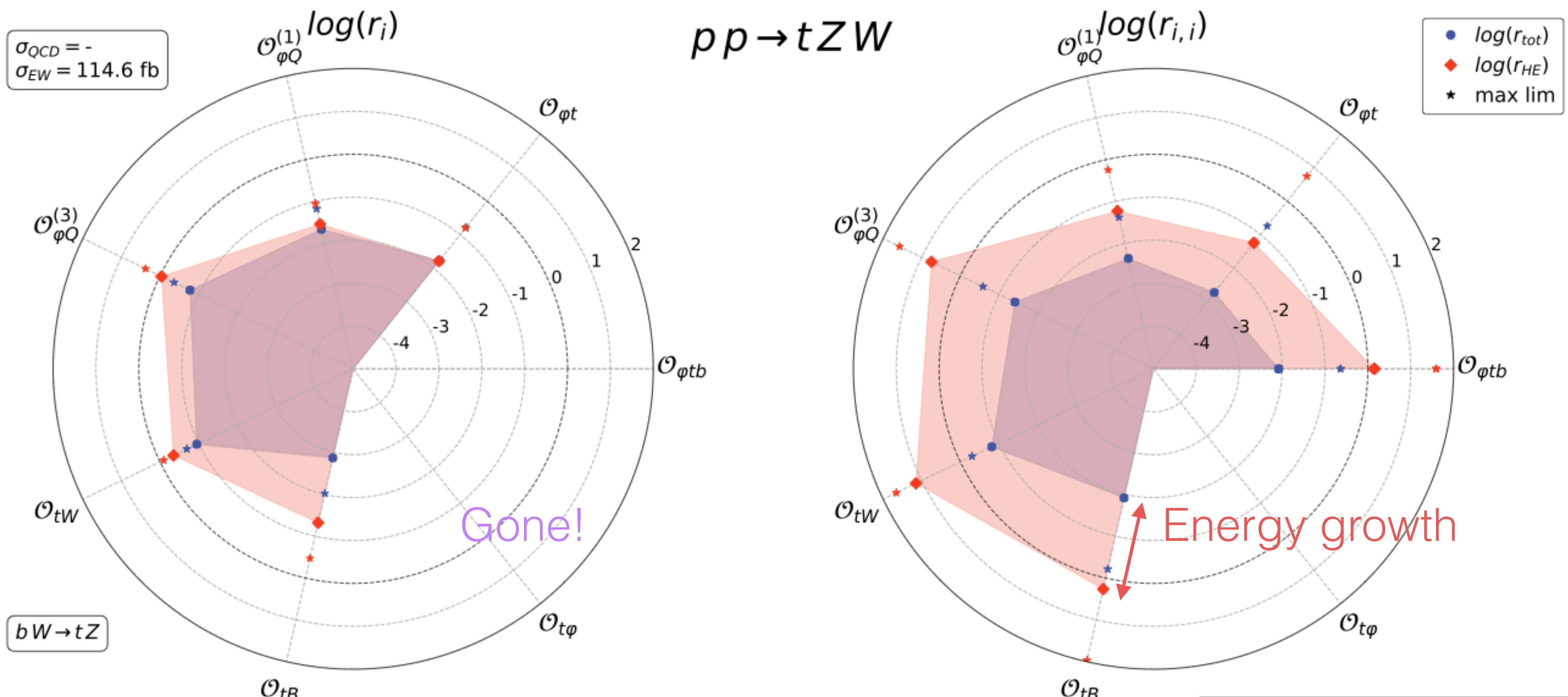
Rate dominated by transverse Z final state

$C_i = 1$
Inclusive
p_T (t,Z)> 500 GeV

bW → tZ : tZj vs tZW

XS ratio:

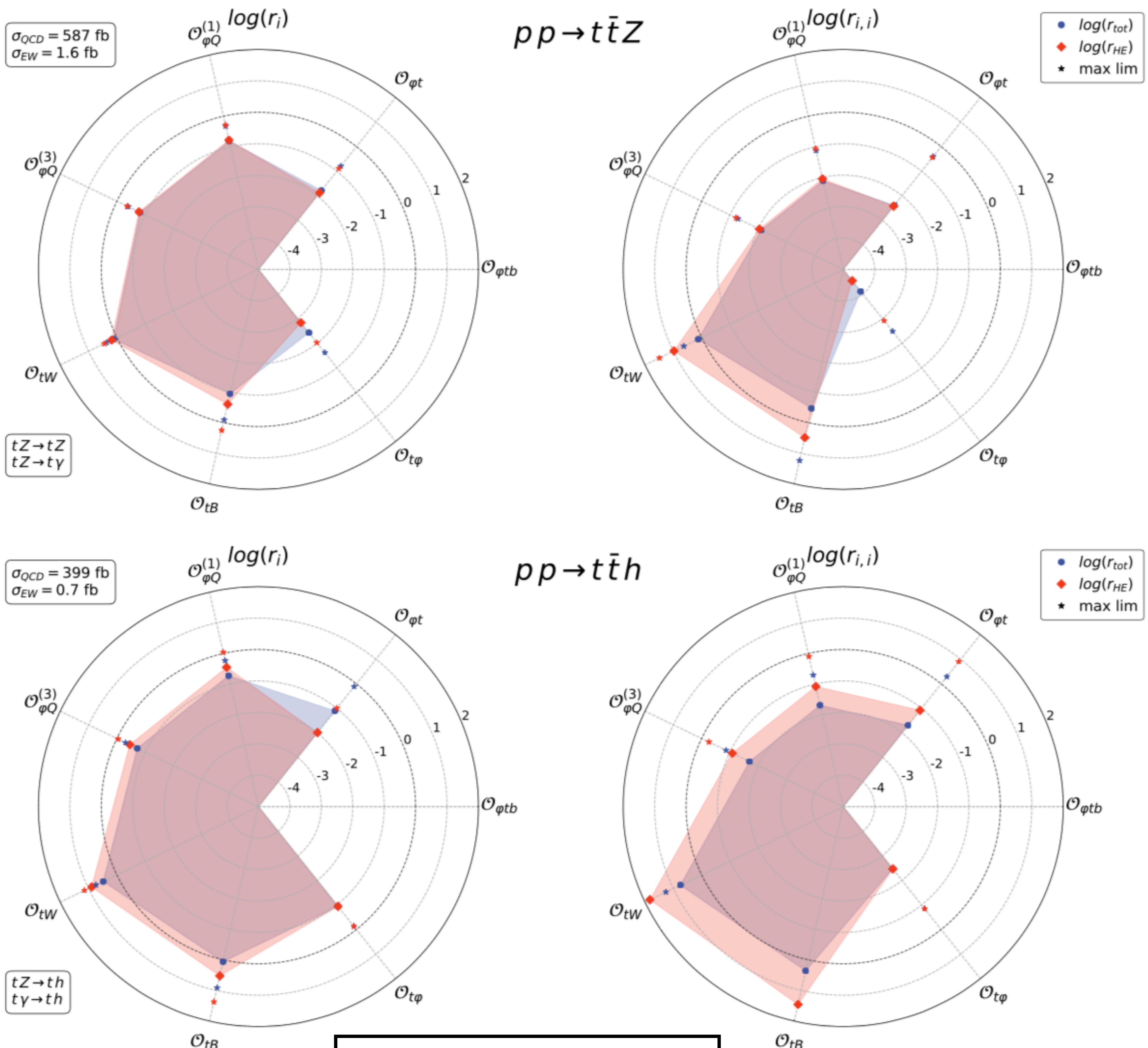
interference/SM square/SM



Growth from interference in b W_L → t Z_L
Access to fully longitudinal final state
tZW > tZj to probe high-energy scattering

C_i = 1
Inclusive
p_T (W,Z)> 500 GeV

ttX for EW-top scattering



$p_T(t,\bar{t}) > 500$ GeV

$\sigma_{QCD} \sim 400 \times \sigma_{EW}$

bb→tt+Z(H) ~90(70)% of EW tt+Z(H)!

Almost no energy growth

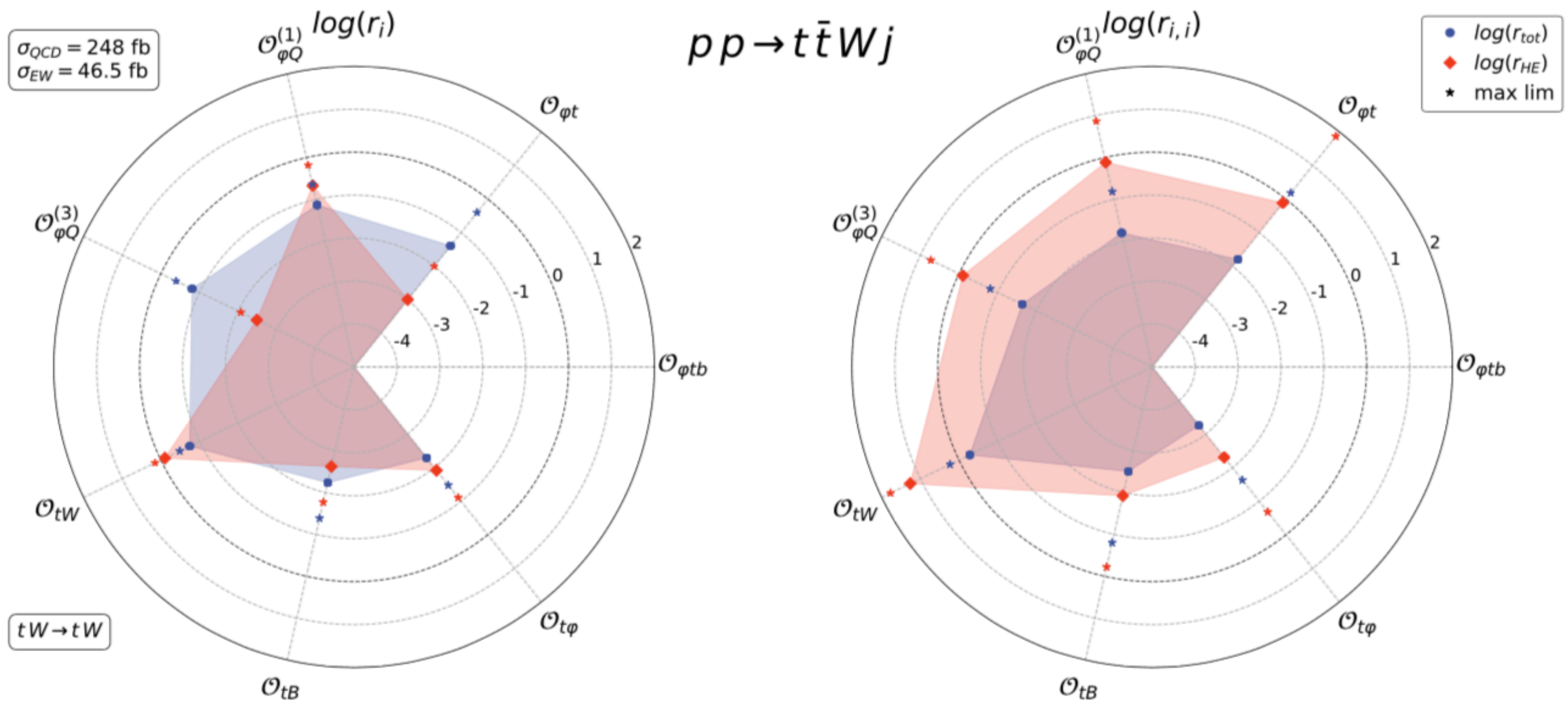
EW coupling modifications affect overall σ_{QCD} rate

Need O(50) enhancements of σ_{EW} to compete

Limited sensitivity

Strong tW scattering

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



σQCD ~ 5 x σEW

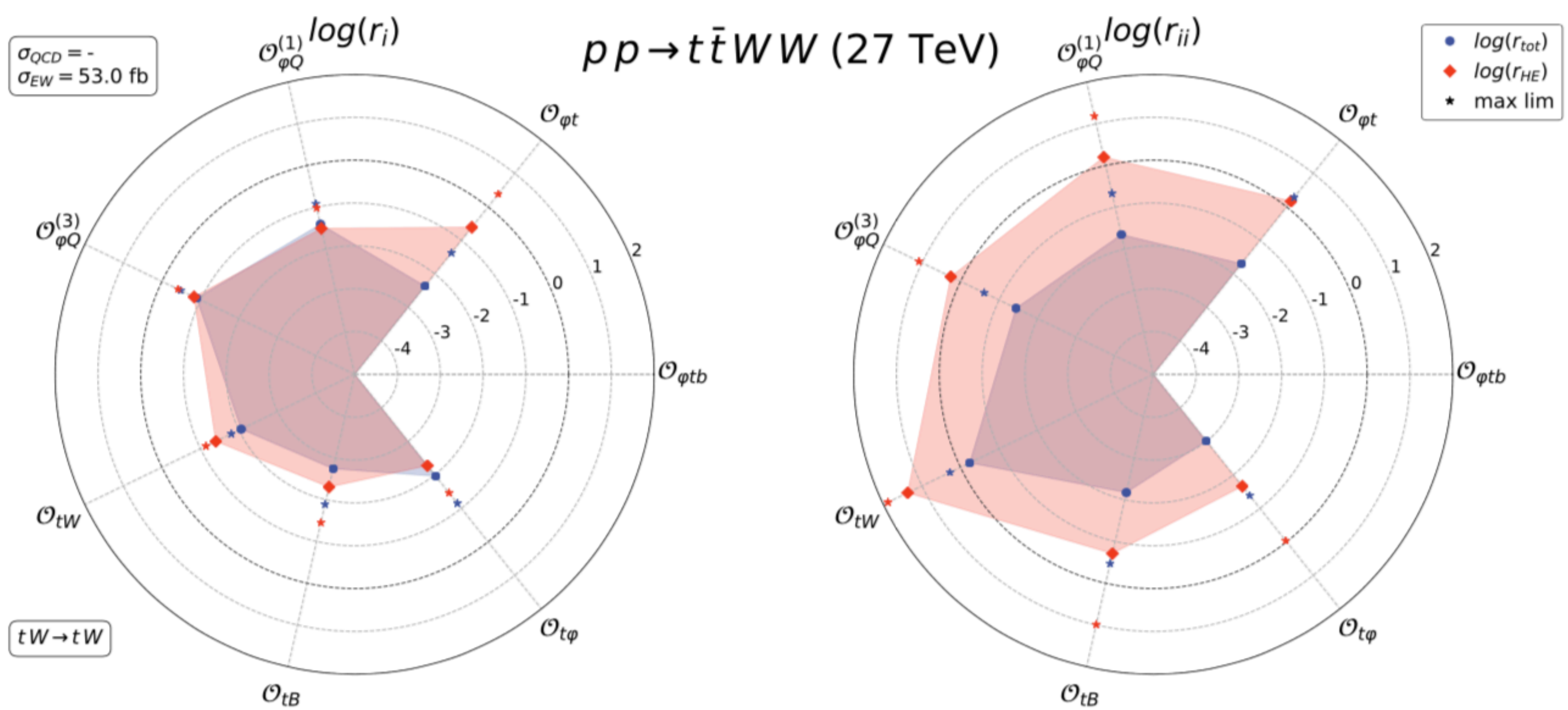
p_T (t | $\bar{t}$, X) > 500 GeV

Cancellations in interference

Also ttZj & ttHj

$\sigma_{QCD} = 444$ fb
$\sigma_{EW} = 6.8$ fb

$\sigma_{QCD} = 320$ fb
$\sigma_{EW} = 3.0$ fb



$\sigma_{13\ \mathrm{TeV}}$ ~8.1 fb

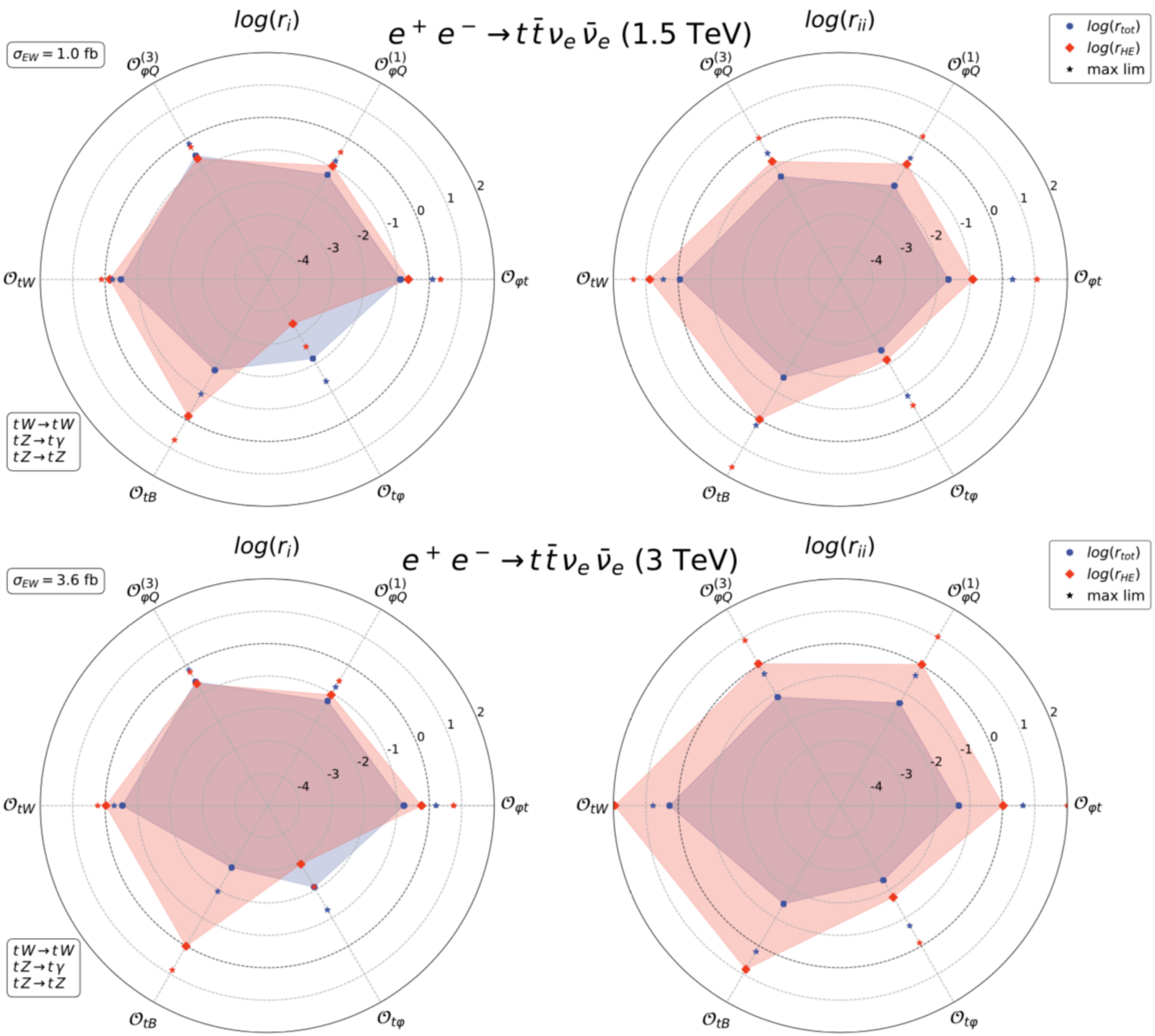
$\sigma_{27\ \mathrm{TeV}}$ ~53 fb

p_T (W) > 500 GeV

Better growth for interference

Also ttZZ, ttZH & ttHH

VBF tt @ CLIC



m_{tt} > 1 TeV

O(0.1-1) effects for c=1

Mild energy growth in interference

m_{tt} > 1.5 TeV

Also tte^+e^- for neutral scatterings

Pheno analysis required…

Conclusion

- High-energy EW top scattering is a rich playground for fingerprinting EWSB
  - Many interesting sources of energy growth & potential SMEFT sensitivity
- Transferred in some cases to LHC accessible processes
  - tt+X not the right place to search
  - Gauge boson final states promising e.g. tZW for accessing V_L
- Many interesting processes could be accessed at future machines (ttXY, ttXj, tHj, …)
  - Larger pp cross sections & L_{int} good for differential measurements
  - VBF tt at e+e- potentially interesting
- Concrete pheno studies required

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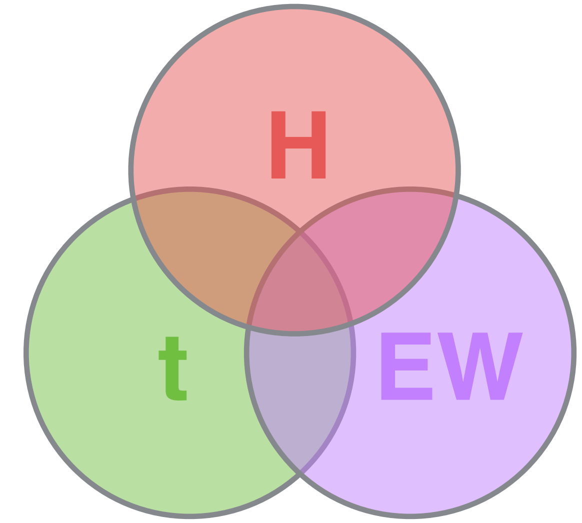
Thank you

Constraints



↓more constrained↓ ↓less constrained↓

Operator	Limit on c_i [TeV^{-2}] Individual	Limit on c_i [TeV^{-2}] Marginalised	Operator	Limit on c_i [TeV^{-2}] Individual	Limit on c_i [TeV^{-2}] Marginalised
$\mathcal{O}_{\varphi D}$	[-0.021,0.0055] [15]	[-0.45,0.50] [15]	$\mathcal{O}_{t\varphi}$	[-6.5,1.3] [6]	[-153,16.5] [15]
$\mathcal{O}_{\varphi \Box}$	[-0.78,1.44] [15]	[-1.24,16.2] [15]	$\mathcal{O}_{tB}$	[-7.09,4.68] [16]	–
$\mathcal{O}_{\varphi B}$	[-0.0033,0.0031] [15]	[-0.13,0.21] [15]	$\mathcal{O}_{tW}$	[-1.31,1.80] [16]	[-4.0,3.4] [16]
$\mathcal{O}_{\varphi W}$	[-0.0093,0.011] [15]	[-0.50,0.40] [15]	$\mathcal{O}_{\varphi Q}^{(1)}$	[-3.10,3.10] [16]	–
$\mathcal{O}_{\varphi WB}$	[-0.0051,0.0020] [15]	[-0.17,0.33] [15]	$\mathcal{O}_{\varphi Q}^{(3)}$	[-2.59,1.50] [16]	[-4.2,2.0] [16]
$\mathcal{O}_{W}$	[-0.18,0.18] [17]	–	$\mathcal{O}_{\varphi t}$	[-9.78,8.18] [16]	–
			$\mathcal{O}_{\varphi tb}$	[-5.28,5.28] [18]	–

Bosonic

Yukawa

weak dipoles

currents

RHCC

- Hierarchy of constraints between bosonic & top
  - EWPO, TGC has a better level of precision

[Butter et al; JHEP 1607 (2016) 152] *[Degrande, Maltoni, KM, Vryonidou, Zhang; JHEP 1810 (2018) 005]*
[Ellis et al; JHEP 1806 (2018) 146] *[Buckley et al; PRD 92 (2015) 9, 091501 & JHEP 1604 (2016) 015]*

SMEFT: the new SM

- Wilsonian approach: our world is a low energy EFT
  - SM: all possible relevant & marginal operators ($D \leq 4$)
  - + EFT: tower of irrelevant operators ($D > 4$)
- Manifest $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge invariance
  - 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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

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

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- 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

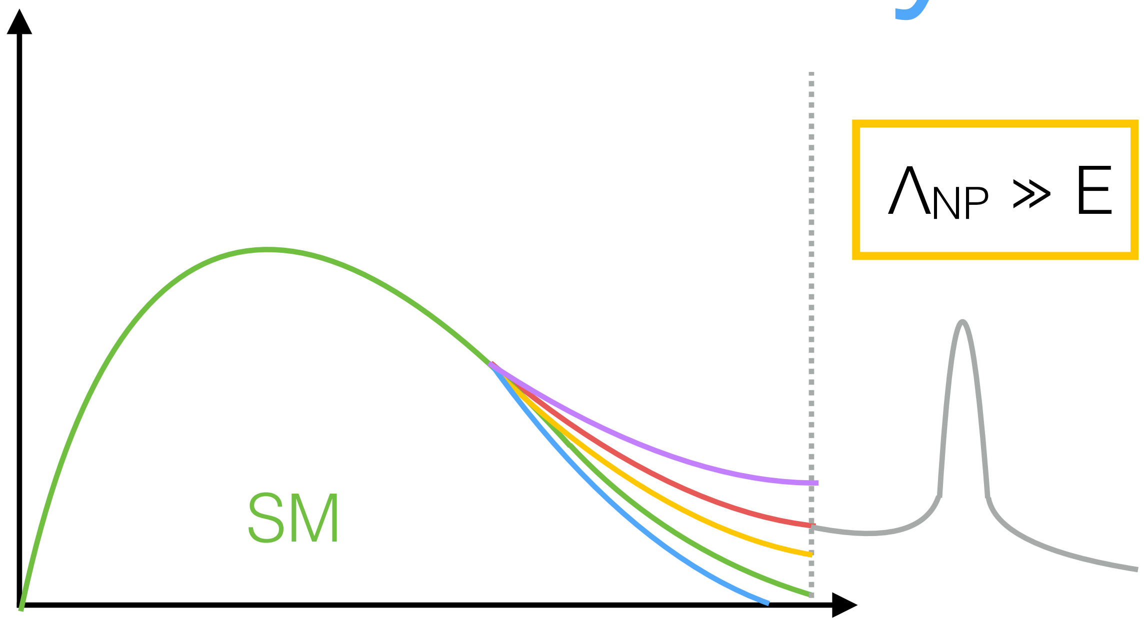
SILH
HISZ
Higgs
…

SMEFT@NLO

- FeynRules/NLOCT/UFO implementation of Warsaw basis
  - Tools for translation between bases [Falkowski et al.; EPJC 75 (12) 1-14] rosetta.hepforge.org
- $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$ flavor symmetry [Aguilar-Saavedra et al.; arXiv:1802.07237]
  - Flavor diagonal fermionic operators
  - Single out those involving the top quark
  - Independent 3rd gen. + universal 1st & 2nd gen.
- + all bosonic operators (Higgs & gauge bosons)
- Validated with existing implementations where available

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]

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

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

- 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

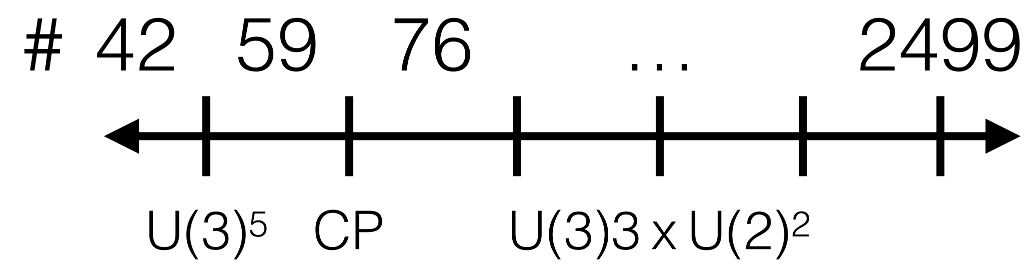
[Contino et al.; JHEP 1607 (2016) 144]

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

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
- Constraints as a function of energy (cuts)
    - Allow a wider range of model interpretations (different NP mass scales)
    - Check perturbativity in Wilson coefficients
- Matching to UV models
    - Correlated Wilson coefficients → better limits
    - Validity & perturbativity in NP couplings
    - Marginalisation over operator subsets generated by target model

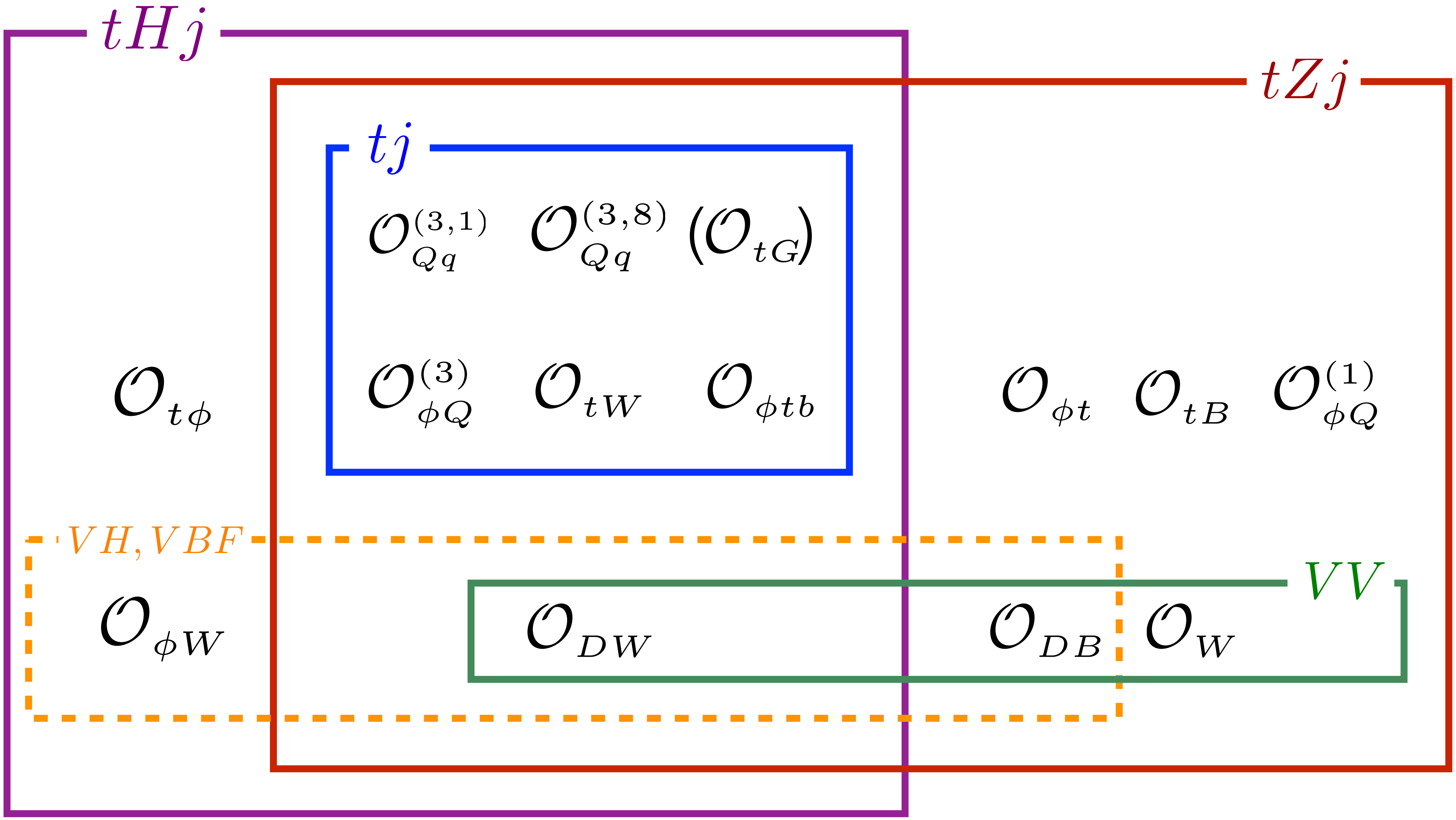
Flavor symmetry



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

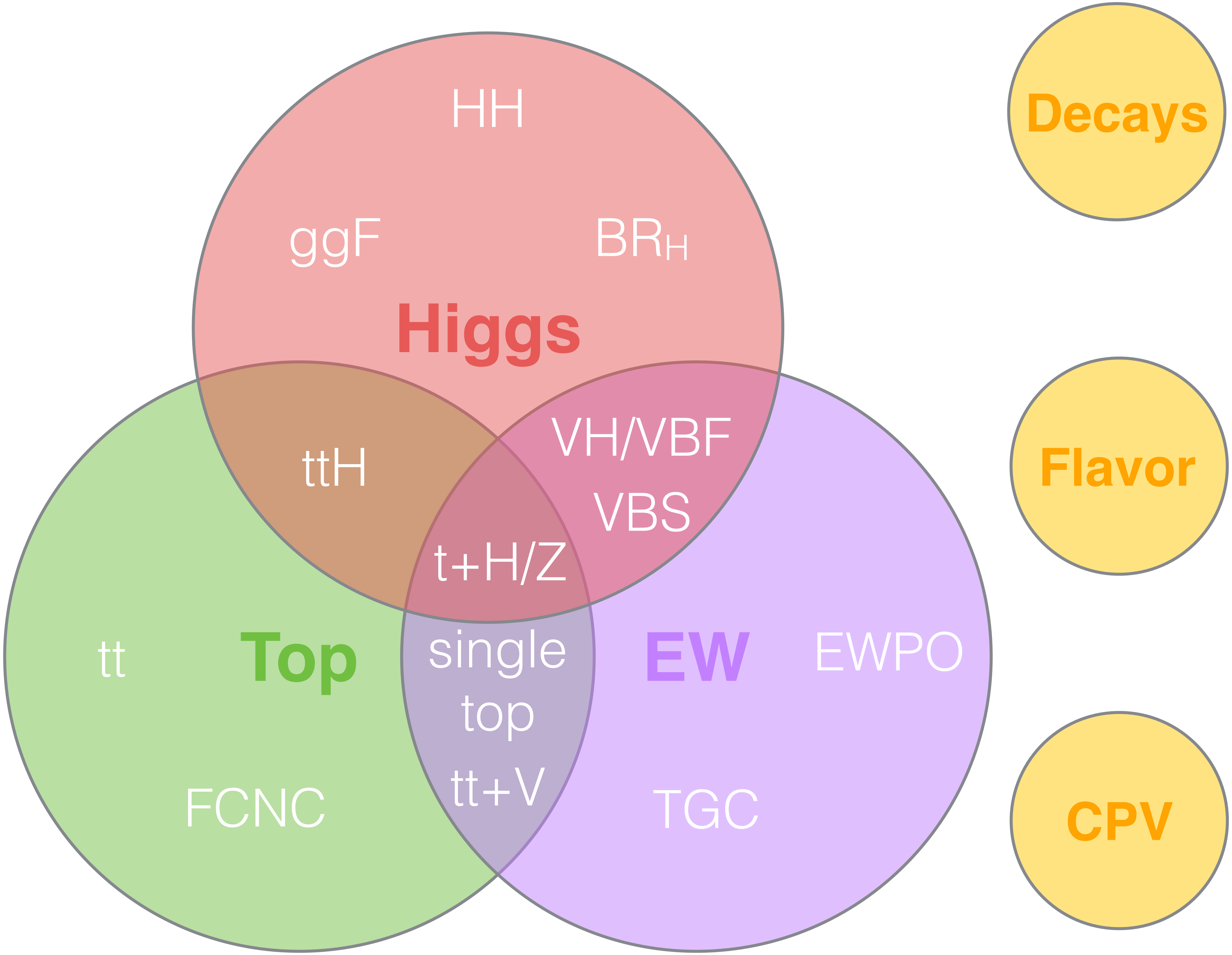
- SM fermion sector $q^i,\, u^i,\, d^i,\, l^i,\, e^i$
  - 5 SU(3) x SU(2) x U(1) representations → $U(3)^5$ flavor symmetry
  - Only broken by Yukawa interactions
- Some SMEFT operators also break it
  - Chirality flipping $F_L f_R$ structures (Yukawa-like)
  - Flavor violating (off diagonal/non-universal) entries
- Staring point: flavor symmetric
  - No chirality flipping & diagonal, universal structure
- Controlled departures
  - Minimal for top physics: $U(3)^3 \times U(2)^2$, single out q^3, u^3
  - Similar to MFV: expansion in Yukawa couplings

Interplay

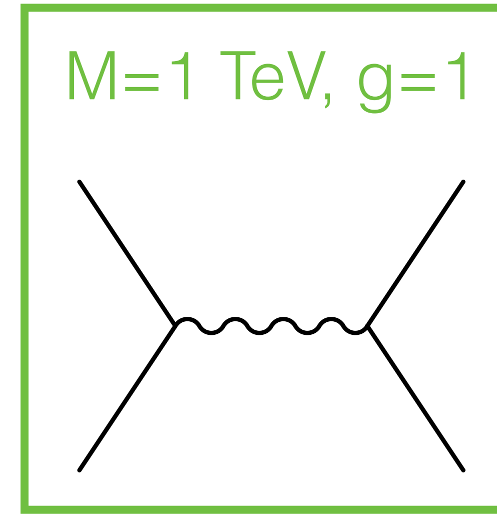


+ ttW/Z/H/γ

SMEFT at the LHC: key players

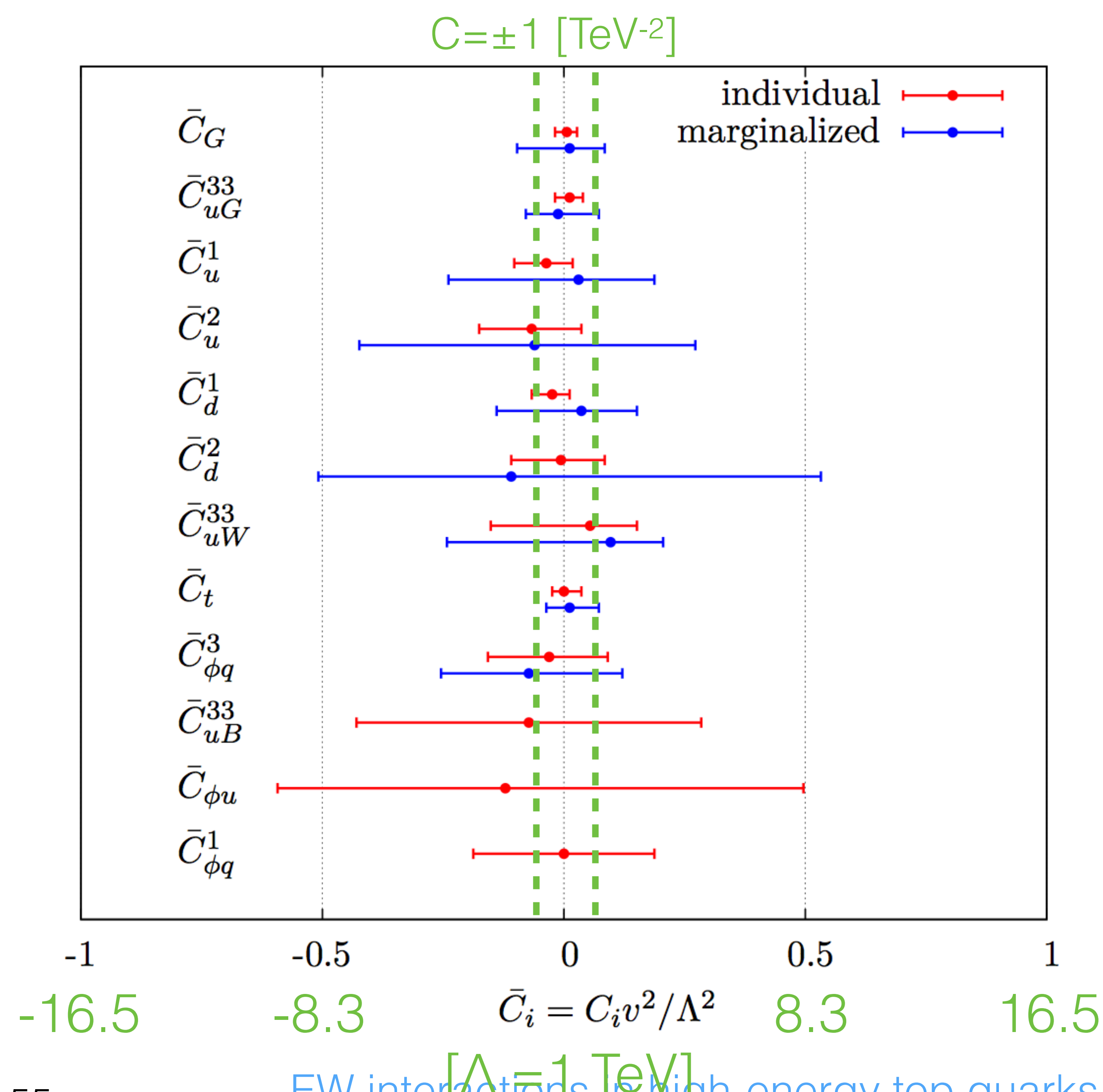


[Buckley et al; PRD 92 (2015) 9, 091501 & JHEP 1604 (2016) 015]



TopFitter

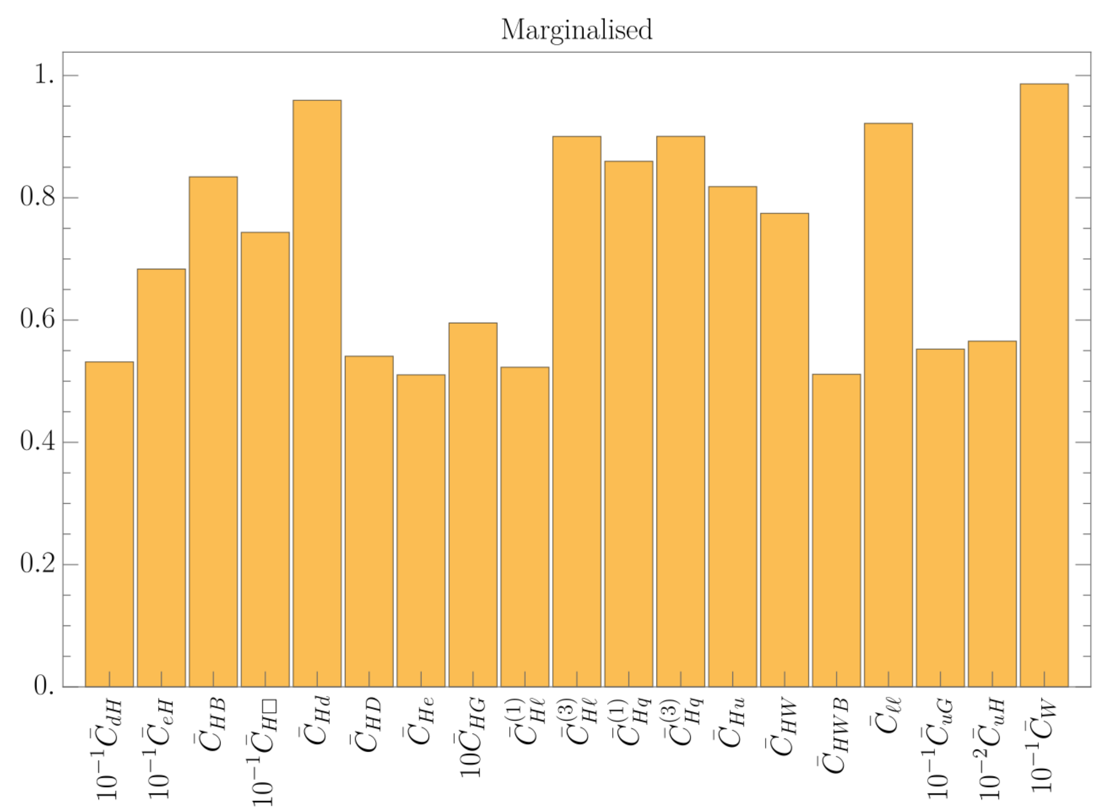
- Global SMEFT analysis of top quark data
  - LO constraints on 12 operators
  - 195 (174 differential) observables
  - tt, single-top & tt+Z/γ
  - Helicity fractions, A_{FB} & A_C
- Selected those that interfere with SM
  - ttg, tbW, ttZ, ggg + linear combinations of 4F operators
  - Probes energy scales of order $\Lambda \sim 0.3 - 1$ TeV
  - Validity assessment necessary

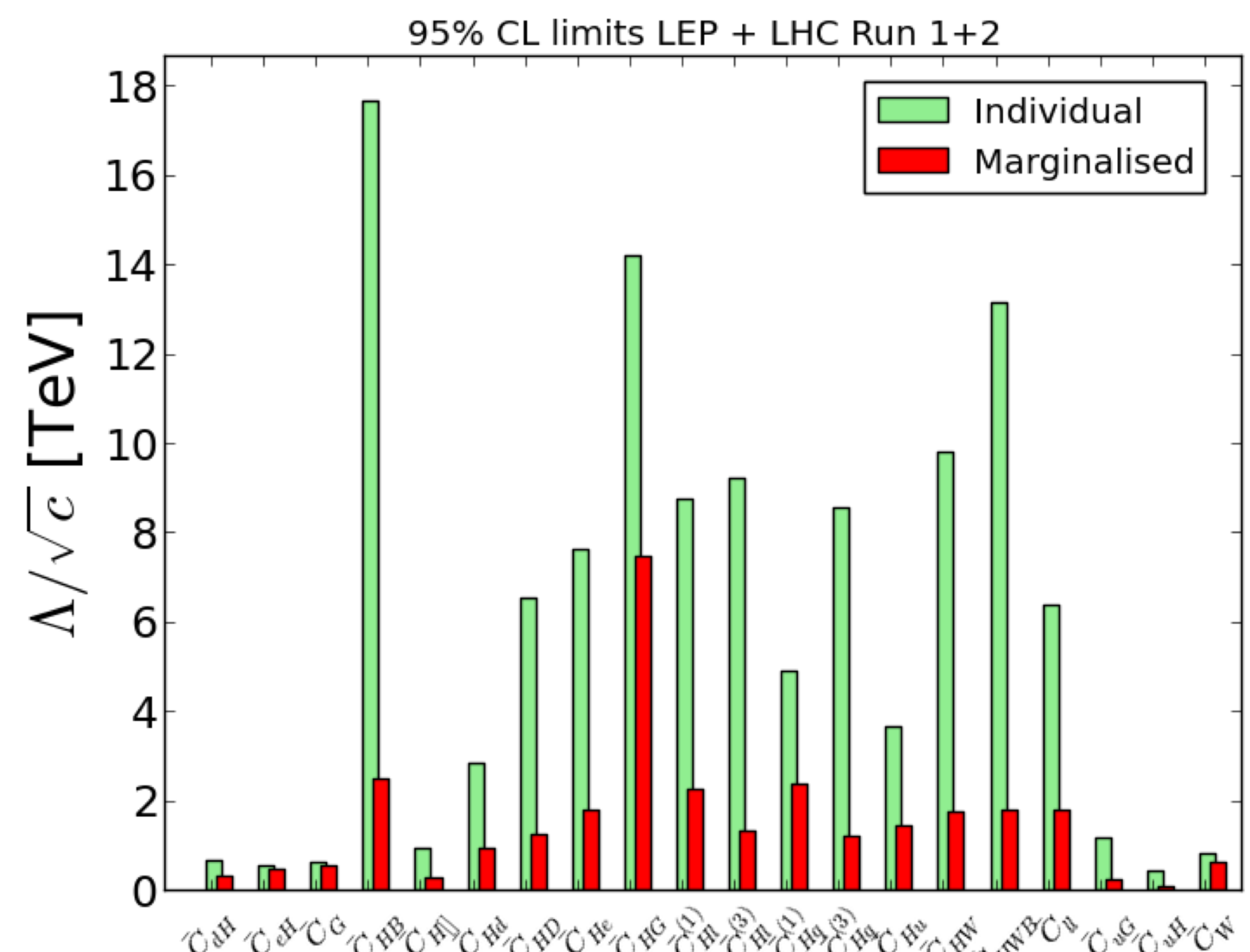


[Ellis et al; JHEP 1806 (2018) 146]

Gauge/Higgs sector fit

- Very recent global fit to LEP + LHC Run I & II data
  - Flavor universal assumption
- New differential information
  - Simplified Template Cross Sections (STXS) for Higgs production
  - High-p_T WW measurements

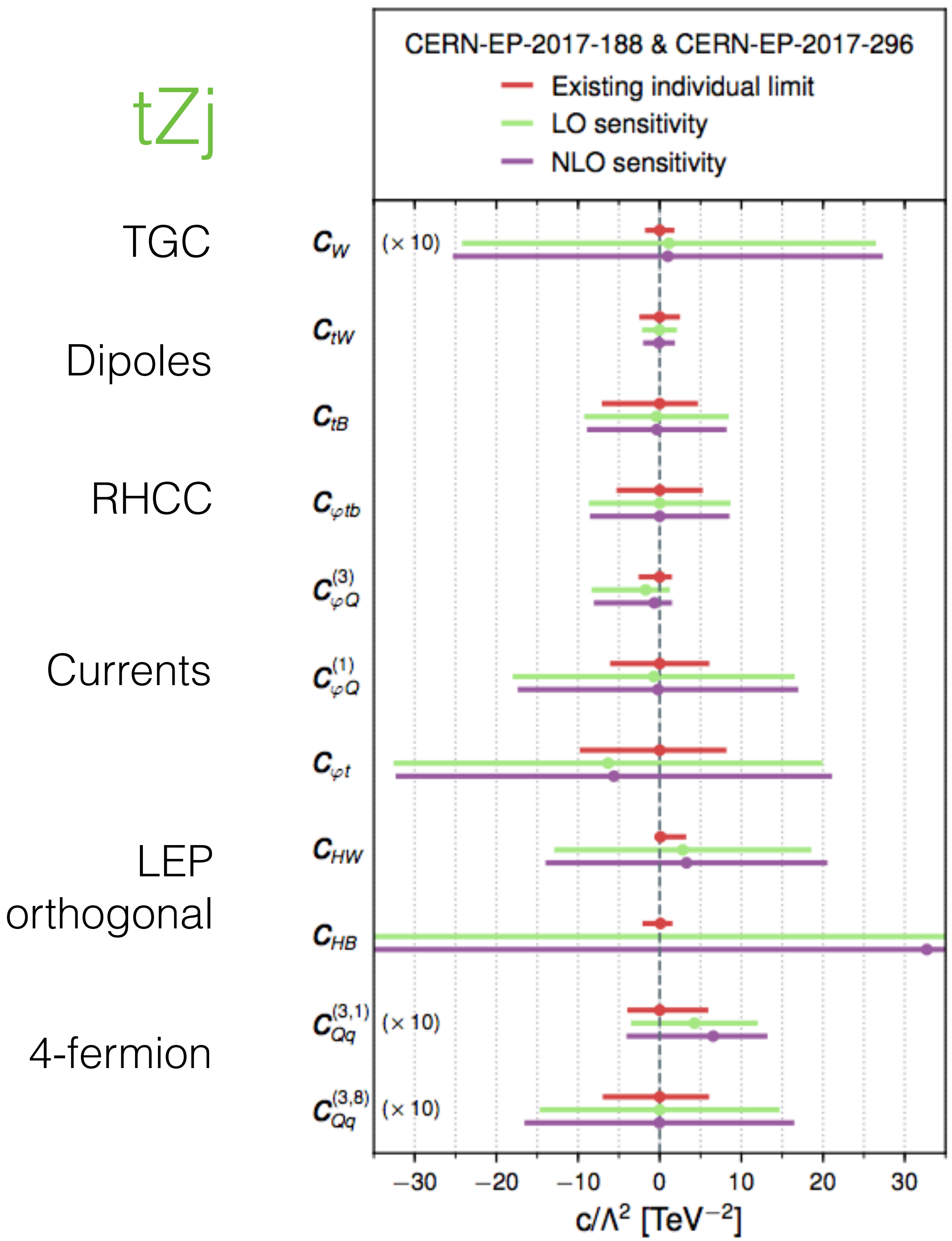


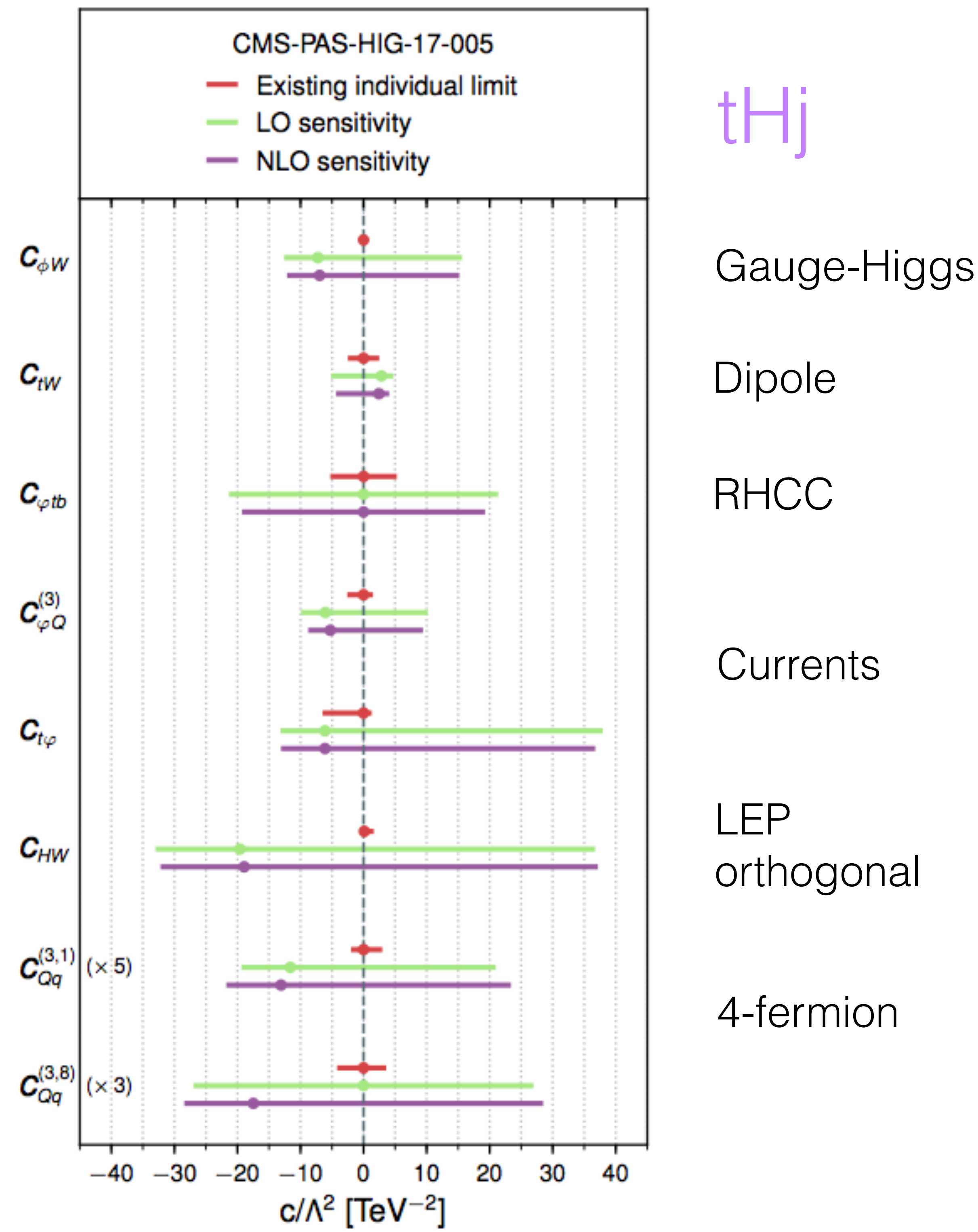


Improvement when adding Run II data

Current sensitivity

Recent tZj measurement
CMS ttH+tH analysis



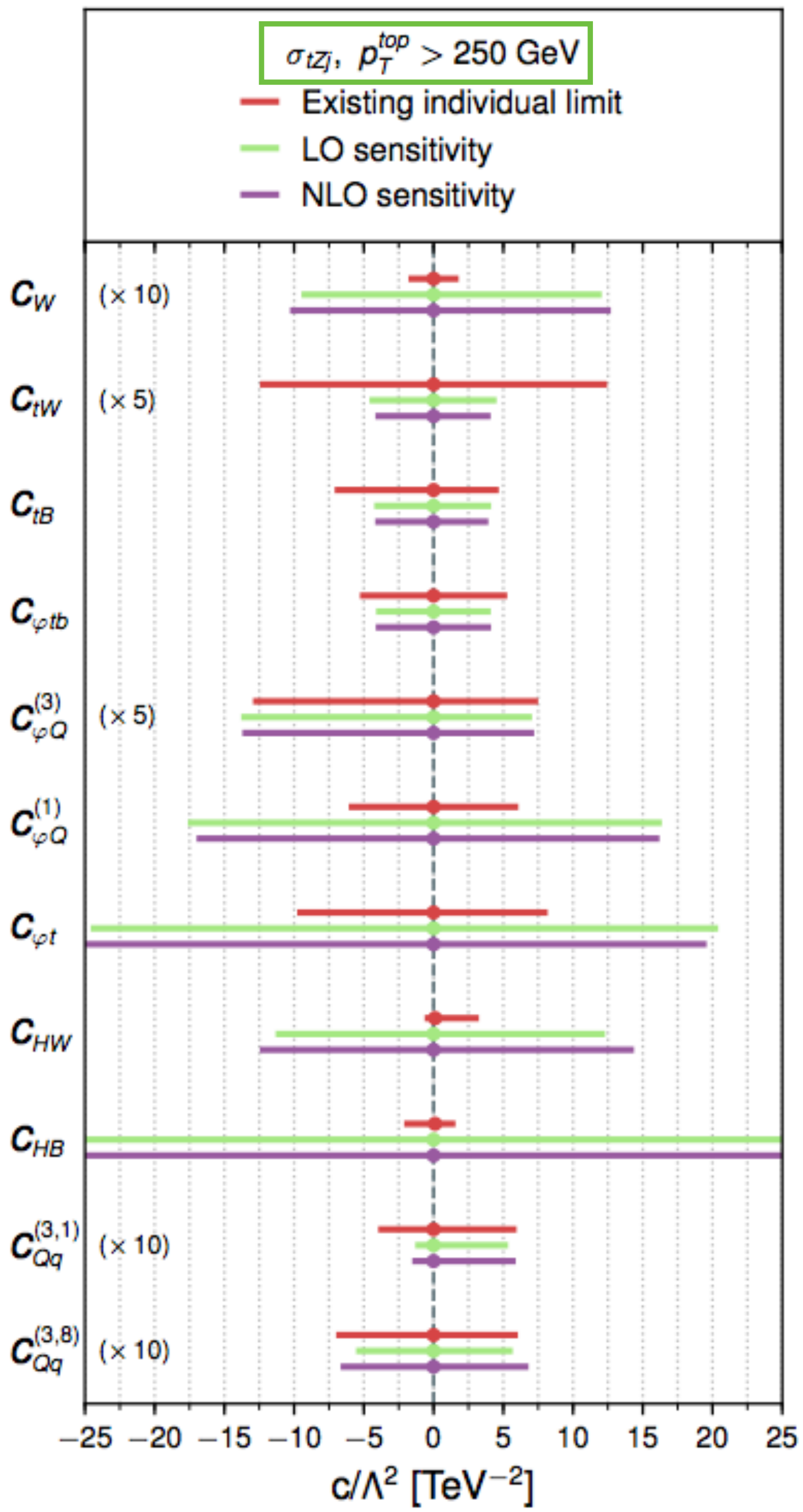


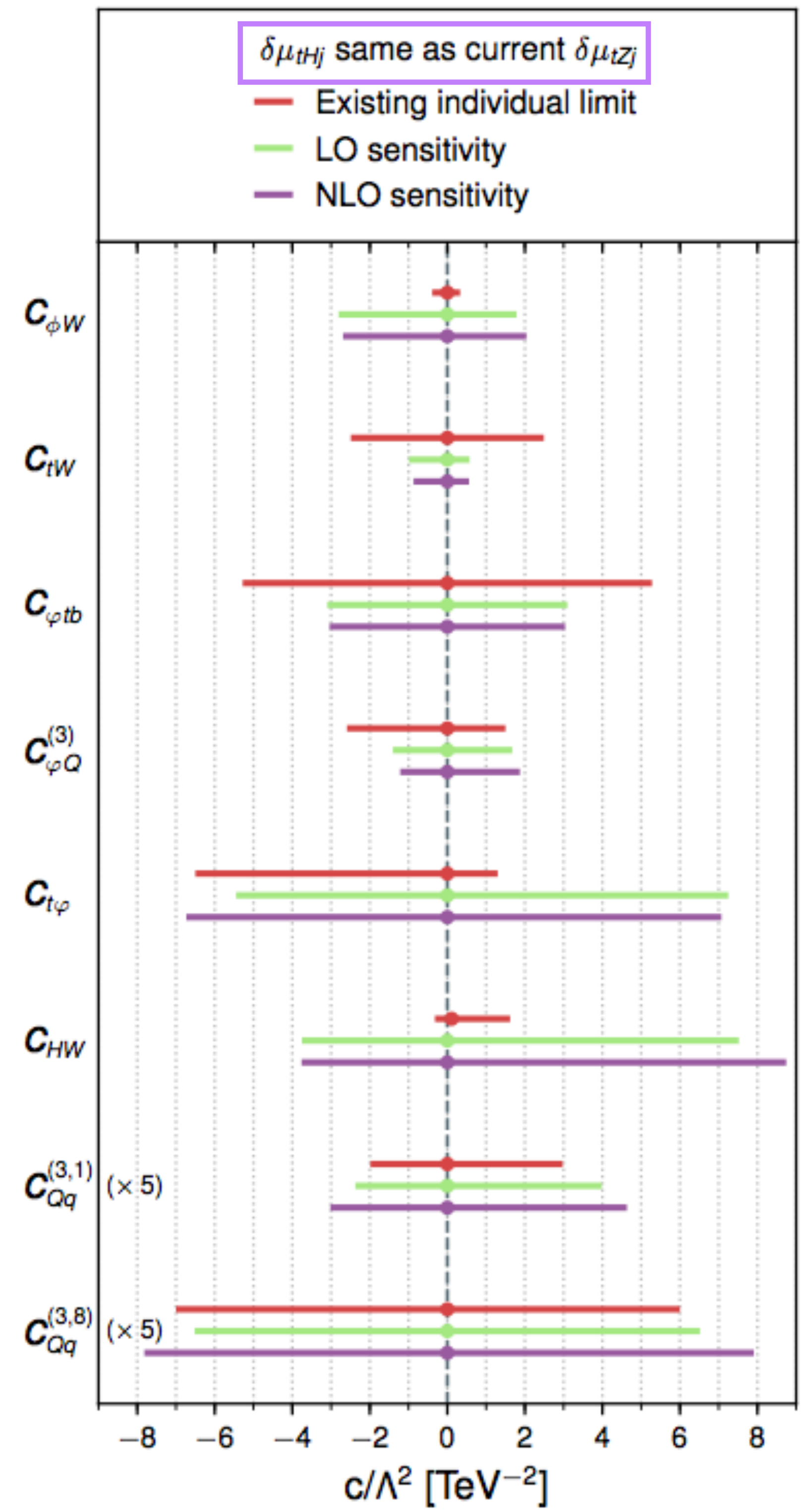
High p_T tZj: end of run II/HL-LHC
tHj: HL-LHC ?

Future sensitivity

tZj

TGC
Dipoles
RHCC
Currents
LEP orthogonal
4-fermion





tHj

Gauge-Higgs
Dipole
RHCC
Currents
LEP orthogonal
4-fermion