Top quark electroweak interactions at high energy

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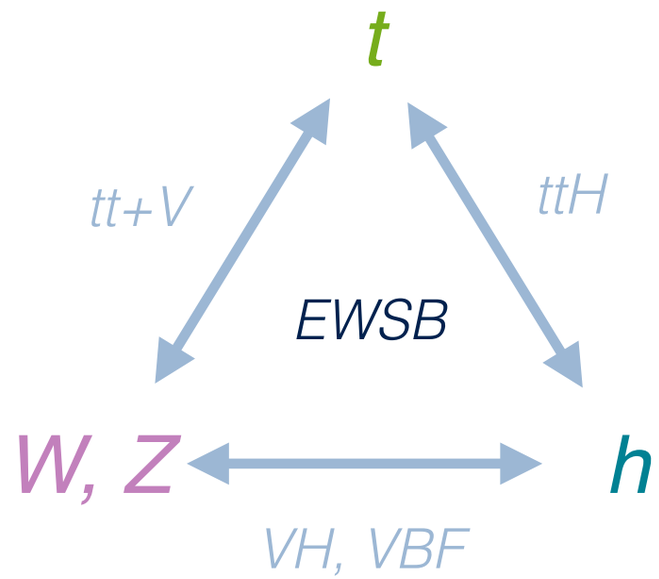
23rd October 2019

Luca Mantani, Fabio Maltoni & KM; arXiv:1904.05637 (to appear in JHEP)

EWSB sector at the LHC

LHC legacy = precise measurements of the interactions that govern EWSB



Key players are in the game

We know that the top is special

- Being most strongly coupled to the Higgs has strong BSM implications
- Big role to play in uncovering the nature of EWSB?
- Through interactions with Higgs and longitudinal W,Z (Goldstone bosons)

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} -iG^+ \\ v + h + iG^0 \end{pmatrix} \qquad \begin{aligned} \partial_\mu G^+ &\leftrightarrow W_\mu^+ \\ \partial_\mu G^0 &\leftrightarrow Z_\mu \end{aligned}$$

Intrinsic connection between measuring couplings to gauge and Goldstone bosons, especially at high energy

EWSB sector at the LHC

SM is a spontaneously broken, gauge-Yukawa theory

Symmetry ↔ Constraints/Relations

$y_f\,\bar{F}_L f_R\,\varphi \quad (D^\mu\varphi)^\dagger\,(D_\mu\varphi)$

Mass ↔ Higgs coupling

$\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu} \qquad i\bar{F}\not{D}F$

Self-interactions ↔ Gauge currents

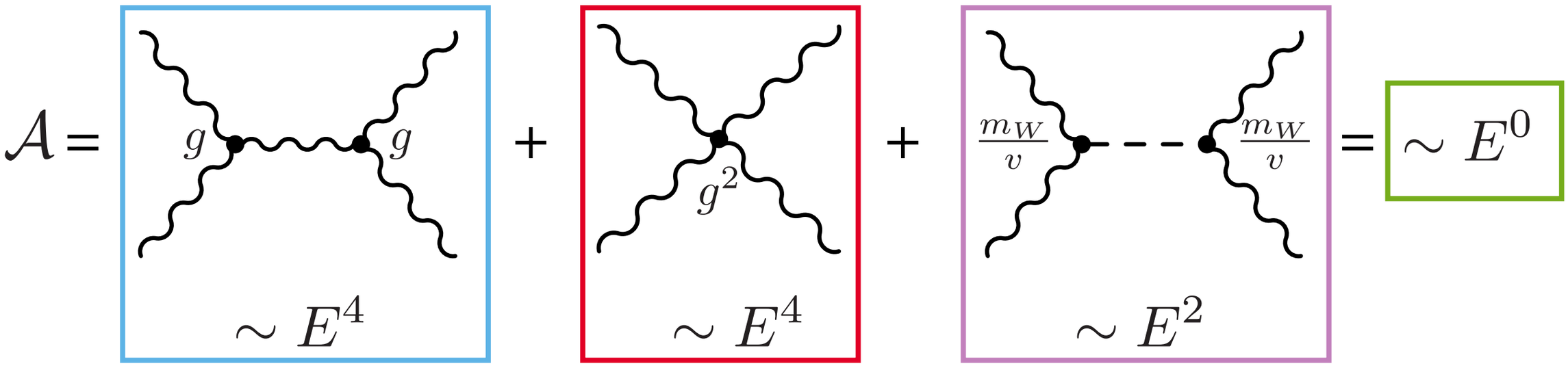
Delicate ‘balance’ conserves **unitarity** & **renormalisability**

Precision measurements of SM interactions target **deviations** & presence of **non-SM** Lorentz structures

Hallmark signature:
Energy growth in scattering amplitudes

Scattering unitarity

$W_L W_L \to W_L W_L$: Unitarity 'cancellations' in the SM



triple-gauge

quartic

EWSB

Diboson (TGC)

VBS (TGC, QGC)

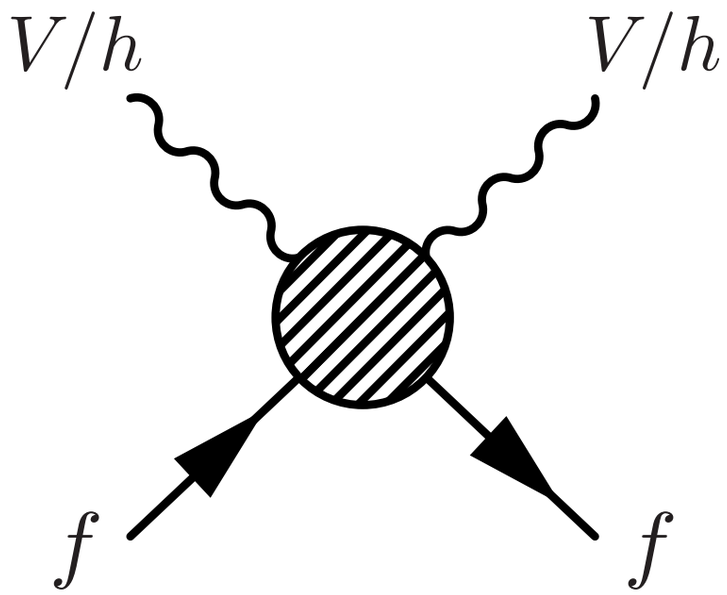
EW Higgs prod./decay

Deviations from SM interactions → energy growth

- Cancellations are a feature of gauge invariance & EWSB mechanism
- E-growth: theory has limited validity range → heavy new physics

Tops and unitarity

Analogous behaviour in scatterings involving fermions



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

$$\mathcal{A} \sim m_f E \to E^{-1}$$ EWSB mechanism

High-energy limit with finite mass effects

- Top quark scattering sector especially rich

Limited validity range

Heavy new physics

→ **SM Effective Field Theory**

Energy growth in SMEFT

Dim-6

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

'Energy helps accuracy'

[Farina et al.; PLB 772 (2017) 210-215]

Rate measurements will become systematics dominated

Increasingly high-energy measurements scale with lumi.

However, inserting an SMEFT operator into an amplitude does not guarantee energy growth…

Operator contribution to a given process:

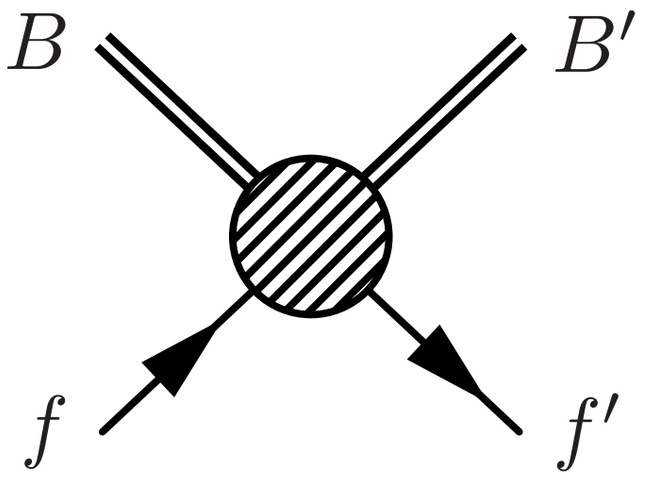
- **May not** grow maximally with energy (E^2)
- Have **suppressed** interference w/ SM

[Azatov et al.; PRD 95 (2017) no. 6, 065014]

There will always be some scattering amplitude that displays maximal (E^2) growth w.r.t the SM

Find and exploit them!

Our study



	Single-top	Two-top $(t\bar{t})$
w/o Higgs	$b\,W \to t\,(Z/\gamma)$	$t\,W \to t\,W$ $t\,(Z/\gamma) \to t\,(Z/\gamma)$
w/ Higgs	$b\,W \to t\,h$	$t\,(Z/\gamma) \to t\,h$ $t\,h \to t\,h$

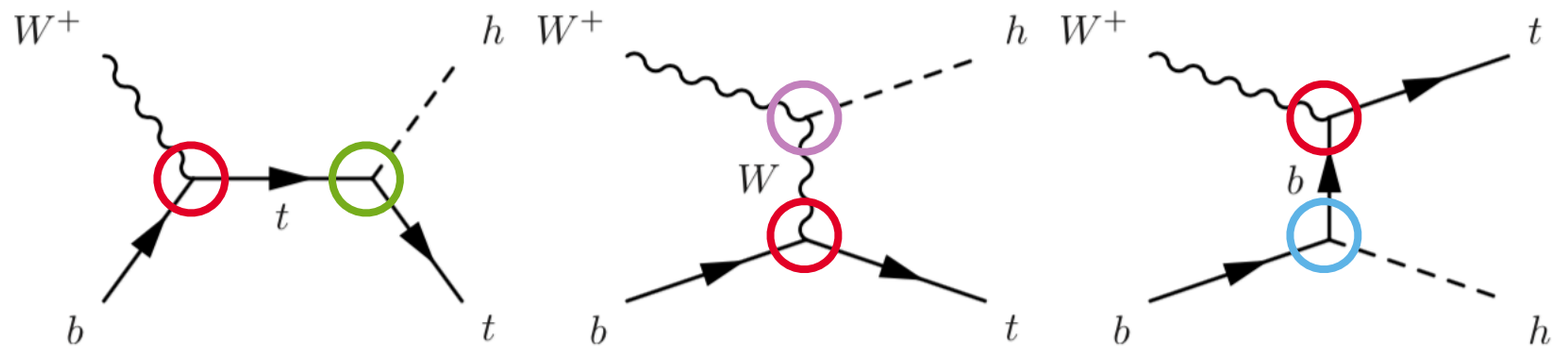
Considered 10, 2 → 2 scattering amplitudes with ≥ one top

- High energy limit: **s ~ l t l** ≫ **v²**
- Max. unitary energy dependence: E^0
- Study unitarity cancellations/energy growth in SMEFT vs. anomalous couplings
- Do they interfere in an energy-growing way with the SM?
- How can we access them through collider processes?

Interesting processes: 'rare' EW top production

tZj, tWj, tHj, tZW, tHW, ttWj, VBF-tt,…

Example: $bW^+ \rightarrow tH$



In the SM, fully left handed, longitudinal W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams → overall rescaling ~ E^0
- bbH vertex: ∝ mb → 0
- HWW & ttH interactions: participate in a unitarity cancellation ~ v E

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

- Fixing couplings to SM values sends it to E^{-1}

bW+ → tH in SMEFT

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

bW+ → tH in SMEFT

SMEFT: many more sources of energy growth

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

bW+ → tH in SMEFT

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	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+,0,+$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-,-,+$	$\frac{1}{s}$	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	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

bW+ → tH in SMEFT

Helicity configurations

W_L

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

bW+ → tH in SMEFT

Helicity configurations

W_L

W_T

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

bW+ → tH in SMEFT

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

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

bW+ → tH in SMEFT

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	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+,0,+$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-,-,+$	$\frac{1}{s}$	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	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

bW+ → tH in SMEFT

Max growth

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

bW+ → tH in SMEFT

Interfering E-growth: SU(2) current operator

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

bW+ → tH in SMEFT

Non-interfering / no E growth in interference

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

bW+ → tH in SMEFT

Non-interfering / no E growth in interference

∝ m_b

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

bW+ → tH in SMEFT

Non-interfering / no E growth in interference

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

∝ m_b

W_T

bW+ → tH in SMEFT

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

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

bW+ → tH in SMEFT

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	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
$+,0,-$	$-$	$-$	$\sqrt{-t}m_t$	$-$	$-$	$-$
$+,0,+$	$-$	$-$	$\sqrt{s(s+t)}$	$-$	$-$	$-$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$	$\sqrt{-t}m_W$
$-,-,+$	$\frac{1}{s}$	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	$-$	$-$	$-$
$+,+,+$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

bW+ → tH in SMEFT

No E-growing interference

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

bW+ → tH in SMEFT

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

$bW^+ \to tH$ in SMEFT

One source of energy growth from modified SM interactions

- Yukawa operator: disconnects kinematical mass from coupling to Higgs

bW+ → tH in SMEFT

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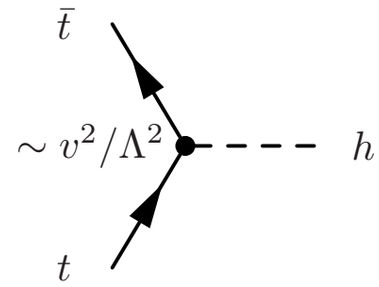
$$\mathcal{O}_{t\varphi} = (\varphi^\dagger\varphi)^2(\bar{Q}\,t\,\tilde{\varphi})$$



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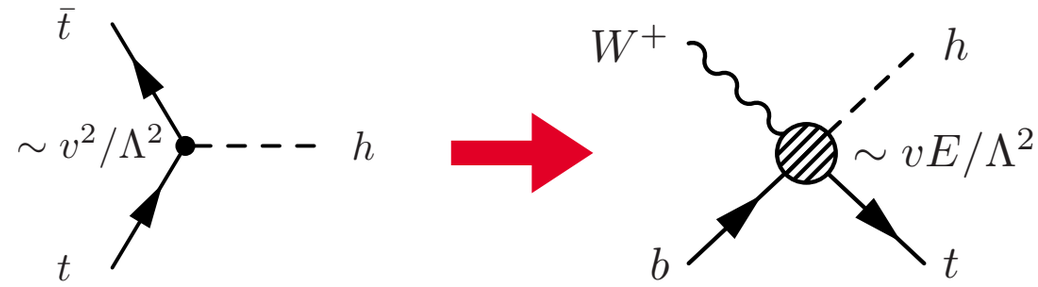

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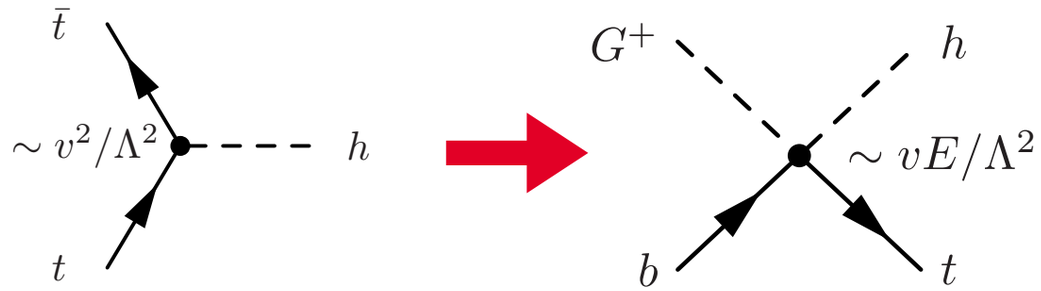

- ‘Unitarity cancellation’ **OR** dim-5 contact-interaction w/ charged Goldstone

bW+ → tH in SMEFT

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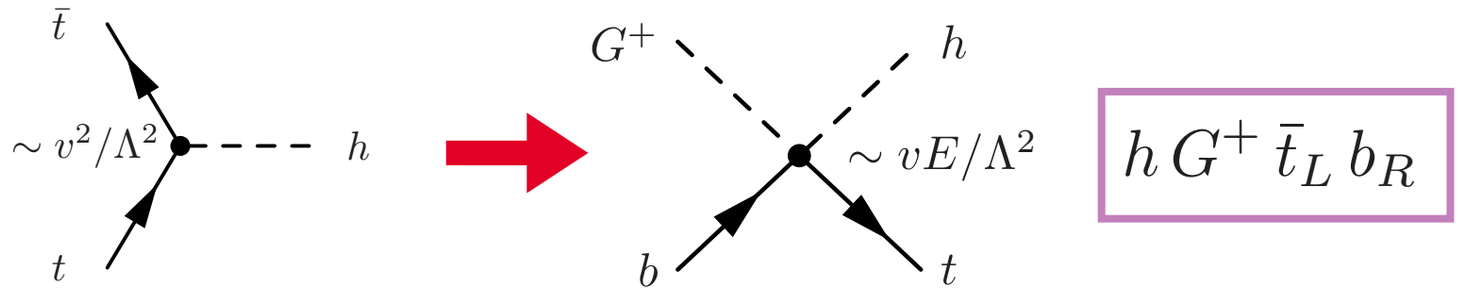

$h\,G^+\,\bar{t}_L\,b_R$

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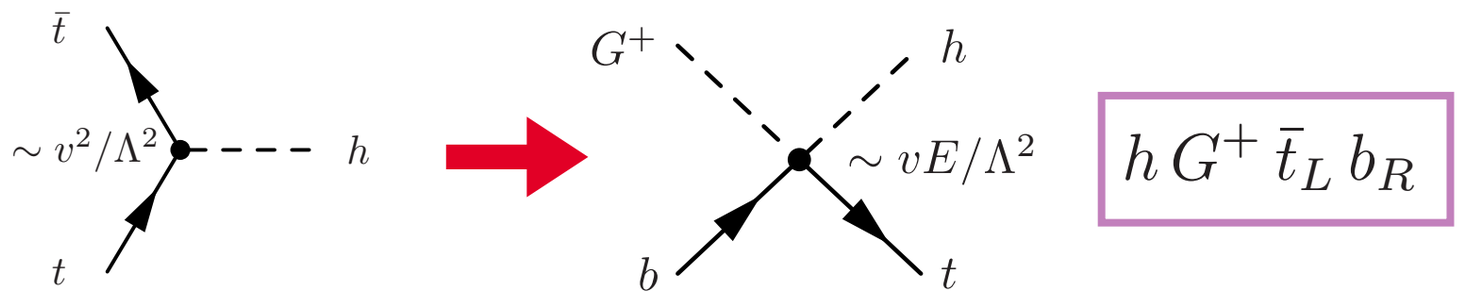

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Max growth from dim-6 contact-terms

bW+ → tH in SMEFT

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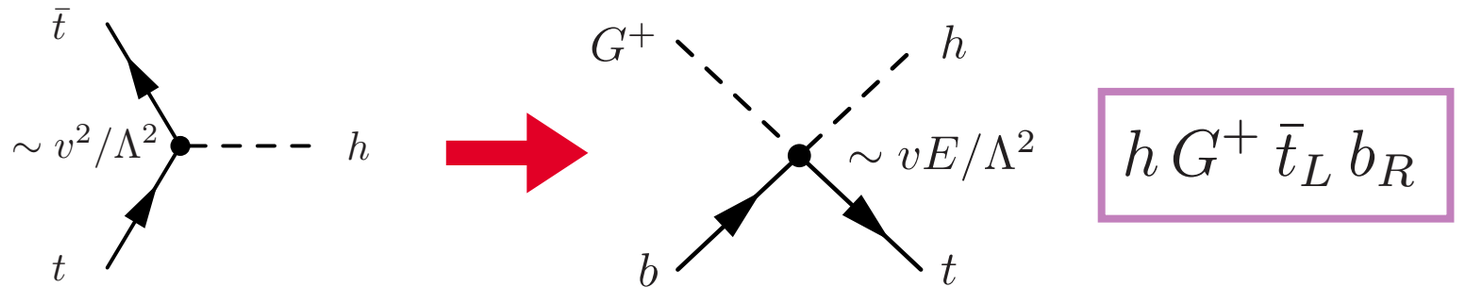

$$h\,G^+\,\bar{t}_L\,b_R$$

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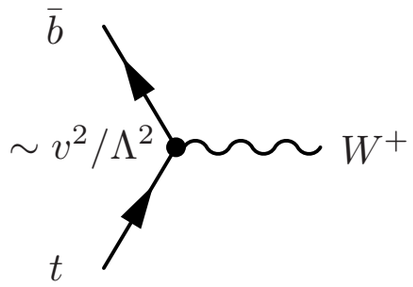
$$\mathcal{O}^{(3)}_{\varphi Q} = i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{Q}\,\gamma^\mu\,\tau_I\,Q)$$
$$\mathcal{O}_{\varphi tb} = i(\tilde{\varphi}\,D_\mu\varphi)(\bar{t}\,\gamma^\mu\,b) + \text{h.c.}$$



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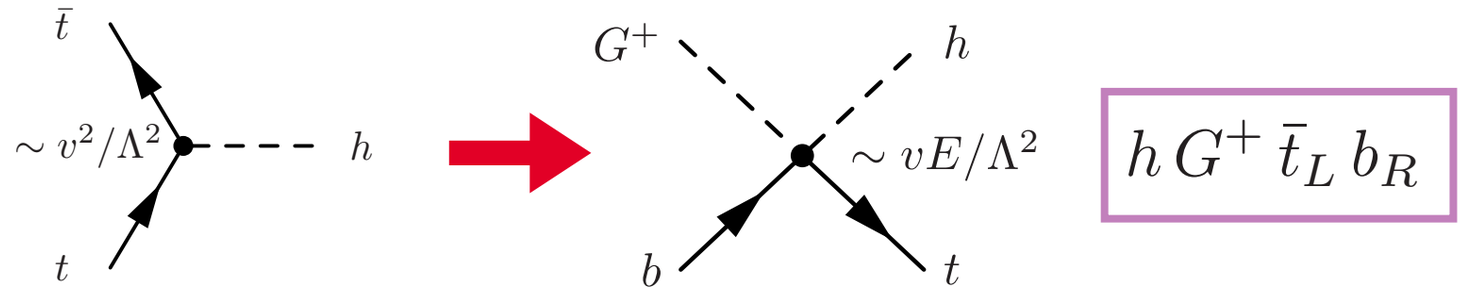

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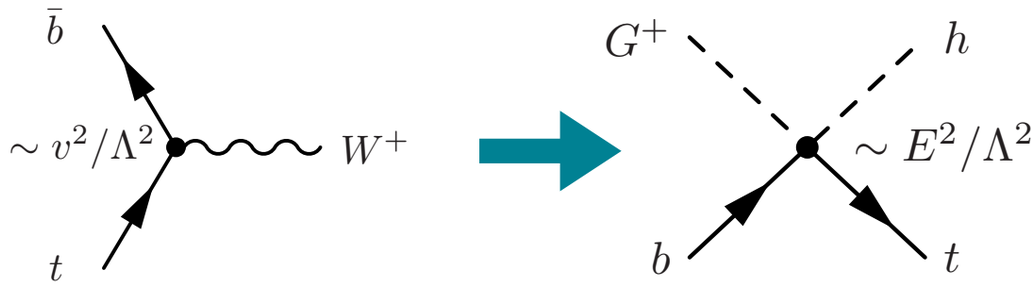

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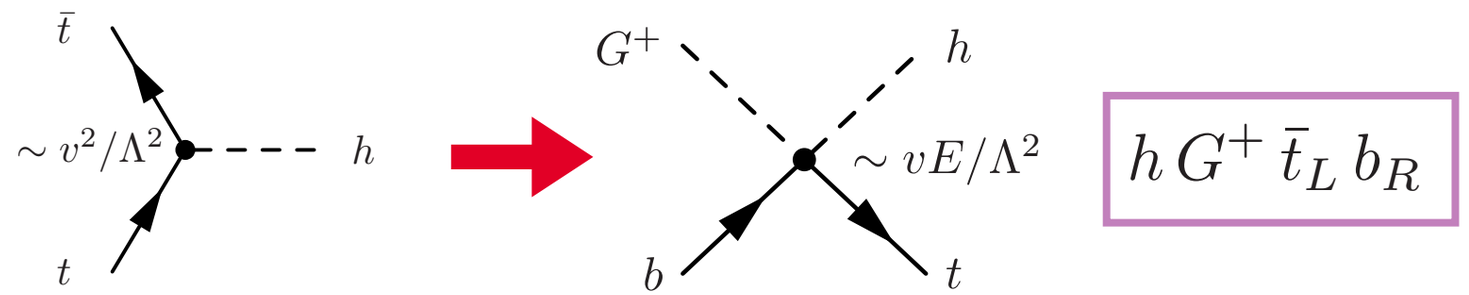

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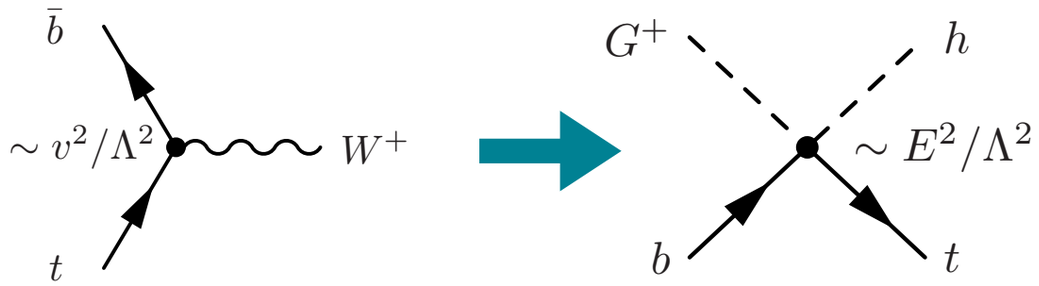

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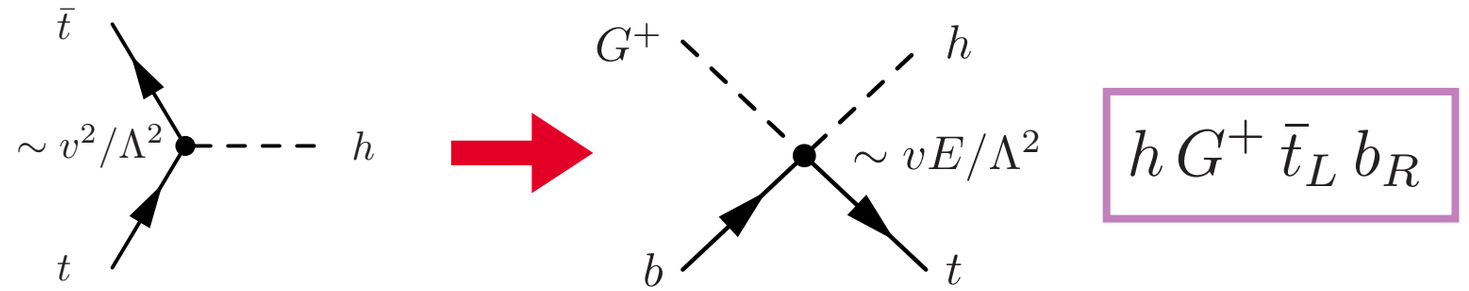

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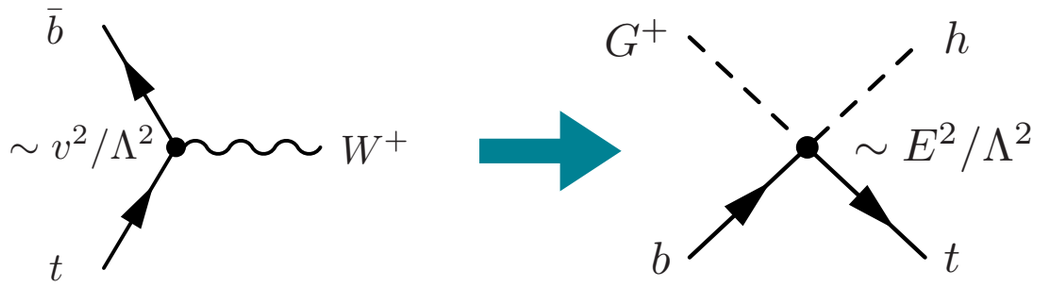


$$h\,\partial_\mu G^+\,\bar{t}\,\gamma^\mu b$$

- No anomalous coupling analogues *(recall Wtb vertex only rescales)*
- Prediction from gauge invariant dim-6 operators

Summary: max growths

gauge/higgs operators ⟸ ⟹ *top operators*

Energy-growing interference

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

single-top

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

two-top w/o Higgs

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

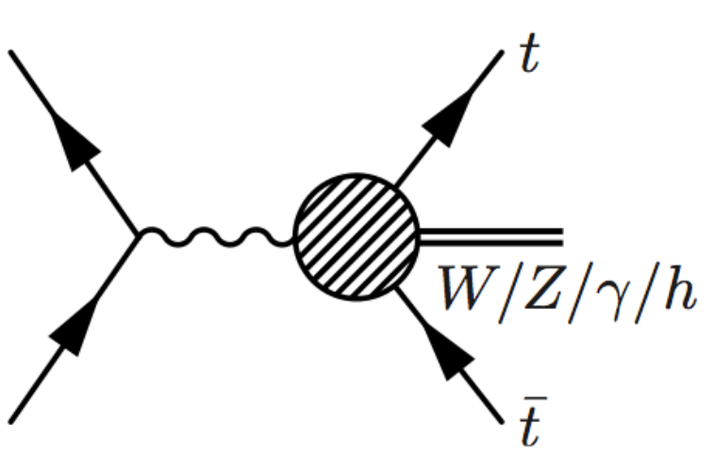
two-top w/ Higgs

Most top operators show max growth somewhere

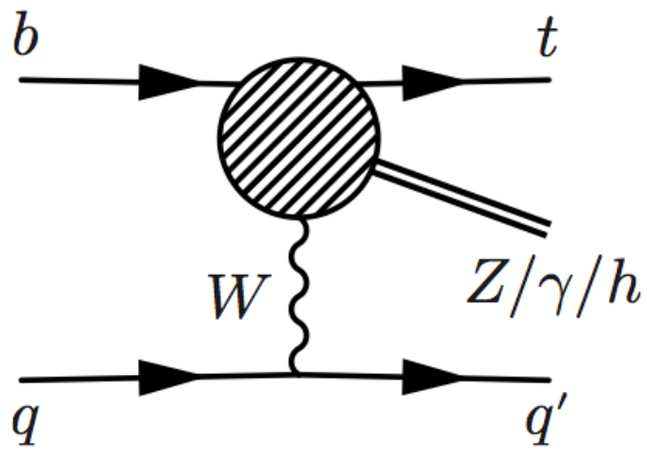
- Interfering growth rare, only in longitudinal configurations (c.f. helicity selection)

Embedding the amplitudes

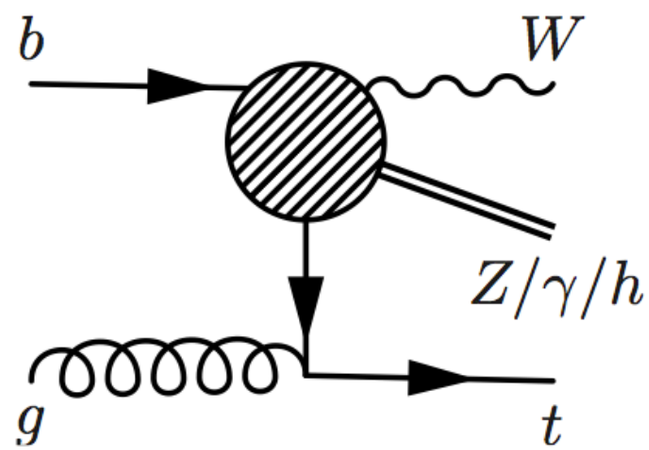
Collider processes: rare top production



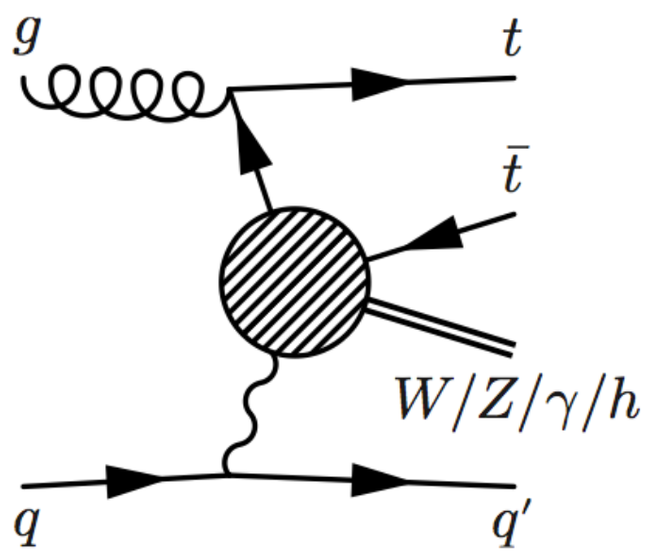
(a) $t\bar{t}X$



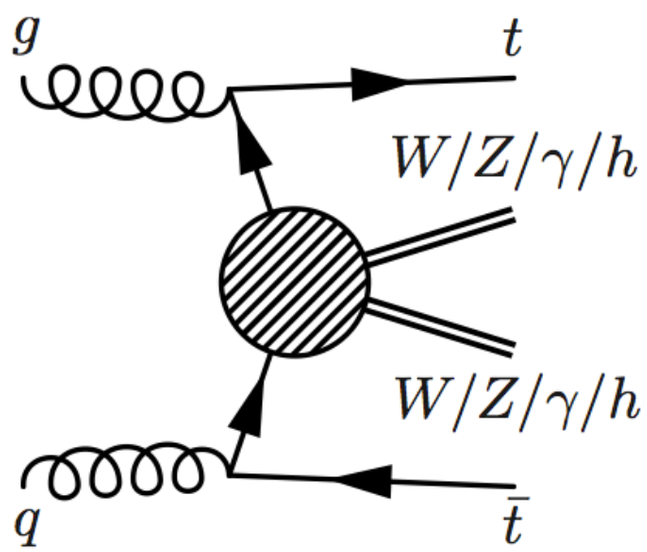
(b) tXj



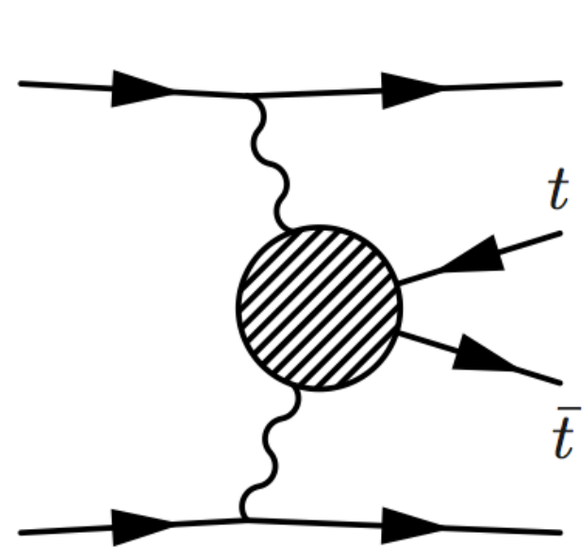
(c) tWX



(d) $t\bar{t}Xj$



(e) $t\bar{t}XY$



(f) VBF

Embedding the amplitudes

Collection of ‘sensitivity’ studies, general discussion

	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

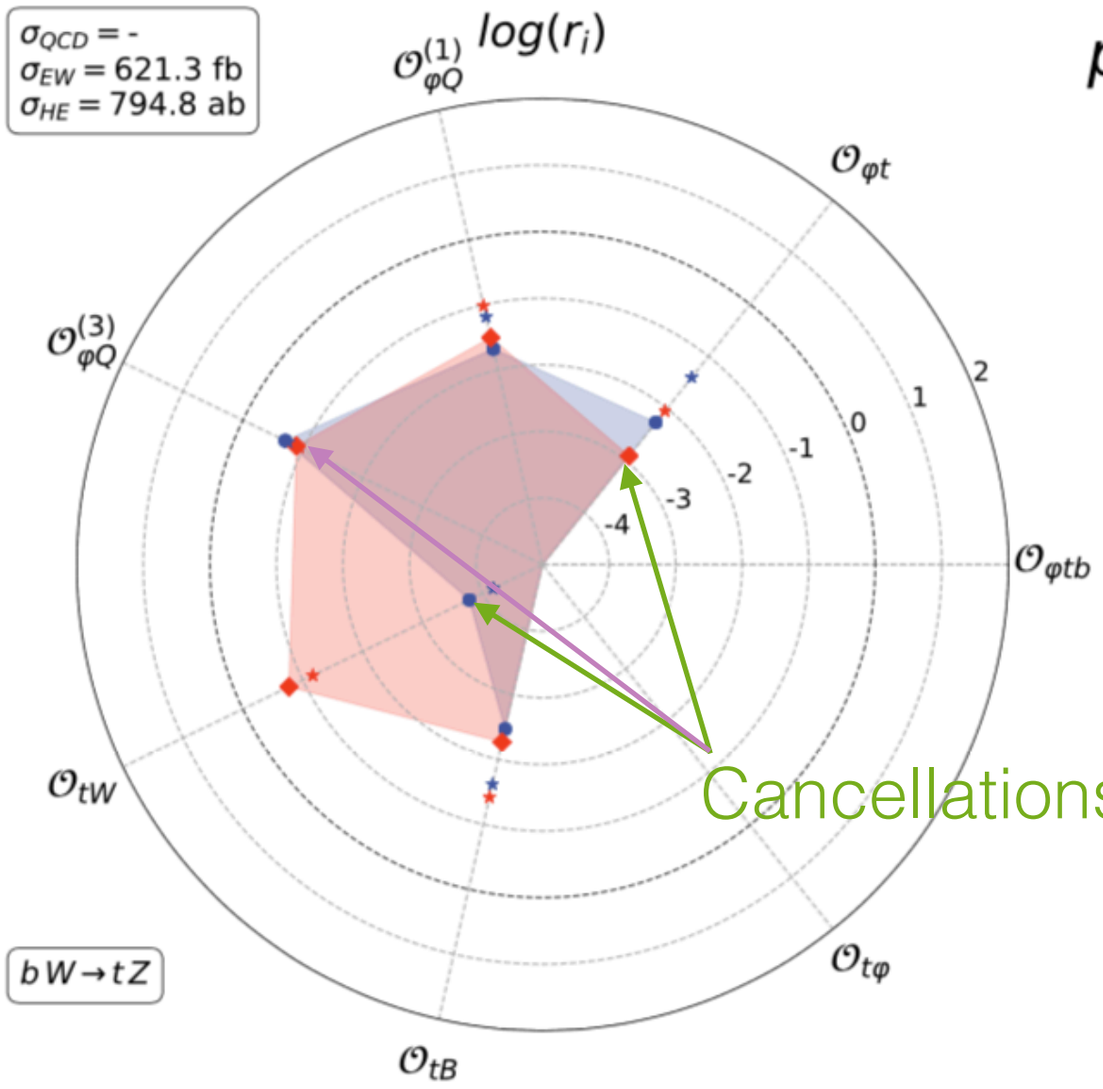
	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

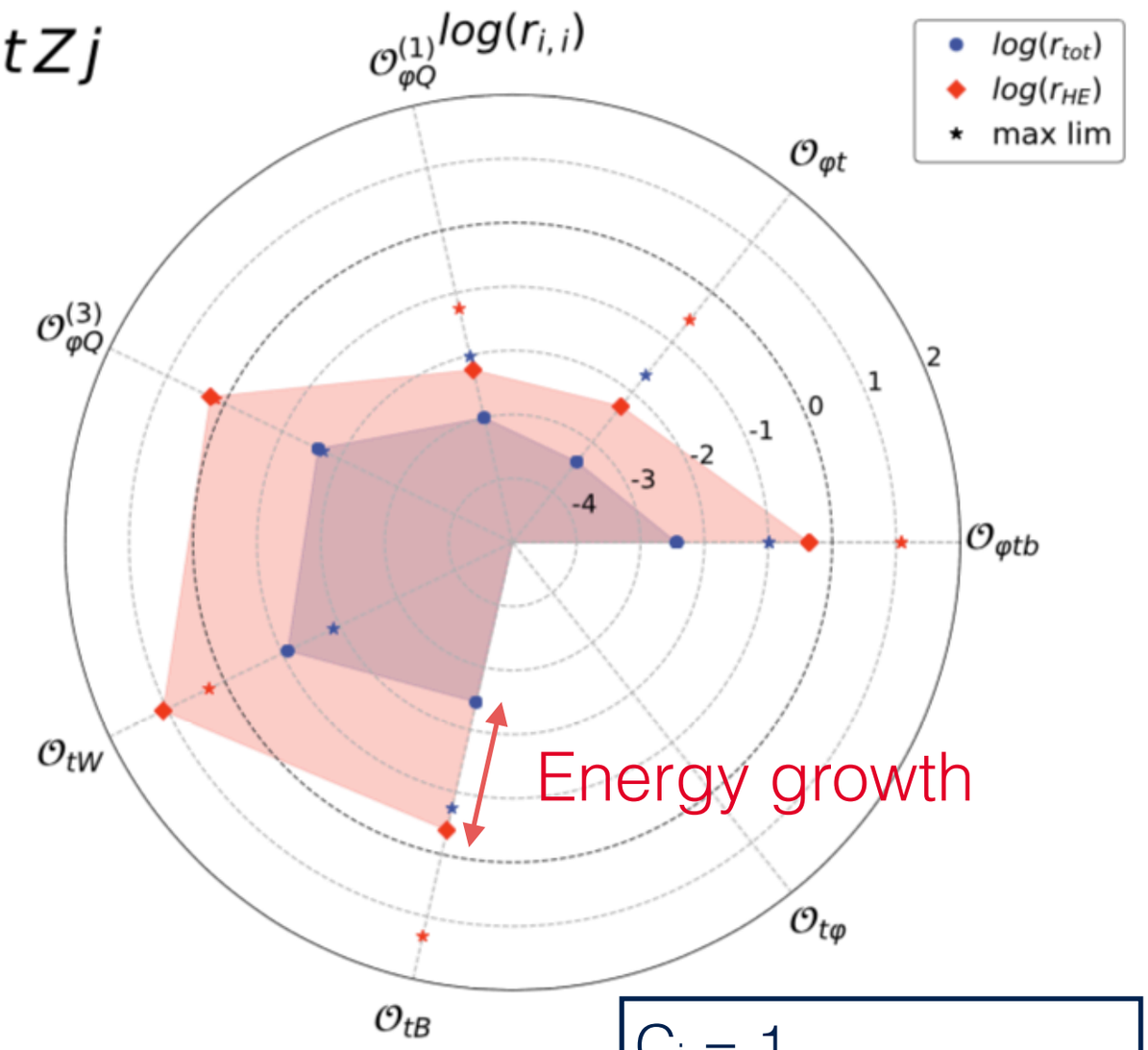
tZj total & high energy xs

interference/SM

square/SM



$pp \to tZj$

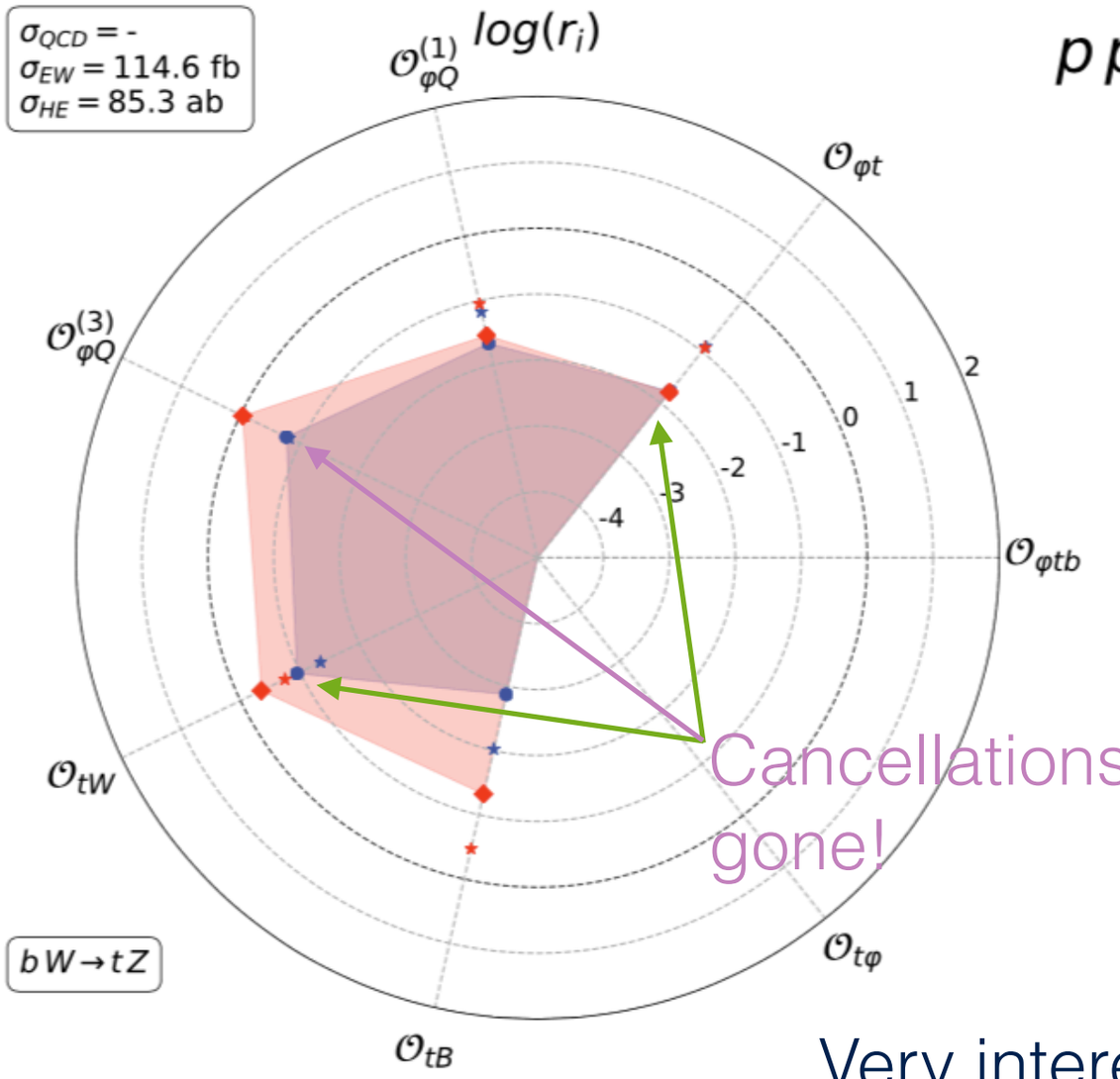


Expected growth from 2→2 absent!

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

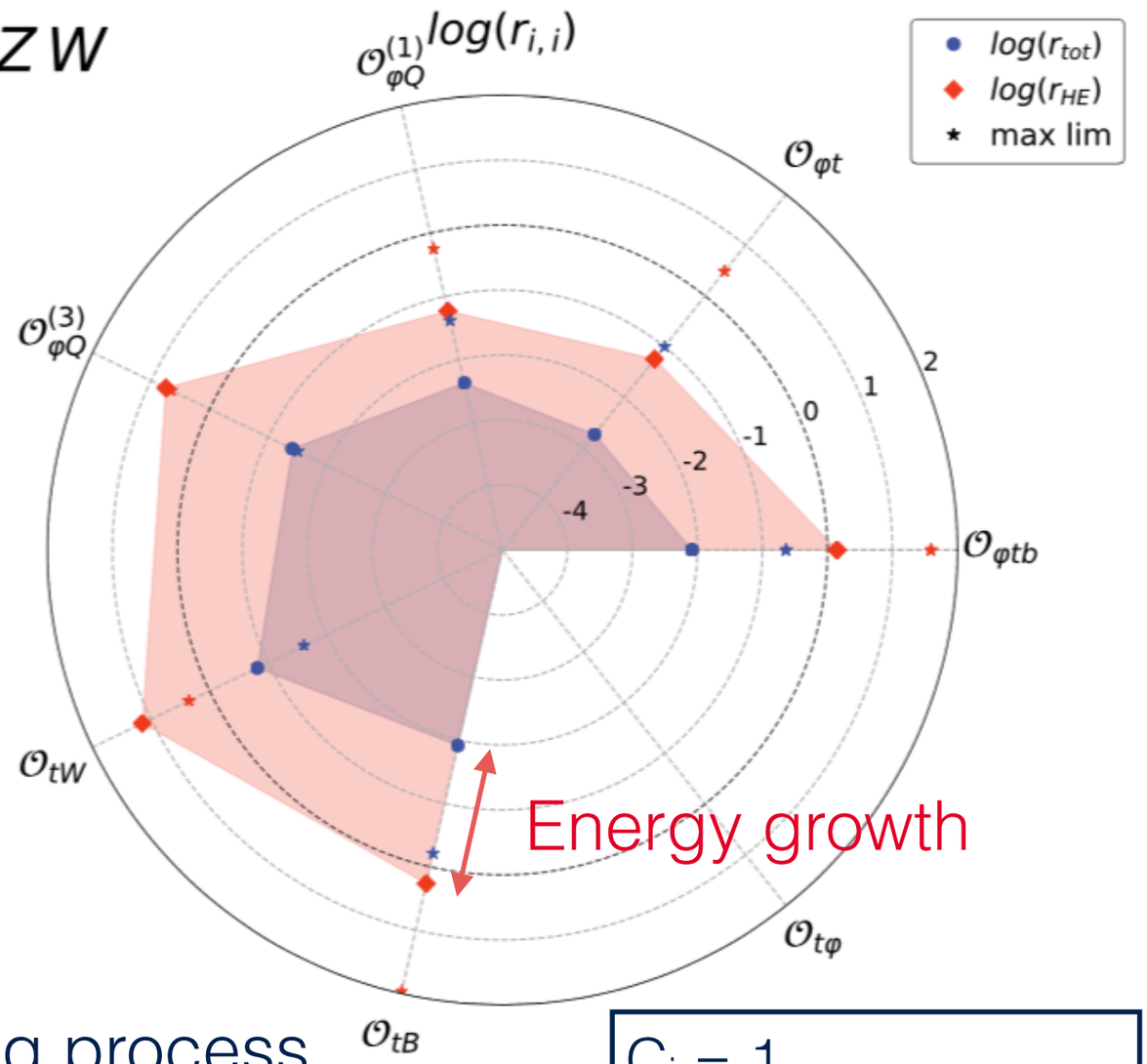
tZW total & high energy xs

interference/SM



$pp \to tZW$

square/SM



Cancellations gone!

Energy growth

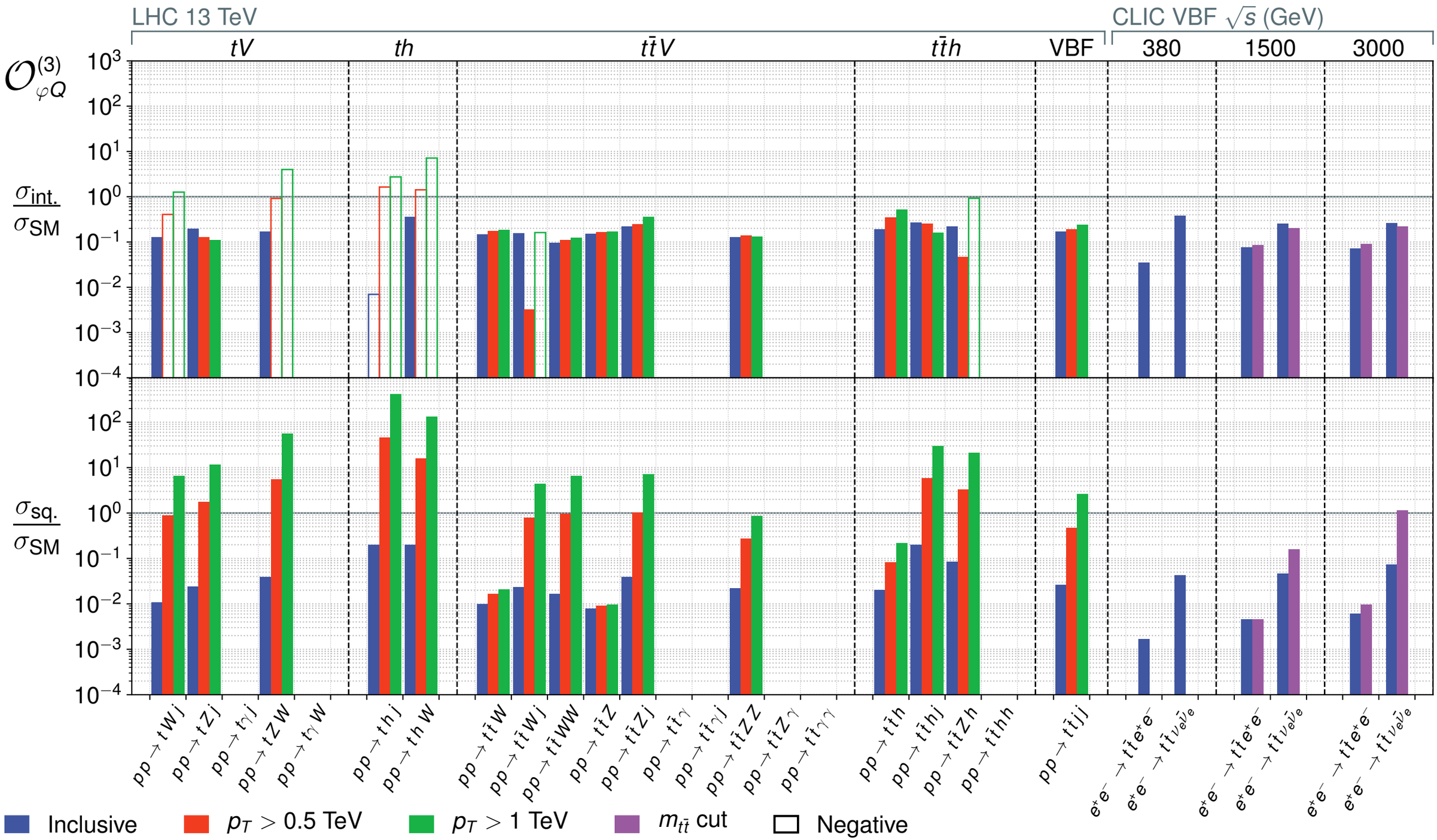
Expected growth is there!

Very interesting process that should be measured at the LHC

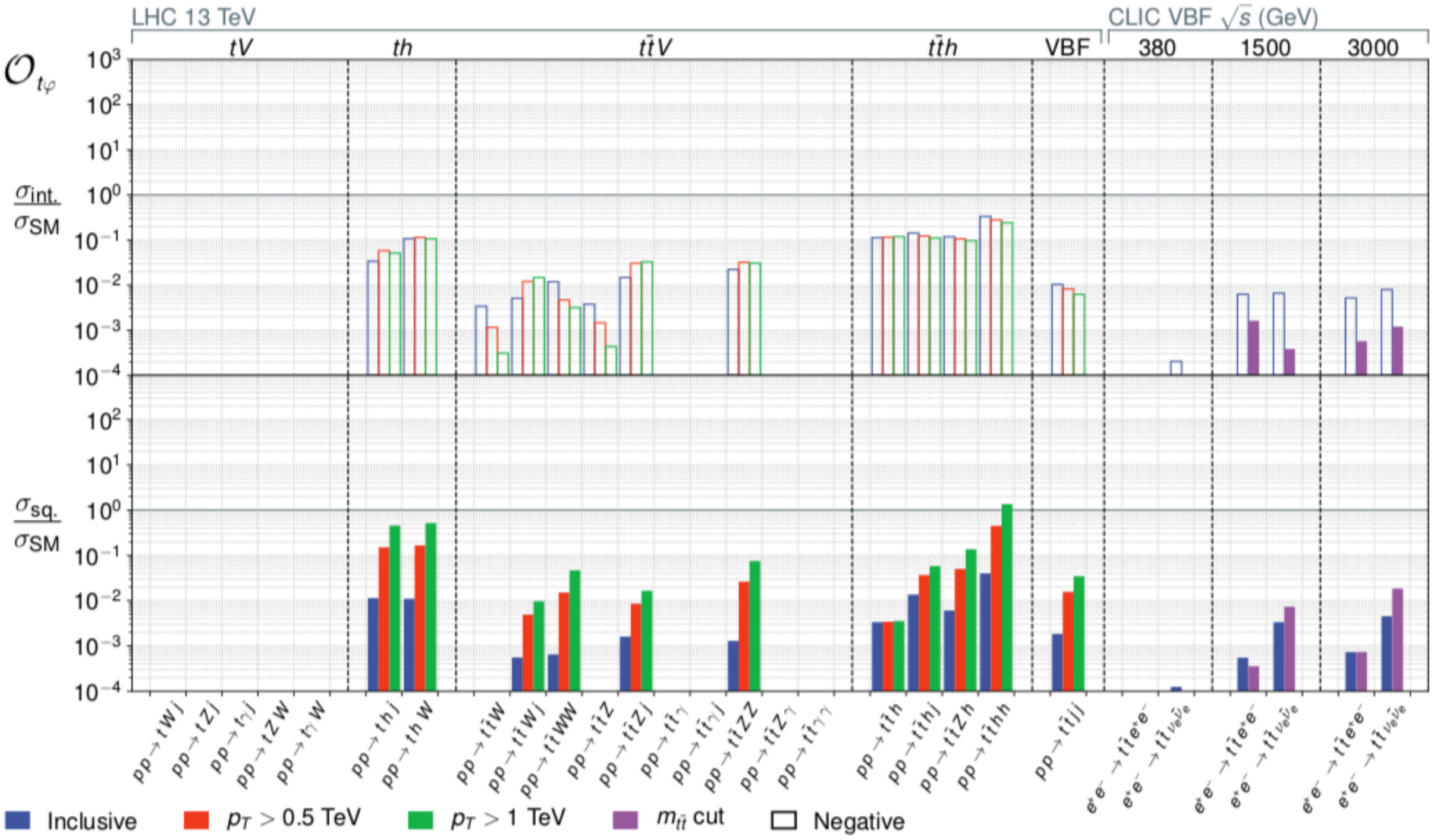
$C_i = 1$
Inclusive
p_T (W,Z)> 500 GeV

[Mantani, Maltoni & KM; arXiv:1904.05637 (accepted by JHEP)]

Charged current operator



Yukawa operator



High-energy EW tops

Sometimes, need to go beyond 4-point scattering

- Yukawa & Triple Higgs operators

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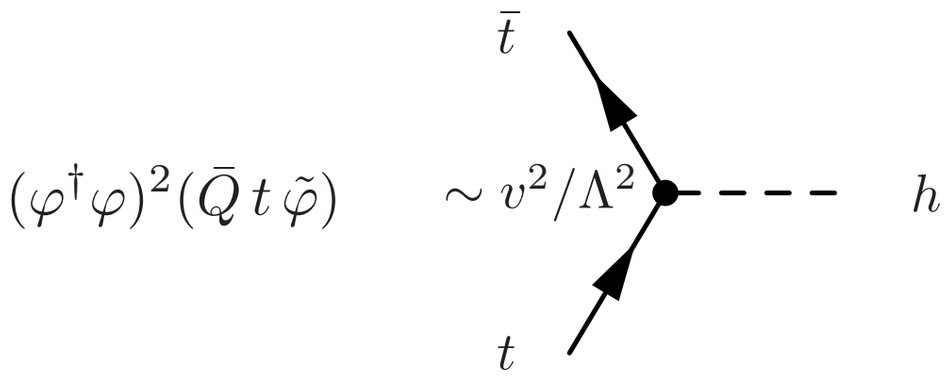
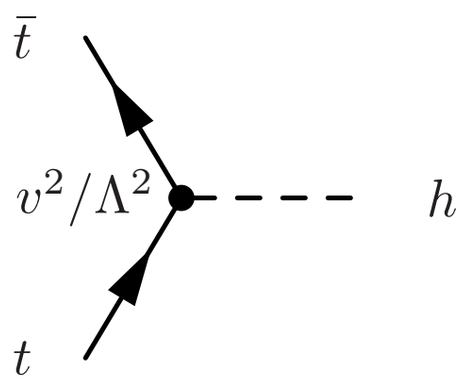


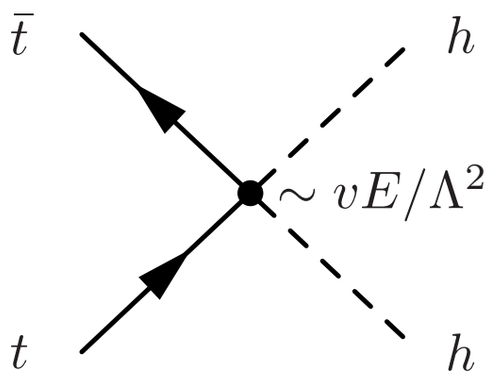
High-energy EW tops

Sometimes, need to go beyond 4-point scattering

- Yukawa & Triple Higgs operators

$(\varphi^\dagger\varphi)^2(\bar{Q}\,t\,\tilde{\varphi})$



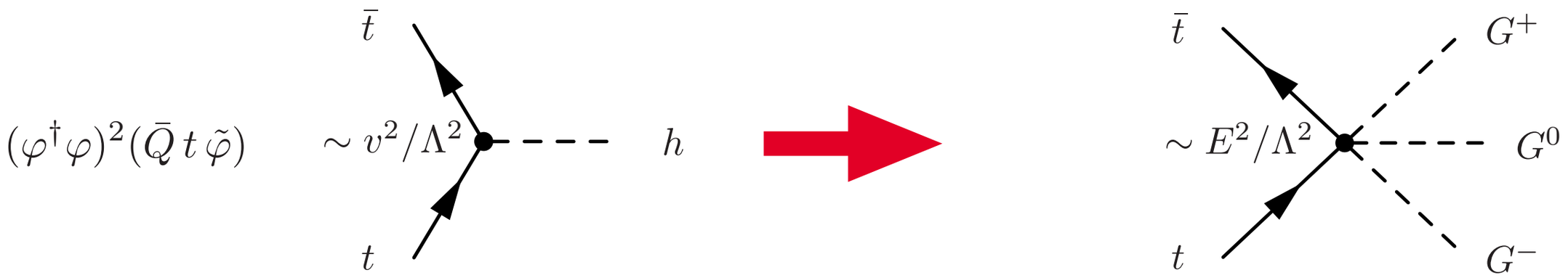


$$t\,h \to t\,h$$
$$t\,W_L \to t\,W_L$$
$$t\,Z_L \to t\,Z_L$$
$$b\,W_L \to t\,h$$

High-energy EW tops

Sometimes, need to go beyond 4-point scattering

- Yukawa & Triple Higgs operators



High-energy EW tops

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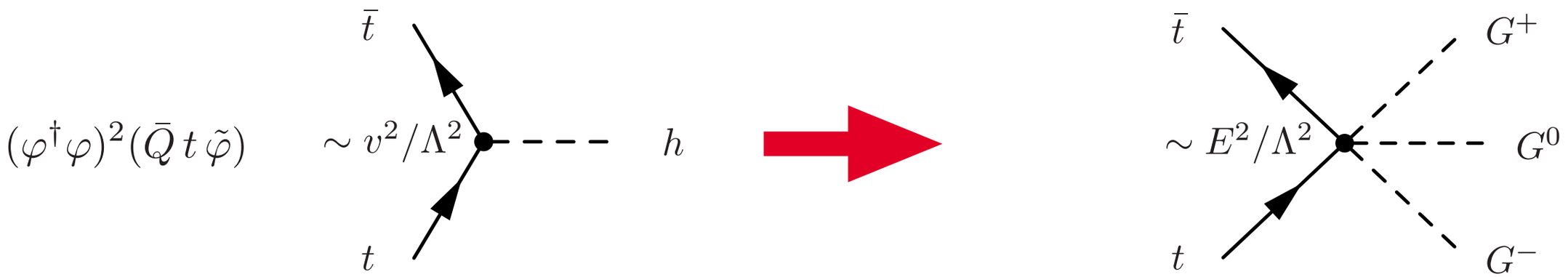


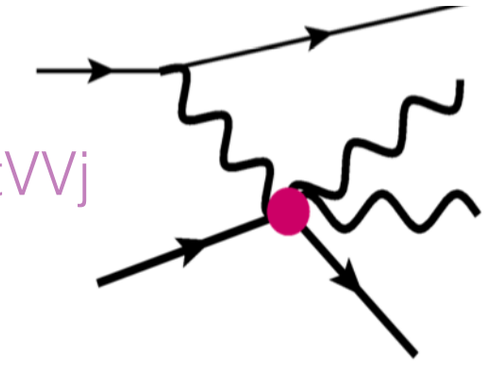
Essential prediction of **SMEFT**

- Higgs & Goldstones in the same multiplet

$$\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix} -iG^+ \\ v + h + iG^0 \end{pmatrix}$$

- Modified ttH, ttZ interactions correlated with modifications to higher multiplicity processes involving longitudinal gauge bosons, Higgs & top quarks

pp → tVVj



[Henning et al.; arXiv:1812.09299]

Conclusions

Broad survey of 2 → 2 scattering amplitudes with tops

- Identified leading & subleading sources of energy growth from SMEFT operators as well as interference structure with SM
- Nearly all operators present maximal (E^2) growth in some configuration
- E-growing interference only present in fully longitudinal configs.
- High-energy EW top scattering is a rich playground for fingerprinting EWSB

First collider sensitivity studies embedding the amplitudes

- Many interesting rare top production modes to consider
- Energy growth from 2 → 2 not always transferred to full process
- Many interesting processes for LHC and future colliders
- Probe operators that do not lead to energy growth in e.g. ttH, ttV
- Essential prediction of SMEFT that should be tested
- Promising programme for the future of precision top physics