Higgs and Effective Theory 2020

Universidad de Granada

Top quark electroweak interactions at high energy

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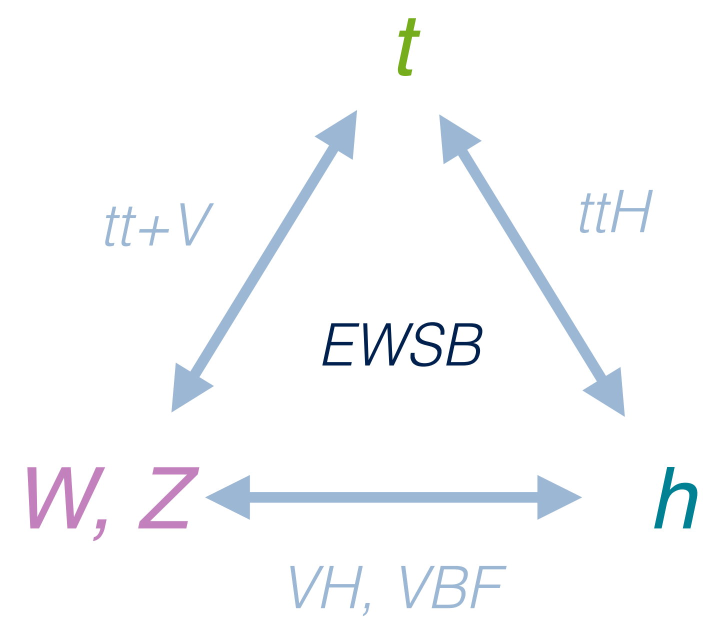
Luca Mantani, Fabio Maltoni & KM; JHEP 10 (2019) 004

Introduction

LHC legacy = precise measurements of the interactions that govern EWSB



How can we optimize/improve?

- Beyond systematics-limited rate measurements
- Towards high energy & high multiplicity

The top is special yet poorly measured

- Being most strongly coupled to the Higgs has strong BSM implications
- Big role to play in uncovering the nature of EWSB?

EWSB: Intrinsic connection between gauge and Goldstone boson interactions, especially at high energy

$$\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix} -iG^+ \\ v + h + iG^0 \end{pmatrix} \qquad \begin{array}{c} \partial_\mu G^+ \leftrightarrow W^+_\mu \\ \partial_\mu G^0 \leftrightarrow Z_\mu \end{array}$$

Testing EWSB at colliders

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**

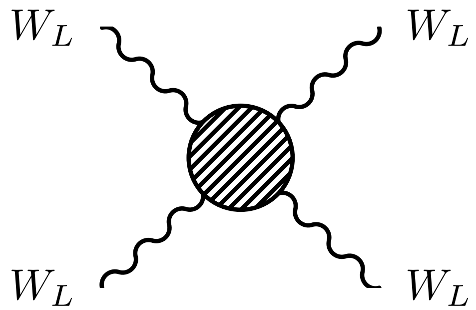
Precision measurements of SM interactions:
Target deviations & non-SM Lorentz structures

Hallmark signature:
Energy growth in scattering amplitudes

Scattering unitarity

Unitarity cancellations in the SM

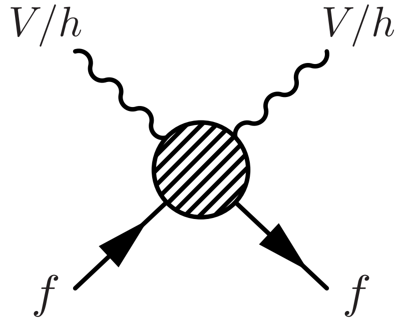
$W_L\, W_L \rightarrow W_L\, W_L$



[Llewellyn-Smith; PLB 46 (1973) 233]

[Lee, Quigg & Thacker; PRD 16 (1977) 1519 & PRL 38 (1977) 883]

$f\, W_L \rightarrow f\, W_L$



[Appelquist & Channowitz; PRL 57 (1987) 2405]

[Maltoni, Niczyporuk & Willenbrock; PRD 65 (2002) 033004]

Structured by gauge invariance & EWSB mechanism

- Deviations from SM → energy growth
- Theory has limited validity range → heavy new physics
- The realm of **Standard Model 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:

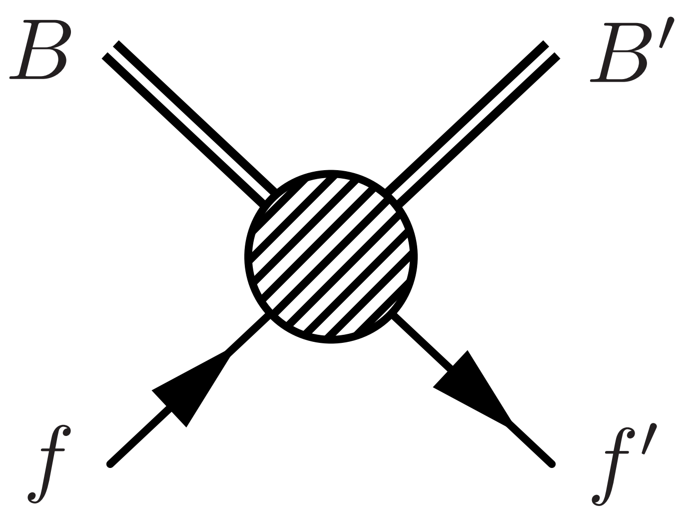
(a) **May not** grow maximally with energy (E^2)

(b) 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

Phenomenologists job: 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	$b\,W \to t\,h$	$t\,(Z/\gamma) \to t\,h$ $t\,h \to t\,h$

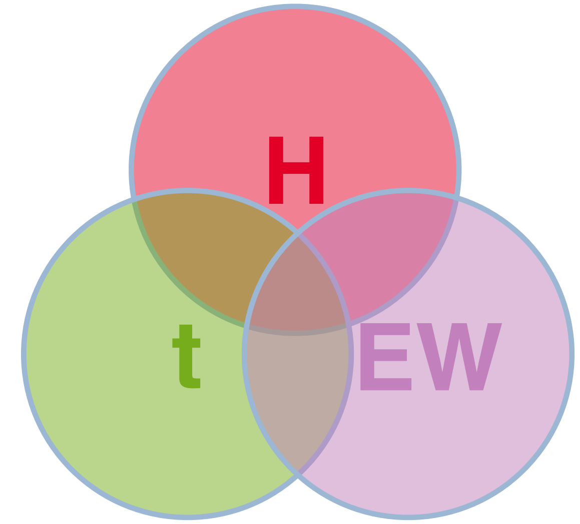
Considered 10, 2 → 2 scattering amplitudes with ≥ one top

- High energy limit: **s ~ | t | ≫ v²** Unitarity: max 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, ttXY…

SMEFT for EWSB



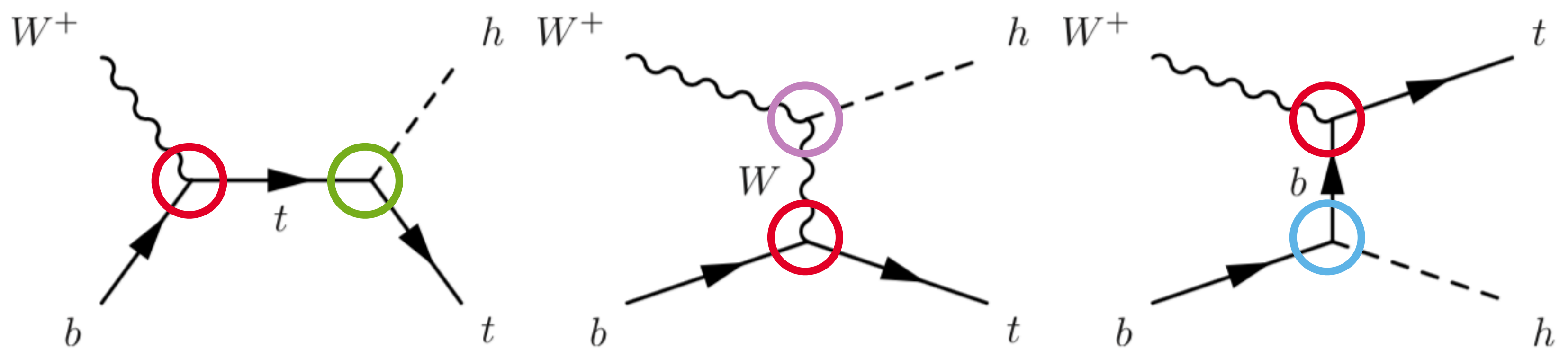
	↓more constrained↓		↓less constrained↓		
Bosonic	$\mathcal{O}_W$	$\varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	Yukawa
	$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}_{tW}$	$i(\bar{Q}\sigma^{\mu\nu}\,\tau_I\, t)\, \tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$	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
	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{t}\, \gamma^\mu\, t)$	
			$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi}\, D_\mu\, \varphi)(\bar{t}\, \gamma^\mu\, b) + \text{h.c.}$	RHCC

Relevant dim-6 operators 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 specific operators

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

Anomalous $bW^+ \to tH$



SM: **left-handed** (t_L, b_L), **longitudinal** W configuration ~ E^0

Anomalous interactions:

- tbW vertex: present in all diagrams → overall rescaling ~ E^0
- bbH vertex: $\propto m_b \to 0$
- 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}

$bW^+ \to tH$ in SMEFT

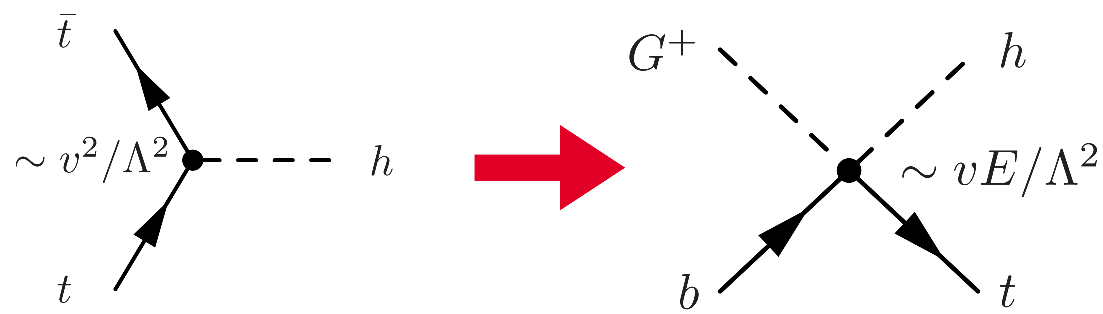
$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi tb}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	s^0	s^0	$-$	s^0	s^0	$\sqrt{s(s+t)}$
$-, 0, +$	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	$-$	$-$	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$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

bW⁺ → tH in SMEFT

Energy growth from EFT-modified SM interactions

- Yukawa operator: disconnects kinematical mass from coupling to Higgs

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

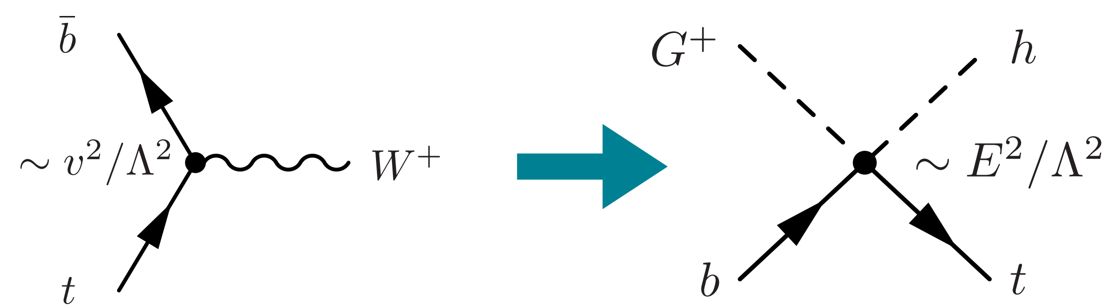


$$h\, G^+\, \bar{t}_L\, b_R$$

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

Max growth from dim-6 contact-terms

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



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

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

Contact interactions

Guess E-growth by inspecting higher dim. contact terms

- 2 → N scattering has mass dimension 2 - N
- Dimension-K operator insertion, maximum growth: $\mathcal{M} \propto \frac{E^{K-N-2}}{\Lambda^{K-4}}$
- Operators with Higgs fields may require vev-insertion (m)
- Every longitudinal external vector, V, can contribute a factor E/M_V (n)

$$\mathcal{M}_{2\to N} \propto \frac{v^m}{\Lambda^{K-4}} \frac{E^{K-N-m-2+n}}{M_V^n} \quad \Rightarrow \quad \mathcal{M}_{2\to 2}^{D=6} \propto \frac{v^m}{\Lambda^2} \frac{E^{2-m+n}}{M_V^n}$$

Only constraint is SM gauge invariance

- Connects contact to lower point interactions via, e.g., field strengths
- SMEFT: max. growth relative to the SM is bounded by operator dimension
- Interactions not respecting, e.g., SU(2) can lead to 'anomalously' large growth

Summary: max growths

gauge/higgs operators $\Longleftarrow$ $\Longrightarrow$ *top operators*

Energy-growing interference

single-top

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

two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$
$tW \to tW$	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/ Higgs

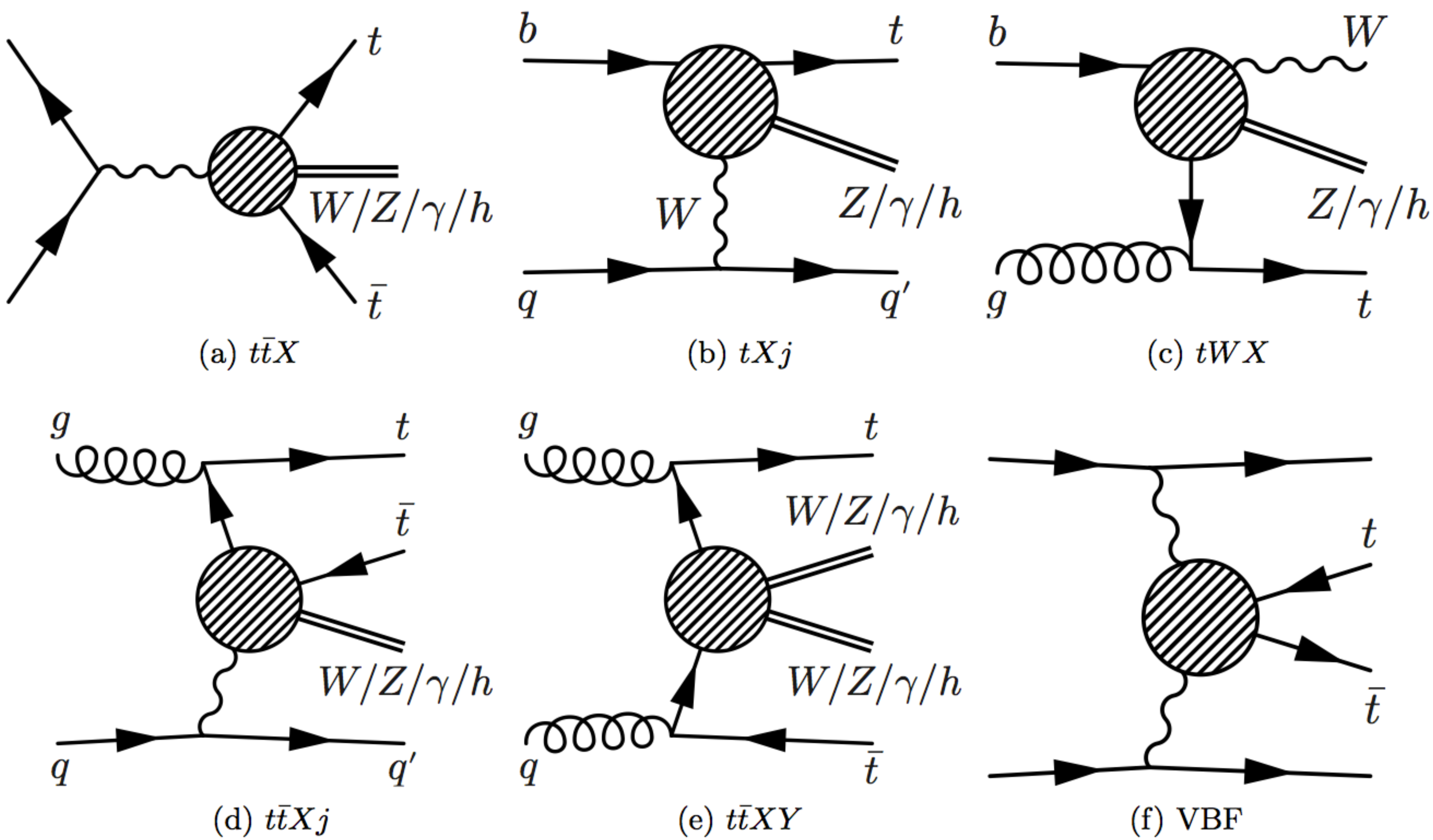
	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi\Box}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	$\mathcal{O}_{W}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tB}$	$\mathcal{O}_{tW}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$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

Most top operators show max growth somewhere

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

Embedding the amplitudes

Collider processes: rare, EW 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
$bW \to tZ$	✓	✓		✓			
$bW \to t\gamma$	✓		✓		✓		
$bW \to th$						✓	✓

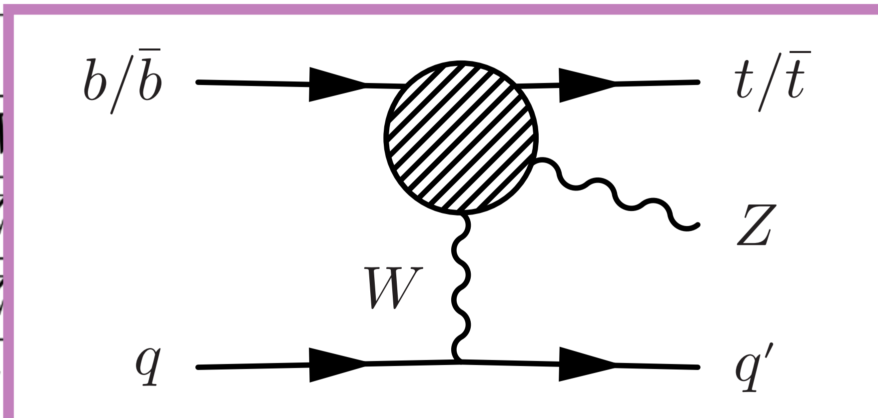
	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

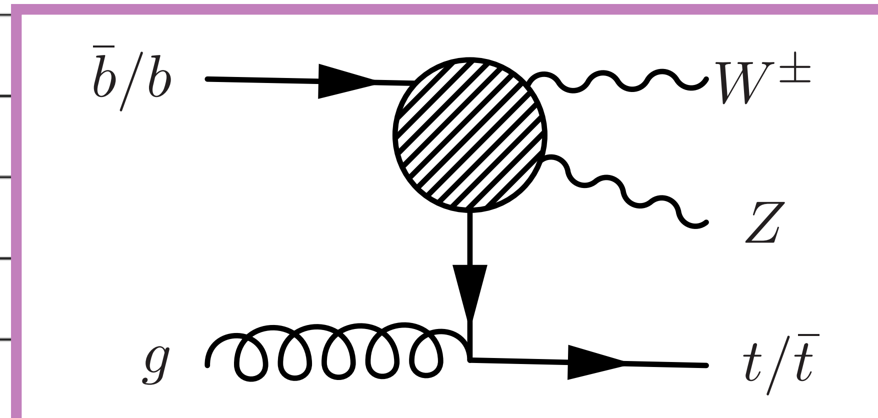
	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

Embedding the amplitudes

Collection of ‘sensitivity’ studies, general discussion

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





$bW \to tZ$

neutral & charged current top quark gauge interactions

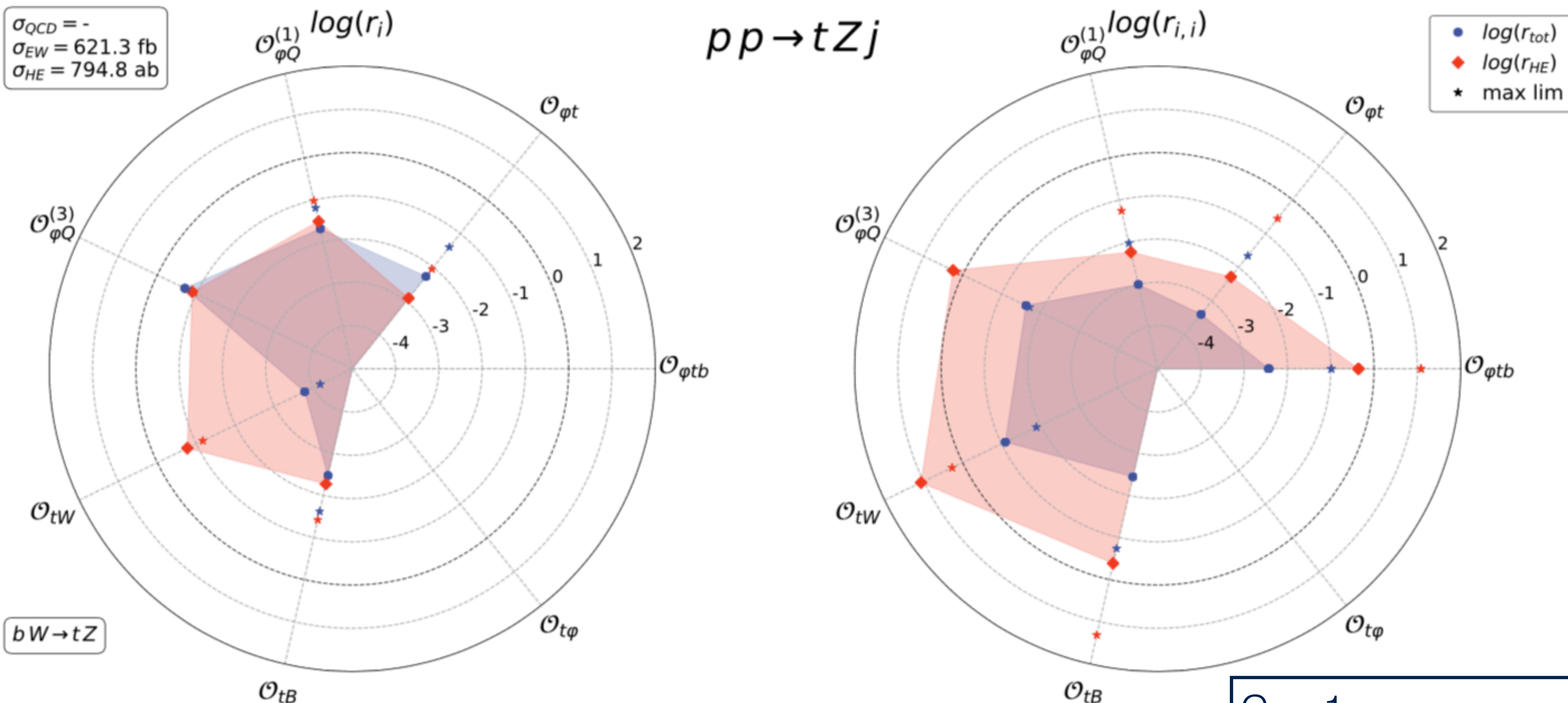
$$\mathcal{O}^{(3)}_{\varphi Q} = i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{Q}\gamma^\mu \tau_I Q)$$

Energy-growing interference

tZj total & high energy xs

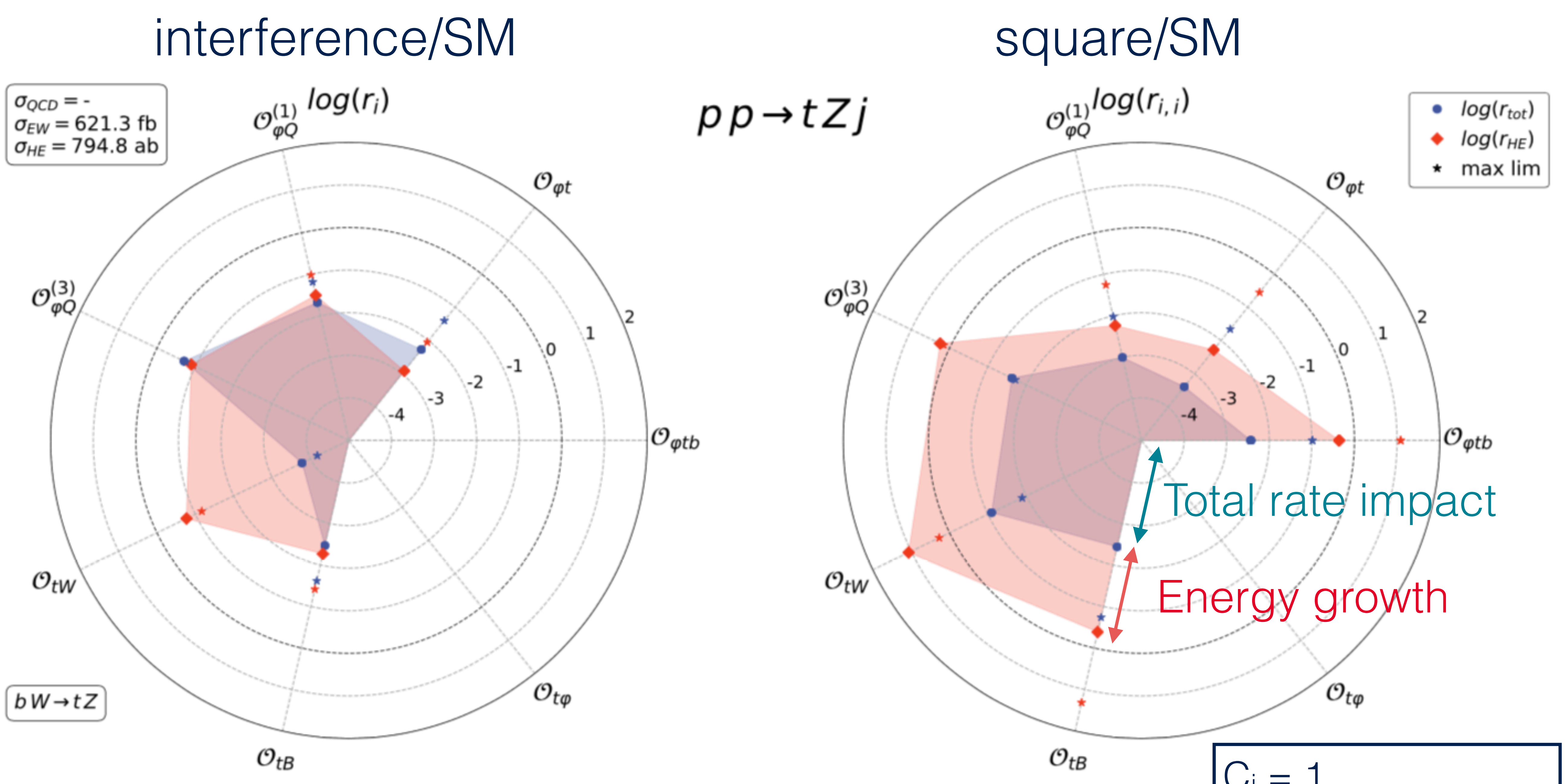
interference/SM

square/SM



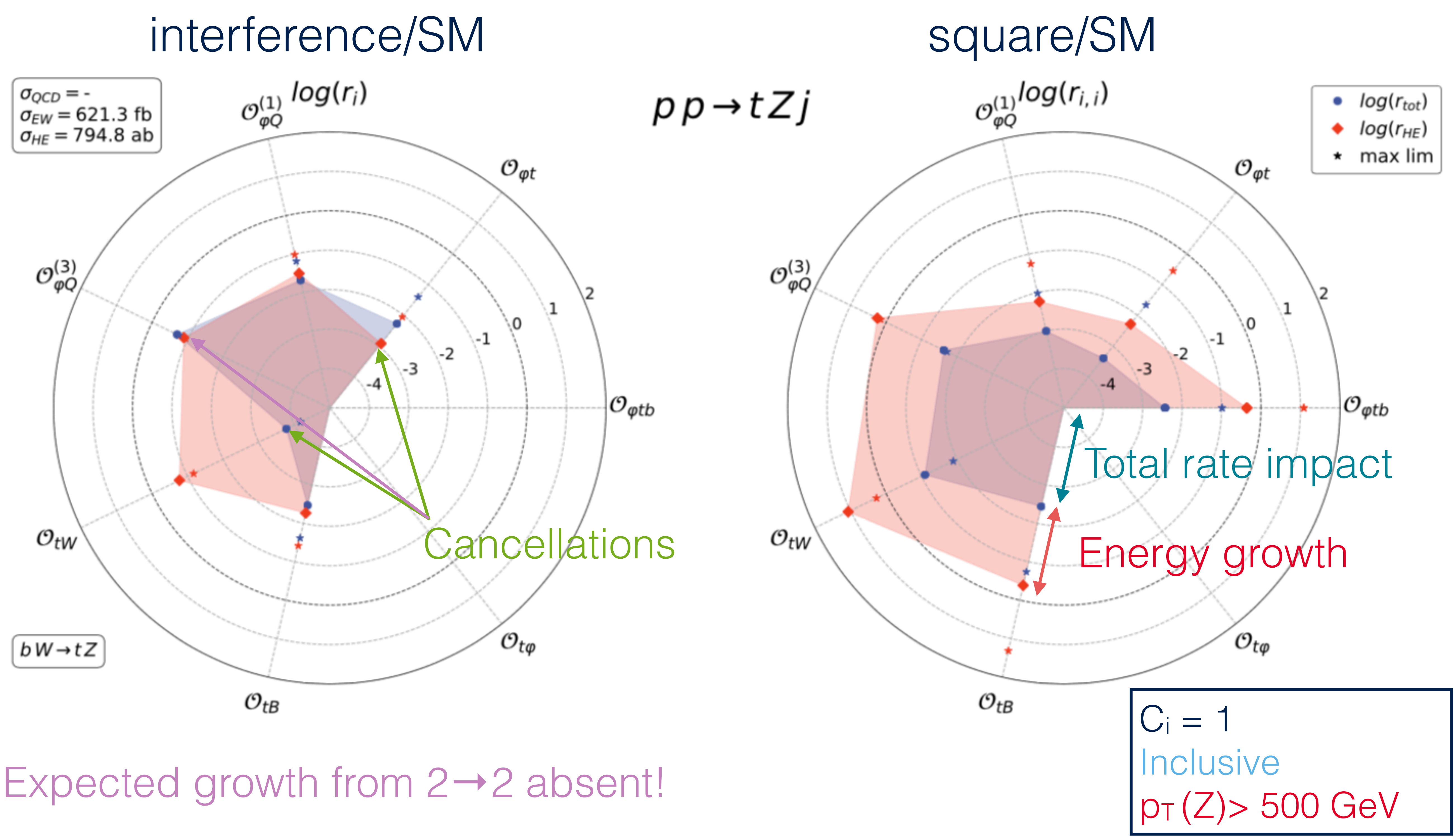
C_i = 1
Inclusive
p_T (Z)> 500 GeV

tZj total & high energy xs



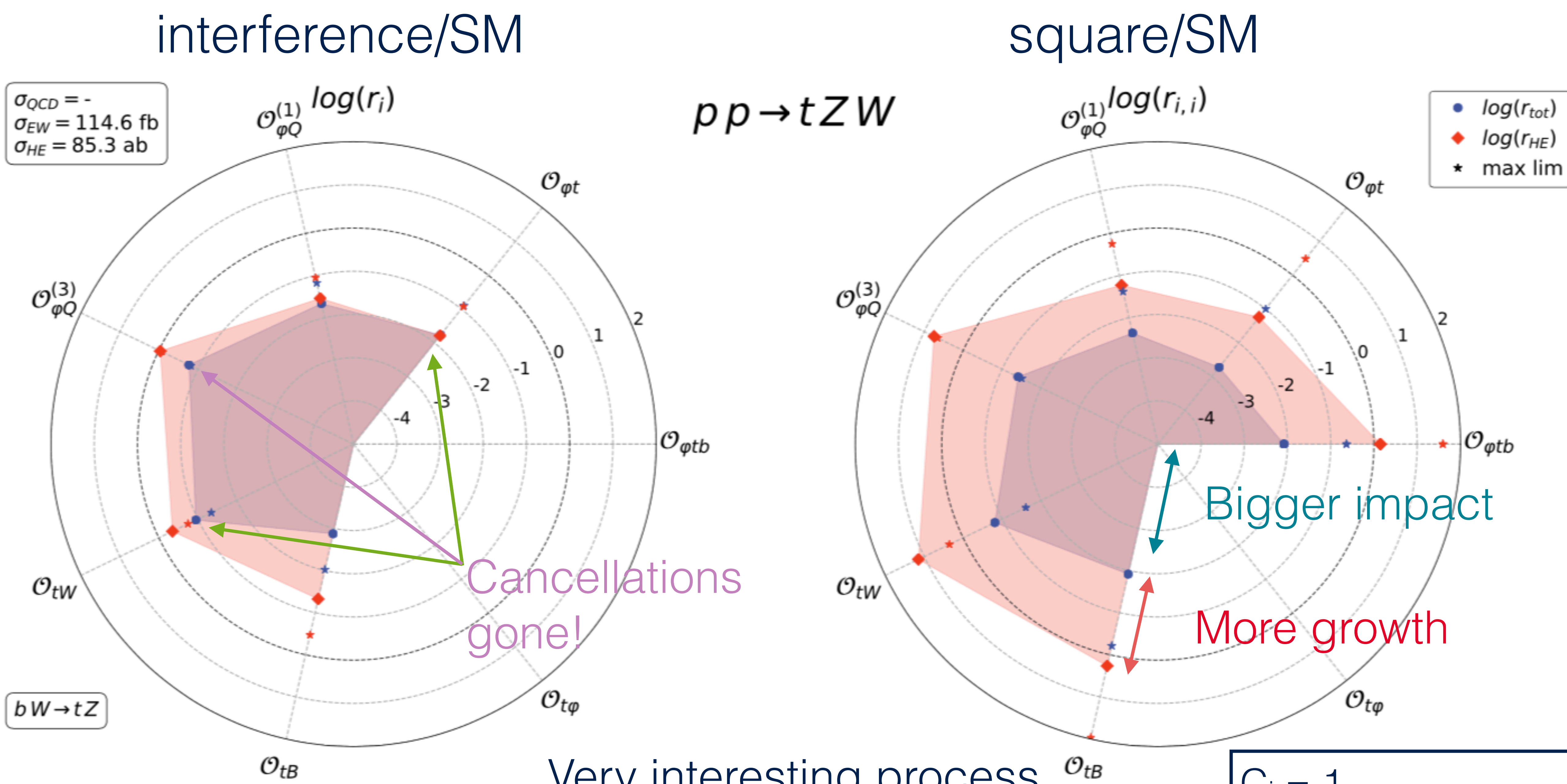
$C_i = 1$
Inclusive
p_T (Z)> 500 GeV

tZj total & high energy xs



Expected growth from 2→2 absent!

tZW total & high energy xs

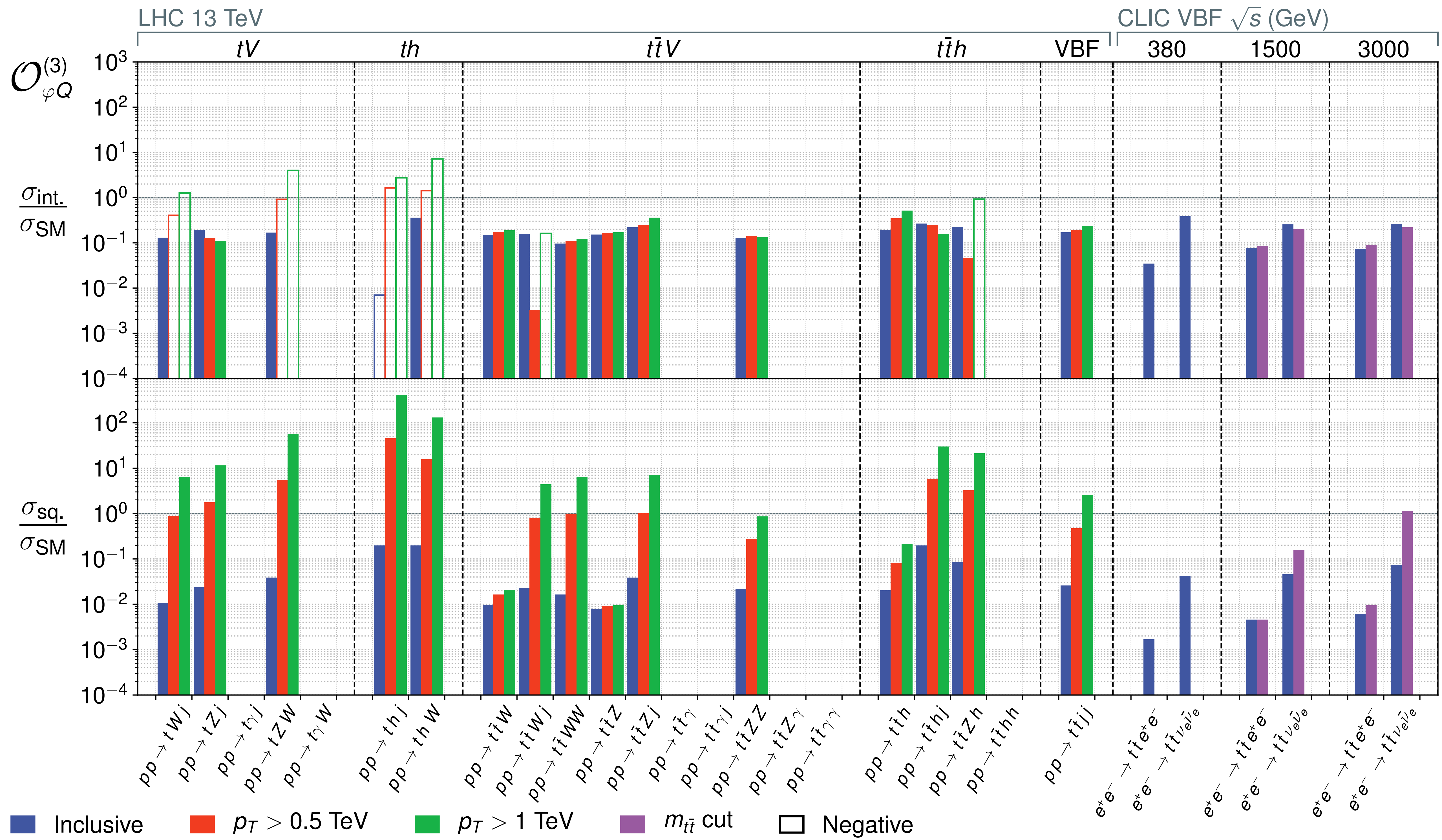


Expected growth is there!

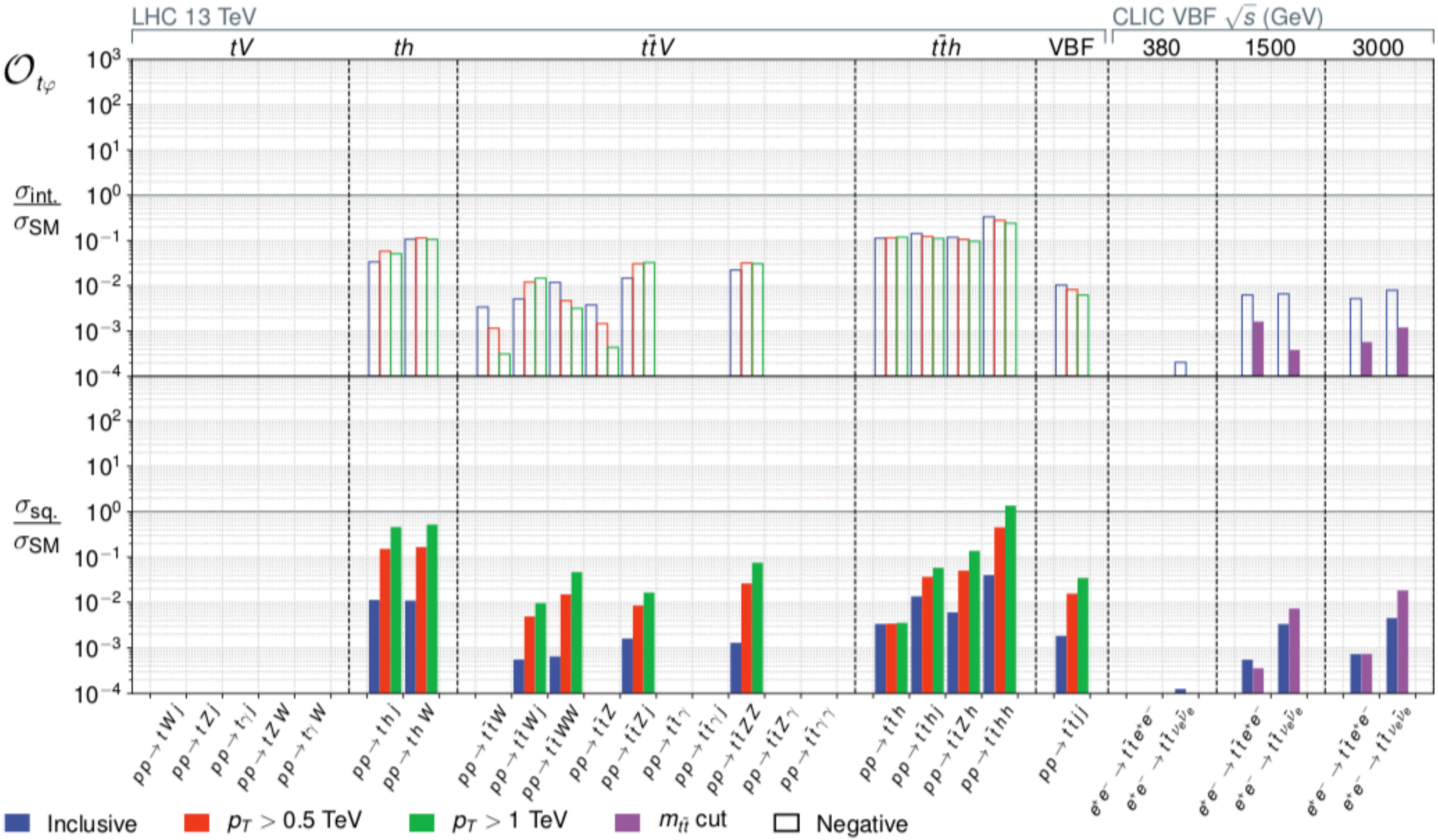
Very interesting process that should be measured at the LHC/FCC

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

Charged current operator



Yukawa operator



Embedding the amplitudes

'Future collider' amplitudes & processes

	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
$tW \to tW$	✓	✓						✓
$tZ \to tZ$			✓				✓	✓
$tZ \to t\gamma$			✓	✓		✓		✓
$t\gamma \to t\gamma$				✓	✓			✓

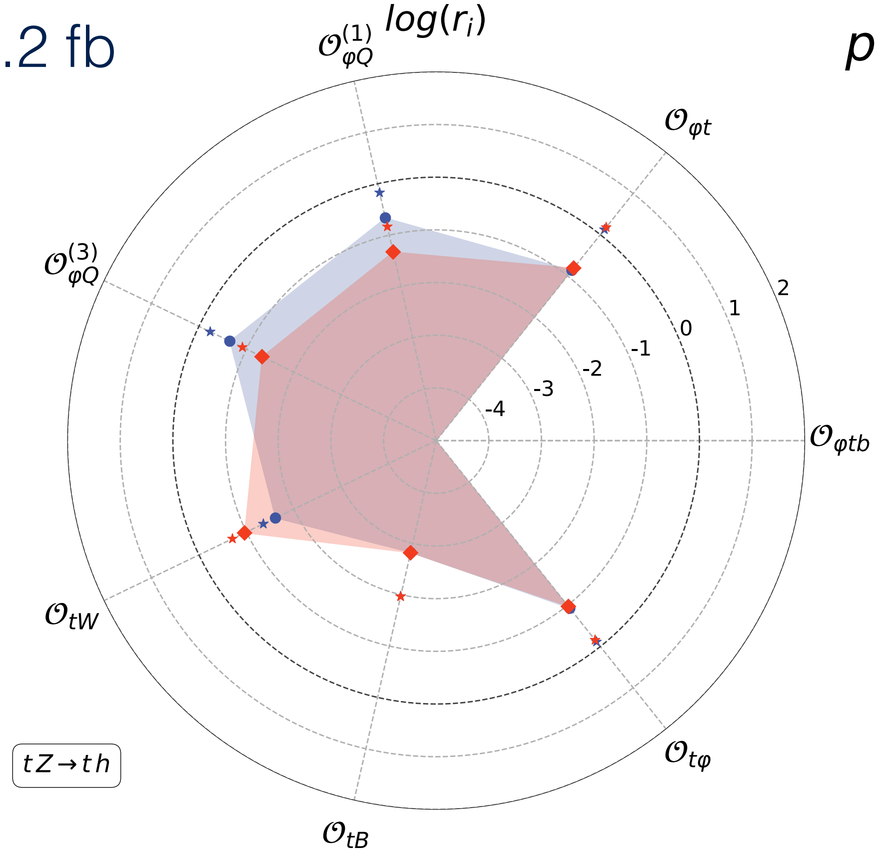
	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \to th$	✓	✓		
$t\gamma \to th$	✓		✓	
$th \to th$				✓

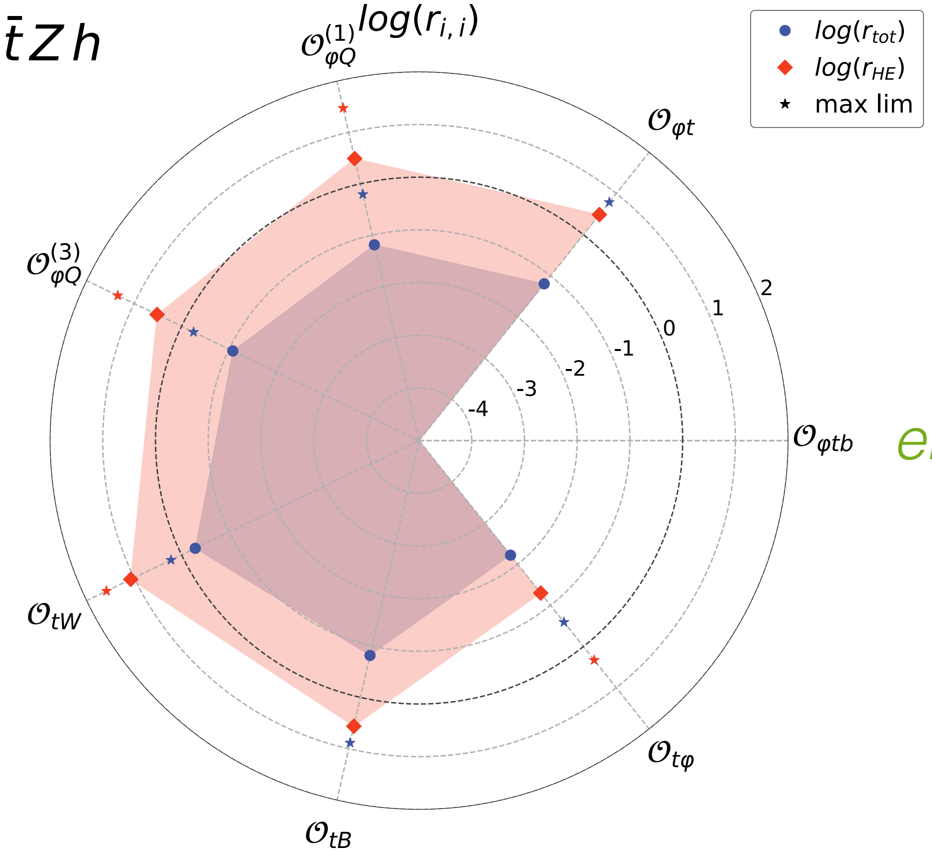
ttZh: LHC vs FCC-hh

High energy: $p_T\,(Z,h) > 500$ GeV

σ_{13} = 1.2 fb

$pp \to t\bar{t}Zh$



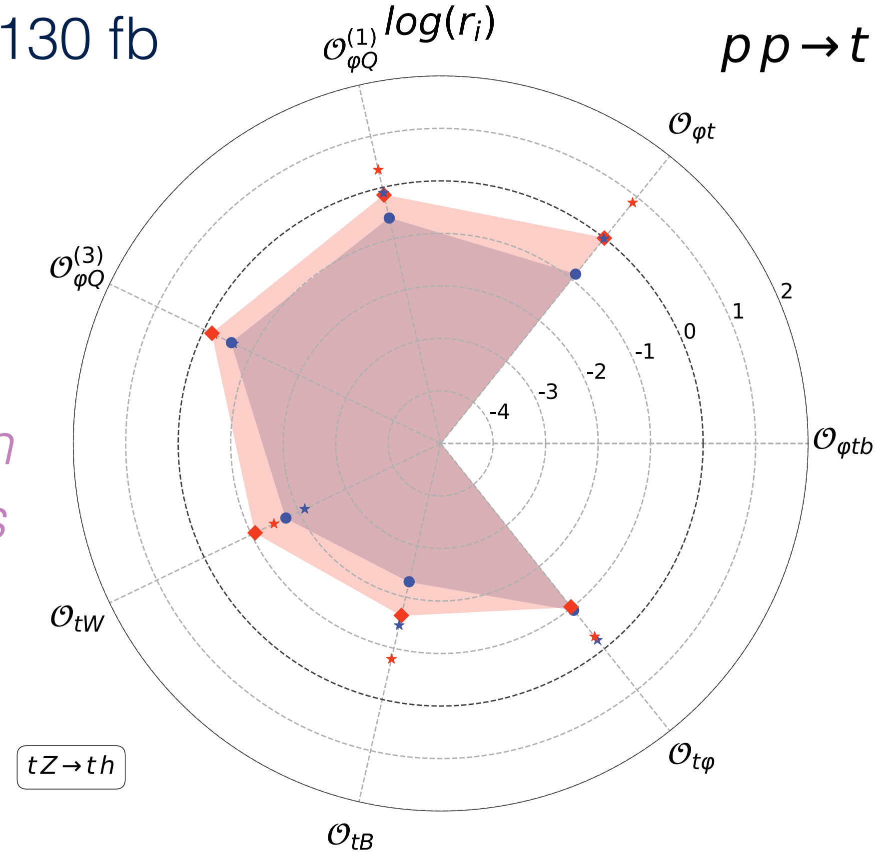


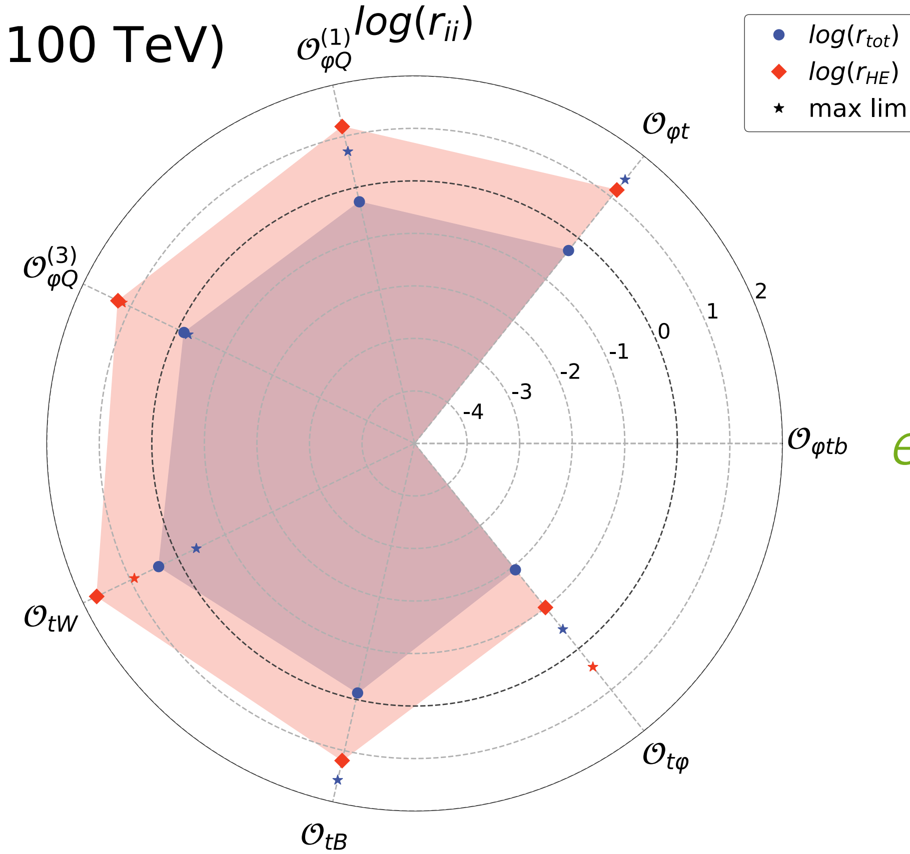
Interference: phase space cancellations

Quadratic: energy growth & O(1-10)

σ_{100} = 130 fb

$pp \to t\bar{t}Zh$ (100 TeV)





Interference: energy growth & O(1) effects

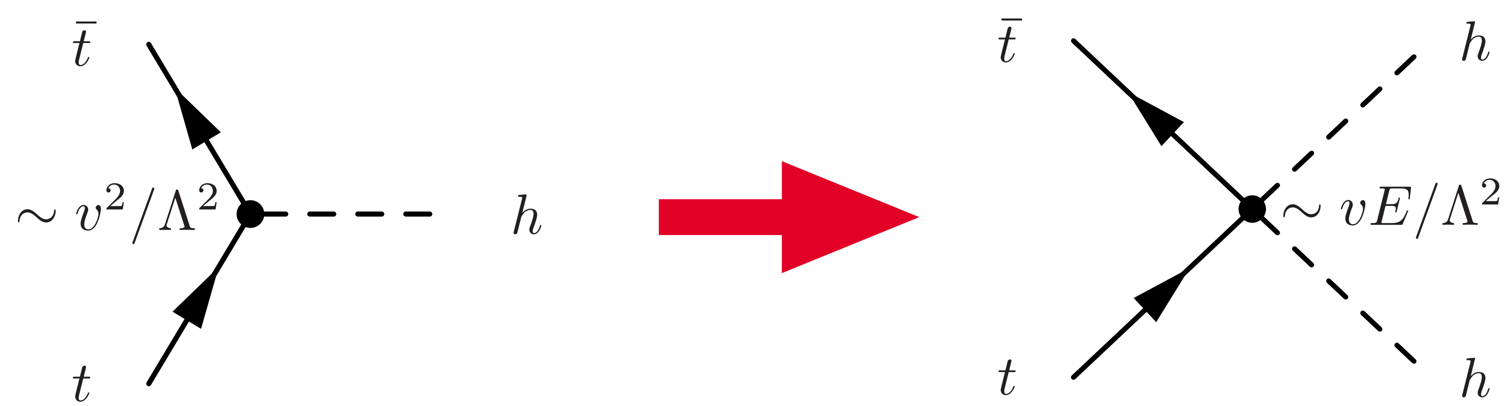
Quadratic: energy growth & O(10-100)

High-energy EW tops

Sometimes, need to go beyond 4-point scattering

- Yukawa & Triple Higgs operators (3 & 6 Higgs fields)

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



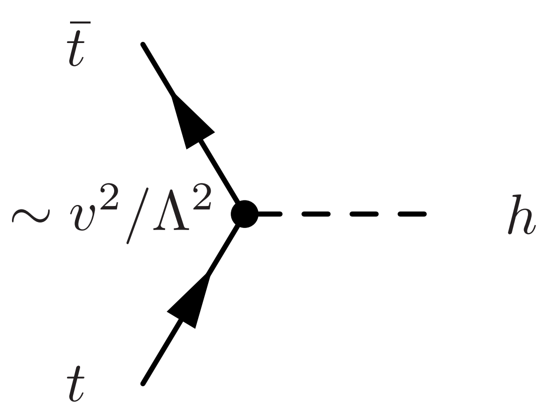
$$t\,h \to t\,h$$
$$t\,W_L \to t\,W_L$$
$$t\,Z_L \to t\,Z_L$$
$$b\,W_L \to t\,h$$

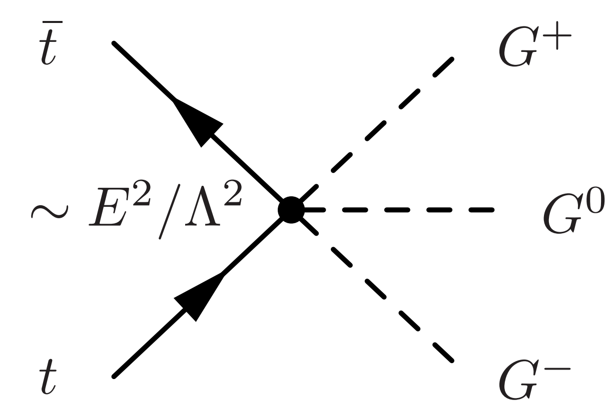
High-energy EW tops

Sometimes, need to go beyond 4-point scattering

- Yukawa & Triple Higgs operators (3 & 6 Higgs fields)

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



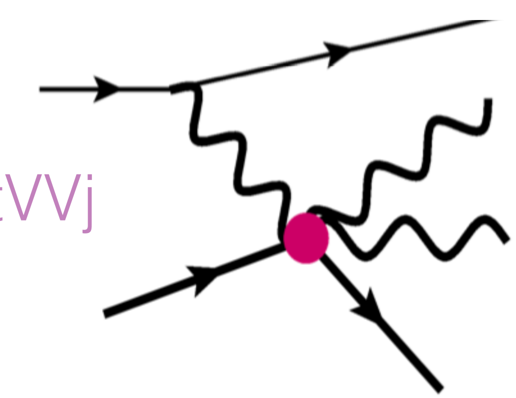


Essential prediction of **SMEFT**

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

- Higgs & Goldstones in the same multiplet
- Modified EW top interactions predict energy growth in higher multiplicity processes involving longitudinal gauge bosons, Higgs & top quarks

pp → tVVj



[Henning et al.; PRL 123 (2019), no.18 181801]

Conclusions

EW top scattering: rich playground for fingerprinting EWSB

- Go beyond rate measurements & access energy growth/unitarity violation
- Increasingly high energy & multiplicity processes: future-proof
- Uncharted territory for the SM & EFT that brings complementary information
- Essential predictions of SMEFT that should be tested

First collider sensitivity studies embedding the amplitudes

- Many interesting rare top production modes to consider
- Energy growth from $2 \to 2$ not always transferred to full process
- E-growing interference only present in fully longitudinal configurations
- Dedicated phenomenological studies required (backgrounds, reconstruction)
- Promising programme for the future of precision top/EW/Higgs physics