

Top quark electroweak interactions at high energy

Ken Mimasu

CP3, UCLouvain

15th April 2020

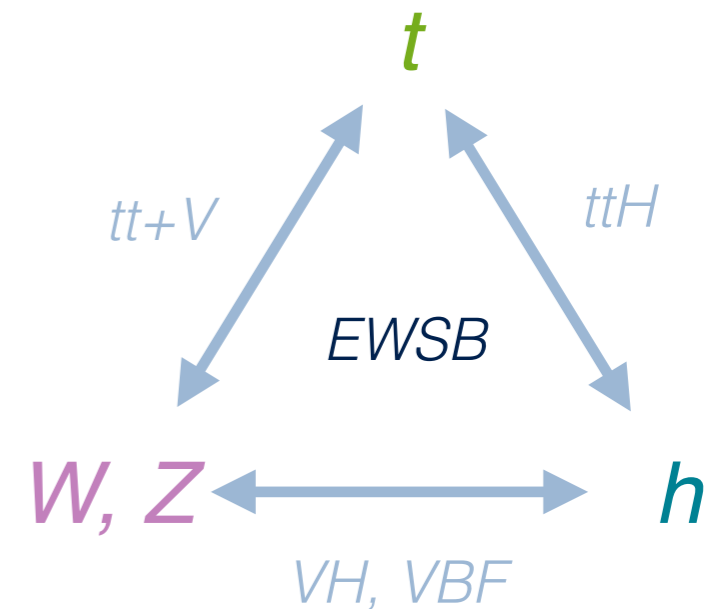
Luca Mantani, Fabio Maltoni & KM; JHEP 10 (2019) 004



Introduction

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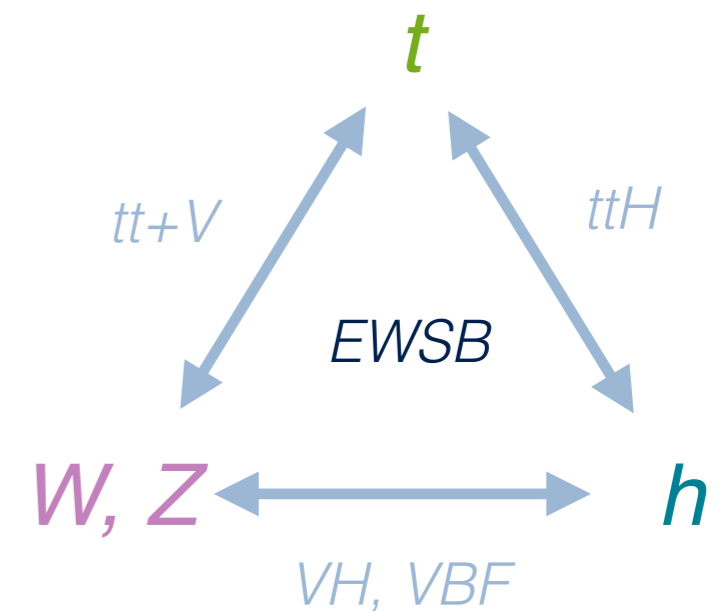
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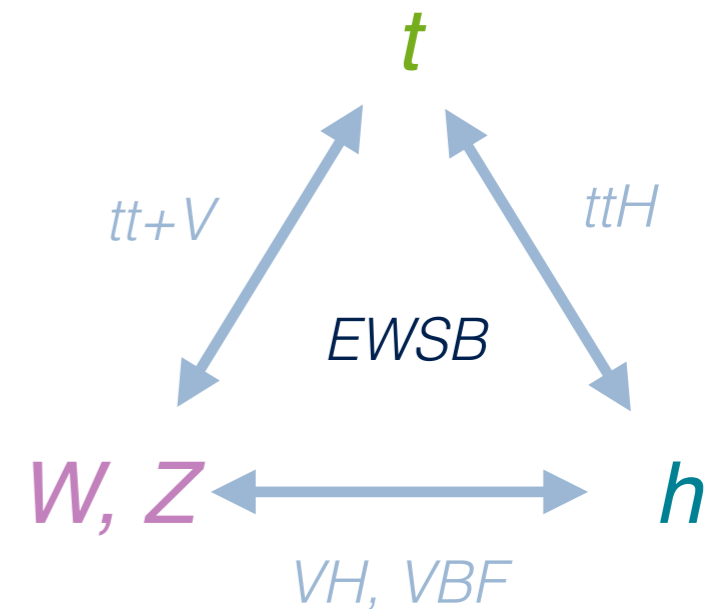


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- Beyond **systematics-limited** rate measurements
- Towards **high energy** & **high multiplicity**



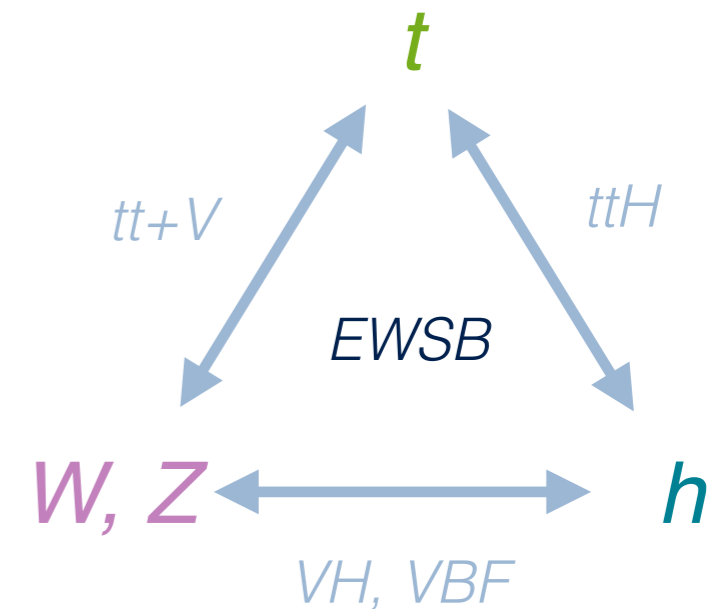
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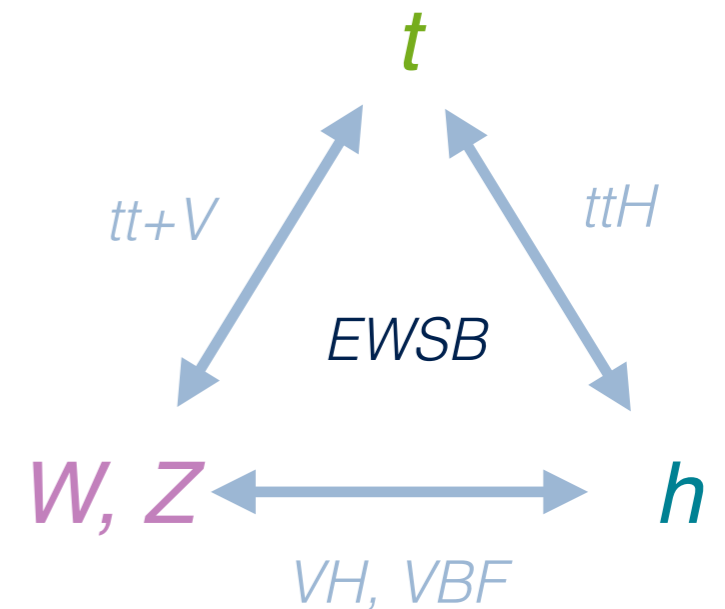
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- Big role to play in uncovering the nature of EWSB?

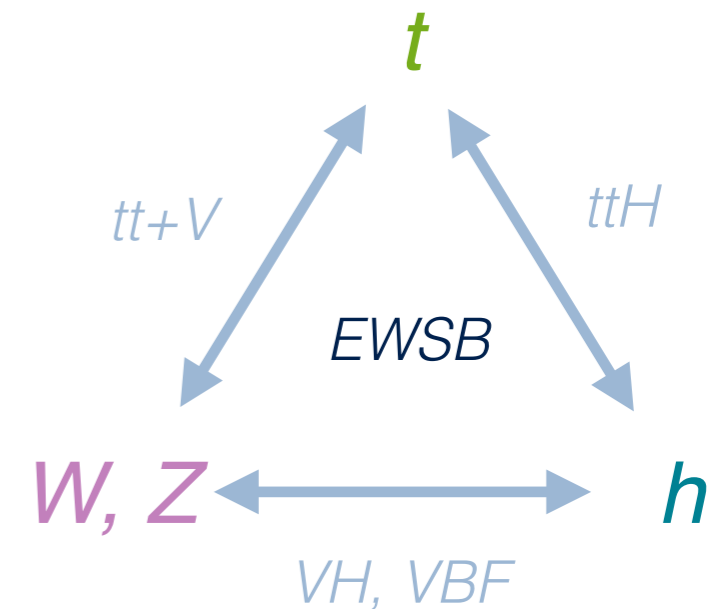


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EWSB: Intrinsic connection between **gauge** and **Goldstone** boson interactions, especially at high energy

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

Testing EWSB at colliders

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Target deviations & non-SM Lorentz structures

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Hallmark signature:

Energy growth in scattering amplitudes

Scattering unitarity

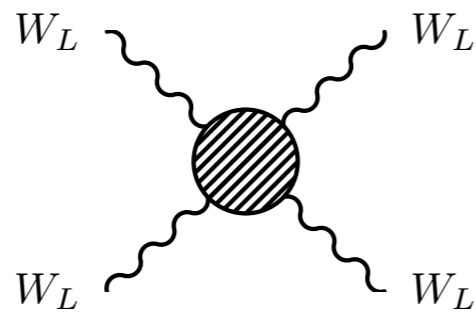
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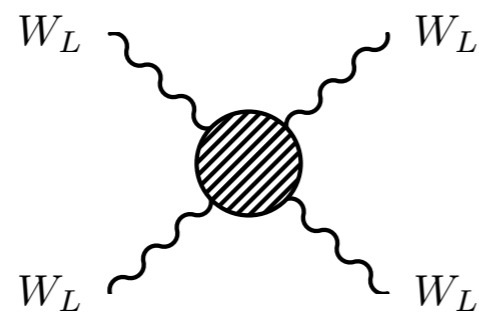
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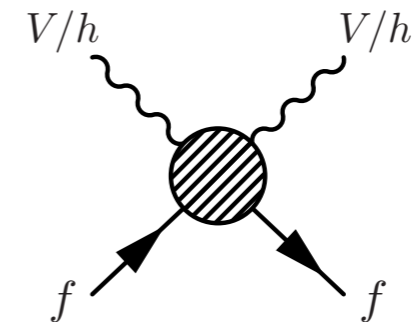
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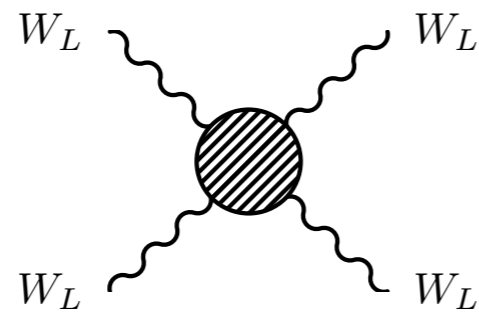
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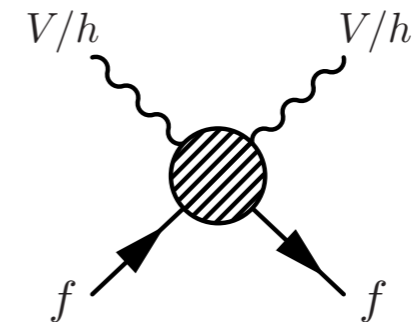
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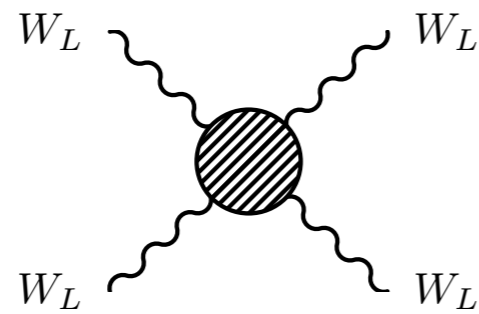
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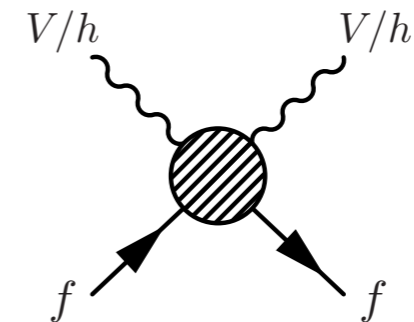
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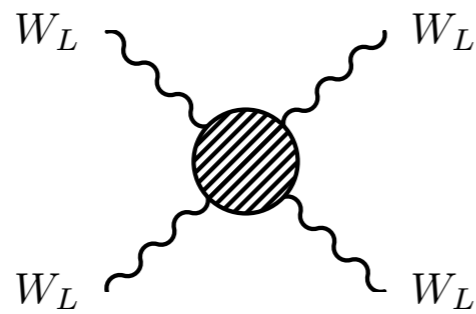
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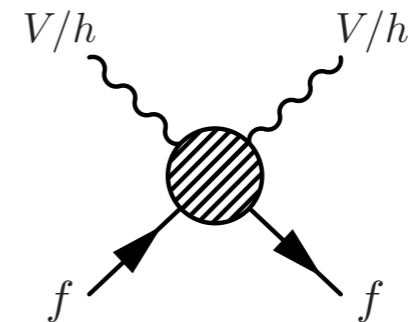
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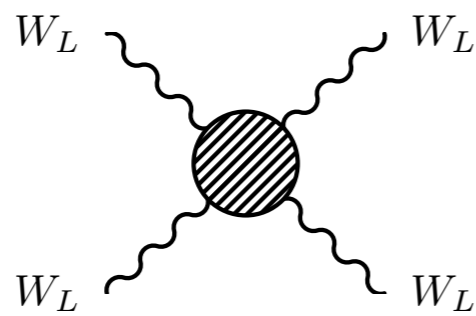
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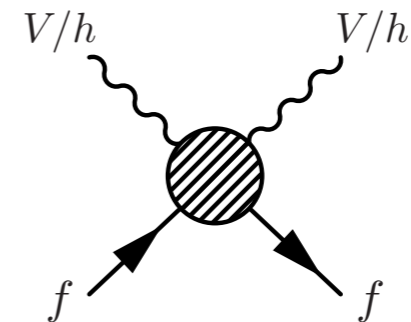
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- The realm of **Standard Model Effective Field Theory**

Energy growth in SMEFT

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$$\text{Dim-6} \\ \mathcal{A} \sim \mathcal{A}_{SM} \left(1 + c_i \frac{v^2}{\Lambda^2} + c_j \frac{v E}{\Lambda^2} + c_k \frac{E^2}{\Lambda^2} \right)$$

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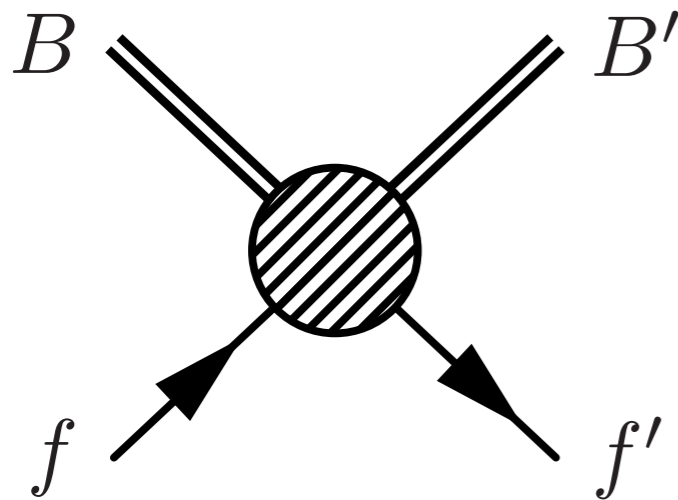
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Phenomenologists job: find and exploit them!

Our study

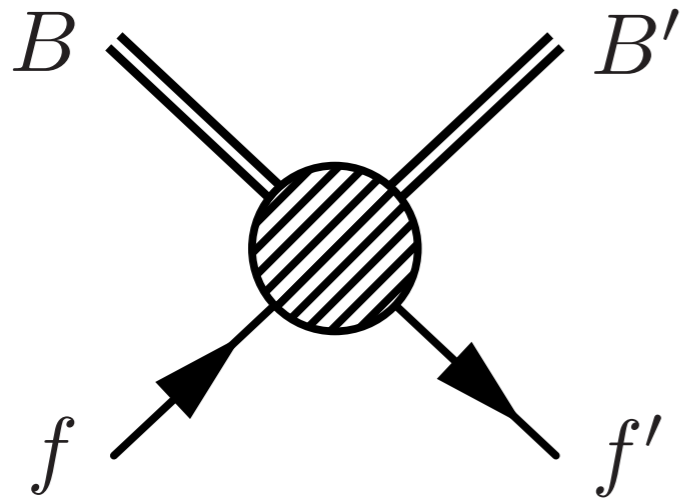
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Considered 10, $2 \rightarrow 2$ scattering amplitudes with \geq one top

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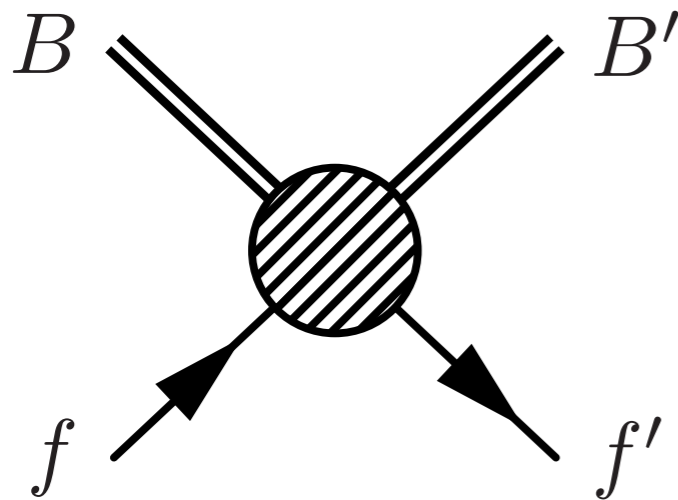


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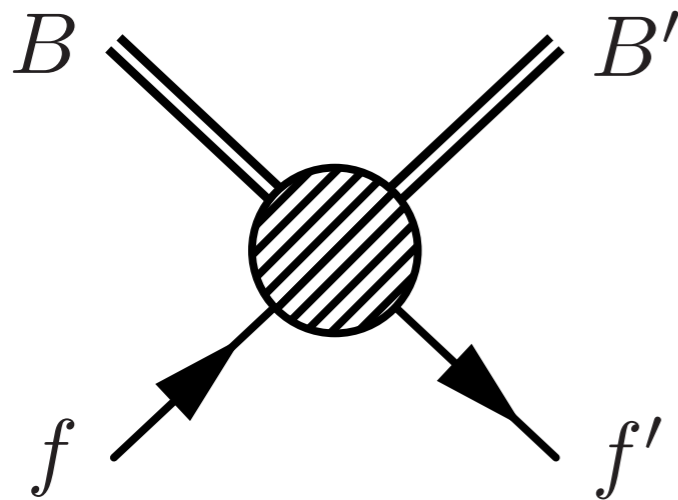
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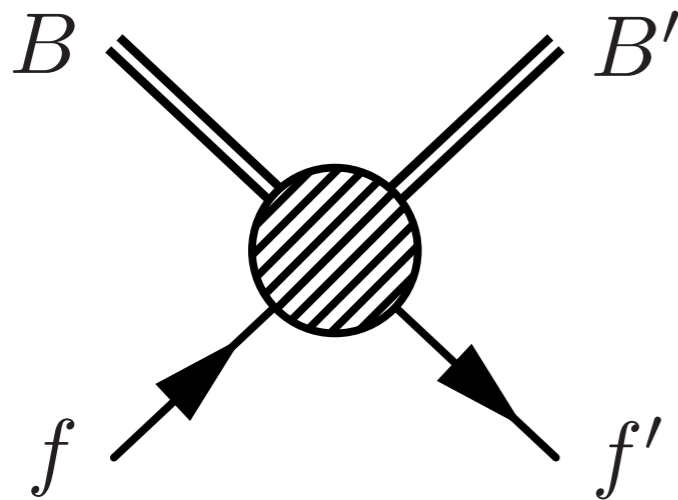


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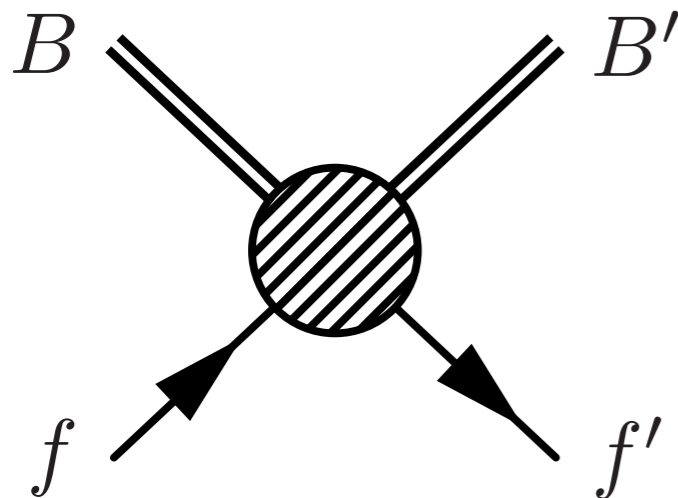


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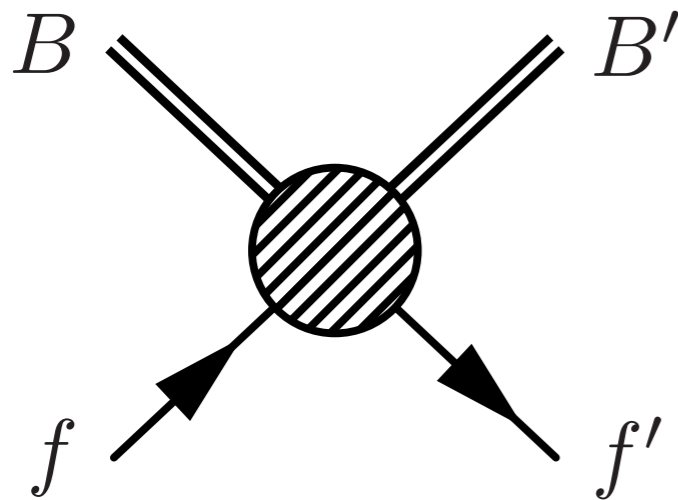


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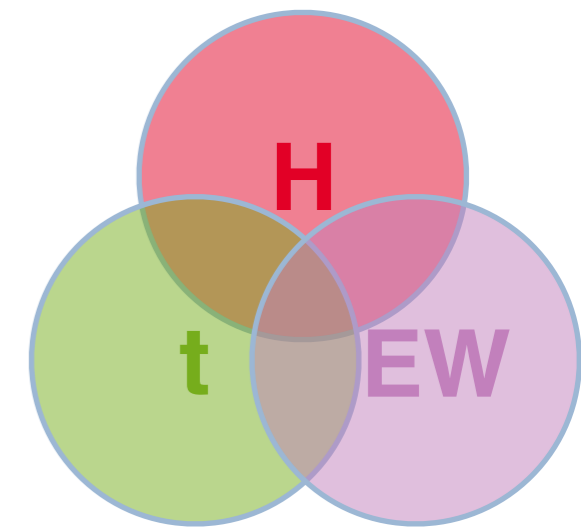
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Interesting processes: ‘rare’ EW top production

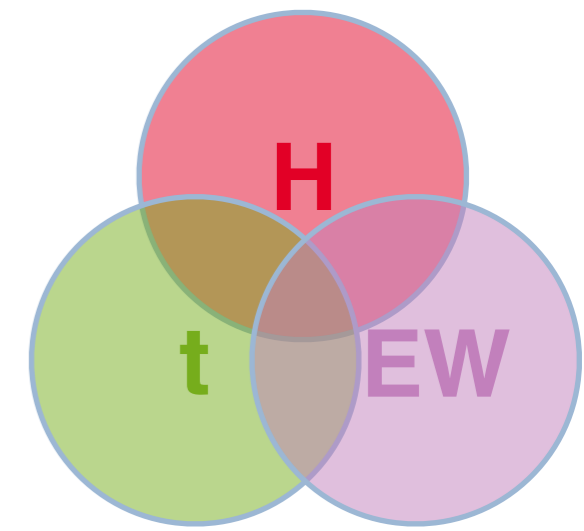
tZj , tWj , tHj , tZW , tHW , $ttWj$, VBF- tt , $ttXY$...

SMEFT for EWSB



\mathcal{O}_W	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W_{\mu\nu}^I$	\mathcal{O}_{tW}	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t) \tilde{\varphi} W_{\mu\nu}^I + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	\mathcal{O}_{tB}	$i(\bar{Q}\sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi)(\bar{Q}\gamma^\mu\tau^I Q)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t)$
		$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu\varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$

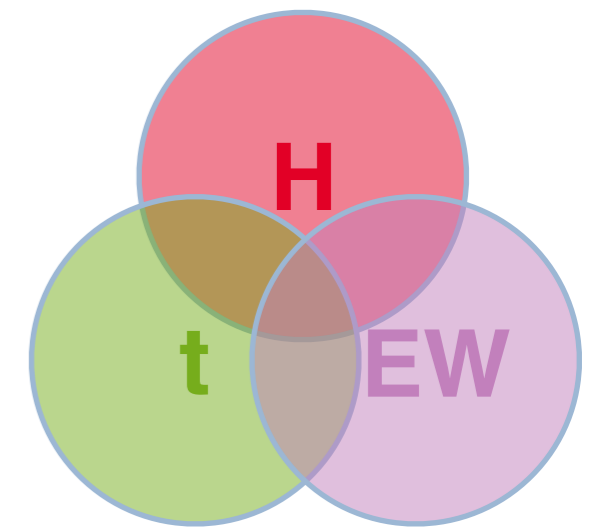
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\mathcal{O}_W	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W_{\mu\nu}^I$	\mathcal{O}_{tW}	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t) \tilde{\varphi} W_{\mu\nu}^I + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	\mathcal{O}_{tB}	$i(\bar{Q}\sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi)(\bar{Q}\gamma^\mu\tau^I Q)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t)$
		$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu\varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$

Relevant dim-6 operators for EW-top scattering

SMEFT for EWSB



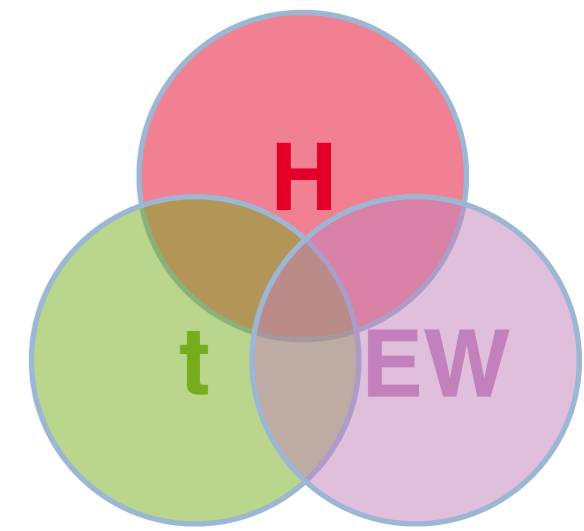
\mathcal{O}_W	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W_{\mu\nu}^I$	\mathcal{O}_{tW}	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t) \tilde{\varphi} W_{\mu\nu}^I + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	\mathcal{O}_{tB}	$i(\bar{Q}\sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi)(\bar{Q}\gamma^\mu\tau^I Q)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t)$
		$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu\varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$

Relevant dim-6 operators for EW-top scattering

- Warsaw basis with $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$ flavor symmetry

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

SMEFT for EWSB



Bosonic

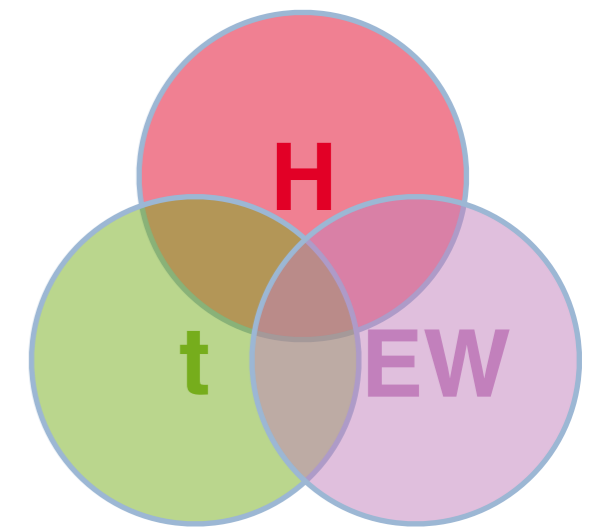
\mathcal{O}_W	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W_{\mu\nu}^I$	\mathcal{O}_{tW}	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t) \tilde{\varphi} W_{\mu\nu}^I + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	\mathcal{O}_{tB}	$i(\bar{Q}\sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi)(\bar{Q}\gamma^\mu\tau^I Q)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t)$
		$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu\varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$

Relevant dim-6 operators for EW-top scattering

- Warsaw basis with $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$ flavor symmetry
- Bosonic + top specific operators

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

SMEFT for EWSB



Bosonic

\mathcal{O}_W	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W_{\mu\nu}^I$	\mathcal{O}_{tW}	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t) \tilde{\varphi} W_{\mu\nu}^I + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	\mathcal{O}_{tB}	$i(\bar{Q}\sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi)(\bar{Q}\gamma^\mu\tau^I Q)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t)$
		$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu\varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$

Yukawa

weak
dipoles

currents

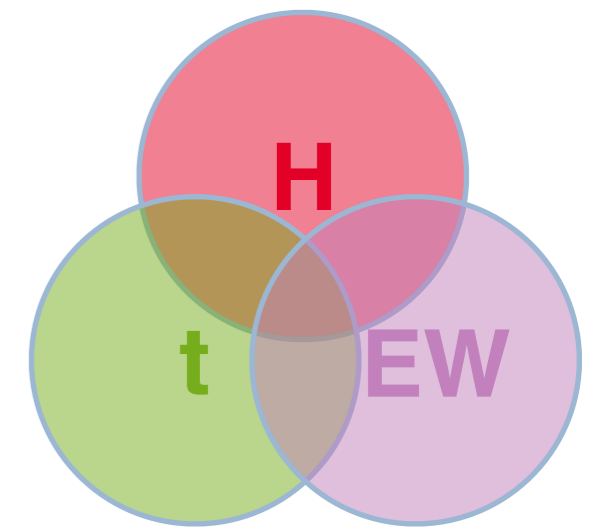
RHCC

Relevant dim-6 operators for EW-top scattering

- Warsaw basis with $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$ flavor symmetry
- Bosonic + top specific operators

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

SMEFT for EWSB



↓ more constrained ↓

Bosonic

\mathcal{O}_W	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu}_{\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W_{\mu\nu}^I$	\mathcal{O}_{tW}	$i(\bar{Q}\sigma^{\mu\nu}\tau_I t) \tilde{\varphi} W_{\mu\nu}^I + \text{h.c.}$
$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	\mathcal{O}_{tB}	$i(\bar{Q}\sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi)(\bar{Q}\gamma^\mu\tau^I Q)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t)$
		$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu\varphi)(\bar{t}\gamma^\mu b) + \text{h.c.}$

Yukawa

weak
dipoles

currents

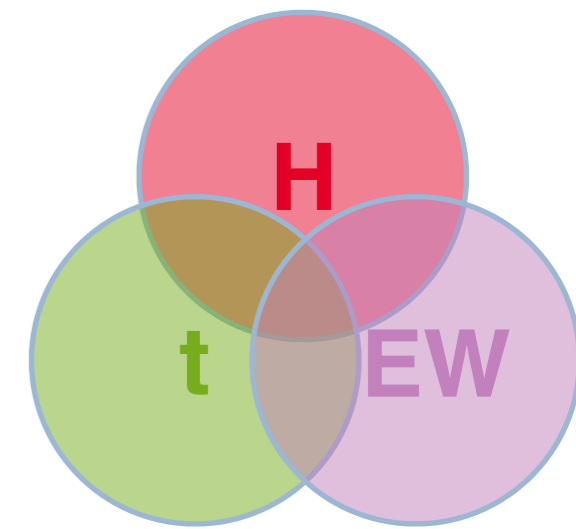
RHCC

Relevant dim-6 operators for EW-top scattering

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SMEFT for EWSB



↓ more constrained ↓

↓ less constrained ↓

Bosonic

\mathcal{O}_W	$\varepsilon_{IJK} W_{\mu\nu}^I W^{J,\nu\rho} W^{K,\mu\rho}$	$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q} t \tilde{\varphi} + \text{h.c.}$
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$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$	\mathcal{O}_{tB}	$i(\bar{Q}\sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi) B^{\mu\nu} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi) (\bar{Q} \gamma^\mu \tau^I Q)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{\varphi Q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi) (\bar{Q} \gamma^\mu Q)$
$\mathcal{O}_{\varphi \square}$	$(\varphi^\dagger\varphi)\square(\varphi^\dagger\varphi)$	$\mathcal{O}_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi) (\bar{t} \gamma^\mu t)$
		$\mathcal{O}_{\varphi tb}$	$i(\tilde{\varphi} D_\mu \varphi) (\bar{t} \gamma^\mu b) + \text{h.c.}$

Yukawa

weak
dipoles

currents

RHCC

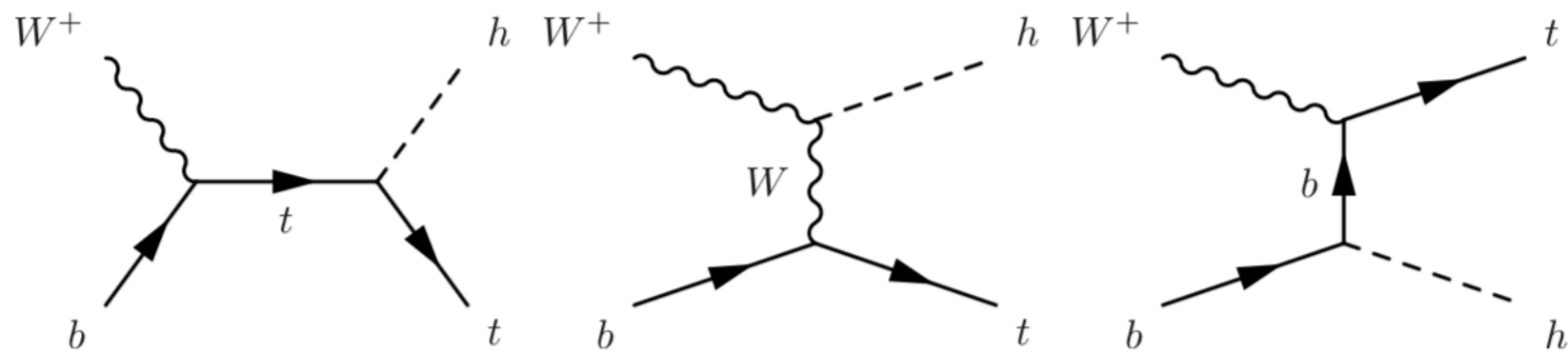
Relevant dim-6 operators for EW-top scattering

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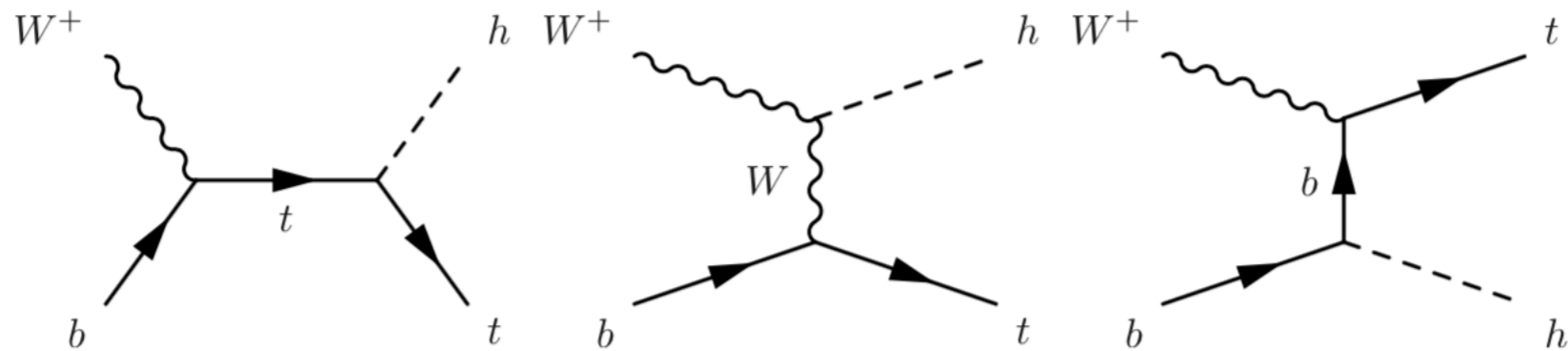
[Aguilar-Saavedra et al.; arXiv:1802.07237]

Anomalous $bW^+ \rightarrow tH$

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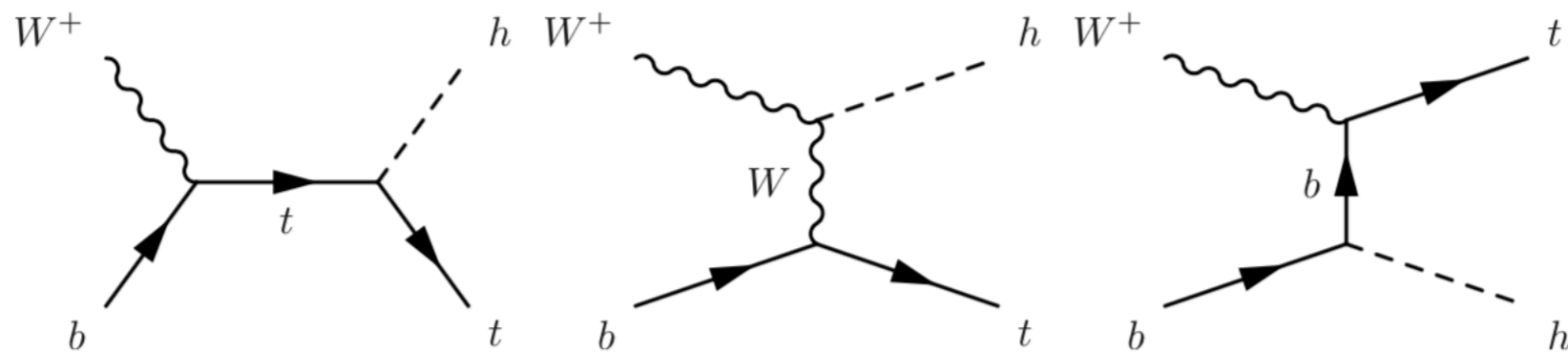


Anomalous $bW^+ \rightarrow tH$



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

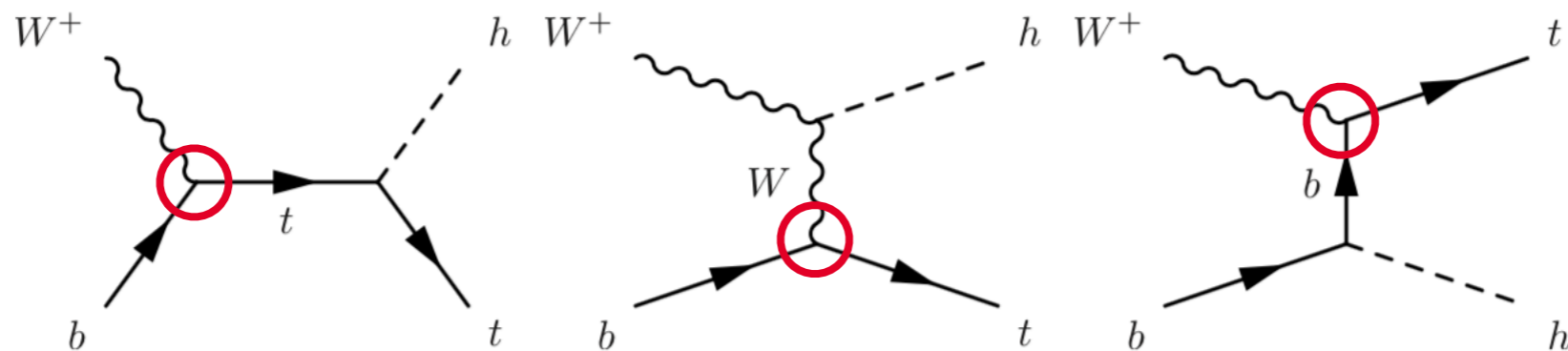
Anomalous $bW^+ \rightarrow tH$



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

Anomalous interactions:

Anomalous $bW^+ \rightarrow tH$

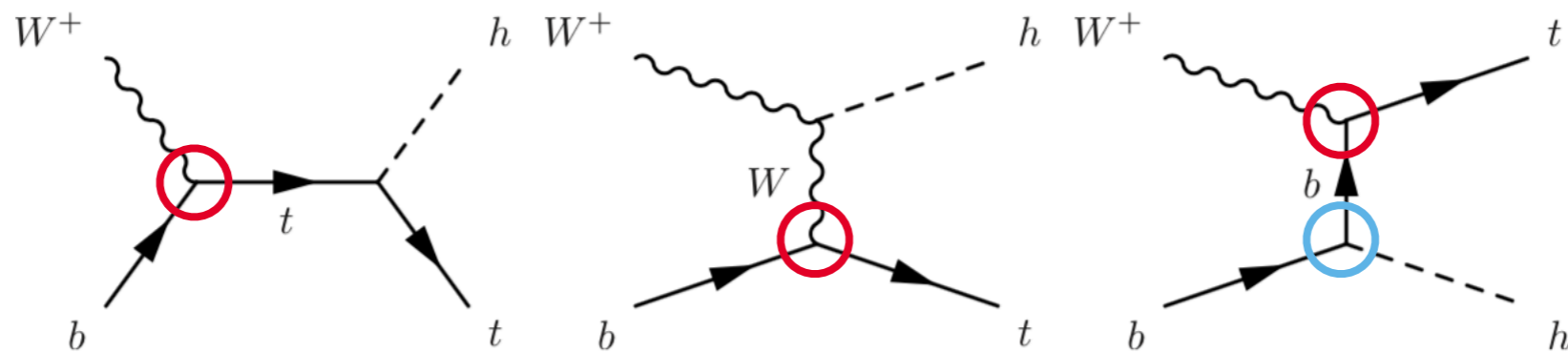


SM: **left-handed** (t_L, b_L), **longitudinal** W configuration $\sim E^0$

Anomalous interactions:

- tbW vertex: present in all diagrams \rightarrow overall rescaling $\sim E^0$

Anomalous $bW^+ \rightarrow tH$

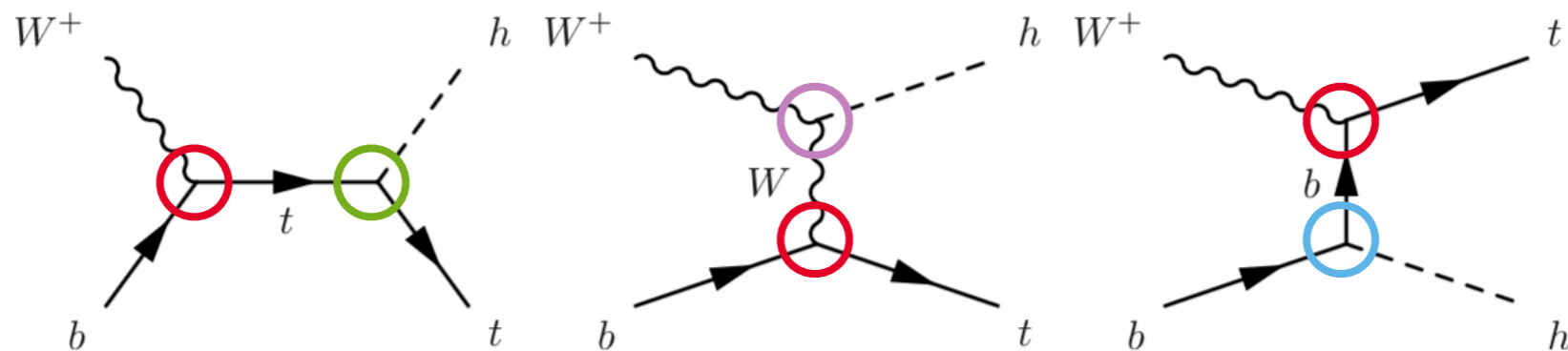


SM: **left-handed** (t_L, b_L), **longitudinal** W configuration $\sim E^0$

Anomalous interactions:

- tbW vertex: present in all diagrams \rightarrow overall rescaling $\sim E^0$
- bbH vertex: $\propto m_b \rightarrow 0$

Anomalous $bW^+ \rightarrow tH$

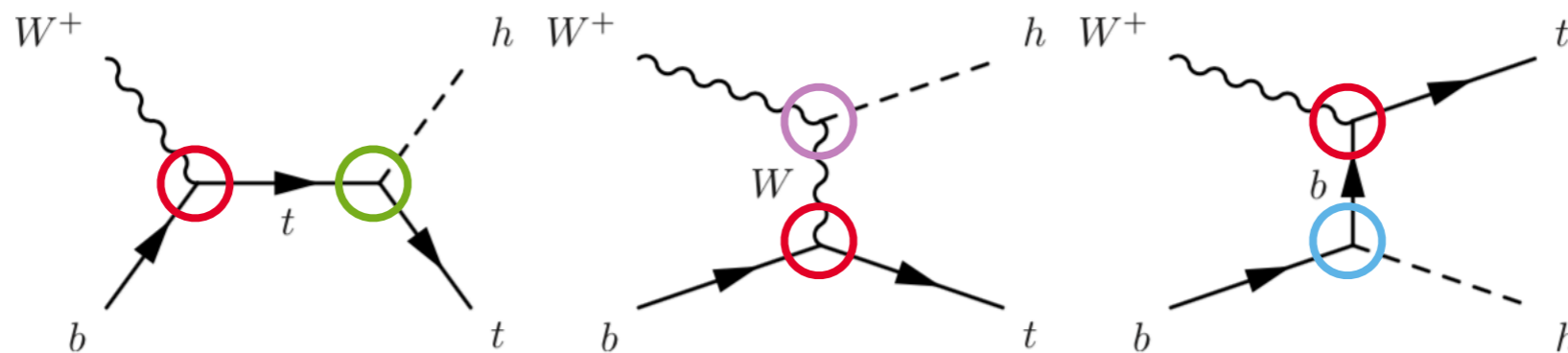


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Anomalous interactions:

- tbW vertex: present in all diagrams \rightarrow overall rescaling $\sim E^0$
- bbH vertex: $\propto m_b \rightarrow 0$
- HWW & ttH interactions: participate in a unitarity cancellation $\sim v E$

Anomalous $bW^+ \rightarrow tH$



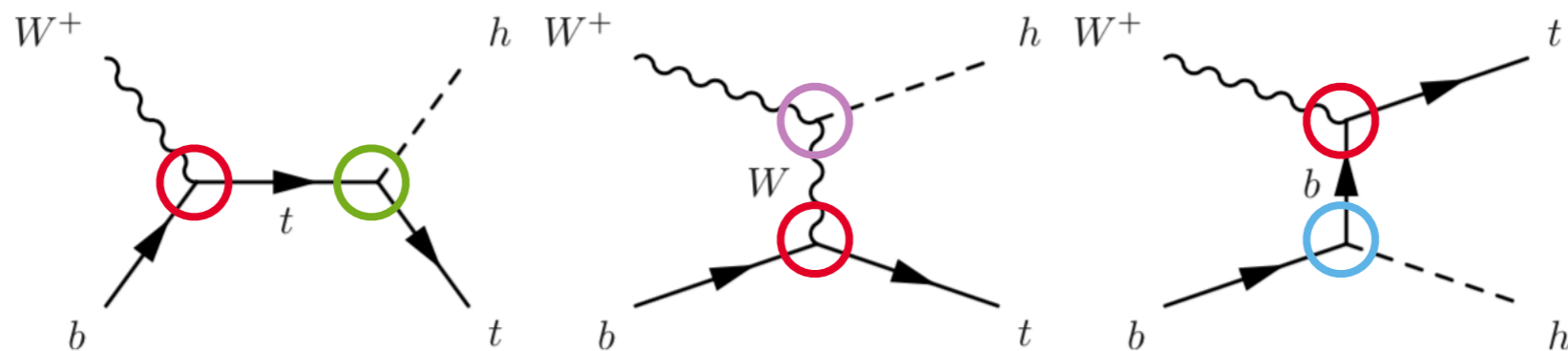
SM: **left-handed** (t_L, b_L), **longitudinal** W configuration $\sim E^0$

Anomalous interactions:

- tbW vertex: present in all diagrams \rightarrow overall rescaling $\sim E^0$
- bbH vertex: $\propto m_b \rightarrow 0$
- HWW & ttH interactions: participate in a unitarity cancellation $\sim v E$

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

Anomalous $bW^+ \rightarrow tH$



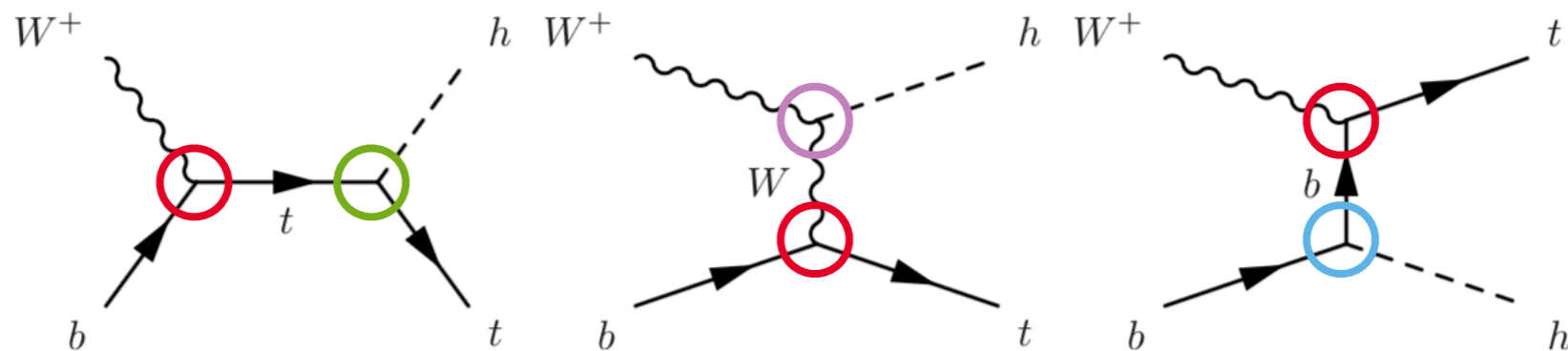
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Anomalous interactions:

- tbW vertex: present in all diagrams \rightarrow overall rescaling $\sim E^0$
- bbH vertex: $\propto m_b \rightarrow 0$
- HWW & ttH interactions: participate in a unitarity cancellation $\sim v E$

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

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

$bW^+ \rightarrow tH$ 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	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

$bW^+ \rightarrow tH$ 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}	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	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

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, +	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	-	-	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-t}m_t$
+, 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}	$\mathcal{O}_{\varphi Q}^{(3)}$
- , 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	-	-	-
+ , + , +	-	-	$\sqrt{-t}m_W$	-	-	-

W_L ←

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}	$\mathcal{O}_{\varphi Q}^{(3)}$
- , 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	-	-	-
+ , +, +	-	-	$\sqrt{-t}m_W$	-	-	-

W_L ← (rows 1-4)
W_T ← (rows 5-12)

$bW^+ \rightarrow tH$ 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}	$\mathcal{O}_{\varphi Q}^{(3)}$
$-, 0, -$	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

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

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, +	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	-	-	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-tm_t}$
+, 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	-	-	-
+, +, +	-	-	$\sqrt{-tm_W}$	-	-	-

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}	$\mathcal{O}_{\varphi Q}^{(3)}$
-, 0, -	s^0	s^0	-	s^0	s^0	$\sqrt{s(s+t)}$
-, 0, +	$\frac{1}{\sqrt{s}}$	$\sqrt{-t}v$	-	-	$\frac{sm_W}{\sqrt{-t}}$	$\sqrt{-tm_t}$
+, 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	-	-	-
+, +, +	-	-	$\sqrt{-tm_W}$	-	-	-

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}	$\mathcal{O}_{\varphi Q}^{(3)}$
−, 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

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	-	-	-
+ , +, +	-	-	$\sqrt{-t}m_W$	-	-	-

$\propto m_b$ ←

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

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}	$\mathcal{O}_{\varphi Q}^{(3)}$
−, 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

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}	$\mathcal{O}_{\varphi Q}^{(3)}$
← 9th $- , 0 , -$	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}	$\mathcal{O}_{\varphi Q}^{(3)}$
-, 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	-	-	-
+, +, +	-	-	$\sqrt{-t}m_W$	-	-	-

$bW^+ \rightarrow tH$ 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	$-$	$-$	$-$
$+, +, +$	$-$	$-$	$\sqrt{-t}m_W$	$-$	$-$	$-$

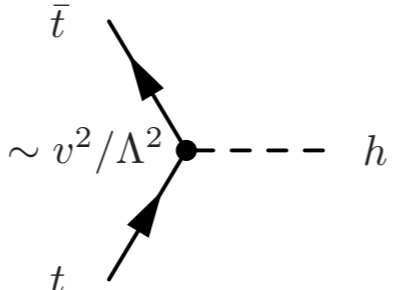
$bW^+ \rightarrow tH$ in SMEFT

Energy growth from EFT-modified SM interactions

$bW^+ \rightarrow tH$ in SMEFT

Energy growth from EFT-modified SM interactions

- Yukawa operator: disconnects **kinematical** mass from **coupling to Higgs**

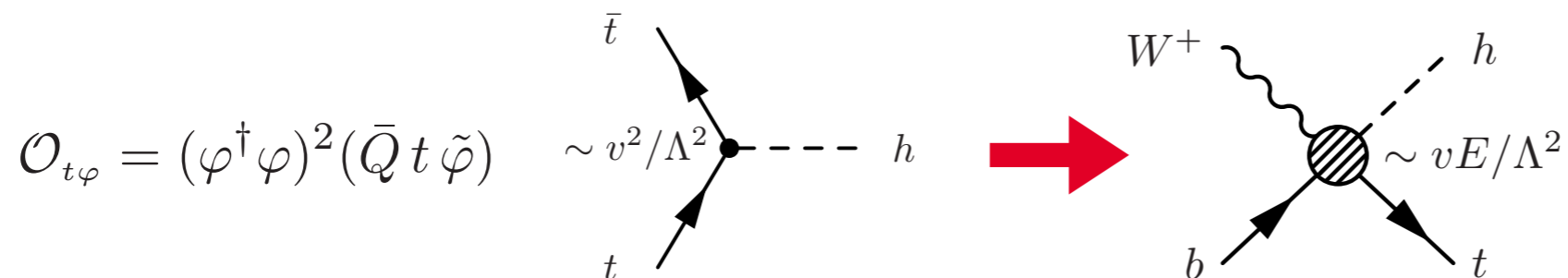
$$\mathcal{O}_{t\varphi} = (\varphi^\dagger \varphi)^2 (\bar{Q} t \tilde{\varphi}) \quad \sim v^2/\Lambda^2$$


The diagram illustrates a vertex where a top quark (t) and an anti-top quark (\bar{t}) meet. A dashed line representing a Higgs boson (h) extends from the vertex. The vertex is labeled with the expression $\sim v^2/\Lambda^2$.

$bW^+ \rightarrow tH$ in SMEFT

Energy growth from EFT-modified SM interactions

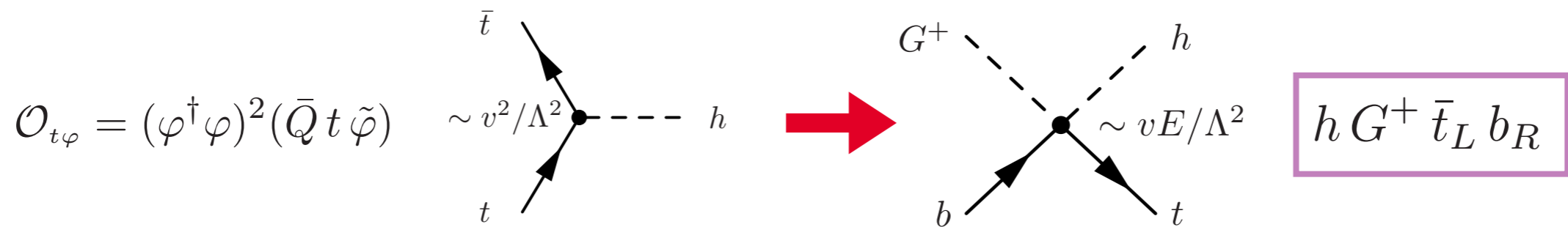
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$bW^+ \rightarrow tH$ in SMEFT

Energy growth from EFT-modified SM interactions

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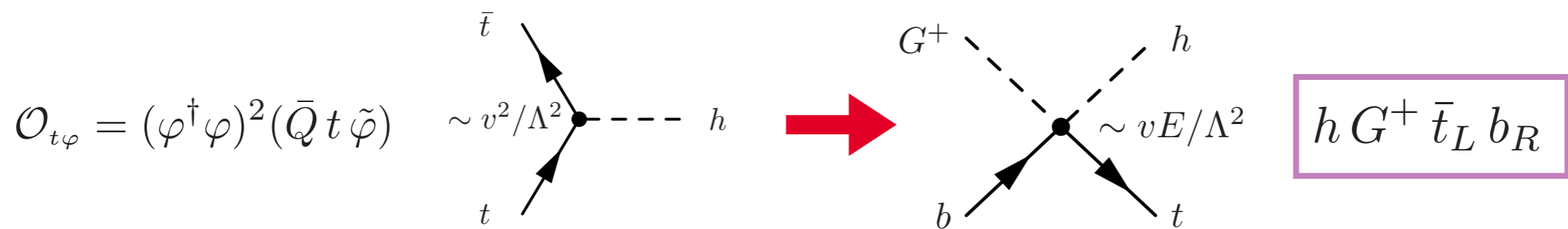


- ‘Unitarity cancellation’ **OR** dim-5 **contact-interaction** w/ charged Goldstone

bW⁺ → tH in SMEFT

Energy growth from EFT-modified SM interactions

- Yukawa operator: disconnects **kinematical** mass from **coupling to Higgs**



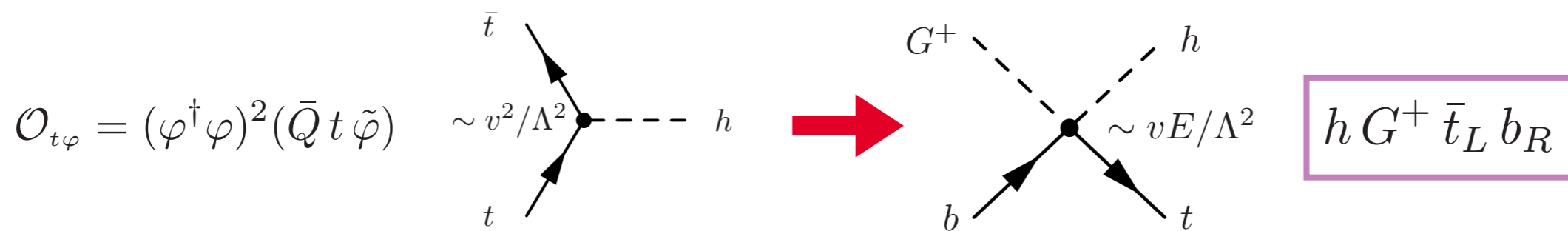
- ‘Unitarity cancellation’ **OR** dim-5 **contact-interaction** w/ charged Goldstone

Max growth from dim-6 contact-terms

bW⁺ → tH in SMEFT

Energy growth from EFT-modified SM interactions

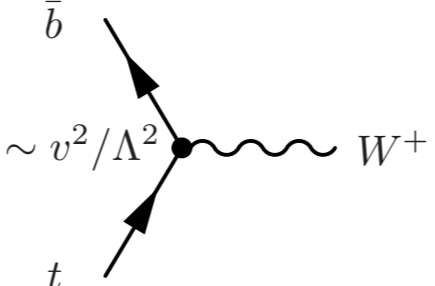
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Max growth from dim-6 contact-terms

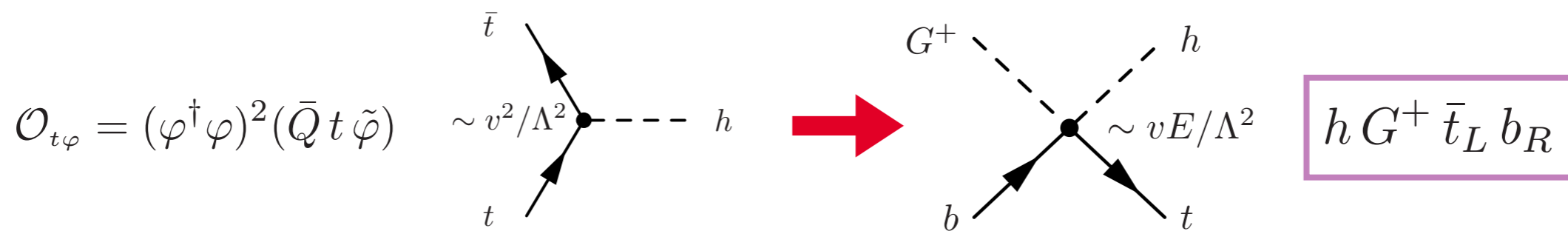
$$\mathcal{O}_{\varphi Q}^{(3)} = i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{Q} \gamma^\mu \tau_I Q)$$

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


bW⁺ → tH in SMEFT

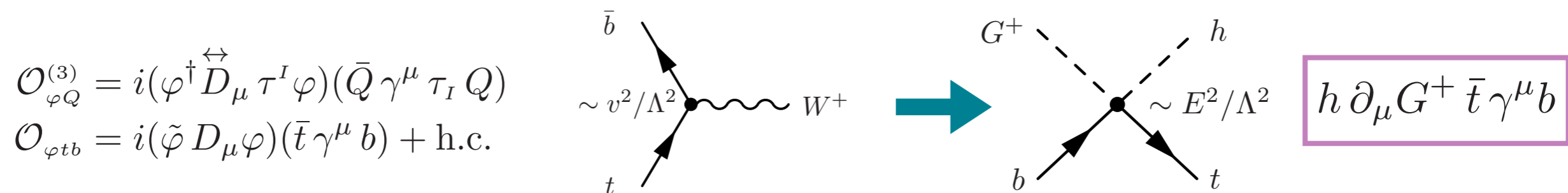
Energy growth from EFT-modified SM interactions

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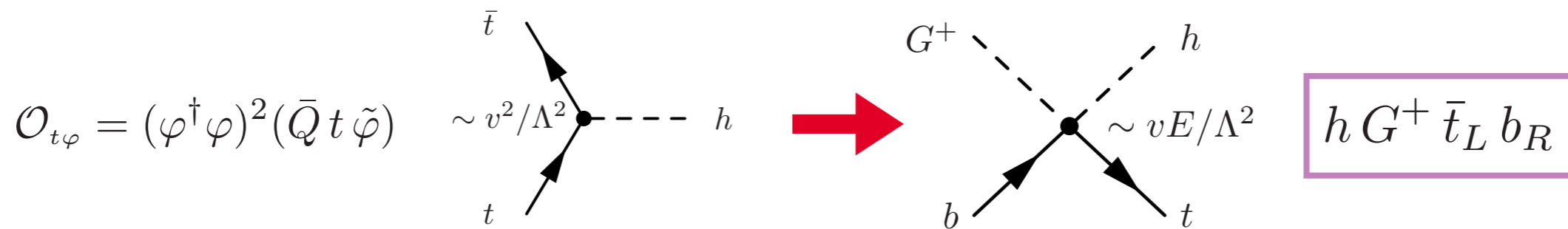
Max growth from dim-6 contact-terms



bW⁺ → tH in SMEFT

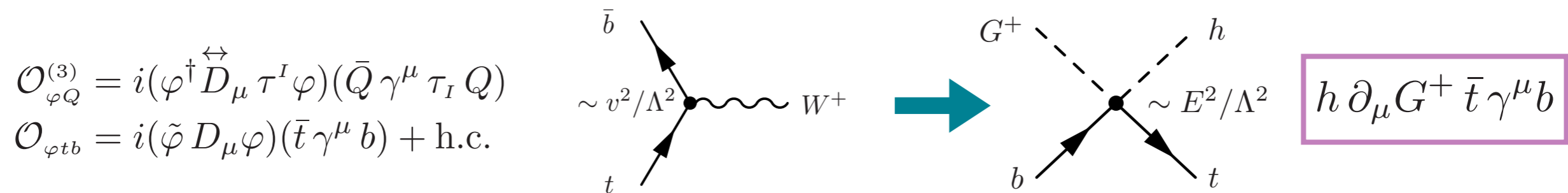
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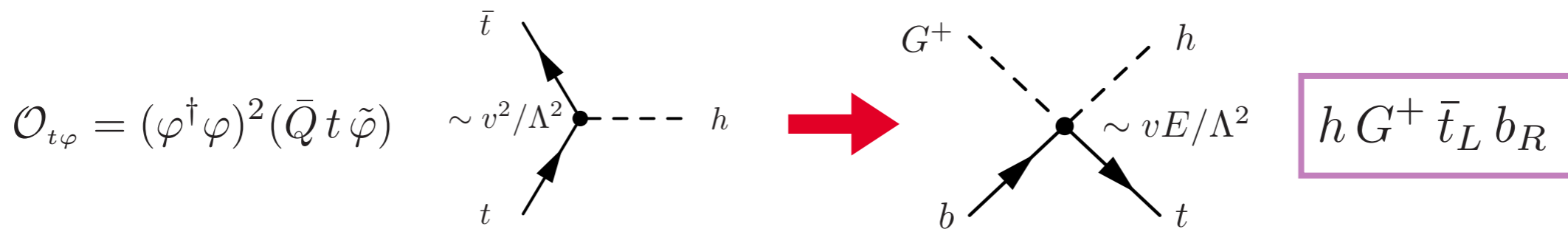


- No anomalous coupling analogues (*recall tbW vertex only rescales*)

bW⁺ → tH in SMEFT

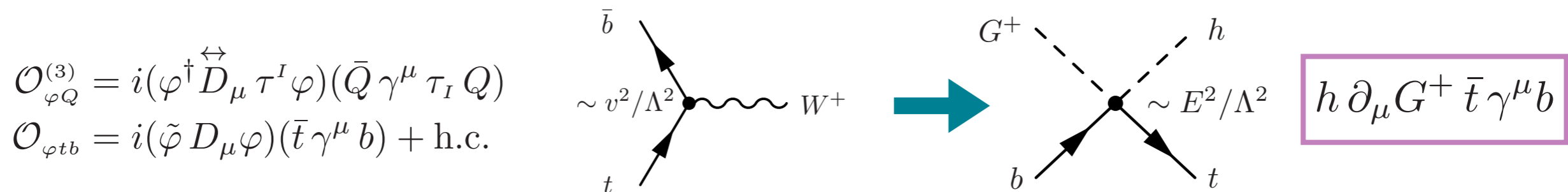
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- ‘Unitarity cancellation’ **OR** dim-5 **contact-interaction** w/ charged Goldstone

Max growth from dim-6 contact-terms



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

Contact interactions

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Guess E-growth by inspecting higher dim. **contact terms**

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- $2 \rightarrow N$ scattering has mass dimension $2 - N$

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- Every **longitudinal** external vector, V , can contribute a factor $E/M_V(n)$

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- Every **longitudinal** external vector, V , can contribute a factor E/M_V (n)

$$\mathcal{M}_{2 \rightarrow N} \propto \frac{v^m}{\Lambda^{K-4}} \frac{E^{K-N-m-2+n}}{M_V^n}$$

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

Contact interactions

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Only constraint is SM gauge invariance

Contact interactions

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- 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)

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

Only constraint is SM gauge invariance

- Connects contact to lower point interactions via, e.g., field strengths

Contact interactions

Guess E-growth by inspecting higher dim. **contact terms**

- $2 \rightarrow N$ scattering has mass dimension $2 - N$
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- SMEFT: max. growth **relative to the SM** is bounded by operator dimension

Contact interactions

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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

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

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \square}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	\mathcal{O}_W	$\mathcal{O}_{t\varphi}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \rightarrow tW$	E	E	—	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \rightarrow tZ$	E	E	E	E	E	—	E	E^2	E^2	E	E	E
$tZ \rightarrow t\gamma$	—	—	E	E	E	—	—	E^2	E^2	—	—	—
$t\gamma \rightarrow t\gamma$	—	—	E	E	E	—	—	E	E	—	—	—

*two-top
w/o Higgs*

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \square}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	\mathcal{O}_W	$\mathcal{O}_{t\varphi}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \rightarrow th$	E	—	E	E	E	—	E	E^2	E^2	E^2	E^2	E^2	—
$t\gamma \rightarrow th$	—	—	E	E	E	—	—	E^2	E^2	—	—	—	—
$th \rightarrow th$	E	E	—	—	—	—	E	—	—	—	—	—	—

*two-top
w/ Higgs*

Summary: max growths

gauge/higgs operators $\Leftarrow \Rightarrow$ *top operators*

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

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \square}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	\mathcal{O}_W	$\mathcal{O}_{t\varphi}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \rightarrow tW$	E	E	—	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \rightarrow tZ$	E	E	E	E	E	—	E	E^2	E^2	E	E	E
$tZ \rightarrow t\gamma$	—	—	E	E	E	—	—	E^2	E^2	—	—	—
$t\gamma \rightarrow t\gamma$	—	—	E	E	E	—	—	E	E	—	—	—

*two-top
w/o Higgs*

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \square}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	\mathcal{O}_W	$\mathcal{O}_{t\varphi}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \rightarrow th$	E	—	E	E	E	—	E	E^2	E^2	E^2	E^2	E^2	—
$t\gamma \rightarrow th$	—	—	E	E	E	—	—	E^2	E^2	—	—	—	—
$th \rightarrow th$	E	E	—	—	—	—	E	—	—	—	—	—	—

*two-top
w/ Higgs*

Summary: max growths

gauge/higgs operators $\Leftarrow \Rightarrow$ *top operators*

Energy-growing
interference

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

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \square}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	\mathcal{O}_W	$\mathcal{O}_{t\varphi}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \rightarrow tW$	E	E	—	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \rightarrow tZ$	E	E	E	E	E	—	E	E^2	E^2	E	E	E
$tZ \rightarrow t\gamma$	—	—	E	E	E	—	—	E^2	E^2	—	—	—
$t\gamma \rightarrow t\gamma$	—	—	E	E	E	—	—	E	E	—	—	—

*two-top
w/o Higgs*

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \square}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	\mathcal{O}_W	$\mathcal{O}_{t\varphi}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \rightarrow th$	E	—	E	E	E	—	E	E^2	E^2	E^2	E^2	E^2	—
$t\gamma \rightarrow th$	—	—	E	E	E	—	—	E^2	E^2	—	—	—	—
$th \rightarrow th$	E	E	—	—	—	—	E	—	—	—	—	—	—

*two-top
w/ Higgs*

Summary: max growths

gauge/higgs operators $\Leftarrow \Rightarrow$ top operators

Energy-growing interference

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

single-top

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \square}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	\mathcal{O}_W	$\mathcal{O}_{t\varphi}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$
$tW \rightarrow tW$	E	E	—	E	E	E^2	E	E	E^2	E^2	E^2	E^2
$tZ \rightarrow tZ$	E	E	E	E	E	—	E	E^2	E^2	E	E	E
$tZ \rightarrow t\gamma$	—	—	E	E	E	—	—	E^2	E^2	—	—	—
$t\gamma \rightarrow t\gamma$	—	—	E	E	E	—	—	E	E	—	—	—

two-top w/o Higgs

	$\mathcal{O}_{\varphi D}$	$\mathcal{O}_{\varphi \square}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi WB}$	\mathcal{O}_W	$\mathcal{O}_{t\varphi}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	$\mathcal{O}_{\varphi Q}^{(1)}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi tb}$
$tZ \rightarrow th$	E	—	E	E	E	—	E	E^2	E^2	E^2	E^2	E^2	—
$t\gamma \rightarrow th$	—	—	E	E	E	—	—	E^2	E^2	—	—	—	—
$th \rightarrow th$	E	E	—	—	—	—	E	—	—	—	—	—	—

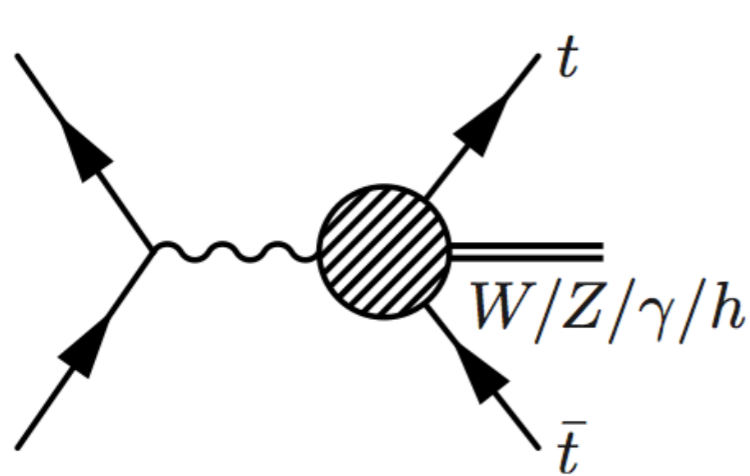
two-top w/ Higgs

Most top operators show max growth somewhere

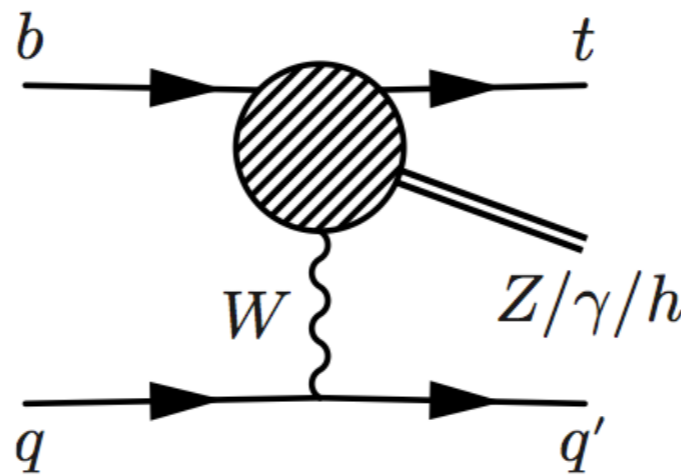
- Interfering growth **rare**, only in longitudinal configurations (c.f. helicity selection)

Embedding the amplitudes

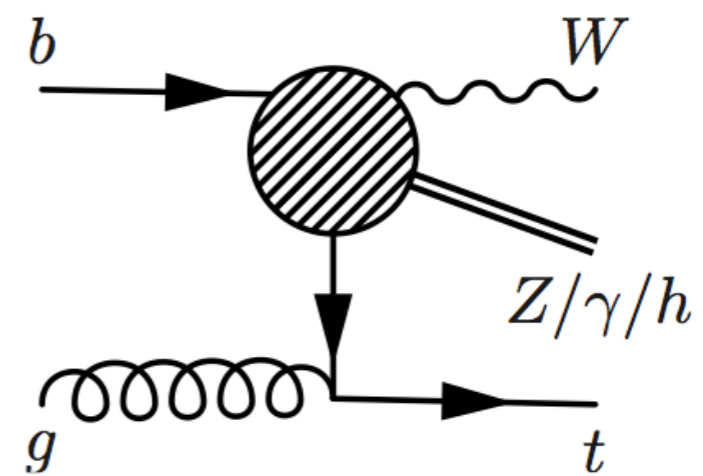
Collider processes: rare, EW top production



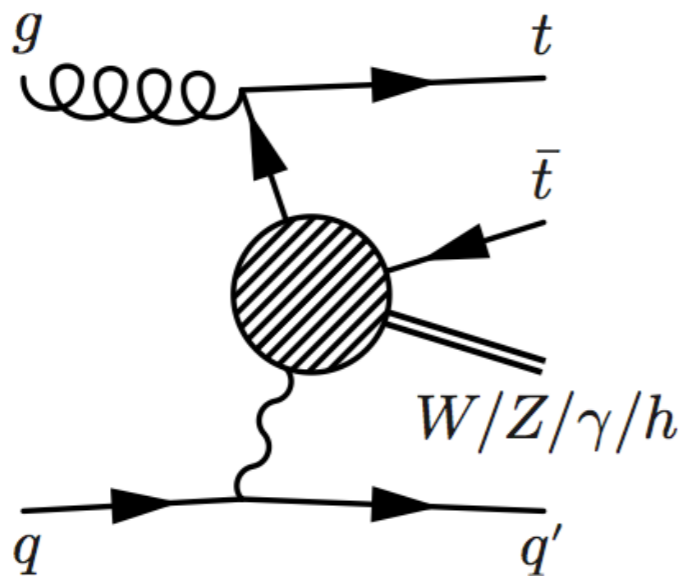
(a) $t\bar{t}X$



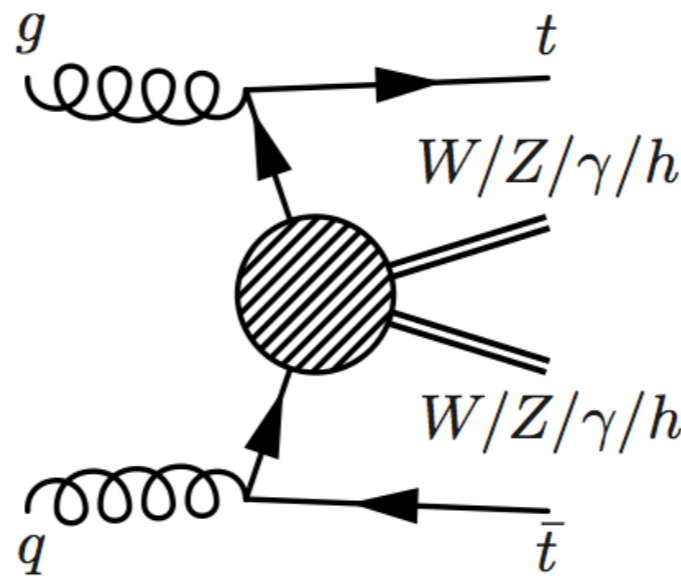
(b) tXj



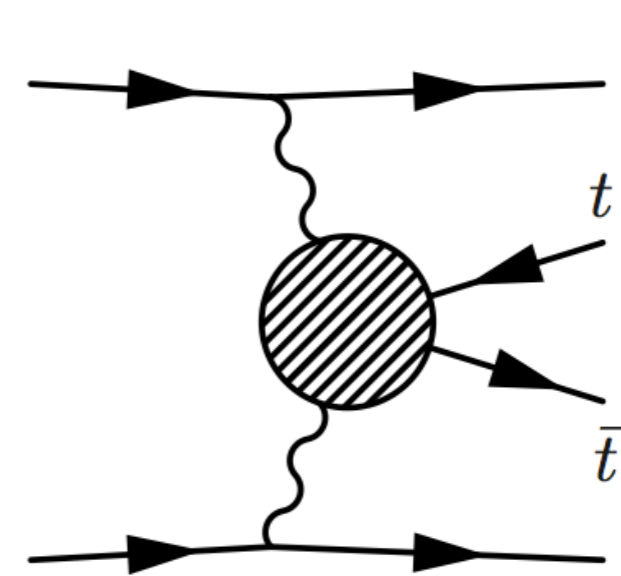
(c) tWX



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



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



(f) VBF

Embedding the amplitudes

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion

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

Embedding the amplitudes

Collection of ‘sensitivity’ studies, general discussion

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

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

Embedding the amplitudes

Collection of ‘sensitivity’ studies, general discussion

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

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

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

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion



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

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

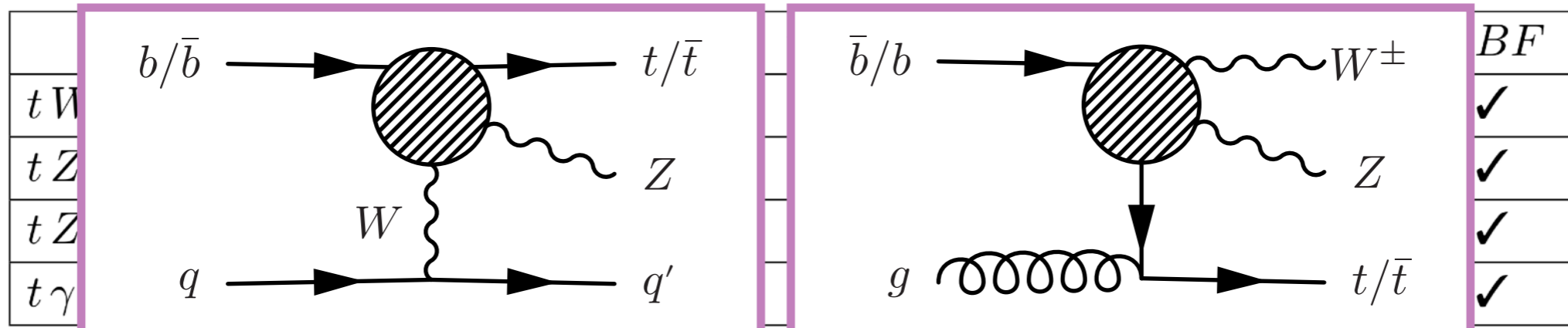
	$t\bar{t}h(j)$	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
$tZ \rightarrow th$	✓	✓		
$t\gamma \rightarrow th$	✓		✓	
$th \rightarrow th$				✓

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion



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



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

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion



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

tW		BF ✓
tZ		✓
tZ		✓
$t\gamma$		✓

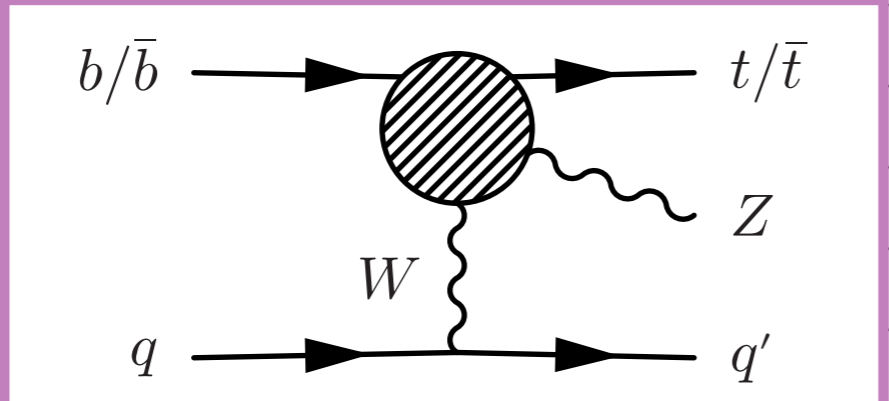
$bW \rightarrow tZ$ neutral & charged current top quark gauge interactions	$t\bar{t}Zh$	$t\bar{t}\gamma h$	$t\bar{t}hh$
	✓		
		✓	
			✓

Embedding the amplitudes

Collection of 'sensitivity' studies, general discussion



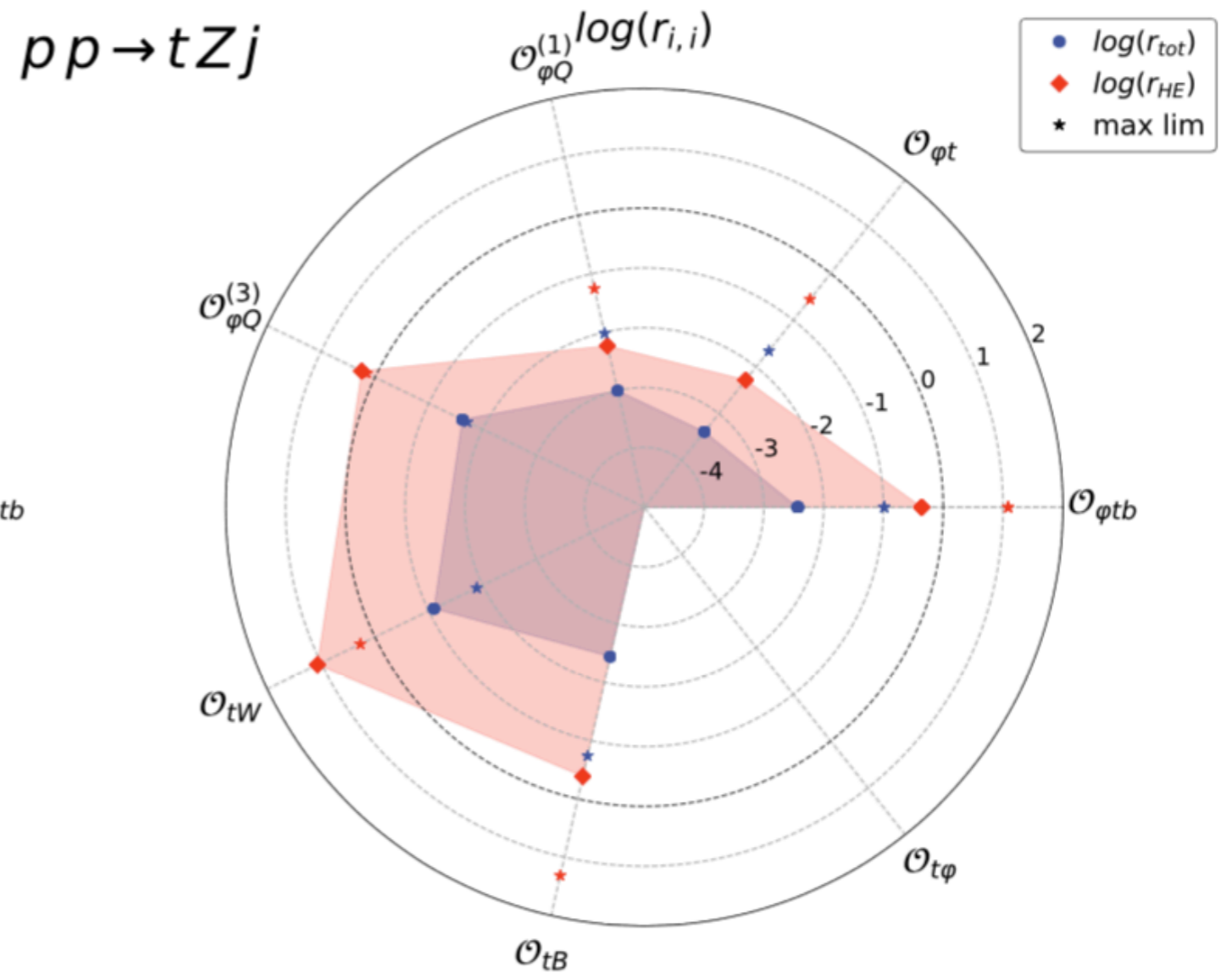
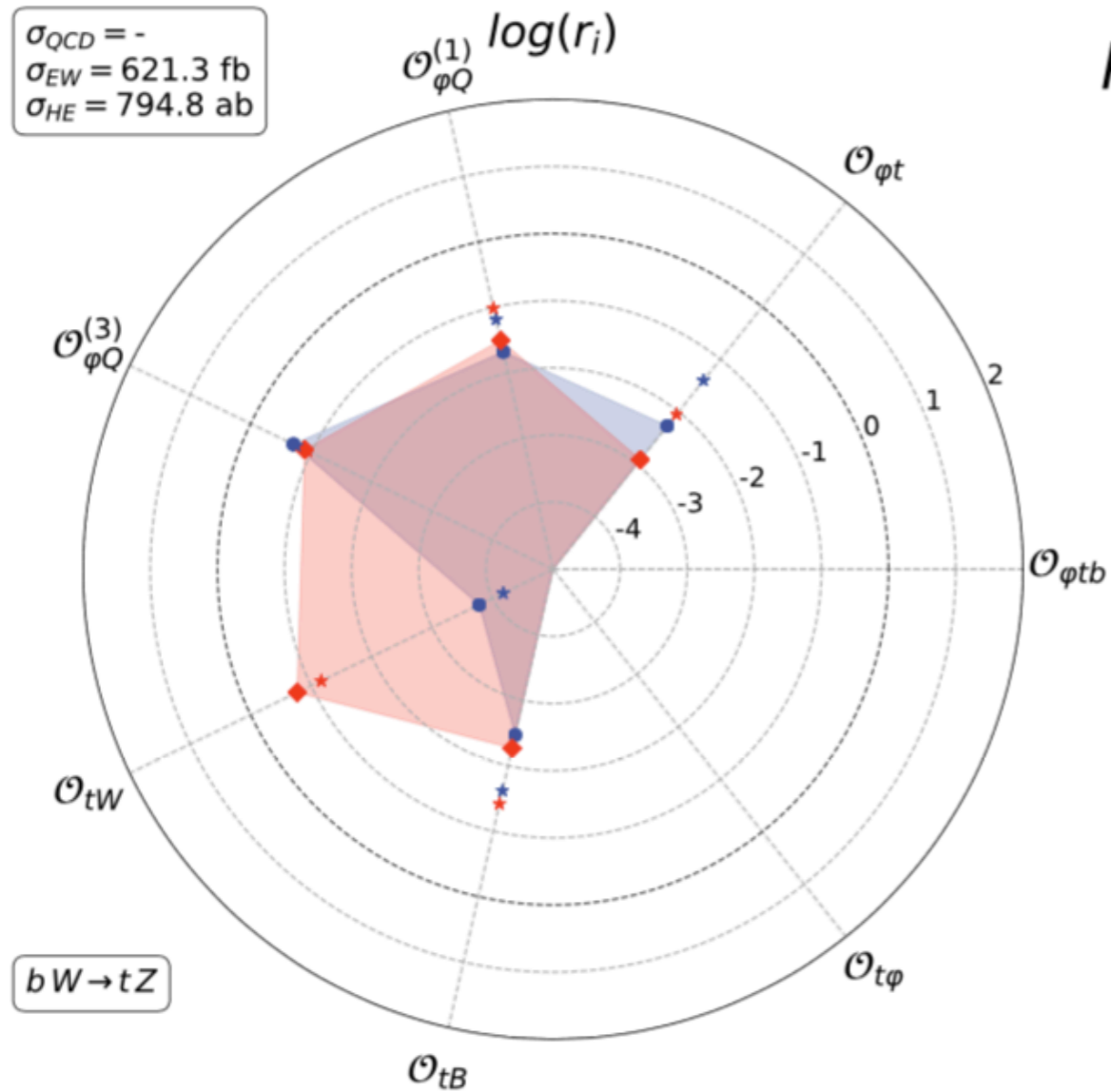
	tWj	tZj	$t\gamma j$	tWZ	$tW\gamma$	thj	thW
$bW \rightarrow tZ$	✓	✓		✓			
$bW \rightarrow t\gamma$	✓		✓		✓		
$bW \rightarrow th$						✓	✓

		
tW		BF ✓
tZ		✓
tZ		✓
$t\gamma$		✓

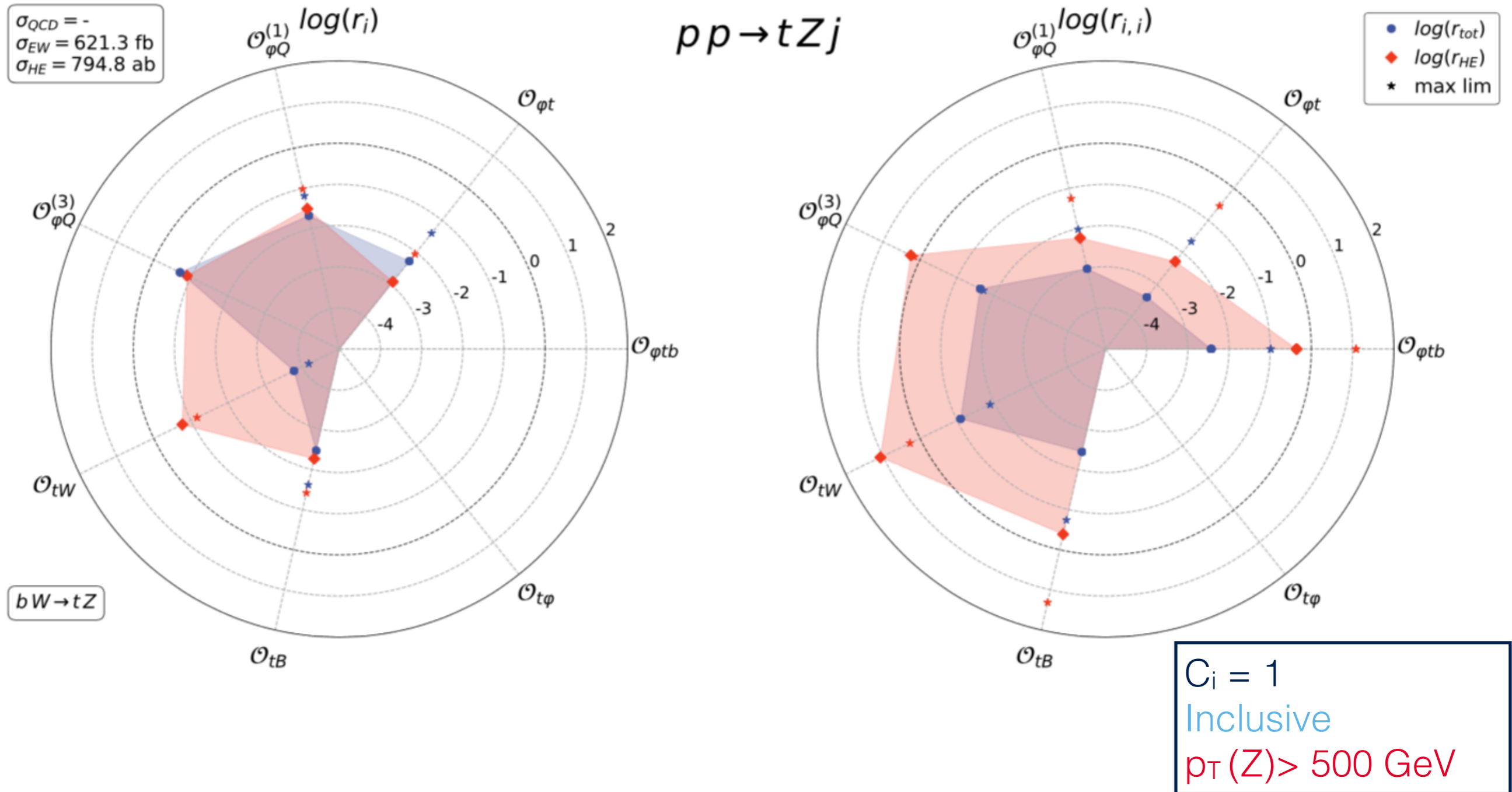
$bW \rightarrow tZ$
 neutral & charged current
 top quark gauge interactions

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

tZj total & high energy xs

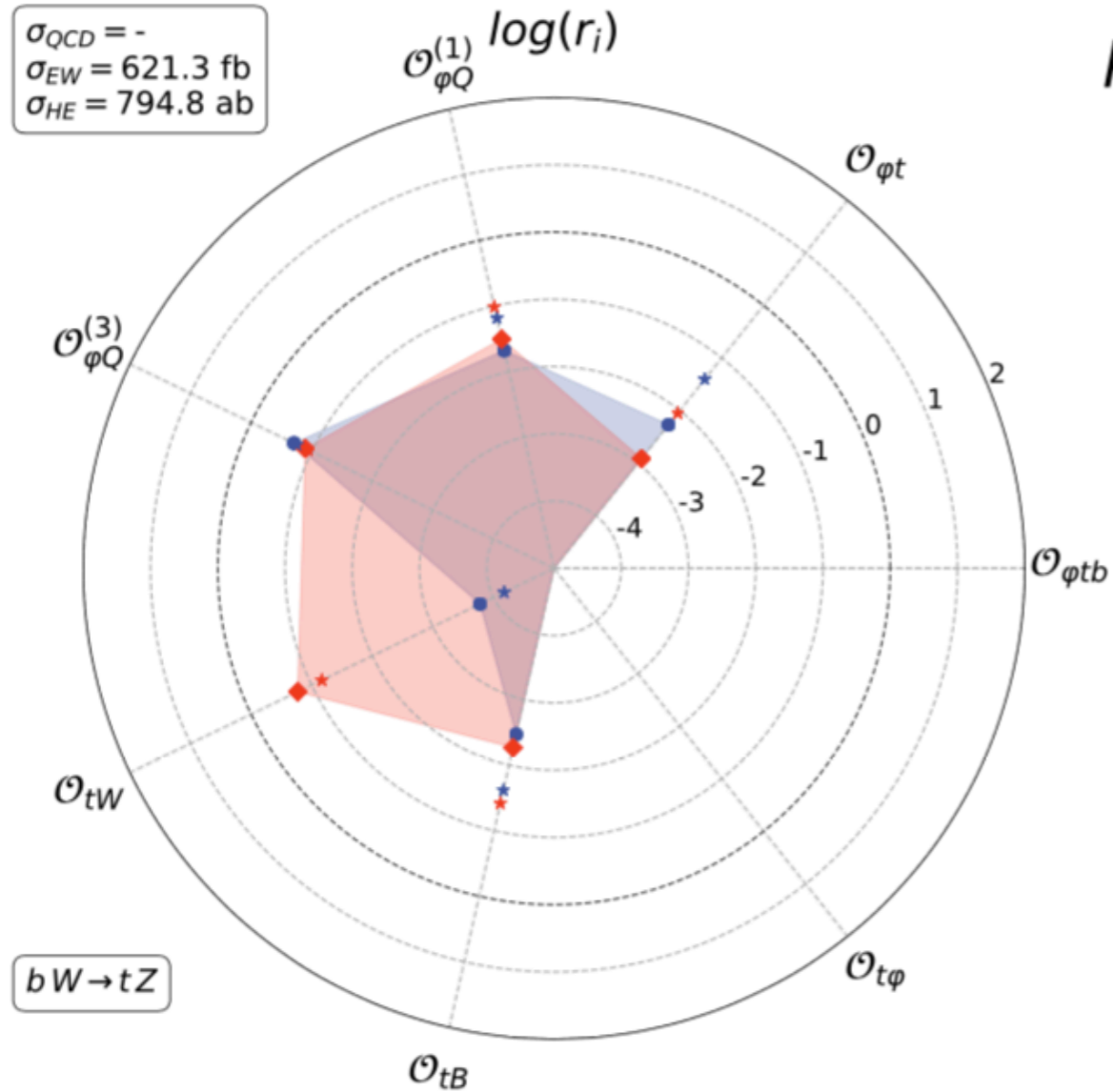


tZj total & high energy xs

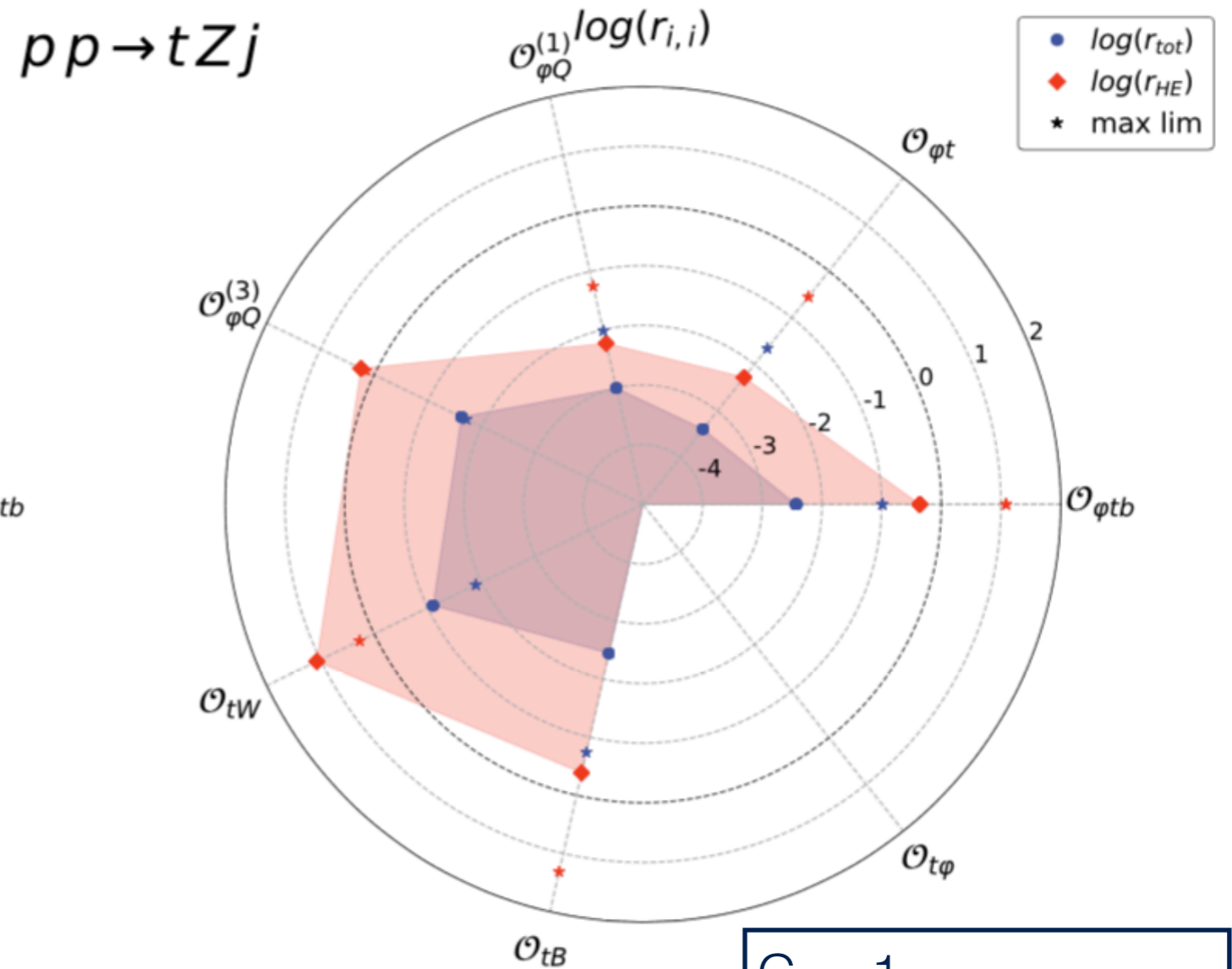


tZj total & high energy xs

interference/SM



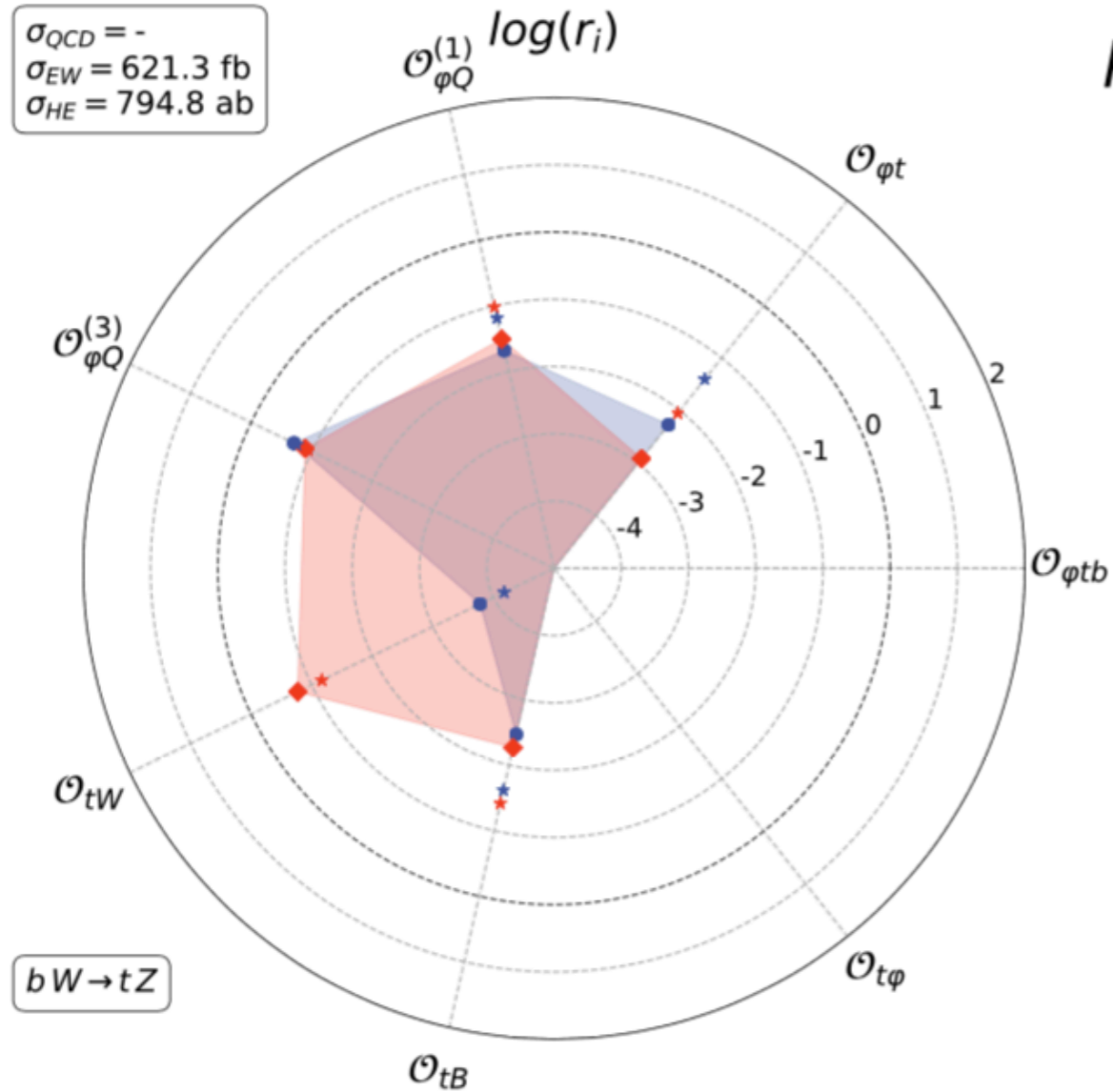
square/SM



$C_i = 1$
 Inclusive
 $p_T(Z) > 500 \text{ GeV}$

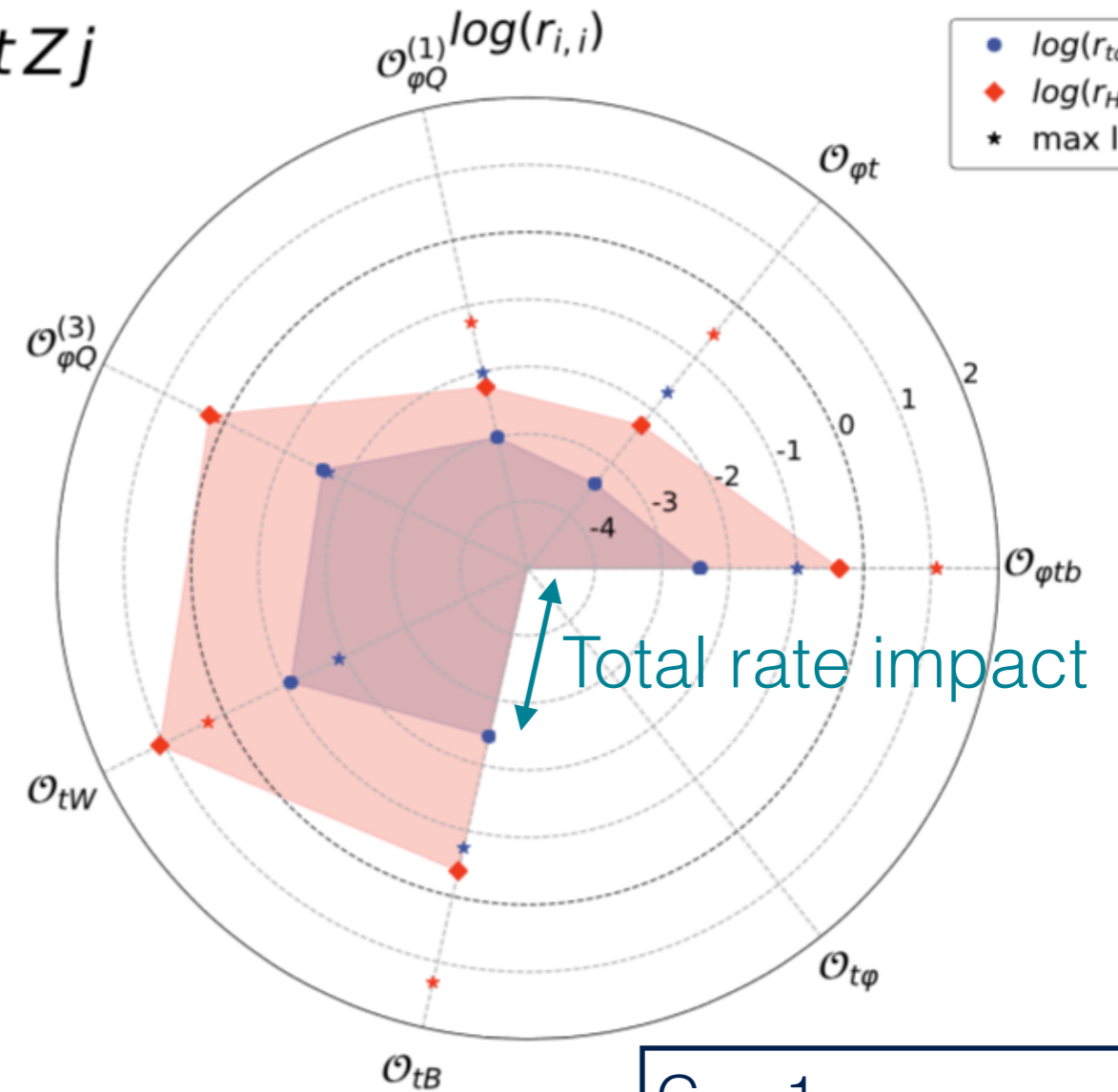
tZj total & high energy xs

interference/SM



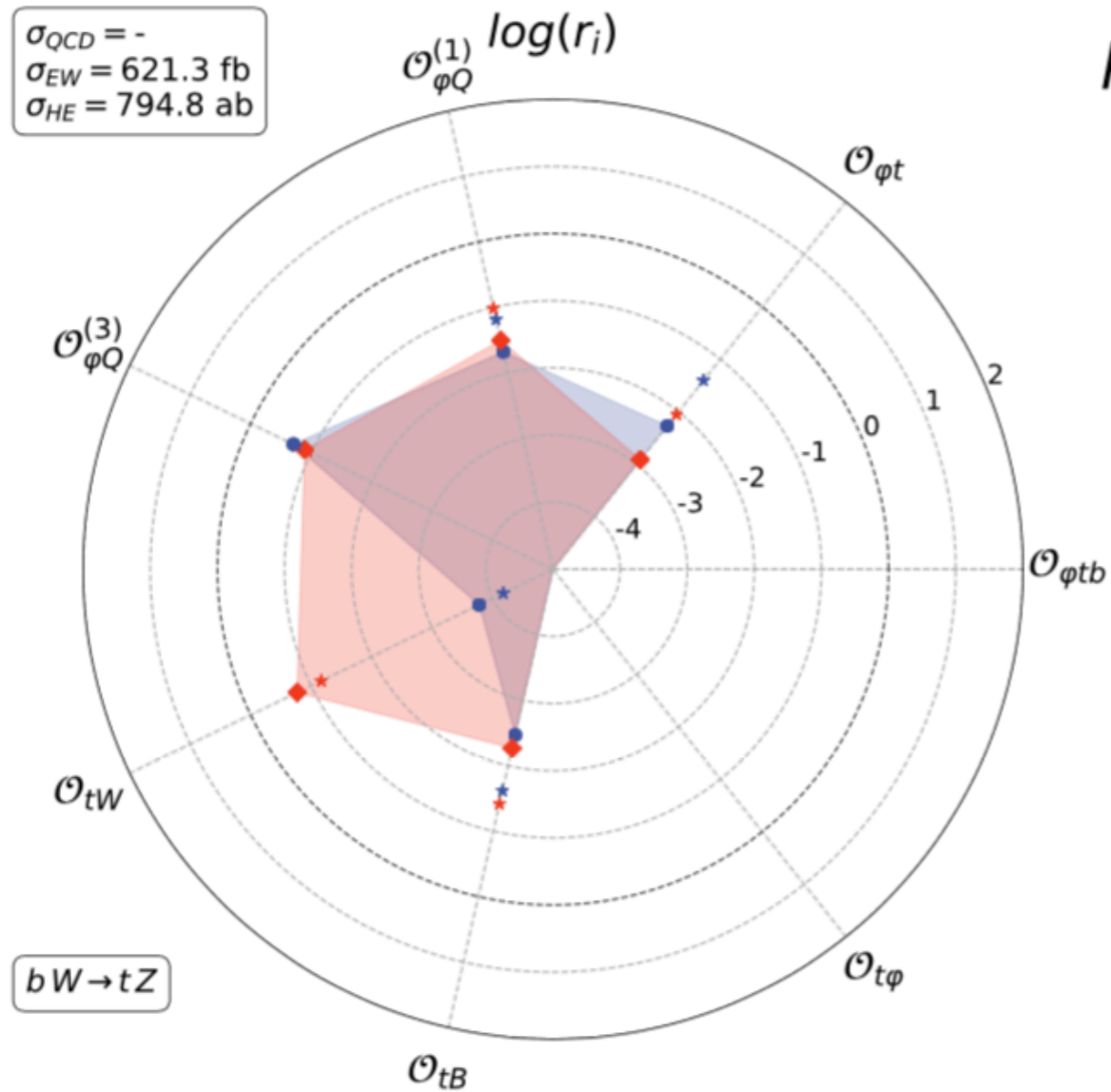
square/SM

$pp \rightarrow tZj$



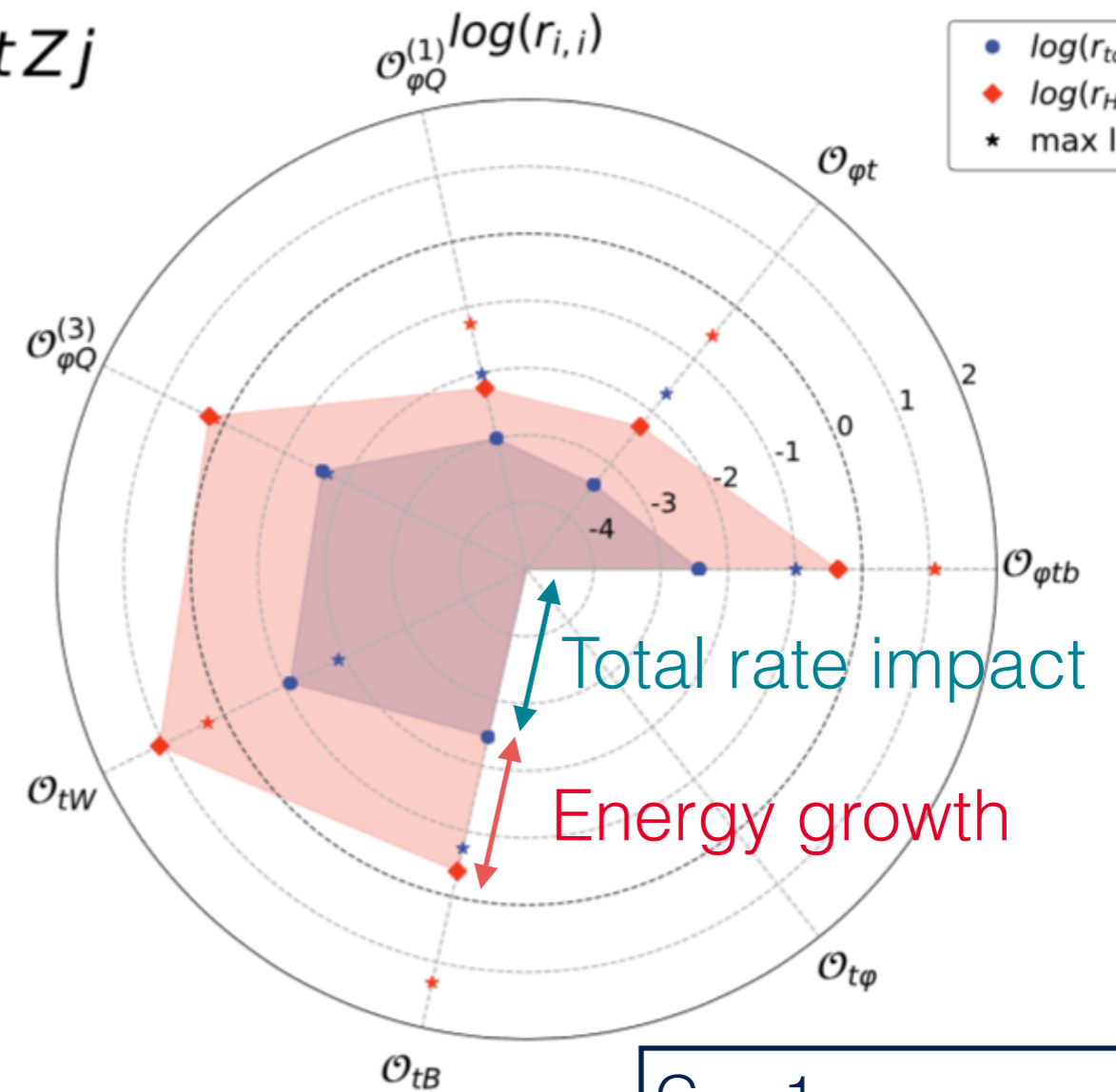
tZj total & high energy xs

interference/SM



square/SM

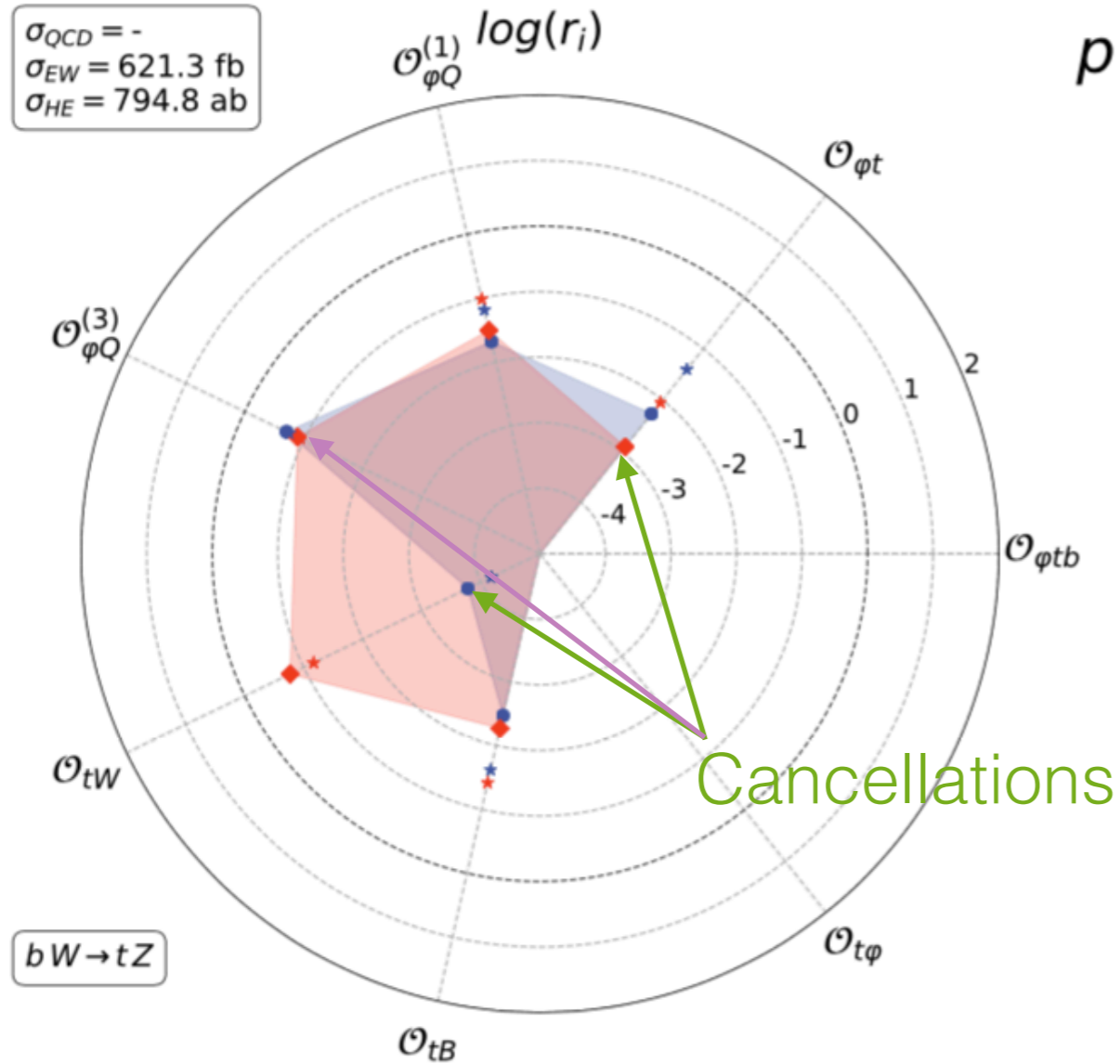
$pp \rightarrow tZj$



$C_i = 1$
 Inclusive
 $p_T(Z) > 500 \text{ GeV}$

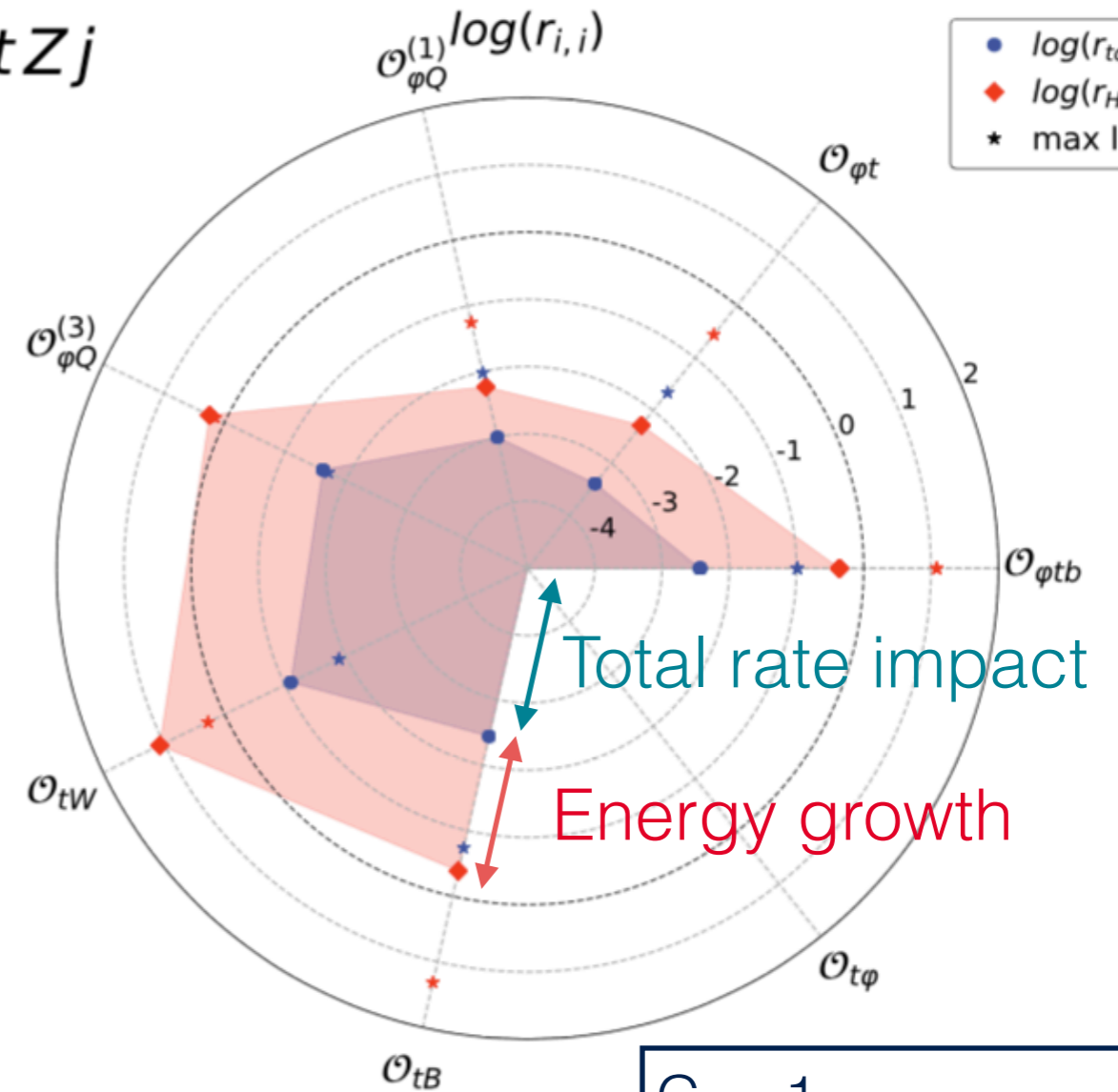
tZj total & high energy xs

interference/SM



square/SM

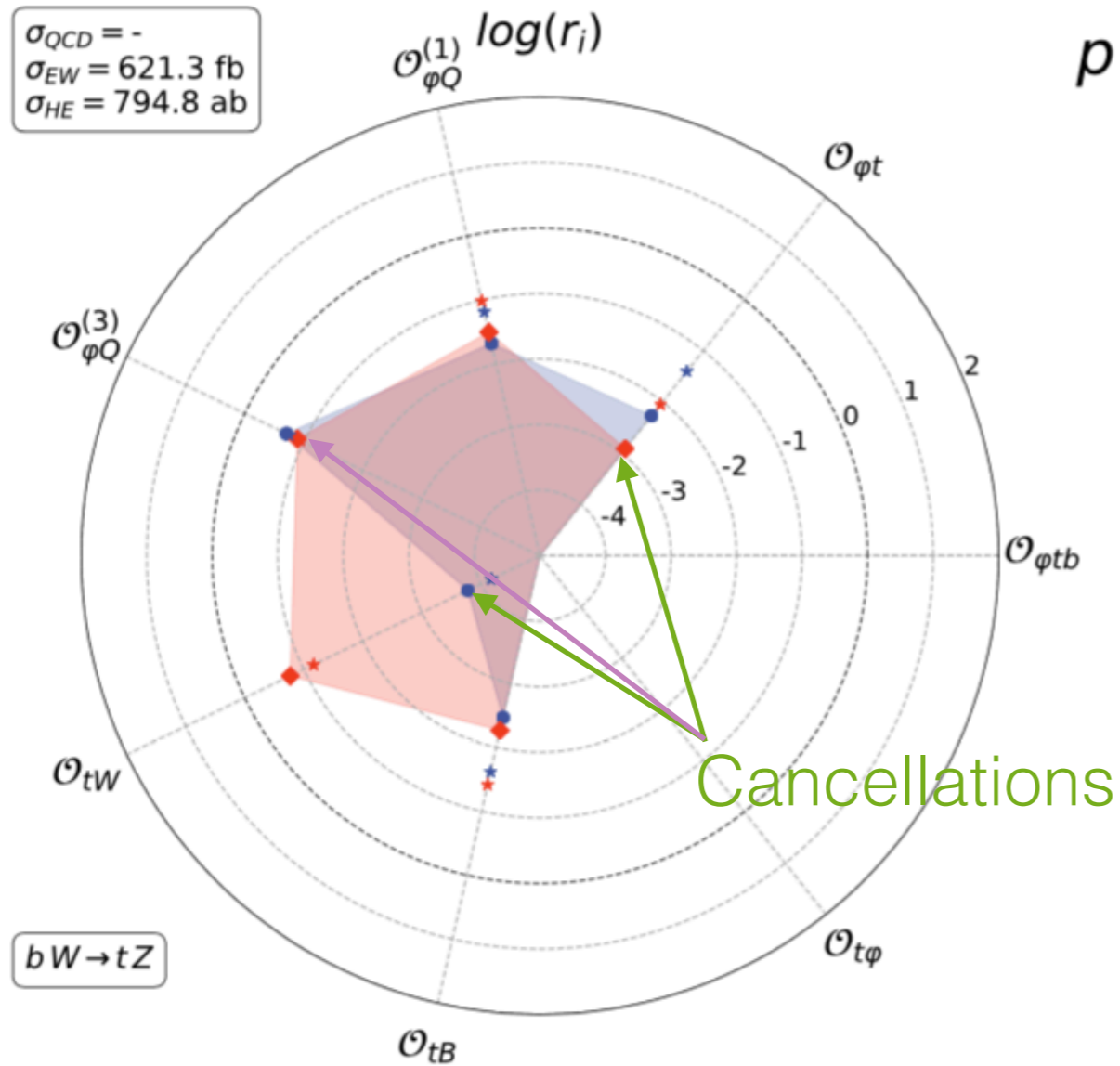
$pp \rightarrow tZj$



$C_i = 1$
 Inclusive
 $p_T(Z) > 500 \text{ GeV}$

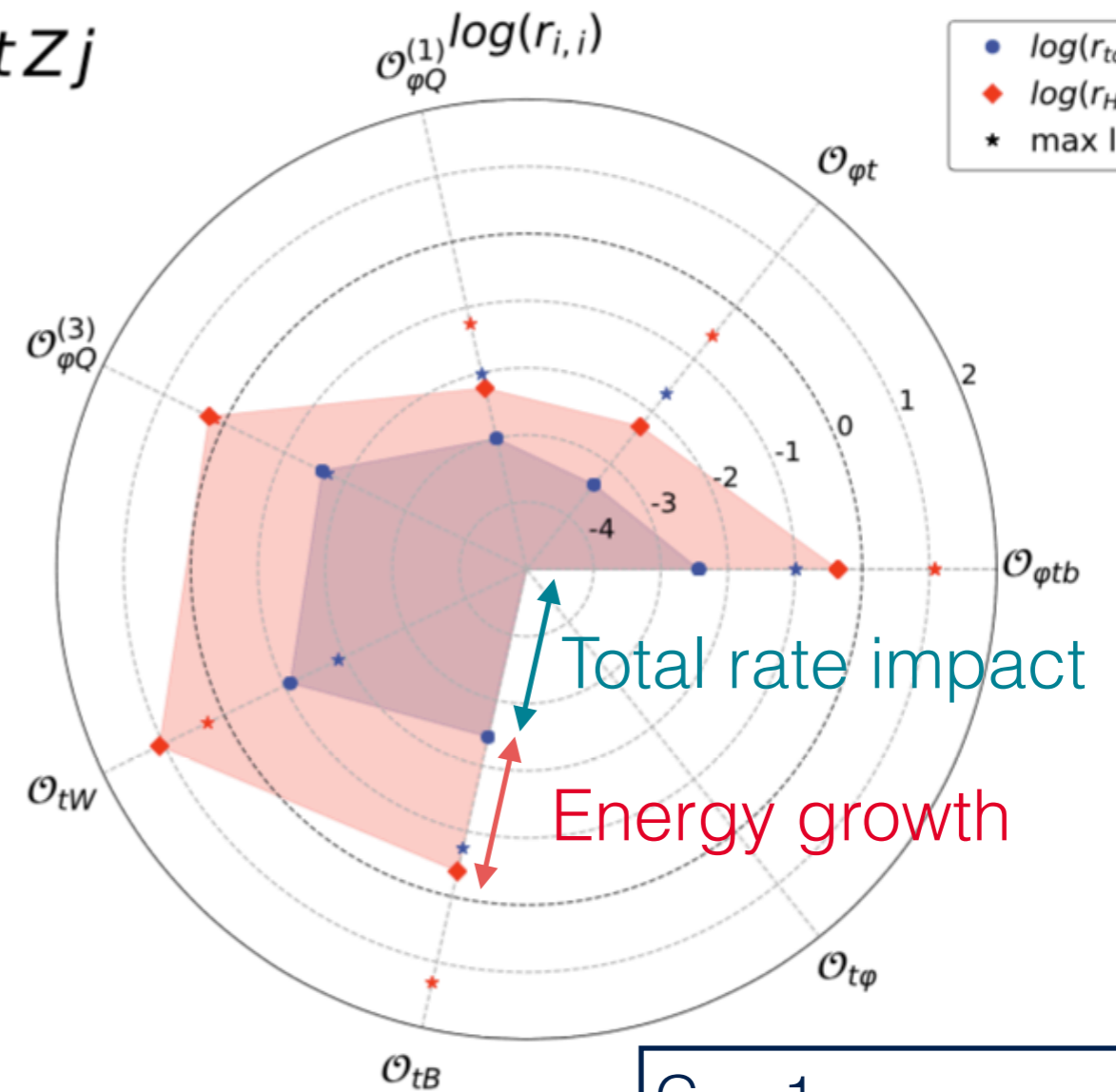
tZj total & high energy xs

interference/SM



square/SM

$pp \rightarrow tZj$

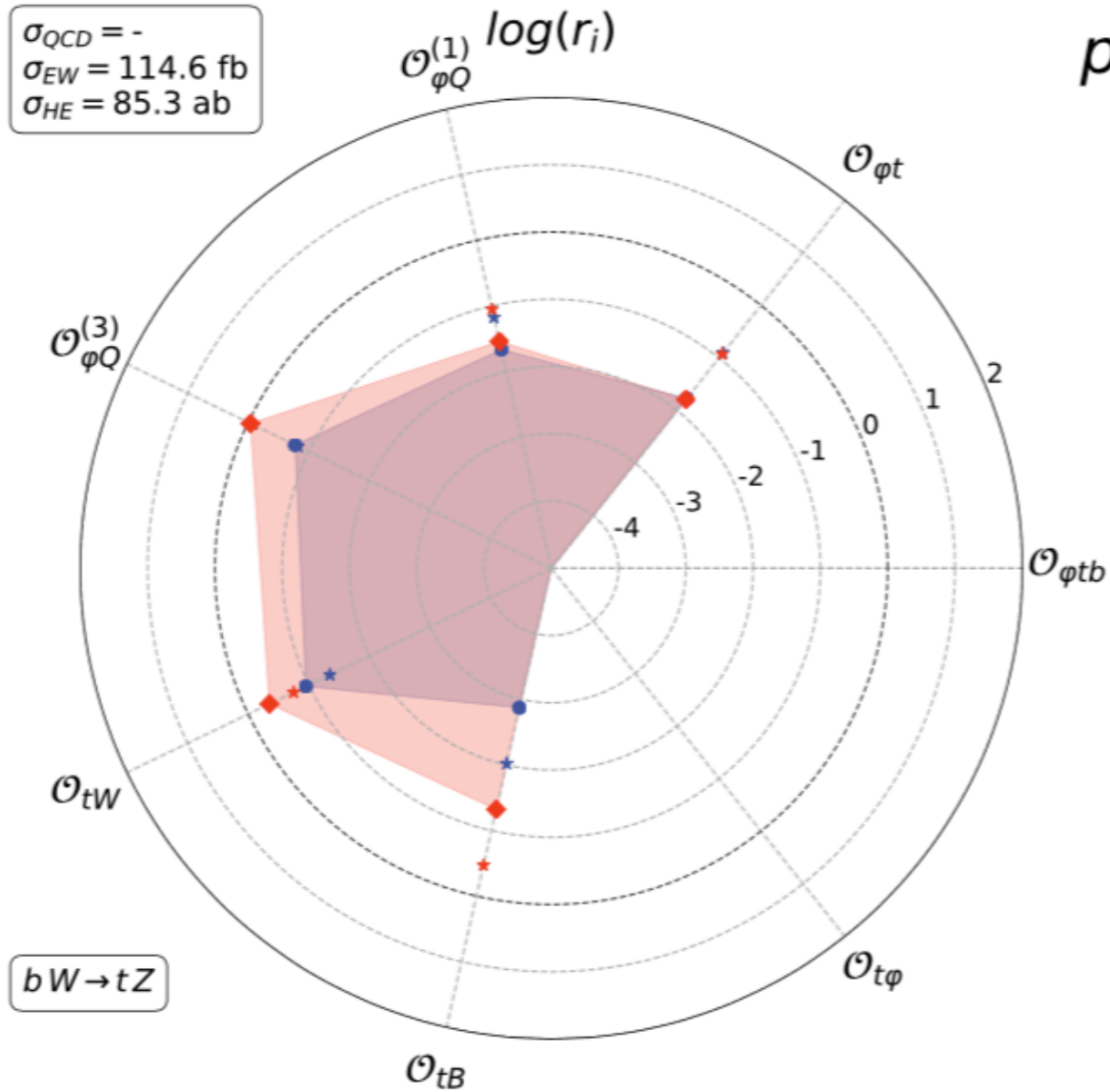


Expected growth from $2 \rightarrow 2$ absent!

$C_i = 1$
 Inclusive
 $p_T(Z) > 500 \text{ GeV}$

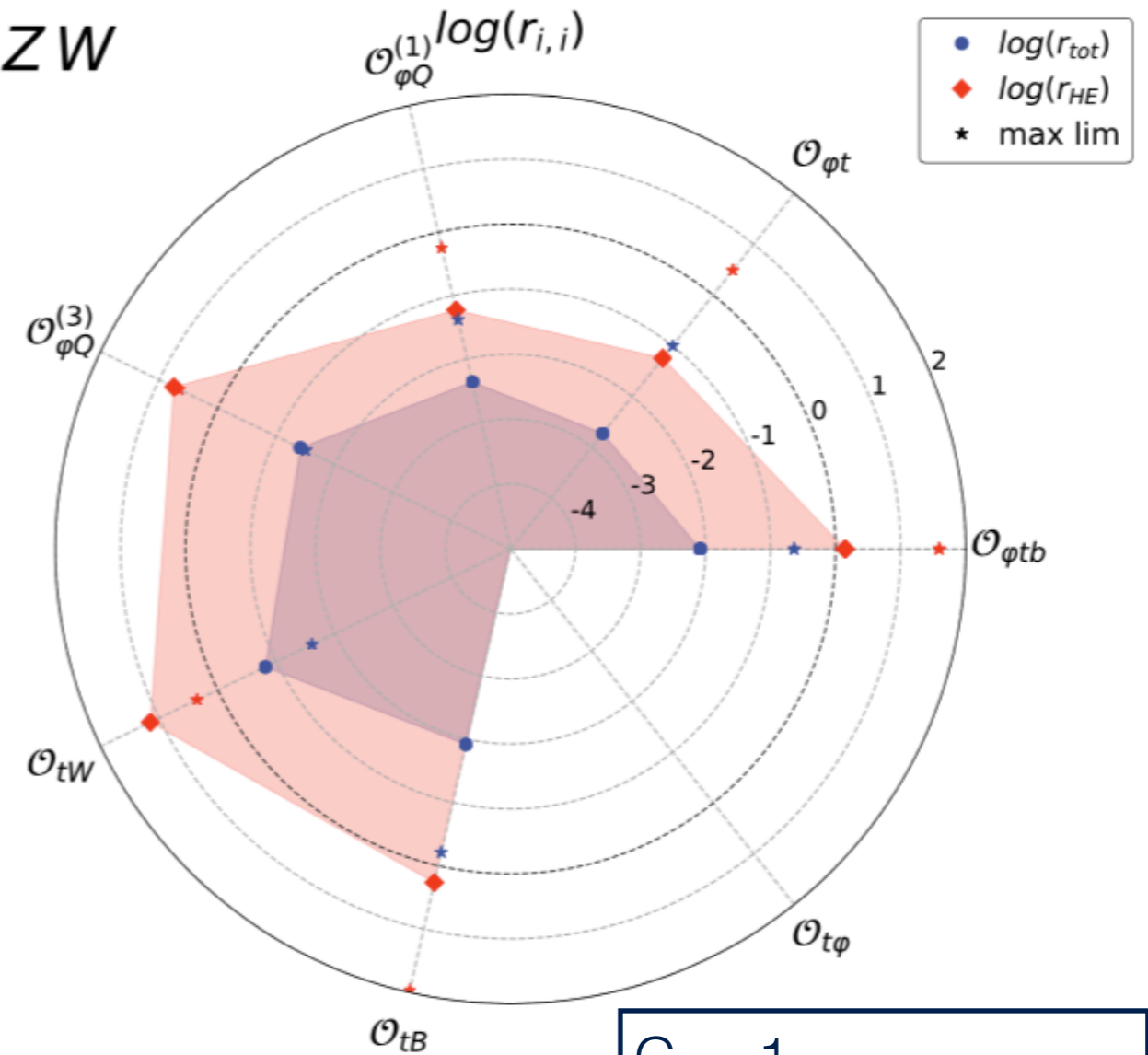
tZW total & high energy xs

interference/SM



square/SM

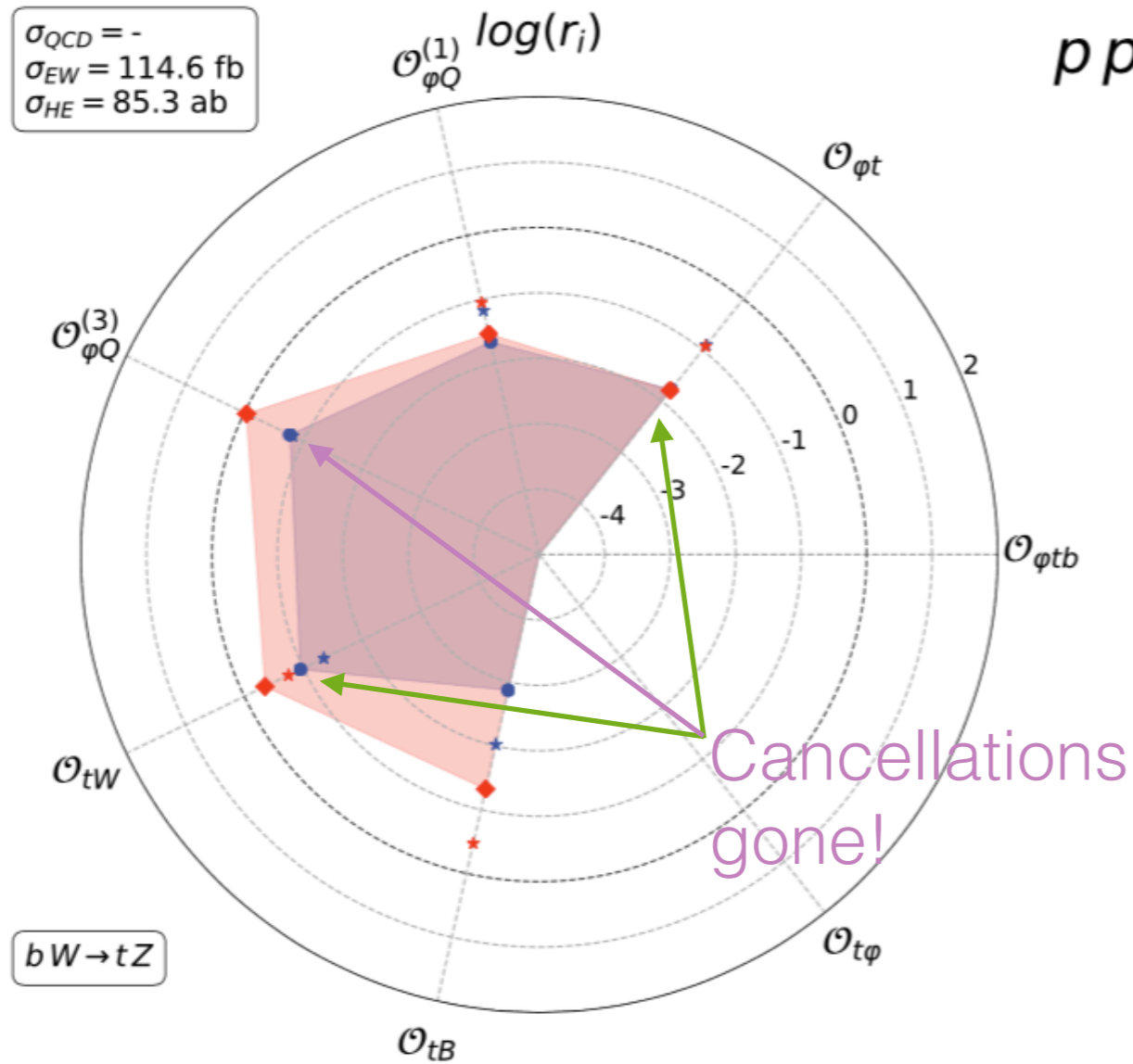
$pp \rightarrow tZW$



$C_i = 1$
 Inclusive
 $p_T(W,Z) > 500 \text{ GeV}$

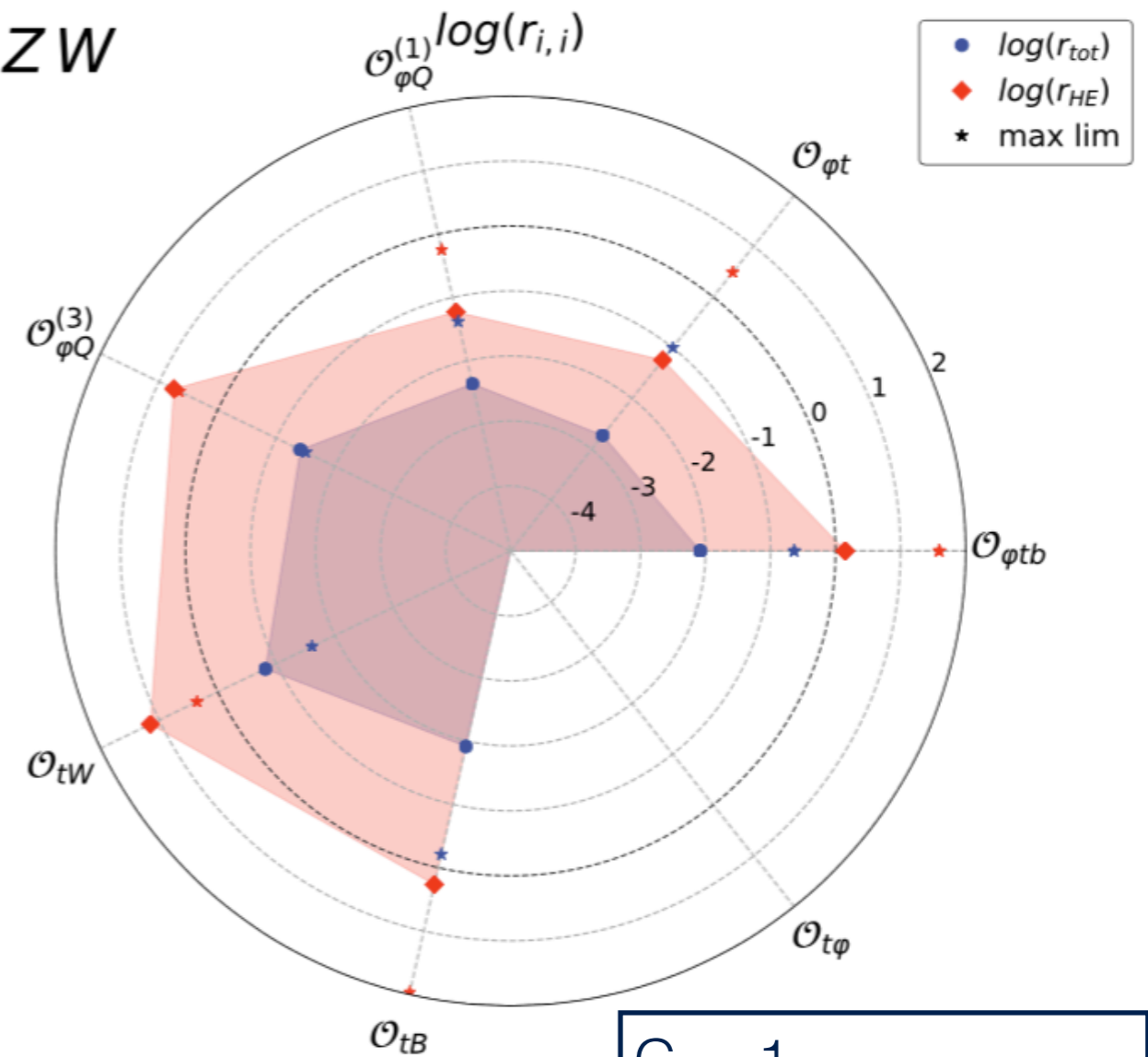
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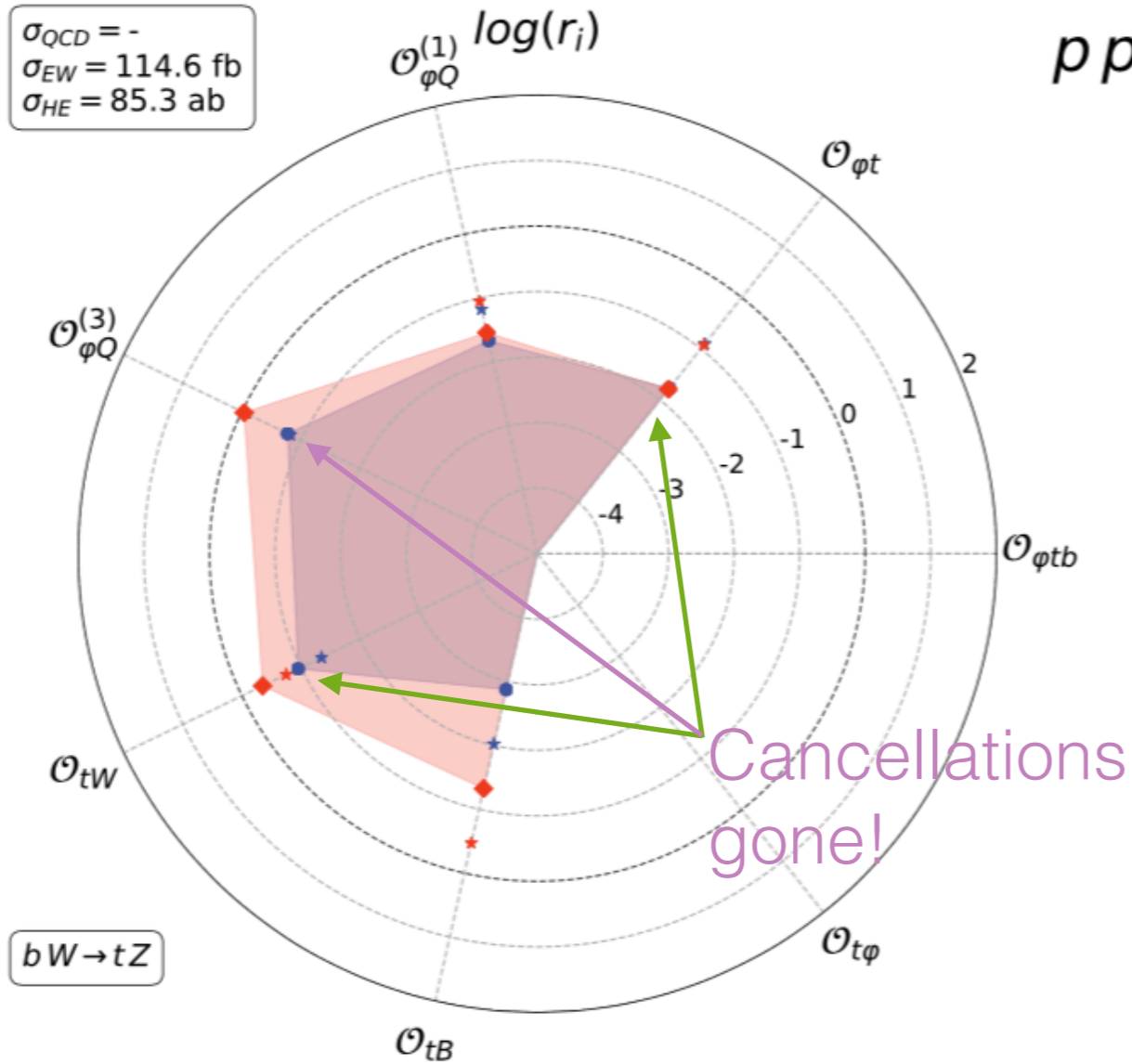
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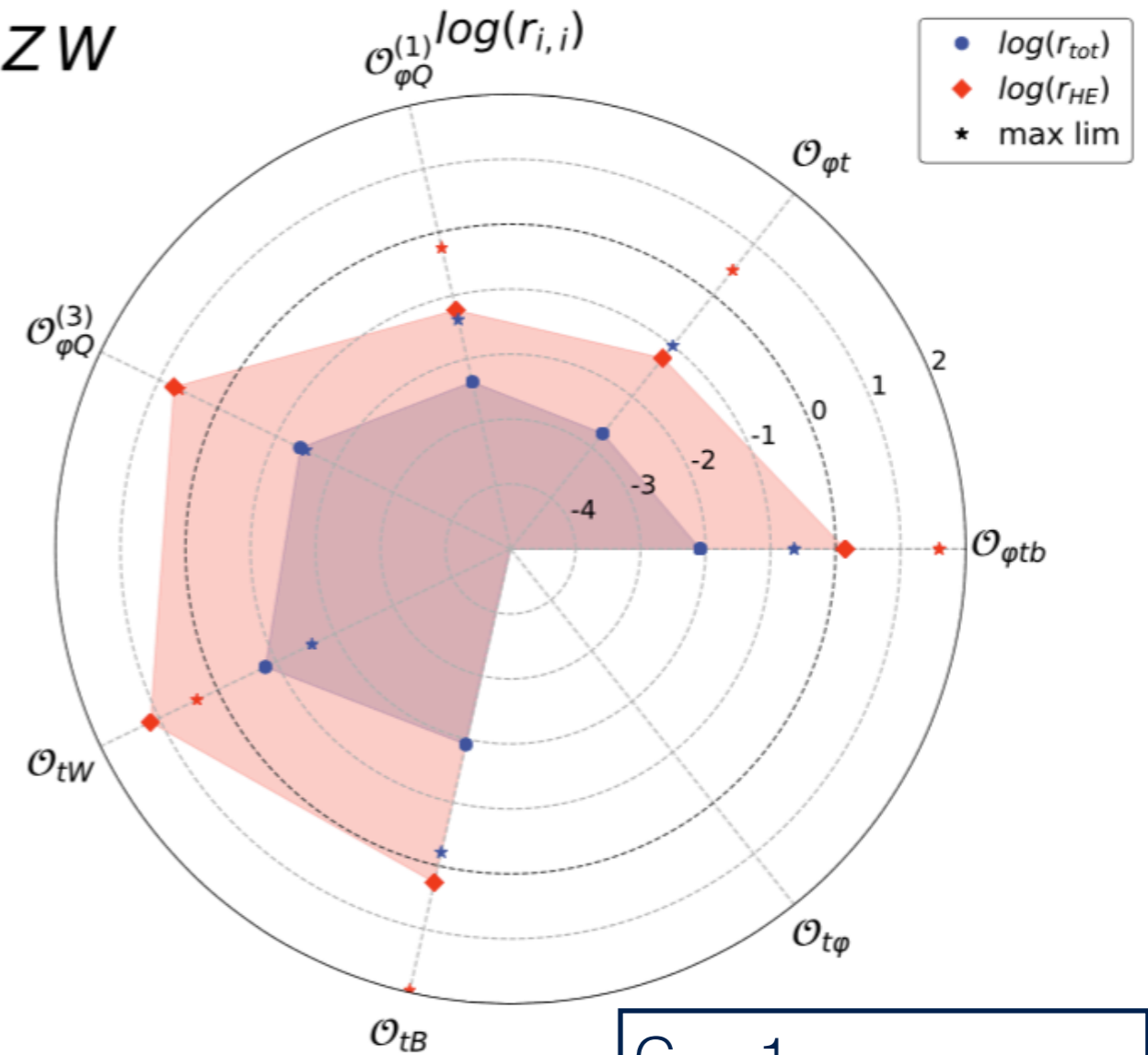
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interference/SM



square/SM

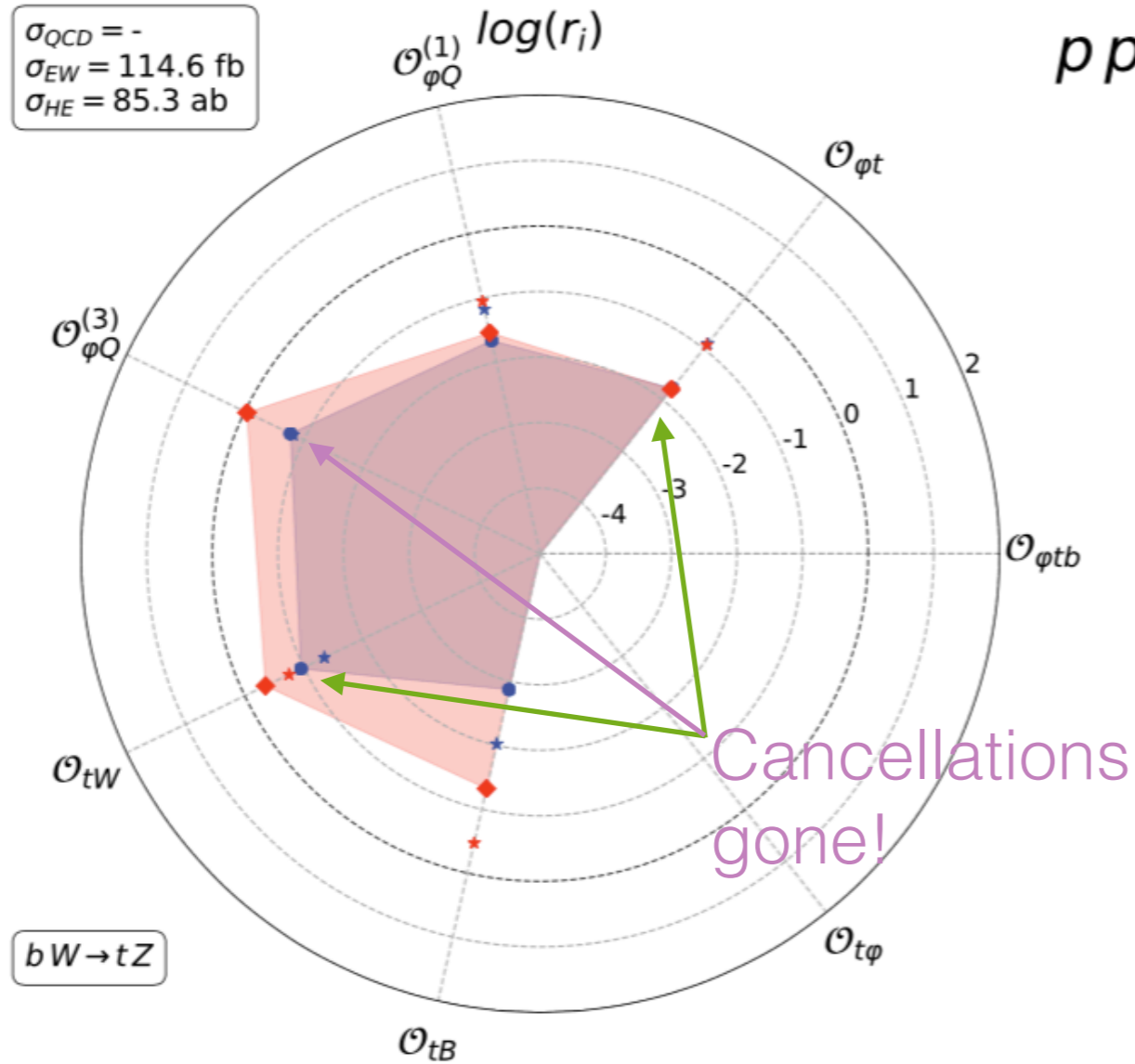
$pp \rightarrow tZW$



Expected growth is there!

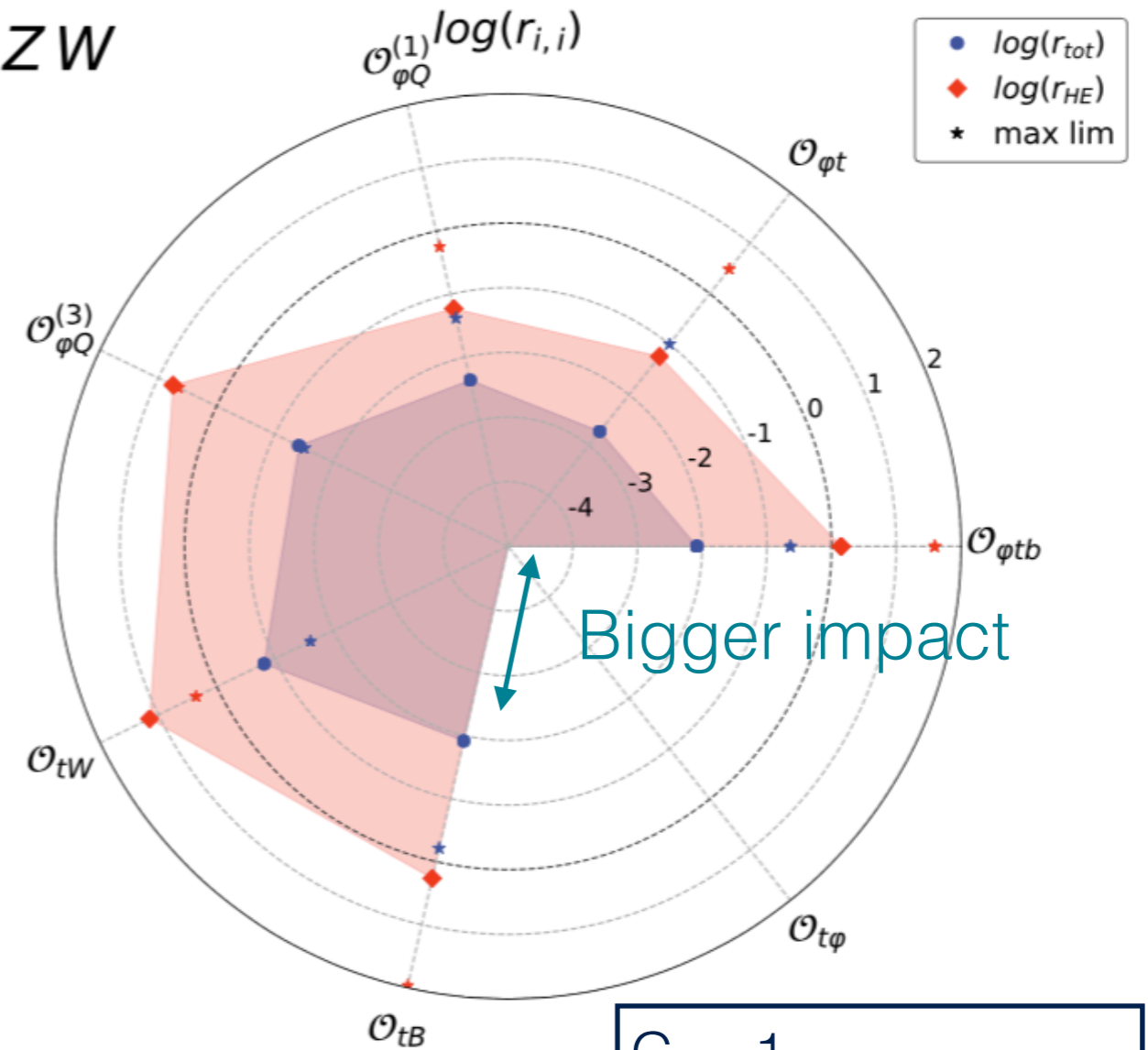
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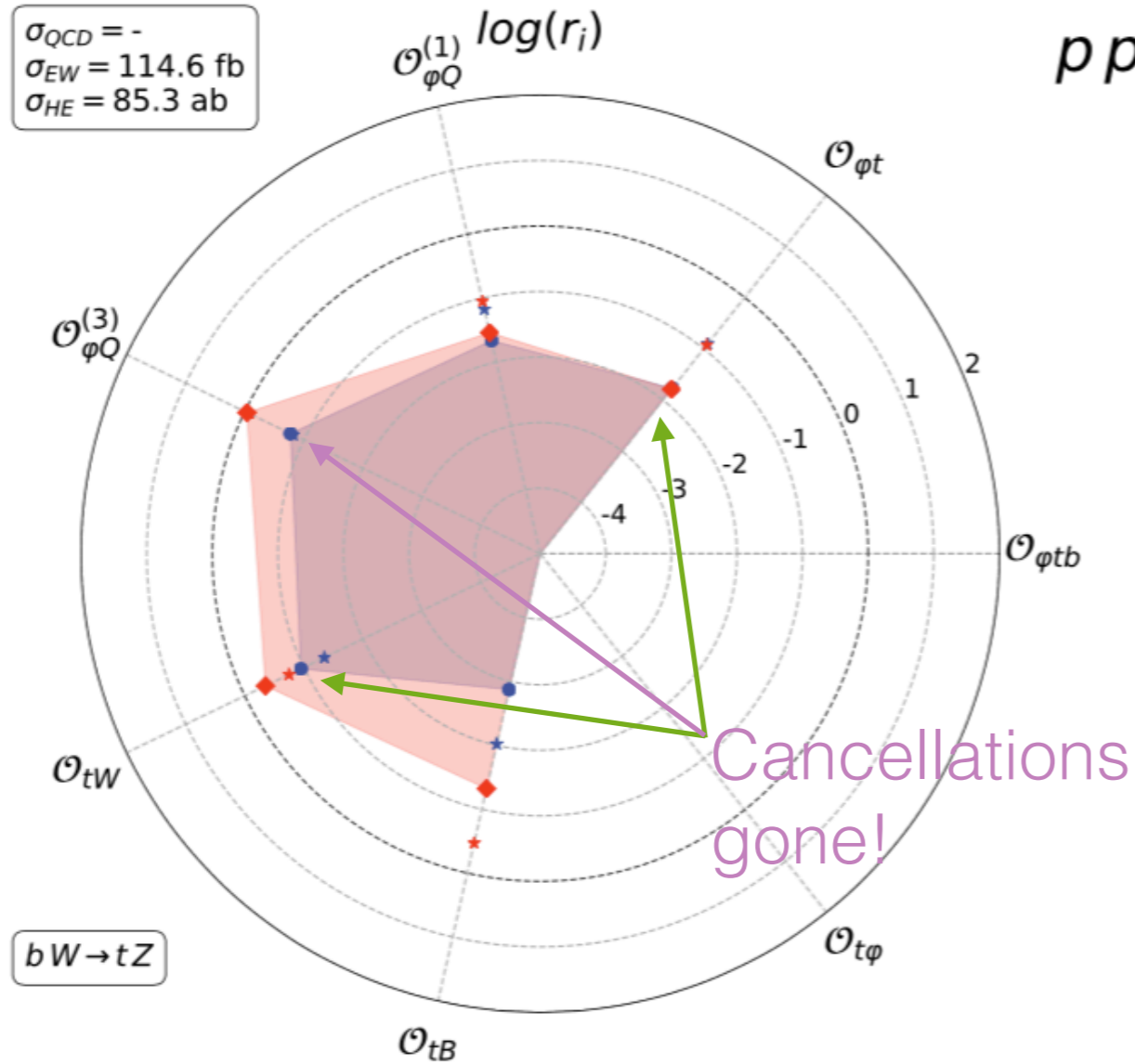
square/SM



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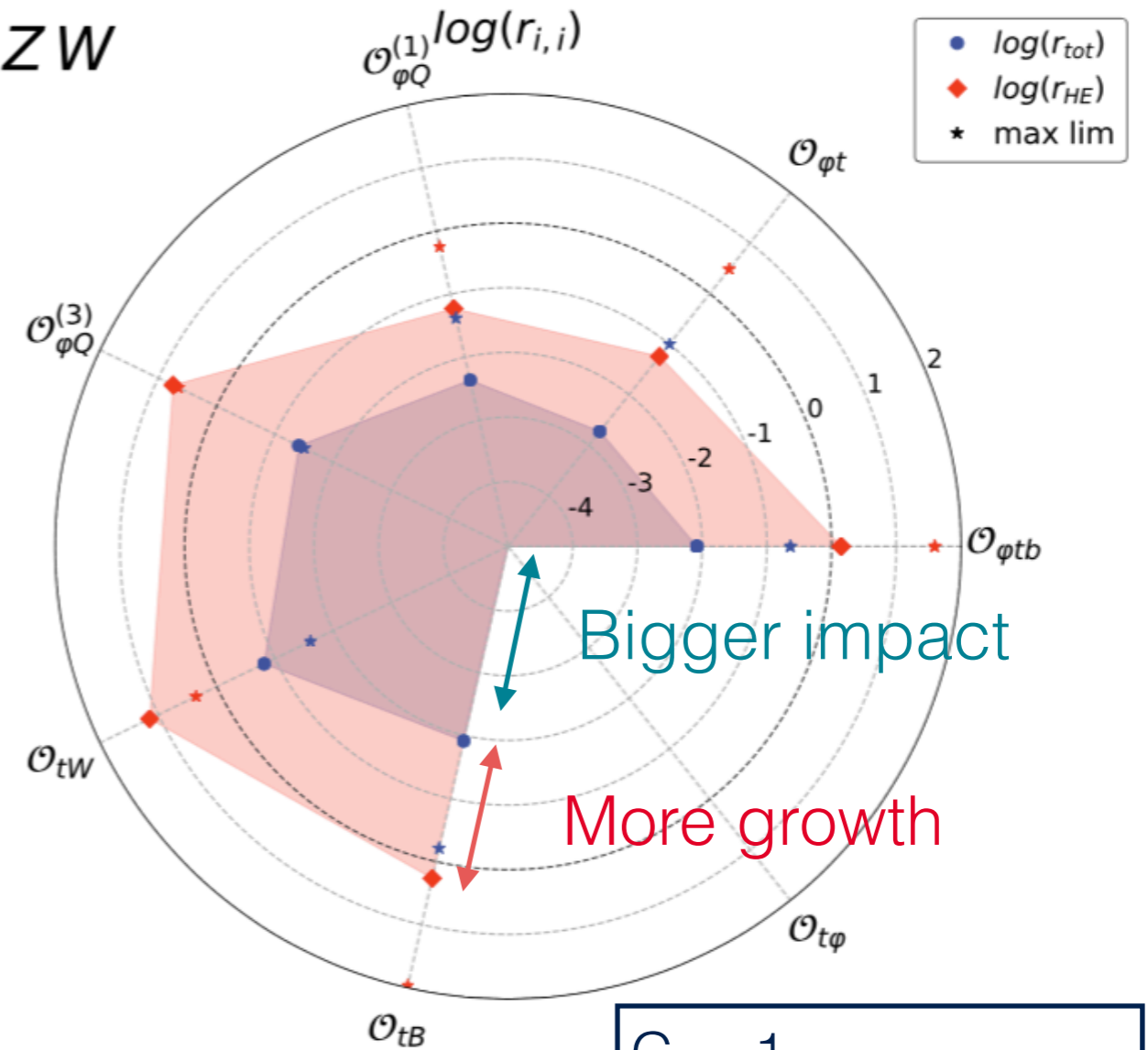
tZW total & high energy xs

interference/SM



square/SM

$pp \rightarrow tZW$

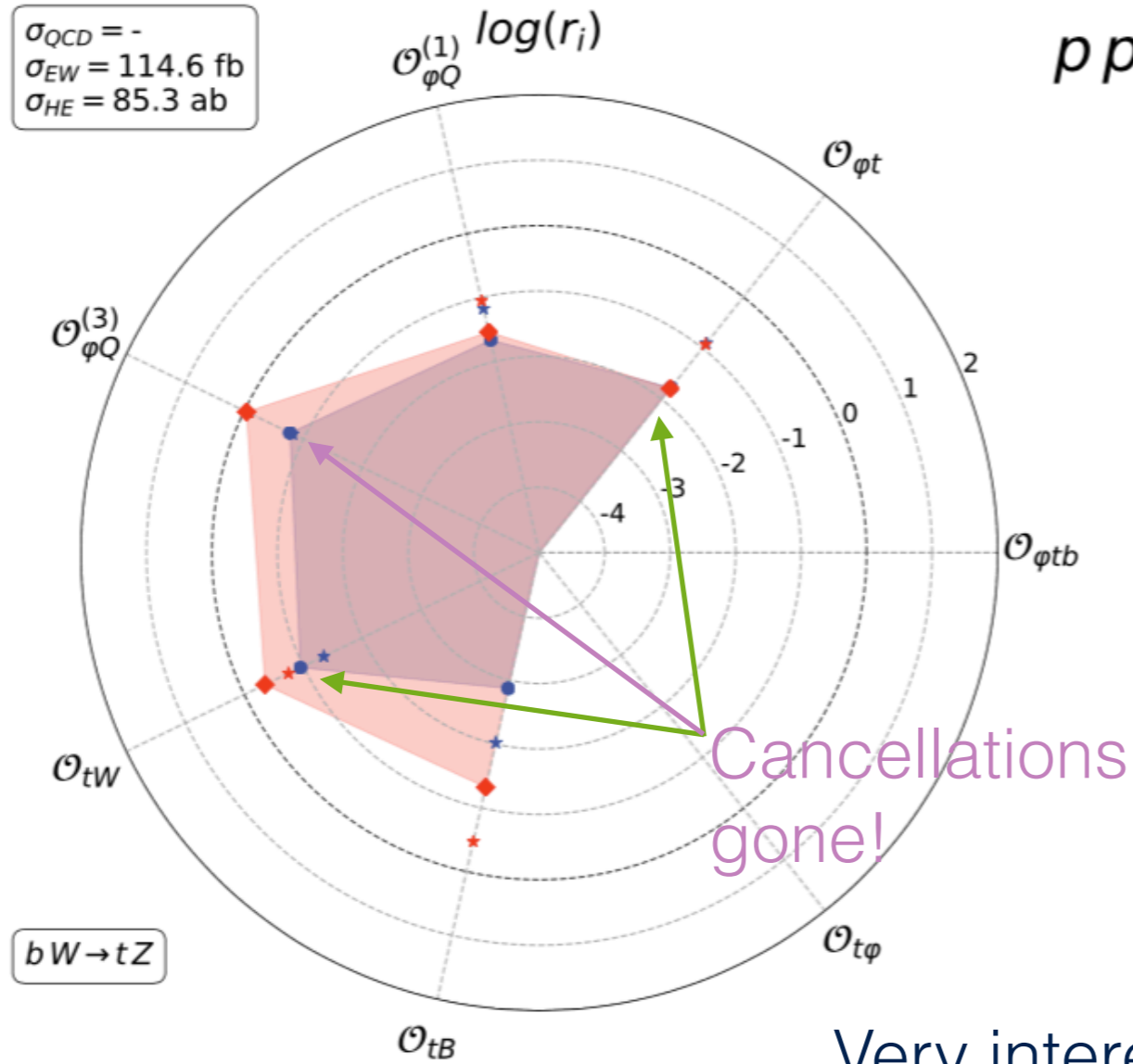


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tZW total & high energy xs

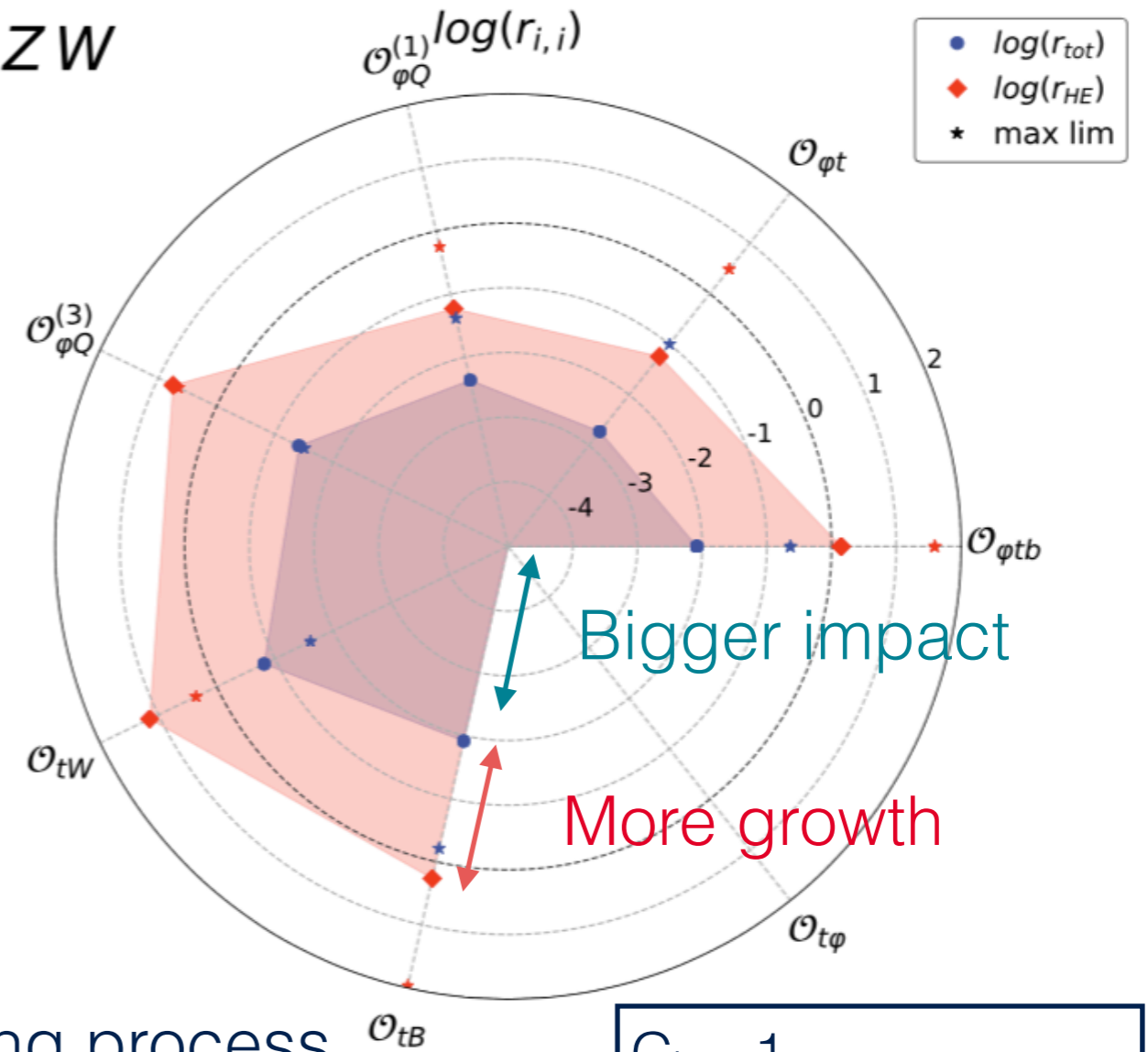
interference/SM



Cancellations gone!

square/SM

$pp \rightarrow tZW$

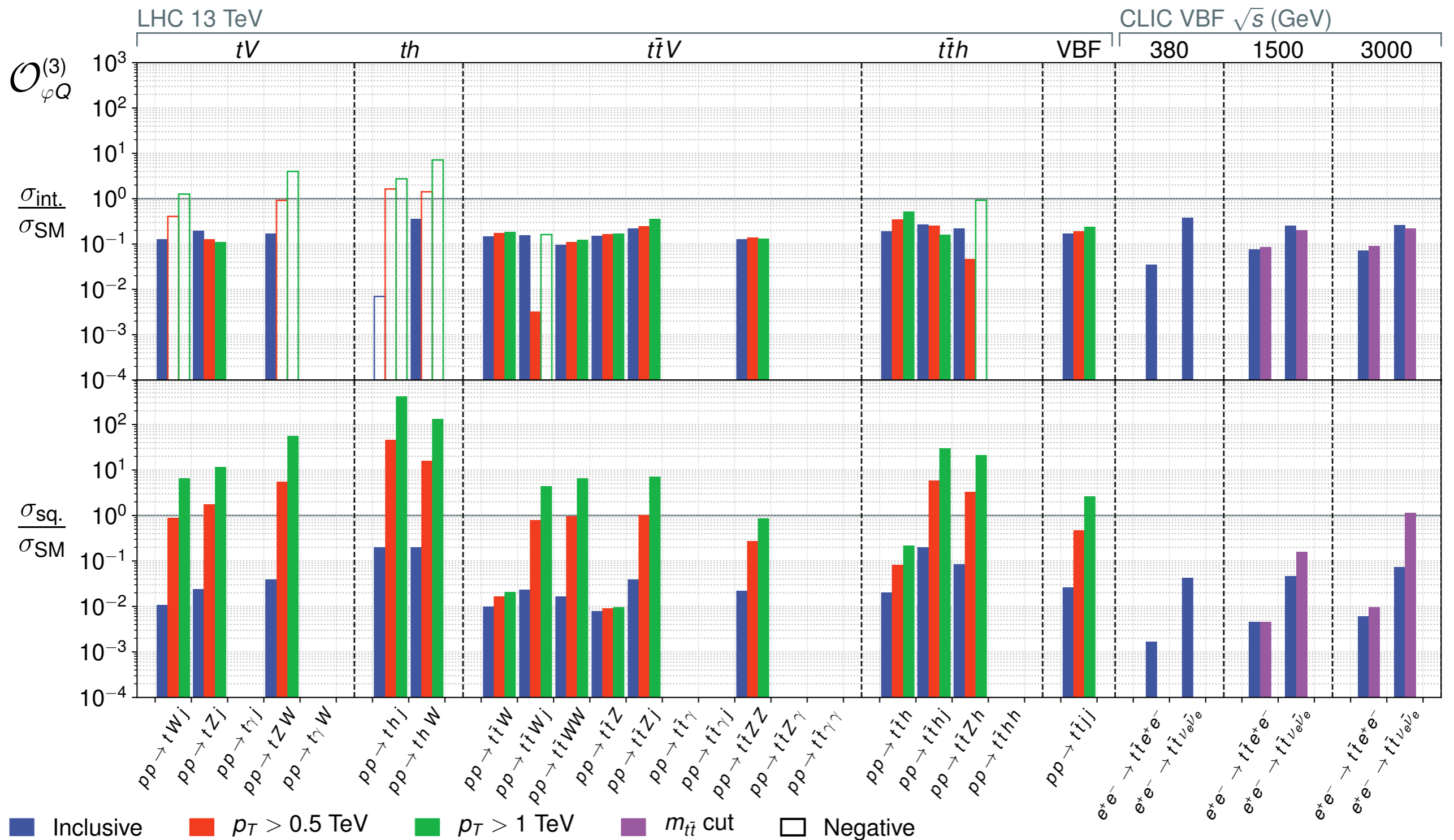


Expected growth is there!

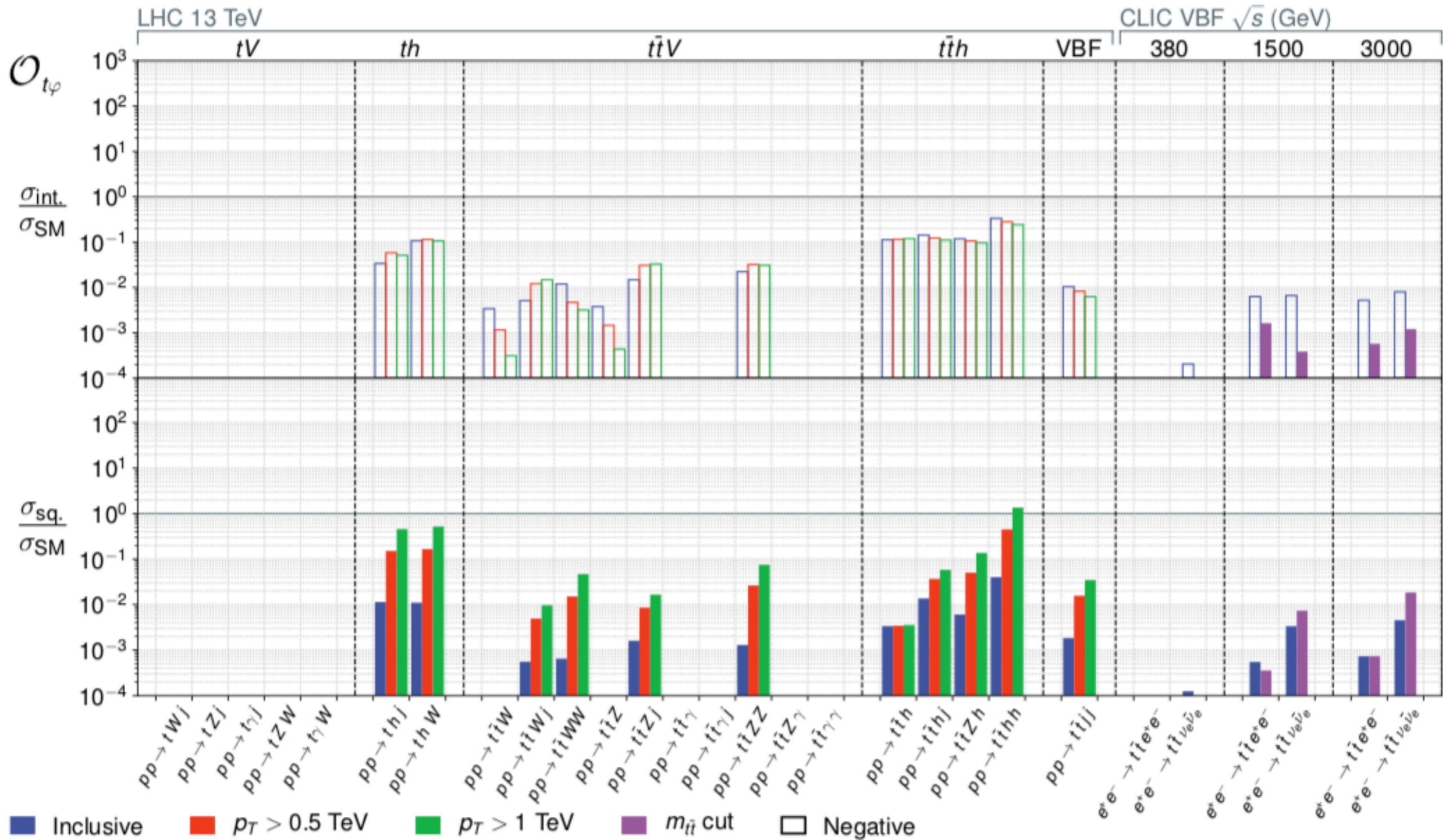
Very interesting process that should be measured at the LHC/FCC

$C_i = 1$
 Inclusive
 $p_T(W,Z) > 500 \text{ GeV}$

Charged current operator



Yukawa operator



Embedding the amplitudes

‘Future collider’ amplitudes & processes

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

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

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

Embedding the amplitudes

'Future collider' amplitudes & processes

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

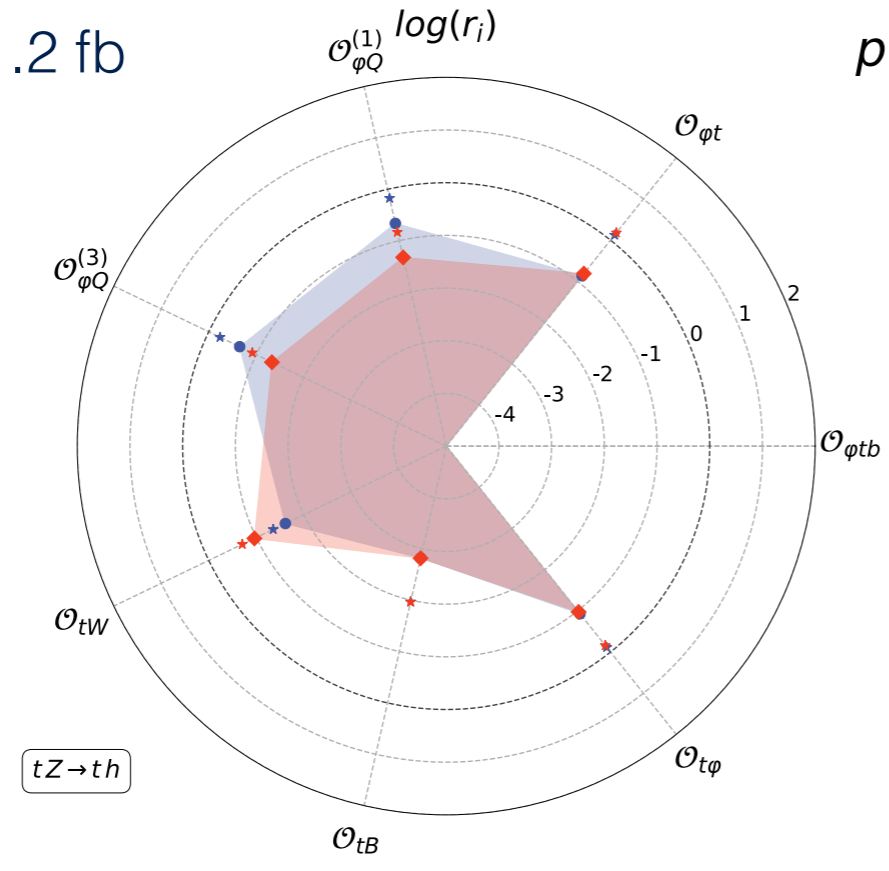
	$t\bar{t}W(j)$	$t\bar{t}WW$	$t\bar{t}Z(j)$	$t\bar{t}\gamma(j)$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma Z$	$t\bar{t}ZZ$	VBF
$tW \rightarrow tW$	✓	✓						✓
$tZ \rightarrow tZ$			✓				✓	✓
$tZ \rightarrow t\gamma$			✓	✓		✓		✓
$t\gamma \rightarrow t\gamma$				✓	✓			✓

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

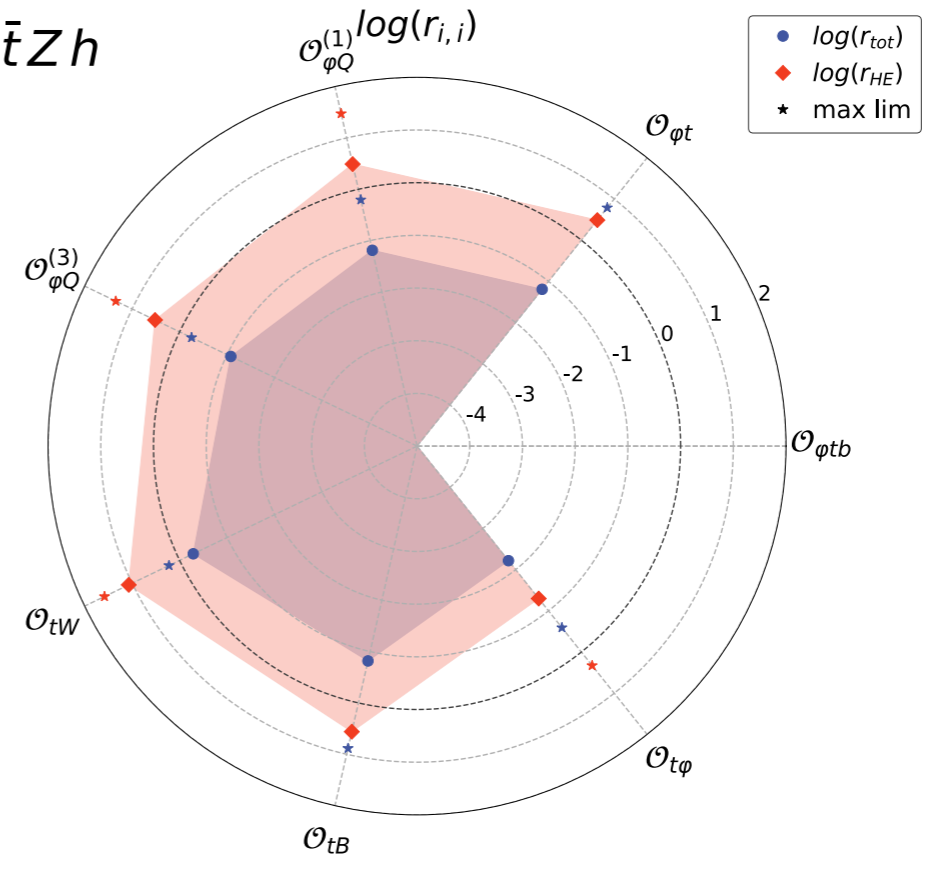
ttZh: LHC vs FCC-hh

ttZh: LHC vs FCC-hh

$\sigma_{13} = 1.2 \text{ fb}$



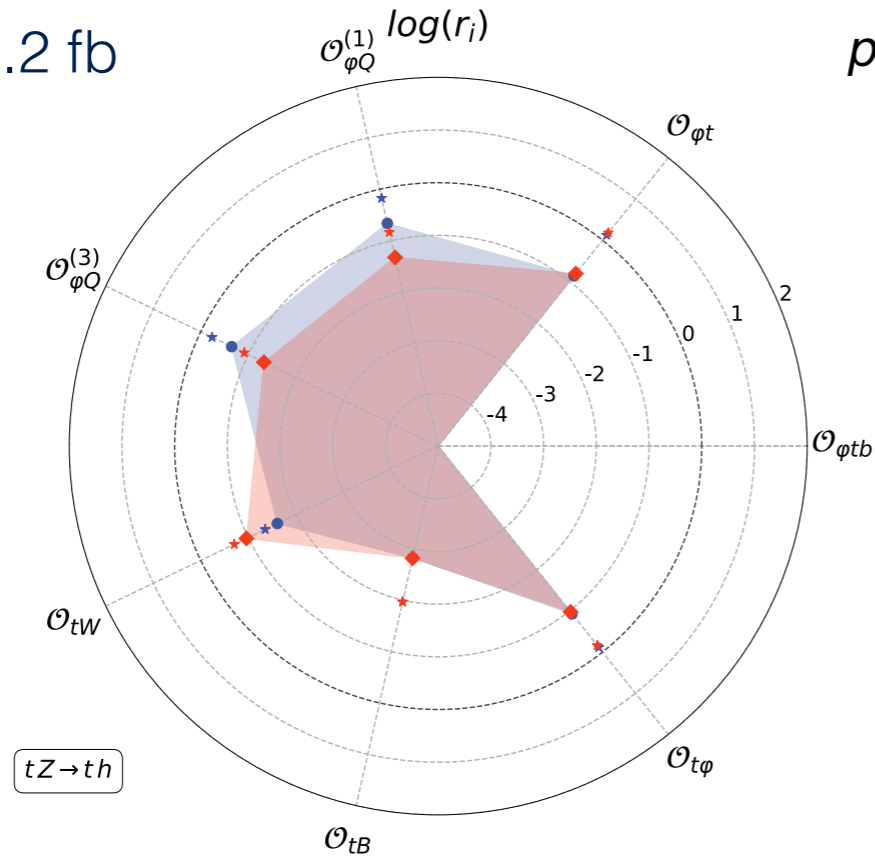
$pp \rightarrow t\bar{t}Zh$



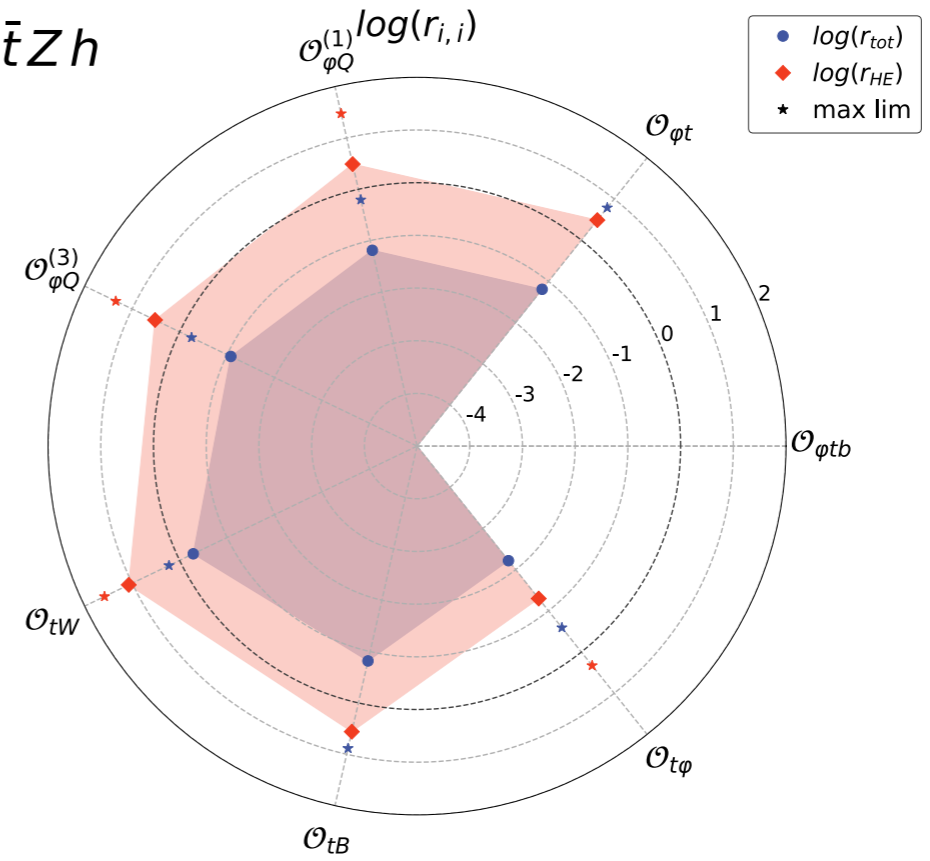
ttZh: LHC vs FCC-hh

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

$\sigma_{13} = 1.2$ fb



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

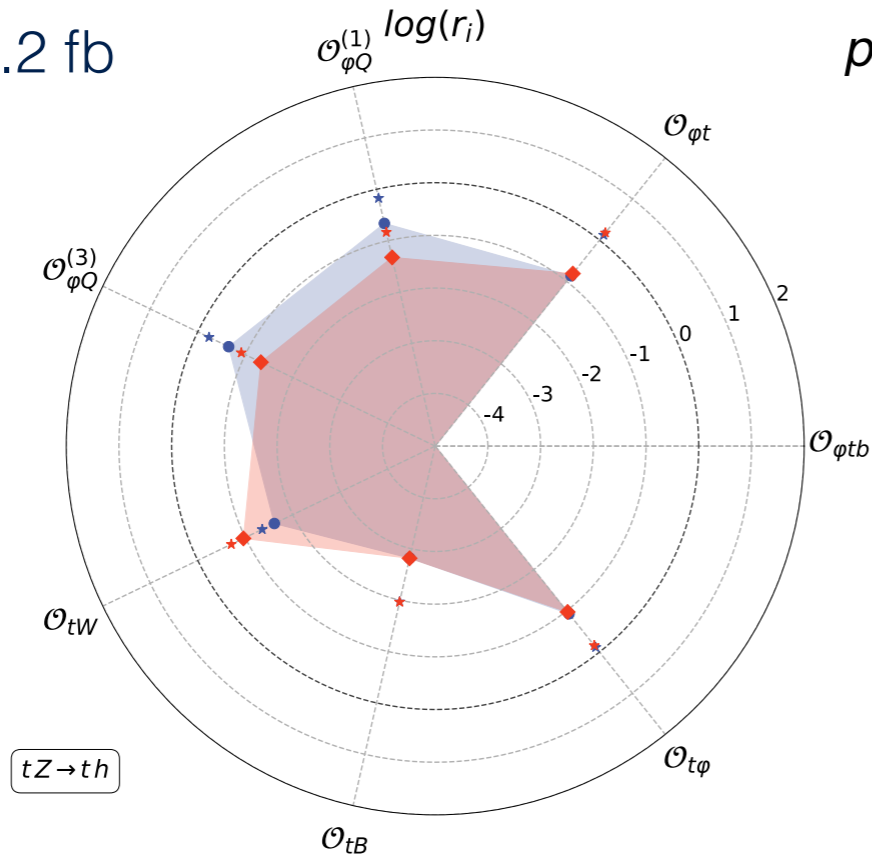


ttZh: LHC vs FCC-hh

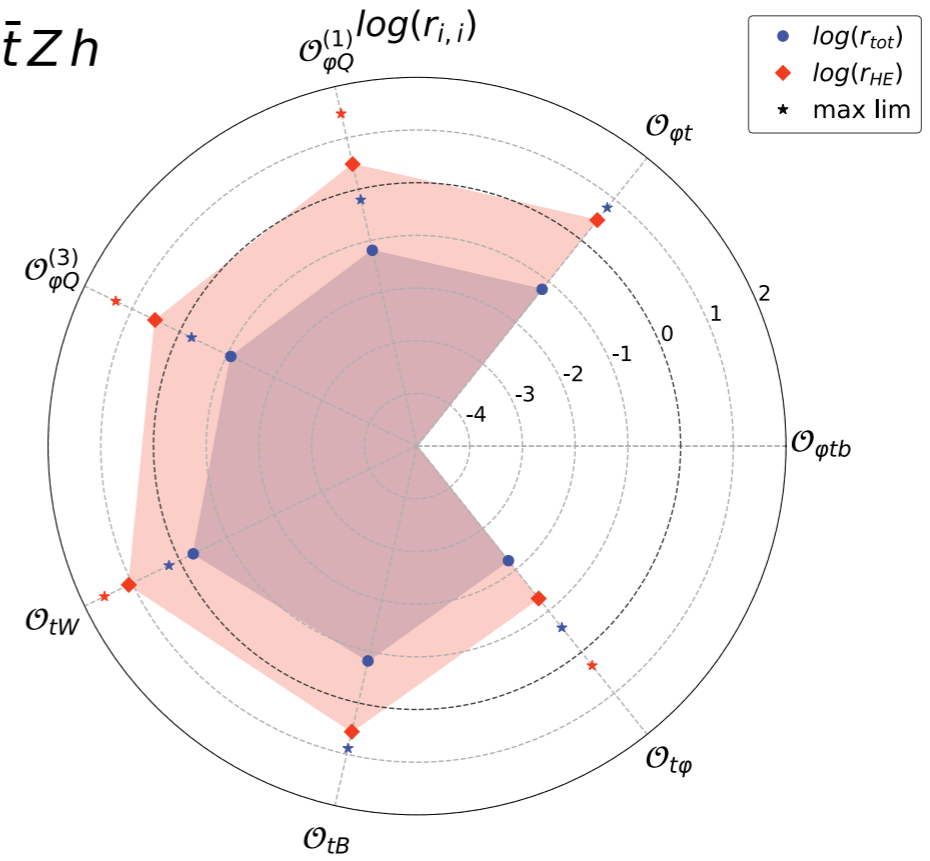
High energy: $p_T(Z,h) > 500$ GeV

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Interference:
phase space
cancellations



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

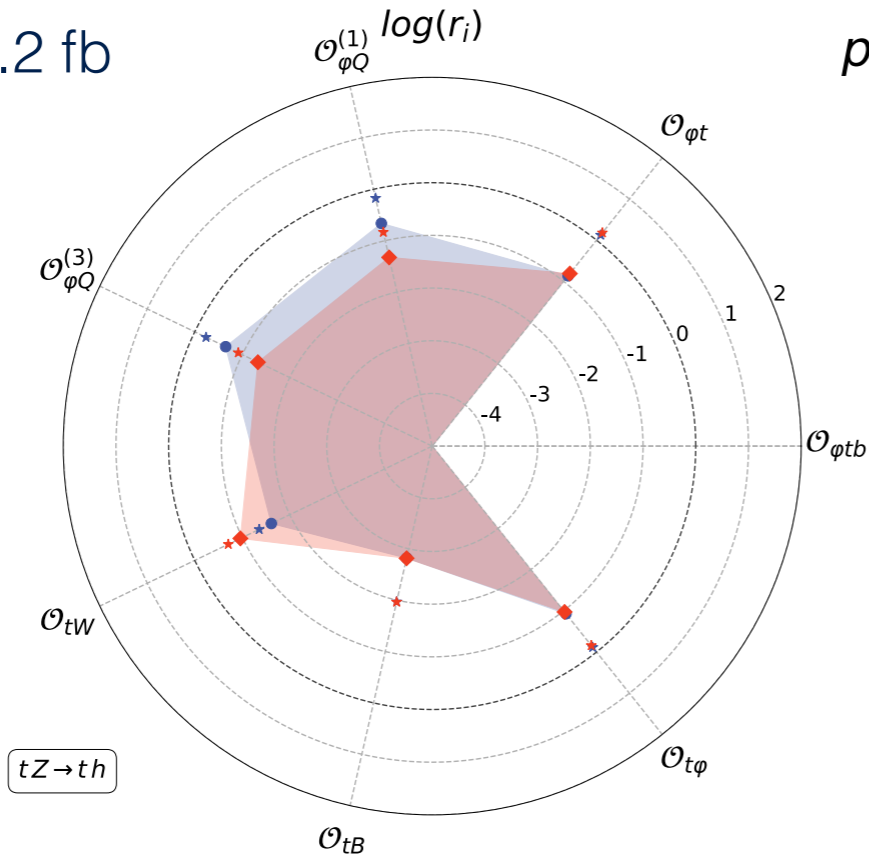


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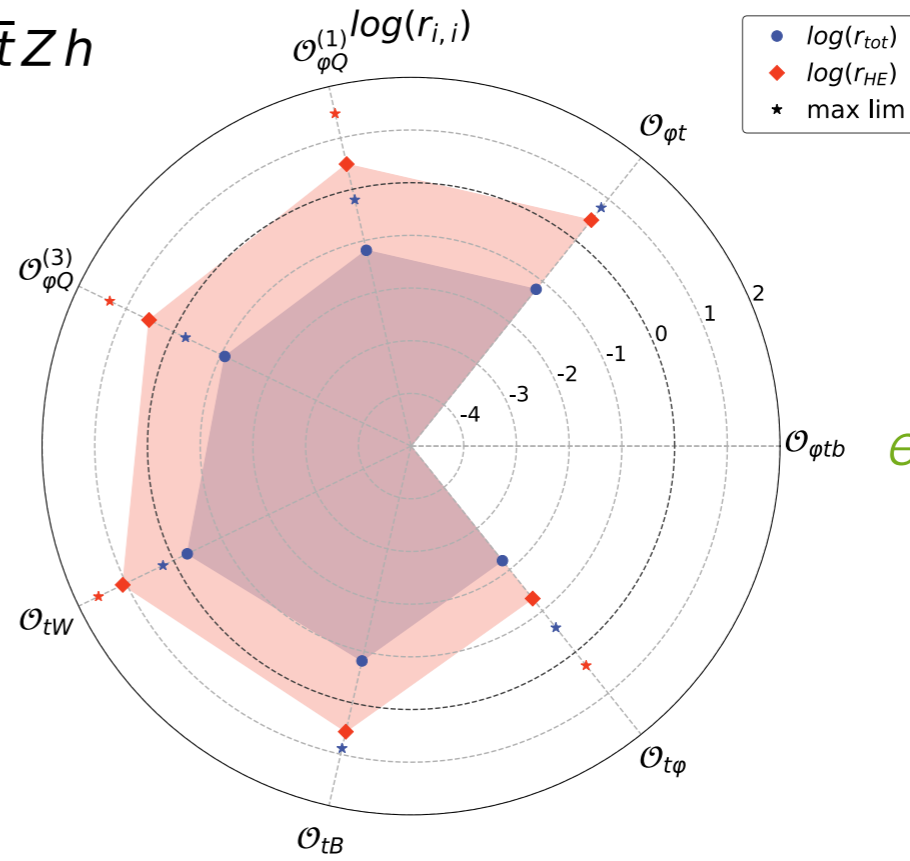
$\sigma_{13} = 1.2$ fb

Interference:
phase space
cancellations



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

Quadratic:
energy growth
& $O(1-10)$

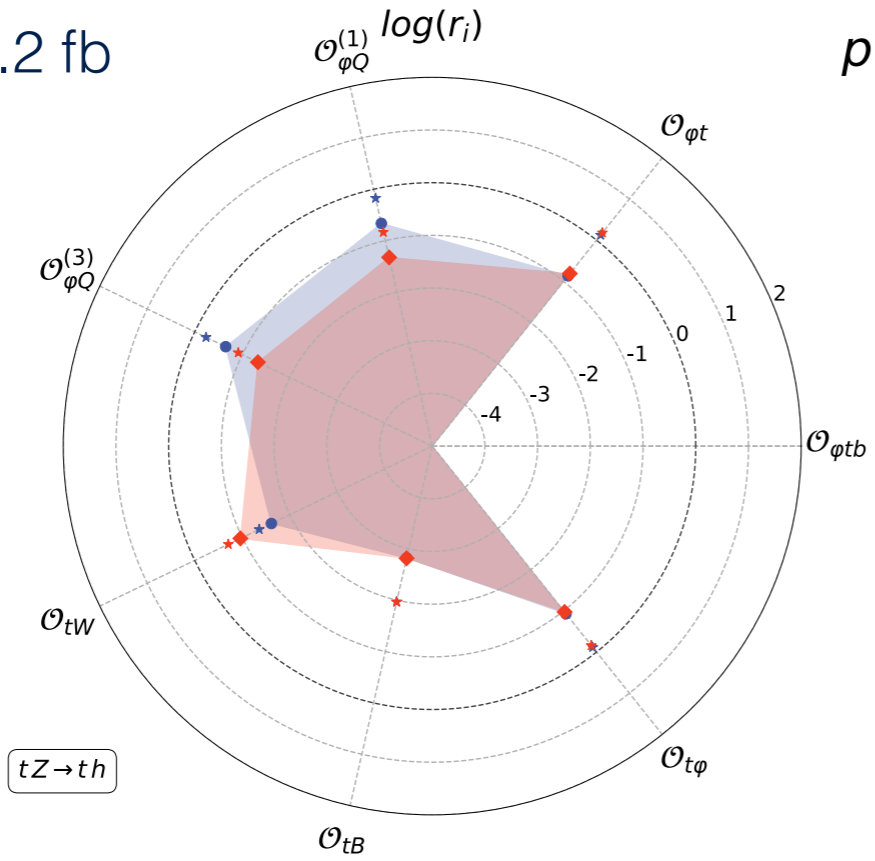


ttZh: LHC vs FCC-hh

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

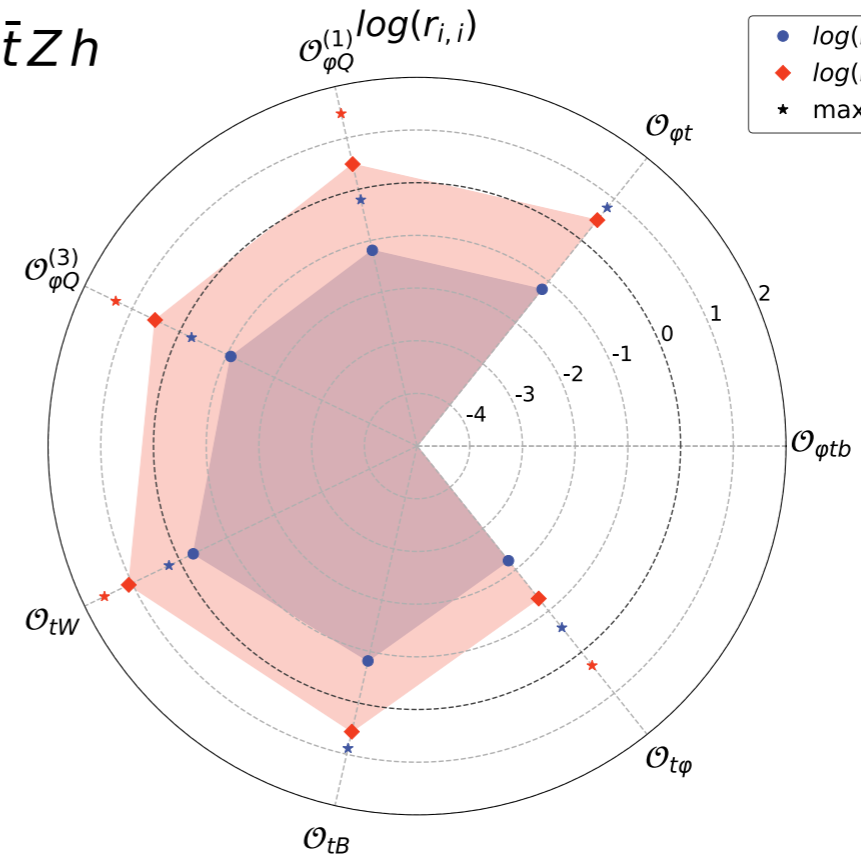
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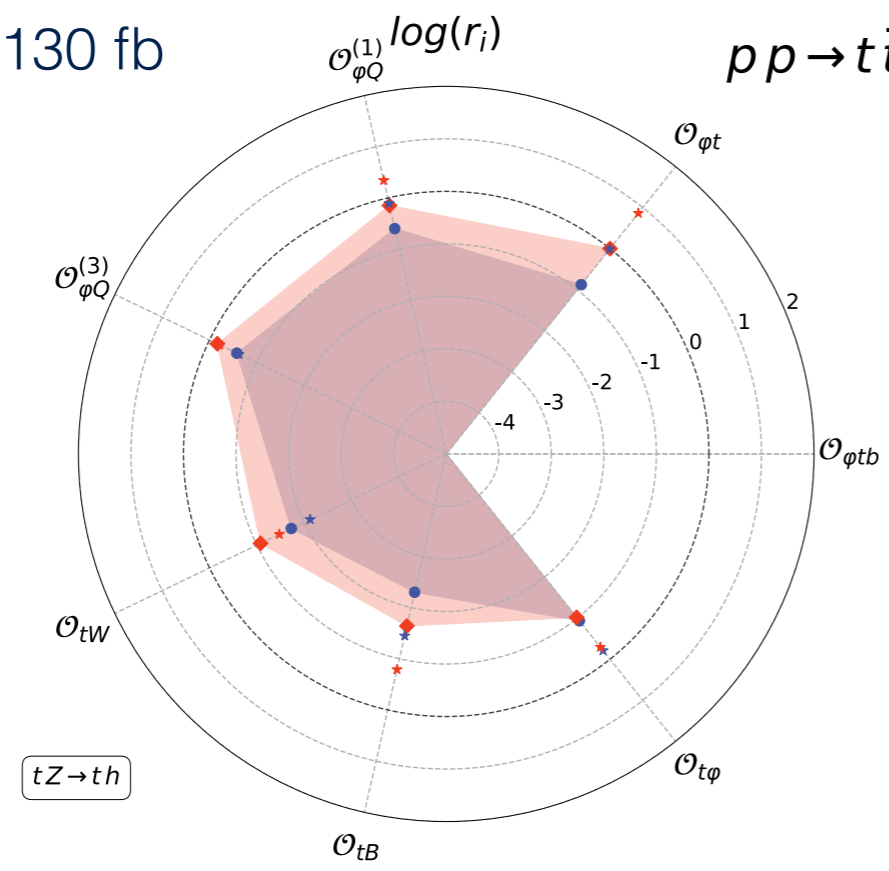


$pp \rightarrow t\bar{t}Zh$

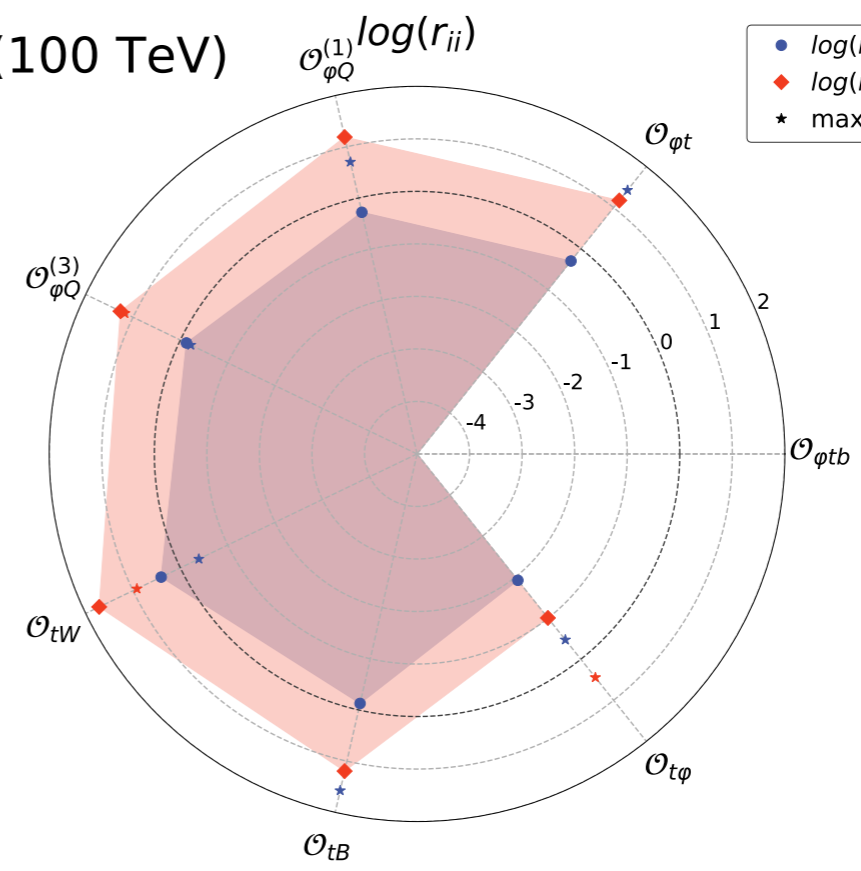
Quadratic:
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$\sigma_{100} = 130$ fb



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

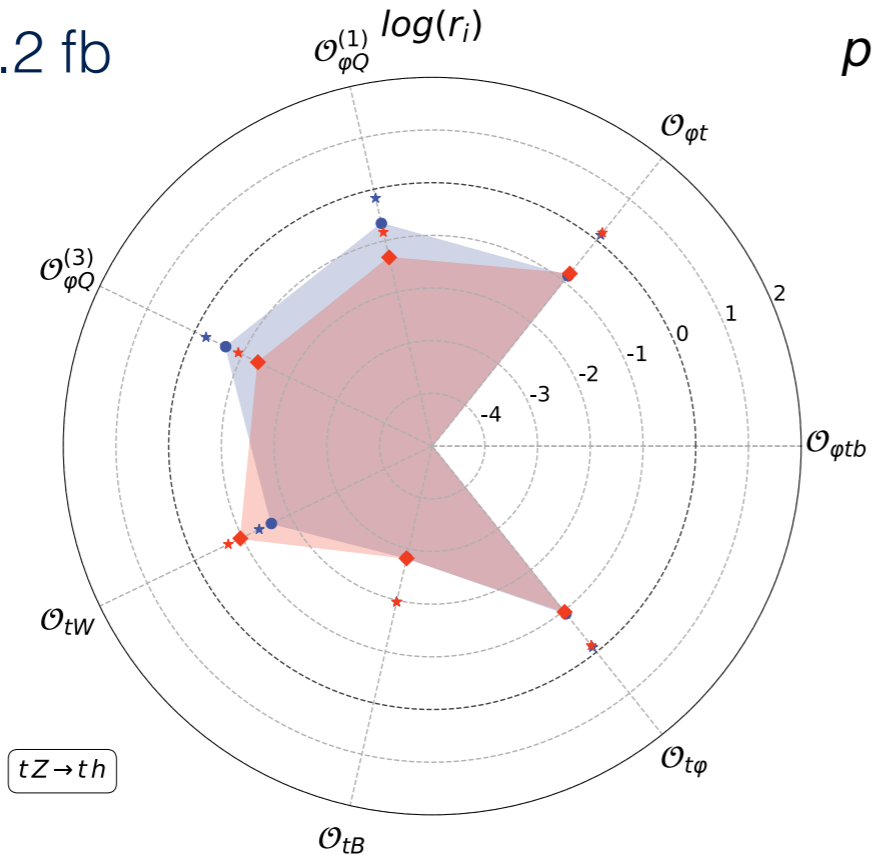


ttZh: LHC vs FCC-hh

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

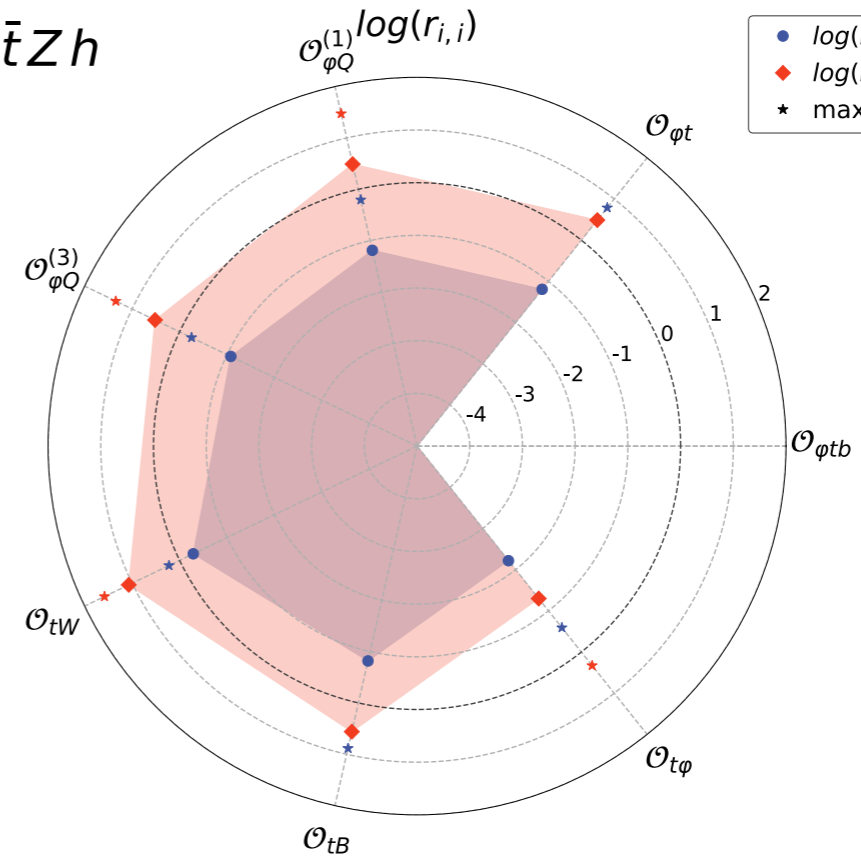
$\sigma_{13} = 1.2$ fb

Interference:
phase space
cancellations



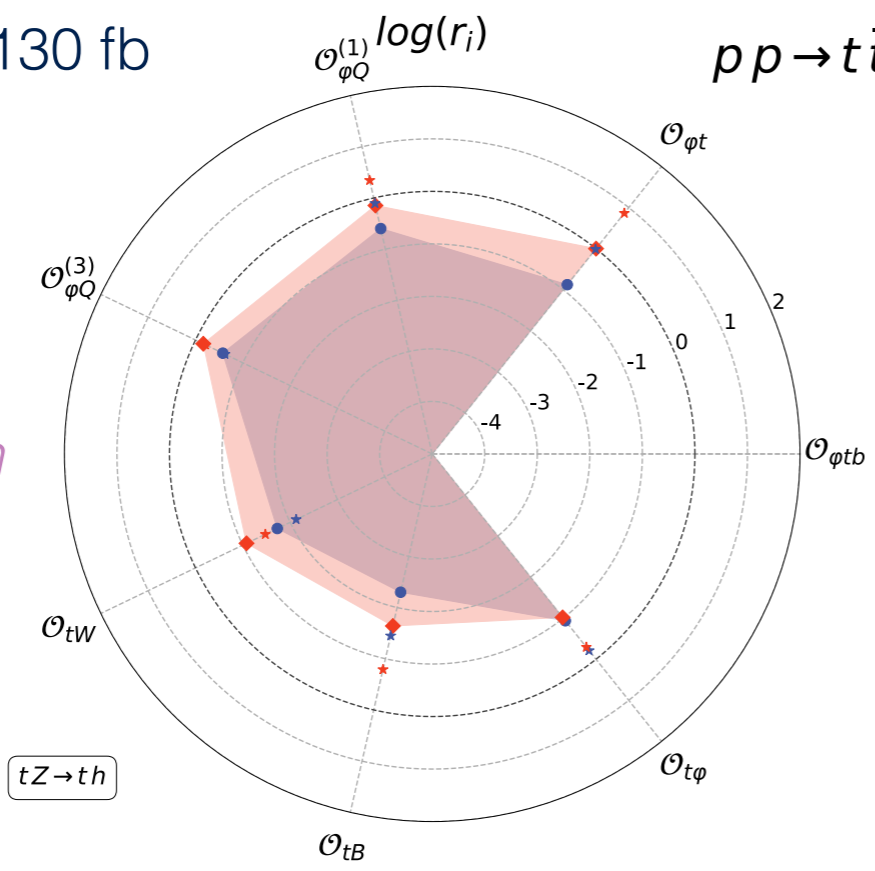
$pp \rightarrow t\bar{t}Zh$

Quadratic:
energy growth
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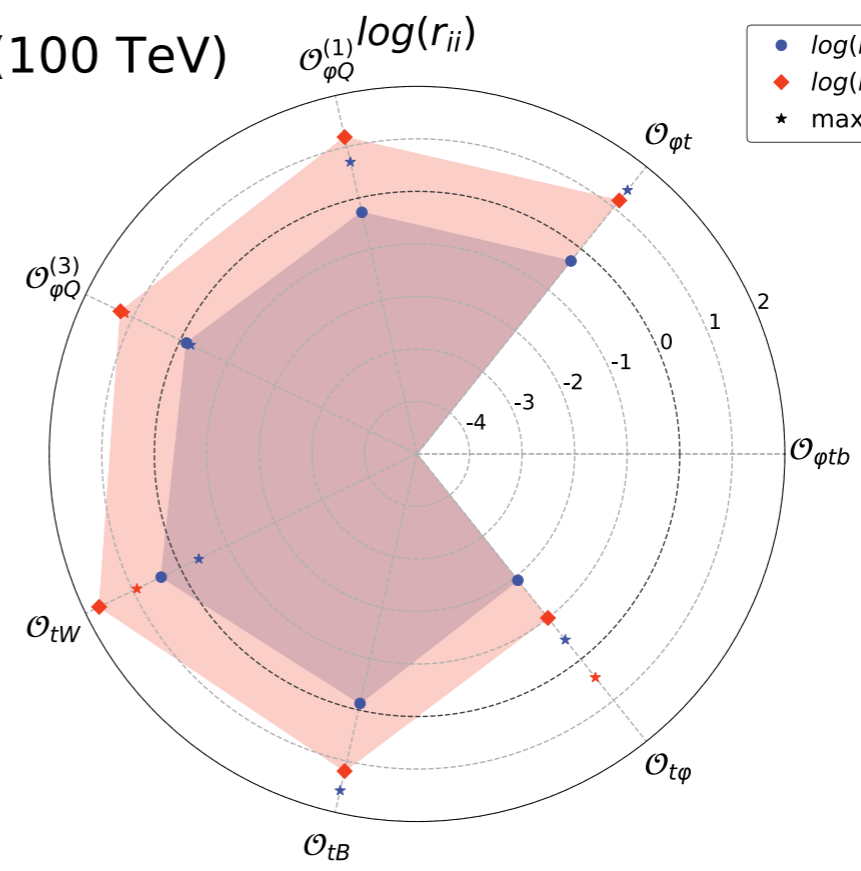


$\sigma_{100} = 130$ fb

Interference:
energy growth
& $O(1)$ effects



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

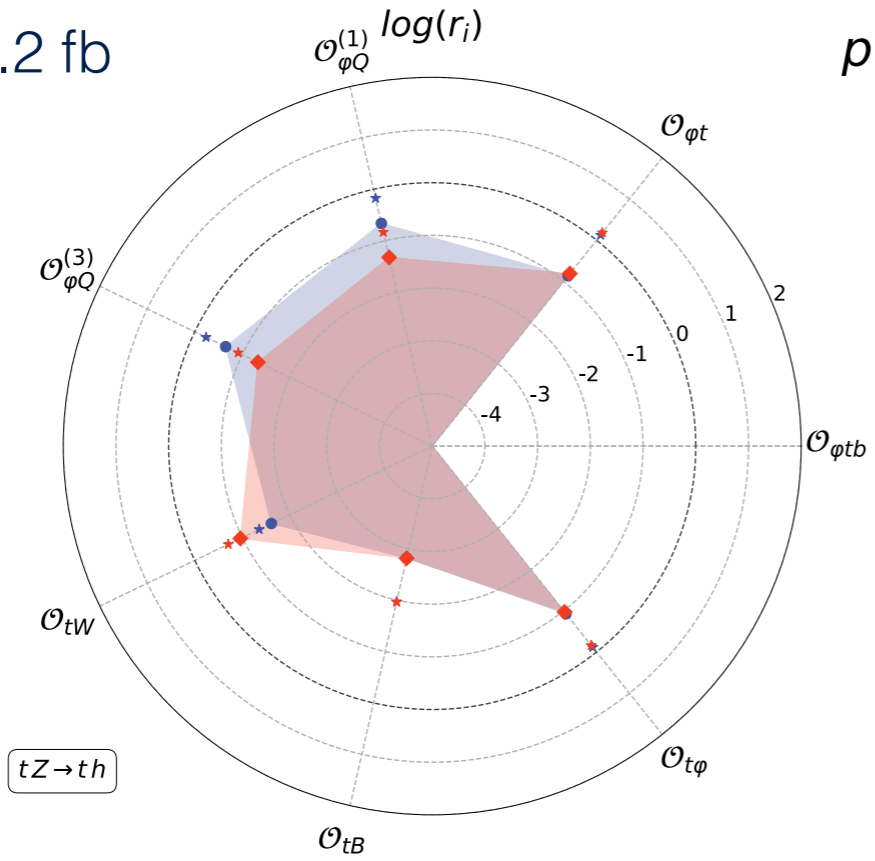


ttZh: LHC vs FCC-hh

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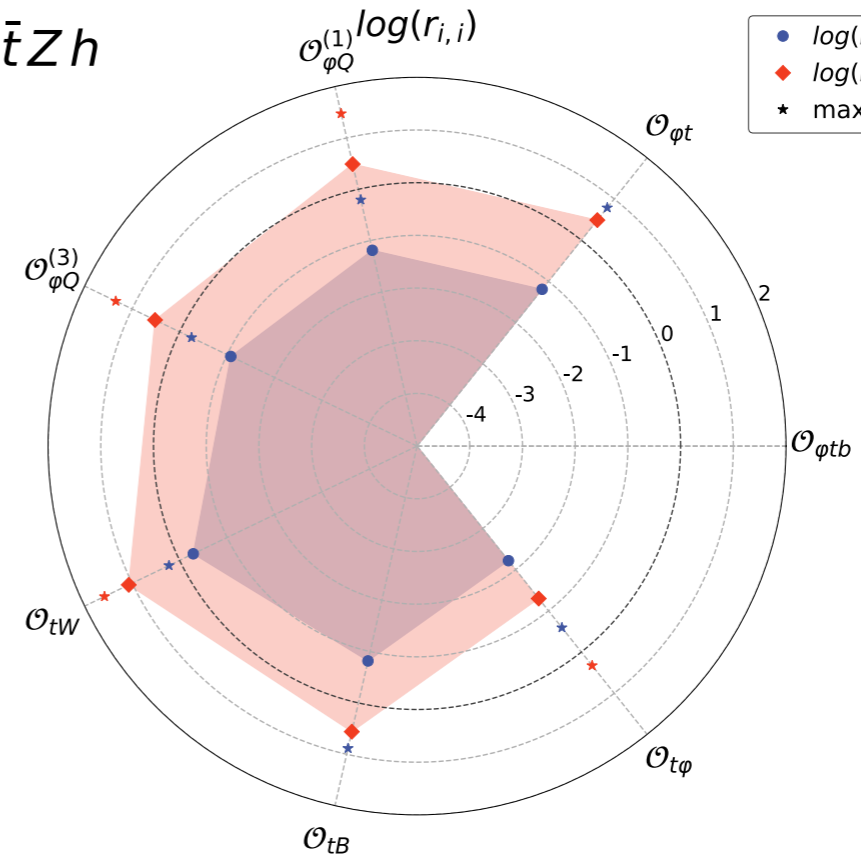
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Interference:
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cancellations



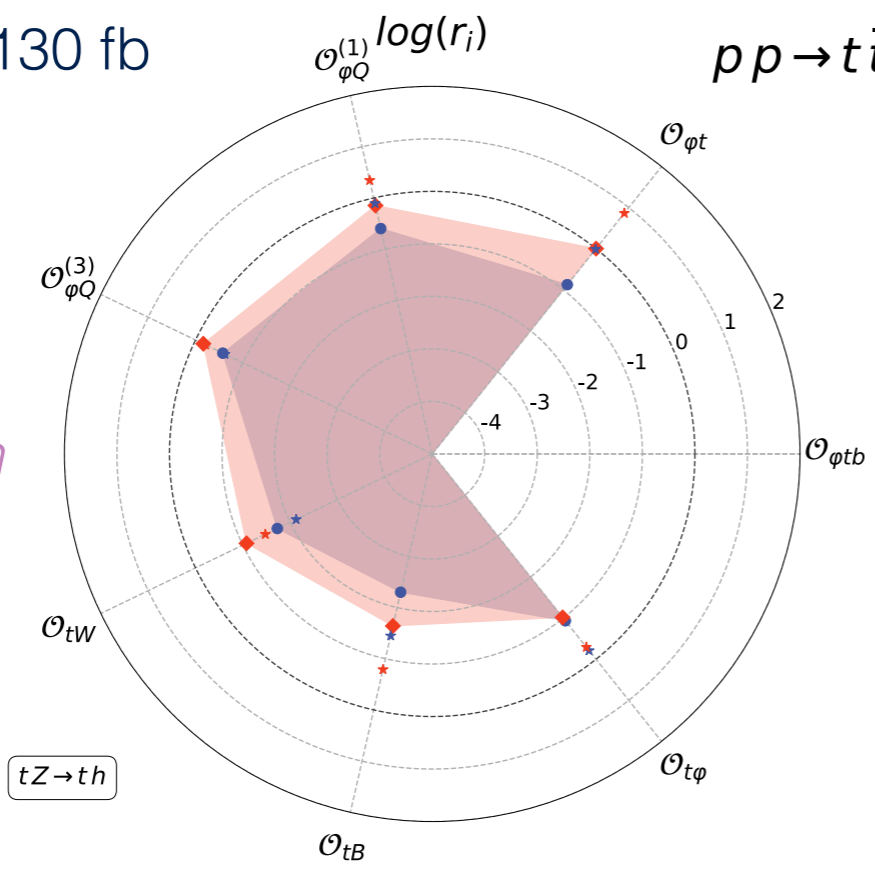
$pp \rightarrow t\bar{t}Zh$

Quadratic:
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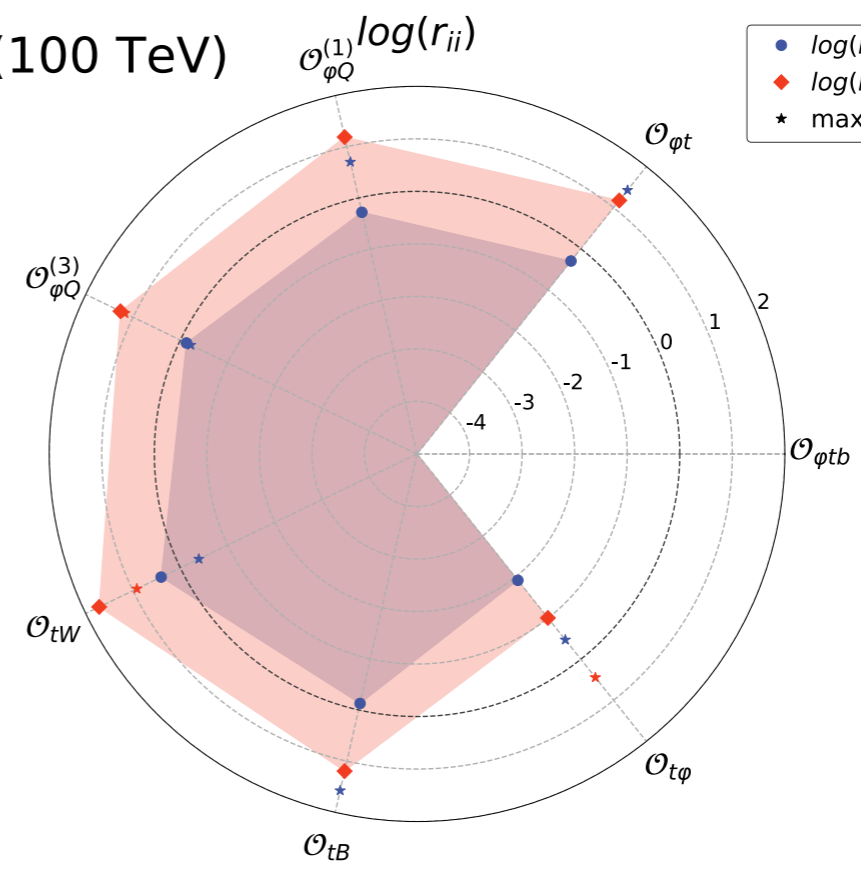
$\sigma_{100} = 130$ fb

Interference:
energy growth
& $O(1)$ effects



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

Quadratic:
energy growth
& $O(10-100)$



High-energy EW tops

High-energy EW tops

Sometimes, need to go beyond 4-point scattering

High-energy EW tops

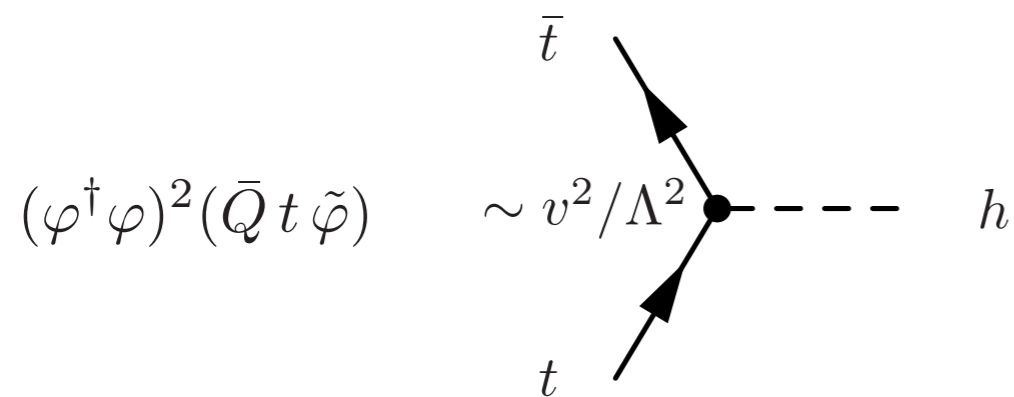
Sometimes, need to go beyond 4-point scattering

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

High-energy EW tops

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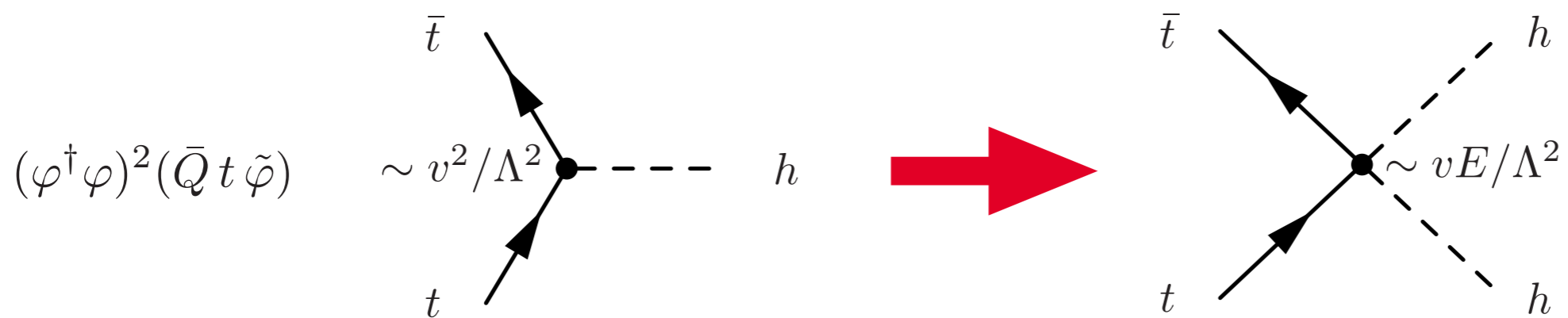
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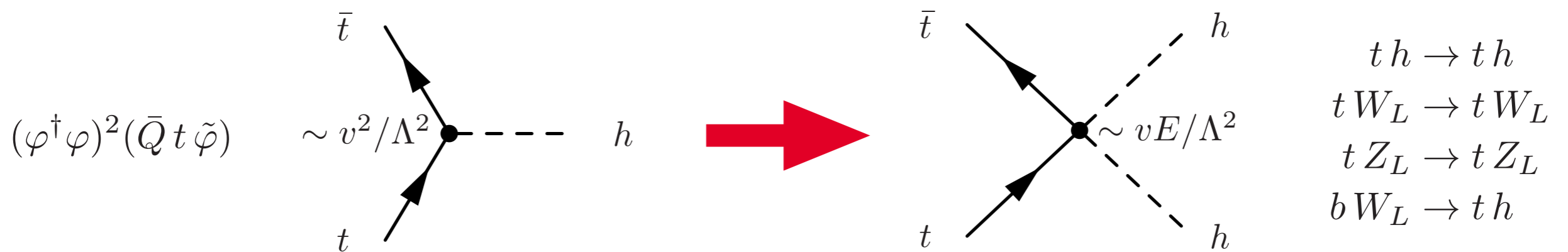
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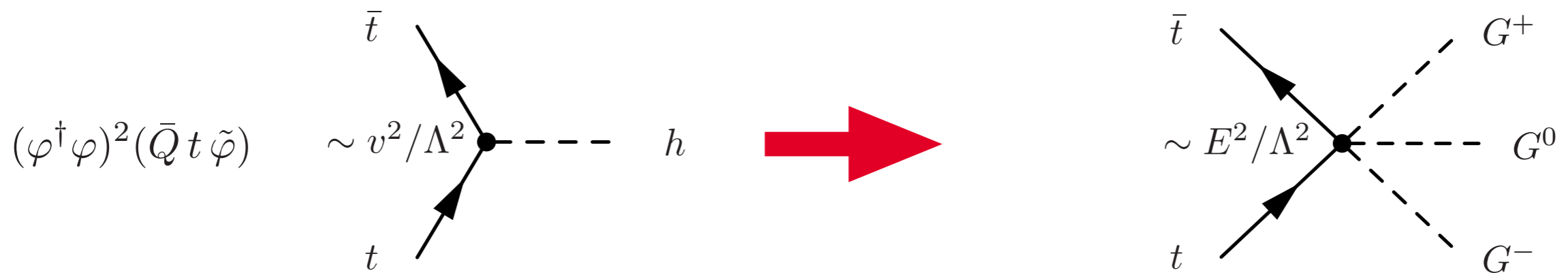
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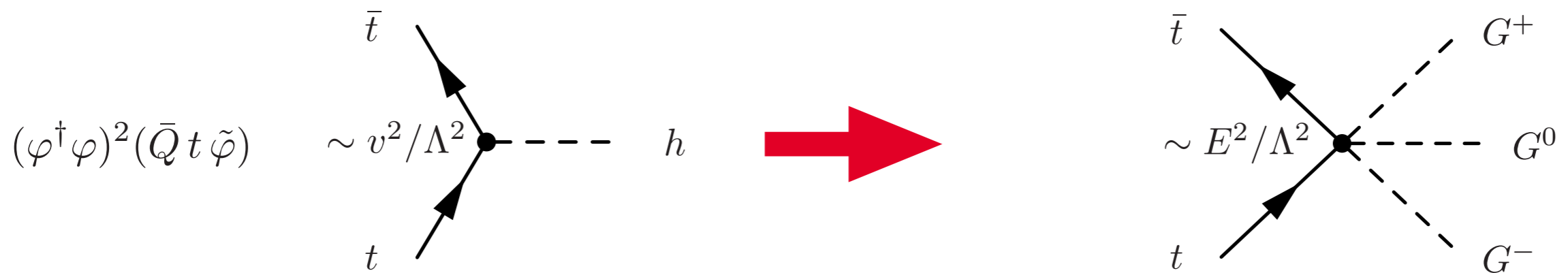
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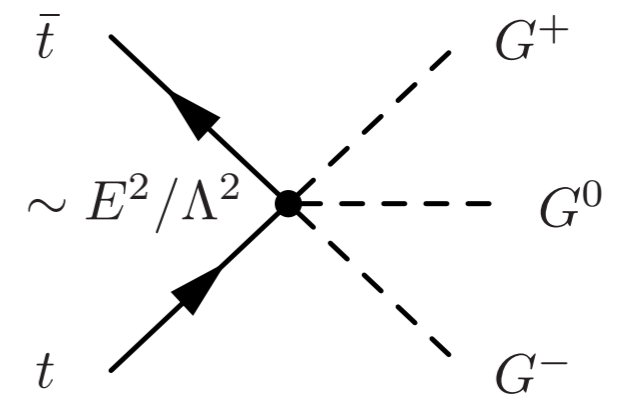
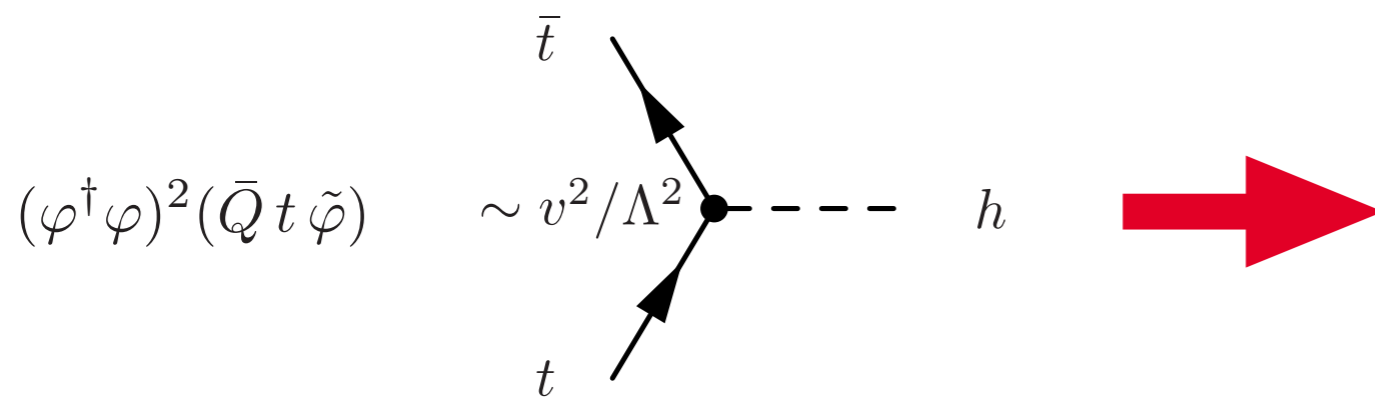


Essential prediction of **SMEFT**

High-energy EW tops

Sometimes, need to go beyond 4-point scattering

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Essential prediction of **SMEFT**

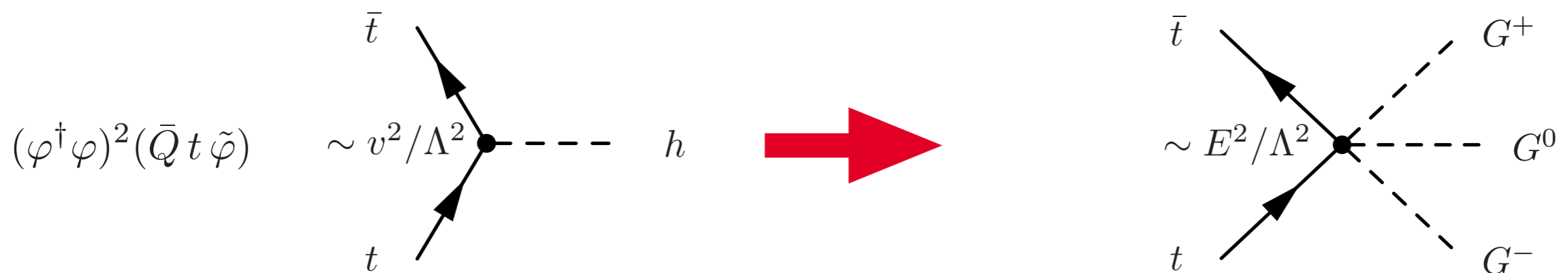
- Higgs & Goldstones in the same multiplet

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

High-energy EW tops

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Essential prediction of **SMEFT**

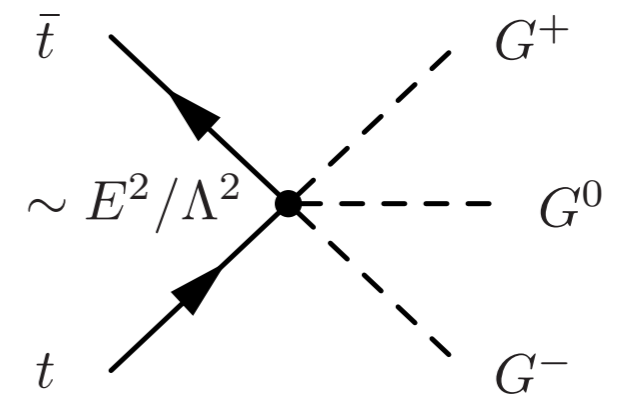
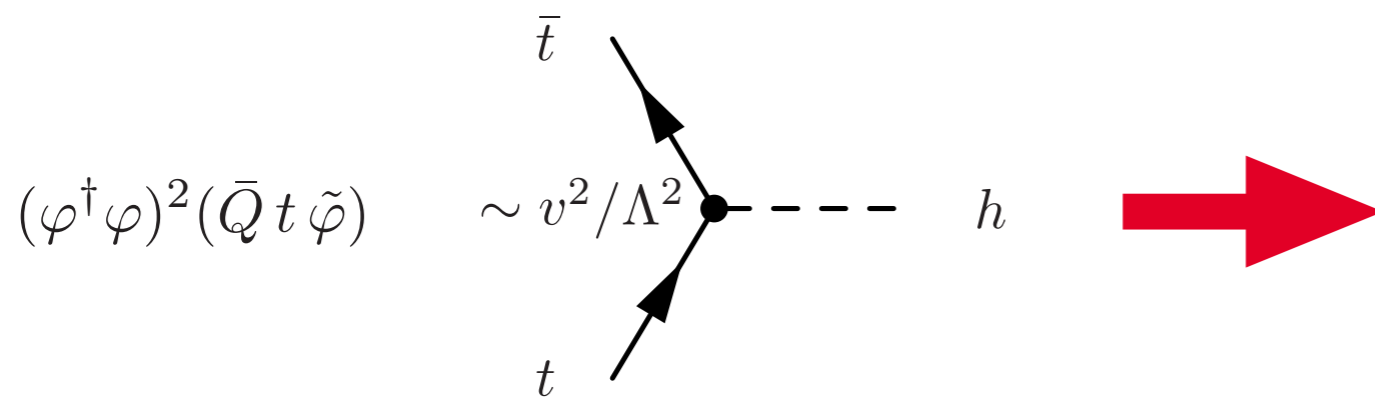
- Higgs & Goldstones in the same multiplet
- Modified EW top interactions predict energy growth in **higher multiplicity processes** involving **longitudinal** gauge bosons, **Higgs** & **top quarks**

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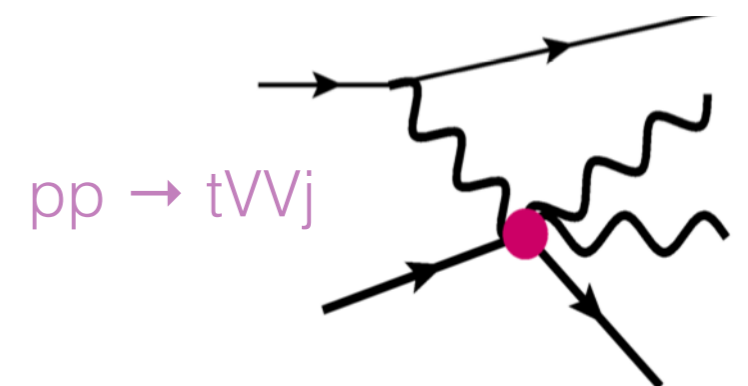
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Essential prediction of **SMEFT**

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[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 $2 \rightarrow 2$ 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