FACULTY OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY
RESEARCH GROUP EXPERIMENTAL PARTICLE PHYSICS AND GRAVITY

EFT analysis of ttVV processes

Kaat Verschueren - 14-03-2025

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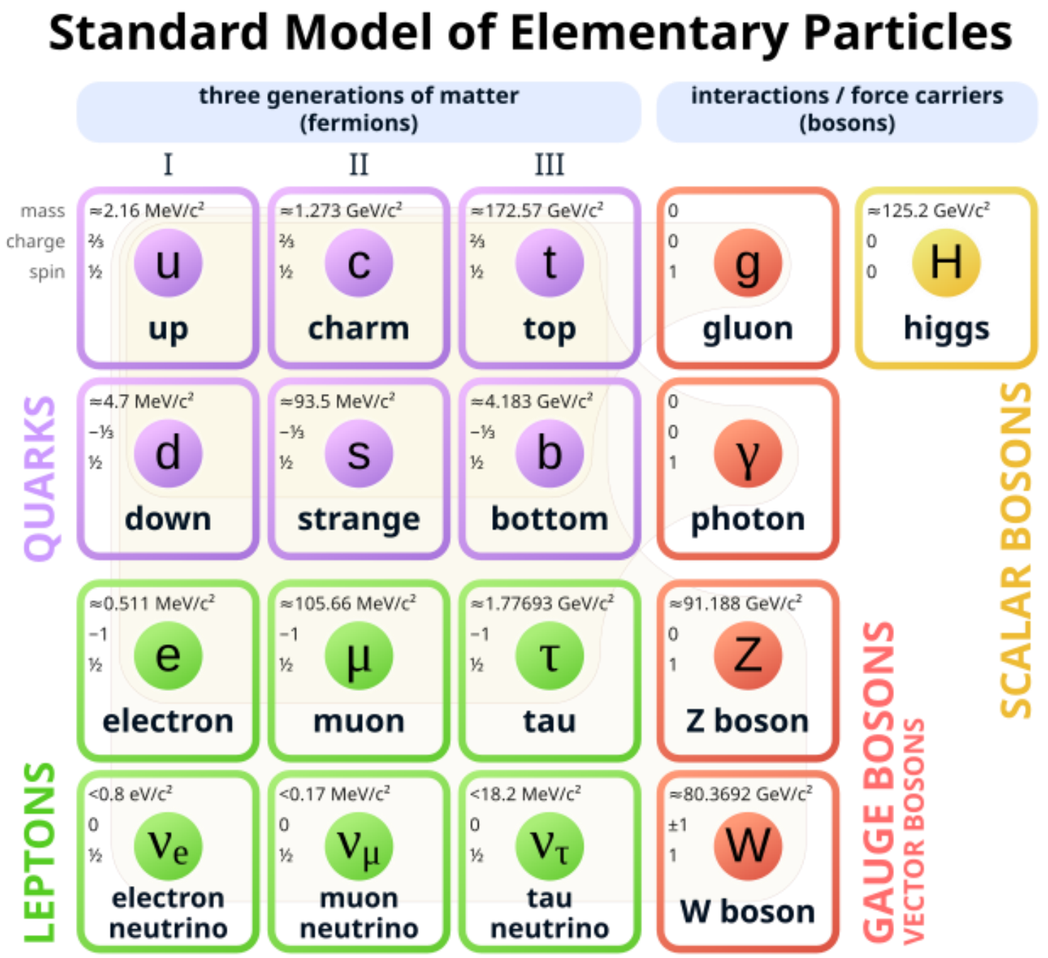
Promotor: Prof. Didar Dobur
Supervisors: Niels Van den Bossche, Dr. Joscha Knolle

Why new physics?

[Wikipedia]

- SM works well, but incomplete
- Beyond SM
- Where to look?



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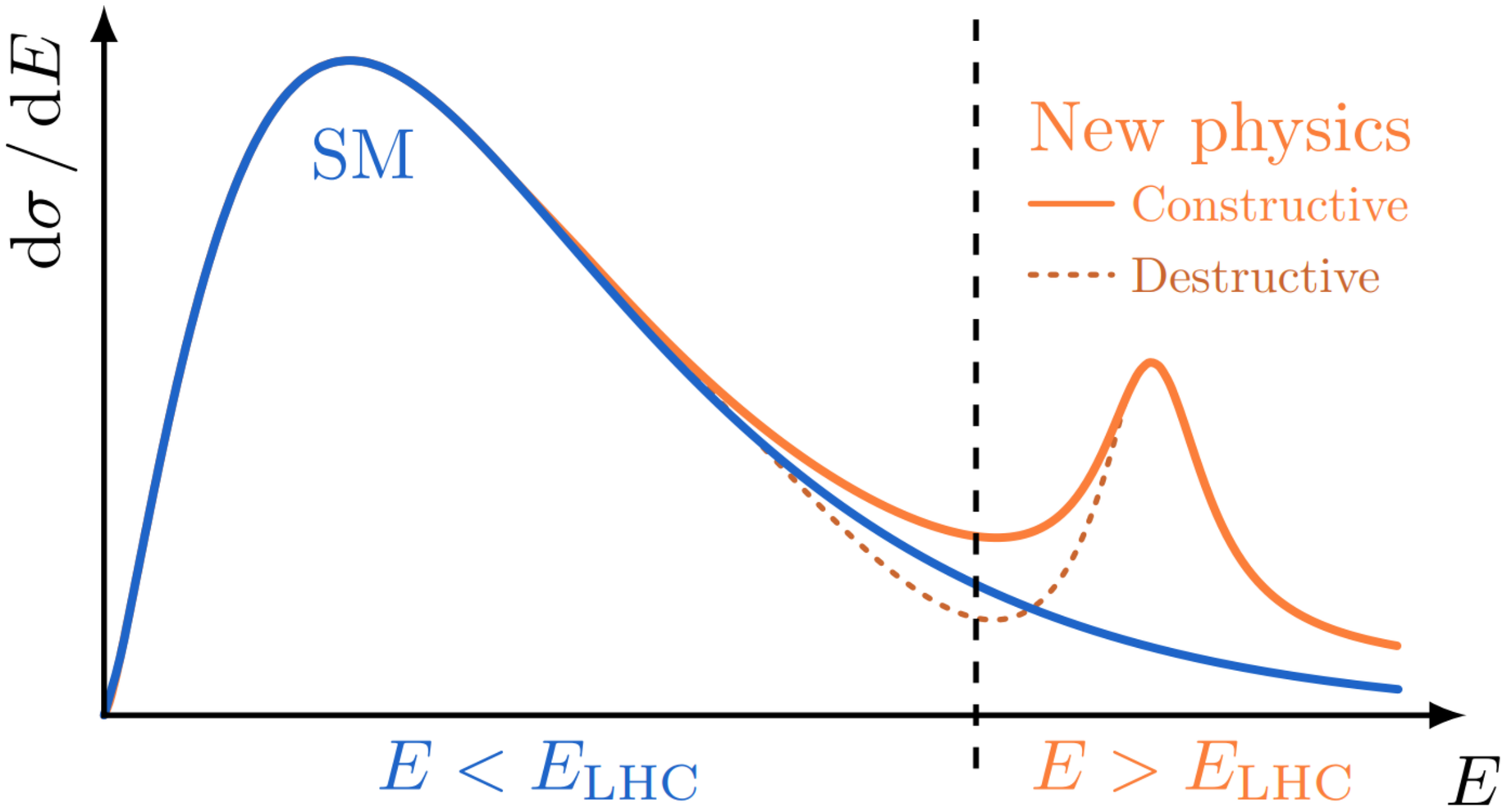
New physics

[Knolle, J.]



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SMEFT

- Deviations interactions SM particles
- Operators
  - Modify interactions
  - Introduce new structures
  - Wilson coefficients

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i C_i \mathcal{O}_i^{(D)}$$

$$C_i \rightarrow \frac{c_i}{\Lambda^{D-4}}$$

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SMEFT

- Deviations interactions SM particles
- Operators
  - Modify interactions
  - Introduce new structures
  - Wilson coefficients
  - $D = 6$

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)}$$

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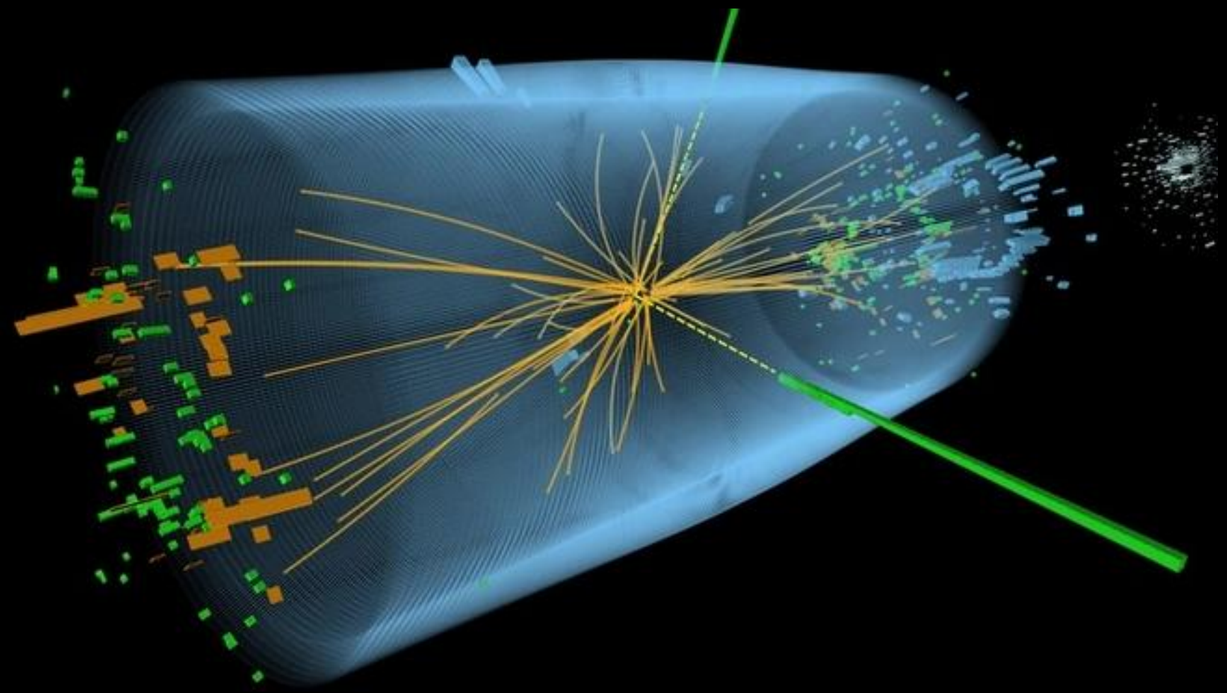
Top quark physics

$t\bar{t} + X$

EW interactions top quark



high mass

high E scales

SM

BSM

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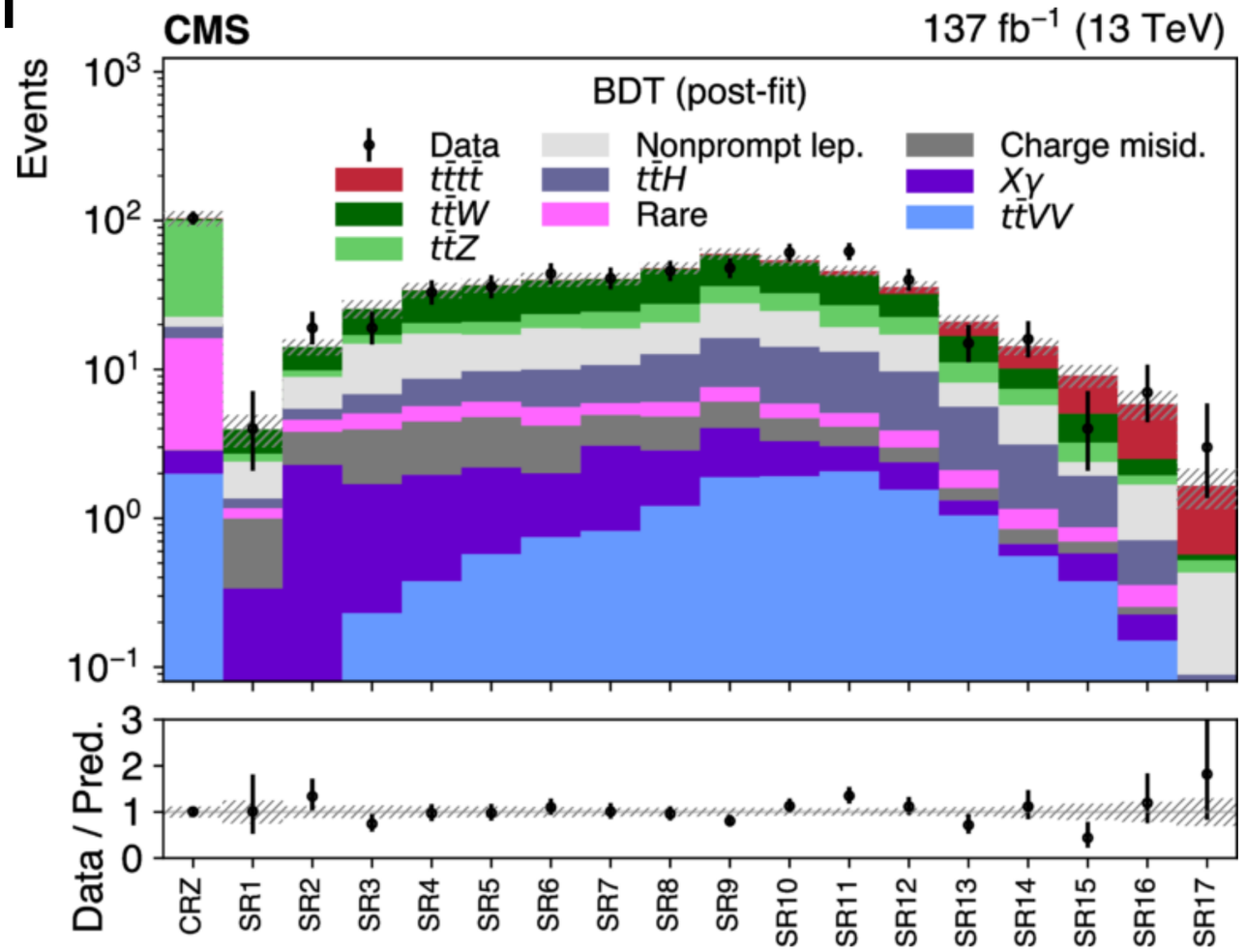
ttVV processes

[Eur. Phys. J. C 80 (2020) 75]

- Background process $t\bar{t}V$ & $t\bar{t}t\bar{t}$
- gg channel



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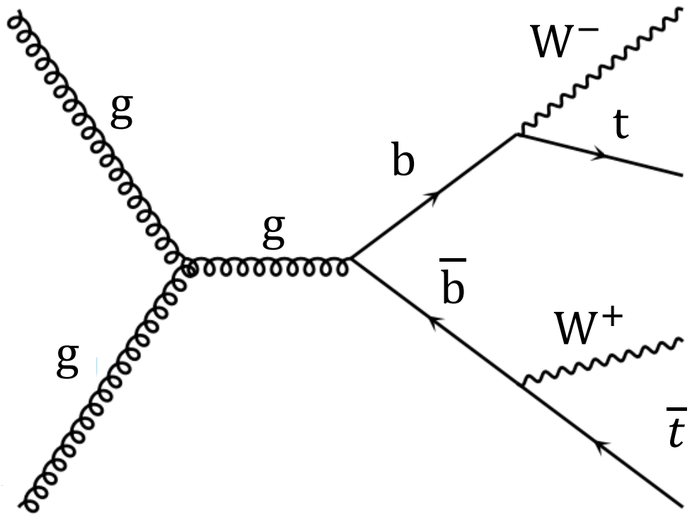
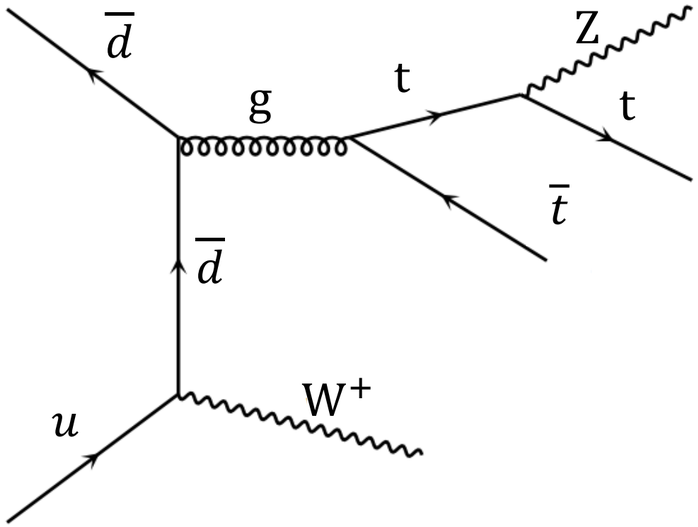
ttVV processes

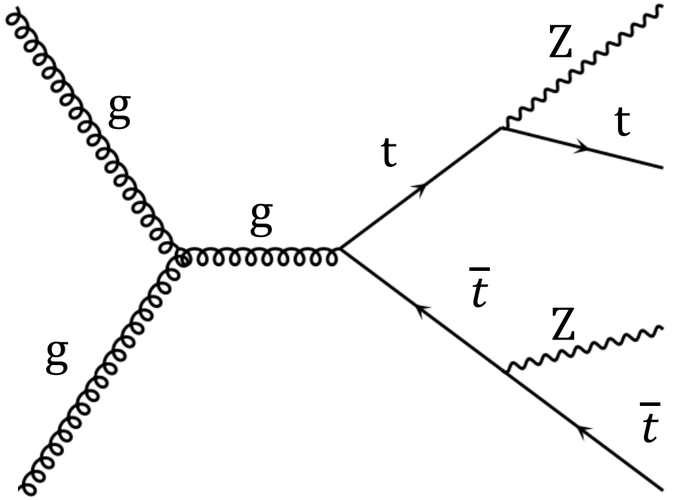
$t\bar{t}W^+W^-$



$t\bar{t}W^{\pm}Z$



$t\bar{t}ZZ$



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Wilson coefficients for ttVV

[Maltoni, F., Mantani, L. & Mimasu, K. (2019)]

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

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

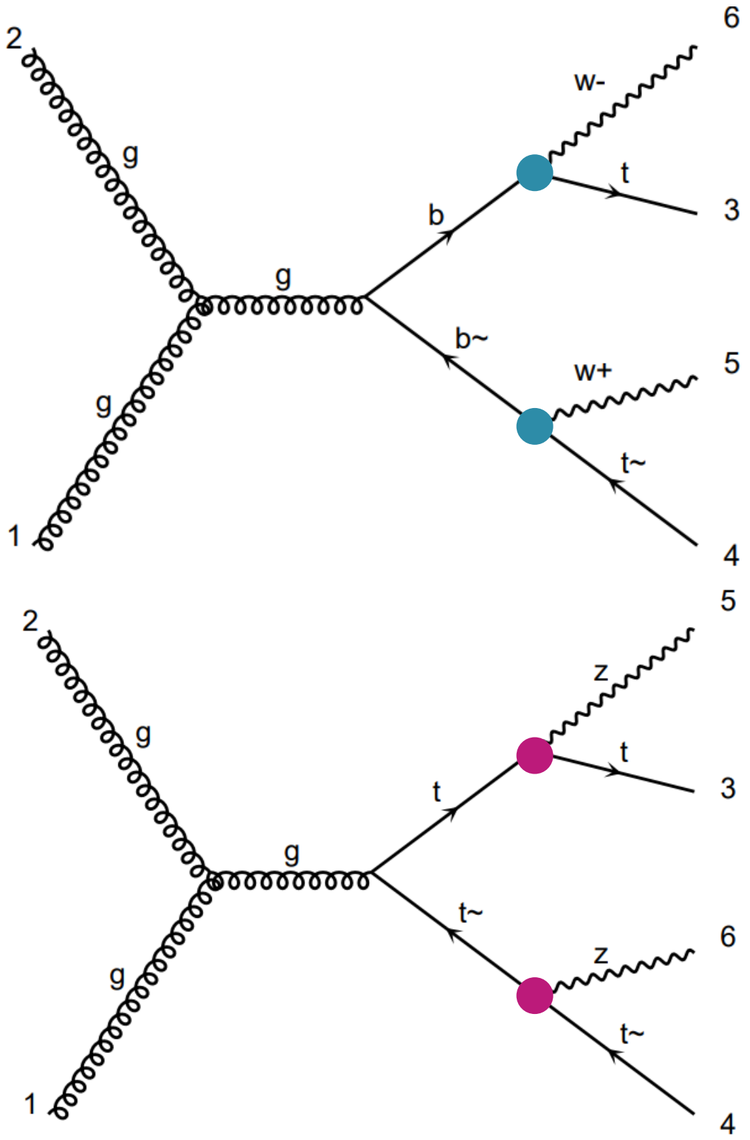
$$\mathcal{O}^{(3)}_{\varphi Q} \quad i\left(\varphi^\dagger \overleftrightarrow{D}_\mu\,\tau_I\varphi\right)\left(\bar{Q}\,\gamma^\mu\,\tau^I Q\right)$$

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

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

$$\mathcal{O}_{t\varphi} \quad \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\,t\,\tilde{\varphi} + \text{h.c.}$$

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



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Event simulations

Monte Carlo

SM ➔ SMEFT: reweighting parameters

`SMEFTsim topU3l`

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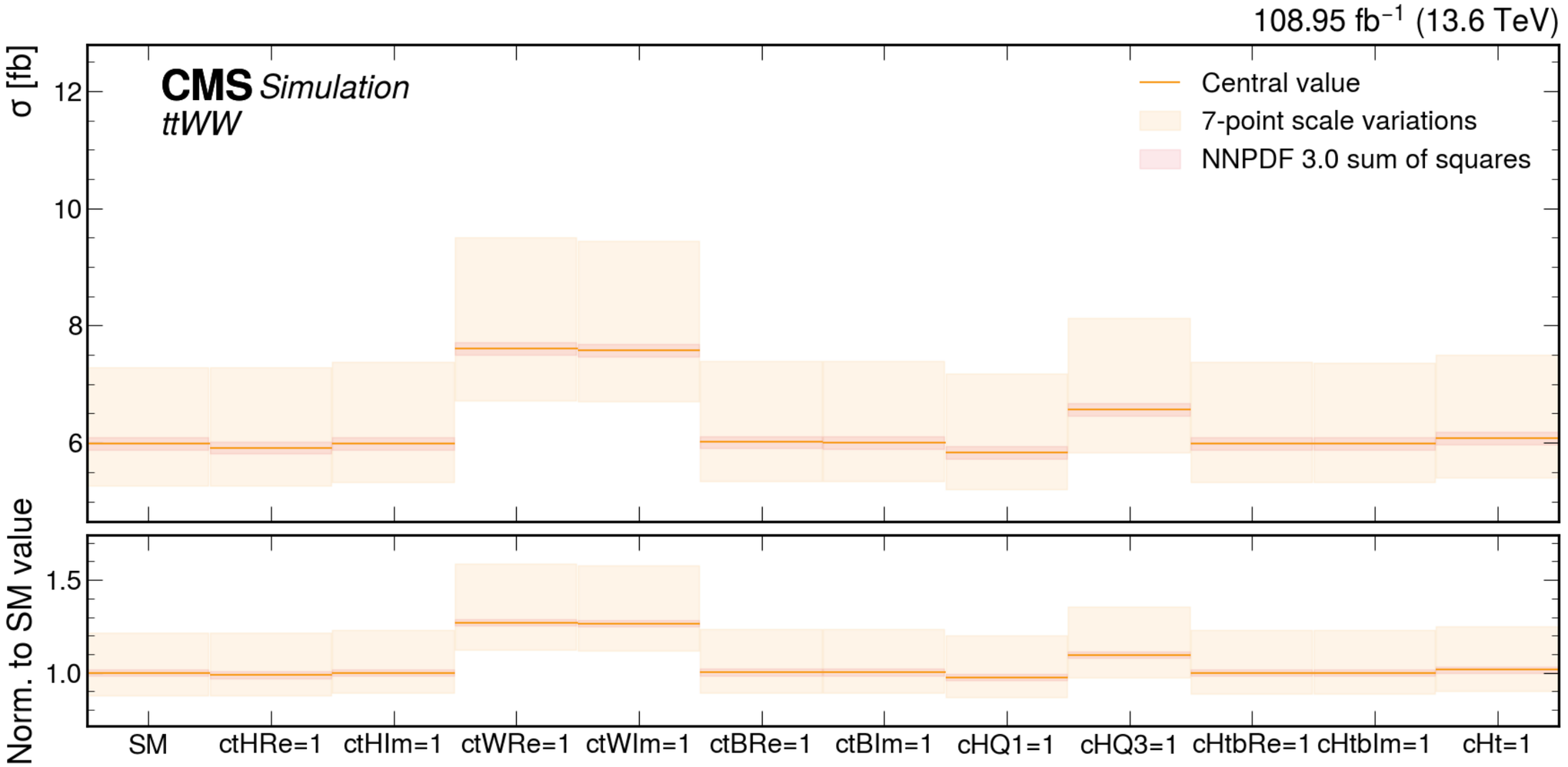
Event simulations



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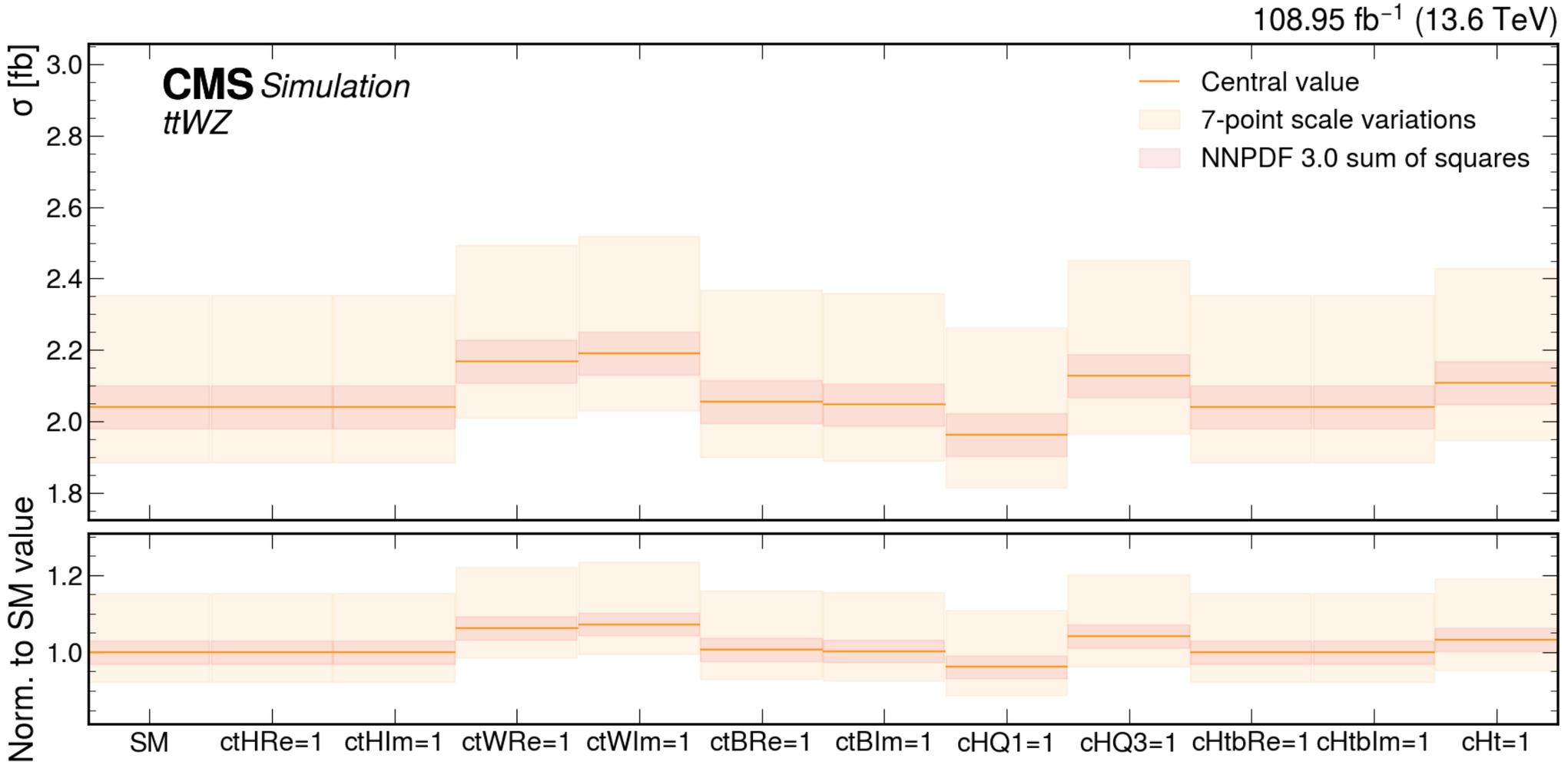
Event simulations



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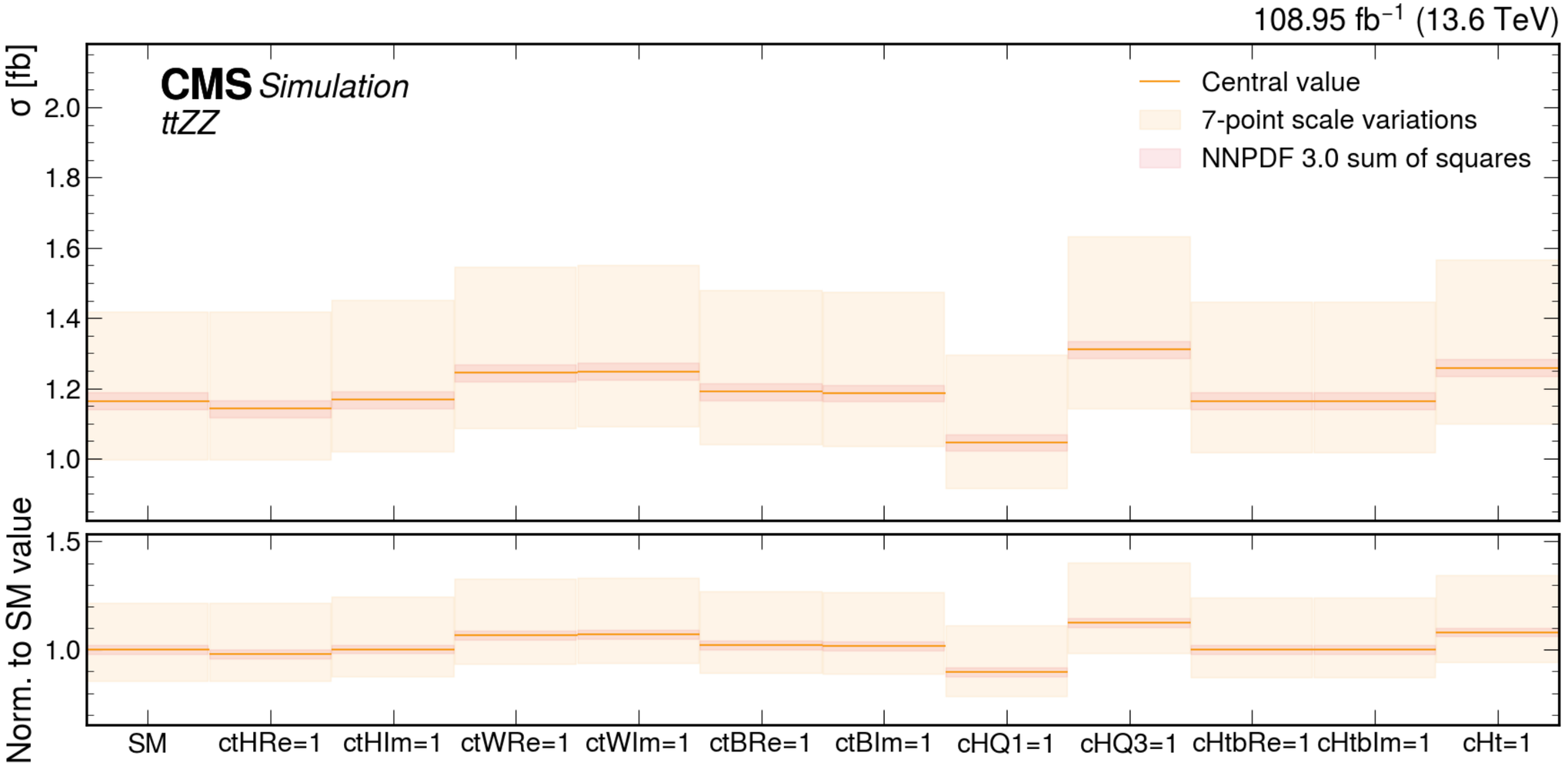
Event simulations



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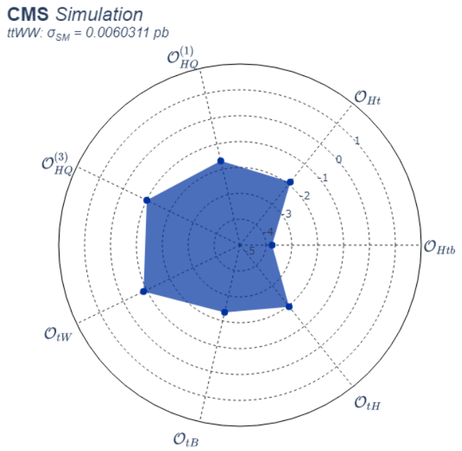
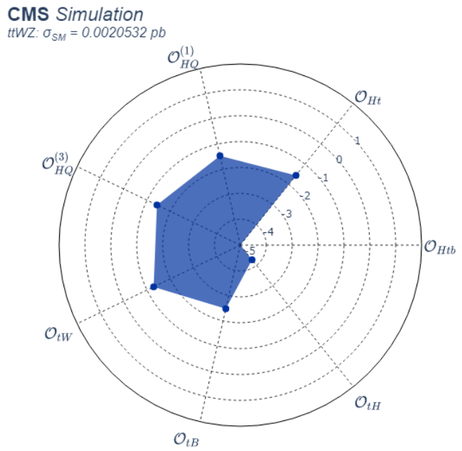
Event simulations

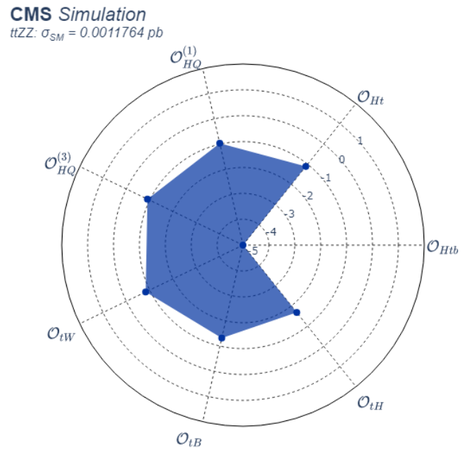
$t\bar{t}W^+W^-$



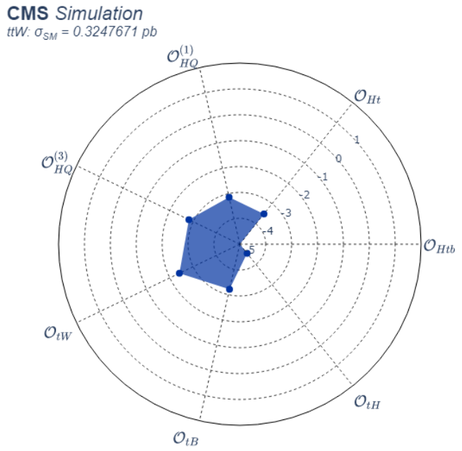
$t\bar{t}W^{\pm}Z$



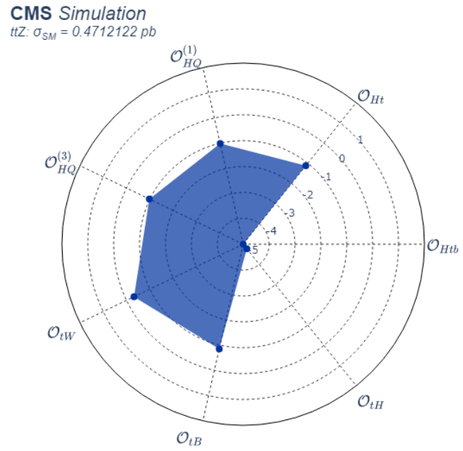
$t\bar{t}ZZ$



$t\bar{t}W^{\pm}$



$t\bar{t}Z$



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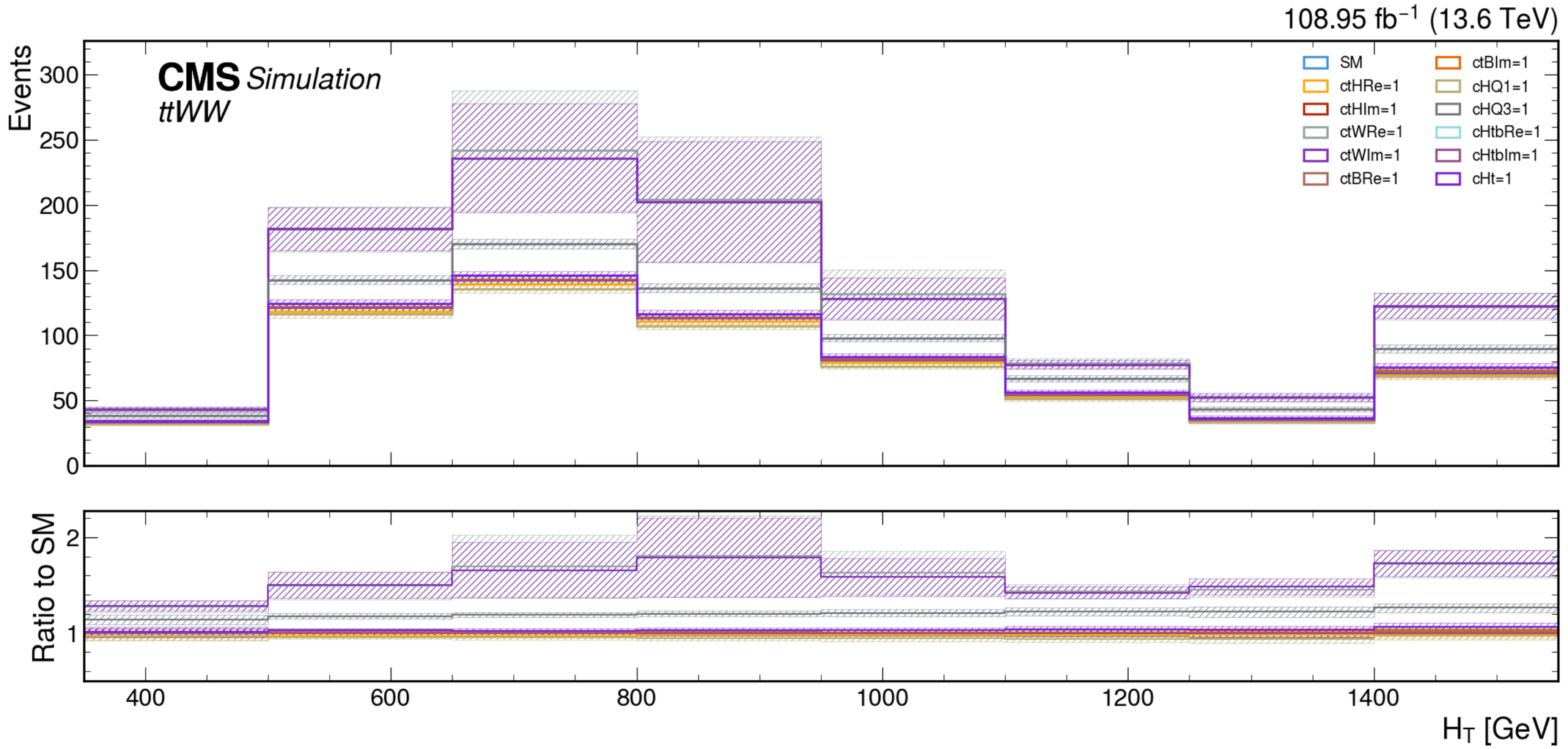
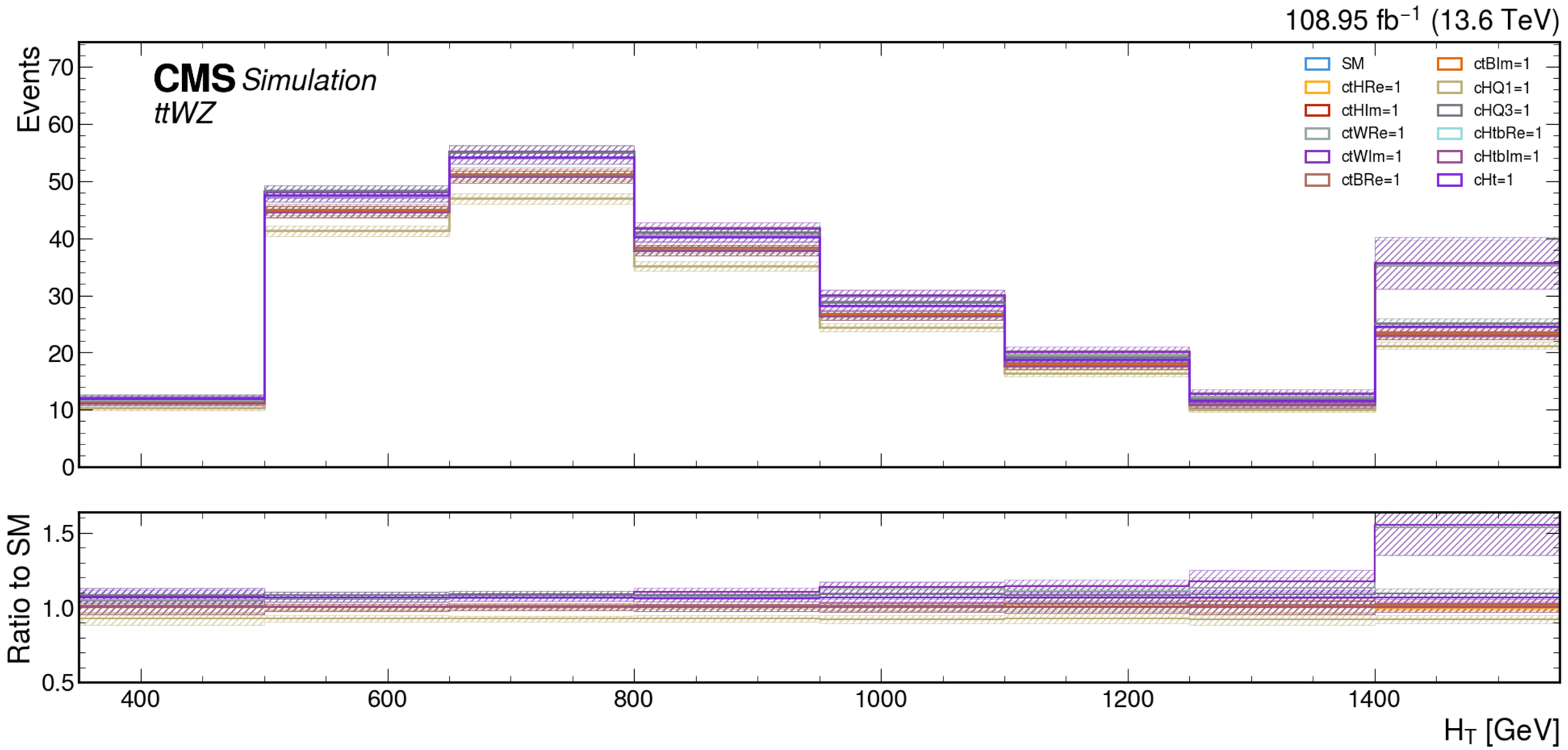
Event simulations



Event simulations



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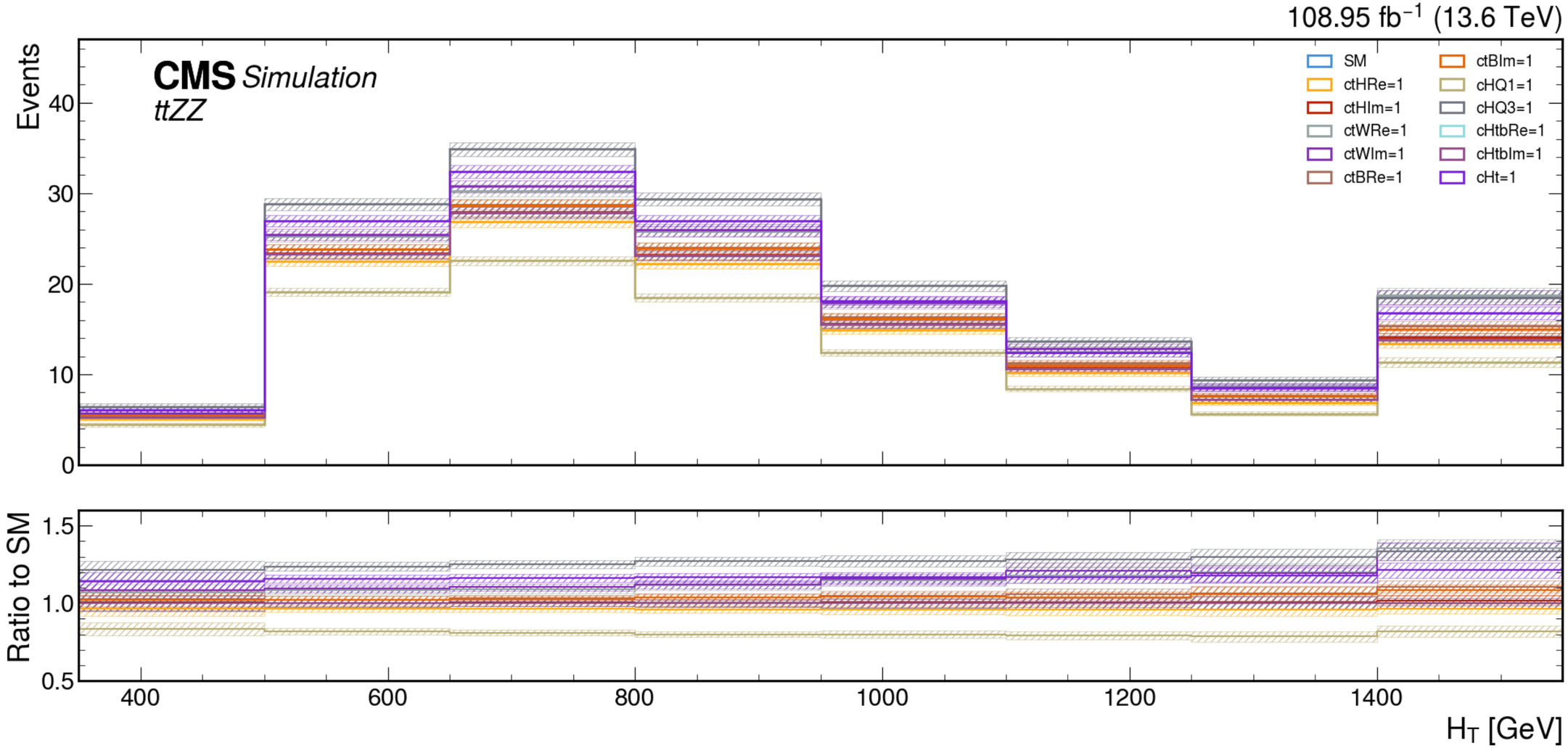
Event simulations



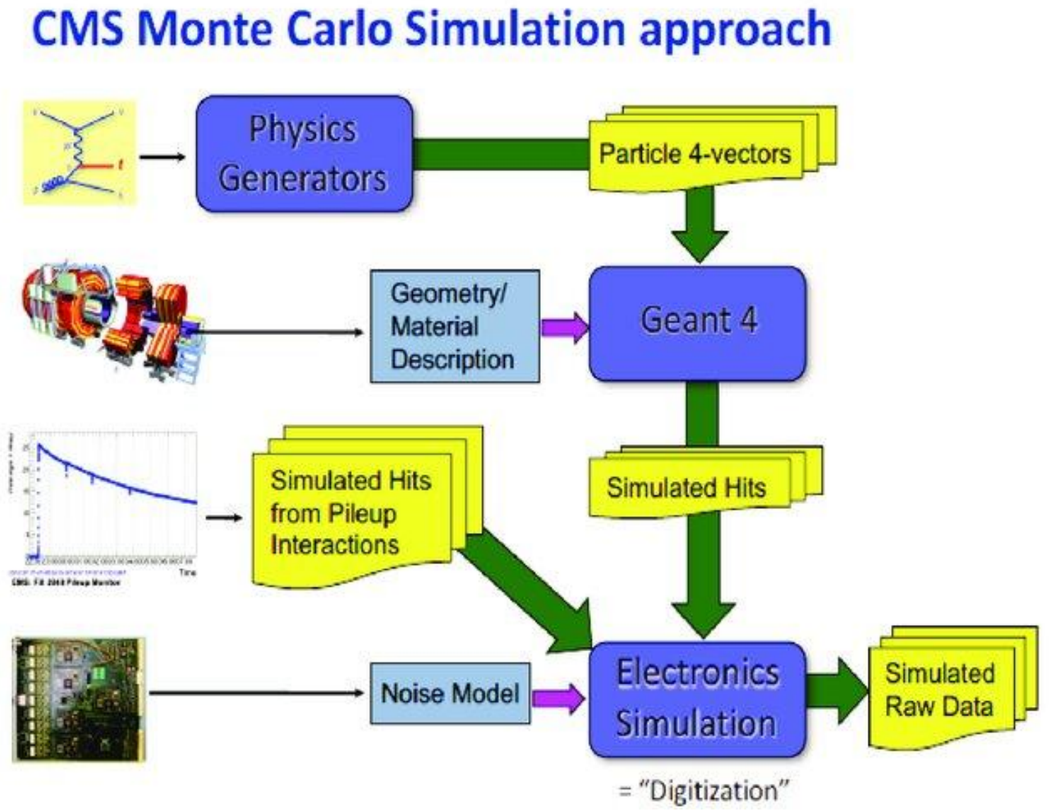
Next steps

[CMS Collaboration]

- FullSim
- Analysis strategy

GOAL: phase space regions

where ttVV is relevant



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References

[1] A. Hayrapetyan, A. Tumasyan, and W. Adam, Journal of High Energy Physics **2023** (2023), 10.1007/jhep12(2023)068.

[2] A. M. Sirunyan, A. Tumasyan, and W. Adam, The European Physical Journal C **80** (2020), 10.1140/epjc/s10052-019-7593-7.

[3] M. Hildreth, V. Ivanchenko, and D. Lange, Journal of Physics: Conference Series **898**, 042040 (2017).

[4] F. Maltoni, L. Mantani, and K. Mimasu, Journal of High Energy Physics **2019** (2019), 10.1007/jhep10(2019)004.

[5] R. Alonso, E. E. Jenkins, A. V. Manohar, and M. Trott, Journal of High Energy Physics **2014** (2014), 10.1007/jhep04(2014)159.

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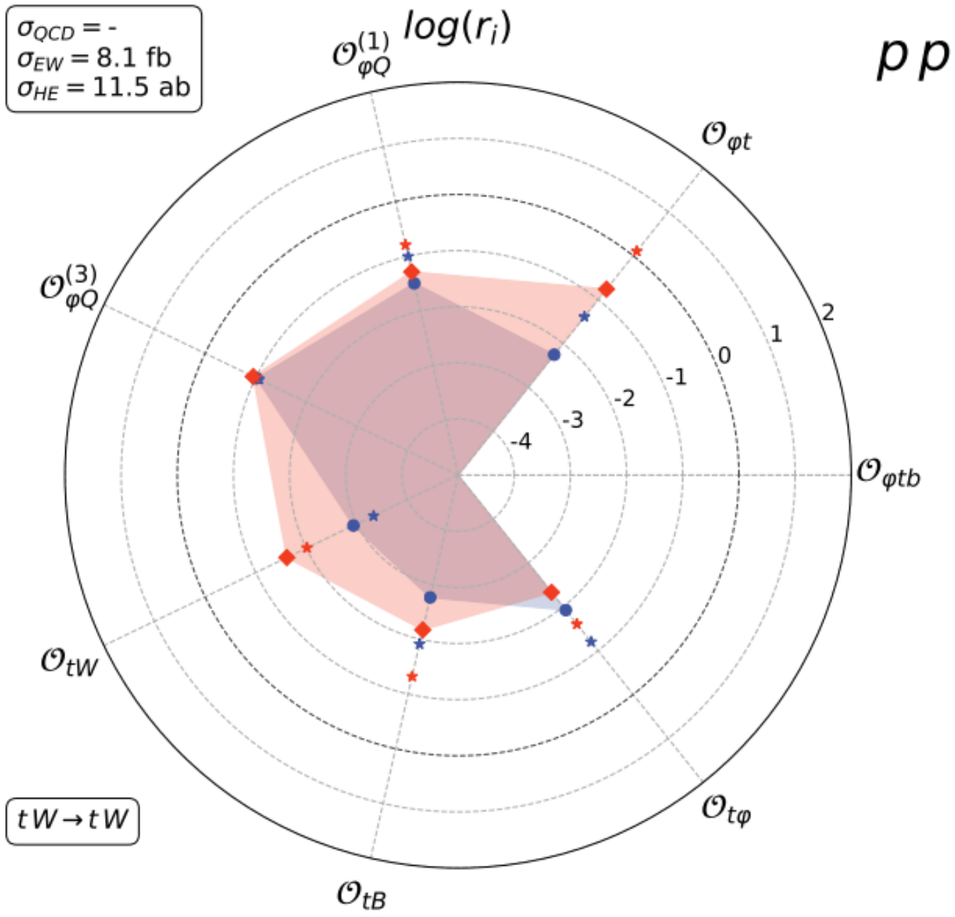
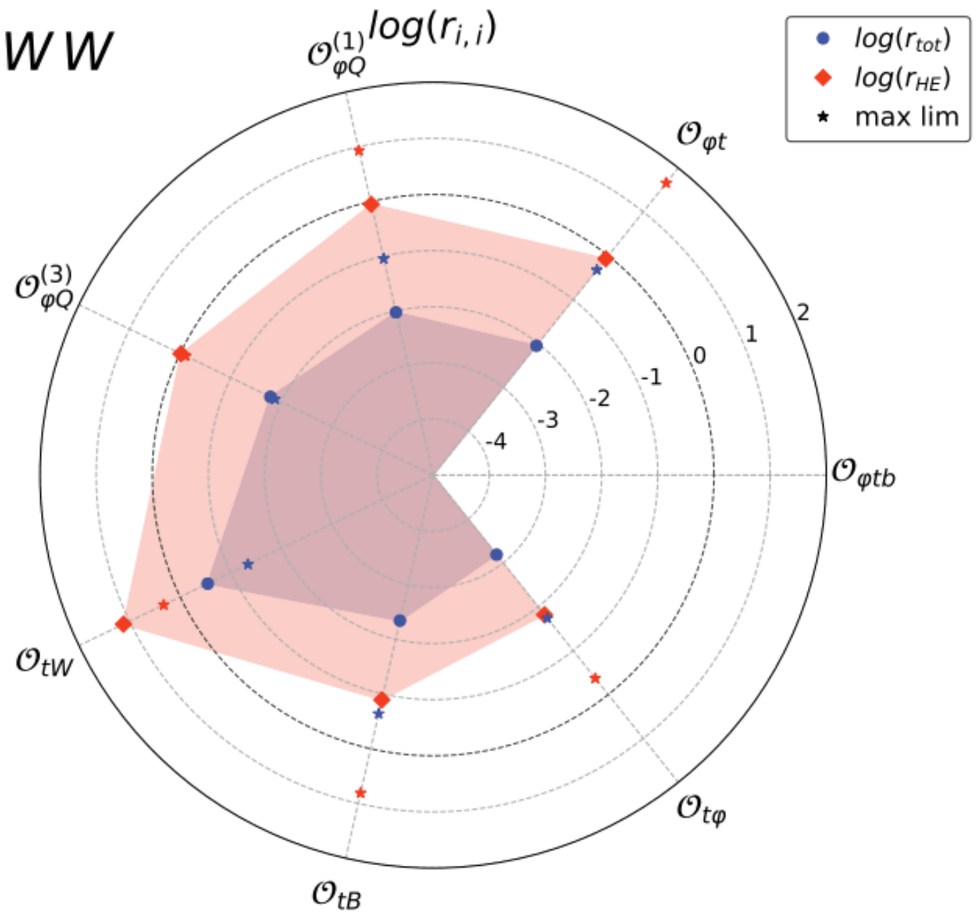
Radar plots

[Maltoni, F., Mantani, L. & Mimasu, K. (2020)]



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



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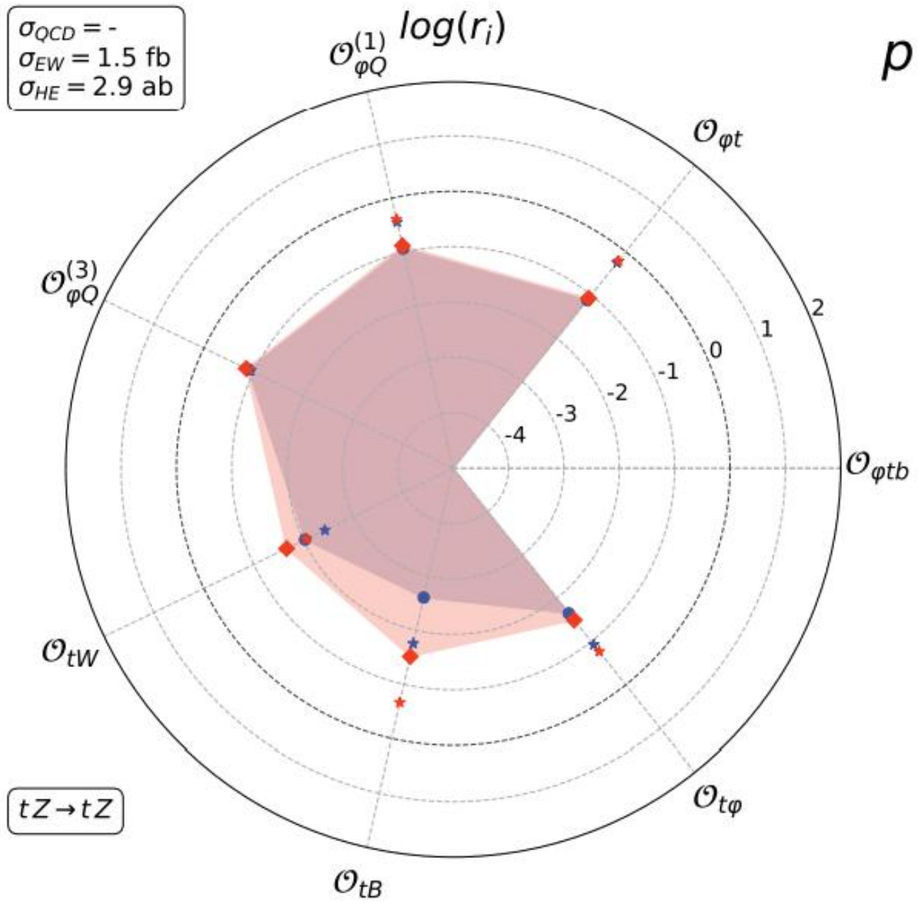

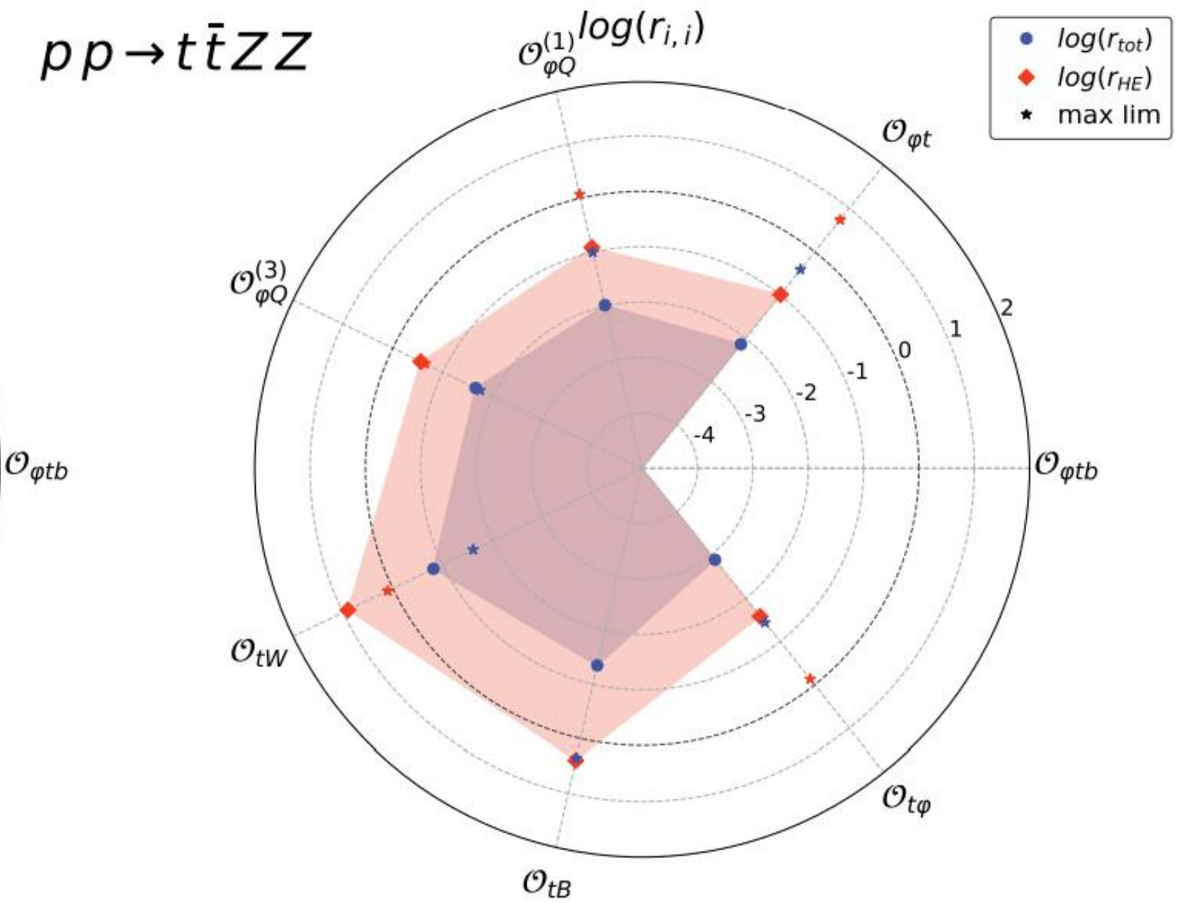

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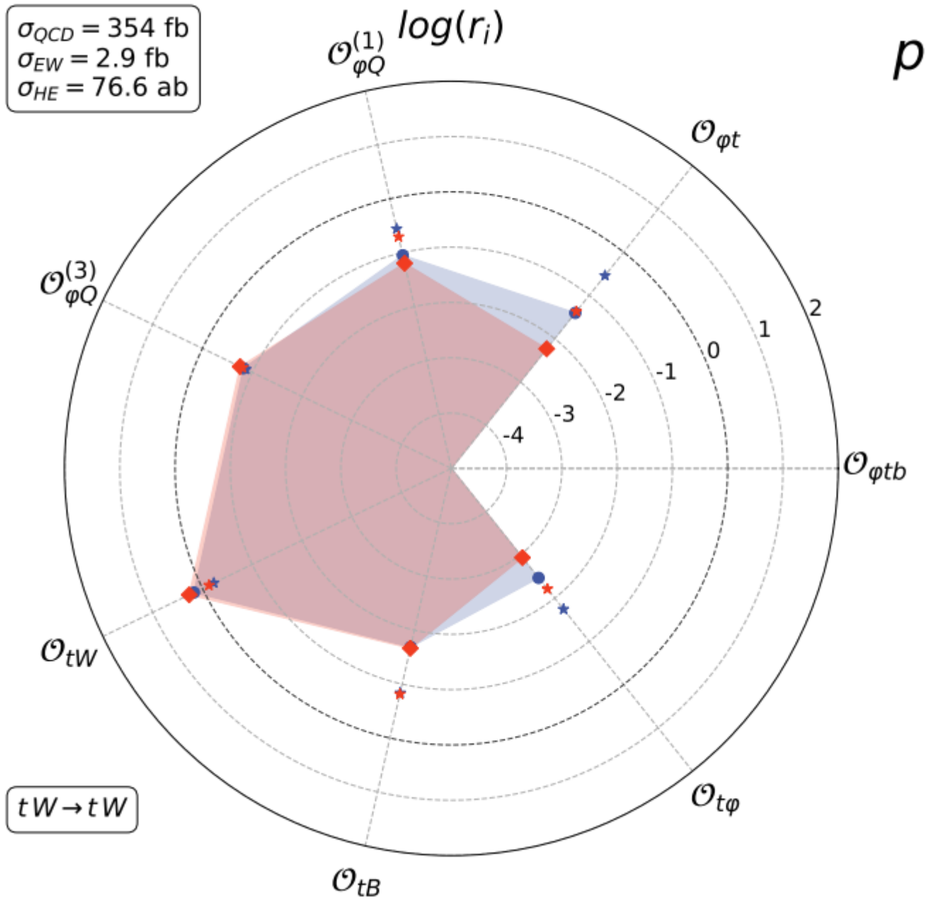
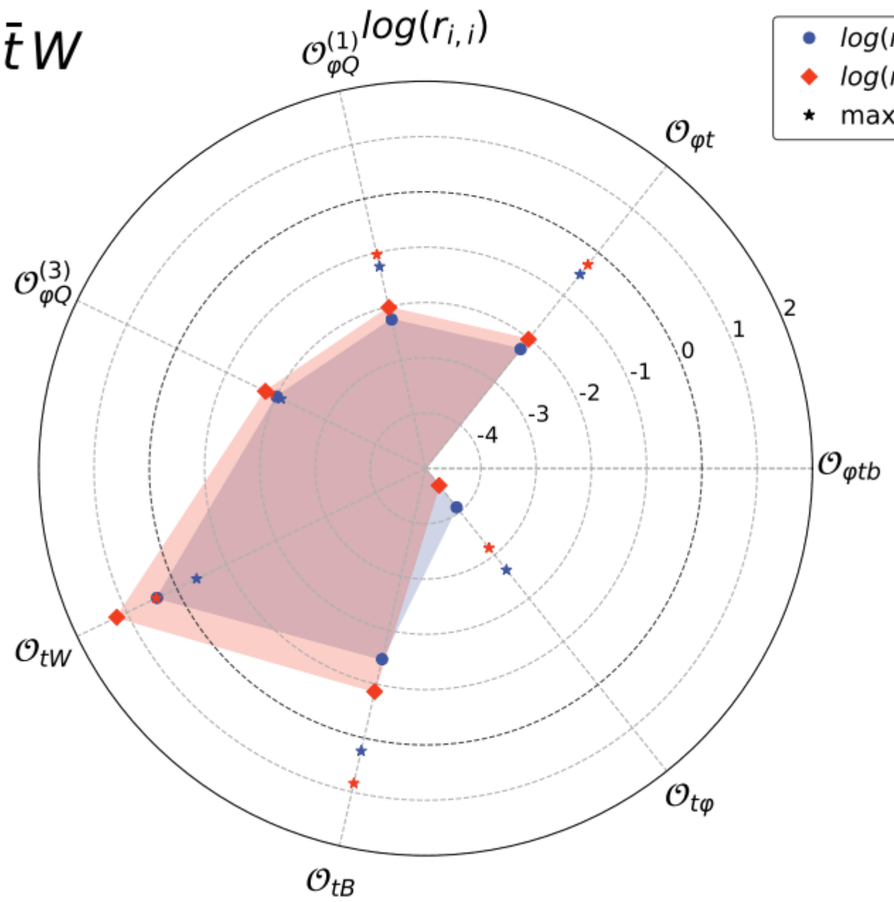


$pp \to t\bar{t}W$



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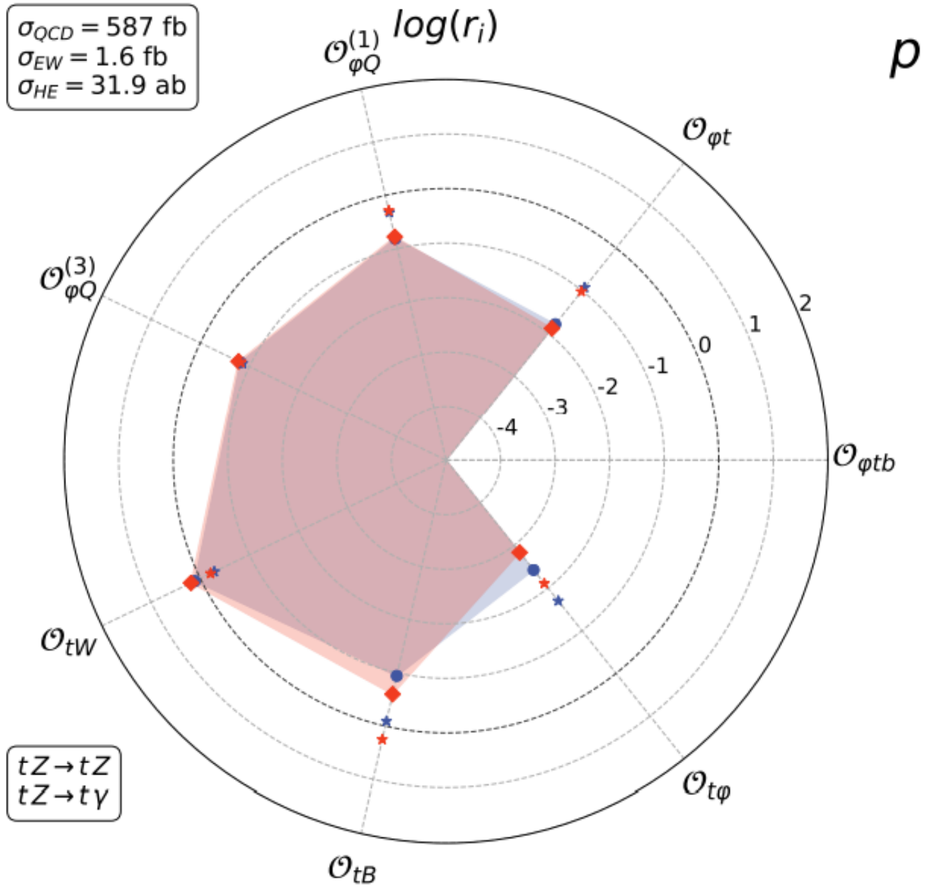

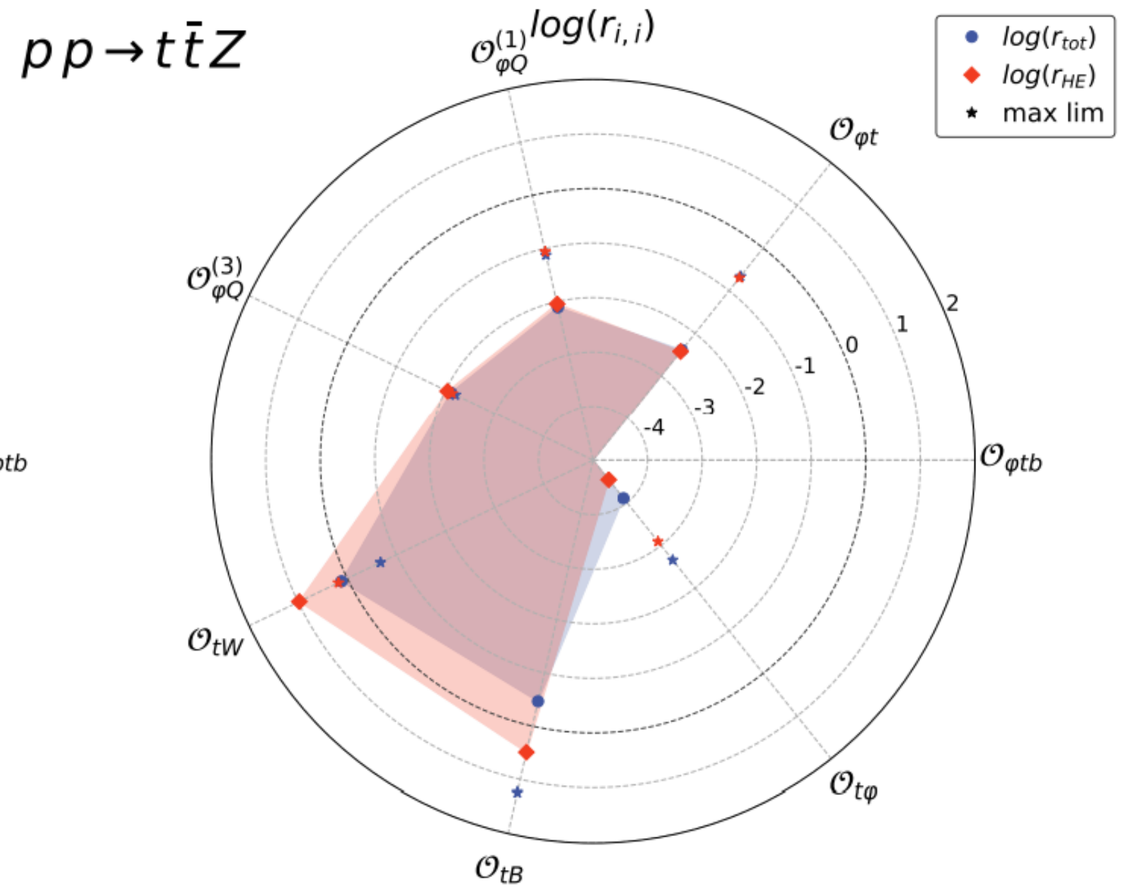

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Wilson coefficients

[Alonso, R., Jenkins, E.E., Manohar, A.V. et al. (2014)]

$1 : X^3$	
Q_G	$f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$
Q_W	$\epsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$

$2 : H^6$	
Q_H	$(H^\dagger H)^3$

$3 : H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5 : \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4 : X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6 : \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7 : \psi^2 H^2 D$	
$Q^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$Q_{Hud} + \text{h.c.}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

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Wilson coefficients

[Alonso, R., Jenkins, E.E., Manohar, A.V. et al. (2014)]

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

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N_ℓ	N_b	N_jets	Region
2	2	$\leq$5	CRW
		6	SR1
		7	SR2
		$\geq$8	SR3
	3	5	SR4
		6	SR5
		7	SR6
		$\geq$8	SR7
	$\geq$ 4	$\geq$5	SR8
$\geq$ 3	2	5	SR9
		6	SR10
		$\geq$7	SR11
	$\geq$ 3	4	SR12
		5	SR13
		$\geq$6	SR14
Inverted resonance veto			CRZ

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