ZH production in the SMEFT from gluon fusion

Marion Thomas
University of Manchester

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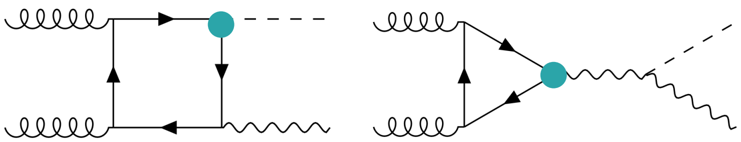
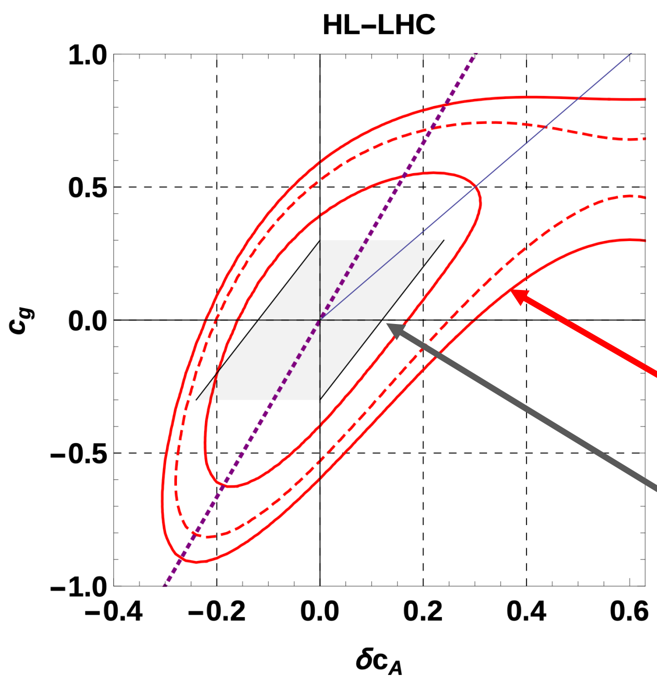
Based on JHEP11(2023)132 (In collaboration with A. Rossia and E. Vryonidou)
And ongoing work

Why study ZH production from gluon fusion?

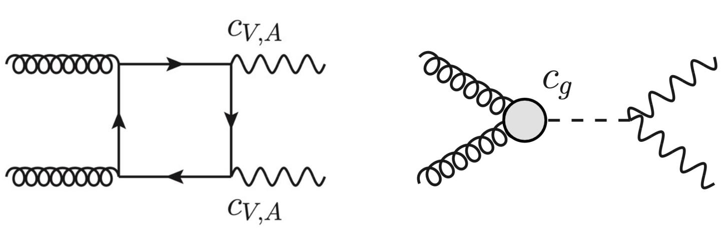
Dominated by top loops → Sensitivity to top couplings



Probe poorly constrained Higgs and top operators



Plot from Azatov, Grojean, Paul, Salvioni
arXiv: 1608.00977



Constraints from $gg \to ZZ$

Constraint from $gg \to ZH$
Englert et al, arXiv:1603.05304

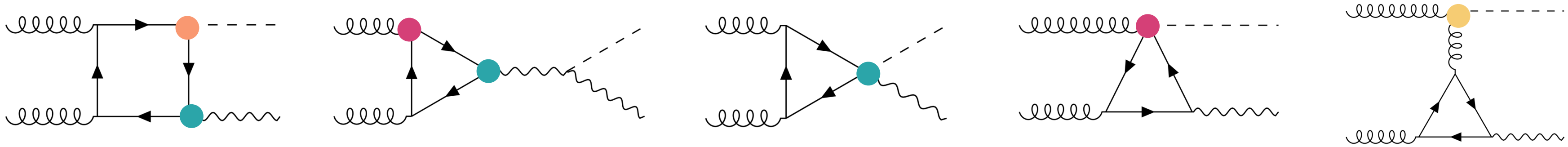
See also: Englert, Soreq, Spannowsky, arXiv:1410.5440
Cao, Yan, Yuan and Zhang, arXiv:2004.02031

Which SMEFT operators can we probe?

Warsaw basis of dim-6 SMEFT operators.
Flavour symmetry: $\mathrm{U}(2)_q \times \mathrm{U}(3)_d \times \mathrm{U}(2)_u$

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda} c^{(5)} \mathcal{O}^{(5)} + \frac{1}{\Lambda^2} \sum_k c_k^{(6)} \mathcal{O}_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

CP-even and **CP-odd** operators



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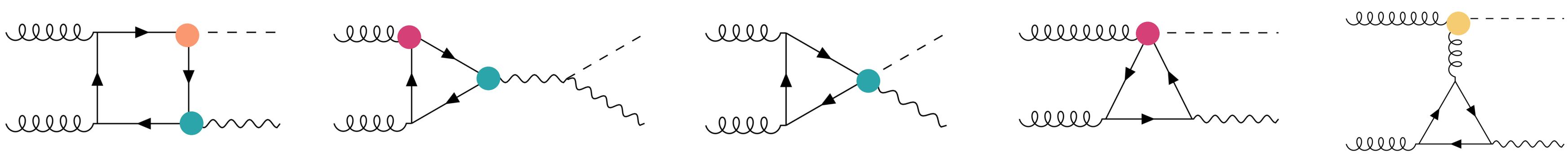
CP-even and CP-odd operators



Higgs Operators

$\mathcal{O}_{\varphi G}$	$c_{\varphi G}$	$\left(\varphi^\dagger \varphi - \frac{v^2}{2}\right) G_A^{\mu\nu} G^A_{\mu\nu}$
$\mathcal{O}_{\varphi \tilde{G}}$	$c_{\varphi \tilde{G}}$	$\left(\varphi^\dagger \varphi - \frac{v^2}{2}\right) \tilde{G}_A^{\mu\nu} G^A_{\mu\nu}$

Yukawa and dipole operators

$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$\left(\varphi^\dagger \varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \mathrm{h.c.}$
$\mathcal{O}_{tG}$	c_{tG}	$igs\, (\bar{Q} \tau^{\mu\nu} T_A\, t)\, \tilde{\varphi}\, G^A_{\mu\nu} + \mathrm{h.c.}$

Top Operators

$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t} \gamma^\mu t)$
$\mathcal{O}^{(1)}_{\varphi Q}$	$c^{(1)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q} \gamma^\mu Q)$
$\mathcal{O}^{(3)}_{\varphi Q}$	$c^{(3)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q} \gamma^\mu \tau^I Q)$
$\mathcal{O}^{(-)}_{\varphi Q}$	$c^{(-)}_{\varphi Q}$	$c^{(1)}_{\varphi Q} - c^{(3)}_{\varphi Q}$

Growing helicity amplitudes

- Calculated analytical helicity amplitudes with **1 insertion of dim-6 SMEFT operators.**
- Studied high-energy behaviour of amplitudes → Which operators grow with energy?

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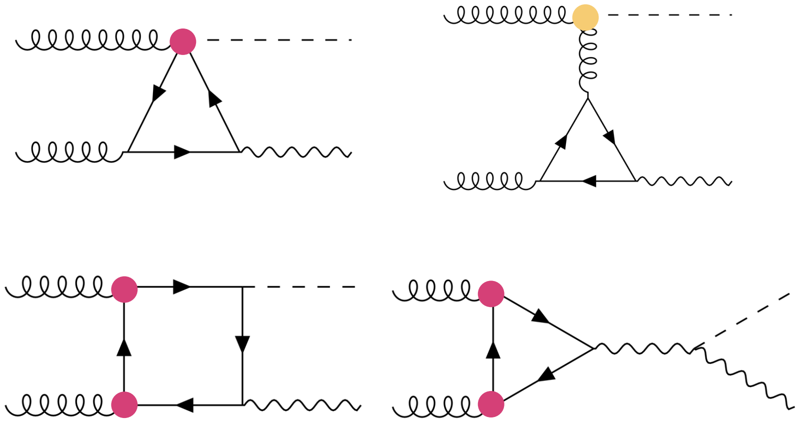
$\lambda_{g_1}, \lambda_{g_2}, \lambda_H, \lambda_Z$	$\mathcal{O}_{tG}$	$\mathcal{O}_{\varphi G}$
$+,+,0,+$	$\sqrt{s}\, m_t \log\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,0,-$	$\sqrt{s}\, m_t \log^2\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,0,0$	$\frac{m_t v^2}{m_Z} \log^2\left(\frac{s}{m_t^2}\right)$	$\frac{m_t^2 v}{m_Z} \log^2\left(\frac{s}{m_t^2}\right)$
$+,-,0,+$	$\sqrt{s}\, m_t$	$-$
$+,-,0,0$	$s\, \frac{m_t}{m_Z}$	$\frac{m_t^2 v}{m_Z} \log^2\left(\frac{s}{m_t^2}\right)$



Tightly constrained

$$0.019 < c_{tG} < 0.180$$

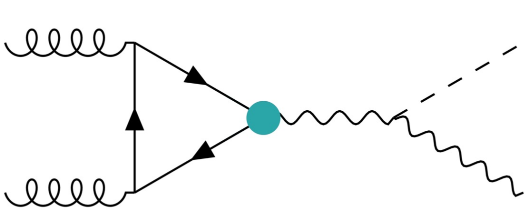
$$-0.018 < c_{\varphi G} < 0.08$$

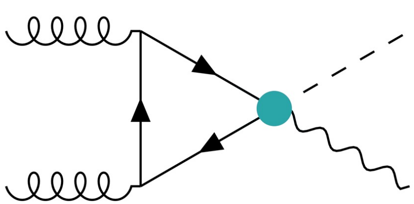
SMEFiT Collaboration, arXiv: 2404.12809

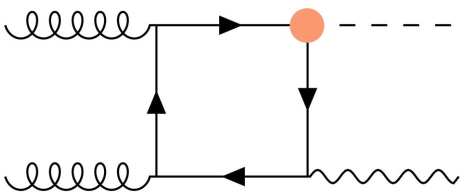
Growing amplitudes in current operators

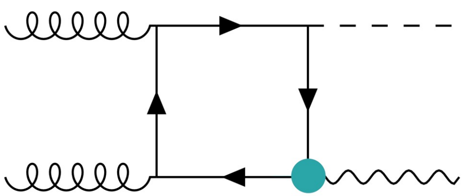
→ Poorly constrained operators
→ Logarithmic growth in the helicity amplitudes

$\lambda_{g_1}, \lambda_{g_2}, \lambda_H, \lambda_Z$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$	$\mathcal{O}_{t\varphi}$
$+,+,0,0$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_{\rm w}\, s_{\rm w}} \left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_{\rm w}\, s_{\rm w}} \left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_{\rm w}\, s_{\rm w}} \left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$





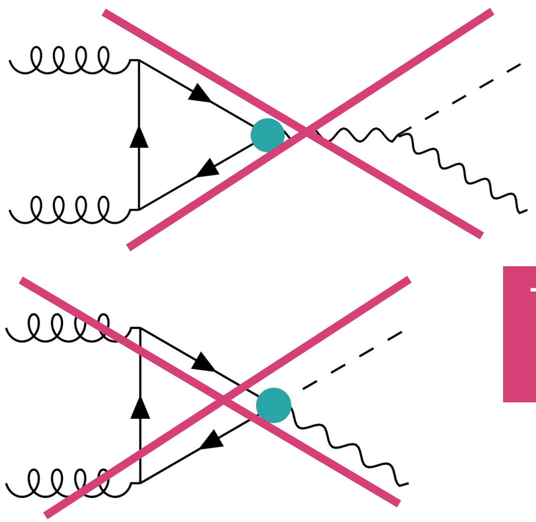




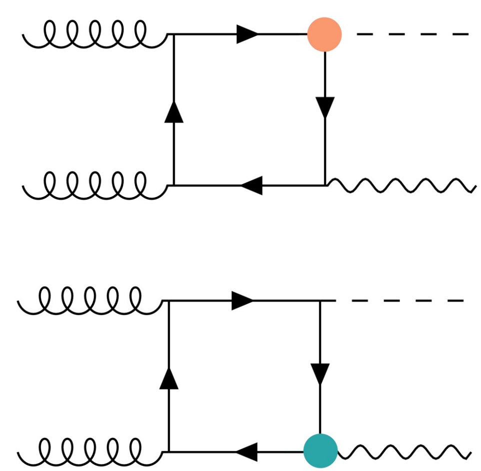
Growing amplitudes in current operators

→ Poorly constrained operators
→ Logarithmic growth in the helicity amplitudes

$\lambda_{g_1}, \lambda_{g_2}, \lambda_H, \lambda_Z$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$	$\mathcal{O}_{t\varphi}$
$+,+,0,0$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_\mathrm{w}\, s_\mathrm{w}}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_\mathrm{w}\, s_\mathrm{w}}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_\mathrm{w}\, s_\mathrm{w}}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$



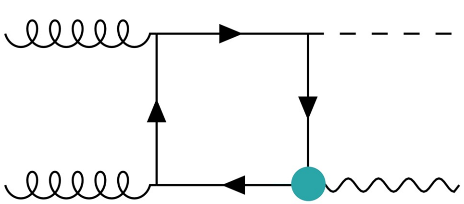
The triangles cancel each other out



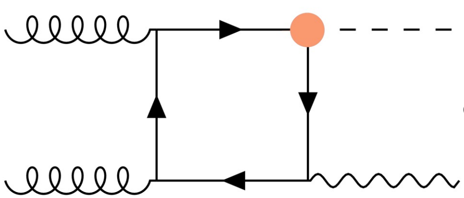
See also: Gauld, Haisch, and Schnell, JHEP01(2024)192

Why do the current operators grow?

$\lambda_{g_1}, \lambda_{g_2}, \lambda_H, \lambda_Z$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$	$\mathcal{O}_{t\varphi}$
$+,+,0,0$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_{\rm W}\, s_{\rm W}}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_{\rm W}\, s_{\rm W}}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_{\rm W}\, s_{\rm W}}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$

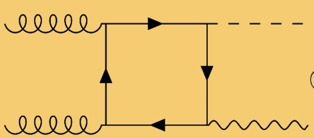


$\propto \log^2\left(\frac{s}{m_t^2}\right)$

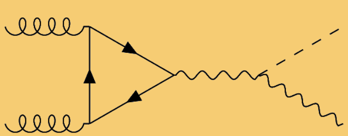


$\propto \log^2\left(\frac{s}{m_t^2}\right)$

$A_{(++00)}$ in the SM:



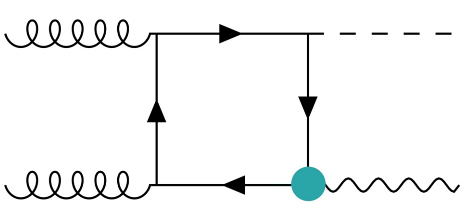
$\propto \log^2\left(\frac{s}{m_t^2}\right)$



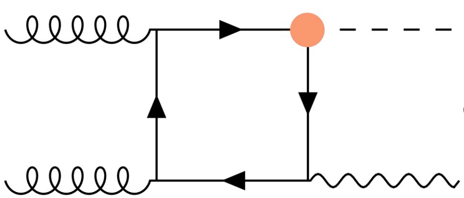
$\propto -\log^2\left(\frac{s}{m_t^2}\right)$

Flat direction in $gg \to ZH$

$\lambda_{g_1}, \lambda_{g_2}, \lambda_H, \lambda_Z$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$	$\mathcal{O}_{t\varphi}$
$+,+,0,0$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$



$\propto \log^2\left(\frac{s}{m_t^2}\right)$

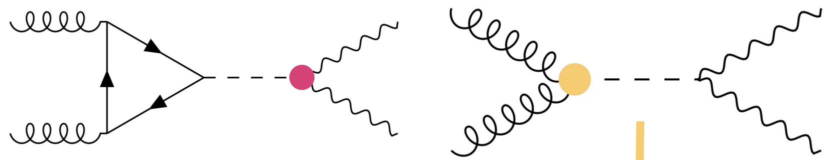


$\propto \log^2\left(\frac{s}{m_t^2}\right)$

We are only sensitive to $c_{\varphi Q}^{(-)} - c_{\varphi t} + \frac{c_{t\varphi}}{y_t}$ → exact degeneracy

Generalisation to other loop-induced processes

Example: $gg \to ZZ$

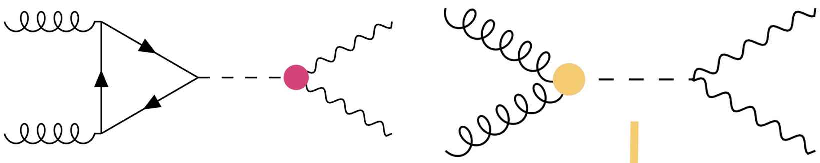


$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi G}$
$+,+,+,+$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$-$
$+,+,-,-$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$-$
$+,+,0,0$	$-$	$-$	$s\,\frac{v^2}{m_Z^2}$

Contact interaction : $gg \to ZZ$ becomes tree-level process

Generalisation to other loop-induced processes

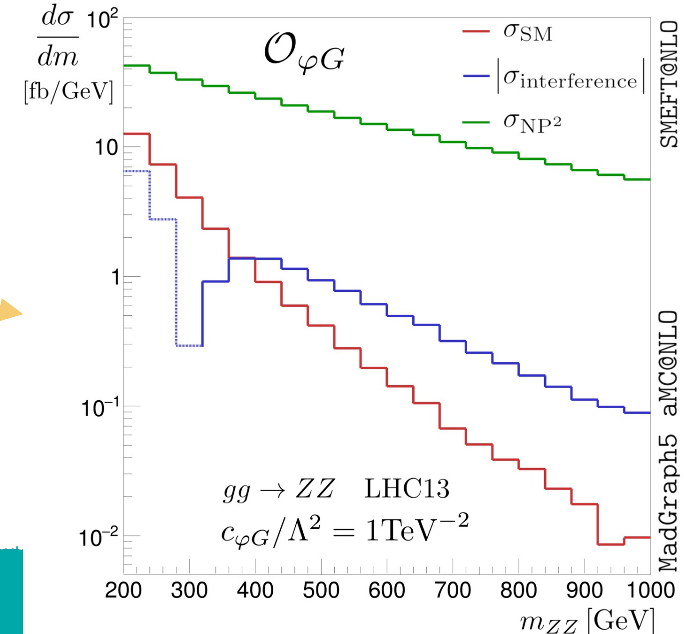
Example: $gg \to ZZ$



$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi G}$
$+,+,+,+$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$-$
$+,+,-,-$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$-$
$+,+,0,0$	$-$	$-$	$s\,\frac{v^2}{m_Z^2}$

Contact interaction : $gg \to ZZ$ becomes tree-level process

Impact of amplitude growths in tails of kinematic distributions

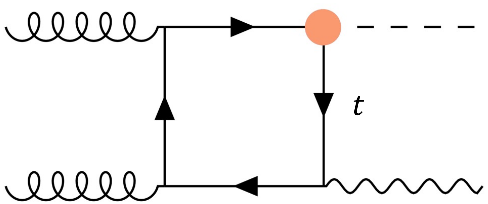


MT, Vryonidou in arXiv:2203.02418

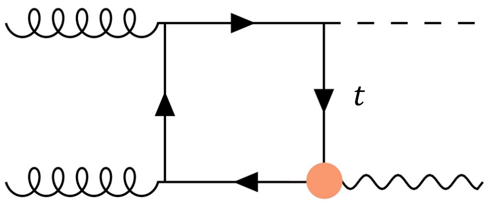
→ Motivates more detailed studies of $gg \to ZZ$

Can measuring $pp \to ZH$ improve the bounds on Higgs and top operators?

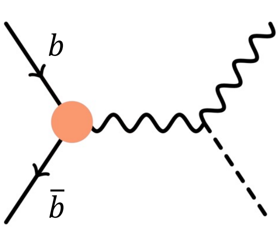
Third generation operators → **Quark and gluon channels interplay**

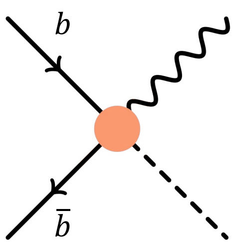


NNLO



$\mathcal{O}_{\varphi Q}^{(1)}$	$c_{\varphi Q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}_{\varphi Q}^{(-)}$	$c_{\varphi Q}^{(-)}$	$c_{\varphi Q}^{(1)} - c_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$





LO

Probed by $gg \to ZH$

Probed by $qq \to ZH$

About the analysis

Used $qq \to ZH$ analysis by Bishara, Englert, Grojean, Panico and Rossia, arXiv:2208.11134.
Predictions obtained with Madgraph in the presence of one operator at a time.

Categories		$p_{T,\text{min}} \in$
0-lepton	boosted	$\{0, 300, 350, \infty\}$
	resolved	$\{0, 160, 200, 250, \infty\}$
2-lepton	boosted	$\{250, \infty\}$
	resolved	$\{175, 200, \infty\}$

$$p_{T,\text{min}} = \min\{p_T^Z, p_T^H\}$$

Background processes
0-lepton: $\nu\bar{\nu}b\bar{b}, t\bar{t}, \nu l b\bar{b}$
2-lepton: $l^+l^-b\bar{b}$

NLO effects
$qq \to ZH$: simulated at NLO in QCD
$gg \to ZH$: rescaled by SM k-Factor

HL-LHC projected bounds from $pp \to ZH$

WC [TeV^{-2}]	95% C.L. Bound (5% syst.)
$c_{\varphi Q}^{(3)}$	$[-0.72, 0.57]$
$c_{\varphi Q}^{(-)}$	$[-1.5, 1.1]$
$c_{\varphi t}$	$[-8.1, 19.6]$
$c_{t\varphi}$	$[-19.4, 8.0]$

Probed by $gg \to ZH$ (loop induced)

Probed by $qq \to ZH$ (tree-level)

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Probed by $gg \to ZH$ (loop induced)
Probed by $qq \to ZH$ (tree-level)

Compare to global fits of LHC data:

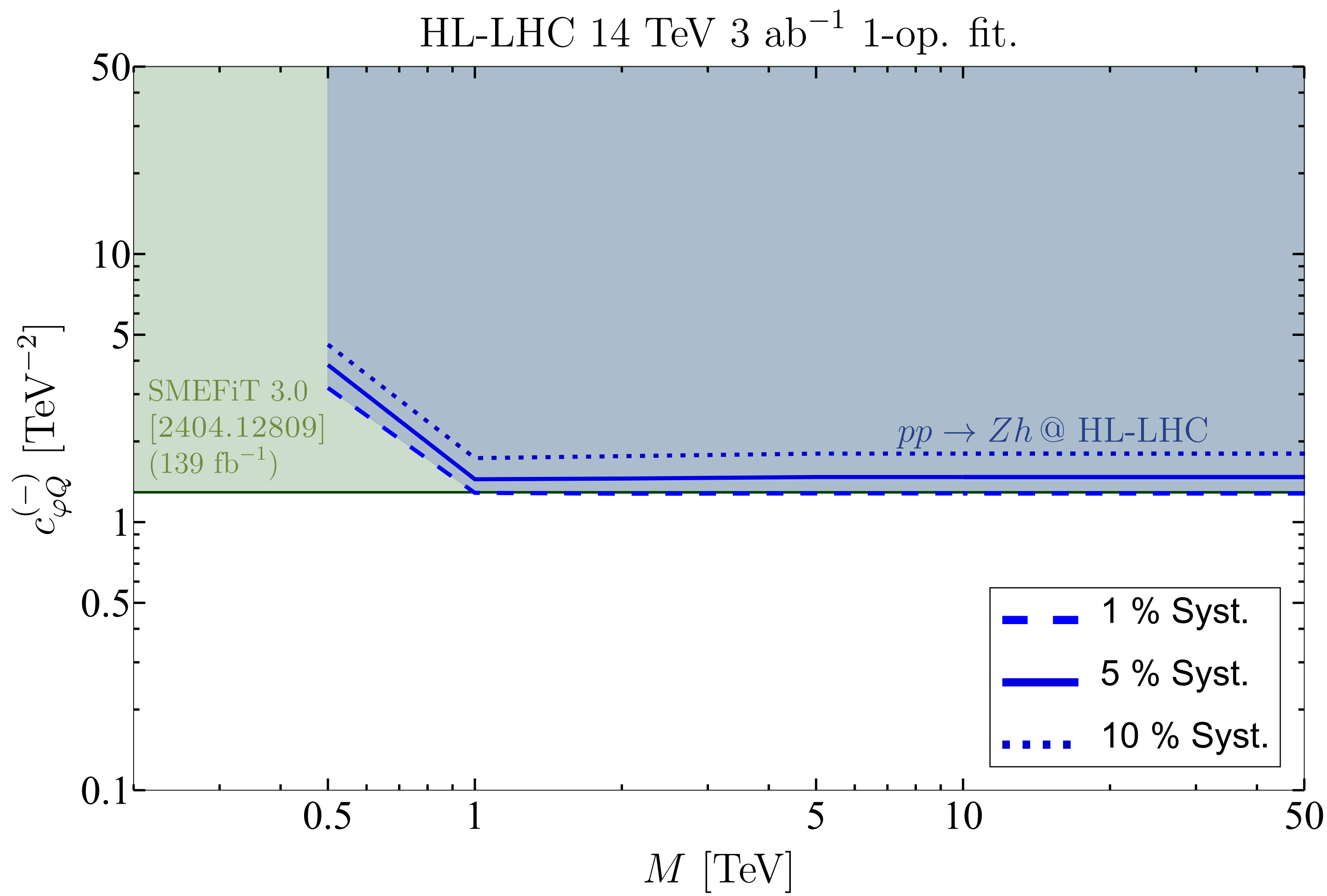
$c_{\varphi Q}^{(3)} \in [-0.7, 0.3]\ \text{TeV}^{-2}$ $\quad c_{\varphi t} \in [-15.6, 1.5]\ \text{TeV}^{-2}$

$c_{\varphi Q}^{(-)} \in [-0.6, 1.3]\ \text{TeV}^{-2}$ $\quad c_{t\varphi} \in [-3.0, 3.5]\ \text{TeV}^{-2}$

SMEFiT Collaboration, arXiv:2404.12809

Competitive against current bounds

HL-LHC projected bounds from $pp \to ZH$



→ Motivates inclusion of $pp \to ZH$ in global fits

What about CP-odd operators?

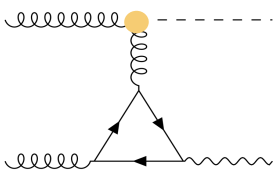
Preliminary

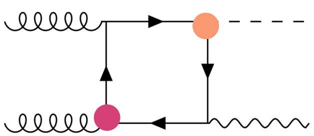
So far only considered CP-even operators → Extension of the study to CP-odd

Hermitian operators

$$c_i = \mathrm{RE}c_i$$

$\mathcal{O}_{\varphi\tilde{G}}$ $\quad c_{\varphi\tilde{G}}$ $\quad \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \tilde{G}^{\mu\nu}_A \, G^A_{\mu\nu}$





Non-hermitian operators

$$c_i = \mathrm{RE}c_i + i\,\mathrm{IM}c_i$$

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

$\mathcal{O}_{tG}$ $\quad c_{tG}$ $\quad i g_S \left(\bar{Q}\tau^{\mu\nu}\, T_A\, t\right) \tilde{\varphi}\, G^A_{\mu\nu} + \mathrm{h.c.}$

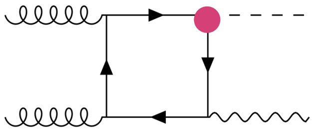
3 ingredients to add to Madgraph UFO

Adding CP-odd operators in SMEFT@NLO

3 ingredients to add to Madgraph UFO

Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang in arXiv:2008.11743

Example: $\mathtt{IM}c_{t\varphi}$



Adding CP-odd operators in SMEFT@NLO

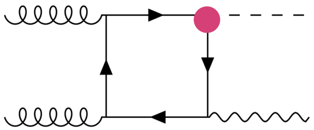
3 ingredients to add to Madgraph UFO

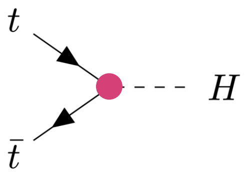
Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang in arXiv:2008.11743

1. Feynman rules

Read from the SMEFT Lagrangian

Example: $\mathtt{IM}c_{t\varphi}$





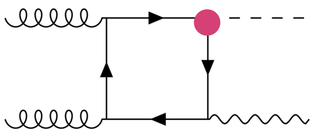
$$= -\frac{\mathtt{IM}c_{t\varphi}\, v^2}{\sqrt{2}\,\Lambda^2}\gamma_5$$

Adding CP-odd operators in SMEFT@NLO

3 ingredients to add to Madgraph UFO

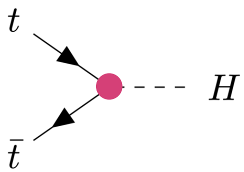
Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang in arXiv:2008.11743

Example: $\mathtt{IM}c_{t\varphi}$



1. Feynman rules

Read from the SMEFT Lagrangian

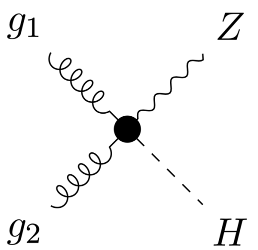


$$= -\frac{\mathtt{IM}c_{t\varphi}\, v^2}{\sqrt{2}\,\Lambda^2}\gamma_5$$

2. Rational terms $\boldsymbol{R_2}$

Calculated from one-loop irreducible diagrams

Ossola, Papadopoulos, Pittau in arXiv:0609007, 0711.3596, 0802.1876
Hirschi et al. in arXiv:1103.0621



$$= 0$$

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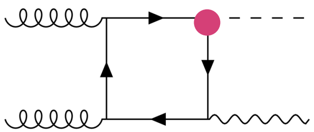
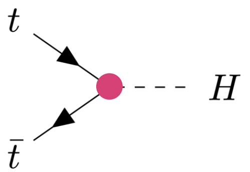
3. **UV Counterterms**
   Checked against the Renormalisation Group Evolution (RGE)

   Alonso, Jenkins, Manohar and Trott in arXiv:1308.2627, 1310.4838, 1312.2014

Example: $\mathtt{IM}c_{t\varphi}$





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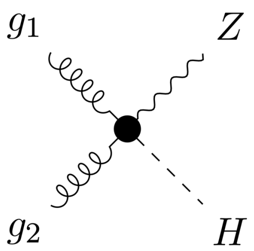
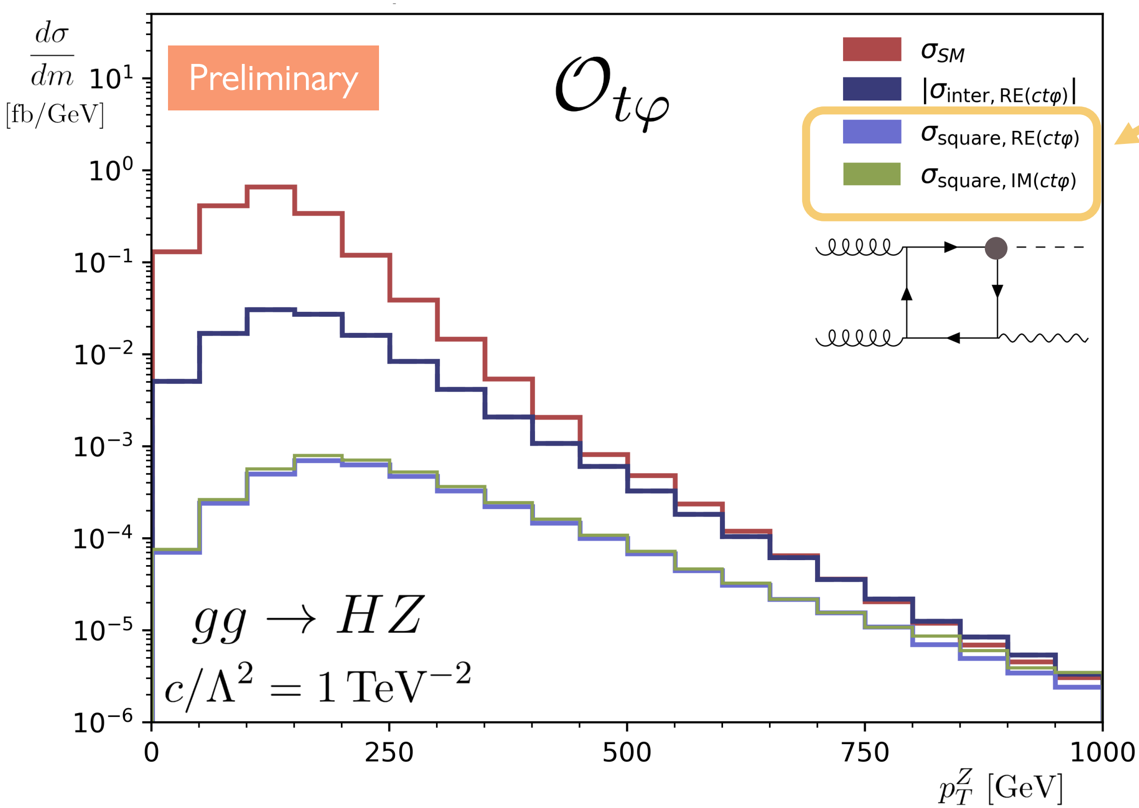


$$= 0$$

Loop-induced process, UV finite

Modified top-Higgs interactions



Overlapping distributions: Same (++00) helicity amplitude, dominates the total amplitude

In progress: study of kinematic and angular observables to distinguish CP-even and CP-odd contributions at colliders.

Conclusion

$gg \to ZH$ helps us study different Higgs and top properties.

In the SMEFT, it can probe poorly constrained Higgs and top operators.

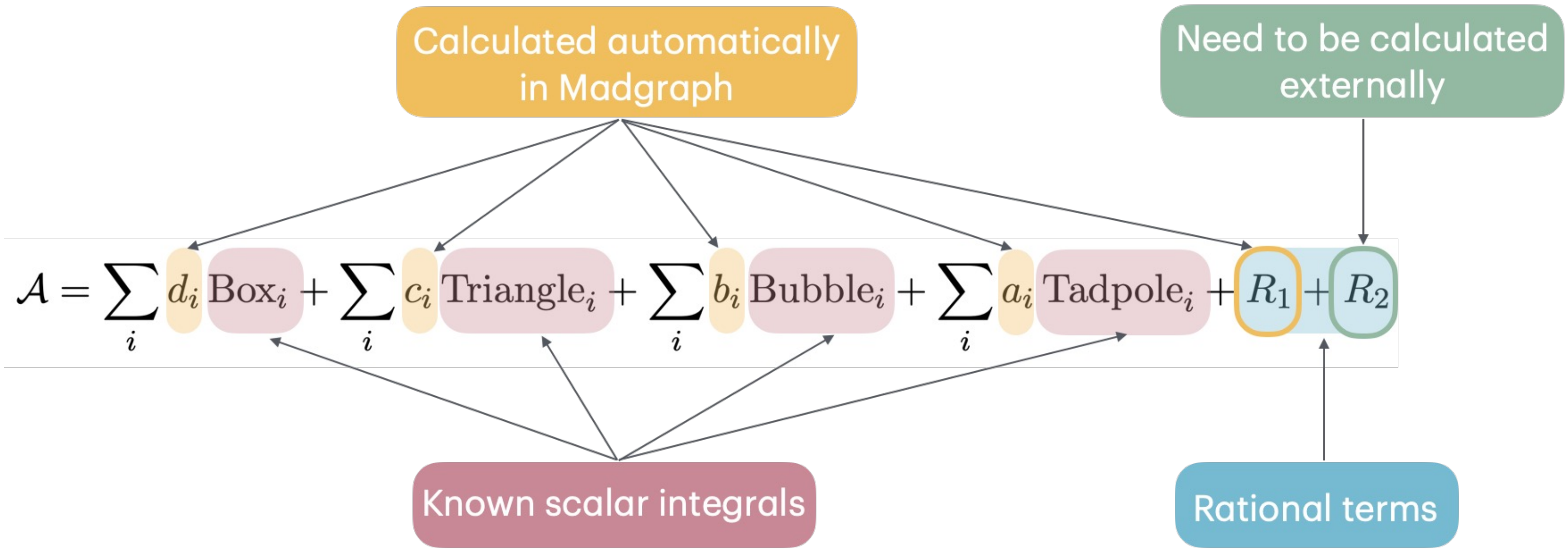
$pp \to ZH$ gives competitive constraints on some third-generation operators → motivates precision measurements and inclusion in global fits.

→ Extension of this study to CP-odd SMEFT operators

Thank you!

What are the rational terms?

Implementation of one-loop QCD calculations in Madgraph relies on Ossola-Papadopoulos-Pittau (OPP) reduction method.



See 't Hooft, Veltman in Nucl. Phys. B 153 (1979) 365,
Ellis, Zanderighi in arXiv:0712.1851,
Van Hameren in arXiv:1007.4716

Ossola, Papadopoulos, Pittau in arXiv:0609007, 0711.3596, 0802.1876 Hirschi et al. in arXiv:1103.0621