Diboson production in the SMEFT from gluon fusion

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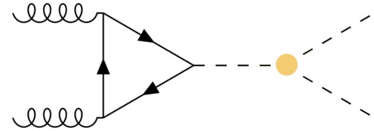
Based on JHEP11(2023)132
In collaboration with A. Rossia and E. Vryonidou

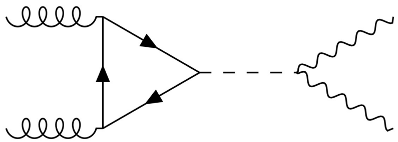
Why study diboson production from gluon fusion?

$gg \to HH, ZH, ZZ, WW$

$gg \to HH$: probes Higgs trilinear coupling



$gg \to ZZ, WW$:



$$\sigma^{\text{onshell}}_{gg\to H\to VV} \sim \frac{c^2_{ggH} c^2_{VVH}}{m_H \Gamma_H}$$

$$\sigma^{\text{offshell}}_{gg\to H\to VV} \sim \frac{c^2_{ggH} c^2_{VVH}}{m^2_{ZZ}}$$

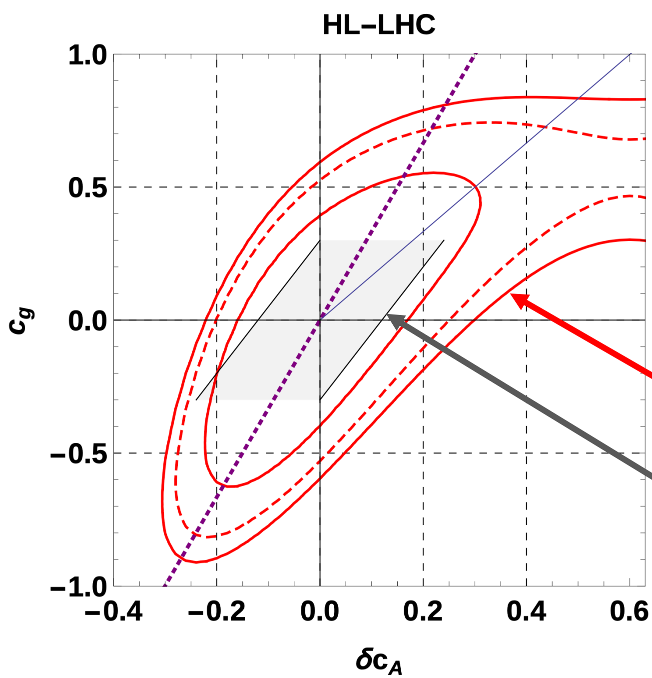
$$\frac{\sigma^{\text{offshell}}}{\sigma^{\text{onshell}}} \sim \Gamma_H$$

ATLAS EXPERIMENT $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
[arXiv: 2304.01532]

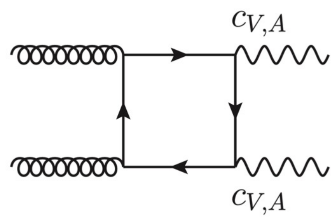
CMS $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV
[cds.cern.ch/record/2871702]

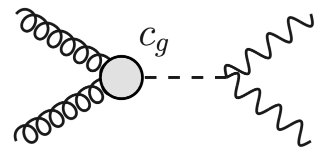
The Higgs can teach us about the top

Diboson sensitivity to top couplings



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





Constraints from $gg \to ZZ$

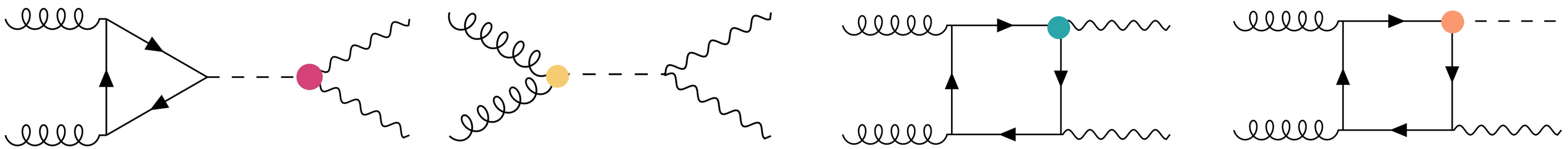
Constraint from $gg \to ZH$
Englert et al, arXiv:1603.05304

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

Top loops: probe poorly constrained Higgs and top operators

Which operators can we probe?

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



Higgs Operators

$\mathcal{O}_{\varphi B}$	$c_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu} B_{\mu\nu}$
$\mathcal{O}_{\varphi W}$	$c_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu} W^I_{\mu\nu}$
$\mathcal{O}_{\varphi G}$	$c_{\varphi G}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G_A^{\mu\nu} G^A_{\mu\nu}$

Top Operators

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

Yukawa operator

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

Growing helicity amplitudes in $gg \to ZZ$

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

Growing helicity amplitudes in $gg \to ZZ$

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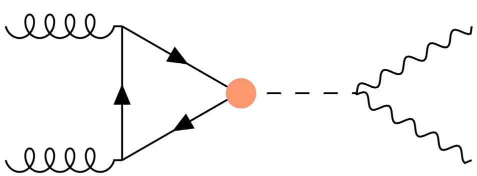
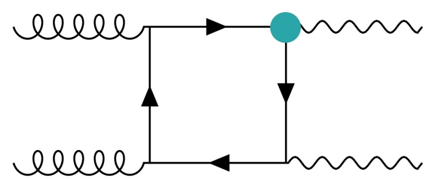
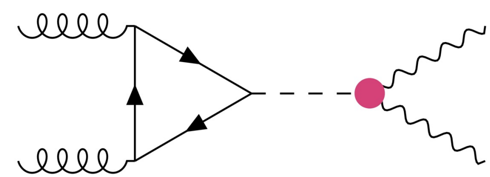
- Studied high-energy behaviour of amplitudes → Which operators grow with energy?

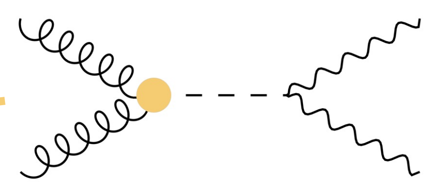
$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$
$+,+,0,0$	$\frac{m_t v^3}{m_Z^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2 v^2}{m_Z^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2 v^2}{m_Z^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$





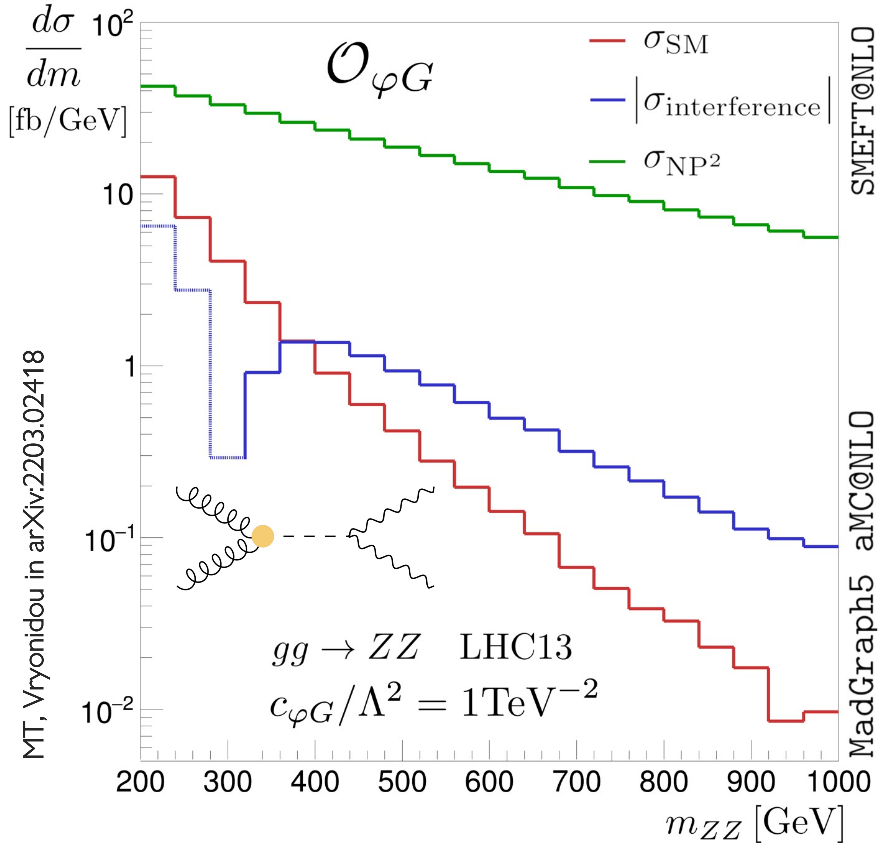
$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi G}$
$+,+,+,+$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$-$
$+,+,-,-$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right)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





Tail effects

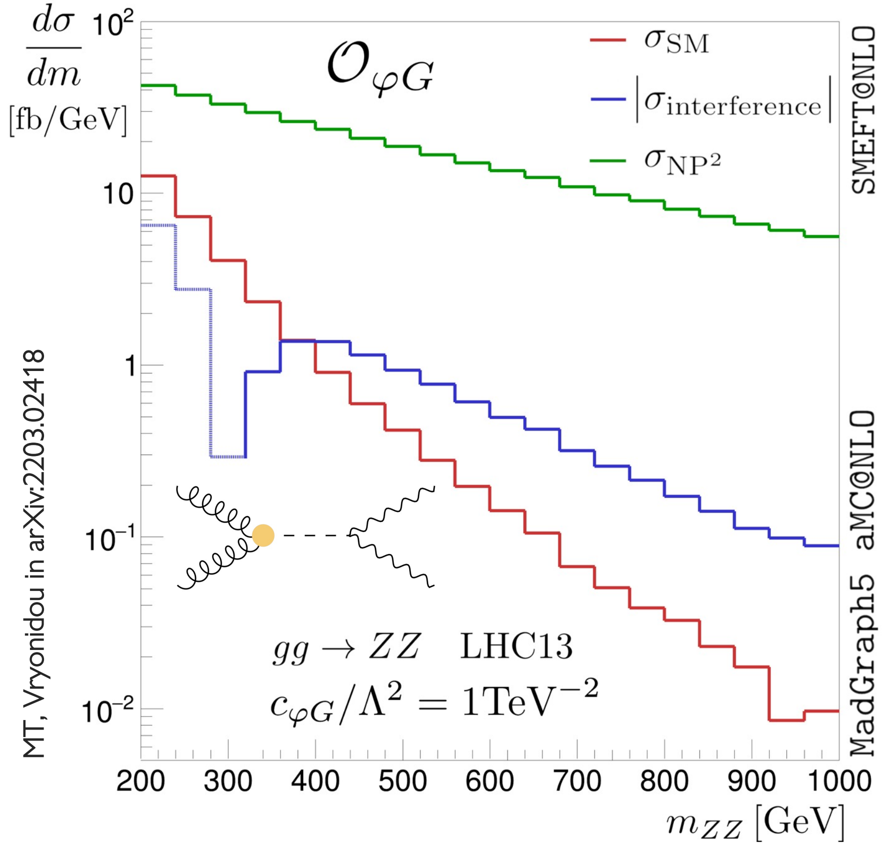
$$\mathcal{O}_{\varphi G}: \; A_{(++00)} \propto s$$

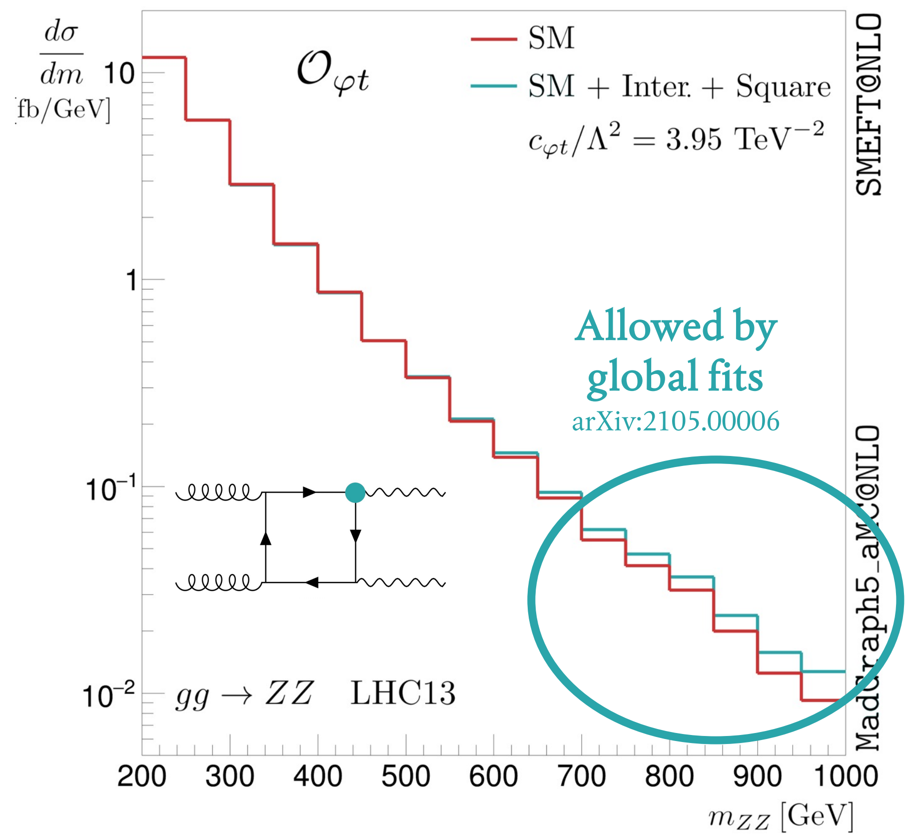


Tail effects

$\mathcal{O}_{\varphi G}: \ A_{(++00)} \propto s$

$\mathcal{O}_{\varphi t}: \ A_{(++00)} \propto \log^2\left(\frac{s}{m_t^2}\right)$



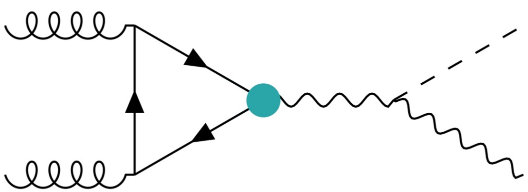


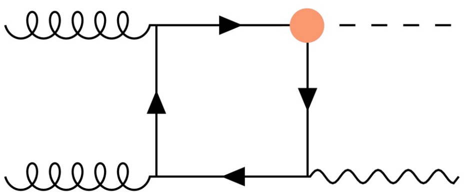
→ Motivates more detailed studies of $gg \to ZZ$

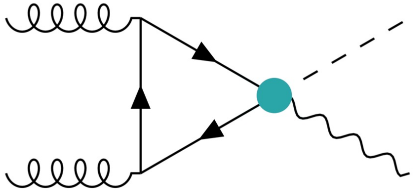
Helicity amplitudes in $gg \to ZH$

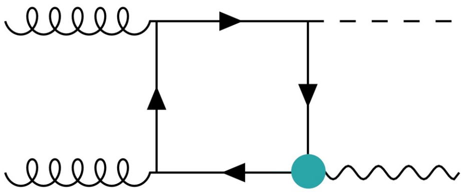
→ Focus on poorly constrained operators
→ Logarithmic growth in the helicity amplitudes

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





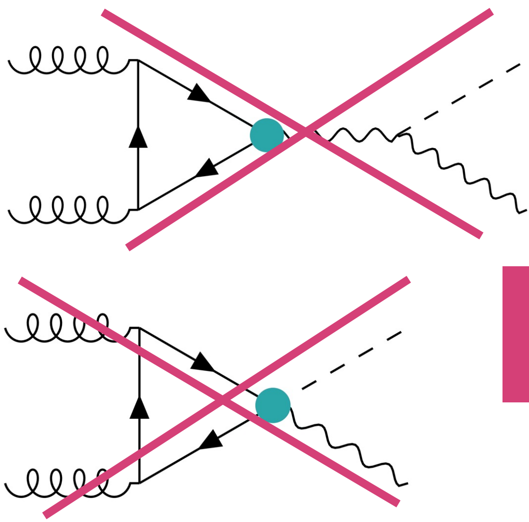




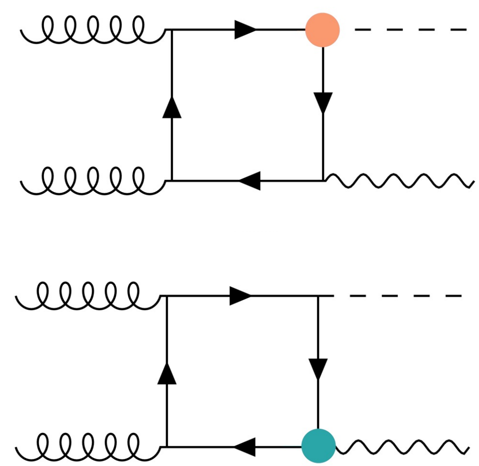
Helicity amplitudes in $gg \to ZH$

→ Focus on poorly constrained operators
→ Logarithmic growth in the helicity amplitudes

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



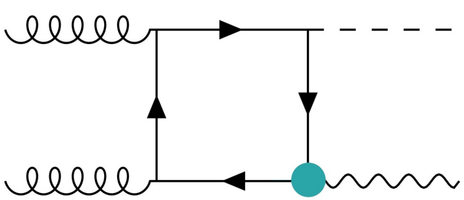
The triangles cancel each other out



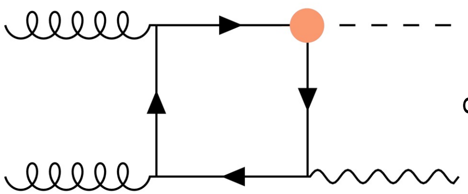
See also: Gauld, Haisch, and Schnell, JHEP01(2024)192

Why do the current operators grow?

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

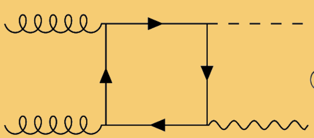


$\propto \log^2\left(\frac{s}{m_t^2}\right)$

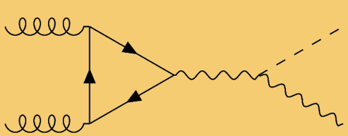


$\propto \log^2\left(\frac{s}{m_t^2}\right)$

$A_{(++\,0\,0)}$ in the SM:



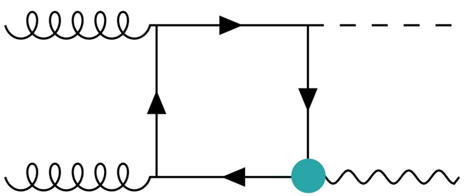
$\propto \log^2\left(\frac{s}{m_t^2}\right)$



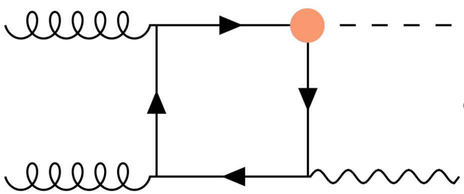
$\propto -\log^2\left(\frac{s}{m_t^2}\right)$

Flat direction in $gg \to ZH$

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



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

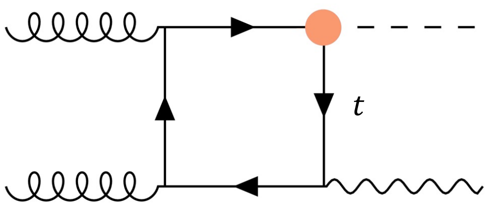


$\propto \log^2\left(\frac{s}{m_t^2}\right)$

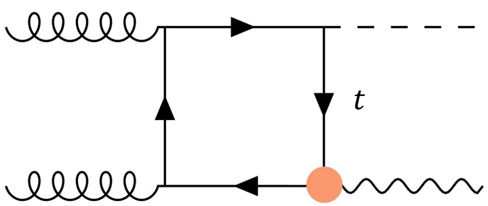
We are only sensitive to $c_{\varphi Q}^{(-)} - c_{\varphi t} + \frac{c_{t\varphi}}{y_t}$ → exact degeneracy

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

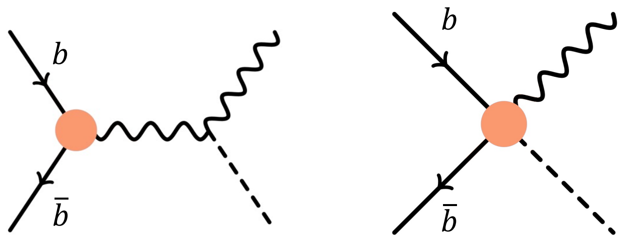
Third generation operators → **Quark and gluon channels interplay**



NNLO



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



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

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

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.)
$c_{\varphi Q}^{(3)}$	$[-0.72,\ 0.57]$
$c_{\varphi Q}^{(-)}$	$[-1.5,\ 1.1]$
$c_{\varphi t}$	$[-8.1,\ \ 19.6]$
$c_{t\varphi}$	$[-19.4,\ \ 8.0]$

Compare to global fits of LHC data:

$|c_{\varphi Q}^{(3)}| \lesssim 0.6\ \text{TeV}^{-2}$ $\quad c_{\varphi t} \in [-13.3, 4.0]\ \text{TeV}^{-2}$

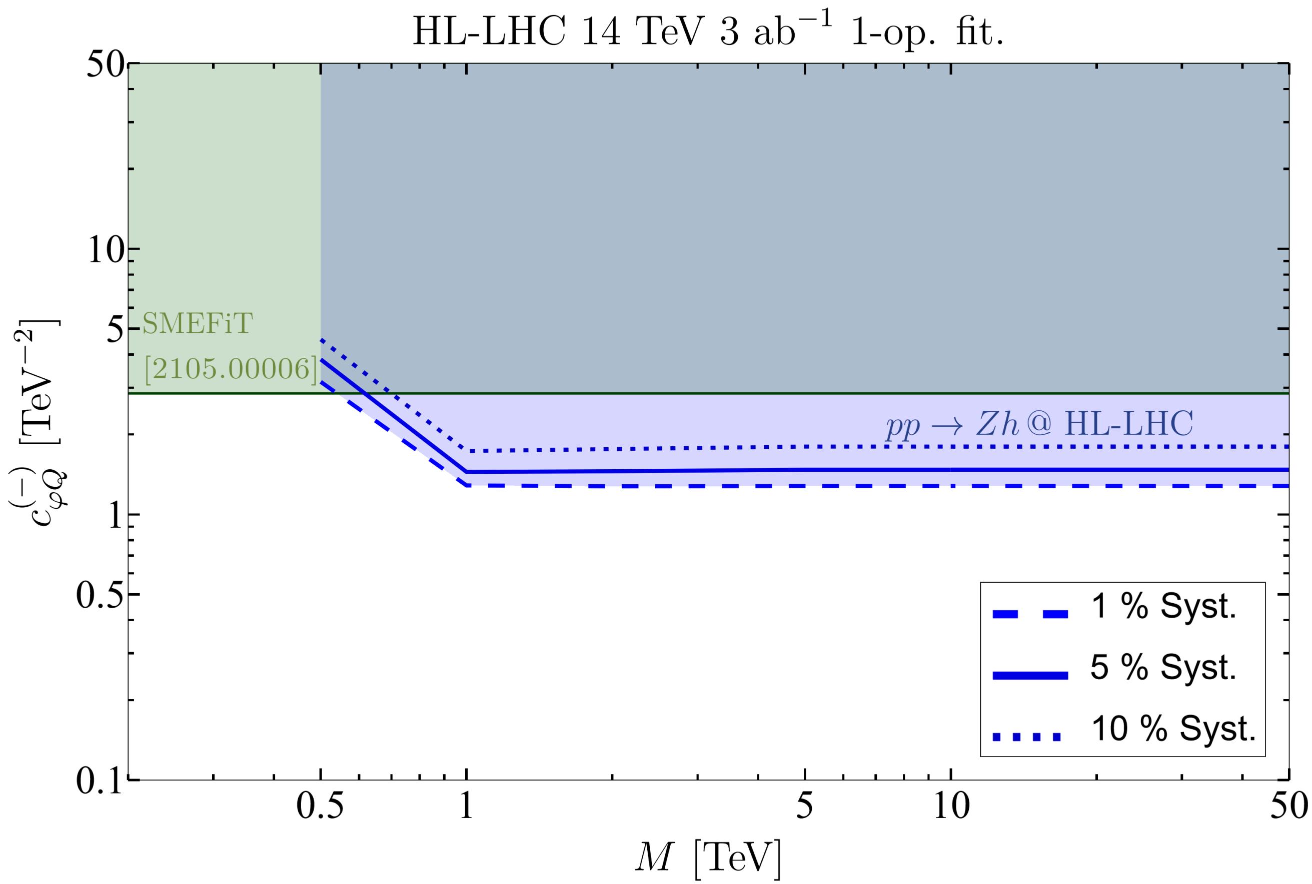
$|c_{\varphi Q}^{(-)}| \lesssim 2.9\ \text{TeV}^{-2}$ $\quad c_{t\varphi} \in [-2.3, 2.8]\ \text{TeV}^{-2}$

SMEFiT Collaboration, arXiv:2105.00006

Competitive against current bounds

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

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

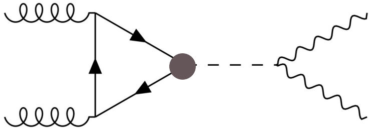


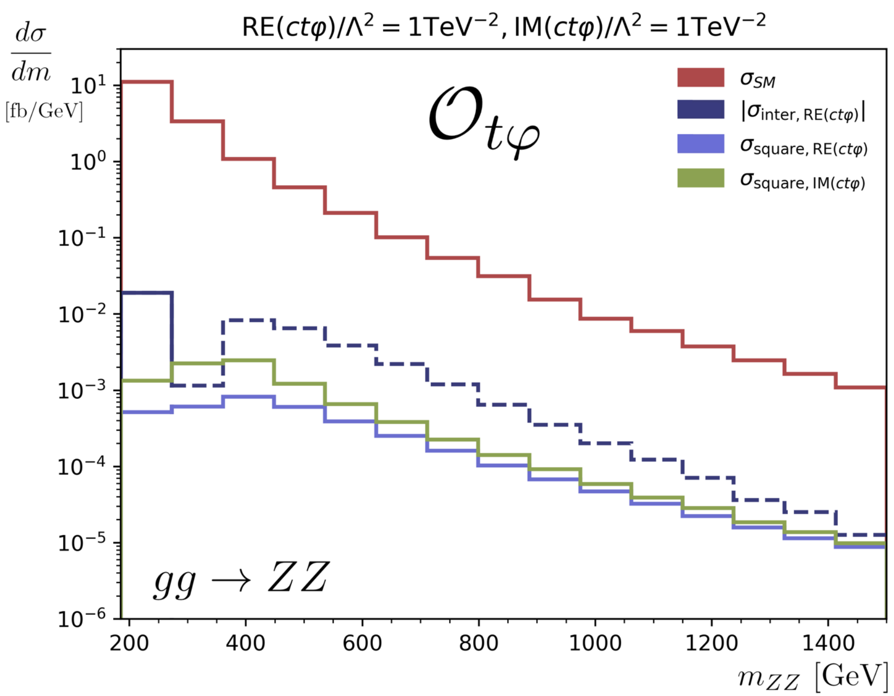
→ Motivates inclusion of $pp \to ZH$ in global fits

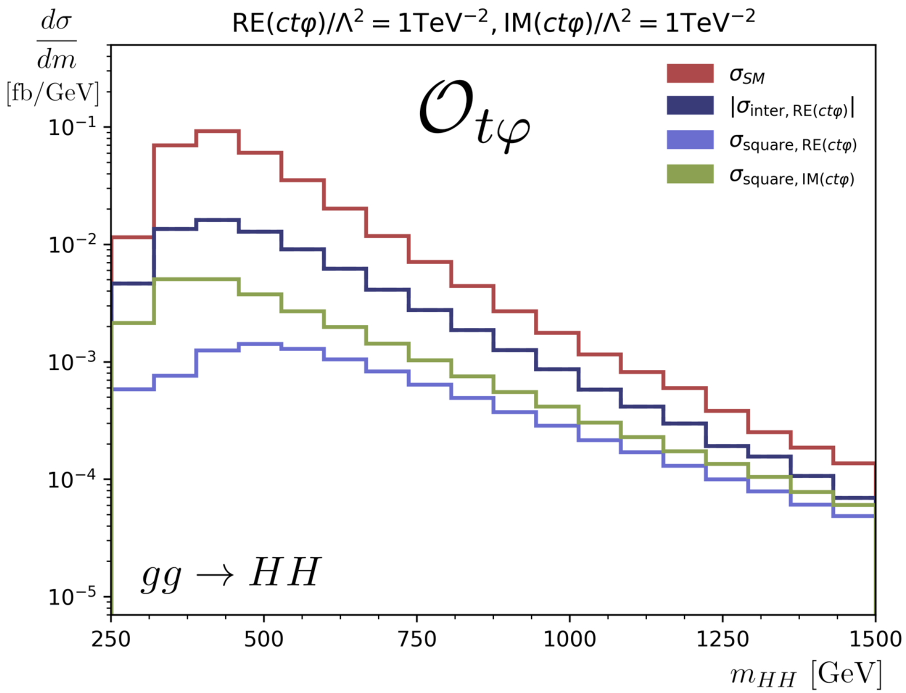
What about CP-odd operators?

Preliminary

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

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





Miralles, MT, Vryonidou, in preparation

Conclusion

$gg \to HH, ZH, ZZ, WW$ help us to study different Higgs and top properties.

In the SMEFT, these processes 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!