Diboson production in the SMEFT from gluon fusion

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SMEFT primer

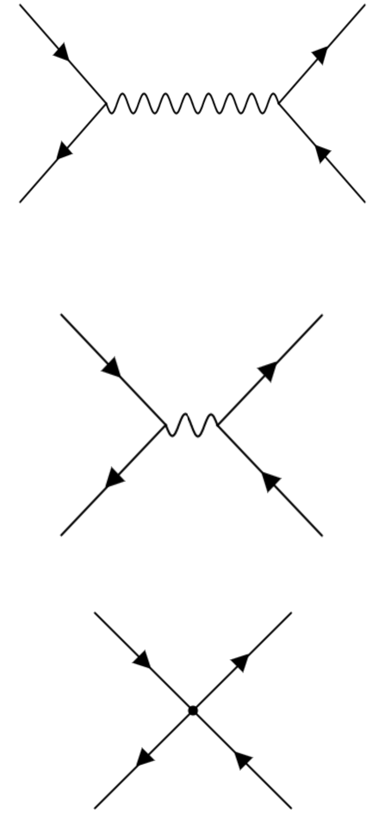
E

Heavy New Physics $\mathcal{L}_{\mathrm{UV}}\ (?)$

Λ

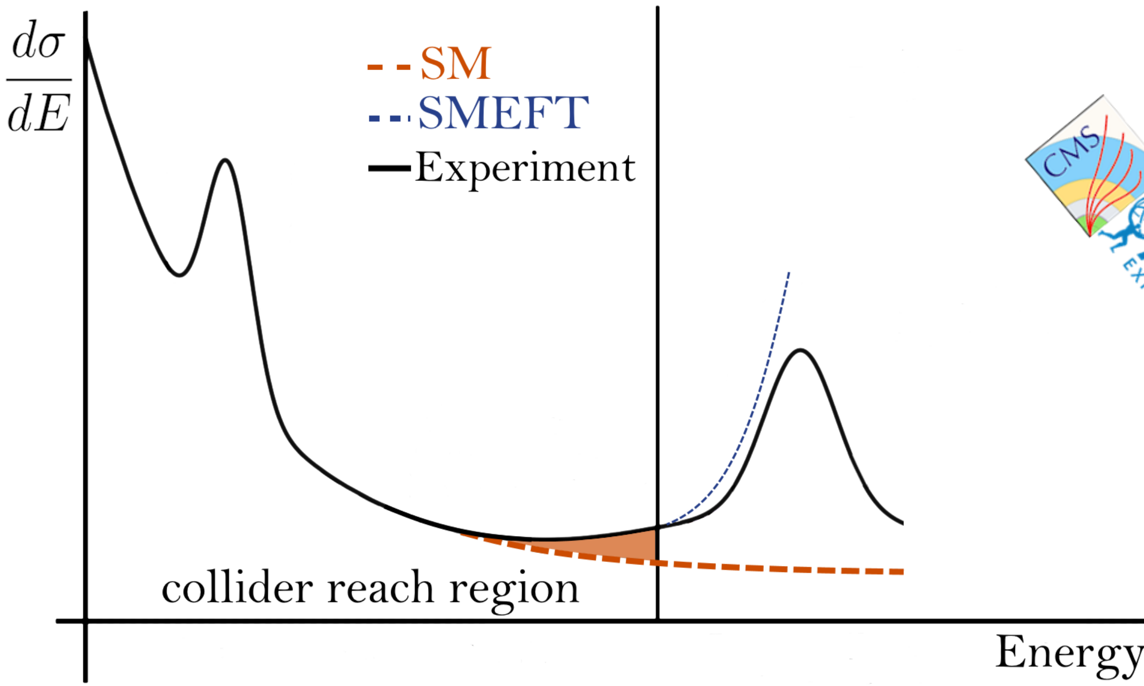
SM Effective Field Theory $\mathcal{L}_{\mathrm{SMEFT}}\left(\psi_{\mathrm{SM}}\right)$

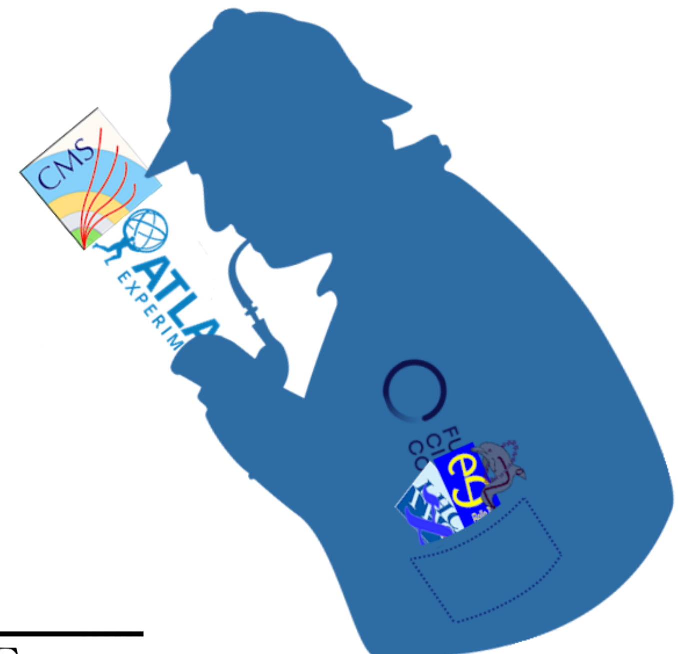
Standard Model $\mathcal{L}_{\mathrm{SM}}\left(\psi_{\mathrm{SM}}\right)$



Wilson Coefficients and how to bound them

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



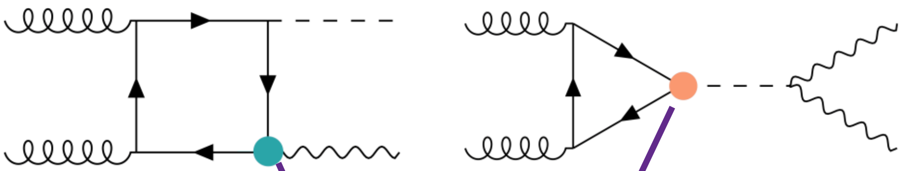


- Dimension-6 operators in Warsaw basis.
- Flavour symmetry: $\mathrm{U}(2)_q \times \mathrm{U}(3)_d \times \mathrm{U}(2)_u$

Why diboson production from gluon fusion?

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

Dominated by top loops

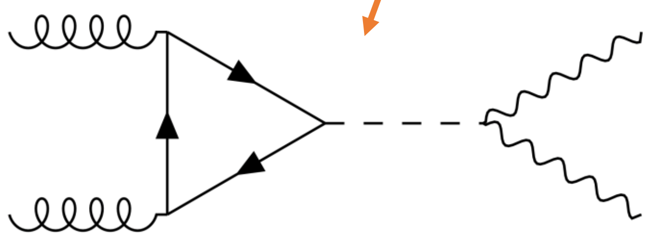


Probe poorly bounded Higgs-top operators

The Higgs teaches us about the top

Why diboson production from gluon fusion?

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



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

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

$$\frac{\sigma^{\text{off shell}}}{\sigma^{\text{on shell}}} \sim \Gamma_H$$

ATLAS EXPERIMENT $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

[arXiv:2304.01532]

CMS $\Gamma_{\rm H} = 3.2^{+2.4}_{-1.7}$ MeV

[arXiv:2202.06923]

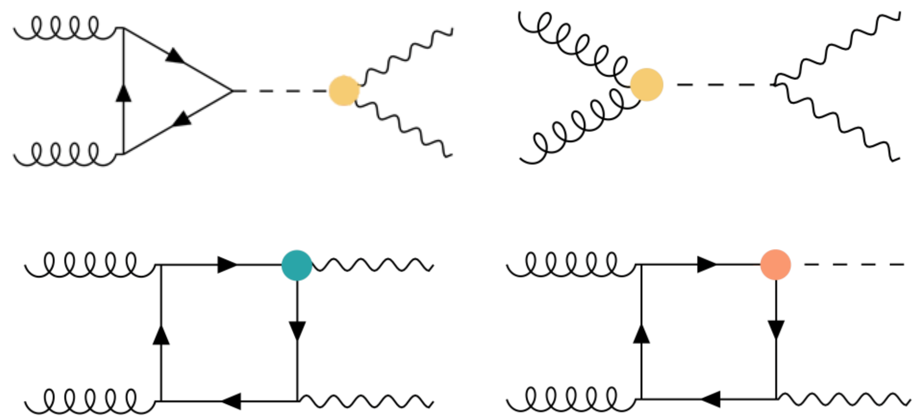
Off-shell lifts flat directions in on-shell data

[arXiv:2203.02418]

Which operators can we probe?

Bosonic Operators

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



Higgs - Top Current Operators

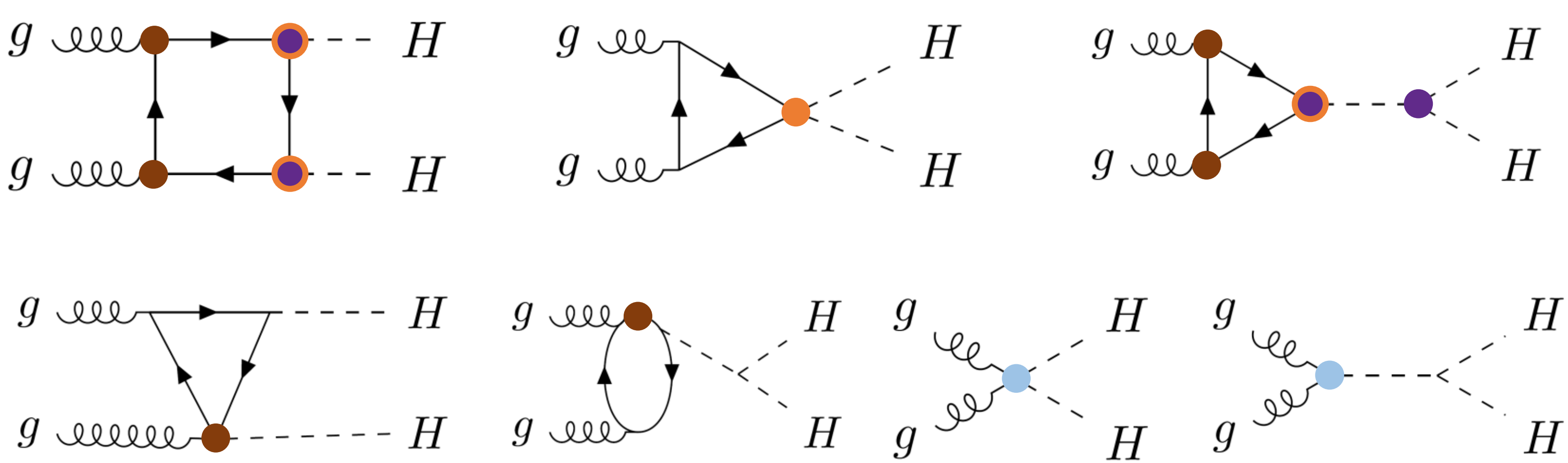
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$
$\mathcal{O}^{(1)}_{\varphi Q}$	$c^{(1)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}^{(3)}_{\varphi Q}$	$c^{(3)}_{\varphi Q}$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

Yukawa and Dipole Operators

$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{tG}$	c_{tG}	$ig_S\, (\bar{Q}\tau^{\mu\nu} T_A\, t)\, \tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tW}$	c_{tW}	$i(\bar{Q}\tau^{\mu\nu} \tau_I\, t)\, \tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$

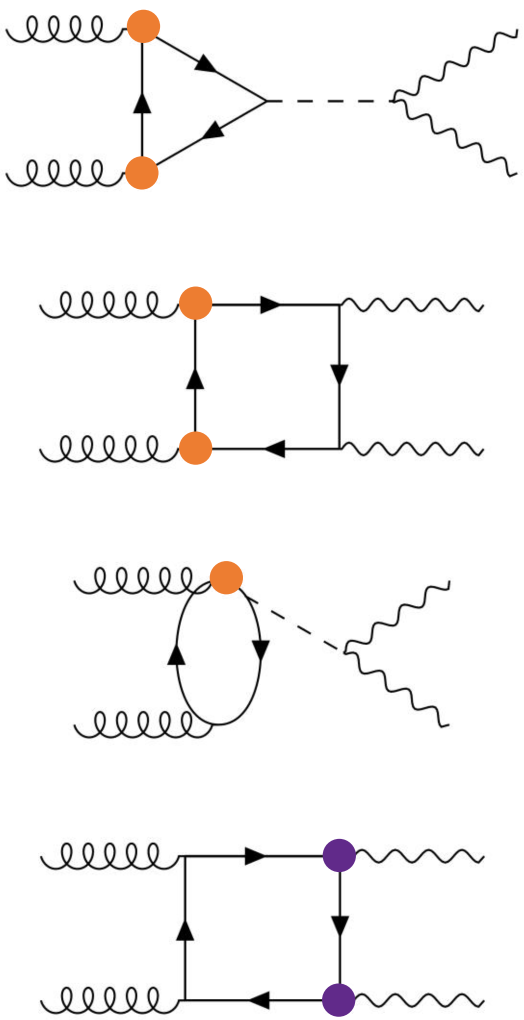
Growing helicity amplitudes in $gg \to HH$

$\lambda_{g_1}, \lambda_{g_2}, \lambda_{H_1}, \lambda_{H_2}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{tG}$	$\mathcal{O}_{d\varphi}$	$\mathcal{O}_{\varphi G}$
$+,+,0,0$	$\frac{3\, m_t\, v\, g_s^2}{32\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$s\,\frac{m_t\, g_s^2}{4\pi^2 v}\left[\log\left(\frac{s}{\mu_{EFT}^2}\,\frac{\sqrt{1-c\theta^2}}{2}\right) - 2\right]$	$\frac{m_t^2\, g_s^2}{8\sqrt{2}\,\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$s\,\sqrt{2}$
$+,-,0,0$	$-$	$s\,\frac{m_t\, g_s^2}{8\pi^2\, v}$	$-$	/



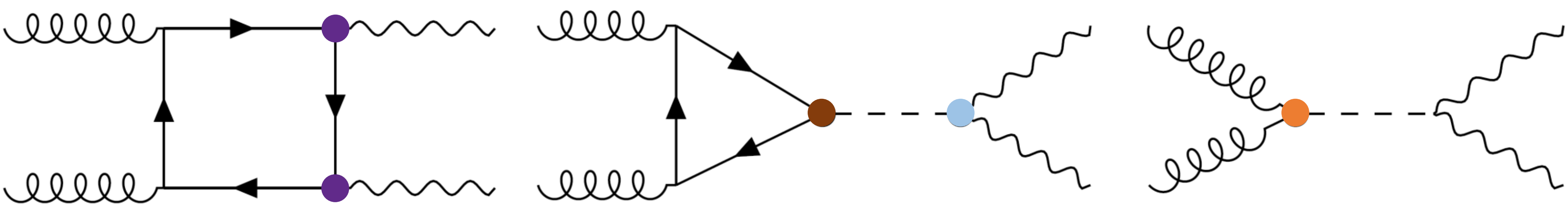
Helicity amplitudes in $gg \to W^+W^-$

$\lambda_{g_1}, \lambda_{g_2}, \lambda_{W^+}, \lambda_{W^-}$	$\mathcal{O}_{tG}$	$\mathcal{O}_{tW}$
$+,+,+,+$	$\frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, s_W^2} \log\left(\frac{\mu_{EFT}^2}{m_t^2}\right)$	$-$
$+,+,+,-$	$\frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, s_W^2} \log\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,-,+$	$\frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, s_W^2} \log\left(\frac{s}{m_t^2}\right)$	$\frac{m_t\, v\, e\, g_s^2}{\pi^2\, s_W} \log^2\left(\frac{s}{m_t^2}\right)$
$+,+,-,-$	$\frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, s_W^2} \log^2\left(\frac{s}{m_t^2}\right)$	$\frac{m_t\, v\, e\, g_s^2}{\pi^2\, s_W} \log^2\left(\frac{s}{m_t^2}\right)$
$+,+,+,0$	$\sqrt{s}\, \frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, m_W\, s_W^2}$	$-$
$+,+,0,+$	$\sqrt{s}\, \frac{m_t\, v\, e^2\, g_s^2\, c\theta}{\pi^2\, m_W\, s_W^2} \log\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,0,-$	$\sqrt{s}\, \frac{m_t\, v\, e^2\, g_s^2\, c\theta}{\pi^2\, m_W\, s_W^2} \log^2\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,0,0$	$s\, \frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, m_W^2\, s_W^2} \log\left(\frac{s}{\mu_{EFT}^2}\right)$	$-$
$+,-,-,-$	$\frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, s_W^2} \log\left(\frac{s}{m_t^2}\right)$	$\frac{m_t\, v\, e\, g_s^2}{\pi^2\, s_W} \log^2\left(\frac{s}{m_t^2}\right)$
$+,-,-,0$	$\sqrt{s}\, \frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, m_W\, s_W^2}$	$-$
$+,-,0,-$	$\sqrt{s}\, \frac{m_t\, v\, e^2\, g_s^2\, c\theta}{\pi^2\, m_W\, s_W^2}$	$-$
$+,-,0,0$	$s\, \frac{m_t\, v\, e^2\, g_s^2}{\pi^2\, m_W^2\, s_W^2}$	$-$



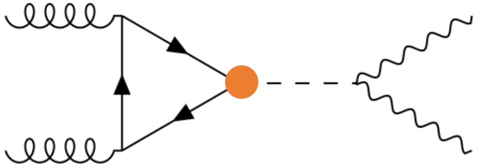
Helicity amplitudes in $gg \to W^+W^-$

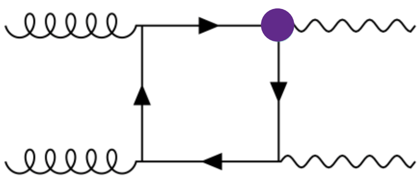
$\lambda_{g1}, \lambda_{g2}, \lambda_{W^+}, \lambda_{W^-}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi G}$	$\mathcal{O}_{\varphi W}$
$+,+,+,+$	$-$	$-$	$-$	$\frac{m_t^2\, g_s^2}{8\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$
$+,+,-,-$	$-$	$-$	$-$	$\frac{m_t^2\, g_s^2}{8\pi^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$
$+,+,0,0$	$\frac{m_t^2\, v^2\, e^2\, g_s^2}{32\pi^2\, m_W^2\, s_w^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^3\, e^2\, g_s^2}{64\sqrt{2}\pi^2\, m_W^2\, s_w^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$s\,\frac{v^2\, e^2}{2\, m_W^2\, s_w^2}$	$-$



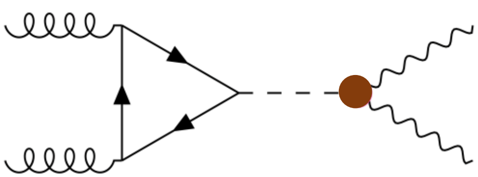
Growing helicity amplitudes in $gg \to ZZ$

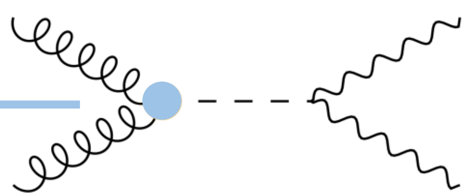
$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{\varphi Q}^{(-)}$
$+,+,0,0$	$\frac{m_t v^3}{m_Z^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2 v^2}{m_Z^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$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



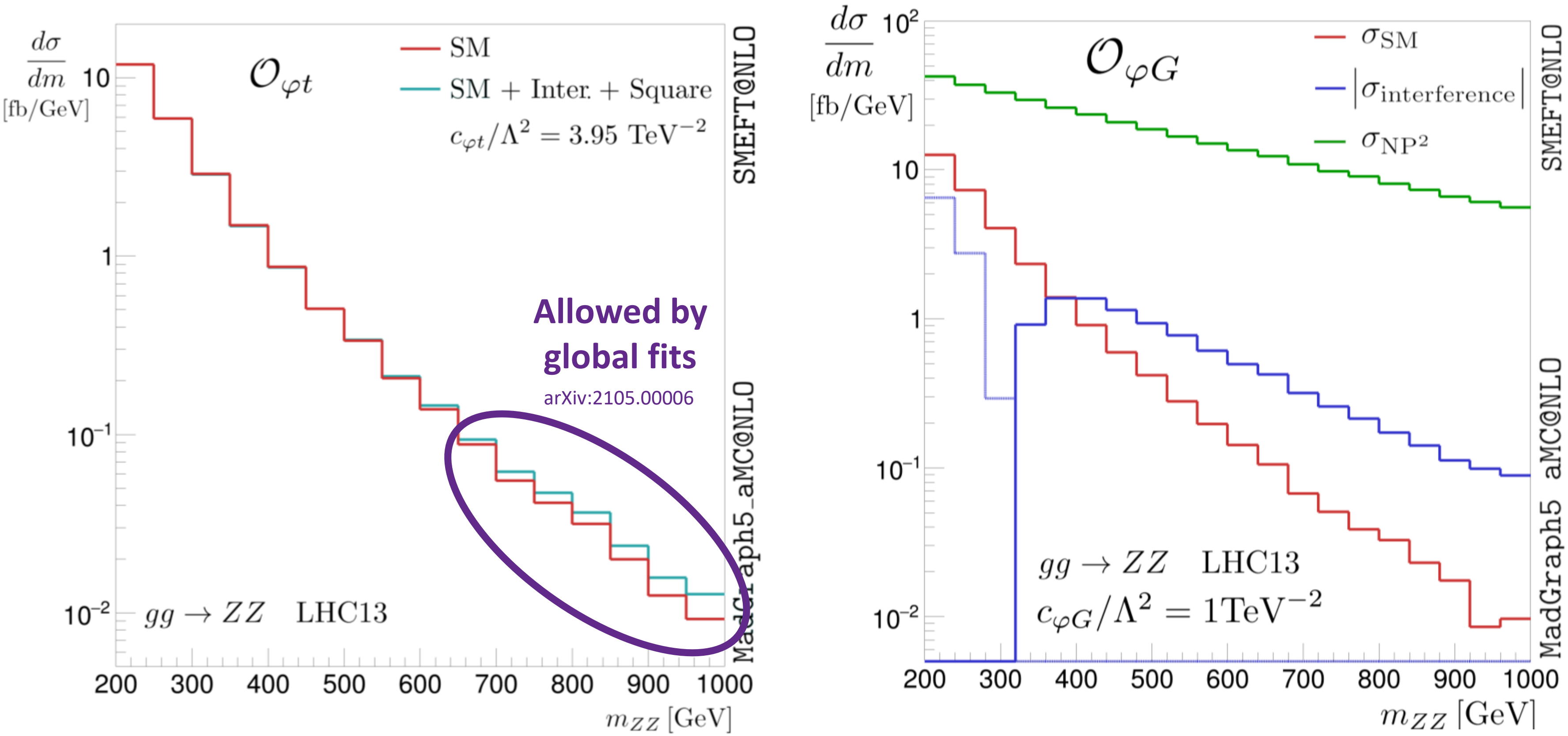


$\lambda_{g_1}, \lambda_{g_2}, \lambda_{Z_1}, \lambda_{Z_2}$	$\mathcal{O}_{\varphi B}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{\varphi G}$
$+,+,+,+$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	–
$+,+,-,-$	$m_t^2\left[\log\left(\frac{s}{m_t^2}\right)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





Tail effects



M. Thomas, E. Vryonidou in arXiv:2203.02418

$$A_{(++00)} \propto \log^2\left(\frac{s}{m_t^2}\right)$$

$$A_{(++00)} \propto s$$

Growing helicity amplitudes in $gg \to ZH$

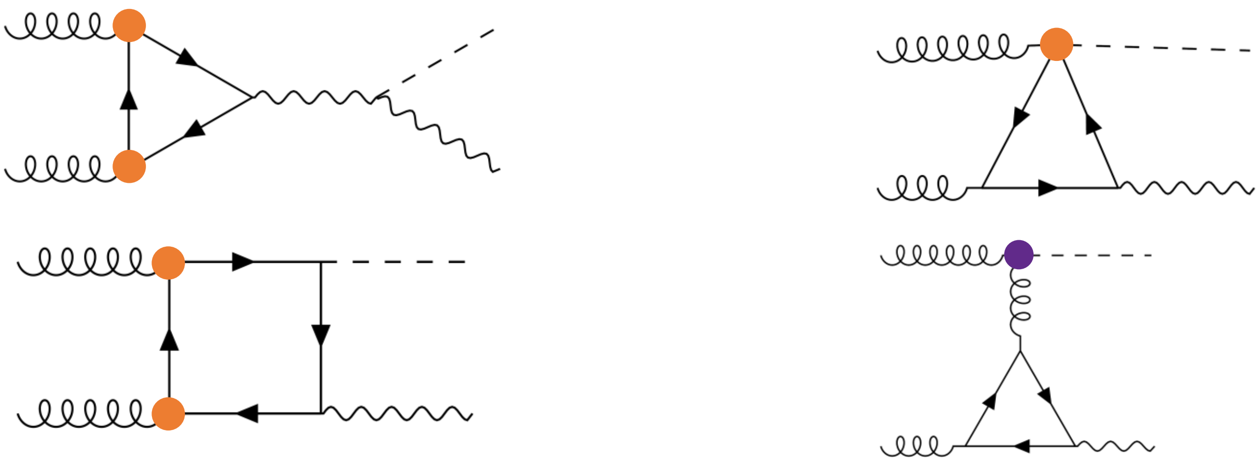
$\lambda_{g_1}, \lambda_{g_2}, \lambda_H, \lambda_Z$	$\mathcal{O}_{tG}$	$\mathcal{O}_{\varphi G}$
$+,+,0,+$	$\sqrt{s}\,\frac{m_t\, g_s^2\, g_{t,A}^Z}{\pi^2}\log\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,0,-$	$\sqrt{s}\,\frac{m_t\, g_s^2\, g_{t,A}^Z}{\pi^2}\log\left(\frac{s}{m_t^2}\right)$	$-$
$+,+,0,0$	$\frac{m_t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

Tightly constrained

$$-0.019\,\mathrm{TeV}^{-2} < c_{\varphi G} < 0.003\,\mathrm{TeV}^{-2}$$

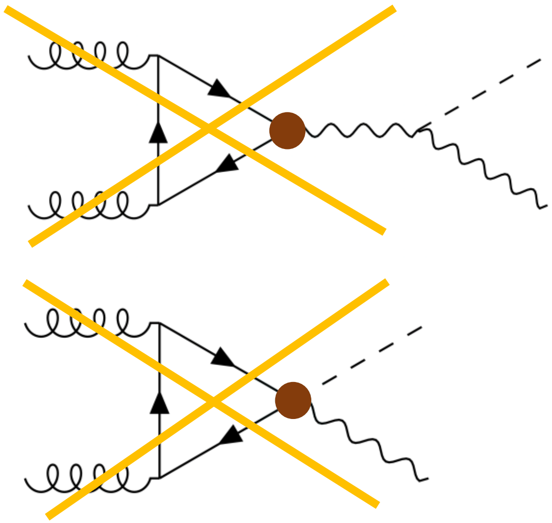
$$0.062\,\mathrm{TeV}^{-2} < c_{tG} < 0.24\,\mathrm{TeV}^{-2}$$

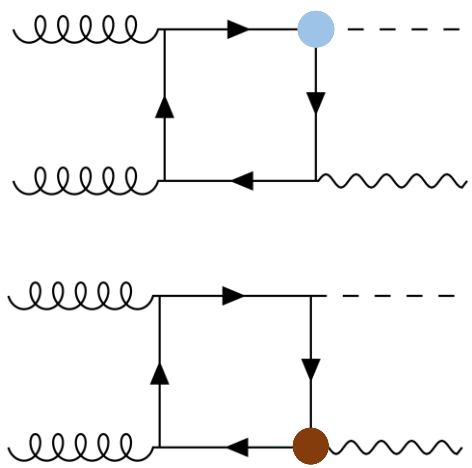
SMEFiT Collab. [arXiv:2105.00006]



Helicity amplitudes in $gg \to ZH$

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

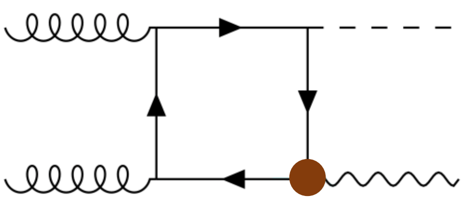




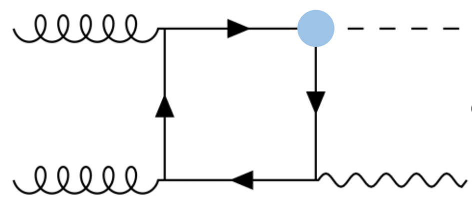
The triangles cancel each other out

Flat directions in $gg \to ZH$

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



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



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

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

Bounds on Higgs and top operators from the tails of $pp \to ZH$

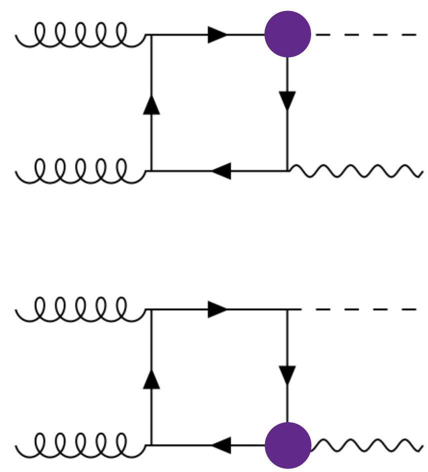
Third-generation operators

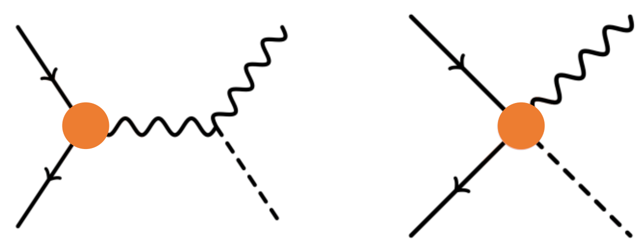
$\mathcal{O}_{\varphi Q}^{(1)}$	$c_{\varphi Q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$
$\mathcal{O}_{\varphi Q}^{(-)}$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

Probed by $gg \to ZH$

Probed by $qq \to ZH$

Quark and gluon channels interplay



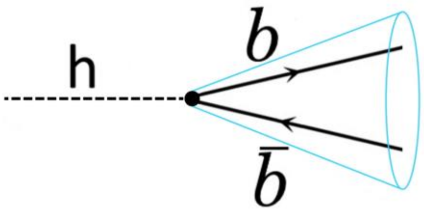


Pheno analysis details

Extended $qq \to ZH$ analysis by Bishara, Englert, Grojean, Panico, ANR

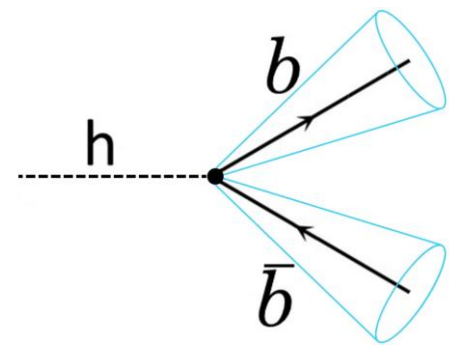
[arXiv:2208.11134]

Boosted



Mass-drop tagging

Resolved



Scale-invariant tagging

Gouzevitch et al [arXiv:1303.6636]
Bishara et al [arXiv:1611.03860]

Adding Resolved category: 10-20% improvement at LHC.

Pheno analysis details

Cut-based analysis, cuts taken from ATLAS VH analyses:

[arXiv:2007.02873] [arXiv:2008.02508]

B-tagger adjusted to match published ATLAS diff. distributions

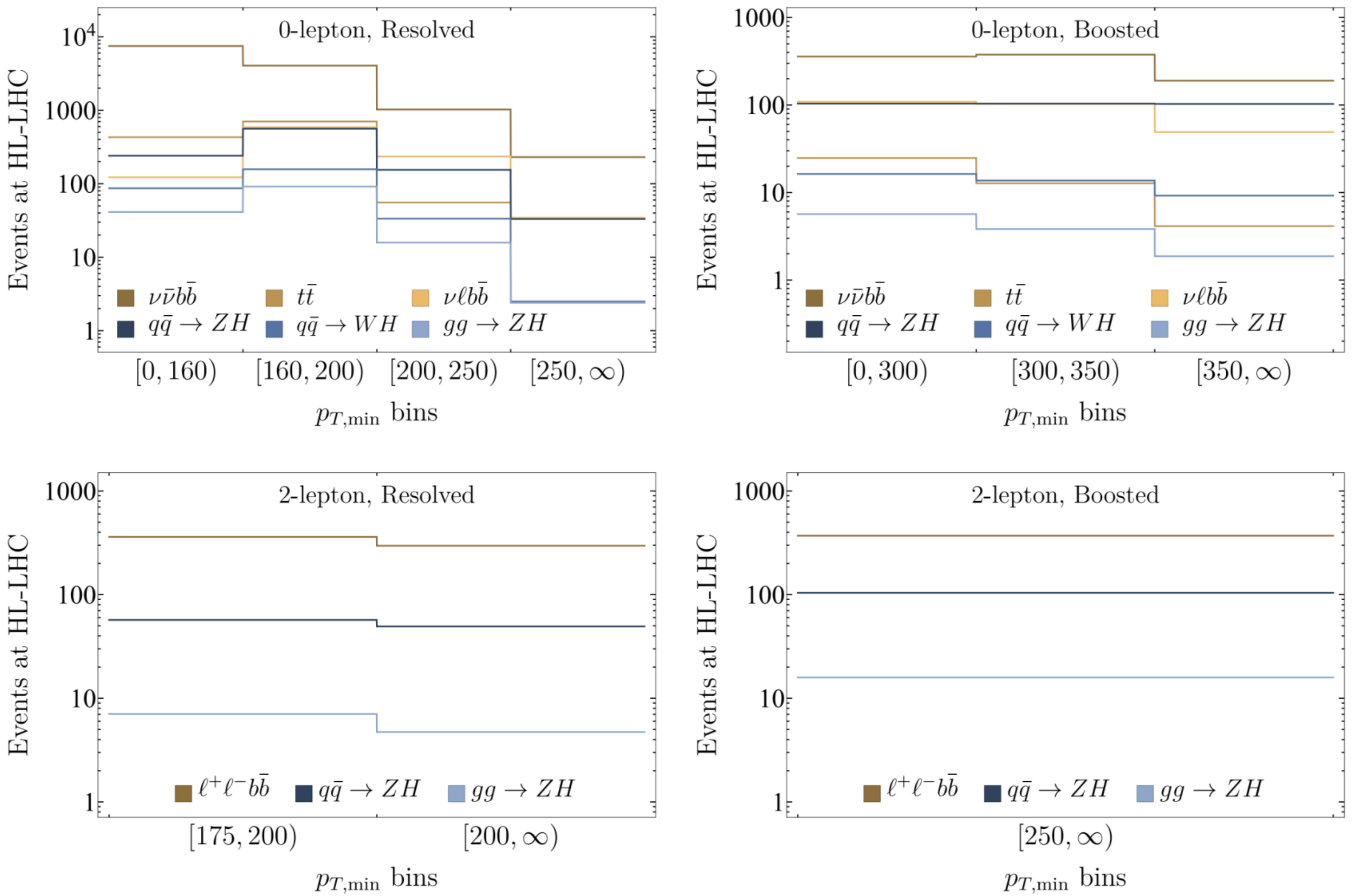
Backgrounds:
0-lep: $\nu\bar{\nu}b\bar{b},\ t\bar{t},\ \nu l b\bar{b}$
2-lep: $l^+l^-\bar{\nu}b\bar{b}$

NLO effects:
$qq \to Zh$: sim. @NLO QCD + EW k-Factor
$gg \to Zh$: NLO QCD k-Factor

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

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

Differential distributions in the SM



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 LHC global fits:

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

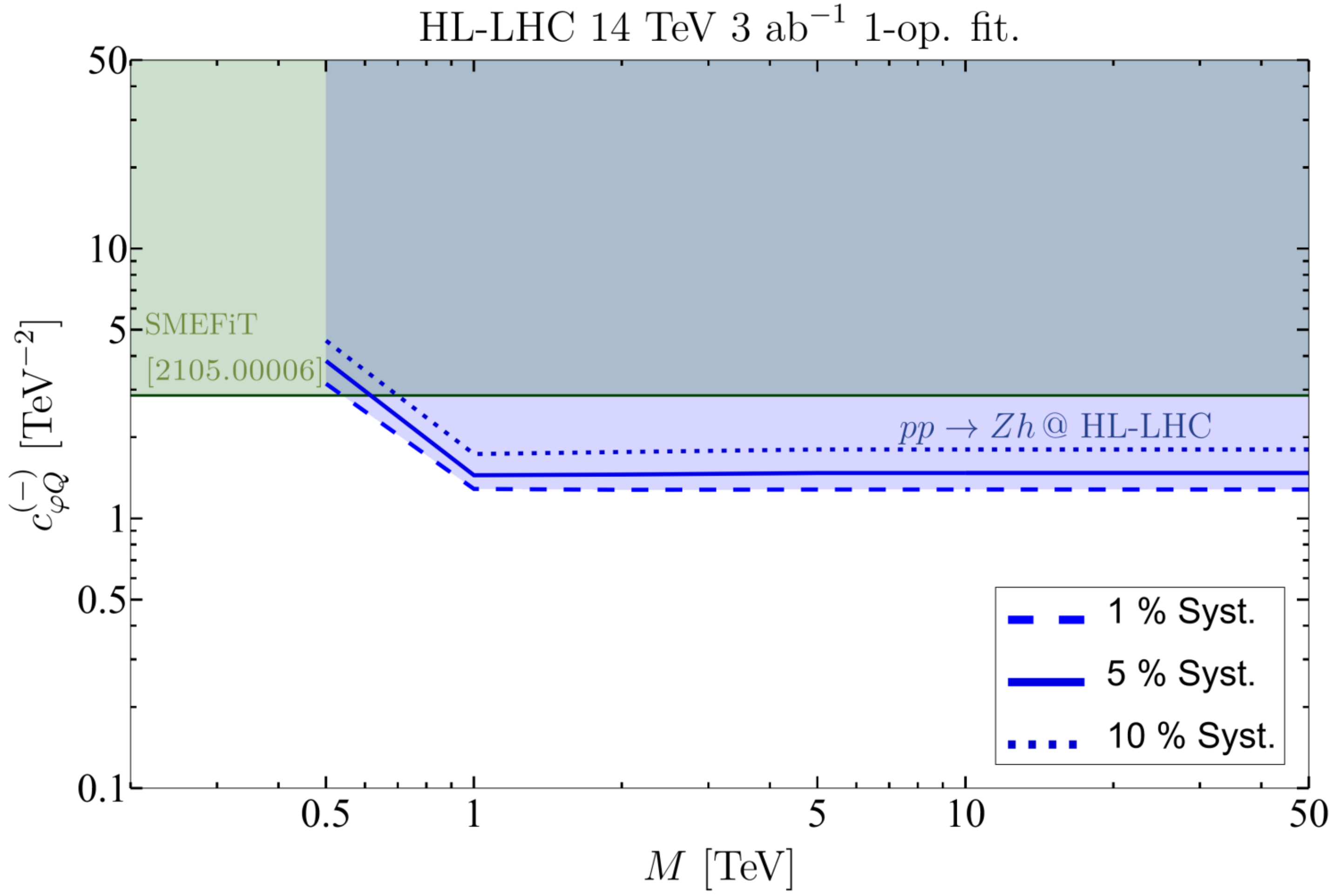
$|c_{\varphi Q}^{(-)}| \lesssim 2.9\ \text{TeV}^{-2}$ $c_{t\varphi} \in [-2.3, 2.8]\ \text{TeV}^{-2}$

SMEFiT Collab. [arXiv:2105.00006]

Competitive against current bounds

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

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



Conclusions

- $gg \to HH, ZH, ZZ, WW$ help to study different Higgs and top properties.
- In the SMEFT, they can probe poorly constrained Higgs and top operators.
- Off-shell Higgs effects lift flat directions.
- Many Higgs and top operators lead to growing amplitudes, hence possible deviations from SM on differential distributions.
- $pp \to ZH$ gives competitive constraints on some third-generation operators → motivates precision measurements and inclusion in global fits.
- Extension to CPV operators on the way.

Thanks for your attention!

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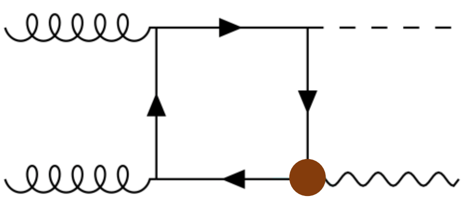
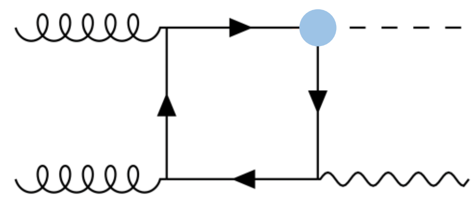
I thank M. Thomas for the slides template.

The reason for the growth

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

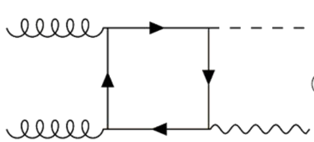


$\propto \log^2\left(\frac{s}{m_t^2}\right)$

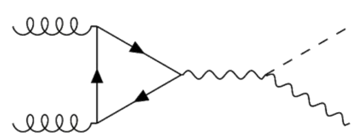


$\log^2\left(\frac{s}{m_t^2}\right)$

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



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



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

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