

New physics searches at LHC run II using SM effective field theory

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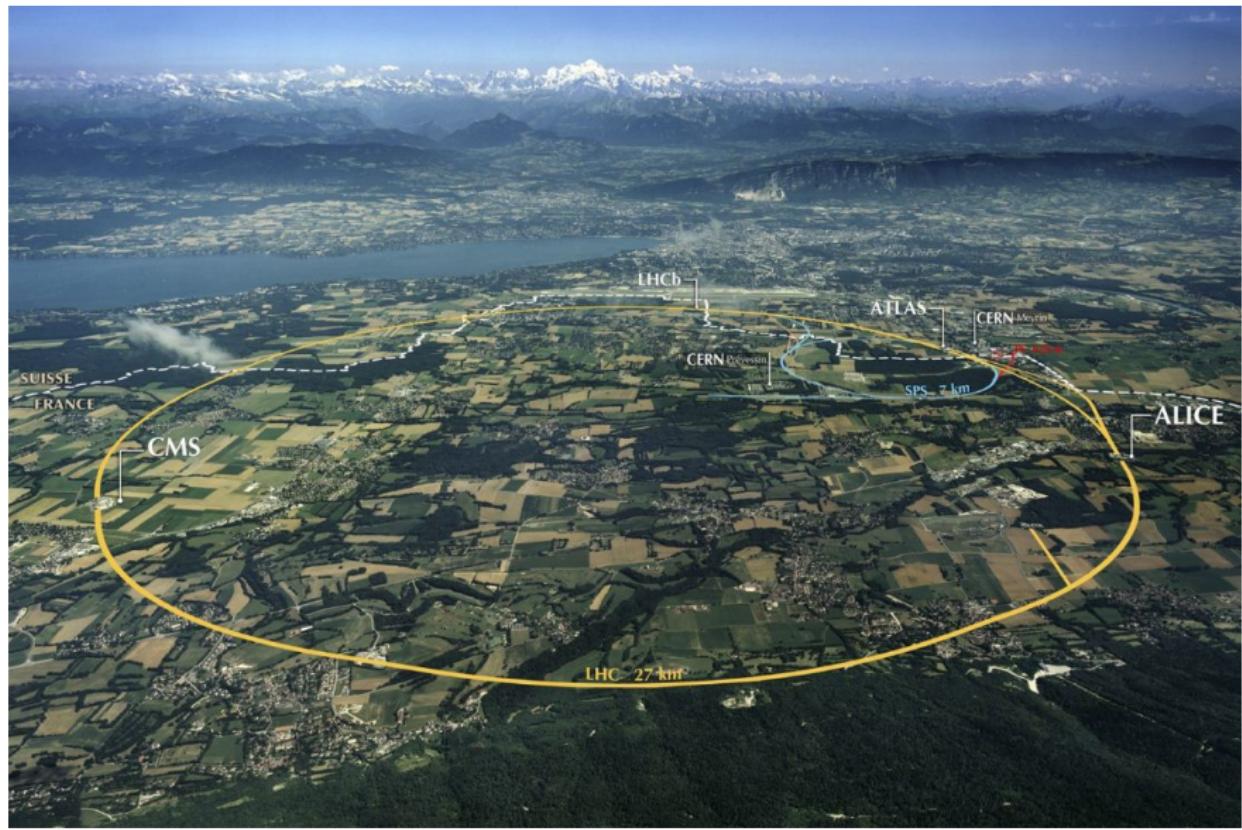
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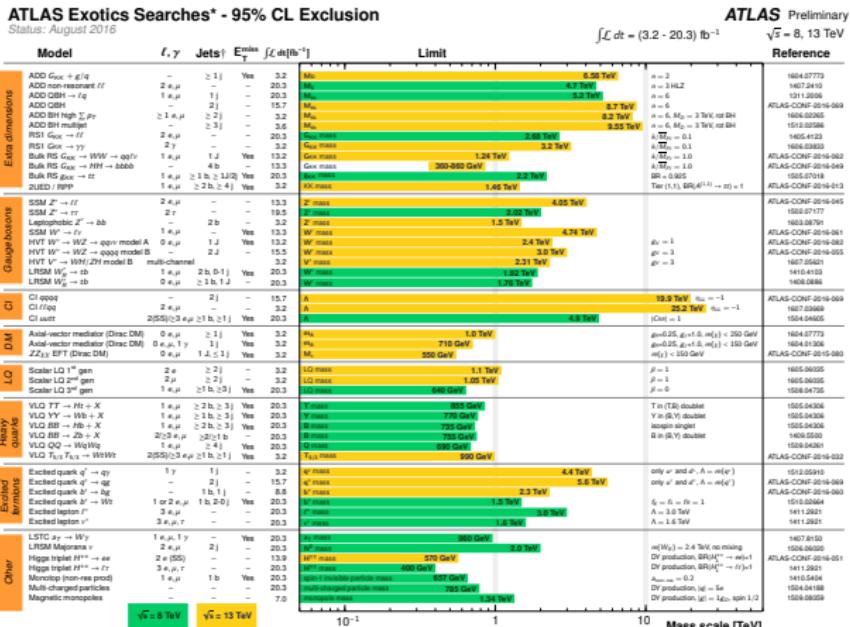


The Large Hadron Collider



Motivations

- No new physics states have been observed so far at the LHC



*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

!Small-radius (large-radius) jets are denoted by the letter (j).

It is plausible that new particles be too heavy to be produced at the LHC

Motivations

- Standard Model lagrangian

$$\mathcal{L}^{\text{SM}} = -\frac{1}{4}F^2 + i\bar{\psi}D\psi - y\bar{\psi}\psi\varphi + D\varphi^\dagger D\varphi - V(\varphi)$$

- If new physics lies at a scale $\Lambda \gg v = 246$ GeV, its effects at low energy ($E \sim v$) are best studied using effective field theory methods and are parametrized by an effective Lagrangian \mathcal{L}_{eff} that includes higher-dimensional operators:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{\text{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \dots$$

where

$$\mathcal{L}^{(5)} = \frac{\alpha^{(5)}}{\Lambda} \mathcal{O}^{(5)} \quad , \quad \mathcal{L}^{(6)} = \sum_i \frac{\alpha_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} \quad , \quad \mathcal{L}^{(8)} = \dots$$

- Contributions to observables arranged as an expansion in E/Λ , leading contributions from dimension-6 operators

Motivations

59 independent SM dim-6 operators [B. Grzadkowski et al. arXiv:1008.4884]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi \square}$	$(\varphi^\dagger \varphi) \square (\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^*$ $(\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\varphi^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Motivations

- The *search for heavy new physics* has become a program of SM precision measurements at LHC, aiming at *testing the existence of one or several of these higher dimensional effective operators* [C. Englert, R. Rosenfeld, M. Spannowsky and AT arXiv:1603.05304, O. Éboli et al. arXiv:1604.03105, C. Grojean et al. arXiv:1604.06444, C. Degrande et al. arXiv:1609.04033]
- It is crucial to have *precise determinations of the modifications induced by higher-dimensional operators* (they alter the total rates, deform the SM differential distributions), in particular when a numerical estimator, like a Monte Carlo tool, is available [S. Fichet, P. R. Teles and AT arXiv: 1611.01165]

Optimal determination of the rates

(w. S. Fichet and P. R. Teles - arXiv: 1611.01165)

- Effective lagrangian for a single dim-6 operator

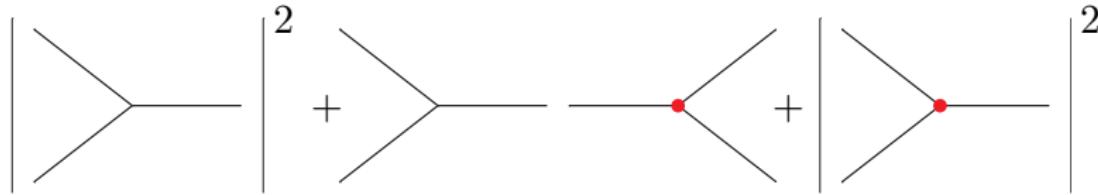
$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{\text{SM}} + \frac{\alpha}{\Lambda^2} \mathcal{O}^{(6)}$$

- Amplitude

$$\mathcal{M} = \mathcal{M}^{\text{SM}} + \frac{\alpha}{\Lambda^2} \mathcal{M}^{\text{BSM}}$$

- Event rate (r bin label)

$$\sigma_r = \sigma_r(\alpha) \equiv \sigma_r^{\text{SM}} + \frac{\alpha}{\Lambda^2} \sigma_r^{\text{int}} + \frac{\alpha^2}{\Lambda^4} \sigma_r^{\text{BSM}}$$



Optimized method for MC simulations

- σ_r^{SM} is obtained by simply setting $\alpha = \alpha_0 = 0$ in the MC
- σ_r^{int} and σ_r^{BSM} are obtained by running the MC for two non-zero values α_1 and α_2 .

$$\begin{aligned}\sigma_r^{\text{SM}} &= \sigma_r^0 \\ \sigma_r^{\text{int}} &= \frac{\Lambda^2}{\alpha_1 \alpha_2} \left[\frac{\alpha_2^2 \sigma_r^1 - \alpha_1^2 \sigma_r^1}{\alpha_2 - \alpha_1} - (\alpha_1 + \alpha_2) \sigma_r^0 \right] \\ \sigma_r^{\text{BSM}} &= \frac{\Lambda^4}{\alpha_1 \alpha_2} \left[-\frac{\alpha_2 \sigma_r^1 - \alpha_1 \sigma_r^2}{\alpha_2 - \alpha_1} + \sigma_r^0 \right]\end{aligned}$$

where $\sigma_r^i = \sigma_r(\alpha_i)$

Results: minimizing the uncertainties

- Relative variance

$$\bar{V}_r^i = \frac{\mathbb{E}[(\hat{\sigma}_r^i)^2] - \mathbb{E}[\hat{\sigma}_r^i]^2}{\mathbb{E}[\hat{\sigma}_r^i]^2} \sim \frac{1}{N_{MC}}$$

- Trace of relative covariance matrix admits a minimum (independent of the value of the interference) for $\alpha_0 = 0$, $\alpha_2 \rightarrow \infty$ and

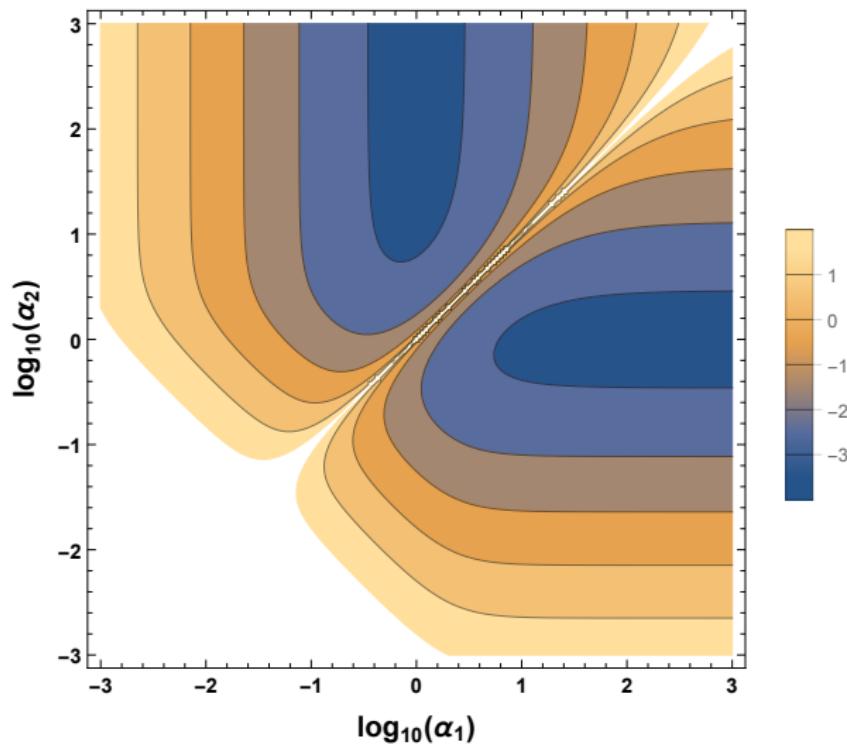
$$\alpha_1 \sim \Lambda^2 \sqrt{\frac{\sigma_r^{\text{SM}}}{\sigma_r^{\text{BSM}}}}$$

- The relative covariance matrix at the minimum ($\bar{\sigma}_r \equiv \sqrt{\sigma_r^{\text{SM}} \sigma_r^{\text{BSM}}}$)

$$\bar{C}_r^{\min} = \frac{1}{N_{MC}} \begin{pmatrix} 1 & -\frac{\bar{\sigma}_r}{\sigma_r^{\text{int}}} & 0 \\ -\frac{\bar{\sigma}_r}{\sigma_r^{\text{int}}} & 1 + 4\frac{\bar{\sigma}_r}{\sigma_r^{\text{int}}} + 6 \left(\frac{\bar{\sigma}_r}{\sigma_r^{\text{int}}} \right)^2 & -\frac{\bar{\sigma}_r}{\sigma_r^{\text{int}}} \\ 0 & -\frac{\bar{\sigma}_r}{\sigma_r^{\text{int}}} & 1 \end{pmatrix}$$

Results: minimizing the uncertainties

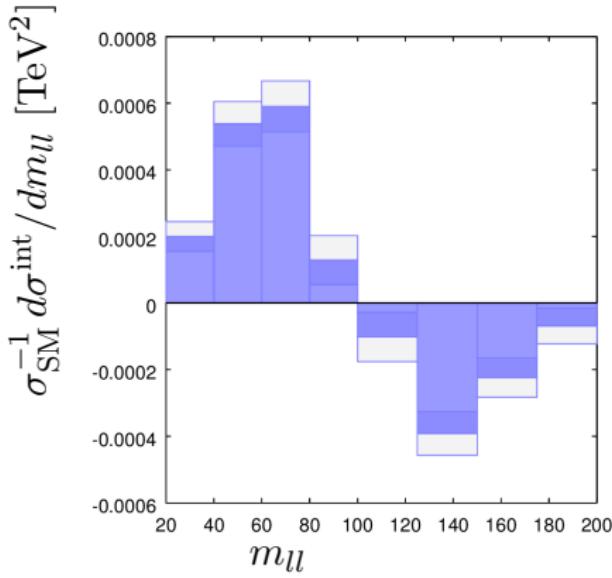
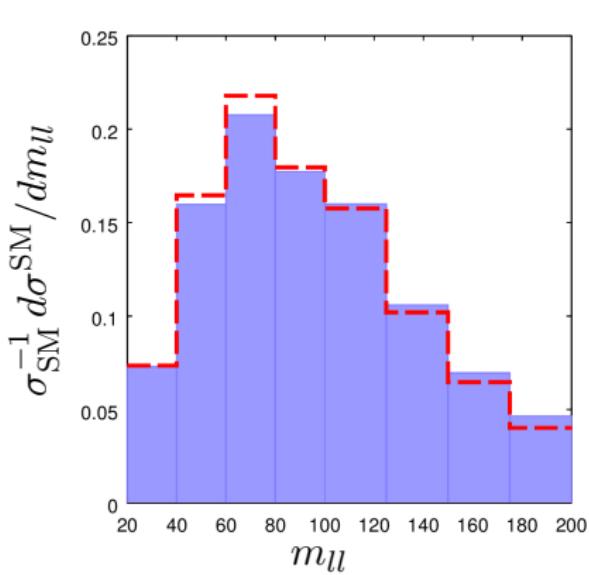
- For fixed α_1 , $\text{tr } \bar{C}_r(0, \alpha_1, \alpha_2)$ is minimized for α_2 going to infinity



Concrete example

Search for the effective operator \mathcal{O}_{3W} in WW production at LHC

$$\mathcal{O}_{3W} = \varepsilon_{ijk} W^i{}_{\mu\nu} W^{j,\nu}{}_{\rho} W^{k,\rho\mu}$$



$$N_{\text{MC}} = 2.4 \cdot 10^6$$

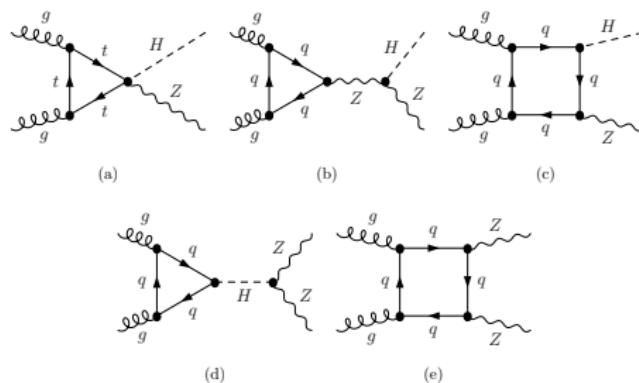
New physics effects in $gg \rightarrow HZ$

(w. C. Englert, R. Rosenfeld and M. Spannowsky - EPL 114 (2016) 3, 31001)

Parametrized by the following dim-6 operators

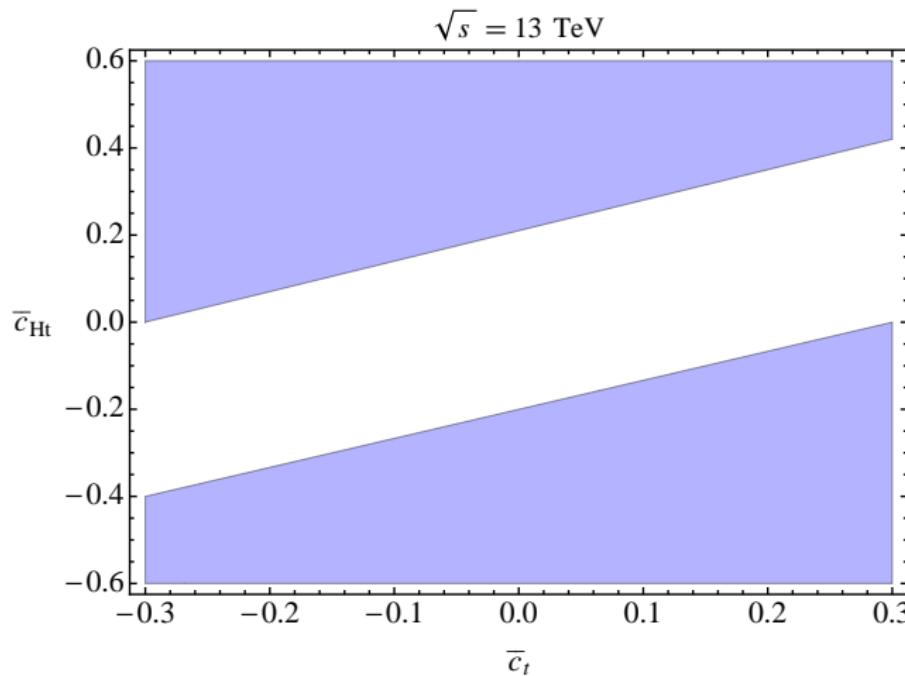
$$\begin{aligned}\mathcal{O}_{Ht} &= \frac{i\bar{c}_{Ht}}{v^2} (\bar{t}_R \gamma^\mu t_R) (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) \\ \mathcal{O}_t &= -\frac{\bar{c}_t}{v^2} y_t \Phi^\dagger \Phi \Phi^\dagger \cdot \bar{Q}_L t_R + \text{h.c.}\end{aligned}$$

Process $gg \rightarrow (H, Z)Z \rightarrow b\bar{b}\ell^+\ell^-$ (decays not shown)



Results: expected exclusion limits

Projected exclusion at 95% CL_S for the boosted analysis including showering and hadronization ($\mathcal{L} = 3 \text{ ab}^{-1}$)



Ongoing/future work

- Searches for DM higher-dimensional operators at LHC
(monojet+MET, monojet+monolepton+MET)

$$\mathcal{O} \sim \frac{1}{\Lambda^3} \chi \chi ll HH \quad \mathcal{O}' \sim \frac{1}{\Lambda^4} \chi \chi q l u d$$

[*N. Bernal, C. S. Fong, N. Fonseca, arXiv:1605.07188*]

- New physics in WW scattering at LHC (strategies for increasing sensitivity to HWW and $WWWW$ couplings)
- Search for higher dimensional operators in double Higgs production at e^+e^- colliders
- Test of top-quark and Higgs compositeness at LHC (scaling laws ?)

Obrigado!