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Probing CP-violating Higgs and gauge boson couplings in the Standard Model effective field theory

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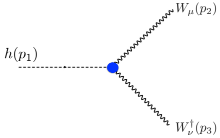
CPV in the EFT Framework

The Dimension-6 EFT Lagrangian

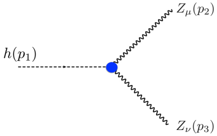
$$\mathcal{L}^6_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{\tilde{c}_i}{m_W^2}\mathcal{O}_i \tag{1}$$

CP-violating operators

$$\begin{aligned}\mathcal{L}_{\rm CP} = {} & ig\frac{\tilde{c}_{HW}}{m_W^2} D^\mu\Phi^\dagger T_{2k} D^\nu\Phi \widetilde{W}^k_{\mu\nu} + ig'\frac{\tilde{c}_{HB}}{m_W^2} D^\mu\Phi^\dagger D^\nu\Phi \widetilde{B}_{\mu\nu} \\ & + g'^2\frac{\tilde{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu} + g_s^2\frac{\tilde{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a \\ & + g^3\frac{\tilde{c}_{3W}}{m_W^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho\widetilde{W}^{\rho\mu k} + g_s^3\frac{\tilde{c}_{3G}}{m_W^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho\widetilde{G}^{\rho\mu c}\ ,\end{aligned} \tag{2}$$



$$i\, g\, m_W \left(\eta_{\mu\nu} - \frac{2\,\tilde{c}_{HW}}{m_W^2}\epsilon_{\mu\nu\alpha\beta}\, p_2^\alpha p_3^\beta\right)$$



$$i\,\frac{g m_Z}{c_W}\left(\eta_{\mu\nu} - \frac{2}{m_Z^2}\left(\tilde{c}_{HW} + t_W^2\tilde{c}_{HB}\right)\epsilon_{\mu\nu\alpha\beta}\, p_2^\alpha p_3^\beta\right)$$

CPV in the EFT Framework

The processes with the operators we want to probe:

Process	$\tilde{c}_g$	$\tilde{c}_\gamma$	$\tilde{c}_{HW}$	$\tilde{c}_{HB}$	$\tilde{c}_{3W}$
$pp \to h \to \gamma\gamma$	$\star$	$\star$			
$pp \to h \to ZZ^{(*)} \to 4\ell$	$\star$		$\star$	$\star$	
$pp \to h \to Z\gamma$	$\star$		$\star$	$\star$	
$pp \to Zh \to \ell^+\ell^- b\bar{b}$			$\star$	$\star$	
$pp \to Zh \to \nu\bar{\nu}b\bar{b}$			$\star$	$\star$	
$pp \to Wh \to \ell\nu b\bar{b}$			$\star$		
$pp \to hjj$ (VBF)			$\star$	$\star$	
$pp \to WW \to \ell\nu\ell'\nu'$			$\star$		$\star$

In this work we are not considering:

- Detector effects.
- NLO QCD correction.

LHC Run I bounds on CPV EFT operators

information from the total cross section:

- $gg \to h \to \gamma\gamma \quad (\tilde{c}_g, \tilde{c}_\gamma)$

$$\mu_{\rm EFT}^{gg\to h\to\gamma\gamma,\ \rm LHC} = 1.0 + 2.0\times 10^7\,\tilde{c}_\gamma^2 - 1.3\times 10^3\,\tilde{c}_\gamma\,\tilde{c}_g + 2.0\times 10^5\,\tilde{c}_g^2\,, \tag{3}$$

- $VH \quad (\tilde{c}_{HW}, \tilde{c}_{HB})$

$$\begin{aligned} \mu_{\rm EFT}^{ZH,\ \rm LHC} &= 1.0 + 145.6\big(\tilde{c}_{HW} + t_W^2\,\tilde{c}_{HB}\big)^2\,, \\ \mu_{\rm EFT}^{WH,\ \rm LHC} &= 1.0 + 52.3\ \tilde{c}_{HW}^2\,, \end{aligned} \tag{4}$$

- WBF $(\tilde{c}_{HW})$

$$\mu_{\rm EFT}^{\rm WBF,\ LHC} = 1.0 + 25.3\,\tilde{c}_{HW}^2\,, \tag{5}$$

- $pp \to h \to 4\ell \quad (\tilde{c}_g, \tilde{c}_{HW}, \tilde{c}_{HB})$

$$\mu_{\rm EFT}^{pp\to h\to 4\ell,\ \rm LHC} = 1.0 + 123.3\big(\tilde{c}_{HW} + t_W^2\ \tilde{c}_{HB}\big)^2\,, \tag{6}$$

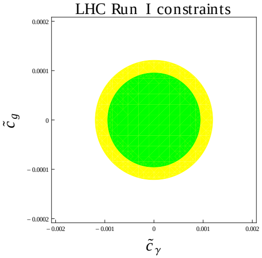
- $pp \to WW \quad (\tilde{c}_{HW}, \tilde{c}_{3W})$

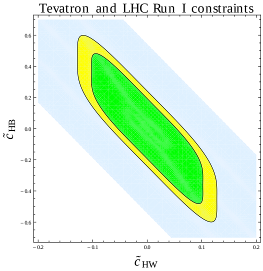
$$\mu_{\rm EFT}^{WW} = 1.0 + 8.0\,\tilde{c}_{3W}^2\,. \tag{7}$$

LHC Run I bounds on CPV EFT operators

$$\frac{\tilde{c}}{m_W^2} \approx \frac{g_{\rm NP}^2}{\Lambda^2} \, . \qquad (8)$$

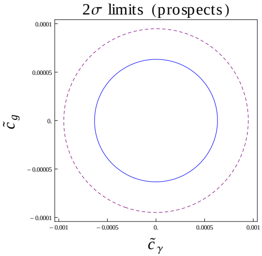
Coefficient	Limit	Λ_s	Λ_w
$\lvert\tilde{c}_g\rvert$	1.2×10^{-4}	92 TeV	4.4 TeV
$\lvert\tilde{c}_\gamma\rvert$	1.2×10^{-3}	29 TeV	1.4 TeV
$\lvert\tilde{c}_{HW}\rvert$	0.06	4.1 TeV	[0.2 TeV]
$\lvert\tilde{c}_{HB}\rvert$	0.23	2.1 TeV	[0.1 TeV]
$\lvert\tilde{c}_{3W}\rvert$	0.18	2.4 TeV	[0.1 TeV]

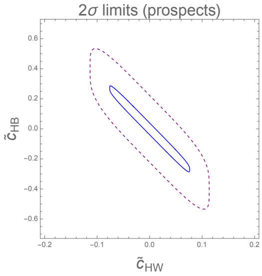




Prospective LHC studies on the basis of inclusive measurements

Channel	$\Delta\mu/\mu$ - 300 fb^{-1}	$\Delta\mu/\mu$ - 3 ab^{-1}
$h \to \gamma\gamma$ (jet veto)	0.13 (0.09)	0.09 (0.04)
$h \to ZZ$ (gluon fusion)	0.12 (0.07)	0.11 (0.04)
$h \to WW$ (jet veto)	0.18 (0.09)	0.16 (0.05)
$h \to \gamma\gamma$ (VBF)	0.47 (0.43)	0.22 (0.15)
$h \to \gamma\gamma$ (WH)	0.48 (0.48)	0.19 (0.17)
$h \to ZZ$ (VH)	0.35 (0.34)	0.13 (0.12)
$h \to ZZ$ (VBF)	0.36 (0.33)	0.21 (0.16)
$h \to WW$ (VBF)	0.21 (0.20)	0.15 (0.09)
$h \to b\bar{b}$ (ZH)	0.29 (0.29)	0.14 (0.13)
$h \to b\bar{b}$ (WH)	0.57 (0.56)	0.37 (0.36)





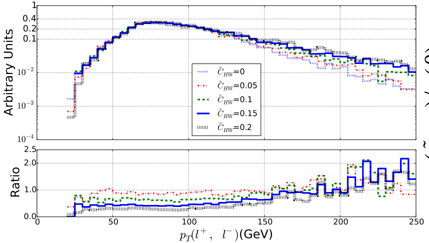
Inclusive cross sections at HL-LHC will not bring us very far. We need to look at differential information, and not just angular variables. We explored many types of variables for WH, ZH and VBF to characterise CPV.

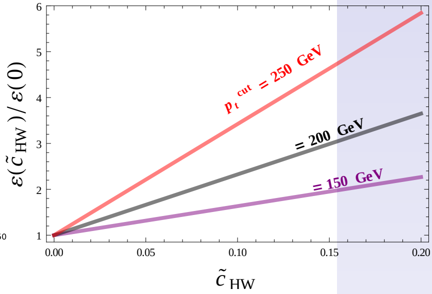
Prospective LHC studies using differential information

- ZH channel

$$p_T(\ell^+, \ell^-) = p_T(\ell^+) + p_T(\ell^-) \; , \qquad (9)$$

$$\varepsilon(\tilde{c}) = \frac{1}{\sigma(\tilde{c})} \int_{p_T^{\mathrm{cut}}}^{\infty} \frac{\mathrm{d}\sigma(\tilde{c})}{\mathrm{d}p_T(\ell^+, \ell^-)} \, \mathrm{d}p_T(\ell^+, \ell^-) \; . \qquad (10)$$



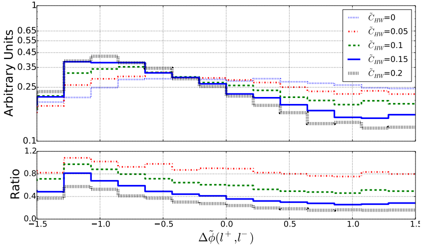


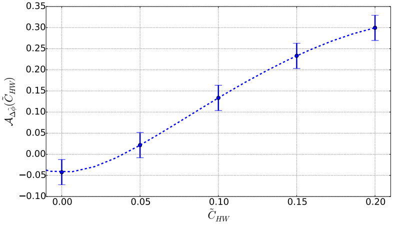
Prospective LHC studies using differential information

- ZH channel

$$\Delta\tilde{\phi}(\ell^+,\ell^-) = |\Delta\phi(\ell^+,\ell^-)| - \frac{\pi}{2}\ . \tag{11}$$

$$\mathcal{A}_{\Delta\tilde{\phi}}(\tilde{c}) = \frac{\mathrm{d}\sigma\left(\Delta\tilde{\phi}(\ell^+,\ell^-)<0\right) - \mathrm{d}\sigma\left(\Delta\tilde{\phi}(\ell^+,\ell^-)>0\right)}{\mathrm{d}\sigma\left(\Delta\tilde{\phi}(\ell^+,\ell^-)<0\right) + \mathrm{d}\sigma\left(\Delta\tilde{\phi}(\ell^+,\ell^-)>0\right)}\ , \tag{12}$$



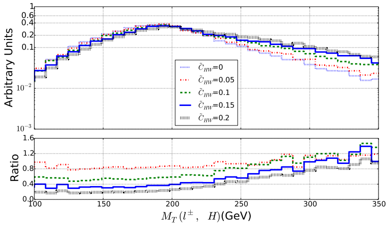


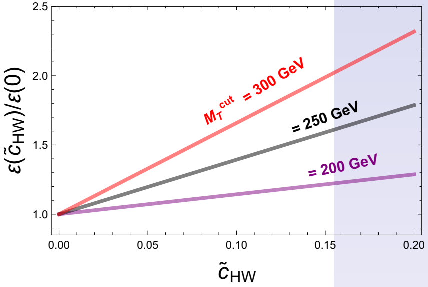
Prospective LHC studies using differential information

- WH channel

$$M_T(\ell, H) \quad (13)$$

$$\varepsilon(\tilde{c}) = \frac{1}{\sigma(\tilde{c})} \int_{M_T^{\rm cut}}^{\infty} \frac{\mathrm{d}\sigma(\tilde{c})}{\mathrm{d}M_T(\ell, H)} \, \mathrm{d}M_T(\ell, H) \; , \quad (14)$$



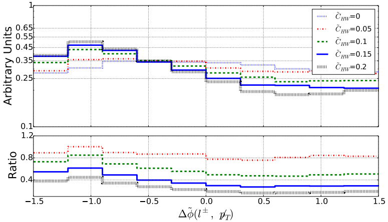


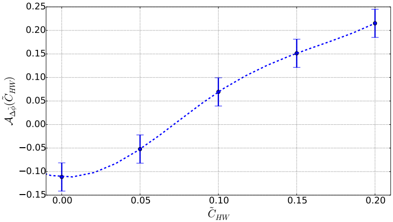
Prospective LHC studies using differential information

- WH channel

$$\Delta\tilde{\phi}(\ell^{\pm}, \not{p}_T) = |\Delta\phi(\ell^{\pm}, \not{p}_T)| - \frac{\pi}{2} \,. \qquad (15)$$

$$\mathcal{A}_{\Delta\tilde{\phi}}(\tilde{c}) = \frac{\mathrm{d}\sigma\left(\Delta\tilde{\phi}(\ell^{\pm}, \not{p}_T) < 0\right) - \mathrm{d}\sigma\left(\Delta\tilde{\phi}(\ell^{\pm}, \not{p}_T) > 0\right)}{\mathrm{d}\sigma\left(\Delta\tilde{\phi}(\ell^{\pm}, \not{p}_T) < 0\right) + \mathrm{d}\sigma\left(\Delta\tilde{\phi}(\ell^{\pm}, \not{p}_T) > 0\right)} \,. \qquad (16)$$



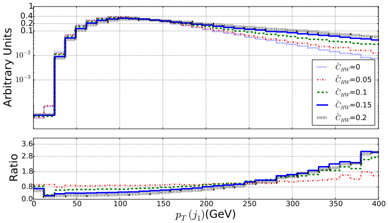


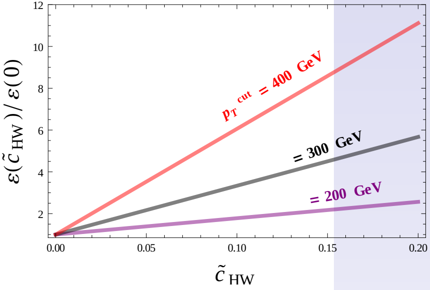
Prospective LHC studies using differential information

- VBF channel

$$p_T(j_1) \tag{17}$$

$$\varepsilon(\tilde{c}) = \frac{1}{\sigma(\tilde{c})} \int_{p_T^{\text{cut}}}^{\infty} \frac{\mathrm{d}\sigma(\tilde{c})}{\mathrm{d}p_T(j_1)}\, \mathrm{d}p_T(j_1)\ . \tag{18}$$



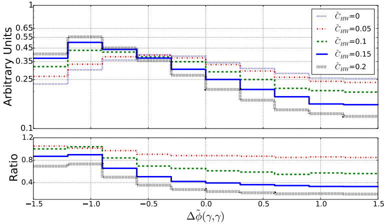


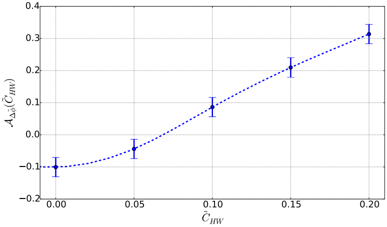
Prospective LHC studies using differential information

- VBF channel:

$$\Delta\tilde{\phi}(\gamma,\gamma) \tag{19}$$

$$\mathcal{A}_{\Delta\tilde{\phi}}(\tilde{c}) = \frac{\mathrm{d}\sigma\left(\Delta\tilde{\phi}(\gamma,\gamma) < 0\right) - \mathrm{d}\sigma\left(\Delta\tilde{\phi}(\gamma,\gamma) > 0\right)}{\mathrm{d}\sigma\left(\Delta\tilde{\phi}(\gamma,\gamma) < 0\right) + \mathrm{d}\sigma\left(\Delta\tilde{\phi}(\gamma,\gamma) > 0\right)} . \tag{20}$$



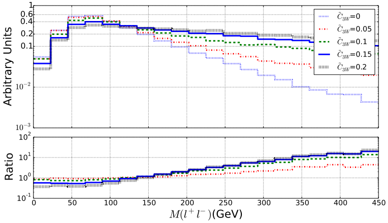


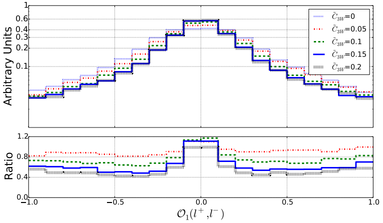
CPV EFT effects in dileptonic W-boson pair production events

- $pp \to WW, W \to l^{\pm}\nu_l$ channel

$$M(\ell^+\ell^-) \tag{21}$$

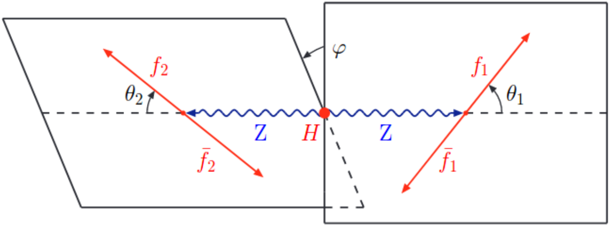
$$\tilde{\mathcal{O}}_1 = \frac{\mathbf{p}_+ \times \mathbf{p}_-}{|\mathbf{p}_+ \times \mathbf{p}_-|}\ \mathrm{sign}\big[(\mathbf{p}_+ - \mathbf{p}_-)\cdot\hat{\mathbf{z}}\big]\ , \tag{22}$$





Revisiting CPV Higgs-boson studies in the four-lepton final state

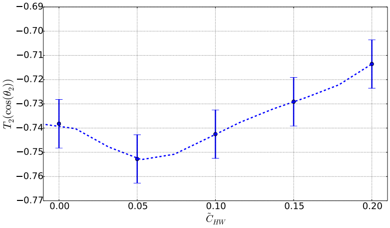
- $M(Z_1)$ in a range $[75, 105]$GeV
- $M(Z_2)$ in a range $[10, 200]$GeV
- The lepton polar angle θ_1 in the rest frame of the parent Z_1
- The lepton polar angle θ_2 in the rest frame of the parent Z_2
- The azimuthal ϕ angle between the two planes formed by the lepton pairs.

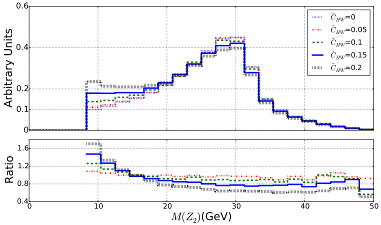


Revisiting CPV Higgs-boson studies in the four-lepton final state

- $gg \to h \to ZZ, Z \to l^+l^-$ channel

$$T_2(x) = \frac{4}{3}\Big[\mathrm{d}\sigma(-1 < x < -1/2) - \mathrm{d}\sigma(-1/2 < x < 1/2) + \mathrm{d}\sigma(1/2 < x < 1)\Big]\,, \tag{23}$$





Summary

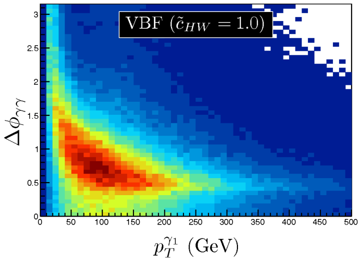
- **VH production**: The dimensionful observable is taken to be the scalar sum of the transverse momenta of the two leptons originating from the decay of Z-boson in the ZH case, and the transverse mass of the system comprised of the reconstructed Higgs boson and the lepton issued from the W-boson decay in the WH case. The angular observable is taken to be the difference in azimuthal angle between the two leptons (the lepton and the missing momentum) in the ZH (WH) case. We have found that this efficiency and the asymmertry built from the angular observable provide an effective handle to distinguish CPV effects

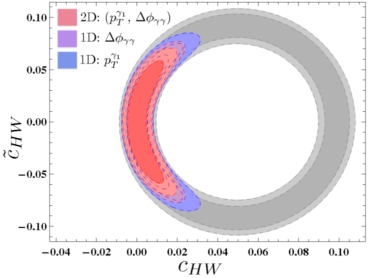
Summary

- **VBF production**: Similarly, we make use of the azimuthal angular separation of the diphoton system arising from the Higgs boson decay and the transverse momentum of the leading jet.
- **Dileptonic W-boson pair production**: Here, we use the invariant mass of the dilepton system for computing the efficiency related to the dimensionful observable, and the triple product observable $\tilde{\mathcal{O}}_1$ as a dimensionless variable.
- **Higgs decays in four lepton final state**: In this case, we rely on the reconstructed off-shell Z-boson stemming from the Higgs boson decay. We consider its invariant mass as a dimensionful variable, and the so-called T_2 function applied on the polar angles of its decay products as the dimen sionless variable.

Prospects and future works.

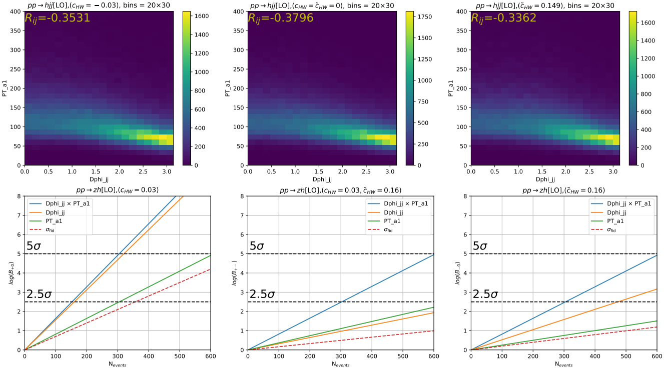
- On new physics searches with multidimensional differential shapes, Phys.Lett. B778 (2018) 35-42. arXiv:1702.05106





Prospects and future works.

- CP properties of the SMEFT Higgs interactions with gauge bosons at Next-to-Leading Order QCD.
- ML and Deep Learning techniques for CP event characterization.



Obrigado.