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Search for CP violating effects in HWW vertex in the WH production channel in 13 TeV pp collisions with the ATLAS detector

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The Standard Model (SM) predicts the Higgs boson to be a CP-even (scalar) particle. Any deviation from a purely CP-even interaction of the Higgs boson with other SM particles would indicate physics beyond the SM. This text presents a search for CP violating effects in Higgs boson production in association with a W boson, using proton-proton collision data collected by the ATLAS detector at the Large Hadron Collider from 2015-2018, corresponding to an integrated luminosity of 139 fb^{-1} at a center-of-mass energy of 13 TeV. The analysis focuses on the Higgs boson decay to bottom quark pairs and the W boson decay to leptons: WH, with $H \to b\bar{b}$ and $W \to \ell\nu$ ($\ell = e, \mu$). Fiducial cross-section measurements are performed using the Simplified Template Cross Section (STXS) formalism in bins of an angular observable and the W boson transverse momentum, providing a sensitive probe to CP-violating components in the HWW vertex. The results are interpreted within the Standard Model Effective Field Theory, and constraints are set on the relevant Wilson coefficient in the Warsaw basis, $c_{H\widetilde{W}}$ (CP-odd operator).

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1. Introduction

The origin of the observed baryon asymmetry in the universe is one of the fundamental open questions in our current understanding of particle physics. In 1967 Sakharov proposed three necessary conditions [1] to explain the generation of the baryon asymmetry. One of these conditions includes Charge-Parity (CP) symmetry violation. But the known sources of CP violation in the Standard Model (SM), which come from the complex phase in the quark mixing matrix, are insufficient to explain the observed matter antimatter imbalance.

While the SM Higgs boson is a scalar particle which is even under CP transformations, CP-violating interactions are still allowed experimentally. Therefore, measurements of the CP structure of the Higgs boson interactions with SM particles can be performed to search for sources of CP violation. Any deviation from the SM predictions would be a sign of physics beyond the SM (BSM).

This text reports on a search for CP violation in the interaction between the Higgs and W bosons, via WH production [2]. This production channel allows for constraining the HWW vertex separately from the HZZ vertex, which is not the case for the searches via vector-boson fusion (VBF) production. A CP-sensitive analysis of WH production with Higgs boson decays into bottom quarks is performed, $WH, H \to b\bar{b}$ based on the analysis described in Ref. [3].

2. Theoretical framework

The results in this note are provided in the context of the Standard Model Effective Field Theory (SMEFT) formalism [4], using the Warsaw basis [5]. In this framework, the Lagrangian of the Standard Model is expanded with higher-dimension ($d > 4$) operators O_i, suppressed by powers of an energy scale Λ. There are 5 dimension-6 operators which affect the $pp \to WH$ process including a single CP-odd operator $O_{H\widetilde{W}}$, that is target of the analysis. The corresponding numerical coefficient is the Wilson coefficient $c_{H\widetilde{W}}$. The resulting SMEFT Lagrangian amplitude is composed by the SM term, the interference between SM and the $O_{H\widetilde{W}}$ operator (linear term, proportional to $c_{H\widetilde{W}}$) and the $O_{H\widetilde{W}}$ term (quadratic, proportional to $c^2_{H\widetilde{W}}$). Only the linear term in the cross-section is CP-odd.

The measurement presented in this note is performed using a dedicated angular observable, designed to retain sensitivity to the CP-odd behavior introduced by the interference between the SM and the SMEFT $O_{H\widetilde{W}}$ term in the Lagrangian. An angular observable $\cos\delta^+$ was introduced in Ref. [6] with the following definition:

$$\cos\delta^+ = \frac{\mathbf{p}_\ell^{(W)} \cdot (\mathbf{p}_H \times \mathbf{p}_W)}{|\mathbf{p}_\ell^{(W)}| \cdot |\mathbf{p}_H \times \mathbf{p}_W|}, \tag{1}$$

where $\mathbf{p}_\ell^{(W)}$ is the momentum of the charged lepton in the W boson rest frame and $\mathbf{p}_W$, $\mathbf{p}_H$ are the momenta of the W and Higgs bosons, respectively, in the laboratory frame. The sensitivity of this observable to CP violating effects can be further increased by multiplying it by the lepton charge, $Q_\ell \cos\delta^+$. This results in a distribution that is asymmetric relative to $Q_\ell \cos\delta^+ = 0$ in the case of a non-null $c_{H\widetilde{W}}$. Furthermore, the dependency of the linear term in $O_{H\widetilde{W}}$ with the energy of initial and final state particles can be exploited by using an energy-related observable, such as the

transverse momentum of the W boson p_T^W . Events are categorised into four bins according to p_T^W : 75-150 GeV, 150-250 GeV, 250-400 GeV, 400 GeV and above.

3. Analysis strategy

The aim of the analysis is to constrain the CP-violating coupling $c_{H\widetilde{W}}$ in the interaction between Higgs and W bosons via the WH production channel. It is based on and follows closely the measurement of VH production with the Higgs boson decaying into bottom quarks presented in Ref. [3]. Since the main focus is on the Higgs couplings to the W bosons, only the WH production channel is considered, with $W \to \ell\nu$ ($\ell = e, \mu$) and $H \to b\bar{b}$. The ZH production process is considered as background.

The proton-proton collision data used in this analysis was collected by the ATLAS detector [7] during Run 2 of the LHC (2015-2018), corresponding to an integrated luminosity of 140 fb^{-1}.

The signal WH process is characterised by an isolated lepton, missing transverse energy from the neutrino, and two b-jets in the final state. The reconstruction strategy for the Higgs boson depends on its transverse momentum, that is correlated with the W-boson transverse momentum. In the *resolved regime*, corresponding to ${p_T}^W < 400$ GeV, the events are required to have exactly two small radius ($R = 0.4$) b-tagged jets, that are combined to form the Higgs candidate. For ${p_T}^W > 400$ GeV (*boosted regime*), the highest p_T large-radius ($R = 1.0$) jet is selected to reconstruct the Higgs boson candidate. It is required to have an invariant mass larger than 50 GeV and exactly two of its three leading matched variable-radius track-jets [8] should be b-tagged.

The dominant backgrounds are top-quark production ($t\bar{t}$ and Wt) and W boson production in association with jets (mainly heavy-flavoured jets). Minor backgrounds include single top (s and t-channels), multi-jet, diboson and Z+jets production. Events are further classified in signal and control regions. Monte Carlo (MC) simulated samples are used to model most of the SM background processes and the SM signal process. Dedicated control regions in data are defined to constrain the main backgrounds, W+jets and top quark production and their different flavour components ($bb + cc$, $bc + bl + cl + l$, where l stands for the light-flavour quark).

Events in all signal and control regions are further categorised into four bins according to p_T^W : 75-150 GeV, 150-250 GeV, 250-400 GeV, 400 GeV and above. In the resolved regime, events are further divided according to the total number of jets (two or three jets regions). Finally, all the signal regions are also divided into two bins of the angular observable ($Q_\ell \cos\delta^+ \leq 0$, $Q_\ell \cos\delta^+ > 0$).

The systematic uncertainties considered include those from experimental and theoretical sources. Experimental systematic uncertainties are defined for all objects (leptons, jets, b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$) and impact both background and signal simulations. The dominant experimental uncertainties originate from the jet energy scale uncertainty related to the flavor composition of small-radius jets in the signal samples. The theoretical modeling of background processes considers uncertainties on the overall absolute normalisation of a background process (unless it floats with no constraints in the fit); uncertainties on the shape of an observable distribution; and relative acceptance uncertainties that take into account differences in relative normalisations between analysis regions. Systematic uncertainties that impact the modeling of the signal distributions (both shape and normalization) include those originating from QCD scale variations, parton distribution functions, parton shower and underlying event models, electroweak corrections and theory uncertainties

on the $H \to b\bar{b}$ branching ratio. The estimation of the QCD scale signal uncertainties follows the same procedure as Ref. [3] via the Stewart-Tackmann method [9].

Fiducial cross section measurements are performed using an extended version of the simplified template cross section (STXS) framework [10], stage 1.2 [11, 12], which splits the signal events into experimentally accessible exclusive kinematic fiducial regions that are relevant for theory interpretations. STXS regions are defined using the *truth* record of the event, classifying the events in a two dimensional grid based on the transverse momentum of the W boson and the angular observable $Q_\ell \cos\delta^+$. The predicted fraction of events in each reconstruction-level category originating from the equivalent STXS region ranges between 60-80%. The cross section measurements obtained are then interpreted in terms of constraints on the CP-odd Wilson coefficient $c_{H\widetilde{W}}$, by considering only the linear term in the SMEFT expression of the $pp \to WH$ cross-section. The interpretation relies on expressing the truth-level cross-section in each STXS bin as a function of $c_{H\widetilde{W}}$ [13] using SMEFTsim 3.0 [14]. The Higgs boson cross-section in each STXS region p can be expressed as $\sigma_p = \sigma_{p,\mathrm{SM}} + \sigma_{p,\mathrm{int}}$, where SM-BSM interference term $\frac{\sigma_{p,\mathrm{int}}}{\sigma_{p,\mathrm{SM}}} = \sum_i A_i{}^{\sigma_p} c_i$. The $A_i{}^{\sigma_p}$ are coefficients independent of c_i and which are determined from simulation. The signal normalisation factors in each $p_T{}^W$ bin are floated in the fit. In this way, the analysis is not sensitive to overall changes in the total cross-section, and effectively measures the relative asymmetry, and is therefore only sensitive to the interference term of the EFT model.

4. Results

The measured signal strength, i.e. the cross section times branching fraction normalised to the SM expectations, for each one of the STXS regions are shown in Figure 1. The experimental precision is generally dominated by the statistical uncertainty, with the exception of the first p_T^W bin where the systematic uncertainties are larger. Overall, the results are in agreement with the SM expectations, with no clear pattern distinguishing the positive or negative bins of the angular observable $Q_\ell \cos\delta^+$.

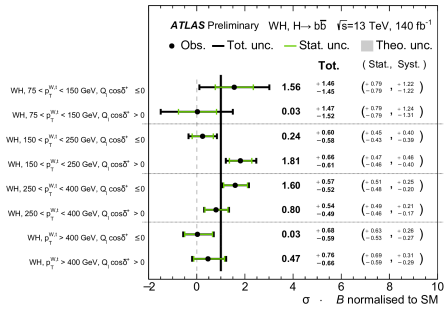

Figure 1: Measured WH production cross sections times the $W \to \ell\nu$ and the $H \to b\bar{b}$. branching ratios. The measured signal significance with its corresponding uncertainty is shown for all regions. The grey band for the theoretical uncertainties is too small to be visible [2].

4.1 CP-odd interpretation

A fit to the STXS regions is performed with 5 parameters of interest: the CP-odd Wilson coefficient $c_{H\widetilde{W}}$ and the signal normalisation factors in each p_T^W bin (correlated across $Q_\ell \cos\delta^+$

regions). This configuration ensures sensitivity to CP-odd effects by explicitly factorizing out the effect on the signal scale. The resulting observed and expected negative profile likelihood scans as a function of $c_{H\widetilde{W}}$ are shown in Figure 2. The expected 95% CL interval on the Wilson coefficient $c_{H\widetilde{W}}$ is [-0.54, 0.54]. The observed profile likelihood scan shows a preference for a non-zero value, $c_{H\widetilde{W}}$ = 0.1, with an observed 95% CL interval of [-0.54, 0.74]. These results are competitive with the best ATLAS measurement obtained for the VBF production of Higgs bosons decaying to tau-lepton pairs [15], with the advantage of less assumptions on other coefficients since there is only one CP-odd dimension-6 operator, $O_{H\widetilde{W}}$, affecting WH production.

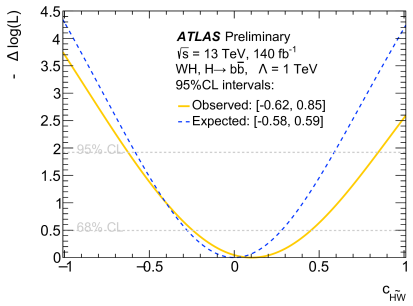

Figure 2: Expected and observed scans of the likelihoods for the CP-odd Wilson coefficient $c_{H\widetilde{W}}$ using a linear-only parameterization. All other Wilson coefficients are set to 0 [2].

5. Conclusion

A Standard Model Effective Field Theory (SMEFT) analysis to probe for CP-violating Higgs boson interactions with W bosons has been performed in the WH associated production channel, with the Higgs decaying to b-quark pairs and the W boson to leptons. The analysis uses 140 fb^{-1} of proton-proton collisions data at 13 TeV center of mass energy collected by the ATLAS detector during the Run 2 LHC data taking period. Two-dimensional fiducial cross sections measurements are performed following the simplified template cross section framework. The data is divided in bins of the W boson transverse momentum and an angular observable sensitive to the CP-violating HWW interactions. The results obtained are consistent with the Standard Model expectations. These measurements are then interpreted in terms of constraints to the only CP-violating dimension-six HWW interaction operator, $c_{H\widetilde{W}}$, following the SMEFT formalism and using the Warsaw basis. The observed (expected) 95% CL limits on the CP-odd Wilson coefficient $c_{H\widetilde{W}}$ are [-0.54, 0.74] ([-0.54, 0.54]). These results represent the first measurements of the CP-odd operator in WH production channel. They are competitive with the most stringent ATLAS limits up to date, obtained with the vector boson fusion production of Higgs decaying to tau-lepton pairs. This measurement, unlike the searches via VBF production channels, allows for constraining the HWW vertex separately from the HZZ vertex.

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