INVESTIGATION OF THE CP PROPERTIES OF VBF HIGGS PRODUCTION USING THE DECAY TO A PAIR OF TAU LEPTONS WITH THE ATLAS DETECTOR*

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Recent studies at the LHC have led to the observation of the Higgs boson decay to tau leptons, with a rate compatible with the Standard Model expectation. The observation opens the way to a more in-depth investigation of the properties of the production and decay of a Higgs boson into tau leptons, including whether or not the Higgs boson couplings involved in this process violate CP conservation. The analysis presented in these proceedings focuses on events collected by the ATLAS experiment where Higgs bosons are produced via vector-boson fusion in order to investigate the tensor structure of their coupling to electroweak gauge bosons. For this, a profile likelihood fit using a matrix-element observable is employed in the decay to tau leptons to test whether a CP-odd component is present in the coupling. A measurement of a non-zero value would be an indication of CP violation in the Higgs sector. No evidence of CP violation was found.

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1. Introduction

The only experimentally confirmed source of CP violation is from quark mixing in weak interactions [1]. That is, however, a very small effect and not sufficient to explain the observed magnitude of CP violation and baryon asymmetry in the universe [2]. Thus, additional sources of CP violation not accounted for by the Standard Model (SM) are expected to exist. The analysis presented in the following [3] exploits proton–proton collision data collected with the ATLAS detector at the LHC at $\sqrt{s} = 13$ TeV and corresponding to an integrated luminosity of 36.1 fb^{-1}. The aim of the study

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is to test the Higgs boson couplings to vector bosons (HVV couplings) for an additional CP-odd contribution. To that end, $H \to \tau\tau$ events where the Higgs boson is produced via vector-boson fusion (VBF) are investigated.

2. Effective field theory

An effective field theory (EFT) approach is employed to construct an extension of the SM that contains CP-violating HVV couplings. For this, dimension-6 operators contributing to HVV couplings are added to the SM Lagrangian $\mathcal{L}_{\text{SM}}$. After electroweak symmetry breaking, the Lagrangian of the resulting model can be written in terms of the Higgs boson H, photon A and the weak vector bosons Z and $W^{\pm}$ fields [4]

$$\begin{aligned}\mathcal{L} \;=\; & \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} \\ & + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu} \,.\end{aligned}$$

Here, $V^{\mu\nu} (V \in \{A, W^{\pm}, Z\})$ describes the field strength and $\tilde{V}_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}$ the dual field strength tensor. The four couplings $\tilde{g}_{HVV}$ are not independent, and due to constraints from $\text{U}(1)_Y$ and $\text{SU}(2)_{I_{W,L}}$ symmetry, they can be expressed in terms of the dimensionless parameters $\tilde{d}$ and $\tilde{d}_B$ [5, 6]

$$\tilde{g}_{HAA} = \frac{g}{2m_W}\left(\tilde{d}\sin^2\theta_{\text{W}} + \tilde{d}_B \cos^2\theta_{\text{W}}\right), \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_{\text{W}}\left(\tilde{d} - \tilde{d}_B\right),$$
$$\tilde{g}_{HZZ} = \frac{g}{2m_W}\left(\tilde{d}\cos^2\theta_{\text{W}} + \tilde{d}_B \sin^2\theta_{\text{W}}\right), \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}\,.$$

In these expressions, g is the weak coupling constant, m_W is the mass of the W boson and θ_{W} is the weak mixing angle.

As the size of $\tilde{d}_B$ relative to $\tilde{d}$ only changes the contribution of specific types of virtual particles to the total VBF production cross section, it cannot be experimentally probed. Therefore, $\tilde{d}_B = \tilde{d}$ is assumed, which implies

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}\,, \qquad \tilde{g}_{HAZ} = 0\,.$$

Thus, the contribution of CP-violating couplings to VBF production can be quantified exclusively by the parameter $\tilde{d}$.

3. The optimal observable

For $\tilde{d} \neq 0$, the squared matrix element of VBF can be written as

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d}\, 2\text{Re}\left(\mathcal{M}^*_{\text{SM}} \mathcal{M}_{\text{CP-odd}}\right) + \tilde{d}^2 \left|\mathcal{M}_{\text{CP-odd}}\right|^2 .$$

The first and third contribution are CP-even, but the interference term is CP-odd, leaving us with a new source of CP violation in the Higgs sector.

In VBF events at leading order, the final state consists of two jets and the Higgs boson. The four-vectors of these objects can be used to evaluate the leading-order VBF production matrix element. These calculations, assuming CP-odd or SM-like HVV couplings, are conducted with the Monte Carlo generator HAWK [7], so that one can construct the Optimal Observable

$$\mathcal{O}_{\text{opt}} = \frac{2\text{Re}\left(\mathcal{M}^{*}_{\text{SM}}\mathcal{M}_{\text{CP-odd}}\right)}{|\mathcal{M}_{\text{SM}}|^2}\,.$$

As $\mathcal{O}_{\text{opt}}$ is a CP-odd observable, a mean value $\langle\mathcal{O}_{\text{opt}}\rangle$ that is incompatible with zero would imply CP violation in HVV couplings, assuming that the effect from rescattering is negligible [8].

4. Event selection

Candidate events are classified according to the decay mode of the tau leptons. The four different decay channels that are considered are the dileptonic same-flavour ($\tau_{\text{lep}}\tau_{\text{lep}}$ SF), the dileptonic different-flavour ($\tau_{\text{lep}}\tau_{\text{lep}}$ DF), the semileptonic ($\tau_{\text{lep}}\tau_{\text{had}}$), and the fully hadronic ($\tau_{\text{had}}\tau_{\text{had}}$) channel. These

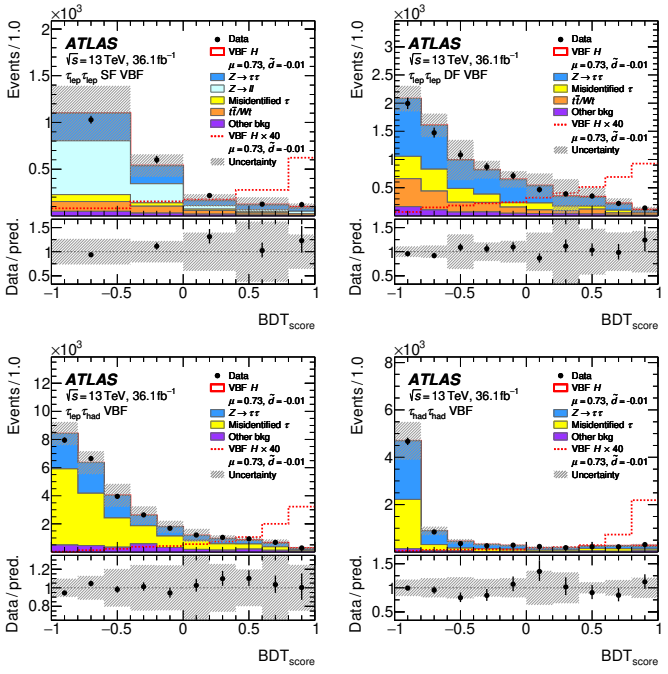


Fig. 1. Post-fit $\text{BDT}_{\text{score}}$ distributions in the four decay channels. The lower panel shows the ratio of observed to predicted events. The dashed line shows the best-fit signal scaled up by a factor of 40 [3].

are separated since the composition of background processes differs greatly. However, the event topology of VBF $H \to \tau\tau$ and VBF $H \to WW^*$, which is also considered as a signal process, is mostly independent from the decay channel: In addition to the Higgs boson decay products, one expects two jets with a large invariant mass and pseudorapidity gap.

After applying basic selection criteria based on this expectation, boosted decision trees (BDTs) are trained to further separate signal and background events, independently in each channel. The resulting $\mathrm{BDT}_{\mathrm{score}}$ distributions are shown in Fig. 1.

5. First CP test

A cut on the BDT scores is applied to improve sensitivity to the signal processes. The resulting region is called signal region (SR). The SR $\mathcal{O}_{\mathrm{opt}}$ distributions are shown in Fig. 2, and if VBF production is CP-conserving, the mean value in data must be consistent with zero. Table I lists the mean values of the distribution in each signal region. None of these values shows a significant inconsistency with zero, hence no sign of CP violation was found.

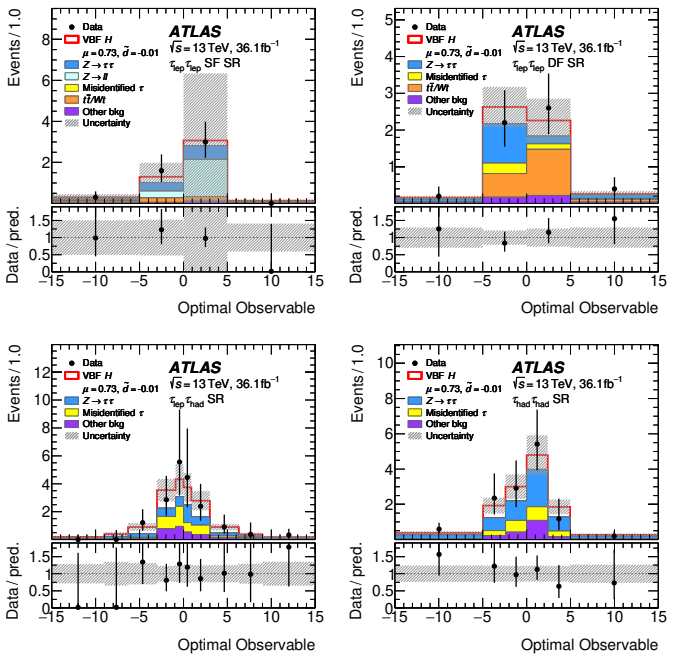


Fig. 2. Post-fit $\mathcal{O}_{\mathrm{opt}}$ distributions in the high-$\mathrm{BDT}_{\mathrm{score}}$ signal regions. The lower panel shows the ratio of observed to predicted events [3].

TABLE I

Mean values of $\mathcal{O}_{\text{opt}}$ in data in the SRs with statistical uncertainties [3].

Channel	$\langle \mathcal{O}_{\text{opt}} \rangle$
$\tau_{\text{lep}}\tau_{\text{lep}}$ SF	-0.54 ± 0.72
$\tau_{\text{lep}}\tau_{\text{lep}}$ DF	0.71 ± 0.81
$\tau_{\text{lep}}\tau_{\text{had}}$	0.74 ± 0.78
$\tau_{\text{had}}\tau_{\text{had}}$	-1.13 ± 0.65

6. Profile likelihood fit

A more sensitive, but also more model-dependent test for CP violation is to estimate the parameter $\tilde{d}$ through profile likelihood fits. The $\mathcal{O}_{\text{opt}}$ distributions in the four SRs, shown in Fig. 2, are used to gain sensitivity to $\tilde{d}$. To control the normalization of the $Z \to \tau\tau$ background, the distributions of the estimated invariant mass of the full di-tau system $m_{\tau\tau}^{\text{MMC}}$ [9] in events that failed the $\text{BDT}_{\text{score}}$ cut is also included in the fit.

Event yield information from three more regions is also included to constrain the normalization factors of $Z \to \ell\ell$ ($\ell \in \{e, \mu\}$) and $t\bar{t}/Wt$ backgrounds in the $\tau_{\text{lep}}\tau_{\text{lep}}$ channels. These regions are defined by either requiring $m_{\ell\ell} \in [80\ \text{GeV}, 100\ \text{GeV}]$, where $m_{\ell\ell}$ is the invariant mass of the two leptons leading in p_{T} (only in $\tau_{\text{lep}}\tau_{\text{lep}}$ SF), or the presence of b-tagged jets.

The fit is conducted with different $\tilde{d}$ hypotheses for the signal without changing the background model. Comparing the resulting likelihood values as a function of $\tilde{d}$ results in the negative log-likelihood (NLL) curves shown in Fig. 3. The minimum of an NLL curve shows the best-fit estimate for $\tilde{d}$. All $\tilde{d}$ scenarios with a value sufficiently high above zero are excluded at 68% or 95% confidence level, as indicated by the dashed red lines.

7. Results and summary

From the observed NLL curve in Fig. 3, one obtains an observed 68% confidence interval (CI) of $\tilde{d} \in [-0.090, 0.035]$, while the expected curve for $\mu = 1$ and $\tilde{d} = 0$ shows an expected 68% CI of $\tilde{d} \in [-0.035, 0.033]$ and a 95% CI of $\tilde{d} \in [-0.21, 0.15]$. The latter cannot be derived for the observed measurement due to the low observed signal strength $\mu = \frac{\sigma^{\text{observed}}_{\text{VBF } H}}{\sigma^{\text{SM}}_{\text{VBF } H}}$, which was measured to be $\mu = 0.73 \pm 0.47$. The drop in sensitivity due to $\mu < 1$ can be seen by the expected curve assuming $\mu = 0.73$, which reaches lower NLL values than when assuming $\mu = 1$.

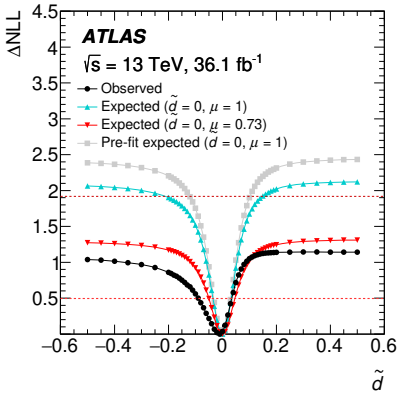


Fig. 3. (Colour on-line) NLL curves as a function of $\tilde{d}$. The observed curve results from a fit to the observed data distributions. Two more curves that were obtained from fits to pseudo-data based on a fit to data using only the control regions, assuming different signal strengths μ are also shown. For comparison, a pre-fit expected curve assuming $\mu = 1$ and $\tilde{d} = 0$ is also shown [3].

In summary, a study has been performed with the ATLAS detector at the LHC, to look for possible CP-violation effects in VBF Higgs production using $H \to \tau\tau$ events. All the measured CIs for the variable $\tilde{d}$, sensitive to CP-violation effects, cover the SM expectation of $\tilde{d} = 0$. Hence, no sign of CP violation in HVV couplings was found.

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