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Measurement of the CP properties of Higgs boson interactions with τ leptons at the LHC

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The ATLAS and CMS experiments have performed measurements of the CP structure of the interaction between the Higgs boson and τ leptons using proton-proton collisions at $\sqrt{s} = 13$ TeV, delivered by LHC during 2016-2018. The measurements are based on the angular correlation between the decay planes of τ leptons produced in Higgs boson decays. The value of the effective mixing angle measured by ATLAS and CMS experiments are found to be $9 \pm 16^\circ$ and $-1 \pm 19^\circ$ at the 68% CL, respectively. The data from ATLAS and CMS experiments disfavour the pure CP-odd hypothesis at 3.4 and 3.0 standard deviations, respectively. The results are compatible with expectations for the standard model Higgs boson.

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1. Introduction

Since the discovery of a Higgs boson by the ATLAS and CMS Collaborations [1–3] a primary objective of the physics program at CERN-LHC is to perform precision measurements of its properties. The properties measured so far [4, 5] are compatible with those of the Higgs boson predicted by the Standard Model (SM) of particle physics. The SM Higgs boson is even under charge-parity (CP) inversion. Any deviation from a pure CP-even interaction of the Higgs boson with any of the SM particles would be a direct indication of physics beyond the SM. The CP nature of the Higgs boson couplings to gauge bosons have been extensively studied at the LHC [6, 7], which excludes pure CP-odd interactions of the Higgs boson with W and Z bosons. However, in these couplings the CP-odd contributions enter only via higher order operators [8], which only yields a small contribution to the coupling. A CP-violating Higgs-to-fermion coupling can occur at tree level, which makes Yukawa couplings of top quark ($Ht\bar{t}$) and τ lepton ($H\tau\tau$) optimal for CP studies at LHC. The first measurements of CP structure of the Higgs couplings to top quarks by the ATLAS and CMS experiments reject the purely CP-odd hypothesis with a significance of greater than 3 standard deviations [9, 10].

Both ATLAS [11] and CMS [12] experiments have probed the CP structure of the Higgs-to-τ lepton Yukawa coupling using pp collisions at centre-of-mass energy of 13 TeV recorded during 2016-2018 [13, 14]. The measurements are carried out using the strategy presented in Refs. [15, 16]. The Lagrangian for the τ Yukawa coupling is parameterised in terms of the coupling strength modifiers κ_τ and $\tilde{\kappa}_\tau$ that parameterise the CP-even and CP-odd contributions, respectively [15, 16]:

$$L_Y = -\frac{m_\tau}{v} H \left(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau\right), \tag{1}$$

where m_τ is mass of the τ lepton, τ denotes the Dirac spinor of τ lepton fields, and v is the vacuum expectation value of the Higgs field with a value of 246 GeV. The effective mixing angle (denoted as ϕ_τ in ATLAS [13] and $\alpha^{H\tau\tau}$ in CMS [14]) is defined as

$$tan(\phi_\tau) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}, \tag{2}$$

with $\phi_\tau = 0(90)^\circ$ corresponding to a pure scalar (pseudoscalar) CP coupling. For any other value of ϕ_τ, the Higgs boson has a mixed coupling with CP-even and CP-odd components, with maximal mixing at a value of $\pm 45^\circ$. The measurement of a nonzero value of ϕ_τ would contradict the SM predictions and indicate the presence of beyond the SM physics.

The signed acoplanarity angle, the angle between the τ lepton decay planes in the Higgs boson rest frame (denoted as φ^*_{CP} in ATLAS and ϕ_{CP} in CMS, as described in Ref. [13, 14]), is sensitive to the transverse spin correlations impacted by the CP-mixing angle of the Yukawa coupling. The angle ϕ_{CP} is related to ϕ_τ in the $H \to \tau\tau$ differential decay rate, which is proportional to $cos(\phi_{CP} - 2\phi_\tau)$ at leading order [16]. A generator level normalised distribution of ϕ_{CP} is shown in Fig. 1, calculated in the rest frame of the Higgs boson, for the scalar, pseudoscalar, and maximally mixed values of ϕ_τ, as well as from the Drell-Yan processes.

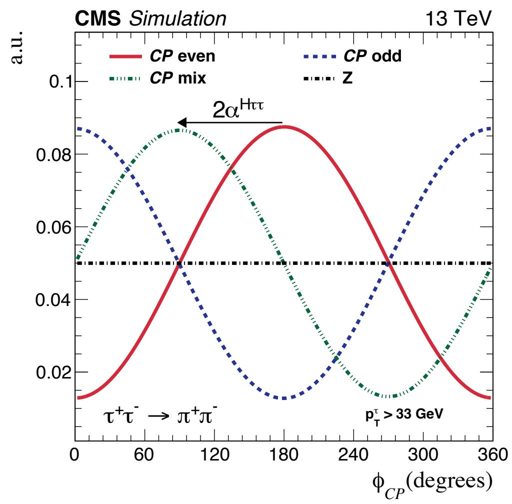

Figure 1: The normalised distribution of ϕ_{CP} between the τ lepton decay planes in the Higgs rest frame at the generator level, for both τ leptons decaying to a charged pion and a neutrino, as presented in Fig.2 of Ref. [14].

2. Reconstruction of ϕ_{CP} angle

The reconstruction of ϕ_{CP} angle depends on the decay topology of the τ leptons. Nearly 35% of the time a τ lepton decays to an electron or a muon, accompanied by a pair of neutrinos, which is denoted here as τ_ℓ. In the rest of the time, the τ lepton decays to hadrons (mostly charged and neutral pions) accompanied by a neutrino, denoted here as τ_h. The electron or muon originating from τ lepton decay are reconstructed using the standard electron or muon reconstruction algorithms [17–20]. ATLAS uses a τ particle-flow algorithm to reconstruct hadronic decay of the τ leptons, which combines charged hadrons and π^0s to reconstruct the decay modes [21]. Multivariate analysis methods (MVAs) based on boosted decision trees (BDTs) are used to identify decay modes by correctly determining π^0s originating from the τ lepton decay. A recurrent neural network (RNN) based discriminator is used to reject jets that are misidentified as τ_h [22, 23]. CMS uses the hadron-plus-strips (HPS) algorithm, which combines particle-flow charged hadron and e/γ candidates to reconstruct individual τ lepton decay modes [24]. A deep-learning based discriminator (DEEPTAU) is used to reject jets, electrons, and muons that are misidentified as τ_h [25]. Furthermore, a BDT is used to improve the purity of decay mode identification by improving the π^0 determination [26].

Depending on the di-τ final states, four methods are used to reconstruct ϕ_{CP}: "impact parameter (IP) method", "neutral pion or ρ/a_1-decay plane method", "combined method", and "polarimetric vector method". These are briefly summarised below.

2.1 Impact parameter method

This method is applied to all events where both τ leptons decay to a single charged particle. The IP is defined as the vector between the primary vertex (PV) and the point on the track where the distance to the PV is minimal. An approximate decay plane is reconstructed using the IP vector and the charged-particle momentum vector. Since the rest frame of Higgs boson can not be reconstructed due to missing neutrinos, the charged decay products of the τ leptons are used to define a zero-momentum frame (ZMF) that approximates the Higgs boson rest frame. The decay planes are boosted to the ZMF. To reconstruct ϕ_{CP} first the angle ϕ^* and O^* are defined using the normalised momentum vectors of charged particles ($\hat{q}^{*\pm}$) and normalised transverse IP vectors ($\hat{\lambda}_{\perp}^{*\pm}$) in ZMF:

$$\begin{aligned} \phi^* &= arccos(\hat{\lambda}_{\perp}^{*+} \cdot \hat{\lambda}_{\perp}^{*-}), \quad \text{and} \\ O^* &= \hat{q}^{*-} \cdot (\hat{\lambda}_{\perp}^{*+} \times \hat{\lambda}_{\perp}^{*-}). \end{aligned} \tag{3}$$

Then, the ϕ_{CP} is reconstructed in a range $[0, 360°]$ as

$$\phi_{CP} = \begin{cases} \phi^* & \text{if } O^* \geq 0 \\ 360° - \phi^* & \text{if } O^* < 0 \end{cases} \tag{4}$$

An additional shift by 180° is applied in case of leptonic decay due to a different sign in the spectral function for the leptonic τ decays.

2.2 Neutral-pion or ρ/a_1-decay plane method

This method is applied to hadronic decay channels where both τ leptons undergo decays involving more than one outgoing hadron, via the decay of an intermediate ρ or $a_1(1260)$ meson. For the ρ meson decays the IP vector is replaced by the four-momentum vector of the π^0 so that the decay plane is reconstructed by the momentum vectors of the charged hadron and the π^0. The same method is also applied to a_1 meson decaying to one charged hadron and two neutral pions by summing the neutral pions in the decay. In the CMS analysis the ZMF is taken as the ZMF of only the charged decay products of the τ lepton pair, while in the ATLAS analysis the ZMF is taken as the rest frame of the ρ-meson pair. In this method an additional requirement is applied depending on the sign of the τ lepton spin-analysing functions, defined as

$$\begin{aligned} y^{\tau^\pm} &= \frac{E_{\pi^\pm} - E_{\pi^0}}{E_{\pi^\pm} + E_{\pi^0}}, \\ y^\tau &= y^{\tau^+} y^{\tau^-}, \end{aligned} \tag{5}$$

where E_π is the energy of the pion in the laboratory frame.

$$\text{If } y^\tau < 0 \text{ then } \phi_{CP} = 360° - \phi_{CP}.$$

This method is also extended to $\tau \to a_1^\pm \nu_\tau,\ a_1^\pm \to \pi^\pm\pi^\mp\pi^\pm$ decay mode. In the CMS analysis the oppositely charged pion pair with invariant mass closest to the intermediate ρ^0 is selected. From this pair the pion with charge opposite of that of the τ_h lepton is considered as though it was a π^0, and the momentum of the pion with the same sign as the τ_h is used for the calculation of the ZMF. After these assignments the neutral-pion method is applied as described for 1-prong decays. In the ATLAS analysis the τ lepton decay plane is defined by the charged pion with the highest transverse momentum and the vector sum of the other two pion momenta. The observable $y^{\tau^\pm}$ is also modified to take the effect of the π masses into account,

$$y^{\tau^\pm} = \frac{E_{2\pi} - E_{\pi_1^\pm}}{E_{2\pi} + E_{\pi_1^\pm}} - \frac{m_{3\pi}^2 - m_{\pi_1^\pm}^2 + m_{2\pi}^2}{2m_{3\pi}^2}, \tag{6}$$

where $m_{3\pi}$ is the invariant mass of the three charged pions from the $a_1^\pm$ decay, and $m_{2\pi}$ ($E_{2\pi}$) is the invariant mass (energy) of the system of the two sub-leading π in the τ decay.

2.3 Combined method

This method combines the impact parameter and neutral-pion or ρ/a_1-decay plane methods discussed above, which is appropriate for events where only one of the two τ leptons decay into multiple hadrons. While the IP method is applied to one τ lepton that decays to $\ell\nu\nu$ or $\pi\nu$ the ρ/a_1-decay plane method is used for the other τ lepton decaying to ρ or a_1 meson. Analogously the shift $360° - \phi_{CP}$ is applied for events with $y^{\tau^\pm} < 0$, where $y^{\tau^\pm}$ is computed for the τ lepton that decays to the intermediate resonance.

2.4 Polarimetric vector method

This method is applied only in the CMS analysis to the final state where both τ leptons decay via $\tau \to a_1\nu \to \pi^\pm\pi^\mp\pi^\pm\nu$ decay mode. In this case the τ lepton rest frames can be reconstructed using the secondary vertices (SVs), which are extracted by fitting the three tracks from the a_1 decays. The reconstructions of SVs allow the reconstruction of τ lepton momenta. The magnitude of the τ lepton momentum is obtained using the method provided in Ref. [27], which can provide up to four pairs of solutions for the momenta of the two τ leptons. This ambiguity is resolved by selecting the pair of solutions with the mass closest to that of the Higgs boson. The direction of the τ lepton in the lab frame is determined by the vector SV-PV. The polarimetric vector $\vec{h}$ can be considered as an estimate of the most likely direction of the spin vector $\vec{s}$ of the τ lepton in the τ lepton rest frame [28]. The polarimetric vectors $\vec{h}_{1,2}$ are retrieved using the $a_1 \to \pi^\pm\pi^\mp\pi^\pm$ resonance model as implemented in the TAUOLA program [29]. The ϕ_{CP} observable is reconstructed from the polarimetric vectors and the τ lepton momenta vectors as discussed in Ref. [14].

3. Analysis strategy

The analyses are performed in the final states with one light lepton (electron or muon) and one hadronically decaying τ lepton ($\tau_\ell\tau_h$) or with two hadronically decaying τ leptons ($\tau_h\tau_h$). Accordingly, in $\tau_\ell\tau_h$ channel events are selected with one isolated electron or muon and an oppositely charged well identified hadronically decaying τ lepton, while in $\tau_h\tau_h$ channel events are selected with a pair of well identified oppositely charged hadronically decaying τ leptons, as described in Refs. [13, 14]. In $\tau_\ell\tau_h$ channel the backgrounds originating from W+jets processes are reduced by rejecting events with an upper threshold on transverse mass m_T of the light lepton and $\vec{p}_T^{miss}$ system. The invariant mass of the τ-lepton-pair system is estimated using the Missing Mass Calculator (MMC) [30, 31] in ATLAS and the SVFit algorithm [32] in CMS, which are likelihood-based algorithms.

In ATLAS analysis events are further categorised to target the vector-boson fusion (VBF category) and gluon–gluon fusion (Boost category) Higgs boson production modes based on the kinematic properties of the associated jets. The VBF category is split in to two sub-categories based on the output of a BDT-based VBF tagger [30], while the Boost category is divided into two sub-categories based on the kinematic properties of Higgs boson (di-τ plus $\vec{p}_T^{miss}$) system. Both categories are divided in to Higgs-enriched signal region and $Z \to \tau\tau$ control region based on di-τ mass. To enhance the sensitivity to ϕ_{CP} signal region events are further divided to “High”, “Medium” and “Low” sensitivity regions based on selection criteria on IP significance (defined as

IP divided by its error) of light leptons and τ_h as well as $y^{\tau^\pm}$ and combination of decay modes as described in Ref. [13]. This results in 12 signal regions in each of the $\tau_\ell\tau_h$ and $\tau_h\tau_h$ decay channels, leading to 24 signal regions in total.

In CMS the sensitivity of this analysis is enhanced by applying MVA discriminants to separate signal from background events. The events are categorised in to three mutually exclusive classes: (1) The "Higgs" category that enhances events from ggH, VBF and VH production processes, (2) The "Genuine" category includes all background processes involving two genuine τ leptons, and (3) The "Mis-ID" category that includes all backgrounds due to one or more misidentified τ_h leptons. The event categorization is performed using a multiclass neural network in $\tau_\ell\tau_h$ channel and using a multiclass BDT in $\tau_h\tau_h$ channel. The input variables to MVA discriminants are kinematic distributions of leptons, jets, $\vec{p}_T^{miss}$, and di-τ system. The events in the "Higgs" category are used to infer the CP properties of the Higgs boson.

The major background processes in this analysis are Z+jets, W+jets, top quark-antiquark pair production ($t\bar{t}$), single top quark, diboson production, and QCD multijet events. The dominant contributions to backgrounds with two genuine τ leptons originate from $Z \to \tau\tau$ process. In ATLAS analysis these background contributions are estimated from simulation while using dedicated control regions to obtain its normalisation from data. In CMS analysis this dominant background is estimated from data using the so-called τ-embedding method [33], where muons in $Z \to \mu\mu$ events are replaced by simulated τ leptons with identical kinematics. The other dominant background contribution arises from jets misidentified as hadronically decaying τ leptons. These consists mostly of W+jets, QCD multijet, and top-quark events in $\tau_\ell\tau_h$ channel, while QCD multijet events dominate in $\tau_h\tau_h$ channel. It is estimated using the fake factor method [13, 14], where the fake factors are calculated as the ratio of the number of events passing the τ_h identification requirements to the number failing them in dedicated background enriched regions. The other minor backgrounds such as events where light leptons being misidentified as τ_h or jets being misidentified as τ_ℓ are estimated from simulation. In all cases appropriate data-to-simulation correction scale factors are estimated and applied.

4. Results

A simultaneous maximum likelihood fit to the data is performed including all signal and background categories with CP-mixing angle ϕ_τ as the parameter of interest. The uncertainties are accounted for as nuisance parameters and the normalisations for the Higgs boson signal are left floating in the fit, such that the signal normalisation does not depend on the SM assumption and only the shape of the ϕ_{CP} distribution is exploited in the estimation of ϕ_τ. In ATLAS analysis the ϕ_{CP} distributions in all signal and control regions are included in the fit. In CMS analysis the ϕ_{CP} distributions in the signal categories are analysed in windows of increasing MVA score, corresponding to progressively higher signal-to-background ratios, which result in a set of 2D distributions built from the MVA score and ϕ_{CP} variables. These distributions are used in the fit to data to extract the results, while for the background categories the MVA score distributions are used.

The post-fit distributions of ϕ_{CP} in "High" sensitive signal regions of $\tau_\ell\tau_h$ and $\tau_h\tau_h$ channels from ATLAS analysis are shown in Fig. 2. The signal distributions for the pure CP-even and

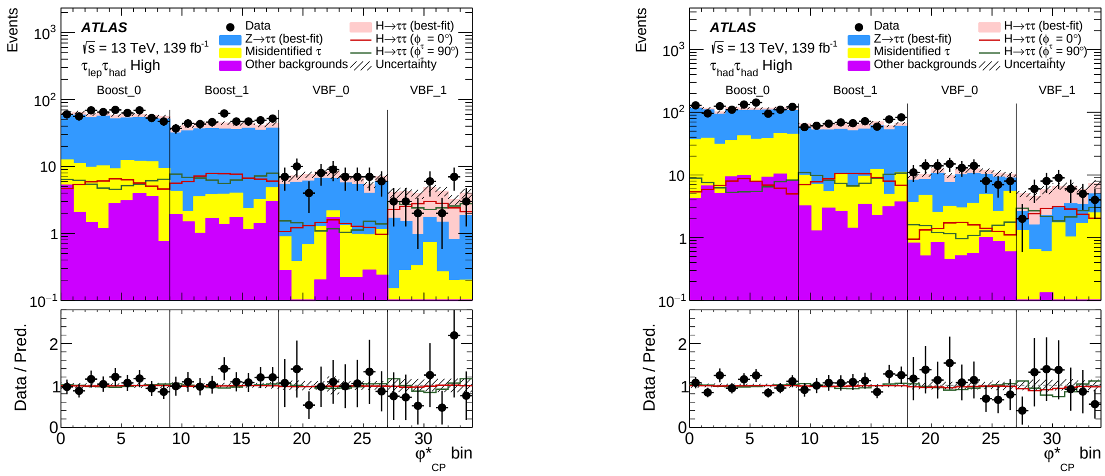

Figure 2: Distribution of ϕ_{CP} in $\tau_\ell\tau_h$ (left) and $\tau_h\tau_h$ (right) "High" sensitive channels, as presented in Fig. 4 of Ref. [13].

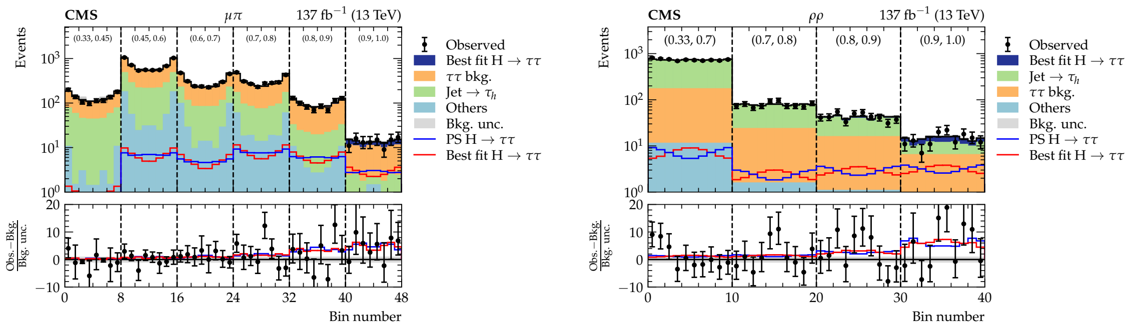

Figure 3: Distribution of ϕ_{CP} in $\mu\pi$ (left) and $\rho\rho$ (right) channels in windows of increasing MVA score, as presented in Fig. 8 & 9 of Ref. [14].

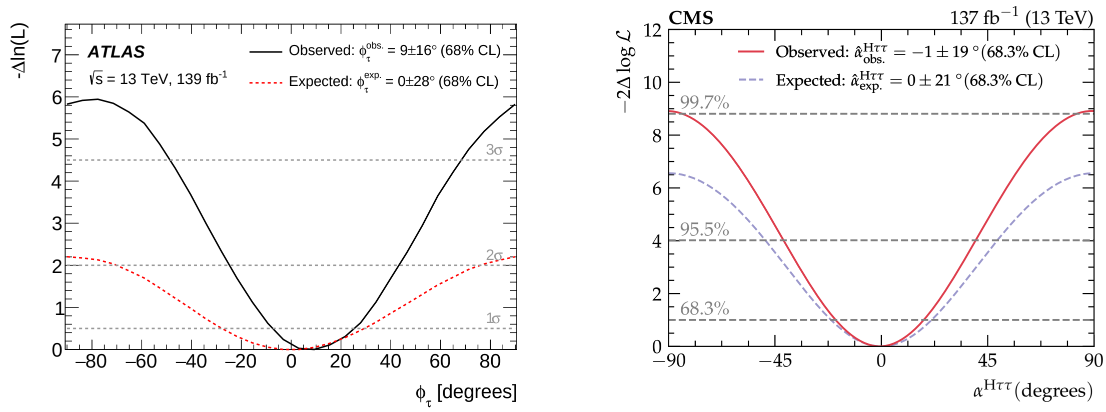

Figure 4: Negative log-likelihood scan of the CP-mixing angle, as presented in Fig.5 & Fig.11 of Refs. [13] & [14], respectively.

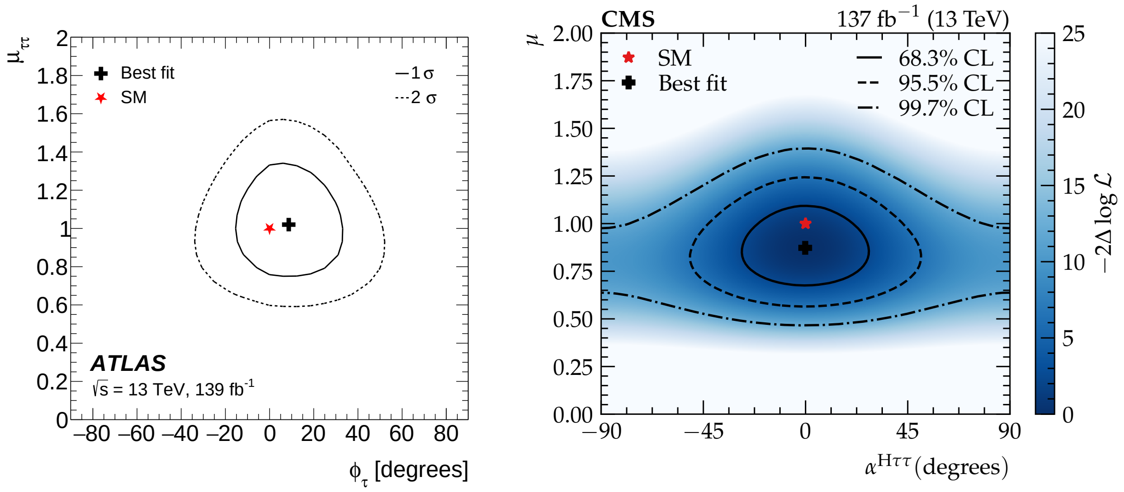

Figure 5: A 2D likelihood scan of the observed signal strength versus the CP-mixing angle. The 1σ and 2σ confidence regions are overlaid, as presented in Fig.6 & Fig.12 of Refs. [13] & [14], respectively.

CP-odd hypotheses are also shown. In each distribution, the ϕ_{CP} bins are counted incrementally through all signal categories and cover the range $[0, 360]$ for each category. Similarly, Fig. 3 shows the ϕ_{CP} distributions in bins of MVA score from two analysed channels of CMS analysis. The distributions of the backgrounds are expected to be flat. However, experimental smearing effects modulate this flat shape for some decay modes. To reduce the statistical fluctuations in the estimates of the background distributions, the background templates are either flattened by merging the bins or symmetrised around $\phi_{CP} = 180°$ depending on the background processes and the analysis channels, as discussed in Ref. [14], assuming their distributions at the generator level. The symmetrisation technique is also applied to signal templates for certain decay modes to reduce the statistical fluctuations.

The observed and expected negative log-likelihood scans for the combination of channels and categories are shown in Fig. 4. The data disfavours the pure CP-odd scenario at 3.4σ (ATLAS) and 3.0σ (CMS), respectively. The corresponding expected exclusions assuming the SM Higgs boson are 2.1σ (ATLAS) and 2.6σ (CMS), respectively. The observed (expected) values of ϕ_τ are found to be $9 \pm 16°$ $(0 \pm 28°)$ and $-1 \pm 19°$ $(0 \pm 21°)$ at the 68% CL in ATLAS and CMS experiments, respectively. The results are compatible with the SM predictions within the experimental uncertainties. The total uncertainty is dominated by the statistical uncertainties of the data sample.

The 2D scans of ΔlnL as a function of the Higgs boson signal strength μ versus ϕ_τ are shown in Fig. 5. No strong correlation between these parameters is observed and the results are compatible with SM prediction. CMS experiment has also performed a 2D scan of κ_τ and $\tilde{\kappa}_\tau$, where the likelihood function is parameterised in terms of κ_τ and $\tilde{\kappa}_\tau$ while all other Higgs couplings are fixed to their SM values. The observed result is shown in Fig. 6. The fit is only sensitive to the relative sign between κ_τ and $\tilde{\kappa}_\tau$ and thus has two best fit points.

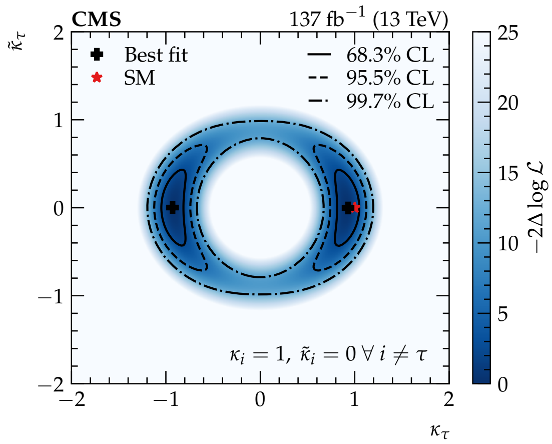

Figure 6: The 2D scan of the (reduced) CP-even (κ_τ) and CP-odd ($\tilde{\kappa}_\tau$) τ Yukawa couplings, as presented in Fig.12 of Ref. [14]

5. Summary

The ATLAS and CMS experiments have performed first measurements of the CP structure of the interaction between the Higgs boson and τ leptons using proton-proton collisions at $\sqrt{s} = 13$ TeV delivered by LHC during 2016-2018. The CP-violating interactions are parameterised by an effective mixing angle. The measurement is based on a maximum-likelihood fit to the CP-sensitive angular observable that is constructed using various methods depending on the τ decay modes. The results from both experiments disfavour the pure CP-odd hypothesis at greater than 3.0 standard deviations. The CP-mixing angle is constrained to less than 19° at 68% CL. The measurement is limited by the statistical uncertainty of the data sample. Thus the precision of the measurement will improve with the accumulation of more collision data.

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