# Tau leptons as a tool to investigate the CP properties of the Higgs boson at CMS

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## Abstract

**Among the Higgs boson decay channels, the one to tau leptons can offer insight into the properties of the Higgs boson. The structure under CP symmetry of the tau Yukawa coupling was investigated in CMS by reconstructing the decay planes of the two tau leptons and measuring their angular separation. Tau decay planes are reconstructed depending on the studied decay channel to take advantage of the correlation between the tau lepton spin and the momenta of its decay products. Using the data collected during the LHC Run 2 data-taking period, the study revealed that the Yukawa coupling is largely dominated by a pure CP-even component. A pure CP-odd Yukawa coupling is excluded with a 99.7% confidence level allowing to constrain the allowed phase space for possible BSM scenarios.**



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## 1 Introduction

The Higgs boson discovery was announced in 2012 by the ATLAS and CMS experiments [1,2]. Its direct couplings to vector bosons were probed using LHC Run 1 data, obtaining results consistent with the hypothesis of a spin-parity $J^P = 0^+$. This finding supported the Standard Model (SM) prediction of a purely scalar Higgs boson.

Subsequent studies further investigated the Higgs sector in search for sources of CP violation. The studies targeting the Higgs boson couplings to the Z and W bosons (HVV couplings) allowed to exclude a pure pseudoscalar hypothesis ($J^P = 0^-$) with a 99.7% confidence level (CL) [3]. Other sources of CP violation could also appear in the Higgs couplings to fermions (Hff couplings) via Yukawa interaction. The most sensitive processes for studying the CP structure of the Hff couplings are:

- gluon-gluon fusion via top quark loop;
- top-associated production of the Higgs boson;

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- Higgs decays to tau leptons.

These proceedings report on a study performed on the latter process, where the CP structure of the Yukawa coupling can be investigated through the spin-correlation between the tau leptons.

## 2 CP violation in Higgs decays to tau leptons

In the Yukawa interaction, the Higgs boson couples with a right handed fermion and a left handed anti-fermion and the corresponding Hermitian conjugates. The corresponding Lagrangian can be written at tree level to include a CP-odd contribution. By neglecting the chiral components of the fermionic fields and the Hermitian conjugate, the Yukawa Lagrangian for Higgs decays to tau leptons takes the form:

$$\mathcal{L}_{Y,\tau} = -\frac{m_\tau}{v}\,\bar{\tau}(\kappa_\tau + i\gamma^5\tilde{\kappa}_\tau)H\tau\,, \tag{1}$$

where $\kappa_\tau(\tilde{\kappa}_\tau)$ represents the CP-even(-odd) coupling, $\tau(\tilde{\tau})$ the tau lepton (antilepton) spinor, $m_\tau$ the tau lepton mass and $H$ and $v$ the excitation of the Higgs field and its vacuum expectation value. In order to quantify the admixture of CP couplings in the Yukawa interaction through a "CP mixing angle", $\varphi_{\tau\tau}$, defined as follows:

$$\kappa = \sqrt{\mu^{\tau\tau}}\cos(\varphi_{\tau\tau})\,, \tag{2}$$

$$\tilde{\kappa} = \sqrt{\mu^{\tau\tau}}\sin(\varphi_{\tau\tau})\,. \tag{3}$$

The parameter $\mu^{\tau\tau}$ is here introduced to quantify the deviation from the SM prediction of the $H \to \tau\tau$ branching fraction.

The CP-mixing alters the correlation between the transverse spins of the two tau leptons [4]:

$$\Gamma(H_{\text{mix}} \to \tau\tau) = \Gamma^{\text{unpol}}(1 - s^-_{/\!/}s^+_{/\!/} + s^-_\perp R(\varphi_{\tau\tau})s^+_\perp)\,, \tag{4}$$

where $\Gamma^{\text{unpol}}$ represents the decay width calculated for unpolarized tau leptons, and the projections of the $\tau^\pm$ spin in the direction orthogonal (parallel) to the $\tau$ direction of flight is represented by $s^\pm_\perp$ ($s^\pm_{/\!/}$). This spin correlation carries over to the $\tau$ decay products.

### 2.1 Spin correlation in tau decays

The correlation between the $\tau$ spin and the momenta of its decay products can be encoded into a vector $h$, generally referred to as *polarimetric vector* or *tau polarimeter*. This is done by characterizing the $\tau$ decay as of the form $\tau^{-(+)} \to X^{-(+)} + \nu_\tau(\bar{\nu}_\tau)$, with $X^\pm$ representing the charged system formed by all $\tau$ decay products besides the tauonic neutrino [5]:

$$\mathrm{d}\Gamma_{\tau\to X+\nu_\tau} = \frac{1}{2m_\tau}|\mathcal{M}|^2(1 + h_\mu s^\mu)\mathrm{d}Lips\,. \tag{5}$$

Combining Eq. 5 with Eq. 4 results in the $H \to \tau\tau$ cross-section acquiring a sinusoidal dependence on the azymuthal difference between the $\tau$ polarimeters [5]:

$$\begin{aligned} &\mathrm{d}\sigma_{H\to\tau\tau}/\mathrm{d}\cos(\theta^+)\,\mathrm{d}\cos(\theta^-)\,\mathrm{d}\phi^+\,\mathrm{d}\phi^- \\ &\quad\propto \left(1 + \cos(\theta^+)\cos(\theta^-) - \sin(\theta^+)\sin(\theta^-)\cos\left(\phi^+ - \phi^- - 2\varphi_{\tau\tau}\right)\right)\,. \end{aligned} \tag{6}$$

The angles $\theta^\pm$ and $\phi^\pm$ are respectively the polar and azymuthal coordinates of the polarimetric vector taken with respect to the $\tau^\pm$ direction of flight. Their definition is illustrated in the left part of Fig. 1.

Measuring experimentally the polarimetric vector can be challenging, as it requires a good estimation of the $\tau$ rest frame, which is generally not accessible due to neutrinos not being reconstructed. However the angle $\Delta\phi = \phi^+ - \phi^-$ coincides with the angle between the decay planes of the two tau leptons, i.e. the acoplanarity angle ($\varphi_{CP}$). This allows to generalize Eq. 6 for decay channels where the polarimetric vectors are not reconstructed:

$$\frac{\mathrm{d}\sigma_{H\to\tau\tau}}{\mathrm{d}\varphi_{CP}} \propto \text{const.} - \cos(\varphi_{CP} - 2\varphi_{\tau\tau})\,. \tag{7}$$

As shown in the right part of Fig. 1 the differential cross-section for $H \to \tau\tau$ decays with respect to the acoplanarity angle is affected by a phase-shift of $2 \times \varphi_{\tau\tau}$.

### 2.2 The acoplanarity angle

In order to experimentally measure the acoplanarity angle it is necessary to reconstruct the $\tau$ decay planes. Each plane is defined by two vectors:

- $P$: the momentum of the tau lepton or of one of its charged decay products;
- $R$: the polarimetric vector, or another vector lying on the decay plane.

As shown in Fig. 2, all four vectors can be boosted in the frame of reference where the two momenta P sum up to 0. The acoplanarity angle is then defined based on the scalar and vectorial products of the components of the two $R$ vectors which are orthogonal to the selected momenta:

$$\varphi_{CP} = \begin{cases} \varphi^*, & \text{if } O \geq 0\,, \\ 2\pi - \varphi^*, & \text{if } O < 0\,, \end{cases} \tag{8}$$

where

$$\varphi^* = \Delta\phi = \arccos\left(R_\perp^- \cdot R_\perp^+\right), \tag{9}$$

$$O = \frac{(R_\perp^+ \times R_\perp^-) \cdot P^-}{\left|(R_\perp^+ \times R_\perp^-) \cdot P^-\right|}\,. \tag{10}$$

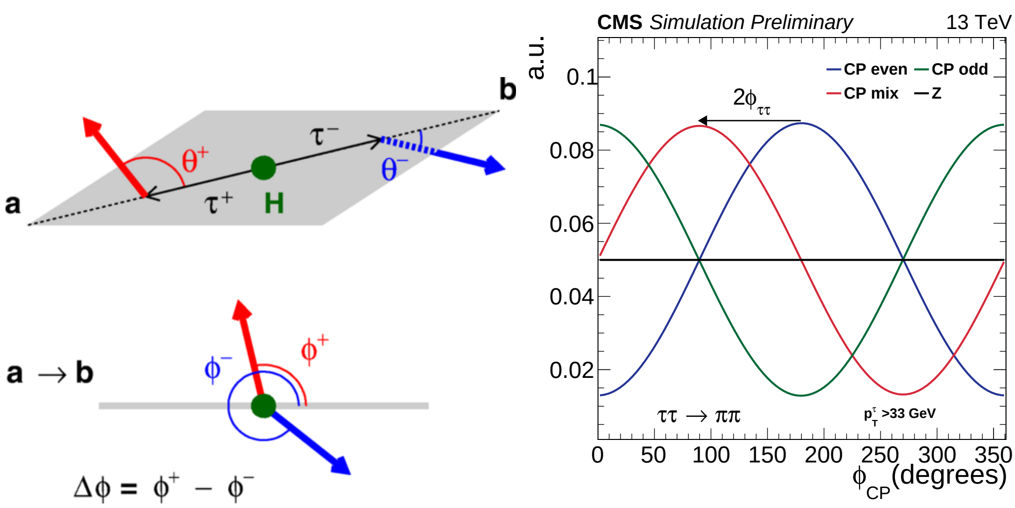
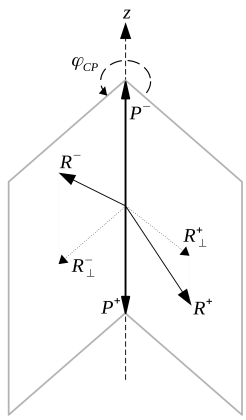



Figure 1: **Left:** Schematic representation of the Higgs decay to polarized tau leptons in the Higgs rest frame [5]. Black (colored) arrows represent the tau leptons momenta (polarimetric vectors). **Right:** Acoplanarity angle distribution for $H \to \tau\tau \to 2\pi 2\nu_\tau$ decay [7]. The distributions are shown for simulated $H \to \tau\tau$ processes, according to three different CP hypotheses and for the DY process in gray.




| Channel | Vectors | | | |
|---|---|---|---|---|
| | P1 | R1 | P2 | R2 |
| $\tau_{\mu,\pi} \times \tau_{\mu,\pi}$ | $\vec{p}_{\mu,\pi}$ | $\overrightarrow{IP}_{\mu,\pi}$ | $\vec{p}_{\mu,\pi}$ | $\overrightarrow{IP}_{\mu,\pi}$ |
| $\tau_{\mu,\pi} \times \tau_{\rho,a_1^{1Pr}}$ | $\vec{p}_{\mu,\pi}$ | $\overrightarrow{IP}_{\mu,\pi}$ | $\vec{p}_{\pi^\pm}$ | $\vec{p}_{\pi^0}$ |
| $\tau_{\mu,\pi} \times \tau^\pm_{a_1^{3Pr}}$ | $\vec{p}_{\mu,\pi}$ | $\overrightarrow{IP}_{\mu,\pi}$ | $\vec{p}_{\pi^\pm}$ | $\vec{p}_{\pi^\mp}$ |
| $\tau_{\rho,a_1^{1Pr}} \times \tau^\pm_{a_1^{3Pr}}$ | $\vec{p}_{\pi^\pm}$ | $\vec{p}_{\pi^0}$ | $\vec{p}_{\pi^\pm}$ | $\vec{p}_{\pi^\mp}$ |
| $\tau_{a_1^{3Pr}} \times \tau^\pm_{a_1^{3Pr}}$ | $\vec{p}_\tau$ | $\vec{h}$ | $\vec{p}_\tau$ | $\vec{h}$ |

Figure 2 & Table 1: **Left:** Schematic representation of the acoplanarity angle reconstruction [6] defining $\tau$ decay planes with a momenta $P$ and a reference vector $R$. **Right:** Summary table [6] of the vectors used to reconstruct the acoplanarity angle in the various decay channels studied in [7].

The use of the vectorial product in Eq. 10 allows to extend the angle definition between 0 and 360° by defining a convention for the angle definition, i.e. the right hand rule with respect to the momenta $P^-$. Table 1 summarizes the vectors chosen to define the $\tau$ decay planes for each separate decay channel. The $\tau$ decay channels are labeled according to the main mesonic resonance involved in the hadronic decay: $\pi$, $\rho$ and $a_1$. Decays via $a_1$ meson resonance are further divided into $a_1^{3Pr}$ and $a_1^{1Pr}$ based on whether the $a_1$ meson decayed into three charged pions, or one charged and two neutral pions. The label $\vec{p}_X$ is used to refer to the momenta of a $\tau$ decay product, while $\overrightarrow{IP}_{\mu,\pi}$ represents the impact parameter of the charged muon or pion trajectory.

# 3 Identification of Higgs decays to tau leptons

## 3.1 Tau identification in CMS

In order to measure the acoplanarity angle it is essential to achieve an accurate identification of genuine $\tau$ decays and determination of their mode. In CMS [8], hadronic tau decays are identified by the hadron-plus-strip (HPS) algorithm [9]. Rejection of jets and leptons is instead performed via the DeepTau convolutional neural network-based algorithm [10]. The decay mode identification was further optimized in the scope of this measurement with a dedicated multivariate-based algorithm [11].

## 3.2 Identification of Higgs decays with NN

Measuring the CP mixing angle in $H \to \tau\tau$ decays requires an efficient rejection of other physical processes which present similar signatures in the detector. This aim was pursued via the use of multivariate analysis (MVA) techniques: a boosted decision tree (BDT) for the fully hadronic final state, and a neural network (NN) for the semileptonic one. As shown in Fig. 3, the MVA algorithms are defined with three target categories: one dedicated to the $H \to \tau\tau$ decays (**higgs**), one for processes involving two genuine tau leptons ($\tau_\mu\tau_\mathbf{h}$) and one for jets or leptons misidentified as hadronically decaying tau leptons (**fakes**).

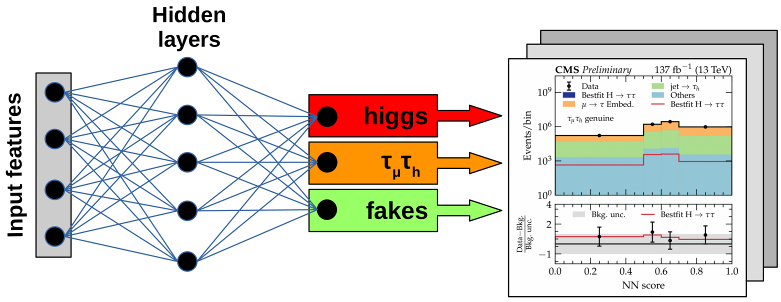



Figure 3: Schematic depiction of the machine learning algorithm used to identify Higgs decays [6].

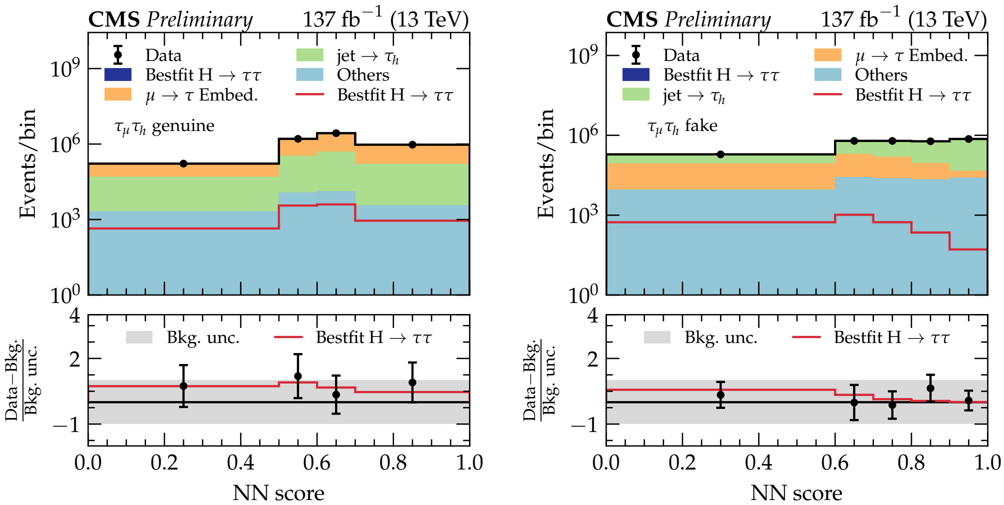



Figure 4: NN score for the background categories: $\tau_\mu\tau_\mathrm{h}$ on the left and **fakes** on the right.

## 4 Measurement of the CP mixing angle

The measurement of the CP mixing angle is performed on the full dataset collected by the CMS experiment during the LHC Run 2 data-taking period, comprising an integrated luminosity of 137 fb$^{-1}$. The CP mixing angle $\varphi_{\tau\tau}$ is extracted from a parametric fit of a $H \to \tau\tau$ template, which considers three distinct production mechanisms for the Higgs boson: the gluon-gluon fusion, the vector boson fusion and the Higgs-strahlung. The fit is performed simultaneously in all years of data taking and all categories defined by the MVA algorithms. For the background categories, the output score of the NN and BDT algorithms was used as input for the fit. The post-fit distribution for the semileptonic final state are shown in Fig. 4.

The **higgs** category is instead split into a total of 13 sub-categories, corresponding to the different combinations of decay modes for the tau lepton pair considered in this analysis. In this category the input to the fit was the two-dimensional distribution of the acoplanarity distribution in different bins of MVA score. Fig. 5 shows the most relevant signal categories in the fit, i.e. the $\tau_\mu\tau_\rho$ and $\tau_\rho\tau_\rho$ channels. All plots include the $H \to \tau\tau$ template both overlayed (in red) and stacked (in blue) on top of the background contributions. For comparison, the distribution of $H \to \tau\tau$ decays under the hypothesis of a pure pseudoscalar (PS) coupling, is also shown in green.

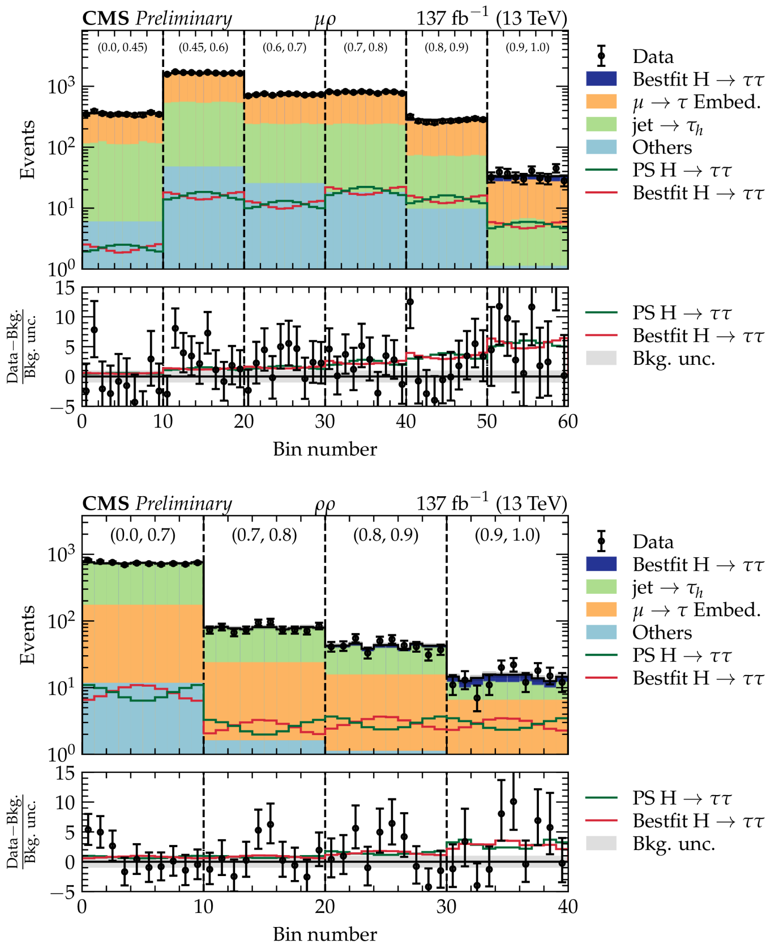



Figure 5: Acoplanarity angle distribution in bins of MVA score for the $\tau_\mu\tau_\rho$ channel on the top and the $\tau_\rho\tau_\rho$ one on the bottom.

## 5 Results

A maximum likelihood scan was performed to measure the CP mixing angle in the recorded data. As shown in the left part of Fig. 6, the best agreement with data was found for a CP mixing angle of

$$\varphi_{\tau\tau} = (4 \pm 17(\text{stat.}) \pm 2(\text{bin-by-bin}^1) \pm 1(\text{syst.}) \pm 1(\text{theory}))^\circ\,, \tag{11}$$

where the uncertainty is split into its various contributions.

The results are consistent with the SM prediction of a pure CP-even Yukawa coupling ($\varphi_{\tau\tau} = 0^\circ$), while a pure CP-odd coupling ($\varphi_{\tau\tau} = 90^\circ$) is excluded at 99.7% confidence level. This can be visualized via the weighted distribution of the acoplanarity angle (right part of Fig. 6), which shows that the SM hypothesis is preferred with respect to the pure CP-odd one.

No deviation from the SM expectation was observed, limiting the allowed CP violation in the Higgs sector. It is possible to use this results to constrain the allowed phase space for theories beyond the SM [12, 13]. Figure 7 shows the comparison between the limits placed by this analysis on the CP-even and CP-odd Yukawa couplings (on the right) with the ones obtained by the inclusive coupling analyses performed by the CMS and ATLAS collaborations

[1]Bin-by-bin uncertainty of signal and background models, representing the effect of the limited statistics for MC simulation and data-driven background estimation.

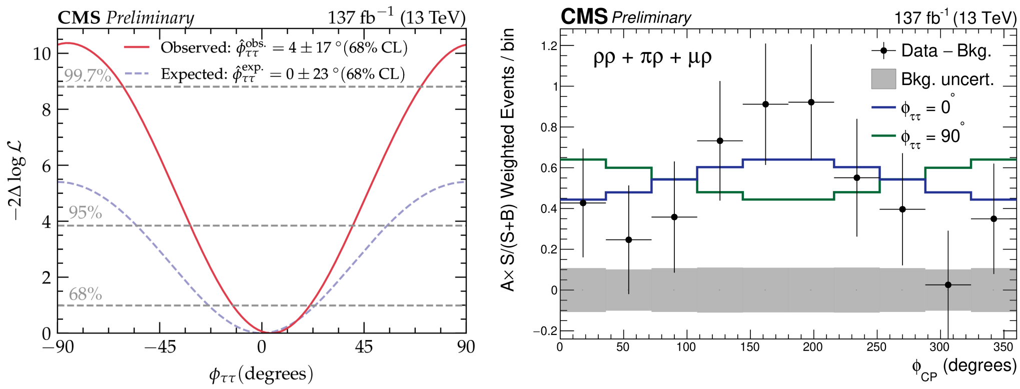



Figure 6: **Left:** negative log-likelihood scan to determine the most probable value of the CP mixing angle. **Right:** weighted acoplanarity angle distribution in recorded data after subtracting the expected background.

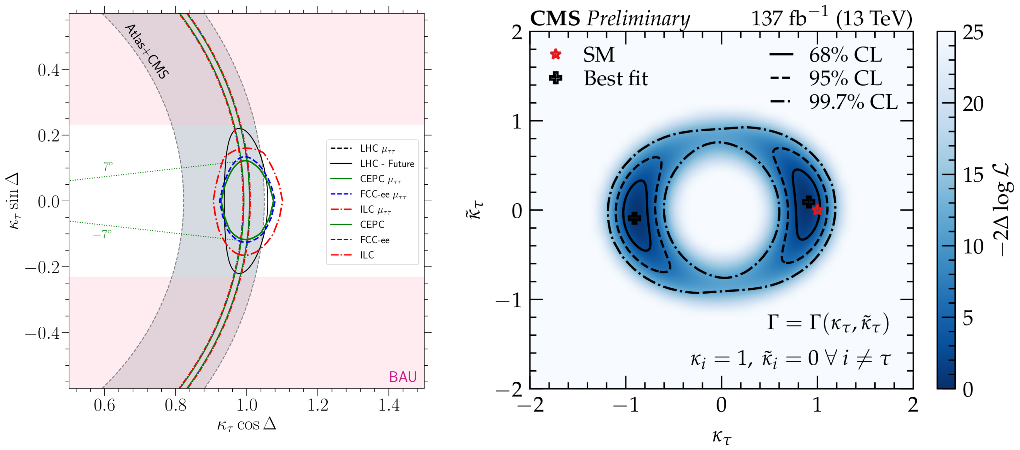



Figure 7: Limits on the CP-even and CP-odd Yukawa couplings between the Higgs boson and tau leptons. **Left:** 95% CL limits are shown on the right for inclusive coupling analyses using CMS and ATLAS data, and projections at the HL-LHC and future electron-positron colliders [12]. **Right:** limits at 68, 95 and 99.7% CL obtained from the analysis described in this proceedings [7].

and the predictions for future hadron and electron-positron colliders [12]. At the current level of precision this analysis is not yet able to exclude the available phase space which would allow to justify the observed baryon asymmetry in the Universe (BAU) beyond the 68% CL.

## 6 Conclusion

The analysis discussed in this proceedings [7] marks the first measurement of the CP structure of the Yukawa coupling between the Higgs boson and tau leptons. The measured CP mixing angle of $\varphi_{\tau\tau} = (4 \pm 17)°$ shows a clear preference for a pure CP-even coupling, consistent with the SM prediction at 68% CL. A pure CP-odd hypothesis is instead excluded at the level of three standard deviations, allowing to constrain the parameter phase space for beyond standard model theories.

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