Available on CMS information server

CMS CR -2023/031

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

09 March 2023 (v4, 13 April 2023)

Search for CP violation in the tau Yukawa coupling with CMS

Mario Sessini for the CMS Collaboration

Abstract

The proceedings present a measurement of the charge-parity (CP) properties of the Higgs boson in its coupling to tau leptons. To date, all measurements of its interactions with fermions and bosons are consistent with the standard model prediction of a purely scalar neutral Higgs boson nature and exclude the purely pseudo-scalar scenario. However an admixture of both CP-even and CP-odd states is still possible. In the presented analysis, the pure pseudo-scalar hypothesis is excluded at 3.0σ in its coupling to the tau lepton with a measured CP mixing angle value $\alpha^{H\tau\tau} = -1 \pm 19^{\circ}$ at 68.3% CL. Some prospects in future LHC operations are also presented.

Presented at *LakeLouise2023 Lake Louise Winter Institute 2023*

Search for CP violation in the τ Yukawa coupling with CMS

Mario Sessini, on behalf of the CMS Collaboration

Institut Pluridisciplinaire Hubert Curien - Strasbourg

Abstract — The proceedings present a measurement of the charge-parity (CP) properties of the Higgs boson in its coupling to tau leptons. To date, all measurements of its interactions with fermions and bosons are consistent with the standard model prediction of a purely scalar neutral Higgs boson nature and exclude the purely pseudo-scalar scenario. However an admixture of both CP-even and CP-odd states is still possible. In the presented analysis, the pure pseudo-scalar hypothesis is excluded at 3.0σ in its coupling to the tau lepton with a measured CP mixing angle value $\alpha^{H\tau\tau} = -1 \pm 19°$ at 68.3% CL. Some prospects in future LHC operations are also presented.

Introduction

The discovery of a new particle with properties consistent with the Higgs boson as predicted by the standard model (SM) [1, 2, 3, 4, 5, 6] was announced in 2012 by the CMS [7, 8] and ATLAS [9] Collaborations. Further studies have been performed to give a better description of several of its properties, including mass measurements, decay width and CP properties. Even though the Higgs boson is described as a purely scalar boson in the SM, the discovery of any non-purely scalar state would have important implications in the search for new physics, as some SM extensions can also include a CP violating Higgs boson. Such properties can be studied through the final products of the several decay channels of the Higgs boson produced in *pp* collisions at the LHC. Although the hypothesis of a purely pseudo-scalar Higgs boson is already excluded in some bosonic couplings [10], CP violation might still occur at tree level in couplings to fermions [11, 12]. The first section of these proceedings will aim to introduce the Yukawa couplings of the Higgs boson and the parameter inducing a CP violation in such couplings. The second section will present the analysis strategy to extract a CP sensitive observable in the $H^0 \to \tau\tau$ decay and the various techniques employed to perform a measurement of this observable at the LHC. The third section will focus on the tau reconstruction and identification within the CMS detector [13] and lastly the results of the analysis will be shown.

Yukawa couplings

Each coupling of the Higgs boson to a fermion is described by a unique interaction called Yukawa coupling through a Lagrangian in which a CP violating term can be added at tree level to the regular SM scalar term:

$$\mathcal{L}_Y = -\frac{m_f \phi}{v}(\kappa_f \overline{\psi}_f \psi + \tilde{\kappa_f} \overline{\psi}_l i\gamma_5 \psi_f), \quad (1)$$

where m_f stands for the fermion mass, ψ_f for its Dirac field, ϕ for the scalar Higgs field, and $v = 246$ GeV for its vacuum expectation value. Also κ_f and $\tilde{\kappa}_f$ are defined as the CP-even and the CP-odd coupling constants respectively, from which the effective mixing angle α^{Hff} of any Yukawa coupling can be expressed as:

$$\tan(\alpha^{Hff}) = \frac{\tilde{\kappa}_f}{\kappa_f}, \quad (2)$$

and its CP-odd fraction f_{CP}^{Hff} as $f_{CP}^{Hff} = \sin^2(\alpha^{Hff})$. The coupling appears to be SM like for $\alpha^{Hff} = 0°$, purely pseudo-scalar for $\alpha^{Hff} = 90°$ and a mixture of both CP states for any other value with a maximum mixing state for $\alpha^{Hff} = 45°$.

Analysis strategy

This section will give an overview of the several strategies used to extract and measure the CP properties of the Higgs boson in the tau Yukawa coupling. First the spin correlations in the $H^0 \to \tau\tau$ decay and relation to the CP properties of the Higgs boson will be described, before presenting various methods to measure these correlations experimentally.

CP sensitive observable extraction

From the scalar nature of the Higgs boson, the sum of the two longitudinal spin components has to be 0 in fermionic decays. Due to this constraint, transverse spin correlations are left as the only CP sensitive effect in the decay. For a pure scalar Higgs boson conserving the CP symmetry, transverse spins components of taus will rather be aligned whereas they will rather be anti-aligned in the CP violating pseudo-scalar decay. The decay rate of the $H^0 \to \tau\tau$ decay can be expressed as follows :

$$\Gamma(H^0 \to \tau\tau) \propto 1 - s_{\parallel}^{-} s_{\parallel}^{+} + s_{\perp}^{-} R(\alpha^{H\tau\tau}) s_{\perp}^{+}, \quad (3)$$

where $R(\alpha^{H\tau\tau})$ is a matrix containing the CP mixing information and acting on the transverse spin part only.

A new CP sensitive observable ϕ_{CP} can therefore be introduced and defined as the angle between each tau decay plane as seen from the Higgs boson rest frame (Fig.1). The $H^0 \to \tau\tau$ differential cross section can be parameterised as follows as a function of ϕ_{CP} and $\alpha^{H\tau\tau}$:

$$\frac{d\Gamma}{d\phi_{CP}} \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau}). \quad (4)$$

As a result, the ϕ_{CP} distribution gives a direct information about the Higgs boson CP state (Fig.1) and a CP-even(odd) Higgs boson will more likely decay when the angle between the decay planes is 180°(0/360°). Oppositely, the Z^0 boson will produce a flat ϕ_{CP} distribution, making it possible to disentangle the two processes. However, the reconstruction of the Higgs boson rest frame remains a tough task at LHC due to the composite nature of protons and the presence of neutrinos in the tau decays. Consequently, optimised methods are needed and will be presented in what follows.

Impact parameter method

The impact parameter method is designed for decay modes where one charged track is reconstructed, such as $\tau^\pm \to \pi^\pm, \mu^\pm, \mathrm{e}^\pm$. The decay planes between which ϕ_{CP} is measured are spanned by the charged track momentum and its own impact parameter in the zero momentum rest frame defined by the sum of two charged tracks momenta (Fig.2). The impact parameter of a track is defined as the vector between the primary vertex and the point of closest approach from the primary vertex on the extrapolated track.

Neutral pion method

This method is used in decay modes with neutral pions and relies on the measurement of the angle between the planes spanned by the charged pions and their associated neutral pion, boosted in the rest frame of the two charged pions (Fig.2). This method can be applied in any decay mode with at least two pions in the final state. In the case of the three-prong decay mode through a charged a_1 resonance, we use the decay plane spanned by the intermediate neutral ρ resonance decaying to two charged pions with opposite charges.

Polarimetric vector method

This method is known as being the most effective and CP sensitive one and relies on the so called polarimetric vector [14]. The latter is involved in the tau decay rate denoted as h :

$$\mathrm{d}\Gamma = \frac{1}{2m_\tau}|\overline{M}|^2\big(1 + h_\mu s^\mu\big)\mathrm{d}Lips, \quad (5)$$

and where s is the spin of the tau lepton, m_τ its mass and M the corresponding matrix element. As a matter of fact, the tau decay rate is maximised when s and h are aligned and therefore the polarimetric vector can be seen as the most probable tau spin direction. ϕ_{CP} is then calculated from the planes spanned by the polarimetric vector and the undecayed tau direction in the Higgs boson rest frame. This method can be applied to any hadronic decay, but the need to fully reconstruct each tau momentum makes it challenging. Nonetheless, this method as already been successfully implemented in the $a_1^{3pr}a_1^{3pr}$ channel using the secondary vertices constraint to reconstruct the tau direction and its momentum based on the Gottfried-Jackson angle [15].

All of these methods can be applied separately on each tau and mixed together for decay modes where the taus are not decaying into the same final state.

Tau identification in CMS

Tau identification and reconstruction is a crucial step in an analysis based on the precise reconstruction of visible tau decay products. More specifically, a pure identification of the various tau decay modes is required to get the best CP sensitivity. This point will be discussed in this section together with the Hadron-Plus-Strip (HPS) algorithm [16] used for tau reconstruction and the DeepTau algorithm [17] used for tau identification.

Hadron-Plus-Strip algorithm

The HPS algorithm [16] is dedicated to the reconstruction of hadronic tau decays within the CMS detector. Initially, the Particle Flow (PF) [18] algorithm is used to reconstruct various objects and particles, namely muons, electrons, photons, charged and neutral hadrons. The objects are subsequently used in jet clustering and missing transverse energy (MET) calculations. From these ingredients, the HPS algorithm takes care of identifying collimated jets and associates within an isolation cone around the jet the charged hadrons measured in the hadronic calorimeter (HCAL) to neutral hadrons. The "strip" term of HPS stems from neutral hadrons decaying to photon pairs measured as strips in the (η, ϕ) plane of the electromagnetic calorimeter (ECAL). The number of associated charged and neutral hadrons inside the jet cone is then used to determine a decay mode among the following :

- $\tau_h \to \pi^\pm$
- $\tau_h \to \pi^\pm + \pi^0$'s
- $\tau_h \to 2\pi^\pm + \pi^\mp$
- $\tau_h \to 2\pi^\pm + \pi^\mp + \pi^0$

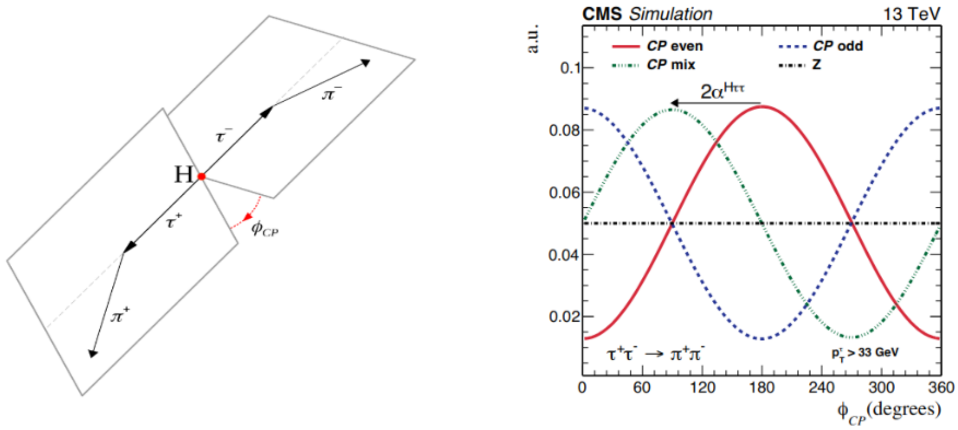

Figure 1: Representation of the tau decay planes in the Higgs boson rest frame, ϕ_{CP} represents the angle between the planes (left). Distribution of ϕ_{CP} for the CP-even scenario (solid red), CP-odd (dashed blue), maximum mixing (dash dotted green) and for Z^0 (dash dotted black) (right). The $\tau^+\tau^-(\nu_\tau\overline{\nu}_\tau) \rightarrow \pi^+\pi^-$ decay mode is considered [12].

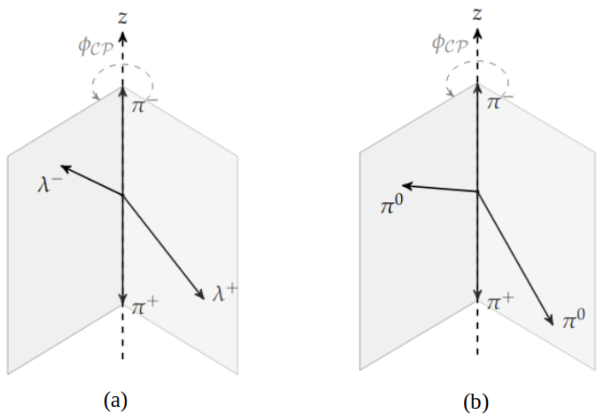

Figure 2: (a) Representation of the impact parameter (IP) method in the $\tau^\pm(\nu_\tau) \rightarrow \pi^\pm$ decay mode, each plane is spanned by the momentum of the pion and its respective IP. (b) Representation of the neutral pion method in the $\tau^\pm(\nu_\tau) \rightarrow \pi^\pm + \pi^0$ decay mode, each plane is spanned by the momentum of the charged pion and the neutral pion [12].

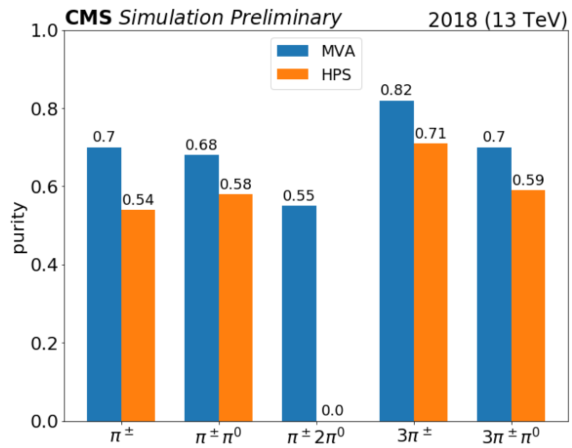

Figure 3: Compared purities of each decay mode for the optimized BDT (blue) and HPS (orange), defined as the percentage of reconstructed taus assigned to the correct decay mode [19].

DeepTau algorithm

DeepTau [17] is a recently developed algorithm used for tau identification against muons, electrons and jets. Its structure is based on a deep neural network and offers a multiclass architecture, whereas three dedicated algorithms were previously needed.

MVA decay modes

In addition, a Boosted Decision Tree (BDT) classifier [19] is used to improve the purity of each decay mode by about 20% (fig.3). The algorithm uses kinematic inputs as well as HPS decay modes and also provides an additional decay mode, namely :

- $\tau_h \rightarrow \pi^\pm + 2\pi^0$.

Results

The last step for this analysis is to extract the signal from the background using a MVA with kinematic variables as input. This MVA is creating three possible output categories, namely :

- Higgs (signal)
- Genuine τ background ($Z \to \tau\tau$)
- Misidentified τ_h background (misidentified jets and leptons)

The background estimation is mainly based on a data driven method for processes with jets misidentified as hadronic taus using the fake factors method, whereas the irreducible $Z \to \tau\tau$ background is estimated using the embedding method [20]. Other processes are otherwise estimated using Monte Carlo samples. The overall consistency is checked in the first place using the two background categories. The signal category is "unblinded" lastly in order to perform a fit of the data using a likelihood function. The parameters extremizing this function are defined as "best fit" parameters.

Following the fit to data providing the "best fit" parameters of the likelihood function $L(\alpha^{H\tau\tau}_{\text{best fit}})$, a negative log-likelihood scan is performed (Fig.4) :

$$-2\Delta \ln L = -2(\ln(L\alpha^{H\tau\tau}) - \ln(L\alpha^{H\tau\tau}_{\text{best fit}}) \qquad (6)$$

The analysis of the previous data taking from 2016 to 2018 (Run 2) with a total integrated luminosity of 137 fb^{-}1 has been performed in a total of 17 channels among 3 categories of decay modes: $\tau_h\tau_h, \tau_h\mu, \tau_h$e. The measurement in data led to an exclusion of the pure CP-odd hypothesis $\alpha^{H\tau\tau}$=±90° with 3.0σ. The observed (expected) value for $\alpha^{H\tau\tau}$ is -1±19° (0±21°) at the 68.3% CL, ±41° (±49°) at the 95.5% CL, and an observed range of ±84° at the 99.7%. Therefore, all measurements performed so far are consistent with the SM prediction of a purely scalar Higgs boson.

Further prospects at the LHC

Current measurement uncertainty is almost entirely due to statistical error. The current data taking (Run 3) with an increased center of mass energy of 13.6 TeV, and an expected integrated luminosity of 300 fb^{-}1 by the end of 2025, combined with the next high luminosity operation of the LHC (HL-LHC) are expected to reduce the dominant uncertainty to a minimal range of ±5° at 3000 fb^{-}1 of integrated luminosity (Fig.5). Improvement of the sensitivity is also expected from a wider use of the polarimetric vector in hadronic decay modes by developping new tau reconstruction techniques based on machine learning.

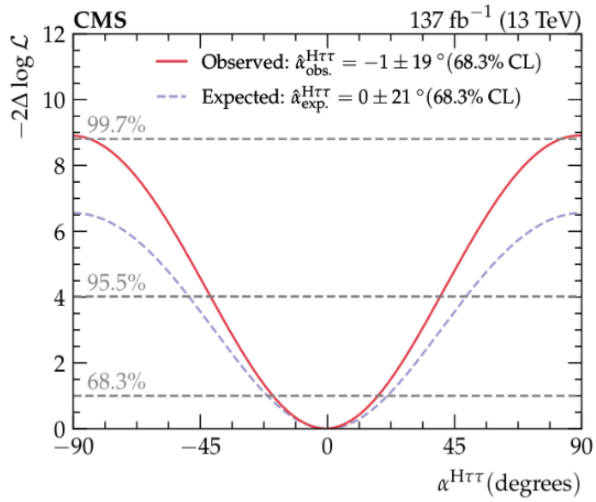

Figure 4: Negative log-likelihood scan for the combination of the $\tau_e\tau_h$, $\tau_\mu\tau_h$ and $\tau_h\tau_h$ channels [12].

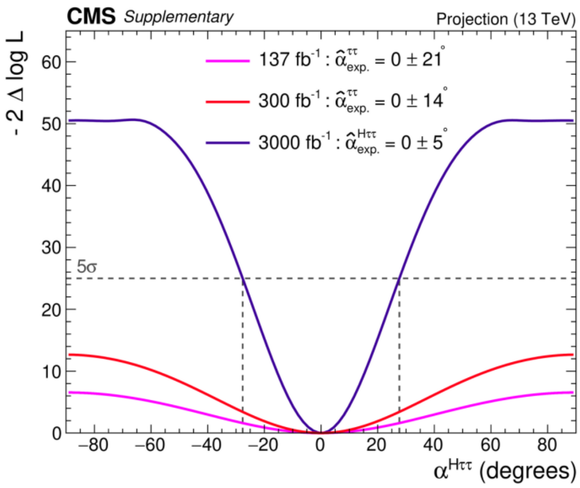

Figure 5: Run 2 (pink), Run 3 (red) and HL-LHC (blue) expected measurement of the $\alpha^{H\tau\tau}$ parameter [21].

Summary

These proceedings presented the analysis of the CP structure of the $H \to \tau\tau$ Yukawa coupling with the CMS experiment using 137 fb^{-}1 of data collected in proton-proton collisions at $\sqrt{s}$ = 13 TeV. The pure pseudo-scalar hypothesis is excluded at 3.0σ with a measured CP mixing angle $\alpha^{H\tau\tau} = -1 \pm 19°$ at 68.3% CL. The various techniques employed in the analysis to extract a CP sensitive observable were shown as well as some prospects for further LHC operations and new data taking.

References

[1] F. Englert and R. Brout, "Broken symmetry and the mass of gauge vector mesons", *Phys. Rev. Lett.* **13** (1964) 321, doi:10.1103/PhysRevLett.13.321.

[2] P. W. Higgs, "Broken symmetries, massless particles and gauge fields", *Phys. Lett.* **12** (1964) 132, doi:10.1016/0031-9163(64)91136-9.

[3] P. W. Higgs, "Broken symmetries and the masses of gauge bosons", *Phys. Rev. Lett.* **13** (1964) 508, doi:10.1103/PhysRevLett.13.508.

[4] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, "Global conservation laws and massless particles", *Phys. Rev. Lett.* **13** (1964) 585, doi:10.1103/PhysRevLett.13.585.

[5] P. W. Higgs, "Spontaneous symmetry breakdown without massless bosons", *Phys. Rev.* **145** (1966) 1156, doi:10.1103/PhysRev.145.1156.

[6] T. W. B. Kibble, "Symmetry breaking in non-abelian gauge theories", *Phys. Rev.* **155** (1967) 1554, doi:10.1103/PhysRev.155.1554.

[7] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021.

[8] CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s}$ = 7 and 8 TeV", *JHEP* **06** (2013) 081, doi:10.1007/JHEP06(2013)081.

[9] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020.

[10] CMS Collaboration, "Measurement of the properties of a Higgs boson in the four-lepton final state", *Phys. Rev. D* **89** (2014) 092007, doi:10.1103/PhysRevD.89.092007.

[11] CMS Collaboration, "Measurements of $t\bar{t}H$ Production and the CP Structure of the Yukawa Interaction between the Higgs Boson and Top Quark in the Diphoton Decay Channel", *Phys. Rev. Lett.* **125** (2020) 061801, doi:10.1103/PhysRevLett.125.061801.

[12] CMS Collaboration, "Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at $\sqrt{s}$=13 TeV", *JHEP* **6** (2022) 012, doi:10.1007/JHEP06(2022)012

[13] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004

[14] V. Cherepanov, E. Richter-Was, Z. Was, "Monte Carlo, fitting and Machine Learning for Tau leptons", arXiv:1811.03969 **[hep-ph]** (2018), 10.48550/ARXIV.1811.03969.

[15] G. Bourgatte, "Étude des propriétés CP du boson de Higgs dans le canal tau tau dans l'expérience CMS auprès du LHC", (2021) CERN-THESIS-2021-004

[16] A.M. Sirunyan *et al.*, "Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s}$=13 TeV", *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005.

[17] A. Tumasyan *et al.*, "Identification of hadronic tau lepton decays using a deep neural network", *JINST* **17** (2022) P07023, doi:10.1088/1748-0221/17/07/P07023.

[18] A.M. Sirunyan *et al.*, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003.

[19] CMS Collaboration, "Identification of hadronic tau decay channels using multivariate analysis (MVA decay mode)", (2020) CMS DP-2020/041

[20] A.M. Sirunyan *et al.*, "An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data", *JINST* **14** (2019) P06032, doi:10.1088/1748-0221/14/06/P06032.

[21] CMS Collaboration, "Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at $\sqrt{s}$=13 TeV", (2021) CMS-HIG-20-006, arXiv:2110.04836