PROCEEDINGS OF SCIENCE

CP structure of the tau Yukawa coupling with CMS

Anne-Catherine Le Bihan[a,*]

[a] *Université de Strasbourg, CNRS, IPHC UMR7178,*
Strasbourg, France

E-mail: anne-catherine.le.bihan@cern.ch

The CMS experiment at LHC has performed the first measurement of the CP structure of the Yukawa coupling between the Higgs boson and tau leptons. The measurement is based on data collected in proton-proton collisions at $\sqrt{s}$ = 13 TeV during 2016-18, corresponding to an integrated luminosity of 137 fb^{-1}. The analysis utilizes the angular correlation between the decay planes of tau leptons produced in Higgs boson decays, where dedicated analysis techniques are used to optimise the reconstruction of tau decay planes. The measured value of CP mixing angle is 4 ± 17°, at 68% confidence level. The pure CP-odd hypothesis is excluded at 3.2 standard deviations. The analysis strategies and the results of the measurement are presented.

The European Physical Society Conference on High Energy Physics (EPS-HEP2021)

[1] on behalf of the CMS Collaboration
[*] Speaker

https://pos.sissa.it/

PoS(EPS-HEP2021)575

1. Introduction

The electroweak symmetry breaking (EWSB) of the Standard Model (SM) predicts the existence of a scalar particle, the Higgs boson (H), even under charge-parity (CP) inversion. A particle with properties compatible with those of the SM Higgs boson was observed by the ATLAS and CMS experiments [1–3]. Any deviation from a pure scalar ($J^{\mathrm{CP}} = 0^{++}$) interaction in any of its coupling to SM particles would be a clear sign of new physics. Previous measurements have excluded pure pseudoscalar couplings ($J^{\mathrm{CP}} = 0^{+-}$) to gauge bosons [4, 5]. Searches for CP-violating effects in fermionic couplings are nevertheless complementary, as they allow to assess the nature of the Yukawa couplings, not taking part in the EWSB. Renormalisable CP-violation may occur in Yukawa couplings at tree level, whereas CP-violating contributions in couplings to gauge bosons are expected to be minor, appearing via higher-order operators suppressed by powers of $1/\Lambda^2$, where Λ is the scale of the physics beyond SM in an effective field theory. The generalised tau Yukawa coupling reads

$$\mathcal{L}_Y = -\frac{m_\tau}{v} H \left(\kappa_\tau \tilde{\tau}\tau + \tilde{\kappa}_\tau \tilde{\tau} i \gamma_5 \tau \right),$$

composed by a CP-even term (κ_τ) and a CP-odd term ($\tilde{\kappa}_\tau$), m_τ is the mass of the τ lepton, and v the vacuuum expectation value of the Higgs boson field. The ratio of these two terms allows to define the effective mixing angle $\phi_{\tau\tau}$ of the tau Yukawa coupling: $\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$.

2. Analysis observables

The effective CP mixing angle is experimentally accessible by studying the angle between the two tau lepton decay planes. Indeed, the decay of a (pseudo)scalar Higgs boson to two fermions gives access to the (pseudo)scalar nature of the Higgs boson. The Higgs boson decay width to two fermions can be written as [6, 7]:

$$\Gamma(H \to f\bar{f}) \propto 1 - s_z \bar{s}_z \pm C s_\perp \bar{s}_\perp,$$

with s and $\bar{s}$ the spin vectors of the tau leptons in the tau lepton rest frames, z and $\perp$ the longitudinal and transverse components respectively, and C a unitary complex number. The sign of the transverse term is positive (negative) if H is a scalar (pseudoscalar). For CP-mixed couplings C takes a complex value. The tau lepton decay products retain the spin information, the tau lepton decay planes can hence be exploited to reconstruct an observable ϕ_{CP}. Depending on the $\tau\tau$ final state different techniques are used to compute ϕ_{CP}, [8–10]. These are presented in the two next subsections.

2.1 Impact parameter method

The impact parameter method (IP) is used for tau lepton decays involving one charged particle, exploiting the finite tau lepton lifetime. The tau lepton decay plane is defined by the impact parameter of the charged particle, defined as the vector spanned between the primary vertex and the point of closest approach of the charged particle track, and the charged particle momentum direction. To enhance the observable's sensitivity, the vectors are boosted in the so called zero

PoS(EPS-HEP2021)575

momentum frame (ZMF), where the sum of the charged particle momenta of the two tau leptons is zero. The observable ϕ_{CP} is reconstructed by defining the angle between the two tau lepton planes in the following way:

$$\begin{aligned} \phi^* &= \arccos(\hat{\lambda}_{\perp}^{*+} \cdot \hat{\lambda}_{\perp}^{*-}), \\ O^* &= \hat{q}^{*-} \cdot (\hat{\lambda}_{\perp}^{*+} \times \hat{\lambda}_{\perp}^{*-}), \\ \phi_{\mathrm{CP}} &= \phi^* \text{ if } \mathrm{O}^* \geq 0,\ 2\pi - \phi^* \text{ if } \mathrm{O}^* \leq 0, \end{aligned} \tag{1}$$

where $\lambda^{*\pm}$ and $q^{*\pm}$ are the IP and momentum defined in the ZMF, $\hat{\lambda}_{\perp}^{*\pm}$ the unitary vector of the transverse component of $\lambda^{*\pm}$ w.r.t. $q^{*\pm}$.

2.2 Neutral pion method

The neutral pion method is used for decays with more than one outgoing hadron. The tau lepton decay plane is defined by the momenta of two hadrons: $\pi^{\pm}$ and π^0 for $\rho^{\pm}$ decays, $\pi^{\pm}$ and $\rho^0(\pi^+\pi^-)$ for $a_1^{3\pi^{\pm}}$ decays. The equation 1 is used in a similar way, λ is defined as the momentum of the second hadron instead. In order to avoid destructive interferences from different polarised states of mesons, the following observable y^{τ} is used:

$$y^{\tau} = y^{\tau^+} y^{\tau^-},\ \ y^{\tau^{\pm}} = \frac{E_{\pi^{\pm}} - E_{\pi^0}}{E_{\pi^{\pm}} + E_{\pi^0}},$$

where $E_{\pi^{\pm}}$ and E_{π^0} the energies of the charged and neutral pions in the laboratory frame. If $y^{\tau} < 0$, ϕ_{CP} is recomputed as $2\pi - \phi_{CP}$.

3. Event reconstruction

The presented analysis [11] relies on 137 fb^{-1} of data recorded in pp collisions at $\sqrt{s}$ = 13 TeV by the CMS experiment [12] in 2016-2018. The $\tau_h\tau_h$ and $\tau_h\tau_\mu$ channels are studied, where τ_h denotes a tau lepton decaying to hadrons, and τ_μ a tau lepton decaying to a muon. About 50% of all possible di-τ states are considered, the most sensitive ones being $\rho^{\pm}\rho^{\mp}$, $\mu^{\pm}\rho^{\mp}$, $\pi^{\pm}\rho^{\mp}$. The analysis reconstructs and selects events similarly to previous Higgs to $\tau\tau$ analyses [13], with some improvements implemented for the particular needs of this measurement.

Hadronically decaying tau leptons are reconstructed with the Hadron-Plus-Strip (HPS) algorithm [14] and identified with a deep neural network called DeepTau to reject jets, electrons and muons [15]. The reconstruction of the tau lepton decay planes necessitates a very good decay mode reconstruction and separation. A boosted decision tree algorithm is applied on top of the τ_h selection to better separate the τ_h decay modes [16]. The primary vertex (PV) position is refitted by an Adaptive Vertex Fitter algorithm. Due to the finite tau lifetime, tracks emanating from its decay do not stem from the PV and are discarded in the fit. A constraint on the beamspot is added and leads to an improvement of the PV resolution in the transverse plane of a factor 3 for signal events, while the z coordinate is largely unaffected. The impact parameter of the charged track from the tau lepton decay is derived using a helical extrapolation of the track parameters.

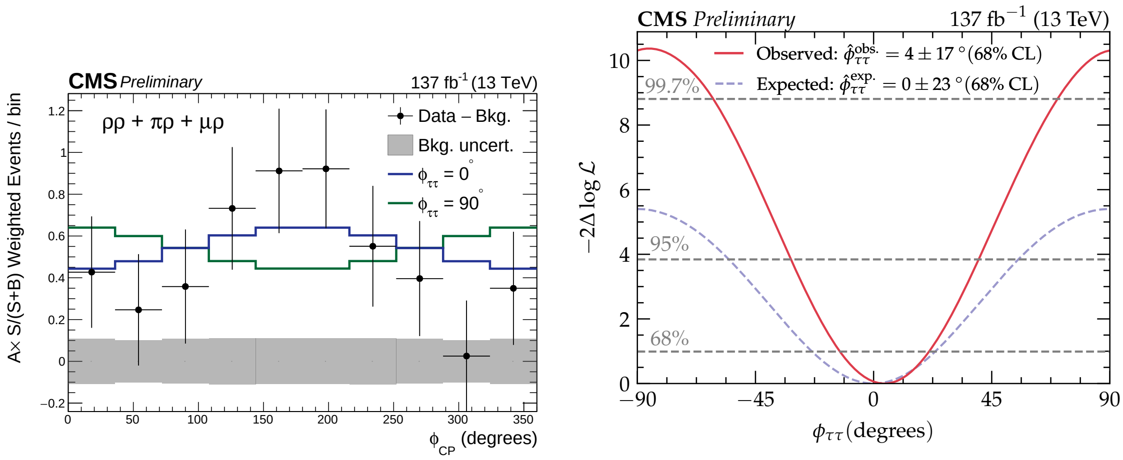

Figure 1: (Left) $\phi_{\rm CP}$ distribution for the $\rho^{\pm}\rho^{\mp}$, $\mu^{\pm}\rho^{\mp}$, $\pi^{\pm}\rho^{\mp}$ channels, compared to the scalar (blue) and pseudoscalar (green) predictions. The grey band displays the background uncertainty. (Right) negative log-likelihood scan of the combination of the $\tau_h\tau_h$, $\tau_h\tau_\mu$ channels [11].

4. Signal inference

The two main backgrounds of this measurement, genuine di-τ events (Z/γ^*, top-antitop and di-bosons events) and multijet events with jets misidentified as τ_h, are estimated by data-driven methods, respectively the embedding method [17] and the fake factor method [13]. Events are caractegorised according to their probability to be signal or background, thanks to multivariate (MVA) classifiers. Each event is classified as belonging to one of these three categories: signal, background with two genuine tau leptons, background with a fake τ_h. The reconstructed $\phi_{\rm CP}$ distributions are split by category and by increasing corresponding MVA score. These distributions are used as input to the profile likelihood ratio used to extract $\phi_{\rm CP}$. Distributions in backgrounds processes involving two genuine tau leptons are known to be flat in absence of reconstruction effects. Distributions in the jet-fake background are not flat but symmetric in $\phi_{\rm CP} = 180°$and are symmetrised, as well as the (pseudo)scalar signal templates. The likelihood function $L(\vec{\mu}, \mu^{\tau\tau}, \phi_{\tau\tau}, \vec{\theta})$ depends on following parameters: $\vec{\mu}$ the Higgs boson production signal strength modifiers w.r.t. the SM value (considering the Gluon Fusion and Vector Boson Fusion processes), $\mu^{\tau\tau}$ the branching fraction modifier w.r.t. the SM value, $\phi_{\rm CP}$ the CP-mixing angle, and $\vec{\theta}$ the nuisance parameters that account for the systematic uncertainties. The adjusted $\phi_{\rm CP}$ observable is displayed in Figure 1 for the most sensitive channels and signal categories. The background is subtracted from data, events are weighted by the average asymmetry A between the even and odd contributions, times $\frac{S}{(S+B)}$, with S and B the signal and background best fit rates. A is defined as $\frac{1}{\rm N_{bins}}\Sigma_{i=1}^{\rm N_{bins}}\frac{|\rm CP_{even}-CP_{odd}|}{\rm CP_{even}+CP_{odd}}$ whith $\rm CP_{even}$ and $\rm CP_{odd}$ the scalar and pseudoscalar contributions per bin. The data favour the CP-even scenario.

5. Conclusion

This is the first measurement of the CP structure of the tau Yukawa coupling. The pure pseudoscalar Higgs boson hypothesis is excluded with 3.2 (2.3) observed (expected) standard deviations. The observed (expected) mixing angle is found to be 4 ± 17 (stat) ± 2 (stat) ± (syst) ± 1 (theory)° (0 ± 23 °) at 68% CL. The measurement is consistent with the SM expectation, and sets first constrains on physics beyond the SM. The result will improve with Run 3 and HL-LHC data thanks to the large datasets that will be recorded.

References

[1] The 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)

[2] The CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Physics Letters B* 716 (2012), no. 1, 30

[3] The 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

[4] The CMS Collaboration, *Study of the Mass and Spin-Parity of the Higgs Boson Candidate via Its Decays to Z Boson Pairs*, *Phys. Rev. Lett.* 110.8 (2013) [hep-ex 1212.6639v2]

[5] The ATLAS Collaboration, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*, *Phys. Lett. B* 726 (2013) 120 [hep-ex 1307.1432]

[6] V. Barger et al., *Higgs bosons: Intermediate mass range at e+e- colliders*, *Phys. Rev. D* 49.1 (1994)

[7] M. Krämer et al., *Prospects of measuring the parity of Higgs particles*, *Zeitschrift für Physik C* Particles and Fields 64.1 (1994)

[8] S. Berge, W. Bernreuther, and S. Kirchner, *Determination of the Higgs CP-mixing angle in the tau decay channels*, *Nucl. Part. Phys.* Proc. 273-275 (2016) 841

[9] S. Berge, W. Bernreuther, B. Niepelt, and H. Spiesberger, *How to pin down the CP quantum numbers of a Higgs boson in its tau decays at the LHC*, *Phys. Rev. D* 84 (2011) 116003 [hep-ex 1108.0670]

[10] S. Berge, W. Bernreuther, and S. Kirchner, *Determination of the Higgs CP-mixing angle in the tau decay channels at the LHC including the Drell-Yan background*, *Eur. Phys. J.* C 74 (2014) 3164 [hep-ex 1408.0798]

[11] The 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*, *CMS-PAS-HIG-20-006* [https://cds.cern.ch/record/2725571]

[12] The CMS Collaboration, *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004

[13] The CMS Collaboration, *Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector*, *Phys. Lett. B* 779 (2018) 283 [hep-ex 708.00373]

PoS(EPS-HEP2021)575

[14] The CMS Collaboration, *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) 10, P10005 [hep-ex 1809.02816]

[15] The CMS Collaboration, *Tau identification in CMS*, *CMS-PAS-TAU-11-001* [https://cds.cern.ch/record/1337004]

[16] The CMS Collaboration, *Identification of hadronic tau decay channels using multivariate analysis (MVA decay mode)*, *CMS-DP-2020-041* [https://cds.cern.ch/record/2727092]

[17] The CMS Collaboration, *An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data*, *JINST* **14** (2019) P06032 [hep-ex 1903.01216v2]