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Determining the CP nature of the Higgs boson using the $H \to \tau\tau$ decay mode at CMS

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Abstract

The joint discovery of the Higgs boson by the CMS [1] and ATLAS [2] collaborations in 2012 is one of the most important Particle Physics experimental results of the decade. In 2020, the CMS collaboration presented the first measurement of the Higgs CP-mixing angle. This quantum number indicates if the boson couples differently to matter and anti-matter [3]. The CMS collaboration found a value of $4 \pm 17°$ which is in good agreement with the SM prediction of $0 \pm 23°$ [4]. This review presents the experimental and theoretical backgrounds to this analysis. It also discusses the CMS result and points towards further work that could be done to reduce the margin of error on their measurement.

1 Introduction

The Standard Model of Particle Physics (SM) is the most successful theoretical model currently available to us. However, this model is known to bear important limitations. It proposes, for example, no explanation for the matter-anti-matter imbalance in the Universe, neither does it offer an explanation for dark matter and energy, which conjointly make up the immense majority of the Universe[5]. Since even before its detection, the Higgs boson has been identified as a very powerful tool to test the SM [6].

2 A formidable experimental set-up

2.1 The LHC

The Large Hadron Collider (LHC) is the largest proton-proton collider ever built [7]. Two beams of proton, produced onsite, are electromagnetically accelerated as they travel, in opposite directions, along the two 27km-long rings. They then collide in one of the 4 experimental sites: CMS, ALTAS, LHCb and ALICE [7] where the particles formed are measured. The LHC's centre of mass energy reached $\sqrt{s} = 13$TeV during Run 2 which is sufficient to produce heavy mesons and Higgs bosons [8].

2.2 The CMS detector

The Compact Muon Solenoid (CMS) is a cylindrical detector centered about the proton beam. It is composed of multiple consecutive layers of detecting materials. The different layers are presented on Figure 1 below. The CMS detector measures 21.6 meters in length and 14.6 meters in diameter [9]. It takes its name from the 3.8T superconducting solenoid enclosing all the sub-detectors except for the muon detection system. The total integrated luminosity collected by the CMS experiment since its launch reached 137fb^{-1} in 2018 [10] before the LHC started its second long shutdown period [8]. After the high luminosity (HL) upgrades to LHC and to the CMS detector, the total integrated luminosity is expected to be 10 times what it is today [11].

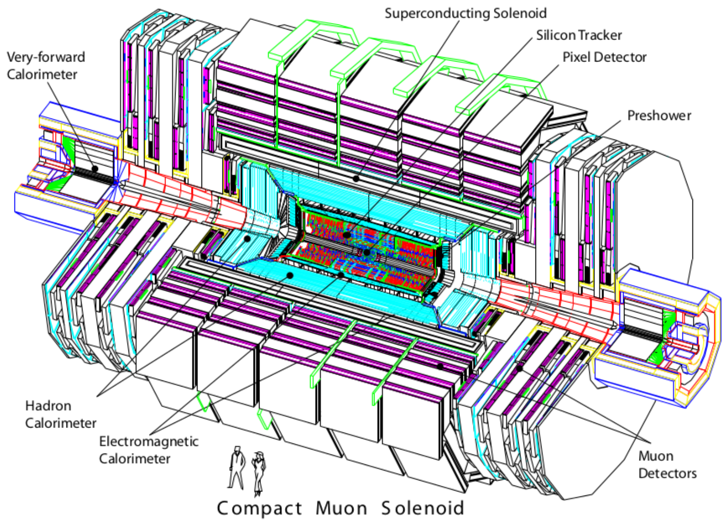


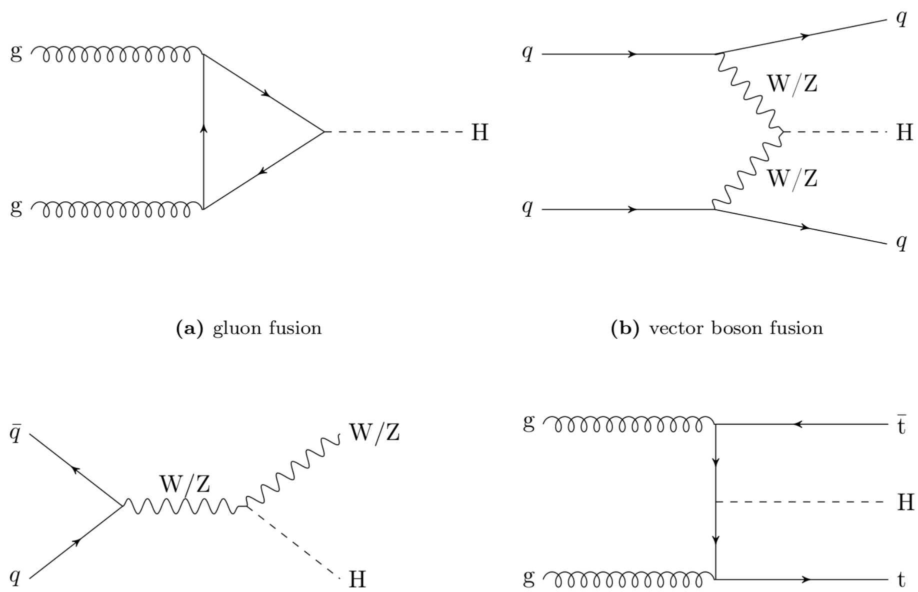
Figure 1: View of the CMS detector showing the different sub-detector. Figure taken from [9].

The centre-most region of the detector, covering 1.2m in radius is the tracker. It consists in a mesh of densely spaced, highly sensitive fast-responding silicon strips which detect the trajectory of charged particles later to be used to reconstruct the primary vertex, i.e. the point in time and space where the first interaction happened [4]. The two subsequent detecting layers are the electromagnetic and hadronic calorimeters (ECAL and HCAL respectively). ECAL is formed by an array of scintillator crystals which produce a bust of light when an electron or a photon passes through them, thus allowing the detection of both of these particles [12, 13]. HCAL is a similar scintillator detector detecting the hadronic showers [9, 14]. Finally, the muon system is the only detector located outside of the 6m diameter superconducting solenoid and consists of three different types of detecting modules inter-spaced between iron plates[15]. This sub-detector identifies the muons and measured their momenta with an unprecedented 99% accuracy [16].

3 Theoretical background

3.1 The SM Higgs boson

Within the Standard Model of Particle Physics, the Higgs boson is the only spin-0 resonance. Through the process of spontaneous symmetry breaking, it gives mass to both leptons and quark [17, 18]. The Higgs boson's production modes observed at CMS are presented in Figure 2 below.



(a) gluon fusion **(b)** vector boson fusion

(c) W/Z-associated production **(d)** $t\bar{t}$-associated production

Figure 2: Feynman diagrams presenting the different production modes (in the SM) of the Higgs boson currently accessible at the LHC. Image taken from [19].

The SM states that the Higgs model is a CP-even particle, which means that it couples identically to matter and anti-matter [20]. The Higg's Yukawa coupling to τ leptons is encoded by the following Lagrangian:

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

where m_τ is the tau mass, $\mathrm{v} = 246\mathrm{GeV}$ is the Higg's vacuum expectation value, H, τ and $\bar{\tau}$ are the Higgs, tau and anti-tau wavefunctions respectively, γ_5 is the product of the four Dirac matrices [21]. Finally, κ_τ and $\tilde{\kappa}_\tau$ are the reduced scalar and pseudoscalar Yukawa coupling constants which have values between 0 and 1 [22]. The coupling constants are often given in the form of the Higgs' effective mixing angle $\phi_{\tau\tau}$ [23]:

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

If $\phi_{\tau\tau} = 0°(90°)$ then the Higgs is a purely CP-even (CP-odd) particle, otherwise and it is a CP-mixture [3]. The coupling of Higgs to the Z, W and γ bosons has already been observed and it has been proven that the Higgs boson is not a CP-odd particle [24].

3.2 Retrieving the Higgs' CP properties from the $H \to \tau\tau$ decay channel

The decay mode $H \to \tau\tau$ is favoured for CP searches at CMS for two main reasons. Firstly, this decay mode represents a relatively high branching ratio, 6.27% of all Higgs decays [25], which, allied to the detector's high luminosity, gives a statistical population large enough to perform analysis on. Secondly, the CP-nature of the Higgs boson can be retrieved from its decay to two taus. Indeed, the distribution of the angle between the two τ decay planes, called ϕ_{CP}, is strongly related to the value of the mixing angle $\phi_{\tau\tau}$ [23]. The relationship has been proven in [23] and is graphically presented in Figure 3 below. In earlier works, ϕ_{CP} was labeled φ^*_{CP} and $\phi_{\tau\tau}$ labeled ϕ_τ or $\varphi_{\tau\tau}$ [4, 26, 27].

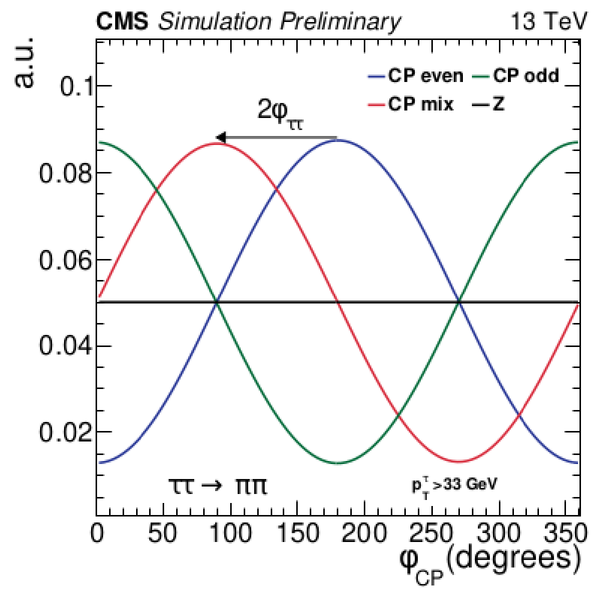


Figure 3: Distribution of the ϕ_{CP} angle for different CP states of the Higgs, CP-even(odd) in blue (green) and maximal CP mixture where $\phi_{\tau\tau} = 45°$ in red. The flat black line shows the distribution of the Drell-Yan bacground process. Figure taken from [4].

The tau leptons have a very short lifetime ($290.3 \pm 0.5 \times 10^{-15}$s [28]) due to their heavy mass, therefore, they decay before CMS can detect them [29] The tau decay modes studied at CMS are presented in Table 1 below.

Decay Mode	$\mu^\pm$	$\pi^\pm$	$\rho^\pm \to \pi^\pm\pi^0$	$a_1^\pm \to \pi^\pm\pi^0\pi^0$	$a_1^\pm \to \pi^\pm\pi^\mp\pi^\pm$
Branching fraction	17.4%	11.5%	25.9%	9.5%	9.8%
Symbol	μ	π	ρ	$a_1^{1\mathrm{pr}}$	$a_1^{3\mathrm{pr}}$

Table 1: Presentation of the different τ decay modes used in CMS' analysis [4] and their respective branching fractions [25]. Only the decays where one or both of the τ decay to hadrons (π,ρ or a_1) are kept. The decay to hadron (muon) is accompanied by a tau neutrino (a tau and a muon neutrino).

The τ decay products are directly observable (like the muon [15]) or easily reconstructed (like the pions which decay to two photons travelling in opposite directions [29]), except for neutrinos which are not detected by CMS. The missing energy, carried by these neutrinos prevents the τ rest frame from being easily reconstructed [3, 9]. To do so, more complicated analysis procedures have to be implemented, as summarised below and presented in greater details in [19, 29, 30]. It is important to note that the main background in this analysis, after the jets misidentified as tau decay products, is the Drell-Yan process $Z/\gamma^* \to \tau\tau$ [31]. The distribution for this irreducible background is flat, as shown on Figure 3, which permits a clean analysis [27].

The two methods used in CMS' analysis are the impact parameter method and the neutral pion method. The impact parameter is an observable defined as the vector between the primary vertex and the point of closest approach of the charged particle [23]. The decay plane of each tau is then defined by the impact parameter vector and charged particle vector. The angle between the decay planes of the two taus is ϕ_{CP}, within a phase flip (depending on which charged particle the τs decay to) [26]. The neutral pion method can only be applied to decay modes with more than one outgoing hadron. In this case the four-momentum vector of the neutral pion is used instead of the impact parameter to define the τ decay plane and extract the ϕ_{CP} angle. In this method, the different polarisation of pions also have to be accounted for [23]. This second method is more precise than the first because CMS' ECAL has a very fine granularity which allows a very fine measurement of the neutral pion's direction [13]. Additionnaly, the τ impact parameter is relatively small compared to the tracking resolution [4] which means that there is a higher uncertainty on this parameter. This is why, even if the impact parameter method can in principle be used for any decay, the neutral pion method is favoured wherever it can be used.

The CMS analysis team used the 2016, 2017 and 2018 datasets, correcting for electrical defaults, triggering and luminosity differences across runs to obtain their result and process the associated error [4, 10, 32, 33]. Only the events which fulfilled both momentum and angular position requirements were kept for analysis to increase the accuracy (see [3, 4] for details). On top of the selections an MVA (multivariant) discrimant has been implemented. The machine learning algorithm was a Neural Network fed with the kinematics recorded by the different sub-detectors and trained to distinguish between the different decay modes. The MVA score was then used to optimise the statistical relevance of the data [4]. More information on the use of Neural Network and its input parameter for different τ decay modes in this analysis can be found at [4, 34].

4 Results and discussion

4.1 Higgs' CP mixing angle

In ref.[4] the distribution of the ϕ_{CP} angle is presented for each decay mode in bins of MVA score i.e. in bins of less to more trusted data. The distribution for the $\mu\rho$ decay mode, which is the most sensitive, is reproduced in Figure 4.

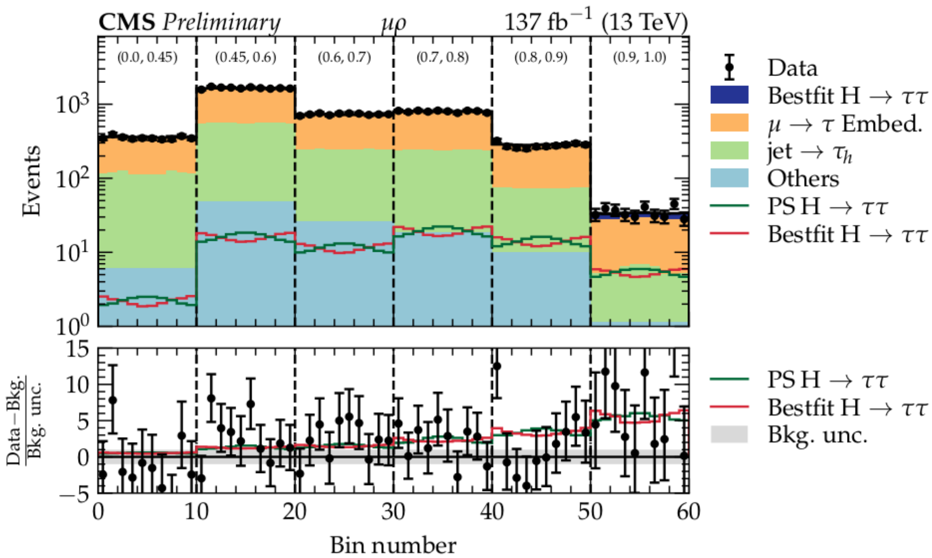


Figure 4: Distribution of the ϕ_{CP} angle in bins of increasing MVA score (indicated on the top of each bin) for the $\mu\rho$ decay mode. The relative distance to the flat background is shown on the bottom plot, with a higher significance but lower statistics as the bin number increases. The best fit distribution is shown in red and the distribution for a CP-odd Higgs boson scenario is shown in green. Figure taken from [4].

A negative log-likelihood scan was performed on the ϕ_{CP} distributions collected over all the decay modes considered to extract the best fit value for the $\phi_{\tau\tau}$ angle. The result is presented in Figure 5.

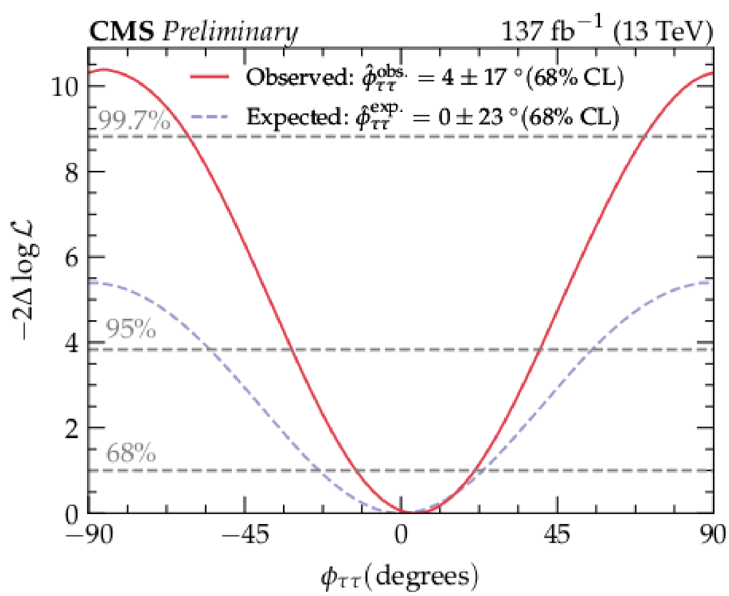


Figure 5: Result of the negative log-likelihood scan for $\phi_{\tau\tau}$ showing the 1, 2 and 3 sigma confidence levels. The best fit result for this analysis is $4 \pm 17°$ (solid line) and is in line with the SM expectation of $0 \pm 23°$ (dashed line). Taken from [4]

The value found by the CMS collaboration for the CP mixing angle is $\phi_{\tau\tau} = 4{\pm}17°$ which is consistent with the SM prediction of $0{\pm}23°$ [4]. The error on the angle is strongly dominated by statistics, with a decomposition of $\phi_{\tau\tau} = 4{\pm}17(\text{stats}){\pm}2(\text{bin-by-bin}){\pm}1(\text{systematic}){\pm}1(\text{theory})°$. In order to refine the quality of this measurement one could increase the available statistics, as is currently being done with the HL-LHC project [8, 11]. One could also think about including more τ decay modes in the analysis which could increase up to twice its current value, as only about 50% of all the $H \to \tau\tau$ decays are currently included in the analysis [4]. Researches are still need to determine which additional decays modes and which cuts have to be applied in order to maximise the measurement's accuracy [35]. Finally, it is worth mentioning that the ATLAS experiment has also laid down the ground work of a similar measurement of the Higgs' CP properties, whose results would be a very useful verification and extension to CMS's analysis [36, 37].

4.2 Future prospects and BSM Physics

Even if CMS measurement of the Higgs's CP state is not in conflict with the SM, the possibility that the Higgs has a small but non-zero CP mixing angle is not yet experimentally discarded [4]. A non-zero mixing angle value would hint at New Physics, Beyond the Standard Model (BSM). Many different models have been put forward [38, 39]. The most promising of those alternatives are 2 Higgs Doublet Models (2HDM). These models permit CP-violation in the Higgs sector by allowing a total of 5 Higgs bosons to exist, two neutral scalar Higgs bosons, one light, h, and one heavy, H, two charged Higgs bosons, $H^{\pm}$, and a neutral pseudoscalar Higgs boson called A [38]. In this case some mixing can occur between the different Higgs states and the observed Higgs resonnace can have a non-zero mixing angle.

Ref [38] presents many models where spontaneous CP-violation occurs in the Higgs sector. These models could be discarded by a more precise CP-measurement of the Higgs boson. These include for example Lee's model [40], some regions of the Next to leading order Minimal Supersymmetric Standard Model ($\mathscr{N}$MSSM) [41] and some Three Higgs Doublets Models [42].

5 Conclusion

LHC's CMS experiment produced the first ever measurement of the Higgs boson's CP mixing angle $\phi_{\tau\tau} = 4 \pm 17°$ which is in good agreement with the SM expected value of $0 \pm 23°$ [4]. This result was obtained from the $H \to \tau\tau$ channel using a combination of two analysis techniques, the impact parameter and the neutral pion methods. A deep Neural Network was used to accurately identify the decay modes and optimise the data sampling. It is thought that including the other available τ decay channels in the analysis could provide a significant improvement to the margin of error which is currently dominated by statistical error.

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