Probing the CP nature of the Higgs sector

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Abstract

CP violation is one of the conditions necessitated by Sakharov for baryogenesis and hence a matter-dominated universe. The Higgs sector remains a possible source of CP violation and the discovery of CP violating effects would constitute new physics beyond the standard model. Here, the history of Higgs physics and post-Higgs research is reviewed. Adopting a CP physics lens, a deeper look into the Higgs boson interaction with the top quark is taken and the experimental results to date are reviewed. The results show consistency with standard model predictions, but are dominated by statistical uncertainties.

Contents

1. Introduction

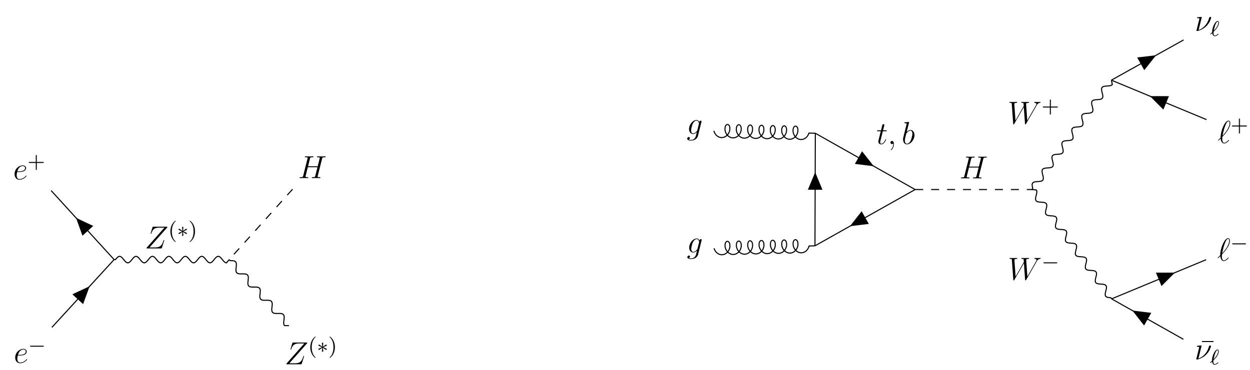
The discovery of the Higgs boson in 2012 [1, 2] completed the standard model of particle physics; however, this pinnacle of discovery was the product of many decades of international collaboration by theorists and experimentalists, having been proceeded by many experiments and development of newer, more sophisticated technologies. Along the way, constraints were set in the ”Higgs-hunting” process, with increasingly heavier masses creatively probed and ruled out.

The hunt finally concluded with the observation of a particle consistent with the standard model Higgs at a significance greater than the gold-standard $>5\sigma$ required to declare observation. Beyond bolstering the reputation of the standard model as a predictive theory, the discovery of the Higgs opened up a new avenue to test the limits of this theory and to probe fundamental questions about the universe.

One of the biggest open questions in physics is why the universe we observe today is dominated by ordinary matter as opposed to anti-matter. CP violation has been identified as a requirement for baryogenesis [3], the process out of which matter-dominance was born, yet the quantity so far measured in nature is insufficient for the scale of the asymmetry. There must be a source of CP violation not yet observed hidden in some fundamental process. The discovery of the Higgs boson is an exciting new frontier for CP physics since its interactions with gauge bosons and fermions could contain CP violating effects [4].

In this dissertation, a brief history of the search for the Higgs boson is discussed, followed by an overview of the state of contemporary Higgs-physics research and precision measurements. Adopting a lens for beyond standard model physics, the CP nature of the Higgs sector is also reviewed, taking a closer look at the CP properties of the top-Higgs Yukawa coupling.

2. Higgs discovery



(a) ”Higgs-strahlung”: $e^+e^- \to Z \to Z$H

(b) gg $\to$ H $\to W^+W^- \to \ell^+\nu_\ell\ell^-\bar{\nu}_\ell$

Figure 2.1: Feynman diagrams showing two of the channels studied in the search for the Higgs boson. (a) e^+e^- annihilation at LEP and (b) gluon-gluon fusion at Tevatron.

2.1. Historical searches for the Higgs boson

With the development of the standard model in the 1970s, physicists began to notice an intimate relationship between two of the four fundamental forces: the electromagnetic and weak forces. The unification of the two theories into electroweak theory was a success in that it accurately described the forces and associated bosons, but with one crucial exception: the theory predicted massless W and Z vector bosons. From experiment, the W and Z bosons have been observed to be massive particles [5–8], so clearly the theory was not complete.

A solution to this problem was proposed by the theorists Robert Brout, François Englert and Peter Higgs in the form of the Brout-Englert-Higgs mechanism. Also known more simply as *the Higgs mechanism*, this mechanism gives mass to the W and Z bosons through their interactions with the Higgs field, whilst preserving the properties of gauge symmetry and renormalisability to ensure that the predicative nature of the theory stays intact. Just like how the electromagnetic field has an associated boson (the photon), the Higgs field also has an associated boson: *the Higgs boson*.

Pre-Higgs discovery, many particle physics collaborations set increasingly stringent constraints on the mass of the Higgs boson [9]. We will now discuss some of the groundwork laid by two notable experiments that paved the way for the eventual discovery of the Higgs boson at the Large Hadron Collider (LHC).

Large Electron-Positron collider

The Large Electron Positron (LEP) collider at CERN first collided electrons and positrons in July 1989 (LEP1) at a centre-of-mass energy of $\sqrt{s} = 91$ GeV, an energy chosen such that the collider was a Z boson factory [10–13]. The Z boson had been discovered at CERN in 1983, so one of the primary goals of LEP was to study in greater detail the components of the electroweak theory [7]. A series of upgrades (LEP2) provided LEP with the required energy to produce pairs of W bosons, ending up with a final accelerating energy of 209 GeV in 2000. LEP would also go on to prove itself as a very important tool in setting constraints on the mass of the Higgs boson.

Prior to LEP's Higgs search, there were very few constraints on the Higgs mass. In 1988, the year before LEP was commissioned, the only constraints on the Higgs mass as listed by the Particle Data Group (PDG) were a strict $M_H >$14 MeV constraint from experiments studying nucleon-nucleus scattering, and a tentative $M_H > 4$ GeV from studying B, Υ and K decays in combination with some theoretical arguments [14]; there were not yet any upper limits to M_H.

During the first run of LEP (LEP1), Higgs searches showed no excess of events above background, setting a lower limit on the Higgs mass of m_H 65.6 GeV. LEP2 saw more accelerating cavities installed, doubling the centre-of-mass energy to $\sqrt{s} = 209$ GeV. This energy came close to the realm of the Higgs mass, yet was just short of that required. With our current knowledge of the Higgs mass being around $m_H = 125$ GeV, it might not be immediately obvious why this energy was not sufficient. The primary decay channel measured at LEP was Higgs-strahlung shown in figure (2.1a), which involves the production of a Z boson in association with a Higgs boson. The required energy for this process is roughly $\sqrt{s} \approx m_H + m_Z \approx 226$ GeV, just a bit more than the capabilities of LEP, hence why the production of the Higgs boson lay just outside the capabilities of LEP. Despite no outright observation of the Higgs boson being made at LEP, the combined data of the four experiments set a lower bound of 114.4 GeV/c^2 on the standard model Higgs boson mass with a 95% confidence level

[15].

Tevatron

Tevatron was a proton-antiproton collider in Fermilab that operated from 1983 to September 2011 and hosted two main collaborations, D0 and CDF [16, 17]. The primary goal and most notable achievement from its first run was the observation of the top quark, a quark whose mass is similar to that of a gold nucleus, yet so short-lived that it is unable to hadronise before decaying [18].

During its second run, Tevatron collided protons and antiprotons at a centre-of-mass energy of $\sqrt{s}$ = 1.96 TeV. Despite the extra energy compared to LEP, Tevatron had to deal with the large QCD backgrounds characteristic of hadron colliders, compared to the relatively "clean" lepton collider processes. Many of the technologies that enabled the eventual Higgs discovery were developed at Tevatron, including the development of sophisticated jet algorithms and multivariate analysis tools [9].

Searches for the Higgs boson around the LEP lower limit to around 200 GeV were carried out at Tevatron. Various channels were tested, with channels selected according to sensitivity. One such channel for a Higgs with a mass $m_H \approx 120$ GeV, was Higgs production in association with a Z or W boson, with the Higgs decaying into a bottom-anti-bottom quark pair and the Z or W decaying leptonically. Another search for a Higgs around $m_H \approx 160$ GeV was via the gluon-gluon fusion route, a dominant process that was integral to the eventual Higgs discovery at the LHC. An example of a gluon-gluon fusion process is shown in figure (2.1b).

An analysis of 10 fb^{-1} collision data by the CDF and D0 collaborations set stringent constraints on the Standard Model Higgs mass, excluding mass regions at a 95% confidence level. A deviation from background at around 120 GeV/c^2 was seen with a significance of 2.5σ [19]. The combined analysis of both collaborations found an excess of events against background in the 120 to 135 GeV range at a global significance of 3.1σ, constituting evidence for the standard model Higgs boson, but falling short of the 5σ required to claim observation [20].

2.2. Higgs discovery by ATLAS and CMS

The LHC was designed with the purpose of completing the standard model of particle physics, a goal only achievable by observing the Higgs boson. Beyond this, the LHC set out to test the standard model and shine a light on the mystery of dark matter.

ATLAS and CMS are two general-purpose particle detectors hosted at CERN [21, 22]. Built independently, but with similar research aims, the two experiments serve as a useful cross-check for each other's discoveries.

In 2012, just two days after the Tevatron announcement, there was a joint announcement by the ATLAS [2] and CMS [1] collaborations. They had observed a new particle at around 125 GeV, consistent with the standard model Higgs boson. With this discovery, the standard model was complete, which naturally leads to the question: what next?

3. Higgs mechanism

The Higgs boson discovery served as confirmation for a long-standing theory of particle physics, the

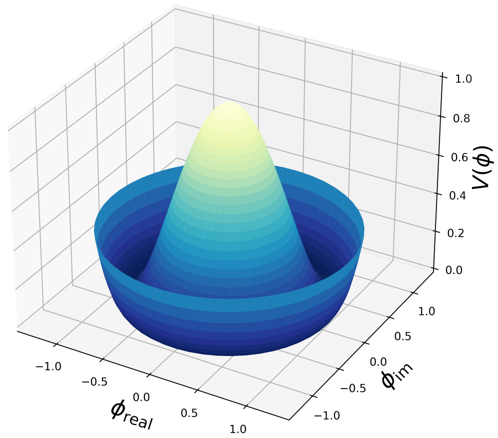


Figure 3.1: Higgs potential $V(\phi)$, also known as a *Mexican hat potential.* The vacuum expectation value is equal to the circular minimum of the potential.

Higgs mechanism.

The Higgs mechanism is a mechanism that gives mass to the gauge bosons in the standard model [23–26]. The theory of gauge invariance implies that the spin-1 gauge bosons should have exactly zero mass. Whilst true in QED and QCD, with photons and gluons being massless, this is not the case for the electroweak particles (W and Z bosons), which are in fact massive particles. This stark issue motivates the introduction of a new type of field that the particles interact with to acquire mass.

Higgs field

The Higgs field is a scalar field that demonstrates peculiar behaviour in the vacuum state (a state containing no particles of any type) [27]. Whilst other fields, such as the electromagnetic field, have zero value in the vacuum state, the Higgs field has a non-zero value. Furthermore, this value is not invariant under gauge transformation, which means that the gauge bosons are no longer required to have zero mass. However, although the vacuum state value of the Higgs field is not invariant under gauge transformation, the interactions of the Higgs field with the gauge bosons are gauge invariant. This particular type of symmetry breaking is known as *spontaneous symmetry breaking.*

The concept of spontaneous symmetry breaking can be described by a simple model. For a scalar field ϕ, the components of its Lagrangian can be split-up:

$$\mathcal{L} = \partial^\mu \phi \partial_\mu \phi - V(\phi), \tag{3.1}$$

where the first term is kinetic, the second is a potential. The potential term contains the symmetry breaking. We assume the form of the potential $V(\phi)$:

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4, \tag{3.2}$$

where μ^2 and λ are real parameters. Potentials of this form are commonly referred to as *Mexican hat potentials*, see figure (**??**).

Furthermore, the field ϕ is invariant under the transformation

$$\phi \to \phi e^{i\beta}, \tag{3.3}$$

where β is an arbitrary phase parameter. Presently, the task is to find the value of the vacuum state. In equation (3.1), the kinetic term is either positive or zero, hence by minimising the potential term we can find the vacuum state value of the scalar field. For the case that $\lambda > 0$, there are two further possible cases: either $\mu^2 > 0$ or $\mu^2 < 0$. For the first case, both terms in equation (3.2) are positive definite, yielding a unique minimum. For the second case, a circle of absolute minimum is formed (see figure (**??**)) with solution

$$\phi_0 = \left(-\frac{\mu^2}{2\lambda}\right)^{1/2} e^{i\theta}, \tag{3.4}$$

where θ is a phase angle that specifies a direction in the complex plane. By convention, $\theta = 0°$, such that the vacuum state value is given by

$$\phi_0 = \left(-\frac{\mu^2}{2\lambda}\right)^{1/2}. \tag{3.5}$$

The interaction of a gauge boson with a non-vanishing vacuum field is what gives it its mass. This is known as the Higgs mechanism.

Higgs boson

As we might expect, there is an associated quantum of the Higgs field: the Higgs boson. The Higgs boson is a massive scalar spin-0 boson, with a mass of 125.25±0.17 GeV [28].

4. Higgs precision measurements

Since the observation of the Higgs boson by the ATLAS and CMS experiments, much research has been focussed on refining the measurements of the properties of the Higgs boson. Although not as glamorous as hunting for new particles, making precision measurements is a necessary part of testing the validity of the standard model, with any significant deviations potentially constituting new physics beyond the standard model. Many measurements, such as those pertaining to the CP properties of the Higgs boson, are still in their infancy and are dominated by statistical uncertainty. Collecting more data is the primary method of reducing this uncertainty, motivating the proposed *High-Luminosity Large Hadron Collider* (HL-LHC) upgrade [29].

The primary way of reducing uncertainties on measurements is by collecting more data (an example of reducing statistical uncertainty), but other methods, such as improving detector resolution (systematic uncertainty), can help to minimise uncertainties.

4.1. Higgs properties

The Higgs field is responsible for giving mass to fundamental particles, including its own quanta the Higgs boson through a self-coupling of the Higgs boson with the Higgs field. Besides being an interesting phenomenon, the Higgs self-interaction strength is tied to the Higgs boson mass in the standard model and as such comparison of precision measurements of these two properties serves as an important test of the standard model.

Mass

Improved collision rate and energy in the second run of the LHC means that an improved measurement of the Higgs boson mass has been made. Detector improvements and upgrades to higher precision components have also improved the measurements. Combined analyses from the ATLAS and CMS collaborations have increased the precision of the Higgs boson mass measurement, with the weighted average given by the Particle Data Group as $m_H = 125.25 \pm 0.17$ GeV [28, 30–32].

Self-coupling strength

The Higgs self-coupling value is difficult to measure at LHC.

The self-coupling value λ from equation (3.2) is related to the Higgs boson mass by:

$$\lambda = \frac{m_H^2}{2\phi_0^2}, \tag{4.1}$$

where m_H is the Higgs boson mass, ϕ_0 is the potential at the vacuum expected value. Hence consistency between the self-coupling value derived from the mass and that directly measured can be checked.

A future collider could improve the precision of the Higgs coupling measurement. A study into a 100 TeV future proton-proton collider, like the Future Circular Collider (FCC) proposed at CERN [33], found that the precision of this measurement could be improved to a range of 3.4-7.8% at a 68% confidence level [34].

Yukawa coupling strength

In 2018, Higgs boson production in association with a pair of top quarks ($t\bar{t}H$) was observed by the ATLAS and CMS experiments [35, 36]. The measurements of the ttH cross section by the two experiments constituted an observation of the Yukawa coupling between the Higgs boson and the top quark. This coupling is of particular interest since the top quark is the heaviest quark and consequently has the strongest interaction with the Higgs boson.

5. Beyond the standard model of particle physics

The observation of the Higgs boson has been considered as a completion of the standard model, yet despite its discovery being an unquestionable success, there are still many open questions that necessitate physics beyond the standard model. Such questions include: what is the nature of dark matter and of dark energy? How can gravity be combined in to a unified theory of the four fundamental forces? How do neutrinos acquire their mass and why does their flavour oscillate? Why does matter dominate over anti-matter in our universe? There are many proposed theories, from supersymmetry to string theory, that might hold the answers to these questions. Experiments and tests accompanying these theories have been conducted or planned, but none have as of yet produced any conclusive observation of new physics [37].

5.1. Matter-antimatter asymmetry

The big bang should have created equal amounts of matter and antimatter, yet the universe we observe today is matter dominated. In the earliest few seconds of the universe, the dense and hot state meant that particle-antiparticle pairs would be produced at an inconceivably rapid rate. If there was a perfect symmetry in the laws governing the production of these particles, each should have annihilated with its partner, leaving a universe purely composed of radiation. Rather than this perfectly symmetrical outcome coming into fruition, a small fraction (on the order of one in a billion) of matter particles survived to create the universe today. One of the most eagerly questioned problems in physics that is not currently explained by the standard model is the source of this matter-antimatter asymmetry. This asymmetry is fundamental to the existence of anything of interest (besides a sea of photons in a universe devoid of matter) in our universe, therefore the elucidation of the origin of this asymmetry are of boundless interest to physicists [38].

One attractive, testable theory that remains popular today is that of electroweak baryogenesis, the process of producing an excess number of matter particles (baryons, as apposed to ant-baryons) in the early universe[39]. Finding success in the weak sector, this theory has been extended to the Higgs sector and is the subject of discussion in a later chapter.

Sakharov conditions

In 1967, Sakharov set out his three conditions for baryogenesis [3]. The first condition is that there must exist, or have existed, baryon number violating processes. In the present day, all known interactions preserve baryon number; however, this might not have been the case in the very early universe due to the extreme energy densities. The second condition is that CP must have been violated. The third condition is that the baryon-number violating processes must have occurred out of thermal equilibrium, such that the two previous conditions do not cancel each other out.

CP violation

CP violation is the combination of C and P transformations. C (charge) conjugation simply changes a particle into its antiparticle, or vice-versa. P (parity) transformation reverses the momentum of a particle, leaving its spin unchanged. Hence the combined CP transformation turns a particle into its antiparticle and reverses its direction of motion whilst leaving its spin unchanged. P violation in beta decay was first observed by Wu in 1957 [40] and combined CP violation observed in the weak decay of kaons by Cronin and Fitch in 1964 [41]. The mechanism for CP violation was included in the standard model by the CKM matrix in 1973 by Kobayashi and Maskawa [42], yet the amount of CP violation observed in the weak sector is not sufficient for the scale of baryogenesis required to produce the universe seen today.

CP-even and CP-odd

To discuss CP-violating models, we first need to introduce the idea of CP-even and CP-odd states, and how the combined CP symmetry can be violated and this violation measured.

CP violation has been shown experimentally in the Cronin and Fitch experiment of neutral kaon decay. Kaons have a mass of around $m_K \approx 498$ GeV and often decay to either two or three pions.

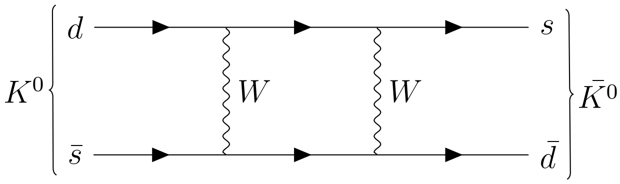


Figure 5.1: Mixed neutral kaon state. The time reversed process is also possible, meaning that neutral kaons can convert between states.

Neutral kaons K_0 are able to convert to their anti-particle $\bar{K_0}$ via the weak interaction and exist in nature as a mixed state represented by the box diagram shown in figure (5.1).

States $|K_0\rangle$ and $|\bar{K_0}\rangle$ do not individually obey CP invariance, however linear superpositions of these states can be constructed that are eigenstates of CP:

$$|K_S^0\rangle = \frac{|K^0\rangle - |\bar{K^0}\rangle}{\sqrt{2}}, \tag{5.1}$$

$$|K_L^0\rangle = \frac{|K^0\rangle + |\bar{K^0}\rangle}{\sqrt{2}}, \tag{5.2}$$

where $|K_S^0\rangle$ is *K-short*, so named due to its shorter lifetime relative to $|K_L^0\rangle$, *K-long*. By applying C and P operators, it can be shown that these states are eigenstates of CP, with $|K_S^0\rangle$ having an eigenvalue of -1, *CP-odd*, and $|K_L^0\rangle$ having an eigenvalue of +1, *CP-even*.

By considering the CP values of the two and three pion final states, it can be shown that the two pion states are CP-even and the three pion states CP-odd. Therefore, if CP invariance is assumed, we would expect the K_S state to only decay to the two pion states and the K_L state to the three pion states. Cronin and Fitch tested this theory with a long tube from a neutral kaon source with a detector at the end that could detect π^+ and π^- particles [41]. The tube was long enough such that the K_S kaons would have decayed away long before reaching the detector, leaving only K_L kaons. Again assuming CP invariance, the detector should have only detected three pion final states. The detector was capable of detecting π^+ and π^- states from the decay $K_L \rightarrow \pi^+\pi^-\pi^0$. Kinematic analysis of the angle of total momentum between the π^+ and π^- states showed a spike at $\theta = 0°$, characteristic of the back-to-back decay to a two pion $\pi^+\pi^-$ state. A CP-odd state decaying to a CP-even state is a clear violation CP invariance, demonstrating the non-universality of this symmetry.

Cronin and Fitch's experiment was the first observation of a CP violating process. Of the approximately 22700 K_L decays, around 45 had a $\pi^+\pi^-$ final state, proving that CP is violated in hadronic weak interactions. Future experiments, such as BaBar [43] and Belle [44] have observed CP violation in the decays of B mesons. The LHCb collaboration [45] has also announced observation of CP violation in neutral D mesons [46]. But CP violation has not yet been observed in any other sector, but that is not to say that is has been ruled out in all sectors - the Higgs sector remains a possible source of CP violation. Extending the standard model Higgs to have a CP-even and CP-odd component, similar to the neutral kaon, allows the CP nature of its interactions to be probed.

6. CP violation in the Higgs sector

As discussed, the standard model in its present state cannot describe all of the physical phenomena observed in the universe. The insufficient scale of CP violation required for a matter dominated universe is one such unexplained phenomenon, and CP violating effects in the Higgs sector remain a possible source of baryogenesis with the discovery of such effects constituting new physics beyond the standard model [47]. The 2012 discovery of the Higgs boson opened a new window into CP physics through study of the CP nature of the Higgs interactions. Here is discussed some of the research to date, with a closer look taken at the Higgs-gauge and top-Higgs Yukawa couplings.

6.1. CP observables

The standard model Higgs is a scalar particle with a definite CP quantum number $J^P = 0^+$. A popular proposed model, the two Higgs doublet model (2HDM), proposes a Yukawa coupling with CP-even (scalar) and CP-odd (pseudo-scalar) components [48]. If observed, an admixture of CP-even and CP-odd states allows for the possibility of CP violation. A pure CP-even or CP-odd Higgs boson would rule out the possibility of CP violation in the Higgs sector.

For the Higgs Yukawa coupling, angular asymmetries between the decays of CP-even and CP-odd states can be exploited to probe the CP nature of the top-Higgs Yukawa coupling. The differences arise from the fact that a CP-odd Higgs boson has a different spin-coupling to the top quarks in the interaction compared to a CP-even Higgs. The different nature of the couplings affects the azimuthal angle between decay products, a measurable effect.

In a 2017 phenomenological report into probing the CP nature of the top-Higgs Yukawa coupling, many possible observables were tested with samples with CP-even and CP-odd components (2HDM) [49]. The report identified two observables sensitive to the CP nature of the top-Higgs Yukawa coupling, $\beta_{b\bar{b}}\Delta\theta^{\ell h}(\ell^+,\ell^-)$ and b_4. $\theta^{\ell h}(\ell^+,\ell^-)$is defined as the angle between the momentum of the two leptons projected onto the plane perpendicular to the h direction, where h here is either the scalar or pseudo-scalar Higgs boson [50]. $\beta_{b\bar{b}}$ gives the sign of the observable and is given by:

$$\beta_{b\bar{b}} \equiv sgn((\vec{p_b} - \vec{p_{\bar{b}}}) \cdot (\vec{p_{l^-}} \times \vec{p_{l^+}})), \tag{6.1}$$

where $\vec{p_b}$ and $\vec{p_{\bar{b}}}$ are the momentum of the b and $\bar{b}$ tagged jets (from the decay of t and $\bar{t}$ respectively. The distributions of this observable for CP-even and CP-odd cases are shown in figure (6.1), top row. The observable relies on having a dileptonic final state.

The second observable b_4 is defined:

$$b_4 \equiv (p_t^z \cdot p_{\bar{t}}^z)/(|\vec{p_t}| \cdot |\vec{p_{\bar{t}}}|). \tag{6.2}$$

Compared to the first observable, b_4 is more general but requires full reconstruction of the top quark four-momenta. The distributions of this observable for CP-even and CP-odd cases are shown in figure (6.1), bottom row.

For both observables, differences in the expected distributions for CP-even (h = H) and CP-odd (h = A) cases are clearly visible in the plots in figure (6.1). This discriminating power allows for the separation of CP-even and CP-odd events, and for testing of a CP-even and CP-odd admixture.

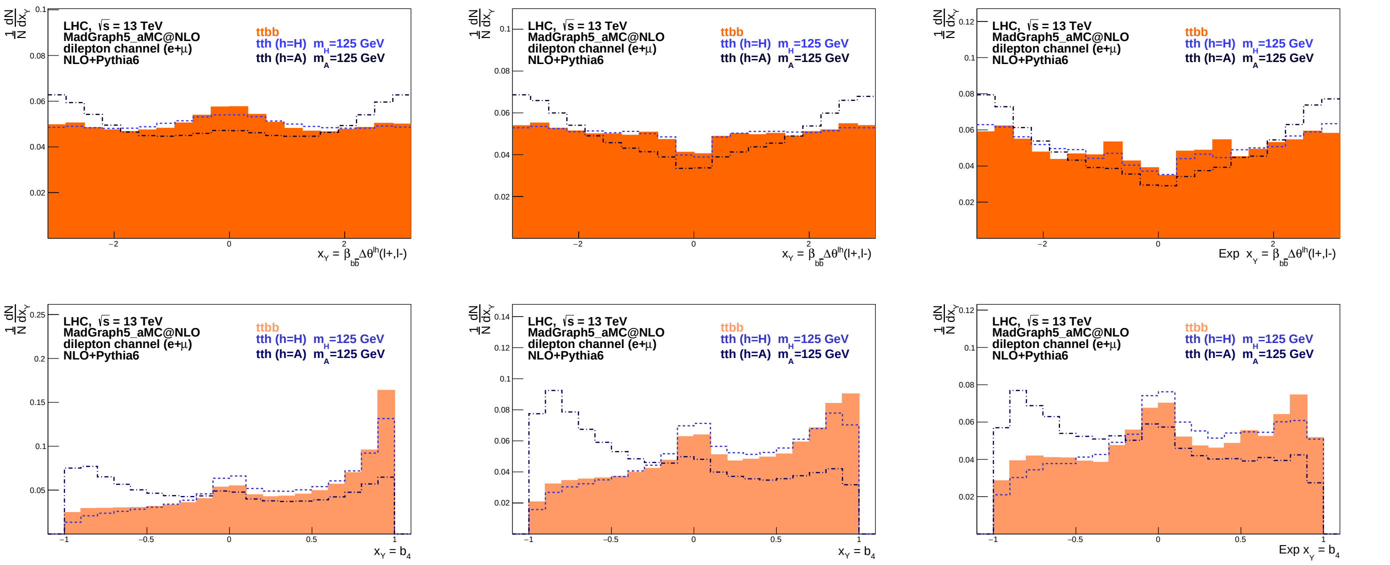


Figure 6.1: $\beta_{b\bar{b}}\Delta\theta^{\ell h}(\ell^+, \ell^-)$ distribution without selection cuts (top left), with selection cuts (top middle) and with selection cuts and full kinematic reconstruction (top right). The b_4 distribution is shown without selection cuts (bottom left), with selection cuts (bottom middle) and with selection cuts and full kinematic reconstruction (bottom right). The dashed line shows the standard model CP-even signal, the dotted-dashed line shows the pure CP-odd signal. The shaded area is the dominant $t\bar{t}b\bar{b}$ background. [49]

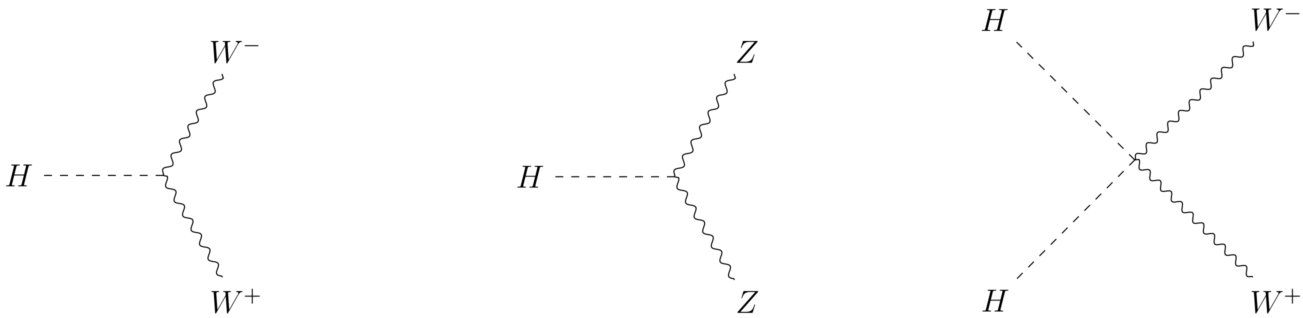


Figure 6.2: Gauge-Higgs vertices. Kinematic reconstruction of the decay products of the gauge bosons provides a window into the CP nature of the Higgs-gauge interaction.

6.2. Higgs-gauge coupling

The Higgs-gauge coupling describes the interaction between gauge bosons and the Higgs boson. Possible Higgs-gauge vertices are shown in figure (6.2). At the LHC, the CP nature of the Higgs-gauge coupling is probed predominantly via vector boson-fusion processes like that shown in figure (6.3). Analyses by ATLAS and CMS have so far yielded results consistent with standard model predictions [51–53]. At first glance disheartening, the results are still in their infancy and dominated by statistical uncertainties.

6.3. Probing the top-Higgs coupling at the LHC

The top-Higgs Yukawa coupling strength impacts the production rates of $t\bar{t}H$ and tH processes, which can be used to probe the CP nature of the coupling. Furthermore, in the presence of CP-mixing in the top Yukawa interaction, the gluon-gluon fusion production rate and $H \to \gamma\gamma$ decay rate are affected

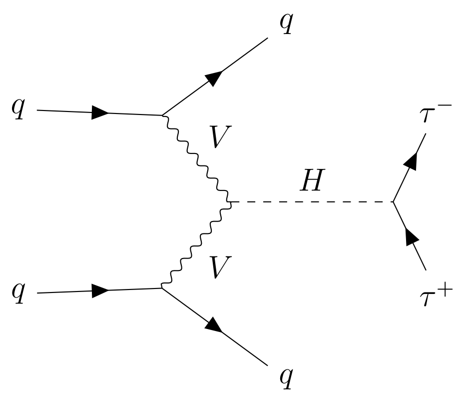


Figure 6.3: Higgs decay to τ pair via vector boson fusion.

[49, 50, 54, 55]. These factors along with the relative strength of the top-Higgs Yukawa coupling (the top quark is the heaviest quark and the coupling is proportional to the fermion mass) make the coupling ideal for investigating the CP nature of the Higgs sector. The top-Higgs coupling vertex is shown in figure (6.4) along with a the production of a top quark pair via a gluon-gluon fusion process, like that found at a hadron collider.

ATLAS and CMS have published analyses studying the top-Higgs coupling through the diphoton decay channel, meaning two of the final state decay products were photons [56, 57]. The analyses built upon the prior observation of the Higgs boson production in association with a top quark pair and the CP properties of the coupling [35, 36]. The basis of each study is an "effective field theory" (modified version of the standard model), wherein the top-Higgs Yukawa coupling has been parametrised by the following effective Lagrangian:

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos\alpha + i\sin\alpha\gamma_5]\psi_t\}H, \tag{6.3}$$

where m_t is the top quark mass, v is the Higgs vacuum value, $\bar{\psi}_t$ and ψ_t are the Dirac spinors, α is the CP-mixing angle, and κ_t is the top Yukawa coupling parameter. A pure CP-odd interaction has $\alpha = \pm\pi/2$, while the standard model CP-even case has $\alpha = 0$, $\kappa_t = 1$.

Monte Carlo event generators take this effective Lagrangian as an input to mimic the interactions happening at the collision point of particle accelerators, such as the LHC. These simulations generate samples for CP-even and CP-odd states that can be used to produce expected values and uncertainty estimation for pure scalar (CP-even) and pure pseudoscalar (CP-odd) hypotheses, or an admixture

Figure 6.4: Higgs-top vertex (left). Using this vertex, the Higgs boson can radiate off of any point along the fermion line of the right diagram.

of the two states.

The greatest challenge for this type of analysis is selecting the signal from the background processes, in this case dominated by $t\bar{t}b\bar{b}$ background. For the ATLAS analysis, a data-driven approach was used to estimate background processes, with additional $t\bar{t}\gamma\gamma$ processes (the final diphoton state was the one analysed) simulated to optimise the event selection. Meanwhile the CMS analysis predominantly used simulated signal and background events to train its discriminants, with the exception of the γ + jets background, which is modelled from a large sample of data events.

To select out the signal processes from background processes, the ATLAS study utilised a Boosted Decision Tree (BDT), a multivariate analysis tool used for classifying data based on input labels such as, for the CP BDT case, the transverse momentum p_t and rapidity η of the diphoton system.

In the ATLAS and CMS analyses, pairs of isolated photon candidates were selected adhering to selection criteria. Events are sorted into leptonic and hadronic channels, depending on their final state decay products. From here, a background BDT discriminant is used to select out signal events from background events.

Once the signal events have been selected from the background events, the CP properties of the top-Higgs Yukawa interaction are tested by comparing the kinematic distribution of the signal to that expected by a pure CP-even or CP-odd hypothesis. For example, after applying the b_4 kinematic variable to data, if the distribution looks similar the dashed line in figure (6.1) (bottom right, after cuts and kinematic reconstruction), this would be indicative of a standard model CP-even Higgs boson. Testing for admixtures can also be done by comparing the kinematic distribution to the expected distribution for the CP-mixing variable α, given in equation (6.3), ranging from the pure CP-even $\alpha = 0$ the pure CP-odd case $\alpha = \pm\pi/2$.

6.4. Constraints set by experiment on CP violation in the Higgs sector

The results of the CP analyses by ATLAS and CMS and shown in figure (6.5). Both analyses disfavour a pure CP-odd Higgs boson, with ATLAS rejecting this hypothesis at 3.9σ and CMS at 3.2σ. ATLAS excludes a CP mixing angle of $|\alpha|$ 43° at a 95% confidence level and CMS constrains a possible CP admixture to $f_{CP}^{Htt} = 0.00 \pm 0.33$ at a 68% confidence level, where $f_{CP}^{Htt} = 0$ is the standard model CP-even hypothesis, $f_{CP}^{Htt} = 1$ is the pure CP-odd hypothesis, and $f_{CP}^{Htt} = 0.72$ is when the CP-even and CP-odd contributions are equal.

The results presented show consistency with standard model predictions and do not suggest any physics beyond the standard model. It is important to note that these results are dominated by statistical uncertainty, which can be remedied through the collection of more data.

7. Discussion

So far there has been no indication that the missing CP violation required in the early universe for baryogenesis lies within the Higgs sector, yet we know that it must be found somewhere. At the time of writing the LHC has just resumed its third run of data taking, meaning the constraints on CP violation in the Higgs sector will be tightened as the statistical uncertainties are reduced. Whether the source of CP violation will be found in the Higgs sector or another sector, such as the neutrino

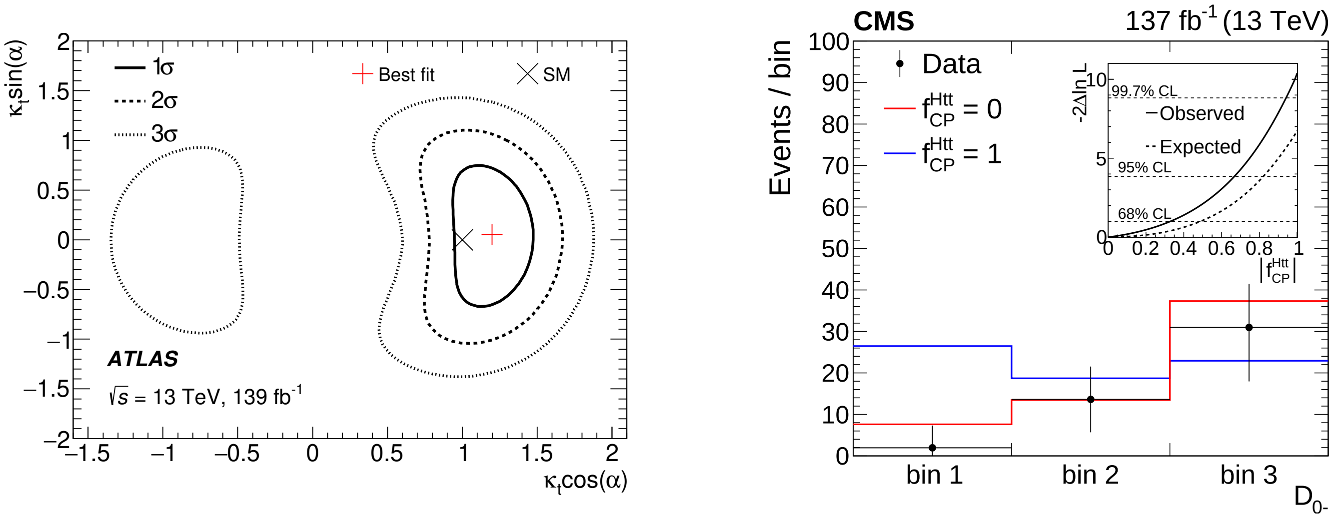


Figure 6.5: Results from the (a) ATLAS [56] and (b) CMS [57] analyses. (a) Two-dimensional contour fits for $\kappa_t cos(\alpha)$ and $\kappa_t sin(\alpha)$. The black cross is the standard model CP-even hypothesis. (b) events binned into three bins of the $\mathcal{D}_0$ discriminant. $f_{CP}^{Htt} = 0$ is the standard model CP-even hypothesis.

sector, remains to be seen.

Although the rate of discovery in particle physics might have slowed down, with collaboration announcements becoming more nuanced and esoteric, many of the frontiers of particle physics still remain largely uncharted and could hold answers to unexplained physical phenomenon. The LHC still has a lot of potential for discoveries beyond the standard model; recent LHCb studies into lepton universality have published evidence lepton universality violation in the decay of b quarks [58]. Other hints at new physics include the 10 year analysis of Tevatron data collected by the CDF collaboration that announced a measurement of the W boson mass with unprecedented precision. Alarmingly, this measurement differs significantly from those measured by other major collaborations and that expected from the standard model [59].

These new results are encouraging and it remains completely plausible that physics beyond the standard model, such as CP violating effects in the Higgs sector, could be unveiled sometime in the near future. Despite the direction that CP violation in the Higgs sector is heading, it is too early to rule out the possibility and research will keeping tightening its constraints until some certainty is reached.

8. Conclusion

The discovery of the Higgs boson marked a considerable milestone for the field of particle physics. So far, the monumental predictive power of the standard model has proved immovable, demonstrated by the experimental findings by ATLAS and CMS of a CP-odd Higgs having been ruled out by 3.9σ and 3.2σ respectively. Despite the severity of these values, statistical uncertainties still dominate the findings and CP violation in the Higgs sector remains a possibility that cannot be ruled out just yet.

References

[1] CMS collaboration, “Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC,” *Phys. Lett. B*, vol. 716, pp. 30–61, 2012. DOI: `10.1016/j.physletb.2012.08.021`. arXiv: `1207.7235 [hep-ex]`.

[2] 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*, vol. 716, pp. 1–29, 2012. DOI: `10.1016/j.physletb.2012.08.020`. arXiv: `1207.7214 [hep-ex]`.

[3] A. D. Sakharov, “Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe,” *Pisma Zh. Eksp. Teor. Fiz.*, vol. 5, pp. 32–35, 1967. DOI: `10.1070/PU1991v034n05ABEH002497`.

[4] J. Shu and Y. Zhang, “Impact of a CP Violating Higgs Sector: From LHC to Baryogenesis,” *Phys. Rev. Lett.*, vol. 111, no. 9, p. 091 801, 2013. DOI: `10.1103/PhysRevLett.111.091801`. arXiv: `1304.0773 [hep-ph]`.

[5] UA1 collaboration, “Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at $\sqrt{s} = 540$ GeV,” *Phys. Lett. B*, vol. 122, pp. 103–116, 1983. DOI: `10.1016/0370-2693(83)91177-2`.

[6] UA2 collaboration, “Observation of Single Isolated Electrons of High Transverse Momentum in Events with Missing Transverse Energy at the CERN anti-p p Collider,” *Phys. Lett. B*, vol. 122, pp. 476–485, 1983. DOI: `10.1016/0370-2693(83)91605-2`.

[7] UA1 collaboration, “Experimental Observation of Lepton Pairs of Invariant Mass Around 95-GeV/c**2 at the CERN SPS Collider,” *Phys. Lett. B*, vol. 126, pp. 398–410, 1983. DOI: `10.1016/0370-2693(83)90188-0`.

[8] UA2 collaboration, “Evidence for $Z^0 \to e^+e^-$ at the CERN $\bar{p}p$ Collider,” *Phys. Lett. B*, vol. 129, pp. 130–140, 1983. DOI: `10.1016/0370-2693(83)90744-X`.

[9] G. Dissertori, “The pre-LHC Higgs hunt,” *Phil. Trans. Roy. Soc. Lond. A*, vol. 373, no. 2032, p. 20 140 039, 2014. DOI: `10.1098/rsta.2014.0039`.

[10] DELPHI collaboration, “The DELPHI detector at LEP,” *Nucl. Instrum. Meth. A*, vol. 303, pp. 233–276, 1991. DOI: `10.1016/0168-9002(91)90793-P`.

[11] OPAL collaboration, “The OPAL detector at LEP,” *Nucl. Instrum. Meth. A*, vol. 305, pp. 275–319, 1991. DOI: `10.1016/0168-9002(91)90547-4`.

[12] ALEPH collaboration, “ALEPH: A detector for electron-positron annnihilations at LEP,” *Nucl. Instrum. Meth. A*, vol. 294, pp. 121–178, 1990, [Erratum: Nucl.Instrum.Meth.A 303, 393 (1991)]. DOI: `10.1016/0168-9002(90)91831-U`.

[13] L3 collaboration, “The Construction of the L3 Experiment,” *Nucl. Instrum. Meth. A*, vol. 289, pp. 35–102, 1990. DOI: `10.1016/0168-9002(90)90250-A`.

[14] Particle Data Group collaboration, "Review of Particle Properties: Particle Data Group," *Phys. Lett. B*, vol. 204, pp. 1–486, 1988. DOI: 10.1016/0370-2693(88)90505-9.

[15] LEP Working Group for Higgs boson searches, ALEPH, DELPHI, L3, OPAL collaboration, "Search for the standard model Higgs boson at LEP," *Phys. Lett. B*, vol. 565, pp. 61–75, 2003. DOI: 10.1016/S0370-2693(03)00614-2. arXiv: hep-ex/0306033.

[16] D0 collaboration, "The D0 Detector," *Nucl. Instrum. Meth. A*, vol. 338, pp. 185–253, 1994. DOI: 10.1016/0168-9002(94)91312-9.

[17] CDF collaboration, "The CDF Detector: An Overview," *Nucl. Instrum. Meth. A*, vol. 271, pp. 387–403, 1988. DOI: 10.1016/0168-9002(88)90298-7.

[18] D0 collaboration, "Observation of the top quark," *Phys. Rev. Lett.*, vol. 74, pp. 2632–2637, 1995. DOI: 10.1103/PhysRevLett.74.2632. arXiv: hep-ex/9503003.

[19] CDF, D0 collaboration, "Updated Combination of CDF and D0 Searches for Standard Model Higgs Boson Production with up to 10.0 fb^{-1} of Data," Jul. 2012. arXiv: 1207.0449 [hep-ex].

[20] CDF, D0 collaboration, "Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron," *Phys. Rev. Lett.*, vol. 109, p. 071 804, 2012. DOI: 10.1103/PhysRevLett.109.071804. arXiv: 1207.6436 [hep-ex].

[21] ATLAS collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider," *JINST*, vol. 3, S08003, 2008. DOI: 10.1088/1748-0221/3/08/S08003.

[22] CMS collaboration, "The CMS Experiment at the CERN LHC," *JINST*, vol. 3, S08004, 2008. DOI: 10.1088/1748-0221/3/08/S08004.

[23] P. W. Higgs, "Spontaneous Symmetry Breakdown without Massless Bosons," *Phys. Rev.*, vol. 145, pp. 1156–1163, 1966. DOI: 10.1103/PhysRev.145.1156.

[24] P. W. Higgs, "Broken Symmetries and the Masses of Gauge Bosons," *Phys. Rev. Lett.*, vol. 13, J. C. Taylor, Ed., pp. 508–509, 1964. DOI: 10.1103/PhysRevLett.13.508.

[25] P. W. Higgs, "Broken symmetries, massless particles and gauge fields," *Phys. Lett.*, vol. 12, pp. 132–133, 1964. DOI: 10.1016/0031-9163(64)91136-9.

[26] F. Englert and R. Brout, "Broken Symmetry and the Mass of Gauge Vector Mesons," *Phys. Rev. Lett.*, vol. 13, J. C. Taylor, Ed., pp. 321–323, 1964. DOI: 10.1103/PhysRevLett.13.321.

[27] B. Martin and G. Shaw, *Particle Physics*, 4th, ser. Manchester Physics Series. Wiley, 2017, ISBN: 9781118911907. [Online]. Available: https://www.wiley.com/en-gb/Particle+Physics%2C+4th+Edition-p-9781118912218.

[28] Particle Data Group collaboration, "Review of Particle Physics," *PTEP*, vol. 2020, no. 8, p. 083C01, 2020. DOI: 10.1093/ptep/ptaa104.

[29] "High-Luminosity Large Hadron Collider (HL-LHC) : Preliminary Design Report," G. Apollinari *et al.*, Eds., Dec. 2015. DOI: 10.5170/CERN-2015-005.

[30] CMS collaboration, "A measurement of the Higgs boson mass in the diphoton decay channel," *Phys. Lett. B*, vol. 805, p. 135 425, 2020. DOI: 10.1016/j.physletb.2020.135425. arXiv: 2002.06398 [hep-ex].

[31] ATLAS collaboration, "Measurement of the Higgs boson mass in the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels with $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector," *Phys. Lett. B*, vol. 784, pp. 345–366, 2018. DOI: 10.1016/j.physletb.2018.07.050. arXiv: 1806.00242 [hep-ex].

[32] ATLAS, CMS collaboration, "Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments," *Phys. Rev. Lett.*, vol. 114, p. 191 803, 2015. DOI: 10.1103/PhysRevLett.114.191803. arXiv: 1503.07589 [hep-ex].

[33] FCC collaboration, "FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3," *Eur. Phys. J. ST*, vol. 228, no. 4, pp. 755–1107, 2019. DOI: 10.1140/epjst/e2019-900087-0.

[34] M. L. Mangano *et al.*, "Measuring the Higgs self-coupling via Higgs-pair production at a 100 TeV p-p collider," *Eur. Phys. J. C*, vol. 80, no. 11, p. 1030, 2020. DOI: 10.1140/epjc/s10052-020-08595-3. arXiv: 2004.03505 [hep-ph].

[35] ATLAS collaboration, "Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector," *Phys. Lett. B*, vol. 784, pp. 173–191, 2018. DOI: 10.1016/j.physletb.2018.07.035. arXiv: 1806.00425 [hep-ex].

[36] CMS collaboration, "Observation of $\mathrm{t\bar{t}H}$ production," *Phys. Rev. Lett.*, vol. 120, no. 23, p. 231 801, 2018. DOI: 10.1103/PhysRevLett.120.231801. arXiv: 1804.02610 [hep-ex].

[37] T. S. Virdee, "Beyond the standard model of particle physics," *Phil. Trans. Roy. Soc. Lond. A*, vol. 374, no. 2075, C. David Garner, Ed., p. 20 150 259, 2016. DOI: 10.1098/rsta.2015.0259.

[38] E. Sather, "The Mystery of the matter asymmetry," *SLAC Beam Line*, vol. 26N1, pp. 31–37, 1996.

[39] D. E. Morrissey and M. J. Ramsey-Musolf, "Electroweak baryogenesis," *New J. Phys.*, vol. 14, p. 125 003, 2012. DOI: 10.1088/1367-2630/14/12/125003. arXiv: 1206.2942 [hep-ph].

[40] C. S. Wu *et al.*, "Experimental Test of Parity Conservation in β Decay," *Phys. Rev.*, vol. 105, pp. 1413–1414, 1957. DOI: 10.1103/PhysRev.105.1413.

[41] J. H. Christenson *et al.*, "Evidence for the 2π Decay of the K_2^0 Meson," *Phys. Rev. Lett.*, vol. 13, pp. 138–140, 1964. DOI: 10.1103/PhysRevLett.13.138.

[42] M. Kobayashi and T. Maskawa, "CP Violation in the Renormalizable Theory of Weak Interaction," *Prog. Theor. Phys.*, vol. 49, pp. 652–657, 1973. DOI: 10.1143/PTP.49.652.

[43] BaBar collaboration, "The BaBar detector," *Nucl. Instrum. Meth. A*, vol. 479, pp. 1–116, 2002. DOI: 10.1016/S0168-9002(01)02012-5. arXiv: hep-ex/0105044.

[44] Belle collaboration, "The Belle Detector," *Nucl. Instrum. Meth. A*, vol. 479, pp. 117–232, 2002. DOI: 10.1016/S0168-9002(01)02013-7.

[45] LHCb collaboration, "The LHCb Detector at the LHC," *JINST*, vol. 3, S08005, 2008. DOI: 10.1088/1748-0221/3/08/S08005.

[46] LHCb collaboration, "Observation of CP Violation in Charm Decays," *Phys. Rev. Lett.*, vol. 122, no. 21, p. 211 803, 2019. DOI: 10.1103/PhysRevLett.122.211803. arXiv: 1903.08726 [hep-ex].

[47] F. U. Bernlochner *et al.*, "Angles on CP-violation in Higgs boson interactions," *Phys. Lett. B*, vol. 790, pp. 372–379, 2019. DOI: 10.1016/j.physletb.2019.01.043. arXiv: 1808.06577 [hep-ph].

[48] G. C. Branco *et al.*, "Theory and phenomenology of two-Higgs-doublet models," *Phys. Rept.*, vol. 516, pp. 1–102, 2012. DOI: 10.1016/j.physrep.2012.02.002. arXiv: 1106.0034 [hep-ph].

[49] S. Amor Dos Santos *et al.*, "Probing the CP nature of the Higgs coupling in $t\bar{t}h$ events at the LHC," *Phys. Rev. D*, vol. 96, no. 1, p. 013 004, 2017. DOI: 10.1103/PhysRevD.96.013004. arXiv: 1704.03565 [hep-ph].

[50] F. Boudjema *et al.*, "Lab-frame observables for probing the top-Higgs interaction," *Phys. Rev. D*, vol. 92, no. 1, p. 015 019, 2015. DOI: 10.1103/PhysRevD.92.015019. arXiv: 1501.03157 [hep-ph].

[51] ATLAS collaboration, "Test of CP Invariance in vector-boson fusion production of the Higgs boson using the Optimal Observable method in the ditau decay channel with the ATLAS detector," *Eur. Phys. J. C*, vol. 76, no. 12, p. 658, 2016. DOI: 10.1140/epjc/s10052-016-4499-5. arXiv: 1602.04516 [hep-ex].

[52] A. V. Gritsan *et al.*, "Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques," *Phys. Rev. D*, vol. 94, no. 5, p. 055 023, 2016. DOI: 10.1103/PhysRevD.94.055023. arXiv: 1606.03107 [hep-ph].

[53] I. Anderson *et al.*, "Constraining Anomalous HVV Interactions at Proton and Lepton Colliders," *Phys. Rev. D*, vol. 89, no. 3, N. A. Graf *et al.*, Eds., p. 035 007, 2014. DOI: 10.1103/PhysRevD.89.035007. arXiv: 1309.4819 [hep-ph].

[54] M. R. Buckley and D. Goncalves, "Boosting the Direct CP Measurement of the Higgs-Top Coupling," *Phys. Rev. Lett.*, vol. 116, no. 9, p. 091 801, 2016. DOI: 10.1103/PhysRevLett.116.091801. arXiv: 1507.07926 [hep-ph].

[55] J. Ellis *et al.*, "Disentangling Higgs-Top Couplings in Associated Production," *JHEP*, vol. 04, p. 004, 2014. DOI: 10.1007/JHEP04(2014)004. arXiv: 1312.5736 [hep-ph].

[56] ATLAS collaboration, "CP Properties of Higgs Boson Interactions with Top Quarks in the $t\bar{t}H$ and tH Processes Using $H \to \gamma\gamma$ with the ATLAS Detector," *Phys. Rev. Lett.*, vol. 125, no. 6, p. 061 802, 2020. DOI: 10.1103/PhysRevLett.125.061802. arXiv: 2004.04545 [hep-ex].

[57] CMS collaboration, "Measurements of $\mathrm{t\bar{t}}H$ Production and the CP Structure of the Yukawa Interaction between the Higgs Boson and Top Quark in the Diphoton Decay Channel," *Phys. Rev. Lett.*, vol. 125, no. 6, p. 061 801, 2020. DOI: 10.1103/PhysRevLett.125.061801. arXiv: 2003.10866 [hep-ex].

[58] LHCb collaboration, "Test of lepton universality in beauty-quark decays," *Nature Phys.*, vol. 18, no. 3, pp. 277–282, 2022. DOI: 10.1038/s41567-021-01478-8. arXiv: 2103.11769 [hep-ex].

[59] CDF collaboration, "High-precision measurement of the W boson mass with the CDF II detector," *Science*, vol. 376, no. 6589, pp. 170–176, 2022. DOI: 10.1126/science.abk1781.