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Higgs CP studies at ATLAS and CMS experiments

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Understanding the properties of CP symmetry of the Higgs boson interactions is one of the most important topics in particle physics today. In the Standard Model, the only source of CP violation comes from CKM phase and the Higgs boson has scalar (CP-even) couplings to SM particles. Current data allow to test these two statements and any CP-odd contribution would be a sign of new physics. The latest results on searches for CP violation in the Higgs couplings to either bosons or fermions are presented here using 13 TeV proton-proton collisions recorded by the ATLAS and CMS detectors at the Large Hadron Collider at CERN. The results are consistent with the SM predictions and a pure CP-odd state is excluded for both couplings to vector bosons and to fermions with 3σ, but admixtures are possible.

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1. Introduction

As the Higgs-boson couplings are measured with greater precision, it becomes possible to explore the charge-parity (CP) properties of its interactions. The Standard Model (SM) predicts that all Higgs boson interactions are CP-conserving (CP-even), and the measurement of even a small CP-violating component in any Higgs-boson coupling would constitute a discovery of physics beyond the SM and would potentially address one of the key open questions in particle physics today: the understanding of the matter-antimatter imbalance in the Universe. CP-violating contributions to the Higgs couplings to vector bosons can only enter via higher-order operators that are suppressed by powers of $1/\Lambda^2$, where Λ is the energy scale of new physics in the effective field theory. However, in the Higgs-fermion interactions, CP-violating terms can enter at the same order as the CP-even terms of the SM and, therefore, such measurements are expected to be more sensitive. Here, the latest experimental probes from the ATLAS [1] and CMS [2] collaborations are discussed.

2. Probing $H\tau\tau$ coupling structure

A measurement of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons, $H\tau\tau$, was carried out by the CMS collaboration using full Run 2 data (137 fb^{-1} at $\sqrt{s}$ = 13 TeV) and by measuring angular correlations between tau lepton-decay products [3]. The Higgs-boson coupling to bosons that enter in the production is assumed to be CP-even. The analysis targets the two most sensitive channels, $\tau_h\tau_h$ (two hadronic tau decays) and $\tau_h\tau_\mu$ (one hadronic and one muon lepton-decay), which are further subdivided depending on the specific τ_h decay modes, including direct decays to a single charged pion as well as the decays to charged and neutral pions via intermediate resonances. Machine learning classifiers are developed to distinguish different τ_h decays, which is essential as they have different CP sensitivity. The CP sensitive variables (ϕ_{CP}) are defined as the angle between the planes spanned by the decay of the τ^+ and τ^-, so the specific definitions depend on the particles in the final state. An example can be seen in Fig. 1-left. Multivariate methods based on neural networks (NN) and boosted decision trees (BDT) are used to provide separation of the Higgs-boson signal from the background. Two-dimensional discriminants are then used to extract the results, where one observable is ϕ_{CP} and the other is the NN/BDT output score. The CP properties of the Yukawa interaction are parametrised in terms of an effective mixing angle $\phi_{\tau\tau}$, defined as $\phi_{\tau\tau} = \arctan(\kappa_\tau/\kappa_\tau)$, where $\bar{\kappa_\tau}$ and κ_τ are the reduced (relative to the SM Higgs-tau Yukawa coupling) CP-odd and CP-even couplings respectively. $\phi_{\tau\tau} = 0°$ would imply a CP-even coupling, $\phi_{\tau\tau} = 90°$ to a CP-odd boson, and any intermediate value to a CP-violating admixture. The value $\phi_{\tau\tau}$ is extracted by a binned maximum likelihood fit to the distribution of ϕ_{CP} observable (see Fig. 1-right) and is found to be $4\pm17°(\pm36°)$ at the 68% (95%) confidence level. The hypothesis of a pure CP-odd pseudoscalar boson is rejected with 3.2 (2.3) observed (expected) standard deviations. The driving uncertainties are of statistical nature, implying that the precision of this measurement will increase with more collision data.

3. Probing the effective Hgg coupling in $H \to WW^* \to e\nu\mu\nu$+ 2 jets

A study conducted by the ATLAS experiment (36 fb^{-1} at 13 TeV) using the $H \to WW^* \to e\nu\mu\nu$ decay mode targets Higgs boson production via gluon fusion in association with two jets and con-

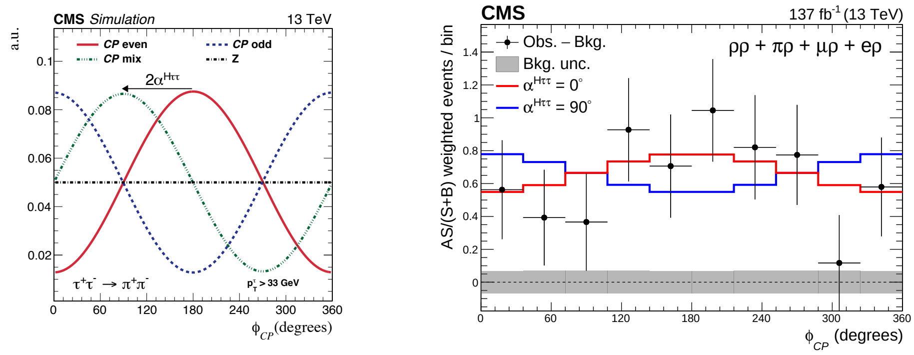

Figure 1: Left: The distribution of $\phi_{\rm CP}$ for a decaying scalar (CP-even, blue), pseudoscalar (CP-odd, green), a maximal mixing angle of 45° (CP-mix, red) and a Z vector boson (black). Right: The $\phi_{\rm CP}$ distribution for the sum of the three most sensitive channels for data (black), the CP-even prediction (blue), and the CP-odd hypothesis (green). The data clearly favour the CP-even hypothesis [3].

strains the CP properties of the effective Higgs-gluon vertex, Hgg [4]. The Higgs-boson coupling to W bosons, HWW, which enters in the decay, is assumed to be CP-even as predicted by the SM. Events with two opposite-sign different-flavour leptons, at least two jets and no b-jets are selected. Additional cuts on the kinematics of the dilepton system and separation between the jets are applied. Machine learning tools are used to further separate signal from backgrounds. The CP discriminant variable is the signed azimuthal angle difference $\Delta\Phi_{jj}$ between the two leading jets: $\Delta\Phi_{jj} = \phi_{j_1} - \phi_{j_2}$ if $\eta_{j_1} > \eta_{j_2}$ and $\Delta\Phi_{jj} = \phi_{j_2} - \phi_{j_1}$ otherwise (see Fig. 2-left). $\Delta\Phi_{jj}$ is probed in various phase space regions (defined based on the BDT output score and $\Delta\eta_{jj}$). The distribution for all those regions combined is shown in Fig. 2-right. The ratio of the CP-odd to CP-even coupling strength scale factors of the effective Higgs-gluon vertex was constrained to $\kappa_{Agg}/\kappa_{Hgg} = 0.0 \pm\ 0.4(\text{stat}) \pm\ 0.3(\text{syst})$, using both the shape and rate information. The result is limited by data statistics and the dominant systematic uncertainties are those associated to the modelling of the main backgrounds ($t\bar{t}$ and WW) and ggF signal. If only shape information is used, the analysed data (only a fraction of Run 2 dataset) are not sensitive enough.

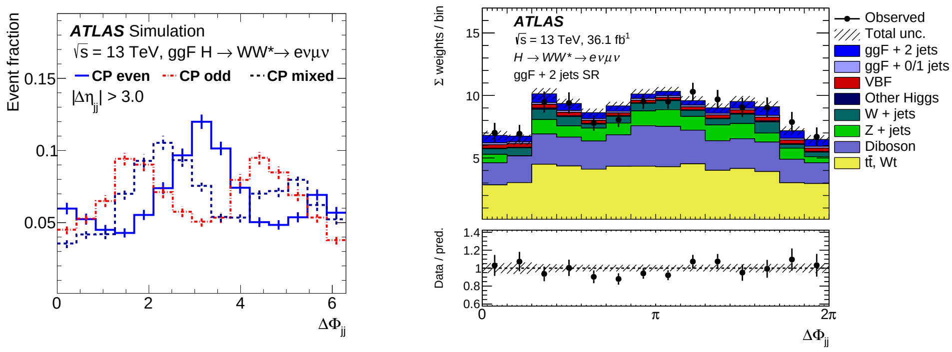

Figure 2: Left: Distributions of the signed $\Delta\Phi_{jj}$ observable shown for a CP-even, (blue), CP-odd (red) and CP-mixed (purple) benchmark models in ggF + 2 jets production. Right: The weighted $\Delta\Phi_{jj}$ post-fit distribution in the ggF + 2 jets signal region, with signal and background yields fixed from the fit to $\kappa_{Agg}/\kappa_{Hgg}$ using shape and rate information. Data-to-simulation ratios are shown at the bottom of the plot [4].

4. $H \rightarrow 4\ell$ to probe Hgg, HVV and Htt couplings

The kinematic effects in the Higgs to four-lepton decay $H \rightarrow VV^* \rightarrow 4\ell$ and its production in association with two jets, a vector boson, or top quarks have been analyzed by the CMS experiment using full Run 2 dataset to test Hgg, HVV and Htt interactions [5]. Each production mode is identified using its kinematic features, and events are assigned to corresponding categories. Two categorization schemes are employed, one targeting Htt and Hgg and the other targeting HVV anomalous couplings. Within each category, the matrix element likelihood approach (MELA) is used to construct CP sensitive observables. The discriminants use a complete set of mass and angular input observables. Two types of discriminants are defined for either the production, the decay, or the full production + decay process: i) to separate a "signal" from an alternative model (e.g. other production modes, background or other Higgs-boson coupling model); ii) the interference between the two model contributions (eg. CP-even/odd). A maximum likelihood fit allows a simultaneous measurement of up to five HVV, two Hgg and two Htt couplings. Some of them are shown in Fig. 3. An interpretation of the loop contribution is made with and without an assumption of top quark dominance. In both cases, combination with the CP sensitive measurement of the Htt coupling in the $t\bar{t}H/tH$ processes allows either simultaneous or separate measurements of the two effective point-like Hgg couplings and the two Htt couplings. To improve the constraints on Htt, the results are combined with those in the $H \rightarrow \gamma\gamma$ channel.

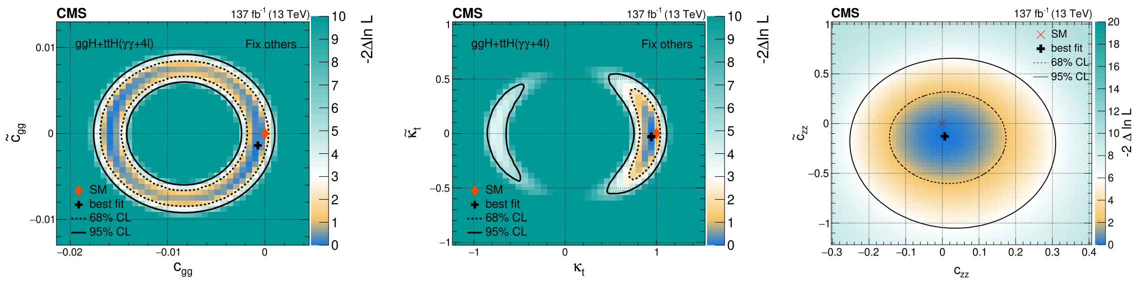

Figure 3: Results of the measurement of the Higgs boson's interactions with gluons (left), top quarks (middle) and vector bosons (right). The x (y) axis show the CP-even (CP-odd) contributions [5].

5. Summary

Understanding the Higgs boson's CP properties is a crucial aspect in particle physics today. ATLAS and CMS have set limits on CP anomalous couplings in the Higgs interactions with vector bosons, gluons and fermions. Results are limited by data statistics and consistent with the SM. Purely CP-odd fermionic and bosonic Higgs couplings are excluded, but admixtures are still possible.

References

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