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Extended scalar sectors at the LHC

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Extensions of the scalar sector of the Standard Model (SM) can provide the needed new sources of CP violation. The ATLAS and CMS collaborations have just started probing C-even CP violating neutral Higgs-fermion Yukawa couplings of the top quark and of the tau lepton. Signals of P-even CP violation, are purely bosonic, and rely on the simultaneous observation of three processes, involving at least one extra scalar, still to be discovered. Even without direct observation of a new scalar, the most general triple Z-boson vertex has a P-even CP-violating term that is nonzero in CP-violating extensions of SM. The three processes involving the new scalars, give a non-zero contribution to this form factor. Hence, there is potential for detecting loop-induced P-even, CP-violating phenomena at the LHC even if the kinematics do not allow for direct detection.

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1. Introduction

The Higgs boson of the Standard Model (SM) is a CP-even scalar. However, the complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix makes such a statement only true to the extent that CP-violating observables in processes involving the Higgs boson are small enough to be neglected. There are a number of reasons to discuss CP violation in the context of Higgs physics. First, any deviation of the 125 GeV Higgs couplings from the SM predictions may hint to an extended Higgs sector. Second, the need for extra sources of CP violation is certainly one of the main motivations to have an extended scalar sector. In fact it is one of the Sakharov's [1] conditions that sets the stage for the observed matter-antimatter asymmetry of the Universe. Finally, it can be that nature just decided to add extra families to mimic the case of fermions and gauge bosons.

I will discuss three main topics related with CP violation and its measurement: the one with origin in P violation, the one that comes from C violation, and the one that can only be seen via quantum corrections. Although the discussion applies to many CP-violating extension of the scalar sector of the SM, I will use as benchmark model the simplest extensions of the SM that allow for this type of phenomena, the complex 2-Higgs doublet model (C2HDM).

2. CP violation from P violation

We start by noting that the current $\bar{f} f$, where f is a fermion, is C-even and P-even while $\bar{f}\gamma_5 f$ is C-even and P-odd. Therefore a Lagrangian with a Yukawa term of the form

$$h_i \bar{f}(a + ib\gamma_5) f \,, \tag{1}$$

where h_i is a spin zero particle, is a CP-violating Lagrangian. Since in a renormalisable model with only integer spin particles, they can all be taken as P-even, this can be seen as a C-even CP-violating interaction. These are present in the Lagrangian already at tree-level in models such as the C2HDM. The C2HDM [2–5] is an extension of the 2HDM first proposed by Lee in 1973 [6] to provide an extra source of CP violation via spontaneous symmetry breaking. Its potential is invariant under the $\mathbb{Z}_2$ symmetry $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$, softly broken by dimension two terms and can be written as

$$\begin{aligned} V_{\rm C2HDM} = {} & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + H.c. \right] . \end{aligned} \tag{2}$$

with m_{12}^2 and λ_5 complex. The $\mathbb{Z}_2$ symmetry is introduced in the model in order to avoid tree-level flavour-changing neutral currents mediated by the neutral scalar. When extended to the fermions we can build four different types of models as defined in Tab. 1. In the C2HDM, the three neutral Higgs bosons mix, resulting in three neutral Higgs mass eigenstates h_i ($i = 1, 2, 3$) with no definite CP quantum number and are ordered as $m_{h_1} \leq m_{h_2} \leq m_{h_3}$. The rotation matrix diagonalising the neutral Higgs sector can be parametrised in terms of three mixing angles α_i ($i = 1, 2, 3$). We also define $\tan\beta = \frac{v_2}{v_1}$ and $v = \sqrt{v_1^2 + v_2^2}$ where v is the SM VEV, $v \approx 246$ GeV.

The a and b in eq. (1) are functions of α_i and $\tan\beta$ in the C2HDM. All Yukawa couplings need to be measured because it is possible to have independent a and b couplings. In fact, it is possible

	u-type	d-type	leptons	Q	u_R	d_R	L	l_R
type I	Φ_2	Φ_2	Φ_2	+	−	−	+	−
type II	Φ_2	Φ_1	Φ_1	+	−	+	+	−
flipped (FL)	Φ_2	Φ_1	Φ_2	+	−	−	+	+
lepton-specific (LS)	Φ_2	Φ_2	Φ_1	+	−	+	+	−

Table 1: Four left rows: Yukawa types of the $\mathbb{Z}_2$-symmetric 2HDM, stating which Higgs doublet couples to the different fermion types. Five right columns: Corresponding $\mathbb{Z}_2$ assignment for the quark doublet Q, the up-type quark singlet u_R, the down-type quark singlet d_R, the lepton doublet L, and the lepton singlet l_R.

to have a Higgs that behaves approximately as a pseudoscalar in its coupling to to τ leptons (type LS) or b quarks (type II) while behaving as a scalar in the couplings to the top quarks [7].

Two Yukawa couplings were already probed at the LHC. The top Yukawa via the production process $pp \to t\bar{t}h_{125}$ and $h_{125} \to \gamma\gamma$ [8, 9] and the τ Yukawa [10] using its decay products. The results are presented in terms of a CP-violating mixing angle defined as $\theta \equiv \arctan(b/a)$, where a and b are given in eq. (1). The purely CP-odd hypothesis was excluded at the level of 3.9 standard deviations, and an observed (expected) exclusion upper limit at 95% CL was obtained for the mixing angle of $\theta = 43°$ $(63°)$. Using data collected at $\sqrt{s} = 13$ TeV (with an integrated luminosity of 137 fb^{-1}), the CMS Collaboration [10] has recently measured the CP mixing angle of the tau lepton, $\theta = 4° \pm 17°$, while setting an observed (expected) exclusion upper limit of 36° (55°).

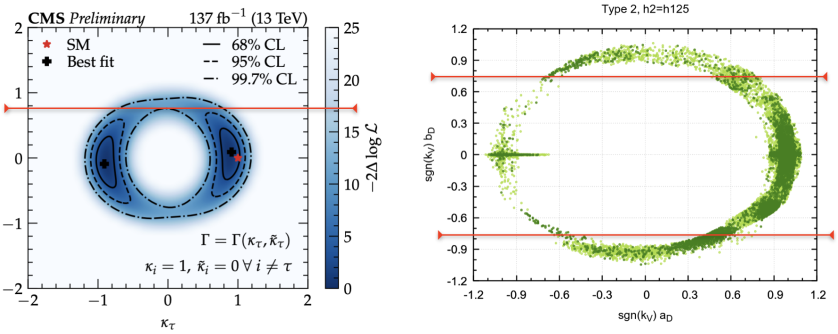

Figure 1: Left: plot from [10] where the exclusion contours for the tau Yukawa CP-odd vs. CP-even couplings are shown. Right: allowed parameter space in the same frame for a type 2 C2HDM; the points shown have passed the most relevant experimental and theoretical constraints including the latest EDM result [11]. The red lines show the exclusion coming from the 95 % C.L. contour.

An interesting and somehow unexpected sign of CP violation is to have one Yukawa almost scalar-like (for instance the top quark one) and the other almost pseudoscalar-like (the tau lepton in type LS or the b-quark one in type II). In figure 1 we present in the right plot the allowed CP-even and CP-odd components of the tau Yukawa when all relevant constraints are taken into account including the latest EDM result [11]. It is clear from the plot that a scenario with a pure CP-odd tau Yukawa was still possible before the LHC search presented on the left plot. A red line was drawn to indicate the 95 % C.L. exclusion contour that is reflected on the right plot (the corresponding two red lines). It is important to point out that this is a clear scenario where the LHC direct measurements yield better constraints than the electron EDM measurements.

3. CP violation from C violation

Let us now discuss P-even, CP-violating interactions (a more detailed discussion can be found in [12]). We will just discuss an example of this phenomena, and refer the reader to previous studies [13–17] where other combinations of vertices were considered. This particular scenario involves the coupling of the Z boson to a pair of neutral scalars h_i via the Zh_ih_j vertex ($i < j$). Since the pair of scalars that couples to a spin-one boson has relative orbital angular momentum equal to one, it implies that h_ih_j must be a CP-odd state. Hence, observation of the three combinations of Zh_ih_j for $i < j$ signals CP violation. Experimentally, these couplings can be probed by observing the three decays $h_3 \to h_2Z$, $h_3 \to h_1Z$ and $h_2 \to h_1Z$. As shown in Refs. [15, 17, 18], the three scalar decays, if kinematically allowed, would be visible at future LHC runs in a significant portion of the parameter space. All other combinations that are a sign of P-even CP violation can be found in [12]. There is also the possibility of having the same combination of vertices at the production level. However, to distinguish the different channels one would need a high-energy lepton collider [12].

4. CP violation from loops

An indirect way to detect the presence of CP violation is to probe the loop contributions to the triple Z form factor [19]. The Lorentz structure of this vertex (with all momenta pointing into the vertex) has a P-even CP-violating term of the form

$$\Gamma_V^{\alpha\beta\mu}(q,\bar{q},P) \supset i f_4^V \left(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}\right). \tag{3}$$

This form factor is generated by the bosonic sector of the extended Higgs sector provided that the scalar potential and/or vacuum is CP-violating. There are calculations of f_4 for the C2HDM [19, 20], for a CP-violating 3-Higgs doublet model [21], and for a model with two Higgs doublets and a singlet [22]. For this last scenario the CP-violating sector is a dark matter sector which would make its detection particularly interesting. In fact, such models cannot be probed by any direct detection method. The observation of a nonzero value of f_4 would signal the existence of P-even CP violation. And this is true even for a completely dark CP-violating sector.

One should note however that the maximal values for f_4 are still an order of magnitude away from the experimentally measured values [23, 24]. Future projection for the measurement f_4 can be found in Ref. [25] for the HL-LHC and in Ref. [26] for the International Linear Collider (ILC).

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