What tell us LHC data about Higgs boson parity

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Recently CMS and ATLAS announced that they had measured the Higgs boson parity.

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**, 081803 (2013); arXiv:1212.6639v2 [hep-ex]; Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV. *Phys. Rev.* **D 92**, 012004 (2015); arXiv:1411.3441 [hep-ex].

The ATLAS Collaboration.Determination of spin and parity of the Higgs boson in the $WW^* \to e\nu\mu\nu$ decay channel with the ATLAS detector. *Eur. Phys. J.* **C75**, 231 (2015); arXiv:1503.03643: Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector, *Eur. Phys. J.* **C**; arXiv:1506.05669 [hep-ex].

Their detailed conclusions are more cautious

They studied correlations in the momentum distributions of leptons produced in decays $h \to ZZ^* \to (\ell_1\bar{\ell}_1)(\ell_2\bar{\ell}_2)$ or $h \to WW^* \to (\ell_1\nu)(\ell_2\nu)$ with leptons $\ell = e,\ \mu$.

This approach was initiated by the proposals of S.Y. Choi, D.J. Miller, M.M. Muhlleitner and P.M. Zerwas, *Phys. Lett.* **B 553**, 61 (2003); arXiv:hep-ph/0210077; C. P. Buszello, I. Fleck, P. Marquard, J. J. van der Bij, *Eur. Phys. J.* **C32**, 209 (2004); arXiv:hep-ph/0212396.

In fact, these results allow to determine parity for a small class of models only. For the majority of models the used approach provides no information on Higgs parity.

Note that

one can speak about value of Higgs parity if it is either CP even or CP odd. In the general case of CP violation the value of Higgs parity is indefinite. In different interactions CP-even and CP-odd contributions can be different.

The SM Higgs boson is P-even. The problem of measuring its parity appears only in the extended models of the Higgs sector (beyond Standard Model – BSM). One can divide such models into two groups.

(1) Models with single scalar like in SM, BSM sector contains no pseudoscalars, possible P (or CP) violating interactions, supplementing SM produce admixture of P-odd state in the decays of Higgs boson. It can be treated as P-odd admixture of Higgs boson.

(2) Many other models are discussed as possible candidates for BSM physics. Their common feature is the existence of additional particles similar to a Higgs boson – both scalars and pseudoscalars with their possible mixing. Examples – Two Higgs Doublet Model (2HDM) with particular case – MSSM, triplet models, etc.

The mentioned results of CMS, ATLAS are valid only for models of the first group.

1-st group of models

In the SM the interaction of Higgs boson with gauge bosons comes from a kinetic term of the Lagrangian $D^\mu\phi^* D_\mu\phi$. The electroweak symmetry breaking (EWSB) gives expansion of ϕ in the form $\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} G^+ \\ v+h+iG^0 \end{pmatrix}$, where $v = 246$ GeV is v.e.v. of the Higgs field, $G^0, G^\pm$ are components of the Goldstone mode.

After substitution of this expansion terms $\propto v^2$ give masses of W, Z and terms $\propto v$ give the interactions hWW and hZZ, in particular

$$(\bar{g}v)\, h\ Z^\mu Z_\mu \qquad .$$

The BSM interactions in this model can produce (in some cases – via radiative corrections) new terms in the effective Lagrangian of the form $\Delta L = \frac{h}{v}(A\, Z^{\mu\nu}Z_{\mu\nu} + B\,\varepsilon_{\mu\nu\alpha\beta}Z^{\alpha\beta}Z^{\mu\nu})$.

The term with B describes a pseudoscalar contribution in the observed process. The CMS, ATLAS data show that this contribution is small. Together with the measured SM-similar cross sections for Higgs observation, it allows to write that the pseudoscalar component of Higgs is absent or small.

This is true only if we limit ourselves to models with a single SM-like Higgs boson – group (1).

2-nd group of models

The simplest example – the widely discussed two-Higgs-doublet model (2HDM), including its particular case of the Higgs sector of MSSM. In the 2HDM the basic Higgs doublet is supplemented by a second scalar doublet. The kinetic term is a sum of two terms, similar to that shown above. The EWSB with standard decomposition for neutral components like the SM case $\phi_i^0 = (v_i e^{i\xi_i} + \zeta_i + i\eta_i)/\sqrt{2}$ gives four neutral fields $\zeta_{1,2}$, $\eta_{1,2}$ (where $v_{1,2}$ are v.e.v.'s of the fields ϕ_1 and $|v_1|^2 + |v_2|^2 = v^2$). One linear combination of $\eta_{1,2}$ gives a neutral component of the Goldstone field G^0, the orthogonal linear combination of η_i is denoted by $\tilde{\eta}$. In the CP-conserving case a linear combination of the fields ζ_i forms two scalar Higgses h and H, while $\tilde{\eta}$ describes a pseudoscalar Higgs A.

In the CP-violating case the fields ζ_i and $\tilde{\eta}$ are mixed, forming three Higgs fields h_a, having no definite P-parity. We denote the observed Higgs boson as h_1. The value of scalar–pseudoscalar mixing for h_1 can be either small or large (with limitations that appear beyond the Higgs sector)

— weak or strong CP violation.

The interaction of h_a with Z comes from a kinetic term in precisely the same way as in SM and can be written as $g^Z_{SM} \sum_a \chi^V_a h_a Z^\mu Z_\mu$.

In this main approximation the $h_a ZZ$ interactions are independent on P-parity of h_a (only the "P-even part of h_a"interacts with Z). The study of processes $h \to ZZ^* \to (\ell_1 \bar{\ell}_1)(\ell_2 \bar{\ell}_2)$ or $h \to WW^* \to (\ell_1 \nu)(\ell_2 \nu)$ do not allow to draw any conclusions about the Higgs boson parity.

In the radiative corrections small terms like $\varepsilon_{\mu\nu\alpha\beta} Z^{\alpha\beta} Z^{\mu\nu}$ can appear. The CMS–ATLAS data support this smallness.

Benchmark examples.

The identical values of the cross sections $gg \to h \to \gamma\gamma$ and $gg \to h \to ZZ$ can be obtained both in SM and in the strongly CP-violating case with suitable choice of parameters. (This opportunity was overlooked in many analyses.)

We use relative couplings, determined for the neutral Higgs bosons h_a with mass M_a and for the charged Higgs bosons $H^\pm$ with mass $M_\pm$:

$$\chi_a^P = \frac{g_a^P}{g_{\text{SM}}^P} \;\; (P = V\,(W,Z), q = (t,b,...))\,, \;\; \chi_a^\pm = \frac{g(H^+H^-h_a)}{2M_\pm^2/v}\,.$$

Using well-known equations for the two-photon and two-gluon widths, we found sets of parameters giving SM-like values for the observed quantities

$$\frac{\sigma(gg \to h_1 \to \gamma\gamma)}{\sigma(gg \to h \to \gamma\gamma)_{SM}} = 1, \quad \frac{\sigma(gg \to h_1 \to ZZ)}{\sigma(gg \to h \to ZZ)_{SM}} = 1, \quad \chi_1^t = 1\,.$$

Two benchmark sets of suitable parameters:

(I) $\chi_1^V = 0.9, \quad \chi_1^\pm = 0.4,$ $Re(\chi_1^t) = 0.9,\ Im(\chi_1^t) = 0.43\,;$	(II) $\chi_1^V = 0.8, \quad \chi_1^\pm = 1.4,$ $Re(\chi_1^t) = 0.74,\ Im(\chi_1^t) = 0.67$

The couplings χ_a^V obey a sum rule $\sum(\chi_a^V)^2 = 1$. Therefore, in case (I) the sum $(\chi_2^V)^2 + (\chi_3^V)^2 = 0.19$, which allows to have $\chi_2^V \approx \chi_3^V \approx 0.3$ (the admixture of the P-odd to P-even components of the Higgs about 0.3). In case (II) the sum $(\chi_2^V)^2 + (\chi_3^V)^2 = 0.36$, which allows to have $\chi_2^V \approx \chi_3^V \approx 0.4$ (the admixture of the P-odd to P-even components of the Higgs about 0.5).

These examples show that a big P-odd admixture in the observed Higgs boson is compatible with SM-like values for many observed rates.

Summary

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The current data give no information about the observed Higgs boson parity in the general case.

However, they can be used for obtaining limitations of parameters separating BSM models.

The signal of indefinite P-parity of the Higgs boson can be obtained at LHC relatively soon in the observations $h_1 \to \tau\bar{\tau}$ and, perhaps, in $h_1 t\bar{t}$ production.

The value of $h_1 WW$ coupling, measurable in the experiments with W fusion, will be very important for the problem considered. If it is found that $\varepsilon^V = (1 - (\chi_1^V)^2) \ll 1$, then the P-odd admixture of the observed Higgs will be $\leq \sqrt{\varepsilon^V}$.