Spherical Parametrization of the Higgs Boson Candidate

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The latest results from the ATLAS and CMS experiments at the CERN Large Hadron Collider unequivocally confirm the existence of a resonance X with mass near 125 GeV which could be the Higgs boson of the standard model. Measuring the properties (quantum numbers and couplings) of this resonance is of paramount importance. Initial analyses by the LHC Collaborations disfavor specific alternative benchmark hypotheses, e.g., pure pseudoscalars or gravitons. However, this is just the first step in a long-term program of detailed measurements. We consider the most general set of operators in the decay channels X → ZZ, WW, Zγ, γγ, and derive the constraint implied by the measured rate. This allows us to provide a useful parametrization of the orthogonal independent Higgs coupling degrees of freedom as coordinates on a suitably defined sphere.

Introduction.—The determination of the spin J and parity P of the putative Higgs boson [1] is of paramount importance. The observed decay to γγ [2] already excludes the case of J = 1 by the Landau-Yang theorem [3]. Spin discrimination and coupling measurements are achieved by studying kinematic correlations of the final state objects, generally leptons. An optimal way of incorporating all available information is through the matrix element method [4–7]. Initial results from ATLAS [8] and CMS [9,10] strongly disfavor JP = 0−, as well as JP = 2+ with gravitonlike couplings. These results represent an important first foray into the general parameter space of generic boson couplings.

In this Letter, we provide a theoretical framework for spin and coupling measurements in full generality, without theoretical prejudice toward specific benchmarks. In contrast to recent global fits of Higgs couplings [11,12], our approach is geared toward a more model independent measurement in a single channel, including all relevant operators and utilizing all available kinematic information. For concreteness and simplicity, we consider the example of a spin-zero X resonance, decaying to four leptons through two intermediate Z bosons [13–16], though our approach can be readily extended to other spins and final states. The complete measurement of the X couplings in full generality will provide insights into the nature of electroweak symmetry breaking and may offer the first glimpses of physics beyond the standard model (SM).

Effective theory.—In what follows, we will consider a spin-zero state X. In general, X has no definite CP properties, and can be considered as a linear combination of some CP-even state H and some CP-odd state A [12]:

\[ X = H \cos \alpha + A \sin \alpha. \]  

In the special case of \( \alpha = 0 \), X is a pure JP = 0+ scalar, as predicted in the standard model, while for \( \alpha = \pm \pi/2 \), X is a pure pseudoscalar with JP = 0−.

The X couplings to two gauge bosons (e.g., ZZ) can be classified according to their symmetries in the CP-eigenstate basis (H, A). Three types of terms are possible:

\[
\mathcal{L} \equiv - \frac{M_Z^2}{v} H Z^\mu Z^\nu f_{\mu \nu}^{(H)} - \frac{1}{2} F_{\mu \nu}^{\mu \nu} f_{\mu \nu}^{(H)} f_{\mu \nu}^{\rho \sigma} F^{\rho \sigma} - \frac{1}{2} A F_{\mu \nu}^{\mu \nu} f_{\mu \nu}^{(A)} F^{\rho \sigma},
\]  

where Fμν is the Z-boson field strength tensor, \( M_Z = 91.1876 \) GeV is the Z-boson mass, \( v = 246 \) GeV is the electroweak scale, and \( f_{\mu \nu}^{(H)} \) and \( f_{\mu \nu}^{(A)} \) are (in general, momentum-dependent) form factors, which, from the effective theory point of view, should be thought of as infinite series expansions in terms of some new physics scale \( \Lambda \). Let us discuss each one in turn.

The form factor \( f_{\mu \nu}^{(H)} \) describes interactions of the CP-even component H that necessarily violate SU(2) gauge invariance. Expanding in powers of \( \Lambda^{-1} \), one obtains

\[
f_{\mu \nu}^{(H)} = g_1 \delta_{\mu \nu} + \frac{g_5}{\Lambda^2} \left( \tilde{\partial}_{\mu} \tilde{\partial}_{\nu} + g_{\mu \nu} \tilde{\partial}^\rho \tilde{\partial}^\rho \right) + \frac{g_6}{\Lambda^4} g_{\mu \nu} (\tilde{\partial} + \tilde{\partial}) + O\left(\frac{1}{\Lambda^6}\right)
\]  

(3)

where \( g_i \) are dimensionless coupling constants, and the derivative operator \( \tilde{\partial} \) (\( \tilde{\partial} \)) acts on the Z field to its left (right). Equation (3) does not include terms containing \( \tilde{\partial}^\mu Z_\mu \), which vanish in the Lorenz gauge.

The second class of CP-even couplings, described by the form factor,
may respect SU(2) gauge invariance, if $H$ is a SM singlet. Note that terms of this sort could be generated by a $(\partial_\mu \partial_\nu - g_{\mu \nu} \partial^\rho \partial_\rho)$ term in Eq. (3), which explains the absence of such a term there. Finally, the couplings of the $CP$-odd component $A$ are given by

$$f_{\mu \nu \rho \sigma}^{(A)} = \frac{g_A}{2\Lambda} \varepsilon_{\mu \nu \rho \sigma} + O\left(\frac{1}{\Lambda^4}\right)$$

(5)

and may be SU(2) gauge invariant as well, if $A$ is a SM singlet. However, we do not make any assumptions about the SU(2) quantum numbers of $H$ and $A$; the terms in Eqs. (4) and (5) will also violate SU(2) gauge invariance if $H$ or $A$ (respectively) transform under SU(2).

We note that the $g_5$ and $g_6$ terms in Eq. (3) are typically omitted in the literature. The contributions to the $X \rightarrow ZZ$ amplitude resulting from the $\square + \Box$ and $\partial^\rho \partial_\rho$ terms are proportional to $M_X^2 + M_Z^2$ and $M_X^2 - M_Z^2$, respectively, where $M_X$ is the mass of the resonance and $M_Z$ and $M_{X_2}$ are the invariant masses of the two $Z$ bosons (in the usual convention where $M_{X_2} > M_Z$). Thus, if both $Z$ bosons were on shell, the contribution from such terms would be essentially constant and therefore could be absorbed into a redefinition of $g_1$. However, in the case of interest where $M_X = 125$ GeV, one or both of the $Z$'s are off shell and $M_{X_1}$ and $M_{Z_2}$ vary from event to event. Thus, strictly speaking, the $g_5$ and $g_6$ terms cannot be absorbed into $g_1$, though their effects (relative to $g_1$) are expected to be rather small, due to the additional $\Lambda^2$ suppression.

It appears that a general analysis of the couplings of the Higgs boson candidate would have to include at the very minimum the terms identified in Eqs. (3)–(5), and perhaps even the higher dimensional operators $\sim \Lambda^{-4}$, $\Lambda^{-5}$, $\ldots$, which were not explicitly listed. Such an analysis may indeed be desirable at some point in the future, when significantly more data will have been accumulated by the LHC experiments. However, there are strong theoretical and experimental motivations for making certain simplifying assumptions for analyses in the immediate future.

First, all experimental evidence so far suggests that the new physics scale $\Lambda$ is high compared to $v$. Second, consistency of the effective theory description requires that $\Lambda$ be sufficiently removed from the relevant experimental energy scale. Finally, the higher dimensional nature of the $1/\Lambda$ couplings suggests a radiative origin and hence suppressions by loop factors. It is therefore reasonable to expect that the higher order terms $g_3$, $g_5$, $g_6$, etc., in the expansions, Eqs. (3)–(5), are negligible relative to the corresponding leading order couplings $g_1$, $g_2$, and $g_4$.

At the same time, the relative size of the leading terms $g_1$, $g_2$, and $g_4$ is a priori unknown. For example, the $g_2$ and $g_4$ terms are equally suppressed by $\Lambda$, and may both preserve gauge invariance; thus, it is difficult to argue that one should be preferred over the other. Similarly, we do not know the extent to which $H$ is involved in breaking SU(2) gauge invariance, and hence we cannot simply assume that the SU(2) breaking term $g_1$ dominates over $g_2$, in spite of the additional $\Lambda$ suppression in the latter [15]. This is why we keep all three terms and consider the effective Lagrangian for the mass eigenstate $X$ to be

$$L = -X\left[\frac{\kappa_1}{\Lambda} \frac{m_X^2}{v} Z^\mu Z^\nu + \frac{\kappa_2}{2v} F_{\mu \nu} F^\mu F^\nu + \frac{\kappa_3}{2v} \bar{F} F_{\mu \nu} \right].$$

(6)

where $\bar{F} F_{\mu \nu}$ is a quadratic function of the $\lambda$'s:

$$\Gamma(X \rightarrow ZZ) = \Gamma_{SM} \sum_{i,j} \gamma_{ij} \kappa_i \kappa_j$$

(8)

where we have factored out the partial width $\Gamma_{SM}$ predicted in the SM in order to define dimensionless coefficients $\gamma_{ij}$ listed in Table I. The measured total rate then provides the overall normalization and constrains the $\kappa_i$ couplings to lie on the closed hypersurface shown in Fig. 1(a). The idea now is to change variables and parametrize the couplings $\kappa_i$ in terms of the two coordinates on this hypersurface. This reparametrization is useful and meaningful, since the

<table>
<thead>
<tr>
<th>Process</th>
<th>$\gamma_{11}$</th>
<th>$\gamma_{22}$</th>
<th>$\gamma_{33}$</th>
<th>$\gamma_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X \rightarrow ZZ$ (DF)</td>
<td>1</td>
<td>0.090</td>
<td>0.038</td>
<td>-0.250</td>
</tr>
<tr>
<td>$X \rightarrow ZZ$ (SF)</td>
<td>1</td>
<td>0.081</td>
<td>0.032</td>
<td>-0.243</td>
</tr>
<tr>
<td>$X \rightarrow \gamma \gamma$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$X \rightarrow WW$</td>
<td>1</td>
<td>0.202</td>
<td>0.084</td>
<td>-0.379</td>
</tr>
<tr>
<td>$X \rightarrow ZZ$ (DF)</td>
<td>1</td>
<td>0.101</td>
<td>0.037</td>
<td>-0.277</td>
</tr>
</tbody>
</table>

After cuts
FIG. 1 (color online). The principle of geolocating: the change of variables, Eq. (9), inflates (a) the hypersurface defined by the measurement, Eq. (8), into (b) a perfect sphere.

(normalized) angular and invariant mass distributions used to measure the Higgs spin and CP properties are insensitive to the overall scale of the couplings \( \kappa_i \). Operationally, we propose to do this by changing variables as

\[
x_i = \sum_j O_{ij} \kappa_j,
\]

where \( O_{21} = O_{31} = O_{32} = 0 \) and

\[
O_{1i} = \gamma_{1i}/\sqrt{\gamma_{11}}, (i = 1, 2, 3),
\]

\[
O_{2i} = \gamma_{12} \gamma_{2i} - \gamma_{1i} \gamma_{22}/\sqrt{\gamma_{11} \gamma_{22} - \gamma_{12}^2}, (i = 2, 3),
\]

\[
O_{33} = \sqrt{\text{det} |\gamma_{ij}|/(\gamma_{11} \gamma_{22} - \gamma_{12}^2)}.
\]

In terms of the new variables \( x_i \), the constraint implied by Eq. (8) is the surface of a sphere, as seen in Fig. 1(b).

Note that in the case of real couplings, \( \gamma_{13} \) and \( \gamma_{25} \) vanish identically [and hence are not listed in Eq. (8)]. This can be understood in terms of parity; interference terms between amplitudes describing the decay of a parity-even scalar and a parity-odd scalar are odd under parity and hence vanish under integration provided the cuts respect parity (as is nearly always the case). The situation in the presence of cuts is less clear if the couplings of the three operators in Eq. (6) are complex valued; however, any \( \gamma_{13} \) or \( \gamma_{25} \) term generated in this case is expected to be very small.

Geolocating the Higgs boson.—A sphere may be parametrized using latitude \( \phi \) and longitude \( \lambda \). Making an obvious analogy, we can think of the tree-level SM Higgs couplings \( (\kappa_1, \kappa_2, \kappa_3) = (1, 0, 0) \) as being represented by the point \( (\phi, \lambda) = (0, 0) \) in the Gulf of Guinea (see Fig. 2). The case of a pure pseudoscalar with \( (\kappa_1, \kappa_2, \kappa_3) = (0, 0, 1) \) corresponds to the north pole with \((\phi, \lambda) = (90, 0)\). Those are the two main benchmark scenarios considered so far by the LHC experiments. The Higgs sphere from Fig. 1(b) now opens up the full range of possibilities. For example, one may consider a certain amount of mixing as in Eq. (1) between the SM Higgs boson and a pseudoscalar, placing us on the Greenwich meridian. Alternatively, one may allow nontrivial values for the two CP-even couplings \( \kappa_1 \) and \( \kappa_2 \), thus spanning the equator. Finally, one could also envision the most general case with nontrivial values for all three couplings, e.g., \( (\kappa_1, \kappa_2, \kappa_3) = (-0.945804, -3.88525, 2.44522) \), corresponding to \( (\phi, \lambda) = (29.64945, -82.3486) \), which happens to be a location in the south end zone of the Swamp.

We note that CMS has recently undertaken an exploration of the sphere along the Greenwich meridian \( (\lambda = 0) \) by measuring the parameter \( \eta_{\lambda} = |A_3|^2/(|A_1|^2 + |A_3|^2) \), parametrizing the relative contributions \( |A_1|^2 \) and \( |A_3|^2 \) to the total cross section of the two benchmark models \( (\kappa_1, \kappa_2, \kappa_3) = (1, 0, 0) \) and \( (\kappa_1, \kappa_2, \kappa_3) = (0, 0, 1) \), respectively.

Selection cut bias.—By definition, the measurement of the Higgs signal rate [and, by association, of the partial width (8)] is done using only events which pass selection cuts. Therefore, it needs to be corrected for the efficiency. Unfortunately, as demonstrated in the bottom right panel in Fig. 2, the signal efficiency is noticeably model dependent; i.e., it is quite sensitive to the actual values of the individual \( \kappa_i \) parameters, and may vary from as low as 35% to as high as 54%. One source of this variation is the cut on \( M_{Z_2} \) (see, e.g., [13]). The effect is quantified in Fig. 3, which shows unit-normalized \( M_{Z_2} \) distributions for several choices of \( \kappa_1 \),

FIG. 2 (color online). The effective couplings \( \kappa_i \) and the signal efficiency after cuts as a function of latitude \( (\phi) \) and longitude \( (\lambda) \) for the different flavor four lepton channel \( X \to ZZ \to 2e2\mu \).
including an example with a high efficiency \([k_1, k_2, k_3] = (0, 0, 1)\), black circles] and a suitably chosen example with a low efficiency \([k_1, k_2, k_3] = (1.8, 5, 0.08)\), red crosses). The \(M_{Z'}\) distribution in the latter case is softer, and many events fall below the minimum accepted \(M_{Z'}\) value of 12 GeV. We conclude that it would be virtually impossible to correct for the efficiency without knowledge of the couplings \(k_i\), which we are trying to measure in the first place, thus falling into a vicious circle.

Here we advocate an alternative approach. It is sufficient to realize that the coefficients \(\gamma_{ij}\), while also affected by the efficiency, do not depend on \(k_i\). Therefore, in defining the Higgs sphere, Eq. (9), one could simply use the corresponding values of \(\gamma_{ij}\) after cuts, which need to be calculated once and for all. As shown in Table I, the changes are subtle, yet noticeable. Note that even without any cuts, the same flavor (SF) and different flavor (DF) coefficients are different, due to the interference effects present in the SF case (see, e.g., [6]).

**Interpretation.**—We emphasize that by studying the angular and invariant mass distributions of the final state leptons in the \(X \rightarrow ZZ \rightarrow 4\ell\) channel it is experimentally possible to determine the exact geolocation of the Higgs boson candidate, without any simplifying theoretical assumptions. A proof of principle is shown in Fig. 4. We consider four benchmark scenarios for \((k_1, k_2, k_3)\): (triangle) \((1, 0, 0)\), (circle) \((0, 1, 0)\), (star) \((0, 0, 1)\), and (plus) \((1, 1, 1)\). We show results from 1000 pseudoexperiments with 300 signal events each after cuts. Figure 4 shows that in each case, the maximum likelihood fit indeed selects the correct geolocation (marked with an open symbol) of the Higgs candidate.

**In**determination of the mixing angle \(\alpha\).—We note that geolocating the Higgs candidate by itself is not sufficient to determine the value of the mixing angle \(\alpha\), and we will still not know the relative composition of \(X\) in terms of \(X\) and \(A\). As seen in Eq. (7), the measurement of all three effective couplings \(k_1, k_2, k_3\) only places three constraints on the four input parameters \(\alpha\), \(g_1\), \(g_2/\Lambda\), and \(g_3/\Lambda\), so 1 degree of freedom (which can be chosen to be the mixing angle \(\alpha\)) will always be left undetermined.

**Music of the spheres.**—Until now, we have been treating the coefficients \(k_i\) of the operators in the effective Lagrangian, Eq. (6), to be real. We term this “Scenario 0.” Of course, this must be the case at tree level, and even beyond, as long as those operators are generated by loop diagrams involving heavy particles, such as the top, which may be consistently integrated out of the full theory to form an effective theory. However, in accordance with the optical theorem, loops with light particles (such as \(b\) quarks, which cannot be integrated out of the theory) will contribute imaginary parts to those couplings. In this case, each of the \(k_i\) is complex and there are five physical degrees of freedom (an overall phase in the \(k_i\) may be removed). Nevertheless, the width constraint \(\Gamma(X \rightarrow ZZ) = \Gamma_{SM} \sum_i |\gamma_{ij}| k_i k_j\) can still be enforced. As before, the diagonalization and rescaling, Eq. (9), renders this a sphere in \(\mathbb{C}^3\) (rather than an ellipsoid, as is the case in general).

Even in this general complexified case, there are three interesting and simple scenarios where the number of degrees of freedom is reduced to three. Namely, if one of \(k_i\) is too small to have observable effects, then the remaining two \(k_i\), taken to be arbitrary complex numbers, also comprise two observable degrees of freedom (as an overall phase may be removed). There are, of course three such scenarios, “Scenario 1” where \(k_1\) is negligible, “Scenario 2” where \(k_2\) is negligible, and “Scenario 3” where \(k_3\) is negligible.

**Other final state channels.**—While we have so far only focused on the \(ZZ \rightarrow 4\ell\) final state, the preceding discussion can be readily applied to the other diboson final states, \(WW, Z\gamma, \gamma\gamma\). The interactions relevant for those channels involve corresponding new couplings \(k_i^{WW}, k_i^{Z\gamma}\), and \(k_i^{\gamma\gamma}\). Assuming \(SU(2)\) gauge symmetry, these new couplings are related, e.g.,

\[
\kappa_{1}^{Z\gamma} = \kappa_{1}^{\gamma\gamma} = 0, \quad \kappa_{1}^{WW} = \kappa_{1}^{ZZ},
\]

\[
\kappa_{i}^{Z\gamma} = \frac{1}{2} (\kappa_{i}^{ZZ} - \kappa_{i}^{\gamma\gamma}) \tan 2\theta_W, \quad (i = 2, 3),
\]

\[
\kappa_{i}^{WW} = \frac{\kappa_{i}^{ZZ} \cos^2 \theta_W - \kappa_{i}^{\gamma\gamma} \sin^2 \theta_W}{\cos^2 \theta_W - \sin^2 \theta_W}, \quad (i = 2, 3),
\]

with obvious definitions of \(\kappa\)’s. As before, the measured rate in each of those channels defines a sphere similar to Eq. (8), where the corresponding values for the coefficients \(\gamma_{ij}\) are given in Table I. It is interesting to note that these spheres are not overlapping (even for the DF and SF cases in the same \(X \rightarrow ZZ\) channel), and, in principle, couplings can be measured from intersecting spheres, although we expect that this method is of only academic interest, since the corresponding precision would be very poor.

**Summary.**—We have proposed several related parametrizations of the couplings of the 125 GeV boson discovered at
the LHC. These parametrizations allow the LHC experiments to go beyond comparing benchmark points, etc. in a relatively simple, yet very general, theoretically motivated fashion. The low dimensionality of the parameter space is helpful experimentally as well as in the visualization and interpretation of results. We look forward to the implementation of this method by the LHC Collaborations [17] and to the continued exploration of the couplings of the putative Higgs boson.

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