Higgs look-alikes at the LHC

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The discovery of a Higgs particle is possible in a variety of search channels at the LHC. However, the true identity of any putative Higgs boson will, at first, remain ambiguous until one has experimentally excluded other possible assignments of quantum numbers and couplings. We quantify the degree to which one can discriminate a Standard Model Higgs boson from "look-alikes" at, or close to, the moment of discovery at the LHC, focusing on the fully-reconstructable "golden" decay mode to a pair of Z bosons and a four-lepton final state.

1 Introduction

The discovery of a Higgs particle is possible in a variety of search channels at the LHC. Even if a deviation from the Standard Model (SM) background-only hypothesis appears in one of these channels, the true identity of any putative Higgs boson will remain unconformed until one has experimentally excluded other possible assignments of quantum numbers and couplings.

We consider the case of a SM Higgs boson, or a Higgs look-alike (HLL), decaying via ZZ or ZZ^* into a four lepton final state. In this final state topology there are a number of observable that allow us to distinguish between HLL's with different values of spin and quantum numbers, and also between HLL signal events and SM backgrounds that populate final state. Specifically, we consider the production angles Θ and Φ, which describe the decay of the Higgs to 2 Z bosons in the H rest frame and the lepton decay angles θ_1, θ_2 and ϕ, which dictate the direction of the decay leptons' momenta in the two Z's rest frames. Additionally, when the mass of the Higgs or HLL is less than that of two Z bosons ($M_H < 2M_Z$) we also use the off-shell Z mass, M_{Z^*}, as a discriminating variables. We denote the collection of these angles observables as $\vec{X}$,

2 Higgs Discovery

In the context of Higgs discovery in this four-lepton channel, we evaluate the potential for improvement in the analysis sensitivity by including information related to the ZZ and lepton decay angles as evaluated in the respective Z rest frames. We explicitly compare the sensitivity of a discovery procedure of an analysis based on an extended and unbinned Maximum Likelihood (ML) fit extraction of the signal yield in the presence of background using only the Higgs invariant mass ($M(ZZ)$) observable with a comparable approach that also includes information about the distributions of $\vec{X}$ in the fit.

Since there is no resonant 4ℓ background in the SM, the $M(ZZ)$ variables is a powerful discriminating variable between $H \to ZZ$ signal and background events. In the presence of a sizable background due to fake Z candidates (such as top decays) the 2ℓ invariant mass distributions can be included in the likelihood. For this case we ignore this possibility and assume for simplicity that the only relevant background is given by events with two real Z candidates.

As an example, we consider the 4μ final state. We select events that have 4 muons with $p_T^\mu > 10$ GeV/c and $|\eta_{mu}| < 2.3$. For the $M(ZZ)$-only fit, we write the likelihood as

$$\mathcal{L} = \frac{1}{N!} \exp\left(-\sum_j N_j\right) \prod_{i=1}^{N} \left(N_S P_S[m^i_{4\mu}] + N_B P_B[m^i_{4\mu}]\right) \quad (1)$$

where N_j $(j = S, B)$ represents the yield of components, $m^i_{4\mu}$ is the 4μ candidate mass for the event i and $P_S[m]$ $(P_B[m])$ is the signal (background) distribution for the variable m.

Similarly, for the $M(ZZ)+\vec{X}$ fit we can express the likelihood as

$$\mathcal{L} = \frac{1}{N!} \exp\left(-\sum_j N_j\right) \prod_{i=1}^{N} \left(N_S P_S[m^i_{4\mu}, \vec{X}^i] + N_B P_B[m^i_{4\mu}, \vec{X}^i]\right) \quad (2)$$

where $P_S[m, \vec{X}]$ $(P_B[m, \vec{X}])$ is now the signal (background) probability distribution function in the 6-dimensional space including the Higgs invariant mass and the 5 Higgs production and decay angles.

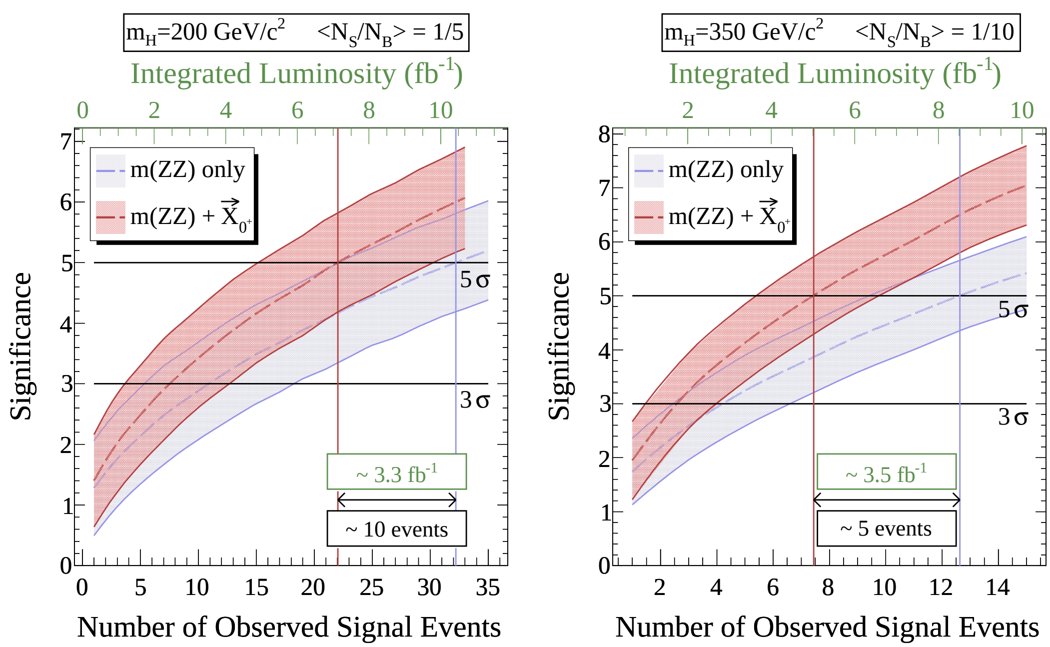

Figure 1: Distribution of signal significance for a 200 GeV/c^2 (left) and 350 GeV/c^2 (right) SM Higgs boson decaying in the $H \to ZZ \to 4\mu$ channel for pp collisions with $\sqrt{s} = 10$ TeV. The mean signal to background ratios used are $\langle N_S/N_B \rangle = 1/5$ (left) and $1/10$ (right).

Fig.1 shows a comparison between the resulting significance for Higgs discovery, using the two different fit configurations, as a function of the number of produced Higgs events for two different Higgs masses. Here, the number of background events refers to the expected background yield in the range 190 GeV/$c^2 < M(ZZ) <$ 600 GeV/c^2. The values of $\langle N_S/N_B \rangle$ used in this example correspond to the nominal expectations for pp collisions at $\sqrt{s} = 10$ TeV. We find that including information about the angles $\vec{X}$ in the ML fit significantly improves the analysis sensitivity for Higgs discovery in the 4ℓ final state.

3 Higgs Look-alikes

In order to quantify our ability to distinguish between a SM Higgs and other HLL resonances decaying to ZZ we write down the most general Lagrangian describing the coupling of an HLL object to two Z bosons, requiring only Lorentz invariance. This is done for $J = 0, 1$ and 2 for operators up to dimension 6. We then explicitly calculate the differential cross-section for production of these HLL's as a function of the observables $\vec{X}$. Events are generated according to these probability distribution functions (*pdfs*), and and a detector simulation is used, including resolution effects on the lepton momenta, along with the application of kinematic cuts on leptons in order to calculate numerically the experimental pdfs for each of the different HLL spin and quantum number possibilities, as a function of the observables $\vec{X}$.

With these experimental pdfs, we can then quantify the relative agreement between data and the different HLL hypotheses. We assume that the data consists of some number of observed signal events N_S. We construct the likelihood of the data corresponding to a particular hypothesis $\mathbb{H}_0$ as $\mathcal{L}(\mathbb{H}_0) \equiv \prod_{i=1}^{N_S} P_{\mathbb{H}_0}(\vec{X}_i)$, where $P_{\mathbb{H}_0}$ is the experimental *pdf* corresponding to the $\mathbb{H}_0$ hypothesis.

We quantify our ability to discriminate between different HLL hypotheses using a Neyman-Pearson hypothesis test. Specifically, we do pairwise comparisons between two different hypotheses, $\mathbb{H}_0$ and $\mathbb{H}_1$, and determine the significance with which the hypothesis $\mathbb{H}_0$ can be rejected in favor of the hypothesis $\mathbb{H}_1$, assuming $\mathbb{H}_1$ is true. For example, Fig. 2 shows the significance for rejecting the the pseudo-scalar hypothesis in favor of a SM Higgs, as a function the number of observed signal events.

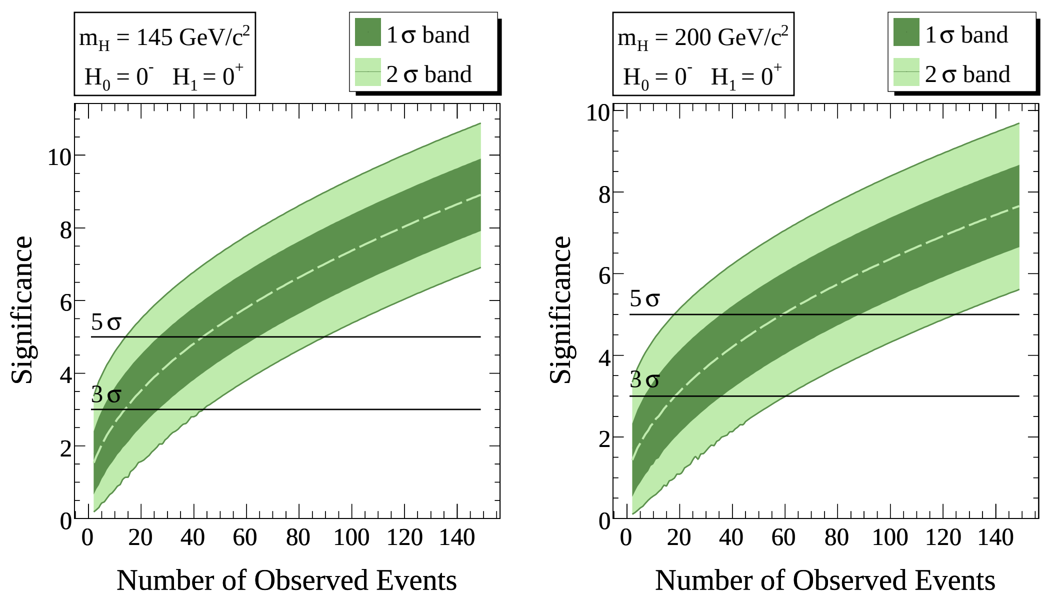

Figure 2: Significance for rejecting the $J^P = 0^-$, pure pseudo-scalar, hypothesis in favor of the $J^P = 0^+$, SM Higgs, hypothesis assuming that the resonance is a SM Higgs for $m_H = 145$ (left) and 200 (right) GeV/c^2.

In addition to comparisons between *simple* hypotheses, i.e. hypotheses corresponding to well-defined J^{PC} values, we also quantify our ability to discriminate between *mixed* hypotheses with CP or C violating components or a composite Higgs. For example, we can parameterize the Lagrangian for a CP-violating, scalar HLL as

$$\mathcal{L}_{\mu\alpha} \propto \cos(\xi_{XP}) g_{\mu\alpha} + \sin(\xi_{XP}) \epsilon_{\mu\alpha} p_1 p_2 / M_Z^2, \tag{3}$$

where ξ_{XP} is a CP-violating parameter that determines the mixing between the $J = 0^+$ and 0^-

couplings. Fig. 3 quantifies one ability to discriminate between a CP-violating hypothesis and an SM Higgs, for different values of the mixing parameter ξ_{XP}.

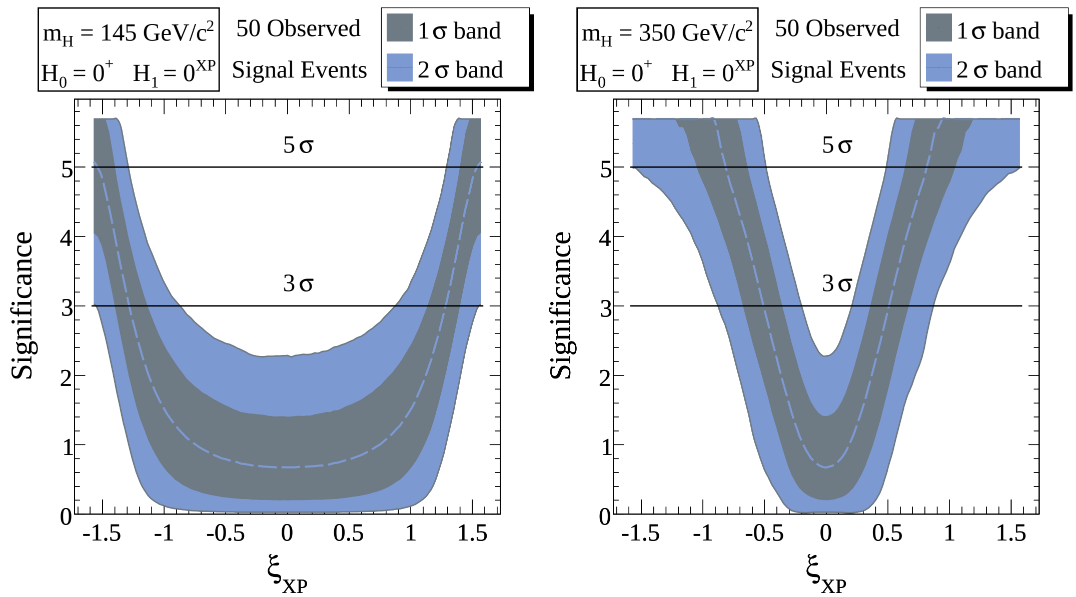

Figure 3: The significance for excluding a pure 0^+ hypothesis in favor of a CP-violating HZZ coupling ($\xi_{XP} \neq 0$), assuming the later to be correct, with ξ_{XP} given by its x-axis values. Example for $N_S = 50$, $m_H = 145$ (left) and 350 (right) GeV/c^2.

Amongst the many comparisons considered in our analysis, the ones between simple hypotheses are the most readily summarized. This we do in Table 1 for $m_H = 145$ GeV for all pure-case comparisons between $J = 0, 1$ parent particles, and in Table 2 (3) for $m_H = 200$ (350) GeV, for all pure-case comparisons between $J = 0, 1, 2$ parent particles.

$\mathbb{H}_0 \Downarrow \mathbb{H}_1 \Rightarrow$	0^+	0^-	1^-	1^+
0^+	–	52	37	50
0^-	44	–	34	54
1^-	33	32	–	112
1^+	54	55	109	–

Table 1: Minimum number of observed events such that the median significance for rejecting $\mathbb{H}_0$ in favour of the hypothesis $\mathbb{H}_1$ (assuming $\mathbb{H}_1$ is right) exceeds $5\,\sigma$ with $m_H = 145$ GeV/c^2

Overall, the discrimination power of the hypothesis tests is very impressive. The $m_H = 200$ GeV/c^2 benchmark example is the one requiring the largest statistics to reach a given discrimination at a given level of confidence. Compared with the $m_H = 350$ GeV/c^2 case, this is because various coefficients of the angular dependences vanish at the $m_H = 2\,M_Z$ threshold. The $m_H = 145$ GeV/c^2 example fares better than the 200 GeV/c^2 one for the same reason, amplified by the extra lever-arm supplied by a non-trivial M_{Z^*} distribution.

The Tables also show that the discrimination power between two given hypotheses is approximately symmetric under the interchange of 'right' and 'wrong'. Telling 1^+ from 1^- is always difficult but not impossible, a fact of relevance for a Z' look-alike analysis. The level of significance does not obey a naïve $N(\sigma) \propto \sqrt{N_S}$ law. However we find by inspection that an approximation of the form $N(\sigma) = a + b\,\sqrt{N_S}$ works well, allowing one to extrapolate to larger numbers of events than presented here.

Other lessons from the Tables are case-by-case specific, reflecting the mass-dependent quantum-

$\mathbb{H}_0 \Downarrow \mathbb{H}_1 \Rightarrow$	0^+	0^-	1^-	1^+	2^+
0^+	–	76	146	203	287
0^-	59	–	60	61	123
1^-	130	57	–	297	156
1^+	182	58	278	–	217
2^+	287	146	178	230	–

Table 2: Minimum number of observed events such that the median significance for rejecting $\mathbb{H}_0$ in favour of the hypothesis $\mathbb{H}_1$ (assuming $\mathbb{H}_1$ is right) exceeds $5\,\sigma$ with $m_H = 200$ GeV/c^2

mechanical entanglement between the decay variables. Some examples are: distinguishing the 'natural-parity' $J = 0^+$ and 1^- hypotheses for $m_H = 145$ GeV/c^2 requires only a dozen signal events for $3\,\sigma$ discrimination. For 200 GeV/c^2, discriminating 0^+ from 0^- is relatively easy, but distinguishing 0^+ from 2^+ is difficult. For 350 GeV/c^2, contrariwise, 2^+ is relatively easy to disentangle from 0^+, but not from 0^-.

We find that direct sensitivity to CP odd, parity odd XP interference effects, or to CP odd, parity even XQ interference effects, will require signal samples about an order of magnitude larger than considered here($\sim$ 500 signal events). We have also shown that with much smaller statistics it may be possible to show conclusively that a mix of X and P (or X and Q) couplings is favored over just the pure X (i.e. 0^+) or pure P (i.e. 0^-) couplings alone. Such a conclusion would be tantamount to demonstrating CP violation in the Higgs sector. However, this scenario relies on large CP violation, and even in this favorable case one cannot tell an X and P mixture from an X and Q mixture without more data.

In the case of a composite Higgs we see that the angular distributions associated to the X and Y couplings are similar after integrating over the decay angles. As a result there can be strong destructive interference between these contributions. For our lighter mass benchmarks we find good discrimination of pure 0^+ from the mixed composites. For the heavier $m_H = 350$ GeV/c^2 example, discrimination based on decay angles is poor unless the strong interference effects are present; here also we observe that substantial enhancement or suppression of the HLL$\rightarrow ZZ$ branching fraction can provide another important discriminator.

For mixed cases, one could worry that certain combinations of exotic couplings might let an HLL successfully masquerade as a 0^+ Higgs, even when all the pure case exotics are excluded. For of spin 1 HLLs we observe that this does not happen. In fact we find that when we in fact have an SM Higgs, the entire family of mixed coupling spin 1 HLLs can be excluded at approximately the same expected level of significance as for the pure 1^- or 1^+ cases. An even stronger result is that the general spin 0 hypothesis can be conclusively discriminated from the general spin 1 hypothesis, at or close to the moment of discovery.

$\mathbb{H}_0 \Downarrow \mathbb{H}_1 \Rightarrow$	0^+	0^-	1^-	1^+	2^+
0^+	–	25	67	77	35
0^-	26	–	68	68	118
1^-	76	68	–	268	149
1^+	83	68	263	–	184
2^+	46	127	181	240	–

Table 3: Minimum number of observed events such that the median significance for rejecting $\mathbb{H}_0$ in favour of the hypothesis $\mathbb{H}_1$ (assuming $\mathbb{H}_1$ is right) exceeds $5\,\sigma$ with $m_H = 350$ GeV/c^2

4 Outlook

We have seen that by exploiting the full decay information in the golden channel , $H \to ZZ \to 4\ell$, one is able to say a lot about the identity of a putative Higgs resonance around the moment of discovery. Our results also show that asymptotically, utilizing the full physics run of the LHC, it should be possible to explore very detailed properties of such a resonance, including it's spin and quantum numbers. A complete discussion of these results can be found in [1].

References

1. A. De Rujula, J. Lykken, M. Pierini, C.S. Rogan and M. Spiropulu, "Higgs look-alikes at the LHC," arXiv:1001.5300 [hep-ph].