Diagnosing Degenerate Higgs Bosons at 125 GeV

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(Received 10 August 2012; published 29 January 2013)

We develop diagnostic tools that would provide incontrovertible evidence for the presence of more than one Higgs boson near 125 GeV in the LHC data.

DOI: 10.1103/PhysRevLett.110.051801 PACS numbers: 14.80.Da, 12.60.Fr, 13.85.Rm

Data from the ATLAS and CMS Collaborations [1,2] provide an essentially 5σ signal for a Higgs-like resonance with mass of order 123–128 GeV. Meanwhile, the CDF and D0 experiments have announced new results [3], based mainly on Vh associated production with $h \to b\bar{b}$, that support the $\sim$125 GeV Higgs-like signal. While it is certainly possible that the observed signals in the various production-decay channels will converge towards their respective standard model (SM) values, the current central values for these channels deviate by about 1–2σ from SM predictions. Clearly, a prime goal of future LHC data taking will be increased statistics, sufficient to clearly rule out or confirm a SM nature for this Higgs-like signal. Meanwhile, it is very interesting to discuss models in which the observed central values for the various channels deviate from the SM along the lines seen in the data.

One of the most significant deviations in the current data is the enhancement in the $\gamma\gamma$ final state for both gluon fusion (gg) and vector boson fusion (VBF) production. Such enhancement can be obtained in a variety of models and is often associated with the observed mass eigenstate at $\sim$125 GeV mixing with a nearby (unobserved or degenerate) state. A particularly appealing supersymmetric model that easily obtains both a Higgs-boson mass of order 125 GeV and significant $\gamma\gamma$ mode enhancements is the next-to-minimal supersymmetric standard model (NMSSM). The NMSSM is very attractive since it solves the μ problem of the minimal supersymmetric extension of the SM (MSSM): the *ad hoc* parameter μ appearing in the MSSM superpotential term $\mu \hat{H}_u \hat{H}_d$ is automatically generated in the NMSSM from the $\lambda \hat{S} \hat{H}_u \hat{H}_d$ superpotential term when the scalar component S of $\hat{S}$ develops a vacuum expectation value $\langle S \rangle = s$: $\mu_{\rm eff} = \lambda s$. The three CP-even Higgs fields, H_u, H_d, and S, mix and yield the mass eigenstates h_1, h_2, and h_3. A 125 GeV Higgs state with enhanced $\gamma\gamma$ signal rate is easily obtained for large λ and small $\tan\beta$ [4]. The h_1 and h_2 are typically close in mass in this case, with one of them being primarily the doubletlike H_u while the other has a large singlet S component. A particularly interesting case arises when the h_1 and h_2 are nearly degenerate [5].

Given this latter possibility, a very crucial issue is how to determine whether or not there are two (or more) Higgs bosons versus just one contributing to the Higgs signals at 125 GeV. One possibility, requiring high statistics given the experimental resolution (of order $\gtrsim 1.5$ GeV), is that the mass peaks in the $\gamma\gamma$ and 4ℓ final states would display a structure of two overlapping peaks. However, for many of the degenerate scenarios it turns out that the $\gamma\gamma$ and 4ℓ final states are dominated by only one of the degenerate Higgs bosons, and the other one would show up primarily in $b\bar{b}$ and/or $\tau\tau$ final states. Unfortunately, mass resolutions in these channels are very poor and detection of a two peak structure using invariant mass distributions would appear to be very difficult. A direct probe of this kind of degeneracy using the full complement of final states is clearly highly desirable.

In this Letter, we therefore develop diagnostic tools that would reveal the presence of two Higgs bosons even if they are extremely close in mass. We illustrate our technique using the NMSSM scenarios generated for Ref. [5] (where NMSSM parameter ranges and all constraints are discussed in detail), in which the two lightest CP-even Higgs bosons, h_1 and h_2, both lie in the 123–128 GeV mass window. The diagnostic tools we suggest are, however, fully general and can be employed for any model or scenario with degenerate Higgs-like states; to exemplify, we comment via references regarding differences and similarities relative to the brane model studied in Ref. [6] in which a Higgs boson and the radion mix to form two mass eigenstates, $h_1 = h$, $h_2 = \phi$ (or vice versa) with $m_h \sim m_\phi$.

The main production channels (denoted by Y) relevant for current LHC data are $gg \to H$ fusion ($Y = gg$) and vector boson fusion ($Y =$ VBF), where VBF stands for the sum of the $WW \to H$ and $ZZ \to H$ vector boson fusion processes. Here, H stands for a generic Higgs boson. Higgs decay channels (denoted by X) include the high resolution $X = \gamma\gamma$ and $X = ZZ^* \to 4\ell$ final states, i.e., $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$, and the poor mass resolution $X = b\bar{b}$ and $X = \tau^+\tau^-$ channels. The most crucial production-decay channels at the LHC are gg, VBF $\to H \to \gamma\gamma$, 4ℓ.

The LHC also probes $V^* \to VH$ ($V = W$ or Z) with $H \to b\bar{b}$, channels for which Tevatron data are relevant, and VBF $\to H$ with $H \to \tau^+\tau^-$. Let us employ the notation h_i for the ith scalar Higgs field, $h_{\rm SM}$ for the SM Higgs boson, and $C_S^{h_i} = g_{Sh_i}/g_{Sh_{\rm SM}}$ is the ratio of the Sh_i coupling to the $Sh_{\rm SM}$ coupling, where $S = \gamma\gamma$, gg, WW, ZZ, bb, $\tau^+\tau^-$ are the cases of interest. The ratio of the gg or VBF induced h_i cross section times BR($h_i \to X$), relative to the corresponding value for the SM Higgs boson, takes the form

$$R_{gg}^{h_i}(X) = (C_{gg}^{h_i})^2 \frac{{\rm BR}(h_i \to X)}{{\rm BR}(h_{\rm SM} \to X)},$$
$$R_{\rm VBF}^{h_i}(X) = (C_{WW}^{h_i})^2 \frac{{\rm BR}(h_i \to X)}{{\rm BR}(h_{\rm SM} \to X)}, \quad (1)$$

where the latter result assumes the custodial symmetry relation $C_{WW}^{h_i} = C_{ZZ}^{h_i}$ as applies in any doublets + singlets model; this latter also implies $R_{\rm VBF}^{h_i}(X) = R_{V^*\to VH}^{h_i}(X)$ and, for either $Y = gg$ or $Y = {\rm VBF}$, $R_Y^{h_i}(WW) = R_Y^{h_i}(ZZ)$. However, if custodial symmetry is broken, there are many more independent R^{h_i}'s [7].

In this Letter we consider the case where there are two nearly degenerate Higgs bosons for which we must combine their signals. The net signal and the effective Higgs-boson mass, respectively, for given production and final decay channels Y and X, respectively, are computed as

$$R_Y^h(X) = R_Y^{h_1}(X) + R_Y^{h_2}(X),$$
$$m_h^Y(X) \equiv \frac{R_Y^{h_1}(X) m_{h_1} + R_Y^{h_2}(X) m_{h_2}}{R_Y^{h_1}(X) + R_Y^{h_2}(X)}. \quad (2)$$

Of course, the extent to which it is appropriate to combine the rates from the h_1 and h_2 depends upon the degree of degeneracy and the experimental resolution, estimated to be of order $\sigma_{\rm res} \sim 1.5$ GeV [8]. It should be noted that the widths of the h_1 and h_2 are of the same order of magnitude as the width of a 125 GeV SM Higgs boson (a few MeV), i.e., very much smaller than this resolution [9].

As already noted, in the context of any doublets plus singlets model not all the R^{h_i}'s are independent; the relations among the R^{h_i}'s were noted above. In supersymmetric two-doublet plus singlets models we have in addition $R_Y^{h_i}(\tau\tau) = R_Y^{h_i}(bb)$. A complete independent set of R^h's can be taken to be [10]

$$R_{gg}^h(WW), \quad R_{gg}^h(bb), \quad R_{gg}^h(\gamma\gamma),$$
$$R_{\rm VBF}^h(WW), \quad R_{\rm VBF}^h(bb), \quad R_{\rm VBF}^h(\gamma\gamma). \quad (3)$$

Let us now look in more detail at a given $R_Y^h(X)$. It takes the form

$$R_Y^h(X) = \sum_{i=1,2} \frac{(C_Y^{h_i})^2 (C_X^{h_i})^2}{C_\Gamma^{h_i}}, \quad (4)$$

where $C_X^{h_i}$ for $X = \gamma\gamma, WW, ZZ, \ldots$ is the ratio of the $h_i X$ to $h_{\rm SM} X$ coupling, as defined above Eq. (1), and $C_\Gamma^{h_i}$ is the ratio of the total width of the h_i to the SM Higgs total width. The diagnostic tools that we propose to reveal the existence of a second, quasidegenerate (but noninterfering in the small width approximation) Higgs state are the double ratios:

$$({\rm I}): \frac{R_{\rm VBF}^h(\gamma\gamma)/R_{gg}^h(\gamma\gamma)}{R_{\rm VBF}^h(bb)/R_{gg}^h(bb)}, \qquad ({\rm II}): \frac{R_{\rm VBF}^h(\gamma\gamma)/R_{gg}^h(\gamma\gamma)}{R_{\rm VBF}^h(WW)/R_{gg}^h(WW)},$$
$$({\rm III}): \frac{R_{\rm VBF}^h(WW)/R_{gg}^h(WW)}{R_{\rm VBF}^h(bb)/R_{gg}^h(bb)}, \quad (5)$$

each of which should be unity if only a single Higgs boson is present but, due to the nonfactorizing nature of the sum in Eq. (4), are generally expected to deviate from 1 if two (or more) Higgs bosons are contributing to the net h signals. This occurs because the h_1 and h_2 will, in general, have different relative production rates in the VBF and gg fusion channels for one or more final states. One can check that in a doublets + singlets model all other double ratios that are equal to unity for single Higgs exchange are not independent of the above three. Of course, the above three double ratios are not all independent. Which one will be most useful depends upon the precision with which the R^h's for different initial-final states can be measured. For example, measurements of R^h for the bb final state may continue to be somewhat imprecise and it is then double ratio (II) that might prove most discriminating. Or, it could be that one of the double ratios deviates from unity by a much larger amount than the others, in which case it might be most discriminating even if the R^h's involved are not measured with great precision.

To explore how powerful these double ratios are in practice, we turn to the NMSSM scenarios with semiunified grand unified theory (GUT) scale soft-supersymmetry-breaking sampled in Ref. [5] (see Ref. [11]). These scenarios obey all experimental constraints (including $\Omega h^2 < 0.136$ and 2011 XENON100 limits on the spin-independent scattering cross section) except that the supersymmetry contribution to the anomalous magnetic moment of the muon, δa_μ, is too small to explain the discrepancy between the observed value a_μ and that predicted by the SM. For a full discussion of the kind of NMSSM model employed, see also Refs. [12,13].

In Fig. 1, we plot the numerator versus the denominator of the double ratios (I) and (II), (III) being very like (I) due to the correlation between the $R_{gg}^h(\gamma\gamma)$ and $R_{gg}^h(WW)$ values discussed in Ref. [5]. We observe that any one of these double ratios will often, but not always, deviate from unity (the diagonal dashed line in the figure). The probability of such deviation increases dramatically if we require (as apparently preferred by LHC data) $R_{gg}^h(\gamma\gamma) > 1$; see the solid (versus open) symbols of Fig. 1. This is further

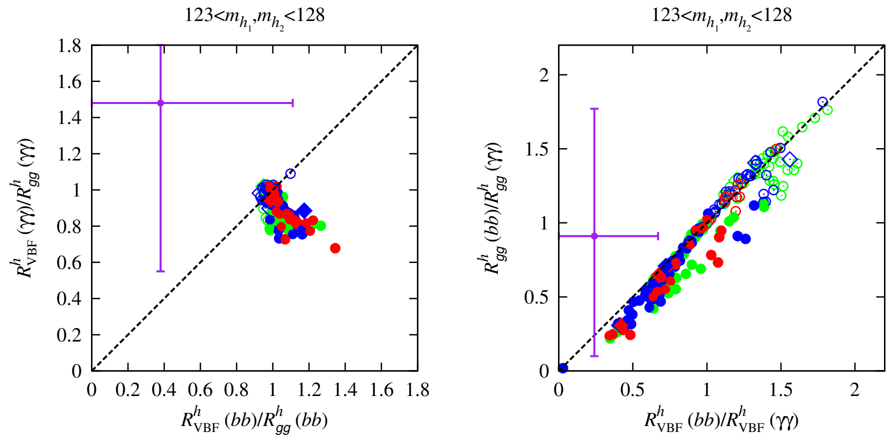

FIG. 1 (color online). Comparisons of pairs of event rate ratios that should be equal if only a single Higgs boson is present. The color code is green (light grey) for points with 2 GeV $< m_{h_2} - m_{h_1} \leq 3$ GeV, blue (dark grey) for 1 GeV $< m_{h_2} - m_{h_1} \leq 2$ GeV, and red (medium grey) for $m_{h_2} - m_{h_1} \leq 1$ GeV. Large diamond points have Ωh^2 in the WMAP window of [0.094, 0.136], while circular points have $\Omega h^2 < 0.094$. Solid points are those with $R^h_{gg}(\gamma\gamma) > 1$ and open symbols have $R^h_{gg}(\gamma\gamma) \leq 1$. Current experimental values for the ratios from CMS data along with their 1σ error bars are also shown.

elucidated in Fig. 2 where we display the double ratios (I) and (II) as functions of $R^h_{gg}(\gamma\gamma)$ (left-hand plots). For the NMSSM, it seems that the double ratio (I) provides the greatest discrimination between degenerate versus nondegenerate scenarios with values very substantially different from unity (the dashed line) for the majority of the degenerate NMSSM scenarios explored in Ref. [5] that have enhanced $\gamma\gamma$ rates. Note in particular that (I), being

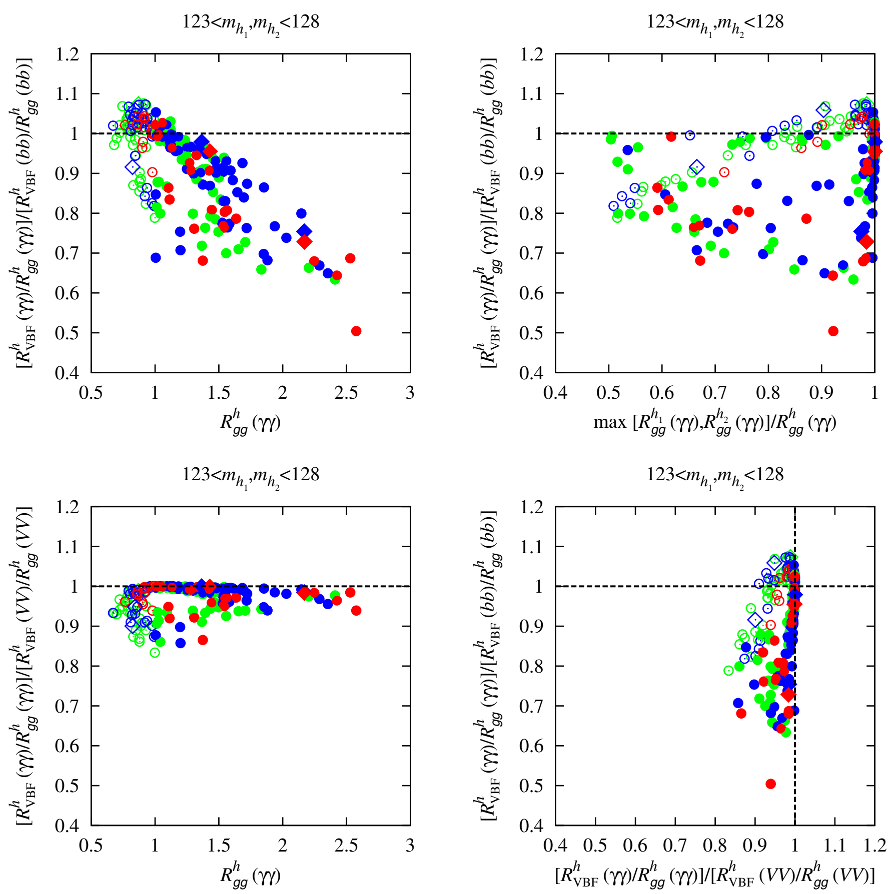

FIG. 2 (color online). Double ratios (I) and (II) of Eq. (5) as functions of $R^h_{gg}(\gamma\gamma)$ (on the left). On the right we show (top) double ratio (I) versus $\max[R^{h_1}_{gg}(\gamma\gamma), R^{h_2}_{gg}(\gamma\gamma)]/R^h_{gg}(\gamma\gamma)$ and (bottom) double ratio (I) versus double ratio (II) for the points displayed in Fig. 1. Colors and symbols are the same as in Fig. 1.

sensitive to the $b\bar{b}$ final state, singles out degenerate Higgs scenarios even when one or the other of h_1 or h_2 dominates the $gg \to \gamma\gamma$ rate; see the top right-hand plot of Fig. 2. In comparison, double ratio (II) is most useful for scenarios with $R^h_{gg}(\gamma\gamma) \sim 1$, as illustrated by the bottom left-hand plot of Fig. 2. Thus, as illustrated by the bottom right-hand plot of Fig. 2, the greatest discriminating power is clearly obtained by measuring both double ratios. In fact, a close examination reveals that there are no points for which *both* double ratios are exactly 1 [14]. Of course, experimental errors may lead to a region containing a certain number of points in which both double ratios are merely consistent with 1 within the errors.

What do current LHC data say about these various double ratios? The central values and 1σ error bars [16] for the numerator and denominator of double ratios (I) and (II) obtained from CMS data [17] are also shown in Fig. 1. Obviously, current statistics are inadequate to discriminate whether or not the double ratios deviate from unity. For a $\sqrt{s} = 14$ TeV run with $L = 100\ \text{fb}^{-1}$ ($300\ \text{fb}^{-1}$) of accumulated luminosity, the SM Higgs cross sections at the relevant energies imply that the number of Higgs events will be about a factor of 25 (77) larger than the number produced for $L \sim 5\ \text{fb}^{-1}$ at $\sqrt{s} = 7$ TeV plus $L \sim 6\ \text{fb}^{-1}$ at $\sqrt{s} = 8$ TeV (as used in computing the error bars shown in Fig. 1). Using statistical scaling only, that means the error bars plotted in Fig. 1 should be reduced by roughly a factor of 5 (9), levels that could indeed reveal a deviation from unity, or at least remove some model points if no deviation within that error is seen. Of course, improvements in the experimental analyses may further increase the sensitivity. We thus conclude that our diagnostic tools will ultimately prove viable and perhaps crucial for determining if the $\sim$125 GeV Higgs signal is really only due to a single Higgs-like resonance or if two resonances are contributing, the latter having significant probability in model contexts if enhanced $\gamma\gamma$ rates are indeed confirmed at higher statistics.

To summarize, we have emphasized the possibility that a $\gamma\gamma$ Higgs-like signal that is significantly enhanced relative to the SM could arise as a result of there being two fairly degenerate Higgs bosons near 125 GeV. This situation arises in several model contexts in which the degeneracy can be such that separate mass peaks could not be observed in even the high-resolution $\gamma\gamma$ and $ZZ \to 4\ell$ final states. We have shown that deviations from unity of certain double ratios of event rates have strong potential for revealing the presence of two (or more) nearly degenerate Higgs bosons within the 125 GeV LHC signal. Such deviations arise when both the quasidegenerate Higgs bosons contribute significantly to at least one production-decay channel. We have employed the NMSSM as a prototype model to illustrate the discriminating power of these double ratios in the case of a doublets-plus-singlets Higgs model. We have also noted that the diagnostic power of the double ratios discussed in this Letter is at least as great in the brane model with Higgs-radion mixing and, in addition, there are more double ratios that can be defined as a result of the sometimes substantial violation of custodial symmetry in the latter type of model. Of course, substantial statistics will be required to reveal the deviations from unity that would signal a degenerate scenario.

This work has been supported in part by U.S. DOE Grant No. DE-FG03-91ER40674 and by IN2P3 under contract PICS FR–USA No. 5872. J. F. G. and S. K. acknowledge the hospitality and inspiring working atmosphere of the Aspen Center for Physics which is supported by National Science Foundation Grant No. PHY-1066293.

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[6] B. Grzadkowski, J. F. Gunion, and M. Toharia, Phys. Lett. B **712**, 70 (2012).
[7] For example, in the Higgs-radion mixing model, $R^{h_i}_{V^* \to VH}(X) \neq R^{h_i}_{\text{VBF}}(X)$, $R^{h_i}_{gg}(WW) \neq R^{h_i}_{gg}(ZZ)$, etc.
[8] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **710**, 403 (2012).
[9] Note that this is not an assumption. The fact that a SM-like Higgs signal in the $\gamma\gamma$ and ZZ modes is even *visible* at the LHC tells us that the widths of any contributing Higgs boson must be very small, at most of order a few MeV as for the SM Higgs. Interference effects are negligible in this case unless one has extreme degeneracy of the two states. Our NMSSM scan points generally have $m_{h_2} - m_{h_1} > 50$ MeV for which interference effects are at most a fraction of a percent.
[10] In other models, more (or fewer) R^h's could be independent and more (or fewer) double ratios compared to those defined below could be useful. In the Higgs-radion mixing model custodial symmetry is violated, leading to *more* independent R^h's. For example, $R^h_{gg}(WW) \neq R^h_{gg}(ZZ)$ and $R^h_{VH}(X) \neq R^h_{\text{VBF}}(X)$.
[11] By "semiunified" we mean universal gaugino mass parameter $m_{1/2}$, scalar (sfermion) mass parameter m_0, and trilinear coupling $A_0 \equiv A_t = A_b = A_\tau$ at the GUT scale, but $m^2_{H_u}$, $m^2_{H_d}$, and m^2_S as well as A_λ and A_κ are taken as nonuniversal at M_{GUT}.
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model and again find that they deviate by substantial, often large, amounts relative to unity. In addition, there are other double ratios (see Ref. [10]) that also have similar discriminating power as well as the ability to detect the custodial symmetry violation implicit in the Higgs-radion mixing model. Details will be presented in Ref. [15].

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[16] For the ratio R_i/R_j, we use $\sigma^{\mathrm{upp,low}} = \frac{R_i}{R_j}\sqrt{(\sigma_i^{\mathrm{upp,low}}/R_i)^2 + (\sigma_j^{\mathrm{upp,low}}/R_j)^2}$ to calculate its combined asymmetric 1σ error bar, where $\sigma_i^{\mathrm{upp/low}}$ is the upper or lower 1σ error for the individual R_i.
[17] CMS Collaboration, Report No. CMS-PAS-HIG-12-020.