Total Width of 125 GeV Higgs Boson

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By using the LHC and Tevatron measurements of the cross sections to various decay channels relative to the standard model Higgs boson, the total width of the putative 125 GeV Higgs boson is determined as $6.1^{+7.7}_{-2.9}$ MeV. We describe a way to estimate the branching fraction for the Higgs-boson decay to dark matter. We also discuss a no-go theorem for the $\gamma\gamma$ signal of the Higgs boson at the LHC.

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The total width of the 125 GeV Higgs-boson signal is of intrinsic interest, but it is generally very difficult to determine the total width $\Gamma_{\rm tot}$ of a narrow resonance like the Higgs boson. Moreover, the determination of this quantity is also an important test of the Higgs mechanism of the Standard Model (SM). A sizable deviation from the SM prediction would directly indicate new physics. The Higgs-boson width can be measured at a γ-γ collider [1] or a $\mu^+\mu^-$ collider [2] through its line shape, and such facilities are under consideration.

We will present a simple method to determine the total width $\Gamma^{\rm tot}_{h^0}$ of the 125 GeV Higgs signal h^0 by using LHC and Tevatron measurements with the SM Higgs boson $h^0_{\rm SM}$ as a benchmark. We will apply this method to the data of the putative Higgs-boson signal with mass 125 GeV. Pre-LHC studies [3–6] were made of a similar ilk.

Outline of the method.—The h^0 total width is given by the sum of partial widths that can be normalized to the $h^0_{\rm SM}$ partial widths:

$$\Gamma^{\rm tot}_{h^0} = \sum_{A\bar{A}} \Gamma_{h^0\to A\bar{A}} = \sum_{A\bar{A}} \gamma_{AA} \Gamma_{h^0_{\rm SM}\to A\bar{A}}, \quad \gamma_{AA} = \frac{\Gamma_{h^0\to A\bar{A}}}{\Gamma_{h^0_{\rm SM}\to A\bar{A}}}. \quad (1)$$

For the 125 GeV Higgs boson, we consider the channels $A\bar{A} = b\bar{b}$, $\tau\tau$, gg, WW^*, ZZ^*, $c\bar{c}$, $\gamma\gamma$, and $Z\gamma$. γ_{AA} is the ratio of the h^0 partial width of the $A\bar{A}$ channel to that of $h^0_{\rm SM}$. The cross section of a given channel relative to the $h^0_{\rm SM}$ expectation is given by

$$XA \equiv \frac{\sigma(X\bar{X} \to h^0 \to A\bar{A})}{\sigma(X\bar{X} \to h^0_{\rm SM} \to A\bar{A})} = \frac{\gamma_{XX}\gamma_{AA}}{\Gamma^{\rm tot}_{h^0}/\Gamma^{\rm tot}_{h^0_{\rm SM}}}, \quad (2)$$

where X is the initial parton in the proton participating in the fusion process. Then, we can obtain $\Gamma^{\rm tot}_{h^0}$ via measurements of the ratios of Eq. (2) following Eq. (1). Equation (2) is derived from the proportionality of $\sigma(X\bar{X} \to h^0 \to A\bar{A})$ to the corresponding decay width $\Gamma_{h^0\to X\bar{X}}$ and the branching fraction $BF(h^0 \to A\bar{A})$, that is, $\sigma(X\bar{X} \to h^0 \to A\bar{A}) \propto \Gamma_{h^0\to X\bar{X}} \times BF(h^0 \to A\bar{A})$.

In Eq. (1), $\Gamma^{\rm tot}_{h^0}/\Gamma^{\rm tot}_{h^0_{\rm SM}}$ is represented by

$$\Gamma^{\rm tot}_{h^0}/\Gamma^{\rm tot}_{h^0_{\rm SM}} \equiv R = 0.58\gamma_{bb} + 0.06\gamma_{\tau\tau} + 0.24\gamma_{VV} + 0.09\gamma_{gg} + 0.03\gamma_{cc}, \quad (3)$$

where we use the BF of $h^0_{\rm SM}$ in Table I, extracted from Ref. [7], and assume $\gamma_{WW^*} = \gamma_{ZZ^*} (\equiv \gamma_{VV})$, as is the case for spontaneous symmetry breaking via the $SU(2)_L$ Higgs doublet [8]. γ_{cc} can be approximated by unity in Eq. (3) since γ_{cc} is a subleading contribution.

Illustrations of width determination.—The five γ parameters (gg, $b\bar{b}$, $\tau^+\tau^-$, VV, and $\gamma\gamma$) can be determined by LHC and Tevatron measurements of the corresponding ratios in Eq. (2). Then, the value of $\Gamma^{\rm tot}_{h^0}$ is determined by

$$\Gamma^{\rm tot}_{h^0} = \Gamma^{\rm tot}_{h^0_{\rm SM}}\left(0.58\gamma_{bb} + 0.06\gamma_{\tau\tau} + 0.24\gamma_{VV} + 0.09\gamma_{gg} + 0.03\right) \quad (4)$$

with $\Gamma^{\rm tot}_{h^0_{\rm SM}} = 4.07$ MeV [7]. The small $\gamma\gamma$ and $Z\gamma$ contributions can be neglected here.

The experimental values of the ratios of Eq. (2) at $m_{h^0} = 125$ GeV reported by CMS [9,10] and by ATLAS [11] are given in Table II, along with the ratio for the $b\bar{b}$ channel

TABLE I. Branching fractions of the SM Higgs boson with mass 125 GeV as predicted in Ref. [7]. The total Higgs width is $\Gamma^{\rm tot}_{h^0_{\rm SM}} = 4.07$ MeV with an uncertainty of ±4%.

Channel	$b\bar{b}$	$\tau^-\tau^+$	WW^*	ZZ^*	gg	$c\bar{c}$	$\gamma\gamma$	$Z\gamma$
Br (%)	57.7	6.32	21.5	2.64	8.57	2.91	0.228	0.154

TABLE II. $XA \equiv \sigma(X\bar{X} \to h^0 \to A\bar{A})/\sigma(X\bar{X} \to h^0_{SM} \to A\bar{A})$: The observed Higgs-signal cross sections at the LHC from various processes relative to the standard model Higgs boson at $m_{h^0} = 125$ GeV are given by CMS [9] and by ATLAS [11]. $VV \to \gamma\gamma$ is determined by CMS from dijet diphoton events [10]. The $b\bar{b}$ signal of the second row is inferred from the recent Tevatron data [12]. R is the h^0 total width relative to that of h^0_{SM} with the same mass. See Eq. (3).

σ/σ_{SM}		CMS [9,10]	ATLAS [11]	Tevatron [12]
$q\bar{q} \to Vb\bar{b}$	$Vb = \gamma_{VV}\gamma_{bb}/R$	$1.2^{+2.1}_{-1.9}$	$-0.8^{+1.8}_{-1.7}$	2.0 ± 0.7
$gg \to \tau^-\tau^+$	$g\tau = \gamma_{gg}\gamma_{\tau\tau}/R$	$0.63^{+1.00}_{-1.28}$	0.0 ± 1.7	
$gg \to \gamma\gamma$	$g\gamma = \gamma_{gg}\gamma_{\gamma\gamma}/R$	1.62 ± 0.68	$1.6^{+0.8}_{-0.7}$	
$gg \to WW^*$	$gW = \gamma_{gg}\gamma_{VV}/R$	0.40 ± 0.55	0.20 ± 0.62	$0.0^{+1.0}_{-0.0}$
$gg \to ZZ^*$	$gZ = \gamma_{gg}\gamma_{VV}/R$	$0.58^{+0.94}_{-0.58}$	$1.4^{+1.3}_{-0.8}$	
$VV \to \gamma\gamma$	$V\gamma = \gamma_{VV}\gamma_{\gamma\gamma}/R$	$3.8^{+2.4}_{-1.8}$ [10]		
$q\bar{q} \to VA\bar{A}$	$qA = \gamma_{VV}\gamma_{AA}/R$			

inferred from the latest Tevatron data [12]. A χ^2 fit gives the estimated values of the γ_{AA} parameters in Table III.

Because of the strong correlations between $\gamma_{bb,\tau\tau}$ and $\gamma_{\gamma\gamma}$, loose upper limits are obtained for these quantities from the present data. We obtain the value $\Gamma^{tot}_{h^0} = 6.1^{+7.7}_{-2.9}$ MeV. However, the determination will be much improved (see, e.g., Refs. [3,5]) as the data increase. The 2012 LHC run is expected to accumulate an integrated luminosity of 15 fb^{-1} per experiment at 8 TeV and those data can be combined with the data from the 5 fb^{-1} at 7 TeV. If all the LHC uncertainties become half the present ones and the central values remain the same, the value of $\Gamma^{tot}_{h^0}$ becomes $\Gamma^{tot}_{h^0} = 3.4^{+2.3}_{-1.5}$ MeV.

$\gamma\gamma$ enhancement.—The $\gamma\gamma$ cross section seems to be enhanced compared with h^0_{SM}, although this could be an upward statistical fluctuation. In the SM, it is given theoretically by the triangle loop diagrams of the W boson and top quark. If a new heavy fermion and/or a heavy scalar couple to the SM Higgs boson, and their masses are generated by the Higgs mechanism, the $\gamma_{\gamma\gamma}$ and γ_{gg} are given (see, e.g., Ref. [13]) by

$$\gamma_{\gamma\gamma} = \left(\frac{\frac{7}{4}1.19 - \frac{4}{9}1.03 - \frac{N_c}{3}Q_f^2 - \frac{N_c}{12}Q_S^2}{\frac{7}{4}1.19 - \frac{4}{9}1.03}\right)^2,$$
$$\gamma_{gg} = \left(\frac{-\frac{1}{6}1.03 - \frac{C_f}{3} - f_S\frac{C_S}{12}}{-\frac{1}{6}1.03}\right)^2, \tag{5}$$

where the 1st (2nd) term in the numerator or denominator in $\gamma_{\gamma\gamma}$ represents the W boson (top quark) loop and 1.19 (1.03) is the correction from the finite $W(t)$ mass. The first terms in the denominator and the numerator in γ_{gg} are from the top quark loop. Here, we have assumed the h^0 couplings to W and t are the same as those of h^0_{SM}. The masses of the new particles are assumed to be sufficiently heavy that the mass corrections can be neglected. The numerators and denominators are normalized in Eq. (5) to a fermion contribution. $Q_{f,S}$ is the electric charge of a new fermion (scalar). N_c is the color degree of freedom of a new particle in the loop. $C_{f,S}$ is the quadratic color Casimir factor of the new fermion (scalar). It is 1/2(3) in the fundamental (adjoint) representation; $f_S = 1(1/2)$ for a complex (real) scalar. It is an important conclusion that a new fermion or scalar contribution, if it does not have a large N_c, works to decrease $\gamma_{\gamma\gamma}$ [14]. For example, in the fourth-generation model, $(\gamma_{\gamma\gamma}, \gamma_{gg}) = (0.21, 8.7)$. The large γ_{gg} of the fourth generation leads to $R(= \Gamma^{tot}_{h^0}/\Gamma^{tot}_{h^0_{SM}}) = 1.66$, and correspondingly the WW^*, ZZ^*, $b\bar{b}$, and $\tau^-\tau^+$ channels from gluon fusion are enhanced by $\gamma_{gg}/R = 5.2$; $\gamma\gamma$ via gluon fusion is $\gamma_{gg}\gamma_{\gamma\gamma}/R = 1.1$, almost the same as the SM, while $\gamma\gamma$ by vector-boson fusion is strongly suppressed, $\gamma_{\gamma\gamma}/R = 0.12$. If the $\gamma\gamma$ enhancement in the diphoton dijet events [10] is mainly from VV fusion and the measured value is confirmed, the fourth-generation model will be excluded mass-independently. See also Ref. [15].

TABLE III. γ_{AA} obtained by the fit to the data in Table II. One-sigma statistical uncertainties are given. Partial widths of the 125 GeV Higgs $\Gamma_{h^0\to A\bar{A}}$ and the BF are also given. The total width is estimated to be $\Gamma^{tot}_{h^0} = 6.1^{+7.7}_{-2.9}$ MeV. The errors of $\Gamma^{tot}_{h^0}$ and $BF(h^0 \to b\bar{b})$ correspond to the one standard deviation of γ_{bb}. The BF errors for the other channels are estimated by treating Γ_{AA} and $\Gamma^{tot}_{h^0}$ as independent quantities. In the SM, all the γ_{AA} are unity and the total width is $\Gamma^{tot}_{h^0_{SM}} = 4.07$ MeV [7].

$A\bar{A}$	$b\bar{b}$	$\tau^-\tau^+$	WW^*	ZZ^*	gg	$\gamma\gamma$
γ_{AA}	$1.8^{+3.1}_{-1.1}$	$1.1^{+3.8}_{-2.7}$	$1.34^{+0.57}_{-0.45}$	$1.34^{+0.57}_{-0.45}$	$0.57^{+0.48}_{-0.25}$	$4.3^{+5.2}_{-1.8}$
$BF(h^0 \to A\bar{A})$ (%)	$68.7^{+14.9}_{-17.1}$	$4.5^{+16.0}_{-11.3}$	$19.1^{+19.1}_{-12.4}$	$2.3^{+2.3}_{-1.4}$	$3.2^{+3.9}_{-2.2}$	$0.65^{+0.98}_{-0.45}$
$\Gamma_{h^0\to A\bar{A}}$ (MeV)	$4.2^{+7.3}_{-2.6}$	$0.3^{+1.0}_{-0.7}$	$1.2^{+0.5}_{-0.4}$	$0.14^{+0.06}_{-0.04}$	$0.20^{+0.16}_{-0.09}$	$0.04^{+0.05}_{-0.02}$

Similarly, if the enhancement of $VV \to h^0 \to \gamma\gamma$ is confirmed, the interpretation of the 125 GeV Higgs-boson signal as the dilaton or radion [16–18] will be discarded, since the vector-boson fusion to the diphoton cross section is strongly suppressed in these models compared with the SM Higgs boson.

The loop contributions of a new scalar or a new fermion are proportional to dimensionless factors $\lambda_{f,S}$,

$$\lambda_f = \frac{y_f v}{m_f}, \qquad \lambda_S = \frac{y_{h^0 SS} v}{2m_S^2}, \tag{6}$$

where $y_f(y_{h^0SS})$ is the Yukawa coupling of the new fermion (scalar) and the v is the Higgs vacuum expectation value $v \simeq 246$ GeV. $\lambda_{f,S} = 1$ corresponds to the case that the fermion (scalar) mass is generated by the Higgs mechanism. For a heavy particle with no Higgs mechanism for its mass generation, $\lambda_{f,S} \ll 1$ and $\gamma_{gg} \simeq \gamma_{\gamma\gamma} \simeq 1$, so the $\gamma\gamma$ cross section becomes the same as the SM Higgs boson. To obtain a large enhancement, a $m_{f,S}$ smaller than v is necessary or alternatively the color factor of the new particle is large.

The cross section ratios of various processes relative to the SM Higgs boson are plotted versus $\lambda_{f,S}$ in the cases of a color-octet fermion (denoted as $F8$, also called leptogluon [19]) and a color-octet scalar ($S8$) in Fig. 1.

The $S8$ [20] is an interesting possibility. It was discussed in the context of Higgs underproduction [21,22] at LHC for the circumstance that this new scalar has light mass and the Higgs boson has a sizable branching fraction to this scalar channel. If the mass of this color-octet scalar is generated by the Higgs mechanism, following Eq. (5), by using $N_c = 8$ ($C_S = 3$), the γ values of a $Q_s = 1$ charged scalar are $(\gamma_{\gamma\gamma}, \gamma_{gg}) = (0.35, 6.0)$. For a new scalar without a Higgs origin for its mass generation, the sign of the coupling λ is arbitrary. In the $S8$ case of Fig. 1, both enhancement factors, $g\gamma$ and $V\gamma$, are less than $\sim$2. Similar results are also obtained for a color-triplet scalar ($S3$: leptoquark) and a color-triplet fermion ($F3$). However, the present data seem to suggest WW^* suppression and $\gamma\gamma$ enhancement in gg fusion and VV fusion. This tendency is not reproduced by $S8$ but may be realized with $F8$, as can be seen in Fig. 2, where the preferred regions of the parameters $\lambda_f N_c Q_f^2$ and $\lambda_f C_f$ by the present data are shown. In the case of $F8$ (leptogluon), the trends of the present data can be reproduced with $\lambda_f \approx -0.31$, as shown by the yellow vertical band of $F8$ in Fig. 1, for which $(g\gamma, gV, V\gamma) = (1.52, 0.67, 2.35)$. If the Yukawa coupling of the leptogluon is the same as the top quark, but the sign of λ is reversed, its mass is estimated to be $m_{F8} = m_t/0.31 \simeq 500$ GeV. The corresponding $Z\gamma$ partial decay width is almost the same as the SM Higgs boson: $\gamma_{Z\gamma} = 1.04$. Then, a $Z\gamma$ cross section ratio via gluon fusion of 0.69 ± 0.09 is predicted, which is almost the same as gV.

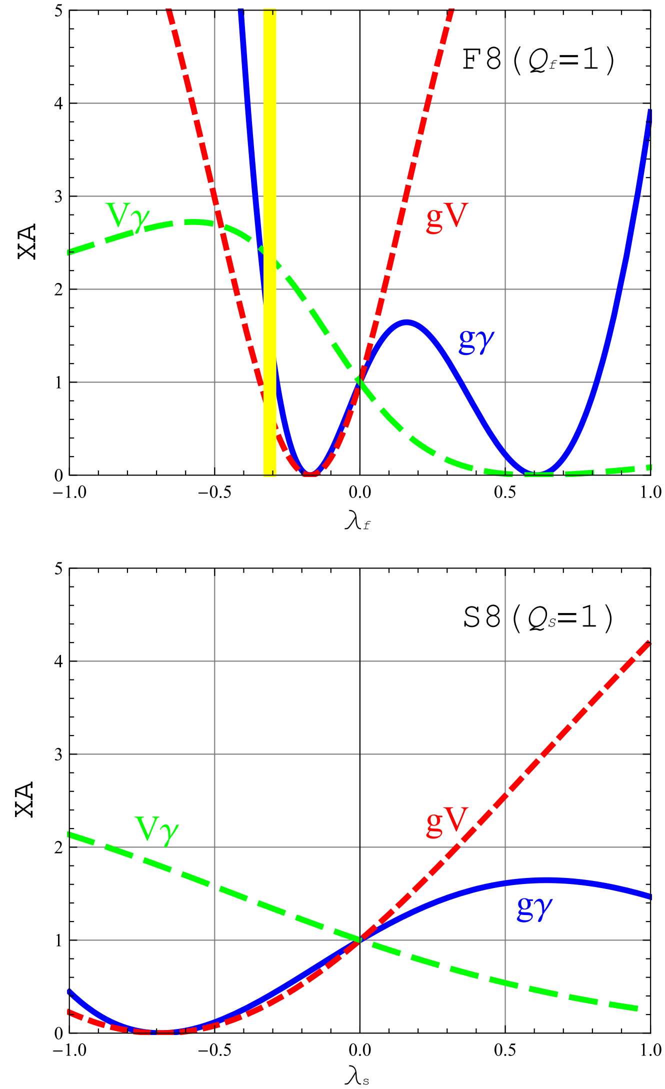

FIG. 1 (color online). $\lambda_{f,S}$ dependence of the cross sections of various processes relative to the SM Higgs boson, for the case of a color-octet fermion (leptogluon: $F8$) with charge $Q_s = 1$ and a color-octet scalar ($S8$) with $Q_s = 1$: $XA \equiv \sigma(X\bar{X} \to h^0 \to A\bar{A})/\sigma(X\bar{X} \to h^0_{\rm SM} \to A\bar{A})$. We consider three quantities, $XA = g\gamma$, gV, and $V\gamma$, corresponding to $gg \to \gamma\gamma$ (solid blue line), $gg \to VV$ (WW^* or ZZ^*) (short-dashed red line), and $VV \to \gamma\gamma$ (long-dashed green line). $\lambda_{f,S}$ is the Higgs coupling normalized by the Yukawa couplings giving the masses by the Higgs mechanism. See Eq. (7) for the definition. The yellow vertical band in the top panel is preferred by the present data, suggesting $\gamma\gamma$ enhancement.

More generally, Fig. 2 is a vector space that can be used in identifying new particle contributions from experimental measurements of the XA.

Solutions satisfying $g\gamma > 1$, $V\gamma > 2$, and $gV < 1$ for lower-dimensional representations of $SU(3)_c$ are summarized in Table IV.

It is very difficult to obtain $V\gamma > 2$ and $g\gamma > 1$. This constitutes a no-go theorem. Only the $F8$ (and $F6$) are

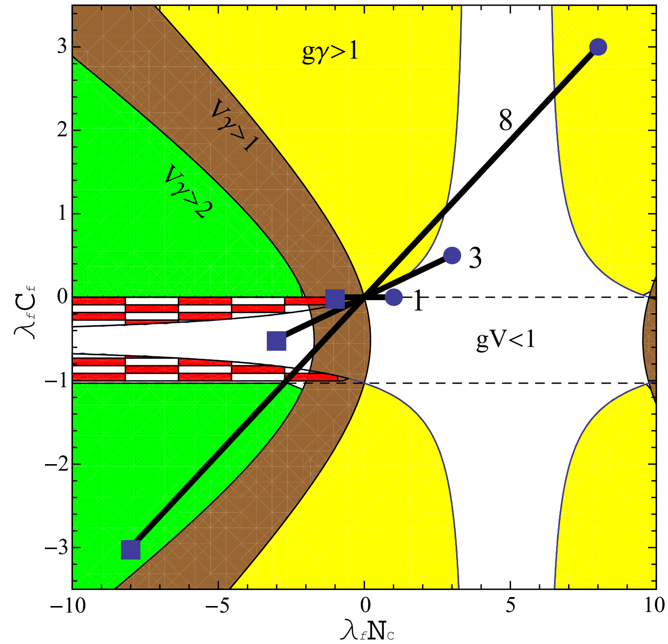

FIG. 2 (color online). Regions of $\gamma\gamma$ enhancement in the $\lambda_f N_c Q_f^2$, $\lambda_f C_f$ plane in the $Q_f = 1$ case. The $g\gamma > 1$ region is divided into four colored regions: $V\gamma < 1$, $1 < V\gamma < 2$, and $2 < V\gamma$ are yellow (light gray), brown (medium gray), and green (dark gray), respectively. The red meshed region, which is preferred by the present experimental data, corresponds to $V\gamma > 1$ and $gV < 1$, where the latter is between the two horizontal lines, $\lambda_f C_f = 0, -1.03$. A color-octet fermion (leptogluon), a color-triplet fermion, and a color-singlet fermion are shown by solid lines with the end points corresponding to $\lambda_f = -1$ (squares) and $\lambda_f = 1$ (circles). In the $Q_f \neq 1$ case, the x coordinates scale with Q_f^2. $\lambda_f = 1$ corresponds to the case of its mass generated by the Higgs mechanism. A color-octet fermion with $Q_f = 1$ is consistent with the red meshed region at $\lambda_f \simeq -0.31$. For a new scalar, the lengths of the theory lines should be scaled by $1/4$; thus, a scalar octet has no overlap with the preferred red meshed region.

possible if we limit the charge of the new particle $Q_f \leq 1$. For still higher-dimensional color representations, the theory lines do not overlap with the preferred region for the $Q \leq 1$ case, as can be deduced from Fig. 2.

The possibilities of light stop and light stau in the minimal supersymmetric standard model are discussed in Refs. [23–26]. The effect of the stop loop is suppressed compared with the top-quark loop because the stop quark is scalar, and the chargino contribution is suppressed by the absence of color. The stau effect is suppressed by both. The $\gamma\gamma$ production ratio generally does not deviate much from unity in supersymmetry.

Similarly, in the universal extra dimension model, where the KK modes of W bosons, quarks, and leptons contribute to the loop, at most a 50% enhancement of $\gamma\gamma$ is found for the allowed region of parameters [27].

TABLE IV. Solution satisfying the $\gamma\gamma$ enhancement for $SU(3)$ representations with dimensions ≤ 27. $F3$ and $S10$ represent the color-triplet fermion and the color-decouplet scalar, for example. The typical values of λ satisfying $g\gamma > 1$, $V\gamma > 2$, and $gV < 1$ are given.

	Q_f	λ_f		Q_s	λ_s
$F1$	5/3(2)	−0.9(−0.7)			
$F3$	5/3(2)	−0.2(−0.3)	$S3$	5/3(2)	−1.0(−0.9)
$F6$	1(5/3)	−0.38(−0.32)			
$F8$	1(4/3)	−0.31(−0.3)			
$F10$	4/3(2)	−0.13(−0.12)	$S10$	4/3(2)	−0.50(−0.45)
$F27$	5/3(2)	−0.034(−0.032)	$S27$	5/3(2)	−0.14(−0.13)

Possible dark matter contribution.—When we consider the possible decay to the dark matter channel, $\Gamma_{h^0}^{\rm tot}$ is replaced by the decay width to the visible channels $\Gamma_{h^0}^{\rm vis}$ in the left-hand sides of Eqs. (1), (3), and (4), while Eq. (2) is unchanged. The $\Gamma_{h^0}^{\rm tot}$ in Eq. (2) now includes the partial decay width to the dark matter channel $\Gamma_{h^0 \to D\bar{D}}$ as [28]

$$\Gamma_{h^0}^{\rm tot} = \Gamma_{h^0}^{\rm vis} + \Gamma_{h^0 \to DD} \equiv F\Gamma_{h^0}^{\rm vis}, \qquad \Gamma_{h^0}^{\rm vis} \equiv \sum_{A\bar{A}=b\bar{b},\tau^-\tau^+,VV,gg,c\bar{c}} \Gamma_{h^0 \to A\bar{A}}. \tag{7}$$

The detection of the Higgs invisible decays at hadron colliders has been studied in Refs. [29,30]. The factor $F(\geq 1)$ is related to the BF to dark matter D by

$$BF(h^0 \to D\bar{D}) = \frac{F-1}{F}. \tag{8}$$

Our method of fitting the quantities of the left-hand side of Eq. (2) now determines $\gamma'_{AA} \equiv \gamma_{AA}/F$, not γ_{AA}, since in Eq. (2) $\Gamma_{h^0}^{\rm tot}/\Gamma_{h^0_{\rm SM}} = F\Gamma_{h^0}^{\rm vis}/\Gamma_{h^0_{\rm SM}} = FR$, where R is given by the second equality of Eq. (3).

In many models, such as the minimal supersymmetric standard model in the decoupling limit, the WW^* and ZZ^* couplings are nearly the same as those of the SM Higgs boson: $\gamma_{VV} \simeq 1$ [31]. In this case, the value of γ_{VV}/F obtained by our method gives directly the value of $1/F$ which in turn gives $BF(h^0 \to DD)$ following Eq. (8). The best-fit value of γ_{VV}/F in Table III is $1.34^{+0.57}_{-0.45}$ which suggests $F \simeq 1$. A very large BF [32] to the invisible decay channel is disfavored [33]. $BF(h^0 \to D\bar{D}) < 0.46$ in a 95% confidence level from the present data.

Concluding remarks.—We have presented a method of determining the total width of the putative 125 GeV Higgs boson. The measurements of the $\gamma\gamma$ cross section of the Higgs signal relative to that of the SM will discriminate amongst many candidate models of new physics. It is difficult to obtain a theoretical enhancement of the $\gamma\gamma$ signal of more than 2. This constitutes a no-go theorem. For a charge $Q \leq 1$, this theorem is evaded with a new light-mass fermion with a color octet (leptogluon) or a color sextet and a negative Higgs coupling. Such a colored state can be directly tested [34] by LHC experiments.

Measurements of the vector-boson fusion process and the vector-boson bremsstrahlung processes (cf. Table II) can significantly improve the uncertainty on the total Higgs width estimate.

Accurate measurement of the ratio of the $\gamma\gamma$ to ZZ^* cross sections would determine $\gamma_{\gamma\gamma}/\gamma_{VV}$, independently of the value of γ_{gg}.

The branching fraction for the decay of the Higgs boson to dark matter can be inferred in the decoupling limit of the WW^* and ZZ^* couplings of any two Higgs doublet models [35].

The methods presented in this Letter should be useful when higher statistics data are acquired on the Higgs signal. One must be cautious about overinterpreting the data until the Higgs signal is fully established.

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