Higgs underproduction at the LHC

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We show that production of the Higgs boson through gluon-fusion may be suppressed in the presence of colored scalars. Substantial destructive interference between the top-quark diagrams and colored scalar diagrams is possible due to cancellations between the real (and also imaginary) parts of the amplitudes. As an example, we consider a color-octet scalar that has a negative, order-one coupling to the Higgs doublet. We find that gluon fusion can be suppressed by more than an order of magnitude when the scalar mass is below a few hundred GeV, while milder suppressions occur for larger scalar masses or smaller couplings. Thus, the standard model extended with only one particle can evade the full range of present LHC exclusion limits on the Higgs mass. The colored scalars, however, would be produced in pairs with a large rate at the LHC, leading to multijet final states to which the LHC experiments are now becoming sensitive.

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I. INTRODUCTION

How effectively can new particles hide the Higgs boson from experiment? With the ATLAS and CMS experiments at the Large Hadron Collider (LHC) having reached exclusion of the standard model Higgs boson throughout a significant range of its mass [1], this question has taken on heightened importance. In this paper we demonstrate that gluon fusion [2]—the dominant production of Higgs boson at the LHC—can be substantially reduced by one or more colored scalars with weak-scale mass and order-one couplings to the Higgs doublet.

Within the standard model, the overwhelmingly dominant contribution to Higgs production through gluon fusion comes from a top-quark loop [3]. Beyond the standard model, there can be one-loop contributions from particles that carry color and that also interact with the Higgs doublet. Fermions with renormalizable couplings to the Higgs doublet have contributions to the gluon-fusion amplitude of the same sign as the top loop (e.g., a fourth generation [4]). Large suppressions to gluon fusion thus appear to require some colored bosons.

In this paper we consider the possible suppression of Higgs production through gluon fusion in the presence of colored scalar fields. One or more scalars ϕ_i transforming under QCD can be coupled to the Higgs doublet through the renormalizable "Higgs portal" interactions $-\kappa\phi_i^\dagger\phi_i H^\dagger H$ in the Lagrangian. We point out that the sign of the parameter κ is not theoretically determined, so that for one choice, *negative* κ, the scalar contribution interferes destructively with the top loop. Examples of models with colored scalars where effects on Higgs production are discussed include, for example, Refs. [5–10].

The reduction of gluon fusion has been noted previously in the minimal supersymmetric standard model (MSSM), where squark loops may partially cancel the top loop for certain regions of parameter space [5]. In that case, the Higgs boson is already required to be rather light in the MSSM, in the mass region that is not yet ruled out by LHC and Tevatron data. Futhermore, supersymmetry requires the assortment of colored superpartners that is being pushed to higher masses by the nonobservation results from the searches for supersymmetry at the LHC. By contrast, we are interested in a more general scenario here, where the suppression of gluon fusion occurs for a wide range of Higgs masses, and the particle responsible for the suppression is harder to detect. The concrete example we study here is the standard model extended by an electroweak-singlet, color-octet real scalar [11–13].

Besides explicit, renormalizable models that include particles running in loops that suppress gluon fusion, one can imagine a strongly-coupled sector [14,15] that generates the dimension-six operator $G_{\mu\nu}G^{\mu\nu}H^\dagger H/(2\Lambda^2)$ in the Lagrangian with the appropriate sign to cancel the top loop. In Ref. [14] it was shown that a coefficient of -1 for this operator leads to complete destructive interference with the standard model contribution for $\Lambda \simeq 3$ TeV. If this operator is generated by a one-loop diagram involving a particle of mass M and coupling of order one to the Higgs doublet, then a naive loop factor of $1/(4\pi)^2$ leads to a value $M \sim \Lambda/(4\pi)$. As we will see, the loop suppression is accidentally stronger, so that M needs to be somewhat smaller than $\Lambda/(4\pi)$. A detailed analysis is required to determine whether such light colored scalars are permitted by existing bounds from collider experiments.

We emphasize that this class of models leaves electroweak symmetry breaking unaffected. As a result, the branching fractions of the Higgs boson remain virtually unaffected throughout the Higgs mass range, especially when the colored scalars are electroweak-singlet. Only the decay width into gluon pairs is reduced when Higgs production through gluon fusion is suppressed, but this decay is very hard to observe and its branching fraction is already smaller than about 9% for any Higgs mass allowed by LEP. This is in contrast to models that modify the mechanism of electroweak symmetry breaking, which, not surprisingly, affect both Higgs production and decay, especially in the light Higgs region [16].

II. MODELS OF UNDERPRODUCTION

The general class of models leading to modifications in Higgs production that we consider consist of the standard model extended to include a set of real or complex scalars ϕ_i transforming under some representations of the color $SU(3)$ group. The renormalizable interactions of the colored scalars are of the form

$$\mathcal{L}(\phi_i) = D_\mu \phi_i^\dagger D^\mu \phi_i - M_i^2 \phi_i^\dagger \phi_i - \kappa_{ij} \phi_i^\dagger \phi_j H^\dagger H - \lambda_{ijkl} \phi_i^\dagger \phi_j \phi_k^\dagger \phi_l \quad (2.1)$$

where suitable color contractions are implicit (for λ_{ijkl}, this can result in several independent interactions). This set of interactions can be recast for real scalar fields under the replacement $(\phi_i, \phi_i^\dagger) \to (\phi_i, \phi_i)/\sqrt{2}$. Additional representation-dependent renormalizable interactions are possible, such as $\epsilon_{\alpha\beta\gamma}\phi_i^\alpha \phi_j^\beta \phi_k^\gamma$ for color triplets, $d_{abc}\phi_i^a \phi_j^b \phi_k^c$ for color octets, etc.

The Higgs portal interactions proportional to κ are our primary interest. Consider the effects of a single scalar field, ϕ_i. Expanding $H = (v + h)/\sqrt{2}$ gives the dimension-three operator $\kappa_{ii} v \phi_i^\dagger \phi_i h$, that leads to the one-loop colored scalar contributions to gluon fusion shown in Fig. 1. For a complex scalar field, the diagrams in Fig. 1 are added to the "gluon-crossed" triangle diagram to obtain a finite result, similar to the calculation of the top-quark loop. For a real scalar field there is no gluon-crossed diagram, but the bubble diagram has a symmetry factor of 1/2 such that the result is again finite.

These new physics contributions combine with the standard model contributions to the gluon-fusion process. For production of a single on-shell Higgs in the narrow width approximation, the gluon-fusion rate is proportional to the partial width of the Higgs boson into gluons,

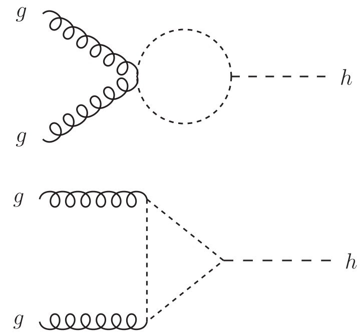

FIG. 1. Feynman diagrams for scalar loop contributions to $gg \to h$. A real scalar field has precisely these diagrams, while a complex field also has a third diagram that can be obtained from the second diagram by swapping the initial state gluons.

$$\hat{\sigma}(gg \to h) = \frac{\pi^2 \Gamma(h \to gg)}{8M_h} \delta(\hat{s} - M_h^2). \quad (2.2)$$

At leading order, that partial width is

$$\Gamma(h \to gg) = \frac{G_F \alpha_s^2 M_h^3}{64\sqrt{2}\pi^3} \left| A_t(\tau_t) + \sum_i c_i \kappa_{ii} \frac{v^2}{2M_i^2} A_i(\tau_i) \right|^2 \quad (2.3)$$

where $c_i = C_A^i$ ($c_i = 2C_A^i$) is equal to (twice) the quadratic Casimir of the QCD representation of the ith scalar in a real (complex) representation. Here $\tau_t \equiv M_h^2/(4M_t^2)$ and $\tau_i \equiv M_h^2/(4M_i^2)$ while A_t and A_i are the contributions to the amplitude from top-quark loops and scalar loops, respectively. For the scalar contribution we obtain

$$\tau_i A_i(\tau_i) = 2M_i^2 C_0(4M_i^2 \tau_i; M_i) + 1 \quad (2.4)$$

in terms of the three-point Passarino-Veltman [17] function C_0, defined by

$$C_0(s; m) \equiv C_0(p_1, p_2; m, m, m) = \int \frac{d^4 q}{i\pi^2} \frac{1}{(q^2 - m^2)[(q + p_1)^2 - m^2][(q + p_1 + p_2)^2 - m^2]} \quad (2.5)$$

where $p_1^2 = p_2^2 = 0$ and $(p_1 + p_2)^2 = s$. The well-known top loop is [2,18]

$$\tau_t A_t(\tau_t) = -4M_t^2(1 - \tau_t) C_0(4M_t^2 \tau_t; M_t) - 2. \quad (2.6)$$

Using these expressions, it is straightforward to calculate the effects of one or more scalars on the gluon-fusion rate.

In the limit where the Higgs mass is small, $M_h \ll M_t$, M_i, the amplitudes are real, and asymptote to mass-independent values: $A_t(0) = -4/3$ and $A_i(0) = -1/3$. This yields the following change in the $h \to gg$ width:

$$\left(\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{\rm SM}} \right)_{M_h \ll M_t, M_i} \approx \left| 1 + \sum_i c_i \kappa_{ii} \frac{v^2}{8M_i^2} \right|^2, \quad (2.7)$$

where $\Gamma(h \to gg)_{\rm SM}$ is the standard model width. This shows that *suppression* of Higgs production occurs for $\kappa_{ii} < 0$.[1] For a single colored scalar, a substantial cancellation between the top and scalar loops is possible when its

[1]This was noted in Ref. [10] in the context of a real scalar color octet, but not explored further.

mass is related to its Higgs portal coupling by $M_i \approx v\sqrt{c_{ii}|\kappa_i|/8}$.

In the particular case $M_h = M_i = M_t$, the amplitudes are $A_t(1/4) = -8(1-\pi^2/12)$ and $A_i(1/4) = -4(\pi^2/9 - 1)$, so that

$$\left(\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{\rm SM}}\right)_{M_h=M_i=M_t} \approx \left|1 + \frac{2}{3}\left(\frac{\pi^2-9}{12-\pi^2}\right)\sum_i c_i \kappa_{ii}\right|^2 \tag{2.8}$$

where we used $v \approx \sqrt{2}M_t$. Substantial cancellation in this case requires $\sum_i c_i \kappa_{ii} \approx -3.7$.

Color-octet real (complex) scalars have $c_i = 3$ (6), so that the above particular cases show that gluon fusion may be strongly suppressed with order-one couplings. We will analyze the color-octets in Sec. III. In the case of color-triplet complex scalars, the Casimir is smaller, $c_i = 1$, so that several triplets are necessary to obtain substantial suppression with order-one κ_{ii} couplings.

Supersymmetric models automatically have color-triplet scalars with substantial couplings to the Higgs sector. The possibility of destructive interference between the top loop and loops of stops has been explored previously [5]. In the supersymmetric case, the coupling to the Higgs is determined by supersymmetric as well as supersymmetry-breaking interactions, and so the size and sign of the contribution is model-dependent. In the limit of no supersymmetry breaking with $\tan\beta = 1$ and $\mu = 0$, there are two mass eigenstates, a pure $\tilde{t}_L$ and $\tilde{t}_R$ with masses equal to the top mass and Higgs portal coupling given by $\kappa = y_t^2$. In the limit $M_h \ll M_t = M_{\tilde{t}}$, the addition of the stops results in an increase in the amplitude by a factor of 3/2, and thus an increase in the Higgs production rate by a factor of 9/4. This is indicative of the size of the correction that colored scalars can provide, but this particular limit does not yield a realistic model of low-energy supersymmetry due to the lack of both tree-level *and* one-loop corrections to the Higgs mass itself.

If the Higgs mass is large enough for an on-shell decay to proceed, the $h \to gg$ amplitude develops an imaginary part. Two on-shell decays could occur: $h \to t\bar{t}$ and/or $h \to \phi_i^{(\dagger)}\phi_i$. This leaves four distinct possibilities:

(i) $M_h < 2M_i, 2M_t$: No imaginary part is generated for the amplitudes; suppression of gluon fusion arises entirely through cancellation of the real parts of the diagrams.

(ii) $2M_i < M_h < 2M_t$: An imaginary part is generated for the amplitude involving colored scalars. It increases rapidly (in magnitude), such that $\mathrm{Im}[A_i(\tau_i)] = \mathrm{Re}[A_i(\tau_i)]$ is achieved already once $M_h \simeq 2.15 M_i$. This results in a significant noncancelable contribution to the amplitude for Higgs production through gluon fusion.

(iii) $2M_t < M_h < 2M_i$: An imaginary part is generated for the amplitude involving top quarks. It increases more slowly, we find $\mathrm{Im}[A_t(\tau_t)] = (1/4, 1/2, 1) \times \mathrm{Re}[A_t(\tau_t)]$ occurs when $M_h \simeq (2.3, 2.5, 3.1)M_t$. Hence, there is a region of parameter space when $2M_t \lesssim M_h$ for which sizeable cancellation in the real parts remains sufficient to suppress Higgs production through gluon fusion.

(iv) $2M_i, 2M_t < M_h$: Imaginary parts are generated for both amplitudes involving colored scalars as well as top quarks. Interestingly, for $2M_i \simeq M_h$ and with $M_h \gtrsim 2M_t$, both the real and imaginary contributions to A_t and A_i are negative. This suggests there is an interesting regime where both the real and imaginary parts of the contributions from top loops and colored scalar loops can *simultaneously* destructively interfere.

We will see all four of these cases arise in the specific model involving a color-octet scalar considered in the next section.

It is also interesting to estimate how small the $gg \to h$ rate could be made in principle. Note that so far we have neglected other quark contributions to the amplitude. While it is possible for scalar loop contributions to cancel the sum of the real parts of the top loop and the much smaller light quark contributions, without extraordinary tuning it is not possible to also cancel the small *imaginary* part that accompanies $h \to b\bar{b}$. Even for the smallest Higgs mass allowed by LEPII, we find the absolute value of the imaginary part of the b-quark loop contribution is smaller than 10% of the absolute value (real part) of the top-quark contribution to the amplitude. Hence, the gluon-fusion Higgs production rate could be as small as 1% of the standard model rate while not running afoul of this lower bound.

III. COLOR-OCTET REAL SCALAR

Let us now consider the standard model plus an electroweak-singlet, color-octet real scalar field Θ^a. The most general renormalizable Lagrangian involving Θ^a is

$$\begin{aligned}\mathcal{L}_\Theta &= \frac{1}{2}(D_\mu \Theta^a)^2 - \frac{1}{2}(M_0^2 + \kappa H^\dagger H)\Theta^a\Theta^a \\ &\quad - \mu_\Theta d_{abc}\Theta^a\Theta^b\Theta^c - \frac{\lambda_\Theta}{8}(\Theta^a\Theta^a)^2 \\ &\quad - \lambda'_\Theta d_{abe}d_{cde}\Theta^a\Theta^b\Theta^c\Theta^d.\end{aligned} \tag{3.1}$$

Here κ, λ_Θ and λ'_Θ are dimensionless real parameters, M_0 and μ_Θ are real parameters of mass dimension +1, and d_{abc} is the totally symmetric $SU(3)$ tensor. After electroweak symmetry breaking, the octet obtains the physical mass

$$M_\Theta^2 = M_0^2 + \frac{\kappa}{2}v^2, \tag{3.2}$$

which we require to be positive definite. This implies a constraint on the bare (mass)^2, $M_0^2 > -\kappa v^2/2$. As we saw in Sec. II, a negative Higgs portal interaction, $\kappa < 0$, is interesting because it leads to destructive interference between the top-quark and scalar loops. To ensure that Θ does not acquire a VEV, one needs to impose $\lambda_\Theta > 0$ and $|\mu_\Theta| \lesssim M_\Theta$ (the precise upper limit depends on M_h, λ_Θ and λ'_Θ, as well as on the sign of μ_Θ).

The effects of a color-octet scalar on the suppression of Higgs production through gluon fusion can be obtained directly from the results of Sec. II, substituting $c = C_A = 3$. We evaluate the Passarino-Veltman function using the LoopTools package [19]. The parameter space is controlled by the Higgs mass and two parameters in the octet model, (M_Θ, κ). In Fig. 2 we show contours of $\sigma(gg \to h)$

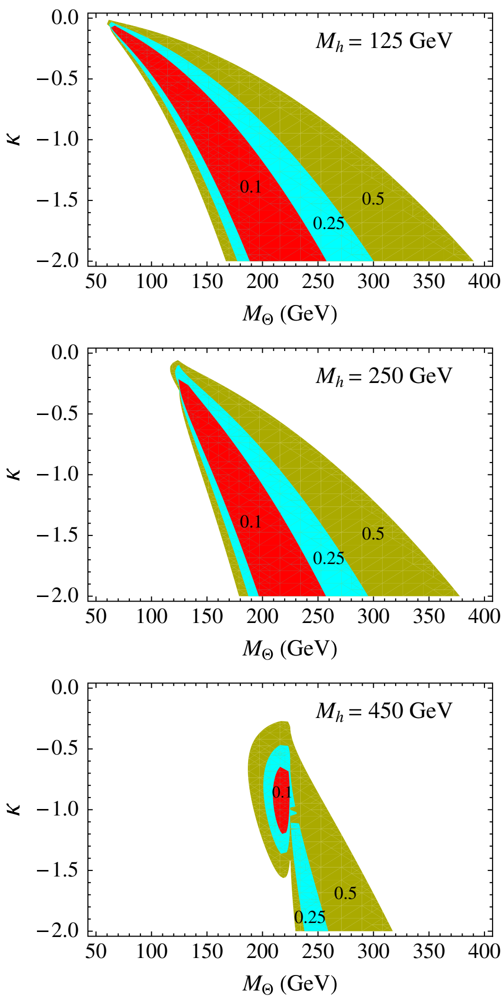

FIG. 2 (color online). Contours of the Higgs production cross section through gluon fusion at leading order, including the effects of a color-octet real scalar having Higgs portal coupling κ and mass M_Θ, normalized to the standard model value. The inner (red), middle (blue), outer (green) regions correspond to $\sigma(pp \to h)/\sigma(pp \to h)_{\rm SM} < 0.1,\ 0.25,\ 0.5$, respectively. The top, middle, and bottom panels show increasing Higgs mass. As thresholds for $h \to$ 2-body decays are crossed, qualitative changes in the suppression of the Higgs production through gluon fusion are evident.

in the M_Θ versus κ plane for three choices of Higgs mass, $M_h = 125,\ 250,\ 450$ GeV. In this contour plot, we have normalized the cross sections to the standard model value at leading order. Working within the narrow width approximation, all parton distribution effects factorize and the ratio of cross sections is simply the ratio of widths, $\Gamma(h \to gg)/\Gamma(h \to gg)_{\rm SM}$.

The striking result is that the Higgs production is substantially reduced in a large region of the (M_Θ, κ) parameter space. In the $M_h = 125$, 250 GeV panels, the contours cut off fairly rapidly near $M_\Theta = M_h/2$, corresponding to when the scalar contribution to the amplitude develops an imaginary part resulting from $h \to \Theta\Theta$ going on-shell.

In the $M_h = 450$ GeV panel, since the decay $h \to t\bar{t}$ goes on-shell, the amplitude again develops an imaginary part from the top loop. Here we see two regions where suppression to Higgs production is possible. The first region, when $M_\Theta > M_h/2$, is analogous to similar regions for lower Higgs masses. However, since there is a noncancelable imaginary part, the size of the cross section suppression is more limited within the range of parameters shown. The second region, when $M_\Theta \lesssim M_h/2$, both the top loop and scalar loops have both real and imaginary parts that partially destructively interfere. Surprisingly, the interference can be just as effective in this region of parameter space as we found when the amplitudes were purely real, $M_h < 2M_t,\ 2M_\Theta$.

In Fig. 3 we again show contours of $\sigma(gg \to h)$, normalized to the SM value, but now in the M_Θ versus M_h plane while holding $\kappa = -0.6,\ -1.2$ fixed at two values. Much of the structure of the contours is determined by the threshold for $h \to \Theta\Theta$ to go on-shell, which is the clear diagonal line in the plots satisfying $M_h = 2M_\Theta$. There are two distinct regions of gluon-fusion suppression. The first is when $M_h < 2M_\Theta$ and $M_h \lesssim 2M_t$ in the lower center of both plots. In this case, the real parts between the two diagrams are destructively interfering, even when $h \to t\bar{t}$ goes (slightly) on-shell, due to the slow rise of the top amplitude's imaginary part. In the second region, $M_h > 2M_\Theta,\ 2M_t$ more clearly seen in the lower plot of Fig. 3 ($\kappa = -1.2$), both real and imaginary parts for the top and scalar amplitudes are present and destructively interfere. It is remarkable that such sizable suppression, between a factor of 2 to 10 in the rate for gluon fusion, persists throughout much of the parameter space of both plots.

For another perspective, we can fix both the coupling κ and the octet mass, then plot the Higgs production cross section as a function of Higgs mass alone. We do this in Fig. 4 for $\kappa = -0.75$ and three different octet masses, 125 GeV, 175 GeV and 250 GeV.

What we see is that Higgs production through gluon fusion can be suppressed throughout the Higgs mass range from the LEP II bound up to largest Higgs masses that the LHC is currently sensitive to. We should note that our

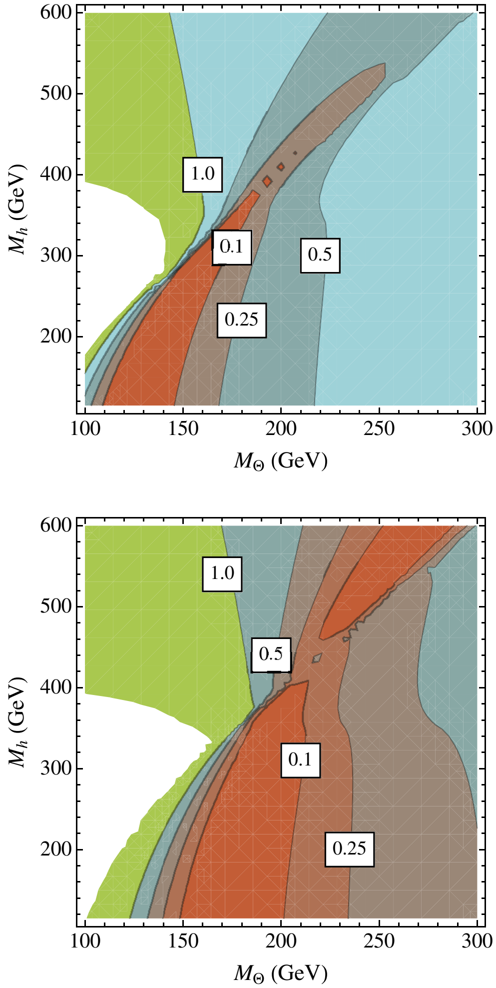

FIG. 3 (color online). Contours of the Higgs production cross section through gluon fusion at leading order, including the effects of a color-octet real scalar, normalized to the standard model value. Unlike Fig. 2, we have fixed the Higgs portal coupling to $\kappa = -0.6$, -1.2 in the upper and lower plots, respectively, while allowing M_h and M_Θ to vary.

calculations of the cross sections have been performed in the narrow Higgs width approximation, and for the largest Higgs masses, the finite width effects become increasingly important.

Higgs production through gluon fusion is well known to have large higher-order corrections [9,20,21]. Extensive higher-order calculations of the effects of a real scalar color octet on Higgs production were also carried out in Ref. [10]. These calculations were applied exclusively to consider *enhancements* in the Higgs production rate, and the extent to which they can be bounded from data. We did, however, apply their results to the negative κ region, to estimate the higher-order corrections to the parameter space shown in Fig. 2. We found that the higher-order corrections enhance the scalar contribution relative to the top loop, and thereby allow for smaller κ, by as much as 25%, holding M_Θ and the Higgs cross section fixed.

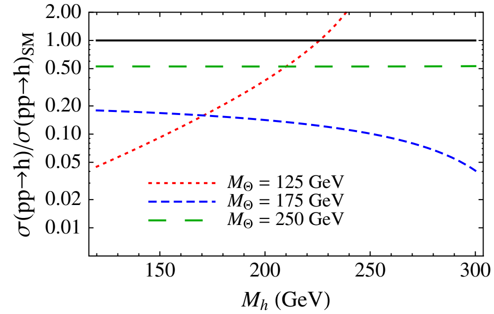

FIG. 4 (color online). Cross section $\sigma(pp \to h)$ relative to the standard model value for octets of mass 125 GeV (dotted line), 175 GeV (small dashes) and 250 GeV (large dashes) and Higgs portal coupling $\kappa = -0.75$.

The requirement of a relatively light colored scalar octet with mass less than a few hundred GeV is obviously of some concern since it can be copiously produced at the LHC. The signature of the color octet critically depends on its decay. Given our Lagrangian, Eq. (3.1), the dominant decay is $\Theta \to gg$, which proceeds at one-loop through diagrams involving a μ_Θ vertex and Θ running in the loop. The width for this process is very small [11],

$$\Gamma(\Theta \to gg) \approx 5 \times 10^{-7} \frac{\mu_\Theta^2}{M_\Theta}, \tag{3.3}$$

but nevertheless leads to prompt decays for $\mu_\Theta^2/M_\Theta > O(10)$ eV.

The QCD production of color-octet scalars at hadron colliders has been studied in various models [11–13,22–24]. Here, Θ production occurs in pairs, so that the signature is a pair of dijet resonances [12,13,24]. The cross section at the LHC is large and depends only on M_Θ and $\sqrt{s}$ [11,13]. The ATLAS Collaboration has searched for this signature using the 2010 data [25], and has set a 95% CL limit on the cross section shown by the dashed line in Fig. 5. We also show the leading-order theoretical prediction for Θ pair production in Fig. 5. Comparing these two lines we find that the octet real scalar is ruled out for M_Θ in the 100–125 GeV range at 95% CL. The inclusion of next-to-leading-order effects would likely increase the theoretical cross section, such that a small mass region around 150 GeV is also ruled out. Note that the production cross section for a real scalar is half of that for a complex scalar [24].

Improving the limits in Fig. 5 is not straightforward, despite the manyfold increase in LHC data. Specifically, the jet p_T requirements in Ref. [25] fall below current trigger thresholds, so the events required to constrain the lighter octet mass range are not written to tape. A recent analysis from CMS (2.2 fb^{-1}) has probed "colorons" (pair produced dijet resonances with a larger production cross section than the octets discussed here) with mass above 320 GeV [26]. However, given the trigger requirements and the increasingly complex QCD environment at higher

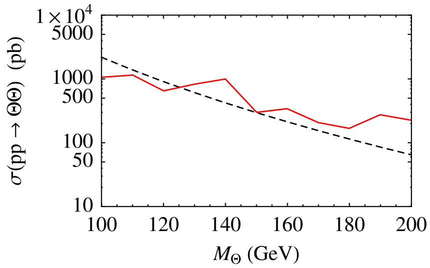

FIG. 5 (color online). Limit on the production cross section for a pair of dijet resonances from ATLAS [25] (solid line), and the leading-order theoretical cross section (dashed line) for pair production of a color-octet real scalar at the 7 TeV LHC.

luminosity, it remains to be seen what improvements can be made for lighter octets.

Single production of Θ is possible at one-loop, through gluon fusion, and is typically too small to be interesting (the cross section can be found in [27] for the case of a weak-doublet color octet).

The cancellation we have demonstrated requires the Higgs portal coupling to be negative. The existence of a negative quartic couplings suggests we consider the vacuum stability of the full scalar potential. At small field values, the requirement of a positive mass squared for Θ ensures small fluctuations are stabilized. At large field values, we need to consider the other terms in the octet Lagrangian (3.1) as well as the Higgs quartic coupling λ_h. For simplicity, let us assume that λ'_Θ and μ_Θ are too small to affect the minimization of the potential (this is easily consistent with the $\mu_\Theta \gtrsim 1$ MeV limit required by prompt Θ decays). The same-field quartics λ_h, λ_Θ are positive, and so stabilize the large H and large Θ directions of field space. However, negative κ could provide a direction with a minima lower than the electroweak symmetry breaking minimum. Positive definiteness of the potential at large field values is automatic if the potential can be written in the form $(\sqrt{\lambda_h}H^\dagger H - \sqrt{\lambda_\Theta}\Theta^a\Theta^a)^2$ plus terms that are positive definite. This yields the tree-level constraint [10]

$$|\kappa| < 2\sqrt{\lambda_\Theta \lambda_h}, \tag{3.4}$$

which would appear to somewhat constrict the parameter space of our color-octet model. However, to properly bound κ, we must consider the effects of renormalization group (RG) running on the couplings in the potential. Evolving to higher energies, the quartic coupling λ_Θ increases. This increase happens fairly quickly, driven primarily by the λ_Θ^2 term in the beta function, and is enhanced by color combinatorial factors. Equally important, the Higgs portal coupling *decreases* in magnitude as we go to higher energy; $\beta(\kappa) \propto \kappa^2$, so an initially large negative κ rapidly evolves to a small negative κ. Hence, there is a considerably larger range of κ and λ_Θ satisfying the constraint of no deeper minimum in the RG-improved effective potential. We leave a detailed study to future work.

IV. DISCUSSION

The gluon-fusion-induced single Higgs production rate at the LHC could be substantially suppressed when the standard model is extended to include a colored scalar sector that interferes destructively with the top-quark loop. The general class of models consists of one or more colored scalars with mass less than a few hundred GeV. Large suppression of the gluon-fusion rate is possible throughout the Higgs mass range while having negligible effect on the Higgs branching ratios, effectively allowing the Higgs boson to exist at any mass given the current LHC limits.

In this paper we have concentrated on a specific model consisting of a color-octet real scalar with a negative Higgs portal coupling. Based on Fig. 2, we find that the interesting range of color-octet masses giving substantial gluon-fusion suppression is roughly $60 \lesssim M_\Theta \lesssim 300$ GeV. In the presence of the cubic coupling given in Eq. (3.1) the color octets decay to a pair of gluons. Only ATLAS has provided experimental constraints that impact the model, ruling out the region 100–125 GeV to 95% CL [25]. Masses above 125 GeV are allowed by current bounds. We are not aware of a robust constraint that rules out the region $60 \lesssim M_\Theta < 100$ GeV, suggesting a more detailed analysis of the viability (or lack thereof) of this region would be interesting for experiments to carry out.

It is interesting to correlate the suppression in single Higgs production with changes in di-Higgs production. The set of diagrams contributing to di-Higgs production consist of both order κ (e.g. triangle diagrams) as well as κ^2 (e.g. box diagrams) contributions to the amplitude. When single Higgs production is suppressed, the order κ diagrams are suppressed. However, larger $|\kappa|$ implies the second class of diagrams proportional to κ^2 remain, and are dramatically enhanced. For the color-octet scalar model, we find the increased di-Higgs production rate between a factor of a few to over 100 times the SM rate for the same Higgs mass [28]. An increase in di-Higgs production can also be found in the presence of cutoff scale operators [29].

We must emphasize that our analysis of Higgs suppression from a single color-octet scalar is merely one model of a large class of colored scalar models. The signals of any given model can be completely different. For example, supersymmetric models with light top squarks can easily have an order-one negative κ, and yet the canonical search strategy for stops involves missing energy (when R-parity is conserved) with detailed considerations of stop decay. A model in which the colored scalars are "quirks" bound by a new strongly-coupled sector would yield completely different signals (e.g. [30]). Thus, while the searches for specific colored scalars are very important, what is more important for Higgs physics is to study the extent to which the Higgs boson can be observed in other channels.

Other Higgs production sources continue to provide a smaller but non-negligible source for single Higgs signals. Specifically, associated production (Wh and Zh) and vector-boson-fusion (VBF) production sources remain unchanged. The VBF process provides a non-negligible single Higgs production rate throughout the Higgs mass range, though the rate is roughly a factor of 10 smaller than gluon-fusion rate for $m_h < 2m_t$. However, existing LHC search strategies have been optimized for a gluon-fusion source, and so as far as we understand, the present Higgs production rate bounds cannot be trivially rescaled. For example, current search strategies involving the $h \to WW \to \ell^+\ell^- + \not{E}_T$ final state allow 0, 1 additional jets in the signal [31]. The VBF process generically produces two (forward) jets. Hence, we suspect that the current Higgs searches are sensitive to only a small fraction of the VBF rate. A more complete study of how effective the LHC experiments are sensitive to VBF production would be really useful.

In addition, some strategies to constrain the light Higgs mass region also depend on a convolution of the gluon-fusion rate with other Higgs production sources. For example, the inclusive selection at CMS [32] for the $h \to \tau\tau$ mode receives a substantial contribution from gluon fusion as well as VBF. Obtaining bounds on the Higgs production cross section in the presence of light colored scalars therefore requires separating out the various sources of Higgs production.

Finally, one new single Higgs production channel is possible: associated production with a pair of scalars $\phi\phi h$. This has been considered before in supersymmetric models [33]. For larger $|\kappa|$ and smaller M_Θ, this process can be considerably larger than the similar standard model process, $t\bar{t}h$ [28]. It would provide the direct confirmation that colored scalars are indeed interacting with the Higgs through the Higgs portal couplings, and thus responsible for modifying the Higgs production rate.

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Note added.—Reference [34] also considers the suppression of Higgs production through colored scalars.

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