Enhancement of $H \rightarrow \gamma\gamma$ in $SU(5)$ model with $45_H$-plet

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Abstract: We show that the low energy effective model derived from $SU(5)$ with 45-plet Higgs can account for the recently reported enhanced diphoton decay rate of the Standard Model (SM)-like Higgs with mass about 125 GeV. This model extends the SM by an extra Higgs doublet and color-octet scalar doublet. We show that the charged octet scalars are not severely constrained by flavor changing neutral current and can be light. However, the $K^0 - \bar{K}^0$ mixing implies that the neutral octet-scalar mass should be larger than 400 GeV for $\tan \beta \sim \mathcal{O}(1)$. The role of charged octet scalar in the loop of Higgs decay into diphoton is investigated. We point out that the most significant impact of this model on the diphoton decay width comes from the suppression of top-quark coupling with SM-like Higgs or even flipping its sign that leads to important enhancement in $\Gamma(h \rightarrow \gamma\gamma)$. We also study the implications of the neutral octet-scalar contributions to the gluon fusion Higgs production cross section in alleviating the apparent tension between enhancement of diphoton decay rate and suppression of $\sigma(gg \rightarrow h)$. 

1 Introduction

The Grand Unified Theory (GUT) $SU(5)$, which was proposed by Georgi and Glashow in 1974\cite{1}, is the simplest extension of the Standard Model (SM) that provides a natural framework for the unification of fundamental interactions. In this model, the SM gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$ are unified into a single simple gauge group and the SM quarks and leptons are combined into irreducible $SU(5)$ representations: $\bar{5}$ and $10$, namely

\begin{align}
5^* &= (\bar{3}, 1)/2 + (1, 2)\_1/2 = (d, \bar{l}), \\
10 &= (3, 2)/6 + (3, 1)\_2/3 + (1, 1)_1 = (q, u, e^c),
\end{align}

where $\bar{l} = i\tau_2 l$ with $l = (\nu, e)^T$ and $q = (u, d)^T$. The Higgs sector in the minimal $SU(5)$ contains adjoint 24-dimensional scalar field representation to break $SU(5) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$ and fundamental 5-dimensional scalar field representation to break $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$.

The minimal $SU(5)$ is very predictive: It naturally predicts the quantization of electric charge, where $\text{Tr}Q_3 = 0$, hence $Q(d) = \frac{1}{3}Q(e^{-})$. It also predicts $\sin^2\theta_W$ in a very good agreement with the current result \cite{2}. It leads to a bottom-tau mass ratio at low energy: $m_b/m_\tau \simeq 3$, which is consistent with the measured masses. However the minimal $SU(5)$ has several drawbacks: It predicts proton decay, $p \rightarrow e^+\pi^0$, with a life-time of order $10^{32}$ years, which is in a clear contradiction with the experimental bound $\gtrsim 5 \times 10^{33}$ \cite{3}. It implies a wrong mass relation: $m_e/m_\mu = m_d/m_s$. Furthermore, in minimal $SU(5)$ the gauge couplings do not unify and the model suffers from a naturalness problem due to the gauge hierarchy problem and a doublet-triplet splitting. Finally, it does not predict right-handed neutrinos, therefore the neutrinos are massless in minimal $SU(5)$ which contradicts the recent neutrinos oscillation results.
There have been several efforts to construct more realistic extensions of the minimal $SU(5)$ through imposing an extra symmetry or extending the fermion and/or Higgs sector [4–10]. For instance, it has been shown that the fermion mass relation, proton stability, and gauge unification can be adjusted by extending the $SU(5)$ Higgs section and introducing another scalar field in the 45-representation [4–6]. One of the salient features of $SU(5)$ model with 45-plet scalar is that the resultant low energy effective model is the SM-like with two Higgs doublets and light octet scalar. This rich Higgs sector has the potential to account for the ATLAS and CMS recent experimental result for $H \rightarrow \gamma \gamma$ signal strength, which is $\sim 1.5$ times larger the SM prediction [11, 12]. This excess is very interesting and it provides a good hint of a possible new physics.

The latest results of ATLAS and CMS collaborations, announced in Moriond conference [13], confirmed the Higgs discovery with mass of order 125 GeV. Both collaborations have independently performed search for the Higgs boson in different decay channels. The most confirmed discovery channels are $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ^{(*)} \rightarrow 4l$, and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ at integrated luminosities of 5.1 fb$^{-1}$ taken with energy $\sqrt{s} = 7$ TeV and 19.6 fb$^{-1}$ taken at $\sqrt{s} = 8$ TeV. While ATLAS confirmed the excess in $H \rightarrow \gamma \gamma$ and found that the best fit of signal strength is given by

$$\frac{\sigma}{\sigma_{SM}} = 1.65 \pm 0.24 \ (stat.)^{+0.25}_{-0.18}(syst),$$

(1.3)

the CMS changed their previous results from $\sigma/\sigma_{SM} = 1.56 \pm 0.43$ to 1.11 $\pm$ 0.31 with cut based events and 0.78 $\pm$ 0.27 with selected and categorized events. Also ATLAS experiment has reported an excess in $H \rightarrow ZZ^{(*)} \rightarrow 4l$ as well with $\sigma/\sigma_{SM} = 1.5 \pm 0.4$ for $m_H = 125.5$ GeV. On the contrary CMS experiment showed that this channel is consistent with the SM expectation with $\sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$. Finally for $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$, ATLAS showed that the signal strength of this process at $m_H = 125$ is 1.01 $\pm$ 0.21$(stat) \pm$ 0.12$(syst)$ and CMS found that it is given 0.76 $\pm$ 0.13$(stat) \pm$ 0.16$(syst)$. From these results, it is clear that much further analysis is needed to reveal the discrepancy between the results of the two experiments. Also it seems that these results are not entirely consistent with the SM predictions, particularly $R_{\gamma\gamma}$. In our effective $SU(5)$ model, we may have significant contributions to $H \rightarrow \gamma \gamma$ decay from the loop of charged octet scalar ($S^\pm$). In addition, the neural octet scalar ($S'^0$) may have important effect on the Higgs production through the gluon fusion $gg \rightarrow H$. Therefore, the expected tension between the enhancement of $\Gamma(H \rightarrow \gamma \gamma)$ and the associated suppression of $\sigma(gg \rightarrow H)$ [14] can be relaxed.

The possibility of light octet scalars arises in several extensions of the SM [15, 16]. The potential discovery of these particles at the LHC has been investigated in Ref.[17]. It is interesting to note that the most robust constraints on the octet scalar masses are due to the direct searches for pair of octet scalars at the LHC, which lead to [18, 19]: $M_S > 287$ GeV at 95% confidence level. In most of octet scalar analysis, the Minimal Flavor Violation (MFV) was assumed. In this case, the Yukawa couplings of octet scalar to the SM quarks are proportional to the Yukawa couplings of the SM-like Higgs to quarks, i.e., $Y_{Sq'} = \text{const.} \times Y_{Hqq'}$. In general, this assumption is not true and $S^\pm$ and $S'^0$ can be source of new flavor violations beyond the SM ones, which are proportional to the quark mixing $V_{CKM}$.

In this paper, we derive the constraints on the octet scalar masses due to the experimental bounds of $K^0 - \bar{K}^0$ mixing and $B^0_q - \bar{B}^0_q$ mixing, where $q = d, s$. We show that the constraints imposed on neutral octet scalars from the current flavor violation limits may be more stringent than the direct
search constraints. While the charged octet scalars are essentially free of flavor changing neutral current constraints, they should be just heavier than $W^\pm$ gauge boson to give contribution less than the SM one. In this respect, we show that $H \rightarrow \gamma\gamma$ decay can be enhanced through the contribution of the charged octet scalars, so that the above mentioned experimental results can be accommodated.

This paper is organized as follows. In section 2, we briefly review $SU(5)$ with 45-plet. In particular, we analyze the Higgs sector at low energy and emphasize that it consists of two Higgs doublets with neutral and charged octet scalars. The interactions of the octet scalars with the SM particles are also provided. In section 3, we study the constraints imposed on the octet scalar masses from $K^0 - \bar{K}^0$ and $B^0_q - \bar{B}^0_q$ mixing, where $q = d, s$, in addition to the constraints obtained from the direct search at Tevatron and LHC. Section 4 is devoted for the octet scalar contribution to the decay rate of $H \rightarrow \gamma\gamma$ and enhancing the signal strength $R_{\gamma\gamma}$. Finally, our conclusions are given in section 5.

2 $SU(5)$ with 45-plet

The Higgs fields in this class of $SU(5)$ is composed of $24_H, 5_H$ and $45_H$ representations, where $24_H$ Higgs fields acquire vacuum expectation value (vev) at GUT scale and break $SU(5)$ group down to the SM. The $5_H$ and $45_H$ Higgs fields contribute in the electroweak symmetry breaking of the SM. In this case, the $SU(5)$ invariant Yukawa Lagrangian is given by

$$
\mathcal{L}_{\text{Yuk}} = Y_1 \delta_{\alpha\beta}(5_H)_{\beta} + Y_2 \delta_{\alpha\beta}(45_H)_{\beta} + \epsilon_{\alpha\beta}\delta_{\lambda}[5_H^0] + Y_3 \delta_{\alpha\beta}10^\gamma(45_H)^{\delta\lambda}.
$$

(2.1)

It is worth remembering that the Higgs bosons $5_H$ and $45_H$ transform under the SM gauge as

$$
5_H = (3, 1)_{-1/3} \oplus (1, 2)_{1/2}
$$

(2.2)

$$
45_H = (8, 2)_{1/2} \oplus (1, 2)_{1/2} \oplus (3, 1)_{-1/3} \oplus (3, 3)_{-1/3} \oplus (6^*, 1)_{-1/3} \oplus (3^*, 2)_{-7/6} \oplus (3^*, 1)_{4/3}.
$$

(2.3)

Also $45_H$ satisfies the following constraints [15]: $45^0_{\gamma\beta} = -45^0_{\beta\gamma}$ and $\sum_{\alpha=0}^5 (45)_{\alpha} = 0$. Thus, the electroweak symmetry $SU(2)_L \times U(1)_Y$ can be spontaneously broken into $U(1)_em$ through the non-vanishing vev of the doublets in $5_H$ and $(45_H)^{A\gamma}$, namely

$$
\langle 5_H \rangle = v_5,
$$

(2.4)

$$
\langle 45_H \rangle^{15} = \langle 45_H \rangle^{25} = \langle 45_H \rangle^{35} = v_{45}, \quad \langle 45_H \rangle^{45} = -3v_{45}.
$$

(2.5)

The $5_H$-doublet is defined as

$$
H \equiv (1, 2)_{1/2} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix},
$$

(2.6)

while the $45_H$-doublet can be written as

$$
D \equiv (1, 2)_{1/2} = \begin{pmatrix} D^4_{4} & D^4_{5} \\ D^4_{4} & D^5_{5} \end{pmatrix} = \begin{pmatrix} -D^4_{4} \\ D^4_{5} \end{pmatrix} = \begin{pmatrix} -D^+ \\ D^0 \end{pmatrix}
$$

In addition, the $45_H$-color octet scalars are defined as [15]

$$
S^{ia} \equiv (8, 2)_{1/2} = (45_H)^{ia} - \frac{1}{3} \delta_{ij}(45_H)^{ma} = \begin{pmatrix} S^+ \\ S^0 \end{pmatrix} \equiv S^A T^A,
$$

(2.7)
where \( i, j = 1, 2, 3 \), \( A = 1, \ldots, 8 \), and \( T^A \) are the \( SU(3) \) generators. It clear that the octet scalars are defined such that they have vanishing vevs. In this case, one can easily show that the fermions masses are given by \([4, 5]\)

\[
M_E = Y_1^T v_5^\ast - 6 Y_2^T v_{45}^\ast,
\]

\[
M_D = Y_1 v_5^\ast + 2 Y_2 v_{45}^\ast,
\]

\[
M_U = 4 (Y_3 + Y_3^T) v_5 - 8 (Y_3^T - Y_3) v_{45}.
\]

Thus, the usual \( SU(5) \) wrong mass relation between the masses of charged leptons and down quarks is resolved. In addition, from Eq.(2.10) one notices that the up-quark masses may depend only on \( v_5 \) and the Yukawa couplings \( Y_3 \) if the Yukawa matrix \( Y_4 \) is symmetric or if one adopted the common bases where the up quark mass matrix is diagonal and down quarks are the only source for the quark mixing matrix \( V_{CKM} \).

Also, it is worth noting that both \( 5_H \) and \( 45_H \) Higgs fields are coupled with \( 24_H \) Higgs fields that acquire vevs of order GUT scale. Therefore, it is a challenging to keep the Higgs doublets of \( 5_H \) and \( 45_H \), in addition to the octet scalar of \( 45_H \) light (of order the electroweak scale) while all other fields are quite heavy. This is known as splitting problem. In minimal \( SU(5) \), this problem was to justify the splitting between the doublet and triplet of \( 5_H \). Now we have an additional splitting among the doublet, octet of \( 45_H \) and its triplets, sextet. In principle, the potential \( V(24_H, 5_H) \) and \( V(24_H, 45_H) \) contain several free parameters that can be adjusted such that the required pattern is obtained. In this case the low energy effective model derived from the non-minimal \( SU(5) \) is the SM extended by an extra Higgs doublet and neutral and charged octet scalars.

### 2.1 \( SU(5) \)-two Higgs doublets

The \( SU(5) \) invariant potential of \( 5_H \) and \( 45_H \) Higgs fields is given by

\[
V(5_H, 45_H) = -\mu_5^2 5_\alpha^\ast 5_\alpha + \lambda_1 (5_\alpha^\ast 5_\alpha)^2 - \mu_{45}^2 45_\alpha^\ast 45_\beta + \lambda_2 (45_\alpha^\ast 45_\beta)^2 + \lambda_3 (45_\alpha^\ast 45_\beta 5_\gamma^\ast 5_\delta) + \lambda_4 45_\alpha^\ast 5_\beta 5_\gamma^\ast 45_\delta + \frac{1}{2} \lambda_5 \left[ 5_\beta 45_\gamma 5_\delta 45_\alpha + 45_\gamma 5_\beta 45_\delta 5_\gamma^\ast + \lambda_6 45_\alpha^\ast 5_\gamma 5_\delta 45_\beta \right] + \lambda_7 5_\alpha^\ast 5_\gamma 5_\delta 45_\beta.
\]

After \( SU(5) \) symmetry breaking, one finds

\[
V(H, D) = -\mu_H^2 H^\dagger H + \lambda_1 (H^\dagger H)^2 - \mu_D^2 D^\dagger D + \lambda_2 (D^\dagger D)^2 + \lambda_3 (D^\dagger D)(H^\dagger H) + \frac{1}{2} \lambda_5 [(H^\dagger D)^2 + (D^\dagger H)^2] + \lambda_6 (\tilde{D} H) (\tilde{D} H)^\dagger,
\]

where \( \lambda_3 = 2 \lambda_3 + \lambda_4, \lambda_6 = 2 \lambda_6 \) and \( \tilde{D} = i \tau_2 D \). Therefore, the scalar potential of neutral Higgs bosons is given by

\[
V(H^0, D^0) = -\mu_H^2 H^0 H^0 + \lambda_1 (H^0 H^0)^2 - \mu_D^2 D^0 D^0 + \lambda_2 (D^0 D^0)^2 + \lambda_3 (D^0 D^0)(H^0 H^0) + \frac{1}{2} \lambda_5 [(H^0 D)^2 + (D^0 H)^2].
\]

These neutral components develop vacuum expectations values: \( \langle H^0 \rangle = v_1 \equiv v_5 \) and \( \langle D^0 \rangle = v_2 \equiv -3v_{45} \). As in two Higgs doublet models, the mass of the \( W \)-gauge bosons is given by \( M_W = g v_1 \), where
\[ v = \sqrt{v_1^2 + v_2^2} \]

and one defines \( \tan \beta = v_2/v_1 \). In addition, the following minimization conditions are obtained:

\[
\begin{align*}
-\mu_H^2 + 2\lambda_1 v_1^2 + (\lambda'_1 + \lambda_5) v_2^2 &= 0, \\
-\mu_D^2 + 2\lambda_2 v_2^2 + (\lambda'_1 + \lambda_5) v_1^2 &= 0.
\end{align*}
\]

In order to obtain the physical Higgs fields and their masses, one should write the two doublets \( H \) and \( D \) around their vacua as follows:

\[
\begin{align*}
H &= (H^+, H^0) = (H^+, v_5 + H_R^0 + i H_I^0), \\
D &= (-D^+, D^0) = (-D^+, v_{45} + D_R^0 + i D_I^0),
\end{align*}
\]

where the real components correspond to the CP-even Higgs bosons and the imaginary components correspond to the CP-odd Higgs and the Goldstone boson. The mass matrix of the CP-even Higgs can be obtained as

\[
M_H^2 = \begin{pmatrix}
-\mu_H^2 + 6\lambda_1 v_1^2 + \lambda v_1^2 & \lambda v_1 v_2 \\
\lambda v_1 v_2 & -\mu_D^2 + 4\lambda_2 v_2^2 + \lambda v_2^2
\end{pmatrix} = \begin{pmatrix}
4\lambda_1 v_1^2 & \lambda v_1 v_2 \\
\lambda v_1 v_2 & 4\lambda_2 v_2^2
\end{pmatrix},
\]

with \( \lambda = \lambda'_1 + \lambda_5 \). The last equality is obtained by using the minimization conditions to write \( \mu_H^2 \) and \( \mu_D^2 \) in terms of \( v_5 \) and \( v_{45} \). Therefore, the mass eigenstates fields \( h \) and \( H \) are given as

\[
\begin{pmatrix}
H \\
h
\end{pmatrix} = \begin{pmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{pmatrix} \begin{pmatrix}
H_R^0 \\
D_R^0
\end{pmatrix},
\]

where the mixing angle \( \alpha \) is defined by

\[ \tan 2\alpha = \frac{\lambda v_1 v_2}{2(\lambda_1 v_1^2 - \lambda_2 v_2^2)}. \]

The masses of the CP-even Higgs bosons \( h \) and \( H \) are given by

\[
M_{h,H}^2 = 2\lambda_1 v_1^2 + 2\lambda_2 v_2^2 \mp \sqrt{(2\lambda_1 v_1^2 - 2\lambda_2 v_2^2)^2 + \lambda_1^2 v_1^4 v_2^2}. \]

It is clear that \( \lambda \) is the mixing parameter between the SM-like \( h \) Higgs and the extra Higgs \( H \). For \( \lambda = 0 \), there is no mixing and the Higgs masses are given by \( m_h = 2\sqrt{\lambda_1} v_1 \) and \( m_H = 2\sqrt{\lambda_2} v_2 \).

Similarly the mass matrix of the CP-odd Higgs and Goldstone boson can be obtained as

\[
M_D^2 = \begin{pmatrix}
-\mu_H^2 + 2\lambda_1 v_1^2 + \lambda v_1^2 & 2\lambda_5 v_1 v_2 \\
2\lambda_5 v_1 v_2 & -\mu_D^2 + 2\lambda_2 v_2^2 + \lambda v_2^2
\end{pmatrix} = \begin{pmatrix}
-2\lambda_5 v_1^2 & 2\lambda_5 v_1 v_2 \\
2\lambda_5 v_1 v_2 & -2\lambda_5 v_2^2
\end{pmatrix}.
\]

Since the determinant of \( M_D^2 \) is zero, one eigenvalue vanishes and corresponds to the Goldstone boson mass, while the other eigenvalue corresponds to the pseudoscalar Higgs, \( A = -\sin \beta H_R^0 + \cos \beta D_R^0 \), with mass given by

\[
M_A^2 = 2\lambda_5 (v_1^2 + v_2^2) = 2\lambda_5 v^2.
\]

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Finally, the mass matrix of the charged Higgs bosons is given by

\[
M^2_{H^\pm} = \begin{pmatrix}
-\mu_H^2 + 2\lambda_1 v_1^2 + (\lambda_5 + \lambda_6) v_2^2 & (-\lambda_5 + \lambda_6) v_1 v_2 \\
(-\lambda_5 + \lambda_6) v_1 v_2 & -\mu_D^2 + 2\lambda_2 v_2^2 + (\lambda_3 + \lambda_6) v_1^2
\end{pmatrix}
\]

One of the eigenvalues of this mass matrix is zero and corresponds to a massless charged Goldstone, while the other eigenvalue corresponds to a charged Higgs boson, \(H^\pm = -\sin \beta H^\pm + \cos \beta D^\pm\), with mass given by

\[
M^2_{H^\pm} = (\lambda_6 - \lambda_5) v_2^2.
\]  

Now we consider the induced Yukawa couplings of the lightest neutral Higgs scalar “SM-like Higgs” to the SM fermions. From the \(SU(5)\) Yukawa interactions in Eq. (2.1), the Higgs doublets \(H\) and \(D\) have the following low energy scale interactions with the SM fermions.

\[
\mathcal{L} = Y_1^T \bar{e}_R H^\dagger l_L + 2Y_2^T \bar{e}_R D^\dagger l_L + Y_1 \bar{u}_R H^\dagger Q_L + Y_3' \epsilon_{\alpha \beta} \bar{u}_R Q_L H^\beta + Y_4' \epsilon_{\alpha \beta} \bar{u}_R Q_L^\dagger D^\beta + h.c.,
\]

where \(Y_3' = 4(Y_3 + Y_4^T)\) and \(Y_4' = 4Y_4\). This indicates that although \(Y_4\) may not contribute in the up quark mass matrix in certain cases, it has an important effect on their interactions with Higgs particles. Also one can express \(Y_1\) and \(Y_2\) Yukawa couplings from the fermion mass relations in terms of the down quark and charged lepton masses:

\[
Y_1 = \frac{3M_D + M_E}{4v_5}, \quad Y_2 = \frac{M_D - M_E}{8v_{45}}.
\]

Therefore, the Yukawa Lagrangian can be expressed in the physical basis as

\[
\mathcal{L} = \bar{e}_R \left[ -\frac{3M_D V^\dagger_{CKM} + M_E}{4v_5} \sin \beta + \left( \frac{m_D V^\dagger_{CKM} - m_E}{4v_{45}} \right) \cos \beta \right] H^\dagger \nu_e L \\
+ \bar{e}_R \left[ \left( \frac{3M_D V^\dagger_{CKM} + M_E}{4v_5} \right) (H \cos \alpha - h \sin \alpha - iA \sin \beta) \\
+ \left( \frac{m_D V^\dagger_{CKM} - m_E}{4v_{45}} \right) (H \sin \alpha + h \cos \alpha + iA \cos \beta) \right] e_L \\
+ \bar{d}_R \left[ -\frac{3M_D V^\dagger_{CKM} + M_E}{4v_5} \sin \beta \right] H^\dagger u_L \\
+ \bar{d}_R \left( \frac{3M_D + M_E V_{CKM}}{4v_5} \right) (H \cos \alpha - h \sin \alpha - iA \sin \beta) d_L \\
+ \bar{u}_R \left[ -Y_3' \sin \beta + Y_4' \cos \beta \right] V_{CKM} H^+ d_L \\
+ \bar{u}_R \left( Y_3' (H \cos \alpha - h \sin \alpha - iA \sin \beta) + Y_4' (H \sin \alpha + h \cos \alpha + iA \cos \beta) \right) u_L + h.c.,
\]

If one assumes flavor diagonal charged leptons and up-quarks, while the down quark mass matrix is diagonalized by left-handed rotation only, \(i.e.,\) \(V^d_L = V_{CKM}\) and \(V^d_R = I\). In this case, one can
Λ = 1
Λ = 4
Λ = −4

0.88
0.90
0.92
0.94
0.96
0.98
1.00

0.8
0.9
0.95
1.0

0.0
0.2
0.4
0.6
0.8
1.0

0.7
0.75
0.8
0.85
0.9
0.95
1.0

Figure 1. (Left panel): The ratio $g_{hW^+W^-}/g_{hW^+W^-}^{SM}$ as a function of $\tan\beta$ for $\lambda = 1, \pm 4$, where $\lambda = 2\lambda_3 + \lambda_4 + \lambda_5$ as defined in Eqs. (2.11)-(2.17). (Right panel): Contour plot of the ratio $Y_{htt}/Y_{htt}^{SM}$ as a function of $\lambda$ and the coupling $Y_4$ of 45-doublet with the top-quark.

summarize the SM-like Higgs couplings to the SM fermions as follows:

\[ Y_{huv} = -Y_3' \sin \alpha + Y_4' \cos \alpha = -\frac{m_U}{v} \sin \alpha + \frac{m_D}{v} \cos \alpha, \]
\[ Y_{hdd} = -\left(\frac{3m_D + m_E V_{CKM}}{4v_5}\right) \sin \alpha, \]
\[ Y_{hec} = -\left(\frac{3m_D V_{CKM}^\dagger + m_E}{4v_5}\right) \sin \alpha + \left(\frac{m_D V_{CKM}^\dagger - m_E}{4v_{45}}\right) \cos \alpha. \]

Similarly, one can derive the Higgs couplings to the electroweak gauge bosons. These coupling are obtained from the kinetic terms of the fields $H$ and $D$ in the Lagrangian

\[ \mathcal{L}_{kin} = (D^\mu H)^\dagger (D_\mu H) + (D^\mu D)^\dagger (D_\mu D). \]

Expanding the covariant derivative $D_\mu$ and performing the usual transformations on the gauge and scalar fields to obtain the physical fields, one can identify the couplings between the Higgs and gauge bosons. In particular, the coupling of the SM-like Higgs to $W^+W^-$ and to $Z^0Z^0$ are given by

\[ g_{hW^+W^-} = gM_W \sin(\beta - \alpha), \]
\[ g_{hZZ} = \frac{gM_Z}{\cos \theta_W} \sin(\beta - \alpha). \]

In Fig. 1 we display the ratio of $g_{hW^+W^-}$ normalized by the SM coupling $g_{hW^+W^-}^{SM} = gM_W$ as function of $\tan\beta$. As can be seen from this plot, large values of $\lambda$ with small $\tan\beta$ lead to $g_{hW^+W^-}$ smaller than the SM result. Note that $\lambda$ is defined as $\lambda = 2\lambda_3 + \lambda_4 + \lambda_5$, hence it can vary from $-4$ to $+4$. However, small $g_{hW^+W^-}$ is not favored, if we are interested in enhancing $\Gamma(h \rightarrow \gamma\gamma)$ respect to the SM expectation \cite{11,12}. Therefore, one may consider the following constraints: $\lambda \sim \mathcal{O}(1)$ or $\tan\beta$ is quite large. In this figure we also provide a contour plot for $Y_{htt}/Y_{htt}^{SM}$ as a function of $\lambda$ and the coupling $Y_4$. As can be seen from this figure for a large region of parameter space $Y_{htt} < Y_{htt}^{SM}$ is
obtained. It is also remarkable that $Y_{htt}$ may flip its sign and becomes negative. In this case, as we will discuss in the next section, the top contribution to $h \to \gamma\gamma$ will have a constructive interference with $W$-contribution that leads to enhancement of $\Gamma(h \to \gamma\gamma)$.

### 2.2 Octet scalar Interactions

The interaction of octet scalars with the gluon is one of their most relevant interactions with the SM particles. This interaction is obtained from the kinetic term of $45_H$: $\text{Tr} \left[(D_\mu 45_H) (D^\mu 45_H)\right]$, where the covariant derivative of $(45_H)_{ij}^\alpha$ is given by

$$D_\mu (45_H)_{ij}^\alpha = \partial_\mu (45_H)_{ij}^\alpha - ig(A_\mu)_{ij}^\alpha (45_H)_{ij}^\alpha - ig(A_\mu)^\alpha (45_H)_{ij}^\alpha - ig(A_\mu)^\alpha (45_H)_{ij}^\alpha,$$

where $A_\mu \equiv A_\mu^A T^A$ is the $SU(5)$ gauge bosons. This leads to the following covariant derivative of octet scalars $S^\mu_{ij}$:

$$D_\mu S^\mu_{ij} = \partial_\mu S^\mu_{ij} - ig \frac{g_s}{2} (G_\mu^a \lambda^a)_{ik} S^\mu_{kj} + ig \frac{g_s}{2} (G_\mu^a \lambda^a)_{jk} S^\mu_{ki} - ig (A_\mu)_{ij}^\alpha (45_H)_{ij}^\alpha,$$

which can be written as

$$L_{\text{gluon}}^S = \frac{g_s}{2} \text{Tr} \left[ S^{\alpha} A^{-T} A G^\mu B T B \partial_\mu S^{D+} T^D + S^{T A} T A G^\mu B T B \partial_\mu S^{D0} T^D + S^{A0} T A G^\mu B T B \partial_\mu S^{D0} T^D \right] + h.c.$$
Therefore, one finds the following interacting vertices among the $S^{\pm,0}, S^{\mp,0}$ and $\eta$:

$$hS^+S^- : -\lambda_3 v_5 \sin \alpha$$
$$hS_0^0S_0^0 : -(\lambda_3 + \lambda_4 - \lambda_5)v_5 \sin \alpha$$
$$hS_0^0S_R^0 : -(\lambda_3 + \lambda_4 + \lambda_5)v_5 \sin \alpha.$$

Finally, it is worth mentioning that after the electroweak symmetry breaking, the octet scalars acquire the following masses from the potential $V(45_H)$ and $V(45_H, 5_H)$:

$$m_{S^{\pm}}^2 = -\mu_s^2 + \lambda_1^{\text{eff}} v_5^2 + \lambda_1^{\text{eff}} v_4^2,$$
$$m_{S_0^0}^2 = -\mu_s^2 + \lambda_2^{\text{eff}} v_5^2 + \lambda_2^{\text{eff}} v_4^2,$$
$$m_{S_i^0}^2 = -\mu_s^2 + \lambda_3^{\text{eff}} v_5^2 + \lambda_3^{\text{eff}} v_4^2,$$

where $\lambda_i^{\text{eff}}$ and $\lambda_i^{\text{eff}}$ are linear combinations of the scalar couplings of $V(45_H)$ and $V(45_H, 5_H)$. Therefore, one concludes that the masses of the octet scalars, in general, are not determined and are not universal. In the next section, we will discuss the experimental constraints imposed on the octet scalar masses.

3 Constraints on octet scalars masses

3.1 Constraints from $K^0 - \bar{K}^0$ and $B^0_q - \bar{B}^0_q$ mixing

In this section we consider possible constraints on the mass of neutral and charged octet scalars, $S^0$ and $S^\pm$, due to the experimental bounds of $\Delta S = 2$ and $\Delta B = 2$ processes. The strength of $K^0 - \bar{K}^0$ mixing is described by the mass difference $\Delta M_K = M_{K_L} - M_{K_S}$, whose present experimental value is $\Delta M_K^{\text{exp}} = 3.483 \pm 0.006 \times 10^{-15}$ GeV, while the SM prediction is given by $\Delta M_K^{\text{SM}} = 2.7018 \times 10^{-15}$ GeV. Therefore, any new contribution from neutral and charged octet scalar exchanges must be limited to the small difference between the measured and the SM results. The lagrangian of the octet scalar interactions with the SM fermions can be derived from Eq.(2.1) as

$$L_{\text{int}}^S = 2Y_2 \left[ d_R S^0 d_L + d_R S^- u_L \right] + Y_4^2 \left[ \bar{u}_R S^+ d_L - \bar{u}_R S^0 u_L \right],$$

where $Y_2$ and $Y_4 = 4(Y_4 - Y_4^T)$ are generic $3 \times 3$ matrices. They contribute to the down and up quark masses as emphasized in Eqs.(2.9),(2.10). If $M_D$ is diagonalized by $V_D^T$ and $V_D^T$, while the $M_U$
is diagonalized by $V^u_L$ and $V^u_R$, then in the mass eigenstate basis, the couplings of the neutral octet scalar with the down and up quarks are given by $Y_{S^0 d_R d_L} = V^d_R V_L^d Y_2$ and $Y_{S^0 u_R u_L} = V^u_R V_L^u Y_4'$, respectively. In minimal flavor violation scenario \[15\], where $Y_2 \propto Y_1$ and $Y_4' \propto Y_3'$, the interactions of $S^0$ with down and up quarks become flavor diagonal and the quark couplings with charged octet scalar depend on the quark mixing matrix $V_{CKM}$. Here we do not adopt this assumption and consider $Y_2$ and $Y_4'$ as generic matrices. From Eqs. (2.8), (2.9), one can represent the Yukawa coupling $Y_2$ in terms of $M_D$ and $M_E$, namely:

$$Y_2 = \frac{M_D - M_E}{8v_{45}},$$  \hspace{0.5cm} (3.2)

which implies that

$$Y_{S^0 d_R d_L} = \frac{1}{4v_{45}} \left[ M_D^{diag} - V^d_R M_E V_L^d \right].$$  \hspace{0.5cm} (3.3)

Due to the miss-match between the diagonalization of $M_D$ and $M_E$, the last term generates flavor violation in the couplings of the neutral octet scalar with down quarks, even in the basis of diagonal charged lepton. One can assume that the quark mixing matrix is generated mainly from the down sector, i.e., $V_L^d = V_{CKM}$, $V_R^d = I$, and $V_L^u = V_R^u = I$. In this case one finds

$$Y_{S^0 d_R d_L} = \frac{1}{4v_{45}} \left[ M_D^{diag} - M_E^{diag} V_{CKM} \right].$$  \hspace{0.5cm} (3.4)

In this case, the coupling of neutral octet scalar with down and strange quarks is given by

$$Y_{S^0 s_R d_L} = \frac{m_\mu \lambda}{4v_{45}} = \frac{3m_\mu \lambda}{4v \sin \beta},$$  \hspace{0.5cm} (3.5)

while its coupling with down and bottom quarks is of order

$$Y_{S^0 b_R d_L} = -\frac{m_\tau \lambda^3}{4v_{45}} = \frac{3m_\tau \lambda^3}{4v \sin \beta},$$  \hspace{0.5cm} (3.6)

where $\lambda \approx 0.21$ and $\tan \beta = v_2/v_1 = -3v_{45}/v_5$ In this respect, the neutral octet scalar may contribute to the $K^0 - \bar{K}^0$ mixing at tree level as shown in Fig. 3, while the charged octet scalar contribution is given by one loops similar to the SM contribution through $W^\pm$-boson exchange. Since the mass of the charged octet scalar $S^\pm$ is larger than the mass of the SM gauge boson $W^\pm$, the contribution from $S^\pm$ to $K^0 - \bar{K}^0$ mixing is typically much smaller than the SM effect. Hence no direct constraint on the charged octet scalar mass can be imposed.
Let us now consider the tree level contribution of neural octet scalar $S^0$ to $\Delta S = 2$ processes, where $S$ refers to the strangeness quantum number. The $K_L - K_S$ mass difference $\Delta M_K$ is defined as

$$\Delta M_K = 2 | M_{12}(K) | = 2 | \langle K | H_{\Delta S=2}^{\text{eff}} | K \rangle |,$$

(3.7)

where $H_{\Delta S=2}^{\text{eff}}$ is the effective Hamiltonian for $\Delta S = 2$ transition and the mass matrix $M_{12}(K)$ can be written as

$$M_{12}(K) = M_{12}^{SM}(K) + M_{12}^{S0}(K).$$

(3.8)

Therefore, one can write $\Delta M_K$ in the form

$$\Delta M_K = \Delta M_K^{SM}[1 + R_K],$$

(3.9)

where the ratio $R_K$ is defined as $R_K = M_{12}^{S0}(K)/M_{12}^{SM}(K)$. In this respect, the experimental limit of $\Delta M_K$ [20] leads to

$$R_K \leq 0.2891.$$

(3.10)

The effective Hamiltonian associated to the neutral scalar exchange is given by

$$H_{\text{eff}} = \sum_{i=1,2} (C_i Q_i + \tilde{C}_i \tilde{Q}_i),$$

(3.11)

Where the operators $Q_i$ are given by

$$Q_1 = (\bar{s}_R d_L)(\bar{s}_R d_L), \quad Q_2 = (\bar{s}_R d_L)(\bar{s}_L d_R),$$

(3.12)

and the Wilson coefficients $C_i$ are defined as

$$C_1 = \frac{Y_{S^0 s_R d_L}^2}{m_{S^0}^2}, \quad C_2 = \frac{Y_{S^0 s_R d_L} Y_{S^0 s_L d_R}}{m_{S^0}^2}.$$

(3.13)
The operators $\tilde{Q}_i$ and Wilson coefficients $\tilde{C}_i$ are obtained from the $Q_i$ and $C_i$ by the exchanging $L \leftrightarrow R$. In this case, one can easily show that \( M_{12}^{S_0}(K) \) is given by

\[
M_{12}^{S_0}(K) = 0.0125 \left[ C_1(\mu) + \tilde{C}_1(\mu) \right] + 2 \times 0.017 \times C_2(\mu)
\]  

(3.14)

In Fig. 4 we show that the ratio \( R_K \) as a function of the mass \( m_{S_0} \) for \( \tan \beta = 0.1, 0.26, 1, 10 \). As can be seen from this figure, for \( \tan \beta \sim \mathcal{O}(1) \), the mass of neutral octet scalar can be as light as 440 GeV. The lower bound of \( m_{S_0} \) is increased with smaller \( \tan \beta \). For instance, with \( \tan \beta \sim 0.2 \) one finds that the lower bound of \( m_{S_0} \) is of order \( \mathcal{O}(1) \) TeV.

Similarly, one can check possible constraints imposed by \( B^0_q - \bar{B}^0_q \) mixing, with \( q = d, s \), on the mass of the neutral octet scalar. The recent experimental results \[20\] for \( \Delta M_{B_d} \) and \( \Delta M_{B_s} \) are given by

\[
\Delta M_{B_d}^{\exp} = (3.337 \pm 0.033) \times 10^{-13} \text{ GeV}, \quad \Delta M_{B_s}^{\exp} = (117.0 \pm 0.8) \times 10^{-13} \text{ GeV},
\]  

(3.15)

while the SM predictions are given by

\[
\Delta M_{B_d}^{SM} = 3.58187 \times 10^{-13} \text{ GeV} \quad \Delta M_{B_s}^{SM} = 104.19 \times 10^{-13} \text{ GeV}.
\]  

(3.16)

This implies that the ratios \( R_{B_{d,s}} \) are constrained as follows:

\[
|R_{B_d}| \leq 0.0683, \quad R_{B_s} \leq 0.1229.
\]  

(3.17)

These constraints on \( R_{B_{d,s}} \) appear more stronger than the constraint imposed on \( R_K \), hence it may lead to more stringent constraints on \( m_{S_0} \). However, it is easy to check that the Wilson coefficients of the \( \Delta B_{d,s} = 2 \) are proportional to the Yukawa couplings \( Y_{bd} \) and \( Y_{bs} \), which are smaller than \( Y_{sd} \). Therefore, the \( S^0 \) contributions to \( B^0_q - \bar{B}^0_q \) mixing are quite suppressed, hence the constraints imposed by these process are weakened. This conclusion is confirmed in Fig. 5, where we plot \( R_{B_d} \) and \( R_{B_s} \) versus the neutral octet scalar mass \( m_{S_0} \) for \( \tan \beta = 0.1, 0.26, 1, 10 \). As can be seen from these figures that for \( \tan \beta \sim 0.6 \), the \( B^0_{d,s} - \bar{B}^0_{d,s} \) mixing implies that \( m_{S_0} \) can be much less than 100 GeV.
3.2 Direct searches constraints

In recent years, there has been a growing interest in searching for the octet scalar at hadron colliders, namely Tevatron and LHC [17]. In this section we describe the recent experimental results, which are interpreted as a lower bound on the mass of octet scalars ($S^\pm, S^0$).

The octet scalars can be pair-produced copiously at the LHC $gg \rightarrow S^0S^0$ or $gg \rightarrow S^+S^-$. This is due to their large couplings to gluons and their large color factors. The octet scalars can then decay to the SM quarks without any missing energy. Therefore, the associated signature is a pair of dijet resonances. However, the direct search of this process is very challenging due to an enormous QCD multi-jets background that exceeds the signal by orders of magnitude.

The production cross section of octet scalar at the LHC depends on the mass $M_S$ and proton-proton collision energy $\sqrt{s}$. Depending on its mass, $S$ may decay to the heaviest fermions, which are kinematically allowed. In particular, $S^0$ decays mainly to $t\bar{t}$ and/or $b\bar{b}$, while $S^+ \rightarrow t\bar{b}$. The latest results with $\sqrt{s} = 7$ TeV have set a 90% CL limit on the cross section of a pair of dijet that ruled out octet scalar masses less than 287 GeV [18]. It is important to note that the pair production cross section is almost model independent.

4 Octet scalar contribution to $h \rightarrow \gamma\gamma$

As advocated in the introduction, CMS and ATLAS collaborations observed a SM-like Higgs boson in the mass range 125-126 GeV [11, 12]. Both collaborations considered the following search channels: $h \rightarrow \gamma\gamma$, $h \rightarrow ZZ^* \rightarrow 4l$, $h \rightarrow WW^* \rightarrow 2l2\nu$ as well $h \rightarrow Z\gamma$, and $h \rightarrow b\bar{b}$, $\tau\bar{\tau}$. Using the full dataset recorded by CMS and ATLAS experiments at the LHC from $pp$ collisions at center of mass energies of 7 and 8 TeV, both experiments reported confirmed excess in the first three decay channels at Higgs mass of order 125 GeV. In $h \rightarrow \gamma\gamma$, CMS experiment observed that the signal strength, $\sigma/\sigma_{SM}$ is given by $0.78 \pm 0.27$ in case of selected event analysis and $1.11 \pm 0.31$ in the cut based analysis [13]. While ATLAS collaboration found that the best fit of this signal strength is given by $1.65 \pm 0.24$ [13].

In $h \rightarrow ZZ^* \rightarrow 4l$, CMS experiment measured the signal strength as $0.91^{+0.31}_{-0.24}$, nevertheless ATLAS experiment reported an excess with signal strength $1.5 \pm 0.4$. Finally in $h \rightarrow WW^* \rightarrow 2l2\nu$ both CMS and ATLAS found an excess of events above background, which is consistent with the expectation from a SM Higgs boson of mass $\simeq 125$ GeV.

It is clear that the statistical significance is not sufficient to claim any deviation from the SM expectation. Nevertheless, the above mentioned results indicate enhancement in the diphoton production, with more than 2$\sigma$ deviation, which could be a very important signal for possible new physics beyond the SM. Indeed, it has motivated many theorists to look for possible new physics explanation. In this section, we will emphasize that this excess can be naturally accommodated in our low energy effective $SU(5)$ model. In the SM, the Higgs boson decays into diphotons through triangle loop diagram with $W^+, W^-$ and $t, \bar{t}$ exchanges. The enhancement of the diphoton decay width requires the presence of charged particles with non-negligible coupling to Higgs boson. In addition, this contribution of the new charged particles should interfere constructively with the dominant SM contribution from $W^\pm$ boson loop. As shown in previous section, the spectrum of the low energy effective theory of $SU(5)$ with 45$_H$ contains charged color-octet scalars, $S^\pm$, that can give a genuine contribution to the SM-like Higgs decay into diphotons. The color-octet scalar effects on Higgs production in gluon fusion and
diphoton decay have been analyzed within extensions of SM with color-octet scalars \[21, 22\]. However, our \(SU(5)\) model is very different from these phenomenological models. Therefore, we expect to obtain new results for both Higgs decay to diphoton and Higgs production cross section.

The contributing Feynman diagrams for the decay \(h \rightarrow \gamma \gamma\) mediated by gauge bosons \(W^\pm\), top quark, and \(S^\pm\) are shown in Fig. 6. In this case, the one-loop partial decay width of the \(H\) decay into two photons is given by \[21\]

\[
\Gamma(h \rightarrow \gamma \gamma) = \frac{\alpha^2 m_h^2}{1024\pi^3} |g_{hWW} m_W^2 Q_W^2 F_1(x_W) + N_{c,i} Q_i^2 \frac{2g_{ht\bar{t}}}{m_t} F_{1/2}(x_t) + N_{c,S} Q_S^2 \frac{g_{hSS}}{m_S^2} F_0(x_S)|^2, \tag{4.1}
\]

where \(x_i = m_i^2/4m_i^2, i = W, t, S\). The color factor and electric charges are given by: \(N_{c,t} = 3, N_{c,S} = 8, Q_W = 1, Q_S = 1,\) and \(Q_t = 2/3\). As explicitly derived in the previous section, the Higgs couplings are given by \(g_{hWW} = gM_W \sin(\beta - \alpha), g_{ht\bar{t}} = -m_t \sin \alpha/v \cos \beta + 4Y_4 \cos \alpha\) and \(g_{hSS} = -\lambda_3 v \cos \beta \sin \alpha\). Finally, the loop functions \(F_i(x_i)\) are given by

\[
F_1(x) = -\left[2x^2 + 3x + 3(2x - 1) \arcsin^2(\sqrt{x})\right]x^{-2},
\]

\[
F_{1/2}(x) = 2\left[x + (x - 1) \arcsin^2(\sqrt{x})\right]x^{-2},
\]

\[
F_0(x) = -\left[x - \arcsin^2(\sqrt{x})\right]x^{-2}.
\]

For Higgs mass of order 125 GeV and octet scalar mass of order 300 GeV, the loop functions \(F_1(x_w), F_{1/2}(x_t)\) and \(F_0(x_S)\) are given by \(-8.32, +1.38,\) and 0.34 respectively. Therefore, within the SM there is a distractive interference between the contributions of \(W\)-gauge bosons and top quark. In this respect it would be preferable to reduce the top Yukawa coupling (specially, if it is not directly related to the top quark mass as in our case), so that \(\Gamma(h \rightarrow \gamma \gamma)\) can be enhanced. In Fig. 1 we have shown that this can be naturally achieved in our model and even \(g_{ht\bar{t}}\) may flip its sign. In this case, \(\Gamma(h \rightarrow \gamma \gamma)\) becomes much larger than the SM expectation. In addition, to allow for constructive interference between \(W\) and \(S\) contributions, that leads to an enhancement of \(\Gamma(h \rightarrow \gamma \gamma)\), the dimensionful coupling \(g_{hSS}\) should be quite large and negative. In Fig. 7, we show the ratio \(g_{hSS}/g_{hWW}\) as function of \(\tan \beta\) and

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**Figure 6.** Feynman diagrams for the decay \(h \rightarrow \gamma \gamma\) mediated by gauge bosons \(W^\pm\), top quark, and charged octet scalars \(S^\pm\).
\( \lambda_3 \) for \( \lambda = 4 \). As can be seen from this figure, the coupling \( g_{hSS} \) is typically much smaller than \( g_{hWW} \). It is typically less than 0.1 of \( g_{hWW} \) and it may reach 0.2 at small \( \tan \beta \). Also lower values of \( \lambda \) lead much smaller \( g_{hSS} \). In this case, it is clear that unless the charged octet scalars are very light, its direct contribution to \( \Gamma(h \rightarrow \gamma\gamma) \) is quite marginal. Therefore, one concludes that the main effect in this class of models is due to the reduction of the top contribution.

In Fig. 8 we present the ratio \( \kappa_{\gamma\gamma} = \Gamma(h \rightarrow \gamma\gamma)/\Gamma(h \rightarrow \gamma\gamma)^{SM} \) in terms of \( m_S^\pm \) for three values of \( Y_4 \) that induce important suppressions on \( g_{ht\bar{t}} \). As can be easily seen, \( \kappa_{\gamma\gamma} \) slightly depends on very light \( m_S^\pm \). However, \( Y_4 \) has a significant impact on \( \kappa_{\gamma\gamma} \). It is remarkable that for \( Y_4 \simeq \mathcal{O}(-1) \), \( \kappa_{\gamma\gamma} \)
can be of order 1.8. In addition, we present a plot for $\kappa_{\gamma\gamma}$ versus $Y_4$ for three different values of $\lambda$: 0.5, 1, 1.5. From these two plots, one can conclude that $\lambda \simeq \mathcal{O}(0.5)$ with $Y_4 \simeq \mathcal{O}(0.5)$ is a perfect choice in order to get $\kappa_{\gamma\gamma} \simeq 1.6 - 2$.

The Higgs signal strength of decay channel, $h \to AA$, relative to the SM expectation is defined as

$$R_{AA} = \frac{\sigma(pp \to h \to AA)}{\sigma(pp \to h \to AA)_{SM}} = \frac{\sigma(pp \to h)}{\sigma(pp \to h)_{SM}} \frac{BR(h \to AA)}{BR(h \to AA)_{SM}} = \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)_{SM}} \frac{\Gamma_{SM}}{\Gamma_{tot}} \frac{\Gamma(h \to AA)}{\Gamma(h \to AA)_{SM}} = \kappa_{gg} \kappa_{tot} \kappa_{AA}, \quad (4.2)$$

where $\sigma(pp \to h)$ is the total Higgs production cross section and $BR(h \to AA)$ is the branching ratio of the corresponding channel. The total Higgs decay width is given by the sum of the dominant Higgs partial decay widths, i.e., $\Gamma_{tot} = \Gamma_{bb} + \Gamma_{WW} + \Gamma_{ZZ} + \Gamma_{\tau\tau}$. Other partial decay widths are much smaller and can be safely neglected. In the SM with 125 GeV Higgs mass, these partial decay widths are given by $\Gamma_{bb} = 2.3 \times 10^{-3}$, $\Gamma_{WW} = 8.7 \times 10^{-4}$, $\Gamma_{ZZ} = 1.1 \times 10^{-4}$, and $\Gamma_{\tau\tau} = 2.6 \times 10^{-4}$. As shown in Fig. 1, the Higgs coupling $g_{hWW}$ remains very close to the SM value for $\lambda \simeq 1$ or at large $\tan \beta$. Therefore, we have $\Gamma_{WW} \simeq \Gamma_{WW}^{SM}$. The bottom Yukawa coupling in our model takes the form

$$Y_{bb} \simeq -\frac{3m_b + m_t}{4v \cos \beta} \sin \alpha, \quad (4.3)$$

which can be of order the SM Yukawa coupling $Y_{b}^{SM} = m_b/v$ if $\sin \alpha \sim \frac{4}{3} \cos \beta$. This condition can be satisfied if $\lambda < 1$. We will adopt this constraint in our analysis so that $\Gamma_{bb}$ remains intact and hence $\Gamma_{tot} \simeq \Gamma_{tot}^{SM}$.

Now we turn to the Higgs production cross section in our $SU(5)$ effective model. At the LHC the dominant process for the Higgs production is the gluon-gluon fusion. In the SM the gluon fusion mechanism is mediated by top-quark via one loop triangle diagram. However, in our model the gluon fusion for the SM-like Higgs can be also obtained through the exchange of neutral and charged color-octet scalars, as shown in Fig. 9. The lowest order cross section can be written as

$$\sigma_{LO}(gg \to h) = \frac{\pi^2}{8m_h} \Gamma_{LO}(h \to gg) \delta(\hat{s} - m_h^2). \quad (4.4)$$

where $\hat{s}$ is the center of mass energy and $\delta(\hat{s} - m_h^2)$ is the Breit-Wigner form of the Higgs boson width, which is given by

$$\delta(\hat{s} - m_h^2) = \frac{1}{\pi} \frac{\hat{s} \Gamma_h/m_h}{(\hat{s} - m_h^2)^2 + \left(\hat{s} \Gamma_h/m_h\right)^2}. \quad (4.5)$$

The partial decay width $\Gamma(h \to gg)$ is given by [21]

$$\Gamma(h \to gg) = \frac{\alpha^2 m_h^3}{128 \pi^3} C(r_t) \frac{2g_{htH}}{m_t} F_{1/2}(x_t) + C(r_S) \frac{g_{hS^tS^t}}{m_{S^t}^2} F_0(x_{S^t}) + C(r_S) \frac{g_{hS^0S^0}}{m_{S^0}^2} F_0(x_{S^0}) \Bigg| \Bigg|, \quad (4.5)$$

where $C(r)$ is the $SU(3)$ representation index, which is defined as $\text{Tr}[T_r T_{r'}] = C(r) \delta^{ab}$ with $C(3) = C(r_t) = 1/2$ and $C(8) = C(r_s) = 3$. In the above expression, it was assumed that $m_{S^0} = m_{S^t}$. Therefore, the coupling $g_{hS^0S^0}$ is given by

$$g_{hS^0S^0} = -(\lambda_3 + 2\lambda_4) v \cos \beta \cos \alpha.$$
Thus, large values of $\lambda_3,4$ and small values of $\tan\beta$ are preferred to enhance the $g_hS^0S^0$ coupling. In Fig. 10 we present the ratio $\kappa_{gg} = \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)^{SM}}$ as a function of the coupling $\lambda_3$ for $\lambda = 0.8, 0.9$ and $m_S = 300$ GeV, $Y_4 = -0.8$, $\lambda_4 = -1$, $\tan\beta = 10$. As can be seen from these plots that the neutral octet-scalar can give a significant contribution to $\Gamma(h \to gg)$, so that it compensates the suppressions caused by: (i) the reduction of top Yukawa coupling, (ii) the negative effect of charged octet scalar. In this case, the region $0.8 < k_{gg} < 1$, which is preferred by best fit analysis of the recent experimental results [14], is quite accessible.

From the results of $\kappa_{\gamma\gamma}$ and $\kappa_{gg}$ with $\Gamma_{tot} \simeq \Gamma_{tot}^{SM}$, one can easily see that the recent experimental measurement of signal strength $R_{\gamma\gamma}$ by ATLAS and CMS collaboration can be easily accommodated in our model. The sign of color octet-scalar couplings can be fixed based on the final results of $R_{\gamma\gamma}$. If it is confirmed that $R_{\gamma\gamma} > 1$, then the coupling $\lambda_3$ should be of order $O(-1)$ and $Y_4 \simeq O(-0.5)$ so that the contribution of top quark is reduced. On the other hand, if $R_{\gamma\gamma}$ is proven to be less than one as indicated by the latest result of CMS experiment, then $\lambda_3$ should be positive and $Y_4$ should quite small so that the top quark effect remains as in the SM or even bigger. In Fig. 11 we display the signal strength $R_{\gamma\gamma}$ as a function of $\tan\beta$ for $\lambda = 0.4, 0.6$ and universal octet scalar mass $m_S = 300$ GeV, $Y_4 = -0.7$, $\lambda_3 = \lambda_4 = -1$. Also we plot $R_{\gamma\gamma}$ versus $\lambda$ for $Y_4 = -0.6, -0.8$ and $m_S = 300$ GeV, $\lambda_3 = \lambda_4 = -1$, $\tan\beta = 10$. 

**Figure 9.** Gluon fusion $gg \to h$ in $SU(5)$ effective model, mediated by top quark, and charged and neutral color-octet scalars.

**Figure 10.** (Left panel): The ratio $\kappa_{gg} = \frac{\Gamma(h \to gg)}{\Gamma(h \to gg)^{SM}}$ as a function of the coupling $\lambda_3$ for $\lambda = 0.8, 0.9$ and $m_S = 300$ GeV, $Y_4 = -0.8$, $\lambda_4 = -1$, $\tan\beta = 10$. (Right panel): $\kappa_{gg}$ versus $\lambda_4$ for $\tan\beta = 5, 10$ and $m_S = 300$ GeV, $\lambda = 0.9$, $Y_4 = -0.8$, $\lambda_3 = -0.5$. 

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5 Conclusions

In this paper we have derived the low energy effective model of $SU(5)$ grand unified field theory with extending the Higgs sector by 45$_H$-plet. We showed that this model is an extension of the SM with another Higgs doublet and color-Octet scalar doublet. We analyzed the flavor violation constraint of the octet-scalar masses. We found that the $K^0 - \bar{K}^0$ mixing impose a stringent bound on the neutral octet scalar mass if $\tan \beta < 1$. We have also studied all possible contributions to the light neutral Higgs decay into diphoton. We emphasized that the charged octet scalars may provide a constructive interference with the SM $W^\pm$ gauge bosons effects, which enables an enhancement of the branching ratio of $h \rightarrow \gamma\gamma$. However, it turns out that the most significant impact on the diphoton decay width in this model is due to a possible suppression for top-Yukawa coupling with SM-like Higgs or even flipping its sign that leads to important enhancement in $\Gamma(h \rightarrow \gamma\gamma)$ that accounts for the measured signal strength. In addition, we have studied the impact of the neutral octet-scalar on the gluon fusion Higgs production cross section. We showed that with this contribution one can keep $\kappa_{gg} \sim \mathcal{O}(1)$, while $\kappa_{\gamma\gamma} \sim \mathcal{O}(1.6)$. So the apparent tension between enhancement of diphoton decay rate and suppression of $\sigma(gg \rightarrow h)$ is resolved in this class of models.

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