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Pair production of 125 GeV Higgs boson in the SM extension with color-octet scalars at the LHC

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Abstract: Although the Higgs boson mass and single production rate have been determined more or less precisely, its other properties may deviate significantly from its predictions in the standard model (SM) due to the uncertainty of Higgs data. In this work we study the Higgs pair production at the LHC in the Manohar-Wise model, which extends the SM by one family of color-octet and isospin-doublet scalars. We first scanned over the parameter space of the Manohar-Wise model considering experimental constraints and performed fits in the model to the latest Higgs data by using the ATLAS and CMS data separately. Then we calculated the Higgs pair production rate and investigated the potential of its discovery at the LHC14. We conclude that: (i) Under current constrains including Higgs data after Run I of the LHC, the cross section of Higgs pair production in the Manohar-Wise model can be enhanced up to even 10^3 times prediction in the SM. (ii) Moreover, the sizable enhancement comes from the contributions of the CP-odd color-octet scalar S_I^A. For lighter scalar S_I^A and larger values of $|\lambda_I|$, the cross section of Higgs pair production can be much larger. (iii) After running again of LHC at 14 TeV, most of the parameter spaces in the Manohar-Wise model can be test. For an integrated luminosity of $100\,\mathrm{fb}^{-1}$ at the LHC14, when the normalized ratio $R = 10$, the process of Higgs pair production can be detected.

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Contents

1 Introduction

In July 2012, both the ATLAS and CMS collaborations at the LHC announced the discovery of a new boson with mass around 125 GeV [1, 2]. The combined data at the LHC indicate that its properties are quite compatible with those of the Higgs boson in the Standard Model (SM) [3–6]. However, whether the new boson is the Higgs boson predicted by the SM or new physics models still need to be further confirmed by the LHC experiment with high luminosity. So far, various new physics models like the low energy supersymmetric models can give reasonable interpretations for the properties of this SM-like Higgs boson around 125 GeV [7–63].

Moreover, discovery of the SM-like Higgs boson is not the end of the story. The next challenge for the experiment is to precisely measure its properties including all the possible production and decay channels. As a rare production channel, the Higgs pair production can be used to test the Higgs self-couplings effectively [64–66], which play an essential role in reconstructing the Higgs potential. The Higgs pair production in the SM at the LHC proceeds through the gluon fusion $gg \to hh$. At the leading order, the main contributions come from the heavy quark loops through the box diagrams and triangle diagrams with the Higgs self-coupling. Due to the weak Yukawa couplings and Higgs self-coupling, as well as the cancelations between these two types of diagrams, the cross section in the SM is too small to be detected with current integrated luminosity. Even at $\sqrt{s} = 14\,\text{TeV}$ with high luminosity, it is still difficult to detect this process. The discovery potential of the LHC to detect this production process has been investigated in [64, 67–81], and the most promising channel to detect it is $gg \to hh \to b\bar{b}\gamma\gamma$, other signal channels such as $hh \to b\bar{b}\tau^+\tau^-$ are swamped by the reducible backgrounds [75].

Compared with the predictions in the SM, the production rate of the SM-like Higgs pair production in new physics models can be enhanced significantly due to relatively large additional couplings of the SM-like Higgs boson with the introduced new particles, such as squarks in supersymmetric models [82–86] or other colored particles [87–90]. Therefore, the Higgs pair production can be a sensitive probe to new physics beyond the SM. In this paper we investigate the effects of color-octet scalars in the Manohar-Wise (MW) model [91] on the Higgs pair production at the LHC. The Manohar-Wise model is a special type of two-Higgs-doublet model and predicts a family of color-octet scalars, which can have sizable couplings with the Higgs boson, since the sign of Higgs coupling with gluons is usually opposite to the prediction in the SM [92]. Also considering the different amplitude structure of Higgs single and pair production, the cross section of Higgs pair production in the Manohar-Wise model may deviate significantly from its predictions in the SM.

This paper is structured as follows. In section 2 we briefly introduce the Manohar-Wise model. Then in section 3 we present the numerical results and discussions of the Higgs pair production in the Manohar-Wise model. Finally, the conclusions are presented in section 4.

2 Model with color octet scalars — The Manohar-Wise model

In the SM, the scalar sector contains only one Higgs scalar doublet, which is responsible for the electroweak symmetry breaking. Additional extensions of the scalar sector is restricted by the principle of minimal flavor violation (MFV). Just motivated by this principle, the Manohar-Wise model extends the SM by adding one family color-octet scalars with $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ quantum numbers $(8, 2)_{1/2}$ [91],

$$S^A = \begin{pmatrix} S^A_+ \\ S^A_0 \end{pmatrix}, \tag{2.1}$$

where $A = 1, \ldots, 8$ denotes color index, S^A_+ and S^A_0 are the electric charged and neutral color-octet scalar fields respectively, and

$$S^A_0 = \frac{1}{\sqrt{2}}(S^A_R + iS^A_I) \tag{2.2}$$

with $S^A_{R,I}$ denote the neutral CP-even and CP-odd color-octet scalar fields. In accordance with the MFV, the Yukawa couplings to the SM fermions are parameterized as

$$\mathcal{L} = -\eta_U Y^U_{ij} \bar{u}^i_R T^A S^A Q^j_L - \eta_D Y^D_{ij} \bar{d}^i_R T^A (S^A)^\dagger Q^j_L + \text{h.c.}, \tag{2.3}$$

where $Y^{U,D}_{ij}$ are the SM Yukawa matrices, i, j denote flavor indices, and $\eta_{U,D}$ are flavor universal constants.

The most general renormalizable scalar potential is given by

$$\begin{aligned} V = {} & \frac{\lambda}{4}\left(H^{\dagger i} H_i - \frac{v^2}{2}\right)^2 + 2m_S^2 \mathrm{Tr}(S^{\dagger i} S_i) + \lambda_1 H^{\dagger i} H_i \mathrm{Tr}(S^{\dagger j} S_j) + \lambda_2 H^{\dagger i} H_j \mathrm{Tr}(S^{\dagger j} S_i) \\ & + \left[\lambda_3 H^{\dagger i} H^{\dagger j} \mathrm{Tr}(S_i S_j) + \lambda_4 H^{\dagger i} \mathrm{Tr}(S^{\dagger j} S_j S_i) + \lambda_5 H^{\dagger i} \mathrm{Tr}(S^{\dagger j} S_i S_j) + \text{h.c.}\right] \\ & + \lambda_6 \mathrm{Tr}(S^{\dagger i} S_i S^{\dagger j} S_j) + \lambda_7 \mathrm{Tr}(S^{\dagger i} S_j S^{\dagger j} S_i) + \lambda_8 \mathrm{Tr}(S^{\dagger i} S_i) \mathrm{Tr}(S^{\dagger j} S_j) \\ & + \lambda_9 \mathrm{Tr}(S^{\dagger i} S_j) \mathrm{Tr}(S^{\dagger j} S_i) + \lambda_{10} \mathrm{Tr}(S_i S_j) \mathrm{Tr}(S^{\dagger i} S^{\dagger j}) + \lambda_{11} \mathrm{Tr}(S_i S_j S^{\dagger j} S^{\dagger i}), \end{aligned} \tag{2.4}$$

where H is usual $(1, 2)_{1/2}$ Higgs doublet, the traces are over color indices with $S = S^A T^A$, i, j denote $\mathrm{SU}(2)_L$ indices and all λ_i $(i = 1, \ldots, 11)$ except λ_4 and λ_5 are real parameters.

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Note that the convention $\lambda_3 > 0$ is allowed by a appropriate phase rotation of the S fields. After the electroweak symmetry breaking, the mass spectrum of the scalars depend on the parameters in the scalar potential, and at the tree-level are given by

$$\begin{aligned} m_{\pm}^2 &= m_S^2 + \lambda_1 \frac{v^2}{4} \equiv m_S^2 + \lambda_{\pm} \frac{v^2}{4}, \\ m_R^2 &= m_S^2 + (\lambda_1 + \lambda_2 + 2\lambda_3) \frac{v^2}{4} \equiv m_S^2 + 2\lambda_R \frac{v^2}{4}, \\ m_I^2 &= m_S^2 + (\lambda_1 + \lambda_2 - 2\lambda_3) \frac{v^2}{4} \equiv m_S^2 + 2\lambda_I \frac{v^2}{4}. \end{aligned} \tag{2.5}$$

The interactions of these scalars with the Higgs boson (labeled as h denoting the SM Higgs boson) are as follows [93],

$$g_{hS_i^{A*}S_i^B} = \frac{v}{2}\lambda_i \delta^{AB}, \qquad g_{hhS_i^{A*}S_i^B} = \frac{1}{2}\lambda_i \delta^{AB} \tag{2.6}$$

with $i = \pm, R, I$, and we take $v = 246\,\text{GeV}$.

3 Calculations and numerical results

In the Manohar-Wise model the Higgs pair production at the LHC mainly proceeds through the gluon fusion shown in figure 1. Compared with the SM, the Manohar-Wise model predicts additional color octet scalars including $S_i^A (i = \pm, R, I)$, which have couplings to the Higgs boson h. Therefore, the pair production of h in the Manohar-Wise model has additional contributions from the loops of the color octet scalars $S_i^A (i = \pm, R, I)$ besides the contributions from the loops mediated by the heavy quarks in the SM, as shown in figure 1. Since the additional contributions are at the same perturbation order as those in the SM, the cross section of the Higgs pair production in the Manohar-Wise model may significantly deviate from the prediction in the SM.

In the numerical calculations we take $m_t = 173\,\text{GeV}$, $m_b = 4.2\,\text{GeV}$, $m_W = 80.0\,\text{GeV}$, $m_Z = 91.0\,\text{GeV}$, and $\alpha = 1/128$ [94], and fix the collision energy of LHC and the mass of Higgs boson to be 14 TeV and 125.6 GeV respectively. Then we use CT10 [95] to generate the parton distribution functions, with the factorization scale μ_F and the renormalization scale μ_R chosen to be $2m_h$. We check that the cross section of the Higgs pair production in the SM is 18.7 fb, which is consistent with the result in [96].

In this work, following our previous work [92], we scan over the parameter space of the Manohar-Wise model considering following theoretical and experimental constraints: (i) the constraints from the unitarity; (ii) the constraints from electroweak precision data (EWPD); (iii) the constraints from the LHC searches for exotic scalars through dijet-pair events. Based on 4.6 fb^{-1} data at 7-TeV LHC for dijet-pair events collected by the ATLAS collaboration, the lower bound on the scalar mass has set to be 287 GeV at 95% confidence level [97, 98]. The lower bound from four-top channel is much higher, but it is based on some assumptions, e.g., the bound is 500 GeV (630 GeV) for the neutral scalar decays into top pair with a branching ratio of 50% (100%) [99, 100]. Since the latter constraint can be escaped from by adjusting η_U, we only require the color octet scalars to be heavier than

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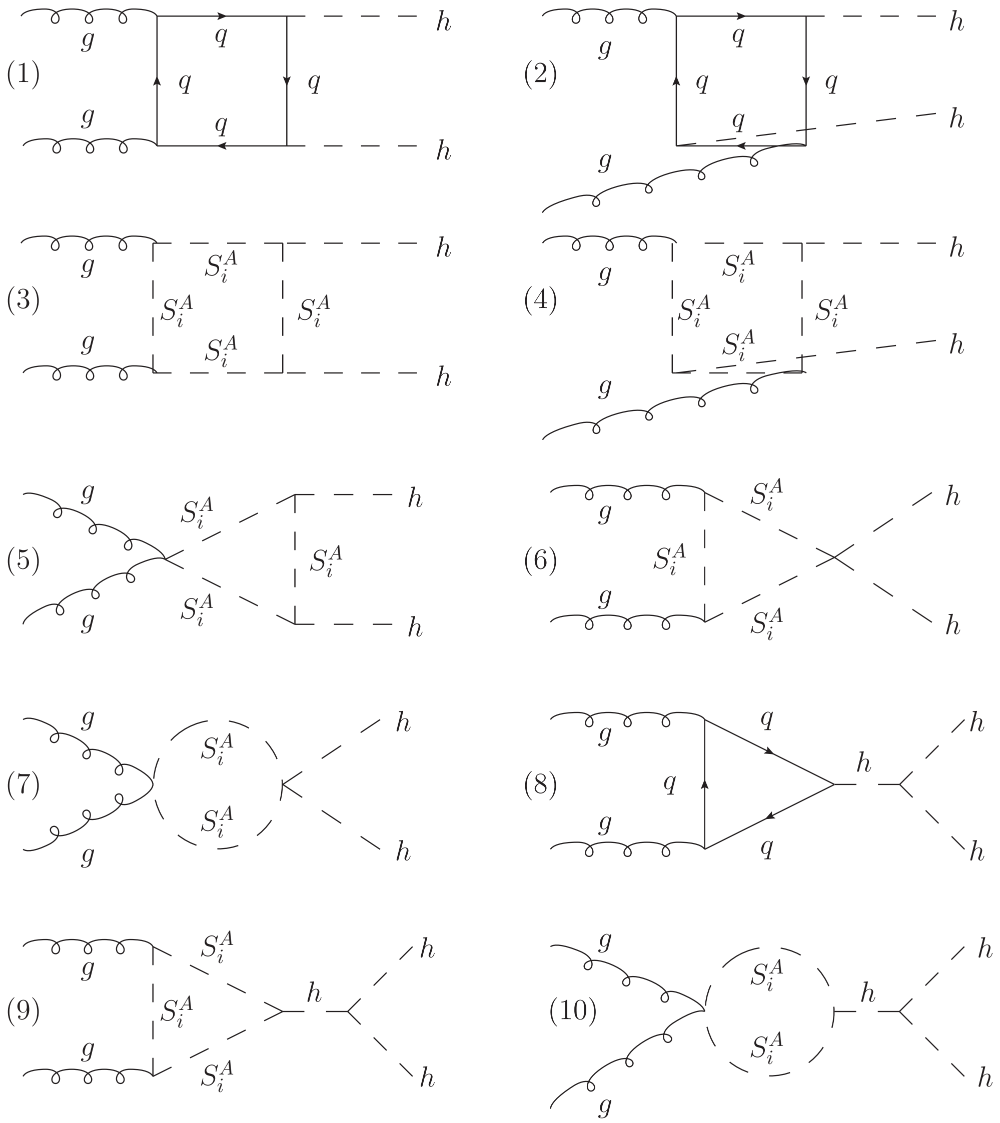

Figure 1. Feynman diagrams for the pair production of the Higgs boson via gluon fusion in the Manohar-Wise model, with S_i^A ($i = \pm, R, I$) denoting the color-octet scalars in the model. The diagrams with initial gluons or final Higgs bosons interchanged are not shown here. Due to the large Yukawa couplings, we only consider the contributions from the third generation quarks.

300 GeV. Here we can comment that, in future running of the LHC the lower bound from dijet-pair events may be higher. According to [101], for a color-octet scalar of 350 GeV (500 GeV), its pair production rate can reach 84.6 pb (11.4 pb) at 14-TeV LHC.

Under the above constraints, we perform fits in this model to the latest Higgs data by using the ATLAS data and CMS data respectively. The detail of the fits can be found in our previous works [92, 102, 103]. From the fits we pick up the 1σ (68% confidence level or $\chi^2_{\rm min} \leq \chi^2 \leq \chi^2_{\rm min} + 2.3$) and 2σ (95% confidence level or $\chi^2_{\rm min} + 2.3 < \chi^2 \leq \chi^2_{\rm min} + 6.18$) samples, which correspond to $5.63 \leq \chi^2 \leq 7.93$ and $7.93 < \chi^2 \leq 11.81$ for the fit to the ATLAS data, and $2.47 \leq \chi^2 \leq 4.77$ and $4.77 < \chi^2 \leq 8.65$ for the fit to the CMS data.

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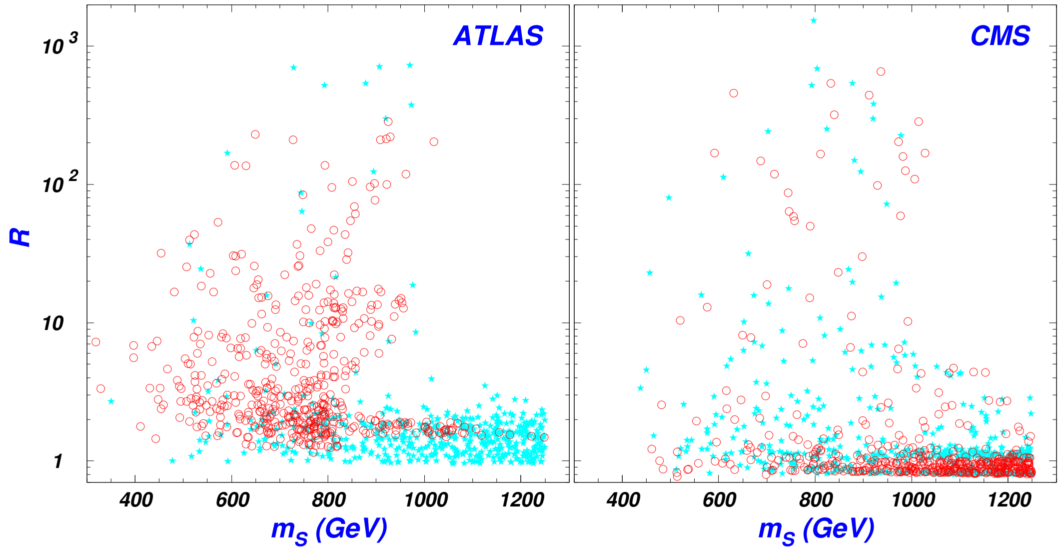

Figure 2. The scatter plots of the surviving samples, showing the normalized ratio R as a function of m_S. The red circles '$\circ$' denote 1σ surviving samples, and the sky blue stars '$\star$' denote 2σ samples.

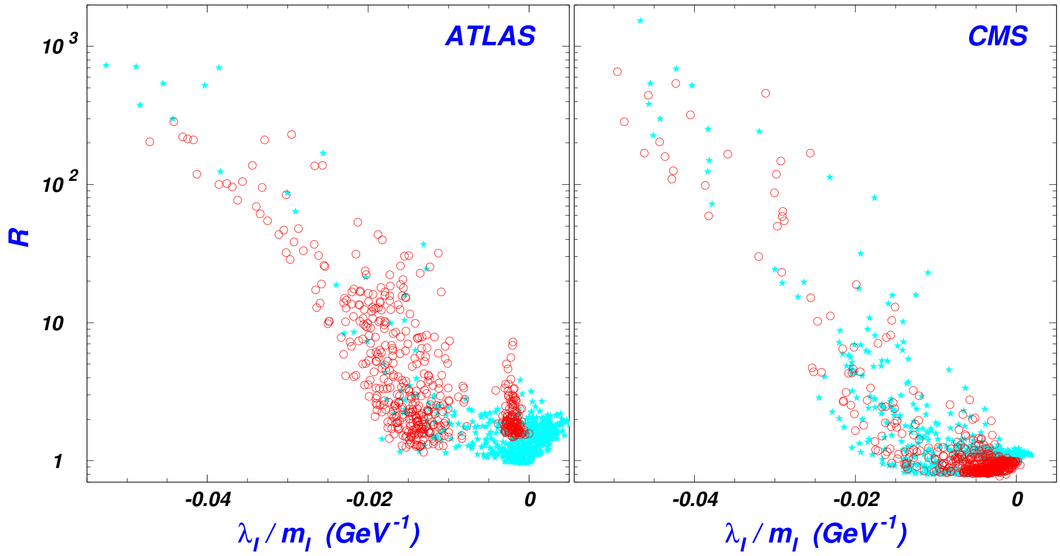

Figure 3. Same as figure 2, but showing the ratio of cross section in the Manohar-Wise model with that in the SM (i.e. R) as a function of λ_I/m_I.

Then with these samples we calculate the cross section of Higgs pair production in the Manohar-Wise model and define R as the ratio normalized to its SM values,

$$R \equiv \sigma_{MW}(gg \to hh)/\sigma_{\rm SM}(gg \to hh) \tag{3.1}$$

In figure 2 we project the 1σ and 2σ samples on the plane of the normalized ratio R versus m_S. The left panel displays the surviving samples in fitting to the ATLAS Higgs data, and the right panel shows that to the CMS data. In the figure, the red circles denote 1σ surviving samples, and the sky blue stars denote 2σ samples. From this figure we can clearly see that the cross section of the Higgs pair production in the Manohar-Wise model can significantly deviate from the SM prediction, and the normalized production rate R can even be up to 10^3. The figure also shows that, for $m_S \gtrsim 1\,\text{TeV}$, the ratio R is relatively small, usually smaller than 10, which reflects the decoupling effect.

Now we give analytical explanations to the deviation of the cross section in the Manohar-Wise model shown in figure 2. The diagrams in figure 1 can be divided into five parts: (1)+(2), (3)+(4), (5), (6)+(7) and (8)+(9)+(10), and each part is UV finite. We numerically check their relative size and find that the contributions to the cross section from the diagrams (3)+(4) and (5) are quite large. This is because the amplitude of these diagrams can be written as

$$\mathcal{M} \sim c_1 \frac{g^2_{hS^{A*}_{\pm}S^A_{\pm}}}{m^2_{\pm}} + c_2 \frac{g^2_{hS^{A*}_{R}S^A_{R}}}{m^2_{R}} + c_3 \frac{g^2_{hS^{A*}_{I}S^A_{I}}}{m^2_{I}} \tag{3.2}$$

where c_i (i=1, 2, 3) are $\mathcal{O}(1)$ coefficients. Considering the couplings shown in eq. (2.6), we rewrite the eq. (3.2) as

$$\mathcal{M} \sim \left(c_1 \frac{\lambda^2_{\pm}}{m^2_{\pm}} + c_2 \frac{\lambda^2_{R}}{m^2_{R}} + c_3 \frac{\lambda^2_{I}}{m^2_{I}} \right) \frac{v^2}{4} \tag{3.3}$$

And the values of λ_i $(i = \pm, R, I)$ are usually large required by the Higgs data [92]. While the amplitude from the other diagrams, such as (6)-(10) are not enhanced by λ_i^2 and usually proportional to $(C_{hgg}/SM)_i$, whose summation can not diverge much from that of the SM, since $|C_{hgg}/SM| \simeq 1$ according to current Higgs data (figure 2 in [92]). Besides, we also find that there are strong cancelation between the diagrams (3)+(4) and (5).

In our calculation, we find that the term involving λ_I^2/m_I^2 are usually much larger than that of $\lambda_{\pm}^2/m_{\pm}^2$ and λ_R^2/m_R^2 in eq. (3.3). The reason can be understood as follows. Firstly, the surviving samples prefer negative λ_I and $|\lambda_I|$ is usually much larger compared with $\lambda_{\pm}$ and λ_R (see figure 1 in [92]). Secondly, eq. (2.5) manifests that, for fixed m_S and negative $\lambda_i(i = \pm, R, I)$, the larger $|\lambda_i|$, the smaller m_i. Therefore, the contributions of the third term are dominant in eq. (3.3), that is, the contributions from the loops mediated by the scalar S_I^A are much larger than that by the scalar $S_{\pm}^A$ and S_R^A. As a proof, in figure 3 we show the ratio R versus λ_I/m_I. The figure clearly shows that larger $|\lambda_I/m_I|$ usually predicts larger value of ratio R. We checked that, for samples with $R \gtrsim 100$, the CP-odd octet scalars are not very light ($300 \lesssim m_I \lesssim 600\,\text{GeV}$), but the coupling λ_I should be very large ($-25 \lesssim \lambda_I \lesssim -8$), which can also be understood from figure 1 in [92]. And these large-R samples can also satisfy the perturbation theory, which suggests $|\lambda_i| \lesssim 8\pi$ $(i = \pm, R, I)$ [104, 105]. Figure 3 also shows that for some special samples with $|\lambda_I/m_I| \sim 0$ in the left panel, the cross section in the Manohar-Wise model can also be enhanced up to 10 times prediction in the SM. For these samples, $|\lambda_R/m_R|$ is near 0.02 and the contributions from eq. (3.3) can be still large, comparable to that for the samples with $|\lambda_I/m_I| \sim 0.02$. That can be understood from figure 3 in [92].

Finally, we investigate the potential for discovery of Higgs pair production at the LHC14. In figure 4, we project samples on the plane of significance $S/\sqrt{B}$ versus the

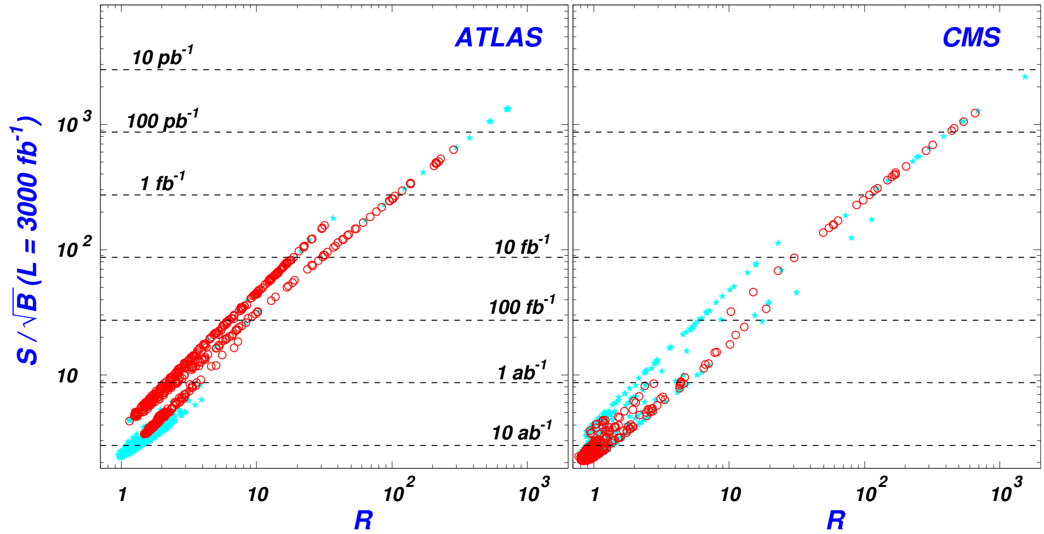

Figure 4. Same as figure 2, but showing the normalized ratio R as a function of $S/\sqrt{B}$, which is calculated at an integrated luminosity of $3000\,\mathrm{fb}^{-1}$, and also marking out the corresponding luminosity for $S/\sqrt{B} = 5$.

normalized ratio R. In calculating $S/\sqrt{B}$, we utilize the Monte Carlo (MC) simulation result of $gg \to hh \to b\bar{b}\gamma\gamma$ in the SM [106]. We assume that in the Manohar-Wise model the $\sigma \times Br$ and acceptances of the background, the acceptances of the signal are the same as that in the SM, while the $\sigma \times Br$ of the signal are calculated by ourselves, which can be expressed as

$$\begin{aligned}(\sigma \cdot Br)_{MW} &= \sigma_{\mathrm{SM}} \times R \times BR(h \to b\bar{b}) \times Br(h \to \gamma\gamma) \\ &\simeq (\sigma \cdot Br)_{\mathrm{SM}} \times R \times (C_{h\gamma\gamma}/SM)^2, \end{aligned} \tag{3.4}$$

thus $S/\sqrt{B}$ in the Manohar-Wise model should be proportional to $R \times (C_{h\gamma\gamma}/SM)^2$. So combined with figure2 and figure3 in [92], we can understand that there are mainly three linear relation in each planes in figure 4 in this paper. Since $S/\sqrt{B}$ is also proportional to $\sqrt{L}$, in this figure we also mark out the lines of $S/\sqrt{B} = 5$ for other values of luminosity, samples above which can be discovered with corresponding luminosity. For example, with the integrated luminosity of $100\,\mathrm{fb}^{-1}$ at the 14 TeV LHC, when the cross section of Higgs pair production in the Manohar-Wise model is enhanced by 10 times the prediction in the SM, i.e. $R = 10$, this process may be detected. Owing to the highly enhanced Higgs pair production rate, many samples in the Manohar-Wise model can be tested very soon after LHC running again.

4 Summary and conclusion

Motivated by the principle of minimal flavor violation, the Manohar-Wise model introduces one family of color-octet scalars, which can have large couplings with the Higgs boson. Since the properties of the SM-like Higgs boson around 125 GeV need to be precisely scrutinized, in this work we studied the Higgs pair production considering the effect of the

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color-octet scalars. Following our previous work [92], we first scanned over the parameter space of the Manohar-Wise model considering the theoretical and experimental constraints and performed fits of the model to the latest Higgs data by using the ATLAS and CMS data separately. Then we calculated the Higgs pair production rate and investigated the potential of its discovery at the LHC14.

Base on our calculation and analysis, we get following conclusions:

- Under current constrains including Higgs data after Run I of the LHC, the cross section of Higgs pair production in the Manohar-Wise model can be enhanced up to even 10^3 times prediction in the SM.
- Moreover, the sizable enhancement comes from the contributions of the CP-odd color-octet scalar S_I^A. For lighter scalar S_I^A and larger values of $|\lambda_I|$, the cross section of Higgs pair production can be much larger.
- After running again of LHC at 14 TeV, most of the parameter spaces in the Manohar-Wise model can be test. For an integrated luminosity of $100\,\text{fb}^{-1}$ at the LHC14, when the normalized ratio $R = 10$, the process of Higgs pair production can be detected.

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