Charged Higgs Decay to $W^\pm$ and Heavy Neutral Higgs Decaying into $\tau^+\tau^-$ in Georgi-Machacek Model at LHC

Swagata Ghosh

Indian Institute of Technology Kharagpur, Kharagpur, India

Abstract

The CMS collaboration at the Large Hadron Collider (LHC) searched for a charged Higgs boson, in the mass range of 300 to 700 GeV, decaying into a $W^\pm$ boson and a heavy neutral Higgs boson of mass 200 GeV, which successively decays into a pair of tau leptons, in proton-proton collisions at $\sqrt{s} = 13$ TeV. In this letter, focusing on the Georgi-Machacek (GM) model, I discuss the parameter space, allowed by the theoretical and experimental constraints, for which the limits on this process obtained by the CMS can be accommodated. The study in this letter also shows that, for the choice of the parameters, the decay of the charged Higgs boson $H_3^\pm$ to $W^\pm$ and a heavy neutral Higgs boson H is preferred over the decay to any gauge boson and any other neutral or charged Higgs bosons. I also present the values of production cross-section times branching ratio for the decay of H to a pair of b-quarks at $\sqrt{s} = 14$ TeV.

1. INTRODUCTION

The discovery of the Higgs boson at the LHC [1, 2] brings the Standard Model (SM) into triumphant, though it cannot explain all of the natural observations and theoretical problems. To resolve these deficiencies, one of the common practices is to add higher multiplets, like additional singlet, doublet, or triplet to the scalar sector of the SM. In this letter, I am interested in a model where two scalar triplets, one real and one complex, are added to the SM, which is popularly known as the Georgi-Machacek (GM) model [3, 4, 5]. The custodial symmetry is preserved in this model, i.e., $\rho = 1$ [6]. The constraints on the parameter space of the model are already well studied in the literature [7, 8, 9, 10, 11, 12, 13, 14, 15], and also a calculator is available [16] to calculate all the constraints. Various phenomenological works [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29] on this model enrich the knowledge of the reader. The articles [30, 31, 32] explore the decay of the CP-odd singly charged Higgs boson, but the channel probed in this letter, first described in the paper of the CMS experiment [33], is still untouched in the literature for the GM model.

The mass $m_{H^\pm}$ of any singly charged Higgs boson $H^\pm$ can be split into three regions, heavy ($m_{H^\pm} > m_t - m_b$), intermediate ($m_{H^\pm} \approx m_t$), and light ($m_{H^\pm} < m_t - m_b$), where m_t and m_b are top quark and bottom quark masses, respectively. This letter addresses the production of heavy-charged Higgs, and as it is associated with top and bottom quarks at LHC, I also consider that production channel, i.e., $pp \to tbH^\pm$.

The Georgi-Machacek model is formulated by the extension of the scalar sector of the SM by one real and one complex triplet with equal vacuum expectation value (vev) which results in the preservation of the custodial symmetry. Besides the two CP-even neutral Higgs bosons h and H, one CP-odd fermiophilic neutral Higgs H_3, and one CP-even but fermiophobic neutral Higgs H_5, GM model consists of four singly charged Higgs $H_3^\pm$, $H_5^\pm$, and two doubly charged Higgs $H_5^{\pm\pm}$. H_3 and $H_3^\pm$ are the members of the custodial triplet and H_5,

$H_5^\pm$, and $H_5^{\pm\pm}$ are the members of the custodial quintuplet sharing the common mass m_3 and m_5, respectively. The production cross-section of $H_5^\pm$ is much lower than that of $H_3^\pm$ and hence, we are interested in the production of singly charged scalar of the custodial triplet via $pp \to tbH_3^\pm$. Next, considering the charged Higgs decay to one gauge boson and one Higgs, this $H_3^\pm$ can decay into $W^\pm h$, $W^\pm H$, $W^\pm H_5$, $W^\mp H_5^{\pm\pm}$, and $ZH_5^\pm$. For the choice of parameter space, it is shown that the branching ratio of $H_3^\pm \to W^\pm H$ is maximum. Also, following [33], I am interested in singly charged Higgs decay to $W^\pm$ and a heavy neutral Higgs further decaying into $\tau^+\tau^-$, and the quintuplet scalars are fermiophobic. My automatic choice is $pp \to tbH_3^\pm$, $H_3^\pm \to W^\pm H$, $H \to \tau^+\tau^-$. To probe this channel, I have also considered the parameter space allowed by the theoretical as well as experimental data and finally showed that the GM model can accommodate the observed limit obtained by the CMS experiment without constraining the parameter space. Besides, I present the possible values of cross-section times branching ratio for the channel $pp \to tbH_3^\pm$, $H_3^\pm \to W^\pm H$, and $H \to b\bar{b}$ at $\sqrt{s} = 14$ TeV.

This letter is arranged as follows. Section 2 describes the model briefly, Section 3 explains the constraints, Section 4 gives the results, and Section 5 finally summarizes and concludes.

2. THE MODEL

In addition to the SM doublet $\Phi = (\phi^+, \phi^0)^T$, the scalar sector of the Georgi-Machacek (GM) model consists of two triplets. Following the notations of [34], the real triplet of hypercharge $Y = 0$ and the complex triplet with $Y = 2$ are $\xi = (\xi^+, \xi^0, \xi^-)^T$ and $\chi = (\chi^{++}, \chi^+, \chi^0)^T$, respectively.

In terms of bidoublet and bitriplet,

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \quad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}, \quad (1)$$

the scalar potential can be written as,

$$V(\Phi, X) = \frac{\mu_2{}^2}{2} \operatorname{Tr}\left(\Phi^\dagger \Phi\right) + \frac{\mu_3{}^2}{2} \operatorname{Tr}\left(X^\dagger X\right)$$
$$+ \lambda_1 \left[\operatorname{Tr}\left(\Phi^\dagger \Phi\right)\right]^2 + \lambda_2 \operatorname{Tr}\left(\Phi^\dagger \Phi\right) \operatorname{Tr}\left(X^\dagger X\right)$$
$$+ \lambda_3 \operatorname{Tr}\left(X^\dagger X X^\dagger X\right) + \lambda_4 \left[\operatorname{Tr}\left(X^\dagger X\right)\right]^2$$
$$- \frac{\lambda_5}{4} \operatorname{Tr}\left(\Phi^\dagger \sigma^a \Phi \sigma^b\right) \operatorname{Tr}\left(X^\dagger t^a X t^b\right) \quad (2)$$
$$- \frac{M_1}{4} \operatorname{Tr}\left(\Phi^\dagger \sigma^a \Phi \sigma^b\right) \left(U X U^\dagger\right)_{ab}$$
$$- M_2 \operatorname{Tr}\left(X^\dagger t^a X t^b\right) \left(U X U^\dagger\right)_{ab},$$

where σ^a are the Pauli matrices. The matrices t^as and U are,

$$t^1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$
$$t^2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix},$$
$$t^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \quad (3)$$
$$U = \frac{1}{\sqrt{2}}\begin{pmatrix} -1 & 0 & 1 \\ -i & 0 & -i \\ 0 & \sqrt{2} & 0 \end{pmatrix}.$$

To preserve the custodial symmetry, the vevs of the two triplets are the same and equal to v_2. The SM doublet vev is equal to $v_1/\sqrt{2}$ leading to $\sqrt{v_1^2 + 8v_2^2} = v \approx 246\,\text{GeV}$. I also consider $\tan\beta = 2\sqrt{2}v_2/v_1$.

The scalar sector of the GM model possesses ten physical scalars, which can be expressed as

$$H_5^{\pm\pm} = \chi^{\pm\pm}, \quad H_5^\pm = \frac{(\chi^\pm - \xi^\pm)}{\sqrt{2}}, \quad H_5^0 = \sqrt{\frac{2}{3}}\xi^0 - \sqrt{\frac{1}{3}}\chi^{0R},$$
$$H_3^\pm = -\sin\beta\phi^\pm + \cos\beta\frac{(\chi^\pm + \xi^\pm)}{\sqrt{2}},$$
$$H_3^0 = -\sin\beta\phi^{0I} + \cos\beta\chi^{0I},$$
$$h = \cos\alpha\phi^{0R} - \sin\alpha\sqrt{\frac{1}{3}}\xi^0 + \sqrt{\frac{2}{3}}\chi^{0R},$$
$$H = \sin\alpha\phi^{0R} + \cos\alpha\sqrt{\frac{1}{3}}\xi^0 + \sqrt{\frac{2}{3}}\chi^{0R}. \quad (4)$$

The mass-squared matrices of h and H are given by $\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}{}^2 & \mathcal{M}_{12}{}^2 \\ \mathcal{M}_{21}{}^2 & \mathcal{M}_{22}{}^2 \end{pmatrix}$, with $\mathcal{M}_{11}^2 = 8\lambda_1 v_1^2$, $\mathcal{M}_{12}^2 = \mathcal{M}_{21}^2 = \frac{\sqrt{3}}{2}[-M_1 + 4(2\lambda_2 - \lambda_5)v_2]v_1$, $\mathcal{M}_{22}^2 = \frac{M_1 v_1^2}{4v_2}$. One may easily obtain the mixing angle α from $\tan 2\alpha = \frac{2\mathcal{M}_{12}{}^2}{\mathcal{M}_{22}{}^2 - \mathcal{M}_{11}{}^2}$. $H_5^{\pm\pm,\pm,0}$ have the mass $m_5 = \sqrt{\frac{M_1}{4v_2}v_1^2 + 12M_2 v_2 + \frac{3}{2}\lambda_5 v_1^2 + 8\lambda_3 v_2^2}$, and $H_3^{\pm,0}$ possess the mass $m_3 = \sqrt{(\frac{M_1}{4v_2} + \frac{\lambda_5}{2})v^2}$. h is considered lighter than H, and the square of their masses is given by $m_{h,H}{}^2 = (\mathcal{M}_{11}{}^2 + \mathcal{M}_{22}{}^2 \mp \sqrt{(\mathcal{M}_{11}{}^2 - \mathcal{M}_{22}{}^2)^2 + 4(\mathcal{M}_{12}{}^2)^2})/2$.

3. CONSTRAINTS FROM THEORY AND LHC DATA

Theoretical constraints in the GM model mainly arise from the perturbative unitarity, electroweak vacuum stability, and the constraints from oblique parameters [7, 34]. For the constraints coming from the LHC Higgs signal data at $\sqrt{s} = 13\,\text{TeV}$ and the LHC data for the decay of doubly charged Higgs to the same sign W bosons, I follow [35, 36, 39]. Here, I consider the CP-even neutral lighter scalar h as the SM-like Higgs with $m_h \approx 125\,\text{GeV}$. The coupling modifiers for h are given by

$$\kappa_f^h = \frac{v}{v_1}c_\alpha, \quad \kappa_V^h = -\frac{1}{3v}\left(8\sqrt{3}s_\alpha v_2 - 3c_\alpha v_1\right). \quad (5)$$

For the $h \to \gamma\gamma$ decay, the charged scalars ($H_5^{\pm\pm}$, $H_{3,5}^\pm$) also take part and hence that is also to be considered in case of the constraints from LHC Higgs data. Following [33], the mass of the CP-even neutral heavier scalar H is set at $200\,\text{GeV}$, and the mass (m_3) of the CP-odd scalars varies from 300 to $700\,\text{GeV}$. Also, the mass (m_5) of the CP-even fermiophobic scalars varies from 80 to $1000\,\text{GeV}$. The other parameters are varied as follows: $5 \leq v_2 \leq 60\,\text{GeV}$, $-1 \leq \sin\alpha \leq 1$, $0 \leq M_{1,2} \leq 1000\,\text{GeV}$. The allowed parameter spaces in the $m_3 - m_5$, $m_3 - v_2$, $\sin\alpha - v_2$, $M_2 - M_1$ plane are shown in Figure 1 as a brief illustration. In this plot, I also showed the production cross-section times branching ratio of the channel $pp \to tbH_3^\pm$, $H_3^\pm \to W^\pm H$, $H \to \tau^+\tau^-$ at $\sqrt{s} = 13\,\text{TeV}$ for some allowed parameter points. I have not shown the cross-section times branching ratio for the points for which this product is too small.
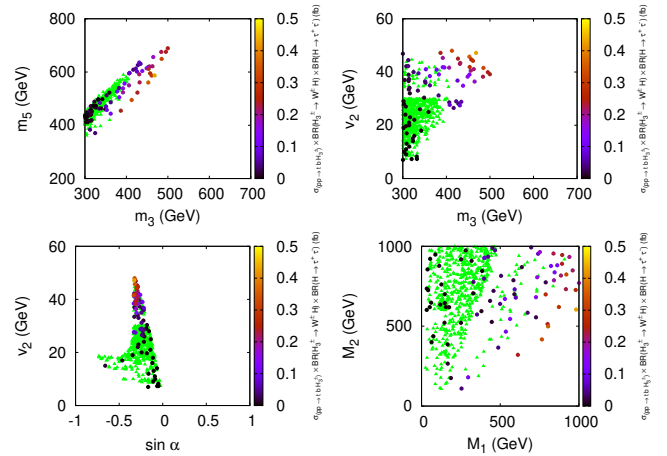
**FIGURE 1:** Allowed parameter space (green and colored points) in the $m_3 - m_5$, $m_3 - v_2$, $\sin\alpha - v_2$, $M_2 - M_1$ plane for $m_h = 125\,\text{GeV}$ and $m_H = 200\,\text{GeV}$ from theoretical constraints and LHC data at $\sqrt{s} = 13\,\text{TeV}$. $\sigma(pp \to tbH_3^\pm) \times BR(H_3^\pm \to W^\pm H) \times BR(H \to \tau^+\tau^-)$ in fb are also shown for points (colored points except green) for which this value is relatively high. The values of this cross-section times branching ratio are relatively lower for green points, and hence not shown in the plots.

4. RESULTS

This letter focuses on the production and decay of a singly charged Higgs boson decaying into one gauge boson and an-

other Higgs boson followed by the decay of this Higgs boson into two tau leptons following the results obtained in the CMS experiment [33]. GM model consists of two types of singly charged Higgs ($H_{3,5}^{\pm}$), but the production cross section of $H_3^{\pm}$ is higher than that of $H_5^{\pm}$ through the $pp \rightarrow tbH^{\pm}$ production mechanism. The decay of $H_3^{\pm}$ to one gauge boson and one Higgs leads to $H_3^{\pm} \rightarrow W^{\pm}h$, $W^{\pm}H$, $W^{\pm}H_5$, $W^{\mp}H_5^{\pm\pm}$, $ZH_5^{\pm}$. Figure 2 shows that for two different choices of the scalar masses, triplet vevs, and mixing angle α, the branching ratio of $H_3^{\pm} \rightarrow W^{\pm}H$ is maximum among all other decay channels. The sets of parameters in this figure are not consistent with the allowed parameter space, but only for illustration purposes. I set $m_H = 200$ GeV throughout this work following the reference paper.
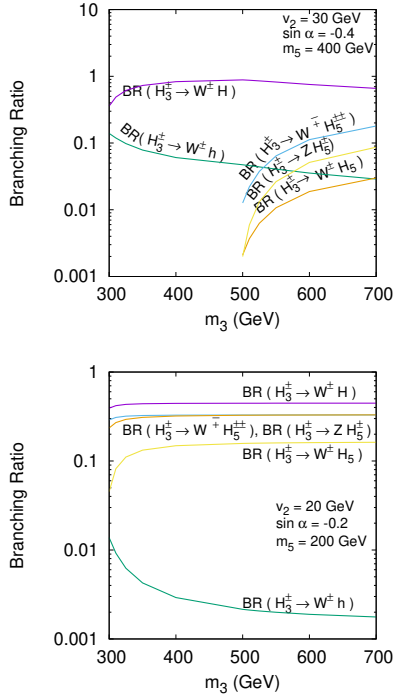

FIGURE 2: Branching ratio of $H_3^{\pm} \rightarrow W^{\pm}h$, $W^{\pm}H$, $W^{\pm}H_5$, $W^{\mp}H_5^{\pm\pm}$, $ZH_5^{\pm}$ for $m_H = 200$ GeV, $M_1 = M_2 = 100$ GeV.

Now, H can decay into a pair of SM as well as BSM particles. Following [33], $H \rightarrow \tau^+ \tau^-$ decay is studied here followed by the study of $H \rightarrow b\bar{b}$ as future reference. In Figure 1, besides the allowed parameter spaces of the GM model (green points), I plot $\sigma(pp \rightarrow tbH_3^{\pm}) \times BR(H_3^{\pm} \rightarrow W^{\pm}H) \times BR(H \rightarrow \tau^+ \tau^-)$ in fb at $\sqrt{s} = 13$ TeV for the allowed points for which this value is relatively large. Next, in Figure 3, I also showed $\sigma(pp \rightarrow tbH_3^{\pm}) \times BR(H_3^{\pm} \rightarrow W^{\pm}H) \times BR(H \rightarrow b\bar{b})$ in fb at $\sqrt{s} = 14$ TeV for the allowed points of the GM model. The points for which this value is relatively small are not shown in this figure. To do this, I implemented the model into the FeynRule file [37] and obtained the UFO model file for MadGraph [38].

In the CMS experimental paper, where $\sigma(pp \rightarrow tbH^{\pm}) \times BR(H^{\pm} \rightarrow W^{\pm}H) \times BR(H \rightarrow \tau^+ \tau^-)$ in pb is plotted as a function of $m_{H^{\pm}}$ in GeV varying from 300 to 700 GeV at $\sqrt{s} = 13$ TeV, $m_H = 200$ GeV, the production cross-section times the

branching ratios have their maximum and minimum value at 0.080 pb at $m_{H^{\pm}} = 300$ GeV and 0.013 pb at $m_{H^{\pm}} = 700$ GeV, respectively. From different allowed parameter points, it can be seen that the production cross-section times branching ratios in pb never reach that value, and hence, it can be inferred that the GM model accommodates the experimental results from [33] very well. Therefore, there is no cut-off in the parameter space from this experimental result.

From different indirect constraints, there are limits on the triplet vev v_2 and the strongest one coming from the $b \rightarrow s\gamma$ data [7], which shows that, for the triplet Higgs mass ranging from 300 to 700 GeV, the vev of the triplet can go upto 50 GeV. Besides, the quintuplet Higgs mass may obtain values as high as 700 GeV. However, these higher values of v_2 or m_5 do not change our observations and the parameter space of the GM model obtains no constraints from the referred CMS result.
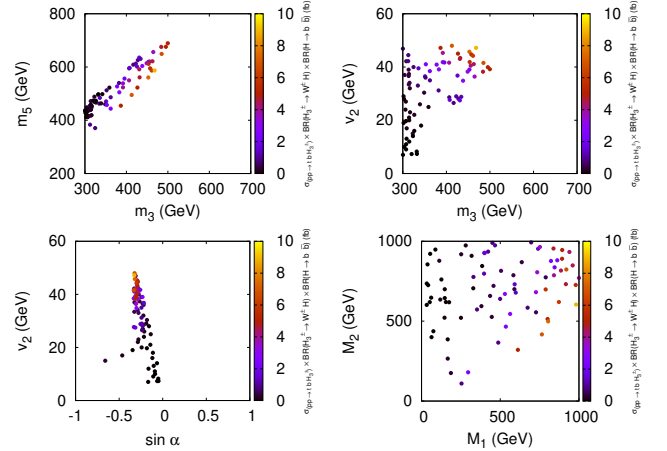
FIGURE 3: Product of cross section and branching ratio for $pp \rightarrow tbH_3^{\pm}$, $H_3^{\pm} \rightarrow W^{\pm}H$, $H \rightarrow b\bar{b}$ at $\sqrt{s} = 14$ TeV for the some allowed points in $m_3 - m_5$, $m_3 - v_2$, $\sin\alpha - v_2$, $M_1 - M_2$ plane.

5. SUMMARY AND CONCLUSIONS

The GM model, where the scalar sector of the SM is extended by one real and one complex triplet, preserves the custodial symmetry, and I choose this model to see whether it can accommodate the observed limit of the production cross-section of singly charged Higgs boson with mass 300–700 GeV times its decay to $W^{\pm}$ and a heavy neutral Higgs with mass 200 GeV, which further decays into a pair of tau leptons as studied in [33]. The scalar sector of the GM model contains ten physical scalars, where four are neutral (h, H, H_3, H_5), four are singly charged ($H_{3,5}^{\pm}$), and two are doubly charged ($H_5^{\pm\pm}$). Among the singly charged particles, the cross-section of $H_3^{\pm}$ is higher, and the decay branching ratio of this to $W^{\pm}H$ is maximum among other possible decays of $H_3^{\pm}$ to one gauge boson and one Higgs boson. Therefore, this letter studies the process $pp \rightarrow tbH_3^{\pm} \rightarrow tbW^{\pm}H \rightarrow tbW^{\pm}\tau^+\tau^-$ for different parameter choices of the GM model and shows that this model can accommodate the observed limit obtained from the CMS experimental result. However, any future modification from the LHC data for this channel can change this inference and also can probe the parameter space of the GM model. This letter

also studies the process $pp \to tbH_3^\pm \to tbW^\pm H \to tbW^\pm b\bar{b}$ for the allowed parameter points and predicts the corresponding cross-section times branching ratio for future reference.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

ACKNOWLEDGMENTS

References

[1] G. Aad et al. [ATLAS], "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," Phys. Lett. B **716**, 1–29 (2012) doi:10.1016/j.physletb.2012.08.020 [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan et al. [CMS], "Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC," Phys. Lett. B **716**, 30–61 (2012) doi:10.1016/j.physletb.2012.08.021 [arXiv:1207.7235 [hep-ex]].

[3] H. Georgi and M. Machacek, "Doubly Charged Higgs Bosons," Nucl. Phys. B **262**, 463–477 (1985) doi:10.1016/0550-3213(85)90325-6.

[4] H. E. Logan and V. Rentala, "All the generalized Georgi-Machacek models," Phys. Rev. D **92**, no.7, 075011 (2015) doi:10.1103/PhysRevD.92.075011 [arXiv:1502.01275 [hep-ph]].

[5] A. Kundu, P. Mondal, and P. B. Pal, "Custodial symmetry, the Georgi-Machacek model, and other scalar extensions," Phys. Rev. D **105**, no.11, 115026 (2022) doi:10.1103/PhysRevD.105.115026 [arXiv:2111.14195 [hep-ph]].

[6] C. W. Chiang and K. Yagyu, "Testing the custodial symmetry in the Higgs sector of the Georgi-Machacek model," JHEP **01**, 026 (2013) doi:10.1007/JHEP01(2013)026 [arXiv:1211.2658 [hep-ph]].

[7] K. Hartling, K. Kumar, and H. E. Logan, "Indirect constraints on the Georgi-Machacek model and implications for Higgs boson couplings," Phys. Rev. D **91**, no.1, 015013 (2015) doi:10.1103/PhysRevD.91.015013 [arXiv:1410.5538 [hep-ph]].

[8] C. W. Chiang, S. Kanemura, and K. Yagyu, "Novel constraint on the parameter space of the Georgi-Machacek model with current LHC data," Phys. Rev. D **90**, no.11, 115025 (2014) doi:10.1103/PhysRevD.90.115025 [arXiv:1407.5053 [hep-ph]].

[9] X. K. Du, Z. Li, F. Wang, and Y. K. Zhang, "Explaining the CDF-II W-boson mass anomaly in the Georgi-Machacek extension models," Eur. Phys. J. C **83**, no.2, 139 (2023) doi:10.1140/epjc/s10052-023-11297-1 [arXiv:2204.05760 [hep-ph]].

[10] C. W. Chiang, A. L. Kuo, and K. Yagyu, "Enhancements of weak gauge boson scattering processes at the CERN LHC," JHEP **10**, 072 (2013) doi:10.1007/JHEP10(2013)072 [arXiv:1307.7526 [hep-ph]].

[11] C. W. Chiang, G. Cottin, and O. Eberhardt, "Global fits in the Georgi-Machacek model," Phys. Rev. D **99**, no.1, 015001 (2019) doi:10.1103/PhysRevD.99.015001 [arXiv:1807.10660 [hep-ph]].

[12] A. Ismail, H. E. Logan, and Y. Wu, "Updated constraints on the Georgi-Machacek model from LHC Run 2," [arXiv:2003.02272 [hep-ph]].

[13] T. K. Chen, C. W. Chiang, C. T. Huang, and B. Q. Lu, "Updated constraints on the Georgi-Machacek model and its electroweak phase transition and associated gravitational waves," Phys. Rev. D **106**, no.5, 055019 (2022) doi:10.1103/PhysRevD.106.055019 [arXiv:2205.02064 [hep-ph]].

[14] Z. Bairi and A. Ahriche, "More constraints on the Georgi-Machacek model," Phys. Rev. D **108**, no.5, 5 (2023) doi:10.1103/PhysRevD.108.055028 [arXiv:2207.00142 [hep-ph]].

[15] R. Ghosh and B. Mukhopadhyaya, "Some new observations for the Georgi-Machacek scenario with triplet Higgs scalars," Phys. Rev. D **107**, no.3, 035031 (2023) doi:10.1103/PhysRevD.107.035031 [arXiv:2212.11688 [hep-ph]]

[16] K. Hartling, K. Kumar, and H. E. Logan, "GMCALC: a calculator for the Georgi-Machacek model," [arXiv:1412.7387 [hep-ph]].

[17] C. W. Chiang, S. Kanemura, and K. Yagyu, "Phenomenology of the Georgi-Machacek model at future electron-positron colliders," Phys. Rev. D **93**, no.5, 055002 (2016) doi:10.1103/PhysRevD.93.055002 [arXiv:1510.06297 [hep-ph]].

[18] C. W. Chiang and T. Yamada, "Electroweak phase transition in Georgi-Machacek model," Phys. Lett. B **735**, 295–300 (2014) doi:10.1016/j.physletb.2014.06.048 [arXiv:1404.5182 [hep-ph]].

[19] C. W. Chiang and K. Tsumura, "Properties and searches of the exotic neutral Higgs bosons in the Georgi-Machacek model," JHEP **04**, 113 (2015) doi:10.1007/JHEP04(2015)113 [arXiv:1501.04257 [hep-ph]].

[20] P. Mondal, "Enhancement of the W boson mass in the Georgi-Machacek model," Phys. Lett. B **833**, 137357 (2022) doi:10.1016/j.physletb.2022.137357 [arXiv:2204.07844 [hep-ph]].

[21] J. Chang, C. R. Chen, and C. W. Chiang, "Higgs boson pair productions in the Georgi-Machacek model at the LHC," JHEP **03**, 137 (2017) doi:10.1007/JHEP03(2017)137 [arXiv:1701.06291 [hep-ph]].

[22] C. Degrande, K. Hartling, and H. E. Logan, "Scalar decays to $\gamma\gamma$, $Z\gamma$, and $W\gamma$ in the Georgi-Machacek model," Phys. Rev. D **96**, no.7, 075013 (2017) [erratum: Phys. Rev. D **98**, no.1, 019901 (2018)] doi:10.1103/PhysRevD.96.075013 [arXiv:1708.08753 [hep-ph]].

[23] R. Zhou, W. Cheng, X. Deng, L. Bian, and Y. Wu, "Electroweak phase transition and Higgs phenomenology in the Georgi-Machacek model," JHEP **01**, 216 (2019) doi:10.1007/JHEP01(2019)216 [arXiv:1812.06217 [hep-ph]].

[24] H. E. Logan and M. B. Reimer, "Characterizing a benchmark scenario for heavy Higgs boson searches

in the Georgi-Machacek model," Phys. Rev. D **96**, no.9, 095029 (2017) doi:10.1103/PhysRevD.96.095029 [arXiv:1709.01883 [hep-ph]].

[25] D. Das and I. Saha, "Cornering variants of the Georgi-Machacek model using Higgs precision data," Phys. Rev. D **98**, no.9, 095010 (2018) doi:10.1103/PhysRevD.98.095010 [arXiv:1811.00979 [hep-ph]].

[26] N. Ghosh, S. Ghosh, and I. Saha, "Charged Higgs boson searches in the Georgi-Machacek model at the LHC," Phys. Rev. D **101**, no.1, 015029 (2020) doi:10.1103/PhysRevD.101.015029 [arXiv:1908.00396 [hep-ph]].

[27] A. Banerjee, G. Bhattacharyya, and N. Kumar, "Impact of Yukawa-like dimension-five operators on the Georgi-Machacek model," Phys. Rev. D **99**, no.3, 035028 (2019) doi:10.1103/PhysRevD.99.035028 [arXiv:1901.01725 [hep-ph]].

[28] A. Adhikary, N. Chakrabarty, I. Chakraborty, and J. Lahiri, "Probing the $H^\pm W^\mp Z$ interaction at the high energy upgrade of the LHC," Eur. Phys. J. C **81**, no.6, 554 (2021) doi:10.1140/epjc/s10052-021-09335-x [arXiv:2010.14547 [hep-ph]].

[29] C. H. de Lima and H. E. Logan, "Unavoidable Higgs coupling deviations in the $Z2$-symmetric Georgi-Machacek model," Phys. Rev. D **106**, no.11, 115020 (2022) doi:10.1103/PhysRevD.106.115020 [arXiv:2209.08393 [hep-ph]].

[30] S. Ghosh, "Fermionic decay of charged Higgs boson in low mass region in Georgi Machacek Model," [arXiv:2205.03896 [hep-ph]].

[31] C. W. Chiang, A. L. Kuo, and T. Yamada, "Searches of exotic Higgs bosons in general mass spectra of the Georgi-Machacek model at the LHC," JHEP **01**, 120 (2016) doi:10.1007/JHEP01(2016)120 [arXiv:1511.00865 [hep-ph]].

[32] J. Y. Cen, J. H. Chen, X. G. He, G. Li, J. Y. Su, and W. Wang, "Searching for a charged Higgs boson with both $H^\pm W^\mp Z$ and $H^\pm tb$ couplings at the LHC," JHEP **01**, 148 (2019) doi:10.1007/JHEP01(2019)148 [arXiv:1811.00910 [hep-ph]].

[33] [CMS], "Search for a charged Higgs boson decaying into a heavy neutral Higgs boson and a W boson in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$," CMS-PAS-HIG-21-010.

[34] K. Hartling, K. Kumar, and H. E. Logan, "The decoupling limit in the Georgi-Machacek model," Phys. Rev. D **90**, no.1, 015007 (2014) doi:10.1103/PhysRevD.90.015007 [arXiv:1404.2640 [hep-ph]].

[35] [CMS], "Combined measurements of the Higgs boson's couplings at $\sqrt{s} = 13\,\text{TeV}$," CMS-PAS-HIG-17-031.

[36] [ATLAS], "Combined measurements of Higgs boson production and decay using up to $80\,\text{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 13\,\text{TeV}$ collected with the ATLAS experiment," ATLAS-CONF-2019-005.

[37] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, "FeynRules 2.0—A complete toolbox for tree-level phenomenology," Comput. Phys. Commun. **185**, 2250–2300 (2014) doi:10.1016/j.cpc.2014.04.012 [arXiv:1310.1921 [hep-ph]].

[38] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations," JHEP **07**, 079 (2014) doi:10.1007/JHEP07(2014)079 [arXiv:1405.0301 [hep-ph]].

[39] Sirunyan, Albert M and others, "Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$," Phys. Rev. Lett. **08**, 120(2018) doi:10.1103/PhysRevLett.120.081801 [arXiv:1709.05822 [hep-ex]].