

Searching for the doubly-charged Higgs bosons in the Georgi-Machacek model at the ep colliders

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The Georgi-Machacek model is one of many Beyond Standard Model scenarios with an extended scalar sector which can group under the custodial $SU(2)_C$ symmetry. There are 5-plet, 3-plet and singlet Higgs bosons under the classification of such symmetry in addition to the Standard Model Higgs boson. Here we study the prospects for detecting the doubly-charged Higgs boson ($H_5^{\pm\pm}$) via the vector boson fusion production at the electron-proton colliders. Typically, we concentrate on our analysis through same-sign $\mu^-\mu^-$ decay mode. The discovery significance are calculated as the functions of the triplet vacuum expectation value and necessary luminosity.

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1. Introduction

The 125 GeV Standard Model (SM)-like particle was observed at the Large Hadron Collider (LHC). Even so, it may still too early to conclude it is the whole story that responsible for the electroweak symmetry breaking and even the mass of all the elementary particles. In fact, from a theoretical point of view, there is no fundamental reason for a minimal Higgs sector, as occurs in the SM. It is therefore motivated to consider additional Higgs representations that also contribute to the symmetry breaking, and by doing this, one may even hold answers to some longstanding questions in particle physics, such as the origin of neutrino mass, the identity of the dark matter, and may establish a relationship with a yet undiscovered sector.

In order to extend the Higgs sector in the SM, we can add isospin singlet or isospin doublet directly to the SM Higgs doublet, or even higher isospin multiplet. No matter which way we use, the following two requirements from the experimental data should be taken into account: one is that the electroweak ρ parameter should be very close to unity and the other is that the tree level flavor changing neutral current processes should be strongly suppressed. Collider experiments are dedicating their efforts to search for signal of additional Higgs particles which arise in a number of scenarios, one of them is the Georgi-Machacek (GM) model.

Here we study the prospects for detecting the doubly-charged Higgs boson ($H_5^{\pm\pm}$) via the vector boson fusion production at the electron-proton (ep) colliders. We concentrate on our analysis through same-sign $\mu^-\mu^-$ decay mode. The talk is arranged as bellow: we review the Georgi-Machacek model in section 2 shortly. Section 3 is arranged to present the signal and background analysis and numerical calculations. The doubly-charged Higgs boson discovery potential is presented here. Finally comes our short summary in the last section.

2. The Georgi-Machacek Model

In the GM model, two $SU(2)_L$ isospin triplet scalar fields, χ (with hypercharge $Y = 1$) and ξ (with $Y = 0$), are introduced to the Higgs sector in addition to the original SM $SU(2)_L$ doublet ϕ (with $Y = 1/2$). The scalar content of the theory can be organized in terms of the $SU(2)_L \otimes SU(2)_R$ symmetry. In order to make this symmetry explicit, we write the doublet in the form of a bidoublet Φ and combine the triplets to form a bitriplet Δ :

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}. \quad (2.1)$$

The custodial symmetry is preserved at tree level by imposing such global $SU(2)_L \otimes SU(2)_R$ symmetry on the scalar potential. The Lagrangian can be obtained and V is the potential where the full formula can be found here:

$$\begin{aligned} V(\Phi, \Delta) = & \frac{1}{2}m_1^2 \text{tr}[\Phi^\dagger \Phi] + \frac{1}{2}m_2^2 \text{tr}[\Delta^\dagger \Delta] + \lambda_1 (\text{tr}[\Phi^\dagger \Phi])^2 + \lambda_2 (\text{tr}[\Delta^\dagger \Delta])^2 \\ & + \lambda_3 \text{tr} [(\Delta^\dagger \Delta)^2] + \lambda_4 \text{tr}[\Phi^\dagger \Phi] \text{tr}[\Delta^\dagger \Delta] + \lambda_5 \text{tr} \left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2} \right] \text{tr}[\Delta^\dagger T^a \Delta T^b] \\ & + \mu_1 \text{tr} \left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2} \right] (P^\dagger \Delta P)_{ab} + \mu_2 \text{tr}[\Delta^\dagger T^a \Delta T^b] (P^\dagger \Delta P)_{ab}. \end{aligned} \quad (2.2)$$

After the symmetry, the scalar fields in the GM model can be classified into different representations under the custodial symmetry transformation. The scalar fields from doublet Φ is decomposed into a 3-plet and a singlet. Those from the triplet Δ is decomposed into a 5-plet, a 3-plet and a singlet. Among these $SU(2)_C$ multiplets, the 5-plet states directly become physical Higgs bosons, *i.e.*, $H_5 = (H_5^{\pm\pm}, H_5^\pm, H_5^0)$. For the two 3-plets, one of the linear combinations corresponds to physical Higgs field, *i.e.*, $H_3 = (H_3^\pm, H_3^0)$, and the other becomes the Nambu-Goldstone bosons G^\pm and G^0 which are absorbed into the longitudinal components of the W^\pm and Z bosons, respectively.

The GM model has some features. It preserves the ρ -parameter unity at the tree level via custodial symmetry. It offers the possibility of implementing the seesaw mechanism to endow the neutrinos with naturally light Majorana masses. The tree level couplings of the SM-like Higgs to fermions and vector bosons may be enhanced in comparison to the SM. The appearance of the $H^\pm W^\mp Z$ coupling at the tree level, and the presence of doubly-charged scalar particles, are phenomenal quite interesting.

3. The Calculation

The fiveplet scalar states are produced primarily through the vector boson fusion (VBF) and associated production (VH₅) mode. Our purpose is to study the prospects for detecting the doubly-charged Higgs boson in the GM model at the ep collider. The proposed ep collider is the Large Hadron Electron collider (LHeC), which is a combination of 60 GeV electron beam and 7 TeV proton beam of the LHC. This may later be extended to 50 TeV proton beam of Future Circular Collider (FCC-eh). Both projects will create new electron facilities. Through ep collision, the most promising channel is via the VBF mechanism. We study three decay modes: one is the same-sign leptonic decay mode (mode A), the second is the semileptonic decay mode (mode B) and the third one is the multi-jet decay mode (mode C):

$$\begin{aligned}
\text{mode A : } & e^- p \rightarrow \nu_e (H_5^- \rightarrow W^- W^-) j \rightarrow \nu_e \bar{\nu}_\ell \bar{\nu}_\ell \ell^- \ell^- j \\
\text{mode B : } & e^- p \rightarrow \nu_e (H_5^- \rightarrow W^- W^-) j \rightarrow \nu_e \bar{\nu}_\ell \ell^- jjj \\
\text{mode C : } & e^- p \rightarrow \nu_e (H_5^- \rightarrow W^- W^-) j \rightarrow \nu_e jjjjj
\end{aligned} \tag{3.1}$$

where j refers to jets with $j = u, c, \bar{d}, \bar{s}$ and other possibilities from w boson decay, $\ell = e, \mu$ are the leptons. The corresponding feynman diagram is plotted in Fig.1[left]. The large multi-jet backgrounds make modes B and C the challenge choices to detect the doubly-charged Higgs bosons. For mode A, by distinguishing e, μ leptons, we can have $e^- e^-, e^- \mu^-$ or $\mu^- \mu^-$ final combinations of the observations. Since electron is the initial collision particle, it's easier to appear in the final states. For $e^- e^-$ and $e^- \mu^-$ combinations, they will be affected by the $e^- p \rightarrow e^- W^- j$ background, which is unfortunately quite large. In contrast, $\mu^- \mu^-$ final state will have much clean environment and become the advantaged one. The scan over the parameter space is performed in Fig.1[right] (figure taken from ref.[1]). The two important parameters are M_{H_5} and $\sin \theta_H$ since our studied coupling and production rate are directly proportional to them. These points were generated by the public available package GMCALC[2], in which various theoretical and experimental constraints are taken into account, for example, the perturbation unitarity, the stability of the electroweak vacuum, the S parameter, as well as those from various B-physics observations, etc. The area above the

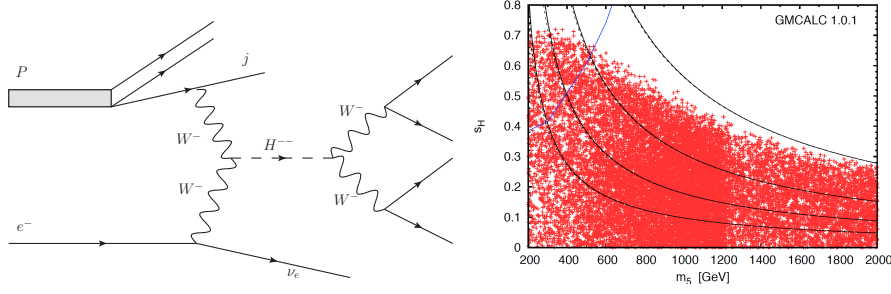


Figure 1: Left: Feynman diagram for the signal process $e^-p \rightarrow \nu_e(H_5^{--} \rightarrow W^-W^-)j$ with $\nu_e\bar{\nu}_\ell\bar{\nu}_\ell\ell^-\ell^-j$, $\nu_e\bar{\nu}_\ell\ell^-\ell^-jjj$ and $jjjjj$ decay modes at the ep collider. Right: The scatter point plot of the allowed parameter space in the plane of $\sin\theta_H$ and M_{H_5} .

blue curve is excluded by the LHC experimental data. We see that when M_{H_5} is less than 600 GeV, middle and large values of $\sin\theta_H$ are ruled out. For area where M_{H_5} larger than 600 GeV, $\sin\theta_H$ is mainly constrained from the other constraints. Considering the doubly-charged Higgs decay, the formula can be found in ref.[3]. When M_{H_5} is not very large, for over 98% of the scan points, $\text{BR}(H_5^{\pm\pm} \rightarrow W^\pm W^\pm)$ were above 99%. Therefore, for simplicity, the $H_5^{\pm\pm}$ state can be assumed to decay entirely into vector boson pairs for masses above the same-sign W pair threshold, say, $\text{BR}(H_5^{\pm\pm} \rightarrow W^\pm W^\pm) = 1$. Before doing the full signal and background simulation, we present a

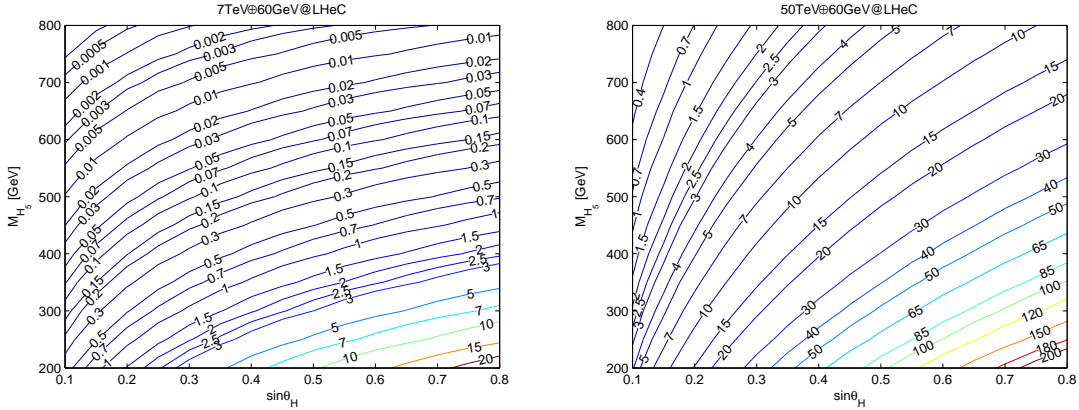


Figure 2: Total cross sections (in fb) for 5-plet Higgs production $e^-p \rightarrow \nu_e H_5^{--} j$ as the functions of M_{H_5} and $\sin\theta_H$. (a),(b) correspond to the 7 TeV LHeC and 50 TeV FCC-eh, respectively. The electron beam is 60 GeV.

general VBF production rate of the doubly-charged Higgs boson at the LHeC and FCC-eh in Fig.2. The total cross sections are plotted in fb as functions of $\sin\theta_H$ and M_{H_5} . The allowed boundary in Fig.1 should be taken into account. The cross section at the LHeC is around the order of only 0.1-1 fb, while at the FCC-eh, it can be much larger. We consider the full simulation chain including the detector effects at both the LHeC and the FCC-eh, thanks to the contributions from the LHeC working group. The studied topology is characterized by a same-sign μ^- lepton pair, a forward rapidity jet plus missing transverse momentum from the undetected neutrinos. The dominant background is simply $e^-p \rightarrow \nu_e \mu^- \mu^- \nu_\mu \nu_\mu j$, including 0- W^- , 1- W^- and 2- W^- contributions, where 2- W^- ($e^-p \rightarrow \nu_e(W^-W^- \rightarrow \mu^- \nu_\mu \mu^- \nu_\mu)j$) is the dominant one. In Fig.3 we present various kine-

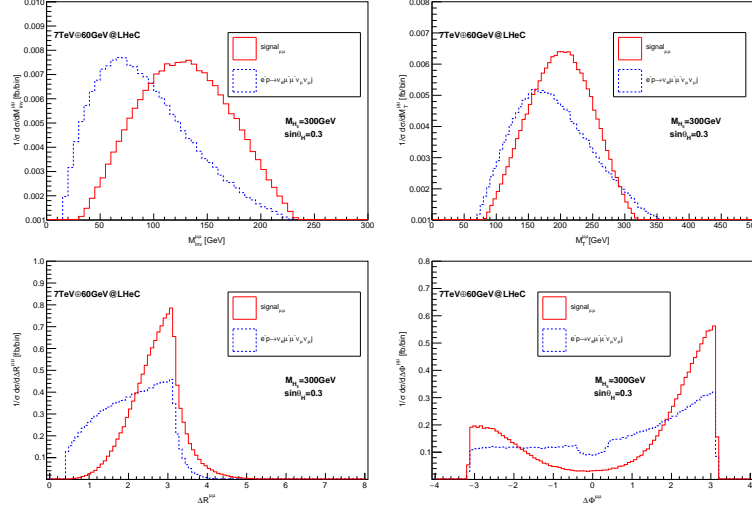


Figure 3: Various kinematical distributions (in units of fb per bin) for the signal and backgrounds at the 7 TeV LHeC. The electron beam is 60 GeV. Here $M_{H_5} = 300$ GeV and $\sin\theta_H = 0.3$. Plots are unit normalized.

matical distributions for both the signal and background. Results are for 7 TeV LHeC while for 50 TeV FCC-eh we can get similar results. We will aim at finding the most efficient selections

7TeV \oplus 60GeV@LHeC [1 ab $^{-1}$]	same-sign $\mu^-\mu^-$	$\Delta R^{\mu\mu}$ > 1.92	$\Delta\Phi^{\mu\mu} \in (-\pi, -1.28)$ or (1.36, π)	$M_{inv}^{\mu\mu}$ >75 GeV	$M_T^{\mu\mu}$ >40 GeV
signal $_{\mu\mu}$ [$\sin\theta_H = 0.3$]	10.46	9.45	9.24	9.21	10.23
B[e $^-$ p \rightarrow $\nu_e\mu^-\mu^- \nu_\mu \nu_\mu$]	10.52	6.43	7.13	6.71	9.58
SS	2.84	3.13	2.96	3.02	2.89
50TeV \oplus 60GeV@FCC-eh [100 fb $^{-1}$]	same-sign $\mu^-\mu^-$	$\Delta R^{\mu\mu}$ > 1.6	$\Delta\Phi^{\mu\mu} \in (-\pi, -0.88)$ or (1.04, π)	$M_{inv}^{\mu\mu}$ >70 GeV	$M_T^{\mu\mu}$ >78 GeV
signal $_{\mu\mu}$ [$\sin\theta_H = 0.3$]	10.16	9.44	9.25	9.13	9.75
B[e $^-$ p \rightarrow $\nu_e\mu^-\mu^- \nu_\mu \nu_\mu$]	8.29	5.88	6.41	5.40	7.04
SS	3.03	3.23	3.08	3.24	3.11

Table 1: Expected number of events and signal significance (SS) evaluated with 1 ab $^{-1}$ integrated luminosity at the LHeC and 100 fb $^{-1}$ at the FCC-eh. Here $M_{H_5} = 300$ GeV and each time take only one cut.

in order to allow the best separation between noise-related and signal-related events. We compare the efficiency of different cuts in Tab.1 include M_{inv} , $\Delta\Phi$, ΔR and M_T for the $\mu^-\mu^-$ system for both the 1 ab $^{-1}$ LHeC and 100 fb $^{-1}$ FCC-eh. We take one cut once so as not cut events too much, otherwise the significance can be reduced. For M_{H_5} not very large, ΔR is the one we use which can lead better significance ($SS = \sqrt{2[(n+b)\log(1+n/b) - n]}$, where n is the number of events and b is the number of backgrounds respectively). In Fig.4 we calculate the lowest necessary luminosity with 3σ and 5σ discovery significance as a function of $\sin\theta_H$. We present the results for the LHeC and FCC-eh with both the unpolarized and polarized ($p_{e^-} = 0.8$) electron beams. It is shown that high integrated luminosity is required to probe small $\sin\theta_H$. At the FCC-eh, the lowest

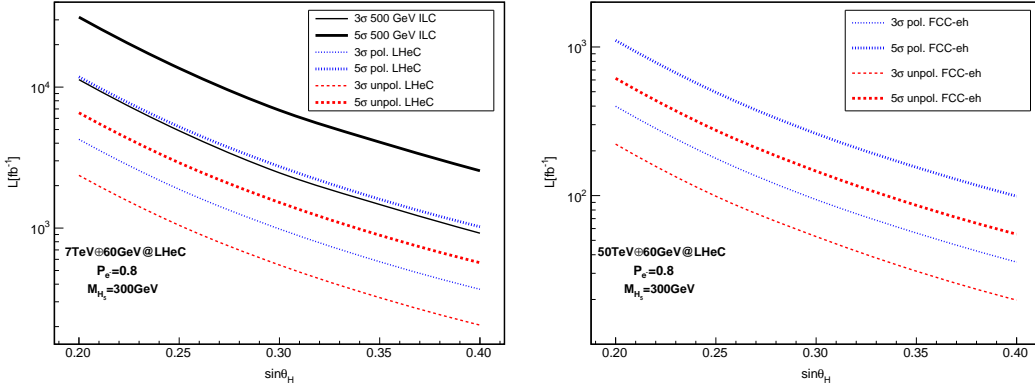


Figure 4: The lowest necessary luminosity with 3σ and 5σ discovery significance as a function of $\sin\theta_H$. Here we used 10% systematic uncertainty for background yields only.

necessary luminosity are much reduced than that at the LHeC as expected. The lowest necessary luminosity are much smaller than that of the related study at the ILC. Polarized beam could make the measurement even better.

4. Summary

The possible existence of heavy exotic particles in new physics beyond the Standard Model are highly expected among the particle physics community. The Georgi-Machacek model is one of such scenarios with an extended scalar sector which can group under the custodial $SU(2)_V$ symmetry. There are 5-plet, 3-plet and singlet Higgs bosons under the classification of such symmetry in addition to the SM Higgs boson. In the GM model, the 5-plets doubly-charged states, so that the distinct phenomenological features should appear. In this talk, we present the 5-plet Higgs production at the LHeC and FCC-eh. We focus on the vector boson fusion channel and decays into final states containing a pair of same-sign μ^- . The discovery significance are calculated as the functions of the triplet vacuum expectation value and the lowest necessary luminosity. We expect the future ep experiments could also measure the strength of the doubly charged Higgs boson production or otherwise put a stringent constraint on it.

References

- [1] Marco Zaro and Heather Logan, *Recommendations for the interpretation of LHC searches for H_5^0 , H_5^\pm , and H_5^\pm in vector boson fusion with decays to vector boson pairs*, LHCHSWG-2015-001.
- [2] K. Hartling, K. Kumar and H. E. Logan, *GMALC: a calculator for the Georgi-Machacek model*, [arXiv:1412.7387].
- [3] Zhaofeng Kang, Jinmian Li, Tianjun Li, Yandong Liu and Guo-Zhu Ning, *Light Doubly Charged Higgs Boson via the WW^* Channel at LHC*, *Eur.Phys.J.C***75** (2015) no.12, 574, [arXiv:1404.5207].
- [4] YuFei Zhang, Hao Sun, Xuan Luo and WeiNing Zhang, *Searching for the heavy charged custodial fiveplet Higgs boson in the Georgi-Machacek model at the International Linear Collider*, *Phys.Rev.D.* (2017), [arXiv:1706.01490].