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Heavy Higgs boson H production at the future multi-TeV muon collider in the context of the $U(1)_{B-L}$ model

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We study in the context of the $U(1)_{B-L}$ model the production and decays of the heavy Higgs boson H via the association between the Z' boson and the new heavy Higgs boson H. We consider the $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ signal with the subsequent decay of Z to pairs of $l^\pm l^\mp$ with $l = e, \mu$ and H to pairs of $W^\pm W^\mp$. The projections of new physics at the muon collider with the benchmark center-of-mass energies of $\sqrt{s} = 3, 4, 5, 6, 7$ TeV and conservative integrated luminosities of $\mathcal{L}_{\text{con}} = 1, 2, 3, 4, 10$ ab^{-1}, is of the order of 684 expected events. This scenario demonstrates the importance of measuring the heavy Higgs boson H at the future muon collider. In another scenario, in addition to the $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ signal, we consider Vector Boson Scattering (VBS) rates of $\mu^+\mu^- \to WWZ$, and the Leptonic, Semi-leptonic, and Hadronic channels of the $W^\pm$ boson for the signal. In this case, the number of events expected to be produced at the future muon collider is $N = 329\,551$, which is a promising scenario.

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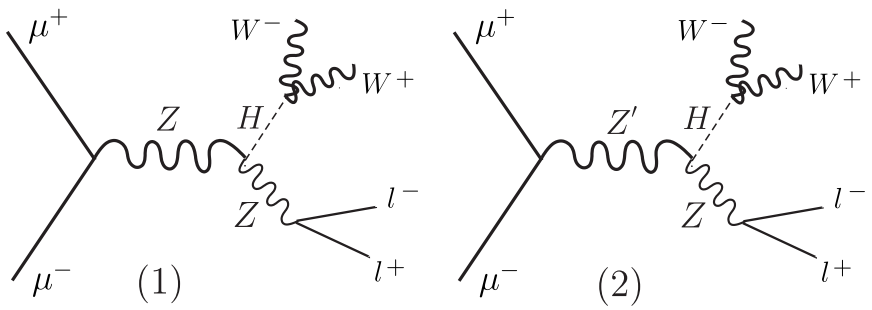

Figure 1: Feynman diagrams illustrating the signal process $\mu^+\mu^- \to (Z, Z') \to ZH \to l^+l^-W^+W^-$, in the B-L model.

1. Introduction

In this paper, we focus on a model with an extended scalar sector, which, depending on the specific model, can help address additional questions that the SM cannot answer. We start from the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ [1–6] and present a study on the production and decay of the heavy Higgs boson H predicted by this model, which is responsible for the $U(1)_{B-L}$ symmetry breaking. In addition, the model also predicts the existence of a new heavy neutral gauge boson, Z', and three heavy Right-Handed (RH) neutrinos. The crucial test is the detection of these new particles. These model characteristics may significantly alter the SM phenomenology and lead to exciting signatures at present and future hadron-hadron, lepton-hadron, and lepton-lepton colliders.

For our study, we incorporated the $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\mp W^\pm$ annihilation process and Vector Boson Scattering (VBS) rates of $\mu^+\mu^- \to WWZ$ [7, 8]. In addition, we consider the Leptonic, Semi-leptonic, and Hadronic channels of the $W^\pm$, which significantly affect signal sensitivity. These decays are characterized by clean leptonic final states and missing energy due to the associated neutrinos. The interested reader can consult Ref. [9] where a more complete study of the process $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\mp W^\pm$ is presented.

2. The $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ signal

The first-order description of the total cross-section of the $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ process is given by the Feynman diagrams shown in Figure 1. The explicit form of the total cross-section is given by:

$$\sigma(\mu^+\mu^- \to ZH) = \frac{G_F^2 M_Z^4}{24\pi} s\sqrt{\lambda}\left[\lambda + 12M_Z^2/s\right]\left(\left[\frac{(g_V^\mu)^2 + (g_A^\mu)^2}{[(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2]}\right]\sin^2\alpha \right. \tag{1}$$

$$+ \left[\frac{(g_V^{'\mu})^2 + (g_A^{'\mu})^2}{[(s-M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2]}\right]\left[f(\theta_{BL}, g_1')\sin\alpha - g(\theta_{BL}, g_1')\cos\alpha\right]^2 + 2\left(g_V^\mu g_V^{'\mu} + g_A^\mu g_A^{'\mu}\right)$$

$$\times \left.\left[\frac{(s-M_Z^2)(s-M_{Z'}^2) + M_Z M_{Z'}\Gamma_Z\Gamma_{Z'}}{[(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2][(s-M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2]}\right]\left[f(\theta_{BL}, g_1')\sin\alpha - g(\theta_{BL}, g_1')\cos\alpha\right]\sin\alpha\right).$$

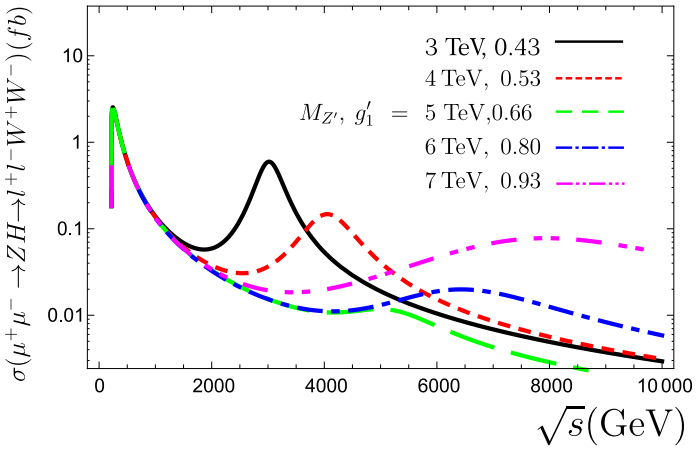

Figure 2: The total cross-section of the process $\mu^+\mu^- \to (Z, Z') \to ZH \to l^+l^-W^+W^-$ as a function of $\sqrt{s}$. The curves are for $M_{Z'} = 3$ TeV and $g'_1 = 0.43$, $M_{Z'} = 4$ TeV and $g'_1 = 0.53$, $M_{Z'} = 5$ TeV and $g'_1 = 0.66$, $M_{Z'} = 6$ TeV and $g'_1 = 0.80$, $M_{Z'} = 7$ TeV and $g'_1 = 0.93$.

For the sequential decay of the Z boson to pairs of l^+l^- and of the heavy Higgs boson H to pairs of W^+W^-, the simple narrow-width approximation method is used to obtain the cross-section. In consequence, the total cross-section of the $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ signal can be approximately written as follows:

$$\sigma_{Tot}\left(\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp\right) \simeq \sigma\left(\mu^+\mu^- \to ZH\right) BR(Z \to l^\pm l^\mp) BR(H \to W^\pm W^\mp). \quad (2)$$

3. Results and Conclusions

In this section, we discuss possible signals at the future multi-TeV muon collider through the $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ process with the subsequent decay of the boson Z to pairs of $l^\pm l^\mp$ with $l = e, \mu$ and the heavy Higgs boson H to pairs of $W^\pm W^\mp$.

We plot the total cross-section of the reaction $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ as shown in the Figure 2 as a function of the center-of-mass energy, $\sqrt{s}$, for the values of the heavy gauge boson mass of $M_{Z'} = 3000, 4000, 5000, 6000, 7000$ GeV and $g'_1 = 0.435, 0.53, 0.66, 0.80, 0.93$, respectively. Figure 2 shows that the cross-section is sensitive to the model's free parameters. From this figure, it is observed that depending on the value of $\sqrt{s} = M_{Z'}$, that is, $\sqrt{s} = 3, 4, 5, 6, 7$ TeV, the height of the resonance peaks for the boson Z' changes. In addition, the resonances are broader for larger g'_1 values, as the total width of the Z' boson increases with g'_1.

To complement our study, Table 1 presents the total production of the process $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$. It can be concluded from Table 1 that due to the incorporation of VBS $\mu^+\mu^- \to WWZ$, in addition to the Leptonic, Semi-leptonic and Hadronic channels of the $W^\pm$ for the signal, the sensitivity of the reaction $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ is greatly improved. For the best case, $N = 329\,551$ events are obtained for $\sqrt{s} = 7$ TeV, $\mathcal{L}_{\text{con}} = 10$ ab^{-1}, $M_{Z'} = 7$ TeV, and $g'_1 = 0.93$.

Other potentially important theoretical and phenomenological processes for the study of the heavy Higgs boson H are those corresponding to the simple H production through the Vector Boson Fusion $\mu^+\mu^- \to \nu_\mu \bar{\nu}_\mu H$ and $\mu^+\mu^- \to \mu^+\mu^- H$, in the context of the $U(1)_{B-L}$ model [10].

The HEP community is in search of physics beyond the SM. In this regard, the building models of new physics with extended Higgs sectors have evolved in recent years into one of the HEP directions, characterized

Table 1: Total production of $\mu^+\mu^- \to (Z, Z') \to ZH \to l^\pm l^\mp W^\pm W^\mp$ and VBS of WWZ with $l = e^-, \mu$, in the B-L model at the future muon collider for $\sqrt{s} = 3, 7$ TeV, $\mathcal{L} = 1, 2, 3, 4, 10$ ab^{-1}, $M_H = 800$ GeV and $\theta_{B-L} = 10^{-3}$. The Leptonic, Semi-leptonic, and Hadronic channels of the $W^\pm W^\mp$ in the final state are considered.

Number of expected events at the future muon collider			
	$\sqrt{s} = 3$ TeV, $M_{Z'} = 3$ TeV, $g'_1 = 0.43$		
$\mathcal{L}$ (ab^{-1})	Leptonic channel	Semi-leptonic channel	Hadronic channel
1	1 422	4 518	14 343
2	2 843	9 036	28 586
3	4 265	13 553	43 025
4	5 687	18 071	57 373
10	14 217	45 178	143 432
	$\sqrt{s} = 7$ TeV, $M_{Z'} = 7$ TeV, $g'_1 = 0.93$		
$\mathcal{L}$ (ab^{-1})	Leptonic channel	Semi-leptonic channel	Hadronic channel
1	3 257	10 348	32 955
2	5 513	20 597	65 710
3	9 770	31 046	98 562
4	13 026	41 394	131 420
10	32 566	103 486	329 551

by massive, vigorous theoretical, phenomenological, and experimental activity. In addition, the search for heavy Higgs bosons at the future muon collider is strongly motivated and is part of the new physics program from this future collider.

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