Detecting the light gauge boson $Z_{\mu\tau}$ via Higgstrahlung process in the $U(1)_{L_\mu-L_\tau}$ model at $e^+e^-$ colliders

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Abstract

We consider the generation of the new light gauge boson $Z_{\mu\tau}$ predicted by the $U(1)_{L_\mu-L_\tau}$ model via $Zh_1$ associated production followed by the SM-like Higgs boson $h_1$ decaying into a $Z_{\mu\tau}$ pair process at future high-energy $e^+e^-$ colliders. Taking into account the experimental constraints on the free parameters of the $U(1)_{L_\mu-L_\tau}$ model and the beam polarizations $P(e^-,e^+) = (0.8, -0.3)$ and $P(e^-,e^+) = (0, 0)$, we calculate the cross sections of $Z_{\mu\tau}$ production and further investigate the observability of $Z_{\mu\tau}$ production through the leptonic channel $e^+e^- \rightarrow Z(\rightarrow l^+l^-)h_1(\rightarrow Z_{\mu\tau}Z_{\mu\tau}) \rightarrow l^+l^- + E_T$ and hadronic channel $e^+e^- \rightarrow Z(\rightarrow jj)h_1(\rightarrow Z_{\mu\tau}Z_{\mu\tau}) \rightarrow jj + E_T$ at $e^+e^-$ colliders. We find that the signal significance above $5\sigma$ for $Z_{\mu\tau}$ detection can be achieved via both these two processes with appropriate parameter values and high integrated luminosity, and that the hadronic channel can offer a more detectable signature compared with the leptonic channel.

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1. Introduction

The standard model (SM) of elementary particle physics has achieved unprecedented successes. It not only provides a description of the vast majority of experiments at the highest energy currently available, but also explains the fundamental interactions of nature over the wide range
of energy scale from eV to TeV. The discovery of Higgs boson at the Large Hadron Collider (LHC) in 2012 [1,2], which is an essential ingredient for the detailed understanding of particle masses and can reveal the complex and fascinating structure of the vacuum, makes the SM more perfect. But, for now, the SM is not a panacea. Some new physics (NP) beyond the SM strongly require extensions of the SM. For instance, the sub-eV masses and peculiar mixing pattern of neutrinos [3,4], the muon $(g - 2)$ anomalous magnetic moment [5], the exploration of Dark Matter (DM) [6] and dark energy [7,8] and so on.

At present, the LHC Run II is intensifying its efforts to promote the high-energy frontier in order to look for clues of NP, but it has not got any obvious signs of NP yet. Therefore, many people place their hopes on the low-energy region expecting to find a faint hint of NP. One example along this direction is the resolution of muon $(g - 2)$ anomaly. The discrepancy between the experimental measurement [9,10] and SM prediction [11–14]

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (28.8 \pm 8.0) \times 10^{-10},$$  \hspace{1cm} (1)

where $a_\mu = (g - 2)_\mu/2 (a_\mu^{th} = 1.1659179090(65) \times 10^{-3}$ and $a_\mu^{exp} = 1.16592080(63) \times 10^{-3}$), motivates people to extend the SM with a new $U(1)$ gauge symmetry and a new boson possessing a mass around the MeV scale phenomenologically. One of the optimal extensions is adding a new local $U(1)_{L_\mu - L_\tau}$ gauge symmetry [15–20]. This scheme features cancellation of the anomalies contributed by the second and third generations of SM fermions automatically [15]. In addition, the nonzero $L_\mu - L_\tau$ charge and the breaking of $L_\mu - L_\tau$ symmetry conduce to provide a DM candidate and offer an explanation for the neutrino masses and mixings simultaneously [15–17]. The extended SM model which has a complete gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{L_\mu - L_\tau}$ is called $U(1)_{L_\mu - L_\tau}$ model [15–20] in this paper. In this model, a new neutral gauge boson $Z_{\mu\tau}$ which does not couple to electron and quarks acquires a mass after spontaneous symmetry breaking of $U(1)_{L_\mu - L_\tau}$. This gauge boson with an MeV-scale mass can resolve the muon $(g - 2)$ anomaly, explain the deficit of cosmic neutrino flux [21–24] and resolve the problem of relic abundance of DM in the scenario with a light weakly interacting massive particle [15,25–27] simultaneously. Therefore, searching for this new gauge boson plays a vital role in exploring NP. Many attempts to discover this particle have been made in the meson decay experiment [28], beam dump experiment [29], electron–positron collider experiment [30] and so on.

Recently, the BABAR collaboration searched for a new gauge boson $Z'$ via the process $e^+e^- \rightarrow \mu^+\mu^-Z'(Z' \rightarrow \mu^+\mu^-)$ but didn’t detect any signals through scanning its mass [31]. Furthermore, the $e^+e^- \rightarrow \gamma Z'(Z' \rightarrow \nu\bar{\nu})$ process in the $U(1)_{L_\mu - L_\tau}$ model at Belle-II has been studied in detail in Ref. [20]. In this paper, we will focus on the light gauge boson $Z_{\mu\tau}$ production from $Zh_1$ associated production channel and explore the possibility of detecting its signature at $e^+e^-$ colliders. We present a full simulation study of the $Z_{\mu\tau}$ production cross section with the beam polarizations $P(e^- , e^+) = (-0.8, 0.3)$, $P(e^- , e^+) = (0.8, -0.3)$ and $P(e^- , e^+) = (0, 0)$ at $\sqrt{s} = 240$ GeV. Then, we investigate the observability of $Z_{\mu\tau}$ production through the $e^+e^- \rightarrow Z(\rightarrow l^+l^-)h_1(\rightarrow Z_{\mu\tau}Z_{\mu\tau}) \rightarrow l^+l^- + E_T$ and $e^+e^- \rightarrow Z(\rightarrow jj)h_1(\rightarrow Z_{\mu\tau}Z_{\mu\tau}) \rightarrow jj + E_T$ channels, respectively. We analyze the signal significance as a function of the integrated luminosity and find that both these two signals are promising to be detected at $e^+e^-$ colliders with

\footnote{In the original text of the reference, $Z'$ is used to denote the new gauge boson, and the representation of the original text is retained here. And this paper uses $Z_{\mu\tau}$ to represent it.}
Table 1

All particles and corresponding charge assignments in the $U(1)_{L_\mu - L_\tau}$ model.

| Gauge group | Scalar fields | Lepton fields |
|-------------|---------------|---------------|
|             | $\varphi_h$  | $\varphi_H$  | $\varphi_{DM}$ | $L_e$ | $L_\mu$ | $L_\tau$ | $e_R$ | $\mu_R$ | $\tau_R$ | $N^e_R$ | $N^\mu_R$ | $N^\tau_R$ |
| $SU(2)_L$   | 2             | 1             | 1              | 2     | 2       | 2       | 1     | 1       | 1       | 1       | 1         | 1         |
| $U(1)_Y$    | 1/2           | 0             | 0              | −1/2  | −1/2    | −1/2    | −1    | −1      | −1      | 0       | 0         | 0         |
| $U(1)_{L_\mu - L_\tau}$ | 0             | 1             | 2              | 0     | 1       | −1      | 0     | 1       | −1      | 0       | 1         | −1        |

| Gauge group | Baryon fields |
|-------------|---------------|
|             | $u_L$ | $d_L$ | $c_L$ | $s_L$ | $t_L$ | $b_L$ | $u_R$ | $d_R$ | $c_R$ | $s_R$ | $t_R$ | $b_R$ |
| $SU(2)_L$   | 2     | 2     | 2     | 2     | 2     | 2     | 1     | 1     | 1     | 1     | 1     | 1     |
| $U(1)_Y$    | 1/6   | 1/6   | 1/6   | 1/6   | 1/6   | 1/6   | 2/3   | −1/3  | 2/3   | −1/3  | 2/3   | −1/3  |
| $U(1)_{L_\mu - L_\tau}$ | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |

appropriate parameter values and high integrated luminosity. Moreover, compared with the leptonic channel, the hadronic channel can offer a more detectable signature.

The paper is organized as follows. In Sec. 2, we briefly review the basic features of $U(1)_{L_\mu - L_\tau}$ model and show the allowed parameter space of this model. We provide a general overview of the future $e^+e^-$ colliders and calculate the cross sections of $Z_{\mu\tau}$ production with different polarizations $\mathcal{P}(e^-, e^+) = (−0.8, 0.3)$, $\mathcal{P}(e^-, e^+) = (0.8, −0.3)$ and $\mathcal{P}(e^-, e^+) = (0, 0)$ at 240 GeV $e^+e^-$ colliders in Sec. 3. In Sec. 4, we calculate the numbers of the signal and the background events and investigate the signal observability and discovery potentiality of the $Z_{\mu\tau}$ production through the leptonic channel and hadronic channel respectively at $e^+e^-$ colliders. Finally, our conclusions are given in Sec. 5.

2. The basic features of $U(1)_{L_\mu - L_\tau}$ model

The gauged $U(1)_{L_\mu - L_\tau}$ extension of the SM can solve the three major problems currently beyond the SM. It can successfully explain the nonzero neutrino masses, explain the muon $(g − 2)$ anomaly and provide a DM candidate simultaneously. Ref. [15] has made a detailed analysis about solving the above puzzles in the context of the $U(1)_{L_\mu - L_\tau}$ model. Besides adding a new $U(1)_{L_\mu - L_\tau}$ gauge symmetry to the SM, the particle content of SM has also been extended by including three right-handed (RH) neutrinos and two SM gauge singlet scalars. All particles included in the $U(1)_{L_\mu - L_\tau}$ model and their charge assignments are listed in Tables 1.

The complete Lagrangian under the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{L_\mu - L_\tau}$ gauge symmetry is [15]

$$\mathcal{L}_{L_\mu - L_\tau} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{DM} + |D_v \varphi_H| ^2 - V - \frac{1}{4} F^\rho_\mu F^\rho_\nu Z^{\mu\nu}_\rho ,$$

(2)

where $\mathcal{L}_{SM}$, $\mathcal{L}_N$ and $\mathcal{L}_{DM}$ represent the SM Lagrangian, RH neutrino Lagrangian and DM Lagrangian respectively. Since DM and RH neutrinos are not related to the process that we will study, the specific forms of their Lagrangians are not given here. In Eq. (2), $|D_v \varphi_H|^2$ is the kinetic term of the extra Higgs singlet $\varphi_H$. $D_v = \partial_v + ig_{\mu\tau}q_{\mu\tau}Z_{\mu\tau}$ represents the covariant derivative, where $g_{\mu\tau}$ and $q_{\mu\tau}$ represent $U(1)_{L_\mu - L_\tau}$ group’s gauge coupling constant and the $L_\mu - L_\tau$ charge assignments that are listed in Tables 1, respectively. Furthermore, the fifth term of Eq. (2), $V$, represents the scalar potential which contains the quadratic and quartic interactions of $\varphi_H$ and its interaction with the SM Higgs doublet. The expression of $V$ is given as
\[ V = \mu_H^2 \psi_H^+ \psi_H + \lambda_H (\psi_H^+ \psi_H)^2 + \lambda_{hH} (\psi_H^+ \psi_h)(\psi_H^+ \psi_H), \]

where the couplings \( \mu_H, \lambda_H \) and \( \lambda_{hH} \) are positive parameters to avoid runaway directions. The last term in Eq. (2) is the kinetic term of the new gauge boson \( Z_{\mu\tau} \) with its field strength tensor denoted by \( F^\rho_{\mu\tau} = \partial^\rho Z^\rho_{\mu\tau} - \partial^\rho Z^\rho_{\mu\tau} \).

In the above theoretical framework, the \( U(1)_{L_\mu-L_\tau} \) symmetry is spontaneously broken below the electroweak scale by which the corresponding new gauge field \( Z_{\mu\tau} \) acquires the mass \( M_{Z_{\mu\tau}} = g_{\mu\tau} v_{\mu\tau} \). The scalar fields \( \varphi_h \) and \( \varphi_H \) can be expanded into

\[ \varphi_h = \left( \frac{\tilde{H}}{\sqrt{2}}, A + i A \right), \quad \varphi_H = \left( \frac{v_{\mu\tau} + H_{\mu\tau} + i \alpha}{\sqrt{2}} \right), \]

where \( \tilde{H}, A \) and \( \alpha \) are massless Nambu–Goldstone Bosons (NGB) absorbed by \( W^+, Z \) and \( Z_{\mu\tau} \), while \( v \) and \( v_{\mu\tau} \) are the Vacuum Expectation Values (VEVs) of \( \varphi_h \) and \( \varphi_H \) respectively. Furthermore, \( H \) and \( H_{\mu\tau} \) represent the physical CP-even scalar bosons. According to the scalar potential, the mass-squared matrix for them is given by

\[ M^2_{\text{scalar}} = \begin{pmatrix} 2\lambda h v^2 & \lambda_{hH} v_{\mu\tau} v \\ \lambda_{hH} v_{\mu\tau} v & 2\lambda_H v_{\mu\tau}^2 \end{pmatrix}. \]

This mass-squared matrix can be diagonalized by an orthogonal matrix. The mass eigenvalues are expressed as

\[ M^2_{h_1} = \sqrt{v^2 v_{\mu\tau}^2 \left( \lambda_{hH}^2 - 2\lambda h \lambda_H \right) + \lambda_{hH}^2 v^4 + \lambda_{hH}^2 v_{\mu\tau}^4 + \lambda h v^2 + \lambda_H v_{\mu\tau}^2}, \]

\[ M^2_{h_2} = -\sqrt{v^2 v_{\mu\tau}^2 \left( \lambda_{hH}^2 - 2\lambda h \lambda_H \right) + \lambda_{hH}^2 v^4 + \lambda_{hH}^2 v_{\mu\tau}^4 + \lambda h v^2 + \lambda_H v_{\mu\tau}^2}. \]

The mixing angle \( \alpha \) and the corresponding mass eigenstates \( h_1 \) and \( h_2 \) are then obtained as

\[ \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H \\ H_{\mu\tau} \end{pmatrix}, \quad \tan 2\alpha = \frac{\lambda_{hH} v_{\mu\tau} v}{\lambda h v^2 - \lambda_H v_{\mu\tau}^2}. \]

When \( \alpha \ll 1 \), the SM-like Higgs boson \( h_1 \) can be identified as the Higgs boson which has already been discovered by the CMS [32] and ATLAS [33] collaborations in 2012. The values of \( M_{h_1} \) and \( v \) are fixed at 125 GeV and 246 GeV respectively.

Compared with the SM Higgs boson, the couplings of \( h_1 \) with the SM particles are slightly suppressed by a factor \( \cos \alpha \). Some relevant couplings of \( h_1 \) with the SM particles and the new gauge boson \( Z_{\mu\tau} \) are given by

\[ g_{Z_{\mu\tau} h_1} = \frac{2M^2_{Z_{\mu\tau}}}{v_{\mu\tau}} \sin \alpha, \quad g_{W^+ W^- h_1} = -\frac{M}{v} \cos \alpha, \quad g_{l_i l_j h_1} = -\frac{M}{v} \cos \alpha, \]

\[ g_{Z_{\mu\tau} h_1} = \frac{2M^2_{Z_{\mu\tau}} \cos \alpha}{v}, \quad g_{W^+ W^- h_1} = \frac{2M^2_{W} \cos \alpha}{v}. \]

In this framework, \( Z_{\mu\tau} \) has a light mass and no couplings to quarks and the electron, so it can only decay to neutrinos. Taking no account of the neutrino masses, the couplings of \( Z_{\mu\tau} \) with neutrinos are expressed as

\[ g_{Z_{\mu\tau} v^\nu} = \frac{M_{Z_{\mu\tau}}}{v_{\mu\tau}}, \quad g_{Z_{\mu\tau} v^\tau} = -\frac{M_{Z_{\mu\tau}}}{v_{\mu\tau}}. \]
The expression of total decay width of $Z_{\mu\tau}$ is given by

$$\Gamma_{Z_{\mu\tau}} = \frac{g_{\mu\tau}^2 M_{Z_{\mu\tau}}}{12\pi},$$  \hspace{1cm} (10)

where we have ignored the neutrino masses and mixings.

The favored regions of the gauge coupling $g_{\mu\tau}$ and the $Z_{\mu\tau}$ mass to explain the muon $(g-2)$ anomaly were summarized in [19]

$$g_{\mu\tau} \simeq [2 \times 10^{-4}, 2 \times 10^{-3}], \quad M_{Z_{\mu\tau}} \simeq [5, 210] \text{ MeV}.$$  \hspace{1cm} (11)

According to Eq. (11), the window of $v_{\mu\tau}$ is given by

$$v_{\mu\tau} = \frac{M_{Z_{\mu\tau}}}{g_{\mu\tau}} \simeq [10, 1000] \text{ GeV},$$  \hspace{1cm} (12)

which indicates that the physical CP-even scalar bosons product after the spontaneous symmetry breaking have masses of the same order with $v_{\mu\tau}$. Ref. [19] has investigated signatures of the new CP-even scalar boson production processes in detail in collider experiments. This work does not do further research for them. Furthermore, the scalar mixing $\sin \alpha$ and the invisible Higgs decay branching ratio, $\text{BR}_{\text{inv}}$ at 95% C. L., are also constrained by analysis of data from the LHC experiment [34] as

$$\sin \alpha \leq 0.3, \quad \text{BR}_{\text{inv}} \leq 0.24.$$  \hspace{1cm} (13)

According to Eq. (13), we can get a factor

$$\chi = \frac{\alpha}{v_{\mu\tau}} \leq 2.2 \times 10^{-4} \text{ GeV}^{-1},$$  \hspace{1cm} (14)

if one takes $\cos \alpha \simeq 1$, which is a good approximation since $v_{\mu\tau} < 1 \text{ TeV}$.

To summarize, in the $U(1)_{\mu-\tau}$ model, three parameters are newly introduced, which are the new gauge coupling constant $g_{\mu\tau}$, the mass of $Z_{\mu\tau}$, and the scalar mixing $\sin \alpha$ respectively. In the following, we will focus on the phenomenology of the gauge boson $Z_{\mu\tau}$ with a mass in the region MeV–GeV given the above allowed parameter spaces.

3. The light gauge boson $Z_{\mu\tau}$ production at $e^+e^-$ colliders

As mentioned in the introduction, after the discovery of the SM Higgs boson, people are trying to find NP. But to our great pity, no unambiguous sign of NP has been found yet. So in recent years, people have turned their eyes to the $e^+e^-$ colliders which have a cleaner environment. It is expected that a deep understanding of electroweak symmetry breaking and the indirect search for NP via precision measurements can be realized on the $e^+e^-$ colliders. At present, the $e^+e^-$ colliders that have been proposed are as follows:

- The Circular Electron Positron Collider (CEPC), proposed by the Chinese high energy physics community, is designed to run around 240 ~ 250 GeV with an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, and will deliver $5 \text{ ab}^{-1}$ integrated luminosity with ten years of running. It is scheduled to run at 350 GeV in the later stages [35–37].

- The Future Circular Collider with $e^+e^-$ (FCC-ee), being implemented at CERN, has high-luminosity and high-precision features [38–40]. The FCC-ee has different center mass energies.
(c.m. energies) at different stages ($\sqrt{s} = 90$, 160, 240 and 350 GeV) and plans to collect multi-ab$^{-1}$ integrated luminosity.

- The Compact Linear Collider (CLIC) would be a multi-ab$^{-1}$ $e^+e^-$ collider in four stages (100 fb$^{-1}$ at the top threshold, 500 fb$^{-1}$ at 380 GeV, 1.5 ab$^{-1}$ at 1.5 TeV, and 3 ab$^{-1}$ at 3 TeV). There is another scenario for this collider. It would collect 500 fb$^{-1}$ at 350 GeV, 1.5 ab$^{-1}$ at 1.4 TeV and 2 ab$^{-1}$ at 3 TeV to study the Higgs boson properties. This collider’s c.m. energy can reach 3 TeV that makes a great contribution to achieving the high precision physics goals [41,42].

- The International Linear Collider (ILC) is a proposed linear particle accelerator. Its c.m. energy range is 200–500 GeV, with the possibility for a later upgrade to 1 TeV. The integrated luminosity would be 500 fb$^{-1}$ during the first four years running and about 1000 fb$^{-1}$ during the first phase of operation [43,44]. ILC has the characteristics of high precision, high luminosity and relatively clean background, which can deeply investigate the nature of Higgs and provide possibilities for NP discoveries.

Given that different colliders have different characteristics and attributes, not all $e^+e^-$ colliders are suitable for the detection of $Z_{\mu\tau}$. Next, we will discuss the experimental strategies for making a detection of the production of $Z_{\mu\tau}$ and filter the several types of colliders mentioned above. As analyzed in the previous theoretical framework section, $Z_{\mu\tau}$ can not establish the couplings with quarks and the electron family, making it very difficult to be produced directly. So it is a good choice to consider the indirect production of $Z_{\mu\tau}$. Besides decaying to the SM particles, the SM-like Higgs boson $h_1$ has an extra decay mode to a pair of $Z_{\mu\tau}$ within this framework. The expression for the decay width of $h_1 \rightarrow Z_{\mu\tau}Z_{\mu\tau}$ is given by

$$\Gamma(h_1 \rightarrow Z_{\mu\tau}Z_{\mu\tau}) = \frac{g_{h_1Z_{\mu\tau}Z_{\mu\tau}}^2 (M_{h_1}^2 - 4M_{Z_{\mu\tau}}^2) (M_{h_1}^2 + 12M_{Z_{\mu\tau}}^2)}{128\pi M_{h_1}^2 M_{Z_{\mu\tau}}^4}.$$  \hspace{1cm} (15)

Under the assumption that $\frac{M_{Z_{\mu\tau}}}{M_{h_1}} \rightarrow 0$, after the simplification of above equation, we can get

$$\Gamma(h_1 \rightarrow Z_{\mu\tau}Z_{\mu\tau}) = \frac{M_{h_1}^3 \sin^2 \alpha}{32\pi v_{\mu\tau}^2},$$  \hspace{1cm} (16)

which indicates that the $Z_{\mu\tau}$ pair production rate is actually determined by the factor $\chi^2 \approx \sin^2 \alpha/v_{\mu\tau}^2$. For this reason, this work will emphasize on the research of the production of $Z_{\mu\tau}$ via the $h_1$ decay and all the results in this work can be expressed as a function of $\chi$.

Like the SM Higgs boson, the SM-like Higgs boson has a variety of production processes in the $U(1)_{L_\mu - L_\tau}$ model [45]. The cross sections of SM-like Higgs boson’s different production channels which as functions of the c.m. energy are calculated at the tree level by employing Madgraph5/aMC@NLO [46]. Fig. 1 shows the numerical results we obtain. From Fig. 1, we can see that the $s$-channel Higgsstrahlung process $e^+e^- \rightarrow Zh_1$ and the $t$-channel charged vector-boson fusion (VBF) process $e^+e^- \rightarrow \nu\bar{\nu}h_1$ have the largest cross sections which are several orders of magnitude larger than those for the other three processes. Although the two main channels both can provide larger SM-like Higgs boson samples, their relative importance are dramatically dif-
Fig. 1. The SM-like Higgs production cross sections at $e^+e^-$ colliders as a function of c.m. energy with the beam polarization $P(e^-, e^+) = (-0.8, 0.3)$ and scalar mixing $\sin \alpha = 0.01$ in the $U(1)_{L_\mu - L_\tau}$ model.

Different with the change of c.m. energy. The contribution of $e^+e^- \rightarrow Zh_1$ process is dominant in the range of 240 GeV to 250 GeV, while the importance of $e^+e^- \rightarrow \nu \bar{\nu}h_1$ process suddenly becomes very significant after the c.m. energy exceeds 500 GeV. As mentioned earlier, $Z_{\mu\tau}$ can only decay to neutrinos in this framework, so the $e^+e^- \rightarrow \nu \bar{\nu}h_1 (h_1 \rightarrow Z_{\mu\tau}Z_{\mu\tau})$ process has an invisible final state. Investigating the possibility of detecting $Z_{\mu\tau}$ through the $t$-channel charged VBF process decaying will not be appropriate. On the contrary, the $Zh_1$ associated production process which has the leptonic and the hadronic final states (arising from $Z \rightarrow l^+l^-$ and $Z \rightarrow jj$, respectively) is worthy of our in-depth analysis. Next, we will search the light gauge boson $Z_{\mu\tau}$ via $Zh_1$ production at the $e^+e^-$ colliders with a c.m. energy of about 240 GeV, which maximizes the SM-like Higgs boson production cross section. Similar to the SM Higgs boson, the SM-like Higgs boson couplings to massive particles are proportional to their masses (square). Hence the event rate of SM-like Higgs boson decay to the light $Z_{\mu\tau}$ can be very small, making the $Z_{\mu\tau}$ detection difficult. This requires that the selected colliders can achieve high integrated luminosity. According to the information about the $e^+e^-$ colliders in the above, not only the circular collider (CEPC and FCC-e+e-) but also the linear collider (ILC) could achieve this scheme with integrated luminosities about 5 ab$^{-1}$ at 240 GeV [47]. The huge amount of data will enable precise measurement of coupling of the SM-like Higgs boson with $Z_{\mu\tau}$ and increase the likelihood of detecting $Z_{\mu\tau}$ with sufficient integrated luminosities. Next, we will discuss gauge boson $Z_{\mu\tau}$ production by the $h_1$ decay via the $Zh_1$ associated production at the $e^+e^-$ colliders (CEPC, FCC-e+e- and ILC). The relevant Feynman diagram is shown in Fig. 2a. In Fig. 2b, we calculate the cross sections of $Z_{\mu\tau}$ production by employing Madgraph5/aMC@NLO [46] at different values of the variable $\chi$ with different beam polarizations $P(e^-, e^+) = (-0.8, 0.3)$ (blue), $P(e^-, e^+) = (0.8, -0.3)$ (orange) and $P(e^-, e^+) = (0, 0)$ (green). From Fig. 2b, it can be seen that the cross section for polarization $P(e^-, e^+) = (0.8, -0.3)$ is smaller by a factor of 1.25 with respect to polarization $P(e^-, e^+) = (-0.8, 0.3)$. So in the following calculation we use the beam polarization $P(e^-, e^+) = (-0.8, 0.3)$, which can maximize the cross section. In Fig. 2b, from the blue solid curve, we can see that the values of the production cross section $\sigma$ increase as the factor $\chi$ increases. For $\sqrt{s} = 240$ GeV and $1 \times 10^{-5}$ GeV$^{-1} \leq \chi \leq 2.2 \times 10^{-4}$ GeV$^{-1}$, its value is in the range $9.067 \times 10^{-5}$ pb $\leq \sigma \leq 3.87 \times 10^{-2}$ pb.
4. Signal and discovery potentiality

In this section, we will perform the Monte Carlo simulation and explore the observability of the gauge boson $Z_{\mu\tau}$ production, via the $Zh_1$ associated production process followed by $h_1 \rightarrow Z_{\mu\tau}Z_{\mu\tau}$ at the $e^+e^-$ colliders with a c.m. energy of about 240 GeV. We will analyse both the leptonic decay $Z \rightarrow l^+l^-$ and hadronic decay $Z \rightarrow jj$ channels (depicted in Fig. 3). As mentioned earlier, $Z_{\mu\tau}$ can only decay to neutrinos in this framework. Thus the $e^+e^- \rightarrow Zh_1$ leptonic decay final state consists of a pair of opposite-sign same-flavor leptons and missing transverse energy, whereas the hadronic decay final state contains two jets and missing transverse energy.

For the following results we use the Madgraph5/aMC@NLO [46] to generate the signal and background events, where the UFO format [48] of the $U(1)_{L_\mu-L_\tau}$ model has been obtained by using FeynRules [49]. Moreover, PYTHIA [50] for parton shower and hadronization, and the fast detector simulations are performed with DELPHES [51] using the DSiD detector card [52]. Finally, MadAnalysis5 [53] is applied for data analysis and plotting.
4.1. Leptonic channel

Although the leptonic channel of $Zh_1$ decay provides a smaller cross section compared to the hadronic channel, it has a cleaner final state. And $Z$ can be reconstructed very efficiently because of the superior momentum resolution. This channel provides a final state that includes two leptons and a large missing transverse energy $E_T$

$$e^+e^- \rightarrow Z (\rightarrow l^+l^-) h_1 (\rightarrow Z_{\mu\tau} Z_{\mu\tau}) \rightarrow l^+l^- + E_T. \quad (17)$$

In this case, the leading SM background is

$$e^+e^- \rightarrow l^+l^- + \nu\bar{\nu} , \quad (18)$$

which arises from the resonant contribution of the channels $e^+e^- \rightarrow ZZ$ and $e^+e^- \rightarrow W^+W^-$ followed by the $Z/W^\pm$ decaying into leptons/neutrinos. Its kinematics is very similar to that of our signal. The cross section for this process is several orders of magnitude larger than our signal.

Another important background is

$$e^+e^- \rightarrow \tau^+\tau^- . \quad (19)$$

This process gives the $l^+l^- + E_T$ events via the leptonic decays of $\tau^+$ and $\tau^-$. This background has influence on the signal, even though the cross section for this process is smaller than the signal by about a factor of $10^{-5}$. The signal and background events are generated with basic cuts [47] implemented in MadGraph5/aMC@NLO [46] as

- lepton transverse momentum $p_T(l^\pm) > 10$ GeV,
- lepton pseudorapidity in the range $|\eta(l^\pm)| < 2.5$,
- missing transverse energy $E_T > 10$ GeV,
- angular separation between any two objects $\Delta R > 0.2$,

where $E_T$ is from the invisible neutrino in the final state. $\eta = 1/2 \ln(\tan \theta)$ is the pseudorapidity, where $\theta$ represents the scattering angle in the laboratory frame. $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ is the particle separation, where $\Delta \phi$ and $\Delta \eta$ represent the rapidity gap and the azimuthal angle gap between the particle pair respectively.

After the basic cuts, we further employ optimized kinematical cuts for separating the signal events from the backgrounds. In our theoretical framework, although the SM backgrounds have a huge effect on the signal, there are many kinematical differences between them that can be exploited. In general, the invariant mass of lepton pair $M(l^+l^-)$ is an appropriate kinematic variable to discriminate the signal from backgrounds. It is defined as

$$M(l^+l^-) = \sqrt{2(E(l^+)E(l^-) - p(l^+)p(l^-))}, \quad (20)$$

where $E(l^\pm)$ is the energy of the single lepton and $p(l^\pm)$ is the momentum of the single lepton. This variable is centered at $M(l^+l^-) = M_Z$ in the signal events. We can also take full advantage of the observation that the neutrinos from $Z/W^\pm$ and $\tau^\pm$ decays are responsible for the $E_T$ in backgrounds, while $h_1$ completely decays in the form of $E_T$ in the signal. Furthermore, the lepton pair momentum $p(l^+l^-)$ is very effective for the background suppression in our case. We use MadAnalysis5 [53] to present our main results.

We show the normalized distributions of the total missing transverse energy $E_T$, the invariant mass of lepton pair $M(l^+l^-)$ and lepton pair momentum $p(l^+l^-)$ in Fig. 4. From Fig. 4 (a)
Fig. 4. Normalized distributions of $E_T$ (a), $p(l^+l^-)$ (b) and $M(l^+l^-)$ (c) for the signal and backgrounds at the $e^+e^-$ colliders with $\sqrt{s} = 240$ GeV and an integrated luminosity of 5 ab$^{-1}$.

and (b), we can see that a large missing transverse energy cut of $30 \text{ GeV} < E_T < 55 \text{ GeV}$ and lepton pair momentum cut of $45 \text{ GeV} < p(l^+l^-) < 55 \text{ GeV}$ could be imposed to effectively remove the backgrounds. On the other hand, we find that the distribution for the signal events shows a clear peak at the $Z$ boson mass from Fig. 4(c). In order to reduce the background events, we thus impose an invariant mass cut of lepton pair as $M_Z - 10 \text{ GeV} < M(l^+l^-) < M_Z + 10 \text{ GeV}$. In principle, there are other variables which we can use to discriminate the signal from backgrounds. But, these variables are remarkably similar, and can not work significantly better than $E_T$, $p(l^+l^-)$ and $M(l^+l^-)$. According to the above analysis, events are selected to satisfy the following cuts:

$$\text{Cut} - 1 : 30 \text{ GeV} < E_T < 55 \text{ GeV};$$
$$\text{Cut} - 2 : 45 \text{ GeV} < p(l^+l^-) < 55 \text{ GeV};$$
$$\text{Cut} - 3 : |M(l^+l^-) - M_Z| < 10 \text{ GeV}. \quad (21)$$

After all these kinematical cuts are applied, the event numbers of signal and backgrounds are summarized in Table 2. The statistical significance is defined as $S/\sqrt{S+B}$ where $S$ and $B$ denote the number of signal and background events, respectively. A statistical significance
Table 2
Effect of individual kinematical cuts on the signal for $\chi = 9 \times 10^{-5}$ GeV$^{-1}$ ($M_{Z_{\mu\tau}} = 0.1$ GeV, $\sin \alpha = 0.01$ and $g_{\mu\tau} = 9 \times 10^{-4}$) and backgrounds. The statistical significance is computed for a luminosity of 5 ab$^{-1}$ (300 fb$^{-1}$). The event selection efficiency has been optimized with respect to the signal.

| Cuts | Signal (S) | Total background (B) | $S/\sqrt{S+B}$ |
|------|------------|----------------------|-----------------|
| Initial (no cut) | 2210 (132) | $1.59 \times 10^4 (9.52 \times 10^3)$ | 0.56 (0.14) |
| Basic cuts | 1674.6 (100.48) | $1.21 \times 10^5 (7.29 \times 10^5)$ | 0.48 (0.12) |
| 30 GeV $< E_T < 55$ GeV | 1343.5 (80.61) | $4.94 \times 10^6 (2.97 \times 10^5)$ | 0.60 (0.15) |
| 45 GeV $< p(l^+l^-) < 55$ GeV | 1193.4 (71.61) | $1.48 \times 10^6 (8.89 \times 10^5)$ | 0.98 (0.24) |
| $|M(l^+l^-) - M_Z| < 10$ GeV | 1186.5 (71.19) | $1.47 \times 10^5 (8.85 \times 10^5)$ | 3.08 (0.75) |

![Graph](image1.png)

Fig. 5. Integrated luminosity required for observing the $Z_{\mu\tau}$ at the 3σ (red line) and 5σ (blue line) statistical significances at different values of $\chi$ at the 240 GeV $e^+e^-$ colliders.

of 3.08 (0.75) can be obtained when we take $\chi = 9 \times 10^{-5}$ GeV$^{-1}$ ($\sin \alpha = 0.01$, $M_{Z_{\mu\tau}} = 0.1$ GeV and $g_{\mu\tau} = 9 \times 10^{-4}$) and an integrated luminosity of 5 ab$^{-1}$ (300 fb$^{-1}$). The integrated luminosities necessary for observing the light gauge boson $Z_{\mu\tau}$ at the 3σ and 5σ levels at the 240 GeV $e^+e^-$ colliders as a function of $\chi$ are given in Fig. 5. From Fig. 5, we see that we can obtain larger significance for larger $\chi$ values within its limit. For instance, the statistical significance can reach 5σ when we take $\chi = 1.8 \times 10^{-4}$ GeV$^{-1}$ ($M_{Z_{\mu\tau}} = 0.1$ GeV, $\sin \alpha = 0.001657$ and $g_{\mu\tau} = 9 \times 10^{-4}$) and an integrated luminosity of 1000 fb$^{-1}$. Thus, with a sufficient integrated luminosity and proper value of $\chi$, the signal of $Z_{\mu\tau}$ might be detected via the leptonic channel at the $e^+e^-$ colliders.

4.2. Hadronic channel

The $Z$ boson hadronic decay has a less clean reconstruction because of the worse energy resolution for jets. But the larger branching ratio of $Z$'s jet decay and the increased phase-space acceptance for jets can compensate it [47]. Hence it is essential to study the $Z$ hadronic decay mode in the current analysis. In the hadronic decay channel, the production of the SM-like Higgs boson $h_1$ in association with a $Z$ boson can provide a distinct signal,
\[ e^+ e^- \rightarrow Z(\rightarrow jj) h_1(\rightarrow Z_{\mu\tau} Z_{\mu\tau}) \rightarrow jj + E_T'. \quad (22) \]

The final state of this signal consists of two jets and a large \( E_T' \). Here, more remarkably, the \( E_T' \) of final state comes from either the jet-energy mismeasurement or neutrinos generated by the \( Z_{\mu\tau} \) boson decay inside the jet showering. The main irreducible SM background is

\[ e^+ e^- \rightarrow jj \nu \bar{\nu}, \quad (23) \]

which mainly comes from \( e^+ e^- \rightarrow ZZ \) followed by the \( Z \) decay into jets/neutrinos. The cross section for this process is two orders of magnitude larger than our signal.

The next important background is

\[ e^+ e^- \rightarrow \tau^+ \tau^- . \quad (24) \]

This process gives the \( jj + E_T' \) events due to mis-identification of \( \tau \)-jet as hadronic jets with a missing transverse energy. The cross section for this process is larger than the signal by about a factor of \( 10^3 \).

The following basic selection cuts \[47] are applied to the hadronic channel of the signal and background events:

- jet transverse momentum \( p_T(j) > 20 \text{ GeV} \),
- jet pseudorapidity in the range \( |\eta(j)| < 5.0 \),
- missing transverse energy \( E_T' > 10 \text{ GeV} \),
- angular separation between any two objects \( \Delta R > 0.4 \).

Similar to the above analysis of leptonic channel, we use the same kinematical variables, just replacing \( M(l^+ l^-) \) with the jet-pair invariant mass \( M(jj) \). Fig. 6 shows the normalized distributions of the total missing transverse energy \( E_T' \), the invariant mass of jet pair \( M(jj) \) and jet pair momentum \( p(jj) \). As we can see from Fig. 6(c), the distribution for signal shows a peak at \( M(jj) = M_Z \). And the image is broader than that of lepton-channel signal. This is because the jet has a worse energy resolution than the lepton. We can also perceive that the distribution for Background-\( ZZ \) also shows a peak around the \( Z \) boson mass and the Background-\( \tau \tau \) shows a broad bump peaked at 160 GeV. In order to reduce the background events, we thus impose an invariant mass cut of jet pair as \( M_Z - 10 \text{ GeV} < M(jj) < M_Z + 10 \text{ GeV} \). From Fig. 6(a) and (b), we find that the Signal shows a distribution peaking around 50 GeV and has a good distinction from the backgrounds. We can make full use of the differences between the signal and backgrounds in missing transverse energy and jet pair momentum to increase the statistical significance. Imposing a large missing transverse energy cut of 35 GeV \( < E_T' < 55 \text{ GeV} \) is very effective in reducing the backgrounds. Furthermore, requiring the jet pair momentum 40 GeV \( < p(jj) < 60 \text{ GeV} \) effectively kills the irreducible Background-\( ZZ \), with a more moderate effect on the Background-\( \tau \tau \). According to the above analysis, events are selected to satisfy the following cuts:

\[
\text{Cut } -1 : 35 \text{ GeV} < E_T' < 55 \text{ GeV}; \\
\text{Cut } -2 : 40 \text{ GeV} < p(jj) < 60 \text{ GeV}; \\
\text{Cut } -3 : |M(jj) - M_Z| < 10 \text{ GeV}. \quad (25)
\]

After all kinematical cuts are applied, the event numbers of signal and backgrounds are summarized in Table 3. It is obvious that the sets of cuts are powerful in the signal event selection.
Fig. 6. Normalized distributions of $E_T$ (a), $p(l^+l^-)$ (b) and $M(l^+l^-)$ (c) for the signal and backgrounds at the $e^+e^-$ colliders with $\sqrt{s} = 240$ GeV and an integrated luminosity of $5 \text{ ab}^{-1}$.

Table 3

Effect of individual kinematical cuts on the signal for $\chi = 9 \times 10^{-5}$ GeV$^{-1}$ ($M_{Z\mu\tau} = 0.1$ GeV, $\sin \alpha = 0.01$ and $g_{\mu\tau} = 9 \times 10^{-4}$) and backgrounds. The statistical significance is computed for a luminosity of $5 \text{ ab}^{-1}$ (300 fb$^{-1}$).

| Cuts                      | Signal (S) | Total background (B) | $S/\sqrt{S+B}$ |
|---------------------------|------------|----------------------|-----------------|
| Initial (no cut)          | 17235 (1034) | $1.49 \times 10^7$ ($8.94 \times 10^5$) | 4.46 (1.09) |
| Basic cuts                | 11944 (716.7) | $2.94 \times 10^6$ ($1.77 \times 10^5$) | 6.94 (1.70) |
| $35 \text{ GeV} < E_T < 55 \text{ GeV}$ | 9173.2 (550.4) | $1.02 \times 10^6$ ($6.09 \times 10^4$) | 9.06 (2.22) |
| $40 \text{ GeV} < p(jj) < 60 \text{ GeV}$ | 8460.3 (507.6) | $3.91 \times 10^5$ ($2.35 \times 10^3$) | 13.38 (3.28) |
| $|M(jj) - M_Z| < 10 \text{ GeV}$ | 5541.4 (332.5) | $7.02 \times 10^4$ ($4.21 \times 10^3$) | 20.13 (4.93) |

A statistical significance of 20.13 (4.93) can be obtained when we take $\chi = 9 \times 10^{-5}$ GeV$^{-1}$ ($\sin \alpha = 0.01$, $M_{Z\mu\tau} = 0.1$ GeV, $g_{\mu\tau} = 9 \times 10^{-4}$) and an integrated luminosity of $5 \text{ ab}^{-1}$ (300 fb$^{-1}$). The statistical significance of hadronic channel is much higher than that of leptonic channel. This is due to the facts that there is a higher number of signal events by $Br(Z \rightarrow jj) > Br(Z \rightarrow l^+l^-)$ and the $e^+e^- \rightarrow W^+W^-$ process does not contribute to the hadronic mode’s backgrounds. The needed luminosity to observe $Z_{\mu\tau}$ at the $3\sigma$ and $5\sigma$ levels...
at the 240 GeV $e^+e^-$ colliders as a function of $\chi$ is given in Fig. 7. From Fig. 7, we see that, similar to in the case of leptonic channel, we can also obtain larger significance for larger $\chi$ values within its limit. Thus, from a phenomenological point of view, this channel is more likely to result in a detection of the new gauge boson $Z_{\mu\tau}$ at a lower integrated luminosity and more achievable experimental conditions.

5. Conclusions

The $U(1)_{L_\mu-L_\tau}$ model, which can explain the muon $(g - 2)$ anomaly, small neutrino masses and provide a candidate of DM, is phenomenologically rich and predictive. In this model, the gauge boson $Z_{\mu\tau}$ has extremely important significances to explore and explain NP. However, the gauge boson $Z_{\mu\tau}$ is difficult to be produced directly because it can not establish the couplings with quarks and electron family. So we consider the production of $Z_{\mu\tau}$ via the SM-like Higgs boson $h_1$ decay. We focus on the $e^+e^-$ colliders, because they have the advantage of background being clean. Compared with other processes of $h_1$ production, the $s$-channel Higgsstrahlung process $e^+e^- \rightarrow Zh_1$ can give the largest cross section and provide a more appropriate signal to study $Z_{\mu\tau}$ production at the $e^+e^-$ colliders. Hence, in this paper, we discuss the possibility of detecting the new gauge boson $Z_{\mu\tau}$ predicted by the $U(1)_{L_\mu-L_\tau}$ model via $Zh_1$ production in the reasonable parameter space $\chi \leq 2.2 \times 10^{-4}$ GeV$^{-1}$ at the $e^+e^-$ colliders.

We first calculate the production cross sections of the process $pp \rightarrow Zh_1(\rightarrow Z_{\mu\tau}Z_{\mu\tau})$ with the different beam polarizations $P(e^-, e^+) = (-0.8, 0.3)$, which can maximize the cross section, $P(e^-, e^+) = (0.8, -0.3)$ and $P(e^-, e^+) = (0, 0)$. And we find that the values of the production cross section are proportional to the factor $\chi^2$. Then, we investigate the observability of the $Z_{\mu\tau}$ boson production via the process $e^+e^- \rightarrow Zh_1$ followed by $h_1 \rightarrow Z_{\mu\tau}Z_{\mu\tau}$, taking into account both the leptonic channel where $Z \rightarrow l^+l^-$ and the hadronic channel where $Z \rightarrow jj$, with a $5 \text{ ab}^{-1}$ ($300 \text{ fb}^{-1}$) integrated luminosity at the 240 GeV $e^+e^-$ colliders. After simulating the signal as well as the relevant backgrounds, and applying suitable kinematic cuts on the variables $E_T, M(l^+l^-)$ and $p(l^+l^-)$ ($M(jj)$ and $p(jj)$), the statistical significance of leptonic channel and hadronic channel can reach 3.08 (0.75) and 20.13 (4.93), respectively, when we take $\chi = 9 \times 10^{-5}$ GeV$^{-1}$ ($M_{Z_{\mu\tau}} = 0.1$ GeV, $\sin \alpha = 0.01$ and $g_{\mu\tau} = 9 \times 10^{-4}$) and an integrated luminosity
of 5 ab$^{-1}$ (300 fb$^{-1}$). We find that both the leptonic and hadronic $Z$ decay modes considerably contribute to detecting the signal of $Z_{\mu\tau}$, but with a quite higher potentiality for the hadronic mode. Thus, with sufficient integrated luminosity and proper values of $\chi$, the signal of $Z_{\mu\tau}$ might be detected at the 240 GeV $e^+e^-$ colliders.

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