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The $B-L+xY$ Model and the Higgs-strahlung Processes at a Collider *

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The gauge extension of the standard model with the $U(1)_{B-L+xY}$ symmetry predicts the existence of a light gauge boson Z' with small couplings to ordinary fermions. We discuss its contributions to the muon anomalous magnetic moment a_μ. Taking account of the constraints on the relevant free parameters, we further calculate the contributions of the light gauge boson Z' to the Higgs-strahlung processes $e^+e^- \to ZH$ and $e^+e^- \to Z'H$.

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The new neutral gauge boson, generically denoted by Z', is known to appear in many popular new physics models beyond the standard model (SM), which extend the SM symmetry groups. The new gauge boson Z' with heavy mass has been a traditional discovery target in high energy collider experiments. Scenarios beyond the SM involving Z' with low mass have also been considered to some extent in various contexts of literature. Recently, there has been a growing interest in a light gauge boson Z', as it might offer explanations for some of the experimental anomalies. For example, a light gauge boson can be used to explain the positron excess puzzle,[1] the $g_\mu - 2$ deviation[2] and the NuTeV anomaly,[3] the gap of high energy neutrinos in IceCube,[4] etc. This fact has generated active searches for a light neutral gauge boson or a new fundamental force in various low energy experiments.

The relevant phenomenology and search schemes of a light gauge boson Z' can be significantly different depending on its couplings to the SM particles. Recently, Lee and Yun[5] have studied the light gauge boson Z' predicted by the minimal gauge extension of the SM with the $U(1)_{B-L+xY}$ symmetry, which is called the $B-L+xY$ model, and considered its implications for the rare Higgs decays and the parity violation. The $B-L+xY$ model requires only three right-handed neutrinos, well-suited to the current neutrino mass and mixing data, and is a plausible new physics scenario. In this Letter, we first discuss the contributions of this kind of light gauge boson Z' to the muon anomalous magnetic moment a_μ. The same as the dark photon model,[6] the $B-L+xY$ model allows the kinetic mixing between the $U(1)_{B-L+xY}$ and SM $U(1)_Y$ groups and thus induces the coupling HZZ'. Thus we focus our attention on calculating the contributions of the light gauge boson Z' to the production cross sections of the Higgs-strahlung processes $e^+e^- \to ZH$ and $e^+e^- \to Z'H$.

Compared with the SM, the $B-L+xY$ model[5] has an extra gauge symmetry $U(1)' = U(1)_{B-L+xY}$, in which $B-L+xY$ is a linear combination of $B-L$ and the hypercharge Y with a real number x, which predicts the existence of a light gauge boson Z'. To generate the Z' mass, the $B-L+xY$ model introduces an extra Higgs singlet S, charged only under the extra $U(1)'$. The scalar kinetic terms are given by

$$\mathcal{L}_{\rm S} = |D_\mu \Phi_{\rm H}|^2 + |D_\mu \Phi_{\rm S}|^2, \tag{1}$$

where

$$D_\mu \Phi_{\rm H} = (\partial_\mu + i\frac{g'}{2}\hat{B}_\mu + igT_3\hat{W}_{3\mu} + ix\frac{g_{Z'}}{2}\hat{Z}'_\mu)\Phi_{\rm H}, \tag{2}$$

$$D_\mu \Phi_{\rm S} = (\partial_\mu + ig_{Z'}Q'_S\hat{Z}'_\mu)\Phi_{\rm S}, \tag{3}$$

with the doublet $\Phi_{\rm H} = \begin{pmatrix} \phi^+ \\ (v+H+i\phi_3)/\sqrt{2} \end{pmatrix}$ and the singlet $\Phi_{\rm S} = (v_{\rm S}+S+i\phi_{\rm S})/\sqrt{2}$. The HZZ and HZZ' couplings can be expressed by

$$C_{HZZ} = \frac{g_Z^2 v}{4}A_Z^2, \quad C_{HZZ'} = \frac{g_Z^2 v}{4}A_Z A_{Z'},$$
$$C_{HZ'Z'} = \frac{g_Z^2 v}{4}A_{Z'}^2, \tag{4}$$

where $A_Z = \cos\xi + \varepsilon_X t_{\rm W}\sin\xi$, $A_{Z'} = \sin\xi - \varepsilon_X t_{\rm W}\cos\xi$, $v \approx 246\,{\rm GeV}$ is the electroweak symmetry breaking scale, $g_{Z'}$ is the $U(1)'$ gauge coupling constant, $g_Z = e/s_{\rm W}c_{\rm W}$, $s_{\rm W} = \sin\theta_{\rm W}$, $c_{\rm W} = \cos\theta_{\rm W}$ and $t_{\rm W} = s_{\rm W}/c_{\rm W}$ with $\theta_{\rm W}$ being the Weinberg angle, ε_X is the kinetic mixing parameter, and ξ is the $Z-Z'$ mixing angle. The relationship between ε_X and ξ has been given in Ref. [5].

The $Z-Z'$ mass mixing is induced by two parts: the $B-L$ and xY parts, which can change the couplings of the SM gauge boson Z to ordinary fermions and make the light gauge boson Z' couple to ordinary fermions. The $B-L$ part provides only vector coupling and the xY part presents axial coupling. Then, in the context of the $B-L+xY$ model,[5] the couplings of the gauge bosons Z and Z' to ordinary fermion pairs in units of $g_Z = e/s_{\rm W}c_{\rm W}$ can be written

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as

$$g_{\rm L}^{Zf\bar{f}} = \cos\xi(T_{3f} - Q_f s_{\rm W}^2) - \sin\xi\Big[\frac{g_{Z'}}{g_Z}(B-L)_f + \varepsilon_X t_{\rm W}(Q_f - T_{3f})\Big], \quad (5)$$

$$g_{\rm R}^{Zf\bar{f}} = -\cos\xi Q_f s_{\rm W}^2 - \sin\xi\Big[\frac{g_{Z'}}{g_Z}(B-L)_f + \varepsilon_X t_{\rm W} Q_f\Big], \quad (6)$$

$$g_{\rm L}^{Z'f\bar{f}} = \sin\xi(T_{3f} - Q_f s_{\rm W}^2) + \cos\xi\Big[\frac{g_{Z'}}{g_Z}(B-L)_f + \varepsilon_X t_{\rm W}(Q_f - T_{3f})\Big], \quad (7)$$

$$g_{\rm R}^{Z'f\bar{f}} = -\sin\xi Q_f s_{\rm W}^2 + \cos\xi\Big[\frac{g_{Z'}}{g_Z}(B-L)_f + \varepsilon_X t_{\rm W} Q_f\Big], \quad (8)$$

where T_{3f} and Q_f are the isospin third component and electric charge of the fermion f, respectively. The values of $B-L$ charge are $1/3$ for quarks and -1 for leptons.

From the above discussions, we can see that there are only three free parameters, the Z' mass $M_{Z'}$, the coupling constant $g_{Z'}$ and the kinetic mixing parameter ε_X, which are related to our calculation. The electroweak precision measurements and the relevant data given by the LHC can produce severe constraints on the $B-L+xY$ model, which have been discussed in Ref. [5]. Comparing with the pure B-L model, one can find that the electroweak precision measurements demand $|\varepsilon_X| \leq 0.03$ for $M_{Z'} < M_Z$, the neutrino-quark scattering experiments require $g_{Z'} < 0.02$ for $M_{Z'} > 10\,\text{GeV}$. If the $B-L+xY$ model satisfies the relevant data given by the LHC with 13 TeV, there should be $M_{Z'} < 30\,\text{GeV}$. In the following we will take account of these constraints.

In the recent years there has been a lot of interest in the emergence of a few $3-4\sigma$ discrepancies between the SM predictions and the measured values. Among those, the muon anomalous magnetic moment a_μ is the most precisely known quantity in the SM, and provides us with a sensitive probe of new physics scenarios.[7] The Brookhaven National Lab (BNL) measurement[8] differs from the SM prediction by at least three standard deviations, $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm th} \approx (288 \pm 80) \times 10^{-11}$.[9] The uncertainties in the experimental measurement might be reduced by a factor of four in the upcoming experiments.[10] If the discrepancy is confirmed by the experiments, it will be clear evidence of new physics beyond the SM. With this motivation, we consider here the contributions of the light gauge boson Z' to a_μ.

The new gauge boson Z' can contribute to the anomalous magnetic moment a_μ through penguin diagrams, which can be readily calculated, following e.g., Ref. [7]. The expression form can be written as

$$\Delta a_\mu(Z') = \frac{m_\mu^2}{8\pi^2 M_{Z'}^2}\int_0^1 dx \frac{g_{\rm V}^2 F_1(x) + g_{\rm A}^2 F_2(x)}{(1-x)(1-\lambda^2 x)+\lambda^2 x}, \quad (9)$$

where $g_{\rm V}$ and $g_{\rm A}$ are the vector and axial couplings of Z' to a pair of lepton muons, respectively. The parameter $\lambda = m_\mu/M_{Z'}$ and there are

$$F_1(x) = 2x^2(1-x),$$
$$F_2(x) = 2x(1-x)(x-4) - 4\lambda^2 x^3. \quad (10)$$

In Fig. 1 we show regions of parameter space that allow us to address the a_μ discrepancy for different values of the Z' mass $M_{Z'}$. One can see from Fig. 1 that, for $M_{Z'} = 10\,\text{GeV}$ and $|\varepsilon_X| \leq 0.03$, there is $0.03 \leq g_{Z'} \leq 0.07$, while for $M_{Z'} = 80\,\text{GeV}$, the $B-L+xY$ model can explain the a_μ deviation only with $0.3 \leq g_{Z'} \leq 0.6$. For $M_{Z'} > 10\,\text{GeV}$, the value of $g_{Z'}$ must be smaller than 0.02, thus it is very difficult for the $B-L+xY$ model to explain the a_μ discrepancy.

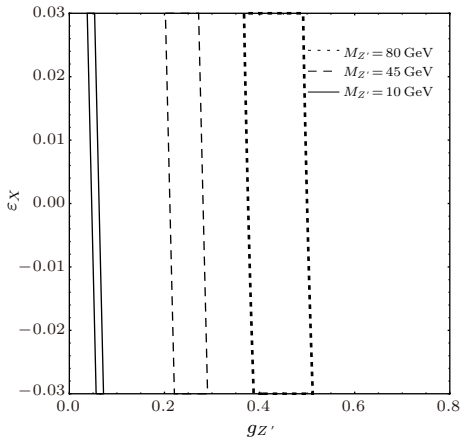

Fig. 1. To explain the a_μ discrepancy, the free parameter ε_X versus the coupling parameter $g_{Z'}$ for $M_{Z'} = 10\,\text{GeV}$, 45 GeV and 80 GeV.

In addition to the LHC, the ILC[11] is another Higgs factory, which can study in detail and precisely determine the Higgs boson properties. At an e^+e^- collider with the c.m. $\sqrt{s} \approx 250\,\text{GeV}$, the Higgs-strahlung process $e^+e^- \to ZH$ is the dominant production channel for the Higgs boson, which can be used to measure the Higgs couplings with unprecedented precision and further to identify new physics effects. For example, at the circular electron–positron collider (CEPC), the production cross section $\sigma(ZH)$ can be measured to an extremely high precision of 0.51%[12] and FCC-ee has claimed an even higher accuracy for this cross section.[13]

In the $B-L+xY$ model, the light gauge boson Z' cannot directly couple to the Higgs boson, while it can couple to it through the $Z-Z'$ mixing. Thus Z' has contributions to the Higgs-strahlung process. The total cross section of the ZH associated production can be written as

$$\sigma_{\rm tot} = \sigma_Z + \sigma_{Z'} + \sigma_{Z,Z'}, \quad (11)$$

where

$$\sigma_Z = \frac{G_F^2 M_Z^4}{3\pi} \frac{A_Z^4}{(1+\varepsilon_X t_W \tan\xi)^2} [(g_L^{Zee})^2 + (g_R^{Zee})^2] \frac{s\sqrt{\lambda}(\lambda + 12M_Z^2/s)}{[(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2]},$$

$$\sigma_{Z'} = \frac{G_F^2 M_Z^6}{3\pi} \frac{A_Z^2 A_{Z'}^2}{(1+\varepsilon_X t_W \tan\xi)^2} [(g_L^{Z'ee})^2 + (g_R^{Z'ee})^2] \frac{s\sqrt{\lambda}(\lambda + 12M_{Z'}^2/s)}{M_{Z'}^2[(s-M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2]},$$

$$\sigma_{Z,Z'} = \frac{G_F^2 M_Z^6 s\sqrt{\lambda}}{3\pi} \frac{A_Z^2 A_{Z'}^2}{(1+\varepsilon_X t_W \tan\xi)^2} \cdot (g_L^{Zee} g_L^{Z'ee} + g_R^{Zee} g_R^{Z'ee}) \Big[\frac{\lambda + 12M_Z^2/s}{M_Z^2} + \frac{\lambda + 6(M_Z^2 - M_{Z'}^2)/s}{M_{Z'}^2} + \frac{s\lambda}{8M_Z^2 M_{Z'}^2}(\lambda - 12M_Z^2/s) \Big] \cdot [(s-M_Z^2)(s-M_{Z'}^2) + M_Z^2 M_{Z'}^2 \Gamma_Z \Gamma_{Z'}] / \{[(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2][(s-M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2]\}, \quad (12)$$

where Γ_Z and $\Gamma_{Z'}$ are the total decay widths of the gauge bosons Z and Z', respectively. The factor λ can be written as

$$\lambda\Big(1, \frac{M_Z^2}{s}, \frac{M_H^2}{s}\Big) = \Big(1 - \frac{M_Z^2}{s} - \frac{M_H^2}{s}\Big)^2 - 4\frac{M_Z^2 M_H^2}{s^2}, \quad (13)$$

which is the usual two-particle phase space function.

To see whether the Z' correction effects on the ZH production cross section can be detected in future e^+e^- colliders, we define the relative correction parameter R as

$$R = \frac{\sigma_{tot} - \sigma_{SM}}{\sigma_{SM}}. \quad (14)$$

In Fig. 2 we plot the ratio R as a function of the Z' mass $M_{Z'}$ for $\sqrt{s} = 250\,\text{GeV}$, $|\varepsilon_X| = 0.03$ and three values of the coupling parameter $g_{Z'}$. One can see from this figure that, for $M_{Z'} \leq 60\,\text{GeV}$, the value of the parameter R is very small. The correction effect of the light gauge boson Z' to the production cross section $\sigma(ZH)$ cannot be detected even at the CEPC and FCC-ee experiments in most of the parameter space.

It is obvious that the light gauge boson Z' can be produced in association with the Higgs boson H at an e^+e^- collider via the couplings HZZ' and $HZ'Z'$. The corresponding expression form of the production cross section for the process $e^+e^- \to Z, Z' \to Z'H$ can be easily given similarly as $\sigma(ZH)$. The production cross section $\sigma(Z'H)$ is plotted in Fig. 3 as a function of the Z' mass $M_{Z'}$ for $|\varepsilon_X| = 0.03$ and different values of the coupling parameter $g_{Z'}$. One can see from this figure that the value of $\sigma(Z'H)$ increases with $M_{Z'}$. This is because the couplings HZZ' and $HZ'Z'$ are proportional to the factor $A_{Z'}$, while its value is enhanced with an increase of $M_{Z'}$. The production cross section $\sigma(Z'H)$ is smaller than 1 fb in most of the parameter space, which is very difficult to detect in future e^+e^- colliders.

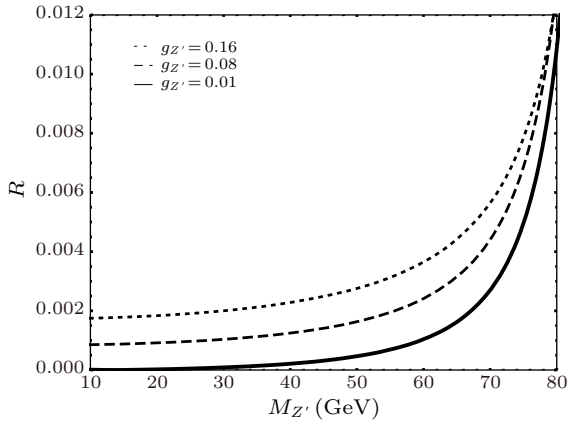

Fig. 2. The parameter R as a function of the Z' mass $M_{Z'}$ for $|\varepsilon_X| = 0.03$ and three values of $g_{Z'}$.

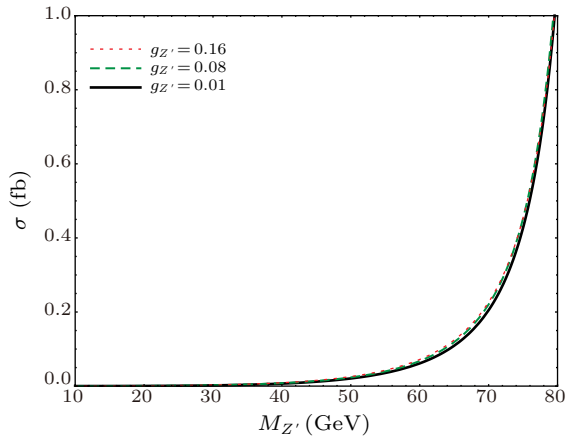

Fig. 3. The production cross section $\sigma(Z'H)$ as a function of $M_{Z'}$ for $|\varepsilon_X| = 0.03$ and three values of $g_{Z'}$.

The $B - L + xY$ model in the presence of the kinetic mixing with the SM hypercharge is a plausible new physics scenario, which can be considered as the pure B-L model with an altered kinetic mixing. We have discussed the contributions of the light gauge boson Z' predicted by this model to the muon anomalous magnetic moment a_μ and have found that it is very difficult to explain the a_μ discrepancy in most of the parameter space allowed by the current data. Taking into account the experimental constraints on this model, we further calculate the contributions of the light gauge boson Z' to the production cross sections of the Higgs-strahlung processes $e^+e^- \to ZH$ and $e^+e^- \to Z'H$. The correction effect of Z' to the production cross section $\sigma(ZH)$ cannot be detected even at the CEPC and FCC-ee experiments. If this kind of light gauge boson Z' indeed exists, its direct signals would not be detected via process $e^+e^- \to Z'H$, but might be detected via other processes.

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