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Bottom partner B' and Zb production at the LHC

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ABSTRACT

Some new physics models, such as "beautiful mirrors" scenario, predict the existence of the bottom partner B'. Considering the constraints from the data for the $Z \to b\bar{b}$ branching ratio R_b and the FB asymmetry $A^b_{\rm FB}$ on the relevant free parameters, we calculate the contributions of B' to the cross section $\sigma(Zb)$ and the Z polarization asymmetry A_Z for Zb production at the LHC. We find that the bottom partner B' can generate significant corrections to $\sigma(Zb)$ and A_Z, which might be detected in near future.

1. Introduction

Over the past several decades, the standard model (SM) has provided a consistent description of particles physics and is tested to per-mille precision by experimented data. Recently, the ATLAS and CMS Collaborations have independently reported the discovery [1] of a neutral scalar particle that seems consistent with the SM Higgs boson with a mass of about 125–126 GeV. However, some observables related to the sector of third generation quarks have been observed large deviations from their SM predictions. The first is the forward–backward (FB) asymmetry of the bottom-quarks, $A^b_{\rm FB}$, which differs by about 2.5σ deviation from the SM value at the Z boson pole according the recent global fit result [2]. The second is the FB asymmetry $A^t_{\rm FB}$ in top quark pairs produced at the Tevatron, which has larger value than the SM prediction [3]. Furthermore, a recent calculation of the $Z \to b\bar{b}$ branching ratio R_b, which includes new two-loop electroweak corrections, now puts the prediction in tension with the measured value [4].

It is well known that the top loop in the SM is the largest contribution to the Higgs mass quadratic divergence. Thus, for the new physics models to solve the fine tuning problem, there must be some new particles constrained by symmetry, which cancel this loop. Most of these new physics models should contain a heavy particle which shares the gauge quantum numbers of the top quark, generally called "top partner" [5]. This new particle should be in an electroweak doublet in order to properly cancel the divergences to the Higgs mass produced by the top loop. So, this kind of new physics models beyond the SM predicts the existence of the heavy partner B' of the bottom quark. Furthermore, if the top and bottom partners have the same mass hierarchy as the SM top and bottom, the new quark B' may be the first to be discovered, which has began to be searched at the Tevatron and LHC [6].

Production of the electroweak gauge boson Z associated with a bottom quark at the LHC is an important background process not only to Higgs boson production and single top production, but also to the search for signals of new physics beyond the SM, which has been calculated at next-to-leading order (NLO) [7]. Recently, Ref. [8] has defined the Z polarization asymmetry A_Z in the subprocess $gb \to Zb$ at the LHC and has shown that A_Z is strictly connected to the FB asymmetry $A^b_{\rm FB}$ and is almost free from the theoretical uncertainties related to QCD scale and parton distribution function (PDF) set variations.

Considering the constraints of the data from LEP for the $Z \to b\bar{b}$ branching ratio R_b and FB asymmetry $A^b_{\rm FB}$ [9] on the $Zb\bar{b}$ couplings g^b_L and g^b_R, we are model-independent of calculating the contributions of the new physics beyond the SM to Zb production at the LHC in Section 2. We find that the correction terms δg^b_L and δg^b_R generated by new physics cannot give significant contributions to the production cross section $\sigma(Zb)$. While it is not this case for the Z polarization asymmetry A_Z. In Section 3, we study the correction effects of the bottom partner B' on the production cross section $\sigma(Zb)$ and the Z polarization asymmetry A_Z. Our numerical results show that, with reasonable values of the relevant free parameters, B' can generate large corrections to $\sigma(Zb)$ and A_Z. Our conclusion is given in Section 4.

2. The new physics and Zb production at the LHC

For the 5-flavor scheme [10], production of the electroweak gauge boson Z associated with a bottom quark at the LHC proceed via two Feynman diagrams with b-quark exchange in the s-channel and the t-channel at leading order. Its production cross section $\sigma(Zb)$ is proportional to the factor $[(g^b_L)^2 + (g^b_R)^2]$. Thus, new physics can produce contributions to $\sigma(Zb)$ via correcting the $Zb\bar{b}$ couplings g^b_L and g^b_R.

The effective $Zb\bar{b}$ couplings can be parameterized by the Lagrangian

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$$\mathcal{L} = \frac{e}{S_W C_W}\bar{b}\gamma^{\mu}\left[\left(g_L^{b,\mathrm{SM}} + \delta g_L^b\right)P_L + \left(g_R^{b,\mathrm{SM}} + \delta g_R^b\right)P_R\right]bZ_{\mu}, \quad (1)$$

with $S_W = \sin\theta_W$ and $C_W = \cos\theta_W$, in which θ_W is the electroweak mixing angle. $P_{L/R} = (1 \mp \gamma_5)/2$ are the chirality projection operators. The SM tree-level couplings $g_L^{b,\mathrm{SM}}$ and $g_R^{b,\mathrm{SM}}$ can be written as: $-\frac{1}{2} + \frac{1}{3}S_W^2$ and $\frac{1}{3}S_W^2$, respectively. δg_L^b and δg_R^b represent the new physics contributions to the $Zb\bar{b}$ couplings. In principle, the corrections of new physics to the $Zb\bar{b}$ vertex may give rise to one magnetic moment-type form factor, proportional to $\sigma^{\mu\nu}q_{\nu}$. However, its contributions to the $Z \to b\bar{b}$ branching ratio R_b and the FB asymmetry A_{FB}^b are very small and thus have been neglected in above equation.

The relative corrections of new physics to R_b^{SM} and $A_{\mathrm{FB}}^{b,\mathrm{SM}}$ can be approximately written as [11]

$$\frac{\delta R_b}{R_b^{\mathrm{SM}}} \simeq 2\left(1 - R_b^{\mathrm{SM}}\right)\frac{g_L^{b,\mathrm{SM}}\delta g_L^b + g_R^{b,\mathrm{SM}}\delta g_R^b}{(g_L^{b,\mathrm{SM}})^2 + (g_R^{b,\mathrm{SM}})^2}, \quad (2)$$

$$\frac{\delta A_{\mathrm{FB}}^b}{A_{\mathrm{FB}}^{b,\mathrm{SM}}} \simeq \frac{4(g_L^{b,\mathrm{SM}})^2(g_R^{b,\mathrm{SM}})^2}{(g_L^{b,\mathrm{SM}})^4 - (g_R^{b,\mathrm{SM}})^4}\left(\frac{\delta g_L^b}{g_L^{b,\mathrm{SM}}} - \frac{\delta g_R^b}{g_R^{b,\mathrm{SM}}}\right), \quad (3)$$

where $\delta R_b = R_b^{\mathrm{exp}} - R_b^{\mathrm{SM}}$ and $\delta A_{\mathrm{FB}}^b = A_{\mathrm{FB}}^{b,\mathrm{exp}} - A_{\mathrm{FB}}^{b,\mathrm{SM}}$. In above equations, we have neglected the new physics corrections to the $Ze\bar{e}$ couplings g_L^e and g_R^e. The experimental results for R_b and A_{FB}^b are [9]

$$R_b^{\mathrm{exp}} = 0.21629 \pm 0.00066, \qquad A_{\mathrm{FB}}^{b,\mathrm{exp}} = 0.0992 \pm 0.0016. \quad (4)$$

The recent SM prediction for R_b, including electroweak two-loop and QCD three-loop corrections is $R_b^{\mathrm{SM}} = 0.21474 \pm 0.00003$, which deviates by 2.4σ deviations below the experimental measured value [2,4], while the recent global fit result for A_{FB}^b is $A_{\mathrm{FB}}^{b,\mathrm{SM}} = 0.1032^{+0.0004}_{-0.0006}$, which is still above the experimental measured value by 2.5σ deviations [2].

Using above experimental and SM prediction values, one can easily obtain the constraints of the electroweak precision data on the new $Zb\bar{b}$ couplings δg_L^b and δg_R^b. It is obvious that the data favor small corrections to δg_L^b and more large shifts in δg_R^b. Considering the discovery of a Higgs-like particle at the LHC, Ref. [12] has updated the constraints of the electroweak precision data on δg_L^b and δg_R^b and there is

$$\delta g_L^b = 0.001 \pm 0.001, \qquad \delta g_R^{b+} = 0.016 \pm 0.005,$$
$$\delta g_R^{b-} = -0.17 \pm 0.05. \quad (5)$$

We use the relative correction parameter $R_1 = [\sigma(Zb) - \sigma^{\mathrm{SM}}(Zb)]/\sigma^{\mathrm{SM}}(Zb)$ to describe the corrections of the new $Zb\bar{b}$ couplings δg_L^b and δg_R^b to the cross section of the process $pp \to Zb$, in which $\sigma(Zb)$ denotes the total production cross section including the contributions from the SM, δg_L^b and δg_R^b. In our calculations, the PDFs of the bottom quark and gluon are taken as the CTEQ6L PDFs [13] with renormalization and factorization scales $\mu_R = \mu_F = M_Z$. To make our numerical results more realistic, we have applied the cuts on the b-jet with transverse momentum $P_T > 15$ GeV and a rapidity range $|\eta| < 2$. It is obvious that the radiative corrections to $\sigma(Zb)$ and $\sigma^{\mathrm{SM}}(Zb)$ are canceled in the relative correction parameter R_1. In Fig. 1 we plot R_1 as a function of δR_b for 1σ and 2σ constraints from the R_b experimental value. One can see that the value of R_1 allowed by the R_b constraints is very small. For the theory value of R_b being consistent with its experimental value with 1σ and 2σ error bars, the values of the parameter R_1 are in the ranges of 0.53%–1.3% and 0.14%–1.7%, respectively, which are much smaller than the QCD corrections [7].

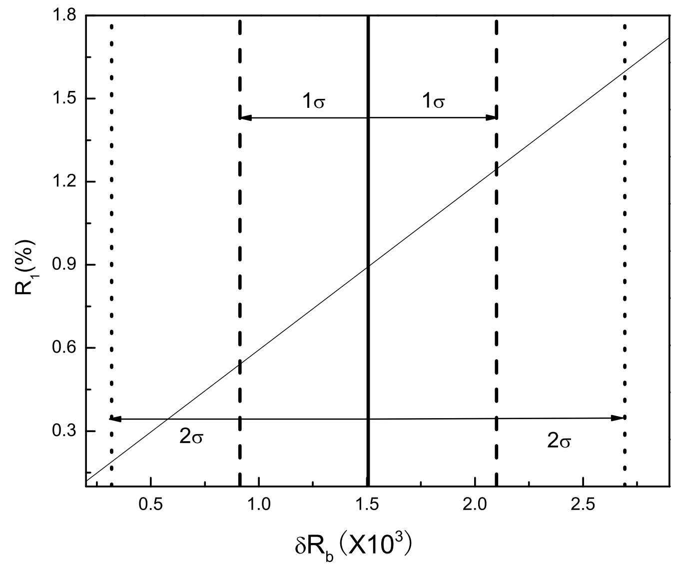

Fig. 1. The relative correction parameter R_1 is presented as a function of δR_b. The regions between dashed lines and between dotted lines correspond 1σ and 2σ allowed regions from R_b constraints, respectively.

Searching for the gauge boson Z produced in association with the bottom quark has been performed at the LHC. Recently, the ATLAS Collaboration [14] has reported their measurement of the Zb production cross section and found that it is in good agreement with the SM prediction including the NLO QCD corrections. Considering the statistical and systematic uncertainties, the ATLAS data cannot give severe constraints on the new $Zb\bar{b}$ couplings δg_L^b and δg_R^b.

Compared to the cross section, decay width, etc., the asymmetry, which is defined as a ratio of observables, is not sensitive to the theoretical uncertainties. The asymmetry can be utilized to study the detail properties of the particles and further to investigate underlying dynamics in and/or beyond the SM. Measurement of the asymmetry at the LEP and Tevatron has provided rich informations about the SM and various new physics models.

The Z polarization asymmetry A_Z in Zb production at the LHC can be defined as

$$A_Z = \frac{\sigma(Z_R b) - \sigma(Z_L b)}{\sigma(Z_R b) + \sigma(Z_L b)}, \quad (6)$$

where $\sigma(Z_R b)$ and $\sigma(Z_L b)$ are the hadronic cross sections of $Z_R b$ and $Z_L b$ production at the LHC, respectively. Ref. [8] has shown that A_Z is connected to the $Zb\bar{b}$ FB asymmetry A_{FB}^b and given its SM prediction value. If the large deviation between the SM prediction and the LEP measurement of A_{FB}^b indeed exists and comes from the new $Zb\bar{b}$ couplings δg_L^b and δg_R^b, then these new couplings should generate significant contributions to A_Z.

To see whether the correction effects of the new $Zb\bar{b}$ couplings δg_L^b and δg_R^b on the Z polarization asymmetry A_Z can be detected at the LHC, we define the relative correction parameter $R_2 = \delta A_Z/A_Z^{\mathrm{SM}}$ with $\delta A_Z = A_Z^{total} - A_Z^{\mathrm{SM}}$. Our numerical results are shown in Fig. 2, in which we plot R_2 as a function δA_{FB}^b to consistent with the experimental value of A_{FB}^b with 1σ and 2σ error bars. One can see that the absolute value of R_2 can reach 6.8%. Considering A_Z almost free from the theoretical uncertainties, we hope that the LHC might detect this correction effects and confirm or obviate the A_{FB}^b anomaly.

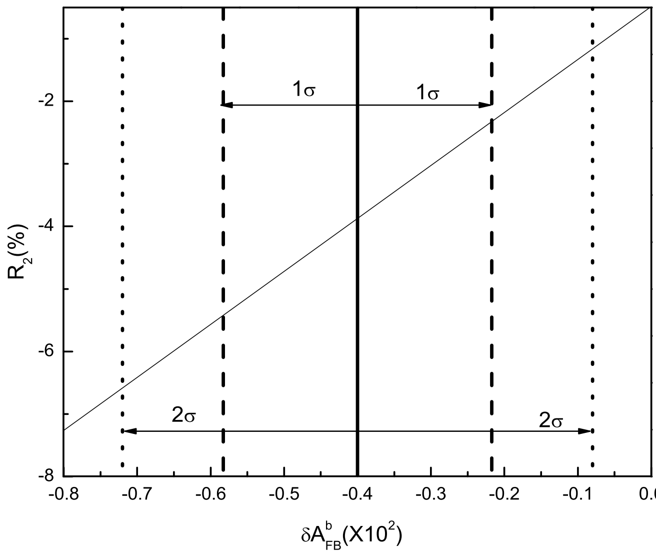

Fig. 2. The relative correction parameter R_2 as a function of $\delta A^b_{\rm FB}$. The regions between dashed lines and between dotted lines correspond 1σ and 2σ allowed regions from $A^b_{\rm FB}$ constraints, respectively.

3. The bottom partner B' and Zb production at the LHC

So far, the $Zb\bar{b}$ FB asymmetry $A^b_{\rm FB}$ measured in Z boson decays at LEP experiments still exist 2.5σ deviations from the SM prediction [2]. Considering modification of the SM $Zb\bar{b}$ couplings $g_L^{b,{\rm SM}}$ and $g_R^{b,{\rm SM}}$, some new physics models have been proposed to cure the large discrepancy [15–17]. Ref. [17] proposed the beautiful mirrors model, which introduces vector-like quarks which mix with the bottom quark subtly affecting its couplings to the gauge boson Z and addressing the observed anomaly in $A^b_{\rm FB}$. This model predicts the existence of the bottom partner B'. Some of their phenomenological consequences have been explored in Refs. [17,18]. Taking into account of the constraints on the relevant free parameters from explaining the current R_b and $A^b_{\rm FB}$ deviations [2,4,12], we consider the contributions of the bottom partner B' to the hadronic cross section $\sigma(Zb)$ and the Z polarization asymmetry A_Z for Zb production at the LHC in this section.

The beautiful mirrors model [17] extends the SM by introducing two sets of vector-like quarks, $\psi_{L,R}$ with quantum numbers $(3,2,-5/6)$ and $\xi_{L,R}$ with quantum numbers $(3,1,-1/3)$, in which the SM Higgs is the only source of electroweak symmetry breaking (EWSB). In terms of its $SU(2)$ components, $\psi_{L,R}$ decomposes as

$$\psi_{L,R} = \begin{pmatrix} \omega_{L,R} \\ \chi_{L,R} \end{pmatrix}, \tag{7}$$

where ω is a charge $-1/3$ quark and χ has charge $-4/3$. It is assumed that the new quarks only couple to the third generation SM quarks, which are governed by the $SU(3)\times SU(2)\times U(1)$ gauge invariance. These new quarks mix with the SM bottom quark to explain the measured value of $A^b_{\rm FB}$ and have small mixing with the two lighter SM generation quarks to satisfying the constraints from rare decay processes of the bottom and strange mesons such as $B\to X_s\gamma$, $B\to l^+l^-X$, $B\to J/\Psi K_s$ and $K\to\pi\nu\bar{\nu}$.

In the beautiful mirrors model, the couplings between the gauge boson Z and the down-type quarks may be written in matrix form [17]

$$\mathcal{L}_Z = \frac{e}{S_W C_W}\bar{d}\gamma^\mu(LP_L + RP_R)dZ_\mu + \text{h.c.}, \tag{8}$$

where $d=(b_1,b_2,b_3)$, in which b_1 is mainly the SM bottom quark field, b_2 is mostly ω and b_3 is mostly ξ. We call b_2 as bottom partner B' and consider its contributions to Zb production at the LHC. The coupling matrices L and R are written as

$$L = U_d^\dagger g_L U_d, \qquad R = W_d^\dagger g_R W_d, \tag{9}$$

where $g_L = {\rm Diag}(-\frac{1}{2}+\frac{1}{3}S_W^2, \frac{1}{2}+\frac{1}{3}S_W^2, \frac{1}{3}S_W^2)$, $g_R = {\rm Diag}(\frac{1}{3}S_W^2, \frac{1}{2}+\frac{1}{3}S_W^2, \frac{1}{3}S_W^2)$. The unitary matrices U_d and W_d transform the left- and right-handed gauge eigenstates into the corresponding mass eigenstates, which can diagonalize the mass matrix,

$$U_d^\dagger M_d W_d = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}, \tag{10}$$

where $m_1 = m_b$, m_2 and m_3 are the SM bottom quark mass, and two new quark masses. The matrix U_d can be parameterized as

$$U_d = \begin{pmatrix} C_{12}^L C_{13}^L & S_{12}^L C_{13}^L & S_{13}^L \\ -S_{12}^L C_{23}^L - C_{12}^L S_{23}^L S_{13}^L & C_{12}^L C_{23}^L - S_{12}^L S_{23}^L S_{13}^L & S_{23}^L C_{13}^L \\ S_{12}^L S_{23}^L - C_{12}^L C_{23}^L S_{13}^L & -C_{12}^L S_{23}^L - S_{12}^L C_{23}^L S_{13}^L & C_{23}^L C_{13}^L \end{pmatrix}, \tag{11}$$

with $C_{12}^L = \cos\theta_{12}^L$ and so on, in which θ_{ij} are the mixing angles. The matrix W_d has an analogous expression but with $\theta_{ij}^L \to \theta_{ij}^R$.

Using above equations, one can write the explicit expression forms for the $Zb\bar{b}$, $ZB'\overline{B'}$, $Zb\overline{B'}$ couplings, etc., and further give the correction terms δg_L^b and δg_R^b to the SM $Zb_L\overline{b_L}$ and $Zb_R\bar{b}_R$ couplings. To predigest our calculation, we set $S_{12}^R = S_R \neq 0$, $S_{13}^L = S_L \neq 0$, and all other mixing angles equal to zero. In this simply case, the couplings, which are related our calculation, can be written as

$$\delta g_L^b = \frac{S_L^2}{2}, \qquad \delta g_R^b = \frac{S_R^2}{2}; \tag{12}$$

$$g_L^{bB'} = 0, \qquad g_R^{bB'} = -\frac{e}{2S_W C_W} S_R C_R. \tag{13}$$

Comparing the experimental measured values of the $Z\to b\bar{b}$ branching ratio R_b and FB asymmetry $A^b_{\rm FB}$ with their current theoretical prediction values [2,4], one can obtain the constraints on the mixing parameters S_L and S_R. To make $A^b_{\rm FB}$ and R_b consistent with their experimental measured values with 1σ and 2σ error bars, the mixing parameters S_L and S_R must satisfy the relation

$$1\sigma: \quad 0 \leqslant S_L^2 \leqslant 0.004, \quad 0.022 \leqslant S_R^2 \leqslant 0.042, \tag{14}$$

$$2\sigma: \quad 0 \leqslant S_L^2 \leqslant 0.006, \quad 0.012 \leqslant S_R^2 \leqslant 0.052. \tag{15}$$

The couplings of the SM quarks and new down-type quarks to the Higgs boson H and the gauge boson W can be obtained from Ref. [17].

The couplings of the new fermions to the SM gauge bosons and ordinary fermions are uniquely fixed by gauge invariance [19]. The general Lagrangian describing the interactions between the SM bottom quark, its partner B' and gluon is fixed by $SU(3)$ gauge invariance to be of magnetic moment type [20,21]

$$\mathcal{L}_{gbB'} = \frac{g_s}{2\Lambda} G^a_{\mu\nu}\bar{b}\lambda^a\left(K_L^b P_L + K_R^b P_R\right)\sigma^{\mu\nu}B' + \text{h.c.}, \tag{16}$$

where $G^a_{\mu\nu}$ is the gluon field strength tensor with the color index $a=1,\ldots,8$, and g_s is the QCD coupling constant, λ^a are the fundamental $SU(3)$ representation matrices. In this Letter, we set the new physics scale Λ to $M_{B'}$ and assume that the coupling constants K_L^b and K_R^b are both of order one in the strongly interacting theory. It is should be noted that, using this type couplings, Ref. [22] has considered the contributions of B' to tW association

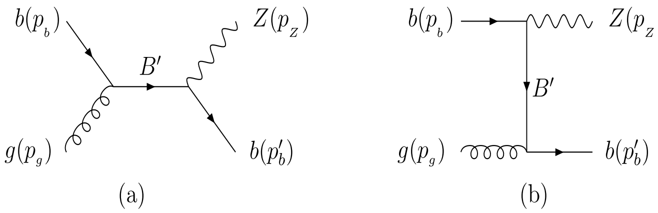

Fig. 3. Feynman diagrams for the B' contributions to Zb production at the LHC.

production and discussed the possibility of detecting the bottom partner B' at the LHC.

From above discussions we can see that the bottom partner B' can contribute to Zb production at the LHC via s-channel and t-channel B' exchanges, as shown in Fig. 3. Our numerical results are obtained by using Madgraph4 [23]. In Fig. 4 we plot the relative correction parameter $R_3 = (\sigma^{total} - \sigma^{\text{SM}})/\sigma^{\text{SM}}$ as a function of the bottom partner B' mass $M_{B'}$, in which σ_{total} includes the contributions from the SM and the bottom partner B'. Since the contributions of the new couplings δg_L^b and δg_R^b to Zb production are very small, we have not included their correction effects in the relative correction parameter R_3. In our numerical calculation, we have considered the constraints of the electroweak precision measurement, such as R_b and A_{FB}^b, on the mixing parameters S_L and S_R, and assumed the total decay width $\Gamma_{total}(B') = \Gamma(B' \to tW) + \Gamma(B' \to Zb) + \Gamma(B' \to Hb) + \Gamma(B' \to gb)$ and $K_L^b = K_R^b = K^b$. One can see from Fig. 4 that, with reasonable values of the relevant free parameters, the bottom partner B' can generate significant contributions to Zb production at the LHC. For the mixing parameter S_R consistent with the experimental values of A_{FB}^b with 1σ and 2σ error bars, $0.5 \leqslant K^b \leqslant 1.5$ and $300\ \text{GeV} \leqslant M_{B'} \leqslant 1500\ \text{GeV}$, the values of R_3 are in the ranges of $1.8 \times 10^{-4} \sim 0.34$ and $9.7 \times 10^{-5} \sim 0.41$, respectively. The correction of the bottom partner B' to Zb production at the LHC is comparable to its NLO QCD correction and might be larger than the NLO QCD correction for taking special values of the free parameters.

In the beautiful mirrors model, the correction effects on the Z polarization asymmetry A_Z for Zb production at the LHC come from two sources: the new $Zb\bar{b}$ couplings δg_L^b and δg_R^b, and the bottom partner B'. The contributions of B' to A_Z is not related the free parameter S_L and the contributions of δg_L^b are much smaller than those for δg_R^b and B', so we fix the value of the free parameter S_L to $S_L^2 = 0.004$. The relative corrections of the beautiful mirrors model to A_Z is presented by the parameter R_4, which is plotted as a function of S_R^2 for $K^b = 1$ and three values of

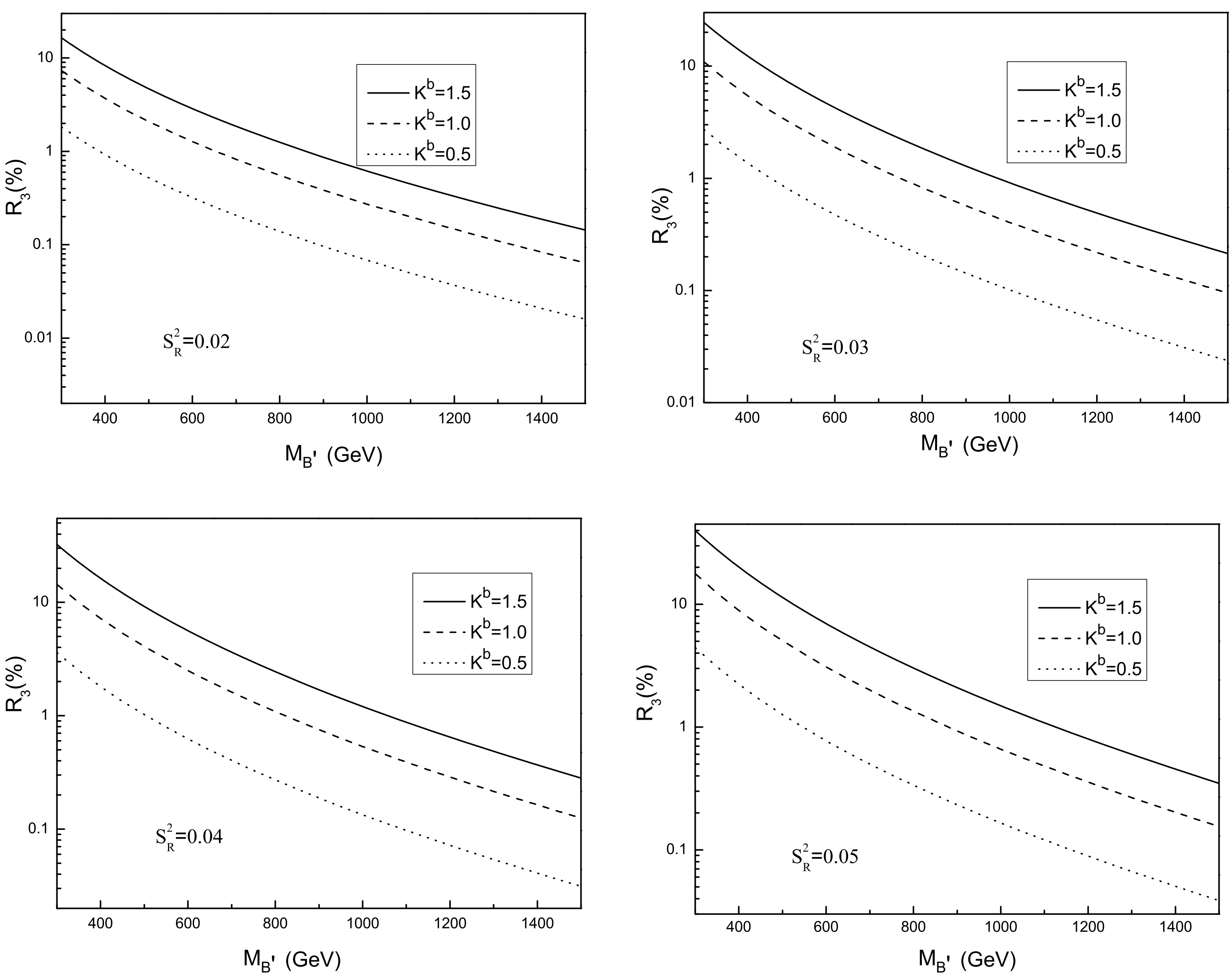

Fig. 4. The relative correction parameter R_3 as a function of the bottom partner B' mass $M_{B'}$ for different values of the free parameters S_R and K^b.

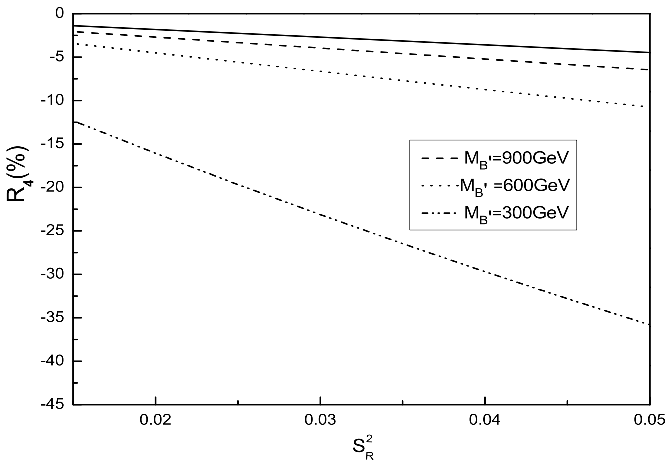

Fig. 5. The relative correction parameter R_4 as a function of S_R^2 for $S_L^2 = 0.004$, $K^b = 1$ and three values of the B' mass $M_{B'}$. The solid line expresses the contributions of the new $Zb\bar{b}$ couplings δg_L^b and δg_R^b and other lines denote the total contributions of the beautiful mirrors model.

the B' mass $M_{B'}$ in Fig. 5. The absolute value of the parameter R_4 increases as $M_{B'}$ decreases and S_R increases. For 300 GeV $\leqslant M_{B'} \leqslant$ 900 GeV and $0.015 \leqslant S_R^2 \leqslant 0.05$, its value is in the range of $-35.8\% \sim -1.4\%$. Thus, the possible signatures of the beautiful mirrors model might be detected at the LHC via measuring its correction effects on the Z polarization asymmetry A_Z in near future.

4. Conclusions

The electroweak precision measurements can generate severe constraints on the new physics beyond the SM. The large deviation between the SM prediction and the LEP measurement of the FB asymmetry A_{FB}^b and the $Z \to b\bar{b}$ branching ratio R_b require that the new physics has large corrections to the SM $Zb_R\overline{b_R}$ coupling $g_R^{b,\text{SM}}$ and small corrections to the SM $Zb_L\overline{b_L}$ coupling $g_L^{b,\text{SM}}$. In this Letter, we first consider the contributions of the new $Zb\bar{b}$ couplings δg_L^b and δg_R^b to the hadronic cross section $\sigma(Zb)$ and the Z polarization asymmetry A_Z for Zb production at the LHC. We find that the relative correction of δg_L^b and δg_R^b to $\sigma(Zb)$ is very small, while can reach 6.8% for A_Z.

Some new physics models beyond the SM predict the existence of the bottom partner B'. Considering the constraints from the electroweak precision measurements on this new physics model, we further calculate the contributions of B' to the production cross section $\sigma(Zb)$ and the Z polarization asymmetry A_Z. Our numerical results show that the "beautiful mirrors" scenario can give significant corrections to the physical observables $\sigma(Zb)$ and A_Z, which might be detected at the LHC in near future.

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