Limits on a Light Leptophobic Gauge Boson

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Abstract

We consider the phenomenology of a naturally leptophobic $Z$-prime boson in the 1 to 10 GeV mass range. The $Z$-prime’s couplings to leptons arise only via a radiatively-generated kinetic mixing with the $Z$ and photon, and hence are suppressed. We map out the allowed regions of the mass-coupling plane and show that such a $Z$-prime that couples to quarks with electromagnetic strength is not excluded by the current data. We then discuss possible signatures at bottom and charm factories.
1 Introduction

In the past few years, the possibility of new leptophobic gauge bosons has been explored as a means of explaining apparent discrepancies in electroweak observables measured with high precision at LEP [1, 2], as well as an apparent high $E_T$ excess in the inclusive dijet spectrum at the Tevatron [3]. While for the most part these anomalies have since gone away, the possibility remains that a $Z'$-prime boson ($Z'$) coupling mostly to quarks and with a mass smaller than $m_Z$ could exist while evading experimental detection [4, 5, 6]. Given the assumptions that (1) the leptons are not charged under the new U(1) gauge interaction, and (2) the couplings to quarks are generation independent (to avoid large flavor-changing neutral current effects) then the normalization of the U(1) can be chosen so that the $Z'$ couples precisely to baryon number. Anomaly cancellation can be achieved at the expense of introducing new exotic states. Two explicit examples of viable, anomaly-free models were presented in Refs. [4, 5], and these models presumably don’t exhaust the possible ways in which anomalies can be cancelled. Therefore, we will set model-building issues aside and focus instead on the phenomenology of the $Z'$. This is of timely interest given the recent stringy suggestion that the Planck scale and weak scale might be identified [7, 8]. In these scenarios, the dimension-5 baryon and lepton number violating operators that arise generically at the string scale would only be suppressed by a TeV, and hence would be phenomenologically lethal. Barring a higher-dimensional solution to the proton decay problem [8], additional gauge symmetries could provide a more prosaic, though equally effective, resolution.

In Ref. [5], a specific mechanism was proposed for maintaining leptophobia in models with gauged baryon number, and we will adopt this mechanism here. The reason that leptophobia is not automatic is that the baryon number and hypercharge gauge fields mix via their kinetic terms

$$L_{\text{kin}} = -\frac{1}{4} (F_{\mu\nu}^Y F_{\mu\nu}^Y + 2cF_{\mu\nu}^B F_{\mu\nu}^Y + F_{\mu\nu}^B F_{\mu\nu}^B).$$

(1.1)

We assume there are no Higgs fields that carry both baryon number and electroweak quantum numbers, so that mass mixing terms are not present. Below the electroweak symmetry breaking scale, there are separate kinetic mixing parameters for the photon and $Z$, which we will call $c_\gamma$ and $c_Z$, respectively. In order that leptophobia be preserved, $c_\gamma$ and $c_Z$ must be sufficiently small at experimental energies. This can be arranged if the parameter $c$ is forced to zero at some high scale $\Lambda$, so that $c_\gamma$ and $c_Z$ are only generated at the one-loop level, via renormalization group running. The boundary condition $c(\Lambda) = 0$ can be achieved, for example, by embedding U(1)$_B$ into a non-Abelian group, as was shown explicitly in Ref. [5]. Here we will be more general and not assume the specific mechanism for achieving this boundary condition. Thus, the boundary condition, together with as-
sumptions (1) and (2) given above, define a class of models that we will consider further in the present analysis.

In Ref. [5], the \( Z' \) mass range \( m_\Upsilon < m_B < m_Z \) was studied, primarily because the coupling \( \alpha_B \) could be taken as large as \( \sim 0.1 \) at points within this interval, without conflicting with the experimental bounds. Possible high energy collider signatures were then considered. Here we will focus instead on \( Z' \) masses between \( \sim 1 \text{ GeV} \) and \( m_\Upsilon \), with the initial goal of determining how tightly we can bound the parameter space of the model. Although the coupling \( \alpha_B \) cannot be as large as 0.1 within this mass range, we will show that current experiment does allow it to be comparable to \( \alpha_{EM} \approx 1/137 \). Given this result, we consider the possibility of detecting the \( Z' \) at charm and bottom meson factories via the decays of various quarkonium states which would be plentifully produced. We will not consider smaller values of \( m_B \), but instead refer the interested reader to the discussion in Ref [9].

This letter is organized in two parts. We will first discuss the current bounds on the parameter space of the model. With the boundary condition on the kinetic mixing terms described above, both the hadronic and leptonic signatures of the \( Z' \) are completely determined by its mass, \( m_B \), and gauge coupling \( g_B = \sqrt{4\pi\alpha_B} \). Therefore, these bounds can be translated into boundaries of excluded regions on a two-dimensional mass-coupling plane. We will then consider possible discovery signals for a \( Z' \) living within these allowed regions.

## 2 Parameter Space

Most of the important phenomenological bounds follow directly from the \( Z' \)-prime’s gauge coupling to quarks. In addition, we take into account the small kinetic mixing effects by treating the mixing term in \( \mathcal{L}_{kin} \) as a perturbative interaction. The Feynman rules corresponding to the \( Z' - \gamma \) and \( Z' - Z \) vertices are

\[
-ic_\gamma \cos \theta_w (p^2 g^{\mu\nu} - p^\mu p^\nu),
\]

and

\[
 ic_Z \sin \theta_w (p^2 g^{\mu\nu} - p^\mu p^\nu),
\]

respectively, where \( c_\gamma = c_Z = c \) above the electroweak scale, and where \( c = 0 \) at some ultraviolet cutoff \( \Lambda \). We will initially set \( \Lambda = m_{top} \approx 180 \text{ GeV} \), since this is probably the lowest scale at which the new physics responsible for the boundary condition \( c(\Lambda) = 0 \) might itself remain undetected. We will describe how our results change with different choices for
Λ as needed. Note that choosing a somewhat higher value for Λ, for example 500 GeV, has only a small effect on the mixing since the dependence on Λ is only logarithmic.

At any desired renormalization scale µ, we may rewrite $c_γ(µ)$ and $c_Z(µ)$ as an explicit function of $α_B$ by solving the one-loop renormalization group equations. These equations follow from the one quark-loop diagrams that connects the $Z'$ to the $γ$ and $Z$, respectively

\[ \mu \frac{\partial}{\partial \mu} c_γ(µ) = -\frac{2}{9\pi} \sqrt{\frac{α_B}{α}} c_w [2N_u - N_d] \]  

and

\[ \mu \frac{\partial}{\partial \mu} c_Z(µ) = -\frac{1}{18\pi} \sqrt{\frac{α_B}{α}} [3(N_d - N_u) + 4(2N_u - N_d)s_w^2] . \]

Here $c_w$ ($s_w$) represents the cosine (sine) of the weak mixing angle, $α$ is the electromagnetic fine structure constant, and $N_u$ ($N_d$) is the numbers of charge 2/3 (-1/3) quarks that are lighter than the renormalization scale. It is straightforward to show, for example

\[ c_γ(m_b) = 0.033\sqrt{α_B} \quad c_Z(m_b) = 0.116\sqrt{α_B} \]

\[ c_γ(m_c) = 0.047\sqrt{α_B} \quad c_Z(m_c) = 0.130\sqrt{α_B} \]

We will use expressions like these to translate bounds on leptonic processes to exclusion regions on the $m_B-α_B$ plane.

The experimental bounds on the model from hadronic decays are summarized in Fig. 1. Beginning with the $Υ(1S)$, the new contribution to the hadronic decay width is given by

\[ ΔR_Υ = \frac{4}{3} \left[ \frac{α_B}{α} \frac{m_T^2}{m_B^2 - m_T^2} + \left( \frac{α_B}{α} \frac{m_T^2}{m_B^2 - m_T^2} \right)^2 \right] , \]  

where $R_T ≡ Γ(Υ \rightarrow \text{hadrons})/Γ(Υ \rightarrow μ^+μ^-)$, and the interference with $s$-channel photon exchange is included. The most stringent bound on this quantity follows from an ARGUS limit on the non-electromagnetic (NE) contribution to the $Υ(1S) \rightarrow 2 \text{ jets}$ branching fraction [10],

\[ BF(Υ(1S) \rightarrow 2 \text{ jets}, \text{NE}) < 0.053 \text{ (95\% CL)} , \]

which we find corresponds to $ΔR_Υ < 2.48$. This bound is stronger than the one obtained from the $Υ(1S)$ hadronic width, discussed in Ref. [4]. Note that we have chosen to restrict Fig. 1 to values of the coupling $α_B > 10^{-3}$, where direct experimental detection of the $Z'$ via rare decays might be feasible. With this choice, finite width effects omitted from Eq. (2.7) have a negligible effect on the segments of the exclusion curves shown.

We may place additional bounds on the parameter space of the model by considering the hadronic decay widths of the $Υ(2S)$ and $Υ(3S)$ respectively. Since no direct experimental
bounds exist on the non-electromagnetic, two jet branching fraction, we compare $R_{\Upsilon(2S)}$ and $R_{\Upsilon(3S)}$ to the perturbative QCD prediction [11],

$$R = \frac{10(\pi^2 - 9)}{9\pi} \frac{\alpha_s^3}{\alpha^2} \left( 1 + \frac{\alpha_s}{\pi} \left\{ -18.2 + \frac{3}{2} \beta_0[1.161 + \ln(\frac{2\mu}{m_\Upsilon})]\right\} \right) \tag{2.8}$$

where $\beta_0 = 11 - 2n_f/3 = 23/3$. We evaluate this expression using $\alpha_s(m_b)$ as determined from the world average value $\alpha_s(m_Z) = 0.119 \pm 0.002$ [12]. We extract the experimental values of $R$ from branching fraction data in the 1998 Review of Particle Properties [12]. This is straightforward, except in the case of the $\Upsilon(3S)$, where the branching fraction to $\mu^+\mu^-$ has not been measured. We assume in this case that $\Gamma(\mu^+\mu^-)$ is approximately equal to $\Gamma(e^+e^-)$, which has been measured. Taking into account experimental uncertainties, we find $\Delta R \lesssim 92$ and $\Delta R \lesssim 33$ for the $\Upsilon(2S)$ and $\Upsilon(3S)$ respectively, at the 95% confidence level. Although these bounds are weak, they nonetheless exclude some additional region of the parameter space immediately around the resonance masses.

Similar bounds may be determined from the hadronic decay widths of the $J/\psi$ and the $\psi(2S)$. Here, however, it is not so straightforward to determine the standard model expectation. The perturbative QCD prediction for the gluonic decay width in Eq. (2.8) is derived in a nonrelativistic bound state approximation, and is therefore subject to $O(v^2/c^2)$ corrections, which are expected to be significant. Therefore, we will use the results of a
recent relativistic potential model analysis [13] as our standard model expectation. In Ref. [13], the \( J/\psi \) hadronic decay width was used to extract \( \alpha_s(m_c) \), yielding \( 0.29 \pm 0.02 \). Comparing to the world average value, we find that the difference \( \Delta \alpha_s(m_c) < 0.068 \) can be tolerated, allowing two-standard deviation uncertainties. Thus, any new contribution to \( R_{\psi} \) is bounded by \( \Delta R \lesssim 3(\Delta \alpha_s/\alpha_s)R \approx 34 \), yielding the contour shown in Fig. 4. We determine the gluonic contribution to \( R_{\psi(2S)} \) from branching fraction data in the Review of Particle Physics [12], and obtain \( R_{\psi} = 123.6 \pm 27.3 \). Since this is so large and uncertain, the bound on the model’s parameter space will clearly be weak. Thus, we simply compare \( R_{\psi(2S)} \) to the perturbative QCD prediction, including a theoretical uncertainty comparable in size to the relativistic corrections in the \( J/\psi \) case; we find \( \Delta R \lesssim 162 \), yielding the curve shown.

Finally, Fig. 1 displays the bound from the hadronic decay width of the \( Z \), labelled \( R_Z \), which we find provides the strongest constraint from the \( Z \)-pole observables. This result includes the contributions from (i) direct \( Z' \) production \( Z \to q\bar{q}Z' \), (ii) the \( Zq\bar{q} \) vertex correction, and (iii) the \( Z - Z' \) mixing. These contributions were discussed in detail in Refs. [4, 5], using old LEP data, and here we simply include an updated bound. We will say nothing further on this point, since the corresponding exclusion curve is superceded by the others shown in Fig. 1.

Other bounds on the parameter depend more crucially on the kinetic mixing. We consider (i) the \( e^+e^- \) cross section to hadrons, (ii) deep inelastic scattering, and (iii) the muon anomalous magnetic moment. In each case, however, we find that the constraints on the model are always weaker than those presented in Fig. 1. Let us briefly consider these topics in turn:

The contribution of the \( Z' \) to \( R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) \) was considered in Ref. [4], and was bounded by the two-standard deviation uncertainty in the experimental data, using a compilation of the experimental data points. While this is a reasonable approximation, it does not take into account that a tighter bound on any new positive contribution to \( R \) from a resonance effect is obtained when the central value of a given data point lies below the standard model prediction. Here we will take this into account, using the most precise measurements of \( R \) in the 5–10 GeV range obtained by the Crystal Ball experiment [14]. Given the standard model prediction for \( R \) in the continuum region between the \( J/\psi \) and the \( \Upsilon \),

\[
R = \frac{10}{3}(1 + \alpha_s/\pi) \approx 3.54
\]

we evaluate the upper bound on the difference between theory and experiment taking into account two standard deviation uncertainties. The tightest bound we obtained from any data point was \( \Delta R/R < 0.05 \), from the measurement \( R = 3.31 \pm 0.10 \pm 0.03 \pm 0.17 \) at \( \sqrt{s} = 6.25 \text{ GeV} \) [14]. The first two experimental errors are statistical and systematic errors.
for the given datum, while the third is an overall systematic uncertainty of 5.2%, which takes into account any average offset of the data. Note that within the allowed parameter space of Fig. [1], $\alpha_B$ is not much larger than $10^{-2}$, and hence the $Z'$ width is typically of order 10 MeV, or smaller. On the other hand, the experimental resolution at Crystal Ball is $\sigma_E/E = (2.7 \pm 0.2)/\sqrt{E/\text{GeV}}$ for electromagnetically showering particles [14], so that the resolution in the $Z'$ invariant mass is comparable or larger to the $Z'$ width. Assuming that $m_B = 6.25$ GeV and $\alpha_B \approx 0.01$ (the largest value allowed for this mass in Fig. [1]), we compute the contribution to $\Delta R/R$ by integrating the resonant and background cross-sections over an energy bin equal to the detector resolution, which we set equal to the $Z'$ width, $\Gamma = 4\alpha_B m_B/9 \approx 28$ MeV. We find

$$\Delta R/R \approx 0.03$$

which is below the experimental bound. Since the other experimental data points present weaker bounds on $\Delta R/R$ than the one just considered, we conclude that $R$ does not allow us to exclude any additional parameter space in Fig. 1. Note that at lower values of $\sqrt{s}$ above the charm threshold, $R$ is not as precisely measured, and no useful bounds on the model can be determined.

Deep inelastic $\nu N$ scattering, parity violating $e N$ scattering, and the muon $g-2$ provide only weak bounds the $Z'$ coupling. Using the results of Ref. [3], together with the boundary condition described earlier, we find the corresponding exclusion regions are given by

$$\alpha_B < 0.33(1 + [m_B/4.47 \text{ GeV}]^2)$$

$$\nu N \text{ scattering} \quad (2.10)$$

$$\alpha_B < 0.35(1 + [m_B/4.47]^2)$$

$$\text{parity-violating } e N \text{ scattering} \quad (2.11)$$

$$\alpha_B < 1.13(m_B/1 \text{ GeV})^2$$

$$\text{muon } g-2 \quad (2.12)$$

which are not even visible in Fig. [1]. Finally, we point out that resonant Bhabha scattering places no additional bounds on the model since the nonstandard contribution to the amplitude is proportional to $c_\gamma^2$, and hence the number of events near the resonance are suppressed relative to the electromagnetic background by a factor of $c_\gamma^4 \sim 10^{-10}$.

Finally, we can ask how our conclusions change if the cutoff scale $\Lambda$ is pushed to its largest possible value. We may use the accurate measurement the $Z$-hadronic width to first bound the mixing parameter $c_Z(m_Z)$; we find for $\alpha_B = 0.01$ that $c_Z(m_Z) \gtrsim 0.02$. This corresponds to the bound $\Lambda < 68$ TeV. We may obtain similar bounds from consideration of $R$; however these are strongly dependent on the value of $m_B$, as well as on the assumptions made in combining uncertainties from different, and often conflicting, experiments. Setting $\Lambda$ to this maximum value, we find $c_\gamma(m_b) \approx 0.007$, a factor of 2 enhancement over the value obtained from Eq. (2.6) for the same choice of $\alpha_B$. Clearly, this is not significant enough to change our qualitative conclusion that the processes involving the kinetic mixing in Eqs. (2.10) and (2.12) do little to constrain the parameter space of the model.
3 Rare Decays

What we gather from the preceding discussion is that Fig. 1 by itself gives a reasonable picture of the allowed parameter space of the model. We also learn that for $m_{\psi} < m_B < m_T$ and for $m_B < m_{\psi}$, there are regions where the $Z'$ coupling can be comparable to $\alpha_{EM}$. Thus, the gauge coupling need not be so small in these models as to require a separate leap of faith. In this section, we will assume that $\alpha_B \approx \alpha$, and consider whether the $Z'$ might eventually be detected via rare two-body decays of charm and bottom mesons.

Since the $Z'$ coupling to fermions is purely vectorial, the Lagrangian is charge conjugation invariant if the $Z'$ is $C$ odd. This discrete symmetry forbids the decays of either the $J/\psi$ or $\Upsilon$ to $\gamma Z'$ or $Z'Z'$ final states. Therefore, we consider instead the possible two-body decays of $B$ and $D$ mesons, as well as the decays of the lowest-lying $C$ even quarkonium states, the $\eta_c$, $\chi_c$, $\eta_b$, and $\chi_b$.

In the first case, we know that for every $B$ or $D$ meson decay involving a photon in the final state, there is an analogous process involving the $Z'$. The only two-body decays involving a photon are the various $b \to s \gamma$ exclusive modes. We estimate

$$\frac{\Gamma(b \to s Z')}{\Gamma(b \to s \gamma)} = \frac{\alpha_B}{\alpha} \frac{1}{2} \frac{m_B^2}{m_b^2} (1 - \frac{m_B^2}{m_b^2})^2$$

(3.13)

where $m_b \approx 4.3$ GeV is the bottom quark mass. While this ratio is not necessarily small, $b \to s Z'$ is probably not the easiest place to look for the $Z'$. Unlike $b \to s \gamma$ which is discerned experimentally by study of the photon energy spectrum, $b \to s Z'$ yields only hadrons in the final states, and would be overwhelmed by the larger background from $b \to s$ glue \cite{16}. On the other hand, the contribution to the (yet unobserved) process $b \to se^+e^-$ involves the kinetic mixing, so that for $\alpha_B \approx \alpha$ any resonance effect in the $e^+e^-$ invariant mass spectrum would be suppressed relative to the QED background by $c_\gamma^2 \sim 10^{-5}$. The standard model prediction for the corresponding radiative decays in the $D$ meson system yield drastically smaller branching fractions, and thus, these decays are not likely to aid in the $Z'$ search.

The situation is more promising in the case of the $C$-even quarkonia states. For example, the decay $\eta_c \to \gamma Z'$ is allowed, with

$$\frac{\Gamma(\eta_c \to \gamma Z')}{\Gamma(\eta_c \to \gamma \gamma)} \approx \frac{1}{4} \frac{\alpha_B}{\alpha} (1 - \frac{m_B^2}{m_{\eta_c}^2})$$

(3.14)

There is an overall suppression factor of $1/4$ relative to the purely electromagnetic decay from the squared ratio of baryon number to electric charge of the charm quark. In this case, one could consider $\eta_c \to \gamma X$, and search for a peak in the photon momentum spectrum. Note that the $\eta_c$ branching fraction to $\gamma +$ hadrons is dominated by the decay to $\gamma Z'$.
the decay $\eta_c \to \gamma g$, where $g$ is a gluon, is forbidden by color conservation, while $\eta_c \to \gamma gg$ is forbidden by charge conjugation invariance. The next possibility $\eta_c \to \gamma gg g$ is down by $\sim (\alpha_s^3/\alpha_B)/(2\pi)^4 \sim 0.001$ relative to the $Z'$ decay due mostly to phase space suppression, and is therefore negligible. It is simply an experimental question of whether single photons from other backgrounds processes can be adequately suppressed. This at least seems possible given that searches of exactly this type for lighter neutral gauge bosons have been undertaken in $\pi$, $\eta$ and $\eta'$ decays [17]. A possible scenario at an $e^+e^-$ machine is to sit on the $\psi(2S)$ resonance, and look for the decay chain

$$\psi(2S) \to \gamma \eta_c \to \gamma \gamma X.$$ 

One would retain events where one photon has precisely the right energy to come from the desired initial two body decay of the $\psi(2S)$, and then study the energy spectrum of the remaining photon. Exactly the same procedure could be applied to $\psi(2S) \to \gamma \chi_c \to \gamma \gamma X$, for the various $\chi_c$ states. At a charm factory with a typical beam luminosity of $10^{34}\text{cm}^{-2}\text{sec}^{-1}$ [18], and taking the $\psi(2S)$ production cross section to be $\sim 600$ nb from published data [19], we find $\sim 10^4 \gamma Z'$ events per year via $\chi_c$ decays, and $\sim 10^3$ events per year via $\eta_c$ decays. Here we have taken the branching fraction of the $\chi_c$ and $\eta_c$ states to $\gamma Z'$ to be approximately $1/4$ the $\gamma\gamma$ branching fractions i.e. $\sim 10^{-4}$. The analogous decay chains of the $\Upsilon(2S)$ in the $b$-quark system could be studied in the same way. However, compared to the charmonium case, one would expect a factor of 400 reduction in the event rates: the production cross section for the $\Upsilon(2S)$ [20] is approximately two orders of magnitude smaller that of the $\psi(2S)$, and the $\gamma Z'$ branching fraction is down by a factor of 4 relative to the same decay in the charmonium case, due to the smaller electric charge of the $b$ quark. Hence, one might still expect $\sim 25$ events/year from $\chi_b$ decays, but the (yet unobserved) $\eta_b$ seems less promising.

4 Conclusions

In this letter we have defined a generic class of naturally leptophobic $Z'$ models, and considered the $Z'$ phenomenology in the 1–10 GeV mass range, a lower range than considered in Ref. [3]. In this mass interval, decays of various quarkonia states present additional bounds on the $Z'$ coupling, but new opportunities for its discovery as well. We found that the experimental bound on $\Upsilon(1S)$ decay to two jets is primarily responsible for defining the allowed parameter space of the model. Bounds from the hadronic decays of the $J/\psi$, $\psi(2S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ only limit the parameter space in the immediate vicinity of the resonance masses; this is a consequence of larger experimental and (in the case of the charmonium states) theoretical uncertainties. We find that a $Z'$ coupling $\alpha_B \approx \alpha_{EM}$ is allowed
in mass intervals above and below the charmonium threshold. This opens the possibility of discovering the \(Z'\) in rare two-body quarkonia decays. We’ve suggested that perhaps the most interesting place to look is in the decay chain \(\psi(2S) \rightarrow \gamma(\eta_c \text{ or } \chi_c) \rightarrow \gamma \gamma Z'\), as well as in analogous decays of the \(\Upsilon(2S)\). If one photon has the right energy to indicate an initial two-body decay to the desired quarkonium state, one could search for a peak in the momentum distribution of the other photon. This could provide a stunning signal of a light and not so weakly-coupled \(Z'\), which, given the current experimental bounds, remains a viable possibility.

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