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Light U(1) Gauge Boson Coupled to Baryon Number*

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Abstract

We discuss the phenomenology of a light U(1) gauge boson, γ_B, that couples only to baryon number. Gauging baryon number at high energies can prevent dangerous baryon-number violating operators that may be generated by Planck scale physics. However, we assume at low energies that the new U(1) gauge symmetry is spontaneously broken and that the γ_B mass m_B is smaller than m_Z. We show for $m_\Upsilon < m_B < m_Z$ that the γ_B coupling α_B can be as large as ~ 0.1 without conflicting with the current experimental constraints. We argue that $\alpha_B \sim 0.1$ is large enough to produce visible collider signatures and that evidence for the γ_B could be hidden in existing LEP data. We show that there are realistic models in which mixing between the γ_B and the electroweak gauge bosons occurs only as a radiative effect and does not lead to conflict with precision electroweak measurements. Such mixing may nevertheless provide a leptonic signal for models of this type at an upgraded Tevatron.

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1 Introduction

The standard model possesses a number of global U(1) symmetries, namely baryon number, and three types of lepton number. It has been argued, however, that global symmetries should be broken by quantum gravity effects [1], with potentially disastrous consequences. Baryon number-violating operators generated at the Planck scale can lead to an unacceptably large proton decay rate, especially in some supersymmetric theories [2]. This problem can be avoided naturally if baryon number is taken instead to be a local symmetry at high energies.

In this talk, we consider the consequences of gauging the symmetry generated by baryon number [3], $U(1)_B$. We assume that the symmetry is spontaneously broken and that the corresponding gauge boson γ_B develops a mass $m_B < m_Z$. Additional electroweak scale fermions are necessary to render the model anomaly free, and a new Higgs field with baryon number B_H is required for spontaneous symmetry breakdown. However, by taking B_H to be small, we can raise the baryon number Higgs mass and effectively decouple it from the problem. Instead we will focus on the γ_B phenomenology [4, 5, 6], which can be described in terms of the parameter space m_B-α_B-c. Here $4\pi\alpha_B$ is the squared gauge coupling[‡], and c is a parameter that describes the kinetic mixing between baryon number and ordinary hypercharge:

$$\mathcal{L}_{kin} = -\frac{1}{4}\left(F_Y^{\mu\nu}F^Y_{\mu\nu} + 2c\,F_B^{\mu\nu}F^Y_{\mu\nu} + F_B^{\mu\nu}F^B_{\mu\nu}\right). \tag{1}$$

Since c is quite small, as we will see in Section 3, the discussion of jet physics can be described in terms of an effective parameter space, the m_B-α_B plane. We show for $m_\Upsilon < m_B < m_Z$ that the γ_B coupling α_B can be as large as ~ 0.1 without conflicting with the current experimental constraints. In this case, a signal might be discerned by reanalysis of existing accelerator data.

2 Parameter Space

Aside from the mixing effects discussed in the next section, the γ_B boson couples only to quarks, so that its most important effects can be expected

[‡] $U(1)_B$ is normalized such that the $(\gamma_B)^\mu\bar{q}\gamma_\mu q$ coupling is $\sqrt{4\pi\alpha_B}/3$

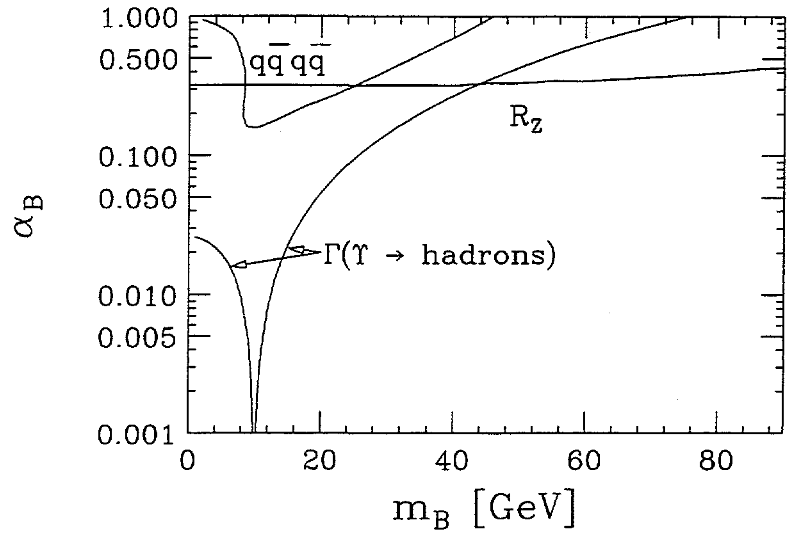

Figure 1: Allowed regions of the m_B-α_B plane, for $c = 0$. The region above each line is excluded.

in the same processes used in measuring the QCD coupling α_s. Thus, we will determine the allowed regions of the m_B-α_B plane by considering the following observables:

R_Z. In the absence of mixing ($c \approx 0$), the γ_B boson contributes to $R_Z = \Gamma(Z \to \text{hadrons})/\Gamma(Z \to \mu^+\mu^-)$ at order α_B through (i) direct production $Z \to \overline{q}q\gamma_B$, and (ii) the $Z\overline{q}q$ vertex correction. We require that the resulting shift in the value of $\alpha_s(m_Z)$ away from the world average [7] to be within two standard deviations of the value measured at LEP, $\alpha_s(m_Z) = 0.124 \pm 0.007$ [7]. As shown in Fig. 1, this roughly excludes the region of parameter space above $\alpha_B \approx 0.3$.

$Z \to$ jets. The γ_B boson contributes to Z decay to four jets, via $Z \to \overline{q}q\gamma_B$, $\gamma_B \to \overline{q}q$. In doing our parton-level jet analysis, we adopt the JADE algorithm. The four-jet cross section is shown in Fig. 2a as a function of y_{cut}, normalized to the lowest order two-jet cross section σ_0, for $\alpha_B = 0.1$ and for a range of m_B [8]. If we require that the fraction of four-jet events that are four-quark jet events be less than 9.1% (95% C.L.) at $y_{\text{cut}} = 0.01$ [9], we exclude the region at the top of Fig. 1. This is only an approximate bound illustrating the region that may be excluded by a rigorous treatment of the angular distributions of the four-jet events involving γ_B exchange. Reanalysis

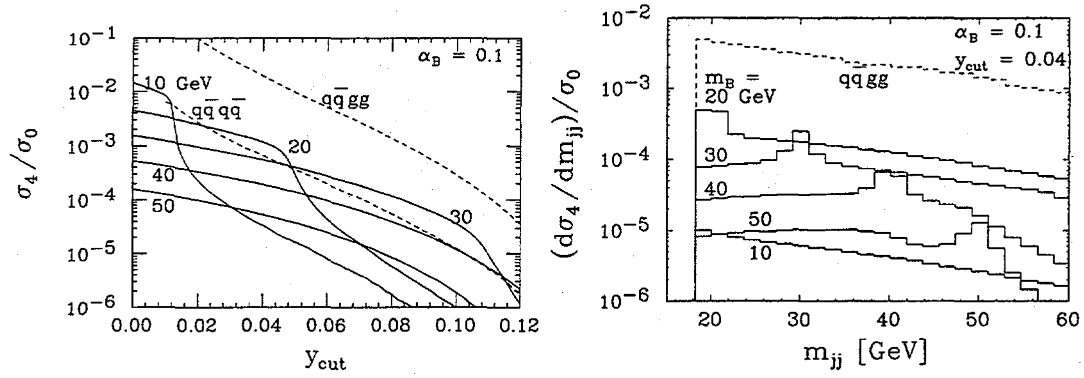

Figure 2: (a) Four-jet cross section as a function of $y_{\rm cut}$ for $\alpha_B = 0.1$, normalized to the leading two-jet cross section. (b) Di-jet invariant mass distribution in four-jet events, for $\alpha_B = 0.1$ and $y_{\rm cut} = 0.04$, normalized to the leading two-jet cross section.

of existing LEP data [10] using a larger value of $y_{\rm cut}$ and taking into account the angular distribution expected for a massive intermediate state would be necessary before we can put further constraints on the m_B-α_B plane. Thus, there is also the potential of finding a signal by reanalysis of existing data.

Di-jet invariant mass peak in $Z \to 4\,jets$. We show the m_{jj} distributions in Fig. 2b for various values of m_B, together with the QCD background. We chose $y_{\rm cut} = 0.04$ to optimize the signal for $m_B = 20$ GeV. It is clear that the signal is overwhelmed by the background, and hence no practical constraint exists from the m_{jj} distribution. Note that existing experimental searches for dijet invariant mass peaks have required associated peaks in both pairs of jets (as one would expect, for example, in charged Higgs production) and thus are irrelevant to our problem.

$\Upsilon(1S)$ Decay. The decay of $\Upsilon(1S)$ is another place to look for the effect of the γ_B boson, through its s-channel contribution to $R_\Upsilon = \Gamma(\Upsilon \to \text{hadrons})/\Gamma(\Upsilon \to \mu^+\mu^-)$. If we again require that the the resulting shift in the value of α_s away from the world average to be within two standard deviations of the value measured in Υ decay, $\alpha_s(m_Z) = 0.108 \pm 0.010$ [7], we exclude the region shown in Figure 1. One can see that the interesting region of large coupling lies above ~ 20 GeV, and thus we do not discuss the region below m_Υ any further.

3 Mixing effects

Clearly, the parameter c must be quite small so that the kinetic mixing does not conflict with precision electroweak measurements. Let us begin by defining separate mixing parameters for the γ_B-photon and γ_B-Z^0 mixing, namely c_γ and c_Z. While $c_\gamma = c_Z = c$ above the electroweak scale, c_γ and c_Z run differently in the low-energy effective theory below m_{top}. Thus, even if c is vanishing at some scale Λ, c_γ and c_Z are renormalized by the one quark-loop diagrams that connect the γ_B to either the photon or Z, and monotonically increase at lower energies.

The most significant constraints on $c_Z(m_Z)$ are shown in Fig. 3a. We have considered the effects of the γ_B-Z mixing on the following experimental observables: the Z mass, hadronic width, and forward-backward asymmetries, and the neutral current νN and eN deep inelastic scattering cross sections [5]. We obtained the strongest constraint from the Z hadronic width. In addition to the contributions described earlier, there is an additional contribution to $Z \to q\bar{q}$ when $c \neq 0$ due to the γ_B-Z mixing, which is included in Figure 3a. The hadronic width places the tightest constraint on $c_Z(m_Z)$, roughly $|c_Z(m_Z)| \lesssim 0.02$.

The coupling c_γ has its most significant effect on a different set of observables. We have considered the effect of the γ_B-γ mixing on the cross section for $e^+e^- \to$ *hadrons*, and on the anomalous magnetic moments of the electron and muon [5]. We obatined the strongest constraint from the additional contribution to R, the ratio $\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. For any m_B of interest, we can constrain c_γ by considering the two standard deviation uncertainty in the value of R measured at $\sqrt{s} \approx m_B$. The results are shown in Fig. 3b, based on the cumulative data on R taken at various values of $\sqrt{s}$ and compiled by the Particle Data Group [7]. Roughly speaking, the allowed region of Fig. 3b corresponds to $|c_\gamma(m_B)| < 0.01$.

Using the approximate bound $c_Z(m_Z) < 0.02$ from above, and assuming $m_{\text{top}} \approx 175$ GeV and $\alpha_B = 0.1$, we find $c(\Lambda) = 0$ for $\Lambda < 1.3$ TeV. This implies that the scale of new physics lies at relatively low energies, just above the electroweak scale.

What type of model can naturally satisfy the boundary condition what we obtained above? Consider a model with the gauge structure $\text{SU}(3)_C \times$

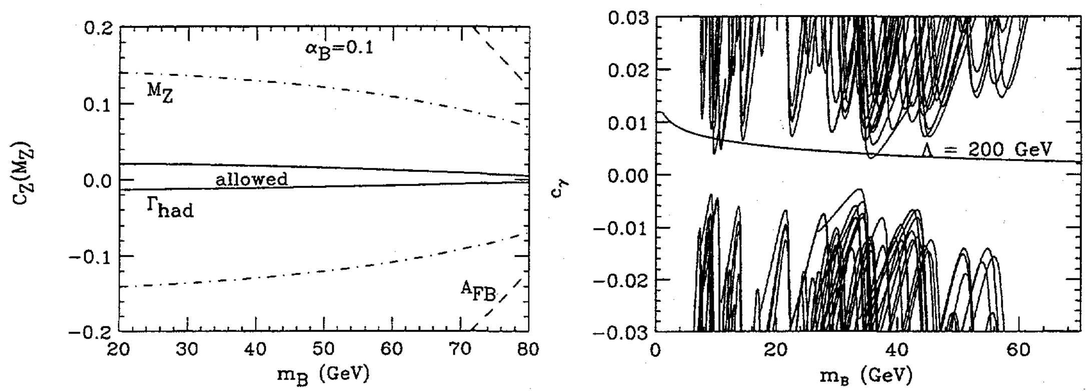

Figure 3: (a) Constraints on $c_Z(m_Z)$ from the two standard deviation experimental uncertainties in the Z mass, hadronic width, and $Z \to b\bar{b}$ forward-backward asymmetry. (b) Constraints on $c_\gamma(m_B)$ from the two standard deviation experimental uncertainty in R measured at various values of s as compiled by the Particle Data Group. The running of c_γ corresponding to $\Lambda = 200$ GeV is shown for comparison.

$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{SU}(4)_H$, where $\mathrm{SU}(4)_H$ is a horizontal symmetry. In addition to the ordinary three families of the standard model, f^i $(i = 1,2,3)$, we assume there is a fourth family F. The horizontal symmetry acts only on the quarks in the four families, which together transform as a **4** under the $\mathrm{SU}(4)_H$. The $\mathrm{U}(1)_B$ gauge group is embedded into $\mathrm{SU}(4)_H$ as $diag(1/3, 1/3, 1/3, -1)$. The horizontal symmetry $\mathrm{SU}(4)_H$ is broken at a scale M_H down to $\mathrm{U}(1)_B$. It is easy to see that the kinetic mixing remains vanishing down to the weak scale: Above M_H, the mixing is not allowed by gauge invariance because $\mathrm{U}(1)_B$ is embedded into the non-abelian group $\mathrm{SU}(4)_H$. Below M_H, the particle content satisfies the orthogonality condition $\mathrm{Tr}(BY) = 0$ and the mixing parameter c does not run. The running begins only after the heaviest particle contributing to $\mathrm{Tr}(BY)$ (i.e. the heaviest fourth generation fermion) is integrated out of the theory, so that the one-loop diagram connecting baryon number to hypercharge is nonvanishing. Since the fourth generation fermions have electroweak scale masses, the mixing term remains vanishing down to the weak scale, *i.e.*, $\Lambda = m_F \sim m_{\rm top}$, and the desired boundary condition is naturally achieved.

4 Leptonic Signals

Finally, we point out that the small kinetic mixing term described above can provide a possible leptonic signature for our model through the Drell-Yan production of lepton pairs at hadron colliders. The quantity of interest is $d\sigma/dM$, the differential cross section as a function of the lepton pair invariant mass. We computed $d\sigma/dM$ in a $p\overline{p}$ collision at $\sqrt{s} = 1.8$ TeV, integrated over the rapidity interval $-1 < y < 1$, using the EHLQ Set II structure functions [11]. Assuming $\alpha_B = 0.1$ and $c_\gamma(m_B) = c_Z(m_B) = 0.01$, we determined the excess in the total dielectron plus dimuon signal in a bin of size dM surrounding the γ_B mass. The results are shown in Table 1, for $m_B = 30$, 40, and 50 GeV. The statistical significance of the signal assuming integrated luminosities of 1 fb^{-1} and 10 fb^{-1} is also shown. These results imply that there would be hope of detecting the γ_B boson at the Tevatron with the main injector, and/or an additional luminosity upgrade.

Table 1: Excess Dielectron plus Dimuon Production at the Tevatron, with $\alpha_B = 0.1$ and $c_\gamma(m_B) = c_Z(m_B) = 0.01$.

m_B (GeV)	dM (GeV)	Background (fb)	Excess (fb)	statistical significance	
				1 fb^{-1}	10 fb^{-1}
30	2	3468	320	5.4 σ	17.2 σ
40	4	2798	208	3.9 σ	12.4 σ
50	4	1422	112	3.0 σ	9.4 σ

5 Conclusions.

We have shown that a new light U(1) gauge boson γ_B coupled to the baryon number evades all existing experimental constraints in the interesting mass region, $m_\Upsilon \lesssim m_B \lesssim m_Z$. In this range, the coupling α_B may be as large as ~ 0.1, and the γ_B may have a visible collider signature, even at existing accelerators. In particular, the new contribution to Drell-Yan dilepton production may yield a detectable signal at the Fermilab Tevatron after the main injector upgrade.

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