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

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We discuss the phenomenology of a light U(1) gauge boson, γ_B, that couples only to baryon number. We assume 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 point out that γ_B exchange can account for rapidity gap events in p-$\bar{p}$ scattering seen at the Tevatron.

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The standard model possesses a number of global U(1) symmetries, namely, baryon number and the three types of lepton number (associated with the electron, muon, and tau). 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. Moreover, it is not even clear whether global phase rotations are consistent with the basic premise of local field theory [3]. For these reasons, and at the very least for esthetics, it is natural to wonder whether any of the global U(1) symmetries of the standard model can be promoted to gauge symmetries in a phenomenologically acceptable way [4].

In this Letter, we will consider the consequences of gauging the symmetry generated by baryon number, $U(1)_B$. We assume that the symmetry is spontaneously broken and that the corresponding gauge boson γ_B develops a mass $m_B < m_Z$. Of course, in the minimal standard model we cannot gauge baryon number alone because it is anomalous. However, by adding a small number of new heavy fermions, we can gauge $U(1)_B$ in an anomaly-free way. Then, the main question of interest to us is whether a γ_B boson with a relatively large gauge coupling could have evaded all the available means of detection. If we call the squared gauge coupling $4\pi\alpha_B$ [5], then we can determine if there are regions of the m_B-α_B plane [6] that are consistent with the current experimental constraints and that also allow α_B to be as large as $\alpha_{\rm QCD}$. This possibility is of interest to us because it may allow visible collider signatures for the new gauge boson at present or near-future experiments. We will see that if $m_B > m_\Upsilon$ there is a significant region of the m_B-α_B plane in which our model is phenomenologically allowed and α_B can be as large as ~ 0.1. Notice that for m_B in this range we immediately evade constraints on exotic decays of hadrons [7], new long-range forces [8], and primordial nucleosynthesis [9]. In addition, for some m_B within the region of large coupling, we show that γ_B exchange can account for the rapidity gap events that have been observed at the Fermilab Tevatron [10].

We will see that the γ_B boson is elusive for some of the same reasons that it is difficult to detect a light gluino [11] or stop [12]. Since the γ_B boson couples only to quarks, its most important effects can be expected 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: $R_Z = \Gamma(Z \to \text{hadrons})/\Gamma(Z \to \mu^+\mu^-)$, the $Z \to 3$ jet and $Z \to 4$ jet total cross sections, the dijet invariant mass distribution in $Z \to 4$ jets, and the hadronic decay width of the $\Upsilon(1S)$. Since the region in which α_B can be large corresponds to $m_B \gtrsim m_\Upsilon$, the γ_B boson decays to $q\bar{q}$ with the width $\Gamma_B = N_F \alpha_B m_B/9$, where $N_F = 5$.

R_Z.—The γ_B boson contributes to the R_Z at order α_B through (1) direct production $Z \to \bar{q}q\gamma_B$, and (2) the $Z\bar{q}q$ vertex correction. Writing these two contributions as F_1 and F_2, we find that the nonstandard contribution to the R_Z, ΔR_Z, is positive and given by

$$\frac{\Delta R_Z}{R_Z} = \frac{\alpha_B}{18\pi}[F_1 + F_2], \tag{1}$$

where

$$F_1 = (1+\delta)^2\left[3\ln\delta + (\ln\delta)^2\right] + 5(1-\delta^2) - 2\delta\ln\delta - 2(1+\delta)^2 \times\left[\ln(1+\delta)\ln\delta + \mathrm{Li}_2\left(\frac{1}{1+\delta}\right) - \mathrm{Li}_2\left(\frac{\delta}{1+\delta}\right)\right], \tag{2}$$

$$F_2 = -2\left\{\frac{7}{4} + \delta + \left(\delta + \frac{3}{2}\right)\ln\delta + (1+\delta)^2 \times\left[\mathrm{Li}_2\left(\frac{\delta}{1+\delta}\right) + \frac{1}{2}\ln^2\left(\frac{\delta}{1+\delta}\right) - \frac{\pi^2}{6}\right]\right\}. \tag{3}$$

Here $\mathrm{Li}_2(x) = -\int_0^x \frac{dt}{t}\ln(1-t)$ is the Spence function, and $\delta = m_B^2/m_Z^2$. We compare Eq. (1) to a two-standard-deviation uncertainty in $\Delta R_Z/R_Z = \Delta\alpha_s/\pi$ with

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$\alpha_s(m_Z) = 0.124 \pm 0.0086$ [13]. As shown in Fig. 1, this roughly excludes the region of parameter space above $\alpha_B \approx 0.2$. Other Z-pole observables do not yield stronger constraints.

$Z \rightarrow$ jets.—The γ_B boson contributes to Z decay to four jets, via $Z \rightarrow \bar{q}q\gamma_B$, $\gamma_B \rightarrow \bar{q}q$. In doing our parton-level jet analysis, we adopt the JADE algorithm, in which we require jets i and j to be separated in phase space by $y_{ij} \equiv 2E_iE_j(1 - \cos\theta_{ij})/m_Z^2 > y_{\rm cut}$, where E_i and E_j are the jet energies and θ_{ij} is the angle between the jets. If any pair of jets has $y_{ij} < y_{\rm cut}$, then these are combined into one jet, and the event instead contributes to the three-jet cross section. Since two of the jets originate from the γ_B, the total four-jet cross section as a function of $y_{\rm cut}$ will drop off as $y_{\rm cut}$ is taken to be greater than m_B^2/m_Z^2. The four-jet cross section is shown in Fig. 2 as a function of $y_{\rm cut}$, normalized to the lowest order two-jet cross section σ_0, for $\alpha_B = 0.1$ and for a range of m_B [14]. We compare our results to the experimental bounds on the fraction of all four-jet events that are four-quark jet events, 9.1% (95% C.L.) with $y_{\rm cut} = 0.01$ [15]. Comparing the γ_B contribution to σ_4/σ_0 at $y_{\rm cut} = 0.01$ to the expected four-jet QCD background $(\sigma_4/\sigma_0)_{\rm QCD} \approx 0.2$ gives us the bound shown at the top of Fig. 1. For the most part, this excludes no new parameter space beyond the region already excluded by our analysis of R_Z.

The events that are not counted as four-jet events contribute to the total three-jet cross section, in principle yielding some enhancement over the expected rate. However, given the large three-jet QCD background, the three-jet analysis will not yield a further constraint.

Dijet invariant mass peak in $Z \rightarrow 4$ jets.—The dijet invariant mass m_{jj} distribution in Z decay has been studied in searches for charged Higgs pairs, associated light and heavy Higgs production in two-Higgs-doublet models, and excited quark pairs that decay via $q^* \rightarrow qg$ [16]. In these studies, peaks in the m_{jj} distribution from both particles were required, so that the results are irrelevant to our problem. In principle, one can look for a peak in the m_{jj} distribution without any other requirements, but then one must contend with a huge QCD background. We show the m_{jj} distributions in Fig. 3 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. A distribution that is more sensitive to the γ_B, especially for $m_B \lesssim 30$ GeV, is the distribution of the smallest invariant mass $m_{\rm min}^2$ among the six possible combinations in four-jet events. We show the distribution of $y_{\rm min} = m_{\rm min}^2/m_Z^2$ in Fig. 4. The background dominates the signal by more than a factor of 7, even on the peak. Moreover, the peak will be further smeared by hadronization effects and the resolution of the hadron calorimetry. Therefore no practical constraint exists from the m_{jj} distribution. The search for a peak in the m_{jj} distribution at hadron colliders is probably hopeless, given the much larger backgrounds.

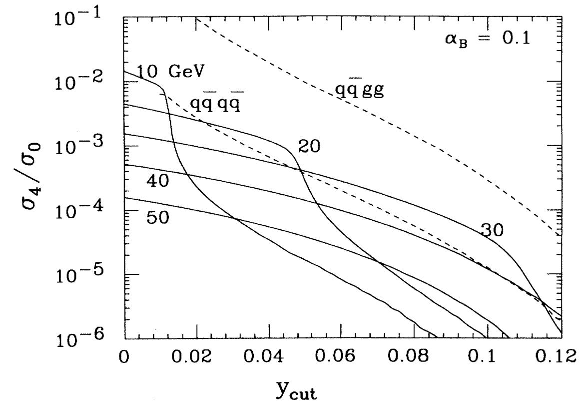

FIG. 2. Four-jet cross section as a function of $y_{\rm cut}$ for $\alpha_B = 0.1$, normalized to the leading two-jet cross section.

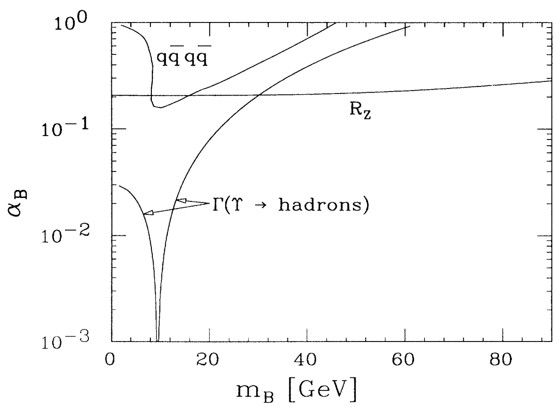

FIG. 1. Allowed regions of the m_B-α_B plane at 95% C.L. or two standard deviations. The bounds shown come from (1) R_Z, (2) the fraction of four-quark jet events in four-jet events, and (3) the hadronic decay width of the $\Upsilon(1S)$. The parameter space above each of the lines shown is excluded. The region below $\approx$250 MeV is excluded for the range of α_B shown by the constraints discussed in [7]. Weaker constraints discussed in the text are not shown.

$\Upsilon(1S)$ decay.—The decay of $\Upsilon(1S)$ is another place to look for the effect of the γ_B boson, through its contribution to $R_\Upsilon = \Gamma(\Upsilon \rightarrow \text{hadrons})/\Gamma(\Upsilon \rightarrow \mu^+\mu^1)$. In the case where $m_B > m_\Upsilon$, the most stringent constraint comes from the additional contribution to the $\Gamma(\Upsilon \rightarrow$ hadrons) from s-channel exchange of the γ_B boson. This additional contribution is

$$\Delta R_\Upsilon = \frac{4}{3}\left[\frac{\alpha_B}{\alpha}\frac{m_\Upsilon^2}{m_B^2 - m_\Upsilon^2} + \left(\frac{\alpha_B}{\alpha}\frac{m_\Upsilon^2}{m_B^2 - m_\Upsilon^2}\right)^2\right], \quad (4)$$

where α is the fine-structure constant. This result includes the interference with s-channel photon exchange [17]. The measured QCD coupling from Υ decay is $\alpha_s(m_Z) = 0.108 \pm 0.010$ [13], which implies $\Delta R_\Upsilon < 17.2$ at two

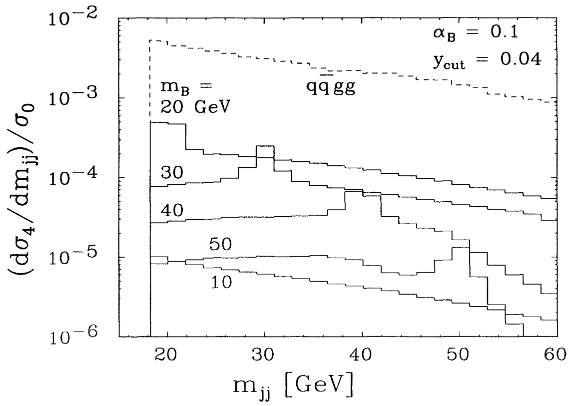

FIG. 3. Dijet invariant mass distribution in four-jet events, for $\alpha_B = 0.1$ and $y_{\text{cut}} = 0.04$, normalized to the leading two-jet cross section.

standard deviations. The resulting constraint on the free parameters of our model is $m_B > m_\Upsilon\sqrt{1 + 43.8\alpha_B}$ which is shown in Fig. 1. For the case where $m_B < m_\Upsilon$, the same argument gives us the constraint $m_B < m_\Upsilon\sqrt{1 - 33.2\alpha_B}$, also shown in Fig. 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.

If $m_B \gtrsim m_\Upsilon$, all analyses of α_s based on deep inelastic scattering data, the lattice QCD calculations of the quarkonia spectrum, and the τ hadronic decay width, will remain unaffected by the existence of the γ_B. Note that these measurements tend to give smaller values of α_s compared to the value extracted from measurements made at LEP, in particular, from the measurement of R_Z. Since the γ_B boson provides an additional positive contribution to R_Z, the data may be viewed as suggesting its existence [18]. However, since the various measurements of $\alpha_s(m_Z)$ seem to be converging, we feel that it is a more conservative approach to restrict the γ_B parameter space based on the

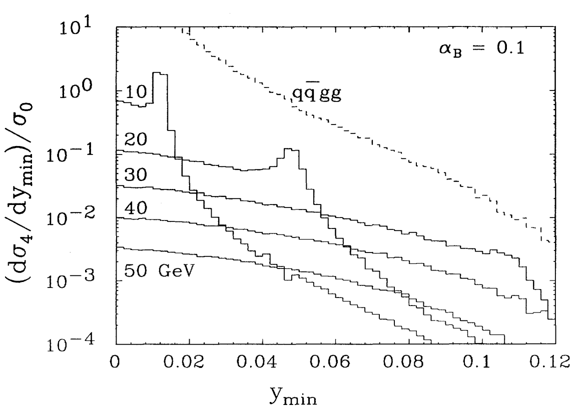

FIG. 4. Four-jet differential cross section as a function of y_{min} for $\alpha_B = 0.1$, normalized to the leading two-jet cross section.

experimental data, rather than to predict specific experimental anomalies.

Finally, we discuss signatures of the γ_B boson that might be discerned by further study of existent accelerator data. In recent analyses of four-jet events [19], the QCD group theory factors N_C and T_F were fitted using the θ_{BZ} and θ_{NR} distributions [20]. The γ_B contribution leads to an enhancement in the number of $q\bar{q}q\bar{q}$ final states, similar to the signature of an Abelian gluon. The fits allow T_F to be roughly twice as large as the QCD prediction, which would allow us to exclude the region above $\alpha_B \simeq 0.1$ if $y_{\text{cut}} \simeq m_B^2/m_Z^2$ (see Fig. 3). However, the results in Ref. [19] for $y_{\text{cut}} = 0.01-0.03$ correspond to m_B in the range 9–16 GeV, which is already excluded down to $\alpha_B \approx 0.04$ by the constraints from Υ decay. Thus, the data must be reanalyzed for larger y_{cut} (up to $\approx$0.12) before we can put further constraints on the m_B-α_B plane. The absence of a next-to-leading order calculation of the QCD background, and the lower statistics at higher y_{cut} will present the main problems in this analysis.

Perhaps the most interesting potential signal of the γ_B boson is events with large rapidity gaps $\Delta\eta_c$ in hadronic collisions, which are expected when scattering proceeds by color-singlet exchange. At the Tevatron, rapidity gap events have been searched for at $E_T >$ 30 GeV and $\Delta\eta_c > 3$. In the large-gap limit ($\Delta\eta_c \gtrsim 4$), two-jet events are dominated by $q\bar{q}$ scattering via gluon exchange because the center-of-mass energy of the subprocess grows exponentially with $\Delta\eta_c$, $\sqrt{\hat{s}} = 2E_T \cosh\Delta\eta_c/2$. The ratio of the events via γ_B exchange to those by gluon exchange is $(\alpha_B^2/18\alpha_s^2)(1 + m_B^2/E_T^2)^{-2}$. Given an estimate of the survival probability of the rapidity gap, $S \simeq 0.1-0.3$ [21], the contribution of γ_B exchange to the rate of events with a large rapidity gap is

$$f(\Delta\eta_c > 4) \sim (0.1-0.3)\,\frac{4 \times 10^{-2}}{(1 + m_B^2/E_T^2)^2}\left(\frac{\alpha_B}{0.1}\right)^2. \quad (5)$$

The rate is remarkably close to the experimental observations [10] when $\alpha_B \simeq 0.1$ and $m_B \lesssim E_T$. While it has been suggested that the data could be explained by the exchange of a QCD Pomeron [22], it is tempting to speculate that γ_B exchange might instead be the origin of the events with large rapidity gaps.

Finally we present one simple extension of the standard model in which $U(1)_B$ is gauged in an anomaly-free way. To gauge the baryon number current, we need to introduce additional fermions to cancel the $U(1)_B\ SU(2)_L^2$, $U(1)_B\ U(1)_Y^2$, $U(1)_B^2\ U(1)_Y$, and $U(1)_B^3$ triangle anomalies. To do so, we introduce N_Q families each consisting of an SU(2) doublet of left-handed fermions $Q_L = (U_L, D_L)$ with zero hypercharge, and two SU(2) singlet right-handed fermions, U_R and D_R with hypercharges 1/2 and −1/2, respectively. We assume that these new fermions acquire degenerate Dirac masses from electroweak symmetry breaking (so that there will be no contribution to the T parameter). Assuming a common baryon number B_Q for each of these fields, all anomalies cancel when $B_Q N_Q = -3$ with N_Q even. The constraint from the S parameter [23] $S_{\rm new} = N_Q/(6\pi) < 0.46$ (95% C.L. [13]) can be easily met when $B_Q \gtrsim 0.35$.

Since we have assumed that the γ_B boson becomes massive through spontaneous symmetry breakdown, there is also an associated Higgs boson. However, since we do not know the Higgs boson's baryon number $B_{\rm H}$, or its quartic self-coupling λ, we cannot predict its mass $\sim \lambda_{m_B}/\sqrt{4\pi\alpha_B}B_{\rm H}$. Notice that if we let $B_{\rm H} \to 0$ while holding λ fixed, we can make the Higgs mass arbitrarily large without violating the triviality bound $\lambda \lesssim O(1)$ [24]. If we assume $B_{\rm H} = 1/3$ and $\lambda \approx 1$, then the mass of the Higgs boson will be around the 100 GeV scale. The Higgs boson decays into a real $\gamma_B\gamma_B$ pair, and thus, to four jets. It can be copiously produced by γ_B fusion in $q\bar{q}$ collisions or by the Bjorken-like process $q\bar{q} \to \gamma_B^* \to \gamma_B H$, but the final state is completely hadronic and difficult to see. It is important to note that the baryon number current of the quarks is still conserved, due to an accidental symmetry, even after the spontaneous breakdown of $U(1)_B$. Therefore there is no constraint from proton decay experiments.

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 comparable to $\alpha_{\rm QCD}$, and the γ_B may have a visible collider signature, even at existing accelerators. We have pointed out that rapidity gap events observed at the Tevatron may be a manifestation of the γ_B.

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