PRL **113,** 061801 (2014) PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2014

Hidden GeV-Scale Interactions of Quarks

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(Received 25 April 2014; published 5 August 2014)

We explore quark interactions mediated by new gauge bosons of masses in the 0.3–50 GeV range. A tight upper limit on the gauge coupling of light Z' bosons is imposed by the anomaly cancellation conditions in conjunction with collider bounds on new charged fermions. Limits from quarkonium decays are model dependent, while electroweak constraints are mild. We derive the limits for a Z' boson coupled to baryon number and then construct a Z' model with relaxed constraints, allowing quark couplings as large as 0.2 for a mass of a few GeV.

DOI: 10.1103/PhysRevLett.113.061801 PACS numbers: 14.80.-j, 12.60.Cn, 13.25.-k

Introduction.—Quarks experience all five known interactions: strong, weak, electromagnetic, Higgs, and gravitational. It behooves us to ask whether additional interactions of quarks exist, and what are the current limits on their strength? Experimental searches for new particles interacting with quarks have been performed at hadron colliders over the last few decades, setting upper limits on their couplings for masses in the 50 GeV–3 TeV range [1,2]. Smaller masses have been less intensely investigated, due to large backgrounds at hadron colliders.

In this Letter, we study existing limits on the coupling of new spin-1 particles that interact with quarks and have masses in the 0.3–50 GeV range. Lighter mediators of quark interactions are possible, but their couplings are strongly constrained [3], and precise limits are harder to derive for masses near the QCD scale.

Spin-1 fields are well behaved at high energies only if they are gauge bosons. While composite spin-1 particles bound by some new dynamics may exist, their coupling to quarks would suggest a compositeness scale above the weak scale ($v \approx 246$ GeV); given that spin-1 states are typically near the compositeness scale, we focus on elementary gauge bosons. Only electrically neutral gauge bosons with highly suppressed couplings to leptons ("leptophobic" bosons) are allowed at masses below 50 GeV. These can be color singlets (i.e., Z' bosons) or octets. The latter are severely constrained by the running of the QCD coupling below M_Z [4]. Thus, leptophobic Z' bosons associated with a $U(1)_z$ gauge extension of the standard model (SM) are the best candidates for mediating new relatively strong quark interactions at low energies.

Z' couplings to quarks.—The renormalizable interactions of a Z' boson of this type are given by

$$\frac{g_z}{2} Z'_\mu (z_{Q_j} \bar{Q}_L^j \gamma^\mu Q_L^j + z_{u_j} \bar{u}_R^j \gamma^\mu u_R^j + z_{d_j} \bar{d}_R^j \gamma^\mu d_R^j), \qquad (1)$$

where j labels the generations, Q_L^j are the left-handed quark doublets, u_R^j and d_R^j are the right-handed quark gauge eigenstates, z_{Q_j}, z_{u_j}, and z_{d_j} are their $U(1)_z$ charges, and g_z is the gauge coupling. Higher-dimensional Z' interactions may exist [5], but their effects for a Z' mass $M_{Z'} \ll v$ are suppressed.

A simple charge assignment that allows quark masses and evades constraints from flavor-changing neutral currents (FCNCs) is $z_{Q_j} = z_{u_j} = z_{d_j} = 1/3$, i.e., charges given by the baryon number. Experimental limits on g_z are loose in this case [6,7], except for $M_{Z'}$ near the Υ or J/ψ resonances. We will show, however, that additional limits on light leptophobic Z' bosons arise from the interplay of collider limits on new fermions and theoretical constraints.

Anomaly cancellation.—Self-consistency of the theory at high energies [8] requires gauge anomaly cancellation. General arguments suggest that $U(1)$ gauge charges are commensurable [9]. If that is the case, then for certain g_z normalizations, the charges are integers, so finding solutions to the $[U(1)_z]^3$ anomaly cancellation is nontrivial.

Even without fermions beyond the SM, leptophobic $U(1)_z$ groups can be anomaly free, e.g., when first- (second-) generation quarks have $U(1)_z$ charge z_1 (z_2) and third-generation quarks have charge $-(z_1 + z_2)$. For $M_{Z'} \ll v$, though, Z'-induced FCNCs are large unless the Q_L^j charges are equal (u_R^j or d_R^j may have j-dependent charges because their gauge and mass eigenstates may be identical): $K^0 - \bar{K}^0$ mixing requires $g_z |z_{Q_2} - z_{Q_1}| < 10^{-5} M_{Z'}/(1\ \text{GeV})$, and $B^0 - \bar{B}^0$ mixing imposes a slightly weaker constraint on $g_z |z_{Q_3} - z_{Q_1}|$. Thus, large values of g_z require $z_{Q_1} = z_{Q_2} = z_{Q_3}$. Then, in the absence of new fermions, the $[SU(2)_W]^2 U(1)_z$ anomaly implies $z_{Q_j} = 0$. The remaining anomaly cancellations [10] imply $z_{u_3} = -z_{u_1} - z_{u_2}$ and $z_{d_3} = -z_{d_1} - z_{d_2}$, as well as

$$\begin{aligned} 2(z_{u_1}^2 + z_{u_2}^2 + z_{u_1} z_{u_2}) &= z_{d_1}^2 + z_{d_2}^2 + z_{d_1} z_{d_2}, \\ -z_{u_1} z_{u_2} (z_{u_1} + z_{u_2}) &= z_{d_1} z_{d_2} (z_{d_1} + z_{d_2}). \end{aligned} \qquad (2)$$

A necessary condition for these equations to have integer solutions is that there exist an integer k such that

$$z_{u_1}^3 - 6z_{u_1}^2 z_{d_1} + 4z_{d_1}^3 = k^2(z_{u_1} + 2z_{d_1}). \quad (3)$$

We have checked numerically that this condition is not satisfied for $|z_{u_1}|, |z_{d_1}| \leq 1000$. Given that larger charges with no common factor are hard to imagine, we conclude that anomaly-free solutions with generation-independent z_{Q_j} require fermions beyond the SM.

A fourth generation of chiral fermions is ruled out by direct searches for new quarks at the LHC [11]. Anomaly-free sets of color-singlet chiral fermions [12] are severely constrained by $h^0 \to \gamma\gamma$ and electroweak measurements.

We are then led to consider fermions that are vectorlike with respect to the SM gauge group and chiral under $U(1)_z$. Among the new fermions required to cancel the various anomalies, there are electrically charged ones. If these are long lived, then LHC searches for slowly ionizing charged tracks set a mass limit $m_f > 450$ GeV (we have compared the experimental limit [13] with the pair-production cross section for a charge-one lepton computed with MADGRAPH [14]). Decays of charged vectorlike fermions into neutral ones may relax the limits. The one-loop mass splitting between the components N^0 and $E^\pm$ of a weak-doublet vectorlike lepton is ~0.3 GeV [15]. For a stable N^0, the process $e^+e^- \to E^+E^-$ leads to a final state with two soft pions and missing energy. The mass limit, using initial state radiation at LEP, is ~90 GeV [16]; for the future LHC reach, see Ref. [17].

Lower limits on vectorlike fermion masses translate into an upper limit on g_z. Note that $M_{Z'} = g_z z_\varphi \langle\varphi\rangle/\sqrt{2}$, where φ is the scalar whose vacuum expectation value (VEV) breaks $U(1)_z$. A new fermion f that is chiral with respect to $U(1)_z$ acquires a mass $m_f = \lambda\langle\varphi\rangle$ via a Yukawa term $\lambda\varphi\bar{f}_L f_R$. Given that the Yukawa coupling blows up in the UV, there is a perturbativity limit on λ; solving the one-loop renormalization group equation for λ with a β function $5\lambda^3/(16\pi^2)$ and imposing that λ is finite at scales below $3m_f$ gives $\lambda \lesssim 3.8$ at the scale m_f. A lower limit on m_f then implies a bound on g_z:

$$g_z = \frac{\sqrt{2}\lambda M_{Z'}}{z_\varphi m_f} \lesssim \frac{5.4 \times 10^{-2}}{z_\varphi}\left(\frac{M_{Z'}}{1\ \text{GeV}}\right)\left(\frac{100\ \text{GeV}}{m_f}\right). \quad (4)$$

For $U(1)_z$ charges given by the baryon number (we refer to this assignment as the Z'_B model), the $[SU(3)_c]^2 U(1)_z$ anomaly cancels, so that all vectorlike fermions may be color singlets [10,18] (solutions with color triplets also exist [2]). To avoid a large Z-Z' mixing, the $U(1)_Y$ and $U(1)_z$ charges must satisfy $\text{Tr}(zY) = 0$. The minimal set of vectorlike fermions consists of a weak doublet ($Y = -1/2$, $z_L = -1$, $z_R = +2$), a weak singlet ($Y = -1$, $z_L = +2$, $z_R = -1$), and a SM singlet ($z_L = +2$, $z_R = -1$ or $z_L = +1$, $z_R = -2$); their masses require $z_\varphi = 3$. If the charged fermions are slightly heavier than the neutral ones, then the collider signal is again soft pions and missing energy, so that $m_f > 90$ GeV, leading to the g_z limit given by the middle straight line in Fig. 1. Without tuning, though, the mass splittings are large, the collider limits on m_f are higher, and the upper limit on g_z decreases (see, e.g., the $m_f = 450$ GeV line in Fig. 1).

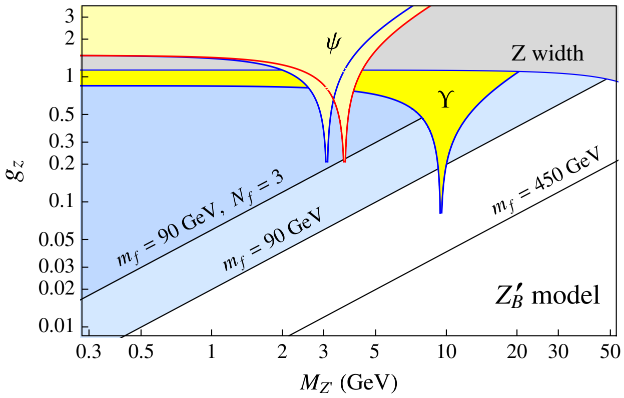

FIG. 1 (color online). Limits in the gauge coupling versus mass plane for Z'_B. Values of g_z above the straight lines are excluded by the anomaly cancellation conditions in conjunction with collider searches for new fermions; for $N_f = 1$ or 3, $m_f > 90$ GeV, and for $N_f = 1$, $m_f > 450$ GeV. The top regions are excluded by quarkonium and hadronic Z decays.

A loophole is that several φ scalars may break $U(1)_z$. If n scalars have equal VEVs and equal charges, the g_z limit is relaxed by a factor of $\sqrt{n}$. Plausible theories, though, do not have n larger than a few. Another loophole is that there can be N_f copies of the minimal vectorlike fermion set with $U(1)_z$ charges smaller by a factor of N_f, implying $z_\varphi = 3/N_f$ and a g_z limit increased by N_f (see the $N_f = 3$, $m_f = 90$ GeV line in Fig. 1).

Promptly decaying vectorlike fermions.—Let us explore whether the mass limits can be relaxed when the vectorlike fermions decay into SM particles. A vectorlike fermion may decay through mixing with a SM one if they couple to φ. The new mass-eigenstate fermion has four decay channels, into a SM fermion and one of the heavy bosons W, Z, h^0, or Z'. The branching fraction involving Z' is typically small, of order $(g_z z_f/g)^2/4 \ll 1$, where z_f is the $U(1)_z$ charge of the mixed component of the new fermion, and $g \approx 0.65$ is the weak gauge coupling. The LHC limits on vectorlike quarks that decay into a SM quark and a W, Z, or h^0 boson are stringent, above 700 GeV [11]. Vectorlike leptons are less constrained. The LHC limits on processes involving weak bosons and missing transverse energy or charged leptons have been recast as mass limits on vectorlike leptons [19]. Weak-doublet leptons must be heavier than about 280 GeV if they decay to τZ and τW (the limit is 460 GeV if the τ is replaced by an e or μ).

If the SM quark doublets are $U(1)_z$ neutral, the vectorlike fermions can be weak singlets, so that production at the LHC cannot proceed through a W, and the g_z limit is relaxed. Weak-singlet charged leptons decaying into eZ or μZ must be heavier than ~100 GeV, while no LHC limit can be derived for the τZ decay [19]. The LEP mass limit on leptons decaying into νW is 101 GeV [20].

Vectorlike fermions lighter than W would decay predominantly into a SM fermion and a Z', which in turn decays into two jets. Pair production of a vectorlike quark decaying into a light quark and a Z' leads to a six-jet final state. Masses between 77 and $\sim$100 GeV are ruled out by a CDF search [21], provided that $M_Z{}'$ is not so small that the jets overlap. Masses below $M_Z/2$ are excluded by measurements of hadronic Z decays. In the 46–77 GeV mass range, there is no limit for a quark decaying into three jets; although this gap should be explored by future searches, we do not discuss it further.

New physics could lead to decays of vectorlike fermions that are harder to detect. If the new fermions do not mix with SM ones, and there are four-fermion operators (induced, e.g., by a very heavy boson), then the vectorlike fermions can decay predominantly into three SM fermions. These can all be light quarks if the vectorlike fermion is a color triplet. The $6j$ CDF search has set a mass limit on gluinos of 140 GeV, but the cross section for quark pair production is smaller by a factor of about 3, so that the lower mass limit on vectorlike quarks is only 100 GeV. Similarly, there are no limits on vectorlike quarks from existing $6j$ CMS searches [22].

Vectorlike leptons might partially evade various collider searches if they decay into τjj. A LEP search for a pair of τj resonances sets a mass limit of 98 GeV on leptoquarks [23]; the extra jet from the vectorlike lepton decay would relax this limit, but it seems unlikely that it would be pushed below $\sim$90 GeV.

Quarkonium decays.—Searches for nonstandard Υ decays constrain the Z' couplings to b quarks. The ratio of branching fractions $\Delta R_\Upsilon \equiv B(\Upsilon \to Z'^*, \gamma^* \to jj)/B(\Upsilon \to \mu^+\mu^-)$ can be used [6,7] to set limits on g_z. The limit on the nonelectromagnetic dijet decay of $\Upsilon(1S)$ [24], $\Delta R_\Upsilon < 2.1$, gives the excluded region shown in Fig. 1 (labeled Υ) for the Z'_B model.

The axial Z' coupling to b quarks is constrained for masses below 7 GeV by the process $\Upsilon \to \gamma Z'$. The search [25] for $\Upsilon(2S) \to \gamma A^0$, where A^0 is a pseudoscalar decaying into hadrons, set a branching fraction limit of 10^{-6} at $M_{A^0} = 1$ GeV. A similar limit applies to $\Upsilon \to \gamma Z'$, with the difference arising from the acceptance, which depends on the spin. This does not affect Z''s that have only a vector coupling [26], such as Z'_B.

Charmonium decays into hadrons set limits on the Z' couplings to c quarks. We focus on exclusive J/ψ and $\psi(2S)$ decays into K^+K^-. The photon contribution appears to saturate the measured branching fractions, although there are uncertainties from interference with QCD effects [27]. The ratio $r_\psi \equiv B(\psi \to Z'^*, \gamma^* \to K^+K^-)/B(\psi \to \gamma^* \to K^+K^-)$ is then bounded on both sides: $1/2 \sim r_\psi^{\rm min} < r_\psi < r_\psi^{\rm max} \sim 2$. Computing the Z' and γ contributions in the Z'_B model, we obtain

$$g_z^2 \lesssim \frac{24e^2}{\varepsilon_s}\left(1-\sqrt{r_\psi^m}\right)\left(1-\frac{M_{Z'}^2}{M_\psi^2}\right), \tag{5}$$

where $r_\psi^m = r_\psi^{\rm min}$ for $M_{Z'} < M_\psi$, and $r_\psi^m = r_\psi^{\rm max}$ for $M_{Z'} > M_\psi$; $\varepsilon_s \sim m_s/\Lambda_{\rm QCD}$ parametrizes the flavor $SU(3)$ violation, and e is the electromagnetic gauge coupling. The excluded regions are shown in Fig. 1 (labeled ψ) for $\varepsilon_s = 1/3$, with excisions at $|M_{Z'}/M_\psi - 1| < 10^{-2}$ where the mixing between ψ and Z' is large. The constraints from inclusive decays are estimated in Ref. [7]. In models with $z_u \neq z_d$, there are stronger constraints from $\psi \to Z'^* \to \pi^+\pi^-$.

Similarly, the Z' couplings to s quarks contribute to ϕ meson decays into $\pi^+\pi^-$, where photon exchange dominates [28]. In the Z'_B model, the effect violates isospin, so it is suppressed by $(m_d - m_u)/\Lambda_{\rm QCD}$, and the limits are not competitive (while they are stringent for $z_u \neq z_d$).

Electroweak observables.—As long as ${\rm Tr}(zY) = 0$, the one-loop kinetic mixings of Z' with Z (c_Z) and γ lead only to mild constraints. The largest effect identified in Refs. [6,7] is a change in the hadronic Z width. The Z'_B model with g_z normalized as in Eq. (1) gives $c_Z \approx 0.01 g_z$ [29] and

$$\frac{\Delta\Gamma_Z^{\rm had}}{\Gamma_Z^{\rm had}} = \frac{2g_z c_Z c_W s_W(2V_u + 3V_d)}{3g(1 - M_{Z'}^2/M_Z^2)(2V_u^2 + 3V_d^2 + 5/16)}, \tag{6}$$

where $V_{u,d} = \pm 1/4 - (3 \pm 1)s_W^2/6$, and $s_W \equiv \sin\theta_W$. This rules out the region labeled "Z width" in Fig. 1.

Down-strange Z' at the GeV scale.—The bounds from Υ and J/ψ decays are avoided if the Z' couplings to b and c quarks vanish. This is consistent with quark mass generation, without inducing tree-level FCNCs, when only right-handed quarks carry $U(1)_z$ charges. If d_R and s_R have opposite charges ($z_{d_1} = -z_{d_2}$) and all other SM fields are $U(1)_z$ neutral (we refer to this assignment as the Z'_{ds} model), then the only anomaly that remains to be canceled is $U(1)_Y[U(1)_z]^2$. A set of vectorlike fermions that achieve that is included in Table I.

Tree-level FCNCs are absent, provided the gauge and mass eigenstates coincide for right-handed down-type quarks. Let us outline a mechanism for quark mass generation that satisfies this condition. The b quark acquires mass from a SM Yukawa term $y_b H \bar{b}_R Q_L^3$, where H is the Higgs doublet. We have chosen a basis where the Yukawa couplings of Q_L^1 and Q_L^2 to b_R vanish. The s and d quark masses are generated by dimension-five operators:

TABLE I. Fields carrying $U(1)_z$ charge in the Z'_{ds} model.

Field	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_z$
d_R, s_R	3	1	$-1/3$	$+1$, -1
f_L, $f_L{}'$	1	1	$+1$	0
f_R, $f_R{}'$	1	1	$+1$	$+1$, -1
φ	1	1	0	$+1$

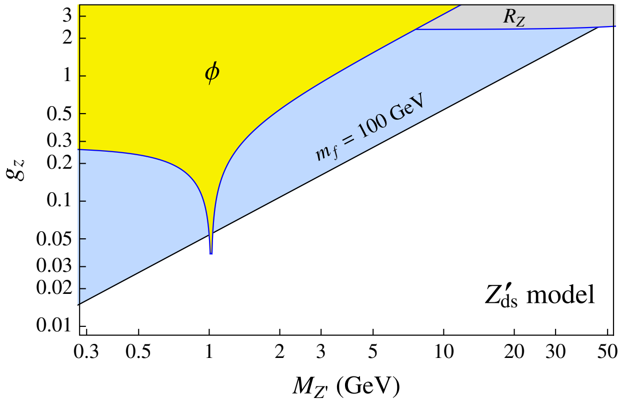

FIG. 2 (color online). Limits in the g_z versus $M_{Z'}$ plane for Z'_{ds}. The shaded regions are excluded (see the caption of Fig. 1).

$$\frac{c_j^s}{m_1^\omega}\varphi^\dagger H\bar{s}_R Q_L^j + \frac{c_j^d}{m_2^\omega}\varphi H\bar{d}_R Q_L^j + \text{H.c.}, \qquad (7)$$

where m_1^ω and m_2^ω are mass parameters, and c_j^s and c_j^d are dimensionless coefficients. Without loss of generality, we take $c_1^s = 0$, so that m_1^ω is related to the strange quark mass by $m_1^\omega = c_2^s v M_{Z'}/(g_z m_s)$. For $c_2^s \lesssim O(1)$, we find $m_1^\omega \lesssim 2.5\ \text{TeV}/g_z$ for $M_{Z'} \approx 1$ GeV, which shows that the mass scale where the strange quark mass is generated may be explored at the LHC.

A renormalizable origin of the operators (7) is provided by two vectorlike quarks ω^i, $i = 1, 2$, which transform as b_R and have Yukawa couplings to the d and s quarks:

$$y_{ij}^\omega H\bar{\omega}_R^i Q_L^j + \lambda_i^s \varphi^\dagger \bar{s}_R \omega_L^i + \lambda_i^d \varphi \bar{d}_R \omega_L^i + \text{H.c.} \qquad (8)$$

A $U(2)_L$ transformation of Q_L^1 and Q_L^2 can set $y_{21}^\omega = 0$. Similarly, the $\bar{b}_R \omega_L^i$ terms can be rotated away, and the vectorlike quark masses can be diagonalized $m_i^\omega \bar{\omega}^i \omega^i$. Comparing the operators (7) with the above Yukawa terms, we find $c_i^s \simeq y_{1i}^\omega$ and $c_i^d \simeq y_{2i}^\omega \lambda_2^d$ for $m_1^\omega \ll m_2^\omega$.

Mass terms involving f_L or $f_L{}'$ (see Table I) and right-handed SM leptons can be kept small by an approximate discrete symmetry. These terms induce mixing of the vectorlike fermions with the SM leptons, so f and f' decay predominantly into $W\nu$. The LEP bound on f and f' masses is then around 100 GeV, and Eq. (4) gives the g_z limit shown in Fig. 2. Assuming equal form factors for vector and axial couplings, the g_z limit from ϕ meson decay is given by Eq. (5) with $\varepsilon_s \to 9$ and $\psi \to \phi$ (Fig. 2). If f and f' have equal mass, then the Z-Z' mixing is suppressed. The change in hadronic Z decays, due to Z' emission and one-loop corrections, excludes the region labeled R_Z in Fig. 2 (based on Ref. [6] with updated $\Delta\alpha_s$).

The Z'_{ds} couplings are chiral, so that g_z is constrained by measurements of nuclear parity violation [30] and electron-quark scattering [31]. Comparing $g_z^2/M_{Z'}^2$ with G_{Fermi}, we find exclusion lines approximately parallel to (and, due to large theoretical uncertainties, slightly above) the m_f bound of Fig. 2.

Additional constraints for $M_{Z'} \lesssim 0.5$ GeV arise from meson decays such as $\eta \to \gamma Z' \to \gamma\pi^+\pi^-$ or $\eta' \to Z'Z' \to \pi^+\pi^-\pi^+\pi^-$. Currently, the limits are weaker than the ones shown in Fig. 2, but future searches in these channels for $\pi^+\pi^-$ resonances may probe lower values of g_z.

Conclusions.—Besides the usual limits on light leptophobic Z' bosons, from Υ decays and electroweak observables, we have found a strong constraint from the requirement that new fermions cancel the gauge anomalies. Collider limits on the new fermion masses imply an upper limit on the gauge coupling.

Nevertheless, the gauge coupling of a baryonic Z' may be relatively large, of order 0.1 for $M_{Z'} \gtrsim 2$ GeV (Fig. 1). Furthermore, we have presented a renormalizable model where the only SM fields charged under the new group are d_R and s_R, allowing even larger couplings (Fig. 2).

Future experiments may search for GeV-scale leptophobic Z''s in various ways, including nonstandard meson decays and LHC signatures of boosted dijet resonances, as well as test them through searches for vectorlike fermions. If the Z' also couples to light dark matter particles, then interesting phenomena may be uncovered in neutrino detectors [32] and other experiments.

We thank P. Agrawal, A. de Gouvea, R. Kitano, A. Kronfeld, S. Mantry, M. Pospelov, and F. Yu for constructive comments.

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