Constraints on universal extra dimensions from W' searches

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We obtain constraints on three universal extra-dimensional models utilizing limits from the CMS Collaboration on W' production and decay into a single-top-quark final state. We find a weak constraint on the minimal universal extra-dimensional model due to small Kaluza-Klein number violating terms. In contrast, the W' search puts a strong limit on the size of the Dirac mass term of the quarks in split universal extra-dimension models. In nonminimal universal extra-dimension models, the W' search constrains the splitting between the boundary-localized kinetic terms of the gauge bosons and the quarks. Each of these bounds can be translated into constraints on the mass splitting between the Kaluza-Klein excitations of the $SU(2)$ charged quarks and the Klauza-Klein excitations of the W boson.

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I. INTRODUCTION

In models of universal extra dimensions (UED) [1], all standard model particles are promoted to higher dimensional fields propagating in flat extra dimensions. In this article we focus on five-dimensional UED models in which the extra dimension is chosen to be the orbifold S^1/Z_2 so as to obtain chiral zero mode fermions. The residual Z_2 parity, called KK-parity, implies that odd-parity Kaluza-Klein (KK) particles can only be pair produced. In addition, it guarantees the stability of the lightest KK-odd particle, which represents a viable dark matter candidate.

Electroweak precision measurements [2], in combination with the LHC Higgs bounds [3] applied to UED [4] and flavor physics [5], impose a bound of $R^{-1} \gtrsim 700$ GeV on the compactification scale. Adding a requirement that the dark matter relic density observed by WMAP [6] is consistent with UED points to a compactification scale of 1.3 TeV $\lesssim R^{-1} \lesssim$ 1.5 TeV for the most commonly considered dark matter candidate [7]—the first KK excitation of the $U(1)_Y$ gauge boson $B^{(1)}$ [8–10]. The collider phenomenology of the five-dimensional UED model has been discussed in Refs. [11,12].

In spite of its minimal field content, UED on S^1/Z_2 contains a large number of undetermined parameters beyond the compactification radius R. UED is nonrenormalizable and, therefore, must be considered as an effective field theory. Naive dimensional analysis [13], unitarity of KK-mode gauge boson scattering [14], and stability of the Higgs potential vacuum [15] imply that the UED cutoff is of $\mathcal{O}(10)$ times the compactification scale. Unless the UED UV completion is specified, this cutoff, as well as parameters of higher-dimensional operators, must be considered as free parameters of the model which have to be constrained by experiment.

The lowest-dimensional operators allowed by all symmetries of the model are additional kinetic terms which are localized at the orbifold fixed points, so-called boundary-localized kinetic terms (BLKTs).[1] In the minimal UED model (MUED) [8], BLKTs are chosen to be zero at the cutoff scale Λ. At lower scales, they are induced via one-loop corrections. Nonzero BLKTs affect the UED KK mass spectrum [16] as well as couplings amongst different KK-mode particles and, therefore, have a large impact on UED phenomenology. BLKTs can change the lightest Kaluza-Klein particle (LKP) from the commonly considered $U(1)$ gauge boson $B^{(1)}$ to the neutral $SU(2)_L$ gauge boson KK-mode $W^{3(1)}$ [17]. Also, the mass splittings between the LKP and other states at the first KK level are altered, which has a strong impact on the relic density [10]. Finally, in the presence of BLKTs, resonant LKP annihilation through second KK-mode excitations is suppressed,[2] while for MUED these processes play an important role [7].

Another possible source of modifications to the KK-mode mass spectrum are fermion bulk mass terms which are introduced in the so-called split-UED model (sUED) [18]. Contrary to BLKTs, such terms are not radiatively induced, as a plain fermion bulk mass term violates KK parity. However, they can be introduced as KK-odd mass terms via a background field.

In both scenarios, nonminimal UED models with boundary-localized kinetic terms (nUED) as well as split-UED, the UED collider phenomenology is altered. Cascade decays, commonly considered for UED collider

[1]Conservation of KK parity requires all boundary-localized operators to be included symmetrically on both fixed points.
[2]The masses of particles at the nth KK mode are not given by $\sim n/R$, as they are in MUED.

signatures, are altered due to the modified mass spectrum. An even more striking signature arises from newly induced couplings between fermion zero modes and even KK-mode gauge bosons. These couplings lead to W', Z', and γ' signatures in the electroweak sector or colored resonance signatures in the QCD sector. In MUED these signatures occur [19], but the corresponding couplings are one-loop suppressed. In split-UED [20] and nUED the couplings are already present at tree-level, and can be large.

In this article, we determine the bounds on the parameter space of minimal universal extra dimensions, nonminimal UED models with boundary-localized kinetic terms, and split-UED from the bounds on W' searches in the single-top-quark decay channel. In Sec. II, we review the MUED, split-UED, and nUED model and summarize the respective couplings and KK mass spectra. In Sec. III, we use constraints on W' masses and couplings obtained by the CMS Collaboration [21] to derive constraints on the MUED, split-UED, and nUED parameter space.

II. PHENOMENOLOGICAL SETUP

At tree level in universal extra dimensions, the standard model fermions, gauge bosons, and Higgs fields are promoted to five-dimensional fields on S^1/Z_2. The Z_2 orbifold condition allows the standard model particles to be identified with the zero modes of these five-dimensional fields. Kaluza-Klein parity is the residual symmetry generated by the breaking of five-dimensional Lorentz invariance due to the boundary conditions. As a five-dimensional theory, UED is nonrenormalizable, and additional sets of operators in the bulk and localized at the boundary can significantly modify the tree-level UED model. In particular, the coupling of second KK-mode gauge bosons like the $W^{(2)}$ to zero mode quarks is no longer vanishing as it would be if only the UED bulk terms were considered.

A. Minimal universal extra dimensions

Minimal universal extra dimensions represent the simplest UED setup in which one-loop corrections are taken into account. The model has two additional parameters as compared to the standard model: the compactification scale R^{-1} and the cutoff scale of the theory Λ. At the scale Λ, all higher-dimensional operators are assumed to be vanishing; however, renormalization group (RG) evolution generates such higher-dimensional local operators at scales below Λ. The $W^{(2)}$ mass in MUED follows from [8]

$$m^2_{W^{(2)}} = m_2^2 + \delta m^2_{W^{(2)}} + \bar{\delta} m^2_{W^{(2)}}, \tag{1}$$

where the bulk-induced correction is

$$\delta m^2_{W^{(2)}} = -m_2^2 \frac{5}{8} \frac{g^2 \zeta(3)}{16\pi^4}, \tag{2}$$

the boundary induced correction is

$$\bar{\delta} m^2_{W^{(2)}} = m_2^2 \frac{15}{2} \frac{g^2}{16\pi^2} \ln\left(\frac{\Lambda^2}{\mu^2}\right), \tag{3}$$

$m_2 = 2/R$, ζ is the zeta-function, Λ is the cutoff scale, and μ is the renormalization scale. One-loop corrections also lead to couplings between zero-mode fermions and the $W^{(2)}$ gauge boson of the form [8]

$$g_{002} = \frac{g_{000}}{\sqrt{2}} \left[\frac{\bar{\delta} m^2_{W^{(2)}}}{m_2^2} - 2 \frac{\bar{\delta} m_{f_2}}{m_2} \right], \tag{4}$$

where g_{000} is the zero-mode coupling which is identified with the standard model coupling and

$$\bar{\delta} m_{f_2} = m_2 \left(3 \frac{g_3^2}{16\pi^2} + \frac{27}{16} \frac{g^2}{16\pi^2} + \frac{1}{16} \frac{g'^2}{16\pi^2} \right) \ln\left(\frac{\Lambda^2}{\mu^2}\right). \tag{5}$$

The coupling in Eq. (4) arises from RG evolution—induced mixing between different KK modes of the same KK parity. An alternative way of understanding these couplings is that the RG evolution induces boundary-localized operators that modify the equations of motion and boundary conditions for the KK modes of the fermions and gauge bosons. As the induced BLKTs for gauge bosons and fermions differ, the wave functions of the zero-mode fermions and the $W^{(2)}$ gauge boson are not orthogonal. Hence, a coupling between $W^{(2)}$ and left-handed zero-mode fermions is induced.[3] Since these effects are only induced at the one-loop level, the couplings between $W^{(2)}$ and left-handed zero mode fermions are suppressed.

B. Split universal extra dimensions

Split universal extra dimensions (split-UED) are a UED extension, initially proposed to explain cosmic-ray observations [18]. In split-UED, a KK parity-odd background field provides an effective five-dimensional Dirac mass term for the 5D fermions of the form

$$\mathcal{L}^{5D}_{s\mathrm{UED}} \supset \mu\theta(y)\bar{\Psi}\Psi, \tag{6}$$

where μ is the induced mass parameter, and $\theta(y)$ denotes the Heaviside step function.

As the gauge bosons are unaffected by this operator, the mass of $W^{(n)}$ is

$$m^2_{W^{(n)}} = m_n^2 + m_W^2, \tag{7}$$

where $m_n = n/R$ and m_W is the standard model W boson mass. The presence of the bulk-mass term modifies the

[3] The presence of these couplings, as well as couplings to all higher even-numbered KK modes, is a consequence of the breaking of five-dimensional translational invariance due to the boundary-localized terms. Couplings between zero-mode fermions and the odd-numbered W-boson KK modes are not induced, because they are forbidden by KK parity.

profiles of the KK fermions in the extra dimension and, in particular, the fermion zero mode. Therefore, overlap integrals between zero-mode fermions and even KK modes of the gauge bosons are nonzero, which for the $W^{(2)}$ leads to a coupling [20]

$$g_{002} = -\sqrt{2} g_{000} \frac{\mu^2 R^2}{\mu^2 R^2 + 1} \coth\left(\frac{\mu \pi R}{2}\right). \tag{8}$$

The KK mass spectrum of the fermions is altered as well. For the first KK mode, the mass is given by [20]

$$m_{\Psi^{(1)}} = \sqrt{\mu_\Psi^2 + R^{-2}}. \tag{9}$$

C. Nonminimal universal extra dimensions

In nonminimal extensions of universal extra dimensions, tree-level boundary-localized operators are included into the model. Parametrizing the fundamental domain of the S^1/Z_2 as $-\frac{\pi R}{2} \leq y \leq \frac{\pi R}{2}$, the electroweak part of the boundary action of nUED is given by

$$\begin{aligned} S_{\rm BLT} = \int d^5x \left[\delta\left(y + \frac{\pi R}{2}\right) + \delta\left(y - \frac{\pi R}{2}\right)\right] \\ \times \left(-\frac{r_B}{4} B_{\mu\nu} B^{\mu\nu} - \frac{r_W}{4} W^a_{\mu\nu} W^{a\mu\nu} \right. \\ + r_H (D^\mu H)^\dagger D_\mu H + \mu_b^2 H^\dagger H \\ \left. - \lambda_b (H^\dagger H)^2 + r_{\Psi_h} \bar{\Psi} i \gamma^\mu D_\mu \Psi_h \right), \end{aligned} \tag{10}$$

where the Ψ_h denotes Q_L, U_R, D_R, L_L, and E_R. The fermion BLKTs r_{Ψ_h} are three 3×3 Hermitian matrices in flavor space of mass dimension -1. Flavor physics dictates them to be proportional to the unit matrix.[4] In principle, boundary Yukawa couplings could also be present, but as they suffer from the same flavor problem and do not affect our later analysis, we set them zero in the above. Our analysis of W KK modes is only affected by the BLKT of the $SU(2)$ charged quarks, i.e., the parameter r_Q. The Higgs BLKT does not have a sizable effect on the W KK mode masses and only marginally influences the couplings of KK fermions to KK gauge modes. The $U(1)$ BLKT does not affect the W KK mode masses and couplings [17]. For concreteness, in what follows we set $r_H = r_B = r_W$, $\mu_b = 0 = \lambda_b$ and restrict ourselves to positive BLKTs.[5]

Under these assumptions the $W^{(n)}$ mass is

$$m^2_{W^{(n)}} = k_n^2 + m_W^2, \tag{11}$$

where k_n is determined by the quantization condition [17],

$$r_W k_n = -\tan\left(\frac{k_n \pi R}{2}\right), \quad \text{for even } n \text{ and} \tag{12}$$

$$r_W k_n = \cot\left(\frac{k_n \pi R}{2}\right), \quad \text{for odd } n. \tag{13}$$

Using the modified boundary conditions, we also find the coupling of the $W^{(2)}$ KK mode to zero-mode quarks to be [23]

$$g_{002} = g_{000} \frac{\sqrt{8}(r_W - r_Q)}{\pi R + 2 r_Q} \sqrt{\frac{1 + \frac{2 r_W}{\pi R}}{\sec^2(\frac{k_2 \pi R}{2}) + \frac{2 r_W}{\pi R}}}. \tag{14}$$

As can be seen, this KK-number violating coupling vanishes for $r_W = r_Q$.[6]

III. THE CMS W' CONSTRAINT

In this section we utilize a constraint on W' boson production and decay to an s-channel single-top-quark final state [21] to place limits on the three distinct UED models discussed above. Combining the cross-section limit of Ref. [21] with the predicted signal for a W' boson with standard model—like couplings, we construct the bound shown in Fig. 1. We find a model-independent constraint [24] on the magnitude of $M_{W^{(2)}}$ and its coupling g' to zero-mode quarks.[7]

A. Bounds on MUED from W' searches

Using Eq. (4) we see that the couplings of $W^{(2)}$ to gauge bosons is dependent on $M_{W^{(2)}}$ and Λ. Using $\mu = 2/R$ (mass of $m_{W^{(2)}}$) as a renormalization scale and $g_3^2 = 4\pi\alpha_s$ with $\alpha_s = 0.12$, the relative coupling $\frac{g_{002}}{g_{000}}$ as a function of the dimensionless cutoff ΛR is given by

$$\frac{g_{002}}{g_{000}} = -.065 \times \ln(\Lambda R/4). \tag{15}$$

With Eq. (15), we can translate the bounds from W' searches displayed in Fig. 1 into constraints on the ΛR vs $1/R$ MUED parameter space. However, due to the logarithmic dependence on the compactification scale, only a very weak bound of $\Lambda R \gtrsim 100$ is obtained for the MUED model.[8] This bound on ΛR is weaker by an order of magnitude than bounds from existing searches [13–15].

[4] In Ref. [22] it has been shown that fermion mass matrices in split-UED induce FCNCs unless the mass matrices are flavor blind, i.e., proportional to the unit matrix in flavor space. The same arguments hold for fermion BLKTs.

[5] For negative gauge or fermion BLKTs, the KK spectrum contains unphysical modes (ghosts and/or tachyons).

[6] In this case, the KK decomposition of the fermion and the gauge fields yields identical wave function bases $\{f_n^W(y)\} = \{f_n^Q(y)\}$, and the orthogonality relations of the wave functions guarantee the absence of KK-number violating operators also for couplings including both Q and W KK modes.

[7] In using the model-independent constraint, we implicitly work in the narrow-width approximation. This is justified because in sUED and the considered nUED parameter space, the coupling g_{002} is bounded by $g_{002} > \sqrt{2} g_{000}$, where g_{000} is identified with the standard model $SU(2)$ coupling.

[8] Taking the running of the strong coupling into account and evaluating the bound with $\alpha_s(\mu)$ leads to an even weaker constraint.

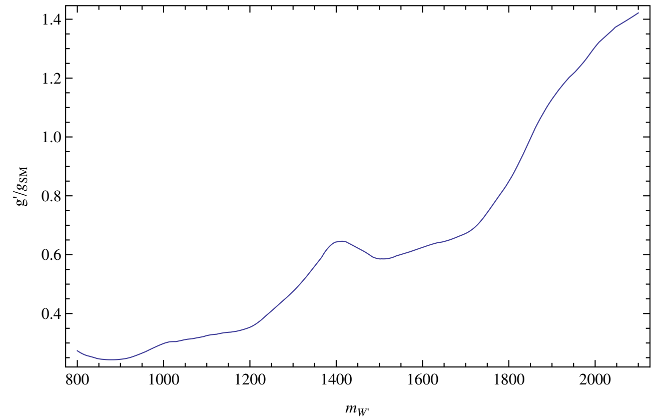

FIG. 1 (color online). Model-independent bound on the relative W' coupling g'/g_{SM} vs $m_{W'}$ at 95% C.L. from the 5.0 fb^{-1} CMS data [21].

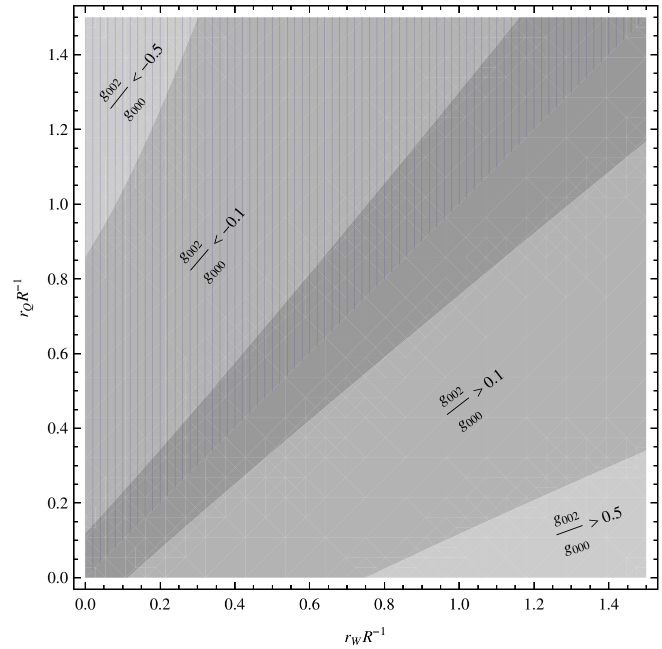

FIG. 2 (color online). Variation of the relative gauge coupling g_{002}/g_{000} to quarks in the $r_W R^{-1} - r_Q R^{-1}$ plane.

B. Bounds on nUED from W' searches

As can be seen from Eq. (14) and the determination of k_2 in Eq. (12), the ratio g_{002}/g_{000} can be expressed in terms of the dimensionless quantities r_W/R and r_Q/R. In Fig. 2 we show the value of the relative coupling g_{002}/g_{000} in the $r_W R^{-1} - r_Q R^{-1}$ plane. As stated in Sec. II C, when $r_W = r_Q$, KK-number violating terms vanish. $r_W > r_Q$ leads to positive g_{002}, which can even become larger than the standard model coupling. For $r_W < r_Q$, g_{002} is negative. When considering a common electroweak boundary parameter $r_H = r_B = r_W$, this parameter region is disfavored because the first fermion KK modes (here: the $Q^{(1)}$) are lighter than the usually considered dark matter candidate $B^{(1)}$. We shade this disfavored parameter region in Fig. 2. If the electroweak boundary parameters are not chosen equal, or if additional dark matter fields are included in an extension of nUED, this region of parameter space can be opened up.

Using Fig. 2, the W' limit in Fig. 1 can be translated into a constraint on the mass of the second KK-excitation of the W gauge boson $m_{W^{(2)}} \equiv m_{W'}$. In the upper panel of Fig. 3, we plot the limit on $m_{W'}$ in the $r_W R^{-1} - r_Q R^{-1}$ plane, where we have assumed a 100% branching ratio of W's to quarks.[9]

Similar to Fig. 2, the dark shaded region is disfavored because the LKP would be the KK mode of a standard model fermion. Constraints are weak in the suppressed coupling region $r_W \approx r_Q$, but become strong when the boundary parameters differ.

With the lower bound on $m_{W^{(2)}}$ in the upper panel of Fig. 3 and the nUED tree-level mass quantization conditions Eq. (12) and (13), a lower bound on the mass of each $W^{(n)}$ KK mode can be obtained. Of particular interest for LHC phenomenology is the first KK mode $W^{(1)}$. If a common electroweak boundary parameter is assumed, its mass coincides with the mass of the $B^{(1)}$ LKP, up to a relative correction of the order $1 - (m_W/m_{W^{(1)}})^2$, and is therefore relevant for dark matter bounds. In the lower panel of Fig. 3, we translate the constraint on $m_{W'} = m_{W^{(2)}}$ into a constraint on $m_{W^{(1)}}$.

The constraints on the parameter space presented in Fig. 3 imply bounds on the allowed mass splitting between the first KK mode of the $SU(2)$ gauge boson $W^{(1)}$ and the $SU(2)$ charged quarks $Q^{(1)}$. For example, for a mass $m_{W^{(1)}} = 600$ GeV and a gauge BLKT of $r_W R^{-1} = 1.0$, the minimally allowed value of $r_Q R^{-1}$ can be read off from the lower panel of Fig. 3 to be $r_Q R^{-1} \geq 0.13$. Using the tree-level mass relations Eqs. (11) and (13), the value of R^{-1} is given by $R^{-1} = 930$ GeV, which via Eq. (13) yields $m_{Q^{-1}} \leq 860$ GeV, so that the relative mass splitting for these values of $m_{W^{(1)}}$ and $r_W R^{-1}$ is given by $(m_{Q^{(1)}} - m_{W^{(1)}})/m_{W^{(1)}} \leq 45\%$.

An absolute bound on the mass splitting for a fixed $m_{W^{(1)}}$ mass, independent of the value of $r_W R^{-1}$, cannot be established in the nUED model, which can be seen as follows: In the limit $r_W R^{-1} \to \infty$, the relative mass splitting $(m_{W^{(2)}} - m_{W^{(1)}})/m_{W^{(1)}} \to \infty$ such that in this limit, $m_{W^{(1)}}$ can be kept constant while the $W^{(2)}$ mode decouples from the model. As the constraints discussed here arise from $W^{(2)}$-mode exchange, no bounds on $r_Q R^{-1}$ are obtained in this limit.

[9]Assuming a branching fraction to quarks similar to that of the standard model ~75% does not significantly modify the contours, and smaller branching fractions to quarks are strongly limited by precision electroweak constraints [23].

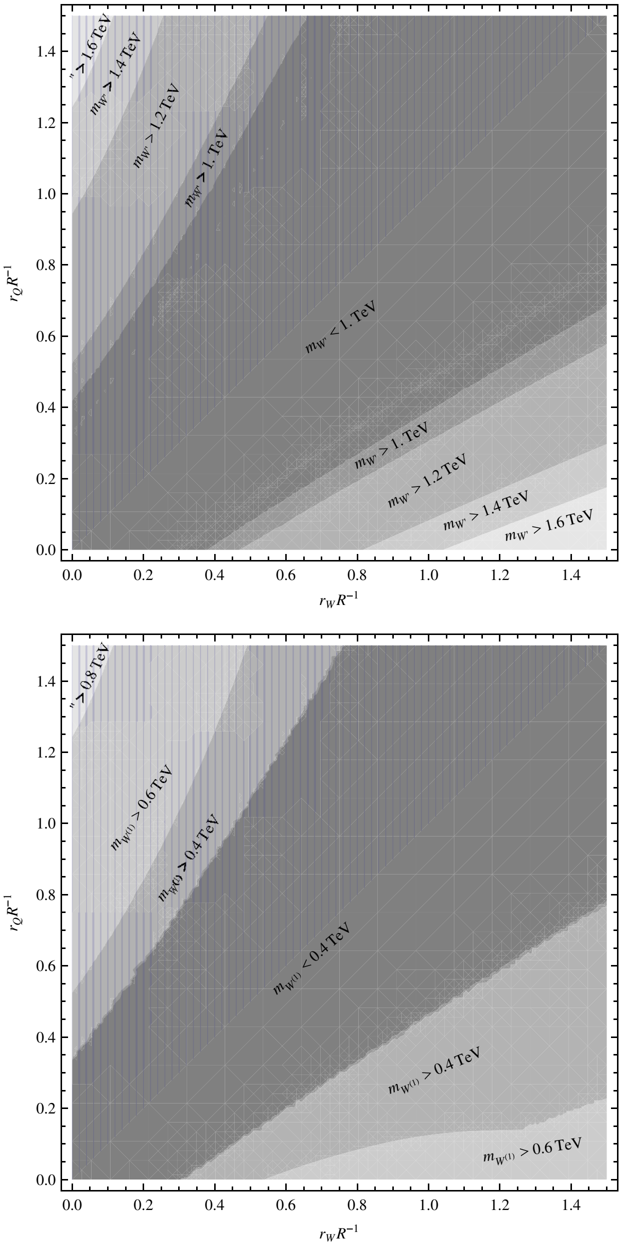

FIG. 3 (color online). Constraints $m_{W^{(2)}}$ (upper) and $m_{W^{(1)}}$ (lower) due to the CMS limit in Fig. 1.

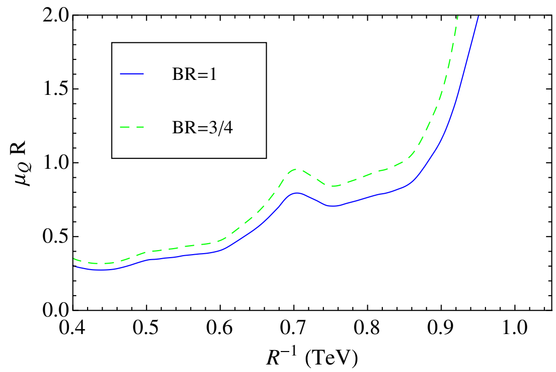

FIG. 4 (color online). $\mu_Q R$ vs R^{-1} split-UED parameter space, where the contour lines correspond to different branching ratios into quarks and leptons for the W' constraint shown in Fig. 1.

C. Bounds on split UED from W' searches

The limits on W' masses and couplings, due to the search in the single-top-quark channel, are especially important for the split-UED model because they put constraints on the quark bulk mass μ_Q. The original motivation for sUED is to raise the quark KK-mode masses while allowing for light KK leptons. Such a split spectrum was proposed in Ref. [18] in order to explain the positron excess observed by the PAMELA experiment while suppressing the antiproton rates. Hence, in such models we expect large values of μ_Q and small values of μ_L.

Using bounds from the W' search in the single-top-quark channel shown in Fig. 1 leads to constraints on the $\mu_Q R$ vs R^{-1} split-UED parameter space shown in Fig. 4. Depending on the magnitude of lepton bulk-mass term μ_L, the branching ratio of the W' can vary, which is illustrated by the different contour lines in Fig. 4. The blue (dark grey) contour is a scenario in which the W' decays only into quarks, and the green (light grey) dashed contour is a scenario in which the W' has branching ratios of 75% to quarks and 25% to leptons, similar to those of the standard model W gauge boson.

As described in Ref. [25], constraints on the four-Fermi contact operator interactions and searches in dileptons and dijets put constraints on the split-UED parameter space. The dijet limit depends on the mass of the KK gluon, which is not necessarily proportional to the mass of the Kaluza-Klein partners of the electroweak sector. Both the dilepton and the four-Fermi contact operator limits depend on the product of the couplings of the KK partners of the electroweak sector to quarks and leptons. Therefore, in the limit of small μ_Q or μ_L, the dilepton and four-Fermi contact operator limits are weak. The W' search limit shown in Fig. 1 allows us to disentangle these effects and puts orthogonal constraints on the μ_L vs μ_Q parameter space.

To illustrate the power of W' search limit shown in Fig. 1, we combine it with the *eedd* four-Fermi contact operator interaction limits of Ref. [25] in Fig. 5. The grey contours correspond to the limits on the $\mu_L R - \mu_Q R$ plane due to the *eedd* four-Fermi contact interaction limit, while the horizontal lines are the limits due to the W' prime search in the single-top-quark channel. The slight weakening of the W' search limit for large μ_L is due to the increasing branching ratio into leptons. The W' search limits for $R^{-1} = 0.7$ TeV and $R^{-1} = 0.8$ TeV are comparable because of the slightly weaker constraint at 1.4 TeV in Ref. [21].

Just as we show for nUED, the bounds of Fig. 1 can be translated into bounds on the relative mass splitting $(m_{Q^{(1)}} - m_{W^{(1)}})/m_{W^{(1)}}$. We consider $m_{W^{(1)}} = 800$ GeV as

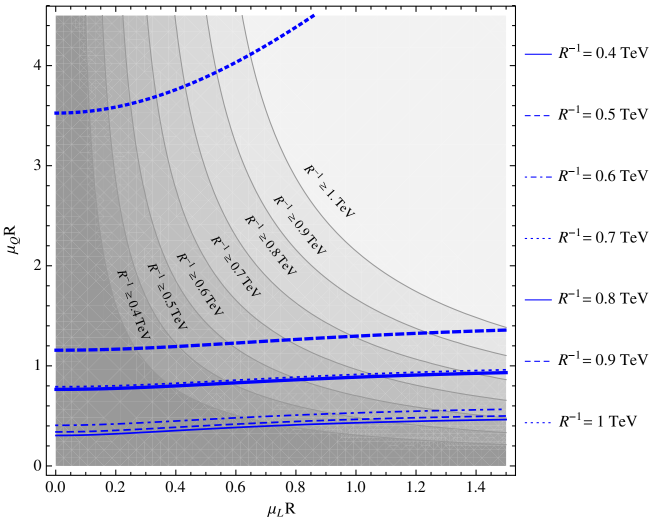

FIG. 5 (color online). Limits on sUED parameter space due to the combination of the four-Fermi contact interactions' constraint and the W' constraint displayed in Fig. 1.

an example. For $\mu_L R = 0$, Fig. 1 gives an upper bound of $\mu_Q R = 0.76$.[10] Using the tree-level masses, Eqs. (7) and (9), we obtain a value of $m_{Q^{(1)}} \leq 1.0$ TeV and, hence, a maximally allowed relative mass splitting of $(m_{Q^{(1)}} - m_{W^{(1)}})/m_{W^{(1)}} \leq 25\%$.

IV. CONCLUSIONS

In this paper we have shown that the W' limit from single-top-quark production leads to strong constraints on split-UED and the nonminimal UED models. For sUED, the W' limit puts a strong upper bound on μ_Q, the bulk mass parameter of the $SU(2)$ charged quarks. The upper bound on μ_Q implies an upper bound on the mass splitting between the $SU(2)$ charged KK quarks and the W KK excitations. This constraint is especially relevant, as the initial motivation for the sUED model required a large splitting between the KK quarks and the LKP (whose mass scale is close to the $W^{(1)}$ mass) in order to suppress the production of antiprotons from dark matter annihilation at late times.

In the nUED model, the coupling of the zero-mode quarks to the $W^{(2)}$ is induced by a splitting between the boundary-localized terms. Hence the W' limit leads to constraints on the difference of $r_W R^{-1}$ and $r_Q R^{-1}$, which—via Eq. (13)—again implies a bound on the mass splitting between $Q^{(1)}$ and $W^{(1)}$.

We emphasize that the $pp \to W' \to tb$ channel is particularly well suited to constrain the parameter space because it only depends on the bulk quark mass parameter μ_Q in sUED and the BLKT parameters of the $SU(2)$ charged quarks r_Q and the $SU(2)$ gauge bosons r_W in nUED. Mass terms or BLKTs for the other fermions U, D, L, E only have a minor effect through altered branching ratios. This allows a direct bound on the mass splitting between $SU(2)$ charged KK quarks and KK W modes to be obtained, because production, as well as decay, of the W' are controlled by the same coupling. Other search channels, like Z', γ', W' in leptonic channels, or searches for colored resonances, depend on products of (linear combinations of) different couplings. Allowing for generic bulk masses or boundary terms, therefore, makes it more difficult to translate such searches into particular mass splittings in the KK spectrum.

[10] Choosing the $\mu_L R$ maximally allowed by the four-Fermi interactions leads to a slightly weaker constraint of $\mu_Q R = 0.92$ for $m_{W^{(1)}} = 800$ GeV. However, the case of $\mu_L R = 0$, $\mu_Q R > 0$ is of particular interest for sUED dark matter searches, because in this limit, the dark matter annihilation rate into positrons is maximized, while the production of antiprotons is maximally suppressed.

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