Warped gravitons at the CERN LHC and beyond

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(Received 3 April 2007; published 31 August 2007)

We study the production and decay of Kaluza-Klein (KK) gravitons at the CERN Large Hadron Collider (LHC), in the framework of a warped extra dimension in which the standard model (SM) fields propagate. Such a scenario can provide solutions to both the Planck-weak hierarchy problem and the flavor puzzle of the SM. In this scenario, the production via $q\bar{q}$ annihilation and decays to the conventional photon and lepton channels are highly suppressed. However, we show that graviton production via gluon fusion followed by decay to longitudinal Z/W can be significant; vector boson fusion is found to be a subdominant production mode. In particular, the golden ZZ decay mode offers a distinctive 4-lepton signal that could lead to the observation at the LHC with 300 fb^{-1} (SLHC with 3 ab^{-1}) of a KK graviton with a mass up to $\sim$2 ($\sim$ 3) TeV for the ratio of the AdS$_5$ curvature to the Planck scale modestly above unity. We argue that (contrary to the lore) such a size of the curvature scale can still be within the regime of validity of the framework. Upgrades beyond the SLHC luminosity are required to discover gravitons heavier than $\sim$4 TeV, as favored by the electroweak and flavor precision tests in the simplest such models.

DOI: 10.1103/PhysRevD.76.036006 PACS numbers: 13.35.−r, 11.10.Kk

I. INTRODUCTION

Solutions to the Planck-weak hierarchy problem of the standard model (SM) invoke new particles at $\sim$TeV scale. Such new physics is likely to give a signal at the upcoming CERN LHC, provided that the new states have a non-negligible coupling to the SM particles. In this paper, we consider the solution to the hierarchy problem based on the Randall-Sundrum (RS1) framework with a warped extra dimension [1]. The most distinctive novel feature of this scenario is the existence of spin-2 Kaluza-Klein (KK) gravitons whose masses and couplings to the SM are set by the TeV scale. Hence, the KK gravitons appear in experiments as widely separated resonances, in contrast to the very light, closely spaced KK gravitons in large extra dimensions [2], with couplings suppressed by the 4D reduced Planck scale $\bar{M}_P$.

A well-motivated extension of the original RS1 model addresses the flavor structure of the SM through localization of fermions in the warped bulk. This picture offers a unified geometric explanation of both the hierarchy and the flavor puzzles, without introducing a flavor problem. In this case, graviton production and decay via light fermion channels are highly suppressed and the decay into photons are negligible. However, finding a graviton spin-2 resonance provides the clearest evidence for a warped extra dimension, on which the RS1 model and its extensions are based. The experimental verification of this framework is then seemingly a challenge, since some of the most promising original signals are no longer available.

Hence, we examine alternative LHC signals for RS1 KK gravitons, assuming the SM fields are in the warped bulk and that the fermions are localized to explain flavor. We show that production of KK gravitons from gluon fusion and their decay into longitudinal gauge bosons W/Z (W_L/Z_L) can be significant. In particular, KK graviton decay into pairs of Z_L's can provide a striking 4-lepton signal for a TeV-scale KK graviton at the LHC; multi-TeV gravitons are shown to be accessible to a luminosity-upgraded LHC. We also consider KK graviton production via vector boson fusion (VBF). However, we find that this production channel is subdominant to that from gluon fusion. Hence, we do not analyze the VBF case in any detail.

II. WARPED EXTRA DIMENSION

The framework is based on a slice of AdS$_5$. Owing to the warped geometry, the relationship between the 5D mass scales (taken to be of order $\bar{M}_P$) and those in an effective 4D description depends on the location in the extra dimension. The 4D (or zero-mode) graviton is localized near the "UV/Planck" brane which has a Planckian fundamental scale, whereas the Higgs sector is localized near the "IR/TeV" brane where it is stable near a warped-down fundamental scale of order TeV. This large hierarchy of scales can be generated via a modest-sized radius of the 5th dimension: TeV$/\bar{M}_P \sim e^{-k\pi R}$, where k is the curvature scale and R is the proper size of the extra dimension; $kR \approx 11$. Furthermore, based on the anti–de Sitter/conformal field theory (AdS/CFT) correspondence [3], RS1 is conjectured to be dual to 4D composite Higgs models [4,5].

In the original RS1 model, the entire SM (including the fermions and gauge bosons) are assumed to be localized on the TeV brane. The key feature of this model is that KK gravitons have a mass $\sim$TeV and are localized near the TeV brane so that KK graviton coupling to the *entire* SM is only $\sim$TeV suppressed. Hence, KK graviton production via $q\bar{q}$ or gg fusion at the LHC [or via e^+e^- at the International Linear Collider (ILC)] followed by decays to dileptons or diphotons gives striking signals [6].

However, in this model, the higher-dimensional operators in the 5D effective field theory (from cutoff physics) are suppressed only by the warped-down scale ~TeV, giving too large contributions to flavor changing neutral current (FCNC) processes and observables related to SM electroweak precision tests (EWPT). Moreover, this setup provides no understanding of the flavor puzzle, i.e., the hierarchies in the SM fermion Yukawa couplings to Higgs.

An attractive solution to this problem is to allow the SM fields to propagate in the extra dimension [7–10]. In such a scenario, the SM particles are identified with the zero-modes of the 5D fields and the profile of a SM fermion in the extra dimension depends on its 5D mass parameter. We can then choose to localize 1st and 2nd generation fermions near the Planck brane so that the FCNC's from higher-dimensional operators are suppressed by scales $\gg$ TeV which is the cutoff at the location of these fermions [10,11]. Similarly, contributions to EWPT from cutoff physics are also suppressed.

As a bonus, we obtain a solution to the flavor puzzle in the sense that hierarchies in the SM Yukawa couplings arise without introducing hierarchies in the fundamental 5D theory [8,10,11]: the 1st/2nd generation fermions have small Yukawa couplings to Higgs which is localized near the TeV brane. Similarly, the top quark can be localized near the TeV brane to account for its large Yukawa.

On the flip side, in this scenario, couplings of KK gravitons to light fermions are highly suppressed since, as mentioned above, KK gravitons are localized near the TeV brane whereas the light fermions are localized near the Planck brane. In fact, we can show that these couplings (made dimensionless by compensating the derivative involved by ~TeV scale) are very roughly of Yukawa strength since KK gravitons have a profile which is similar to that of the Higgs. As a result, $q\bar{q}$ annihilation at the hadron collider (or e^+e^- at ILC) to KK gravitons is negligible. In contrast, SM gluons have a flat profile so that coupling to KK gravitons is suppressed only by a factor of the size of the extra dimension (in units of radius of curvature), i.e., $k\pi R$, relative to gluons being on the TeV brane. This factor is basically $\sim \log(\bar{M}_P/\text{TeV})$ due to the solution to the hierarchy problem. Thus, although suppressed compared to the original RS1 model, the coupling of gluons to KK gravitons and hence KK graviton production via gg fusion is still non-negligible (cf. the case of light fermions).

Furthermore, decays of KK gravitons are dominated by the top quark and Higgs due to their profile being near the TeV brane, resulting in couplings to KK gravitons (which are also localized there) being only ~TeV-suppressed just like in the original RS1 model. The problem is that none of these are easily detectable modes. Just as with production of KK gravitons, the branching ratio (BR) to the usual golden modes, such as a pair of photons, is volume suppressed, whereas to light fermions is Yukawa-suppressed and hence negligible. Thus, *a priori*, the combination of these 2 factors—suppression in production and in decays to the previously considered "golden" modes—makes the signal for the KK graviton very difficult [12–14].

The crucial point of our paper is that, by the equivalence theorem, $W_L^\pm$ and Z_L are effectively the *unphysical* Higgs ("would-be" Goldstone bosons) and are therefore localized near the TeV brane (just like the physical Higgs). So, the decay widths in the W_L/Z_L channels are the same size as in those of the physical Higgs/top quark.[1] Clearly, branching ratio to a pair of Z/W's is sizable; in particular, Z_LZ_L is a golden channel. As a corollary, *production* of KK gravitons via longitudinal W/Z fusion can be important. Such effects were not analyzed before.

Next, we comment on the mass scale of KK gravitons. In this scenario, there are new contributions to EWPT and FCNC's calculable in the 5D effective field theory from KK modes. Because of various symmetries (approximate flavor or analog of the Glashow-Iliopoulos-Maiani mechanism of the SM [10,11,15] and custodial isospin [16]), gauge KK masses as small as ~3 TeV are consistent with oblique electroweak (EW) data [16] (we comment on nonoblique effects such as $Zb\bar{b}$ later) and FCNC's [17]. As a result, KK gravitons have to be heavier than ~4 TeV since the ratio of the lightest KK masses for gravitons and gauge bosons is ~1.5 in the simplest such models (see next section).

III. COUPLINGS OF KK GRAVITON

A general formula for couplings of mth and nth modes of the bulk field (denoted by F) to the qth level KK gravitons (denoted by G) is [12]:

$$\mathcal{L}_G = \sum_{m,n,q} C_{mnq}^{FFG} \frac{1}{\bar{M}_P} \eta^{\mu\alpha}\eta^{\nu\beta} h_{\alpha\beta}^{(q)}(x) T_{\mu\nu}^{(m,n)}(x), \quad (1)$$

where $h_{\alpha\beta}^{q}(x)$ corresponds to the KK graviton, $T_{\mu\nu}^{(m,n)}(x)$ denotes the 4D energy-momentum tensor of the modes of the bulk field, $\bar{M}_P \approx 2.4 \times 10^{18}$ GeV is the reduced 4D Planck scale, and C_{mnq}^{FFG} is the overlap integral of the wave functions of the 3 modes.

We will consider only those couplings relevant for production and decay. Since $q\bar{q}$ annihilation to KK gravitons is Yukawa-suppressed, the production is dominated by gluon fusion. The coupling of gluons to KK gravitons is given by the above formula with [12]:

[1]The longitudinal channels are dominant compared to those of the transverse W/Z or gluon/photon by a volume factor: in this sense, massive gauge bosons are different from the massless ones.

$$C_{00n}^{AAG} = e^{k\pi R}\frac{2[1 - J_0(x_n^G)]}{k\pi R(x_n^G)^2|J_2(x_n^G)|}, \quad (2)$$

where $J_{0,2}$ denote Bessel functions and $x_n^G = 3.83$, 7.02, 10.17, 13.32 gives masses of the first 4 KK gravitons: $m_n^G = ke^{-k\pi R}x_n^G$. Gauge KK masses are given by $m_n^A = ke^{-k\pi R} \times (2.45, 5.57, 8.7, 11.84)$. For simplicity, we neglect brane-localized kinetic terms for both graviton and gauge fields. Thus, we have

$$m_1^G \approx 1.5 m_1^A, \quad (3)$$

for the lightest KK masses for graviton and gauge fields.

As mentioned above, the decays of KK gravitons are dominated by the top quark and Higgs (including longitudinal W/Z using equivalence theorem). Let us consider the top and bottom sector in detail to determine the couplings to KK gravitons. Because of the heaviness of the top quark combined with the constraint from the shift in $Zb\bar{b}$, one possibility is to localize t_R very close to the TeV brane with $(t, b)_L$ having a profile close to flat [16]. Even with this choice of the profiles, the gauge KK mass scale is constrained by $Zb\bar{b}$ to be $\gtrsim 5$ TeV, i.e., a bit higher than that allowed by oblique EW data. However, a custodial symmetry to suppress $Zb\bar{b}$ [18] can relax this constraint on the gauge KK mass scale and moreover allows the other extreme case: $(t, b)_L$ very close to the TeV brane and t_R close to flat and also the intermediate possibility with both t_R and $(t, b)_L$ being near, but not too close to TeV brane. The bottom line is that, with this custodial symmetry and for certain choices of profiles for t_R and $(t, b)_L$ in the extra dimension, gauge KK masses as low as ~3 TeV can be consistent with $Zb\bar{b}$ as well [19]. For simplicity, we will consider the extreme case with t_R localized very close to the TeV brane, with $(t, b)_L$ having close to a flat profile. It is straightforward to extend our analysis to the other cases. Moreover, we will assume that this helicity of the top quark and similarly the Higgs are *exactly* localized on the TeV brane. In reality, these particles have a profile *peaked* near the TeV brane, but this will result in at most an $O(1)$ difference.

With this approximation, the couplings relevant for decay are

$$\mathcal{L}_G \ni \frac{e^{k\pi R}}{\bar{M}_P}\eta^{\mu\alpha}\eta^{\nu\beta}h_{\alpha\beta}^{(q)}(x)T_{\mu\nu}^{t_R,H}(x) \quad (4)$$

giving the partial decay widths [20]

$$\Gamma(G \to t_R\bar{t}_R) \approx N_c\frac{(cx_n^G)^2 m_n^G}{320\pi}, \quad (5)$$

$$\Gamma(G \to hh) \approx \frac{(cx_n^G)^2 m_n^G}{960\pi}, \quad (6)$$

$$\Gamma(G \to W_L^+ W_L^-) \approx \frac{(cx_n^G)^2 m_n^G}{480\pi}, \quad (7)$$

$$\Gamma(G \to Z_L Z_L) \approx \frac{(cx_n^G)^2 m_n^G}{960\pi}, \quad (8)$$

where $N_c = 3$ is the number of QCD colors, $c \equiv k/\bar{M}_P$, and we have neglected masses of final state particles in phase space factors. These are the only important decay channels for the $n = 1$ graviton KK mode which is the focus of our analysis in this work. For the case where $(t, b)_L$ is localized very close to the TeV brane (with t_R being close to flat), we multiply the 1st formula by a factor of 2 to include decays to b_L. In this case, production of KK gravitons from $b\bar{b}$ annihilation can also be important. The last 2 formulas correspond to decays to longitudinal polarizations: we have used the equivalence theorem (which is valid up to $M_{W,Z}^2/E^2$ effects, where $E \sim m_1^G$) to relate these decays to the physical Higgs. As mentioned above, we can neglect decays to transverse W/Z (and similarly to gluon, photon) due to volume [$\sim \log(\bar{M}_P/\text{TeV})$] suppression (in amplitude) relative to longitudinal polarization. Similarly, decays to light fermions are negligible (due to the Yukawa-suppressed coupling to KK gravitons). We can also show that the decays of KK gravitons to other KK modes are suppressed.

Finally, for the intermediate possibility mentioned above (with both t_R and $(t, b)_L$ being near, but not too close to TeV brane), the partial width of KK gravitons to top/bottom quarks (and hence the total width) will be smaller and hence the BR to ZZ will be larger.

IV. KK GRAVITON PRODUCTION

The relevant matrix elements for the process $gg \to VV$, with $V = W, Z$, via KK gravitons are [21]

$$\mathcal{M}_{\lambda_1\lambda_2\lambda_3\lambda_4}^G(g^a g^b \to VV) = -C_{00n}^{AAG}e^{-k\pi R}\left(\frac{x_n^G c}{m_n^G}\right)^2 \times \sum_n \frac{\delta_{ab}[\mathcal{A}_{\lambda_1\lambda_2\lambda_3\lambda_4}]}{\hat{s} - m_n^2 + i\Gamma_G m_n}, \quad (9)$$

where λ_i refer to initial and final state polarizations, a, b are color factors,

$$\Gamma_G = \frac{13(cx_n^G)^2 m_n^G}{960\pi} \quad (10)$$

is the total decay width of KK gravitons in our treatment, and we have used $\bar{M}_P e^{-k\pi R} = m_n^G/(x_n^G c)$. As mentioned before, $x_1^G = 3.83$ for the first graviton resonance. We have

$$\mathcal{A}_{++00} = \mathcal{A}_{--00} = 0, \quad (11)$$

$$\mathcal{A}_{+-00} = \mathcal{A}_{-+00} = \frac{(1 - 1/\beta_V^2)(\beta_V^2 - 2)[(\hat{t} - \hat{u})^2 - \beta_V^2\hat{s}^2]\hat{s}}{8M_V^2}, \quad (12)$$

where $\beta_V^2 = 1 - 4M_V^2/\hat{s}$ and the hatted variables are in the parton center of mass frame. To repeat, the other amplitudes with transverse polarizations for V's (i.e., $\lambda_{3,4} = +, -$) can be neglected since these are suppressed relative to the above by $\sim \log(M_{\rm Pl}/\text{TeV})$. Note that the above formula includes both the virtual exchange of KK gravitons and resonant production. One can show that $\mathcal{A}_{+-00} \to -\sin^2\hat{\theta}\hat{s}^2/2$ as $\beta_V \to 1$.

The parton-level signal ($V = Z$) cross section, averaged over initial state spins and colors, is given by

$$\frac{d\hat{\sigma}(gg \to ZZ)}{d\cos\hat{\theta}} \approx \frac{|\mathcal{M}_{+-00}|^2}{1024\pi\hat{s}}, \tag{13}$$

where a factor of $1/2$ has been included for identical bosons in the final state, initial helicity averaging has been accounted for by a factor of $1/4$, and a factor of $1/8$ accounts for color averaging. Note that $\mathcal{M}_{+-00}$ is the only independent nonzero matrix element for the above process. The total parton-level cross section $\hat{\sigma}$ is related to the proton-level total signal cross section as usual:

$$\sigma(pp \to ZZ) = \int dx_1 dx_2 f_g(x_1, Q^2) f_g(x_2, Q^2)\hat{\sigma}(x_1 x_2 s), \tag{14}$$

where f_g are the gluon parton distribution functions (PDF's) and $Q^2 \sim (m_n^G)^2$ is the typical momentum transfer in the partonic process for resonant production of a KK graviton.

Finally, we discuss a new production mechanism for KK gravitons which has not been considered before, namely, VBF via WW or ZZ. The probability for emission of (an almost) collinear longitudinal W/Z by a quark (or antiquark) is suppressed by an electroweak factor of $\sim\alpha_{EW}/(4\pi)$ [22]. However, the coupling of longitudinal W/Z to KK gravitons is $\log(\bar{M}_P/\text{TeV})$-enhanced compared to that to gluon (or to transverse W/Z). Moreover, VBF can proceed via valence quarks, i.e., uu or ud, scattering in addition to $u\bar{u}$ and $d\bar{d}$ annihilation (which are suppressed by the smaller sea quark content). So, we find that the ratio of KK graviton production via longitudinal W/Z fusion and gluon fusion is $\sim[\alpha_{EW}/(4\pi)]^2 \times [\log(\bar{M}_P/\text{TeV})]^2 \times$ ratio of $(u\,\text{PDF})^2$ vs$(g\,\text{PDF})^2$. Since $(u\,\text{PDF})^2$ is roughly an order of magnitude larger than $(g\,\text{PDF})^2$ at the relevant x's, we estimate that the cross section for gg fusion is about an order of magnitude larger than the WW/ZZ fusion—our detailed, partonic level, calculation confirms this expectation. Further details are discussed in the appendix.

V. SM BACKGROUND

In the next section, we focus mainly on the leptonic decay mode of the two Zs (4ℓ), based on considerations of background as we now discuss. We begin with the irreducible background to the ZZ final state, i.e., SM contribution to $pp \to ZZ + X$. It is dominated by $q\bar{q}$ annihilation: gluon fusion is very small in the SM since it proceeds via loop. Hence, the interference of the KK graviton signal (dominated by gg and WW/ZZ fusion) with the SM background is negligible. The parton-level cross section, averaged over quark colors and spins is given by [23]

$$\frac{d\hat{\sigma}(q_i\bar{q}_i \to ZZ)}{d\hat{t}} = \frac{\pi\alpha^2(L_i^4 + R_i^4)}{96\sin^4\theta_W\cos^4\theta_W\hat{s}^2}\left[\frac{\hat{t}}{\hat{u}} + \frac{\hat{u}}{\hat{t}} + \frac{4M_Z^2\hat{s}}{\hat{t}\,\hat{u}} - M_Z^4\left(\frac{1}{\hat{t}^2} + \frac{1}{\hat{u}^2}\right)\right], \tag{15}$$

where $L_u = 1 - 4/3\sin^2\theta_W$, $R_u = -4/3\sin^2\theta_W$, $L_d = -1 + 2/3\sin^2\theta_W$, and $R_d = +2/3\sin^2\theta_W$ This cross section exhibits forward/backward peaking due to t/u channel exchange, whereas the KK graviton signal does not have this feature [see the approximate $\hat{\theta}$ dependencies given below Eqs. (12) and (A2)]. Hence, a cut on pseudorapidity η is useful to reduce this background keeping the signal (almost) unchanged. Thus as we shall see below our signal is typically significantly larger than the SM ZZ background.

The smallness of the irreducible background to the ZZ final state leads us to consider the reducible background which depends on the decay mode of the Z pair. For the dominant purely hadronic decay mode, there is a huge QCD background (4 jets) so that this decay mode is not useful. Next, we consider the semileptonic decay mode. The problem is that for such energetic Z's, the opening angle between 2 jets from Z decay $\sim M_Z/1$ TeV ~ 0.1, whereas the typical cone size for jet reconstruction is ~ 0.4 (see for example [24]). Hence, it is likely that we cannot resolve the 2 jets from Z decay so that they will appear as a single jet ("Z-jet"). Therefore, we need to consider the background from $Z + 1$ jet which we calculate is roughly an order of magnitude larger than our signal (over the same mass window)—note that, based on the above discussion, this statement is true irrespective of the value of c. However, we note that more sophisticated means of reducing the $Z + 1$ jet background, for example, via a better set of cuts or by looking for a substructure inside the Z-jet from KK graviton decay (this will give a hint that the jet is neither a light jet nor a b-jet), might make this channel useful.

Also, VBF has the feature of 2 additional highly energetic forward-jets which can be tagged [22]. However in this case and with semileptonic decay of Z pair, we will have to consider background from $Z + 3$ jets, with its associated QCD uncertainties. Moreover, VBF is subdominant to gg fusion and hence VBF might not have enough statistics (for the interesting range of KK masses) which are required for an analysis involving forward-jet tagging. In view of these difficulties with the semileptonic decay mode, here we will follow a conservative approach and not consider this decay mode, but we note that it is worthy of a future study. So, for now, we will focus on the purely (charged) leptonic decay mode for ZZ for which the dominant background is the irreducible one and hence is smaller than our signal. The channel with one Z decaying to neutrinos, whereas the other Z decays to charged leptons is also interesting. The BR for this channel is larger than for the $4l$ mode, but the invariant mass of the Z pair cannot be reconstructed in this case so that we cannot apply the mass window cut (see below) to enhance the ratio of signal over background. However, the distribution of kinematic variables such as missing p_T will still be different for the signal as compared to the SM background, which will help in discriminating between the two—we will defer this analysis for a future study.

VI. SIGNALS AT THE LHC

Our results for the KK graviton signal (S) and irreducible SM background (B) cross sections, both within the ZZ invariant mass window[2] $m_1^G \pm \Gamma_G$, are presented in Figs. (1 and 2), without a cut on η and with such a cut, respectively. The shaded region shows where we expect the KK graviton mass to be in the simplest models according to the relation in Eq. (3) and the limit on gauge KK mass from precision tests. As expected from the above discussion, these results show that implementing a cut with $\eta < 2$ on the final state Z's enhances S/B. With this cut on η we find that the signal is larger than the background by a factor of a few (or even an order of magnitude) over a wide range of KK graviton masses. We consider the range $0.5 \leq c \leq 2$; a discussion of the upper limit on c is given later. We have used the CTEQ6L1 PDF's, evaluated at $Q^2 = m_1^{G2}$ in our (partonic level) calculations (both for the signal and the background). Note that, based on Eqs. (9), (10), and (A1), the dependence on c parameter (roughly) cancels in parton-level signal cross section (or equivalently the proton-level *differential* cross section) *near the peak of the resonance*. Hence, the ratio of signal to background in this mass window is (almost) independent of c.

Based on the preceding discussion, we are led to consider the purely leptonic $(e^+e^-, \mu^+\mu^-)$ decay of the Z pair. However, this decay mode has a small BR of $\approx 0.45\%$. Hence, the main issue is whether the number of 4ℓ events from signal and also the $S/\sqrt{B}$ is large enough, especially given the small BR of this mode. The *total* signal cross section and hence the number of 4ℓ events scales as c^2. The reason is that (as explained above) the *differential* cross section at the peak of the resonance is (roughly) independent of c, but the size of the mass window $\sim\Gamma_G \propto c^2$. Similarly, $S/\sqrt{B}$ scales as c.

Range of c. Therefore, it becomes crucial to study the allowed range of $k/\bar{M}_P$. Recall that there is an upper limit on c such that the assumption of neglecting higher curvature terms is valid [1,12]. The common lore is that $c \sim 1$ is outside the domain of validity of the model. However, we

[2]The ratio of signal to background is maximized when KK graviton is on shell and, therefore, we focus on this region.

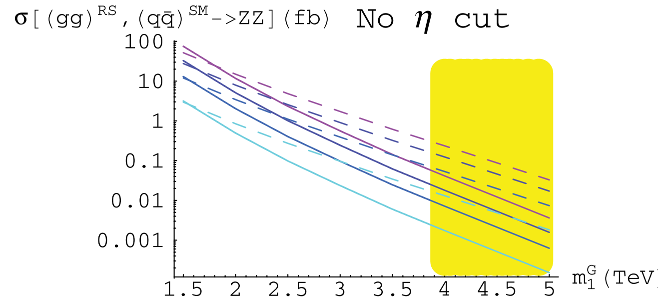

FIG. 1 (color online). The cross sections (integrated over one width) for $gg \to ZZ$ via KK gravitons (solid lines) and the corresponding SM background (dashed lines). We show the cross sections for $c \equiv k/\bar{M}_P = 0.5, 1, 1.5, 2$ (from bottom to top). See the text for an explanation of the upper limit on c. The shaded region shows where we expect the KK graviton mass to be in the simplest models according to relation in Eq. (3) and the limit on gauge KK mass from precision tests.

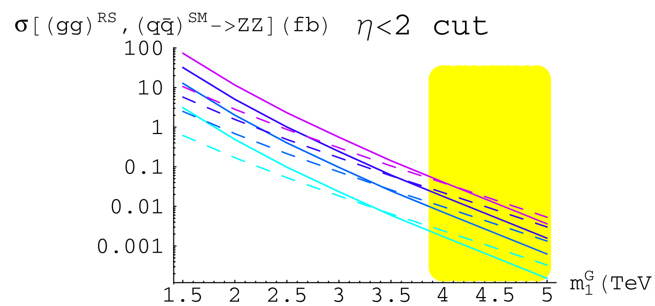

FIG. 2 (color online). Same as Fig. 1, but with $\eta < 2$.

now show that $c \sim 1$ is still *within* the range of validity of the model. The point is that the higher curvature terms in the 5D action are suppressed by powers of R_5/Λ^2, rather than R_5/M_5^2, with $R_5 = 20k^2$ the size of the 5D curvature [12] and M_5 the 5D Planck scale. Here Λ is the energy scale at which the 5D gravity theory becomes strongly coupled and its naive dimensional analysis estimate is given by $\Lambda^3/(24\pi^3) \sim M_5^3$ [25]. We can show that loop effects and local higher-dimensional operators in the 5D theory are also suppressed by a similar factor. Using the relation $\bar{M}_P^2 \approx M_5^3/k$, we require $k/\bar{M}_P < \sqrt{3\pi^3/(5\sqrt{5})}$ so that we can trust our above calculation of the tree-level effects of KK gravitons. Although there are $O(1)$ uncertainties in these estimates, we thus expect that for $k/\bar{M}_P \sim 1$, higher-order corrections to our results can be neglected. In fact, even c modestly larger than 1 can still be within the regime of validity of the model since the edge of validity of the model is $k/\bar{M}_P \approx 3$. Hence, we will consider values of c as large as 2 in our results.[3]

[3]Note that for values of c larger than $\sim$2, the KK graviton width becomes larger than $\sim$20% of its mass, making some of the approximations used in our calculations less reliable and also introducing additional detection issues.

Other decay modes of KK graviton. Before presenting our results based on the 4ℓ events, we would briefly like to mention other decay modes of the KK graviton, beginning with the dominant decay mode to top quarks (BR $\approx$ 70%). The purely leptonic decay mode for the top pair (i.e., W's from both tops decaying leptonically) has very small BR ($\approx$ 5%) and hence is too inefficient. The semileptonic decay mode has large BR ($\approx$ 30%), but it was shown in Ref. [26] that for p_T of top quark $\gtrsim$ 1 TeV (as would be the case for KK graviton masses of interest), the $C4$ jet algorithm [24] is unable to resolve the 3 jets from hadronic top decay (b-jet and 2 jets from W decay), just like for the case of hadronic decay of Z mentioned above. Hence the conventional hadronic top reconstruction methods for $t\bar{t}$ invariant masses $\lesssim$ 600 GeV [27] are inefficient for such energetic tops. The new methods proposed in Ref. [26], based on this "top-jet", results in a total efficiency of ~1% (including BR, b-tagging efficiency and kinematic effects) for the case of a 3 TeV KK *gluon* decaying into top pairs [26]. We expect a similar small efficiency for KK graviton masses $\gtrsim$ 2 TeV. The case of decays of KK gravitons to WW followed by leptonic decays of both W is also problematic, since the neutrinos' p_T will tend to be almost back to back, due to the high boost of the W's. Thus in many cases the missing energy information will be lost and the W mass cannot be reconstructed efficiently. Of course the hadronic decay of W faces the same problem as above for top/Z hadronic decay. Thus, we conclude that the other decay modes of KK graviton might be more challenging and less clean that the 4ℓ mode we are considering, but these other decay modes certainly deserve a separate and more detailed study (especially the decays to top quarks since the top decays, in turn, carry useful spin information).

Results. In Fig. 3, we show the number of 4ℓ events for the LHC with 300 fb^{-1} luminosity and in Figs. 4 and 5 we show the statistical significance of the signal ($S/\sqrt{B}$), with and without the η cut, respectively—we again see the importance of the η cut in improving the significance of the signal. We define the reach to be the largest KK mass for which the number of 4ℓ events $\geq$ 10, provided also that $S/\sqrt{B} \geq 5$. (We assume for simplicity 100% efficiency since our signal is known to be one of the cleanest at the LHC.) In Table I, we show this reach of the LHC from which we see that for $c \lesssim 2$, the LHC can probe KK graviton masses up to ~2 TeV. Recall that the constraints from FCNC and EWPT on gauge KK masses in the simplest *existing* models in the literature require KK graviton masses $\gtrsim$ 4 TeV.

We also note that higher luminosities of 3 ab^{-1} are being discussed in the community for the SLHC (see, for example, Refs. [28,29]). The number of 4ℓ events and $S/\sqrt{B}$ for the SLHC can be easily obtained by multiplying the corresponding numbers for the LHC by 10 and $\sqrt{10}$, respectively. From Table II, we see that the SLHC can extend the reach for the KK graviton to ~3 TeV. Similarly, upgrades of the center of mass energy to 28 TeV (see, for example, Ref. [29]) can extend the reach in KK masses. Note that the 4-lepton signal is the cleanest (in terms of background) of the possible KK graviton decay modes. This feature makes it a very promising discovery mode for KK gravitons even at higher luminos-

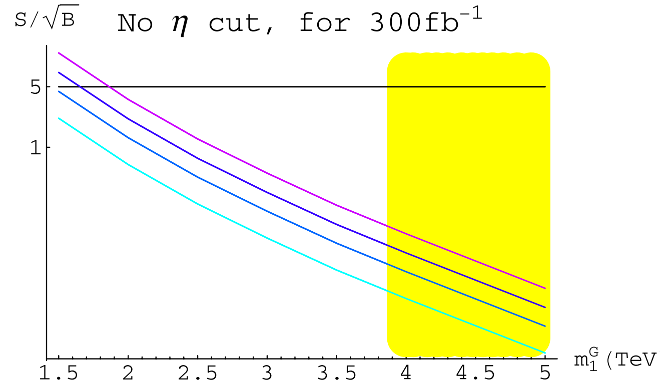

FIG. 4 (color online). Significance for the purely leptonic decay mode for Z pairs from KK graviton using 300 fb^{-1}. See also Fig. (1).

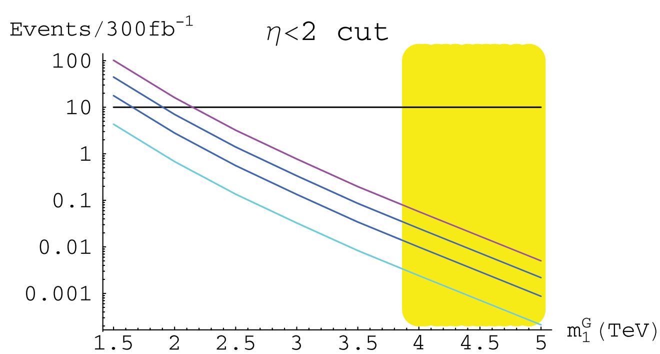

FIG. 3 (color online). The total number of expected events for the purely leptonic decay mode for Z pairs from KK graviton decay using 300 fb^{-1} with $\eta < 2$. See also Fig. (1).

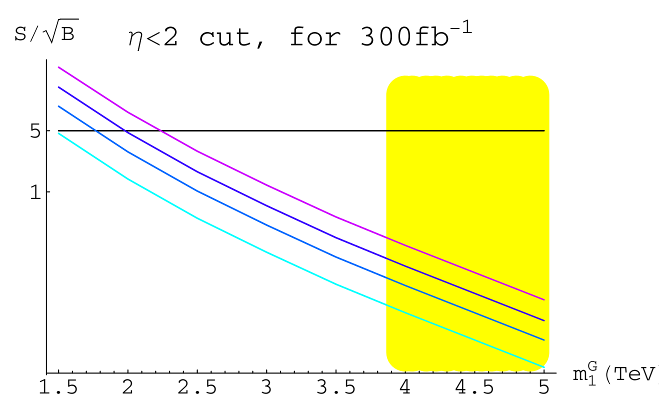

FIG. 5 (color online). Same as Fig. 4, but with $\eta < 2$.

TABLE I. The mass of the first KK graviton for which the number of signal events is 10 at the LHC, for various choices of c. See the text for an explanation of the upper limit on c. The significance $S/\sqrt{B}$ of each result is also given. These numbers correspond to 300 fb^{-1} of integrated luminosity.

$c \equiv k/\bar{M}_P$	0.5	1.0	1.5	2.0
m_1^G (TeV)	<1.5	1.6	1.9	2.2
$S/\sqrt{B}$	$\cdots$	7.0	6.1	6.1

TABLE II. Same as Table I, except for the SLHC with 3 ab^{-1} of integrated luminosity.

$c \equiv k/\bar{M}_P$	0.5	1.0	1.5	2.0
m_1^G (TeV)	1.9	2.3	2.6	2.9
$S/\sqrt{B}$	6.1	4.3	4.3	4.3

ity/energy, cf. other modes (including the dominant decay mode to top quarks) which involve hadrons.

An alternate possibility is that new model-building avenues or mechanisms to suppress EWPT and FCNC allow lower gauge (and hence graviton) KK masses, just as the custodial symmetries to suppress contributions to T parameter and $Zb\bar{b}$ coupling relaxed the constraints on the KK masses before.[4]

Finally, it is interesting that, although we might not have enough statistics for a few TeV KK graviton masses, the Z/W pairs from KK gravitons can be discriminated from the SM background as follows. First of all, the (reconstructed) Z/W pairs from KK gravitons have a characteristic spin-2 angular distribution as opposed to the SM background. Also, the SM ZZ's are mostly transverse, whereas the ones from KK gravitons are mostly longitudinal. Hence, the angular distribution of decay products of Z in the Z *rest* frame (or their energy distribution in the lab frame) can also distinguish the KK graviton signal from the SM background.

VII. CONCLUSIONS

In this work, we have studied the discovery potential, at the LHC and its future upgrades, for the first RS1 graviton KK mode, assuming bulk SM. Such a discovery will provide strong evidence in favor of the RS1 model as the resolution of both the Planck-weak and the flavor hierarchy puzzles. We considered gluon fusion and VBF production modes and found that the VBF mode is subdominant. We focused on a remarkably clean 4-lepton signal, originating from the decay of the graviton to 2 longitudinal Z's. With this signal, the reach of the LHC for the first graviton KK mode extends to around 2 TeV, for an integrated luminosity of 300 fb^{-1} and for the ratio of the AdS_5 curvature to $\bar{M}_P$ modestly above unity, which as we argued (and contrary to the lore) can still be within the regime of validity for our computations. On the other hand, within the (simplest) current theory understanding, the electroweak and flavor precision tests disfavor KK graviton masses below ~4 TeV. However, the discovery reach can be extended at the upgraded SLHC luminosity of order 3 ab^{-1} and approach 3 TeV. Finally, we discussed briefly how the semileptonic decay mode of the Z pairs from KK graviton can be useful with a more refined analysis designed to reduce the background.

[4]For example, Refs. [30] discuss the possibility of suppressing the S parameter while keeping the solution to the flavor puzzle intact.

ACKNOWLEDGMENTS

We thank Tao Han, Tadas Krupovnickas, Seong-Chan Park, Maxim Perelstein, David Rainwater, Tom Rizzo, and Joseph Virzi for useful discussions and the Aspen Center for Physics for hospitality during part of this project. K. A. is supported in part by the U. S. DOE under Contract No. DE-FG-02-85ER 40231. H. D. and A. S. are supported in part by the DOE Grant No. DE-AC02-98CH10886 (BNL).

Note added.—While this work was being finalized, Ref. [31] appeared containing a similar discussion, in the context of bulk SM, of the couplings of KK gravitons to longitudinal W/Z, based on the equivalence principle, but focusing on the search for the KK graviton at the LHC using its decays to top quarks.

APPENDIX

The relevant matrix elements for the process $VV \to ZZ$ via KK graviton exchange are given by

$$\mathcal{M}^G_{\lambda_1\lambda_2\lambda_3\lambda_3}(VV \to ZZ) = \left(\frac{x_n^G c}{m_n^G}\right)^2 \sum_n \frac{\mathcal{A}_{\lambda_1\lambda_2\lambda_3\lambda_3}}{\hat{s} - m_n^2 + i\Gamma_G m_n}, \tag{A1}$$

where $V = W$, Z and

$$\mathcal{A}_{0000} = (\beta_V^2 - 1)(\beta_V^2 - 2)(\beta_Z^2 - 1)(\beta_Z^2 - 2) \times \frac{[3(\hat{t} - \hat{u})^2 - \hat{s}^2\beta_V^2\beta_Z^2]\hat{s}^2}{96\beta_Z^2\beta_V^2 M_Z^2 M_V^2}. \tag{A2}$$

From the above discussion, it is clear that the other amplitudes with transverse polarizations for initial or final state bosons can be neglected due to the smaller couplings to the KK graviton. We can show that in the limit $\beta_{W,Z} \to 1$, $A_{0000} \to \hat{s}^2/2(2/3 - \sin^2\theta)$.

The parton-level cross section is given by

$$\frac{d\hat{\sigma}(V_L V_L \to ZZ)}{d\cos\hat{\theta}} \approx \frac{|\mathcal{M}_{0000}|^2}{64\pi\hat{s}}, \tag{A3}$$

where the subscript L on V denotes longitudinal polarization.

The probability distribution for a quark of energy E to emit a longitudinally polarized gauge boson of energy xE and transverse momentum p_T (relative to quark momentum) is approximated by [22]:

$$\frac{dP^L_{V/f}(x, p_T^2)}{dp_T^2} = \frac{g_V^2 + g_A^2}{4\pi^2}\frac{1-x}{x}\frac{(1-x)M_V^2}{[p_T^2 + (1-x)M_V^2]^2}. \quad \text{(A4)}$$

The proton-level cross section can then be written as

$$\sigma(pp \to ZZ) \ni \int dx_1 dx_2 dx_1^W dx_2^W dp_{T1}^2 dp_{T2}^2 \frac{dP^L_{W/u}(x_1^W, p_{T1}^2)}{dp_{T1}^2}\frac{dP^L_{W/d}(x_2^W, p_{T2}^2)}{dp_{T2}^2} f_u(x_1, Q^2) f_d(x_2, Q^2)\hat{\sigma}(\hat{s}) + (u \leftrightarrow d)$$
$$\approx \int dx_1 dx_2 dx_1^W dx_2^W f_u(x_1, Q^2) f_d(x_2, Q^2) \times P^L_{W/u}(x_1^W) P^L_{W/d}(x_1^W)\hat{\sigma}(s x_1 x_2 x_1^W x_2^W) + (u \leftrightarrow d), \quad \text{(A5)}$$

where in the second line, we have used the fact that [based on Eq. (A4)] the average p_T^2 of the longitudinal V is given by $\sim(1-x)M_V^2 \ll (x_{1,2}^W E)^2$. Here, $x_{1,2}^W E \sim m_n^G \sim$ TeV is roughly the energy of the longitudinal V in order to produce an *on* shell KK graviton.[5] Hence, we can neglect p_T's in the parton-level cross section, i.e., set $\hat{s} \approx s x_1 x_2 x_1^W x_2^W$ and integrate over p_T's to obtain total probabilities, $P^L_{W/d}(x) = P^L_{W/u}(x) \approx g^2/(16\pi^2) \times (1-x)/x$. Also, $f_{u,d}$ are the u, d PDF's; the u quark (or W^+) can come from the first proton and d quark (or W^-) from the second proton or vice versa. Expressions for contributions from W/Z_L emission from various other combinations of quarks and antiquarks inside the protons can be similarly obtained.

[5] As mentioned before, the ratio of signal to background decreases rapidly as we go outside the resonance region.

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