Big Signals of Little Randall-Sundrum Models

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We examine signals at the Large Hadron Collider (LHC) of Kaluza-Klein modes, in volume-truncated “Little Randall-Sundrum” (LRS) models of flavor, characterized by 5D cutoff scales $M_5$ that are small compared to the 4D Planck mass $M_P \sim 10^{19}$ GeV. In particular, for the phenomenologically viable choice $M_5 \sim 10^4$ TeV, the discovery of a 2 (3)-TeV “Little” $Z'$ at the LHC requires about $1 \times 10^4 \text{fb}^{-1}$ at $\sqrt{s} = 10 \text{ TeV}$, in the clean di-lepton channel. Our results highlight the possibility of probing interesting values of $M_5$, starting with the early LHC data. With $M_5 \sim 10^4$ TeV, discovering the second KK mode $Z''$, at about $4.3 \text{ TeV}$, requires $O(100) \text{ fb}^{-1}$ at $\sqrt{s} = 14 \text{ TeV}$, providing a probe of the warped nature of the bulk that is encoded in the mass ratio of the first two KK modes, at design luminosity. By comparison, discovering a 3-TeV $Z'$ of the Planck-weak hierarchy models (with $M_5 \sim M_P$), in any channel, would require upwards of $O(300) \text{ fb}^{-1}$ at $\sqrt{s} = 14 \text{ TeV}$. We also point out that discovery prospects markedly improve for Little KK gluons as well, but the challenging reconstruction of their $t\bar{t}$ decay products may not allow an appreciable advantage for early discovery, over the Little $Z'$ case.

Introduction: The Higgs condensate, $\langle H \rangle \simeq 250$ GeV, sets the electroweak scale in the Standard Model (SM). Yet, the SM Higgs potential is unstable against quantum corrections from the cutoff scale, often assumed to be near the Planck scale $M_P \sim 10^{19}$ GeV. This gives rise to the hierarchy problem, which is the puzzling smallness of the ratio of $\langle H \rangle / M_P \sim 10^{-17}$. The Randall-Sundrum (RS) model was initially proposed to explain the hierarchy by gravitationally red-shifting the 5D fundamental scale $M_5 \sim M_P$ down to the TeV-scale, along a warped 5th dimension. This geometry is based on a slice of $\text{AdS}_5$, truncated by flat 4D boundaries often referred to as the UV (Planck) and IR (TeV) branes. The RS metric is given by

$$ds^2 = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^n - r_c^2 d\phi^2,$$

where $\sigma = kr_c |\phi|$, $k \lesssim M_5$ is the 5D curvature scale, $r_c$ is the radius of compactification, $-\pi \leq \phi \leq \pi$, and a $\mathbb{Z}_2$ orbifolding of the 5th dimension is assumed. Henceforth, we will assume $\phi \in [0, \pi]$ in our calculations.

In the original model, it was assumed that all SM fields, and in particular the Higgs, are localized on the IR brane, where the 5D parameter $\langle H \rangle_5 \sim M_5$ is exponentially red-shifted: $\langle H \rangle = e^{-kr_c \pi} \langle H \rangle_5$. For $kr_c \approx 12$, the Planck-weak hierarchy is then generated. The distinct signature of this model is weak scale spin-2 Kaluza-Klein (KK) excitations of the graviton, appearing as resonances in high energy collisions. However, the cutoff scale in the 4D effective theory is also red-shifted to near the weak-scale, leading to unsuppressed higher dimensional operators, such as those for unwanted flavor-changing neutral currents.

The situation can be improved by noting that the resolution of the hierarchy only requires the Higgs to be localized near the IR brane and SM gauge and fermion fields could propagate in the 5D bulk. A mild modulation of bulk fermion masses provides a natural mechanism for generation of SM fermion masses and also suppression of unwanted 4-fermion operators. This is a result of the exponential localization of fermion zero modes. Small 4D Yukawa couplings are naturally obtained, if light flavor zero modes are UV brane localized, and operators containing light flavors are suppressed by scales much larger than $\langle H \rangle$.

While it is quite desirable to have a simultaneous resolution of hierarchy and flavor puzzles, the experimental signals of these warped models are now much more challenging. For example, localizing the light fermions near the UV brane suppresses their couplings to IR-localized KK modes. Therefore, KK production via light fermions and decay into light clean di-lepton final states are suppressed. This is a generic feature of warped models of hierarchy and flavor.

Even though localization of fermions alleviates many of the constraints on warped models, precision data still require additional symmetries in order for the new KK states to be as light as 2-3 TeV. Generally speaking, it has been shown that a very likely new state in these models to be discovered at the LHC is the first KK gluon, $\langle H \rangle \simeq 14 \text{ TeV}$. The analysis of Refs. suggests that KK gluons as heavy as 4 TeV will be within the reach of the LHC. However, for the KK modes of the weak sector, the corresponding reach is in the 2-3 TeV range and typically requires several hundred fb$^{-1}$. For gauge KK masses in the above ranges, the graviton KK modes are most likely not accessible, even with an upgraded LHC luminosity. Of course, even the gauge KK sector remains barely accessible and would, in any event, require a very large integrated luminosity.

In this work, we will concentrate on examining the...
Experimental prospects for the discovery of the lightest neutral electroweak gauge KK mode, referred to here as a $Z'$, in “Little Randall-Sundrum” (“LRS”) models \cite{17}, via easy-to-establish and clean final states. These models are volume truncations of the original RS background and are characterized by UV-brane scales $M_5 \ll M_P$. One can still generate a natural hierarchy between the weak scale and the sub-Planckian UV scale, leading to warped KK modes at the TeV scale. However, the complications involved with other sub-leading final states suffer from large irreducible backgrounds. However, the complications involved with other sub-leading final states suffer from large irreducible backgrounds. Nonetheless, several contributions to precision data can be suppressed because of the truncation. For example, by taking $M_5 \sim 10^3$ TeV, corresponding to $kr_c \pi \approx 6$, one can construct a model of flavor that avoids many of the usual constraints and enjoys a stable hierarchy, as a result of 5D warping \cite{17}. A remarkable aspect of these models is the enhancement of certain clean signals due to truncation. Simply put, the smaller 5D volume enhances the detection of warped KK modes by itself is afforded us a valuable opportunity to achieve this goal.

Before going further, we would like to mention that the prospects for “Little” KK gluons are also enhanced by the LRS truncation \cite{17}. The best final state for discovering the KK gluon will continue to be $t \bar{t}$ given that other sub-leading final states suffer from large irreducible backgrounds. However, the complications involved with $t \bar{t}$ event reconstruction makes this channel an unlikely early path towards establishment of a KK discovery. We will also examine the utility of forgoing a fully reconstructed resonance and looking for early hints of the Little KK gluon in a lepton-counting measurement.

**Setup:** We will adopt the bulk gauge group $G_B = SU(2)_L \times SU(2)_R \times U(1)_X$, so that our 4D effective theory has a custodial symmetry protection and could accommodate KK modes of mass in the 2-3 TeV range. We note that there may be more severe bounds from flavor data that could push the KK masses to significantly higher values \cite{18}; these considerations may require added assumptions \cite{22, 23} and structures \cite{24}, in order to arrive at a realistic model. Here, the gauge group $G_B$ and the basic form of couplings among the various states are the same as in Ref. \cite{12}. Given that truncation does not change the structure of the 4D effective Lagrangian, we refer the interested reader to Ref. \cite{12} for further details. We only note that, in warped models, the couplings of KK modes to various UV- and IR-localized states depend on the bulk volume parameter $kr_c \pi$, and thus we could use the known results scaled by the appropriate powers of $y$. Specifically, the coupling of gauge KK modes to UV- (IR-) localized fermions, in a warped model, is suppressed (enhanced) by $1/\sqrt{kr_c \pi}$ ($\sqrt{kr_c \pi}$), compared to the SM coupling. We will not specify a particular flavor model and will use the approximate formulas for the coupling of gauge KK modes to fermions \cite{17}, presented in the appendix. We note that a more careful analysis, based on realistic models of flavor, could modestly change some of our results.

$Z' \rightarrow \ell^+ \ell^-$: We will start by giving simple estimates of the improvement in the LHC discovery reach that can be attained upon truncation to LRS models \cite{17}. Based on the above discussion, the partial width $\Gamma^Z_{q^2}$ for $Z' \rightarrow f \bar{f}$, where $f = e, q, \ldots$ is a UV-localized (light) fermion, is enhanced as $y$. However, the total width $\Gamma^Z_{T'}$ of the $Z'$ is still mostly controlled by the coupling to the heavy IR-localized states, such as $W_L \pm$ and $t$. In this case, we expect $\Gamma^Z_{T'}$ to be reduced by $1/y$ after truncation. This means that the branching ratio

$$\text{Br}(Z' \rightarrow \ell^+ \ell^-) \sim y^2 \text{Br}(Z' \rightarrow \ell^+ \ell^-),$$

with $\ell = e, \mu$, under truncation. Using the narrow width approximation, the Drell-Yan process $q \bar{q} \rightarrow Z' \rightarrow \ell^+ \ell^-$ has a cross section

$$\sigma_{DY} \propto \Gamma^Z_{q^2} \text{Br}(Z' \rightarrow \ell^+ \ell^-).$$

Using the above scaling arguments, we then see that

$$\sigma_{DY} \rightarrow y^3 \sigma_{DY},$$

under truncation and could be significantly larger in LRS models. We also note that the relevant SM background under the $Z'$ peak shrinks as $1/y$, given the scaling of $\Gamma^Z_{T'}$. Hence, we expect that

$$S \rightarrow y^3 S; \quad S/B \rightarrow y^4 S/B,$$

after truncation to an LRS model \cite{17}. We will next show that the above estimates are generally confirmed by more detailed numerical calculations of the experimental reach for the Little $Z'$. Figs. 3 and 4 respectively show the total width and the leptonic Br of a 2-TeV $Z'$, averaged over the three neutral states, as a function of $kr_c \pi$: the Br shown is into each lepton ($e$ or $\mu$, not the sum). These plots confirm the scaling suggested by the
In Fig. 3, we present \( \ell \) background (for \( \ell = e \) or \( \mu \), not the sum) versus \( M_{Z'} \), at \( \sqrt{s} = 10 \) TeV, for \( k_{\pi}r = 7, 21, 35 \), in the upper (lower) panel. Fig. 3 again shows the leptonic cross section for \( M_{Z'} = 2 \) TeV, after cuts, but as a function of \( \eta, \pi, r \). Given the sufficiently low level (\( \sim 10^{-3} \)) of leptonic jet-fakes expected \( [21] \), we have included only the SM irreducible backgrounds. As can be deduced from these figures, for \( M_{Z'} \gtrsim 2 \) TeV, once \( kr, \pi \lesssim 20 \), corresponding to \( y \gtrsim 2 \), we find that \( S/B \gg 1 \) and the measurements become essentially background free.

The luminosity required for a 5 \( \sigma \) discovery of the \( Z' \) at the LHC, as a function of \( M_{Z'} \), is given in Fig. 4. We consider \( \sqrt{s} = 10(14) \) TeV, in the upper (lower) panel, and \( kr, \pi = 7, 21, 35 \). In determining the luminosity required, we require at least 3 events be observed, and if the number of events is small we use Poisson statistics to compute the significance equivalent to 5\( \sigma \). Given that \( S/B \gg 1 \)
for parameters of interest to our analysis, these events are basically background-free, as mentioned before. Hence, the use of only a handful of events to establish a discovery is reasonable.

We can see from the upper panel in Fig. 5 that even at $\sqrt{s} = 10$ TeV, as may be the case during the initial phase of the LHC operation, one can begin to place meaningful bounds on $kr_{c,\pi}$, for $M_{Z'} \approx 2$ TeV, with a modest integrated luminosity of about 1 fb$^{-1}$. At $\sqrt{s} = 14$ TeV, a 5σ discovery of a 3-TeV $Z'$ requires about 4 fb$^{-1}$. Note that the plots represent only one leptonic decay channel and the final reach is attained by summing over both $e^\pm$ and $\mu^\pm$ channels. The lower panel of the same figure shows that, assuming $kr_{c,\pi} \approx 7$ and $\sqrt{s} = 14$ TeV, the reach for the $M_{Z''}$ will be about 5 TeV, with $\mathcal{O}(300)$ fb$^{-1}$.

Our results demonstrate that, for phenomenologically viable parameters, the reach for the Little $Z'$ in clean di-lepton channels is greatly enhanced in truncated models. By contrast, as can also be seen from these plots, for $M_{Z'} \gtrsim 2$ TeV, in models that explain the Planck-weak hierarchy ($kr_{c,\pi} \approx 35$) an integrated luminosity of order 1000 fb$^{-1}$ is required. Even utilizing other decay channels, such as $W_L^\pm$, discovery at $M_{Z'} \sim 3$ TeV in the RS model will require upwards of $\mathcal{O}(300)$ fb$^{-1}$.

**Level-$2$ KK modes:** Given the much improved discovery reach for the $Z'$ in truncated LRS models, we would like to examine the possibility of detecting the second level of resonances in the KK tower, collectively denoted by $Z''$, in the clean di-lepton channel. Discovering the $Z''$ allows one to confirm the prediction for the ratio $M_{Z''}/M_{Z'}$ in warped models (which is different from, say, those in models with flat extra dimensions). We note that the prospects for achieving this in the full RS model with $kr_{c,\pi} \approx 35$ is practically nil.

To estimate the reach for $Z''$ in LRS models, we take $kr_{c,\pi} = 7$, near the lower bound allowed for a warped model of flavor largely unconstrained by precision data. For this point in the parameter space, we have $M_{Z''}/M_{Z'} \approx 2.65/5.80 \approx 0.46$; the prediction in the RS model with $kr_{c,\pi} = 35$ is $M_{Z''}/M_{Z'} \approx 2.45/5.57 \approx 0.44$. Such a difference in mass ratios is expected to be measurable, as the clean $e^\pm$ final state is quite accessible for this LRS example. We have checked that the coupling of the $Z''$ to the light SM fermions will be smaller by the ratio $\approx 0.14/0.18$, compared to those of the $Z'$. This can be easily verified using typical wavefunctions for fermion zero modes in our LRS model.

Using the set of cuts (7) and setting $M_{Z'} = 2$ TeV, we find that the Little $Z''$ with $M_{Z''} \approx 4.3$ TeV can be discovered, with $\mathcal{O}(100)$ fb$^{-1}$ at $\sqrt{s} = 14$ TeV. Hence, for $kr_{c,\pi} \approx 7$, compatible with the requirements of a viable flavor scenario, we see that the second KK resonance can be discovered. This will in turn provide further information on the warped nature of the underlying geometry.

We close this discussion by noting that we have limited our analysis to the effects of UV-truncations in this work. In principle, one could also imagine deforming the RS background in the IR, by adding brane-localized gauge kinetic terms, resulting in modulations of gauge KK masses and their couplings to the IR-localized fields [19, 22]. We have implicitly assumed that brane kinetic terms are generated at quantum level and are small. However, one could also study the effects of such terms on collider phenomenology [22]. These brane terms generally change the relation between KK masses and couplings in a way that is quite different from that resulting from truncation. For example, the IR-brane kinetic terms required to get $\mathcal{O}(1)$ reductions in the gauge KK couplings to the IR-brane yield $M_{(1)}/M_{(2)} \lesssim 1/3$ for the ratio of the first two KK masses [22, 27]. As we have seen, this is not the case in the truncated models examined in this work.

**$g^{(1)} \to t\bar{t}$:** Finally, we comment on the expected enhancements in the reach for the KK gluon in truncated flavor models. In particular, the lightest gluon KK mode $g^{(1)}$ in warped models generally has the largest production rate [1, 1]. Here, the same enhanced coupling to light fermions as for the $Z'$ would also lead to an enhanced production rate for $g^{(1)}$. However, although the decay into light fermions would also be enhanced, the
di-quark final state is swamped by a large di-jet background, and since the KK gluon does not directly couple to leptons, no clean di-lepton final state exists. Thus, one would use the $t\bar{t}$ final state to look for Little KK gluons of the LRS model, as in the RS model with $kr_c\pi \approx 35$ \cite{10,11}. Using the couplings presented in the appendix, we find the width of $g^{(1)}$ into $t\bar{t}$, $\text{Br}(g^{(1)} \rightarrow t\bar{t}) \approx 1$, over most of the relevant parameter space. Hence, the predicted width of Little KK gluons will decrease roughly as $1/y$. Parametrically, we then predict $S \sim y$, $S/\sqrt{B} \sim y^{1/2}$, and $S/B \sim y^2$ for $pp \rightarrow g^{(1)} \rightarrow t\bar{t}$. This behavior can significantly extend the reach for Little KK gluons, well above KK masses ($\sim 4$ TeV \cite{10,11}) accessible at the LHC with $O(10^2)$ fb$^{-1}$ in untruncated models. In addition, one may expect that the enhanced Little $g^{(1)}$ production could provide very early hints of new physics at the LHC.

Before a detailed numerical analysis, to get an estimate of the early Little $g^{(1)}$ signal, we will use the results of Ref. \cite{10} that imply a 3-TeV KK gluon can be detected at the 5$\sigma$ level with about 25 fb$^{-1}$ of integrated luminosity\footnote{However, we note that further refinement of this analysis may be possible, using a more detailed understanding of top-jet morphology \cite{20}.}. On the other hand, our Fig. 3 roughly suggests that for $kr_c\pi \approx 7$ we could expect a production cross-section enhancement of about 20 in going from 3 TeV to 2 TeV in the KK mass, whereas going from $\sqrt{s} = 14$ TeV to $\sqrt{s} = 10$ TeV reduces the cross section by a factor of about 4 ($BR_{t\bar{t}}$ doesn’t change much in these translations, and can be factored out of Fig. 3). We also note that for $kr_c\pi \approx 7$ we get $\text{Br}(g^{(1)} \rightarrow t\bar{t}) \approx 1/2$, using the rough expressions in the appendix. Given these considerations, for $y \approx 5$ ($kr_c\pi \approx 7$), we estimate that a 5$\sigma$ signal for a 2-TeV Little KK gluon only requires about 300 pb$^{-1}$ at $\sqrt{s} = 10$ TeV (early LHC operation), whereas a 3-TeV state would require roughly 2 fb$^{-1}$ at $\sqrt{s} = 14$ TeV.

The preceding analysis, on the first look, seems to suggest that we may be able to establish the RS-type properties of the Little KK gluon somewhat ahead of the Little $Z'$. However, we note that the results of Ref. \cite{10} are based on cuts involving missing transverse momenta from the leptonic decays of one of the $W$ bosons in the top decay chain, and reconstructing the top. Such measurements may not be well-understood at the early stages of the LHC experiments. One could instead focus on the leptonic decays of both $W$ bosons, coming from the decays of the $t\bar{t}$ pair, to see if the di-lepton signal is large enough compared to the background to afford an early hint of new physics. The price to pay is the branching fraction of $W$ into $e$ or $\mu$ plus $\nu$, which is 2/9, and our inability to form the highly effective $t\bar{t}$ invariant mass since the event cannot be fully reconstructed due to the presence of two missing neutrinos. We will look at this possibility more carefully below. We will begin with a more accurate numerical assessment of the preceding scaling estimates for KK gluon detection.

To find roughly what the LHC reach for the KK gluon is, we have implemented its couplings in the Monte Carlo package CalcHEP \cite{30}. For a 3 TeV $g^{(1)}$ we find that the total width in GeV ($\text{Br}_{t\bar{t}}$ in parentheses) is 71 (0.55), 196 (0.9), 344 (0.93) for $kr_c\pi = 7$, 21, 35 respectively. Since the Br into $t\bar{t}$ is large and the backgrounds can be brought under control, we will focus on this decay mode.

In Fig. 6, we show the $t\bar{t}$ invariant mass distribution from $pp \rightarrow g^{(1)} \rightarrow t\bar{t}$ without any top decay BRs included. We show the signal and irreducible SM background without any cuts, and in addition, also the SM background curve with $p_{Tt} > 1100$ GeV cut. If one can reconstruct the tops fully, we see that with the large $p_T$ cut $p_{Tt} > 1100$ GeV, the signal is comfortably above background. Note that in this plot, the signal is not shown after the cut, and the total cross section is reduced only by about a factor of two (three) for $kr_c\pi = 7$ (35) after the cut, as we can infer from Table 1 which shows the total cross section before and after cuts. Since reconstructing the (boosted) top is not completely achievable in a hadron collider, this clear signal peak will be somewhat degraded after taking into account top decays. We will discuss next the LHC signals for specific top decay chan-

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
$T_{bb}$ (fb) & $kr_c\pi = 7$ & $kr_c\pi = 21$ & $kr_c\pi = 35$ & SM \\
\hline
No cuts & 197 & 127 & 91 & $4 \times 10^5$ \\
$p_{Tt}, y_{t}$ cuts & 100 & 52 & 30 & 11 \\
\hline
\end{tabular}
\caption{The total cross section for $pp \rightarrow t\bar{t}$ in fb before and after the cuts $p_{Tt} > 1100$ GeV, $|y_{t}| < 3$. The $g^{(1)}$ signal and irreducible SM background are shown.}
\end{table}
rough estimate for the semi-leptonic mode, but we note respectively. Here, we will content ourselves with this

channels of the top.

In the semi-leptonic channel one can reconstruct the \( t \bar{t} \) event in the transverse plane. Applying \( W \) and top mass constraints, one can even fully reconstruct the event. However, the large boost of the tops will bring in additional complications. We will leave a detailed analysis of this channel to future work. Here, we will perform a simple-minded estimate for the reach in the semi-leptonic channel. Assuming a 5\% efficiency \([11]\) for reconstructing a hadronic top (which includes \( b \)-tagging efficiency and kinematic acceptances), we find, for a 3 TeV KK gluon, that the integrated luminosity needed for a 5\( \sigma \) discovery at the LHC is about 2, 8, 21 fb\(^{-1}\) for \( kr_c, \pi = 7, 21, 35 \) respectively. Here, we will content ourselves with this rough estimate for the semi-leptonic mode, but we note that we have good agreement for the \( kr, \pi = 35 \) case with the conclusions of the more complete study in Ref. \([11]\), and for the \( kr, \pi = 7 \) case with our scaling estimate.

The di-lepton channel is experimentally cleaner given that we have two hard leptons. However, due to the two missing neutrinos, the event cannot be fully reconstructed. Here, we will restrict ourselves to a simple di-lepton counting analysis. Given that the lepton \( p_T \) is correlated with the \( p_T \) of its parent top, and our observations in Fig. 6, the simplest thing one could do is to cut hard on the lepton \( p_T \) and count the di-lepton events. To see how well this can work, we show the \( p_T \) distribution of the lepton from the top for the signal and the irreducible SM background in Fig. 6. Based on this distribution, we apply the hard cut \( p_T > 400 \) GeV, in addition to the other soft cuts \( |\eta_{b,b} < 3, p_T > 20 \) GeV. We find that, for a 5\( \sigma \) discovery at the LHC, we need an integrated luminosity of 4, 15, 109 fb\(^{-1}\) for \( kr, \pi = 7, 21, 35 \) respectively, for a 3 TeV KK gluon. Taking into account the 2 \( b \)-jets that are present in the events can undoubtedly improve the reach, however, our focus in this paper is on the dilepton signal. A full analysis must also take into account the complication of the isolation being spoiled due to the presence of the \( b \)-jet close to the lepton, owing to the large top boost.

**Holographic interpretation:** Here, we note that, based on the AdS/CFT correspondence \([31]\), RS-type models have a 4D dual interpretation, in terms of some unknown strong dynamics \([22, 23]\). In the dual 4D picture, the hierarchy is related to the dynamical emergence of a conformal theory below the UV scale (originally taken to be \( M_5 \sim M_P \sim 10^{19} \) GeV). Upon breaking of the conformal symmetry an IR scale of order the weak scale appears, as signaled by the appearance of various composite resonances (such as the KK modes). In LRS-type models, the conformal energy interval is truncated in the UV and spans a smaller range. Our preceding discussion regarding the signals of truncated models was geometrical. However, using the duality, one can interpret our results as providing clues on the size of the conformal interval (corresponding to \( kr, \pi \)), as well as the nature of the corresponding 4D dynamics (duality with warping).

**Summary:** In this work, we considered the possibility that the UV scale of warped 5D models could be well-below the 4D scale of gravity \( M_P \). In this case, one could still achieve a natural though smaller hierarchy between a high UV scale and the weak scale. These truncated LRS backgrounds can accommodate realistic warped flavor models that are free from some of the constraints that exist when the UV scale is near \( M_P \). At the same time, the truncated models offer greatly improved LHC discovery prospects. We concentrated on the neutral \( Z' \) resonances that arise in warped models with bulk custodial symmetry. We found that for sufficiently truncated yet viable models (\( M_5 \sim 10^4 \) TeV), the LHC discovery of a 2(3)-TeV Little \( Z' \) in the experimentally clean \( e^+e^- \) and \( \mu^+\mu^- \) channels may require only about 1 (4) fb\(^{-1}\), at \( \sqrt{s} = 10 (14) \) TeV. At \( \sqrt{s} = 14 \) TeV, with \( O(100) \) fb\(^{-1}\), the corresponding reach is about 5 TeV, well into the region allowed by EW precision data. For similar truncations, one may be able to discover the second level resonance \( Z'' \) in the same channels. The precision afforded by the di-lepton final states can then result in determining the ratio of \( Z' \) and \( Z'' \) masses. The sensitive dependence of the cross section for \( pp \rightarrow Z' \rightarrow \ell^+\ell^- \) on truncation allows one to probe the size of the hierarchy generated by the 5D gravitational redshift (4D conformal dynamics). If the masses of successive resonances can be measured, as may be the case in LRS models, the warped nature of the 5D picture can also be corroborated. We also considered the expected enhanced discovery prospects for other KK modes, such as KK gluons, in truncated models. Significant enhancements in the reach for warped Little \( W' \) resonances \([32]\), based on considerations similar to those presented above may also be expected. Even though the experimental prospects for Little KK gluons improve considerably, our analysis suggests that they do not offer a
substantial advantage for early detection, compared to the leptonically decaying Little $Z'$ modes; this is due to our conservative assumptions regarding the early reconstruction efficiency for the $t\bar{t}$ final state, which will presumably improve once the experiments mature. In any event, a more detailed study using improved boosted topjet reconstruction techniques may enhance the Little KK gluon early detection prospects.

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APPENDIX

Here, we present the set of approximate expressions for the couplings of various fermions to the gauge first KK modes, used in our analysis. The following are in units of the appropriate SM gauge couplings. With $\xi \equiv \sqrt{kr_p}\pi$, for $t_R$ and $(t, b)_L$ we take [12]

$$-1.13/\xi + 0.7\xi$$

and

$$-1.13/\xi + 0.2\xi,$$

respectively. For all other fermions we assume

$$-1.13/\xi.$$ [A.9]

We note that these formulas were used only as a rough guide to the behavior of the couplings under truncation. However, in principle, a more detailed study would choose different fermion profiles at different values of $kr_p\pi$. Sample profiles for the case $kr_p\pi \sim 7$ have been provided in Refs. [17, 18].

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