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LHC Signals from Warped Extra Dimensions

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Abstract

We study production of Kaluza-Klein gluons (KKG) at the Large Hadron Collider (LHC) in the framework of a warped extra dimension with the Standard Model (SM) fields propagating in the bulk. We show that the detection of KK gluon is challenging since its production is suppressed by small couplings to the proton's constituents. Moreover, the KK gluon decays mostly to top pairs due to an enhanced coupling and hence is broad. Nevertheless, we demonstrate that for $M_{KKG} \lesssim 4$ TeV, 100 fb^{-1} of data at the LHC can provide discovery of the KK gluon. We utilize a sizeable left-right polarization asymmetry from the KK gluon resonance to maximize the signal significance, and we explore the novel feature of extremely highly energetic "top-jets". We briefly discuss how the detection of electroweak gauge KK states (Z/W) faces a similar challenge since their leptonic decays ("golden" modes) are suppressed. Our analysis suggests that other frameworks, for example little Higgs, which rely on UV completion via strong dynamics might face similar challenges, namely (1) Suppressed production rates for the new particles (such as Z'), due to their "light-fermion-phobic" nature, and (2) Difficulties in detection since the new particles are broad and decay predominantly to third generation quarks and longitudinal gauge bosons.

I. INTRODUCTION

Solutions to the Planck-weak hierarchy problem of the SM typically invoke new particles charged under the SM at the TeV scale. The lore is that such particles will be readily accessible at the LHC, especially the strongly interacting ones. In this paper, we consider the solution to the hierarchy problem based on the Randall-Sundrum I (RS1) framework of a warped extra dimension [1]. Specifically, we consider this framework with the SM gauge and fermion fields propagating in the bulk of the warped extra dimension, which provides a solution to the flavor puzzle of the SM as well. We focus on detecting the Kaluza-Klein (KK) partner of the SM gluon at the LHC – as we explain, KK gluon is probably the best channel to probe the RS1 framework. We show that, despite it being strongly interacting, it is quite challenging to see a signal from this particle with a mass of several TeV at the LHC. The reason is related to the special (but well-motivated) nature of its couplings which are non-universal and are "proton-phobic". The consequence of such couplings is that our signal (an excess of top pairs) is comparable in size to the SM background. With the techniques developed herein, it should be possible to extract a signal for the KK gluon (in this framework) at the LHC with $\simeq$ 100 fb^{-1} of data.

The framework involves a slice of AdS$_5$ [1]. Due to the warped geometry, the relationship between the $5D$ mass scales (taken to be of order the $4D$ Planck scale) 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 protected by a warped-down fundamental scale of order TeV. This large hierarchy of scales can be generated via a modest-size radius of the extra dimension. Furthermore, based on the AdS/CFT correspondence [2], the RS1 model is conjectured to be dual to $4D$ composite Higgs models [3]. Hence, our results might apply in general to $4D$ models with TeV-scale strong dynamics driving electroweak symmetry breaking (EWSB).

In the RS1 model, the entire SM (including the fermions and gauge bosons) is assumed to be localized on the TeV brane. The higher-dimensional operators in the $5D$ effective field theory (from cut-off physics) are suppressed only by the warped-down scale $\sim$ TeV, giving too large contributions to FCNC processes and observables related to SM electroweak precision tests (EWPT). Moreover, this set-up provides no understanding of the flavor puzzle.

An attractive solution to this problem is to allow the SM fields to propagate in the extra dimension [4, 5, 6]. In this 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 cut-off at the location of these fermions [6, 7]. Similarly, contributions to EWPT 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 [5, 6, 7]. 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 coupling.

In this scenario, there are new contributions to EWPT and FCNC's calculable in the $5D$ effective field theory (EFT) from KK modes. In particular, the couplings of SM fermions to gauge KK modes are non-universal due to the different profiles for the SM fermions, resulting in FCNC's. However, the gauge KK modes are localized near the TeV brane while the light fermions are near the Planck brane and hence it can be shown that the non-universal part of these couplings are proportional to the SM Yukawa couplings [6, 7]. Thus, most of the couplings to the new degrees of freedom are small and hierarchical, leading to the same symmetry structure which suppresses the SM flavor-violating contributions [8] (for recent related discussions and the experimental status see [9]). The gauge KK modes also give contributions to EWPT. The constraints from the oblique (S and T) parameters can be satisfied with a KK mass scale as low as ~ 3 TeV if a custodial isospin symmetry is incorporated [10].

Let us examine the top/bottom sector in detail since the associated couplings will be relevant for the signals. It is clear that both $t_{L,R}$ being near the Planck brane gives too small a top Yukawa coupling. On the other hand, the fact that $(t,b)_L$ is close to the TeV brane leads to its large coupling to KK Z and, in turn, results in a non-universal shift in its coupling to the SM Z via mixing of KK Z with zero-mode Z [10]: $\delta g_Z^{b_L} \sim g_{Z^{\rm KK}}^{b_L} \xi \frac{m_Z^2}{M_{KKZ}^2}$ where $\xi \equiv \sqrt{\log\left(M_{Pl}/\ \text{TeV}\ \right)}$ and $g_{Z^{\rm KK}}^{b_L}$ is the corresponding non-universal KK Z coupling. The constraint from data is that $\delta g_Z^{b_L}/g_Z \lesssim 1/4\%$.

Thus, for a KK scale $\simeq$ a few TeV, there is a tension between obtaining large top mass and EWPT (i.e., $Z\bar{b}_L b_L$ coupling) which can be relaxed by the following setup: (i) $(t,b)_L$ quasi-localized near TeV brane so that the shift in coupling of b_L to Z is on the edge, (ii) t_R localized very close to TeV brane to obtain large top quark mass and (iii) largest dimensionless $5D$ Yukawa consistent with perturbativity. Note that the resulting coupling of b_L to gauge KK modes (including gluon) is comparable to the SM couplings and thus is still larger than what is expected on the basis of m_b alone, since it is dictated by the large top mass instead. Even with these choices, the KK scale is required to be rather high, $\lesssim$ 5 TeV. In this case, the couplings of t_R, which is localized very near the TeV brane, to the gauge KK modes are enhanced: $g_{\rm SM^{KK}}^{t_R} \sim g_{\rm SM}\xi$.

However, such corrections to $Z\bar{b}_L b_L$ coupling can be suppressed by suitable choice of representation of top and bottom quarks under the custodial isospin symmetry [11]. In this case, we can have the other extreme situation: $(t,b)_L$ can be localized very close to the TeV brane with t_R being close to flat. Also, there is an intermediate possibility with both $(t,b)_L$ and t_R being localized close (but not too close) to the TeV brane. The KK scale can then be as low as ~ 3 TeV for certain choice of profiles for t_R and $(t,b)_L$ in the extra dimension [12].

In this paper we will consider models with the assignment of reference [10] for the quantum numbers of top and bottom quarks. Based on the above profiles, it can be shown that the couplings of KK gluon (and in general all gauge KK modes) to light fermions (including b_R) are suppressed by ξ with respect to the SM gauge couplings. The coupling to t_L, b_L is neither suppressed nor enhanced and only the coupling to t_R (which is practically on the TeV brane or composite in the dual $4D$ picture) is enhanced by ξ. It can also be shown that there is no coupling of single KK gauge field to two SM gauge bosons at leading order due to orthonormality of profiles of these particles. To summarize (see for example [8] for more details) the relevant coupling to the KK gauge states can be described, neglecting effects related to EWSB, via ratio of RS1-to-SM gauge coupling

$$\begin{aligned} \frac{g_{\rm RS}^{q\bar{q},l\bar{l}\,G^1}}{g_{\rm SM}} &\simeq \xi^{-1} \approx \frac{1}{5}\,, \quad \frac{g_{\rm RS}^{Q3\bar{Q}3G^1}}{g_{\rm SM}} \approx 1\,, \\ \frac{g_{\rm RS}^{t_R\bar{t}_R G^1}}{g_{\rm SM}} &\simeq \xi \approx 5\,, \quad \frac{g_{\rm RS}^{GGG^1}}{g_{\rm SM}} \approx 0\,, \end{aligned} \tag{1}$$

where $q = u, d, s, c, b_R$, l = leptons, $Q^3 = (t,b)_L$, G, G^1 correspond to SM and first KK states of the gauge fields respectively and $g_{\rm RS}^{xyz}, g_{\rm SM}$ stands for the RS1 and the three SM (i.e., $4D$) gauge couplings respectively.

It is straightforward to modify our analysis as to accomodate generic couplings of the KK gauge fields to the SM third generation quarks. This will cover the signals of models with custodial symmetry for $Zb\bar{b}$ [11]. However, we choose to show the explicit results within one scenario to make the steps of our analysis and our results more transparent. A brief discussion of the signals in the case where the custodial symmetry for $Zb\bar{b}$ [11] is realized is given in section III A.

We will mostly focus on LHC signals from KK gluons which have the largest production rate. The KK mass scale is assume to be $\simeq$ a few TeV. In cases where a specific mass was required for our analysis a 3 TeV mass was used. We also briefly discuss other interesting signals related to the electroweak gauge KK sector whose detection might be more challenging than KK gluon, partly due to lower production rates than for KK gluons and also due to suppression of decays to "golden" modes such as leptons. In general, the EW sector is also more model dependent. Earlier studies of KK gluon production at the LHC [13, 14] did not consider the effect of the fermion profiles which now is understood to be mandatory for the phenomenological viability of the framework.

II. LHC SIGNALS

The primary challenge in obtaining a signal at the LHC for gauge KK modes is that the production is suppressed due to the small couplings to the proton constituents as seen in Eq. 1.

We used both CalcHEP 2.42 [15] and Sherpa version 1.0.8 [16] [1] for the numerical calculations. The CTEQ6M parton distribution function (PDF) with the QCD renormalization and factorization scales equal to the KK gluon mass (M_{KKG}) was used in CalcHEP 2.42. The CTEQ6L1 PDF set was used in Sherpa, employing a running scheme for α_S with $\alpha_S(M_Z) = 0.118$. We find that the results do not change significantly between the two PDF sets [2].

For KK gluons, CalcHEP yields a moderate cross-section of $\sim 100\,\text{fb}$ for $M_{KKG} \sim 3\,\text{TeV}$ as indicated in Fig. 1. The cross section falls very quickly for higher KK masses, where for $M_{KKG} \sim 5$ TeV the cross-section drops to ~ 10 fb - probably beyond the reach of LHC (as discussed below). The dominant production mechanism is through $u\bar{u}, d\bar{d}$ annihilation. We note the production rate for the EW KK gauge fields is suppressed by $(g_Z/g_{QCD})^2$ relative to KK gluon production.

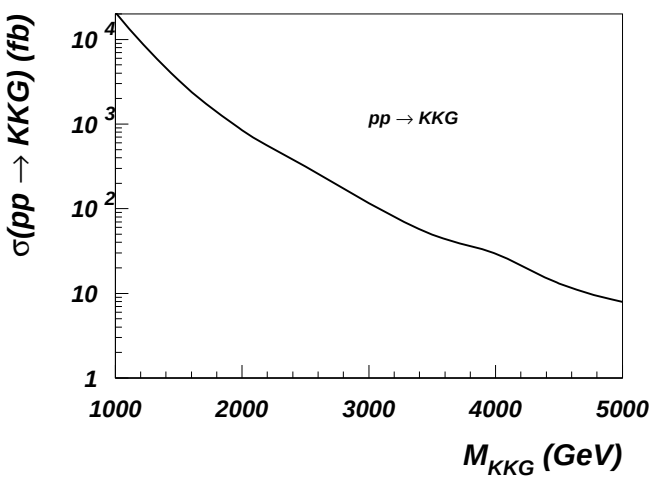

FIG. 1: The total cross section of KK gluon production at the LHC as a function of its mass (M_{KKG}).

Another challenge is that, based again on the couplings in Eq. 1, the fermionic decays of the gauge KK particles (in general) are expected to be dominated by the 3rd generation quarks, especially the top quark, due to enhancement of the corresponding couplings. For example, the branching ratios for KK gluon decay are shown in Fig. 2. In the case of EW gauge KK modes (W/Z), decays to

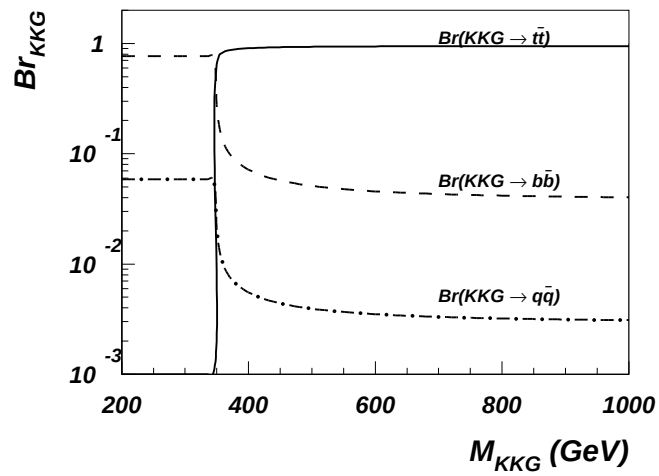

FIG. 2: The branching ratios of the KK gluon as a function of its mass.

longitudinal weak gauge bosons and the Higgs field are also important due to similarly enhanced couplings. In particular, the leptonic decay channel for KK Z is highly suppressed. In the absence of golden decays modes for KK Z/W, we focus on signals for the KK gluon which has the larger production cross-section. [3]

A third challenge is related to the fact that due to the strong coupling to top pair (and in case of KK W/Z to Higgs and longitudinal W/Z), a heavy gauge KK mode is rather broad. For example, a KK gluon above 1 TeV (as required by precision tests) has decay width of about $M_{KKG}/6$ as presented in Fig. 3. Decay widths of KK Z/W are smaller by $\sim (g_Z/g_{QCD})^2$. This large width of KK gauge states creates additional problems for discriminating signal against the background.

A. KK gluons

In the interesting region of M_{KKG}, well above the $t\bar{t}$ threshold, the KK gluon decays mainly to $t\bar{t}$ with the branching ratio of about 95% (see Fig. 2). Hence, our main focus here will be on the (ultra-relativistic) $t\bar{t}$ pairs from decays of KK gluons. [4] Within the SM there are two dominant production mechanisms for $t\bar{t}$, namely gg (gluon fusion) and $q\bar{q}$ (quark pair annihilation). At the LHC, $t\bar{t}$ production proceeds primarily

[1] The authors are grateful to the Sherpa team, especially Tanju Gleisberg, for the help in embedding the RS1 KK gluon into Sherpa.

[2] This should not be interpreted as indication of small uncertainties due to PDF's in the cross section since the two PDF sets might be correlated. One of the main points of our study is to identify observables which depend rather weakly on the PDF's uncertainties.

[3] For a related work on KK gluon but with universal couplings see [13, 14].

[4] For the decays of KK gluon to light quarks (which has small BR in any case), the SM QCD background will also be very large.

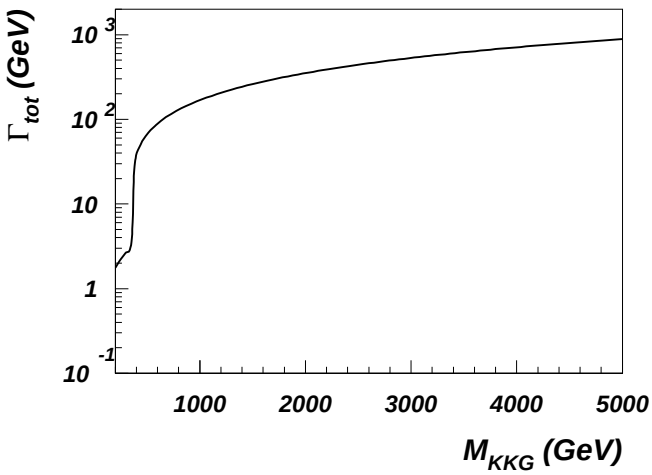

FIG. 3: The total decay width of KK gluon as a function of its mass

through gluon fusion [17]. [5] $t\bar{t}$ (top pair) production near threshold has been extensively studied (see *e.g.* [18] and references therein). Away from threshold, this simple picture is modified due to the presence of states of higher angular momentum. In the other extreme, ultra-relativistic case ($m_{t\bar{t}}^2 \gg 4m_t^2$) which is the focus of this paper, another rather simple and very interesting description emerges [19]. We make use of the fact that in this limit the SM effects related to EWSB are small and also the top quark chirality is conserved (the relevant issues are discussed below when the polarization asymmetry is studied).

The crucial point is that we find, unlike the case in previous studies [13, 14], the cross-section for SM $t\bar{t}$ production (in the region $m_{t\bar{t}} - M_{KKG} \sim \pm\Gamma$) is *comparable* to $t\bar{t}$ production from KK gluons. Moreover, the SM cross-section has a large uncertainty from gluon PDF's in the large x-region [20]. Hence, even with M_{KKG} lighter than 5 TeV obtaining a clear and robust signal is a non-trivial task. In particular, a simple "number-counting" experiment is not enough. We follow a multi-step strategy to get clear and significant results. We first consider the differential top pair cross-section. Then we analyse a left-right polarization asymmetry, expected to have a clean and robust prediction for ultra-relativistic top quarks [19] in the SM and our framework. The combination of the two observables yields a powerful tool to probe our class of models.

[5] In the region of interest here, i.e., $m_{t\bar{t}}^2 \approx (3\text{ TeV})^2$, the rate for gluon fusion into top pairs in SM is roughly 4 times larger than the $q\bar{q}$ annihilation rate.

1. Event Generation and Jet Reconstruction

Sherpa version 1.0.8, using a customized class to implement the appropriate vertices, was used to generate events, using LHC parameters. A cone jet algorithm with $\Delta R = 0.4$ [21], or C4 for short, was used to reconstruct jets ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$). Events were generated with cross sections calculated to leading order. We do not analyze the effects of pile-up, nor characterize the underlying event. In addition, we do not include detector effects.

2. Details of analysis

In this section, we discuss in more detail how we performed our analysis. Our preferred reconstruction mode is $t\bar{t} \to b\bar{b}jjl\nu$ (semileptonic), whose signature we refer to simply as "*lepton+jet*" (lj). We use the terms hadronic- and leptonic tops to refer to those quarks which decay into the hadronic mode and leptonic modes, respectively. We focus primarily on the SM irreducible background from $t\bar{t}$ production and discuss several crucial aspects of the dominant reducible background, W+jets and single top production.

For the leptonic side reconstruction, we searched for high P_T leptons, presumably excluded from jets. We will refer to this condition as isolation, and we will discuss this point in more detail below. We assumed that the W from the decay of a top quark further decayed leptonically, inferring an (undetected) neutrino to account for the missing transverse energy. A b-jet was required to combine with the W to form an on-mass-shell top quark, via an invariant mass condition ($m_{Wb} = M_t^{lep} = M_t \pm 50\,\text{GeV}$).

We now develop the methods of hadronic side reconstruction, but we must first place them in context. The extremely energetic nature of the top quarks in our signal ($P_T > 1\,\text{TeV}$) leads us to deviate from the hadronic top reconstruction methods (see *e.g.* [22]), where they studied $t\bar{t}$ production with $m_{t\bar{t}} \lesssim 600\,\text{GeV}$. [6] Top quarks with $P_T > 1.0$ TeV tend to produce highly collimated jets. We focused on the C4 algorithm, which will not resolve higher jet multiplicities in high P_T $t\bar{t}$ events. Reducing the cone size to $R = 0.2$, for example, only masks this issue, and we eventually succumb to the same problem. This renders the hadronic top quark ($t \to bjj$) reconstruction mode in [22] far too inefficient for our purposes. Note also that the ΔR lepton to b-jet isolation criterion (from the leptonic top) falls into this trap for the same reasons. We propose a different strategy as follows:

(1) In searching for an isolated lepton, we modify the (ΔR) leptonic top reconstruction mode (see *e.g.* [22]), augmenting the lepton to b-jet isolation criteria with an

[6] The energy regime $P_T \gtrsim 600\ GeV$ for jet reconstruction has not been extensively studied.

energy scale-invariant cut. The lepton is considered isolated from a given jet (light jet, b-jet, etc.) if they are separated by an angular distance $\Delta R > 0.4$. If a lepton is found inside the cone of a b-jet, the lepton is removed from the b-jet and the b-jet is reclustered, in which case the invariant mass of the lepton and b-jet system must satisfy $m_{bl} > 40\,\mathrm{GeV}$. m_{bl} provides a measure of the relative transverse momentum between the lepton and the b-jet. So, for b-quark and lepton isolation we apply $\Delta R > 0.4$ *or* $m_{bl} > 40\,\mathrm{GeV}$ cut, while $\Delta R = 0.4$ isolation criterion between lepton and all other jets remains in effect.

(2) If the jet multiplicity allows (2 b-jets and ≥ 2 light jets), we require that the invariant mass of the light jets reconstruct a W according to parameters in Table I. The invariant mass, M_t^{had} of the (W + hadronic b-jet)-system is required to reconstruct a top quark according to parameters is Table I.

In a dijet event with 1 b-jet, if the other jet has $P_T > 800$,GeV, we tag it as "top (or t)-jet", keeping only ϕ, η and transverse energy information from the reconstruction. [7] We *impose* a top-mass hypothesis on the jet, setting $M_{jet} \to M_{top} = 174.3\,\mathrm{GeV}$.

$$\begin{aligned} P_x &= P_T \cos(\phi) \\ P_y &= P_T \sin(\phi) \\ P_z &= P_T \sinh(\eta) \\ M &= \sqrt{E^2 - P^2} \to 174.3\,\mathrm{GeV} \end{aligned}$$

The t-jet reconstructed mode dominates the reconstructed signal for $m_{t\bar{t}} \gtrsim 2$ TeV ($m_{t\bar{t}}$ stands for the top pair invariant mass). We recuperated a large sample of signal events that we otherwise would have lost via more conventional reconstruction methods. It would appear the top jet approach would introduce a large background from such processes as W+jets (Wjj) and single top production, especially since we relax the b-jet tagging on the hadronic side. The P_T cut is crucial in reducing this background to almost negligible levels. We examined the effect of the background by simulating the largest possible sources Wjj (the dominant background), using both CalcHep and Sherpa. We found that the cross section that satisfies our preselection cuts, $m_{Wj_1} = m_t \pm 50\,\mathrm{GeV}$, $p_{Tj_2} > 800\,\mathrm{GeV}$ and the relevant KKG mass window $2.5\,\mathrm{TeV} < m_{Wjj} < 3.5\,\mathrm{TeV}$ is 25fb. Applying a b mistag probability of 3% (see [13]) and leptonic BR of 2/9 for W further reduced this cross section to about 0.2 fb. We compare this to our top pair production cross section (signal+background) satisfying these cuts of 80 fb which is reduced to about 5 fb after applying b-tagging and including BR's (see details below). Thus, we conclude the Wjj background to be small. We found that $Wb\bar{b}$ and single top production with these same cuts have even smaller cross section than Wjj after including BR and b-tagging efficiency. The results of our particle level analysis can be seen in Fig. 5.

Following the procedure in [22], the neutrino is reconstructed using a zero transverse momentum hypothesis on the event, with the neutrino carrying away the missing momentum. We required the lepton and neutrino to reconstruct an on-mass-shell W ($M_{l\nu} = M_W = 81\,GeV$). This information is sufficient to reconstruct the neutrino momentum, modulo a quadratic ambiguity. In the case where we obtain two solutions, we used the one which better reconstructs the top ($|M_W^{lep} - M_{top}| < 50\,\mathrm{GeV}$). Additional studies, beyond the scope of this work, are required to characterize the effects of W reconstruction when the lepton and neutrino are nearly collinear at high energies. We address this issue by noting that in our data sample, we were able to impose a $\Delta R = 0.15$ separation between the lepton and neutrino with minimal loss of statistics. The cuts and other kinematical constraints are summarized in Table I.

In the following sections, we present our results from both partonic- and particle-level analyses. We shall see that these two analyses are consistent with each other, and that no significant bias was introduced due to our selection cuts or reconstruction procedures. [8] We remind the reader that we did not perform detailed detector simulation and hence, have not included the resulting smearing effects. We expect that, due to the nature of our kinematical region, the dominant smearing will be of $\mathcal{O}(3\%)$ (see *e.g.* [23]) which will induce small corrections to our mass resolution. A study of how the detector effects will modify the polarization asymmetry (discussed below) is beyond the scope of this work and will discussed in [19].

Selection	**Variables**	**Cuts**
Kinematic and acceptance	lepton	$p_T > 10\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$
	≥ 2 jets	$p_T > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$
	tagged b-jets	≥ 1
	missing energy (ν)	$p_T^{miss} > 20$ GeV
	lepton isolation	$\Delta R \geq 0.4$ (non-b-jets)
	b-jet lepton isolation	$\Delta R \geq 0.4$ *or* $m_{bl} \geq 40$ GeV
Reconstruction quality for #jets> 2, 2 b-jets required	$\lvert M_W^{\mathrm{had}} - M_W\rvert$	< 50 GeV
	$\lvert M_t^{\mathrm{had}} - M_t\rvert$	< 50 GeV
	$\lvert M_t^{\mathrm{lep}} - M_t\rvert$	< 50 GeV
Reconstruction quality a b-jet+t-jet	$\lvert M_t^{\mathrm{lep}} - M_t\rvert$	< 50 GeV
	"top-jet"	$p_{Tt} > 800$ GeV

[7] In principle, a more sophisticated analysis would consider substructure resolution within this jet. The authors thank Frank Paige for discussions on this issue.

[8] The lepton P_T and m_{bl} cuts are particularly scrutinized. Their impact on phase space will directly affect our polarization analysis.

TABLE I: *Selection cuts in the semileptonic $t\bar{t}$ channel.*

3. *Differential cross section*

The SM top pair production rate falls steeply as a function of the invariant mass. The uncertainty from PDF's in this *shape* is far less than that in the total cross-section. Hence we look for a signal from KK gluons in the *differential* $t\bar{t}$ cross-section as opposed to simply counting the total number of $t\bar{t}$ events. We do not expect a sharp resonance in this distribution due to the large width of the KK gluon, but we do obtain a statistically significant "bump" as discussed below.

The differential cross section as a function of $m_{t\bar{t}}$ is shown in Figs. 4 and 5 for $M_{KKG} = 3\,\text{TeV}$ produced at the LHC. In Fig. 4 we compare the total (signal + background) distribution to the SM (background) distribution, based on a partonic-level analysis. In Fig. 5, we focus on the area near the peak and we consider contributions from the reducible background (from Wjj). We show the particle level results and the corresponding statistical uncertainties of event reconstruction. The predictions for the SM and SM+RS models, based on partonic-level analysis (same as in Fig. 4), are also shown for comparison. We see that, since the partonic and particle level data are consistent with each other, we do not expect a large bias in the ability to reconstruct the KKG mass.

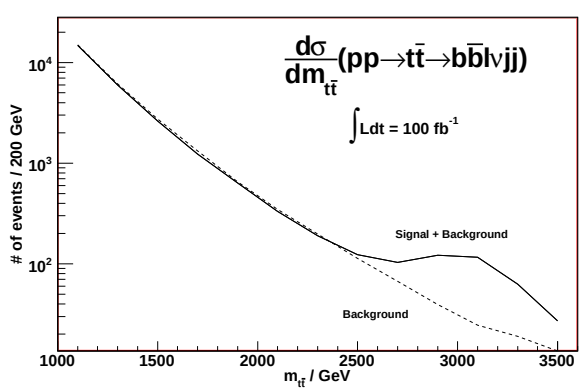

FIG. 4: Invariant $t\bar{t}$ mass distribution for $M_{KKG} = 3\,\text{TeV}$ production at the LHC. The solid curve presents signal+background distribution, while the dashed curve presents the $t\bar{t}$ SM background, based on partonic level analysis.

In the following we describe the reconstruction efficiency and how we estimate our signal to background ratio and the sensitivity to the KK gluon mass based on this analysis. Following [13], we assume a 20% efficiency

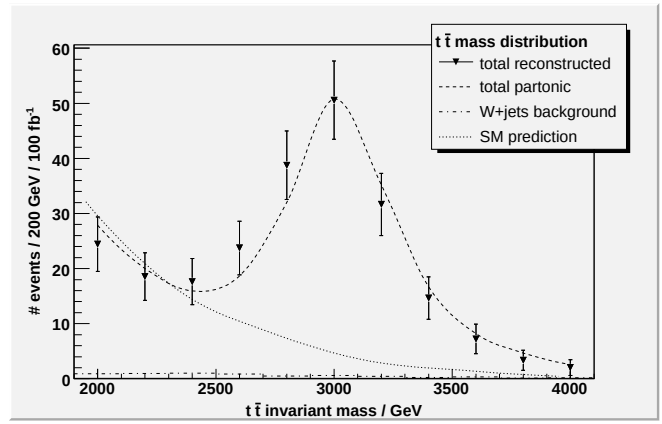

FIG. 5: Invariant $t\bar{t}$ mass distribution for 3 TeV KKG, focusing on the area near the peak. The error bars correspond to statistical uncertainties and represent our particle level analysis. The dotted line stands for the SM prediction. The dashed-dotted line shows the Wjj background. The dashed line shows the signal+background from Sherpa's partonic level analysis.

for tagging b-jets (ϵ_b), independent of the b-jet energy. Our particle level study shows that the efficiency of the additional cuts described, ϵ_{cut}, in Table I for the reconstruction of $t\bar{t}$ system in the mass window around KKG is about 20(21)% for $m_{t\bar{t}} = 3(4)$TeV. We find that for the SM the reconstruction efficiency is lower, 9(10)% for $m_{t\bar{t}} = 3(4)$ TeV. The signal+background (BG+KKG) and background (BG) reconstruction efficiencies differ because the BG and BG+KKG events have different kinematics. The background is dominated by gg fusion events which are more forwardly-peaked in the top pair center of mass (cm) frame than the $q\bar{q}$ fusion events. Hence, the gg events have a smaller P_T[9] than the $q\bar{q}$ events. Since KK gluon signal comes only from $q\bar{q}$ fusion, the p_T cut on the top-quark reduces background more than the signal.

In addition, the branching ratio for the lj decay is given by $BR_{lj} = 2 \times 2/9 \times 2/3 \simeq 0.3$. The total efficiency is given by $BR_{lj} \times \epsilon_{\text{cut}} \times \epsilon_b \sim 1\%$.

We estimate the statistical significance of our signal by looking at the bump. An invariant $t\bar{t}$ mass window cut $0.85M_{KKG} < M_{t\bar{t}} < 1.5M_{KKG}$ is applied. The lower bound corresponds roughly to the width. The upper bound is not particularly important due to the steep falloff in cross section. Below the M_{KKG} threshold, the signal+background distribution is actually below the background one due to destructive interference. Therefore, we choose an asymmetric mass window cut. We estimate the ratio of the signal, S, to the statistical error in the the background, $\sqrt{B}$, via our particle level

[9] Note that, inside the mass window, the total momentum/energy of each top quark in cm frame is roughly fixed at $M_{KKG}/2$.

analysis in the mass window, for 100 fb^{-1} We find

$$S/\sqrt{B} \approx 11.0 \quad \text{for} \quad M_{KKG} = 3\,\text{TeV}\,,$$
$$S/\sqrt{B} \approx 4.2 \quad \text{for} \quad M_{KKG} = 4\,\text{TeV} \tag{2}$$

In addition we find the following values for signal over background:

$$S/B \approx 2.0 \quad \text{for} \quad M_{KKG} = 3\,\text{TeV}\,,$$
$$S/B \approx 1.6 \quad \text{for} \quad M_{KKG} = 4\,\text{TeV} \tag{3}$$

where the total number of events inside the mass window for $M_{KKG} = 4\,\text{TeV}$ that pass all cuts is $\mathcal{O}(10)$. Thus for 100fb^{-1} we estimate the LHC reach to be below 4 TeV for the KK gluon mass. We discuss below the use of discriminators which may improve this analysis. One should stress that Figs. 4 and 5 demonstrate a clear evidence for a bump in the differential cross-section. Such a deviation in shape from the background distribution as well as good $S/B \simeq 2$ ratio guarantee that the KKG signal will be clearly seen for M_{KKG} below about 4 TeV. A more sophisticated analysis could possibly improve further the significance and signal-to-background ratio.

4. *Polarization asymmetry*

We now consider how measurement of the polarization of the ultra relativistic top pairs provides us with an important tool for detection of the KK gluon. The fact that the KK gluon decays mostly into two tops turns out to be advantageous because the top quark decays before it hadronizes. Therefore, the top spin/chirality information is encoded in the distribution of its decay products. Moreover, since we are dealing with very energetic top quarks, their masses can be neglected and their chirality is conserved. The SM top pair production is dominated by parity invariant QCD processes, so we expect to generate an (almost) equal number of left- and right-handed pairs. However, in the RS1 model that we are considering, we expect a strong bias towards RH tops (from KK gluon decays) so a *large* left-right (LR) asymmetry is expected.

We can include EW production processes in the SM. Note that in the ultra-relativistic case we can neglect effects related to EWSB. In this case, the SM EW production processes can be characterized by the hyper-charge and weak coupling separately. The latter is stronger and couples only to LH particles [19]. Thus we get a sharp prediction that the deviation of P_{LR} from zero in the SM (due to EW processes) carries the opposite sign compared to the above RS1 KK gluon signal (again, in the latter, the RH top dominates). The EW processes can only be mediated via $q\bar{q}$ annihiliation processes. To summarize, the SM P_{LR} is suppressed by $g_2^2/g_{QCD}^2 \sim 0.35$ and the ratio between the $q\bar{q}$ and gg production rates[10] and, hence is much smaller than the $O(1)$ asymmetry expected in the RS1 model from KK gluon decays, in addition to having the opposite sign to the RS1 signal.

The RS1 prediction can be tested via measurement of P_{LR} of the top pairs sample as follows. The angular distribution of the positron from a purely RH and LH top quark decay is given by[22, 24]:

$$\frac{dN}{d\cos\theta} \sim (1 \pm \cos\theta) \tag{4}$$

where θ is angle between the positron direction in the *rest* frame of the top and the direction of the top quark boost (in the parton/$t\bar{t}$ center of mass frame).[11] It is useful to define the *polarization asymmetry* via a "forward-backward" asymmetry as

$$P_{LR} \equiv 2 \times \frac{N_+ - N_-}{N_+ + N_-}, \tag{5}$$

where $N_+ \equiv \int_0^{\pi/2} d\cos\theta dN/d\cos\theta$ is the number of positrons emitted (in the rest frame of the top) along the direction of the top quark boost (and similarly for N_-). For purely RH (LH) top quark, we get $P_{LR} = \pm 1$.

We used Sherpa, which supports spin/helicity amplitudes, to numerically analyze the signal and background. As mentioned above, the asymmetry is measured relative to the direction of the top quark boost in the center of mass frame of the top pair. The challenge here is to reconstruct the top rest frame from observables in the event. The lepton is boosted into the cm frame, and subsequently reboosted into the top quark rest frame, using essentially the P_T of the top quark.

The LR polarization asymmetry as a function of $m_{t\bar{t}}$ is shown in Fig. 6 for $M_{KKG} = 3\,\text{TeV}$ with $100\,\text{fb}^{-1}$ data. The error bars correspond to statistical uncertainties and represent our particle level analysis using Sherpa. We also show the signal+background from partonic level analysis using Sherpa.

Note that the leptons from t_R tend to be emitted in the forward direction, whereas the opposite is true for leptons from t_L. Therefore, the P_T cut of the lepton will non-trivially impact the asymmetry, due to the kinematics and small masses of the leptons. We chose a P_T cut of 10 GeV, whose effects were manageable as we checked via Monte Carlo simulations.

We see that the partonic and particle level data are consistent with each other. Therefore, we have not introduced any significant bias in the observed asymmetry as a result of the above cuts and reconstruction procedure. We remind the reader that we do not characterize herein the detector effects on the P_{LR}, which will add to the

[10] this is probably the only source of uncertainty for the value of this asymmety.

[11] the latter is also the top spin quantization axis.

uncertainty in reconstruction of the $t\bar{t}$ cms and top rest frame.

Note that for $m_{t\bar{t}} \ll M_{KKG}$ the asymmetry is negative and close to zero (for both curves) as expected since the SM production is dominant here [19]. On the other hand, for $m_{t\bar{t}} \sim M_{KKG}$, a sizable asymmetry is obtained for the signal+background curve with a *positive* sign which implies a significant excess of RH $t\bar{t}$ as expected in the RS1 model [8, 10]. Correlated observations of such a sizable asymmetry and an excess in the differential cross-section for the *same* $m_{t\bar{t}}$ (as in Figs. 4 and 5) will be a strong evidence for a KK gluon. Also, the asymmetry for SM background increases (but still remains small) with $m_{t\bar{t}}$ since the ratio of $q\bar{q}$ fusion (which gives the asymmetry) to gg fusion (which is symmetric) increases with higher $m_{t\bar{t}}$.

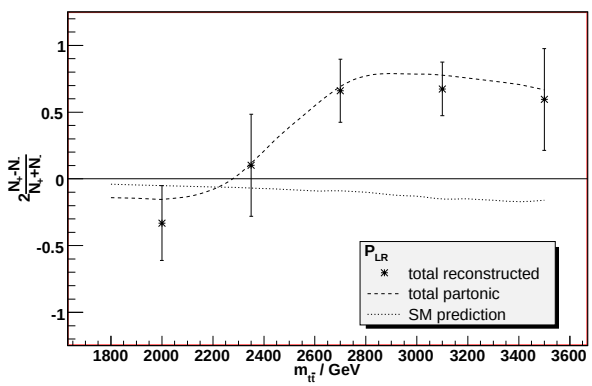

FIG. 6: $P_{LR}(m_{t\bar{t}})$ for $M_{KKG} = 3\,\text{TeV}$: The error bars correspond to statistical uncertainties and represent particle level analysis. The dotted line stands for the SM prediction. The dashed line shows the signal+background from Sherpa's partonic level analysis.

As already mentioned, we are in the relativistic limit for the tops produced from the KK gluon so that the spins of the top pair are correlated, independent of RH or LH dominating in the KK gluon decay (this holds for any chiral theory). Therefore, an analysis similar to that for the lepton from t decay (mentioned above) can be applied for the b and light jets emitted from $\bar{t}$ decay on the other side (although these decay products are not as powerful spin analysers as the lepton). This would further increase the statistics and the significance of our signal. The required analysis is more involved and beyond the scope of this work. However, we expect that such an analysis, even though less precise, may allow us to eliminate some of the uncertainties due to biases and other systematic effects.

5. *Signal versus background optimization*

As we already indicated in section II A 3, the P_T cut reduces background more as compared to signal. In this section, we discuss possible *additional* cuts which can be applied to the analyses of the differential cross-section and P_{LR} to improve the significance of our results.

A cut on the forwardness of the $t\bar{t}$ pairs in cm frame is useful for removal of the background. The reason is that (as already mentioned in section II A 3) the top quarks produced from gluon fusion (via top t-channel exchange) tend to be more forwardly-peaked than the ones produced from $q\bar{q}$ annihilation. KK gluons are produced only through $q\bar{q}$ annihilation, whereas the SM background is dominated by gg fusion. Therefore, an appropriate cut on η^* (rapidity in cm frame) of each top quark will eliminate a substantially larger part of the SM QCD background, at the expense of a smaller fraction of the signal.

We applied the cut $|\eta|^* < 1.8$ to find that it has virtually no effect on the signal (as desired and as expected). Whereas, we find that the SM background reduced (and hence our significance increased) by only $O(10\%)$, perhaps unlike the expectation of a more significant reduction in background. The reason is that we find the P_T cut on hadronic top (the top jet), which is part of our event selection cuts, and the $|\eta|^* < 1.8$ cut to be correlated (as expected from the discussion in section II A 3).

Note that the only reason we included this P_T cut as part of our event selection was that we could not reconstruct the hadronic top in the conventional manner. With a more sophisticated analysis for reconstruction of the hadronic top (for example, resolving sub-structure in top-jet as mentioned before), this P_T cut might *not* be required as part of event selection. In the absence of P_T cut, the $|\eta^*| < 1.8$ cut might then reduce background more significantly. However, given our P_T cut, the only possibility for the $|\eta^*|$ cut to be useful in removing background seems to be to cut on smaller values of $|\eta^*|$. Due to limited statistics for $M_{KKG} \sim 3\,\text{TeV}$ and $100\,\text{fb}^{-1}$, we might not be able to apply such a stronger cut. However, we note that such a cut can be applied in case of higher luminosity or a lower KK mass. We leave a more detailed study for the future.

Next, we apply the $|\eta^*| < 1.8$ cut to the analysis of polarization asymmetry. We find that the (negative) asymmetry for the SM background increases by $O(10\%)$ after applying this cut. The reason is that these cuts increase the fraction of $q\bar{q}$ fusion events (compared to gg fusion) in the sample – again, only $q\bar{q}$ fusion contributes to the asymmetry. Furthermore we find that signal+background P_{LR} is not significantly affected (within the statistical errors). Again, the reason for only a small effect of $|\eta^*|$ cut is the correlation between the $|\eta^*| < 1.8$ and P_T cuts (as mentioned above in the case of differential cross-section).

Finally we want to comment about the possibility of using a cut on the boost to distinguish signal vs. background which may be useful for lower KK masses as follows. The gluonic content of the protons is symmetric between the two incoming protons, implying that the $t\bar{t}$ pairs from the gg fusion production will be mostly produced with a small boost. The $q\bar{q}$ annihilation pro-

duction, however, proceeds through the asymmetric $q\bar{q}$ content of the proton [25]. Thus, we expect the corresponding top pairs to exhibit a larger boost. This in principle implies that by applying suitable cuts on this boost ($\beta_{\rm cm}$) one can purify the (signal) sample, obtaining a larger polarization asymmetry and a larger significance from the differential cross-section analysis. However, using a partonic level study, we find that this cut is effective only for rather low KK gluon masses (at or below the 1 TeV scale).

III. ELECTROWEAK SECTOR & ALTERNATIVE QUARK CONFIGURATION

We now discuss briefly the electroweak (EW) gauge KK modes. As mentioned before, the cross-section for KK Z/W production (via $q\bar{q}$ fusion) is smaller than that of the KK gluon by $\sim g_Z^2/g_{QCD}^2$. As for the KK gluon, fermionic decays of KK Z are dominated by top quarks. Its leptonic decays are highly suppressed. Thus, the KK Z also contributes to the excess $t\bar{t}$, but is subdominant to the KK gluon signal in this channel.

However, there is a new feature in the excess $t\bar{t}$ sample due to the KK Z contribution. The couplings of the KK Z to the *initial* state are non vector-like, unlike in the case of the KK gluon. Combined with non vector-like couplings to the final state top quarks, we obtain the usual forward/backward asymmetry A_{FB} at the level of $\sim g_Z^2/g_{QCD}^2$ in the excess top pair sample. Note that an asymmetry of this size is present even in the SM due to Z exchange. The crucial point is that sign of this asymmetry is different than in the SM since t_R dominates in the final state as opposed to t_L in the SM. We can measure this asymmetry (both in the SM and in RS1 model) since we know the direction of q or forward (vs. $\bar{q}$ or backward) based on the direction of the boost [19].

As mentioned before, the KK W/Z also have sizable decays to Higgs, including longitudinal W/Z. As a corollary, *production* of KK Z/W via longitudinal W/Z fusion can be important. We plan to study such signals in the future.

A. Effects of enhanced b_L coupling to KK gluon

As indicated above, the b_L coupling to the KK gluon is larger ($\sim g_{QCD}$) than to light quarks (including b_R). In fact, with the symmetry protection for Zb_Lb_L coupling [11], $(t,b)_L$ can be localized very close to the TeV brane so that the b_L coupling to the KK gluon can be as large as ξg_{QCD}. Hence, $b_L\bar{b}_L$ fusion might become the dominant production mechanism for KK gluon.

Since both b and $\bar{b}$ are sea partons and have the same content inside a proton, the excess top events from $b_L\bar{b}_L$ fusion into KK gluon are less boosted events, but are also less forward than from gg fusion. Recall that the excess from $q\bar{q}$ fusion is more boosted and less forward than gg fusion. Hence, the η^* cut might still be useful, as before, to enhance the signal over background, but the $\beta_{\rm cm}$ cut might be less useful in enhancing the signal.

A new feature from $b_L\bar{b}_L$ fusion into KK gluon is that, due to vector-like couplings in both initial (cf. coupling to light quarks) and final states, it will result in a A_{FB} in KK *gluon* top events (cf. A_{FB} in $q\bar{q}$ fusion events is only from SM or KK Z). However, we cannot measure this A_{FB} since we do not know forward (b) vs. backward ($\bar{b}$) direction due to absence of sizable boost (cf. in $q\bar{q}$ fusion).

The excess top events from $b_L\bar{b}_L$ fusion into KK gluon will have the same non-zero P_{LR} as the excess from $q\bar{q}$ fusion (again, the excess from b_L fusion will be in less boosted events compared to that from $q\bar{q}$ fusion into KK gluon). In fact, in the extreme case of $(t,b)_L$ being very close to the TeV brane and t_R having close to a flat profile, we see that the sign of P_{LR} in signal will be reversed compared to what we discussed before (i.e., will be < 0). This sign is same as in the SM, but the crucial point is that the $O(1)$ size is much larger than that expected in the SM.

IV. CONCLUSIONS

In summary, the framework of a warped extra dimension provides a novel and very interesting resolution to the Planck-weak *and* flavor hierarchy problem of the SM. It tends to generically single out the top quark with enhanced couplings to the new states, whereas couplings to light fermions, in particular to proton's constituents, are suppressed. These features make it challenging to detect the new states.

In spite of this challenge, we have shown that the production of the KK gluon with subsequent decays to top pairs at the LHC is a very interesting channel, which would be worthwhile to explore further. In particular, for 100 fb^{-1} integrated luminosity, we demonstrated that one can discover the KK gluon with the mass $M_{KKG} \lesssim 4$ TeV based on the *correlated* observations of an excess in the top pair differential cross-section and a sizable left-right polarization asymmetry (P_{LR}). This asymmetry is much larger than in the SM due to very different couplings of the KK gluon to RH and LH top quarks. We discussed how a cut on transverse momentum of top quarks reduces background compared to the signal and how it might be possible to further improve the signal to background ratio by imposing cuts on the boost of the top center of mass frame in the laboratory frame and forwardness of top pairs in the parton center of mass frame. We briefly discussed the EW sector which requires more study. Its detection is similarly challenging due to suppressed couplings to the proton's constituents – in fact, it has lower production rate than for the KK gluon – and suppression of decays to leptons ("golden" decay modes).

Finally, we emphasize that, via the AdS/CFT duality [2], the RS framework should be viewed as a tool to study

$4D$ strong dynamics. In fact, the idea of a composite, pseudo-Goldstone boson (PGB), Higgs in $4D$ has been studied in the RS framework (called "holographic" PGB Higgs) [26] It is therefore likely that our results apply (in general) to $4D$ TeV-scale strong dynamics responsible for EWSB. In particular, our analysis with regards to the LHC signals leads to the following observation about other frameworks which address the little hierarchy problem and rely on UV completion via strong dynamics (*i.e.*, little Higgs and some flat extra dimensional models). According to the belief that the RS1 framework can be used to obtain intuition about such models [12], our studies suggest that these models might be characterized by LHC signals which are somewhat different from those usually emphasized in the literature. The reason is that the couplings between the extended electroweak sector and the light (heavy) *SM* particles may be actually highly suppressed (enhanced), unlike what is typically assumed in other LHC studies. [13] Generically, the new particles will be broad, with small production rates and non-leptonic decay channels. As such, these models may face similar challenges as that for the KK gluon, in the detection of new states.

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[12] In fact, see reference [27] for UV completion of the Litte*st* Higgs model using RS framework.

[13] References [28] do mention, in the context of LHC signals, that suppressed couplings of light fermions to Z', W' are motivated in order to satisfy electroweak precison tests. However, most of these studies still assume *universal* fermionic couplings so that couplings to top quark are also suppressed in this case. Whereas, we emphasize that top quark couplings to the new states are likely to be enhanced, leading to difficulties in detection of new states.

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