Discovery potential of Kaluza-Klein gluons at hadron colliders: A Snowmass whitepaper

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(Dated: August 6, 2013)

We investigate the discovery potential of Kaluza-Klein gluons as a dijet resonance at hadron colliders with different center-of-mass energies, from 14 TeV to 33 TeV to 100 TeV. We also present the current bounds from dijet searches at UA2, Tevatron, and LHC.

Models with Universal Extra Dimensions (UED) provide a phenomenologically interesting framework for both collider and dark matter physics [1] and have been studied extensively [2–19]. The 5D UED Lagrangian is a straightforward generalization of the standard model (SM) Lagrangian to 5 dimensions. Upon compactification, we recover bulk interactions among various Kaluza-Klein (KK) modes and their SM counterparts. Since translational invariance holds in the bulk, bulk interactions conserve both KK number and KK parity. Yet “boundary” interactions localized on the fixed points of the $S_1/Z_2$ orbifold may exist: these do not respect translational invariance and hence break KK number by even units. Such interactions may already appear at the cutoff scale $\Lambda$, if generated by the new physics arising from the ultraviolet completion of UED.

Minimal UED (MUED) models assume no such terms present at the scale $\Lambda$. Even so, upon renormalization to lower energy scales, boundary terms are radiatively generated from bulk interactions, and an effective coupling between a level-2 KK gauge boson ($A_{2\mu}$) and two SM fermions ($\bar{\psi}_0$ and $\psi_0$) is generated at one loop from a diagram with level-1 KK particles running in the loop. This effective coupling $-i g \sqrt{2} \left( \frac{\delta m_{A_3}^2}{m_2} - 2 \frac{\delta m_f^2}{m_2} \right) \bar{\psi}_0 \gamma^\mu T^a P_+ \psi_0 A_{2\mu}$ can be expressed in terms of the boundary contributions to the one-loop mass corrections ($\delta m_{A_3}^2$ and $\delta m_f^2$) [4]. The explicit form of this effective coupling is summarized in Ref. [2] for each type of level-2 KK gauge boson and for the various possible SM fermion pairs. Ignoring electroweak corrections, the interaction vertex between level-2 KK gluons and SM quarks is

$$ i g_3 \frac{\lambda^a}{2} \gamma^\mu \left[ \frac{1}{\sqrt{2}} \frac{1}{16\pi^2} \ln \left( \frac{\Lambda R}{2} \right)^2 \left( -\frac{11}{2} \right) g_3^2 \right], $$

where $\lambda^a$ are the Gell-Mann matrices and $g_3$ is the $SU(3)$ coupling constant. The Kaluza-Klein mass spectrum in MUED relies on two parameters, the radius of extra dimension $R$ and the cutoff scale $\Lambda$ [2–4], and is fixed by RG running between electroweak scale and $\Lambda$.

A simple extension of MUED, called non-minimal UED (nUED), was proposed in Ref. [15] and includes boundary terms at the two fixed points of the $S_1/Z_2$ orbifold. A separate UED extension with fermion bulk mass terms (known as Split-UED or SUED) has been also studied [16–19]. The simultaneous presence of both boundary and bulk mass terms has been considered only recently in Ref. [19]. In this next-to-minimal UED (NMUED) model, there are two parameters in addition to $R$ and $\Lambda$: the boundary parameter ($r$) and bulk mass ($\mu$). For convenience, we introduce the dimensionless parameters, $r/L$ and $\mu L$, where $L = \frac{2R}{\pi}$, and we will assume universal boundary and bulk terms. In NMUED, the level-$n$ KK boson mass is given by $m_{A_n} = \sqrt{k_n^2 + m_0^2}$, where $m_0$...
FIG. 1: (Left panels) Current limits and projected 5σ discovery and (right panels) current limits and projected 95% C.L. exclusion limits for the level-2 KK gluon as a dijet resonance in MUED. The dotted continuation of each projection line indicates an extrapolation to low multijet trigger thresholds.

is the zero mode mass induced by electroweak symmetry breaking: note $m_0 = 0$ for the level-2 KK gluon. Here, $k_n$ is determined by

$$\cot(k_n L) = r k_n \text{ for odd } n,$$

$$\tan(k_n L) = -r k_n \text{ for even } n.$$  \hfill (2)

In the limit of $r \to 0$, corresponding to the nUED limit, $k_n$ is simply $k_n = n R$. The coupling of the level-$(2n)$th gauge bosons to the SM fermion pair is generated at tree-level as

$$g_{2n00} = g_{SM} F_{00}^{2n}(x = \mu L)$$

$$= g_{SM} \frac{x^2 \left[ 1 - (-1)^n e^{2x} \right] \left[ 1 - \coth x \right]}{\sqrt{2(1 + \delta_{0n}) (x^2 + n^2 \pi^2 / 4)}} \bigg|_{x=\mu L}.$$  \hfill (3)

We note that the KK boson mass depends on the boundary term $r$ and is independent of the bulk mass term $\mu$, while its interaction only depends on $\mu$. For $F_{00}^2 \lesssim 0.1$, the one-loop contributions to the $g_{200}$ coupling should be included, as in the case of MUED.

Using the color octet vector resonance results in Ref. [20] and reweighting the dijet coupling by the appropriate factors including $F_{00}^2$, we obtain the current limits for the level-2 KK gluon in MUED, shown in the top left panel of Fig. 1: the current limits follow from Refs. [21–29]. We also use the projected color octet vector resonance sensitivities discussed and presented in Ref. [30] for 14 TeV, 33 TeV, and 100 TeV and 10 fb$^{-1}$, 300 fb$^{-1}$, and 3 ab$^{-1}$ integrated luminosity and map those projections to the ($R^{-1}$, AR) plane. The resulting 5σ discovery reach, and 95% C.L.
exclusion limits are shown in the left panels and right panels of Fig. 1 respectively. Note the dotted extension of each projection roughly indicates the turn-on of the multijet trigger threshold for each collider.

We see that the current limit barely reaches $\Lambda_R \approx 20$, but the 14 TeV LHC with 3 ab$^{-1}$ integrated luminosity may probe to $\Lambda_R = 10$. The shape of limits and sensitivity curves from higher energy machines below $\Lambda_R \approx 10$ is due to the smallness of the $g_{200}$ coupling, which is about 1% of the SM coupling strength. In terms of mass sensitivity, however, higher energy machines perform much better and especially, a 100 TeV machine will have discovery potential reaching several TeV in $R^{-1}$.

For NMUED, we present results in $(R^{-1}, \mu L)$ for $r/L = 0$, $r/L = 0.2$ in Figs. 2 and 3. The main effect of changing $r/L$ is to start each curve at higher $R^{-1}$ as well as stretch each curve in $R^{-1}$. The current limit is $\mu L > -0.2$, while the future run of LHC and other high energy machines will probe up to $\mu L \approx -0.05$, corresponding to a coupling that is a few percent of the SM strong coupling constant.

One peculiar feature of UED models is the repetition of KK modes. Hence, resonance searches at future colliders not only probe the mass scale of the KK gluon but also provide information on the cutoff scale in MUED as well as the size of allowed boundary terms in NMUED. The discovery prospects for KK gluons in various model contexts remains promising at the 14 TeV LHC, high luminosity LHC upgrade, and higher $\sqrt{s}$ hadron colliders.

FIG. 2: (Top left) Current limits, (top right) with current limits and projected 95% C.L. exclusion limits, and (bottom panels) current limits and projected $5\sigma$ discovery reach in NMUED for $r/L = 0$. The dotted continuation of each projection line indicates an extrapolation to low multijet trigger thresholds.
FIG. 3: The same as in Fig. 2 but for $r/L = 0.2$.

Acknowledgments

This work is supported in part by the U.S. Department of Energy through grant No. DE-FG02-12ER41809. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

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