WM-05-116

Kaluza-Klein Mesons in Universal Extra Dimensions

Erin De Pree[1] and Marc Sher[2]

Particle Theory Group

Department of Physics

College of William and Mary, Williamsburg, VA 23187, USA

In models with universal extra dimensions, the isosinglet Kaluza-Klein (KK) quarks (q^1) have very narrow widths, of $O(5-10)$ MeV, and will thus hadronize. Studies of KK-quarkonia ($\overline{q}^1 q^1$) show very sharp resonances and dramatic signatures at the Linear Collider. In this Brief Report, we consider the possibility of detecting KK-mesons, ($\overline{q}^1 q$), and show that detection at a Linear Collider is unlikely.

In order for hadronic bound states to form, the constituents must have lifetimes longer than the hadronization time scale. When the top quark was discovered to have a mass well in excess of 130 GeV, it became clear that hadrons containing top quarks could not exist. In models beyond the standard model, strongly interacting states with sufficiently long lifetimes can certainly exist. For example, a fourth generation quark, with very small mixings with lighter generations, could exist, and their bound states have been studied [1]. In supersymmetric (SUSY) models in which the gravitino is the lightest SUSY particle and in which a squark is the next-to-lightest, squarkonium [2] and mesino [3] bound states have been studied.

Recently, Carone et al. [4] considered bound states in models with universal extra dimen-

[1]Email: ekdepr@wm.edu
[2]Email: sher@physics.wm.edu

sions [5]. In these models, all states propagate in the higher dimensional space, and the existence of a Kaluza-Klein (KK) parity makes the lightest KK-state (LKP) stable. It also allows for the compactification scale to be remarkably low, as low as 300 GeV. The other KK-states have masses only slightly greater than this lightest state, and they are thus long-lived. Carone et al. analyzed bound states of KK-quarks, or KK-quarkonia. In particular, the isosinglet KK-quarks will decay into a monochromatic quark and missing energy, leading to dramatic resonances, reminiscent of the J/ψ and Υ states, with very clear signatures. In this Brief Report, we study the possibility of detecting KK-mesons, consisting of a KK-quark and a zero-mode antiquark (or vice-versa).

In universal extra dimensions, the masses of the lightest excitations of the quarks, q^1, are degenerate with most of the other KK-states at tree level. Radiative corrections [6] will break this degeneracy, leading to the KK-quarks being roughly $50 - 100$ GeV heavier than the LKP. They calculated the widths for the KK-quarks and found that the isosinglet d^1, s^1 and b^1 KK-quarks were $O(5 - 10)$ MeV, for the decay into a quark and the LKP (which is mostly the KK-photon). The widths of the $Q = 2/3$ isosinglet KK-quarks are four times larger than those of the $Q = -1/3$ KK-quarks and will not be discussed further.

In Ref. [4], it was claimed that the isosinglet KK-top quark was very long-lived (with a width of tens of keV), but they neglected mixing between the isosinglet and isodoublet KK-quarks. The mass matrix for the KK-top modes is [6]

$$\begin{pmatrix} 1/R + \delta m_{T^1} & m_{top} \\ m_{top} & -1/R - \delta m_{t^1} \end{pmatrix} \tag{1}$$

where the δm's are small radiative corrections. This leads to a mixing angle which is given by $\tan 2\theta_1 = 2m_{top}R/(2 + \delta m_{T^1}R + \delta m_{t^1}R)$. This factor leads to an isosinglet top quark coupling to the b-quark and the KK-W boson given by the usual coupling times $\sin\theta_1$, and thus allow the KK-top to decay into those states directly. We find the lifetime to be (assuming $|V_{tb}| = 1$)

given by

$$\Gamma = \sin^2\theta_1 \frac{G_F}{\sqrt{2}} \frac{M_W^2}{3\pi m_{t^1}^3 M_{W^1}^2}(m_{t^1}^2 - M_{W^1}^2)(m_{t^1}^2 + 2M_{W^1}^2). \quad (2)$$

For $1/R \sim 500$ GeV, this is 10 MeV. As shown by in Ref.[4], the signature will be a monochromatic b-quark, a monochromatic lepton and missing energy.

Given this width, hadronization will occur. How could one detect the KK-mesons? Recall how B mesons are detected. There are three signatures. First, the $\Upsilon(4s)$ resonance is just above the threshold for a pair of B mesons, and thus the strong decay causes the $\Upsilon(4s)$ to be much, much broader than the three lighter Υ states. Second, well above threshold, one can look at the B meson decay products. Third, one can look for $B - \overline{B}$ mixing, and like sign dileptons. We now examine each of these in turn.

One can produce copious numbers of $\overline{q}^1 q^1$ mesons at a linear collider on resonance. Above the threshold energy for the $\overline{q}^1 q^1$ to decay to a $\overline{q}^1 q$ meson and its antiparticle, the widths of the resonances become much larger. In the WKB approximation, the number of states below threshold [7] is approximately $2\sqrt{m_{q^1}/m_{J/\Psi}}$, which gives 2 for the J/Ψ system, 3 for the Υ system, and approximately 12 for the KK-quarkonium system. As a result, one must look at the $13s$ state of KK-quarkonium. However, Carone et al.[4] show that the production cross-section scales as $1/n^3$ [4], and thus only the first 3 resonances can be detected clearly. As a result, this method of producing KK-mesons fails.

If one goes above threshold, could one detect the mesons through their decays? Recall that the KK-quark will decay into a large amount of missing energy (typically 80 to 90 percent of the mass) plus a soft, monochromatic quark. Given beamstrahlung (expected [8] to be several GeV) and the expected beam resolution of at least 50 MeV, plus the huge amount of missing energy, it is hard to see how one could distinguish between a free KK-quark decay and one decaying in a meson.

Alternatively, one can look at the KK-meson decay, rather than the spectator quark decay.

Ignoring CKM angles, the KK-meson can annihilate through a KK-W into a KK-electron plus a neutrino, and the KK-electron then decays into a KK-photon plus an electron. The width is given by

$$\frac{f_M^2 g^4}{64\pi m_{q^1}^3}\frac{m_{e^1}^2(m_{q^1}^2 - m_{e^1}^2)^2}{(m_{q^1}^2 - m_{W^1}^2)^2} \tag{3}$$

where f_M is the meson decay constant, which is $O(\Lambda_{QCD})$. Numerically, this is $O(10^{-7})$ GeV, which is negligible compared with the free KK-quark width of a few MeV. One can also consider the "electromagnetic" decay of a flavor-neutral KK-meson into a KK-photon plus a photon (analogous to $\pi^o \to \gamma\gamma$). We have calculated this width, and find it to be approximately 5×10^{-6} GeV, which is also negligible. None of this is surprising, since the decay constants give factors of Λ_{QCD}^2, which is much, much smaller than the other scales in the problem.

What about mixing? In the case of the isosinglet KK-top quark, the mixing angles in the decay to a KK-W and a b-quark are large, and the sign of the lepton in the decay of the KK-W tags its charge, and thus the charge of the KK-top quark. With mixing, one would see two like sign monochromatic leptons, which is a striking signature. Sarid and Thomas [3] showed that a mesino-antimesino oscillation, through this signature, could allow the discovery of mesinos, even if they couldn't otherwise be detected. One must calculate the box diagram in which a W and a KK-W are exchanged. For the KK-mesons $t^1\overline{q}$, we find the mass difference between the KK-meson and its antiparticle to be

$$\Delta m = 2\left(\frac{G_F}{\sqrt{2}}\frac{\alpha}{8\pi}\right)\left(\frac{1}{M_W \sin\theta_W}\right)^2 \sum_{Q,Q^1} \Re\left[M_W^4 V_{qQ}^* V_{t^1Q} V_{Q^1q}^* V_{Q^1t^1}\frac{4}{3} f_{t^1q}^2 m_{t^1\overline{q}} A(m_Q, m_{Q^1})\right] \tag{4}$$

where Q is summed over d, s, b and Q^1 is summed over d^1, s^1, b^1. and

$$A(m_Q, m_{Q^1}) = -\sum_{i=1}^{4}\frac{M_i^4 \ln M_i^2}{\prod_{j\neq i}(M_i^2 - M_j^2)} \tag{5}$$

where $M_i = (M_Q, M_W, M_{Q^1}, M_{W^1})$. Alas, Δm turns out to be utterly negligible, of the order of a few eV. The reason is a double-GIM mechanism—the d, s, b quarks are nearly degenerate (they are all very light compared to the other scales in the problem), and the d^1, s^1, b^1 KK-quarks are also, in universal extra dimensions, very nearly degenerate. In the limit of exact degeneracy, the sum over the three generations will yield the product of two columns in the CKM elements from the first two CKM factors of Eq. (3), and the product of two rows from the latter two CKM elements. Thus, this mechanism will also fail.

This is in sharp contrast with bound states of fourth generation quarks and supersymmetric quarks. Fourth generation quarks can have longer lifetimes, neutral current (thus no missing energy) decays and the $Q = 2/3$ quark will give a large GIM violation, leading to large mixing. Supersymmetric quarks can also have longer lifetimes, less missing energy in their decays, and the mixing can occur through flavor-changing gluino interactions. Thus, while bound states in those models are detectable, it appears as if Kaluza-Klein mesons are not.

We thank Chris Carone, Craig Dukes and Josh Erlich for many fruitful discussions. This work was supported by the National Science Foundation grant PHY-023400.

References

[1] H. Ciftci and S. Sultansoy, Mod. Phys. Lett. A **18**, 859 (2003) [arXiv:hep-ph/0107321]; E. Arik *et al.*, Phys. Rev. D **58**, 117701 (1998); R. Ciftci, A. K. Ciftci, E. Recepoglu and S. Sultansoy, Turk. J. Phys. **27**, 179 (2003) [arXiv:hep-ph/0203083];

[2] M. Drees and M. M. Nojiri, Phys. Rev. Lett. **72**, 2324 (1994) [arXiv:hep-ph/9310209], Phys. Rev. D **49**, 4595 (1994) [arXiv:hep-ph/9312213]; M. Antonelli and N. Fabiano, Eur. Phys. J. C **16**, 361 (2000) [arXiv:hep-ph/9906535],

[3] U. Sarid and S. Thomas, Phys. Rev. Lett. **85**, 1178 (2000) [arXiv:hep-ph/9909349].

[4] C. D. Carone, J. M. Conroy, M. Sher and I. Turan, Phys. Rev. D **69**, 074018 (2004) [arXiv:hep-ph/0312055].

[5] T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001) [arXiv:hep-ph/0012100].

[6] H. C. Cheng, K. T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 036005 (2002) [arXiv:hep-ph/0204342].

[7] V. D. Barger and R. J. N. Phillips, "Collider Physics", Frontiers in Physics, vol. 71, Addison-Wesley, 1996.

[8] See K. Monig, LC-PHSM-2000-60-TESLA, and G. Wilson, LC-PHSM-2001-009-TESLA, available at httop://www.flc.desy.de/lcnotes/ and references therein.