

# Distinguishing Kaluza-Klein Resonances From a $Z'$ in Drell-Yan Processes at the LHC

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(Dated: September 20, 2001)

We explore the capability of the LHC to distinguish the production of Kaluza-Klein(KK) excitations in Drell-Yan collisions from an ordinary  $Z'$  at the LHC in the case of one extra dimension with the fermions localized at the orbifold fixed points. In particular, we demonstrate that this capability is dependent on both the mass of the KK state as well as whether or not the quarks and leptons lie at the same fixed points.

## I. INTRODUCTION: THE PROBLEM

The possibility of KK excitations of the Standard Model(SM) gauge bosons within the framework of theories with TeV-scale extra dimensions has been popular for some time[1]. Given the many fields of the SM it is possible to construct a large number of interesting yet different models of this class depending on, *e.g.*, whether all the gauge fields experience the same number of dimensions or whether the fermions and/or Higgs bosons are in the bulk. Perhaps the simplest model of this kind is the case of only one extra dimension where all of the SM gauge fields are in the bulk and the fermions lie at one of the two orbifold fixed points associated with the compactification on  $S_1/Z_2$ [2]. In this scheme the couplings of the KK excitations of a given gauge field are identical to those of the SM apart from an overall factor of  $\sqrt{2}$  and their masses are given, to lowest order in  $(M_0/M_c)^2$ , by the relationship  $M_n^2 = (nM_c)^2 + M_0^2$ , where  $n$  labels the KK level,  $M_c \sim 1$  TeV is the compactification scale and  $M_0$  is the zero-mode mass obtained via spontaneous symmetry breaking for the cases of the  $W$  and  $Z$ . Note for the cases of the photon and  $Z$  that their first excitations will be highly degenerate in mass, becoming more so as  $M_c$  increases. For example, if  $M_c = 4$  TeV the splitting between the  $Z$  and  $\gamma$  KK states is less than  $\sim 2.5$  GeV. An updated analysis[2] of precision electroweak data implies that  $M_c \geq 4$  TeV, independently of the location of the Higgs field, which is in a range accessible to the LHC. Of course this implies that the LHC experiments will at best observe only a *single* bump in the  $\ell^+\ell^-$  channel and a corresponding single Jacobian peak in  $\ell^\pm + \text{missing } E$  channel as the next set of KK states is too massive to be seen even with an integrated luminosity of  $100 - 300 \text{ fb}^{-1}$ [3].

How will this observation be interpreted? Through straightforward measurement of the lepton pair angular distribution it will be known immediately that the resonance is spin-1 and not, *e.g.*, a spin-2 graviton resonance as in the Randall-Sundrum[4] model[5]. Perhaps the most straightforward possibility is that of an extended gauge model[6] which predicts the existence of a degenerate  $W'$  and  $Z'$ ; many such models exist in the literature[7]. Is it possible to distinguish this  $Z'/W'$  model from KK excitations? In earlier work[3] it was demonstrated that once the mass of the first KK excitation was determined at the LHC, a linear collider(LC) with an integrated luminosity of order  $300 \text{ fb}^{-1}$  and a center of mass energy of  $0.5(1)$  TeV could be used to distinguish the two scenarios for KK masses as high as  $\simeq 5(7)$  TeV by examining how such new states would modify fermion pair production cross sections and asymmetries. (Note that these measurements are taking place far below the actual mass of the new excitation.) The question we would like to address here is whether or not one has to wait for the LC in order to make this distinction, *i.e.*, what can be done at the LHC itself? Can measurements at the LHC distinguish the two scenarios? We report here the preliminary results of a first analysis designed to address this issue.

## II. ANALYSIS: THE SOLUTION

The only possible approach to this problem is to make precision measurements of the lepton pair invariant mass distribution. To get an idea of what this distribution would look like we show a representative example in Fig. 1 for the case when  $M_c = 4$  TeV. (This very closely resembles the same plot after being put through a fast ATLAS detector simulation[8] giving us some confidence in our numerical study below.) Here we consider two

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Work supported by Department of Energy, Contract DE-AC03-76SF00515.

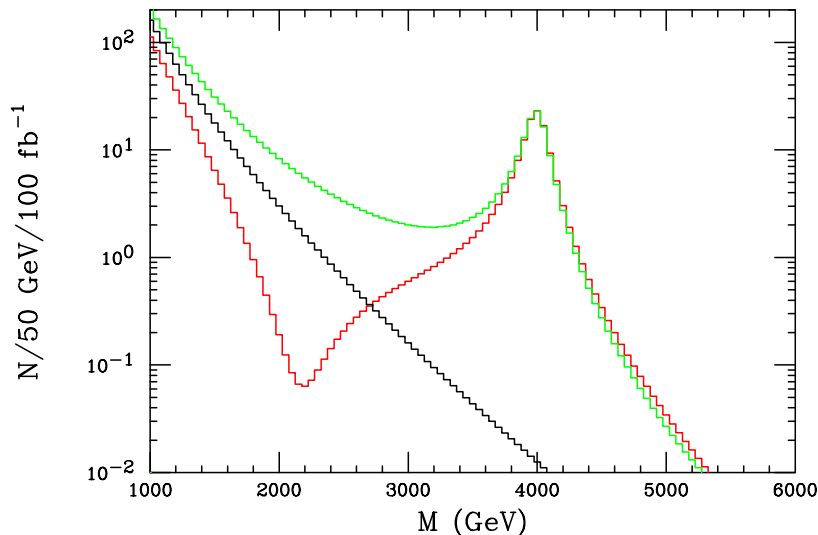


FIG. 1: Binned  $\mu^+\mu^-$  Drell-Yan mass spectrum for the SM (black) and for the case of a 4 TeV KK excitation when all fermions are at the same orbifold fixed point (red) and when quarks and leptons are at opposite fixed points (green) thus separated by a distance  $D = \pi R_c$  in the extra dimension. Rapidity cuts, K-factors and efficiencies are included.

cases: (i) all SM fermions are at the same orbifold point ( $D = 0$ ) and (ii) quarks and leptons are at opposite fixed points separated by a distance  $D = \pi R_c$  in the extra dimension where  $R_c = 1/M_c$ . The later model may be of interest in addressing, *e.g.*, the issue of proton decay. Note that in the LC analysis the value of  $D$  did not enter since only leptonic data was employed. Here one may easily imagine that the capability of the LHC to distinguish the  $Z'$  and KK scenarios may depend on  $D$ . Note that for  $D = 0$  ( $\pi R_c$ ) there is a strong destructive (constructive) interference between the SM and KK contributions.

What portion of the lepton mass spectrum is useful for this analysis? The resonance peak region is *not* useful (at least by itself) since, as many earlier  $Z'$  analyses have shown [6], for such a heavy  $Z'$ -like state the only useful data obtainable there are the total cross section, the full width and the forward-backward asymmetry,  $A_{FB}$ . The first two of these are sensitive to other potential non-SM decay modes and are thus highly model dependent while  $A_{FB}$  is insufficient as a useful discriminator. Beyond the peak region the cross section is quite small yielding too poor a set of statistics to be valuable; this implies that only the low mass range is useful. To be specific we first generate Drell-Yan  $\mu^+\mu^-$ -pair cross section ‘data’ for both the  $D = 0$  and  $D = \pi R_c$  cases integrated over 100 GeV wide mass bins covering a dilepton mass region between 250 GeV and 1850 (2150) GeV for the case of  $M_c = 4(5)$  TeV with an assumed integrated luminosity of  $300 fb^{-1}$ . (To go lower in mass would not be very useful as we are then dominated by either the  $Z$  peak or the photon pole. For larger masses the cross section is either too small or is dominated by the heavy resonance.) Next, under the assumption that a  $Z'$  of known mass is actually being produced, we vary its couplings in order to obtain the best  $\chi^2$  fit to the dilepton mass distribution and obtain the relevant confidence level (CL) for the fit. (In this approach, the overall normalization of the cross section is determined at the  $Z$ -pole which is outside of the fit region.) In performing this analysis we make the following simplifying assumptions: (i) the  $Z'$  couplings are generation independent and (ii) the generator to which the  $Z'$  couples commutes with those of the SM. These conditions are satisfied by GUT-inspired  $Z'$  models as well as by many others in the literature [6] and reduces the number of fit parameters to 5: the left-handed couplings of the quark and lepton doublets and the right-handed couplings for  $u, d$  and  $e$ . We then perform a fine-grained scan over a large volume of this parameter space testing more than  $10^{10}$  coupling combinations for each of the cases we consider to obtain the best fit.

The results of this analysis are as follows. For the most naive case, where all the SM fermions are at the same orbifold fixed point, *i.e.*,  $D = 0$ , we find that the largest value of the CL obtained by our fitting procedure to be  $\sim 10^{-10}$  (0.003) for the case  $M_c = 4(5)$  TeV. This implies that the assumption that the KK state is actually a  $Z'$  does not provide a good fit and we can conclude that the two cases are distinguishable. However as we clearly see the CL of the fit in this case rises rapidly as  $M_c$  increases since the influence of the resonance in the below peak region to which we are fitting is rapidly diminishing. For  $M_c = 6$  TeV CL’s in the range 0.5 – 1 are easily obtained and the two scenarios are no longer separable. The results for the case  $D = \pi R_c$  are quite different from those for  $D = 0$  since there is now constructive interference between the SM and KK contributions. In this case for  $M_c = 4(5)$  TeV the CL of the fits ranged as high as  $\simeq 0.7(1)$  implying very good fits to the KK data with the  $Z'$  hypothesis were possible even for relatively light masses. This implies that in this case the

LHC will not be able to distinguish the KK and  $Z'$  cases when the quarks and leptons are not at the same fixed points. This is seen to hold true for any value of  $M_c$  which is in excess of the current bounds from precision electroweak data.

### III. SUMMARY AND CONCLUSIONS

The identification of new physics after its discovery is an important issue for both present and future colliders. In the preliminary analysis presented above we considered the capability for the LHC to distinguish a KK excitation from a more conventional  $Z'$  in the mass range at and above 4 TeV. Earlier analyses have shown that such a model separation is possible at a LC running at a fixed center of mass energy provided the mass of the excitation is already known from LHC measurements. In the case of the LHC we demonstrated that in the most naive scenario where all of the SM fermions are located a single orbifold fixed point the LHC is able to distinguish the two scenarios up to KK excitation masses in the 5-6 TeV range. On the otherhand, in the case where the quarks and leptons are at different fixed points, we have found that the LHC would find the two scenarios to be indistinguishable. It is possible that some extension of the current analysis may lead to a strengthening of the LHC's ability at model discrimination; this is currently under investigation. A detector simulation along the lines of the present analysis would be highly useful in verifying our results.

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