Kaluza-Klein states at the LHC in models with localized fermions

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Abstract
We give a brief review of some aspects of physics with TeV size extra-dimensions. We focus on a minimal model with matter localized at the boundaries for the study of the production of Kaluza-Klein excitations of gauge bosons. We briefly discuss different ways to depart from this simple analysis.

1. INTRODUCTION
Despite the remarkable success of the Standard Model (SM) in describing the physical phenomena at the energies probed at present accelerators, some of its theoretical aspects are still unsatisfactory. One of the lacking parts concerns understanding the gravitational interactions as they destroy the renormalizability of the theory. Furthermore, these quantum gravity effects seem to imply the existence of extended objects living in more than four dimensions. This raises many questions, as:

Is it possible that our world has more dimensions than those we are aware of? If so, why don’t we see the other dimensions? Is there a way to detect them?

Of course, the answer to the last question can only come for specific class of models as it depends on the details of the realization of the extra-dimensions and the way known particles emerge inside them. The examples discussed in this review are the pioneer models described in Refs. [1–5], when embedded in the complete and consistent framework given in [6, 7]. We focus on such a scenario as our aim is to understand the most important concepts underlying extra-dimension physics, and not to display a collection of hypothetical models.

Within our framework, two fundamental energy scales play a major role. The first one, $M_s = l_s^{-1}$, is related to the inner structure of the basic objects of the theory, that we assume to be elementary strings. Their point-like behavior is viewed as a low-energy phenomena; above $M_s$, the string oscillation modes get excited making their true extended nature manifest. The second important scale, $R^{-1}$, is associated with the existence of a higher dimensional space. Above $R^{-1}$ new dimensions open up and particles, called Kaluza-Klein (KK) excitations, can propagate in them.

2. MINIMAL MODELS WITH LOCALIZED FERMIONS
In a pictorial way, gravitons and SM particles can be represented as in Fig. 1. In particular, in the scenario we consider:

- the gravitons, depicted as closed strings, are seen to propagate in the whole higher-dimensional space, $3+d_{\parallel}+d_{\perp}$. Here, $3+d_{\parallel}$ defines the longitudinal dimension of the big brane drawn in Fig. 1, which contains the small 3-dimensional brane where the observed SM particles live. The symbol $d_{\perp}$ indicates instead the extra-dimensions, transverse to the big brane, which are felt only by gravity.
- The SM gauge-bosons, drawn as open strings, can propagate only on the $(3+d_{\parallel})$-brane.
- The SM fermions are localized on the 3-dimensional brane, which intersects the $(3+d_{\parallel})$-dimensional one. They do not propagate on extra-dimensions (neither $d_{\parallel}$ nor $d_{\perp}$), hence they do not have KK-excitations.

The number of extra-dimensions, $D = d_{\parallel}+d_{\perp}$ or $d_{\parallel}+d_{\perp}$, which are compactified on a $D$-dimensional torus of volume $V = (2\pi)^D R_1 R_2 \cdots R_D$, can be as big as six [7] or seven [8] dimensions. Assuming periodic conditions on the wave functions along each compact direction, the states propagating in the
$(4 + D)$-dimensional space are seen from the four-dimensional point of view as a tower of states having a squared mass:

$$M_{KK}^2 \equiv m_0^2 + \frac{n_1^2}{R_1^2} + \frac{n_2^2}{R_2^2} + \cdots + \frac{n_D^2}{R_D^2},$$

with $m_0$ the four-dimensional mass and $n_i$ non-negative integers. The states with $\sum_i n_i \neq 0$ are called KK-states. Assuming that leptons and quarks are localized is quite a distinctive feature of this class of models, giving rise to well defined predictions. An immediate consequence of the localization is that fermion interactions do not preserve the momenta in the extra-dimensions. One can thus produce single KK-excitations, for example via $f \bar{f} \rightarrow V^{(n)}_{KK}$ where $f, f'$ are fermions and $V^{(n)}_{KK}$ represents massive KK-excitations of $W, Z, \gamma, g$ gauge-bosons. Conversely, gauge-boson interactions conserve the internal momenta, making the self-interactions of the kind $VV \rightarrow V^{(n)}_{KK}$ forbidden. The experimental bounds on KK-particles that we summarize in the following, as well as the discovery potential of the LHC, depend very sensitively on the assumptions made.

Electroweak measurements can place significant limits on the size of the extra-dimensions. KK-excitations might affect low-energy observables through loops. Their mass can thus be constrained by fits to the electroweak precision data [9–15]. In particular, the fit to the measured values of $M_W, \Gamma_H$ and $\Gamma_{had}$ has led to $R^{-1} \geq 3.6$ TeV.

3. WHAT CAN BE EXPECTED FROM THE LHC?

The possibility to produce gauge-boson KK-excitations at future colliders was first suggested in Ref. [4]. Unfortunately, from the above-mentioned limits, the discovery at the upgraded Tevatron is already excluded (see for instance [16]). Also expectations of a spectacular explosion of new resonances at the LHC are sorely disappointed. In the most optimistic case, the LHC will discover just the first excitation modes.

The only distinctive key from other possible non-standard models with new gauge-bosons would be the almost identical mass of the KK-resonances of all gauge bosons. Additional informations would be however needed to bring clear evidence for the higher-dimensional origin of the observed particle. Despite the interpretation difficulties, detecting a resonance would be of great impact.

We could also be in the less favorable case in which the mass of the KK-particles is bigger than the energy-scale probed at the LHC. In this unfortunate but likely scenario, the indirect effect of such
Fig. 2: (a) Resonances of the first KK-excitation modes of $Z$ and $\gamma$ gauge-bosons. (b) Resonances of the first KK-excitation mode of the $W$-boson. (c) Resonances of the first KK-excitation mode of the gluon. (d) Under-threshold effects due to the presence of $g_{KK}^{(n)}$, given in terms of the number of standard deviations from the SM predictions. The results have been obtained for the LHC with $\sqrt{s}=14$ TeV and $L=100$ fb$^{-1}$.

particles would only consists in a slight increase of the events at high energies compared to the SM predictions. In this case, the luminosity plays a crucial role. In the last few years, several analysis have been performed in order to estimate the possible reach of the LHC (see for example [4, 16–23]).

The three classes of processes where the new KK-resonances could be observed are:

- $pp \rightarrow l^+l^-$,
- $pp \rightarrow l\nu_l$, where $l\nu_l$ is for $l^+\nu_l + \bar{\nu}_ll^-$,
- $pp \rightarrow q\bar{q}$, where $q = u, d, s, c, b$.

The first class can be mediated by the KK-excitations of the electroweak neutral gauge-bosons, $Z_{KK}^{(n)}$ and $\gamma_{KK}^{(n)}$, while the second one can contain the charged $W_{KK}^{(n)}$ gauge-boson modes. Finally, the third class can receive contributions from all electroweak gauge-bosons plus the KK-modes $g_{KK}^{(n)}$ of the gluons.

Typically, one can expect a kind of signal as given in Fig. 2. In the case where both outgoing particles are visible, a natural observable is the invariant mass of the fermion pair. Distributions in such a variable are shown in the upper and lower left-side plots, which display the interplay between $Z_{KK}^{(n)}$ and $\gamma_{KK}^{(n)}$ resonances, and the peaking structure due to $g_{KK}^{(n)}$, respectively. In presence of a neutrino in the final state, one can resort to the transverse mass distribution in order to detect new resonances. This is shown in the upper right-side plot of Fig. 2 for the charged-current process with $W_{KK}^{(n)}$ exchange. Owing to the PDFs, the effective center-of-mass (CM) energy of the partonic processes available at the LHC is not really high. The discovery limits of the KK-resonances are thus rather modest, $R^{-1} \leq 5$-6 TeV. This estimate finds confirmation in more detailed ATLAS and CMS analyses [24]. Taking into account the present experimental bounds, there is no much space left. Moreover, the resonances due to the gluon excitations have quite large widths owing to the strong coupling value. They are thus spread and difficult to detect already for compactification scales of the order of 5 TeV.

But, what represents a weakness in this context can become important for indirect searches. The
large width, ranging between the order of a few hundreds GeV for the KK-excitations of the electroweak
gauge-bosons and the TeV-order for the KK-modes of the gluons, can give rise to sizeable effects even if
the mass of the new particles is larger than the typical CM-energy available at the LHC. This is illustrated
in the lower right-side plot of Fig. 2, where the number of standard deviations quantifies the discrepancy
with the SM predictions, coming from $g_{KK}^n$ contributions. The under-threshold effects are driven by
the tail of the broad Breit-Wigner, which can extend over a region of several TeV, and are dominated
by the interference between SM and KK amplitudes. They thus require to have non-suppressed SM
contributions. Their size, of a few-per-cent order for large compactification radii, can become statistically
significant according to the available luminosity. In the extreme case of Fig. 2, we have a KK-gluon with
mass $M_1 = R^{-1} = 20$ TeV and width $\Gamma_1 \approx 2$ TeV. Assuming a luminosity $L = 100 fb^{-1}$, the interference
terms give rise to an excess of about 2000 events. Similar conclusions hold for the indirect search of
the KK-excitations of the electroweak gauge-bosons. At 95% confidence level, the LHC could exclude
values of compactification scales up to 12 and 14 TeV from the $Z_{KK}^{(n)} + \gamma_{KK}^{(n)}$ and $W_{KK}^{(n)}$ channels,
respectively. The indirect search is exploited in the ATLAS and CMS joint analysis of Ref. [24].

4. GOING BEYOND MINIMAL

We have carried the discussion above for the case of one extra-dimension with all fermions localized on
the boundaries. One can depart from this simple situation in many ways:

- **More extra-dimensions**
  New difficulties arise for $D \geq 2$: the sum over KK propagators diverges [2]. A simple regularization
  is to cut off the sum of the KK states at $M_s$. This would be natural if the extra-dimension were
  discrete, however in our model we assumed translation invariance of the background geometry (be-
  fore localizing any objects in it). String theory seems to choose a different regularization [2,25]. In
  fact the interaction of $A^\mu(x, \vec{y}) = \sum_n A^\mu_n(x) \exp i \frac{2\pi n_0}{R} \cdot \vec{y}$ with the current density $j_\mu(x)$, associated
to the massless localized fermions, is described by the effective Lagrangian:

$$\int d^4x \sum_n e^{-\ln \delta \sum_i \frac{n_i^2 l_i^2}{2R_i^4}} j_\mu(x) A^\mu_n(x),$$

which can be written after Fourier transformation as

$$\int d^4y \int d^4x \left( \frac{1}{l_s^2 2\pi \ln \delta} \right)^2 e^{-\frac{\sigma^2}{2 l_s^2 \ln \delta}} j_\mu(x) A^\mu(x, \vec{y}).$$

This means that the localized fermions are felt as a Gaussian distribution of charge $e^{-\frac{\sigma^2}{2 l_s^2 \ln \delta}} j_\mu(x)$
with a width $\sigma = \sqrt{\ln \delta} l_s \sim 1.66 l_s$. Here we used $\delta = 16$ corresponding to a $Z_2$ orbifolding. The couplings of the massive KK-excitations to the localized fermions are then given by:

$$g_{\vec{n}} = \sqrt{2} \sum_n e^{-\ln \delta \sum_i \frac{n_i^2 l_i^2}{2R_i^4}} g_0$$

where the factor $\sqrt{2}$ stands for the relative normalization of the massive KK wave function ($\cos(\frac{2\pi n_0}{R})$)
with respect to the zero mode, and $g_0$ represents the coupling of the corresponding SM gauge-
bozon.

The amplitudes depend on both $R$ and $M_s$ and thus, as phenomenological consequence, all bounds
depend on both parameters (see [16]).

- **Localized kinetic and/or mass terms for bulk fields**
  Let us denote by $S_0(p, R, M_s)$ the sum of all tree-level boson propagators weighted by a factor
  $\delta \frac{-\sigma^2}{R^4 m^2}$ from the interaction vertices. For simplicity we take $m_0 = 0$, and define $\delta S_0$ by

$$S_0(p, R, M_s) = \frac{1}{p^2} + \delta S_0.$$
In order to confront the theory with experiment, it is necessary to include a certain number of corrections. The obvious one is a resummation of one-loop self-energy correction to reproduce the gauge coupling of the massless vector-bosons. Here we parametrize these effects as two kinds of bubbles to be resummed:

- the first, denoted as $B_{\text{bulk}}$ represents the bulk corrections. This bubble preserves the KK-momentum,

- the second, denoted as $B_{\text{bdary}}$ represents the boundary corrections. This bubble does not preserve the KK momentum. In fact, this can represent a boundary mass term or tree-level coupling, but also localized one-loop corrections due to boundary states [2] or induced by bulk states themselves [26].

Here, two simplifications have been made: (a) the corrections are the same for all KK-states, and (b) the boundary corrections arise all from the same boundary. This results in the corrected propagator [2]:

$$S_{\text{corr}}(p, R, M_s) = \frac{S_0}{1 - B_{\text{bulk}} - B_{\text{bdary}} - p^2 \delta S_0 B_{\text{bdary}}}.$$  \hspace{1cm} (6)

If we define the “renormalized coupling” as $g^2(p^2) = \frac{g^2}{1 - B_{\text{bulk}} - B_{\text{bdary}}}$, the result is

$$g^2 S_{\text{corr}} = g^2(p^2)S_0 - \delta S_0 \frac{g^2(1 - p^2 \delta S_0) B_{\text{bdary}}}{(1 - B_{\text{bulk}} - B_{\text{bdary}})(1 - B_{\text{bulk}} - B_{\text{bdary}}p^2 \delta S_0)}.$$ \hspace{1cm} (7)

The first term in Eq. (7) is the contribution that was taken into account in all phenomenological analysis, the second is the correction which depends crucially on the size of $B_{\text{bdary}}$.

- **Spreading interactions in the extra dimensions**

In the simplest scenario, all SM gauge-bosons propagate in the same compact space. However, one may think that the three factors of the SM gauge-group can arise from different branes, extended in different compact directions. In this case, $d_{\parallel}$ TeV-dimensions might be longitudinal to some brane and transverse to others. As a result, only some of the gauge-bosons can exhibit KK-excitations. Such a framework is discussed in [16].

These are simplest extensions of the work we presented above. The experimental limits depend now on many parameters $M_s, B_{\text{bdary}}, ...$ in addition to the different size of the compactification space felt by the gauge-bosons.

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