RS MODEL WITH BULK MATTER: THE POSSIBILITY OF AN LHC PHENOMENOLOGY

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We study the Randall-Sundrum (RS) scenario with Standard Model fields in the bulk, which is motivated by several phenomenological issues like the possibility of generating geometrically the fermion flavour structure. In particular, we consider some examples of fermion locations along the extra dimension which reproduce quark/lepton masses (Flavour Changing Neutral Current and ElectroWeak precision constraints are also considered). We show that for these locations, which fix the effective couplings between fermions and Kaluza-Klein (KK) excitations of the gauge bosons, if the first KK masses are about a few TeV (so that the gauge hierarchy problem is addressed) then the KK gauge bosons induce effects detectable at the Large Hadron Collider. For that purpose, we concentrate on the contributions of KK gauge boson exchanges to the Drell-Yan processus. Generally speaking, our result means that the RS model of fermion masses is testable at LHC.

1 Introduction

The possibility of the presence of additional spatial dimensions has recently received a considerable attention. Among the several higher-dimensional models proposed during the last decade, the scenario with a small warped extra dimension suggested by Randall and Sundrum (RS) [1] is particularly attractive as it addresses the so-called gauge hierarchy problem without introducing any new energy scale in the fundamental theory.

The extension of the original RS set-up, where the Standard Model (SM) particles (except the Higgs boson) are promoted to bulk fields, has turned out to offer various other interests. Indeed, in this framework, the unification of gauge couplings becomes possible at high energy scale within a Grand Unified Theory (GUT) [2]. Furthermore, this RS version provides viable WIMP candidates, of Kaluza-Klein (KK) type, for the dark matter of the universe [3]. Finally, it

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provides an original interpretation[4] for the large mass hierarchies prevailing among the different flavours and types of SM fermions[b]. This interpretation is purely geometrical: the SM fermions acquire various localizations along the extra dimension (depending on their flavour/type) which give rise to different effective 4-dimensional Yukawa couplings, and thus to strong hierarchical mass patterns[c]. Based on such a geometrical approach, the quark masses and CKM mixing angles can be indeed accommodated[8], as well as the lepton masses and MNS mixing angles in both cases where neutrinos possess masses of type Majorana[9] or Dirac[10,11].

In the context of the RS model with bulk fields, if the gauge hierarchy problem is to be solved, the mass of the first KK excitation of SM gauge bosons must be of order of the TeV scale. Hence, KK excitations of gauge bosons are expected to be produced significantly at the forthcoming Large Hadron Collider (LHC), which provides a center-of-mass energy of 14 TeV, for KK gauge boson couplings to quarks of the same order as the SM gauge boson couplings.

In the present work, we develop a test of KK excitation effects at LHC, in the RS scenario with bulk fields generating the SM fermion masses: we study the direct contributions of KK excitations of photon and Z boson to the Drell-Yan process, namely $pp \to \gamma^{(n)}/Z^{(n)} \to \ell^+\ell^-$. Our motivation for considering this process is that the KK excitations can be produced as resonances, tending to increase considerably the amplitude. Moreover, the dilepton final state constitutes a particularly clean signature in an hadronic collider environment.

In the framework of the RS model with bulk matter, the collider phenomenology and flavour physics are interestingly connected: the effective 4-dimensional couplings between KK gauge boson modes and SM fermions depend on fermion localizations along the extra dimension which are fixed (non-uniquely) by fermion masses.

A preliminary study on the reaction $pp \to \gamma^{(n)}/Z^{(n)} \to \ell^+\ell^-$ at LHC was performed in the RS model with bulk matter [12]. In this previous study, in contrast with the present one, the assumption of universal fermion location was made so that quark/lepton mass hierarchies were not able to be reproduced[d].

In our analysis, we have to take into account the indirect phenomenological constraints on the mass of first KK gauge boson excitation M_{KK} ($M_{KK} = M(\gamma^{(1)}) = M(g^{(1)}) \approx M(Z^{(1)}) \approx M(W^{(1)})$) holding in the RS model with bulk matter. First, the experimental limits on Flavour Changing Neutral Current (FCNC) processes translate into a lower bound on M_{KK}. It was shown recently[11] that this bound can be softened down to $M_{KK} \gtrsim 1$ TeV for certain geometrical configurations of fermions (see[8,14] for other analyzes of FCNC reactions within the RS model). Secondly, ElectroWeak (EW) precision data place a severe bound of typically $M_{KK} \gtrsim 10$ TeV [12,15]. Nevertheless, various scenarios were suggested in the literature in order to relax this bound. For example, the scenarios with brane-localized kinetic terms for fermions [16] or gauge bosons [17] allow to relax the bound down to a few TeV (see [18] for gauge boson kinetic terms and [19] for fermion ones). In another kind of scenario [20], enhanced to a left-right EW gauge structure in the bulk, the bound was reduced to $M_{KK} \gtrsim 3$ TeV. Hence, in a sense, the EW bound on M_{KK} is model-dependent.

2 Fundamental parameters

Our framework is the RS scenario with SM fields residing in the bulk, except the Higgs boson which is stuck on the TeV-brane (see below) in order to address the gauge hierarchy problem.

[b]In the RS context, there exist other higher-dimensional mechanisms [5] applying specifically to neutrinos and aimed at explaining their lightness compared to SM fermions.

[c]The idea of displacing fermions along extra dimension(s) was previously used in the context of large flat extra dimension(s), in order to generate the quark (see e.g. [6]) and lepton (see e.g. [7]) masses/mixings.

[d]We also mention a study [13] on virtual effects of $\gamma^{(n)}/Z^{(n)}$ in precision measurements concerning the reaction $e^+e^- \to t\bar{t}$ at ILC, in an RS scenario where the first KK gauge boson masses would be larger than 10 TeV.

Let us discuss the values of fundamental parameters. While on the Planck-brane the effective gravity scale is equal to the (reduced) Planck mass: $M_{Pl} = 2.44\ 10^{18}$ GeV, on the TeV-brane the gravity scale, $M_\star = w\ M_{Pl}$, is suppressed by the exponential 'warp' factor $w = e^{-\pi k R_c}$, where $1/k$ is the curvature radius of Anti-de-Sitter space and R_c the compactification radius. We see that for a small extra dimension $R_c \simeq 11/k$ (k is taken close to M_{Pl}), one finds $w \sim 10^{-15}$ so that $M_\star \doteq \mathcal{O}(1)$ TeV, thus solving the gauge hierarchy problem. For this R_c value, the 5-dimensional gravity scale M_5 is close to the effective 4-dimensional gravity scale M_{Pl}. The first KK mass is given by: $M_{KK} = 2.45\ k\ w = 2.45\ k\ M_\star/M_{Pl} \sim M_\star = \mathcal{O}(\text{TeV})$. Hence, one can take a maximal M_{KK} value of 10 TeV. This value corresponds to: $kR_c = 10.11$ As a matter of fact, the maximal value of M_{KK} is fixed by the kR_c value and the theoretical consistency bound on the 5-dimensional curvature scalar $|R_5| = |-20k^2| < M_5^2$ which leads to: $k < 0.105\ M_{Pl}$. The value chosen for kR_c gives rise to $M_\star = 39.2$ TeV. Since we are interested here in the search for KK states at LHC, we will take M_{KK}, instead of k, as the free parameter, which is equivalent.

Additional parameters must be introduced. Indeed, in order to generate the SM fermion masses through the higher-dimensional mechanism [4] mentioned in the introduction section, the zero-mode fermions must possess different localizations along the extra dimension. For that purpose, each 5-dimensional fermion field Ψ_i ($i = \{1,2,3\}$ being the family index in the interaction basis) is coupled to a distinct 5-dimensional mass m_i in the fundamental theory:

$$\int d^4x \int dy\ \sqrt{G}\ m_i \bar{\Psi}_i \Psi_i, \tag{1}$$

where G is the determinant of the RS metric. The necessary condition to modify the location of fermions is that the masses m_i have a non-trivial dependence on the fifth dimension, more precisely a 'kink' profile. An attractive possibility is to take [21]:

$$m_i = c_i\ \frac{d\sigma(y)}{dy} = \pm\ c_i\ k, \tag{2}$$

the c_i being dimensionless parameters.

3 Phenomenological constraints

• **Fermion masses:** In this paper, we consider two examples of complete set for the c_i parameter values: sets A and B presented in Appendix.
The two fermion localization configurations, corresponding to the two sets A and B, have been shown in [11] to reproduce all the present data on quark/lepton masses and mixing angles (in case of Dirac neutrino masses induced by the presence of 3 right-handed neutrinos), through the geometrical mechanism [4] described in Section 1. The effective quark/lepton mass matrices, generated via this mechanism, only depend on the RS parameter product kR_c, which was fixed in [11] to the same amount as here.

• **FCNC bounds:** Within the context of the RS scenario creating fermion masses, FCNC processes are induced at tree level by exchanges of KK excitations of neutral gauge bosons. Indeed, these KK states possess FC couplings to fermions. The reason being that the mass hierarchies and mixing amounts of SM fermions require different c_i parameter values (as discussed in previous paragraph), or equivalently, flavour and nature dependent locations for quarks/leptons.
These FC couplings between KK gauge bosons and fermions are significantly suppressed for c_i values giving rise to certain configurations of fermion localizations [11]. For these localization configurations, upper experimental limits on KK-induced FCNC effects are satisfied even for rather low KK masses. Sets A and B of c_i values given in Appendix fit fermion masses *and* correspond to such configurations: for these two sets, it was *also* shown in [11] that FCNC reactions in both

the hadron and lepton sectors (like $b \to s\gamma$, $B^0 - \bar{B}^0$, $\mu^- \to e^-e^+e^-$, $K \to \mu^+\mu^-$,...) respect their experimental limit if $M_{KK} \gtrsim 1$ TeV.

• **EW measurements:** The mixing between the EW gauge bosons and their KK modes induces modifications of the boson masses/couplings, and thus deviations to EW precision observables. Hence, the fit of EW precision data imposes a lower bound on M_{KK}. We consider the scenario with the EW gauge symmetry enhanced to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [20], which allows to achieve an acceptable fit of EW precision data for a mass as low as $M_{KK} \approx 3$ TeV. This result was obtained for a characteristic configuration of the c_i parameters (as the couplings of KK gauge bosons to fermions depend on fermion locations).
Set A of c_i values (in Appendix) is approximatively compatible with this typical c_i configuration chosen in [20] (with $kR_c \approx 10$, like here). Indeed, set A corresponds to c(light fermions) $>$ 0.5, $0.3 \lesssim c_3^Q < 0.5$, $-0.5 \lesssim c_3^u < 0.5$, $c_{1,2}^Q \sim 0.5$ and $c_i^L \sim 0.25$. Nevertheless, although a detailed study of the $SU(2)_L \times SU(2)_R$ scenario is beyond the scope of our work, a more precise analysis of the constraints originating from EW precision measurements in this context would be needed. As a matter of fact, first, the contributions to the shift in coupling of $Zb\bar{b}$ coming from $b^{(0)} - b^{(n)}$ mixings (as estimated in [22] for $Zt\bar{t}$) and KK state loop exchanges should be taken into account. Furthermore, strictly speaking, the effective couplings between KK gauge bosons and fermions should involve the SM fermion mixing angles, those entering via the basis transformation matrices. These mixings could reduce significantly the couplings, and thus the corrections of EW observables. Finally, for our values $c_{1,2}^Q, c_i^L \lesssim 0.5$, the y quantity affecting the fermionic operators cannot be exactly field-redefined into the purely "oblique" parameters S, T as done in [20] (besides, EW constraints tend to disappear as c_i goes to 0.5).
Set B conflicts with the c_i configuration considered in the left-right model analysis [20] where the EW bound on M_{KK} has been softened down to a few TeV. We will consider set B in order to illustrate a case with larger couplings (between KK bosons and SM fermions) than for set A [e], keeping in mind that the final EW constraint on M_{KK} involves the whole physics underlying the SM.

4 LHC investigation

We concentrate on the reaction $pp \to \gamma^{(n)}/Z^{(n)} \to e^+e^-$ at LHC. The associated amplitude depends on the effective couplings between KK gauge boson modes and SM fermions, and thus on the localizations of fermions along the extra dimension.
In Fig.(1), we present the absolute distribution of final state dielectron invariant mass $\sqrt{(p_{e^+} + p_{e^-})^2}$ obtained for the localizations of fermions corresponding to sets A and B of c_i parameters, which reproduce the quark/lepton masses (as discussed in Section 3). Only the zero-mode up to second KK excitation of photon and Z boson (as well as the interferences between those) were taken into account when deriving the results presented in this figure, since the contributions of $\gamma^{(n)}$, $Z^{(n)}$ [with $n \geq 3$] to the Drell-Yan cross section are not significant. The explanation being that the masses (couplings to fermions) of $\gamma^{(n)}$, $Z^{(n)}$ increase (decrease) as the KK-level n gets higher [12]. For $n = 2$, the second KK mass is already at $M(\gamma^{(2)}) = (5.57/2.45)M_{KK} = 5.57kw$. We have taken $M_{KK} = 3$ TeV, typically the minimal value satisfying the phenomenological constraints (described in Section 3), in order to optimize the number of events. The resonance peak around $\sqrt{(p_{e^+} + p_{e^-})^2} = M_{KK}$ is clearly visible on Fig.(1).
The first important information provided by this figure, is that the process $pp \to \gamma^{(0,1,2)}/Z^{(0,1,2)} \to e^+e^-$ yields a large number of events for an integrated luminosity of $\mathcal{L} = 96.6 fb^{-1}$ (one year

[e] The c_i parameters of set B are typically smaller (except for the top quark, or more precisely c_3^u) than in set A, so that for set B the (light) fermions are localized closer to the TeV-brane where are also located KK gauge bosons.

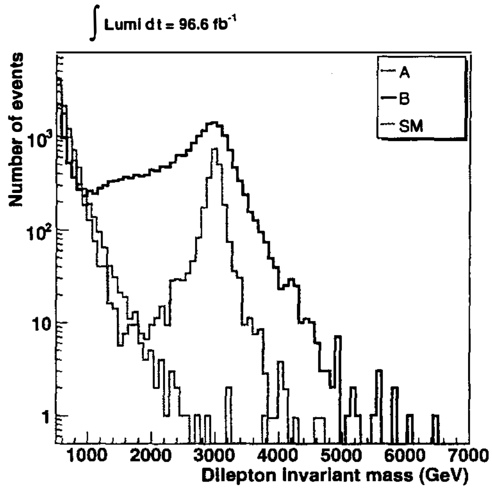

Figure 1: Distribution of the invariant mass $\sqrt{(p_{e^+}+p_{e^-})^2}$ (in GeV) of the electron and positron in final state of reaction $pp \to \gamma^{(0,1,2)}/Z^{(0,1,2)} \to e^+e^-$ at LHC, for $M_{KK} = 3$ TeV and sets A (grey curve) or B (black curve) of c_i parameters (*c.f.* Appendix) within the RS model. The absolute number of events corresponds to an integrated luminosity of $\mathcal{L} = 96.6 fb^{-1}$, as indicated. We also show the invariant mass distribution for the pure SM Drell-Yan process $pp \to \gamma/Z \to e^+e^-$ (green line). This plot was obtained by generating events, after implementation of the studied processus in the PYTHIA *Monte Carlo* simulator.

of LHC running at high luminosity). The other information is that the RS signal can be easily extracted from the physical SM background (which comes mainly from the Drell-Yan processus): in this example, the RS signal can be detected via an excess (coming from the contributions of KK gauge boson excitations) of Drell-Yan events $pp \to e^+e^-$, compared to the pure SM expectation. As a conclusion, the considered RS signal is expected to be visible at LHC.

5 Conclusion

We have considered the RS model with bulk matter addressing the gauge hierarchy problem, with in particular some examples of fermion localizations along the extra dimension which generate a realistic structure in flavour space (reproduce quark/lepton masses and satisfy FCNC constraints). Then, we have shown that these geometrical scenarios can be effectively tested at LHC.

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Appendix

We call set A the following set of c_i value for each SM fermion,

$$\begin{array}{lll} c_1^Q = 0.37\ ; & c_2^Q = 0.37\ ; & c_3^Q = 0.37 \\ c_1^d = 0.716\ ; & c_2^d = 0.728\ ; & c_3^d = 0.615 \\ c_1^u = 0.607\ ; & c_2^u = 0.607\ ; & c_3^u = 0.050 \end{array} \qquad \begin{array}{lll} c_1^L = 0.200\ ; & c_2^L = 0.200\ ; & c_3^L = 0.261 \\ c_1^l = 0.737\ ; & c_2^l = 0.696\ ; & c_3^l = 0.647 \\ c_1^\nu = 1.496\ ; & c_2^\nu = 1.503\ ; & c_3^\nu = 1.463 \end{array} \tag{3}$$

Set B is defined by:

$$\begin{array}{lll} c_1^Q = 0.2\ ; & c_2^Q = 0.2\ ; & c_3^Q = 0.2 \\ c_1^d = 0.728\ ; & c_2^d = 0.740\ ; & c_3^d = 0.628 \\ c_1^u = 0.62\ ; & c_2^u = 0.62\ ; & c_3^u = 0.35 \end{array} \qquad \begin{array}{lll} c_1^L = -1.5\ ; & c_2^L = -1.5\ ; & c_3^L = -1.5 \\ c_1^l = 0.760\ ; & c_2^l = 0.833\ ; & c_3^l = 0.667 \\ c_1^\nu = 1.512\ ; & c_2^\nu = 1.513\ ; & c_3^\nu = 1.468 \end{array} \tag{4}$$

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