Warped Unification, Proton Stability, and Dark Matter

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We show that solving the problem of baryon-number violation in nonsupersymmetric grand unified theories (GUT's) in warped higher-dimensional spacetime can lead to a stable Kaluza–Klein particle. This exotic particle has gauge quantum numbers of a right-handed neutrino, but carries fractional baryon number and is related to the top quark within the higher-dimensional GUT. A combination of baryon number and SU(3) color ensures its stability. Its relic density can easily be of the right value for masses in the 10 GeV–few TeV range. An exciting aspect of these models is that the entire parameter space will be tested at near future dark matter direct detection experiments. Other exotic GUT partners of the top quark are also light and can be produced at high energy colliders with distinctive signatures.

One of the most interesting aspects of the dark matter (DM) puzzle (that $\sim 80\%$ of the matter in the Universe is nonbaryonic and of yet-unknown nature) is that it is likely to be related to new physics at the TeV scale. Indeed, particles with weak scale size interactions and a mass at the electroweak breaking scale (WIMPs) are typically predicted to have the good relic density today to account for dark matter, provided that they are stable. The favorite DM candidate to date is the lightest supersymmetric particle (LSP) in supersymmetric extensions of the standard model (SM) with conserved R parity. R parity is not imposed just for the purpose of having a DM candidate but as the simplest solution to baryon-number conservation in the supersymmetric theory. As a very appreciated spinoff, one gains a stable DM candidate.

Lately, alternative models for physics beyond the SM that make use of extra dimensions rather than supersymmetry to solve the gauge hierarchy problem, have been suggested. The one which attracted much attention being the Randall–Sundrum (RS1) model [1], where the hierarchy between the electroweak (EW) and the Planck scales arises from a warped higher-dimensional spacetime. Variants of the original setup have matured over the years. Eventually, all SM fields except the Higgs boson (to solve the hierarchy problem, it is sufficient that just the Higgs—or alternative dynamics responsible for electroweak symmetry breaking—be localized at the TeV brane) have been promoted to bulk fields rather than brane fields. Indeed, it has been realized that placing gauge fields in the bulk could lead to high scale unification because of the logarithmic running of gauge couplings in AdS$_5$ [2]. In addition, allowing fermions to propagate along the extra dimension offers a simple attractive mechanism for explaining the structure of Yukawa couplings without introducing hierarchies at the level of the five-dimensional action [3]. More recently, it has been

shown that EW precision constraints are much ameliorated if the EW gauge symmetry is enhanced to SU(2)$_L$ × SU(2)$_R$ × U(1)$_{B-L}$ [4]. The AdS/CFT correspondence suggests that this model is dual to a strongly coupled CFT (conformal field theory) Higgs sector [5]. Also, the SU(2)$_L$ × SU(2)$_R$ gauge symmetry in the RS bulk implies the presence of a global custodial isospin symmetry of the CFT Higgs sector, thus protecting EW observables from excessive new contributions [4]. This gauge structure in warped space has also been used to construct Higgs-less models of EW symmetry breaking [6]. Our qualitative results will apply to these models as well.

One of the remaining phenomenological issues which has not been addressed in RS is the DM puzzle. No generic WIMP dark matter candidate has been identified yet. In this work, we would like to consider the possibility of Kaluza–Klein dark matter [7,8], so far restricted to models with flat TeV^{-1} universal extra dimensions (UED), in warped geometries. In UED, the Lightest Kaluza–Klein Particle (LKP) can be stable because of KK parity, a remnant of translation invariance along the extra dimension, after the orbifold projection has been implemented. Note that for KK parity to be an exact symmetry, one has to assume that the boundary Lagrangians at the two orbifold fixed points are symmetric. Models with flat toroidal TeV^{-1} extra dimensions contain a light, typically meV-mass, gravitationally coupled radion, which can lead to cosmological catastrophe like overclosure of the Universe by radion oscillations [9]. In contrast, this problem does not arise in RS geometry where the radion field has an EW mass and couples strongly [10]. Cosmology of RS has attracted tremendous interest. In particular, it was shown that standard Friedmann cosmology can be recovered [10,11] and normal expansion is expected at least up to a TeV temperatures above which a phase transition occurs where the TeV

brane is replaced by an event horizon [5,12]. As far as WIMP dark matter is concerned, we do not rely on what happens at these high temperatures since the freeze out temperature is typically a few tens of GeV and we can safely make a standard cold dark matter relic density calculation in the RS context.

Obviously, there is no translational invariance in RS geometry, hence there is no analog of KK parity conservation. Instead, the stability of a light KK mode will be related to baryon-number symmetry. In RS, dominant baryon-number violation arises through effective four fermion interactions localized near the TeV brane thus suppressed by the TeV scale only. One solution is to localize fermions very close to the Planck brane where the effective cutoff is Planckian. However, it turns out that this suppresses too much the 4D Yukawa couplings to the Higgs on the TeV brane and is incompatible with the spectrum of SM fermion masses. In this Letter, we impose a bulk (gauged) baryon-number symmetry. We are also interested in RS GUTs. So far, such studies have focused on SU(5) only [13,14]. We will instead assume SO(10) or Pati–Salam, in which the left-right gauge structure mentioned above can easily be embedded. *A priori*, grand unification is at odds with imposing baryon-number symmetry. However, baryon-number symmetry can be consistent with higher-dimensional GUT [13,14] if the unified gauge group is broken by boundary conditions (BC) so that SM quarks and leptons are obtained from different bulk multiplets of the unified gauge group. Let us start with a simple example where SO(10) is broken to the SM on the Planck brane by BC and the number of **16** representations is replicated 3 times per generation:

$$\begin{pmatrix} \mathbf{u_L}, \mathbf{d_L} \\ u_R^{lc} \\ d_R^{lc} \\ \nu_L', e_L' \\ e_R^{lc} \\ \nu_R^{lc} \end{pmatrix}_{B=1/3}, \begin{pmatrix} u_L', d_L' \\ \mathbf{u_R^c} \\ \mathbf{d_R^c} \\ \nu_L', e_L' \\ e_R^{lc} \\ \nu_R^{lc} \end{pmatrix}_{-1/3}, \begin{pmatrix} u_L', d_L' \\ u_R^{lc} \\ d_R^{lc} \\ \mathbf{\nu_L}, \mathbf{e_L} \\ \mathbf{e_R^c} \\ \mathbf{\nu_R^c} \end{pmatrix}_{0}.$$

Only states in boldface characters have zero modes, they correspond to $(++)$ BC ($+$ denotes Neumann, $-$ Dirichlet, first sign is for Planck brane, second for TeV brane) and are identified with the SM fermions. Other states are $(-+)$. GUT multiplets are assigned the baryon-number of the zero modes contained in them. A Z_3 symmetry follows from requiring baryon-number as a good quantum number:

$$\Phi \rightarrow e^{2\pi i[B - ((n_c - \bar{n}_c)/3)]}\Phi. \tag{1}$$

B is baryon number of Φ and n_c ($\bar{n}_c$) is its number of color (anticolor) indices. Clearly, SM fields are not charged under Z_3. X, Y, X', Y', and X_s gauge bosons of SO(10) are charged under Z_3 as well as leptonlike states within

16's which carry baryon-number and quarklike states which carry nonstandard baryon-number. These exotic states do not have zero modes. Consequently, the lightest Z_3 charged particle (LZP) cannot decay into SM particles and is stable. Note that the baryon-number gauge symmetry has to be broken since we do not want an extra massless gauge boson in the theory. We break it spontaneously on the Planck brane. If it is broken in such a way that $\Delta B \neq \frac{1}{3}, \frac{2}{3}$, we can show that proton decay is Planck suppressed [15]. In order to guarantee this, we impose the Z_3 symmetry. As a result, the LZP is stable, and, like in supersymmetry, dark matter can arise as a consequence of solving proton stability.

The question is now to identify the LZP and see whether one can naturally expect it to be neutral. In warped space, the spectrum of fermionic KK modes is governed by two things. First, the *c-parameter* [3] which determines the localization of wave function of massless modes along the 5th direction and therefore the size of their 4D Yukawa couplings. Second, it depends crucially on BC reflecting the dynamics taking place at the TeV and Planck brane. The interesting thing about $(-+)$ fermionic states is that they are lighter than gauge KK modes for $c < 1/2$ and actually much lighter for $c < 0$. In the past, studies have focused on $(++)$ KK fermions, which are always heavier than gauge KK modes, thus are difficult to observe at colliders since the constraints on the gauge KK mass is $M_{KK} \gtrsim 3$ TeV [4]. Figure 1 shows the dependence on c (exponential for $c < -1/2$) of the mass of the first KK excitation of $(-+)$ fermions. Very light ($\sim$ GeV) KK fermions are natural. This plot is telling us that the LZP will belong to the multiplet whose c is the smallest, namely, the multiplet with right-handed top zero mode which has c in the range $[-1/2, 0]$ to account
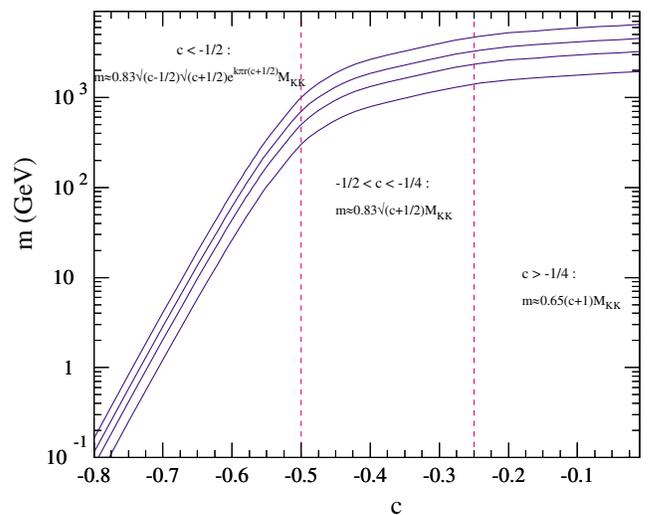

FIG. 1 (color online). Lightest mass of $(-+)$ KK fermion as a function of its c parameter. From bottom to top, $M_{KK} = 3, 5, 7, 10$ TeV. $e^{k\pi r} \sim M_{Pl}/\text{TeV}$ is the warp factor of RS geometry.

for $\mathcal{O}(1)$ Yukawa. From now on, we will concentrate on that particular **16**. Mass splittings between different KK states belonging to the same **16** will arise from radiative corrections. In addition, and maybe most importantly, we expect splittings in the c's due to bulk GUT breaking effects [14]. Such effects (actually desired to achieve unification through threshold type corrections) can lead to Δc's as large as ± 0.5 therefore making the c's of the $(-+)$ states within the same **16** almost free parameters. Phenomenologically, the LZP has to be the right-handed neutrino. Indeed, it is well known that heavy left-handed neutrino dark matter is excluded by elastic scattering experiments (unless its mass is larger than several tens of TeV) because of its large coupling to the Z^0 gauge boson, e.g. [8]. From now on, we will therefore assume that the KK RH neutrino has the smallest c, thus is the LZP. In warped SO(10) or Pati–Salam, the KK right-handed neutrino behaves as a WIMP as follows. Its couplings to KK gauge bosons like Z', the extra U(1) of SO(10), or X_s, are actually enhanced compared to SM couplings, as understood from the CFT dual interpretation of KK modes as strongly coupled composites. However, KK gauge bosons have at least a 3 TeV mass, making cross sections effectively of the right weak scale size. It turns out that the LZP has actually a non-negligible coupling to Z^0 because of Z'–Z^0 mixing after EW symmetry breaking as well as LZP–ν'_L mixing from the large Yukawa coupling between the **16** of t_R and the **16** of (t_L, b_L). Such Yukawa coupling may also generate a significant LZP-Higgs coupling.

We are now ready to evaluate the relic density of the LZP. There are essentially four types of annihilation channels: s-channel exchanges of Z^0 into any SM fermions, of Z' into $t\bar{t}$, $b\bar{b}$, W^+W^-, Z^0h, of Higgs into $t\bar{t}$, W^+W^-, Z^0Z^0 and t-channel exchange of X_s into $t_R\bar{t}_R$. Note that only fields localized near the TeV brane (t, b, h, longitudinal $W^\pm$ and Z^0) have large couplings to Z' and that the only zero mode the LZP directly couples to is t_R. In a first approximation, we have not included the Higgs exchange in our analysis. However, as explained in [15], it becomes significant (but subdominant) only for LZP masses between m_t and m_h and also dominates at the resonance, $m_{\text{LZP}} \sim m_h/2$, thus modifies the predictions of Fig. 2 for these masses. There are at least 6 parameters entering the relic density calculation: c_{LZP} which fixes not only the LZP mass but also the LZP couplings, M_{KK}, the gauge KK mass (mass of Z' and X_s) constrained to be $\gtrsim$ 3 TeV but also favored to be as low as possible not to reintroduce a hierarchy problem, c_{t_R}, c_{b_L}, $c_{\nu'_L}$ and finally g_{10}, the 4D SO(10) gauge coupling. Because of UV sensitive bulk threshold effects and finite, universal 1–loop corrections, g_{10} can vary from g' to g_s [15]. In order to get a large 4D top Yukawa without pushing the 5D theory to strong coupling, $c_{t_R} = -1/2$ is actually favored. Our qualitative results do not depend much on the precise
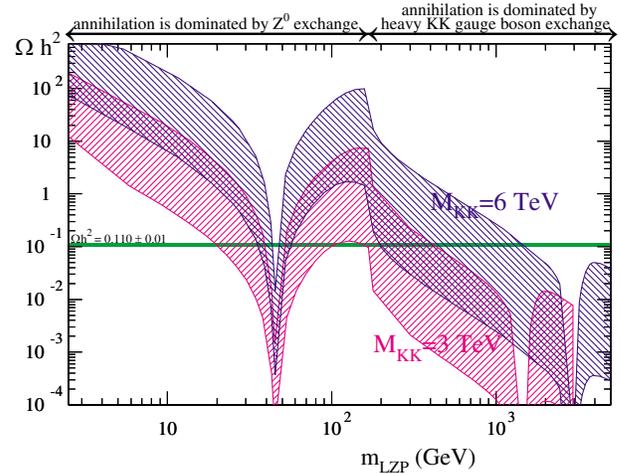

FIG. 2 (color online).   An example of relic density predictions in warped SO(10) for two values of M_{KK}. $c_{t_R} = -1/2$, $c_{t_L,b_L} = 0.4$, all c's for other fermions being larger than $1/2$. Each region is obtained by varying both g_{10} (from g' to g_s) and $c_{\nu'_L} \in [c_{t_L} - 0.5, c_{t_L} + 0.5]$.

nature of the EW symmetry breaking sector. However, detailed quantitative predictions do. As an illustration, Fig. 2 shows our prediction for the relic density in the attractive case where the Higgs is a pseudo-Goldstone boson (PGB) [16] which is not exactly localized on the TeV brane but has some profile in the bulk. For LZP masses below the top mass, annihilation is dominated by Z^0 exchange, then annihilation through X_s exchange takes over until the LZP mass reaches the Z' pole. The result is that there is a large parameter space and particularly a large range of LZP masses for which we can get the right relic density.

Our LZP being a Dirac particle, with significant coupling to the Z^0, we predict large cross sections for its elastic scattering off nuclei (the calculation is similar to the one in [8]). Comparatively, scattering via Higgs exchange is always negligible. As shown in Fig. 3, the entire parameter space will be tested at near future direct detection experiments. As an illustration, we show the $M_{\text{KK}} = 10$ TeV case, disfavored as far as fine tuning of the Higgs mass is concerned. Even this extreme case, in which discovery of KK modes at colliders would be hopeless, could easily be probed by direct DM searches.

Pair production of our WIMP at future accelerators can be observed only for the largest values of the Z^0–LZP coupling, which are already ruled out by DM direct searches. However, there are very promising collider signatures associated with the pair production of the next lightest exotic KK modes, in the same **16** as the LZP. Those are also expected to have $c \sim -1/2$ with masses in the few hundred GeV–1 TeV range. Such KK modes cannot decay easily. Details will be presented in [15]. As an example, we show in Fig. 4 the decay of b'_L, which has to go through a 4-body decay: two LZPs, a top and a W,

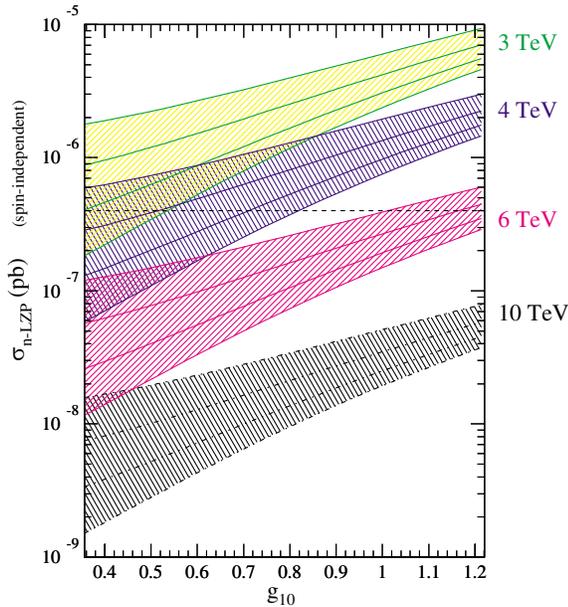P H Y S I C A L   R E V I E W   L E T T E R S

FIG. 3 (color online).   An example (where the Higgs is a PGB) of predictions for elastic scattering cross sections between the LZP and a nucleon (independent of LZP mass). For each M_{KK} region, the four lines denote different values of the Z^0-LZP coupling corresponding to, from top to bottom, $c_{\nu'_L} = -0.1, 0.1, 0.4, 0.9$. The horizontal dotted line indicates the present experimental limit, which only applies for some range of WIMP masses; see [17] for instance. For this range of LZP masses, only g_{10} values below 0.55 survive in the $M_{KK} = 3$ TeV case.

leading to quite a unique signature. In a significant part of parameter space, such 4-body decay will be forbidden kinematically and b'_L may lead to a ionization track in the detector, something also easy to search for.

In summary, we showed that solving the problem of baryon-number violation in higher-dimensional warped GUT by imposing a Z_3 symmetry leads to the stability of a light KK fermion, which acts as a viable dark matter candidate. We also emphasized the interesting phenomenology associated with KK fermions with $(-+)$ type of boundary conditions in warped geometry,
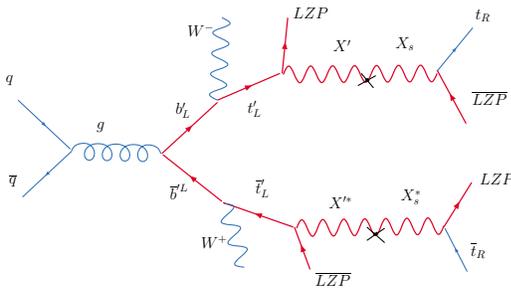

FIG. 4 (color online).   Pair production and decay of b'_L, GUT partner of the LZP. Decay occurs through X'–X_s mixing due to bulk SO(10) breaking.

our DM candidate being one of them. It is expected that all fields within a multiplet may not have the same BC, in particular, in GUT theories where the gauge symmetry is broken by BC. We predict the KK modes in the GUT multiplet whose zero mode is t_R to be light ($\lesssim$ TeV) and observable at future colliders. Model building issues, further phenomenological aspects and technical details of these models will be provided elsewhere [15].

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