PROCEEDINGS OF SCIENCE

Dark Matter from Lorentz Invariance and the LHC

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In extra dimensional models, a Dark Matter candidate can be present thanks to a Kaluza-Klein parity which makes the lightest resonances stable. However, compactifications considered sofar need the symmetry to be imposed by hand on the model: here we propose the unique orbifold in 6 dimensions where such parity arises naturally as part of the unbroken 6D Lorentz invariance. As an example we introduce a model of universal extra dimensions where all standard model fields propagate in the extra dimensions. The dark matter candidate is a scalar photon and its preferred mass range lies below 300 GeV. Due to the small splitting between states in the same Kaluza-Klein tier, discovery of the lightest tiers is challenging at the LHC.

European Physical Society Europhysics Conference on High Energy Physics, EPS-HEP 2009,
July 16 - 22 2009
Krakow, Poland

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PoS(EPS-HEP 2009)250

1. Introduction

Both cosmological and astrophysical observations confirmed that most of the matter content of the Universe is dark and non-barionic, however the nature of such matter is still a mystery. On the theoretical side, one hypothesis is the presence of massive weakly interacting particle (WIMP) whose relic density could explain the dark matter abundance and also be compatible with the structure formation. Many models contain such a candidate: among others the lightest supersymmetric particle, the lightest T-odd particle in Little Higgs models and the lightest Kaluza-Klein state in extra dimensional models. All those models are built by extending the symmetries of the Standard Model. However, a common feature to most of those scenarios is that the symmetry keeping the dark matter candidate stable or long lived is not required by the model and it is added by hand: R-parity in supersymmetric models, also ensuring the stability of the proton; T-parity in Little Higgs models and the KK parity which constraints the physics on special points of the compact space in extra dimensional models. Therefore, the presence of a Dark Matter candidate is not a generic prediction of those models. On the other hand, in extra dimensions, the KK parity in the bulk is a relic of the extended Lorentz invariance therefore is it part of a fundamental symmetry. However, requiring a chiral spectrum for the lightest states (the standard model) introduces singular points in the compactified space which only respect 4D Lorentz invariance and therefore break the KK parity: it is usually reintroduced by imposing special constraints on such points [1]. This is what happens in the compactifications considered sofar in the literature both in 5D [1] and 6D [2].

Here we show that there exist a class of compact spaces where the KK parity is indeed part of the unbroken Lorentz invariance and therefore is an exact and unavoidable symmetry of the model [3]. The crucial point is the absence of fixed points (singular points that are transformed into themselves by all the symmetries of the compact space). No such case is possible in 5D, while in 6D there is a single compact space: the real projective plane [4]. The phenomenology of the model depends on the chosen compactification, which determines the field content of each KK tier and the one loop corrections, crucial to calculate mass splittings and decay widths.

2. KK parity

Out of the 17 orbifold compactification of 2 dimensions, only the real projective plane combines the presence of chiral light fermions and the absence of fixed points [3]. The compact space can be defined in terms of 2 symmetries of R^2: a rotation by π and a glide

$$r : \begin{cases} x_5 \sim -x_5 \\ x_6 \sim -x_6 \end{cases}, \qquad g : \begin{cases} x_5 \sim x_5 + \pi R_5 \\ x_6 \sim -x_6 + \pi R_6 \end{cases}. \tag{2.1}$$

Two translations can be defined by $t_1 = g^2$ and $t_2 = (gr)^2$ and, because $r^2 = (g^2 r)^2 = 1$ the only possible parity assignments are ± 1; therefore all fields are periodic. The rotation changes sign to all extra coordinates and this is the condition to have chiral zero modes, however it also possesses 4 fixed points: $(0,0)$, $(0,\pi R_6)$, $(\pi R_5, 0)$ and $(\pi R_5, \pi R_6)$. The glide does not leave any fixed points, and it identifies $(0,0) \leftrightarrow (\pi R_5, \pi R_6)$ and $(0, \pi R_6) \leftrightarrow (\pi R_5, 0)$. The space therefore contains two singular points where 4 dimensional interactions can be introduced: such interactions are actually

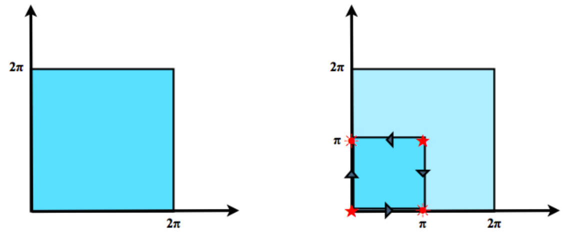

Figure 1: Fundamental domain for a torus (left) and real projective plane (right). The red stars indicate the singular points.

required to regularize Ultraviolet divergencies of the theory and are therefore generated by the UV completion of the model.

The fundamental domain of the space compared to the one of a torus is in Figure 1. It is also invariant under a rotation by π around the center of the square (or equivalently a translation by $(\pi R_5, \pi R_6)$): this symmetry is the KK parity. Note that this is the same symmetry as in the chiral square [2] previously studied in the literature: the crucial difference is that in our case the singular points do respect the symmetry, while on the chiral square two of the fixed points must be identified: this is equivalent to an ad-hoc global symmetry of the UV completion of the model. In our scenario, on the other hand, such symmetry is a fundamental symmetry of the model and cannot be broken. A generic KK mode with momenta along the extra directions $(k/R_5, l/R_6)$, where k and l are integers due to the periodicity of the fields, will pick up a phase $(-1)^{k+l}$. Note also that one may impose a second KK parity, a translation by π along one of the coordinates, however this would require the identification of the two singular points.

3. Phenomenology of the SM on the real projective plane

As a simple example, we will discuss a model where al the SM particles are allowed to propagate in the extra dimensions [3]. The tree level spectrum is determined by the parity assignment of each SM field under the two symmetries. The modes are labelled by two integers (l,k), and each mode has a tree level mass

$$m^2_{(l,k)} = \frac{l^2}{R_5^2} + \frac{k^2}{R_6^2}\,; \tag{3.1}$$

for simplicity, in the following we will also set $R_5 = R_6 = 1$. For gauge bosons, the parities must be $(+,+)$ in order to have a vector zero mode to be identified with the SM gauge bosons. The spectrum contains a scalar field in the tiers $(2l+1,0)$ and $(0,2k+1)$, a massive vector in the tiers $(2l+1,0)$ and $(0,2k+1)$ and both a vector and a scalar when both integers are non-zero. For the Higgs boson, we chose also $(+,+)$ to allow for a vacuum expectation value: in this case, the VEV does not depend on the extra coordinates and, due to the orthonormality of the wave functions, it does not induce mixing among tiers. The spectrum consists of a massive resonance in the levels $(2l,0)$, $(0,2k)$ and (l,k).

Finally, for the fermions, the parity under the rotation determines the chirality of the zero mode: left-handed if $(+)$ and right handed if $(-)$. The spectrum of the KK modes is the same: one

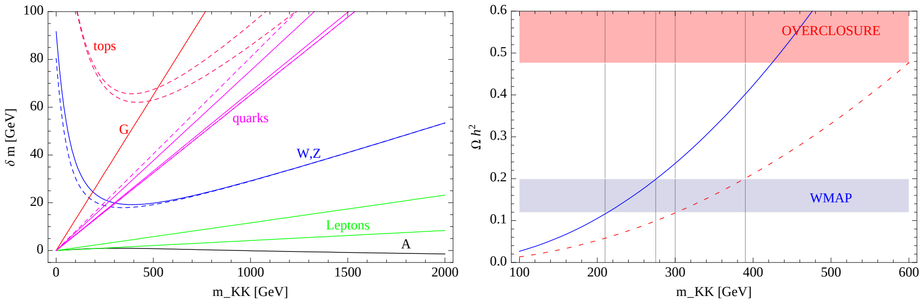

Figure 2: LEFT: Mass splitting between the different states in the lightest tier as a function of the KK mass m_{KK}: in black the scalar photon, in blue the W and Z, in solid red the gluon, in green the leptons, in magenta the light quarks, in dashed red the tops. RIGHT: relic abundance including two (solid blue) and one (dashed red) tiers. Both plots are from [3].

single massive fermion in the tiers $(l,0)$ and $(0,k)$ and two degenerate states in each tier with both non-zero indices. The parity under the glide does not affect the spectrum, however it determines the couplings of the fermions: for instance, in order to write down a Yukawa coupling in the bulk both fermions must have the same glide parity. This could be used to avoid Yukawa couplings between leptons and quarks by assigning them different glide parities.

At three level, all the states in each tier are degenerate. There are three mechanisms that generate splittings between states in each tier: the Higgs vacuum expectation value, loop corrections and operators localized on the singular points (kinetic terms). The Higgs VEV does not generate mixing inter tiers: at the level $(0,0)$, therefore, the spectrum is exactly the same as in the standard model and no tree level corrections to precision electroweak observables are generated. In massive tiers, the correction to the masses, both for fermions and bosons, is of the form $m^2 = m^2_{(l,k)} + m_0^2$, where m_0 is the mass of the corresponding standard model particle. Such correction therefore is large for small KK mass (m_{KK} is the mass of the lightest tier, all the other tree level masses are proportional to it). In absence of other contributions, the weak mixing angle between the gauge vectors or scalars in the tier is equal to the standard model one. Loop corrections on the other hand respect less symmetries than the full 6D Lorentz invariance, therefore tier mixing is allowed. Nevertheless, at leading order the off diagonal terms can be neglected. For a boson, the contribution Π to the mass squared can in general be written as

$$\Pi = \Pi_T + p_g \Pi_G + p_g p_r \Pi_{G'} + p_r \Pi_R \,, \tag{3.2}$$

where p_x is the parity of the field in the loop; Π_T is the contribution of the torus, it is divergent, but the divergence is eaten by the renormalization of the bulk kinetic term; Π_G and $\Pi_{G'}$ are the finite contributions from the glide (where $g' = gr$); finally Π_R is the contribution of the rotation. The latter contains a log divergence: this divergence is of geometrical origin, in fact it can be regularized by including a counterterm on the singular points of the orbifold. Therefore, kinetic terms localized on the singular points are required and they can in principle be as large as a one-loop contribution. Note finally that the loop contributions to the masses are proportional to the KK mass. We computed the loop contribution for the entire tier $(1,0)$ and $(0,1)$ [3]: those are phenomenologically crucial to determine the nature of the dark matter candidate and calculate the preferred mass range to explain the Dark Matter abundance. Finally, one can add two kinetic terms on the two singular points. In general they do respect even less symmetries, therefore they can for instance induce a splitting between the $(1,0)$ and $(0,1)$ tiers (which would be left degenerate by Higgs and loop corrections). We expect those contribution to be small as they do correspond to higher order operators in the 6D model, and they are required at one loop only. A more detailed discussion of the splitting structure can be found in [3]: an important point is that the loop corrections will reduce the mixing angle in the weak gauge sector and it will become very small for large KK masses. On the left panel of Figure 2 we plotted the total corrections to the masses in the lightest tier: the lightest state is a neutral scalar gauge boson corresponding to the photon up to the different weak mixing angle.

As the mass splittings are small, the scattering of all the states in the lightest tier contribute to determining the Dark Matter abundance: in fact, all states will be in thermal equilibrium and only after freeze out they decay to the lightest state. To estimate the preferred mass range, we used the analytical method outlined in [5] including all the main coannihilation channels: the result is in Figure 2. The preferred mass is between 200 GeV and 300 GeV ($300 \div 400$ GeV if only one tier contributes). This result is only an estimate as a more precise calculation is required due to the large number of coannihilation channels, and other channels (like resonant annihilation via a Higgs [6] or a tier $(2,0)$ and $(0,2)$ at loop level).

The light KK mass has an important phenomenological consequence: the resonances will be copiously produced at the LHC and they will cascade decay to the lightest stable particle. However, due to the small splittings, the energy available for the standard model particles in the decay is very small (typically less than 20 GeV). Such soft particle will easily escape the detection or the trigger, therefore the whole lightest tier will appear as missing energy. The even tiers will decay into standard model stuff without missing energy: it is the observation of the missing energy, smoking gun of the presence of a dark matter candidate, that is a challenge. On the other hand, it also offers the possibility for spectacular events: for instance an odd $(2,1)$ state can decay via a loop into a $(0,1)+(0,0)$: as the lightest tier is invisible, one can see a single charged particle plus missing energy in the final state (as an example: $Z_{(2,1)} \to e^+_{1,0} e^-$).

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