Physics from extra dimensions

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Abstract. Lowering the string scale in the TeV region provides a theoretical framework for solving the mass hierarchy problem and unifying all interactions. The apparent weakness of gravity can then be accounted by the existence of large internal dimensions, in the submillimeter region, and transverse to a braneworld where our universe must be confined. I review the main properties of this scenario and its implications for observations at both particle colliders, and in non-accelerator gravity experiments.

1. Introduction

During the last few decades, physics beyond the Standard Model (SM) was guided from the problem of mass hierarchy. This can be formulated as the question of why gravity appears to us so weak compared to the other three known fundamental interactions corresponding to the electromagnetic, weak and strong nuclear forces. Indeed, gravitational interactions are suppressed by a very high energy scale, the Planck mass $M_P \sim 10^{19}$ GeV, associated to a length $l_P \sim 10^{-35}$ m, where they are expected to become important. In a quantum theory, the hierarchy implies a severe fine tuning of the fundamental parameters in more than 30 decimal places in order to keep the masses of elementary particles at their observed values. The reason is that quantum radiative corrections to all masses generated by the Higgs vacuum expectation value (VEV) are proportional to the ultraviolet cutoff which in the presence of gravity is fixed by the Planck mass. As a result, all masses are “attracted” to become about $10^{16}$ times heavier than their observed values.

Besides compositeness, there are two main theories that have been proposed and studied extensively during the last years, corresponding to different approaches of dealing with the mass hierarchy problem. (1) Low energy supersymmetry with all superparticle masses in the TeV region. Indeed, in the limit of exact supersymmetry, quadratically divergent corrections to the Higgs self-energy are exactly cancelled, while in the softly broken case, they are cutoff by the supersymmetry breaking mass splittings. (2) TeV scale strings, in which quadratic divergences are cutoff by the string scale and low energy supersymmetry is not needed. Both ideas are experimentally testable at high-energy particle colliders and in particular at LHC. Below, I discuss their implementation in string theory.

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2. Strings and extra dimensions

The appropriate and most convenient framework for low energy supersymmetry and grand unification is the perturbative heterotic string. Indeed, in this theory, gravity and gauge interactions have the same origin, as massless modes of the closed heterotic string, and they are unified at the string scale $M_s$. As a result, the Planck mass $M_P$ is predicted to be proportional to $M_s$:

$$M_P = M_s/g,$$

(1)

where $g$ is the gauge coupling. In the simplest constructions all gauge couplings are the same at the string scale, given by the four-dimensional (4d) string coupling, and thus no grand unified group is needed for unification. In our conventions $\alpha_{\text{GUT}} = g^2 \approx 0.04$, leading to a discrepancy between the string and grand unification scale $M_{\text{GUT}}$ by almost two orders of magnitude. Explaining this gap introduces in general new parameters or a new scale, and the predictive power is essentially lost. This is the main defect of this framework, which remains though an open and interesting possibility [1].

The other perturbative framework that has been studied extensively in the more recent years is type I string theory with D-branes. Unlike in the heterotic string, gauge and gravitational interactions have now different origin. The latter are described again by closed strings, while the former emerge as excitations of open strings with endpoints confined on D-branes [2]. This leads to a braneworld description of our universe, which should be localized on a hypersurface, i.e. a membrane extended in $p$ spatial dimensions, called $p$-brane (see Fig. 1). Closed strings propagate in all nine dimensions of string theory: in those extended along the $p$-brane, called parallel, as well as in the transverse ones. On the contrary, open strings are attached on the $p$-brane. Obviously, our $p$-brane world must have at least the three known dimensions of space.

![Figure 1](image.png)

**Figure 1.** In type I string framework, our Universe contains, besides our 3 spatial dimensions (denoted by the blue line), some extra dimensions ($d_\parallel = p - 3$) parallel to our world $p$-brane (green plane) where endpoints of open strings are confined, as well as some transverse dimensions (yellow space) where only gravity (described by closed strings) propagate.

But it may contain more: the extra $d_\parallel = p - 3$ parallel dimensions must have a finite size, in order to be unobservable at present energies, and can be as large as TeV$^{-1} \sim 10^{-18}$ m [3]. On the other hand, transverse dimensions interact with us only gravitationally and experimental
bounds are much weaker: their size should be less than about 0.1 mm [4]. In the following, I review the main properties and experimental signatures of low string scale models [5, 6].

2.1. Framework of low scale strings
In type I theory, the different origin of gauge and gravitational interactions implies that the relation between the Planck and string scales is not linear as (1) of the heterotic string. The requirement that string theory should be weakly coupled, constrain the size of all parallel dimensions to be of order of the string length, while transverse dimensions remain unrestricted. Assuming an isotropic transverse space of \( n = 9 - p \) compact dimensions of common radius \( R_\perp \), one finds:

\[
M_P^2 = \frac{1}{g_s^2} M_s^{2+n} R_\perp^n, \quad g_s \simeq g^2. \tag{2}
\]

where \( g_s \) is the string coupling. It follows that the type I string scale can be chosen hierarchically smaller than the Planck mass [7, 5] at the expense of introducing extra large transverse dimensions felt only by gravity, while keeping the string coupling small [5]. The weakness of 4d gravity compared to gauge interactions (ratio \( M_W/M_P \)) is then attributed to the largeness of the transverse space \( R_\perp \) compared to the string length \( l_s = M_s^{-1} \).

An important property of these models is that gravity becomes effectively \((4+n)\)-dimensional with a strength comparable to those of gauge interactions at the string scale. The first relation of Eq. (2) can be understood as a consequence of the \((4+n)\)-dimensional Gauss law for gravity, with

\[
M_s^{(4+n)} = M_s^{2+n} / g^4 \tag{3}
\]

the effective scale of gravity in \( 4+n \) dimensions. Taking \( M_s \simeq 1 \) TeV, one finds a size for the extra dimensions \( R_\perp \) varying from \( 10^8 \) km, .1 mm, down to a Fermi for \( n = 1, 2, \) or 6 large dimensions, respectively. This shows that while \( n = 1 \) is excluded, \( n \geq 2 \) is allowed by present experimental bounds on gravitational forces [4, 8]. Thus, in these models, gravity appears to us very weak at macroscopic scales because its intensity is spread in the “hidden” extra dimensions. At distances shorter than \( R_\perp \), it should deviate from Newton’s law, which may be possible to explore in laboratory experiments (see Fig. 2).

![Figure 2. Torsion pendulum that tested Newton’s law at 55 µm.](image)

3. Large number of species
Here, we open a parenthesis to describe that low scale gravity with large extra dimensions is actually a particular case of a more general framework, where the ultraviolet (UV) cutoff is
lower than the Panck scale due to the existence of a large number of particle species coupled to gravity [9]. Indeed, it was shown that the effective UV cutoff $M_*$ is given by

$$M_*^2 = M_P^2 / N,$$  \hspace{1cm} (4)

where the counting of independent species $N$ takes into account all particles which are not broad resonances, having a width less than their mass. The derivation is based on black hole evaporation but here we present a shorter argument using quantum information storage [10].

Consider a pixel of size $L$ containing $N$ species storing information. The energy required to localize $N$ wave functions is then given by $N/L$, associated to a Schwarzschild radius $R_s = N/L M_P^2$. The latter must be less than the pixel size in order to avoid the collapse of such a system to a black hole, $R_s \leq L$, implying a minimum size $L \geq L_{\text{min}}$ with $L_{\text{min}} = \sqrt{N}/M_P$ associated precisely to the effective UV cutoff $M_* = L_{\text{min}}$ given in eq. (4). Imposing $M_* \approx 1$ TeV, one should then have $N \sim 10^{32}$ particle species below the TeV scale!

In the string theory context, there are two ways of realizing such a large number a particle species by lowering the string scale at a TeV (without changing the behavior of gravity at large distances):

(i) In large volume compactifications with the Standard Model (SM) localized on D-brane stacks, as described in the previous section. The particle species are then the Kaluza-Klein (KK) excitations of the graviton (and other possible bulk modes) associated to the large extra dimensions, given by

$$N = R_{\perp}^{n} l_{s}^{n},$$  \hspace{1cm} (5)

up to energies of order $M_* \approx M_s$.

(ii) By introducing an infinitesimal string coupling $g_s \approx 10^{-16}$ with the SM localized on Neveu-Schwarz NS5-branes in the framework of little strings [11]. In this case, the particle species are the effective number of string modes that contribute to the black hole bound [12]:

$$N = 1/g_s^2.$$  \hspace{1cm} (6)

and gravity does not become strong at $M_s \sim \mathcal{O}(\text{TeV})$.

Note the both TeV string realizations above are compatible with the general expression (2), but in the second case there is no relation between the string and gauge couplings.

4. Experimental implications in accelerators

We now turn to the experimental predictions of TeV scale strings. Their main implications in particle accelerators are of three types, in correspondence with the three different sectors that are generally present: (i) new compactified parallel dimensions, (ii) new extra large transverse dimensions and low scale quantum gravity, and (iii) genuine string and quantum gravity effects.

On the other hand, there exist interesting implications in non accelerator table-top experiments due to the exchange of gravitons or other possible states living in the bulk.

4.1. World-brane extra dimensions

In this case $RM_s \gtrsim 1$, and the associated compactification scale $R_{\parallel}^{-1}$ would be the first scale of new physics that should be found increasing the beam energy [3, 13, 14]. The main consequence is the existence of KK excitations for all SM particles that propagate along the extra parallel dimensions. Their masses are given by:

$$M_{m}^2 = M_0^2 + \frac{m^2}{R_{\parallel}^2}; \quad m = 0, \pm 1, \pm 2, \ldots$$  \hspace{1cm} (7)
where we used $d_{\parallel} = 1$, and $M_0$ is the higher dimensional mass. The zero-mode $m = 0$ is identified with the 4d state, while the higher modes have the same quantum numbers with the lowest one, except for their mass given in (7). There are two types of experimental signatures of such dimensions [13, 15, 16]: (i) virtual exchange of KK excitations, leading to deviations in cross-sections compared to the SM prediction, that can be used to extract bounds on the compactification scale; (ii) direct production of KK modes.

On general grounds, there can be two different kinds of models with qualitatively different signatures depending on the localization properties of matter fermion fields. If the latter are localized in 3d brane intersections, they do not have excitations and KK momentum is not conserved because of the breaking of translation invariance in the extra dimension(s). KK modes of gauge bosons are then singly produced giving rise to generally strong bounds on the compactification scale and new resonances that can be observed in experiments. Otherwise, they can be produced only in pairs due to the KK momentum conservation, making the bounds weaker but the resonances difficult to observe.

In addition to virtual effects, KK excitations can be produced on-shell at LHC as new resonances [15] (see Fig. 3). There are two different channels, neutral Drell–Yan processes $pp \to l^+l^-X$ and the charged channel $l^+\nu$, corresponding to the production of the KK modes $\gamma(1)$, $Z(1)$ and $W_{\pm}(1)$, respectively. The discovery limits are about 6 TeV, while the exclusion bounds 15 TeV.

On the other hand, if all SM particles propagate in the extra dimension (called universal), KK modes can only be produced in pairs and the lower bound on the compactification scale becomes weaker, of order of 300-500 GeV. Moreover, no resonances can be observed at LHC, so that this scenario appears very similar to low energy supersymmetry. In fact, KK parity can even play the role of R-parity, implying that the lightest KK mode is stable and can be a dark matter candidate in analogy to the LSP [17].

![Figure 3](image-url)  

**Figure 3.** Production of the first KK modes of the photon and of the $Z$ boson at LHC, decaying to electron-positron pairs. The number of expected events is plotted as a function of the energy of the pair in GeV.

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4.2. Extra large transverse dimensions

The main experimental signal is gravitational radiation in the bulk from any physical process on the world-brane. In fact, the very existence of branes breaks translation invariance in the transverse dimensions and gravitons can be emitted from the brane into the bulk. During a collision of center of mass energy \( \sqrt{s} \), there are \( (\sqrt{s} R_{\perp})^n \) KK excitations of gravitons with tiny masses, that can be emitted. Each of these states looks from the 4d point of view as a massive, quasi-stable, extremely weakly coupled (\( s/M_{P}^{2} \) suppressed) particle that escapes from the detector. The total effect is a missing-energy cross-section roughly of order:

\[
\frac{(\sqrt{s} R_{\perp})^n}{M_{P}^{2}} \sim \frac{1}{s} \left( \frac{\sqrt{s}}{M_{s}} \right)^{n+2}.
\]  

(8)

Explicit computation of these effects leads to the bounds given in Table 1.

![Image](image.png)

**Table 1.** Limits on \( R_{\perp} \) in mm.

| Experiment | \( n = 2 \) | \( n = 4 \) | \( n = 6 \) |
|------------|-----------|-----------|-----------|
| Collider bounds |
| LEP 2 | \( 5 \times 10^{-1} \) | \( 2 \times 10^{-8} \) | \( 7 \times 10^{-11} \) |
| Tevatron | \( 5 \times 10^{-1} \) | \( 10^{-8} \) | \( 4 \times 10^{-11} \) |
| LHC | \( 4 \times 10^{-3} \) | \( 6 \times 10^{-10} \) | \( 3 \times 10^{-12} \) |
| NLC | \( 10^{-2} \) | \( 10^{-9} \) | \( 6 \times 10^{-12} \) |
| Present non-collider bounds |
| SN1987A | \( 3 \times 10^{-4} \) | \( 10^{-8} \) | \( 6 \times 10^{-10} \) |
| COMPTEL | \( 5 \times 10^{-3} \) | - | - |

**Figure 4.** Missing energy due to graviton emission at LHC, as a function of the higher-dimensional gravity scale \( M_{*} \), produced together with a hadronic jet. The expected cross-section is shown for \( n = 2 \) and \( n = 4 \) extra dimensions, together with the SM background.
and angular distribution of the produced gravitons that arise from the distribution in mass of KK states of spin-2. This can be contrasted to other sources of missing energy and might be a smoking gun for the extra dimensional nature of such a signal.

In Table 1, there are also included astrophysical and cosmological bounds. Astrophysical bounds [19, 20] arise from the requirement that the radiation of gravitons should not carry on too much of the gravitational binding energy released during core collapse of supernovae. The best cosmological bound [21] is obtained from requiring that decay of bulk gravitons to photons do not generate a spike in the energy spectrum of the photon background measured by the COMPTEL instrument. Bulk gravitons are expected to be produced just before nucleosynthesis due to thermal radiation from the brane. The limits assume that the temperature was at most 1 MeV as nucleosynthesis begins, and become stronger if temperature is increased.

4.3. String effects
At low energies, the interaction of light (string) states is described by an effective field theory. Their exchange generates in particular four-fermion operators that can be used to extract independent bounds on the string scale. In analogy with the bounds on longitudinal extra dimensions, there are two cases depending on the localization properties of matter fermions. If they come from open strings with both ends on the same stack of branes, exchange of massive open string modes gives rise to dimension eight effective operators, involving four fermions and two space-time derivatives [22, 23]. The corresponding bounds on the string scale are then around 500 GeV. On the other hand, if matter fermions are localized on non-trivial brane intersections, one obtains dimension six four-fermion operators and the bounds become stronger: $M_s \gtrsim 2 - 3$ TeV [23, 6]. At energies higher than the string scale, new spectacular phenomena are expected to occur, related to string physics and quantum gravity effects, such as possible micro-black hole production [24, 25, 26]. Particle accelerators would then become the best tools for studying quantum gravity and string theory.

Direct production of string resonances in hadron colliders leads generically to a universal deviation from Standard Model in jet distribution [27]. In particular, the first Regge excitation of the gluon has spin 2 and a width an order of magnitude lower than the string scale, leading to a characteristic peak in dijet production; similarly, the first excitations of quarks have spin 3/2. The dijet cross-section is shown in Fig. 5 for LHC energies. The reason for the universal behavior is that tree $N$-point open superstring amplitudes involving at most two fermions and gluons are completely model independent from the details of the compactification, including the number of supersymmetries that are left unbroken in four dimensions (even if all are broken). Such tree-level amplitudes do not receive contributions from KK, string winding or closed string graviton modes, but are given as a universal sum over exchanges of open string Regge excitations lying in Regge trajectories with masses

$$M_n^2 = M_s^2 n^2; \quad n = 0, 1, \ldots$$

and maximal spin $n + 1$.

The relevant partonic cross-sections for dijet production, involving at most two quarks are $|\mathcal{M}(gg \rightarrow gg)|^2$, $|\mathcal{M}(gg \rightarrow q\bar{q})|^2$, $|\mathcal{M}(q\bar{q} \rightarrow gg)|^2$ and $|\mathcal{M}(qq \rightarrow gg)|^2$, where $g$ and $q$ denote gluons and quarks, respectively. They can be obtained from the first two, up to crossing symmetries, at the full (tree) string level and they are model independent [28]. The low energy expansion of these amplitudes reproduce the usual QCD expressions, while higher order terms describe the string corrections due to the exchange of Regge excitations. Besides these amplitudes, there are also those involving four quarks, such as $|\mathcal{M}(q\bar{q} \rightarrow q\bar{q})|^2$ and $|\mathcal{M}(qq \rightarrow qq)|^2$. These are model dependent, because the details of the compactification do not decouple. The reason is that they involve four vertices containing twist fields that describe quark states arising from open strings stretched in brane intersections. However, taking into account
Figure 5. Production of the first Regge excitations at LHC in the dijet channel, for $M_s = 2$ TeV. The cross-section is plotted as a function of the dijet invariant mass $M$.

QCD color factors, their contribution is suppressed because parton luminosities in proton-proton collisions at TeV energies favor at least one gluon in the initial state. As a result, the dominant contribution comes from the model independent cross-sections described above, leading to the effect of Fig. 5.

We finish this section with some comments related to the possible micro-black hole production. Independently on the unresolved issue of the convergence of string perturbation theory in the kinematic region relevant to micro-black hole formation, there is a simple argument showing that at least within the perturbative TeV string framework, the energy threshold for black hole production is far above the LHC reach. Indeed, a string size black hole has a horizon radius $r_H \sim 1$ in string units, while the $d$-dimensional Newton’s constant behaves as $G_N \sim g_s^2$. It follows that the mass of a $d$-dimensional black hole is [29]:

$$M_{BH} \sim r_H^{d/2-1}/G_N \sim 1/g_s^2.$$  

(10)

Thus, for a weakly coupled theory, this energy threshold is much higher than the string and the higher dimensional Planck scales $M_s$ and $M_*$ of eq. (3). Comparing this energy threshold with the mass of Regge excitations (9), one finds $n \sim 1/g_s^4$ which is actually compatible with the relation one obtains by identifying the black hole entropy $S_{BH} \sim 1/G_N \sim 1/g_s^2$ with the perturbative string entropy $S_{\text{string}} \sim \sqrt{n}$. Using now relation (2), and the value of the Standard Model gauge couplings $g_s \simeq g^2 \sim 0.1$, one finds that the energy threshold $M_{BH}$ of micro-black hole production is about four orders of magnitude higher than the string scale, implying that one would produce $10^4$ string states before reaching $M_{BH}$.

5. Supersymmetry in the bulk and short range forces

5.1. Sub-millimeter forces

Besides the spectacular predictions in accelerators, there are also modifications of gravitation in the sub-millimeter range, which can be tested in “table-top” experiments that measure gravity
at short distances. There are three categories of such predictions:

(i) Deviations from the Newton’s law $1/r^2$ behavior to $1/r^{2+n}$, which can be observable for $n = 2$ large transverse dimensions of sub-millimeter size.

(ii) New scalar forces in the sub-millimeter range, related to the mechanism of supersymmetry breaking, and mediated by light scalar fields $\varphi$ with masses $[30, 5]$

$$m_\varphi \simeq \frac{m_{s\text{usy}}^2}{M_P} \simeq 10^{-4} - 10^{-6} \text{ eV}, \quad (11)$$

for a supersymmetry breaking scale $m_{s\text{usy}} \simeq 1 - 10 \text{ TeV}$. They correspond to Compton wavelengths of 1 mm to 10 $\mu$m. $m_{s\text{usy}}$ can be either $1/R_9$ if supersymmetry is broken by compactification [30], or the string scale if it is broken “maximally” on our world-brane [5].

A universal attractive scalar force is mediated by the radion modulus $\varphi \equiv M_P \ln R$, with $R$ the radius of the longitudinal or transverse dimension(s). For $n = 2$, there may be an enhancement factor of the radion mass by $\ln R \parallel M_\varphi \simeq 30$ decreasing its wavelength by an order of magnitude [31].

The coupling of the radius modulus to matter relative to gravity can be easily computed and is given by:

$$\sqrt{\alpha_\varphi} = \frac{1}{M} \frac{\partial M}{\partial \varphi} ; \quad \alpha_\varphi = \begin{cases} \frac{\partial \ln \Lambda_{\text{QCD}}}{\partial \ln R} \simeq \frac{1}{6} & \text{for } R \parallel \\ \frac{2n}{n+2} = 1 - 1.5 & \text{for } R \perp \end{cases} \quad (12)$$

where $M$ denotes a generic physical mass. Such a force can be tested in microgravity experiments and should be contrasted with the change of Newton’s law due the presence of extra dimensions that is observable only for $n = 2$ [4, 8]. The resulting bounds from an analysis of the radion effects are [32]: $M_\varphi \gtrsim 6 \text{ TeV}$.

(iii) Non universal repulsive forces much stronger than gravity, mediated by possible abelian gauge fields in the bulk [19, 33]. Such fields acquire tiny masses of the order of $M_\varphi^2/M_P$, as in (11), due to brane localized anomalies [33]. Although their gauge coupling is infinitesimally small, $g_A \sim M_s/M_P \simeq 10^{-16}$, it is still bigger that the gravitational coupling $E/M_P$ for typical energies $E \sim 1 \text{ GeV}$, and the strength of the new force would be $10^6 - 10^8$ stronger than gravity.

In Fig. 6 we depict the actual information from previous, present and upcoming experiments [8, 31]. The solid lines indicate the present limits from the experiments indicated. The excluded regions lie above these solid lines. Measuring gravitational strength forces at short distances is challenging. The horizontal lines correspond to theoretical predictions, in particular for the graviton in the case $n = 2$ and for the radion in the transverse case. These limits are compared to those obtained from particle accelerator experiments in Table 1.

6. Standard Model on D-branes

The gauge group closest to the Standard Model one can easily obtain with D-branes is $U(3) \times U(2) \times U(1)$. The first factor arises from three coincident “color” D-branes. An open string with one end on them is a triplet under $SU(3)$ and carries the same $U(1)$ charge for all three components. Thus, the $U(1)$ factor of $U(3)$ has to be identified with gauged baryon number. Similarly, $U(2)$ arises from two coincident “weak” D-branes and the corresponding abelian factor is identified with gauged weak-doublet number. Finally, an extra $U(1)$ D-brane is necessary in order to accommodate the Standard Model without breaking the baryon number [34].

It turns out that there are two possible ways of embedding the Standard Model particle spectrum on these stacks of branes [34], which are shown pictorially in Fig. 7. The quark doublet $Q$ corresponds necessarily to a massless excitation of an open string with its two ends on the two different collections of branes (color and weak). As seen from the figure, a fourth brane stack is needed for a complete embedding, which is chosen to be a $U(1)_b$ extended in
Figure 6. Present limits on new short-range forces (yellow regions), as a function of their range $\lambda$ and their strength relative to gravity $\alpha$. The limits are compared to new forces mediated by the graviton in the case of two large extra dimensions, and by the radion.

Figure 7. A minimal Standard Model embedding on D-branes.

the bulk. This is welcome since one can accommodate right handed neutrinos as open string states on the bulk with sufficiently small Yukawa couplings suppressed by the large volume of the bulk [35]. The two models are obtained by an exchange of the up and down antiquarks, $u^c$ and $d^c$, which correspond to open strings with one end on the color branes and the other either on the $U(1)$ brane, or on the $U(1)_b$ in the bulk. The lepton doublet $L$ arises from an open string stretched between the weak branes and $U(1)_b$, while the antilepton $\bar{L}$ corresponds to a string with one end on the $U(1)$ brane and the other in the bulk. For completeness, we also show the two possible Higgs states $H_u$ and $H_d$ that are both necessary in order to give tree-level masses.
to all quarks and leptons of the heaviest generation.

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