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String Theory Phenomenology

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Abstract. We review the qualitative features of string theory compactifications with low energy effective theory close to (supersymmetric versions of) the Standard Model of Particle Physics. We cover Calabi-Yau compactifications of heterotic strings, intersecting brane models, and the recent setup of F-theory models.

1. String theory

1.1. Generalities

String theory is the theoretically best motivated proposal to provide a unified description of gravitational and gauge interactions, in a framework consistent at the quantum level. The main idea underlying string theory is to include additional degrees of freedom at high-energies to get rid of the ultraviolet divergences arising in the standard quantization of gravity. In this sense, it is very analogous to the role of electroweak theory in solving the ultraviolet problems of the Fermi theory of weak interactions, by the addition of new high-energy degrees of freedom, the W and Z bosons. The new degrees of freedom introduced by string theory however show up at a new scale, the string scale M_s. Although in particular constructions it might be close to the familiar TeV scale, it is in general expected to be much higher, in the fantastically high regime close to the GUT scale of 10^{16} GeV or the Planck scale $M_p \sim 10^{19}$ GeV.

The main novelty of string theory is the nature of the proposed new degrees of freedom. They are not given by a few new massive particles. String theory rather proposes that all particles are actually not point-like, but extended one-dimensional objects, *strings*, with characteristic size $L_s \sim 1/M_s$. Different particles are just different oscillation modes of a single kind of object, the string, endowing the theory with a great unification power. Even though there is an infinite number of such oscillation modes, the mass of the corresponding particle increases with the oscillation excitation number, with steps of order M_s. Hence at familiar energies $E \ll M_s$, only the string groundstates are observable. In this regime there is not enough resolution to detect the extended nature of the string, and these particles look like point-like. At higher energies however, the additional excited states of the string become accessible, leading to a tower of new particles, whose role is to control the ultraviolet properties of the theory.

The light particle spectrum of string theories is model dependent, as we will precise later on, but there are some general features, for both closed and open strings. A general property of string theory is that the massless spectrum of closed strings contains a spin-2 particle which behaves as a graviton. Thus string theory naturally includes Einstein's General Relativity description of gravitational interactions. Moreover, the light spectrum of open strings produces (possibly non-abelian) gauge bosons, and matter fields charged under them, like spin-1/2 matter fermions, or

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spin-0 bosons. It is remarkable that such particles are of the same kind as those encountered in Nature, and this underlies the potential application of string theory as a unification framework for all particles and interactions.

1.2. Compactification, 4d physics and the landscape

The nice ultraviolet properties of string theory require a high-energy oscillation spectrum corresponding to vibration modes in 10 dimensions. In fact there are five perturbatively different 10d string theories with these well-behaved properties, known as the type IIA, type IIB, type I, $SO(32)$ heterotic and $E_8 \times E_8$ heterotic string theories. They are however closely related in the regime beyond perturbation theory. Thus the structure of string theory when formulated in 10d is a beautiful construct, with many gists of new symmetries, known as string dualities, and a yet mysterious unique underlying structure, often referred to as M-theory.

Although it is remarkable that a physical theory can fix the number of spacetime dimensions in which it must be formulated, the result may seem disappointing. This however does not imply that the number of dimensions observable at low energies $E \ll M_s$ is 10. There is a standard mechanism, known as compactification, by which the number of observable dimensions can be reduced to four. The idea is to consider the 10d spacetime to be $M_4 \times \mathbf{X_6}$, the product of 4d Minkowski space and a 6d internal manifold, which should be compact, i.e. have a finite volume. Introducing a characteristic size L, which we take $L \gg 1/M_s$, the theory at energies $E \ll 1/L \ll M_s$ appear to have only four dimensions, since there is not enough resolution to explore the extra dimensions.

As we describe below, the geometry and other ingredients in the internal dimensions however encode many physical properties of the resulting 4d theory, like the gauge group, matter content, and quantitative data like the values of couplings constants, etc. This implies that, since there are many many many different ways of compactifying the 10d theory, there is a multitude of possible 4d string vacua, each leading to completely different physical theories. This is the recently popularized view of the landscape of vacua in string theory, whose interpretation and potential usefulness is still subject to much controversy and leads to not few coffee time discussions. Although the situation may seem to spoil the uniqueness and beauty of the theory, for our present purposes we may regard it as not dissimilar to General Relativity, where despite the uniqueness of the theory leads to a multitude of possible solutions. In General Relativity, the crucial point is to focus on the relevant physical properties to pick the right solution to describe a given system, e.g. spherical symmetry to describe the Solar System. In a similar spirit, our point is to focus on particular string constructions containing the basic building blocks of Particle Physics.

1.3. Purpose of String Phenomenology

If string theory is realized in Nature, it should be able to describe not just vague sectors of gauge interaction, but a very precise one: the Standard Model, or some of its promising extensions at the TeV scale. The aim of string phenomenology is thus first the study of general classes of constructions with at least a chance to lead to the Standard Model. By this we mean the appearance of non-abelian gauge interactions, replicated fermions charged under them, scalar fields coupling to them, possibly supersymmetry, etc. Subsequently, and within each class, it pursues the construction of explicit models as close as possible to the Standard Model, with the hope of learning more about its high energy regime when realized in string theory. The field is relatively old, dating back to the mid-eighties, yet there is continuous progress, with recent insights into the questions of compactifications with fluxes, and the inclusion of non-perturbative effects.

For the purposes of this talk, we illustrate the approach of string phenomenology with several classes of constructions. We start with heterotic string compactifications on Calabi-Yau spaces in section 2. Next we move on to brane world models in section 3, realized in terms of intersecting or magnetized D-branes. We conclude with some recent developments on moduli stabilization in section 4, and their application to supersymmetry breaking at energies accessible to the LHC, and the computation of the spectrum of hopefully soon-to-be-observed sparticles.

2. Heterotic string Calabi-Yau compactifications

Heterotic string theory in 10d contains a set of massless fields given by the graviton (and some supersymmetric partners), gauge bosons of the (very large) groups $E_8 \times E_8$ or $SO(32)$, and their supersymmetric gaugino partners in the adjoint representation. In the following we review the construction in [1] of compactifications of the $E_8 \times E_8$ theory, on 6d spaces preserving 4d $\mathcal{N} = 1$ supersymmetry, known as Calabi-Yau compactifications.

As described above we choose the 10d spacetime to have a geometry $M_4 \times \mathbf{X}_6$, with compact $\mathbf{X}_6$. Consistency of the compactification requires turning on non-trivial magnetic fields F_a^{mn} for the internal components $m, n = 4, \ldots, 9$ of some of the 10d gauge bosons. This leads to a breaking of the gauge group in the compactification, so that the observable 4d gauge group is given as the subgroup commuting with the magnetic fields turned on in $\mathbf{X}_6$. Choosing the magnetic fields along suitable generators of e.g. one of the E_8 gauge factors, it is possible to construct explicit models with a quite realistic 4d gauge group, like $SU(5)$ or $SU(3) \times SU(2) \times U(1)$ (possibly times additional $U(1)$ factors, and additional decoupled non-abelian sectors, known as 'hidden sectors'). In the following we denote this sector as the Standard Model (SM) sector of these compactifications.

The introduction of magnetic fields has a second interesting effect. Since the 10d spin-1/2 fermions (the gauginos) transform in the adjoint representation of the 10d group, they couple to these magnetic fields. This modifies the spectrum of light particles they give rise to in the 4d theory. In fact they behave as charged particles in a magnetic field, with a spectrum of Landau levels. The number of groundstates of such system corresponds to a multiplicity for the corresponding massless charged fermions in the 4d theory, in other words, the number of families of the resulting SM sector. Although there is no universal prediction for this number, in particular no hint for a special role of 3-family models, it is remarkable that heterotic string theory leads naturally to the appearance of replicated sets of charged fermions. This natural replication is also a general feature in other realistic constructions in coming sections.

There are several constructions leading to models very close to the SM, but their detailed discussion requires heavy mathematical tools, well beyond this overview. For a flavor of these examples, some references describing recently constructed models are [2, 3]. We instead turn to a back-of-the-envelope computation of the value of the string scale M_s in the general class of heterotic compactifications.

The structure of the 10d action for gravitational and gauge interactions is sketchily

$$S_{\text{het},10d} = \int d^{10}x \, \frac{M_s^8}{g_s^2} \, R_{(10d)} + \int d^{10}x \, \frac{M_s^6}{g_s^2} \, (\text{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu})_{(10d)} \tag{1}$$

where $R_{(10d)}$ and $\mathcal{F}$ are the 10d curvature scalar and non-abelian gauge field strength. The M_s prefactors are included for dimensional reasons, while the g_s dependence arises because both gravitational and gauge interactions arise from closed string in heterotic string theory.

Compactification on $\mathbf{X}_6$ can be implemented by simply performing the integral over the six internal dimensions, and truncating the 10d dynamical fields to the massless 4d fields. This leads to additional factors of the $\mathbf{X}_6$ volume V_6

$$S_{\text{het},4d} = \int d^4x \, \frac{M_s^8 V_6}{g_s^2} \, R_{(4d)} + \int d^4x \, \frac{M_s^6 V_6}{g_s^2} \, (\text{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu})_{(4d)} \tag{2}$$

where now $R_{(4d)}$ and $\mathcal{F}$ are the 4d curvature scalar and non-abelian gauge field strength. The coefficients of this 4d action can be compared with the observed values of the strength of gravitational and gauge interactions, i.e. the 4d Planck mass M_p and SM gauge coupling constants (which for simplicity we consider unified at some value $g_{\rm SM} \sim \mathcal{O}(10^{-1})$, as suggested by renormalization group extrapolation of observed couplings to high scales). Namely

$$M_p^2 = \frac{M_s^8 V_6}{g_s^2} \sim 10^{18}\,\text{GeV} \quad , \quad \frac{1}{g_{\rm SM}^2} = \frac{M_s^6 V_6}{g_s^2} \sim \mathcal{O}(10^{-1}) \tag{3}$$

This leads to the equality

$$M_s = M_p\, g_{\rm SM} \sim 10^{17}\,\text{GeV} \tag{4}$$

The string scale is therefore fantastically high, compared with any experimental Particle Physics scale, but tantalizingly close to other theoretical scales, like the GUT scale of the Planck scale. The electroweak hierarchy problem is usually addressed by invoking 4d $\mathcal{N}=1$ supersymmetry, as we had anticipated with hindsight. The question of supersymmetry breaking and its scale is postponed until section 4.

3. D-brane models and their generalizations

In this section we turn to an alternative and very popular model building setup in string theory, based on IIA and IIB string theories. Although these theories do not contain gauge bosons in 10d, they arise when considering the theory in the presence of a new kind of object, the D-branes. The models hence lead to the localization of gauge sectors on lower-dimensional subspaces of spacetime, the volume of D-branes, while gravity still propagates in 10d spacetime. This is the so-called brane world picture.

3.1. D-branes

Some of the most successful setups to realize the Standard Model in string theory are based on D-branes. For the purposes of this talk, Dp-branes are higher-dimensional planes, with p space dimensions and propagating in time, and on which open strings can have their endpoints. Consequently, open string oscillation modes correspond to gauge and matter particles which must propagate on the volume of these D-branes, while closed strings lead to the graviton still propagating in full 10d spacetime, see Figure 1.

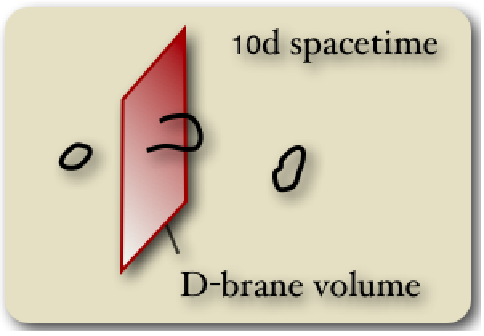

Figure 1. In the presence of a D-brane, open strings localized on its volume, while closed string still propagate over full 10d spacetime.

This has several important consequences. For instance, it implies a modification of the above argument to compute the value of the string scale. In this new setup, the structure of the 10d action for gravitational and gauge interactions is sketchily

$$S_{\mathrm{D}p,10d} \,=\, \int d^{10}x\, \frac{M_s^8}{g_s^2}\, R_{(10d)} \,+\, \int d^{p+1}x\, \frac{M_s^{p-3}}{g_s}\, (\mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu})_{(p+1)d} \tag{5}$$

where $R_{(10d)}$ is the 10d curvature scalar and $\mathcal{F}$ is the non-abelian gauge field strength on the $(p+1)$-dimensional volume of the Dp-brane. The M_s prefactors arise dimensional reasons, while the g_s dependences follow because in this setup gravitational and gauge interactions arise from closed and open string sectors, respectively.

Upon compactification on $\mathbf{X}_6$ to 4d, the gravitational term picks up a factors of $V_{\mathbf{X}_6}$, while the gauge term get a factor V_{p-3}, the volume of the $(p-3)$ dimensions of $\mathbf{X}_6$ actually wrapped by the D-brane volume.

$$S_{\mathrm{D}p,4d} \,=\, \int d^4x\, \frac{M_s^8 V_6}{g_s^2}\, R_{(4d)} \,+\, \int d^4x\, \frac{M_s^{p-3} V_{p-3}}{g_s}\, (\mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu})_{4d} \tag{6}$$

This leads to the expression of the 4d Planck mass and gauge couplings as

$$M_p^2 \,=\, \frac{M_s^8 V_6}{g_s^2} \sim 10^{18}\,\mathrm{GeV} \quad , \quad \frac{1}{g_{\mathrm{YM}}^2} \,=\, \frac{M_s^{p-3} V_{p-3}}{g_s} \sim \mathcal{O}(10^{-1}) \tag{7}$$

Assuming for simplicity $\mathbf{X}_6$ to factorize into dimensions along and transverse to the D-brane, with volumes satisfying $V_6 = V_{p-3} V_\perp$, we obtain

$$M_p^2 g_{\mathrm{SM}}^2 \,=\, \frac{M_s^{11-p} V_\perp}{g_s} \,\sim 10^{17}\,\mathrm{GeV} \tag{8}$$

This richer formula leads to several possibilities for the string scale. It can be assumed to be very large, as in heterotic models, invoking 4d $\mathcal{N}=1$ supersymmetry to address the electroweak hierarchy problem. Alternatively, the string scale can be lowered, even to the TeV range, by allowing the transverse dimensions to have a very large volume $V_\perp$. Since the latter cannot be explored by gauge sector particles, but only by the graviton, their size is only very mildly constrained by experiment, and can be as large as a fraction of a millimiter. This geometric generation of a large 4d Planck scale from a low fundamental scale can provide an alternative explanation for the hierarchy between the electroweak and Planck scales [4].

A second important property of D-brane models is that they provide a geometrization of many features of the gauge sectors. For instance, the appearance of non-abelian $SU(n)$ gauge interactions from D-brane open string sectors is achieved by considering a stack of n overlapping D-branes. There are n^2 possible open string sectors, defined by the n possible D-branes on which the open strings can start, times those on which they can end, see figure 2. This leads to a natural $n \times n$ matrix structure, signaling the existence of a $U(n)$ gauge symmetry, whose gauge bosons are the massless oscillation states of the corresponding open strings (in the following and for simplicity, we are somewhat cavalier in our treatment of $U(1)$ factors). Geometrization of other features will be manifest in the explicit model building setups, to which we turn in next sections.

3.2. Intersecting D-brane models

In this section we overview intersecting brane models in string theory, see [5, 6] for original reference or e.g. [7] for a pedagogical review.

A natural generalization of configurations of overlapping D-branes is to consider D-branes which overlap on the 4d Minkowski directions, but intersect non-trivially in the internal

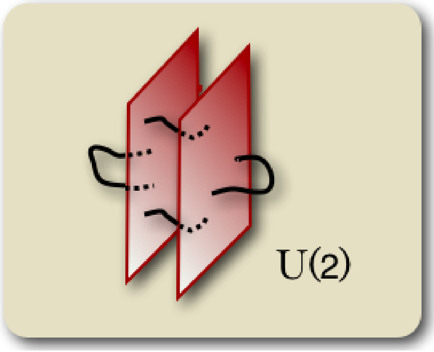

Figure 2. Stacks of n overlapping D-branes lead to n^2 possible open string sectors, and lead to non-abelian $U(n)$ gauge symmetries. The figure illustrates the case of $n = 2$.

directions of $\mathbf{X}_6$. As shown in [8], there are new sectors of open strings stretching between the two intersecting D-brane stacks. Remarkably, for particular configurations, like D6-branes intersecting at points in $\mathbf{X}_6$, the corresponding oscillation state spectrum contains massless 4d chiral fermions, which moreover couple to the two gauge symmetry factors carried by the D-branes. For instance, the intersection of two stacks with 3 and 2 D-branes, respectively, leads to a non-abelian gauge group $SU(3) \times SU(2)$, and chiral fermions charged under these 'color' and 'weak isospin' interactions (in the correct $(\overline{3}, \overline{2})$ representation).

Interestingly, a general feature of the internal geometry is that several D-brane in general intersect at several points in $\mathbf{X}_6$, see figure 3. This results in a multiplicity of 4d fermions with precisely the same gauge quantum numbers, i.e. a replication of fermion families. In other words, in the present string theory setup the existence of several fermion families is natural (although admittedly there is no preference for 3-family models).

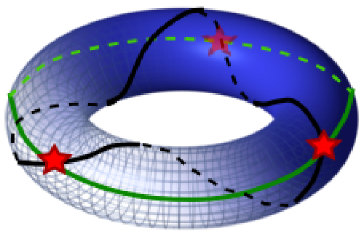

Figure 3. Pictorial representation of D-branes wrapped in the extra dimensions and intersecting at three points, leading to a 4d theory with three families of charged fermions.

This turns the problem of embedding the SM gauge group and fermion content in string string theory into a question about the geometry of D-branes in the internal dimensions and the multiplicity of their intersections. There are indeed concrete proposed patterns of intersections which accommodate the SM gauge group and all SM matter fermions and the Higgs multiplet, with correct non-abelian and hypercharge quantum numbers, and explicit string compactifications realizing them [9], see figure 4.

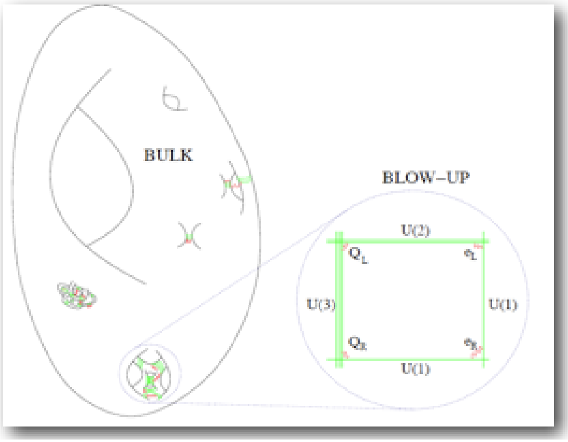

Figure 4. Pictorial representation of intersecting D-branes in the extra dimensions, producing the gauge group and matter content of the SM. For simplicity the picture displays one intersection of each kind instead of the three required for SM family replication.

3.3. Magnetized branes and F-theory

The duality symmetries of string theory in 10 dimensions persist through compactification, and lead to equivalent realization of the same 4d model in terms of different geometrical structure in the internal space. For instance, the intersecting D-brane models of previous section admit a dual realization in terms of D-branes with non-trivial magnetic fields on their volumes.

This picture, known as magnetized D-brane models [10, 5], is interesting in its own. In analogy with heterotic models in section 2, the 4d gauge group and spectrum of massless fermions are determined by properties of the magnetic fluxes turned on the (D-brane volume subspace of) the internal space $\mathbf{X}_6$. An important difference with respect to heterotic models is that the original gauge group is not E_8, and can be chosen to be closer to the SM one. This is particularly helpful to get rid of unwanted massless matter and hence to construct more economical Particle Physics models. A popular choice is to consider stacks of five overlapping D7-branes, leading to an $SU(5)$ gauge group, subsequently broken in the compactification by non-trivial magnetic flux along the $U(1)$ hypercharge generator. This provides a string theory generalization of 4d GUT models, in which the breaking exploits the presence of the extra dimensions and does not require the presence of large GUT multiplets in the 4d theory. This approach has been intensely pursued in a non-perturbative generalization of D7-brane systems, going under the name of F-theory. We refer the reader to e.g. [11] for further details on the construction of these F-theory GUTS, and move on to consider some general phenomenological properties of Particle Physics models in string theory.

3.4. Some phenomenological properties

In the following we sketch the status of several phenomenologically interesting questions in the above string compactifications. Lack of space prevents a systematic discussion in the different classes of string models, and we switch rather freely among them to describe the insights from the most successful such models. Hence, although many properties are actually realized in explicit string models, it is fair to say that there is no example displaying all of them simultaneously. Still, the interest of explicit examples lies, as already mentioned, not in themselves but rather in the general lessons they can teach.

Gauge coupling unification

In many string models the different gauge factors of the SM arise from a single gauge factor in higher dimensions. In these models gauge coupling unification occurs at the string scale, so if taken high enough (around $10^{16} - 10^{17}$ GeV, reproduces in a qualitatively correct way the picture of gauge coupling unification suggested by extrapolation of the observed couplings to high energies.

Yukawa couplings

In intersecting brane models, Yukawa couplings are mediated by so-called 'open worldsheet instantons', morally open strings propagating among the intersections corresponding to the fields in the coupling of interest. This process is exponentially suppressed in the area swept out by such open strings. Since different SM families lie at different intersections, the above process suggests a tantalizing mechanism to generate hierarchically different fermion masses. This idea has been pursued further in the dual magnetized brane picture (or rather, its F-theory generalization), in which Yukawa couplings arise as overlap integrals of the wavefunctions of the Landau groundstates corresponding to the fields in the coupling of interest. These wavefunctions have Gaussian profiles, with different SM families localized at points in the internal space. Hence, the overlap integrals for the different SM families have hierarchically different values. These ideas have led to quite explicit proposals to generate interesting fermion mass textures.

String scale

As already mentioned, the value of the string scale M_s is necessarily high $\sim 10^{17}$ GeV in heterotic models. In D-brane models, it can also be chosen to be large. In these models with a high fundamental scale, the usual proposed solution to the electroweak hierarchy problem is supersymmetry.

In D-brane models there is the alternative possibility to allow for a lower string scale. The extreme case is to lower it down to the TeV scale. An in-between possibility is to consider the string scale around the so-called intermediate scale $\sim 10^{11}$ GeV. The latter is interesting for an appealing mechanism of supersymmetry breaking.

Proton decay

An important issue in any extension of the SM is proton decay, in particular in models with not too high fundamental scale, where higher dimensional operators violating baryon number might not be sufficiently suppressed. In D-brane models leading to the SM gauge group already at the string scale, baryon number is often a global symmetry unbroken in perturbation theory. The only baryon number violating processes are thus non-perturbative, and hence exponentially suppressed, leading to negligible proton decay rates. In models with underlying GUT groups at the string scale (including certain D-brane models, as well as F-theory GUTs and heterotic models), baryon number violating operators are possible, and it is necessary to engineer the configuration to have no such dimension-5 couplings. For a choice of high string scale $M_s \sim 10^{16}$ GeV, natural for such models, the resulting proton decay rates are close to the present experimental bounds.

4. Flux compactifications

In the discussion of previous models we have purposely overlooked a phenomenologically very relevant question. String compactifications as we have described them lead to 4d theories with typically hundreds of massless neutral scalars coupling to matter with gravitational strength. These fields, known as moduli, have actually a flat potential, and hence can have arbitrary vevs at no energetic cost. These moduli vevs parametrize the quantitative values of parameters in the compactification. For instance, the parameters determining the size and shape of the compactification space, the value of the string coupling constant, etc. These moduli fields are troublesome from the phenomenological viewpoint, since they generically lead to unobserved fifth forces, or potentially to problems in the cosmological evolution of the Universe.

There is by now a quite general mechanism for moduli stabilization, namely for the construction of string models where these vevs are fixed dynamically by a moduli potential is known as the moduli stabilization. It is based on the use of 'flux compactifications' [12, 13], in which one turns on magnetic fluxes for the internal components of generalized gauge fields, described by antisymmetric tensors with p indices, and which are related to the graviton by 10d supersymmetry. These are analogous to the magnetic fluxes on the D-brane volumes in magnetized brane setups in section (3.3), with the difference that they belong to the gravitational sector of the theory, rather than being localized on the D-branes.

The introduction of these fluxes produces a non-trivial potential energy for the compactification moduli as follows. Change in the moduli vevs correspond to changes in the compactification geometry, for instance a change in the overall size of the internal space $\mathbf{X}_6$. Such changes in the geometry modify the vacuum energy of the configuration, since they change the magnetic flux density, e.g. it dilutes when $\mathbf{X}_6$ gets larger, and becomes denser when $\mathbf{X}_6$ gets smaller. A vacuum energy depending on the moduli vev is precisely a potential for the moduli fields, which fixes their vevs to the corresponding minimum. Hence the geometry of the compactification is fixed by a dynamical process of energy minimization.

Flux compactifications lead to another interesting effect. Fluxes gravitate and in compactifications with large flux density in localized regions of the internal space, they can lead to gravitational potential wells in the extra dimensions. This produces a gravitational redshift of 4d energy scales, depending on the position in the extra dimensions. These models, known as warped compactifications, thus reproduce the physics of the warped extra dimension or Randall-Sundrum scenario [14], which can potentially address the generation of the electroweak hierarchy.

Finally, flux compactification lead to an appealing mechanism of supersymmetry breaking and its mediation to the SM [15, 16, 17]. Consider as starting point any 4d $\mathcal{N}=1$ supersymmetric compactification of the kind studied in previous sections, e.g. the D-brane models in section 3, leading to a realistic SM sector. The model requires the introduction of fluxes in order to trigger moduli stabilization, and these fluxes in general may not be supersymmetry preserving. This leads to a breaking of supersymmetry of order M_s in the gravitational sector of the theory, which is eventually transmitted to the D-brane SM sector. The order of magnitude of the supersymmetry breaking scale in the SM sector is generically

$$M_{\rm SUSY} = \frac{M_s^2}{M_p} \tag{9}$$

where the M_p denominator arises from the gravitational strength of the mediation mechanism. In general this favors models of intermediate string scale $M_s \sim 10^{10} - 10^{12}$ GeV, since they lead naturally to TeV scale supersymmetry breaking in the visible SM sector. However, particular models with other choices of string scale may still yield the correct supersymmetry breaking scale if they produce additional factors in the analog of (9).

Concrete models allow a precise computation of the MSSM soft terms at the string scale, and allow the computation of their renormalization group evolution to low energies. This provides precise determination of the superparticle spectrum for the models at hand. We refer the reader to the literature, e.g. [19, 18] for such detailed analysis.

5. What is it good for?

A clear conclusion from the above overview of string phenomenology is that there are many string models leading to semi-realistic Particle Physics models, yet none reproduces all features of the SM to the last quantitative details.

Given the large set of string vacua, and even of these semi-realistic string vacua, it would be naive to expect to find the correct one by simple inspection, i.e. by directly constructing an explicit example. This may seem disappointing. However, as already emphasized in the introduction, the main purpose of building explicit SM-like examples in string phenomenology is learning about new properties and mechanisms of interest for Particle Physics, which may be valid more generally than in the particular example where they are uncovered.

Along these lines, string theory has proven extremely useful in motivating and realizing, in a ultraviolet complete setup, several scenarios which provide a fruitful arena for phenomenological model building of Physics beyond the SM. For instance, extra dimensions, the brane world scenario, compactifications with warped dimensions, to name a few.

String theory moreover provides well defined patterns for the scales and ranges of parameters for these scenarios, which may very well be subject to experimental test in the near future. Although such finding would not prove string theory right, it would conform important supporting evidence for it. An example of such precise patterns is given by the structure of soft terms in supersymmetric models with flux supersymmetry breaking, explained in section 4

Finally, certain string theory scenarios lead to smoking gun signatures, which if observed would be hard to explain in any other theory. An example in (admittedly contrived for some tastes) TeV scale string models is the existence of string resonances (i.e massive particles corresponding to excited oscillation states of strings) at experimentally accessible energies.

All in all, string theory and its potential application to Particle Physics is a very rewarding enterprise. In particular string phenomenology is a field reaching its mature age, and for which LHC data will undoubtedly pave the way towards a second youth.

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