APPLIED STRING THEORY

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1 Introduction

The observation that the structure of string theory is rich enough to include the standard model in rough outline is an old one, starting with the early constructions of free field constructions, orbifold theories, and in particular Calabi-Yau compactifications in the late 1980s and early 1990s. At the time these constructions provided a large collection of different vacua, with thousands of explicitly constructed Calabi-Yau manifolds [30], and estimates of vast numbers of bosonic models [85], each one associated with its own moduli space. It was clear even then that it would be impossible to systematically search this string vacua landscape. This, however, is not a fundamental problem. Adopting the point of view that any physical theory has to describe not only our universe, but all possible consistent universes, leads to the obvious strategy of using some phenomenological input to select viable models among the ocean of models that obviously do not describe physics as we know it.

Beyond the generic predictions made by all string models, such as the existence of additional dimensions, and new particles, such as the dilaton, a detailed phenomenological analysis of a few three-generation Calabi-Yau manifolds [116, 104], lead to very specific phenomenological features. The literature on this first phase of string phenomenology is vast and it would be quite impossible to summarize even these early developments in a short review.

A venerable explosion of papers took place after Polchinski’s introduction of D-branes into the string theoretic landscape. A great many attempts were made to generalize the notion of a brane, and to incorporate them into ad-hoc models, purely phenomenological constructions that aimed at scenarios not necessarily embedded in a complete fundamental theory. The possibility provided by branes of restricting physical modes to lower dimensional submanifolds embedded in a higher dimensional spacetime was used first in a class of models based on the simplest possible toroidal framework in which all of the extra dimensions are of equal size. Refinements of this first step have opened a vast playground in which such ad hoc models were further explored, making different assumptions about which fields are confined to the low-dimensional brane, and which fields are allowed to propagate in the bulk. One of the most interesting consequences of this exploration in the late 1990s was the observation, first made in [13, 14], that if the compact dimensions are large this may have consequences for the hierarchy problem. The brane scenario made the notion of large compact dimensions, initially put forward much earlier by Antoniadis in the pre-brane era of string theory in the
context of supersymmetry breaking, more plausible. It was pointed out in [5] that the compact dimensions do not necessarily have to be of Planck scale, and that models can be constructed that allow even TeV sized dimensions. A different class of models, involving an alternative, warped, factorization of the higher dimensional spacetime into a fourdimensional and a smaller compact part was considered in a simple context by Randall and Sundrum [100, 101].

The realization that extra dimensions might be large compared to the Planck scale has lead to a renaissance in model building. In the present review the focus will be mostly on the interplay between purely phenomenological models and string theory inspired constructions which aim at the embedding of the resulting new ideas into full-fledged fundamental theories, thus completing the cycle. It will become clear in the process that essential progress has been made over the past few years in the development of new string technology. As a result string theoretic and string inspired model building has reached the point where it is constrained by precision measurements. String theory thus has become an experimental science.

2 String theory

2.1 Theoretical aspects

Several excellent introductions to string theory have been published over the past twenty years, starting with Green-Schwarz-Witten [62], and continued by Polchinski [97]. An updated summary of the most recent developments has appeared in the volume by Becker-Becker-Schwarz [20], and a more phenomenologically oriented review has been published by Dine [49]. In its simplest formulation string theory can still be viewed very roughly as the description of 1–dimensional objects, open or closed, embedded in some ambient spacetime, although higher dimensional objects play an important role.

The richness of string theory derives for the most part from its most dramatic prediction, the fact that a consistent quantum theory of strings implies the existence of new dimensions or, put differently, new degrees of freedom. One of the early successes of string theory was the insight that the specific structure of the low energy fourdimensional particle spectrum as well as their couplings are linked to the detailed fine structure of the geometry of the compact dimensions. One implication of this relation is an unexpected economy, in that very rough
phenomenological input, e.g. the observed number of generations, leads to severe restrictions for experimentally viable string solutions, excluding e.g. most of the Calabi-Yau solutions found early on [29, 30]. The link between the field theoretic content of the models to the specific geometry of the compact dimensions therefore provides a unification, and also an explanation, of the fourdimensional spectrum. While the details of the spectrum therefore clearly must depend on the specific starting point of the theory, certain of the characteristic features are universal, leading to model independent predictions. Among these are the already mentioned existence of additional dimensions, and the model independent prediction of new particles, such as the dilaton.

The idea of extra dimensions is of course an old one, formulated in the context of electromagnetism and gravity by Kaluza [77] and Klein [81], and revived after a long period of dormancy around 1980 in the context of supergravity theories. In supergravity the introduction of additional dimensions was mainly a tool of convenience, because formulating the various models in higher dimensions made the derivation of the fourdimensional actions and their symmetries much more manageable. String theory is different from these previous attempts in that the extra dimensions are a necessity, not a convenience.

A second source of complexity arises from the fact that the worldsheet, swept out by the string as it propagates through spacetime, supports a rich spectrum of different fields. This, of course, is not independent of the structure of the ambient spacetime, but it has not been clear in the past how to construct a precise relation between the physics on the worldsheet and the geometry of spacetime. The picture of spacetime as a given, if dynamical, input must be considered as preliminary. Since string theory is to be viewed as a fundamental theory it should eventually lead to a construction of space and time purely in terms of the physics on the worldsheet. Progress in this direction has recently been made via the theory of arithmetic modular forms, associated to both, the conformal field theory on the worldsheet on the one hand, and the arithmetic geometry of the compact dimensions on the other [105].

In the mid 1990s it became clear through the discovery of several string theoretic dualities [73, 114], in combination with Polchinski’s D-branes [96] that, although the theory is conceptually simpler than previously thought, it is also structurally much richer than expected, and that higher dimensional structures play an essential role. The simplicity arises from the fact that the string dualities relate apparently distinct string theories as being duals of each other. In
this way quite different looking theories, such as the heterotic, type IIA and IIB, type I and I’ superstrings, as well as M-theory and F-theory, emerge as limiting formulations of a single underlying theory. The picture of a universal moduli space connecting all the known theories as limits of a fundamental one is illustrated in Fig. 1 [95].

Figure 1: An illustration of the universal moduli space that is expected to link all known string theories.

The added complexity introduced into the theory by D-branes provides, on the other hand, an enhanced tool box that not only allows to probe the theory in deeper ways but, more importantly, makes it possible to envision completely new constructions that were thought impossible during the early phase of string phenomenology. Furthermore, the introduction of D-branes and their generalizations has not only changed the face of string theory itself, but it has opened an extensive playing ground for many different kinds of ad-hoc models which allow to test a number of different ideas in simple ways, such as the notion of large extra dimensions. String phenomenology in its early phase adopted the then natural view that the compact dimensions were at scales close to the Planck scale, and that all fields could propagate in all dimensions. Branes on the other hand can be used to confine fields selectively, and this opens the way to adjust the size of the compact dimensions to a dramatic extent. This makes it possible to realize ideas that had already been used in the pre-brane era of string theory, such as TeV dimensions [5] and warped compactifications [110], and to construct purely phenomenological models without any reference to a fundamental theory [13, 100, 101]. The main motivation for these ad-hoc models has been to provide new ways to think about the hierarchy problem, allowing to translate a puzzle about energy scales into a geometric puzzle of a disparity of volumes.
In the current phase of string phenomenology much work is focused on the embedding of these ideas back into string theory in the context of different types of D-brane and flux enhanced compactification schemes. It is in this context that experimental results ranging from tabletop experiments to astrophysical probes are beginning to put constraints on string theoretic and string inspired models.

2.2 Experimental constraints

Experimental techniques that allow to constrain string theoretic constructions also impact purely phenomenological models with similar features, such as extra dimensions, additional fields etc. The following remarks are concerned with some of the generic predictions of string theory. Further experimental aspects will be discussed in the next section.

2.2.1 Extra dimensions

One of the basic tools in constraining new physics have been tests of Newton’s inverse-square law. This law, earlier envisioned by Hooke, receives corrections from large extra dimensions and the propagation of other scalar and vector fields. The new theoretical developments in string theory, as well as their phenomenological descendants over the past decade, have renewed interest in experiments searching for such deviations from Newtonian gravity [86, 108, 2, 80]. In particular the idea that large compact dimensions might play a prominent role in string theory, supersymmetry breaking, as well as for the understanding of the hierarchy problem, has motivated new attempts to test Newtonian gravity at small distances, where the existing constraints a decade ago have been rather weak. A review describing the status of these earlier experiments is given in [86], while an extended review of the more recent efforts that have gone into improving the constraints for such deviations can be found in [3].

Complementary early experiments, performed by the Irvine group [70], two Russian groups [44, 92], and more recently by Lamoureaux [83], have been analyzed in some detail in [86], covering between them distance scales between 1cm and 1μm. In the recent past several groups have pursued tabletop gravity experiments, among them the Washington group [71, 3, 72, 2, 80], the Colorado group [86, 87], the Stanford group [33, 108], and the Purdue group [55, 41, 42].
The deviations from the inverse square law (ISL) are often parametrized by a Yukawa type potential

\[ U(r) = -G_N \frac{m_1 m_2}{r} \left( 1 + \alpha \exp \left( -\frac{r}{\lambda} \right) \right), \]

with a priori free parameters \( \alpha \) and \( \lambda \) parametrizing the strength of the new interaction relative to gravity, and the Compton wavelength, respectively. A summary of the current constraints for extra dimensions is given in Fig. 2 [80].

The constraints for the strength of possible new interactions depend dramatically on the distance. While at a length scale of 0.1mm additional forces with a tenth of the strength of gravity are allowed, at 1/100 mm the allowed strength is already \( 10^5 \) times that of gravity. Extending these experiments to shorter distance scales involve Casimir type experiments, which test higher \( \alpha \)-ranges, hence they are more relevant for ad-hoc models, which are less constrained than string theory. Current results for these searches will be summarized below in the discussion of purely phenomenological models.
2.2.2 Constraints on the dilaton mass

Precision measurements of Newtonian gravity also lead to constraints on the dilaton, a scalar partner of the graviton. For the exchange of scalar bosons with mass $m$ between two non-relativistic fermions generically leads to a potential $U(r) = -g_1 g_2 \exp(-r/\lambda)/4\pi r$, with Compton wavelength $\lambda$. The analyses of the coupling of the dilaton to strongly interacting matter shows that the coefficient $\alpha$ for the dilaton exchange is constrained as $1 \leq \alpha \leq 1000$ [79]. If follows from this result that at the 95% confidence level the bound on the dilaton mass is given by [2]

$$mc^2 \geq 3.5\text{meV}.$$ 

2.2.3 Moduli

A generic feature of superstring theory, and more generally supersymmetric models, is the appearance of scalar particles associated to moduli, fields that parametrize the size and the shape of the compact dimensions. They couple with gravitational strength and are massless to all orders in perturbation theory. It may happen that they become very heavy via nonperturbative effects, in which case they are not relevant to low-energy phenomenology. If they remain massless nonperturbatively their mass is determined by the supersymmetry breaking scale $F$, i.e. $m_{\text{mod}} \sim F/M_p$, where $M_p = 2.4 \times 10^{18}\text{GeV}$ is the reduced Planck mass. In gravity mediated theories these moduli have weak scale masses and are gravitationally coupled, hence they are not relevant to phenomenology. In gauge-mediated theories the moduli can be quite light if the scale of supersymmetry breaking is $(10\text{TeV})^2$, leading to Compton wavelengths that are macroscopic [47]. In theories with weak-scale compactification the moduli can have Compton wavelengths of the order of a millimeter. If the scale of supersymmetry breaking ranges from $F = 1\text{TeV}^2$ to $(10\text{ TeV})^2$ the range for the wavelengths is from $\sim 1\text{mm}$ to $10\mu\text{m}$ [9, 54]. Since the moduli are gravitationally coupled their existence would lead to deviations in Newton’s inverse-square law at these distances.

Radion exchange e.g. will produce a Yukawa force of the type above [37, 8] with a strength and a range given by [3, 72, 2]

$$\alpha = \frac{n}{n + 2}$$  (1)
and
\[ \lambda \sim \sqrt{\frac{\hbar^3}{cG M^4}} \sim 2.4 \left[ \frac{1\text{TeV}}{M c^2} \right]^2 \text{mm}, \quad (2) \]
where \( M \) is the unification mass. In many cases the radion-mediated force is the longest range effect of dimensions because it does not diminish as the number of new dimensions increases [13]. For \( n = 1 \) and \( n = 6 \) the data of [80] gives
\[ M(n = 1) \geq 5.7 \text{ TeV}/c^2 \]
\[ M(n = 6) \geq 6.4 \text{ TeV}/c^2. \quad (3) \]

Fig. 2 above shows experimental constraints for moduli, among other modes.

2.3 Cosmological constraints

Cosmological models based on string compactifications are constrained by recent astrophysical data, in particular the three-year results for the cosmic background radiation obtained from the three-year data of WMAP. Of particular interest in this context are the values of the scalar spectral index \( n_s \), defined via the power spectrum \( P_s \) as
\[ n_s = 1 + \frac{d \ln P_s}{d \ln k}. \]

The best fit for CMB only is given by \( n_s = 0.96 \pm 0.017 \), while the combination of CMB with large scale structure leads to a slightly lower result \( n_s = 0.958 \pm 0.015 \).

A further parameter that has been the focus of some attention is the ratio \( r \) of the tensor to scalar perturbations. Although the current limits on the gravity wave contribution \( P_t/P_s < 0.6 \) at 95\% confidence level with CMB data alone is much larger than what is typically encountered in string inflationary models, the actual discovery of a gravitation contribution would provide an extremely important constraint for string models.

3 Brane models with large dimensions

A fundamentally new point of view of string theory was suggested by Polchinski’s introduction of D-branes as regions in spacetime on which physical modes associated to open strings are confined [96]. These higher dimensional objects have turned out to be important in particular for the many string theoretic dualities that suggest a unified picture of string theory. For
example, mirror symmetry [30, 63] emerges as a kind of T-duality [111, 69], which in turn has implications for the construction of spacetime from the string worldsheet [105].

### 3.1 Ad hoc models

The D-brane idea has transcended string theory. One purely phenomenological application that has had an impact on current string model building is an attempt to understand the hierarchy problem by combining ad-hoc brane scenarios with an earlier, at the time provocative, idea that arose in the context of string theory. Antoniadis suggested in [5] the idea that the existence of large dimensions, possibly as large as 1 TeV, would provide a strategy to address the difficult issue of supersymmetry breaking in string theory (see also [88]). Arkani-Hamed, Dimopoulos and Dvali (ADD) [13] later observed that if such large dimensions exist they have implications for our thinking about the hierarchy problem, i.e. the puzzle that the weak scale in four dimensions $\sim 250\text{GeV}$ is very much lower than the Planck scale in four dimensions $\sim 10^{19}\text{GeV}$, a huge step for which one would like to have an explanation.

In the context of large compact dimensions the problem of a large hierarchy can be traded for the problem of explaining a large volume, since the four-dimensional Planck scale $M_p = \sqrt{\hbar c/G}$ is related via the effective action to the fundamental (bulk theory) scale $M_f$ as

$$M_p^2 = M_f^{n+2}V^n.$$  

Here the bulk theory is assumed to have $(n + 4)$ dimensions and the Lorentzian spacetime $M^{1,n+3}$ splits into a fourdimensional part and a compact manifold $K^n$ as $M^{1,n+3} = M^{1,3} \times K^n$, and units with $c = 1 = \hbar$ have been used. The basic observation now is that the fundamental scale in the bulk could be much lower than the fourdimensional Planck scale because the two are linked via the volume $V^n$ of the compact manifold $K^n$. If the size of these extra dimensions is large this would explain the huge value of the Planck scale in terms of a relatively low fundamental scale $M_f$.

### 3.2 Experimental constraints

In the simplest possible compactification scheme the realization of the brane picture formulated by ADD involves only circles, leading to a toroidal structure of the extra-dimensional
part of spacetime. Assuming that all radii are the same introduces only a single new scale, the radius $R$ of the circles. It is determined by the number $n$ of dimensions considered, $R = (M_p/M_f)^{2/n}(1/M_f)$, and experimental data provides constraints on the number of possible dimensions. If $M_f$ is chosen to be 1TeV the case $n = 1$ would be readily excluded because this model leads to an astronomically sized fifth dimension. Increasing $n$ within the limits of interest to string theory shows that they are all unacceptably large because particle accelerators should have seen them. This is where the D-brane picture enters. Assuming that all the fields of the standard models are confined to a D3-brane leaves only gravity as a possible probe of the compact dimensions.

Fig. 2 above shows that the constraints provided by gravity are surprisingly weak, leaving a wide open window for new interactions at large scales. This observation, made already in [47], not only triggered new interest in experimental tests of Newton’s law on small scales, as pointed out already, but also in phenomenological analyses of possible bounds on the string scale from collider processes [64, 66]. In the context of phenomenological models a wider range of possible interaction strengths is of interest than indicated in Fig. 2. Data constraining new interactions on shorter distance scales are shown in Fig. 3 [3], which is adapted from [55].

![Figure 3: Constraints on ISL-violating interactions, summarized from data in with 1nm < $\lambda$ < 1µm.](image)

The individual constraints in the diagram are based on the data from different experiments, notably Lamoreaux [83], Casimir [44], Mohideen [65], Ederth [52] and van der Waals (vdW)
The theory underlying experiments measuring Casimir forces is much more involved, because they deal with surfaces of real metals, and several corrections have to be taken into account, among them the roughness of the surfaces, as well as finite temperature corrections. The importance of these corrections, and their impact on constraining new physics, has been controversial. A review of the current status of these issues is provided in [93]. Long distance constraints, finally, are summarized in Fig. 4.

Figure 4: Constraints on ISL-violating interactions, summarized from data in with $1\text{mm} < \lambda < 10^{15}\text{m}$.

The assumption of ADD type models that all fields except the graviton propagate on a three-dimensional brane, and only the graviton propagates in the bulk, implies that new contributions to collider processes arise from the Kaluza-Klein excitations of the graviton. Although the contributions of individual Kaluza-Klein modes, with 4D gravitational strength, to collider processes is extremely small, a very large number of such modes contribute in a TeV-scale collider process because the compactification scale is so small. The net Kaluza-Klein effect can cause a significant deviation from the standard model production rates. Bounds on the string scale from analyses of various collider processes are typically of the order of a TeV for these symmetric compactification models [107, 91, 60, 66].
3.3 Embedding of the D-brane scenario into string theory

In order to make the scenario considered in [13] into a consistent physical picture it is necessary to derive this class of models from string theory. It was outlined in [7] that such an embedding can be achieved by considering the so-called type I theory, a model which contains open and closed strings [98]. The realization considered in [7] involves the localization of the standard model fields to a D3-brane, while gravity also propagates in the bulk.

More generally, one can envision scenarios where the standard model can be viewed as localized on a $p$-dimensional brane with $p \geq 3$ while closed strings can move in the bulk. In the simplest compactification schemes this would give rise to the production of massive standard model Kaluza-Klein towers in colliders once the energies reach the compactification scale of the 'longitudinal' $(p - 3)$-dimensions. The characteristic signal in particle colliders is graviton emission into the bulk, leading to missing energy that escapes detection.

4 Universal and mixed extra dimensions

4.1 UEDs

The original assumption in the pre-D-brane period of string theory was that all fields propagate in the compact dimensions. This notion has since been renamed in the context of phenomenological ad-hoc models with large dimensions as the so-called universal extra dimensions (UED) scenario, in distinction to D-brane models. In this case momentum conservation in the extra dimensions implies the conservation of Kaluza-Klein mode number at tree level. This controls all the couplings of these fields, and each vertex involves at least two such excitations, hence direct production is only possible in pairs of Kaluza-Klein states, and there are no tree-level contributions to the electroweak observables. The main constraint observed in [10] comes from weak-isospin violation effects. The mass bounds for the first excited modes are relatively low [10, 45, 102]. For one extra dimension the limits on $R^{-1}$ are between 300 GeV and 500 GeV, depending on the Higgs mass [11]. This opens the possibility of discovering Kaluza-Klein states in this class of models in upcoming collider experiments.

The fact that in UED models Kaluza-Klein-parity conservation leads to a stable lightest
Kaluza-Klein state has the consequence that in these models a lightest state of this type could provide a dark matter candidate. It can constitute cold dark matter if its mass is approximately 600 GeV [106, 28, 82], well above current collider limits. The LHC might be able to test these models up to $R^{-1} \sim 1.5$TeV [32].

4.2 Mixed extra dimensions

The ‘pure’ scenarios of fixing the standard model on a D3-brane, or allowing them to propagate into all compact dimensions in the UED models, raises the obvious question whether phenomenological constraints change in mixed models, in which some of the fields are confined to the brane and others are allowed to propagate in the bulk. Non-universal models in which the gauge bosons propagate in the extra dimensions, but the fermions are confined to the standard model D3-brane [1, 39], do provide different collider bounds than completely confined models. These include effects on electroweak precision measurements [103], Drell-Yan processes in hadronic colliders [90, 94], $\mu^+\mu^-$ pair production in electron-positron colliders [90, 94], electroweak processes in high energy electron-positron colliders, as well as multijet production in hadronic colliders [46].

5 Warped compactifications

5.1 Randall-Sundrum models

An alternative compactification scheme in the context of producing phenomenological models with large hierarchies involves the warping of the four-dimensional part of spacetime of the compact dimensions. Traditionally the ansatz for a metric in a Kaluza-Klein or string theory framework on a $D-$dimensional spacetime for spacetime with coordinates $(x^\mu, y^m), \mu = 0, ..., 3, m = 1, ..., D - 4$ has been a simple product

$$ds^2 = \sum g_{\mu\nu}(x^\kappa)dx^\mu dx^\nu + \sum g_{mn}(y^k)dy^m dy^n,$$

where the $x^\mu$ are the standard four-dimensional coordinates and the $y^m$ parametrize the compact dimensions. In the warped case generalized solutions of the equations of motion are considered for which the normalization of the four-dimensional metric varies in the transverse
direction

\[ ds^2 = e^{A(y^k)} \sum_{\mu \nu} g_{\mu \nu}(x^\kappa) dx^\mu dx^\nu + e^{-A(y^k)} \sum_{mn} g_{mn}(y^k) dy^m dy^n. \]

In this scenario a given invariant energy scale can give rise to many four-dimensional scales, depending on the position-dependent gravitational redshift in the transverse space. This mechanism has played an important role in particular in the Randall-Sundrum models [100, 101]. In the compact version [100] a five-dimensional spacetime is considered with a metric of the form

\[ ds^2 = e^{-2kr_c|\phi|} \eta_{\mu \nu} dx^\mu dx^\nu + r_c^2 d\phi^2, \]

where \( x^\mu \) are the four-dimensional Minkowski space coordinates, \(-\pi \leq \phi \leq \pi\), with identification of \((x, \phi)\) and \((x, -\phi)\), and \( r_c \) sets the compactification scale. Two 3-branes are located at \( \phi = 0 \) and \( \phi = \pi \) respectively. This set-up is similar to a compactified version of the Horava-Witten scenario where M-theory is compactified on Calabi-Yau manifolds [67, 68, 115].

The generation of a hierarchy via redshift has a number of interesting consequences. It can be shown that the effective four-dimensional Planck scale \( M_p \) is given by

\[ M_p^2 = \frac{M^3}{k} (1 - e^{-2kr_c\pi}). \]

This implies that even at large \( kr_c \), the Planck scale is of the same order as the fundamental scale. A further implication of the warp factor in the metric is that a field confined to the 3-brane at \( \phi = \pi \) with mass parameter \( m_0 \) will have a physical mass given by \( m = m_0 e^{-kr_c\pi} \). For \( kr_c \) about 12 this implies that the weak scale therefore is dynamically generated on the visible brane from the fundamental Planck scale. Furthermore, thresholds to the production of Kaluza-Klein modes can be reached at low energies, in the TeV range, and scattering at low energies can reach the fundamental Planck scale, due to the relative redshift.

These results also suggest the possibility of experimental probes of Planck- or string scale physics at energies far below the apparent four-dimensional Planck scale. As an example the possibility has been suggested in [12, 53] that black holes could be produced at relatively low energy scales, leading to the idea that the CERN Large Hadron Collider could become a black hole factory. Such TeV black holes radiate mainly on the brane [53], and detailed aspects of possible LHC signatures have been discussed in [57, 58, 48].
5.2 Embedding of warped models into string theory

Warped metrics have been considered in string theory early on by Strominger [110], who observed that fluxes can be considered if the metric is generalized from a pure product to a twisted form. They have been revived in the context of M-theory by Becker-Becker [18] and in the framework of F-theory in [38]. A realization of the compact Randall-Sundrum scenario within string theory was first discussed in detail by Giddings-Kachru-Polchinski (GKP) in [56], developing further a construction by Verlinde of the warp in terms of $N$ coincident D3-branes on a Calabi-Yau manifold [113]. The particular importance of the GKP discussion of warped compactifications in string theory derives from their observation that it is possible in this framework to fix in several classes of string models many of the large number of moduli usually associated to supersymmetric vacua. This represents important progress from a practical point of view, because the stabilization of these moduli opens the door to a much more precise phenomenological analysis of these models than previously possible.

In order to fix the moduli it is necessary to break conformal invariance and most of the supersymmetry. The strategy to achieve the necessary reduction of symmetry is to place $D3$–branes not at a smooth point of the transverse space, but at a singularity. A detailed construction involving the introduction of O3-planes, D7-branes, and fluxes in addition to the D3-branes of Verlinde within type-IIB solutions has been given by GKP. Concrete examples are constructed as orientifolds of CY compactifications, and also as F-theory compactifications. The latter are of interest because they allow larger fluxes and hierarchies. In many cases the resulting solutions stabilize the dilaton and the complex structure moduli at a high scale, and further corrections to the leading order action are needed to generate a potential for the remaining ones.

The GKP construction of [56] was enhanced by Kachru-Kallosh-Linde-Trivedi (KKLT) [75] by taking nonperturbative corrections to the superpotential into account, and by adding anti-D3-branes into the mix as a further ingredient. The combination of these two ingredients allows not only to stabilize the remaining (Kähler) moduli, but also to lift the resulting anti-de Sitter space to a solution with a positive cosmological constant. By tuning the flux superpotential to be very small it is possible to obtain gravitino masses of $\mathcal{O}(1 – 10 \text{TeV})$. This has triggered much work on the distribution of flux vacua, testing whether one can achieve the required small values necessary for supersymmetric vacua at large volume [15, 43, 59].
A somewhat different approach to realize the warping idea within string theory has been pursued in the 'large volume compactification' approach, introduced in [17], and developed further in [36, 4, 35]. It is based on the observation [16] that the inclusion of string corrections to the tree-level supergravity effective action, previously computed in [19], leads to interesting modifications of the models considered by GKP and KKLT. This class of vacua preserves the main ingredients of the GKP-KKLT scenario as far as the orientifold and D-brane structure within type IIB theory is concerned, leading again to a stabilization of all the moduli, but allowing a limit with a large overall volume modulus and all the remaining moduli small. Fluxes stabilize the dilaton and the complex structure at a high scale, while the flux superpotential does not have to be fine tuned to small.

It is argued in [16] that the maximum value that the flux induced superpotential can achieve scales as the square root of the Euler number of the Calabi-Yau fourfold giving rise to the type IIB model considered. The construction in [89] of the class of about $10^6$ Calabi-Yau fourfolds derived from Landau-Ginzburg potentials shows that these values can easily be of order $10^3$. Masses derived for the gravitino for a specific compactification manifold lead to intermediate scales, and are independent of the fluxes. Thus this framework provides a realization of the intermediate scale string scenario considered in [21, 27]. Inflationary models based on Kähler moduli considered in [34] lead to spectral indices in the $1 - 2/N_e \sim 0.96$ range, where $N_e$ is the number of e-foldings. This result is consistent with the three-year WMAP results [109]. The tensor-to-scalar ratio is extremely low, much smaller than the current experimental limit of about 0.3. An observation of tensor modes would therefore invalidate this class of models, along with many others [76]. An extension of the framework of large volume compactification to incorporate the effects of strong warping has been discussed in [26], while the inclusion of further corrections has been pursued in [22].

6 Concluding remarks

Many different interesting (classes of) string theoretic, or string inspired, models exist that could not be described in any detail in this brief summary. The focus here is on the general structure of string theoretic models, as well as on ideas that are on the interface between string theory in particular, and particle physics in general. The models reviewed are not only
of interest merely as ad hoc models, but they emerge as limits of fundamental, string theoretic, solutions.

Some of the prominent models, such as the KKLT model [75], and the large volume model (see e.g. [17, 36]), are analyzed in greater detail in ref. [78]. This paper addresses the interesting ‘inverse problem’ in the context of the LHC: it treats the issue whether phenomenological data from the LHC can in principle be used to distinguish between the large number of different types of string models that have been proposed to date. Among those considered are not just the KKLT and the large volume models, but also a number of heterotic constructions. A discussion of the issues introduced by the fine-tuning of the cosmological constant can be found in [40].

A subject that could barely be mentioned here, and that deserves its own review, is that of the implications of the recently considered classes of warped flux compactification models for early cosmology. An update of these developments can be found in [99, 25, 76].

The great advances in string technology that have been achieved over the past few years, in combination with new experiments, such as much more precise table top gravity tests, the WMAP probe, and the upcoming LHC, have transformed string theory as a discipline. They have triggered a renaissance in string phenomenology, leading to a continuous spectrum of ideas that spans the range from full-fledged string models to much simpler and easily accessible ad-hoc constructions. They have also done much to strengthen the links between experimenters, particle physics phenomenologists, and string theory model builders.

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**7 Glossary**

**Compactification.**

The notion that a higher dimensional spacetime factors into a the standard observable universe
of (3+1) dimensions plus an additional number of compact dimensions of finite volume. In the context of the standard big bang model this is a misnomer — it would be more appropriate to think of a dynamical process that decompactifies some dimensions while keeping others small. The first idea in this direction came from Brandenberger and Vafa [24], and has more recently been pursued in [51].

**D-branes.**

In any theory with open strings a D-brane is a region of spacetime on which open strings can end. The name derives from the choice of Dirichlet boundary condition at the ends of the open string, as opposed to Neumann conditions.

**Fluxes.**

In string theory in general, and type II and F-theory in particular, there are several tensor fields that generalize the vector potential of electromagnetism. The associated field strengths lead to fluxes that are constrained by a tadpole cancellation condition.

**Hierarchy problem.**

The idea that the small number given by the ratio of the weak scale and the Planck scale should have an explanation in terms of some fundamental aspects of a unified theory.

**Kaluza-Klein modes.**

In a compactification scheme with periodic boundary conditions in some dimensions any field can be expanded in a Fourier series along these compact directions. This results in an infinite tower of massive states whose masses are determined by the winding number and the length scale associated with the compact dimension.

**Large extra dimensions.**

Any dimension much larger than the Planck scale is considered to be large.

**Moduli.**

Parameters that describe the shape of the compact manifold which appears as a factor of the higher dimensional manifold in string theory. In terms of the underlying conformal field theory
moduli are marginal operators with no potential to all orders in perturbation theory. Two prominent classes of moduli associated to Calabi-Yau manifolds are the moduli associated to the Kähler deformations, determined by the (Kähler) metric on the manifold, and the moduli associated to complex deformations.

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Further reading.

A comprehensive introduction to the developments in string theory in the past decade can be found in [20]. A more phenomenologically oriented discussion can be found in Dine’s review [49]. An elementary introduction to the basics of lower dimensional Kaluza-Klein theory is given in Sundrum’s lectures [112]. More recent developments along the lines of incorporating the warped dimensions idea into string theory have been reviewed extensively in [61, 50, 23]. A review on black hole aspects at the LHC for TeV quantum gravity can be found in [84]. An extended introduction to the potential aspects of string phenomenology at the LHC is given in [78].