Particle Physics from String Compactifications

Wilfried Buchmüller[1], *Jan Louis*[2]

[1]DESY, Hamburg, Germany
[2]II. Institut für Theoretische Physik, Universität Hamburg, Germany

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We briefly review the work carried out in project A1 of the SFB 676. This includes in particular string compactifications to vacua containing the Standard Model. We compare heterotic compactifications with F-theory, and we mention a number of technical developments. Motivated by string compactifications, several aspects of six-dimensional field theories are described, which shed some light on supersymmetry breaking, moduli stabilization and the little hierarchy problem. We highlight some virtues of flux compactifications and conclude with a brief discussion of LHC phenomenology.

1 Introduction

String theory remains the most promising framework for a unification of the Standard Model with gravity. The key features of the Standard Model, chiral gauge interactions and the Brout–Englert–Higgs mechanism of mass generation for chiral fermions, naturally emerge in string compactifications. On the other hand, the vacuum structure of string theories is complicated, which makes it difficult to understand details of the Standard Model as consequences of a string compactification. It has been the goal of project A1 to contribute to the work needed to bridge the gap between particle physics and string theory.

A major effort has been made to study in detail phenomenologically promising string compactifications, starting from the heterotic string with symmetry group $E_8 \times E_8$, and also from F-theory. As an intermediate step, compactifications to six dimensions have been investigated. Six-dimensional supergravity theories with gauge unification turned out to be a good starting point for deriving four-dimensional supersymmetric extensions of the Standard Model with some specific predictions for experiments at the Large Hadron Collider (LHC), which we have also studied.

In 2012, right in the middle between beginning and end of the Collaborative Research Center 676, the Higgs boson was discovered with a mass of 125 GeV. This mass value allows a consistent extrapolation of the Standard Model as a weakly coupled theory from the electroweak scale up to the scale of grand unification. This is in accord with expectations based on supersymmetric theories. On the other hand, so far extensive searches at the LHC have shown no signs of supersymmetry. Hence, the scale of supersymmetry breaking may lie much above the electroweak scale, so that the mass of the Higgs boson cannot be entirely protected by supersymmetry. The matching of the Standard Model to a supersymmetric theory at scales far above the electroweak scale has therefore been an important topic during the second phase of the project A1.

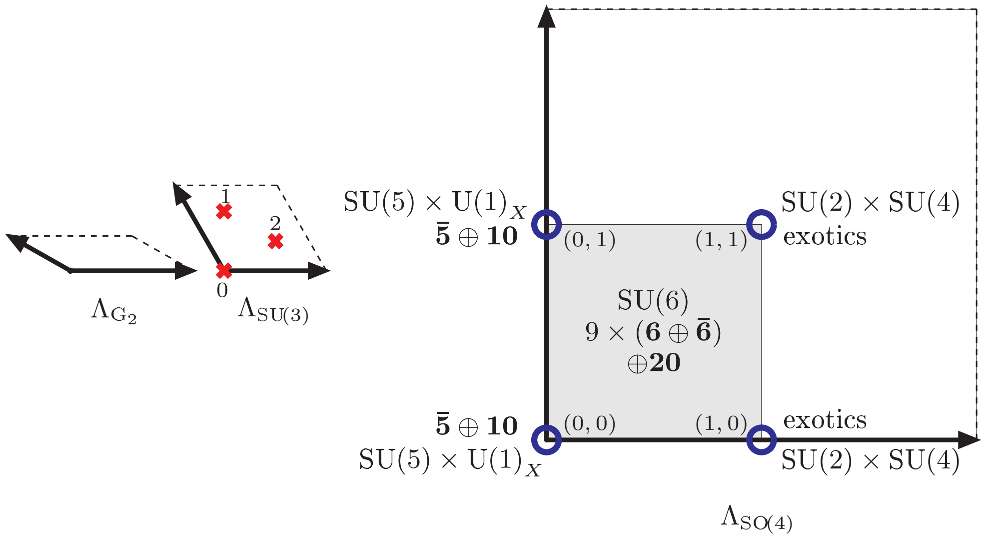

Figure 1: The six-dimensional orbifold GUT model with the unbroken non-Abelian subgroups of the visible E_8 and the corresponding non-singlet hyper and chiral multiplets in the bulk and at the $SU(5)$ fixed points, respectively. Fixed points under the $\mathbb{Z}_2$ subtwist in the $SO(4)$ plane are labelled by tupels (n, m), those under the $\mathbb{Z}_3$ subtwist in the $SU(3)$ plane are indicated by the red crosses. The $\mathbb{Z}_6$ fixed point in the G_2 plane is located at the origin. Reprinted from Ref. [3], with permission from Elsevier.

In the report we shall first discuss results on string compactifications. Subsequently, we will deal with *string inspired* supersymmetric models in six and four dimensions as well as some specific predictions for collider physics. We shall conclude with an outlook on *Particle physics from string compactifications*. It is impossible to give adequate references to all the work that motivated and stimulated the research carried out within the project A1. Excellent reviews of basics and recent developments of supergravity and string theory are [1,2]. These reviews also contain extensive references. Beyond that we refer the reader to the references given in the papers described below.

2 String compactifications

During the first phase of the project the focus has been on compactifications of the $E_8 \times E_8$ heterotic string. This was partly motivated by the success of orbifold GUTs, higher-dimensional field theories with grand unified gauge groups compactified on orbifolds. In these theories the GUT gauge groups can be broken in an elegant way by means of boundary conditions, and one can easily understand why the Higgs doublet has no colour-triplet partner, which is the so-called doublet-triplet splitting problem. In [4,5] it was shown that a six-dimensional (6d) orbifold GUT can indeed be obtained as intermediate step in an anisotropic compactification of the heterotic string on a $\mathbb{Z}_6$ orbifold. First, the ten-dimensional string is compactified on the orbifold $T^4/\mathbb{Z}_3$ to six dimensions where one obtains a theory with $\mathcal{N} = 2$ supersymmetry and unbroken gauge group

$$G_6 = SU(6) \times U(1)^3 \times [SU(3) \times SO(8) \times U(1)^2] \,,$$

where the brackets denote the unbroken subgroup of the second E_8. In a second step, the 6d theory with one Wilson line is compactified to four dimensions, with unbroken $\mathcal{N} = 1$ supersymmetry. The intersection of unbroken subgroups at the two pairs of inequivalent fixed points yields the Standard Model gauge group,

$$G_{SM} = SU(3) \times SU(2) \times U(1) \subset SU(5) \times U(1) \cap SU(2) \times SU(4) \,.$$

Two quark-lepton families are located at the $SU(5)$ fixed points of the $SO(4)$ plane, and a third family consists of split multiplets of the 6d bulk hypermultiplets, see Figure 1. As a consequence, there is only one large Yukawa coupling, the top quark coupling, which is related to the 6d gauge coupling. All other Yukawa couplings are generated by higher-dimensional operators.

In a parallel development M-theory compactifications on seven-dimensional manifolds with SU(3) structure were studied [6], which lead to $\mathcal{N} = 2$ supersymmetric theories in four dimensions. These compactifications were shown to be dual to compactifications of the heterotic string on $K3 \times T^2$, with background gauge field fluxes on T^2. The low energy effective action was derived, and the Kähler potential, the superpotential and the D-terms were computed in terms of geometrical quantities. For comparison with anisotropic orbifold compactifications with an intermediate 6d orbifold GUT, heterotic compactifications on generalized $K3$ manifolds with $SU(2)$ structure are particularly interesting. Such compactifications were investigated in [7] where the kinetic terms and the scalar potential were derived. Directly relevant for the orbifold compactification of [4] is the computation of the $\mathcal{N} = 1$ low-energy effective action for the compactification of the heterotic string on a smooth $K3$-surface to six dimensions [8, 9]. The gauge symmetry breaking was studied at the level of the effective Lagrangian and special attention was payed to the couplings of the charged matter multiplets to the geometrical moduli fields. It turned out that these couplings are heavily contrained by gauge invariance together with supersymmetry. Possible embeddings of line bundles into the ten-dimensional gauge groups of heterotic strings were systematically investigated in [10] and the associated gauge symmetry breakings and spectra were analyzed. The naive expectation that one may be able to construct an infinite number of MSSM-like models by varying the line bundles appears to be incorrect [11]. It is possible, however, to construct supersymmetric as well as non-supersymmetric Standard Model-like compactifications to four dimensions for the three ten-dimensional gauge groups $E_8 \times E_8$, $SO(32)$ and $SO(16) \times SO(16)$, respectively [12–14]. Generically, in heterotic orbifold compactifications magnetic gauge flux in the compact dimensions is not incorporated. In higher-dimensional field theories magnetic flux can be taken into account, which leads to interesting effects. According to the index theorem, a multiplicity of quark-lepton families can arise as zero modes, and the supersymmetry breaking scale is determined by the size of the compact dimensions, yielding a picture of *split symmetries* with respect to GUT gauge symmetries on the one hand, and supersymmetry on the other hand [15–17].

A challenging topic is the relation between heterotic orbifold models and their smooth counterparts. In [18] a specific Borsea-Voison manifold of the form $(K3 \times T^2)/\mathbb{Z}_2$ was identified which corresponds to a specific blow-up of the $T^6/\mathbb{Z}_6$ orbifold considered in [4]. The blow-up process is illustrated in Figure 2. At the top $T^4/\mathbb{Z}_3$ is shown, a singular $K3$ that is elliptically fibered over the base $T^2/\mathbb{Z}_3$. Over the singular points of the base, the torus degenerates to

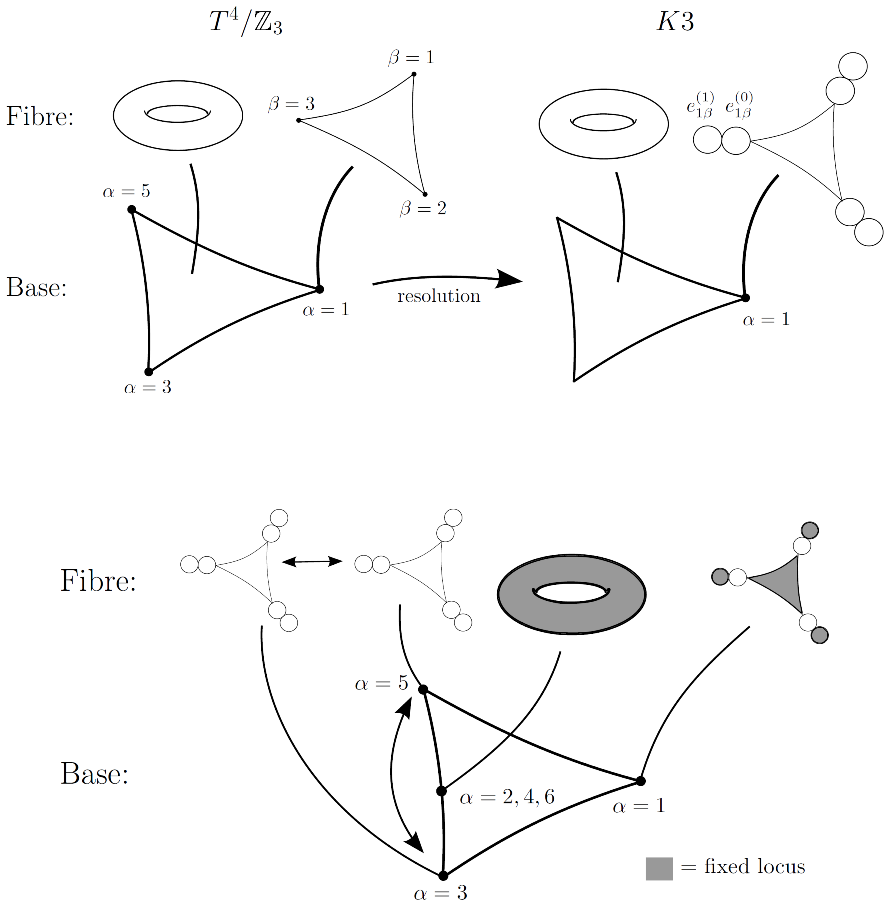

Figure 2: Top: The singular space $T^4/\mathbb{Z}_3$ (left) is blown up to a smooth $K3$ manifold (right). In this process each singularity is replaced by two spheres. Bottom: $\mathbb{Z}_2$ fixed locus on the smooth $K3$. Figures taken from Ref. [18].

$T^2/\mathbb{Z}_3$. $T^4/\mathbb{Z}_3$ has nine singularities, see Figure 1. The transformation of the shrinking cycles under the $\mathbb{Z}_2$ involution is illustrated at the bottom of Figure 2. Surprizingly little was known about the moduli space of the Borsea-Voison manifolds. We found that the vacuum expectation values (VEV) needed to blow up the orbifold completely, break the orbifold gauge group to a small subgroup. Moreover, by going to a smooth point in moduli space, all massless twisted states, which correspond to geometric moduli, aquire non-zero VEVs, breaking the orbifold gauge group. It turns out that the resulting light spectrum is non-chiral with respect to the unbroken gauge group, which matches with the results obtained for smooth compactifications. Phenomenologically, one wants a massless chiral spectrum with respect to the Standard Model gauge group. To fully understand the connection between successful singular orbifold constructions and compactifications of the ten-dimensional $E_8 \times E_8$ supergravity theory on smooth manifolds, further investigations are necessary.

An important technical aspect in the construction of 4d effective actions for orbifold com-

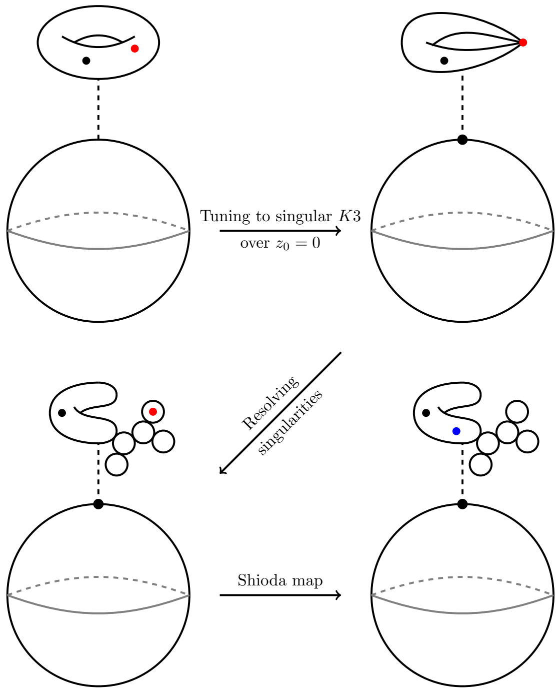

Figure 3: Construction of $SO(10) \times U(1)$ models. The fibration of the torus over $\mathbb{P}^1$ (top left) turns via tuning into a singular $K3$ manifold (top right). Resolution of the singularity generates five $\mathbb{P}^1$s with intersections corresponding to the extended $SO(10)$ Dynkin diagram (bottom left); after the Shioda map has been carried out, the $U(1)$ divisor intersects the affine node $\mathbb{P}^1_0$ (bottom right). Figure taken from Ref. [29].

pactifications of 5d and 6d supergravity theories are the brane-bulk couplings, since at the orbifold fixed points supersymmetry is broken. Several subtle points could be clarified in [19–23]. The boundary conditions also affect the fluctuations of the various bosonic fields around the gravitational background [24] and the stability of gauge flux compactifications [25]. In the effective 4d supergravity actions a crucial role is played by Fayet–Iliopoulos (FI) D-terms. The relation between computations of such D-terms in field theory and string theory was studied in [26].

An important and lasting result is the complete classification of six-dimensional symmetric toroidal orbifolds which yield $\mathcal{N} \geq 1$ supersymmetry in four dimensions for the heterotic string [27]. The starting point was a classification of the crystallographic space groups in six dimensions. In total 520 inequivalent toroidal orbifolds were found, 162 of them with Abelian point groups such as $\mathbb{Z}_3$, $\mathbb{Z}_4$, $\mathbb{Z}_{6-I}$ etc. and 358 with non-Abelian point groups such as S_3, D_4 etc. For some of these orbifolds the Hodge numbers were calculated and possible mechanisms of gauge symmetry breaking were explored. Particle spectra for heterotic compactifications on non-Abelian orbifolds were studied in [28].

During the course of the project the emphasis shifted from heterotic compactifications to F-theory where four-dimensional theories are obtained by compactifications on elliptic Calabi–

Yau fourfolds. In order to obtain chiral models it is necessary to turn on four-form flux G_4 on the fourfold. In [30, 31] a new construction of globally well defined G_4 flux was given which relies on identifying certain algebraic cycles in the Weierstrass equation of the fourfold. Subsequently, in [32] explicit chiral models were constructed with moduli stabilized in terms of magnetized D7-branes on smooth Calabi–Yau spaces. The previously encountered problems, such as the tension between chiral matter and moduli stabilization, the tension between Freed-Witten anomaly cancellation, nonperturbative effects and shrinking induced by D-terms, were overcome. This was extended in [33] where quasi-realistic models on branes at singularities were constructed with a fully consistent global embedding (including tadpole, K-theory charges and Freed-Witten anomaly cancellation) combined with moduli stabilization. The connection between heterotic and F-theory to six dimensions was analyzed in [34]. Using the Weierstrass description the complex structure of the Calabi–Yau threefold could be restricted such that the gauge group and the matter spectrum of the heterotic compactification on singular $T^4/\mathbb{Z}_N$ orbifolds were reproduced.

As we shall see in the following section, 6d supergravity models with gauge symmetry $SO(10) \times U(1)$ provide phenomenologically interesting GUT extensions of the Standard Model. This raises the question whether such models can be embedded in string theory. This question was systematically investigated in the context of F-theory. In [29], using toric geometry, 6d F-theory vacua with gauge group $SO(10)$ were completely classified, taking into account Mordell–Weil $U(1)$ and discrete gauge factors. The full matter spectrum of these models was determined, including charged and neutral $SO(10)$ singlets. Based solely on the geometry, all matter multiplicities were computed and the cancellation of gauge and gravitational anomalies was confirmed independent of the base space. The principle of the construction of the models is illustrated in Figure 3.

3 Model building

The compactifications of the heterotic string described above yield the Standard Model (SM) gauge group and a supersymmetric extension of the chiral SM matter spectrum with two Higgs doublets (MSSM). However, in addition a large number of massless SM singlet fields occur. Their vacuum expection values are largely undetermined since the superpotential of the theory is only partially known. This leads to a large vacuum degeneracy of the theory. Different vacua, corresponding to different sets of singlet vacuum expectation values, can differ significantly in their physical properties. For instance, they can realize gauge-Higgs unification or partial gauge-Higgs unification (for only one Higgs doublet) [3], and they also have different unbroken discrete R-symmetries [3, 35, 36]. These R-symmetries can be used to suppress perturbative contributions to the μ-term and the expectation value of the superpotential, i.e. the gravitino mass. Nonperturbative contributions can then generate large hierarchies. The many SM singlets in heterotic compactifications can partly also play the role of sterile neutrinos, which significantly modifies the seesaw mechanism [37]. In general, the discrete symmetries of heterotic vacua have important phenomenological implications for axion-like particles [38], family symmetries [39], the proton lifetime [40] and neutrino masses [41]. Interesting discrete symmetries also arise in MSSM type quiver models [42]. Flavour symmetries are more hidden in flux compactifications where the multiplicity of quark-lepton generations is generated by magnetic flux in the compact dimensions [43]. Nevertheless, there exist a number of relations between Yukawa couplings, remnants of the underlying GUT symmetry and the wave function

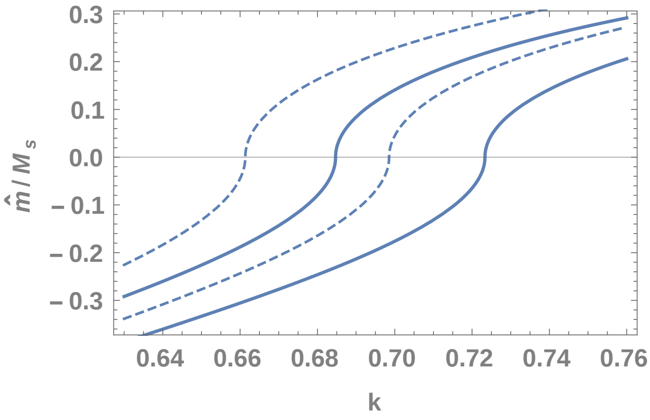

Figure 4: The scale ratio $\hat{m}^2/M_s^2$ as function of the mass ratio $k = M_{1/2}/m_0$ for $\lambda_0 = 0.4, 0.001$ (left to right) and $\tan\beta = 6, 15$ (dashed, full). $M_s = 3$ TeV. Figure taken from Ref. [47].

profiles of the zero modes. This can lead to a successful flavour phenomenology, including thermal leptogenesis [44].

One of the SM singlets in heterotic compactifications can play the role of a singlet Higgs field, extending the minimal supersymmetric standard model (MSSM) to the next-to-minimal supersymmetric standard model (NMSSM) [45,46]. Here the μ-parameter becomes a field, which alleviates the *μ-problem* of the MSSM. However, since no superparticles were discovered at the LHC so far, both the MSSM and the NMSSM have a *little hierarchy problem*: The ratio between the Fermi scale of electroweak symmetry breaking and the scale of supersymmetry breaking is much smaller than one, contrary to early expectations, which calls for an explanation.

Characteristic parameters for the scale of electroweak symmetry breaking and supersymmetry breaking are $\hat{m}$, a function of the two soft Higgs mass parameters, together with $\tan\beta$, the ratio of the Higgs VEVs, and the geometric mean M_s of the scalar top masses, respectively,

$$\hat{m}^2 = \frac{m_{h_d}^2 - \tan^2\beta \, m_{h_u}^2}{\tan^2\beta - 1}\,, \quad M_s = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}\,.$$

The little hierarchy problem then corresponds to the unexpected observational fact

$$\hat{m}^2/M_s^2 \ll 1\,.$$

In typical gravity mediation schemes, such as dilaton domination [48], this inequality can only be satified by a rather fine-tuned choice of the soft supersymmetry breaking parameters. One may hope that such fine-tuned parameters are an automatic consequence of relations between supersymmetry breaking terms at the GUT scale, predicted by supersymmetry. This can indeed happen, for instance, in hybrid gauge-gravity mediation [49] due to a particular choice of messenger fields [50]. Alternatively, one can hide the fine-tuning in a particular mass relation between the universal gaugino and scalar masses at the GUT scale, $M_{1/2} = km_0$ [51]. An example of this type is shown in Figure 4 for the NMSSM, where the ratio of mass scales $\hat{m}^2/M_s^2$ is plotted as function of k for different choices of the Yukawa coupling λ_0 between SM singlet and doublet Higgs fields and $\tan\beta$ [47,52]. For values of k around 0.7, which can be derived in

Parameters	P1	P2	P3	P4
λ_0	0.33	10^{-4}	0.1	10^{-3}
M_0 [GeV]	2000	2500	3000	3500
m_0^2 [GeV^2]	$7 \cdot 10^6$	$9.5 \cdot 10^6$	$1.35 \cdot 10^7$	$1.75 \cdot 10^7$
m_{h_s} [GeV]	1850	114.5	907.4	178.3
m_h [GeV]	123.6	126	125.7	127.9
$m_H, m_{H^\pm}, m_A$ [GeV]	2824	3434	4067	4660
m_{a_s} [GeV]	1040	66.65	561	108.8
$m_{\tilde{\chi}_s}$ [GeV]	1659	93.65	814.4	147.8
$m_{\tilde{\chi}_{\mu_1}}$ [GeV]	491	695	693	766.2
$m_{\tilde{\chi}_{\mu_2}}$ [GeV]	497	700	696	770
$m_{\tilde{\chi}_{\text{bino}}}$ [GeV]	880	1106	1335	1569
$m_{\tilde{\chi}_{\text{wino}}}$ [GeV]	1642	2056	2473	2893
$m_{\tilde{g}}$ [GeV]	4070	5145	6104	7047
m_{squark} [GeV]	2680-3760	3330-4630	3930-5480	4540-6310
m_{slepton} [GeV]	667-1300	840-1620	1000-1940	1180-2250

Table 1: Higgs and superparticle masses for typical parameter sets P1, P2, P3, P4, with $\tan\beta = 15$ and $M_s = 3.0, 3.8, 4.5, 5.0$ TeV (from left ro right). Table taken from Ref. [47].

a higher-dimensional model with gaugino mediation, a small ratio $\hat{m}^2/M_s^2$ can be obtained. It is instructive to work out the mass spectrum of Higgs bosons, higgsinos, gauginos, squarks and sleptons. As Table 1 demonstrates, except for the Higgs boson h, and possibly the higgsinos h_s and the singlino $\tilde{\chi}_s$, all superparticles have masses outside the discovery range of the LHC. The lightest superparticle is typically the gravitino with a mass in the range between 10 GeV and 100 GeV. Such a Higgs and superparticle mass spectrum, containing as light particles only singlinos in addition to the Higgs boson, is typical for models that address the little hierarchy problem. In the MSSM the supersymmetry breaking scale M_{SS} cannot exceed a value of about 10^{10} GeV. Otherwise, the running quartic Higgs coupling $\lambda(M_{SS})$ of the SM cannot be matched to the corresponding combination of gauge couplings in the MSSM. Note that this situation changes in the NMSSM where the effective quartic Higgs coupling is modified. As a consequence, in the NMSSM the supersymmetry breaking scale can be as large as the GUT scale [53].

A notoriously difficult problem in string compactifications is the stabilization of all moduli fields at a vacuum with vanishing or very small cosmological constant. Contributions from various perturbative and non-perturbative effects to the stabilization of bulk moduli were studied for explicit heterotic orbifold compactifications. Several de Sitter solutions could be found which, however, all turned out to be unstable [54]. As already mentioned in the previous section, considerable progress was made in stabilizing Kähler moduli for chiral D7-brane models within the framework of type IIB flux compactifications. World-volume fluxes can be chosen to obtain GUT- or MSSM-like theories. Moreover, TeV-scale supersymmetry breaking can be realized [32, 33].

It is instructive to study moduli stabilization also in higher-dimensional field theories. Here one only has a few moduli and the system is simple enough that quantum corrections can be

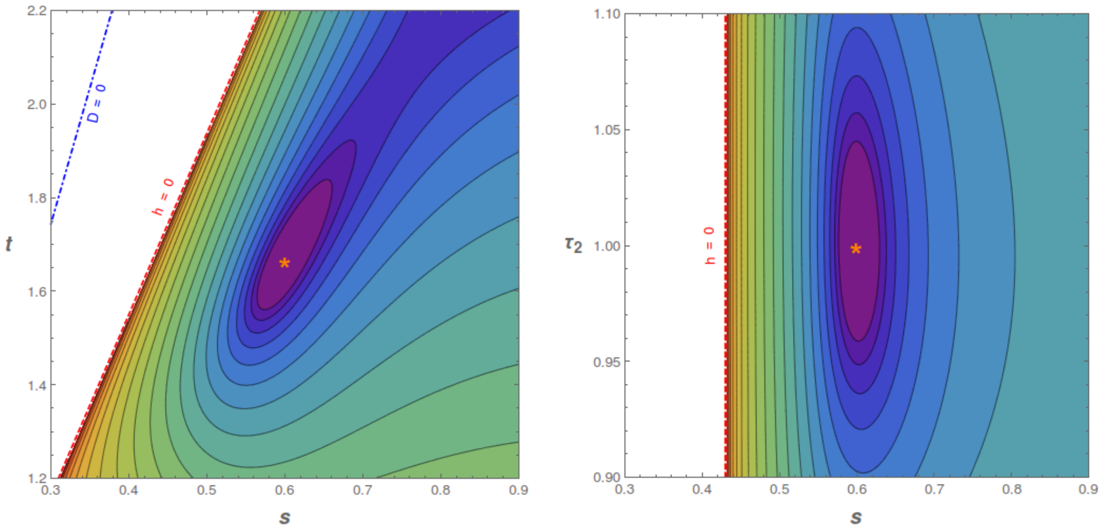

Figure 5: Contour plot of the moduli potential as function of the 3 fields s, t and τ_2 in the $s - t$ plane, $\tau_2 = 1$ (left) and in the $s - \tau_2$ plane, $t = 5/6$ (right). The remaining 3 moduli are stabilized at the origin. The size of the volume is $V = L^2/2$, with $L = 200$ in Planck units. Reprinted figure with permission from Ref. [60]. Copyright (2016) by the American Physical Society.

taken into account. In [55–57] it was shown that the Casimir energy together with localized FI terms can lead to a stabilization of shape and volume moduli. Moreover, the interplay of quantum corrections of the Kähler potential, localized FI terms and the Casimir energy can yield *almost no-scale* models with light moduli [58]. Particularly interesting are 6d orbifold models with magnetic flux. The D-term potential contains two FI terms which are induced by the flux and by the Green–Schwarz term canceling the gauge anomalies, respectively. The Green–Schwarz term also leads to a correction of the gauge kinetic function which turns out to be crucial for the existence of Minkowski and de Sitter vacua. The stabilization of all 6 moduli is achieved by the interplay of the D-terms and a nonperturbative superpotential [59–61], see Figure 5.

Moduli fields have important cosmological implications. For instance, a light axion-dilaton system can lead to recurrent acceleration [62, 63]. An interesting aspect of heterotic orbifold compactifications with several axions is the possible alignment of more than one axion, which can lead to inflation with trans-Plankian field values [64]. In the superpotential of these models gaugino condensates play an important role. Here one has to take into account that hidden Yang–Mills sectors are cosmologically strongly constrained by possible dark glueball overproduction during the cosmological evolution [65].

Since no hints for supersymmetry have been observed at the LHC, one is left with some kind of hierarchy problem in supersymmetric theories, maybe a *little hierarchy problem* or a *GUT hierarchy problem*. It is clear that supersymmetry alone is not sufficient to protect the Higgs mass and the question arises whether higher-dimensional theories can provide other mechanisms to screen the Higgs mass from quadratic divergencies. In recent work it was observed that in flux

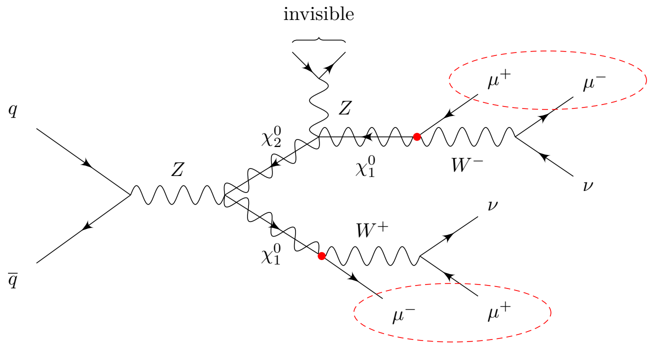

Figure 6: Typical R-parity violating decay chain involving higgsinos at the LHC. The secondary vertices as well as the two possibilities of interesting muon combinations are highlighted. The Z-boson decay is invisible, due to the small mass difference between the heavier higgsino and the lightest higgsino. Figure taken from Ref. [68].

compactifications, contrary to the case without flux, a cancellation of quadratic divergencies occurs, which can be traced back to a spontaneously broken symmetry of the higher-dimensional field theory [66]. In fact, in the 4d effective theory this manifests itself as a shift symmetry of a complex scalar, which forbids the generation of a mass term to all orders in perturbation theory [67]. So far the described cancellation of quadratic divergencies has only been studied in a toy model, an Abelian gauge theory in six dimensions. It remains to be seen whether the mechanism also works for more realistic non-Abelian gauge theories.

4 Connection to collider phenomenology

Collider phenomenology did not play a significant role in project A1. Nevertheless, trying to derive particle physics from string theory, some phenomenological signatures at the LHC, aside the main stream, were studied for a few aspects of the theoretical models described above.

An intriguing aspect of the models described in [47,49–51], which address the little hierarchy problem, and also of the model [15,43] with high-scale supersymmetry breaking, is the occurence of light higgsinos, with masses between hundred and a few hundred GeV. This is not too surprizing, since their mass is protected by a Peccei–Quinn type symmetry, contrary to gauginos. At the LHC one can search for light higgsinos by means of monojet events, but this is very challenging. A further possibility exists in the case of a light gravitino and small R-parity breaking, which is of particular interest also in connection with leptogenesis. Gravitinos can then be the dark matter of the universe, and their decay to neutrino-photon pairs produces monochromatic γ-rays, which in particular the Fermi-LAT collaboration has searched for. This has led to a current upper bound on the R-parity breaking parameter ζ of about 10^{-8}. Such a small breaking of R-parity can be understood, for instance, by dynamical symmetry breaking in a strongly interacting hidden sector of the theory [69]. Gravitino decays and R-parity violating decays of the lightest higgsino χ_1^0 are controlled by the same parameter ζ,

$$\Gamma_{3/2} \propto \zeta^2 \frac{m_{3/2}^3}{M_P^2}\,, \qquad \Gamma_{\chi_1^0} \propto \zeta^2 m_{\chi_1^0}\,,$$

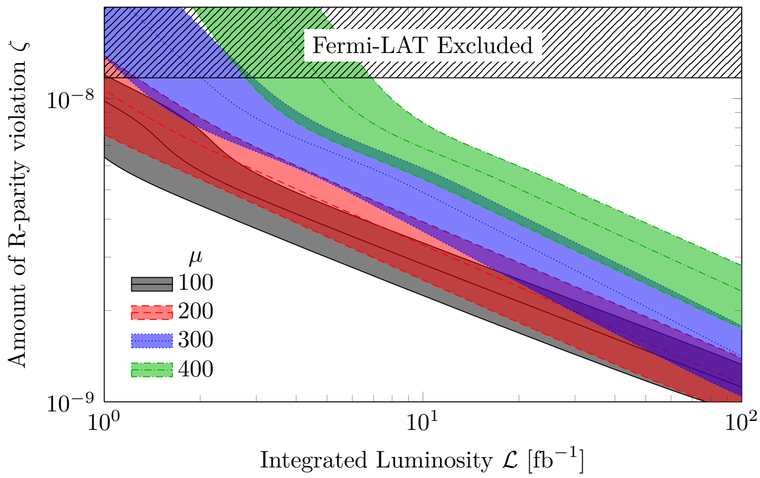

Figure 7: Estimation of the discovery reach for R-parity breaking higgsino decays at the LHC with 14 TeV center-of-mass energy. Each coloured band represents a value of the higgsino mass parameter μ. Figure taken from Ref. [68].

which implies interesting direct relations between astrophysics and collider physics. Moreover, R-parity violating higgsino decays, e.g. $\chi_1^0 \to W^\pm \mu^\mp$, can significantly help in the search for light higgsinos at the LHC [68,70]. A typical R-parity violating decay chain involving higgsinos with two $\mu^+\mu^-$-pairs is shown in Figure 6. Based on these and similar R-parity violating decay chains, the discovery reach at the LHC for R-parity breaking supersymmetry has been derived in a detailed investigation, see Figure 7. It is remarkable that the current run at 13 TeV center-of-mass energy is about one order of magnitude more sensitive to R-parity breaking than the astrophysical searches for monochromatic gamma-ray lines [68].

A characteristic feature of the models with flux compactification [15,43] is the difference of supersymmetry breaking in the matter sector and the Higgs sector, respectively. Quarks and leptons, which come in three copies of complete GUT representations, have very heavy superpartners, with masses at the GUT scale. On the contrary, the Higgs sector consists of split multiplets, one pair of Higgs doublets and higgsinos, and has $\mathcal{N} = 1$ supersymmetry at tree-level. Note that gauge coupling unification is realized with acceptable accuracy. To verify the consistency of such a scheme, one has to show that the running couplings of the Higgs potential can be matched to a supersymmetric theory at the GUT scale, where they are known functions of the gauge couplings, satisfying also constraints from vacuum (meta)stability. It was shown that, contrary to the SM with one Higgs doublet, this is indeed possible [71]. The results severely constrain the ratio of Higgs VEVs, and the Higgs masses,

$$\tan\beta \lesssim 2\,, \quad m_A, m_H, m_{H^\pm} \gtrsim 1 \text{ TeV}\,.$$

The precise bounds depend on the values of Higgs mass and top mass. They are shown in Figure 8. Clearly, the search of such heavy Higgs bosons at the LHC is very challenging.

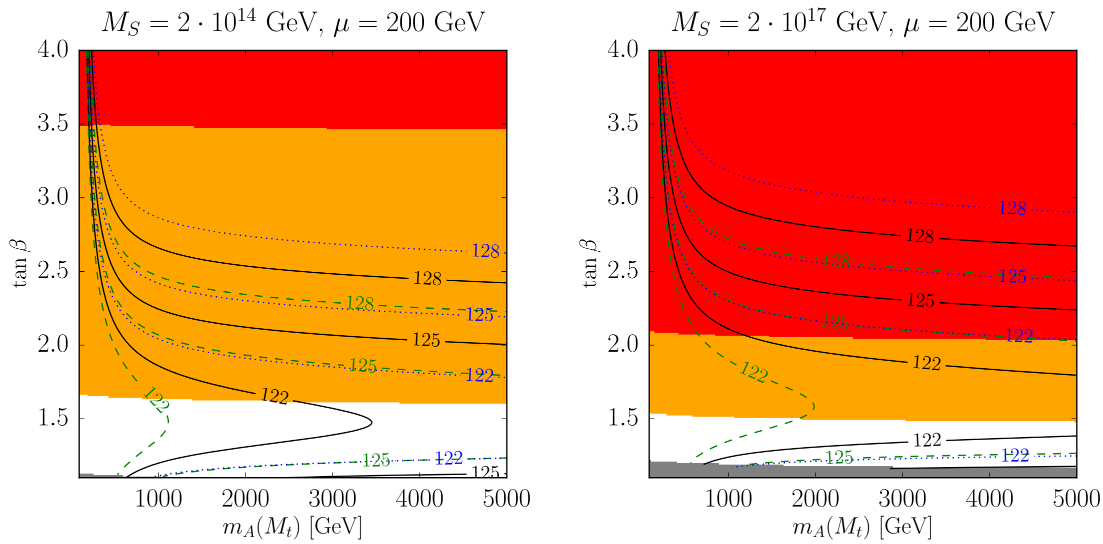

Figure 8: Contours of the lightest Higgs mass M_h in the $m_A(M_t) - \tan\beta$ plane for a two-Higgs-doublet model with higgsinos, with mass $\mu = 200$ GeV. Supersymmetry matching scale: $M_S = 2 \cdot 10^{14}$ GeV (left) and $M_S = 2 \cdot 10^{17}$ GeV (right). The Higgs mass prediction is computed for $M_t = 173.34 \pm 0.76$ GeV (solid black, dashed green, dotted blue). Unshaded regions are allowed by vacuum stability. In the orange regions, the electroweak vacuum is metastable, i.e. its lifetime is larger than the age of the universe. Red regions are excluded by vacuum (meta)stability. Figures taken from Ref. [71].

5 Outlook

We have briefly reviewed the work carried out within the project A1, which has been focussed on string compactifications and string-inspired model building, with a few phenomenological applications to LHC physics. The central goal has been to contribute to bridging the gap between string theory and particle physics.

During the course of the project our studies of string compactifications have shifted from the heterotic string to F-theory. Both versions of string theory can accomodate the Standard Model gauge group and its matter spectrum, with an embedding in the exceptional group E_8. The heterotic string as well as F-theory also provide an appealing geometrical picture of the localization of matter in the compact dimensions and the generation of Yukawa couplings. F-theory is more flexible to construct GUT gauge groups at intermediate steps and to vary matter representations. Also the separation between matter fields and moduli fields is more transparent and, consequently, the problem of moduli stabilization can be more satisfactorily treated. On the other hand, in F-theory the compact space is a del Pezzo surface. In this way one looses the attractive mechanism of Wilson-line breaking of symmetries, which is one of the advantages of heterotic compactifications. An interesting direction for future research would be to generalize the approach of F-theory to compact surfaces with non-trivial topology, and therefore beyond del Pezzo surfaces.

We have concentrated on anisotropic compactifications, with two compact dimensions larger than the other four, and we have also studied compactifications to six dimensions, which are technically considerably simpler. A physical motivation has been that the size of the two larger dimensions may be related to the scale of grand unification. The six-dimensional theory can then be treated as an effective field theory. For this simplified system some problems could be studied in greater depth compared to a full string theory compactification. Particularly interesting are compactifications from six to four dimensions with magnetic flux. In this case Minkowski and de Sitter vacua can be obtained with complete stabilization of all moduli. Flux compactifications also lead to phenomenologically interesting models which realize high-scale supersymmetry.

Since no hints of supersymmetry have been observed at the LHC, particle physics has to deal with a hierarchy problem, maybe a little hierarchy problem or even a GUT hierarchy problem. Supersymmetry alone is clearly not sufficient to protect the Higgs mass. In supersymmetric models that address this hierarchy problem one typically finds a superparticle mass spectrum, which is almost completely outside the discovery reach of the LHC. A possible exception are light higgsinos, as well as additional Higgs bosons. It is therefore mandatory to search for these particles at the LHC, despite the fact that these searches are very demanding.

It is an attractive, and at the same time challenging aspect of string theory, that in studies of particle physics problems also gravity is always present. For example, the requirement to have vanishing or very small cosmological constant, relates D-term and F-term breaking of supersymmetry. As illustrated by the examples discussed above, in this way the cosmological constant directly influences gaugino masses. Furthermore, the complicated vacuum structure manifests itself in the presence of many moduli with important cosmological consequences. In principle, this is very interesting, but in practice this often limits the possible progress in string compactifications.

A related problem is the huge range of mass scales, which have to be explained as ratios of vacuum expectation values: the cosmological constant (10^{-12} GeV), the scale of electroweak symmetry breaking (100 GeV), the Planck mass (10^{18} GeV), the unknown scale of supersymmetry breaking etc. It appears that further progress will depend most crucially on experimental hints for the scale of supersymmetry breaking.

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