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M-Phenomenology[1]

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Abstract

Recent developments involving strongly coupled superstrings are discussed from a phenomenological point of view. In particular, strongly coupled $E_8 \times E_8'$ is described as an appropriate long-wavelength limit of M-theory, and some generic phenomenological implications are analyzed, including a long sought downward shift of the string unification scale and a novel way to break supersymmetry. A specific scenario is presented that leads to a rather light, and thus presently experimentally testable, sparticle spectrum.

1 Introduction

The standard model (SM) of particle physics, an $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group with the appropriate field representations, seem to fit all presently available experimental data, including, notably, the LEP high precision electroweak tests[?]. Most remarkably, a supersymmetric extension of the standard model (SSM), while it more than doubles the SM particle content in the mass range ($\mathcal{O}(100\text{GeV} \to 1\text{TeV})$), it does not only escape unscathed from all the LEP severe tests[?], but it provides the first evidence

[1]Based on invited talks delivered during the summer, 1997.

for Superunification[?]. Indeed, renormalization group extrapolation of the three coupling constants (α_3, α_2, α_1), as measured at LEP, at very high energy show that they do converge at some scale

$$M_{\rm GUT} \equiv M_{\rm LEP} \simeq \mathcal{O}(10^{16}{\rm GeV}), \tag{1}$$

at a common value

$$\alpha_{\rm GUT} \simeq \frac{1}{25}, \tag{2}$$

as theoretically predicted a long time ago[?]. While very suggestive, this value of the Grand Unified scale brings us suspiciously close to the SPlanck scale:

$$M_{\rm SPl} \equiv \frac{M_{\rm Pl}}{\sqrt{8\pi}} = \frac{1}{\sqrt{8\pi G_N}} \simeq 2.4 \times 10^{18}{\rm GeV}, \tag{3}$$

implying that gravitational effects may be non-negligible and should be taken into account.

Supergravity is the local extension of rigid supersymmetry (SUSY), that automatically involves gravity. While Supergravity (SUGRA) cannot provide a finite quantum field theory, and thus a consistent quantum theory of gravity, still it may serve as an *effective theory* for energy scales below the SPlanck scale (3). Usually, SUGRA models are plagued by a major catastrophe, namely by an unacceptably large value for the cosmological constant, Λ_c, at the classical level. Interestingly enough, there is a specific class of models consisting of the so called *no-scale supergravity framework*[?], that

- provides a naturally vanishing cosmological constant, Λ_c, *at least* at the classical level due to the available flat directions (T_i) of the scalar potential: $V(T_i) = 0$[?]

- supergravity is spontaneously broken, but the gravitino mass, $m_{3/2}$, is *undetermined* at the classical level:[?]

$$m_{3/2} = m_{3/2}(T_i) \neq 0. \tag{4}$$

- quantum corrections curve, in principle, the flat directions of the scalar potential V, thus creating *dynamically* a $V_{\rm min}$, and provide vev's to the T_i's. In other words, we have not only succeeded to get radiative electroweak breaking (REWB), but we do also have a dynamical determination of the SUGRA breaking scale: $m_{3/2} = m_{3/2}(\langle T_i \rangle)$. In principle, in the no-scale supergravity, as it is suggested by its name, all mass scales are dynamically determined in terms of a single scale (our yardstick), say the SPlanck scale[**?**, **?**, **?**].

- the flat directions of the scalar potential V, corresponding to usually called moduli fields T_i trace their origin to the existence of non-compact continuous global symmetry, duality group, *e.g.* $SU(1,1)$, abundant in extended supergravity theories[**?**, **?**, **?**].

These rather unique characteristics find their natural habitat in string theory, whose infrared limit is nothing else but no-scale supergravity[**?**]. Sections 2 and 3 describe the weak and strong coupling limits of superstrings, respectively, while section 4 provides a phenomenological profile of strongly coupled $E_8 \times E_8'$ viewed as an appropriate limit of M-theory. M-theory inspired supersymmetry phenomenology is discussed in section 5 and some conclusions are drawn in section 6

2 Superstrings: Weak Coupling (10-D $\rightarrow$ 4-D)

Superstrings, one-dimensional extended objects, provide a consistent quantum theory of gravity and a natural framework for realistic unification of all fundamental interactions. While superstrings are intrinsically different from point-like particles in many respects, one may still, at least, initially try to use perturbation theory in order to get out some physics. The initial stages of this (perturbative) programme has yielded rather interesting results

- useful gauge groups are available, $SU(3)_c \times SU(2)_L \times U(1)_Y$, $SU(5) \times U(1)$, ...

- useful particle content is present, fitting into highly desirable representations of the above gauge groups, such as, three generations of quarks and leptons, two Higgs doublets, etc.

- useful superpotential form, yielding among other things successful Yukawa couplings, *e.g.*
$$\lambda_t \simeq g^2 \sim 0.7, \qquad (5)$$

at the string scale implying a top quark mass[?, ?]

$$m_t \simeq 160 - 190\text{GeV}, \tag{6}$$

or successful fermion mass relations[?], *e.g.*,

$$\frac{m_c}{m_t} \simeq \frac{1}{2}(\frac{m_e}{m_\tau})^{1/2}. \tag{7}$$

More generally, the "technology" has been developed to understand the so called, in the late 70's, generation problem and the fermion mass problem at the most fundamental level of dynamics, *i.e.* at the string scale. Dynamically calculable "*non-renormalizable*" terms[?], may provide the rather intrigued textures needed to explain the observed fermion mass spectrum.

- Supersymmetry emerges *naturally* due to the highly constrained form of string dynamics, in other words supersymmetry is a prediction of string theory. Furthermore, the low-energy limit of string theory is, generically, described by an effective theory belonging to the no-scale supergravity framework[?].

Despite all the above remarkable, indeed, successes of weakly coupled strings, there are enough stumbling blocks in the way towards a realistic superunification, that shed shadows of doubt on the whole picture, such as

- it has not delivered yet a unique theory at the string scale. Actually, the problem is not that we are short of "theories". On the contrary, we seem to have more than it is necessary. Instead of *one*, we got *five* theories: type I, type IIA, type IIB, heterotic SO(32), and heterotic $E_8 \times E_8'$. A rather unpleasant proliferation of Theories Of Everything (TOE). Things are getting worse, if we just recall the fact that the above five consistent string theories live in D=10 dimensions, and it is through compactification that we eventual reach D=4 dimensions. Since the compactification procedure, even if it is severely constrained, is rather arbitrary, at least in perturbation theory, we are landing in a D=4 landscape made of myriads and myriads of consistent string vacua. Non-perturbative string effects may help (and do help!), but one wants to make sure that they don't undo hard-earn successes of perturbation theory, *e.g.* Yukawa couplings, no-scale structures and the likes.

- while supersymmetry is a highly desirable symmetry, we better make sure that it gets broken. Weakly coupled string theory has not produced a clear-case SUSY breaking mechanism. Even if certain scenaria, *e.g.* gaugino condensation, has been the usual playground for string phenomenologists, clearly not pinning down the SUSY breaking mechanism implies not pinning down the SUSY particle mass spectrum, in other words no *hard* string predictions

- it suffers from an embarrassing disparity between the observed, apparent scale of (grand) gauge unification $M_{\rm LEP}$ and the dynamically calculable string unification scale[**?**].

  $$M_{\rm string} \simeq 5 \times g_{\rm GUT} 10^{17} {\rm GeV}, \tag{8}$$

  i.e. a discrepancy of about a factor of 20. Certain ways out in the present framework (that of weakly coupled strings) have been proposed, including large threshold effects, extra matter multiplets, non-minimal Kac-Moody levels and the likes[**?**]. They all suffer from a common inadequacy. They turn a wonderful prediction of the supersymmetric standard model (1) to a mere fitting of parameters. On the other hand, we may have yet another case where non-perturbative string effects may play a major role. But how?

Since the, observed at LEP, superunification of the gauge coupling constants is of such obvious fundamental importance, it is worthwhile unearthing the origin of the discrepancy between the $M_{\rm LEP}$ and $M_{\rm string}$. The heterotic string, the most relevant for phenomenology, will be used as a working example. It is well known that[**?**], in the heterotic string both gravitational and gauge interactions are produced from the closed string sector, thus establishing a relation

$$G_N \sim \frac{\alpha_{\rm GUT}^{4/3}}{M_{\rm GUT}^2 \alpha_{10}^{1/3}} \tag{9}$$

with α_{10} the 10-D string coupling constant, while $\alpha_{\rm GUT} (\equiv \alpha_4)$ is the 4-D one. It is pretty clear that, with the values of $M_{\rm GUT}$ and $\alpha_{\rm GUT}$ as given by (1) and (2) respectively, and assuming weakly coupled strings in 10-dimensions ($\alpha_{10} < 1$), we overshoot in the "prediction" of Newton's constant (G_N) by about three orders of magnitude! On the other hand, if one "fits in" the observed value of G_N, one gets a value for α_{10}, much bigger than 1 indicating that we are really probing the strong coupling limit of the string in 10-dimensions. By recalling the fact that

$$\alpha_{\rm GUT} \sim \frac{(\alpha')^3 \alpha_{10}}{V_6} \tag{10}$$

with α', the inverse of the string tension and V_6 the compactified 6-D volume, one may entertain the hope that there is a suitable strong coupling limit, such that $\alpha_{\rm GUT} \ll 1$ while V_6, and α_{10} go both to infinity in a suitable manner. Then, one may recover *both* the standard prediction of the SSM about $M_{\rm GUT}$ and the right value of G_N. In such a case, the strong coupling behavior can be deduced from what happens in the *strongly coupled 10-dimensional theory*. It is highly remarkable that the bottom-up approach that we have followed until now has lead us to deduce that the "vacuum of the world" seems to be a "strongly coupled heterotic string vacuum in 10-D," which has also been the focus of stunning theoretical developments (top-down approach) the last few years[**?**]. So let us shift our attentions to

3 Superstrings: Strong Coupling (10-D)

The strong coupling limit of quantum systems is usually fairly complicated. Sometimes, we may be lucky and get into the following situation. Consider a quantum system A with its fundamental degrees of freedom (d.o.f) denoted as X_A, and let some relevant parameter, say g_A to go to infinity (strongly coupled limit). It may happen that in this limit ($g_A \to \infty$) some of the fundamental d.o.f, X_A turn into some new d.o.f say Y_B, that describe the fundamental d.o.f of another quantum system B, but such that the corresponding relevant parameter say g_B is much smaller than one (weakly coupled limit). In such a situation, by using the mapping $A \leftrightarrow B$, we can extract information about the physics of the strongly coupled A system, by working in the familiar perturbation regime of relevance to us, of the system B! While all the above may sound and look as a pipe-dream, that is exactly what is happening in string theory. Intense theoretical work of the last few years[**?**] have indicated that all *five string theories*, discussed in the previous section, are interrelated in a similar way that systems A and B are related above, with $g_{A,B}$ referring to the corresponding string coupling constants. The magic property that is responsible for all these correlations is called *string duality*. This is nothing else but a non-trivial generalization of the electromagnetic duality, observed by Dirac, and which lead him to his famous charge quantization condition[?], in the presence of magnetic monopoles

$$q_E \cdot q_M = 2\pi n, \quad n = 1, 2, \ldots, \tag{11}$$

where q_E and q_M refer to electric and magnetic charges respectively. In the modern counterpart of non-Abelian gauge theories, the existence of 't Hooft-Polyakov type magnetic monopoles, which are not point-like, but extended objects of solitonic nature resurrected Dirac's ideas. Properly modified by Montonen and Olive[?], put to work in supersymmetric Yang-Mills theories. It was shown that in the E-weak limit ($q_E \ll 1$), the solitonic monopoles become superheavy ($M_{\text{monopole}} \propto \frac{1}{q_E^2}$) and thus decouple, while in the M-weak limit ($q_M \ll 1$), corresponding through (11) to $q_E \gg 1$, the solitonic monopoles become massless and provide the new fundamental degree of freedom! Actually, extended supergravities, as mentioned in the introduction, contain naturally non-compact continuous global symmetries, that act as duality symmetries, that is, exchange ordinary particles with solitons corresponding to *weak-strong coupling interchange*. Since, string theory yields naturally extended supergravities in its long-wavelength limit (*e.g.* $N = 1$ in $D = 10 \to N = 4$ in $D = 4$), it shouldn't be that surprising that *string duality* is present with all its spectacular consequences. While, grosso mondo, the generic analysis above for super Yang-Mills theories hold true, even more exciting tricks are involved in string theory. String duality multiplets may contain, vibrating strings (the basic quanta of string theory), smooth classical objects of solitonic type, singular classical objects (black holes) and D-branes[?], stringy type of topological defects. It all depends on the specific string theory and strong coupling limit chosen, which of the above objects will become massless and will provide the "new" fundamental degree of freedom. In 10-dimensions, the strong coupling limit of type I ($SO(32)$) string theory is given by the weakly coupled heterotic $SO(32)$ theory, while the IIB string is self dual. Things become more interesting in the case of IIA strings. IIA strings in 10-D contain D-0 branes, topological defects with point-like particle behavior, of mass $M_{D-0} \sim \frac{M_{\text{string}}}{g}$, which in the weakly coupled limit ($g \ll 1$) are superheavy and leave the vibrating strings to provide the fundamental d.o.f. Witten[?] has shown that in IIA strings we get towers of n D-0 brane supersymmetric bound states of mass

$$M_{\text{n-th bound state}} \sim n \cdot \frac{M_{str}}{g}, \quad n = 2, 3, \ldots. \tag{12}$$

In the strong coupling limit ($g \gg 1$) the D-0 bound states form a continuum, recastable as

$$M_n \sim \frac{n}{R_{11}}, \quad R_{11} \equiv \frac{g}{M_{\rm str}} \tag{13}$$

which, of course, is nothing else but the definition of an extra *11th-dimension*, á la Kaluza-Klein! The strongly coupled limit of IIA strings is the weakly coupled limit of some theory in 11-dimensions, compactified on a circle of radius R_{11}, as given in (13). This new, 11-D theory is called *M-theory*[**?**]. Actually as Horava and Witten[**?**] have shown, a different compactification of M-theory, this time on a semicircle (or segment) $\frac{S_1}{Z_2}$ of radius ρ, it provides the strong coupling limit of 10-D heterotic $E_8 \times E_8'$ string, to be discussed in detail later. Thus, we see that through string duality, we have been able to inter-connect all five string theories in 10-D, and in addition, we lead to the discovery of a new *M(ysterious) Theory* in 11-D. Of course, as (13) indicates, if we insist on the weakly coupled limit ($g \ll 1$) R_{11}, (or ρ) are much smaller than the string scale ($\frac{1}{M_{str}}$) and thus *invisible.* Hopefully, all the above analysis will help understand the string duality motto:

- The strongly coupled limit of any string theory is the weakly coupled limit of another "string" theory,

with the understanding that "string" theory contains also M-theory.

Non-perturbative string effects, attainable through string dualities, have lead to a much more satisfactory picture of string theory. Nowadays, all five string theories in 10-D and the M(ysterious) theory in 11-D are considered as the limits of *one theory.* In other words, over most of the theory space, $g \gg 1$, except various specific limits where $g \ll 1$, corresponding to the above mentioned string theories, and M-theory. In fact, currently the expression M-theory is used to describe an unknown, fundamental, 11-D theory, that *cannot* formulated as a traditional quantum theory, due to the lack of a parameter to be utilized in some perturbation expression, and approximates to 11-D supergravity at long wavelengths. A further speculative theory may exist in twelve-dimensions, dubbed as *F-theory*[**?**], which gives upon reduction on a two torus the type IIB theory. Whatever is the name of the *new theory*, it is clear that it resolves one of the problems of weakly coupled strings, that of the existence of five different theories in 10-D, by considering them as different limits of a *single* 11-D or 12-D theory. On the other hand, the excursion in 11 or 12-dimensions shouldn't be taken lightheartedly, since D=10 has been advertized as the critical dimension of consistent superstring theories.

What's going on? How these extra dimensions (11 or 12) popped out in string theory?

While the jury is still out in answering the above kind of fundamental questions, let me describe a resolution proposed recently by Ellis, Mavromatos and myself[**?**] in the framework of the so-called *non-critical* or *Liouville strings*[**?**, **?**]. It is well known that string theory contains a degree of freedom, that of the Liouville filed ϕ, that *decouples* both at the classical and quantum levels in the critical D=10 superstrings. It does not decouple, though, at the quantum level, if we go away from D=10. Actually, one may employ this new available d.o.f to construct exact string solutions involving *curved space-times*, such as a Robertson-Walker expanding Universe[**?**, **?**, **?**], 2-dimensional black-holes[**?**], or to get new solitonic solutions like NS five-branes[**?**] and the likes, that play an important role in non-perturbative string theory[**?**]. Sometimes these solutions are referred to as the *linear dilaton* solutions, because the dilaton is proportional to time (cosmological solution) or to some specific space direction (soliton solution). Taking into account the Liouville filed ϕ in the world-sheet dynamics, allows for extrapolation between critical points (corresponding to conformal field theories), thus providing a way to get out of D=10 and still obtain a consistent string theory. We have shown[**?**] that in the Liouville string theory, one may introduce worldsheet topological defects of the Liouville field, like vortices and monopoles, described by a deformed sine-Gordon model. D-branes in target space can be described in terms of these worldsheet topological defects, and their connection to black holes become apparent in our framework[**?**, **?**]. The statistical system of vortices and monopoles suffers a Kosterlitz-Thouless phase transition at a *dynamically determined* critical dimension which turns out to be $D = 11$! Away from criticality, $D' = D + 1 = 12$, since the Liouville field ϕ, is not decoupled. It is highly tempting to identify[**?**] such an emerging $D = 11$ target space theory with M-theory while the corresponding $D' = 12$ with F-theory! What such an identification buys us? Well, to start with, even if we cannot provide a traditional quantum field theory in 11 or 12 dimensions, we may have at least a world-sheet renormalizable theory that represents them. As we have stressed, *in dissent* and *for several years*[**?**, **?**], we may be in for surprises on the form of quantum field theory that is descenting from string theory. A further indication of the real worth of the Liouville string framework, is provided by contemplating on the well known fact that the maximum number of dimensions in which supersymmetry can exist is $D' = 12$, provided that the signature of spacetime is (10,2). The tale of two times! Our proposal[**?**] for managing the appearance of these two times is to identify the zero modes of the *a priori* distinct quantum fields $X^0(\equiv t$ in critical strings) and ϕ, in the neighborhood of each fixed point corresponding to the five string theories, and the 11-dimensional theory. In other words, each fixed point in the space of "string" theories has its own time-like coordinate X^0, which is a *reversible* coordinate, in the Einstein sense, so that a fixed point is Lorents invariant. In addition, in the bulk of the theory space there is a second time-like coordinate, the Liouville field ϕ, with respect to which evolution is *irreversible* in general. This means that the general 12-dimensional target space F-theory is "non-equilibrium" and does not have a simple field-theoretic interpretation. Thus it is possible to turn an apparent embarrassment of riches, that of signature (10,2) to our advantage and resolve a hundred year mystery, that of the (microscopic) origin of the arrow of time, while keeping Einstein physics basically intact. Last and not least, our approach reestablishes the singular importance of strings. Maybe, *L(iouville) theory will come to be known as the theory formerly known as M/F theory.*

4 Strongly coupled $E_8 \times E_8' \to$ M-theory: A phenomenological profile

The heterotic $E_8 \times E_8'$ string, in its weakly coupled form has been the focus of intense phenomelogical studies, due to its rich structure that yields realistic models describing the world at long wavelengths. In the strong coupling limit, $E_8 \times E_8'$ emerges with certain unique characteristics, that once more make it a very promising framework to study phenomenology. One may, up front, question the meaning of the whole exercise, by noticing that we don't know what M-theory is, so what we are talking about, its compactification and the likes? The idea here is the following: we do know that the infrared limit of M-theory has to be $11-D$ *superqravity*, since there is no other consistent quantum field theory available! Furthermore, since $11-D$ supergravity (or $5-D$ supergravity) are fairly well-studied, we may get quite a lot of information about M-theory, by studying $11-D$ SUGRA, if it happens that ρ, the 11-th (or 5-th) compactified dimension is much bigger than the 11-th Planck scale ($\frac{1}{M_{11}}$). As we are going to see soon, phenomenological requirements put us in a $\rho \cdot M_{11} \gg \mathcal{O}(1)$ regime and thus enabling us to study *M-phenomenology*. The low-energy consequences of the unknown, at microscopic level ($\sim M_{11}^{-1}$), M-theory may be unveiled by studying suitably tailored $11 - D$ SUGRA (or $5 - D$ SUGRA). After all, Fermi's theory of β-decay, augmented with parity violation and Cabibbo currents, provided a pretty good picture of low energy weak interactions ($\gg M_W^{-1}$), we didn't have to wait till the '70s, when a microscopic ($\sim M_W^{-1}$) theory of electroweak interaction was available, in order to study low energy weak interactions!

As discussed in the previous section, the strongly coupled $10-D$ $E_8 \times E_8'$, is described by M-theory compactified on a segment (or semicircle) $\frac{S_1}{Z_2}$, of dimension ρ[**?**]. Of course, realistically one considers $R_4 \otimes X_{CY}$ compactifications of the strongly coupled $E_8 \times E_8'$, which corresponds to a $R_4 \otimes X_{CY} \otimes \frac{S_1}{Z_2}$ compactification of M-theory, with X_{CY} denoting an appropriate Calabi-Yau threefold (= 6 space dimensions). The 11-th dimension (ρ) has an orbifold structure $\frac{S_1}{Z_2}$ that is instrumental:

- at one end live the observable fields contained in E_8, at the other end live the hidden sector fields contained in E_8', and in the middle ("bulk") propagate the gravitational fields. The fields that live on the two boundaries, may be considered as comprising the "twisted" sector, while the gravitational fields in the bulk make up the "untwisted" sector.

- as such, the fields living at the boundaries, are *oblivious* to the existence of the 11-th dimension (ρ), whatever is its compactification scale! Such a property has far-reaching phenomenological consequences:

    1. Since the observable fields live in the $10-D$ ($4-D$ after compactification) boundaries, *chirality* is not an issue, in sharp contrast to conventional manifold compactifications of $11-D$ SUGRA where it is fatal.

    2. There are no Kaluza-Klein towers of particles, based on the boundary living fields. Thus, a standard severe problem of the "large compactification radius" type models[**?**], that of the breakdown of perturbation theory at the compactification radius ($\gg M_{\rm GUT}^{-1}$), is naturally evaded. Gauge unification, and for that matter, Yukawa coupling unification proceeds normally as in the SSM, *i.e.*, $M_{\rm GUT} = M_{\rm LEP}$ independent of the size of ρ!

Furthermore, one may naturally identify the 11-th dimensional Planck mass (M_{11}) with $M_{\rm LEP}$, which also provides the characteristic Calabi-Yau compactification scale. One then finds that (9) is replaced by[?, ?]

$$G_N = \frac{1}{4}\left(\frac{\alpha_{\rm GUT}}{M^2_{\rm LEP}}\right)\left(\frac{\rho_0^{-1}}{M_{\rm LEP}}\right) \tag{14}$$

which for ρ_0, the compactification radius of the 11-th dimension,

$$\rho_0^{-1} \sim (10^{12} - 10^{13}){\rm GeV} \tag{15}$$

gives the right value for G_N! Of course what we have realized here[?] is what we have foresaw in section 2, but with a "twist". Indeed, the existence of an extra 11-th dimension ρ, has allowed us to enlarge suitably the compactified volume $(V_6 \times \frac{S_1}{Z_2})$, such that $\alpha_{\rm GUT}$ remains much smaller than one, while at the same time the 11-th dimension is large enough (see (15)) so that an 11-D SUGRA approach is justifiable! At an intuitive level what is really happening is the following. While the three gauge coupling constants evolve dynamically with energy, and meet at $M_{\rm LEP}$, because they are *11-th dimension blind*, the gravitational constant after we hit ρ_0, it is replaced by a 5-dimensional one, so that for $E > \rho_0^{-1}$, instead of considering $G_N E^2$ as the dimensionless relevant constant, we ought to work with $G_N E^2(\frac{E}{\rho_0^{-1}})$ that increases much faster with energy and enables unification of all interactions at $M_{\rm LEP}$! The reader may have already noticed that all the above marvelous picture depends on the specific value of ρ_0^{-1} as given by (15). In order to claim that we have resolved the GUT scale-string scale disparity problem (see section 2), we need to determine *dynamically* the value of ρ_0^{-1}, and hopefully it will be given still by (15). This issue brings us naturally to our next point.

The scalar potential V is *independent* of ρ, thus it contains a *flat direction*, at the classical level, that may serve as the basis for implementing the *no-scale supergravity framework* (4)[?]. Indeed, several groups[?, ?, ?, ?, ?, ?] have reached the same conclusion, namely that no-scale supergravity is the long wavelength limit of M-theory in 4-dimensions. In particular, we provided the first explicit calculation[?] that supports the above remarks. Upon compactification of M-theory, in its 11-D SUGRA form, on a Calabi-Yau manifold with Hodge numbers $h_{(1,1)} = 1$ and $h_{(2,1)} = 0$ and boundary $\frac{S_1}{Z_2}$, a no-scale Kähler potential, superpotential and gauge kinetic function were obtained explicitly[?]. In four dimensions, this result is related to the previous weakly-coupled string no-scale supergravity result, obtained by Witten[?], through a field transformation, which means that they are equivalent in 4-dimensions. This robust behavior of the no-scale supergravity framework[?], all the way from the weakly coupled to strongly coupled heterotic string is rather remarkable, and highly suggestive that (4) may be implemented at the phenomenologically relevant strong coupling limit of $E_8 \times E_8'$ heterotic string. After all, no-scale supergravity traces its origins[?, ?, ?] in the non-compact continous global symmetries of extended supergravities, whose subgroups, suitably treated, provide *string duality*!

Supersymmetry breaking may be supplemented at the string level by employing[?, ?, ?, ?] the Scherk-Schwarz (SS) mechanism[?] on the 11-th dimension. As is well known, the Scherk-Schwarz SUSY breaking mechanism makes use of a symmetry of the theory transforming the gravitino nontrivially. In our case, since the 5-th dimension is compactified on $\frac{S_1}{Z_2}$, the symmetry under discussion must be a 2π rotation on the plane of the 5-th dimension and one of the internal Calabi-Yau coordinates. In a way, such a symmetry acts on the 5-D fields as the space-time parity $(-1)^{2s}$, *i.e.*, changes sign for the fermions and leave bosons invariant[?]. Thus

$$m_{3/2} = \frac{1}{2\rho}. \tag{16}$$

Notice that, it is only the fermions in the "bulk" ("untwisted" sector) that receive a uniform shift in their p_5 momentum ($\sim (n+1/2)\rho^{-1}$, while both fermions and bosons on the boundaries ("twisted" sector), as living on the semicircle edges have no p_5 momenta and thus no supersymmetry breaking contributions. Supersymmetry breaking will, then, be communicated from the "bulk" by gravitational interactions. It is highly amazing, how closely the above scenario resembles the *no-scale framework*[?]. Indeed, the SS mechanism provides a flat potential (no-cosmological constant at the classical level) along the 11-th (or 5-th) dimension ρ, with SUSY breaking at the classical level (see (16)), but with the magnitude of the SUSY breaking (alias gravitino mass) *undetermined* at the classical level. But this is the no-scale SUGRA framework! We then can employ quantum corrections to *dynamically* determine everything, á la (4), including the magnitude of the compactification scale of the 11-th (or 5-th) dimension ρ_0, as promised above. In fact, one may see that what we expect to get out is in the right ballpark, *i.e.* (15) gets satisfied. Indeed, one expects naively that the no-scale mechanism will dynamically fix, as usual, the amount of the observable SUSY breaking scale, relevant for the gauge hierarchy problem, at $\tilde{m} \sim \mathcal{O}(1\text{TeV})$, which is related to $m_{3/2}$ by $\frac{m_{3/2}^2}{M}$, with M some scale in the $(10^{16} - 10^{18}\text{GeV})$ range, and thus fixing dynamically $m_{3/2}$, and thus ρ^{-1} through (16) to be in the right domain, given by (15)! Work in progress[**?**] indicates that such an optimistic scenario is not far from reality. All the above results depend critically on the *stability* of the no-scale framework, which in turn depends strongly on the fact, that there are no quadratic divergences in the effective supergravity. Indeed, another, of utmost importance, result of the specific SS SUSY breaking mechanism considered here is the vanishing of $\mathrm{Str}M^2$ after supersymmetry breaking[**?**].

The communication of supersymmetry breaking to the observable sector, attached to one of the boundaries, from the "bulk", where it was originated, through gravitational interactions, is rather intrigued and maybe not very clear, at the time of writing. Horava[**?**] has argued that supersymmetry breaking ($m_{3/2} \neq 0$) is not felt immediately in the observable sector because of a topological obstruction (essentially the 11-th dimension of length ρ_0 that separates the two sectors). In fact he has argued[**?**] that there is a hidden 11-D supersymmetry, broken only by the *global topology* of the *orbifold dimension* (ρ_0), that explains the "conspiracy" that leads in the weakly coupled heterotic string theory to the *no-scale structure*, with SUSY breaking and vanishing cosmological constant, at the classical level. Supersymmetry breaking becomes apparent only after the renormalization scale is low enough to not reveal the presence of the 11-th dimension anymore. In practice, one is to allow for non-vanishing SUSY breaking parameters only for scales $Q < \rho_0^{-1}$[**?**]. A similar conclusion can be reached by looking in the dual, strongly coupled $E_8 \times E_8'$ theory, where as Witten has shown[**?**], one reaches a strongly coupled $E_8'(a_{8'} > 1)$, suitable for gaugino condensation, only when ρ gets some critical value, ρ_{crit}. In fact, $\rho_{\mathrm{crit}} \sim \frac{\alpha_{\mathrm{GUT}}}{16\pi^2} M_{\mathrm{LEP}}$, very close, at least numerically, to ρ_0^{-1}, as given by (15). Thus, once more $Q < \rho_{\mathrm{crit}}^{-1}$ in order to "feel" the SUSY breaking in the observable sector. This effect can leave a deep imprint on the low energy sparticle spectrum, which depends quantitatively on the amount of "running" of these parameters[**?**]. Until now I have tried to present general characteristics of the anticipated M-phenomenology, without resorting to a specific scenario or model. In order to get some experimentally testable predictions, we need now to be more specific in the selection of boundary conditions for the softly broken parameters at $\Lambda_{\mathrm{SUSY}} \sim \rho_0^{-1}$[**?**]. Opinions are divided on this issue, and it is fair to say that things are not yet crystal clear. We have chosen[**?**] to take $m_0 = 0$, at Λ_{SUSY}, as it avoids FCNC problems and make the effect of taking $\Lambda_{\mathrm{SUSY}} \sim \rho_0^{-1}$ most noticeable. While this choice arises in certain scenaria, cannot be claimed to be indispensible.

Anyways, let us see what type of SUSY phenomenology is coming out.

5 M-theory Inspired Supersymmetry phenomenology

We now proceed to the analysis of the low-energy sparticle spectrum under the assumptions of $\Lambda_{\rm susy} = \rho_0^{-1}$ and $m_0 = A_0 = 0$. Thus, the only free parameters are $m_{1/2}$ and $\tan\beta$. We find that the requirement of radiative electroweak symmetry breaking plus two basic phenomenological requirements, allow solutions in the $(m_{1/2}, \tan\beta)$ plane for only one sign of μ and only within a completely bounded region. For the case of $\Lambda_{\rm susy} = 10^{13}\,{\rm GeV}$, this region is shown in Fig. 1, where to facilitate comparison with experiment we also show the region in the $(m_{\chi^\pm}, \tan\beta)$ plane. The upper limit on $m_{1/2}$ (for a fixed value of $\tan\beta$) follows from the requirement that the lightest supersymmetric particle be neutral[**?**]. Above the upper boundary the right-handed selectron ($\tilde{e}_R$) becomes lighter than the lightest neutralino (χ). The bottom boundary is obtained by imposing the absolute lower limit on the sneutrino mass from LEP 1 searches ($m_{\tilde{\nu}} > 43\,{\rm GeV}$). The area to the right of the right-most tip of the region is excluded by these two conflicting constraints. The $\tan\beta$ dependence of these constraints may be understood from the D-term contribution to the $\tilde{e}_R$ and $\tilde{\nu}$ mass formulas

$$\widetilde{m}_i^2 = c_i\, m_{1/2}^2 - d_i\, \frac{\tan^2\beta - 1}{\tan^2\beta + 1}\, M_W^2 \ , \tag{17}$$

where the c_i are some RGE-dependent constants and $d_{\tilde{e}_R} = -\tan^2\theta_W < 0$ whereas $d_{\tilde{\nu}} = \frac{1}{2}(1 + \tan^2\theta_W) > 0$. The dotted line indicates the lower bound on $\tan\beta$ that is consistent with the top-quark mass ($m_t = 175\,{\rm GeV}$) and perturbative Yukawa couplings up to the unification scale. In practice, the LEP 172 lower bound on the chargino mass ($m_{\chi^\pm} > 83\,{\rm GeV}$)[**?**] gives the strongest constraint on the parameter space (dashed line on bottom panel in Fig. 1). Nonetheless, a portion of the parameter space remains allowed, and in fact it is within the reach of future LEP 2 energy upgrades, as we discuss below.

To give a more detailed picture of the low-energy spectrum, in Fig. 2 we display representative sparticle masses as a function of the chargino mass for $\Lambda_{\rm SUSY} = 10^{13}\,{\rm GeV}$ and $\tan\beta = 3$. This choice of $\tan\beta$ allows the widest range of sparticle masses (see Fig. 1). This figure shows that the spectrum "terminates" when m_χ approaches $m_{\tilde{e}_R}$ from below, as mentioned above in connection with the upper boundary in Fig. 1. It is interesting to note the significant splitting of the top-squark ($\tilde{t}_{1,2}$) masses around the average squark ($\tilde{q}$) mass.

In the LEP 172 allowed region in Figs. 1 and 2 we find $m_{\chi_1^\pm} < 95\,\mathrm{GeV}$ and $m_{\tilde{e}_R} < 70\,\mathrm{GeV}$. Both of these particles appear within the reach of LEP 2. More to the point, one might wonder whether the such light right-handed selectron masses might have already been excluded by LEP 2 searches, as they have been certainly kinematically accessible. We have calculated the cross section $\sigma(e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-)$ at LEP 161, for which explicit limits have been released by the OPAL Collaboration[?]. We find $\sigma < 0.2\,\mathrm{pb}$, which in $\mathcal{L} = 10.1\,\mathrm{pb}^{-1}$ would have yielded a maximum of two events. Indeed, the experimental sensitivity to this mode is at the 0.5 pb level[?]. Thus, past LEP 2 searches in the selectron channels do not restrict the allowed parameter space any further. Moreover, near the upper end of the parameter space the experimental detection efficiency should be greatly reduced because $m_{\tilde{e}_R}$ approaches m_χ. One should also consider the predictions for trilepton events at the Tevatron. We find $\sigma(p\bar{p} \to \chi^\pm\chi') \approx (1.0 - 0.7)\,\mathrm{pb}$ for $m_{\chi^\pm} = (83-95)\,\mathrm{GeV}$. The leptonic decays of the chargino and neutralino are maximally enhanced because of the lighter right-handed sleptons and sneutrinos, respectively. That is, $B(\chi^\pm \to \ell\nu_\ell\chi) \approx 2/3$ and $B(\chi' \to \ell^+\ell^-\chi) \approx 1/2$, where $\ell = e+\mu$. Combining these numbers we arrive at a single channel (*i.e.*, any single one of eee, $ee\mu$, $e\mu\mu$, or $\mu\mu\mu$) cross section of $(0.16-0.11)$ pb. This result is slightly below the sensitivity reached at the Tevatron in trilepton searches[?], and thus these also do not constrain the allowed parameter space any further.

6 Conclusions

Strongly coupled strings, as studied by the use of string duality, seem to provide one *single theory* and hold the potential to lead us to a unique string vacuum, hopefully involving $E_8 \times E_8'$. Stringy new M-theory may cause a *paradigm-shift* in the way we are understanding low-energy physics. A new way of understanding gauge-gravitational unification is suggested and already put to work, a new way of SUSY breaking is emerged, which, while contains seeds of the past, it resolves several severe problems and may lead eventually, into a clear-cut SUSY spectrum, among other things, that may provide a smoking gun for physics at the (11-th dimension) Planck scale. For example, a deeper understanding of proton stability ($\tau_p > 10^{33}$years) in SUSY theories may be needed, and such constraints may reduce considerably the class of acceptable M-compactifications[**?**]. On a different wavelength, black hole dynamics may be studied explicitly and quantum mechanics may suffer modifications, similar to the ones occurred to the Newtonian gravity after the innocent looking *equivalence principle* was implemented correctly by Einstein. Here, duality symmetries are realized *only* at the quantum level, and while, once more, innocent looking, may carry the seeds to a complete revision of quantum theory[**?**]. It is not, yet, judgment day, it is only the beginning excellent and fair…

Acknowledgments

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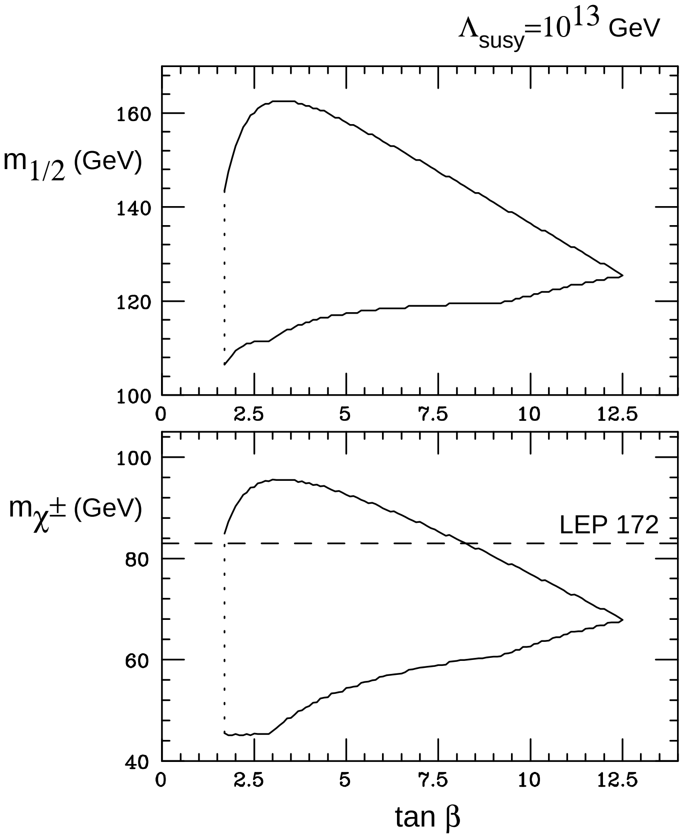

Figure 1: The allowed region in $(m_{1/2}, \tan\beta)$ [top panel] and correspondingly $(m_{\chi^\pm}, \tan\beta)$ [bottom panel] in no-scale supergravity $(m_0 = A_0 = 0)$ with $\Lambda_{\rm susy} = 10^{13}\,{\rm GeV}$. Above the top boundary $m_{\tilde{e}_R} \approx m_{\tilde{\tau}_1} < m_\chi$, whereas below the bottom boundary $m_{\tilde{\nu}} < 43\,{\rm GeV}$. The dashed line [bottom panel] represents the lower bound on the chargino mass from LEP 172 searches.

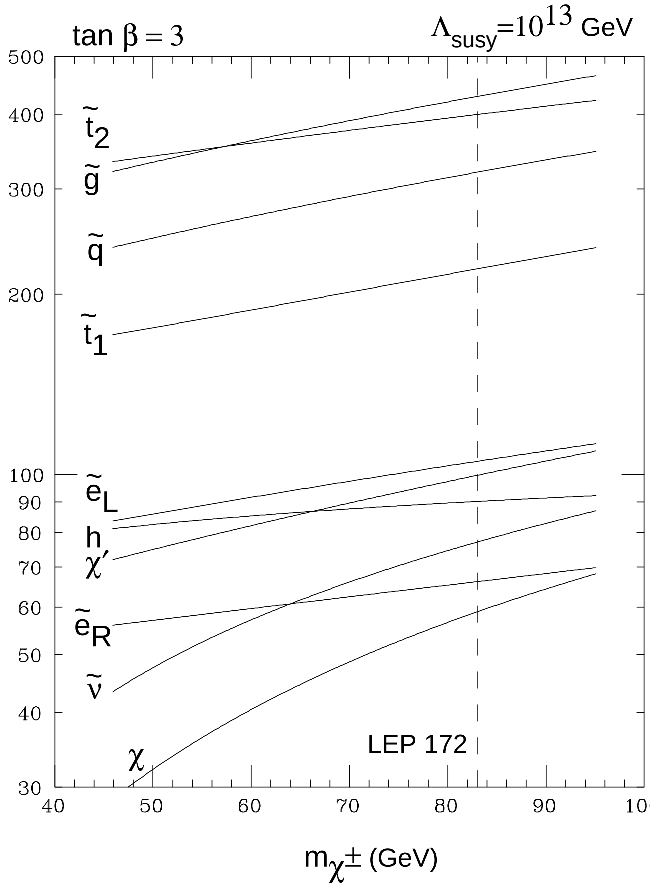

Figure 2: Calculated values of representative sparticle masses versus the chargino mass for $\Lambda_{\rm susy} = 10^{13}$ GeV and $\tan\beta = 3$. The spectrum terminates when m_χ approaches $m_{\tilde{e}_R}$ from below. The dashed line represents the lower bound on the chargino mass from LEP 172 searches.