Strongly coupled strings phenomenology

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Abstract

A brief review of the recent developements in the strong coupling regime of string theories and their consequences for phenomenology is given, in particular for string unification and supersymmetry breaking.

1 Weakly and strongly coupled heterotic strings

Old picture (before 1994)

The only known (up to now) consistent quantum theories including Einstein gravity are the superstrings. They are therefore promising candidates for a unifying picture of elementary particles and fundamental interactions.

It was known since a long time that there are five independent consistent (anomaly free) superstring theories in ten dimensions, namely

- The heterotic closed string theories, with gauge groups $SO(32)$ and $E_8 \times E_8$ and $N = 1$ spacetime supersymmetry, corresponding after a toroidal compactification to $N = 4$ supersymmetry in four dimensions.

- The Type IIA, non-chiral and Type IIB, chiral closed string theories with $N = 2$ spacetime supersymmetry, corresponding after a toroidal compactification to $N = 8$ supersymmetry in four dimensions.

- The Type I open string theory with gauge group $SO(32)$ with $N = 1$ supersymmetry. In this case the gauge quantum numbers sit at the ends of the string. This theory can be defined as a projection (orientifold) of the Type IIB string.

The massless modes of the above string theories and their interactions are described by effective ten dimensional supergravity theories, namely

- The low energy limit of the the two heterotic theories and the Type I open string is described by the ten dimensional $N = 1$ supergravity coupled to super Yang-Mills system based on the gauge groups $SO(32)$ and $E_8 \times E_8$, respectively.

- The low energy limit of the Type II strings is described by the $N = 2$ Type IIA, nonchiral, and Type IIB, chiral, supergravity.

The common features of all the effective ten dimensional string theories is the presence of the $N = 1$ multiplet containing in the bosonic sector the graviton $g_{\mu\nu}$, the dilaton ϕ and the antisymmetric tensor $B_{\mu\nu}$. The string coupling constant is a dynamical variable $\lambda = exp\phi$ and the only free parameter of the theories is the string slope α'.

The four dimensional theories are defined after a compactification process similar to the old Kaluza-Klein scenario, with a decomposition of the ten dimensional spacetime $M_{10} = M_4 \times K_6$, where M_4 is our four dimensional Minkowski spacetime and K_6 is a compact manifold whose volume V defines the compactification scale M_c

$$V = M_c^{-6} \equiv M_{GUT}^{-6} , \tag{1}$$

which sets the scale of the Kaluza-Klein mass excitations in the compact space. The compactification scale was also identified above with the grand unified scale M_{GUT} in the string unification picture, because the field theory description breaks down above M_c.

The four dimensional fields in a toroidal compactification are the zero modes of the ten dimensional fields, which depend on the topology of the compact space K_6. If we denote by A, B ten dimensional indices, μ, ν four dimensional ones and I, J six dimensional compact indices, then we have, for example, the following decompositions:

$$\begin{aligned} g_{AB} &: \; g_{\mu\nu} \;\; g_{IJ} \;\; g_{\mu I} \\ B_{AC} &: \; B_{\mu\nu} \;\; B_{IJ} \;\; B_{\mu I} \;\; , \end{aligned}$$

where in four dimensions $g_{\mu\nu}$ is the graviton, $g_{\mu I}, B_{\mu I}$ are gauge fields, g_{IJ} are scalars describing the shape of the compact space and $B_{\mu\nu}, B_{IJ}$ are psedoscalar, axion-type fields.

In the early days of the first string revolution and until 1995, only the compactified four dimensional heterotic strings (and especially $E_8 \times E_8$) were considered to be relevant for particle phenomenology, due to the progress made in the compactification from ten to four dimensions, gauge groups able to contain the standard model one $SU(3) \times SU(2) \times U(1)$ and in addition hidden gauge factors, interacting only gravitationally with our observable world, useful for supersymmetry breaking and cosmology. The Type II strings were considered to be unable to reproduce the standard model gauge group and the properties of the compactified Type I open string were studied by very few people [3].

New picture (after 1994)

The above picture evolved in a dramatic way over the last few years (see, for more details, A. Bilal and E. Poppitz talks [4]). First of all, it was a puzzle that the heterotic $SO(32)$ and the Type I ten dimensional strings had the same low-energy theory. Indeed, the low energy actions coincide if the following identifications are made

$$\lambda_I = \frac{1}{\lambda_H} \quad , \quad M_I = \frac{M_H}{\sqrt{\lambda_H}} \; , \tag{2}$$

where M_I, M_H are the heterotic and the Type I string scales and λ_I, λ_H are the corresponding string couplings. A natural conjecture was made, that the full-fledge string theories are dual (in the weak-coupling strong-coupling sense) to each other [2]. New arguments in favor of this duality came soon:

- The heterotic $SO(32)$ string can be obtained as a soliton solution of the Type I string

- There is a precise mapping of states and their masses betwwen the two theories. If we compactify, for example, both theories down to nine dimensions on a radius $R_I(R_H)$ in Type I (heterotic) units, we can relate states with the masses

$$M_I^2 = l^2 R_I^2 + \frac{m^2 R_I^2}{\lambda_I^2} + \frac{n^2}{R_I^2} \leftrightarrow M_H^2 = m^2 R_H^2 + \frac{l^2 R_H^2}{\lambda_H^2} + \frac{n^2}{R_H^2} , \tag{3}$$

where $n, l(m, n)$ are Kaluza-Klein and winding numbers on Type I (heterotic) side. It is interesting to notice in this formula how heterotic perturbative winding states m become non perturbative on the Type I side. An important role in checking dualities in various dimensions is played by extended objects called Dirichlet (D) branes, which correspond on the heterotic side to non perturbative states [4].

A second, far more amazing, conclusion was reached in studying the strong coupling limit of the ten dimensional Type IIA string. It was already known that a simple truncation of the eleven dimensional supergravity on a circle of radius R_{11} gives the Type IIA supergravity in ten dimensions and the string coupling λ is related to the radius by $R_{11} = \lambda^{2/3}$. On the other hand, if we consider Kaluza-Klein masses of the eleven dimensional supergravity and map them in Type IIA supergravity units, we find

$$m_n = \frac{n}{R_{11}} \leftrightarrow m_n = \frac{n}{\lambda} . \tag{4}$$

Therefore, on Type IIA side, these can be interpreted as non perturbative, and (with a bit more effort) BPS states. The natural conclusion is that in the strong coupling limit of the Type IIA string $\lambda \to \infty$, a new dimension appears and the low energy theory becomes the uncompactified eleven dimensional supergravity [1], [2]! As there was no known quantum theory whose low energy limit describes the eleventh dimensional supergravity, a new name was invented for this, the M-theory (M could here be membrane, magic, mistery, matrix).

Very soon after this, Horava and Witten gave convincing arguments that the same eleven dimensional supergravity compactified on a line segment S^1/Z_2 (or a circle with opposite points identified) should describe the strong coupling limit of the $E_8 \times E_8$ heterotic string, with the two gauge factors sitting at the ends at the interval, very much like the gauge quantum numbers in the open strings are sitting at the string ends [5]. The basic argument is that only half (a Majorana-Weyl) of the original (Majorana) eleven dimensional gravitino live on the boundary. This would produce gravitational anomalies unless new, 248 Majorana-Weyl fermions appear at each end. This is exactly the dimension of the gauge group E_8.

The compactification pattern of this theory down to four dimensions is different according to the value of the eleventh radius compared to the other radii, denoted collectively R in the following, assuming for simplicity an isotropic compact space

$$\begin{aligned} R_{11} < R \ &: \ 11d \to 10d \to 4d \\ R_{11} > R \ &: \ 11d \to 5d \to 4d \ . \end{aligned} \tag{5}$$

In the strong coupling limit $R_{11} > R$ there is therefore an energy range where the spacetime effectively is five dimensional [7], [8], [9].

Finally, let's us notice that in ten dimensions the Type IIB string is self-dual and by compactifying one dimensions, the $SO(32)$ heterotic compactified on a radius R is dual to $E_8 \times E_8$ heterotic compactified on a radius $1/R$. By combining all the above information we find a whole web of dualities, which becomes richer and richer when compactifying new space dimensions.

2 Gauge coupling unification in heterotic strings

Four dimensional string couplings and scales are predicted in terms of the string mass scale and various dynamical fields, dilaton, volume of compact space, etc. In contrast to usual GUT models, which do not incorporate gravity and so make no prediction for Newton's constant, these perturbative string models do make a definite prediction for the gravitational coupling strength, a prediction that comes out too large. Since neither the length scale of string theory $\sqrt{\alpha'}$ nor the volume V of the compact manifold, nor the expectation value of the dilaton field ϕ is directly known from experiment, one might naively think that by adjusting α', V, and $\langle\phi\rangle$ one can fit to any desired values of Newton's constant, the GUT scale M_{GUT}, and the GUT coupling constant α_{GUT}. However, things do not work out that way for the weakly coupled heterotic string. In ten dimensions, the low energy supergravity effective action looks like

$$S_{eff} = -\int d^{10}x\sqrt{g}e^{-2\phi}\left(\frac{4}{(\alpha')^4}R + \frac{1}{(\alpha')^3}\mathrm{tr}F^2 + \ldots\right) . \tag{6}$$

After compactification on a Calabi-Yau manifold of volume $(2\pi)^6 V$ (in the string metric), one gets a four-dimensional effective action that looks like

$$S_{eff} = -\int d^4x\sqrt{g}e^{-2\phi}V\left(\frac{4}{(\alpha')^4}R + \frac{1}{(\alpha')^3}\mathrm{tr}F^2 + \ldots\right). \quad (7)$$

Notice that the same function $Ve^{-2\phi}$ multiplies both R and $\mathrm{tr}F^2$. From (7) we get, by defining $M_H = \alpha'^{-1/2}$

$$M_H = \left(\frac{\alpha_{GUT}}{8}\right)^{1/2} M_P \ , \ \lambda_H = 2(\alpha_{GUT}V)^{1/2}M_H^3 \ , \quad (8)$$

where $M_P = G_N^{-1/2}$ is the Planck mass. Then we find $M_H \sim 10^{18}GeV$ and therefore a serious discrepancy between the GUT scale M_{GUT} and the string scale M_H. The problem might be improved by considering an anisotropic Calabi-Yau space and a lot of effort in this direction was done over the years.

In the light of the new picture described in the preceding paragraph, let's see what changes in strong coupling regime and to see whether the problem has a natural solution in a region of *large* string coupling constant. The behavior is completely different depending on whether one considers the $SO(32)$ or $E_8 \times E_8$ heterotic string.

Let's first consider the $SO(32)$ heterotic string. We repeat the above discussion, using the Type I dilaton ϕ_I, metric g_I, and scalar curvature R_I. The analog of (6) is

$$L_{eff} = -\int d^{10}x\sqrt{g_I}\left(e^{-2\phi_I}\frac{4}{(\alpha')^4}R_I + e^{-\phi_I}\frac{1}{(\alpha')^3}\mathrm{tr}F^2 + \ldots\right) . \quad (9)$$

Contrary to the heterotic string case, the gravitational and gauge actions multiply different functions of ϕ_I, namely $e^{-2\phi_I}$ and $e^{-\phi_I}$, respectively, since one is generated by a world-sheet path integral on a sphere and one on a disc. The analog of (7) is then

$$L_{eff} = -\int d^4x\sqrt{g}_I V_I\left(\frac{4e^{-2\phi_I}}{(\alpha')^4}R + \frac{e^{-\phi_I}}{(\alpha')^3}\mathrm{tr}F^2 + \ldots\right), \quad (10)$$

where V_I is the Calabi-Yau volume measured in the Type I metric and the couplings become

$$M_I = \left(\frac{2}{\alpha_{GUT}^2 M_P^2}\right)^{1/4} V^{-1/4} \ , \ \lambda_I = 4\alpha_{GUT}M_I^6 V \ . \quad (11)$$

Hence

$$M_I = (\frac{\alpha_{GUT}\lambda_I}{8})^{1/2} M_P \ , \tag{12}$$

showing that after taking α_{GUT} from experiment one can make M_I as small as one wishes simply by taking e^{ϕ_I} to be small, that is, by taking the Type I superstring to be weakly coupled.

We will now argue that the $E_8 \times E_8$ heterotic string has an analogous strong coupling behavior: one keeps the standard GUT relations among the gauge couplings, but loses the prediction for Newton's constant, which can be considerably smaller than the weak coupling bound.

The ten-dimensional $E_8 \times E_8$ heterotic string has for its strong coupling limit M-theory on $R^{10} \times S^1/Z_2$. The gravitational field propagates in bulk over $R^{10} \times S^1/Z_2$, while the $E_8 \times E_8$ gauge fields propagate only at the Z_2 fixed points. We write M^{11} for $R^{10} \times S^1$ and M_i^{10}, $i = 1, 2$ for the two components of the fixed point set. The gauge and gravitational kinetic energies take the form

$$L = -\frac{1}{2\kappa^2} \int_{M^{11}} d^{11}x\sqrt{g}R - \sum_i \frac{1}{8\pi(4\pi\kappa^2)^{2/3}} \int_{M_i^{10}} d^{10}x\sqrt{g}\mathrm{tr}F_i^2 \ , \tag{13}$$

where κ is here the eleven-dimensional gravitational coupling. F_i, for $i = 1, 2$, is the field strength of the i^{th} E_8, which propagates on the i^{th} component of the fixed point set, that is on M_i^{10}.

Now compactify to four dimensions on a Calabi-Yau manifold whose volume (in the eleven-dimensional metric from now on) is V. Let the $\S^1$ have radius ρ or circumference $2\pi\rho$ and define the eleven dimensional scale $M_{11} = 2\pi(4\pi\kappa^2)^{-1/9}$. Upon reducing (13) to four dimensions, one can express M_{11} and ρ in terms of four-dimensional parameters

$$M_{11} = (2\alpha_{GUT}V)^{-1/6}, \rho^{-1} = (\frac{2}{\alpha_{GUT}})^{3/2} M_P^{-2} V^{-1/2}. \tag{14}$$

From the first relation we find that $M_{11} \sim M_{GUT}$. The second one, for $V = M_{GUT}^{-6}$ gives $\rho \sim 10^{13} GeV$. That is again a favorable result, since for ρ to be large compared to the eleven-dimensional Planck scale is a necessary condition for validity of the eleven-dimensional description.

The presence of the new dimension in the Horava-Witten theory can be used in order to breaks supersymmetry through the compactification from five dimensions to four dimensions [9], [8], by using the Scherk-Schwarz field theoretical mechanism [10]. In this scenario, at tree level supersymmetry is broken only in the gravitational sector, with soft masses of the order the gravitino mass

$$m_{3/2} \sim \frac{1}{\rho} \tag{15}$$

The matter fields living on the boundary feel the breaking only through gravitational suppressed interactions, acquiring soft masses $\tilde{m}$ typically of order

$$\tilde{m} \sim \frac{\rho^{-2}}{M_P} \tag{16}$$

The scenario has close analogies to the one considering gaugino condensation in this context [11]. This, intermediate scale scenario breaking predicts intermediate scale gravitationally interacting particles (gravitino, moduli fields), which could play an important role in cosmology.

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