STATUS REPORT ON FOUR-DIMENSIONAL STRINGS

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A B S T R A C T

The present status of four-dimensional strings is reviewed, in both the bosonic and fermionic constructions. We discuss their general properties, as well as the main problems in model building.

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Status report on four-dimensional strings

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Two of the most attractive properties of string theories are, on the one hand, the quantization of general relativity which is always present, and on the other hand, the automatic unification of all elementary interactions including gauge, matter and Higgs sectors [1]. String theories replace the notion of the elementary point particles with one-dimensional extended loops and are believed to be free of ultra-violet divergences [1]. Their motion in space-time describes a two-dimensional surface (world-sheet) and is parametrized with some co-ordinates $x^\mu(\sigma, \tau)$ depending on the two-dimensional variables σ and τ .

The first "string miracle" is that all space-time gauge symmetries and the decoupling of negative norm states are a simple consequence of the natural requirement that physics does not depend on the general possible reparametrizations of the world-sheet [1]. Space-time spinors are produced among the string excitations if two-dimensional fermions $\psi^\pm(\sigma, \tau)$ carrying Lorentz vector index are added on the string [2]. In this case one needs a new local symmetry, namely supersymmetry, to get rid of the extra negative norm states associated to $\psi^\pm(\sigma, \tau)$. It is a second "string miracle" that correct spin-statistics emerges as a simple consequence of super-reparametrization invariance of the world-sheet.

A remarkable property of string theories is that the number of space-time dimensions is not an external parameter but rather a parameter of the particular vacuum. Moreover, their notion becomes ill-defined when their size becomes of the order of the Planck length. As an example, string propagation in a circle of radius $R = \sqrt{2}$ (in appropriate units) is completely equivalent to its propagation on a three-dimensional sphere of radius $R = 1$ in the presence of some antisymmetric tensor background, etc. Assuming D-flat co-ordinates, consistent, tachyon free, superstring theories can be constructed in any number of dimensions $D < 10$. The underlying world-sheet dynamics is governed by the two-dimensional Lagrangian

$$L^{(2)} = (\partial X_\mu)^2 + \psi^\mu \partial \psi_\mu + L_I \quad (1)$$

where L_I corresponds to some unitary (super) conformal field theory describing the internal quantum numbers.

The general perturbative requirements for constructing a consistent string model are the following:

- (a) local reparametrization invariance, which consists of two-dimensional diffeomorphisms and local Weyl rescalings and leads to two independent anomaly cancellation conditions for the left and right movers, depending on $(\sigma+\tau)$ and $(\sigma-\tau)$ respectively; their sum implies the correlation of the conformal anomaly [3], while their difference implies the cancellation of the two-dimensional gravitational anomaly [4]; these relations fix the central charge c_I of the internal system L_I in (1) to be $c_I = 26-D$ ($c_I = 15 - 3/2-D$) for a purely bosonic (supersymmetric) sector, which can be satisfied for any $D < 10$ and in particular at $D = 4$;
- (b) local world-sheet supersymmetry which is present only in the left-movers for the heterotic string [5], or both in left and right movers for the type II;
- (c) multiloop modular invariance corresponding to two-dimensional diffeomorphisms which are not continuously connected with the identity and applied to topologically non-trivial surfaces; they consist of cutting the surface along a non-contractible loop, performing a 2π -rotation and glue it again. It turns out that this gives severe restrictions on the possible boundary conditions of the internal degrees of freedom [6];
- (d) finally, perturbative unitarity requires the factorization of a higher genus surface to surfaces of lower genus when these are pulled infinitely apart [6].

There are several constructions of four-dimensional string theories depending on the form of L_I . Historically, the first models that appeared are of the simplest kind, namely "Gaussian": the internal degrees of freedom are free bosons [7,8] or free fermions [9-12] and the different models correspond to the various possible choices of their boundary conditions when parallelly transported around the string. Besides these models, there are recently other constructions based on a different type of (super) conformal field theories: group manifolds with Wess-Zumino-Witten terms [13], collections of minimal models from the discrete series of central charges [14], Liouville theory and its generalizations [15], and so on. Recently there also appeared some non-trivial cosmological string solutions [16] in which the four space-time co-ordinates are not flat but describe some non-trivial Robertson-Walker universes. We will not discuss this issue in the present talk.

The study of all possible four-dimensional string vacua is thus reduced to the problem of classification of all unitary two-dimensional (super) conformal field theories with central charges $c_L = 9$ and $c_R = 22$ or 9 for the heterotic or type II string. For the moment, such a complete classification is known only for the minimal models with $c < 1$ and the symmetric $c = 1$ system, as well as their

supersymmetric extensions ($c \leq 3/2$) [17]. The generalization of these classifications is very important, since it provides an alternative way to the string field theory approach with its known difficulties [18]. An interesting question is whether for integer central charge all conformal theories can be described in terms of "Gaussian" models. If the answer is positive, as suggested by a few preliminary indications, there will be a big simplification towards the understanding of the string vacuum.

In what follows we will restrict ourselves to four-dimensional Gaussian models described by adding extra free bosons or free fermions on the world-sheet. Although the fermionic and bosonic languages are essentially equivalent, they have complementary merits. The advantage of using free fermions is that the realizations of the two-dimensional supersymmetry are fully classified [9] and that all consistency requirements can be formulated directly on the world-sheet as described above [11,12]. Moreover, they give rise to some algebraic constraints which can be solved in a systematic way. The advantage of using free bosons is that one can easily be away from enhanced-symmetric points as well as count the number of continuous parameters whose existence is manifest in this approach [7].

The internal field content is determined by the requirement (a) of local reparametrization invariance. In the heterotic case, it is satisfied if one adds in the left movers an extra of 18 free real fermions χ^i or nine free bosons ϕ_L^I and in the right movers an extra of 44 free real fermions η^a or 22 free bosons ϕ_R^A which give a contribution 9 and 22 in the internal central charge, respectively.

Once the two-dimensional field content is fixed, the arbitrariness left concerns the boundary conditions. In the fermionic construction these are given by two orthogonal matrices A_L, A_R such that $\chi^i \rightarrow A_L^{ij} \chi^j$ and $\eta^a \rightarrow A_R^{ab} \eta^b$ when parallelly transported around the string. In the bosonic formulation the freedom is to choose the bosonic zero-modes which are the left and right momenta p_L, p_R corresponding to ϕ_L^I and ϕ_R^A . In addition, the fermionic co-ordinates ψ^μ may be antiperiodic or periodic giving rise to space-time bosons (Neveu-Schwarz sector) or spinors (Ramond sector) [2].

The next requirement is world-sheet supersymmetry which, in the fermionic construction, has to be non-linearly realized [19,9] among the free fermions χ^i . The corresponding supercurrent having the correct conformal dimension 3/2, is

$$T_F = \phi_\mu \partial X^\mu + 1/3 f_{ijk} \chi^i \chi^j \chi^k \quad (2a)$$

Its operator product expansion with itself produces the energy momentum tensor only if f_{ijk} are the structure constants of a semi-simple Lie group G with dimension 3(10-D). In four dimensions there are three choices: $SU(2)^6$, $SU(3) \times SO(5)$ and $SU(5) \times SU(2)$ [9,20]. In the bosonic formulation the general form of the supercurrent is

$$T_F = \psi_\mu \partial X^\mu + \sum_\alpha c_\alpha^\dagger e^{i\vec{\alpha} \cdot \vec{\phi}_L} + \sum_\beta \tilde{c}_\beta^\dagger \partial \vec{\phi}_L e^{i\vec{\beta} \cdot \vec{\phi}_L} \quad (2b)$$

and has conformal dimension $3/2$ if $\vec{\alpha}^2 = 3$, $\vec{\beta}^2 = 1$ and $\vec{\beta} \cdot \vec{c}_\beta^\dagger = 0$. Imposing the supersymmetry algebra, its general form is not yet fully classified [21,22].

World-sheet supersymmetry imposes further constraints to the boundary conditions, since T_F has to have well-defined periodicity properties given by those of ψ^μ [see first term in Eqs. (2)]. This implies that the boundary condition matrix A_L ($-A_L$) in a Ramond (Neveu-Schwarz) sector has to be an automorphism of the group G , since it has to leave invariant its structure constants [12]. In the bosonic formulation, it implies that the vectors α and β belong to the lattice of the allowed momenta [8,21,22].

Last requirements are modular invariance and factorization. Since modular transformations mix boundary conditions, one must sum over them to obtain an invariant expression. It turns out that in the fermionic construction the set $\mathcal{E}$ of the various boundary condition matrices forms a group [11,12] which can be generated by some basis $\{B_1, \dots, B_N\}$. This group is Abelian when all matrices are commuting and can be diagonalized simultaneously producing vectors of phases: $A = \text{diag}(-e^{i\pi\alpha_1} 1)$ with $\alpha_1 \in (-1,1)$. It can be shown [11,12] that to each element α of $\mathcal{E}$ there corresponds a sector $\mathcal{H}_\alpha$ of the string Hilbert space and to each element b_1 of the basis a generalized, GSO type, two-dimensional fermion number projection determined by some phase-coefficient $c(\alpha_{b_1})$. The string states are then constructed by acting on the vacuum of each sector with free fermionic or bosonic oscillators satisfying these projections. The multiloop modular invariance constraints lead to some algebraic equations for the basis elements and the coefficients c 's which are solved and provide a well-defined algorithm for constructing consistent theories.

In the bosonic formulation, one-loop modular invariance implies that the set of momenta p forms a Lorentzian lattice Γ (there is a relative minus in the metric between left and right movers) which, in the simplest case, has to be even ($p^2 = p_L^2 - p_R^2$ even) and self-dual ($\Gamma = \Gamma^*$) [7]. In this case, the left-moving fermionic superpartners of the six internal co-ordinates are not bosonized and two-dimensional chirality cannot be obtained. This difficulty is evaded in orbifold constructions [23] which correspond to string propagation in flat spaces with canonical singularities and consist in moding out a lattice theory by some (discrete) automorphism and adding a twisted sector where some bosonic co-ordinates instead of being periodic, pick up phases dictated by modular invariance. An alternative construction to obtain chiral theories is obtained by a generalization to covariant lattices [8] where everything is bosonized, including the super-reparametrization ghosts.

It is crucial that in two dimensions there is an equivalence among fermions and bosons, based on equating the two currents $\partial\phi = f^*f$, where f is a complex (Weyl) fermion and ϕ its corresponding real boson. This leads to a simple relation between the momentum p and the boundary condition $\alpha: p = \alpha/2 + F$, where F is the fermion number which counts each f oscillator once and each f^* minus once [10,24]. As a consequence, there are many equivalent bosonic and fermionic descriptions of the same model depending on the particular basis one chooses, which determines also the form of the supercurrent T_F [see Eqs. (2)]. It has been shown that the fermionic constructions with complex two-dimensional fermions and commuting boundary conditions are equivalent to the bosonic covariant lattices with restricted forms of T_F [10,24]. Also, the rank 22 orbifolds are equivalent to the corresponding covariant lattices with, in general, complicated two-dimensional supercurrents [22]. It is suggested that allowing non-commuting boundary conditions there is a complete equivalence between fermionic constructions, orbifolds and covariant lattices [25,26]. Note finally that some chiral models are equivalent to a non-singular string propagation on twisted $SU(2)$ group manifolds [27].

In contrast to the "plethora" of four-dimensional models, there are some general common properties which characterize all of them: (a) the graviton, dilaton and two-index antisymmetric tensor, being a pseudoscalar in four dimensions, are inevitably present in any consistent theory; (b) the gauge group is practically arbitrary with rank $r < 22$ for the heterotic and $r < 6$ for the type II; the massless matter representations can be only vectors and spinors of orthogonal groups or any antisymmetric of $SU(N)$ groups; moreover, a very important restriction for chiral models is the absence of massless scalars in the adjoint or higher self-conjugate representations, which seems to be a general property [12,28]; this puts severe constraints on GUT model building, as it forbids "conventional" simple groups like $SU(5)$, $SO(10)$, etc.; (c) the existence of a massless spin-3/2 gravitino, which is required by space-time supersymmetry, implies the absence of tachyons in the spectrum and the vanishing of the vacuum energy [11,29]; (d) the low energy Lagrangian of most $N = 2$ and $N = 1$ supersymmetric models is automatically derived [30], since these are related to $N = 4$ through particular projections (e.g., Z_2 's) [11]; (e) the type II strings, although very economical, cannot lead to the standard model with the correct chiral family content [31].

Although from a first point of view there is a lot of arbitrariness in the string model building [32], it seems in practice very hard to find an example that can lead to the known strong and electroweak low energy theory with the correct spectrum and properties. There are many difficulties concerning the separation of the "observable" from a hidden sector out of a group with in principle a huge rank, the right Higgs content, the breaking of extra $U(1)$ factors that usually

appear, the right couplings with no fast proton decay and flavour changing neutral currents, the generation of the observed fermion mass hierarchies, and so on. Many of these properties, which seem completely ad hoc at the level of $SU(3) \times SU(2) \times U(1)$ appear naturally in a grand unified theory which, however, has the problem of the absence of adjoint Higgses mentioned above. The first "realistic" three-family model has been constructed using the fermionic formulation of four-dimensional strings and is based on a flipped $SU(5) \times U(1)$ GUT group [33]. The low energy gauge group is given by the (supersymmetric) standard model and an interesting hierarchical fermion mass matrix is extracted. Recently, some progress is also made for constructing directly the standard model in the orbifold approach [34].

One of the main problems in string theory is the existence of an infinity of four-dimensional consistent models. An important question is whether some of them are corrected and if yes to determine the real number of distinct theories modulo continuous or discrete deformations. Although this issue still remains open, one knows that there are many continuous parameters which characterize the string vacuum at least at the lowest order in string perturbation theory [7,24,35]. They correspond to the freedom of introducing continuous phases in the fermionic construction [24] or of Lorentz boosting the charge lattice of string states in the bosonic formulation [7]. As an example, for the lattice $F(n_L, n_R)$ any "Lorentz" $SO(n_L, n_R)$ transformation Λ preserves inner products and thus leaves the modular invariance conditions unchanged. Therefore, the transformed lattice Γ_Λ defines a new consistent string model, in which the masses of all states are shifted by $\delta M^2 = \frac{1}{2}[(\Lambda_P^T)^2 - p_{L(R)}^2]$. Clearly, these mass shifts do not vanish only for Lorentz boosts $\Lambda \in SO(n_L, n_R)/SO(n_L) \times SO(n_R)$ which depend on $n_L \times n_R$ continuous parameters.

These continuous deformations at the ten-dimensional level are related to the freedom of changing radii and background gauge and antisymmetric fields [36]. From the four-dimensional point of view, however, they correspond to vacuum expectation values of massless scalar fields which realize an ordinary Higgs phenomenon [24]. The existence of such flat directions in the scalar potential is very important, since gauge symmetries are spontaneously broken at scales which are undetermined classically and they could thus be hierarchically smaller than the Planck mass. A general rule which selects out all possible flat directions is proposed and the mass formula for all the string states is derived [24,26,37]. It is quite remarkable that the mass shifts are given in terms of the charges of the states with respect to some $U(1)$ currents which in turn correspond to some massless or massive gauge bosons. In fact a four-dimensional massless scalar field ϕ corresponds to a flat direction iff its vertex operator at zero momentum is written in the form $\phi \sim \int J_L J_R$, where J_L, J_R are two (in general complex) $U(1)$ currents. When ϕ gets a non-zero v.e.v., the mass shifts are non-zero only for

those string states which correspond to boundary conditions that leave the currents periodic; in the case of real currents, they are given by

$$\delta M^2 = \frac{1}{2}(Q_L^2 + Q_R^2) \operatorname{sh}^2 \theta + Q_L Q_R \operatorname{sh} \theta \operatorname{ch} \theta \quad (3)$$

where Q_L, Q_R are the charges of the states with respect to the two $U(1)$ currents J_L, J_R and $\langle \phi \rangle \sim \operatorname{sh} \theta$. In addition to the existence of continuous parameters, there are examples of discrete deformations which may or may not correspond to v.e.v.'s of scalar fields [35]; no classification of those is known up to now.

Another important problem concerns the supersymmetry breaking scale which we expect to be of the order of the weak scale in order to protect the gauge hierarchy.

In addition of its own interest and its connection to the gauge hierarchy and the cosmological constant, the problem of supersymmetry breaking is very serious for many other reasons as well: it is needed in the string model building to be able to make definite predictions for masses and couplings. It may also play an important rôle to destroy many of the flat directions, which most likely remain flat to all orders as long as supersymmetry remains unbroken, and determine the various mass scales. One might finally hope to get a mass for the dilaton, which, if it remains massless, presents a serious problem in string phenomenology [38].

It turns out that the breaking of space-time supersymmetry in string theories, at a scale infinitesimal in Planck units, is a very hard problem in perturbation theory. Unitarity arguments of $N = 2$ superconformal theories show that supersymmetry cannot be broken continuously by a v.e.v. of a scalar field of an analytic point and in a flat direction of its potential [39]. This does not, however, rule out a number of interesting possibilities; it could be for instance that the scale of supersymmetry breaking m_s is not tuned by a Higgs field, as is the case in supergravity field theories. Moreover there could exist vacua with hierarchically suppressed m_s which cannot be continuously connected to supersymmetric ones; or m_s could be proportional to some internal radii with a constant of proportionality of the order, say, of 10^{-6} ; or finally, broken supersymmetry could characterize only the nearly massless, but not all the massive string modes.

It is shown in the context of "Gaussian" models, although it is believed to be a general statement, that in string perturbation theory the supersymmetry breaking scale can be small only if it is linked to the size of some internal dimension which is decompactified to a scale, roughly of the same order of magnitude [40]. More precisely, without assuming some particular mechanism of supersymmetry breaking, it can be proved that the existence of a slightly massive gravitino or gaugino implies the existence of an entire tower of such states below the Planck mass, which is a signal of decompactification of some internal dimensions, so that the corresponding momenta become quasi-continuous. Similar conclusions are found

in the particular case of string solutions with supersymmetry breaking by a Scherk-Schwarz mechanism [41].

This phenomenon seems to be a characteristic stringy property and may suggest the existence of some extra dimension at, say, 1-100 TeV. Although there is no direct experimental contradiction, such a scenario has the serious difficulty that [42], by naive dimensional analysis, all couplings become huge very early above the extra dimension scale, invalidating the semi-classical string description. If one excludes the idea of having an extra dimension at relatively low energies, non-perturbative effects are left as the final alternative to realize supersymmetry breaking.

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