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String Phenomenology

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Outline

- What is string phenomenology ?
- Compactification to four dimensions : moduli fields, orbifolds
- String models with intersecting branes

- some phenomenological features

- Supersymmetry breaking and moduli stabilization

- Scherk-Schwarz, non-BPS, anomalous $U(1)$

- Cartoon of moduli stabilization

- Challenges for String Phenomenology

Related talks :

Strings and D-brane: C. Bachas

Low-energy string effects : I. Antoniadis and D. Lust

Heterotic models : A. Faraggi, J. Rizos

Orientifolds: P. Anastasopoulos, M. Berg, C. Condeescu, C. Kokorelis

F-theory models : R. Blumenhagen, M. Wijnholt and R. Tatar

What is String Phenomenology ?

- Embed Standard Model and GUT's into a consistent string construction : gauge group, spectrum, couplings.

- Stabilize all moduli fields.

- Break supersymmetry in a stable vacuum.

- address unification of gauge couplings : tree-level values, threshold corrections.

- provide correct dark matter.

- provide testable predictions : low-scale strings, large extra dims, light moduli, anomalous couplings.

- Recently new applications : AdS/QCD, holography in condensed matter (CFT/TCM): talks K.Skenderis,A.Pomarol.

Compactification to four-dimensions

The 4d theories are defined after compactification

$$M_{10} = M_4 \times K_6 \ ,$$

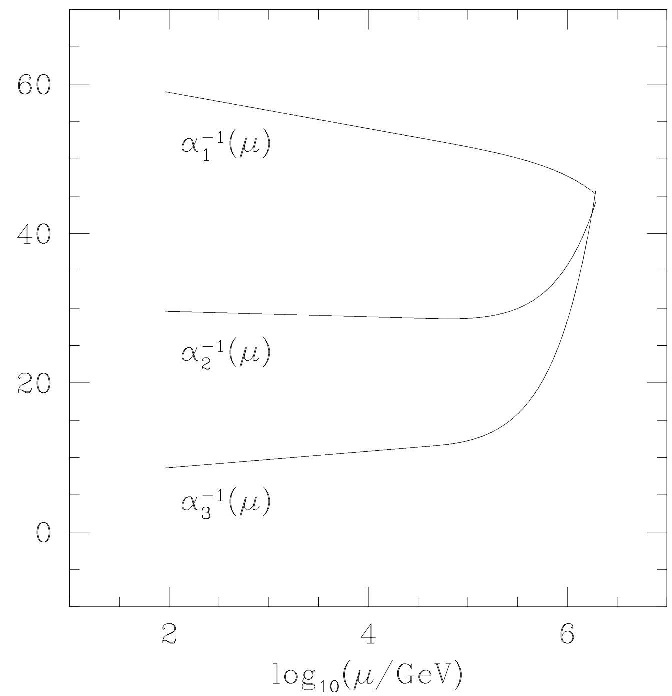
where M_4 is the Minkowski spacetime and K_6 is the internal manifold; volume V traditionally defines the compactification scale M_c

$$V \ = \ M_c^{-6} \ \equiv \ M_{GUT}^{-6} \ .$$

The GUT scale M_{GUT} is identified with the compactification scale in a naive string unification picture.

- Not true in string models with large extra dims.

Ex : low scale unification (Dienes,E.D.,Gherghetta)



The massless fields in a toroidal compactification are the zero modes of the 10d fields, that in more general settings depend on the topology of the compact space K_6. If we denote by i, j six dimensional internal indices, then we have, for example, the following decompositions:

$$g_{AB} \;:\; g_{\mu\nu}\ (graviton)\ ,\ g_{mn}\ (scalars)\ ,\ g_{\mu m}\ (vectors) \quad ,$$
$$B_{AC} \;:\; B_{\mu\nu}\ (axion)\ ,\ B_{mn}\ (axions)\ ,\ B_{\mu m}\ (vectors)$$

Toroidal compactification of superstring theories to four dimensions gives rise to spectra with $\mathcal{N}=4$ SUSY.

Simple ways to reduce nb. SUSY : Calabi-Yau spaces, orbifold compactifications, and intersecting branes.

We will be interested in 4d $\mathcal{N}=1$ orbifold models (Dixon,Harvey,Vafa,Witten).

Introduce the three complex internal coordinates

$$z_1 = \frac{1}{\sqrt{2}}(x_4+ix_5)\ ,\ z_2 = \frac{1}{\sqrt{2}}(x_6+ix_7)\ ,\ z_3 = \frac{1}{\sqrt{2}}(x_8+ix_9)\ ,$$

twisted by

$$\theta\ (z_1,z_2,z_3) = (e^{2i\pi v_1}z_1, e^{2i\pi v_2}z_2, e^{2i\pi v_3}z_3)\ ,$$

where $\mathbf{v} \equiv (v_1,v_2,v_3)$ is the twist vector.

For a Z_N orbifold $\theta^N = 1$. If

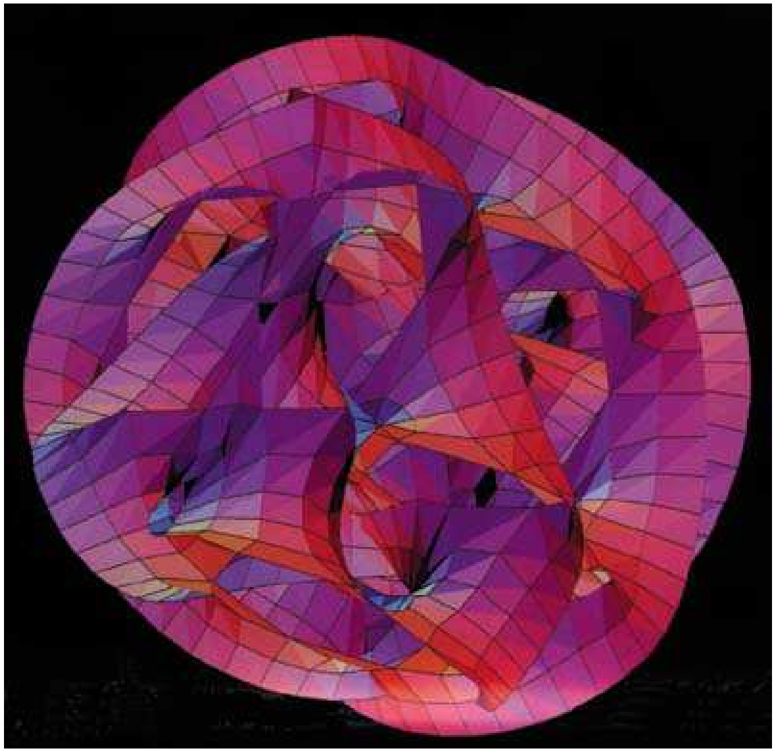
$$v_1 \pm v_2 \pm v_3 = 0$$

with all $v_i \neq 0$, the holonomy group is $SU(3)$ and the orbifold has generically $\mathcal{N} = 1$ supersymmetry (1/4 of original SUSY).

The compact space is flat, up a finite number of singularities, defined as the fixed points of the orbifold operation, whose number is given by

$$N_f = det\,(1 - \theta) = 64 \prod_{i=1}^{3} \sin^2(\pi v_i)\ .$$

String compactifications have moduli fields, related to the sizes and the shape of the compact space, including the original 10d dilaton.



Simple example : two torus.

Geometric fields : the metric (symmetric) g_{ij} and antisymmetric tensor $B_{ij} = \epsilon_{ij} B$. From the 4d point of view, two complex fields

$$T \ = \ \sqrt{detg} + iB \quad , \quad U \ = \ \frac{\sqrt{detg} + ig_{12}}{g_{22}} \ ,$$

$T =$ Kähler (volume) modulus, $U =$ complex structure (shape) modulus.

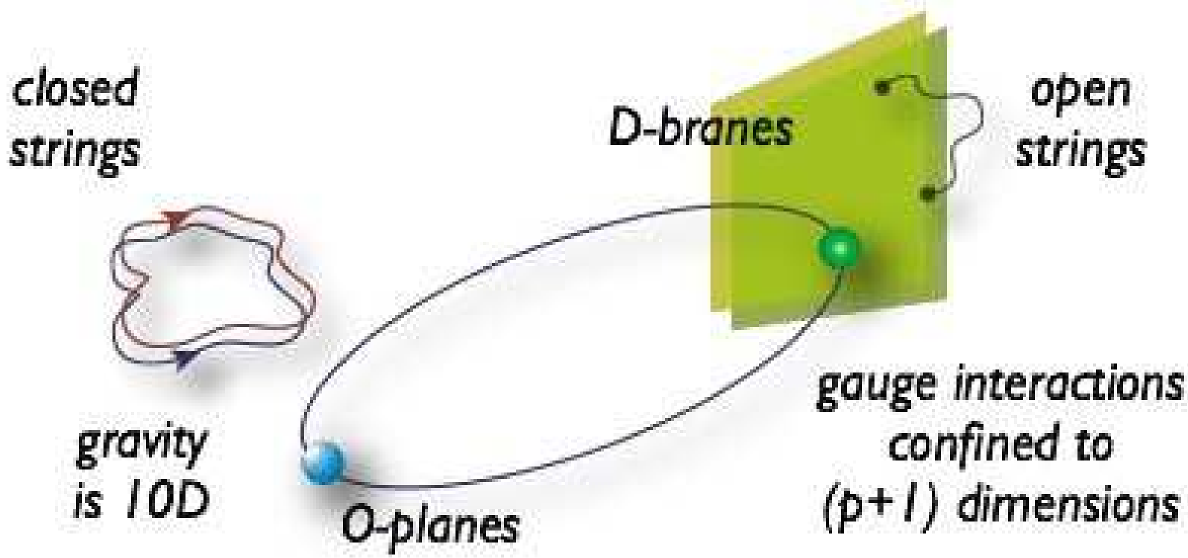
• In a flat space (no fluxes or warping) susy compactifications, moduli fields have no scalar potential and are therefore *flat directions* of the 4d theory, associated to massless 4d fields $\longrightarrow$

unacceptable modifications of the gravitational force by inducing new macroscopic forces.

• Lifting flat directions (stabilization of moduli fields) is one of the most important problems in string phenomenology.

String models

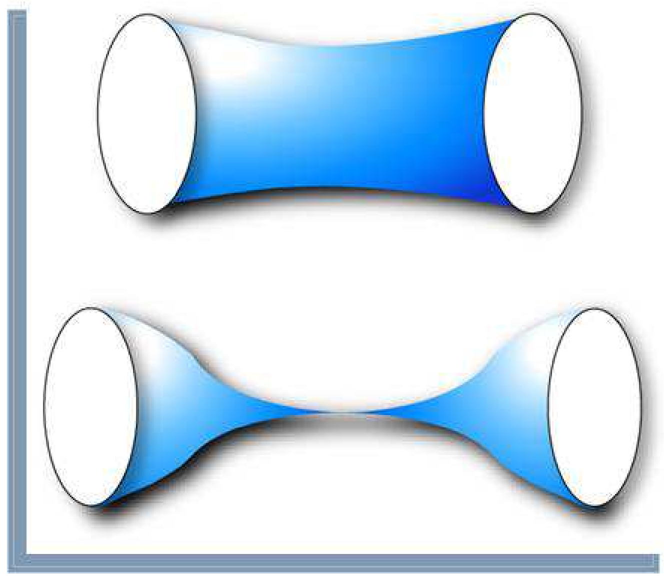
Cartoon picture of type II orientifolds (Sagnotti) : open/closed strings, Dp-branes/O-planes →



D-brane/O-planes have tension and charges (T_p, q_p).

Crucial constraint: RR tadpole constraints $\leftrightarrow$ UV finiteness $\leftrightarrow$ Gauss law in internal space

$$\sum_{Dp} q_{Dp}^{(n)} + \sum_{Op} q_{Op}^{(n)} = 0 \quad ; \quad SUSY \rightarrow T_p = q_p$$



Branes at angles : Intersecting brane worlds

(Bachas; Blumenhagen, Kors, Lust;

Angelantonj,Antoniadis,E.D.,Sagnotti)

Simple way of partially or totally breaking SUSY is by rotating the branes in the compact space.

Type IIA orientifolds : there are three angles $\theta_1, \theta_2, \theta_3$ that D6 brane(s) can make with the horizontal axis x_4, x_6, x_8 of the three torii of the compact space. Preserved supercharge is (Berkooz,Douglas,Leigh)

$$Q \ + \ P \ \tilde{Q} \ ,$$

P is the parity in the space transverse to the D6 brane(s).

For two distinct stacks of D-branes/O-planes $D^{(1)}$ and $D^{(2)}$, relevant quantities are the relative angles

$$\theta_i^{(12)} \ = \ \theta_i^{(1)} - \theta_i^{(2)}$$

The supercharges preserved by each stack are

$$Q \ + \ P^{(1)} \ \tilde{Q} \quad , \quad Q \ + \ P^{(2)} \ \tilde{Q}$$

Two branes: The number of unbroken SUSY's is

$$\begin{aligned}
&\theta_3^{(12)} = 0 \quad , \quad \theta_1^{(12)} \pm \theta_2^{(12)} \ = \ 0 \quad \rightarrow \ \mathcal{N} = 2 \text{ SUSY} \ , \\
&\theta_1^{(12)} \pm \theta_2^{(12)} \pm \theta_3^{(12)} \ = \ 0 \quad \rightarrow \ \mathcal{N} = 1 \text{ SUSY} \ , \\
&\theta_1^{(12)} \pm \theta_2^{(12)} \pm \theta_3^{(12)} \ \neq 0 \quad \rightarrow \ \mathcal{N} = 0 \text{ SUSY} \ .
\end{aligned}$$

Compact space : two important additional ingredients:

• rotations of branes in the compact space are quantized, according to

$$\tan\theta_i^{(a)} = \frac{m_i^{(a)} R_{i2}}{n_i^{(a)} R_{i1}} ,$$

where $(m_i^{(a)}, n_i^{(a)})$ are the *wrapping numbers* of the brane(s) $D^{(a)}$ along the two compact directions of the compact torus T_i^2.

The total internal volume of the brane $D^{(a)}$ is then

$$V^{(a)} = (2\pi)^3 \prod_{i=1}^{3} \sqrt{m_i^{(a),2} R_{i2}^2 + n_i^{(a),2} R_{i1}^2} .$$

For two stacks of branes $D^{(a)}$ and $D^{(b)}$, the number of times they intersect in the compact torus T_i^2 is given by the *intersection number*

$$I_i^{(ab)} = m_i^{(a)} n_i^{(b)} - n_i^{(a)} m_i^{(b)} .$$

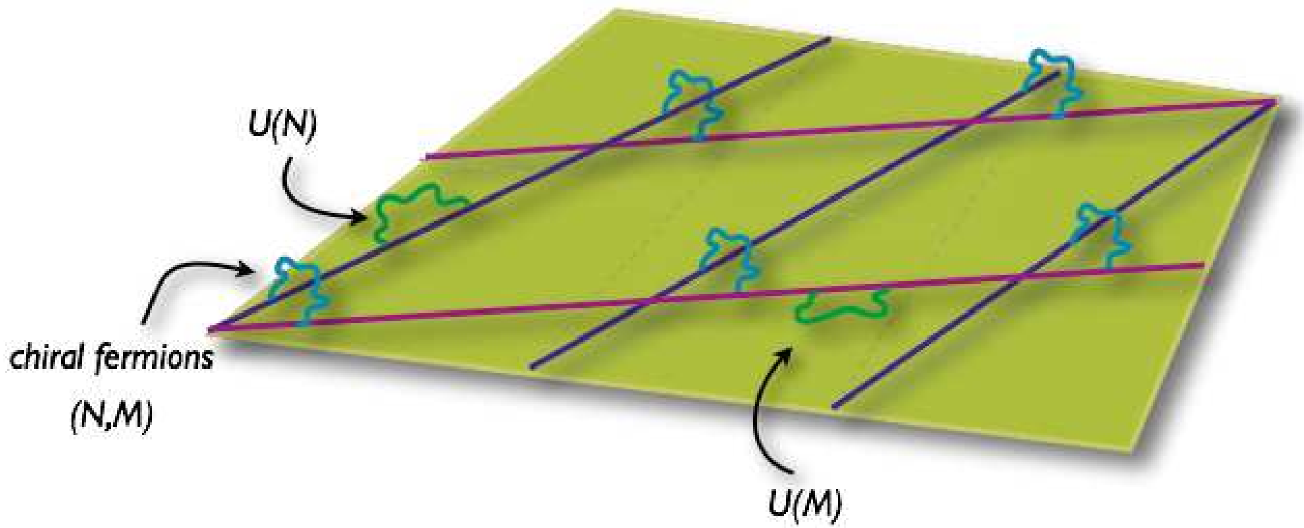
Branes at angles generate 4d chirality. Example: type IIA string with two sets of M_a coincident $D^{(a)}$ and M_b coincident $D^{(b)}$ intersecting branes in toroidal compactification :

- the gauge group is $U(M_a) \otimes U(M_b)$.

- strings stretched between the two D-branes have chiral fermions $(M_a, \bar{M}_b)$

Multiplicity equal to the total number of times the branes intersect in the compact space

$$D^{(a)}\!-\!D^{(b)} \quad : \quad I^{(ab)} = \prod_{i=1}^{3} I_i^{(ab)} = \prod_{i=1}^{3} \left(m_i^{(a)} n_i^{(b)} - n_i^{(a)} m_i^{(b)}\right) .$$



• Second important ingredient in compact space : RR tadpole consistency conditions in SUSY compactifications can be satisfied only by including the negative charge O-planes in orientifolds of type II strings.

For a general configuration of D6-branes $D^{(a)}$ the RR tadpole conditions are

$$\sum_a M_a n_1^{(a)} n_2^{(a)} n_3^{(a)} = 16 \quad , \quad \sum_a M_a n_1^{(a)} m_2^{(a)} m_3^{(a)} = -16\ \epsilon_1 \ ,$$
$$\sum_a M_a m_1^{(a)} n_2^{(a)} m_3^{(a)} = -16\ \epsilon_2 \quad , \quad \sum_a M_a m_1^{(a)} m_2^{(a)} n_3^{(a)} = -16\ \epsilon_3$$

where

$$(\epsilon_1, \epsilon_2, \epsilon_3) = (0, 0, 0) \quad \text{toroidal comp.} \ ,$$
$$(\epsilon_1, \epsilon_2, \epsilon_3) = (\pm 1, \pm 1, \pm 1) \quad \text{in } Z_2 \times Z_2 \text{ comp.} \ .$$

In the IIA language with D6 branes at angles, the type I O9 plane becomes an O6 plane with wrapping numbers

$$O6 \quad : \quad (m_i, n_i) = (0,1)\ ,\ (0,1)\ ,\ (0,1)\ ,$$

whereas the three different type of $O5_i$ planes, $i = 1,2,3$ of type I strings become $O6_i$ planes with wrapping numbers

$$\begin{aligned} O6_1 \quad &: \quad (m_i, n_i) = (0,-\epsilon_1)\ ,\ (1,0)\ ,\ (1,0)\ , \\ O6_2 \quad &: \quad (m_i, n_i) = (1,0)\ ,\ (0,-\epsilon_2)\ ,\ (1,0)\ , \\ O6_3 \quad &: \quad (m_i, n_i) = (1,0)\ ,\ (1,0)\ ,\ (0,-\epsilon_3)\ . \end{aligned}$$

Each stack of D-branes preserve the same $\mathcal{N}=1$ SUSY if

$$m_1^{(a)} n_2^{(a)} n_3^{(a)} \mathsf{v}_2 \mathsf{v}_3 + n_1^{(a)} m_2^{(a)} n_3^{(a)} \mathsf{v}_1 \mathsf{v}_3 + n_1^{(a)} n_2^{(a)} m_3^{(a)} \mathsf{v}_1 \mathsf{v}_2 = \prod_{i=1}^{3} m_i^{(a)}$$

where v_i are the volumes of the three compact torii.

In IIA with D6 branes at angles, each stack $D^{(a)}$ has a mirror $D^{(a')}$ with respect to the O6 planes, of wrapping numbers $(-m_i^{(a)}, n_i^{(a)})$.

The chiral spectrum for toroidal compactification contains chiral fermions in

sector	representation	multiplicity of states
$D^{(a)} - D^{(b)}$	$(M_a, \overline{M_b})$	I_{ab}
$D^{(a)} - D^{(b')}$	(M_a, M_b)	$I_{ab'}$
$D^{(a)} - D^{(a')}$	$\frac{M_a(M_a-1)}{2}$	$\frac{1}{2}(I_{aa'} + I_{aO})$
$D^{(a)} - D^{(a')}$	$\frac{M_a(M_a+1)}{2}$	$\frac{1}{2}(I_{aa'} - I_{aO})$.

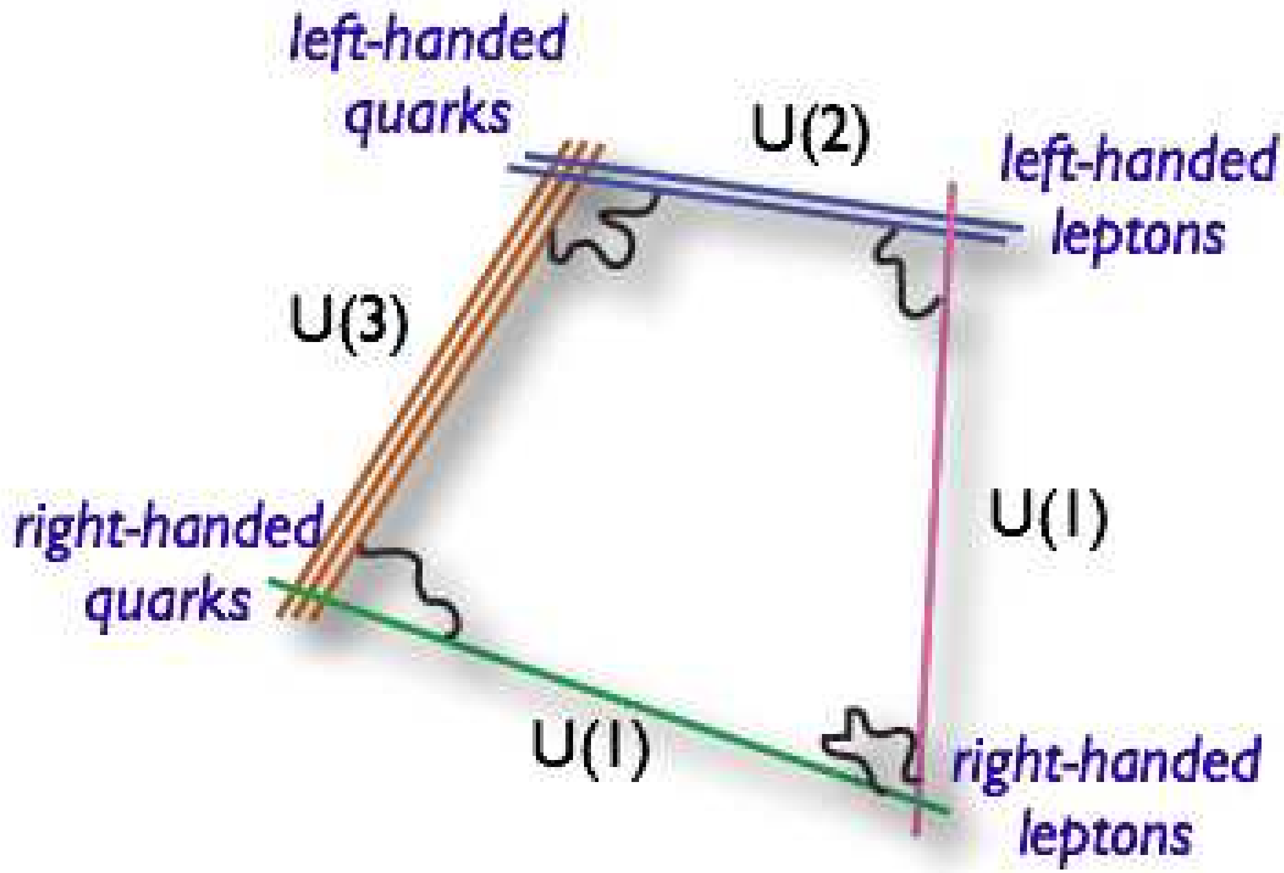
Some phenomenology of intersecting branes models

Standard Model like spectra

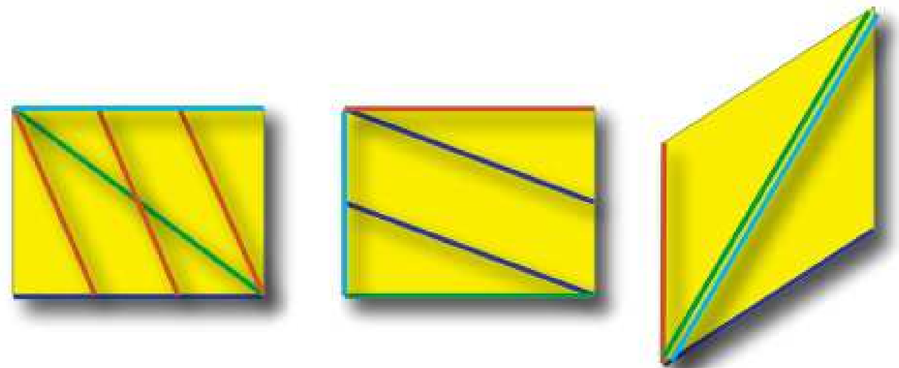
(Cvetic,Shiu,Uranga; Madrid group; Munich group)

Quasi-realistic models with intersecting were constructed in the last couple of years. The generic Standard Model type construction contains four (or more) stacks, containing D-branes with a minimal gauge group $U(3) \times U(2) \times U(1)^2 = SU(3) \times SU(2) \times U(1)^4$.

"Standard Model" quiver



Intersection pattern



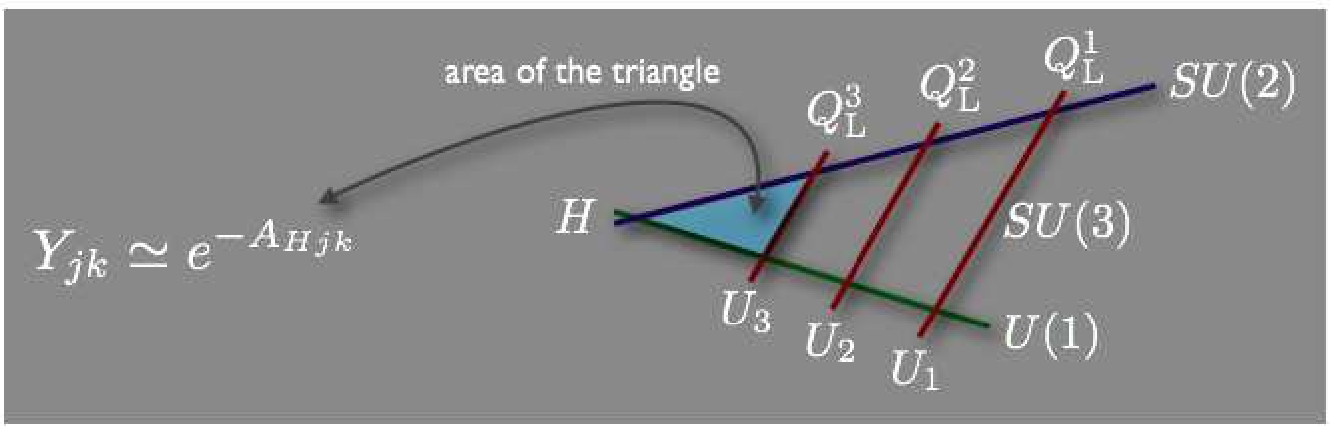
U(3)	(1,0)	(2,-1)	(1,0)
U(2)	(1,-1)	(1,0)	(1,1)
U(1)	(1,-3)	(1,0)	(0,1)
U(1)	(1,0)	(0,1)	(1,1)

Yukawa couplings

Number of Generation = number of intersections between branes.

Then Yukawa couplings have a nice geometrical intepretation

(Cremades,Ibanez,Marchesano)



• Out of the four abelian gauge factors, three are anomalous by Stueckelberg mixing with axions and get string scale masses. One linear combination is massless and is the hypercharge Y.

(Some) problems:

• SUSY realistic models (MSSM) difficult to realize.

• Gauge coupling unification is not automatic.

• For $SU(5)$ GUT's, top coupling 10 10 5_H perturbatively forbidden.

• No $SO(10)$ spinor representations in the perturbative spectrum → heterotic or F-theory models

Stringy instanton effects

(Witten,Ganor, ...Blumenhagen,Cvetic,Weigand; Ibanez,Uranga)

Stringy instantons : nonperturbative (non-gauge) instantonic effects on D-branes . Ex :

- E1 effects on D9 branes in type I
- E3 effects on D3 branes in type IIB
- E2 effects on D6 branes in IIA

Effects of the type $e^{-S_i}\,\mathcal{O}$, where instanton action S_i $(>> 1)$ = volume wrapped by the instantonic brane.

They arise from instanton couplings to D-brane fields.

Two different types of zero-modes: - neutral : x_μ, θ^α...

- charged : η, in the byfund. repres. of E1-D9. Ex :

$$S_{\text{inst}} = S_{\text{E1}} + \sum_{i,j=1}^{4} \eta_i \, \Phi_{ij} \, \eta_j \,,$$

where Φ_{ij} is a D-brane field. If the E1 instanton has only 2 neutral fermionic zero-modes θ^α, integration over charged zero-modes $\eta \to$ non-pert. superpotential

$$\mathcal{W}_{\text{non-pert}} = e^{-S_{\text{E1}}} \sum_{i,j,k,l=1}^{4} \epsilon_{ijkl} \Phi_{ij} \Phi_{kl}$$

mass term for Φ_{ij}.

Phenomenological interest :

• Generation of perturbatively forbidden couplings. Ex:

$$W = e^{-T} \prod_i \Phi_i$$

where under "anomalous" $U(1)_X$ gauge trans.

$$V_X \rightarrow V_X + \Lambda + \bar{\Lambda} \ , \ T \rightarrow T + \delta \Lambda ,$$
$$\sum_i X_i = \delta \ .$$

Applications :

- Majorana neutrino masses $M_{ij} N_i N_j$

- Higgs μ-term in MSSM $\mu H_1 H_2$

- top Yukawa couplings in SU(5) GUT's λ_T 10 10 5_H, but naturally suppressed $\longrightarrow$ F-theory ?

• Moduli stabilization: moduli-dependent corrections to superpotential, Kahler and gauge kinetic functions.

• Instanton breaking of perturbative conformality.

• Open string tadpoles : gauge symmetry breaking, potentials for open moduli.

- Supersymmetry breaking and gauge mediation ?

Mechanisms for supersymmetry breaking

- Scherk-Schwarz
- non-BPS configurations
- internal magnetic fields $\leftrightarrow$ branes at angles
- internal fluxes
- nonperturbative effects

The Scherk-Schwarz mechanism

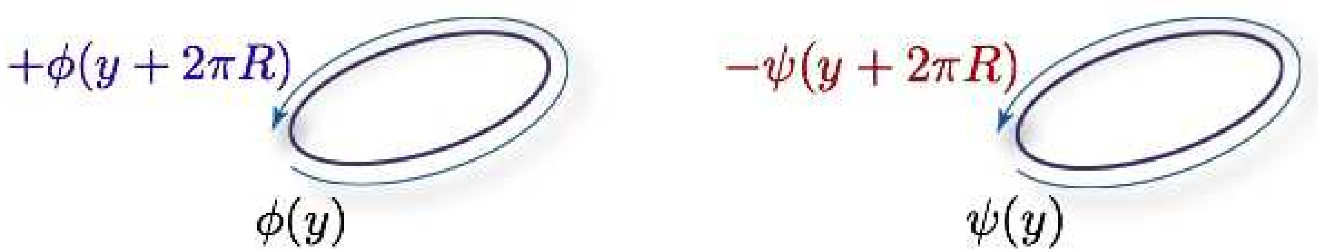
(Scherk-Schwarz;Fayet;Ferrara,Kounnas,Porrati,Zwirner)

Main idea : use symmetries $\mathcal{S}$ of the higher-dimensional theory which do not commute with supersymmetry : R-symmetries or the fermion number $(-1)^F$.

After being transported around the compact space, bosonic and fermionic fields Φ_i return to the initial value (at $y = 0$) only up to a symmetry operation

$$\Phi_i(2\pi R, x) = U_{ij}(\omega)\Phi_j(0, x) \ ,$$

where the matrix $U \in \mathcal{S}$ is different for bosons and fermions.



$$\Phi(y,\mathbf{x}) = \sum_k e^{\frac{iky}{R}} \Phi(\mathbf{x})^{(k)} \to M_k = \frac{k}{R} \ ,$$

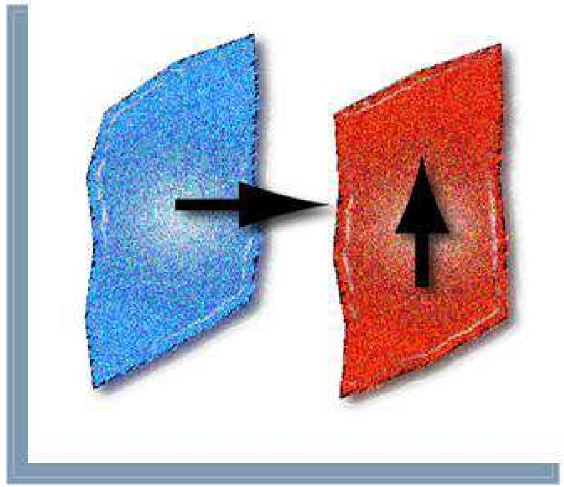
$$\Psi(y,\mathbf{x}) = \sum_k e^{\frac{i(k+1/2)y}{R}} \Phi(\mathbf{x})^{(k)} \to M_k = \frac{(k+1/2)}{R}$$

• This procedure is very similar to the breaking of supersymmetry at *finite temperature* $\to$ the terms breaking supersymmetry are UV finite, even at the field theory level.

In models with D-branes there are two different ways in which supersymmetry can be broken by compactification (Antoniadis,E.D.,Sagnotti):

- The D brane is parallel to the direction of breaking ; massless D brane spectrum has tree-level SUSY breaking. This is the analog of the heterotic constructions.
- the D brane is perpendicular to the direction of the breaking; massless D brane spectrum is SUSY at tree-level. SUSY breaking transmitted by radiative corrections from the brane massive states or from the gravitational sector.

Parallel and perpendicular Scherk-Schwarz breaking



Parallel dims → TeV radii $M_{SUSY} \sim R^{-1}$.

Perpendicular dims → intermediate radii $M_{SUSY} \sim R^{-2}/M_P$.

Problem : large cosmological constant.

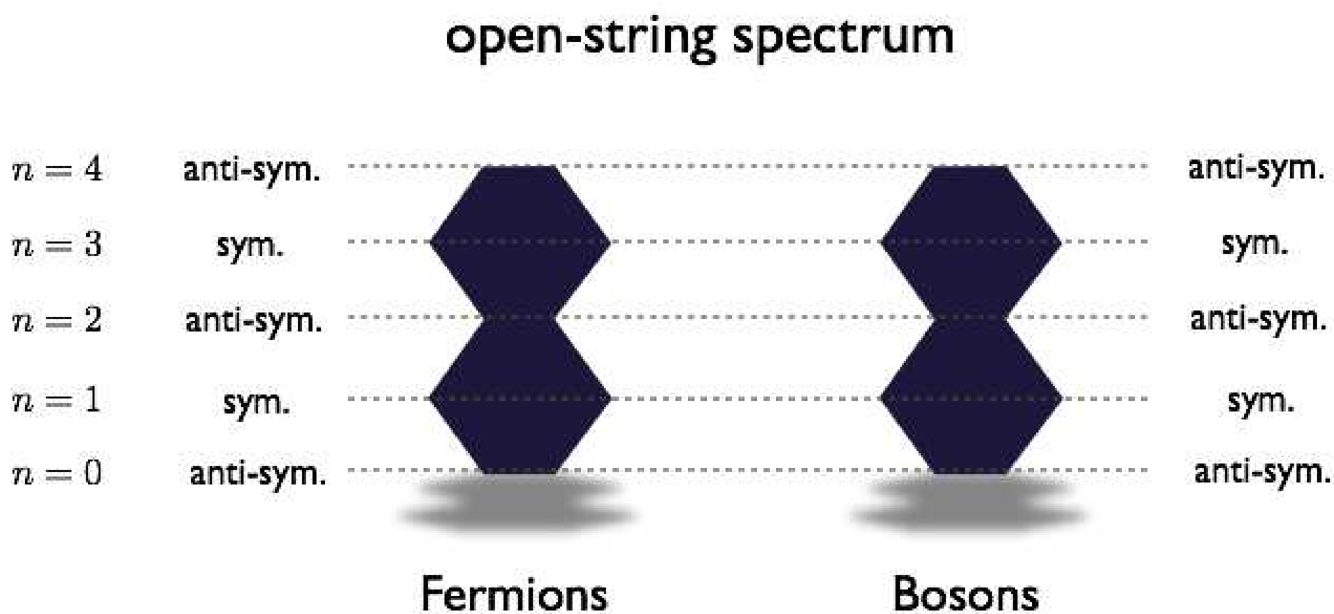
Non-BPS systems: Brane supersymmetry breaking

(Sugimoto; Antoniadis, E.D.,Sagnotti)

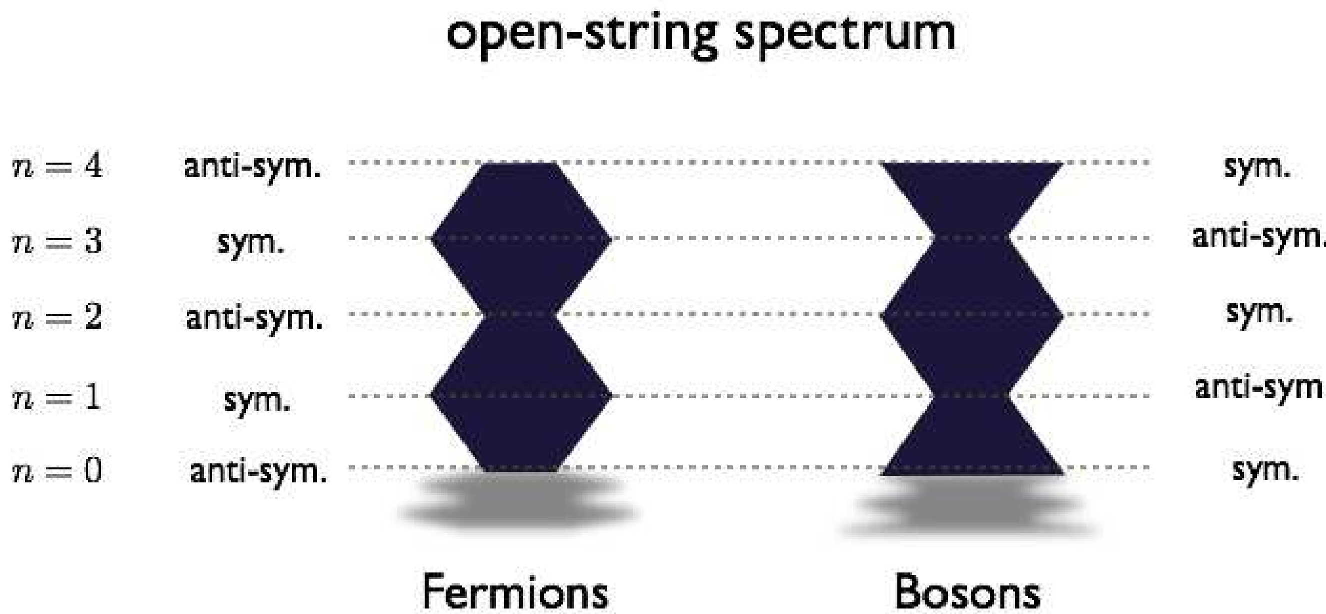
In these constructions, the closed (bulk) sector is SUSY to lowest order, whereas SUSY is broken at the string scale on some stack of (anti)branes.

- String consistency asks for the existence of exotic $O9_+$ planes of positive RR charge. Then charge conservation /RR tadpoles ask for antibranes in the open sector.

SUSY case (SO gauge group) : Bose-Fermi degeneracy



Brane SUSY breaking case (USp gauge group): spectrum is "misaligned"



- $\overline{Dp}-Op_+$ system is non-BPS but tachyon-free. Breaks SUSY at string scale.

- There is a NS-NS dilaton tadpole

$$\sum_{Dp} T_{Dp}^{(n)} + \sum_{Op} T_{Op}^{(n)} \neq 0$$

- Singlet in the open string fermionic spectrum which can be correctly identified with the goldstino realizing a nonlinear SUSY on antibranes (E.D.,Mourad).

- No obvious candidate for decay to a SUSY vacuum (folklore : non-SUSY vacua decay into SUSY ones). Suggestion : nonperturbative instabilites (Angelantonj,E.D.)

- low-string scale $\to$ light moduli $m \sim M_s^2/M_P$.

Internal magnetic fields / intersecting branes
(Bachas)

Particles of different spin couple differently to magnetic field, breaking supersymmetry. Define

$$\theta_i = arctan(\pi q_L^{(i)} H_i) + arctan(\pi q_R^{(i)} H_i)$$

Mass splittings of string states are

$$\delta m^2 = (2n+1)|\epsilon_i| + 2\Sigma_i \epsilon_i \ ,$$

where n are the Landau levels of the charged particles in the magnetic field and Σ_i are internal helicities.

Generic problem : NS-NS tadpoles.

Anomalous $U(1)$ + gaugino condensation breaks SUSY

(Binetruy,E.D.; E.D.,Vempati;Viladoro,Zwirner)

The hidden sector is an asymptotically free gauge theory, ex. super Yang-Mills, dynamical scale Λ

$$\Lambda \; = \; M_P \; e^{-\frac{1}{2b_0 g_0^2}},$$

b_0= beta function of the hidden sector gauge theory.

In string (or brane) context, gauge couplings are vev's of moduli fields.

Modulus $T = t + ia$; hidden sector gauge coupling is

$$\frac{1}{g_0^2} = \langle t \rangle$$

Gaugino condensation generate nonperturbative moduli potentials

$$\text{non} - \text{SUSY} \quad : \quad V(t) \sim \Lambda^4 = e^{-\frac{2t}{b_0}}$$

$$\text{SUSY} \quad : \quad W(T) \sim e^{-\frac{3T}{2b_0}}$$

SUSY example in type IIB (if all other moduli stabilized): gaugino cond. on D7 branes or E3 instantons

$$K = -3\ln(T + \bar{T})$$

$$W = W_0 + e^{-\frac{3T}{2b_0}}$$

Refine previous ex : add a magnetic flux on another D7 brane which wraps an internal 4-space of volume $\mathcal{V} = T + \bar{T}$

$$\int d^8x \; e^{-\phi} \; \sqrt{g_8} F_{ij} F^{ij} \rightarrow \frac{c}{(T+\bar{T})^3}$$

By doing this, the axionic partner of $\mathcal{V}$, $T = \mathcal{V} + ia$, becomes charged under gauge transformations of the " magnetized"' brane

$$V_X \rightarrow V_X + \Lambda + \bar{\Lambda} \quad , \quad T \rightarrow T + \delta_{GS} \Lambda \; .$$

The Kahler potential of T is of the form

$$K(S, \bar{S}) \; = \; - \, 3 \ln \, (T + \bar{T} - \delta_{GS} \; V_X)$$

Condensation term e^{-bT} not gauge-invariant. Hidden sector (N_c D7) intersect N_f times $U(1)$ brane: charged fields $Q, \bar{Q}$, condense into "mesons" $M = Q\bar{Q}$:

$$W = W_0 + a\left(\frac{e^{-bT}}{detM}\right)^{\frac{1}{N_c - N_f}} + \Phi M$$

A careful anomaly analysis shows that the nonperturbative term is gauge invariant. The gauge (D-term) contribution to the vacuum energy is

$$V_D \sim \frac{1}{T+\bar{T}}\left(-|\Phi|^2 + Tr(\bar{M}M)^{1/2} + \frac{3\delta_{GS}}{2(T+\bar{T})}\right)^2$$

- The dynamics of the model breaks SUSY, with

$$M_{SUSY} \sim \frac{\Lambda^2}{\xi} \quad , \quad \xi^2 = \frac{3\delta_{GS}}{2(T+\bar{T})}$$

Cartoon of moduli stabilization in type IIB

• Stabilize all moduli by

- adding all possible 3-form fluxes : stabilize the dilaton, shape (complex structure) moduli in type IIB strings, but not volume (Kahler) moduli T_i

- add non-perturbative effects (gaugino condensation on D7 branes) to stabilize T_i

$\longrightarrow$ end up in anti-de Sitter SUSY space.

• " Uplift " vacuum energy to zero (or positive) by a dynamical SUSY breaking sector.

In practice, these two steps are not really decoupled.

Obs: D-terms generically not enough for the "uplift" :

(too small vacuum energy), unless $m_{3/2} \gg TeV$.

- Dynamical F-term SUSY breaking and uplifting (E.D.,Papineau; Nilles et al.)

Use a sector which dynamically breaks SUSY by F-terms in the global limit (ex. ISS model). Then

$$V_{uplift} \sim \Lambda_{dyn}^4 \sim 3m_{3/2}^2 M_P^2$$

could lead to a TeV gravitino mass, for $\Lambda \sim 10^{11}$ GeV.

Several constraints : Λ depends on stabilized moduli (ex. $D3$ branes).

Typically metastable vacua, but very large lifetime.

Challenges for string phenomenology

D-branes and low-scale strings triggered important phenomenological activity, some of predictions are testable (low string or KK scale). The main goals of string phenomenology are however still ahead of us :

• Progress in stringy instantonic effects, but not yet in quasi-realistic models.

• No explicit string example with full moduli stabilization.

• Simplest toroidal orbifold models too simple; need more involved models.

- Supersymmetry breaking still an open problem.
- Implementation of inflation in string theory not satisfactory.
- $\cdots\cdots$
- No hint for a small cosmological constant.