The Standard Model from D-branes in String Theory

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Outline

- Motivation/Introduction
- Intersecting D-branes
- Compactification and model building
- Phenomenological properties
- Conclusions

String Phenomenology

- String theory describes gravitational and gauge interactions in a unified framework, consistent at the quantum level

- If string theory is realized in Nature, it should be able to describe a very specific gauge sector: Standard Model

- Aim of String Phenomenology:

  - Determine classes of constructions with a chance to lead to SM
    Non abelian gauge interactions, replicated charged fermions, Higgs scalars with appropriate Yukawa couplings, ...

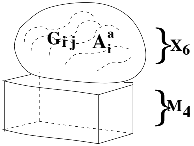
  - Within each class, obtain explicit models as close to SM as possible with the hope of learning more about the microscopics of SM in string theory

- Old program, yet continuous progress
  Moduli stabilization, non-perturbative effects, ...

Prototypical example: Heterotic string models

[Candelas, Horowitz, Strominger, Witten, '85]

- The 10d heterotic string has as effective theory 10d N=1 sugra coupled to E8xE8 (or SO(32)) gauge multiplets
- Compatification: six extra dimensions parametrize small Calabi-Yau space, on which we also turn on a non-trivial gauge field background



- Gauge group is reduced to transformations leaving bckgnd invariant Possible to break down to something close to SM gauge group

- 4d charged chiral fermions arise from zero modes of 10d gauginos, in the Kaluza-Klein reduction of the spectrum

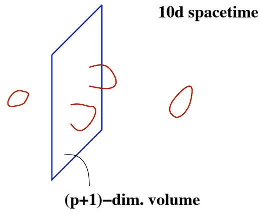
- Within this general class, very explicit models close to (MS)SM

[e.g, Braun, Donagi, He, Ovrut, Pantev, '06]

D-branes [Polchinski, '95]

- In this talk, focus on D-brane models in type II string compactifications
- Dp-branes are solitonic states in string theory, with p extended spatial dimensions, and tension $1/g_s$

  - At weak coupling g<<1, behave as part of background
  - Described as subspaces of 10d space on which open strings end
  - Equivalently, particles described by oscillation modes of open strings propagate only on volume of Dp-brane ⇒ Brane world



D-branes (cont.)

- D-branes usually preserve part of the susy of the compactification

  BPS states, with relation tension = charge

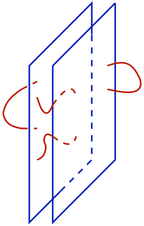
- N overlapping Dp-branes lead to U(N) gauge symmetry on brane

  World-volume effective action

$$S_{D_p} = \int d^{p+1}x \, \frac{1}{g_s} \sqrt{-\det(G+F)} +$$

$$+ \int_{p+1} (\, C_{p+1} + C_{p-1} \wedge F + C_{p-3} \wedge \mathrm{tr}\, F^2 + \dots)$$

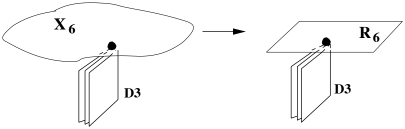
reduces to SYM at low energies



U(2)

D-branes and chirality

- Isolated D-branes in smooth geometries cannot lead to chiral gauge theories



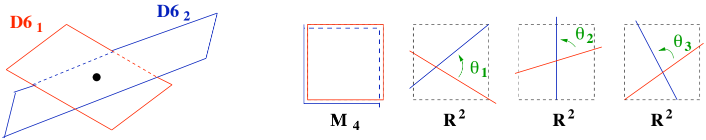
- Two setups for SM model building
  - D-branes at singularities
    [Aldazabal, Ibanez, Quevedo, AU, '00; Verlinde, Wijnholt, '05]
  - Intersecting D-branes
    [Blumenhagen, Gorlich, Kors, Lust; Aldazabal, Franco, Ibanez, Rabadan, AU; '00]
    (or magnetized branes [Bachas '95; Angelantonj, Antoniadis, Dudas, Sagnotti, '00])

- Focus on intersecting D-branes Related to others by string dualities

Intersecting D-branes in flat space

[Berkooz, Douglas, Leigh,'96]

- Consider type IIA string theory with two stacks of D6-branes (hence 7d subspaces) intersecting over a 4d subspace of their volumes



- Three sectors of open strings
  - $D6_1$-$D6_1$: $U(N_1)$ on 7d plane 1
  - $D6_2$-$D6_2$: $U(N_2)$ on 7d plane 2
  - $D6_1$-$D6_2$: 4d chiral fermion in $(N_1,\overline{N}_2)$ on 4d intersection

- Chirality is a consequence of the geometry of the intersection

  e.g. two D5's intersecting over 4d leads to non-chiral fermions

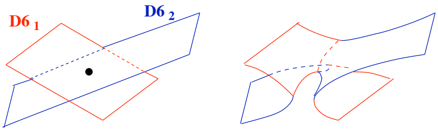
Scalars

- In addition, the $D6_1$-$D6_2$ sector contains 4d scalars, which are generically massive, and potentially light

$$M^2 = \frac{1}{2}(\,\theta_1 \pm \theta_2 \pm \theta_3\,)\, M_s^2$$

- Could be tachyonic, massless or massive

  Possible instability corresponds to possible brane recombination



- Nice geometric interpretation in terms of volume minimization

[Douglas, '01]

Supersymmetry

- Each flat D6-brane preserves 16 of the 32 supercharges of type II
- The condition that the two D6's preserve a common set of susys is that the SO(6) rotation taking one into the other is actually in SU(3)

$$R = \mathrm{diag}\,(\, e^{i\theta_1}, e^{-i\theta_1}\, ;\, e^{\theta_2}, e^{-i\theta_2}\, ;\, e^{i\theta_3}, e^{-i\theta_3}\,)$$

$$\theta_1 \pm \theta_2 \pm \theta_3 \;=\; 0\,(\,\mathrm{mod}\, 2\pi\,)$$

- Precisely the condition to have one 4d massless complex scalar field
- Enhanced N=2 supersymmetry for one zero angle e.g.

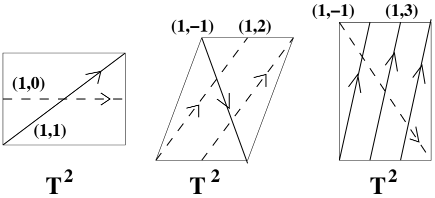
$$\theta_1 \pm \theta_2 \;=\; 0 \quad ; \quad \theta_3 = 0$$

Geometric interpretation of structure of preserved supersymmetry

Toroidal compactification

[Blumenhagen, Gorlich, Kors, Lust; Aldazabal, Franco, Ibanez, Rabadan, AU; '00]

- To obtain 4d gravity, need to compactify
- Simplest compactification, on $T^6 = T^2 \times T^2 \times T^2$



- Configurations of D6-branes in sets of N_a $D6_a$-branes wrapping 3-cycles Π_a described as products of 1-cycles (n_a^i, m_a^i) on each $(T^2)^i$

Spectrum of light 4d fields

- Closed string sector is maximally supersymmetric
  4d N=8 supergravity multiplet
  (will be more realistic 4d N=1 supergravity in forthcoming models)

- Open string spectrum:
  - Chiral part can be determined with just the above topological data

Gauge group $$\prod_a U(N_a)$$

Chiral fermions $$\sum_{a,b} I_{ab}\,(N_a,\overline{N}_b)$$

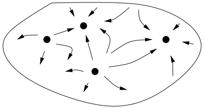
$$I_{ab} = (n_a^1 m_b^1 - n_b^1 m_a^1) \times (n_a^2 m_b^2 - n_b^2 m_a^2) \times (n_a^3 m_b^3 - n_b^3 m_a^3)$$

Intersection number = geometric origin of family replication!

- Non-chiral features of the spectrum (susy, scalars,...) depend on detailed configuration

RR tadpoles and anomalies

- In a compact space, the total D6-brane charge must be zero

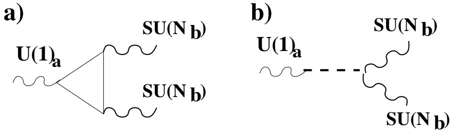


Gauss' law

- Deeply related to consistency of 4d theory: anomaly cancellation

  - $SU(N_a)^3$ non-abelian vanish identically

  - $U(1)_a$-$SU(N_b)^2$ mixed cancel via Green-Schwarz mechanish involving the D6-brane couplings $\sum_{k,a}\int_{4d} B_k \wedge \mathrm{tr}\, F_a$ & $\sum_{k,a}\int_{4d} a_k\, \mathrm{tr}\,(F_b \wedge F_b)$



U(1)'s

- Due to BF couplings, all 'anomalous' and some 'non-anomalous' U(1)'s become massive, with mass of order the string scale

$$\sum_{k,a} \int_{4d} B_k \wedge \mathrm{tr}\, F_a = - \sum_{k,a} \int_{4d} \partial_\mu a_k \, A_\mu^a$$

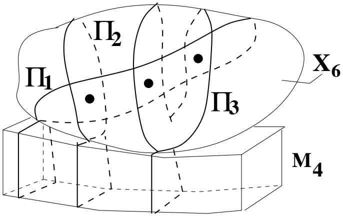
$= m^2 A_\mu^2$

- Consequences

  - Impose that hypercharge generator remains massless
  - Additional U(1)'s removed
    remain as global symmetries exact in perturbation theory
  - Operators violating the latter can appear non-perturbatively
    D-brane instantons, see later

Generalization

- All properties admit a simple* generalization beyond torus (e.g. CY)



General class of models in terms of D6-branes wrapped on intersecting 3-cycles in a Calabi-Yau compactification ⇒

General class of string compactifications with non-abelian gauge symmetry and replicated charged chiral fermions

* Simple only in principle: maths of special lagrangian 3-cycles on CY spaces is poorly known

Orientifolds

- In fact, models as described are non-supersymmetric

  If susy, then BPS would imply total tension = total charge.
  Since Gauss requires zero total charge, hence zero tension,
  the only susy state is no D-brane at all!

- Susy model can be obtained by introducing orientifold projections

  Take type IIA on CY X, and mod out by ΩR, where Ω flips the string orientation, and R is a Z2 symmetry of the CY X

- Fixed points of R are regions where string orientation can flip:

  $\Rightarrow$ Orientifold planes

  Focus on R flipping 3 coords of CY X, then O6-plane on 3-cycle

- O6-planes carry negative charge and negative tension

  Supersymmetric D6/O6 systems with zero total charge/tension can still be non-trivial

- Technical modifications of configuration, tadpoles, anomalies,... skip!

  - Every D6-brane stack has an orientifold image D6'
  - Intersections ab and ab'
  - D6-brane staks on top of O6 have SO/Sp group rather than U(N)

Towards the SM

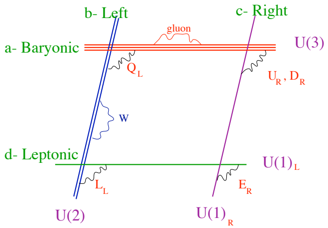
- Simplest road to SM

[Ibanez, Marchesano, Rabadan; Cremades, Ibanez, Marchesano;'01]

Introduce four stacks of D6's a,b,c,d with

$$U(3)_a \times USp(2)_b \times U(1)_c \times U(1)_d$$

$$I_{ab} = 3 \rightarrow \quad Q_L$$
$$I_{ac} = -3,\ I_{ac'} = 3 \rightarrow \ U_R,\ D_R$$
$$I_{db} = 3 \ \rightarrow \quad L$$
$$I_{dc} = -3,\ I_{dc'} = -3 \rightarrow \ E_R,\ \nu_R$$



Spectrum of SM with hypercharge

$$Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d$$

- Not a complete model yet: need realization of intersection numbers

Explicit toroidal realizations

- Explicit realization in toroidal models [Cremades, Ibanez, Marchesano]

N_α	(n_α^1, m_α^1)	(n_α^2, m_α^2)	(n_α^3, m_α^3)
$N_a = 3$	(1,0)	(1,3)	(1,-3)
$N_b = 1$	(0,1)	(1,0)	(0,-1)
$N_c = 1$	(0,1)	(0,-1)	(1,0)
$N_d = 1$	(1,0)	(1,3)	(1,-3)

(need few extra branes, adding few extra matter)

- Supersymmetric for suitable choices of T^2 geometry

  MSSM with pair of Higgs doublets in non-chiral bc sector

- Realizations in other setups

  Orientifolds of type II Gepner models leads to some 200.000 models [Dijkstraa, Huiszoon, Schellekens,'04]

- Towards more detailed analysis of properties

Phenomenological properties

[Aldazabal, Franco, Ibanez, Rabadan, AU]

- Gauge couplings

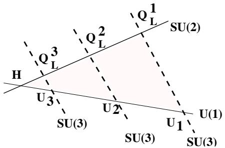
  No natural unification at string scale

  Each coupling depends on wrapped volume $$\frac{1}{g_a^2} = \frac{V_{\Pi a}}{g_s}$$

  Still, for realistic models, better than expected
  (hidden Pati-Salam) [Blumenhagen, Lust, Stieberger]

- Yukawa couplings

  Mediated by open string worldsheet instantons $$Y_{jk} \simeq e^{-A_{Hjk}+i\phi_{jk}}$$



Exponential dependence potentially explains fermion mass hierarchy

Extensive computations of general formula

[Cremades, Marchesano, Ibanez; Cvetic, Papdimitriou;'02]

Complicated functions of open and closed string (Kahler) moduli

Need to face moduli stabilization

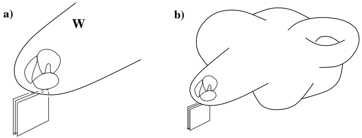
Geometrical interpretation possibly useful in search for textures

String scale

- In susy models, can 'choose' string scale (until susy breaking is specified)
- In non-susy models, can alleviate hierarchy by large volume

[Arkani-Hamed, Dimopoulos, Dvali,'98]

Not possible in toroidal, but possible in more general [AU]



TeV strings contrived e.g. bounds from rare processes

[Abel, Massip, Lebedev, Santiago]

Proton decay

Forbidden in perturbation theory by $U(1)_a$ baryon number

Violated by instantons, just like in SM

Susy breaking and soft terms

See later...

D-brane instantons and effective operators

[Blumenhagen, Cvetic, Weigand; Ibanez, AU;'06]

- Interesting SM operators forbidden by U(1) symmetries in perturbation theory e.g. Majorana mass for ν_R (singlet in cd' sector)

- Can be generated by non-perturbative D2-brane instantons

Euclidean D2-branes wrapped on 3-cycles Π_M on CY and point like in 4d

If 3-cycle Π_M intersects the D6's Π_a the instanton induces a 4d effective operator (e.g. in superpotential)

$$e^{-T}\,\Phi_1\ldots\Phi_n$$

with n given by the intersection number of the two 3-cycles I_{Ma}

- New constraints on models

Ex. of Majorana mass, need rigid 3-cycle with $I_{Mc} - I_{Mc'}=2$, $I_{Md} - I_{Md'}=2$

Reduces drastically number of models

- Mechanism applies to other interesting operators

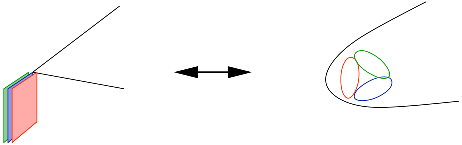
μ-term, certain GUT Yukawas, etc

Mirror symmetry

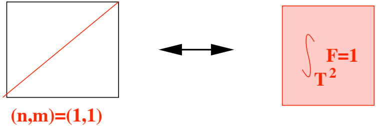
- Duality relation to other setups

  Mirror symmetry to type IIB on CY with D9, D7, D5, D3-branes

- Example D-branes at singularities



- Example Magnetized D-branes



- Similar properties in other setups

  Unity of model building setups via duality

  Can translate to intersecting setup computations in IIB duals

Moduli stabilization and fluxes

- Simplest compatifications ⇒ moduli, massless scalars w/ no potential

  e.g. parametrize sizes of 2- and 3-cycles in CY (Kahler and complex)

- Moduli stabilization from fluxes in the compactification

  Field strength fluxes on cycles, geometric fluxes, ...

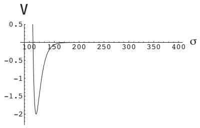
  Nontrivial dependence on moduli ⇒ scalar potential

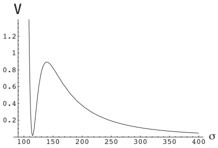
- Explicit models of (MS)SM with (partial) flux moduli stabilization

[Blumenhagen, Lust, Taylor; Cascales, AU; Camara, Font, Ibanez; Villadoro, Zwirner; '03-'06]

Moduli stabilization & susy breaking in Minkoswki (full stab. in AdS)

Going to dS is open question, with interesting but not yet explicit proposals





[KKLT '03]

Fluxes, susy breaking and soft terms

- An appealing scenario: Susy MSSM D-brane sector and non-susy flux

- Soft terms arise from effect of non-susy flux on susy D-branes

  Explicitly computable using D-brane world-volume action in general supergravity background, or using 4d effective theory approach

  [Grana; Camara, Ibanez, AU; Lust, Mayr, Reffert, Stieberger; '03-'04]

- Flux components work as vevs for auxiliary fields of chiral multiplets of (complex structure) moduli

  ⇒ Realization of gravity-mediated susy breaking

  - Flavour problem: Decoupling of flavor physics and soft terms
    Geometrization squark masses determined by intersection angles

  - μ-problem: susy components of flux induce it on the branes

- Very explicit discussion of susy spectrum etc is possible in specific models

  e.g. in 'large volume compactifications' [Quevedo et al '06-'07]

Conclusions

- It is amazing that something close to the SM can be realized in string theory

- Intersecting D-branes are a tractable setup for SM model building in string theory

  Not more fundamental, but more manifest geometric intuition

- Program is not closed: Very recent developments

  - Moduli stabilization
  - Neutrino masses, non-perturbative operators
  - Realizations in other setups

- Expect continuous progress and new results and useful input from LHC