I. Antoniadis

CERN

Physics with

magnetized branes

4th Regional Meeting in String Theory

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Outline

- Framework

- Moduli stabilization

Oblique internal magnetic fields

- Effective field theory

- Standard Model embedding

- Supersymmetry breaking

A new gauge mediation mechanism

General framework

Type I string theory with magnetic fluxes on 2-cycles of the compactification manifold

- Dirac quantization: $H = \frac{m}{nA} \equiv \frac{p}{A}$

  H: constant magnetic field

  m: units of magnetic flux

  n: brane wrapping

  A: area of the 2-cycle

- Spin-dependent mass shifts for charged states

  $\Rightarrow$ SUSY breaking

- Exact open string description:

  $qH \rightarrow \theta = \arctan qH\alpha'$ weak field $\Rightarrow$ field theory

- T-dual representation: branes at angles

(m, n): wrapping numbers around the 2-cycle directions

Moduli stabilization with 3-form fluxes:
significant progress but

- no exact string description
  low energy SUGRA approximation

- fix only complex structure

Type I with internal magnetic fluxes:
alternative/complementary approach

- exact string description

- Kähler class stabilization
  T^6: all geometric moduli fixed

- natural implementation in intersecting
  D-brane models

Magnetic fluxes can be used to stabilize moduli

I.A.-Maillard '04, I.A.-Kumar-Maillard '05, '06

e.g. T^6: 36 moduli (geometric deformations)

internal metric: $6 \times 7/2 = 21 = 9 + 2 \times 6$

type IIB RR 2-form: $6 \times 5/2 = 15 = 9 + 2 \times 3$

$$\text{complexification} \Rightarrow \begin{cases} \text{Kähler class} & J \\ \text{complex structure} & \tau \end{cases}$$

9 complex moduli for each

magnetic flux: 6×6 antisymmetric matrix F

complexification $\Rightarrow$

$F_{(2,0)}$ on holomorphic 2-cycles: potential for τ

$F_{(1,1)}$ on mixed (1,1)-cycles: potential for J

T^6 parametrization/complexification

$x^i \equiv x^i + 1 \quad y_i \equiv y_i + 1 \quad i = 1, 2, 3$

$z^i = x^i + \tau^{ij} y_i$

τ: 3×3 complex structure matrix

$\delta g_{i\bar{j}}$: Kähler deformations

$\rightarrow J = \delta g_{i\bar{j}} i dz_i \wedge d\bar{z}_j$

W : covering map

of the brane world-volume over T^6

$N = 1$ SUSY conditions:

1. $F_{(2,0)} = 0 \quad \Rightarrow \tau$

   $\tau^{\mathsf{T}} p_{xx} \tau - (\tau^{\mathsf{T}} p_{xy} + p_{yx} \tau) + p_{yy} = 0$

2. $J \wedge J \wedge F_{(1,1)} = F_{(1,1)} \wedge F_{(1,1)} \wedge F_{(1,1)} \quad \Rightarrow J$

   vanishing of a Fayet-Iliopoulos term

   $\xi \sim F \wedge F \wedge F - J \wedge J \wedge F$

   e.g. $T^6 = \prod_{i=1}^3 T_i^2 \leftarrow$ orthogonal 2-torus

   $\tau_i = i R_i^x / R_i^y \quad J_i = R_i^x R_i^y \quad H_i^a = F_i^a / J_i$

   $H_1 + H_2 + H_3 = H_1 H_2 H_3 \Leftrightarrow \theta_1 + \theta_2 + \theta_3 = 0$

3. $\det W(J \wedge J \wedge J - J \wedge F \wedge F) > 0$

   action positivity

Main ingredients for moduli stabilization

- "oblique" (non-commuting) magnetic fields

  $\Rightarrow$ fix off-diagonal components of the metric

  e.g. can be made diagonal

- Non linear DBI action $\Rightarrow$ fix overall volume

  not valid in six dimensions: $J \wedge F = 0$

Stabilization of RR moduli

- Kähler class: absorbed by massive $U(1)$'s

  kinetic mixing with magnetized $U(1)$'s

  10d : $dC_2 \wedge \star(A^a \wedge \langle F^a \rangle)$

  $\Rightarrow$ need at least 9 brane stacks

- Complex structure: get potential

  through mixing with NS moduli

Bianchi-Trevigne '05

Stack $\sharp$	Fluxes	Fixed moduli	$5-$brane localization
$\sharp 1$ $N_1 = 1$	$(F^1_{x_1y_2}, F^1_{x_2y_1}) = (1,1)$	$\tau_{31} = \tau_{32} = 0$ $\tau_{11} = \tau_{22}$ $\mathrm{Re}J_{1\bar{2}} = 0$	$[x_3, y_3]$
$\sharp 2$ $N_2 = 1$	$(F^2_{x_1y_3}, F^2_{x_3y_1}) = (1,1)$	$\tau_{21} = \tau_{23} = 0$ $\tau_{11} = \tau_{33}$ $\mathrm{Re}J_{1\bar{3}} = 0$	$[x_2, y_2]$
$\sharp 3$ $N_3 = 1$	$(F^3_{x_1x_2}, F^3_{y_1y_2}) = (1,1)$	$\tau_{13} = 0\,,\ \tau_{11}\tau_{22} = -1$ $\mathrm{Im}J_{1\bar{2}} = 0$	$[x_3, y_3]$
$\sharp 4$ $N_4 = 1$	$(F^4_{x_2x_3}, F^4_{y_2y_3}) = (1,1)$	$\tau_{12} = 0$ $\mathrm{Im}J_{2\bar{3}} = 0$	$[x_1, y_1]$
$\sharp 5$ $N_5 = 1$	$(F^5_{x_1x_3}, F^5_{y_1y_3}) = (1,1)$	$\mathrm{Im}J_{1\bar{3}} = 0$	$[x_2, y_2]$
$\sharp 6$ $N_6 = 1$	$(F^6_{x_2y_3}, F^6_{x_3y_2}) = (1,1)$	$\mathrm{Re}J_{2\bar{3}} = 0$	$[x_1, y_1]$

Last column: 5-brane charge localization on the 2-cycles $[x_i, y_i]$

Fix areas of the 3 T^2's $\Rightarrow$ add 3 more stacks:

Stack$\sharp$	Multiplicity	Fluxes
$\sharp$7	$N_7 = 1$	$(F^7_{x_1y_1}, F^7_{x_2y_2}, F^7_{x_3y_3}) = (-4, -4, 3)$
$\sharp$8	$N_8 = 2$	$(F^8_{x_1y_1}, F^8_{x_2y_2}, F^8_{x_3y_3}) = (-3, 1, 1)$
$\sharp$9	$N_9 = 3$	$(F^9_{x_1y_1}, F^9_{x_2y_2}, F^9_{x_3y_3}) = (-2, 3, 0)$

$$\Rightarrow \begin{pmatrix} F^7_1 & F^7_2 & F^7_3 \\ F^8_1 & F^8_2 & F^8_3 \\ F^9_1 & F^9_2 & F^9_3 \end{pmatrix} \begin{pmatrix} J_2J_3 \\ J_1J_3 \\ J_1J_2 \end{pmatrix} = \begin{pmatrix} F^7_1F^7_2F^7_3 \\ F^8_1F^8_2F^8_3 \\ F^9_1F^9_2F^9_3 \end{pmatrix}$$

here: $i = 1, 2, 3 \equiv i\bar{i}$

$$\Rightarrow \tau_{ij} = i\delta_{ij} \quad (J_{x_1y_1}, J_{x_2y_2}, J_{x_3y_3}) = 4\pi^2\alpha'\sqrt{\tfrac{3}{22}}(44, 66, 19)$$

- large volume:

\- rescale all fluxes and all J_I $\Rightarrow$ three large T^2

tadpole conditions remain invariant

Tadpole conditions

$Q_9 = \sum_a N_a \det W_a = 16$ $\leftarrow$ O9 charge

$Q_5 = \sum_a N_a \det W_a \epsilon^{\alpha\beta\gamma\delta\sigma\tau} p^a_{\gamma\delta} p^a_{\sigma\tau} = 0$

$\forall$ 2-cycle $\alpha, \beta = 1, \ldots, 6$

SUSY + tadpole conditions seem incompatible

- use 9 magnetized branes to fix all moduli

  impose SUSY conditions

- introduce an extra brane(s)

  to satisfy RR tadpole cancellation

  $\Rightarrow$ dilaton potential from the FI D-term

$\Rightarrow$ two possibilities:

- keep SUSY by turning on charged scalar VEVs

I.A.-Kumar-Maillard '06

D-term condition (2) is modified to:

$$qv^2(J\wedge J\wedge J - J\wedge F\wedge F) = -(F\wedge F\wedge F - F\wedge J\wedge J)$$

- EFT validity $\Rightarrow$ $v < 1$ in string units

- Infinite family of (large volume) solutions

  invariance: $\{F_a, J\} \to \{\Lambda F_a, \Lambda J\}$ for $\Lambda \in \mathbb{N}$

- fixing the dilaton?

combine magnetic and 3-form fluxes

3-brane charge $\Rightarrow$ $T^6/\mathbb{Z}_2$ with O3 planes

magnetized D7-branes

- break SUSY in a AdS vacuum

I.A.-Derendinger-Maillard in preparation

add a 'non-critical' dilaton potential

Tadpole cancellations + fix charged scalar VEVs

Stack $\sharp$	Multiplicity	Fluxes
$\sharp 7$	$N_7 = 1$	$(F^7_{x_1y_1}, F^7_{x_2y_2}, F^7_{x_3y_3}) = (-4, -4, 3)$
$\sharp 8$	$N_8 = 2$	$(F^8_{x_1y_1}, F^8_{x_2y_2}, F^8_{x_3y_3}) = (-3, 1, 1)$
$\sharp 9$	$N_9 = 3$	$(F^9_{x_1y_1}, F^9_{x_2y_2}, F^9_{x_3y_3}) = (-2, 3, 0)$
$\sharp 10$	$N_{10} = 2$	$(F^{10}_{x_1y_1}, F^{10}_{x_2y_2}, F^{10}_{x_3y_3}) = (5, 1, 2)$
$\sharp 11$	$N_{11} = 2$	$(F^{11}_{x_1y_1}, F^{11}_{x_2y_2}, F^{11}_{x_3y_3}) = (0, 4, 1)$

$$\Rightarrow \ \tau_{ij} = i\delta_{ij} \quad (J_{x_1y_1}, J_{x_2y_2}, J_{x_3y_3}) = 4\pi^2\alpha'\sqrt{\frac{3}{22}}(44, 66, 19)$$

$$v_{10}^2\alpha' \simeq \frac{0.71}{q} \simeq 0.35 \quad v_{11}^2\alpha' \simeq \frac{0.31}{q} \simeq 0.15$$

v_{10}, v_{11}: antisymmetric reps $(q = 2) \Rightarrow$

$$SU(2)\times SU(3)\times U(2)^2 \to SU(2)\times SU(3)\times SU(2)^2$$

Effective field theory

Magnetized branes with stabilized moduli:

$N = 1$ SUSY + a second SUSY in the bulk

non-linearly realized on the branes

'away' from the orientifold

gauge multiplet$\Big|_{N=2}$ = (vector W + chiral X)$_{N=1}$

$$\mathcal{L}_{Maxwell} = \frac{1}{4}\int d^2\theta \left(W^2 - \frac{1}{2}X\overline{DDX}\right) + c.c.$$

Non-linear constraint: $\frac{1}{\kappa}X = W^2 - \frac{1}{2}X\overline{DDX}$

Rocek-Tseytlin 78, 98

$\Rightarrow$ X can be solved in terms of W

goldstino multiplet of NL SUSY

Bagger-Halperin 96

$\delta W = \frac{i}{\kappa}\eta + \ldots \leftarrow$ linear susy

$$\Rightarrow \mathcal{L}_{N=2} = \frac{1}{4\kappa g^2}\int d^2\theta X + c.c. = \mathcal{L}^{\text{DBI}}_{N=1}$$

$$X = \kappa W^2 - \kappa^3 \bar{D}^2 \frac{W^2\overline{W}^2}{1+A_+ + \sqrt{1+2A_+ + A_-^2}}$$

where $A_\pm = \frac{\kappa^2}{2}\left(D^2W^2 \pm \bar{D}^2\overline{W}^2\right) = \pm A_\pm^*$

The FI term is also invariant under NL SUSY

$$\mathcal{L}_{FI} = \xi \int d^4\theta V \quad ; \quad W = -\tfrac{1}{4}\bar{D}^2 DV$$

$$\delta V = \frac{i}{2\kappa}\left(\eta D + \bar{\eta}\bar{D}\right)\theta^2\bar{\theta}^2 + \ldots$$

General form of the localized dilaton potential:

$$V(\phi, d) = \frac{e^{-\phi}}{g^2}\left\{\left(\sqrt{1-\underset{\text{DBI action}}{d^2}} - 1\right) + \underset{\text{FI-term}}{\xi d} + \delta T\right\}$$

d: D-auxiliary in $2\pi\alpha'$-units

δT: tension leftover RR tadpole cancellation

$$\Rightarrow \ \delta T = 1 - \sqrt{1-\xi^2}$$

d elimination $\Rightarrow \ d = \frac{\xi}{\sqrt{1+\xi^2}}$

$$V_{\text{min}} = \delta\bar{T} e^{-\phi} \quad ; \quad \delta\bar{T} = \sqrt{1+\xi^2} - \sqrt{1-\xi^2}$$

Dilaton fixing: add a non-critical (bulk) term

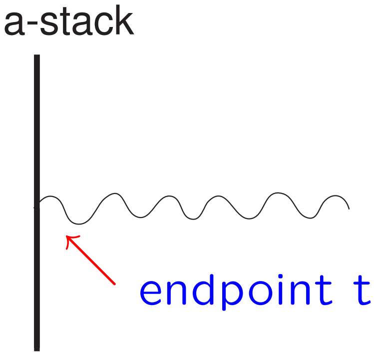
$V_{\text{non-crit}} = \delta c\, e^{-2\phi}$ $\quad$ δc: central charge deficit

Einstein frame minimization $\Rightarrow \delta c < 0$ AdS:

$$e^{\phi_0} = -\frac{2\delta c}{3\delta\bar{T}} \qquad V_0 = \frac{\delta c^3}{3\delta\bar{T}^2} \qquad R_0 = -\delta\bar{T} e^{3\phi_0}$$

Generic spectrum

N coincident branes $\Rightarrow U(N)$



endpoint transformation: $\mathbf{N}_a$ or $\bar{\mathbf{N}}_a$

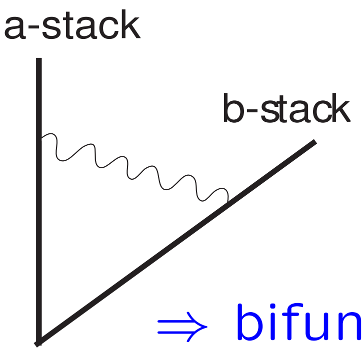
$U(1)_a$ charge: $+1$ or -1

$U(1)$: "baryon" number

- open strings from the same stack

  $\Rightarrow$ adjoint gauge multiplets of $U(N_a)$

- open strings stretched between two stacks



$\Rightarrow$ bifundamentals of $U(N_a) \times U(N_b)$

Non oriented strings $\Rightarrow$ orientifold planes

where closed strings change orientation

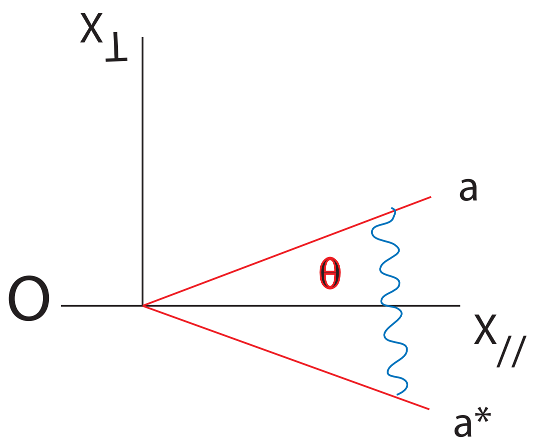
$\Rightarrow$ mirror branes

identified with branes under orientifold action

- strings stretched between two mirror stacks

Orientifold $\rightarrow$

$X_\perp \rightarrow -X_\perp$



$\Rightarrow$ antisymmetric or symmetric of $U(N_a)$

Minimal Standard Model embedding

- oriented strings $\Rightarrow$

  need at least 4 brane-stacks

- also for non-oriented strings

  with Baryon and Lepton number symmetries

I.A.-Kiritsis-Tomaras '00

I.A.-Kiritsis-Rizos-Tomaras '02

- General analysis using 3 brane stacks

  $\Rightarrow \ U(3) \times U(2) \times U(1)$

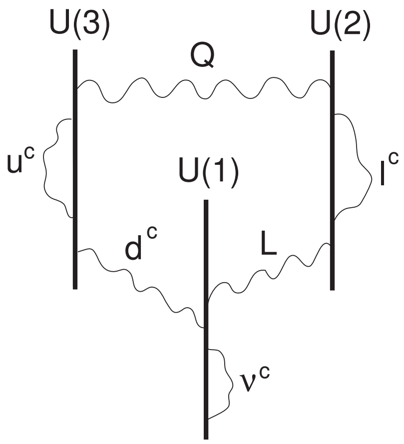
antiquarks u^c, d^c $(\bar{3}, 1)$:

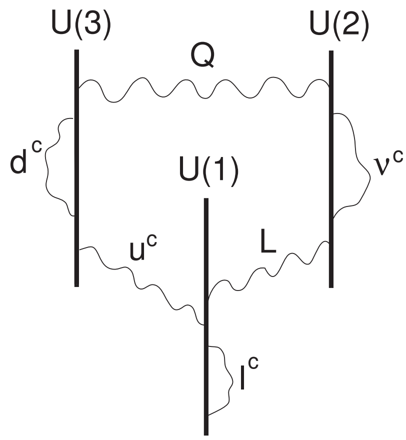
antisymmetric of $U(3)$ or

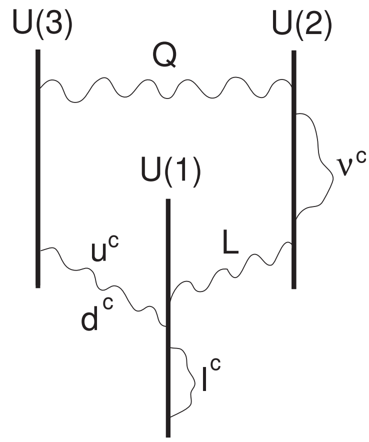
bifundamental $U(3) \leftrightarrow U(1)$

$\Rightarrow$ 3 models: antisymmetric is u^c, d^c or none

I.A.-Dimopoulos '04







	Model A	**Model B**	**Model C**
Q	$(\mathbf{3},\mathbf{2};1,1,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$	$(\mathbf{3},\mathbf{2};1,\varepsilon_Q,0)_{1/6}$
u^c	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,1)_{-2/3}$
d^c	$(\bar{\mathbf{3}},\mathbf{1};-1,0,\varepsilon_d)_{1/3}$	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{1/3}$	$(\bar{\mathbf{3}},\mathbf{1};-1,0,-1)_{1/3}$
L	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_L)_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_L,1)_{-1/2}$
l^c	$(\mathbf{1},\mathbf{1};0,2,0)_{1}$	$(\mathbf{1},\mathbf{1};0,0,-2)_{1}$	$(\mathbf{1},\mathbf{1};0,0,-2)_{1}$
ν^c	$(\mathbf{1},\mathbf{1};0,0,2\varepsilon_\nu)_{0}$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_{0}$	$(\mathbf{1},\mathbf{1};0,2\varepsilon_\nu,0)_{0}$

$$Y_A = -\frac{1}{3}Q_3 + \frac{1}{2}Q_2 \qquad\qquad Y_{B,C} = \frac{1}{6}Q_3 - \frac{1}{2}Q_1$$

Model A : $$\sin^2\theta_W = \frac{1}{2+2\alpha_2/3\alpha_3}\Big|_{\alpha_2=\alpha_3} = \frac{3}{8}$$

Model B, C : $$\sin^2\theta_W = \frac{1}{1+\alpha_2/2\alpha_1+\alpha_2/6\alpha_3}\Big|_{\alpha_2=\alpha_3} = \frac{6}{7+3\alpha_2/\alpha_1}$$

D-term SUSY breaking $\Rightarrow$

problem with Majorana gaugino masses

- lowest order: exact R-symmetry

- higher orders: suppressed by the string scale

I.A.-Taylor '04, I.A.-Narain-Taylor '05

However in toroidal models:

- gauge multiplets have extended SUSY

$\Rightarrow$ Dirac gaugino masses without $\not{R}$

- non chiral intersections have $N = 2$ SUSY

$\Rightarrow$ Higgs in $N = 2$ hypermultiplet

$\Rightarrow$ New gauge mediation mechanism

I.A.-Benakli-Delgado-Quiros '07

SM observable sector: SUSY

gauginos: extended susy, Higgs hypermultiplet

Hidden (secluded) sector: SUSY breaking

messengers: $N = 2$ hypermultiplets

with mixed quantum numbers

- Dirac gaugino masses: $\sim \frac{\alpha}{4\pi}\frac{D}{M}$
- Higgs potential:

$$V = V_{\text{soft}} + \frac{1}{8}(g^2 + g'^2)(|H_1|^2 - |H_2|^2)^2$$

$$+ \frac{1}{2}(g^2 + g'^2)|H_1 H_2|^2 \quad \Rightarrow$$

- lightest higgs h behaves as in SM

- heaviest H plays no role in EWSB, $g_{ZHH} = 0$

- same as MSSM in $\tan\beta \to \infty$

$\Rightarrow$ "little" fine tuning is greatly reduced

- Distinct collider signals different from MSSM