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Physics with magnetized branes

String Phenomenology 2008

UPenn, 28 May-1 June 2008

Outline

- Framework

Type I string with internal magnetic fields

- Moduli stabilization

Oblique magnetic fluxes

- Supersymmetry breaking

D-term gauge mediation

- A SUSY $SU(5)$ GUT with stabilized moduli

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:

  $qH \to \theta = \arctan qH\alpha'$ 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
$\sharp 1$ $N_1 = 1$	$(F^1_{x_1 y_2}, F^1_{x_2 y_1}) = (1,1)$	$\tau_{31} = \tau_{32} = 0$ $\tau_{11} = \tau_{22}$ $\mathrm{Re} J_{1\bar{2}} = 0$	$[x_3, y_3]$
$\sharp 2$ $N_2 = 1$	$(F^2_{x_1 y_3}, F^2_{x_3 y_1}) = (1,1)$	$\tau_{21} = \tau_{23} = 0$ $\tau_{11} = \tau_{33}$ $\mathrm{Re} J_{1\bar{3}} = 0$	$[x_2, y_2]$
$\sharp 3$ $N_3 = 1$	$(F^3_{x_1 x_2}, F^3_{y_1 y_2}) = (1,1)$	$\tau_{13} = 0\,,\ \tau_{11}\tau_{22} = -1$ $\mathrm{Im} J_{1\bar{2}} = 0$	$[x_3, y_3]$
$\sharp 4$ $N_4 = 1$	$(F^4_{x_2 x_3}, F^4_{y_2 y_3}) = (1,1)$	$\tau_{12} = 0$ $\mathrm{Im} J_{2\bar{3}} = 0$	$[x_1, y_1]$
$\sharp 5$ $N_5 = 1$	$(F^5_{x_1 x_3}, F^5_{y_1 y_3}) = (1,1)$	$\mathrm{Im} J_{1\bar{3}} = 0$	$[x_2, y_2]$
$\sharp 6$ $N_6 = 1$	$(F^6_{x_2 y_3}, F^6_{x_3 y_2}) = (1,1)$	$\mathrm{Re} J_{2\bar{3}} = 0$	$[x_1, y_1]$

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

$$\Rightarrow \begin{pmatrix} F^7_1 & F^7_2 & F^7_3 \\ F^8_1 & F^8_2 & F^8_3 \\ F^9_1 & F^9_2 & F^9_3 \end{pmatrix} \begin{pmatrix} J_2 J_3 \\ J_1 J_3 \\ J_1 J_2 \end{pmatrix} = \begin{pmatrix} F^7_1 F^7_2 F^7_3 \\ F^8_1 F^8_2 F^8_3 \\ F^9_1 F^9_2 F^9_3 \end{pmatrix}$$

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

Tadpole cancellations + fix charged scalar VEVs

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

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

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

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

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

- break SUSY in a dS or AdS vacuum

I.A.-Derendinger-Maillard to appear

General form of the localized dilaton potential:

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

DBI action FI-term

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:

1) by 3-form fluxes in a SUSY way

$\Rightarrow$ dS vacuum with positive energy

D-term uplifting possible from flat space

2) add a 'non-critical' (bulk) dilaton potential

$\Rightarrow$ AdS vacuum with tunable string coupling

$$V_{\text{non-crit}} = \delta c\, e^{-2\phi}$$

central charge deficit

minimization of $V = V_{\text{non-crit}} + V_{\text{min}} \Rightarrow \delta c < 0$

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

curvature in Einstein frame

e.g. replace a free coordinate by a CFT minimal model

with central chage $1 + \delta c$

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

Spectrum multplicities

$(N_a, \bar{N}_b)$: $I_{ab} = \mathrm{det}W_a \mathrm{det}W_b \int_{T^6} \left(F^a_{(1,1)} - F^b_{(1,1)}\right)^3$

(N_a, N_b): $I_{ab^*} \leftarrow F^{b^*} = -F^b$

$T^6 = \prod_i T_i^2 \Rightarrow I_{ab} = \prod_i (m_i^a n_i^b - n_i^a m_i^b)$

$$I_{aa^*} = \prod_i \left\{\tfrac{1}{2}(2m_i^a n_i^a \mp 2m_i^a) \pm 2m_i^a\right\}$$

number of intersections along orientifold axis $(0, x)$

$$= \begin{cases} \text{Antisymmetric}: \frac{1}{2}\left(\prod_i 2m_i^a\right)\left(\prod_j n_j^a + 1\right) \\ \text{Symmetric}: \frac{1}{2}\left(\prod_i 2m_i^a\right)\left(\prod_j n_j^a - 1\right) \end{cases}$$

- non-chiral multiplicity: extract the vanishing factors
- $I_{ab^*} = 0 \rightarrow I_{ab}$ even $\Rightarrow$

  odd nb of generations: constant NS B-field

quantization $\rightarrow$ magnetic fluxes m half-intergers

SUSY $SU(5)$ with stabilized moduli

I.A.-Panda-Kumar '07

12 brane-stacks: $U_5,\ U_1,\ O_1,\ldots,O_8,\ A,\ B$

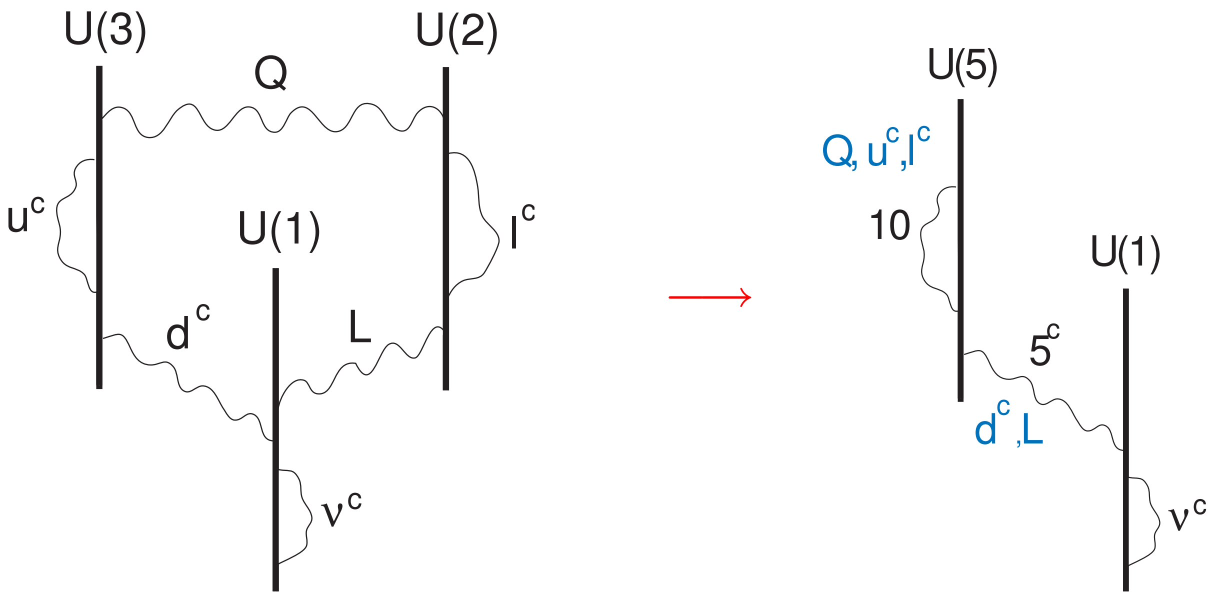
$$\underbrace{U(5)\times U(1)}\quad \times \quad U(1)^{10}$$

winding matrix $W = \mathbb{1}$, B-field $B_{x_i y_i} = \frac{1}{2}$

- $I_{U_5 U_5^*} = I_{U_5^* U_1} = 3 \Rightarrow$ 3 generations $(\mathbf{10} + \bar{\mathbf{5}})$
- $I_{U_5 U_1} = 0 \Rightarrow$ Higgs pairs $(\mathbf{5} + \bar{\mathbf{5}})$
- $I_{U_5 a} + I_{U_5 a^*} = 0,\ \forall a \neq U_5, U_1$

  $\Rightarrow$ no other $SU(5)$ chiral states
- $O_1,\ldots,O_8$: set of oblique fluxes for $B \neq 0$

  with diagonal induced 5-brane tadpoles



Q	$(\mathbf{3},\mathbf{2};1,1,0)_{1/6}$
u^c	$(\bar{\mathbf{3}},\mathbf{1};2,0,0)_{-2/3}$
d^c	$(\bar{\mathbf{3}},\mathbf{1};-1,0,\varepsilon_d)_{1/3}$
L	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_L)_{-1/2}$
l^c	$(\mathbf{1},\mathbf{1};0,2,0)_1$
ν^c	$(\mathbf{1},\mathbf{1};0,0,2\varepsilon_\nu)_0$

$$Y_A = -\frac{1}{3}Q_3 + \frac{1}{2}Q_2$$

$$\Rightarrow \qquad \sin^2\theta_W = \left.\frac{1}{2+2\alpha_2/3\alpha_3}\right|_{\alpha_2=\alpha_3} = \frac{3}{8}$$

• SUSY conditions on $U_5, O_1, \ldots, O_8 \Rightarrow$

fix all geometric moduli to diagonal metric

$U(1)^9$ massive (absorb the RR Kähler moduli)

• Tadpole cancellation $\Rightarrow$ add branes A, B

• SUSY D-flatness on $U_1, A, B \Rightarrow$

charged scalar VEVs $\neq 0$ on their intersections:

- satisfy perturbativity constraint

- break $U(1)^3$

$\Rightarrow$ leftover gauge group: $SU(5)$

gauge non-singlet chiral spectrum:

three generations of quarks + leptons

Conclusions

Internal magnetic fields:

simple framework, exact string description,

$N = 1$ SUSY with chiral fermions

Moduli stabilization: 'oblique' magnetic fluxes

general: Kähler $\Rightarrow$ complem. to 3-form fluxes

toroidal: all geometric $+$ eventually the dilaton

Model building

natural implementation in intersecting branes

D-term SUSY breaking $\Rightarrow$

new mechanism of gauge mediation

Dirac gauginos, $N = 2$ Higgs potential