Physics with magnetized branes

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1. main questions in string phenomenology
   general issues of high string scale
2. framework of magnetized branes
   moduli stabilization, model building, Yukawa couplings
   SUSY breaking and D-term gauge mediation

STRINGS 2008
CERN | Geneva

- Are there low energy string predictions testable at LHC ?
- What can we hope from LHC on string phenomenology ?

Very different answers depending mainly on the value of the string scale M_s

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV
- physical motivations $\Rrightarrow$ favored energy regions:

- High : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$

- Intermediate : around 10^{11} GeV ($M_s^2/M_P \sim$ TeV)

  SUSY breaking, strong CP axion, see-saw scale

- Low : TeV (hierarchy problem)

• Low string scale $\Rightarrow$ experimentally testable framework

- spectacular model independent predictions

perturbative type I string setup

see Lust's talk for recent developments

- radical change of high energy physics at the TeV scale

explicit model building is not necessary at this moment

but unification has to be probably dropped

• Intermediate string scale :

not directly testable but interesting possibility with several implications

$\rightarrow$ 'large volume' compactifications

• High string scale :

perturbative heterotic string : the most natural for SUSY and unification

prediction for GUT scale but off by almost 2 orders of magnitude

introduce large threshold corrections or strong coupling $\rightarrow M_s \simeq M_{\rm GUT}$

but loose predictivity

$\Rightarrow$ other string theories:

- intersecting branes in extra dimensions: IIA, IIB, F-theory
- Heterotic M-theory
- internal magnetic fields in type I

Main problems: - gauge coupling unification is not automatic

different coupling for every brane stack, or incomplete GUT representations

- No top Yukawa coupling in D-brane GUT constructions

Maximal predictive power if there is common framework for :

- moduli stabilization
- model building (spectrum and couplings)
- SUSY breaking (calculable soft terms)
- computable radiative corrections (crucial for comparing models)

Possible candidate of such a framework: **magnetized branes**

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

- Dirac quantization: $H = \frac{m}{nA} \equiv \frac{p}{A}$ [10] $\Rightarrow$ moduli stabilization

  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: $\Rightarrow$ calculability

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

- T-dual representation: branes at angles $\Rightarrow$ model building

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

Magnetic fluxes can be used to stabilize moduli

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

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

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

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

$$\text{complexification:} \begin{cases} \text{Kähler class} & J \\ \text{complex structure} & \tau \end{cases} \quad \text{9 complex moduli for each}$$

magnetic flux: 6×6 antisymmetric matrix F complexification $\Rightarrow$

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

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

$N=1$ SUSY conditions $\Rightarrow$ moduli stabilization

1. $F_{(2,0)} = 0 \;\Rightarrow \tau$ matrix equation for every magnetized $U(1)$

   need 'oblique' (non-commuting) magnetic fields to fix off-diagonal components of the metric $\leftarrow$ but can be made diagonal

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

   vanishing of a Fayet-Iliopoulos term: $\xi \sim F \wedge F \wedge F - J \wedge J \wedge F$

   magnetized $U(1) \rightarrow$ massive absorbs RR axion

   one condition $\Rightarrow$ need at least 9 brane stacks

3. Tadpole cancellation conditions : introduce an extra brane(s)

   $\Rightarrow$ dilaton potential from the FI D-term $\rightarrow$ two possibilities:

   - keep SUSY by turning on charged scalar VEVs
   - break SUSY in a dS or AdS vacuum $d = \xi/\sqrt{1+\xi^2}$ [11]

I.A.-Derendinger-Maillard '08

$F_{(2,0)} = 0 \Rightarrow \qquad \tau^{\mathrm{T}} p_{xx} \tau - (\tau^{\mathrm{T}} p_{xy} + p_{yx} \tau) + p_{yy} = 0$ [7]

T^6 parametrization: $(x^i, y^i) \quad i = 1, 2, 3 \qquad z^i = x^i + \tau^{ij} y^i$

Non-trivial VEVs v for charged brane scalars $\Rightarrow$

D-term condition is modified to:

$$q\, v^2 \, (J \wedge J \wedge J - J \wedge F \wedge F) = -(F \wedge F \wedge F - F \wedge J \wedge J)$$

charge

New gauge mediation mechanism

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

D-term SUSY breaking:

- problem with Majorana gaugino masses   lowest order R-symmetry broken at higher orders but suppressed by the string scale

  I.A.-Taylor '04, I.A.-Narain-Taylor '05
- tachyonic squark masses

However in toroidal models gauge multiplets have extended SUSY $\Rightarrow$

- Dirac gauginos without $\not{R}$ $\Rightarrow m_{1/2} \sim d/M$
- Squark masses can arise dominantly from gauginos $\Rightarrow m_0^2 \sim d^2/M^2$

Also non-chiral intersections have $N = 2$ SUSY $\Rightarrow$ $N = 2$ Higgs potential

oblique fluxes $\Rightarrow$ non-commuting boundary conditions

boundary CFT similar to non-abelian orbifolds

However spectrum involves only 2 branes : $a, b \leftarrow$ can be orientifold image

$$\Rightarrow \text{depends on relative flux : } R_a R_b^{-1} \qquad R_a \equiv (\mathbb{1} - F^a)(\mathbb{1} + F^a)^{-1}$$

Bianchi-Trevigne '05

can go to a basis where $R_a R_b^{-1}$ is diagonal $\rightarrow$ mass eigenvalues

Multiplicities : 'intersection' matrix $N^{ab} = F^a - F^b$

gives no of fermion 0-modes in all $(1,1)$-cycles

$$\Rightarrow \text{total mutiplicity : } I^{ab} = \det N^{ab}$$

Non-commutativity shows in ineractions e.g. 3-pt functions

Yukawa couplings $\equiv$ overlap integral of 3 wave functions

$$\lambda_{ijk} = g\sigma_{ijk} \int_{T^6} \psi_i^{N^{ab}} \psi_j^{N^{bc}} \psi_k^{N^{ca}} \qquad N^{ab} + N^{bc} + N^{ca} = 0$$

commuting case in factorized $T^6 = (T^2)^3 \Rightarrow \lambda$'s products over 3 T^2's

on a T^2 : chirality $\rightarrow$ analyticity

$$\psi_i^N \propto \begin{cases} \theta_i(N\tau, Nz) & N > 0 \quad + \text{ve helicity} \\ \theta_i^*(N\bar{\tau}, N\bar{z}) & N < 0 \quad - \text{ve helicity} \end{cases}$$

fusion of 2 wave functions $\rightarrow$ orthogonality : Riemann theta identity

$T^2 \rightarrow T^6$ with oblique fluxes $\rightarrow$ 2 main problems :

1. wave function : analyticity vs general helicity

   N : eigenvalues of different sign

2. fusion generalization $\rightarrow$ express Yukawa's in a closed form

special case: $N\,\mathrm{Im}\tau$ orthogonal and positive definite

$\Rightarrow$ generalized θ-functions $\theta_i(N\tau, N\vec{z})$ Cremades-Ibanez-Marchesano '04

wave functions and Yukawa's for oblique fluxes

General solution: I.A.-Panda-Kumar '09

1. wave function : relax extra conditions

   (i) fluxes : general hermitian matrices

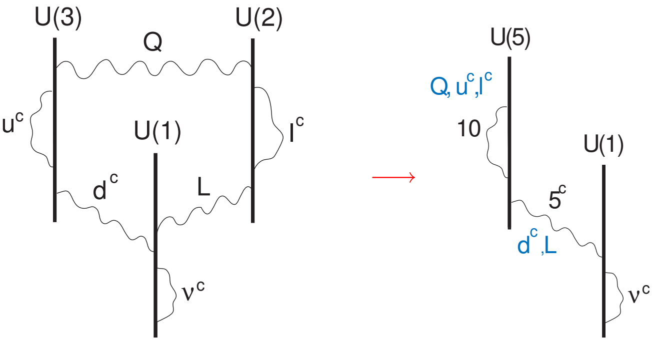
   (ii) relax positivity $\Rightarrow$ general helicity

   map from all positive helicities to sign flip of one eignevalue

   $\Rightarrow \tau \rightarrow \hat{\tau}\tau$ where $\hat{\tau}[N^{ab}]$

2. Yukawa couplings : generalize Riemann θ-function identity

   new mathematical identities not given in Mumford Tata lectures



Full string embedding with all geometric moduli stabilized:

- all extra $U(1)$'s broken $\Rightarrow$ gauge group just susy $SU(5)$
- gauge non-singlet chiral spectrum: 3 generations of quarks + leptons
- SUSY can be broken in an extra $U(1)$ factor by D-term [18]

SUSY $SU(5)$ with stabilized moduli

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

$$\underbrace{U(5)}_{\to U_5} \times \underbrace{U(1)}_{\to U_1} \times \underbrace{U(1)^{10}}_{\to O_1,\ldots,O_8}$$

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

- 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:

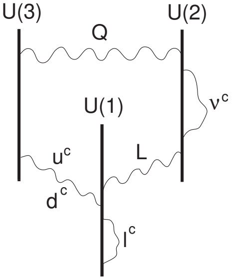
- satisfy perturbativity constraint
- break $U(1)^3$

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

gauge non-singlet chiral spectrum: 3 generations of quarks + leptons

Problem common in all D-brane GUTs: absence of top Yukawa coupling

can be avoided in a $U(3) \times U(2) \times U(1)$ 3-stack model



$\Rightarrow HQu^c, H'Qd^c \neq 0$ all Yukawa's exist

but unification is not guaranteed

although not excluded

e.g. $\alpha_2 = \alpha_3$ at 1% is guaranteed by:

(i) the correct SM spectrum: no chiral color sextets, weak triplets and antiquark doublets

(ii) weak magnetic fields $\Rightarrow M_{\mathrm{GUT/comp}} \sim M_s/3$

Conclusions

Internal magnetic fields:

simple framework, exact string description,

$N = 1$ SUSY with chiral fermions

Moduli stabilization: 'oblique' magnetic fluxes

general: Kähler $\Rightarrow$ complementary 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