Physics with magnetized branes

I. Antoniadis

CERN

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1. main questions in string phenomenology
2. phenomenology of low string scale
3. general issues of high string scale
4. 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

- 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

- particle accelerators
  - TeV extra dimensions $\Rightarrow$ · KK resonances of SM gauge bosons
  - Extra large submm dimensions $\Rightarrow$ missing energy: gravity radiation
  - string physics and possible strong gravity effects :
    - · string Regge excitations [6]
    - · production of micro-black holes ? [9]
- microgravity experiments

  change of Newton's law, new forces at short distances [11] [12] string realization of large extra dimensions

I.A.-Arkani Hamed-Dvali-Dimopoulos '98

by 'swiss cheese' Calabi-Yau's ('large volume' compactifications) :

Balasubramanian-Berglund-Cicoli-Conlon-Quevedo-Suruliz '05-'08

Requirements:

- CY with $h_{21} > h_{11} > 1$
- 3-form fluxes as KKLT
- SM on D7-branes wrapped small cycles
- at least one blow-up mode (point-like singularity)
- blow-up mode fixed by non-perturbative effects

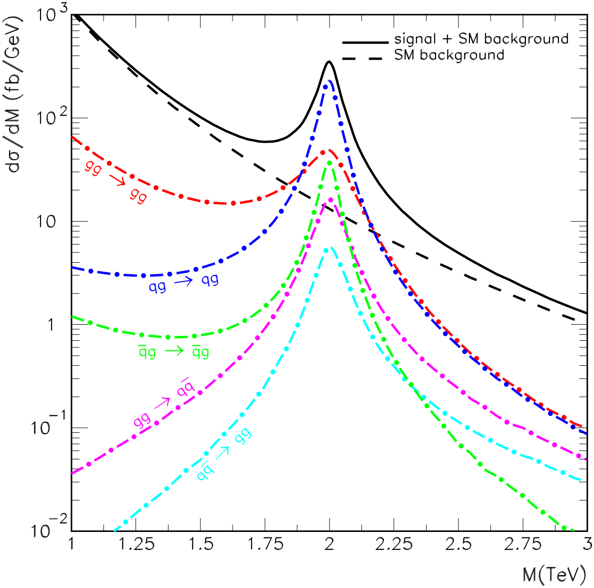
  volume by α'-corrections $\rightarrow$ exponentially large

Universal deviation from Standard Model in jet distribution

$M_s = 2$ TeV

Width $=$ 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08 [4]



Tree N-point superstring amplitudes in 4 dims

involving at most 2 fermions and gluons:

completely model independent for any string compactification

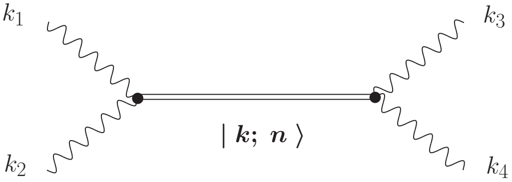
any number of supersymmetries, even none

No intermediate exchange of KK, windings or graviton emmission

Universal sum over infinite exchange of string Regge (SR) excitations:

masses: $M_n^2 = M_s^2\, n$

maximal spin: $n + 1$



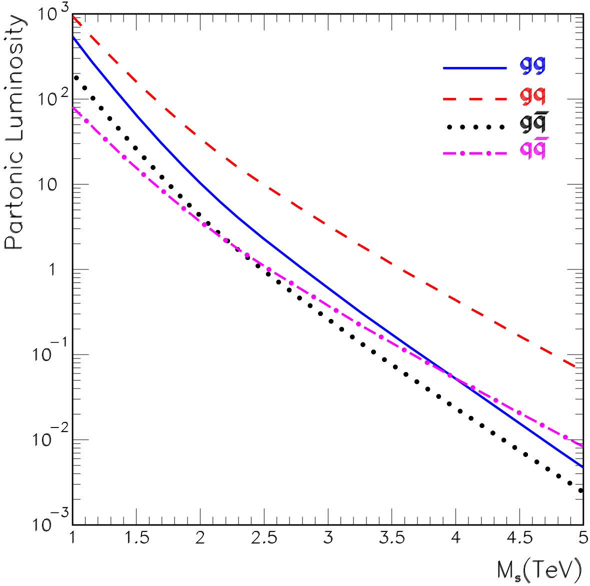
Parton luminosities in pp above TeV

are dominated by gq, gg

$\Rightarrow$ model independent [6]

$gq \to gq$

$gg \to gg$, $gg \to q\bar{q}$



Energy threshold for black hole production :

$$E_{\rm BH} \simeq M_s/g_s^2 \quad \leftarrow \text{ string coupling}$$

Horowitz-Polchinski '96, Meade-Randall '07

weakly coupled theory $\Rightarrow$

strong gravity effects occur much above M_s, $M_P^* \simeq M_s/g_s^{2/(2+d_\perp)}$

higher-dim Planck scale bulk dimensionality

$g_s \simeq \alpha_{\rm YM} \sim 0.1$; Regge excitations : $M_n^2 = M_s^2 n \Rightarrow$

gauge coupling

Energy threshold of n-th string excitation: $E_n \simeq M_s\sqrt{n} \Rightarrow$

production of $n \sim 1/g_s^4 \sim 10^4$ string states before reach $E_{\rm BH}$ [4]

- Newton constant: $G_N \sim g_s^2$ in string units $l_s = M_s = 1$

- string size black hole: $r_H \sim 1$

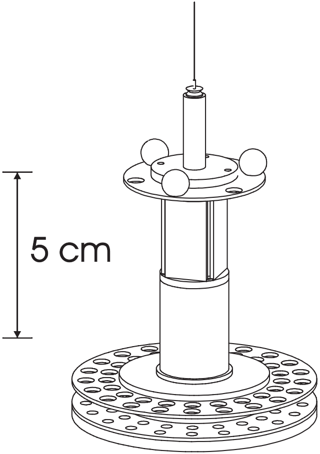
  $\Rightarrow$ black hole mass: $M_{\rm BH} \sim 1/G_N \simeq 1/g_s^2$

  $\uparrow$

  valid in any dimension d: $r_H^{d/2-1}$

- black hole entropy $S_{\rm BH} \sim 1/G_N \sim 1/g_s^2 \sim \sqrt{n}$: string entropy

Adelberger et al. '06



$R_\perp \lesssim 45\ \mu$m at 95% CL

- dark-energy length scale $\approx 85\mu$m [4]

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

$M_s = g_H\, M_P \simeq 50\, M_{\mathrm{GUT}} \qquad g_H^2 \simeq \alpha_{\mathrm{GUT}} \simeq 1/25$

introduce large threshold corrections or strong coupling $\to\ M_s \simeq M_{\mathrm{GUT}}$

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: $H = \frac{m}{nA} \equiv \frac{p}{A}$ [17] $\Rightarrow$ 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 $d = \xi/\sqrt{1+\xi^2}$ [20]

I.A.-Derendinger-Maillard '08

$F_{(2,0)} = 0 \;\Rrightarrow\; \tau^{\mathrm{T}} p_{xx} \tau - (\tau^{\mathrm{T}} p_{xy} + p_{yx}\tau) + p_{yy} = 0$ [14]

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 $\Rrightarrow$

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

break SUSY in a dS or AdS vacuum

I.A.-Derendinger-Maillard '08

$N = 2$ non-linear supersymmetry $\Rightarrow$

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

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

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

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

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

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

curvature in Einstein frame

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

with central chage $1 + \delta c$

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

New problem: extra adjoint scalars $\Rightarrow$ new tachyons and tadpoles

$\rightarrow$ extra conditions: work in progress   Anastasopoulos-I.A.-Vichi

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

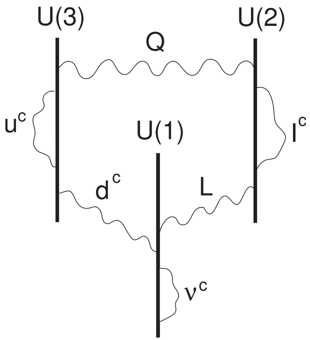
   (ii) relax positivity $\Rightarrow$ general helicity

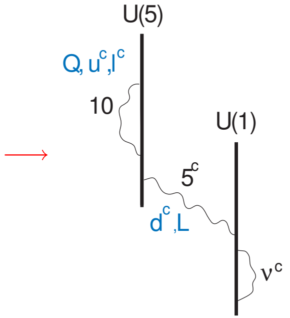
   map from all positive helicities to sign flip of one eignevalue

   $\Rightarrow \tau \rightarrow \hat{\tau}\tau$ 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 [27]

SUSY $SU(5)$ with stabilized moduli

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

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

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

- $I_{U_5U_5^*}=I_{U_5^*U_1}=3 \Rightarrow$ 3 generations $(\mathbf{10}+\bar{\mathbf{5}})$
- $I_{U_5U_1}=0 \Rightarrow$ Higgs pairs $(\mathbf{5}+\bar{\mathbf{5}})$
- $I_{U_5a}+I_{U_5a^*}=0,\ \forall a\neq U_5,U_1 \Rightarrow$ no other $SU(5)$ chiral states
- $O_1,\dots,O_8:$ 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:

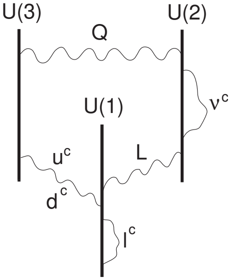
- satisfy perturbativity constraint
- break $U(1)^3$

$\Rightarrow$ 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 $\Rightarrow M_{\rm GUT/comp} \sim M_s/3$

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