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Magnetic Fluxes

Split Supersymmetry

and

Moduli Stabilization

Outline

- Motivations
- Framework

  Type I string theory with magnetized D9 branes

- Spectrum — with S.Dimopoulos
- gauge coupling unification

  Non abelian

  Standard Model embedding with $\sin^2\theta_W = \frac{3}{8}$ at M_{GUT}

- Mass scales
- Coupling to gravity
- Gaugino masses
- Split extended supersymmetry

  with K.Benakli, A.Delgado, M.Quirós, M.Tuckmantel

Physics beyond the Standard Model $\leftrightarrow$

stabilization of mass hierarchy?

- SUSY
- Extra dimensions
- Low string scale
- Compositeness
- Little Higgs

However actual precision tests + bounds $\Rightarrow$

already some degree of fine tuning a few % !

Need very clever theory beyond the SM

OR

Live with the hierarchy

still unknown explanation perhaps related to the cosmological constant problem

Split Supersymmetry: raise SUSY breaking scale

but keep SUSY main predictions:

unification + dark matter candidate $\Rightarrow$

keep all MSSM fermions light

but let squarks and sleptons become heavy

TeV physics: SM with a 'fine tuned' light Higgs

+ gauginos + a pair of higgsinos

All MSSM 'problems' solved:

FCNC, B/L violation, CP, nb of parameters,...

Main signatures of split susy:

- squarks superheavy $\Rightarrow$ long lived gluino

$$\tau_g \simeq \left(3 \times 10^{-2}\mathrm{s}\right)\left(\frac{m_0}{10^9\mathrm{GeV}}\right)^4\left(\frac{1\,\mathrm{TeV}}{m_g}\right)^5$$

$\Rightarrow$ display vertices

late decays captured near the detector, etc

- susy unification of 5 couplings at m_0:

$$\Delta\mathcal{L} = \sqrt{2}g_u H^\dagger \tilde{W}\psi_u + \sqrt{2}g_d H\tilde{W}\psi_d +$$

$$\frac{1}{\sqrt{2}}g'_u H^\dagger \tilde{B}\psi_u - \frac{1}{\sqrt{2}}g'_d H\tilde{B}\psi_d - \frac{\lambda}{2}(H^\dagger H)^2$$

higgsinos

susy relations: $g_u = g\sin\beta,\ g_d = g\cos\beta,\ g'_u = g'\sin\beta$

$$g'_d = g\cos\beta,\ \lambda = \frac{1}{4}(g^2 + g'^2)\cos^2 2\beta$$

$\Rightarrow$ 5 relations in terms of one parameter

General framework

- Type I string theory compactified in 4d on 6d Calabi-Yau

$\Rightarrow$ $N = 2$ SUSY in the bulk, $N = 1$ on branes

- Magnetic fluxes on 2-cycles

$\Rightarrow$ SUSY breaking

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 all charged states

$[p_i, p_j] = iqH\epsilon_{ij}$ $\qquad$ q: charge

$\Rightarrow$ Landau spectrum

6d $\to$ 4d on T^2 with abelian magnetic field H

$\delta M^2 = (2k+1)|qH| + 2qH \cdot \Sigma$ $\leftarrow$ spin operator

$k = 0, 1, 2, \ldots$: Landau level

Landau multiplicity: mn

- spin-0: $\Sigma = 0 \Rightarrow$ mass gap

- spin-1/2: $\Sigma = \pm 1/2 \Rightarrow$ chiral 0-mode

$k = 0 \quad : \quad \delta M^2 = |qH| \pm qH$

$\Rightarrow \quad \delta M^2 = 0 \quad$ for $\Sigma = -1/2$ $(qH > 0)$

- spin-1: $\Sigma = \pm 1 \Rightarrow$ tachyon

Nielsen-Olesen instability

$k = 0 \quad : \quad \delta M^2 = |qH| \pm 2qH$

$\Rightarrow \quad \delta M^2 = -qH \quad$ for $\Sigma = -1$ $(qH > 0)$

Exact open string description:

$q \longrightarrow q_L + q_R$ endpoint charges

$qH \longrightarrow \theta_L + \theta_R \quad ; \quad \theta_{L,R} = \text{arctan}\, q_{L,R} H \alpha'$

weak field limit $\Rightarrow$ field theory

H constant $\Rightarrow$ $F_{kl} = \epsilon_{kl} H \quad A_k = -\frac{1}{2} F_{kl} x^l$

world-sheet boundary action:

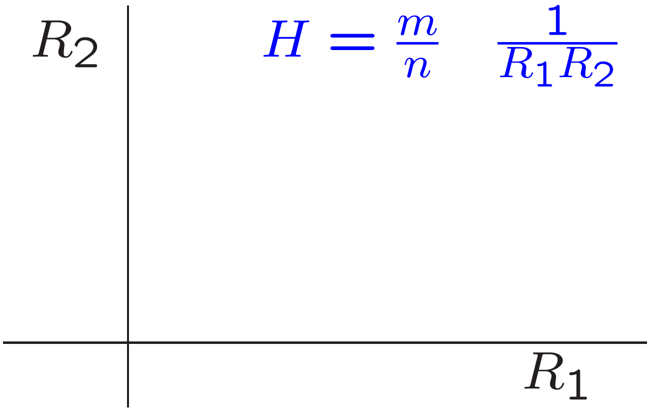
$$q \int A_k \partial x^k = -H \int \left(q_L x^k \overset{\leftrightarrow}{\partial} x^l \Big|_{\sigma=0} + q_R x^k \overset{\leftrightarrow}{\partial} x^l \Big|_{\sigma=\pi} \right)$$

internal rotation current

$\Rightarrow$ frequency shift by $\theta_{L,R}$: $\tan \theta_{L,R} = q_{L,R} H$

T-dual representation: branes at angles

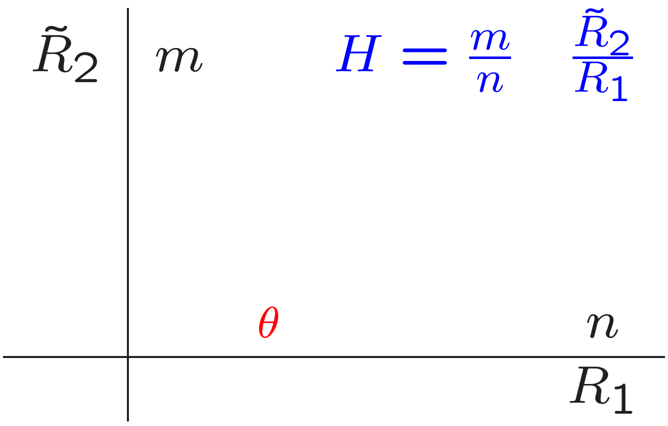
magnetized D9-brane wrapped on T^2



$$H = \frac{m}{n} \quad \frac{1}{R_1 R_2}$$

$$R_2 \to \alpha'/R_2 \equiv \tilde{R}_2 \quad \Rightarrow \text{ D8-brane}$$

wrapped around a direction of angle θ in T^2



$$H = \frac{m}{n} \quad \frac{\tilde{R}_2}{R_1} \quad = \tan\theta$$

m, n : wrapping numbers

$(T^2)^3$ generalization: H_I with $I = 1, 2, 3$

$$\delta M^2 = \sum_I \{(2k_I + 1)|qH_I| + 2qH_I\Sigma_I\}$$

- spin-1/2: one chiral 0-mode

$\delta M^2 = 0$ for $k_I = 0$ and $\Sigma_I = -1/2$ $(qH_I > 0)$

- spin-1: tachyon can be avoided   Bachas 95

$$\begin{array}{rcccccl} & |H_1| & + & |H_2| & - & |H_3| & > 0 \\ & |H_1| & - & |H_2| & + & |H_3| & > 0 \\ - & |H_1| & + & |H_2| & + & |H_3| & > 0 \end{array}$$

massless scalar $\Leftrightarrow$ partial brane susy restoration

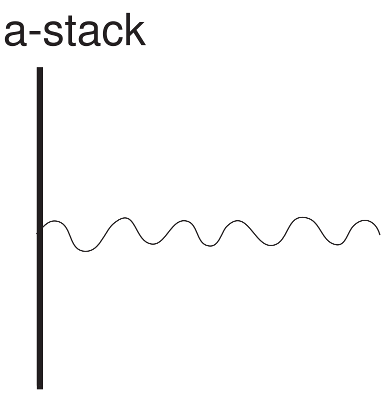
Angelantonj-I.A.-Dudas-Sagnotti 00

$$\theta_1 + \theta_2 + \theta_3 = 0$$

Generic spectrum

Turn on H_I^a in several $U(1)_a$ directions

$\Rightarrow$ Gauge group: $\prod_a U(N_a) \leftarrow SU(N_a) \times U(1)_a$



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

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

- Neutral strings: adjoint representations

  $\Rightarrow$ massless gauge supermultiplets

- Charged strings $\Rightarrow$ massless chiral fermions same stack: antisymmetric or symmetric

$$\text{multiplicities}: \begin{cases} A: \ \frac{1}{2}\left(\prod_I 2m_I^a\right)\left(\prod_J n_J^a + 1\right) \\ S: \ \frac{1}{2}\left(\prod_I 2m_I^a\right)\left(\prod_J n_J^a - 1\right) \end{cases}$$

different stacks: bifundamentals

$$\text{multiplicities}: \begin{cases} (N_a, N_b): \ \prod_I (m_I^a n_I^b + n_I^a m_I^b) \\ (N_a, \bar{N}_b): \ \prod_I (m_I^a n_I^b - n_I^a m_I^b) \end{cases}$$

$\Rightarrow$ Generic spectrum of split SUSY:

- massless gauginos
- massive squarks and sleptons
- massless Higgs $\Leftrightarrow$ non chiral susy intersection
  two Higgs multiplets

Gauge couplings

I.A.-Dimopoulos '04

$$SU(N_a): \quad \frac{1}{\alpha_{N_a}} = \frac{V}{g_s} \prod_I |n_I^a| \sqrt{1 + (H_I^a \alpha')^2}$$

g_s: string coupling

V: compactification volume in string units

$U(1)$ DBI action on T^2:

$$\sqrt{\det(\delta_{ij} + F_{ij}\alpha')} = \sqrt{1 + (H\alpha')^2}$$

$$\det(\delta_{ij} + F_{ij}\alpha') = \begin{pmatrix} 1 & H\alpha' \\ -H\alpha' & 1 \end{pmatrix}$$

$$U(1)_a: \quad \alpha_{U(1)_a} = \frac{\alpha_{N_a}}{2N_a}$$

non-abelian generators: $\mathrm{Tr} T^a T^b = \frac{1}{2}\delta^{ab}$

abelian: $T_{U(1)} = \mathbb{1}_{N\times N} \leftarrow$ **N** has unit charge

Gauge couplings

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g_s: string coupling

V: compactification volume in string units

$$U(1)_a: \quad \alpha_{U(1)_a} = \frac{\alpha_{N_a}}{2N_a}$$

Non abelian unification conditions:

(i) $\prod_I |n_I^a|$ independent of a

follows from absence of chiral symmetric reps

no color sextets and weak triplets $\Rightarrow \prod_I n_I^a = 1$

(ii) $|H_I^a| \begin{cases} \text{independent of } a \\ << M_s^2 = \alpha'^{-1} \end{cases}$

$\Rightarrow$ more quantitative analysis

$$\frac{1}{\alpha_{N_a}} = \frac{V}{g_s} \prod_I \sqrt{1 + (H_I^a \alpha')^2}$$

1% error in $\alpha_3 = \alpha_2 \quad \Rightarrow \quad H_I^a \alpha' \lesssim 0.1$

$\Rightarrow V = \prod_I V_I \gtrsim 10^3$

too high to keep strings weakly coupled?

$\alpha_{\rm GUT} \simeq 1/25 \to g_s \gtrsim \mathcal{O}(10)$

can be partly relaxed if $H_I^3 = H_I^2$ for some I:

it follows from the absence of chiral $(\bar{3}, 2)$

no antiquark doublets

$\Rightarrow$ keep $g_s \lesssim \mathcal{O}(1)$

Minimal Standard Model embedding

New possibilities using intersecting branes

- no large dimensions for low string scale
- no need for B or L conservation
- but need $\sin^2 \theta_W = \frac{3}{8}$

General analysis using 3 brane stacks

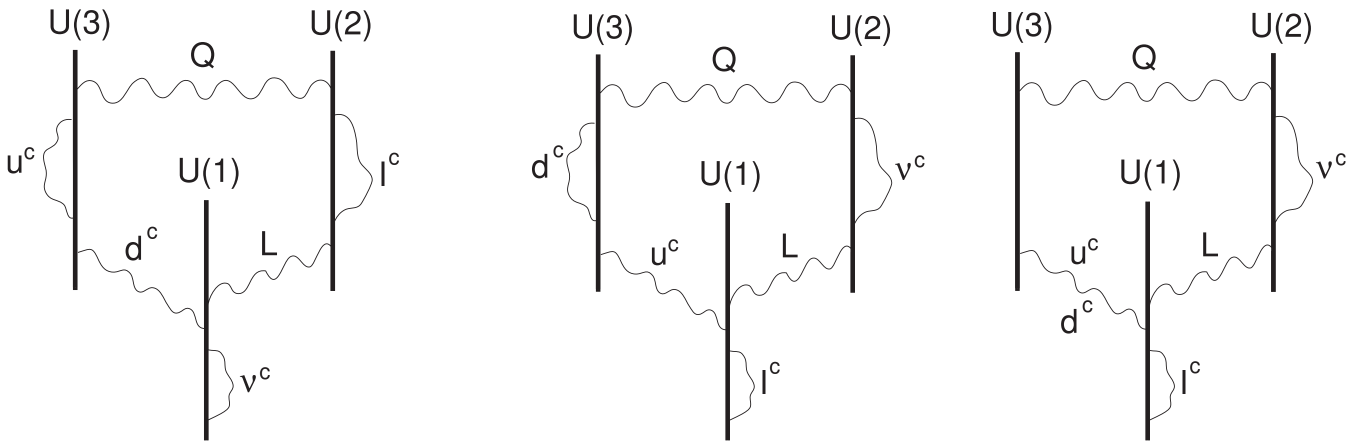
$\Rightarrow$ $U(3) \times U(2) \times U(1)$

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



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

$$Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow$$

$$\frac{1}{\alpha_Y} = \frac{2c_1^2}{\alpha_1} + \frac{4c_2^2}{\alpha_2} + \frac{9c_3^2}{\alpha_3}$$

$$\sin^2\theta_W = \frac{\alpha_Y}{\alpha_2+\alpha_Y} = \frac{1}{\alpha_2/\alpha_Y+1}$$

$$= \frac{1}{1+4c_2+2c_1^2\alpha_2/\alpha_1+6c_3^2\alpha_2/\alpha_3}$$

- Higgs can be easily implemented

  massless $\Rightarrow$ susy intersection

  $H_1, H_2 \,:\; U(2) \leftrightarrow U(1)$ like L

	Model A	**Model B, C**
H_1	$(\mathbf{1},\mathbf{2};0,-1,\varepsilon_{H_1})_{-1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_{H_1},1)_{-1/2}$
H_2	$(\mathbf{1},\mathbf{2};0,1,\varepsilon_{H_2})_{1/2}$	$(\mathbf{1},\mathbf{2};0,\varepsilon_{H_2},-1)_{1/2}$

- 2 extra $U(1)$'s

\- One combination can be $B-L$

$$(\varepsilon_d = \varepsilon_L = \varepsilon_\nu = -\varepsilon_{H_1} = \varepsilon_{H_2})$$

$$B-L = -\tfrac{1}{6}Q_3 + \tfrac{1}{2}Q_2 - \tfrac{\varepsilon_d}{2}Q_1$$

broken by a SM singlet VEV at high scale

or survive at low energies

\- The other/both is/are anomalous

Green-Schwarz anomany cancellation:

shifting of axions $\Rightarrow U(1)_A$ become massive

$\delta A = d\Lambda \quad \Rightarrow \quad \delta a = -M\Lambda$

$$-\frac{1}{4g_A^2}F_A^2 - \frac{1}{2}(da + MA)^2 + \frac{a}{M}k_I^A \mathrm{tr} F_I \wedge F_I$$

cancel the anomaly

$\Rightarrow U(1)_A$ mass: $M_A = g_A M$

a: Poincaré dual of a 2-form B_2 $\qquad da = *dB_2$

Mass scales

- $M_{\mathrm{GUT}} \simeq$ smallest compactification scale
  $\simeq 10^{16}$ GeV

- smallest $H_I^a \alpha' \sim 0.1 \Rightarrow$
  $M_s \simeq 3 \times M_{\mathrm{GUT}}$

- $m_{\mathrm{susy}} \sim$ largest scalar mass m_0
  : free parameter

branes: $m_0^2 \sim \delta H^a \equiv \epsilon_1 H_1^a + \epsilon_2 H_2^a + \epsilon_3 H_3^a$

brane intersections: $m_0^2 \sim \delta H^{ab} \equiv \delta H^a - \delta H^b$

"natural" scale: $m_0 \sim M_{\mathrm{GUT}}$

but can be much smaller stable due to SUSY

Gravity coupling and fermion masses

Brane vacuum energy (DBI action):

$\Lambda_{\text{brane}} \sim (\delta H)H \simeq m_0^2 M_{\text{GUT}}^2$

Compensate by bulk vacuum energy:

$\Lambda_{\text{bulk}} \sim m_{3/2}^2 \Lambda^2 \leftarrow$ UV cutoff

$$\Rightarrow m_{3/2} \sim m_0 \frac{M_s}{\Lambda} \sim \begin{cases} 10^{-3}\, m_0 & \Lambda \sim M_p \\ m_0 & \Lambda \sim M_s \\ (m_0 M_s)^{1/2} & \Lambda \sim m_{3/2} \end{cases}$$

Sherk-Schwarz along an interval $\perp$ branes

e.g. 11th dim of M-theory

gravity strength $\Rightarrow R^{-1} = \frac{2}{\alpha_G^2} \frac{M_s^3}{M_p^2} \sim 10^{13}$ GeV

$\Rightarrow m_{3/2} \sim 1/R \qquad m_0 \sim 10^{10} - 10^{16}$ GeV

Scherk-Schwarz (SS) SUSY breaking

Scherk-Schwarz '79, Rohm '84, Fayet '85

Ferrara-Kounnas-Porrati-Zwirner '88, I.A. '90

Periodicity up to R-symmetry transformation

$\Phi(y+2\pi R) = U\Phi(y) \qquad U = e^{2\pi i Q} \qquad \Rightarrow$

KK-momentum: $p = \frac{m+Q}{R} \Rightarrow$ mass-shifts

R-symmetry: discrete internal rotation $U^N = 1$

$\Rightarrow Q$ quantized in units of $1/N$

Closed strings: modular invariance $\Rightarrow$

windings $n \to n$, $Q \to Q-n$

Open strings: $R_{\parallel} \Rightarrow$ like in field theory

$R_{\perp} \Rightarrow$ brane supersymmetry

I.A.-Dudas-Sagnotti '98

Gaugino masses: protected by R-symmetry

However problem with SUGRA:

- keep R-symmetry at low energies

- generate light gaugino masses

Two possible solutions:

(1) brane susy $\Rightarrow$ generate $m_{1/2}$ from $m_{3/2}$

one gravitational loop: 1 handle + 1 boundary

$$\Rightarrow m_{1/2} \sim g_s^2 \frac{m_{3/2}^2}{M_s^2}$$ I.A.-Taylor '04

(2) keep gravity subdominant $\Rightarrow$

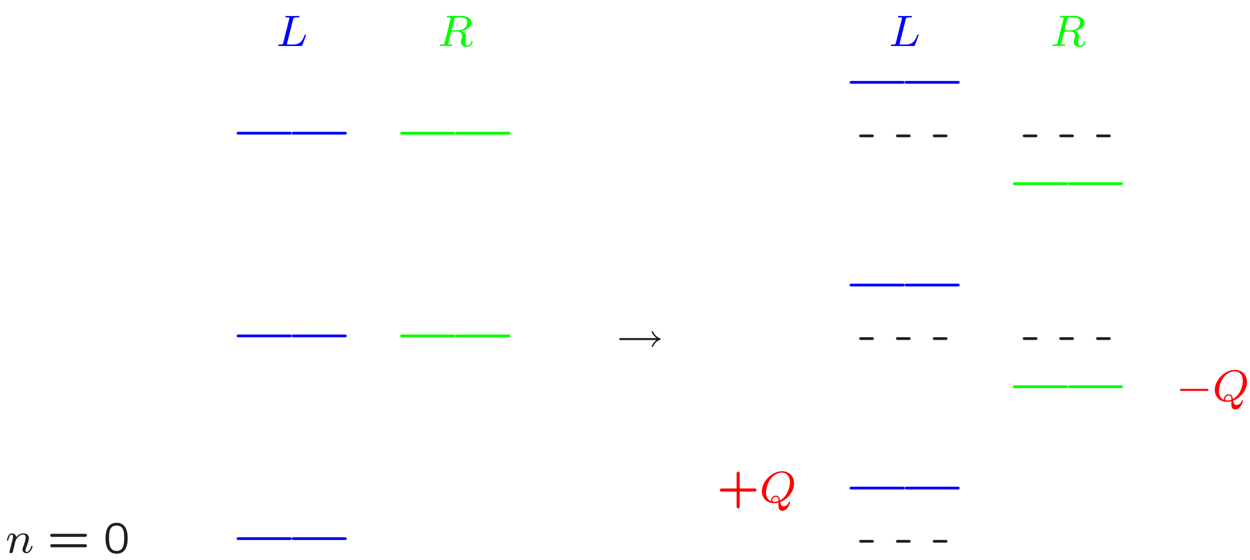
generate $m_{1/2}$ from brane α'-corrections

two gauge loops: 3 boundaries

$$\Rightarrow m_{1/2} \sim g_s^2 \frac{m_0^4}{M_s^3}$$ I.A.-Narain-Taylor to appear

Break SUGRA keeping R-symmetry

SS breaking on $S^1/\mathbb{Z}_2 \perp$ brane $\Rightarrow$ 3/2-KK states



- generic shift Q $\Rightarrow$ Majorana masses, $\not{R}$

  $E << Q/R \Rightarrow$ 4d non-SUSY

  $Q/R < E < 1/R \Rightarrow$ 4d SUGRA

  $E >> 1/R \Rightarrow$ 5d SUGRA

- $Q = 1/2$ $\Rightarrow$ pairing $|n{+}Q\rangle_L$ with $|n+1{-}Q\rangle_R$

  $\Rightarrow$ Dirac masses, unbroken R-symmetry

  no intermediate regime $\Rightarrow$ no 4d SUGRA description

Effective QFT description: D-breaking

magnetic field $H \sim \langle \mathrm{D} \rangle$-term of $U(1)$

$\langle \mathrm{D} \rangle \sim m_0^2$ $\qquad$ $U(N)$ brane stack

gaugino masses: protected by R-symmetry

broken by string corrections

$\Rightarrow$ higher-dim effective operators:

$F_{(0,3)} \int d^2\theta \mathcal{W}^2 \mathrm{Tr} W^2$ $\qquad$ $\langle \mathcal{W} \rangle = \theta \langle \mathrm{D} \rangle$

↖

topological partition function at genus-0 with 3 holes

I.A.-Narain-Taylor to appear

$\Rightarrow \; m_{1/2} \sim \epsilon^2 \frac{m_0^4}{M_s^3}$ $\qquad$ ϵ^2: 2-loop factor

$\sim$ TeV for $m_0 \sim 10^{13} - 10^{14}$ GeV

Simple toroidal models

gauge multiplets: $N=4$ (or $N=2$) SUSY

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

$\int d^2\theta \mathcal{W} \mathrm{Tr} W A \;\Rightarrow\; m_D \sim \epsilon \frac{m_0^2}{M_s}$ 1-loop factor

$N=2$ vector $=$ $N=1$ vector W $+$ chiral A

they can still be consistent with unification

I.A.-Benakli-Delgado-Quirós-Tuckmantel to appear

	$M_{\rm GUT}$	m_0	m_D	$m_{1/2}$
$N=4$	M_P	$10^{16}-10^{17}$	10^{13}	10^6
$N=2$	10^{18}	10^{13}	10^7	10^{-5}
$N=2/2$ higgses	10^{16}	$10^{13}-10^{14}$	10^9	10^2

• Dark matter: higgsinos?

no vector-like couplings up to 50 TeV

$\Delta m \gtrsim 100$ keV $\Rightarrow m_D \lesssim 10^5$ GeV

$\Rightarrow$ need Binos with $m_D = 0$ and $m_{1/2} \neq 0$

$\Rightarrow N = 4/1$ higgs or $N = 2/2$ higgses

• Higgsino mass

- $\int d^2\theta \mathcal{W}^2 \bar{D}^2 \bar{H}_1 \bar{H}_2 \Rightarrow \mu \sim \epsilon \frac{m_0^4}{M_s^3} \sim m_{1/2}$

$\psi_1 \psi_2$ ok for $N = 2$

- or free parameter : $N = 4$

DM constraints $\Rightarrow m_{1/2} \gtrsim \mu$

- $m_{1/2} \sim \mu \Rightarrow$ LSP: higgsino + Bino

only for $N = 2$

- $m_{1/2} >> \mu \Rightarrow$ LSP=higgsino $\mu \simeq 1.1$ TeV

• gauginos lifetime:

$\tau_g \simeq \left(\frac{m_0}{10^{13}\text{GeV}}\right)^4 \left(\frac{10^2\text{GeV}}{m_g}\right)^5 \tau_{\text{universe}} \Rightarrow$

$N = 1$ split susy:

$m_0 \lesssim 10^{13} - 10^{15}$ GeV for $m_g \sim 0.1 - 10$ TeV

$N = 2$: ok

$N = 4$: replace m_0 with M_s for one pair

of gauginos $\Rightarrow$ ok

• low energy signals:

charged higgsinos

decays $\rightarrow$ leptons + LSP, neutralinos