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String Phenomenology

IOP string school

Bhubaneswar, September 2006

Hierarchy problem: why gravity is so weak compared to the other interactions?

Quantum theory: all particle masses $\nearrow M_P \sim 10^{19}$ GeV

- Supersymmetry: protection of hierarchy due to cancellations between fermions and bosons

  $\Rightarrow m_{\text{susy}} \sim$ TeV

- TeV strings: low UV cutoff

  $\Rightarrow M_s \sim$ TeV

- Split supersymmetry: unknown solution live with the hierarchy

  $\Rightarrow m_0$ heavy, fermions light

→ all of them testable at LHC

- Heterotic string:

Natural framework for susy and unification

However mismatch between string and GUT scales

$M_s = gM_P \simeq 50 M_{\text{GUT}}$

- Framework of type I string theory

$\Rightarrow$ D-brane world

Natural separation of

global SUSY from gravity

$\swarrow \qquad\qquad \searrow$

D-branes/open strings closed strings

$\Rightarrow$ 2 new scenaria besides ‘conventional’

low energy susy Standard Model

- low string scale
- split supersymmetry

OUTLINE

- Framework of low scale strings

  large extra dimensions, low scale gravity

- Experimental predictions

  strong gravity, TeV dimensions, string effects

- SUSY in the bulk

  brane SUSY breaking, short range forces

- Electroweak symmetry breaking

- D-brane embedding of the Standard Model

  unification, proton stability, Right-neutrinos

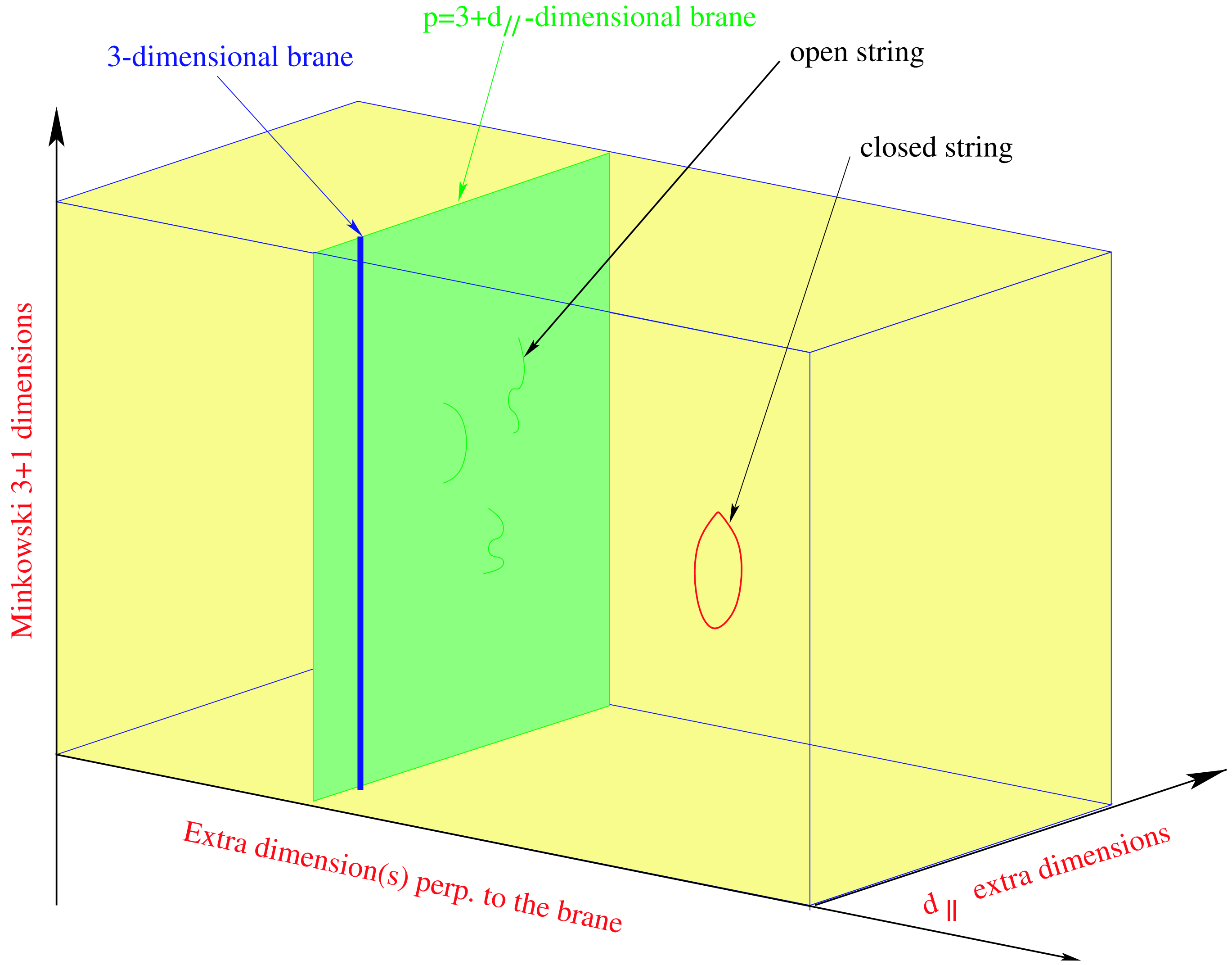
- SUSY breaking by internal magnetic fields

  or equivalently branes at angles

- Gaugino masses

  Split supersymmetry, Dirac masses

Braneworld



two types of compact extra dimensions:

- parallel ($d_\parallel$): can be as large as 10^{-16} cm (TeV^{-1})

I.A. '90

- transverse ($\perp$): can be as large as 0.1 mm

Dimensions of finite size: $p-3$ parallel

$n = 9 - p$ transverse

calculability $\Rightarrow R_{\parallel} \simeq l_{\text{string}}$; $R_{\perp}$ arbitrary

$$M_P^2 \simeq \frac{1}{\alpha^2} M_s^{2+n} R_{\perp}^n$$

↖

Planck mass in $4+n$ dims: M_*^{2+n}

small $M_s/M_P \Rightarrow$ extra-large $R_{\perp}$

$M_s \sim 1$ TeV $\Rightarrow R_{\perp} \sim .1-10^{-13}$ mm $(n=2-6)$

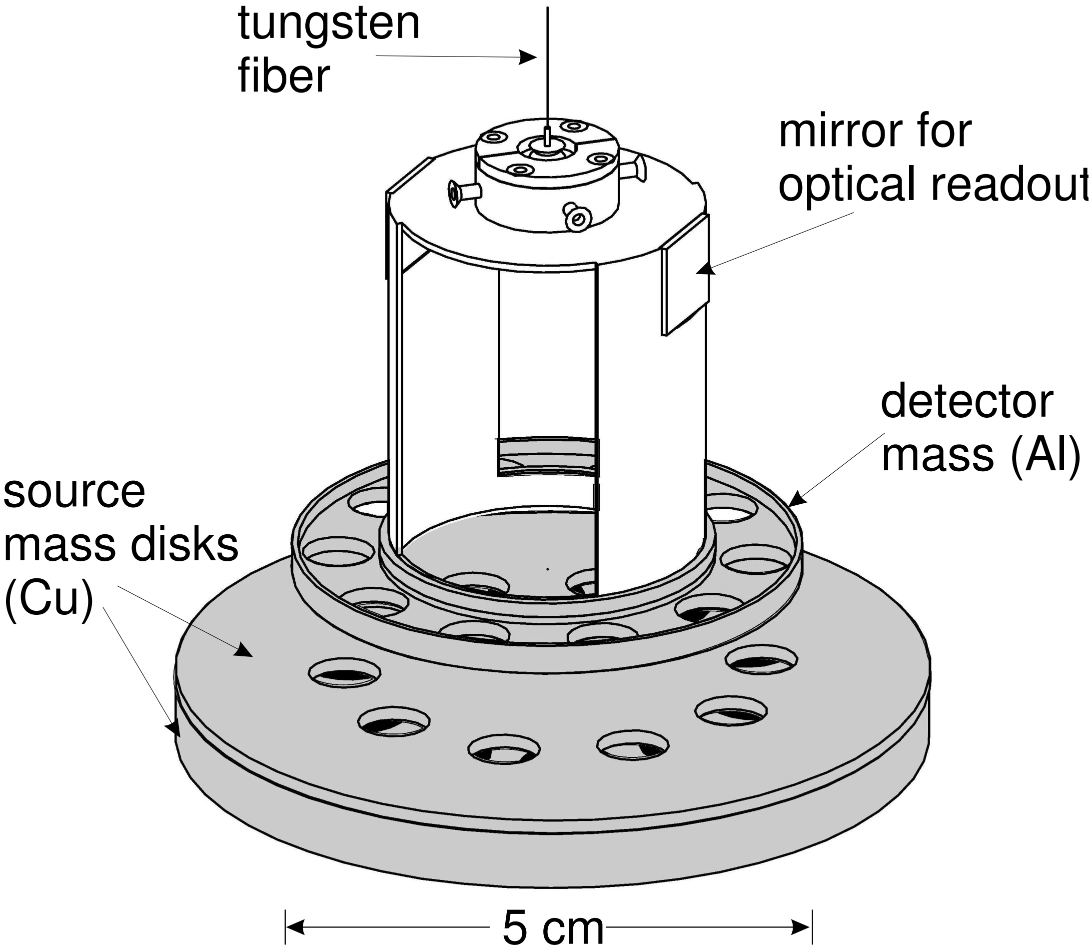
I.A.-Arkani Hamed-Dimopoulos-Dvali '98

- weak string coupling: $g_s = \alpha$
- gravity strong at $M_* \sim M_s << M_P$

  10^{30} stronger than thought previously!

  deviations from Newton's law at distances $< R_{\perp}$

Adelberger et al. '04



$R_\perp \lesssim 130\ \mu\mathrm{m}$ at 95% CL

Supernova constraints

cooling due to graviton production

e.g. $NN \to NN+$ graviton

number of gravitons: $\sim (TR_\perp)^n$ $\quad T >> R_\perp^{-1}$

$\nearrow$

$\sim$ 10 MeV

$\Rightarrow$ production rate:

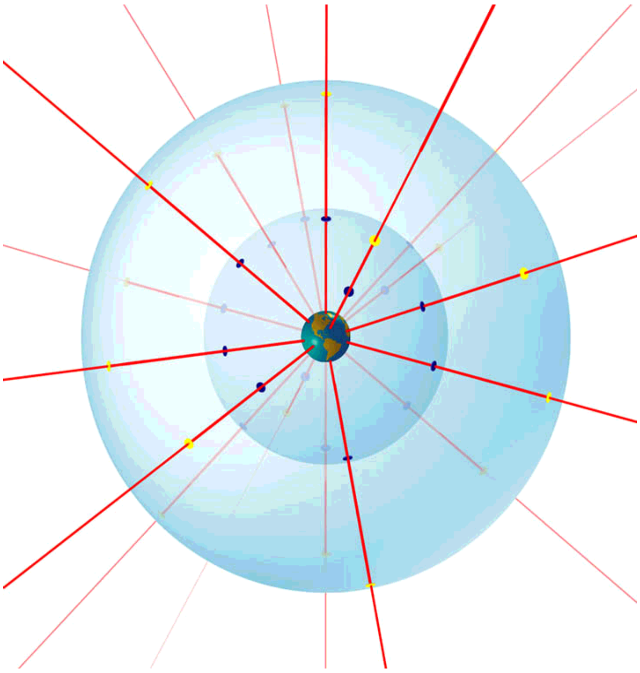
$$P_{\text{gr}} \sim \frac{1}{M_p^2}(TR_\perp)^n \sim \frac{T^n}{M_*^{(2+n)}}$$

$$P_{\text{gr}} < P_\nu \quad \Rightarrow \quad M_*\Big|_{n=2} \gtrsim 50 \text{ TeV}$$

$$\Rightarrow \quad M_s \gtrsim 10 \text{ TeV}$$

Gravity modification at submillimeter distances

Newton's law: force decreases with area



3d: force $\sim 1/r^2$

(3$+n$)d: force $\sim 1/r^{2+n}$

observable for $n = 2$: $1/r^4$ with $r \lesssim .1$ mm

Hidden submillimeter dimensions

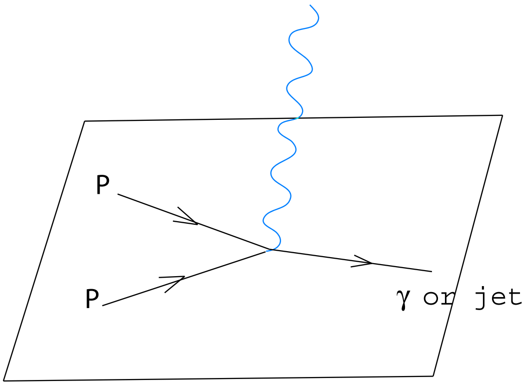
$\Rightarrow$ strong gravity at the TeV

Gravitational radiation in the bulk

3d: Kaluza Klein gravitons very light

$\Rightarrow$ high energy: huge number of particles produced

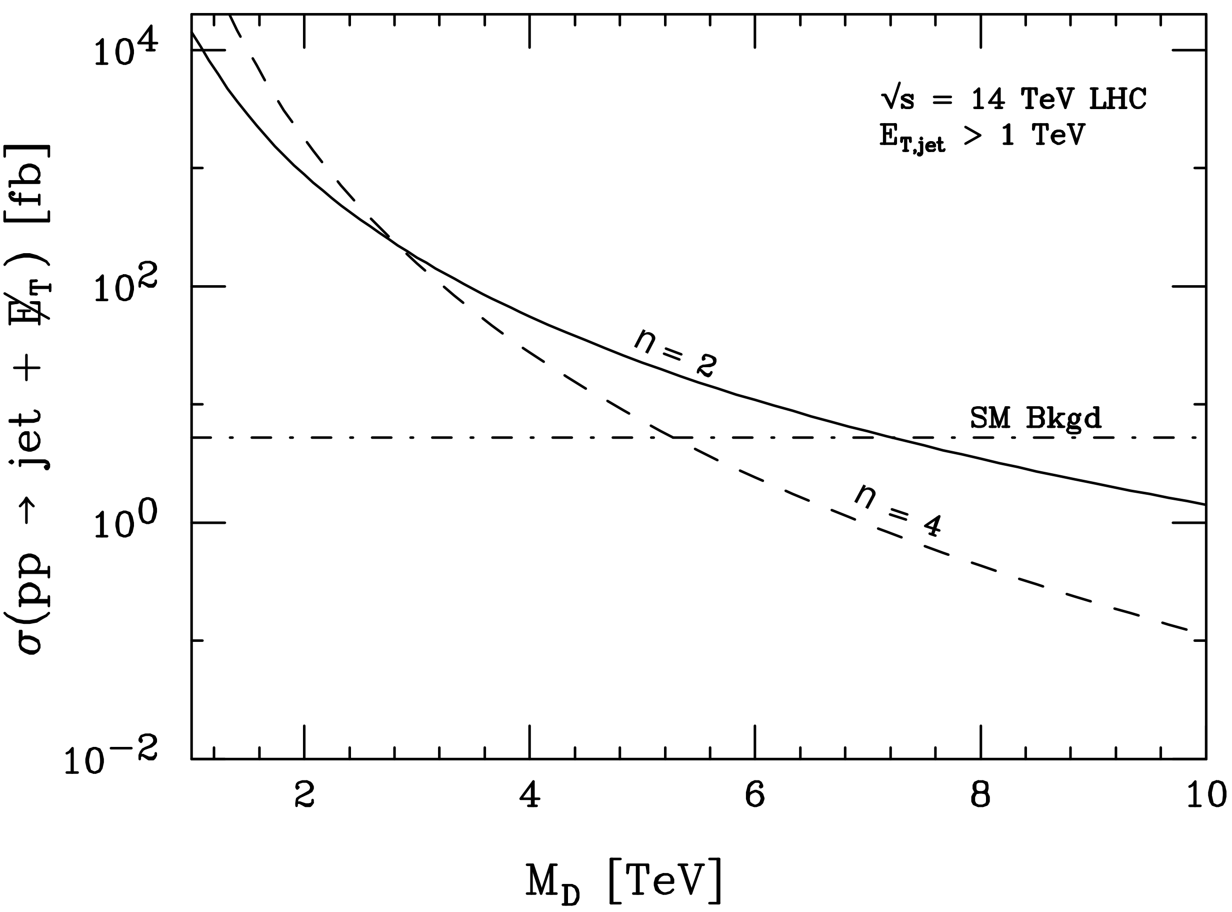
LHC: 10^{30} massive gravitons of intensity 10^{-30} each



Signal: missing energy

Angular distribution $\Rightarrow$ spin of the graviton

Giudice-Rattazzi-Wells '98



no observation ⇒

$R_\perp \lesssim 10^{-2} - 10^{-12}$ mm ($n = 2 - 6$); 95% CL

- more dimensions ⇒ weaker limits

Limits on $R_\perp$ in mm

Experiment	$R_\perp(n=2)$	$R_\perp(n=4)$	$R_\perp(n=6)$
Collider bounds			
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}
NLC	1.2×10^{-2}	1.2×10^{-9}	6.5×10^{-12}
Astrophysics/cosmology bounds			
SN1987A	3×10^{-4}	1×10^{-8}	6×10^{-10}
COMPTEL	5×10^{-5}	-	-

Large TeV dimensions

longitudinal dimensions: $R^{-1} \lesssim M_s \Rightarrow$

R^{-1} first scale of new physics I.A. '90

increasing the energy

- could happen for some of the internal dims
- explain coupling constant ratios g_2/g_3
- susy breaking
- fermion masses displace light generations

Massive tower of Kaluza Klein modes

for Standard Model particles

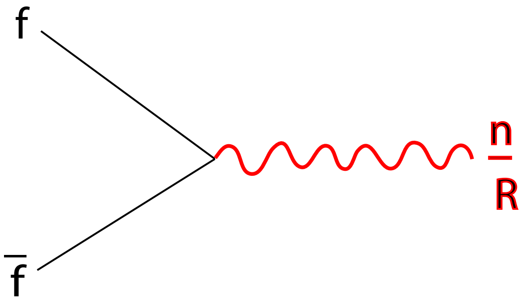
$$M_n^2 = M_0^2 + \frac{n^2}{R^2} \quad ; \quad n = \pm 1, \pm 2, \ldots$$

$\Rightarrow$ excited states of photon, $W^\pm$, Z, gluons

Localized fermions (on 3-brane intersections)

$\Rightarrow$ single production of KK modes

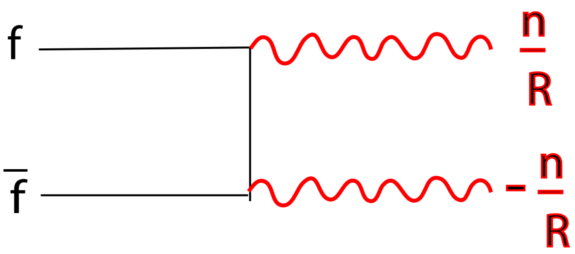
I.A.-Benakli '94



- strong bounds   indirect effects: $R^{-1} \gtrsim$ 3TeV
- new resonances   but at most $n = 1$

Otherwise KK momentum conservation

$\Rightarrow$ pair production of KK modes (universal dims)

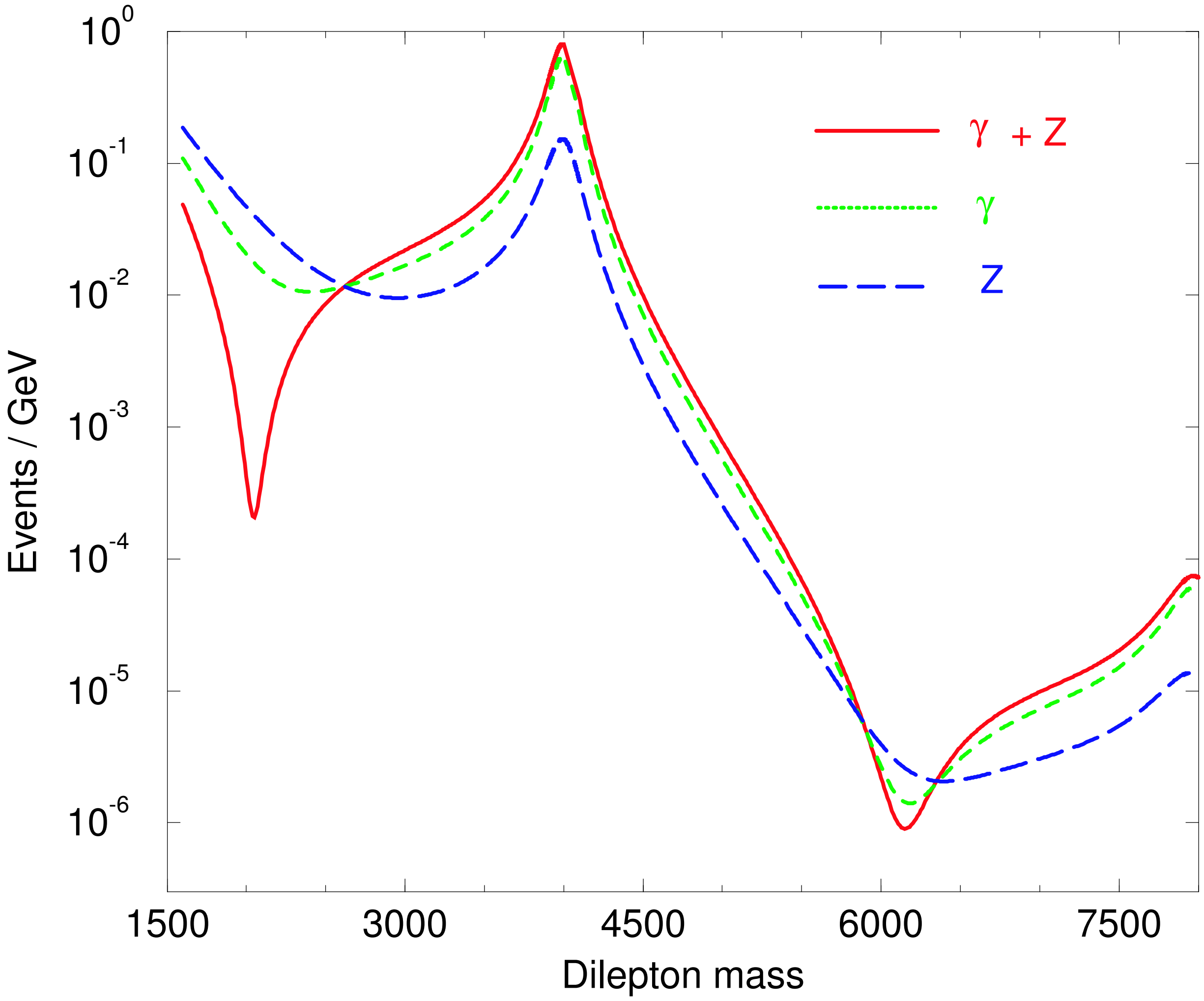


- weak bounds $R^{-1} \gtrsim$ 300-500 GeV
- no resonances
- lightest KK stable $\Rightarrow$ dark matter candidate

Servant-Tait '02

I.A.-Benakli-Quiros '94, '99

$R^{-1} = 4$ TeV



- no observation in dijets

$$\Rightarrow R^{-1} \gtrsim 20 \text{ TeV} \; ; \; 95\% \text{ CL}$$

- more than one dimension ⇒ stronger limits

Massive string vibrations ⇒ indirect effects

virtual exchanges ⇒ effective interactions

e.g. four-fermion operators

Actual limits: Matter fermions on

- same set of branes ⇒ $M_s \gtrsim 500$ GeV

dim-8: $\frac{g^2}{M_s^4}(\bar{\psi}\partial\psi)^2$ Cullen-Perelstein-Peskin '00

- brane intersections ⇒ $M_s \gtrsim 2-3$ TeV

dim-6: $\frac{g^2}{M_s^2}(\bar{\psi}\psi)^2$ I.A.-Benakli-Laugier '00

High energies ⇒

- direct production: string physics
- strong gravity: production of micro-black holes?

Giddings-Thomas, Dimopoulos-Landsberg '01

- global SUSY:

- No need to be there at least for hierarchy

- New ways of breaking

  using extra dimensions

  branes at angles/internal magnetic fields

- SUGRA: probably unbroken in the bulk $\Rightarrow$

  very weakly broken

- New forces at submm scales

  e.g. radion, graviphoton

- Non linear realization on branes

  SM + (light) goldstino

Energy density: Λ_{bulk}, Λ_{brane}

generic non-SUSY string model $\Rightarrow$

$\Lambda_{\text{bulk}} \sim M_s^{4+n} \Rightarrow \Lambda_{\text{brane}} \sim M_s^{4+n} R_\perp^n \sim M_s^2 M_P^2$

analog in softly broken SUSY: $m_{\text{SUSY}}^2 \Lambda_{UV}^2$

quadratic divergence to Λ

vanishing if bulk is (approximately) SUSY

$\Lambda_{\text{brane}} \sim M_s^4 \Rightarrow \Lambda_{\text{bulk}} \sim M_s^4 / R_\perp^n$

Prediction: possible new forces at submm scales

e.g. radion $\equiv \ln R_\perp$

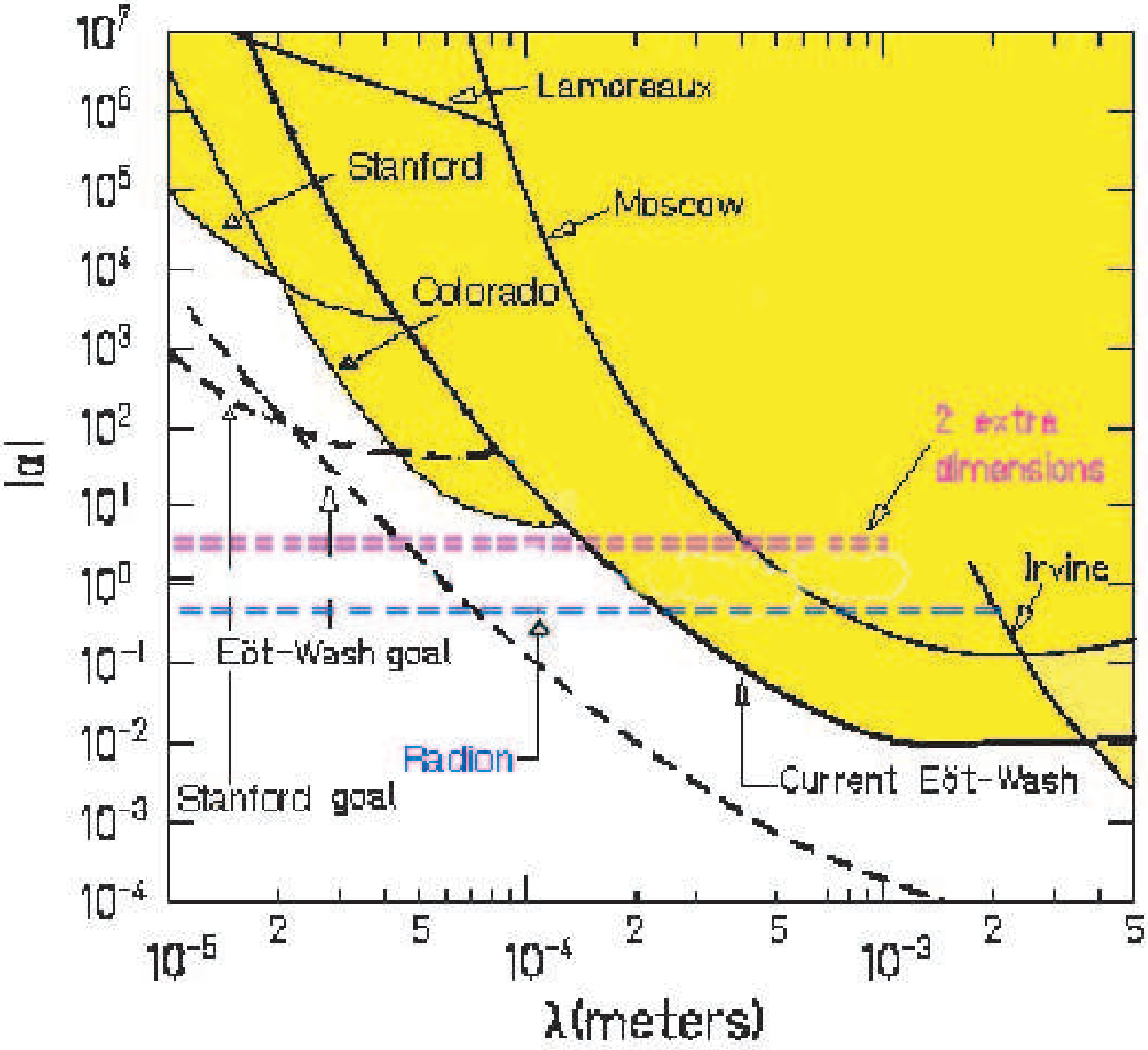
mass: $(\text{TeV})^2/M_P \sim 10^{-4}$ eV → mm range

coupling: $\frac{1}{m}\frac{\partial m}{\partial \ln R_\perp} = \sqrt{\frac{n}{n+2}} \times$ gravity

$\Rightarrow$ can be experimentally tested for all $n \geq 2$

I.A.-Benakli-Maillard-Laugier '02

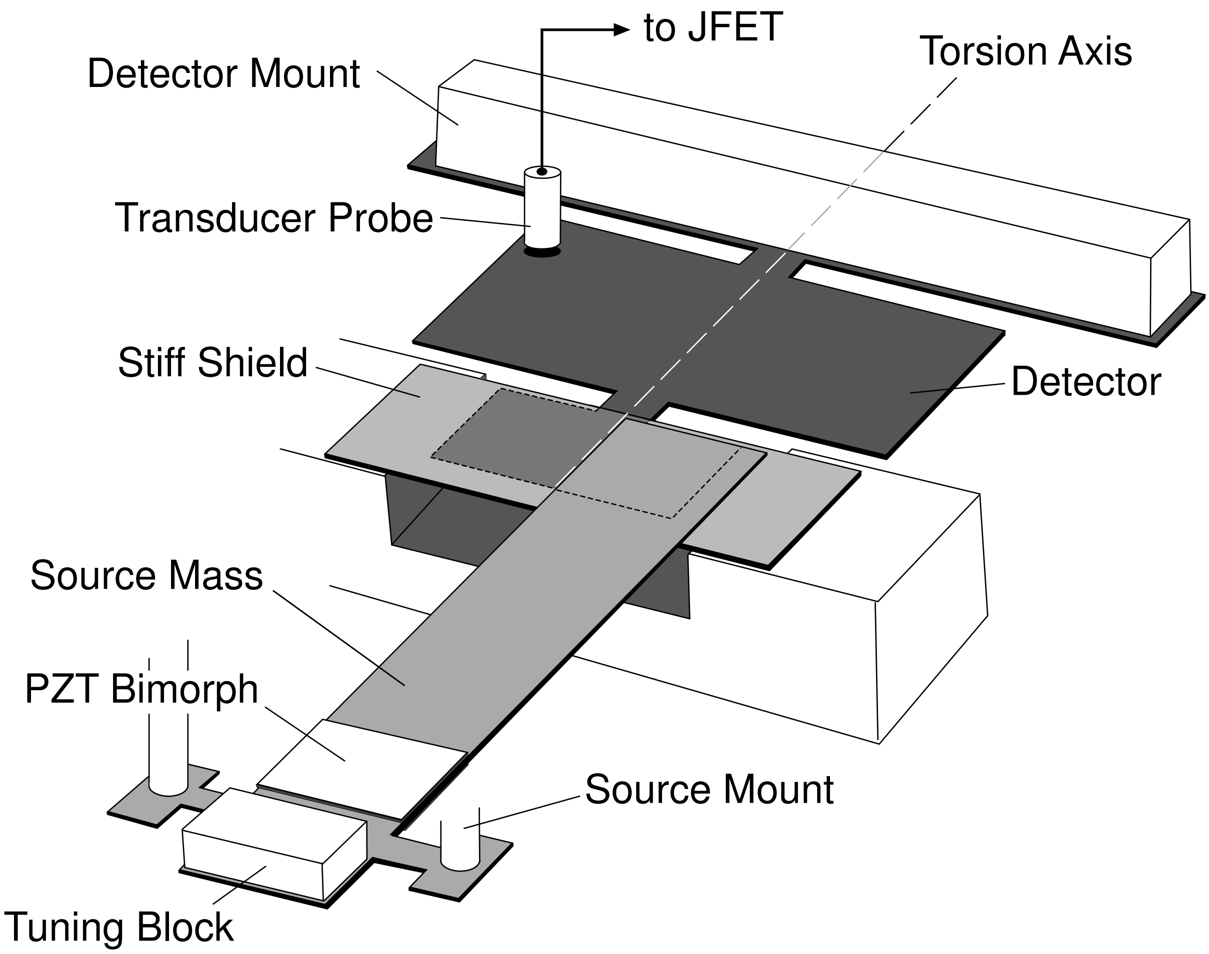
$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



Radion $\Rightarrow M_* \gtrsim$ 3 - 4.5 TeV 95% CL (n=2-6)

Adelberger et al. '04

Long-Chan-Churnside-Gulbis-Varney-Price '03



Light $U(1)$ gauge bosons

I.A.-Kiritsis-Rizos '02

$U(1)$ anomalies ⇒ Green-Schwarz mechanism

$$\underset{\text{gauge field}}{\delta A} = d\Lambda \quad \Rightarrow \quad \underset{\text{axion}}{\delta a} = -M\Lambda$$

$$-\frac{1}{4g_A^2}F_A^2 - \frac{1}{2}(da+MA)^2 + \frac{a}{M}\underset{\text{cancel the anomaly}}{k_I^A}\,\mathrm{Tr}F_I \wedge F_I$$

⇒ $U(1)_A$ mass: $m_A = g_A M$

- a: Poincaré dual of a 2-form

  from RR closed string sector $da = *dB_2$

- $U(1)_A$ global symmetry remains

  (in perturbation)

ex. Baryon and Lepton number needed to prodect proton decay and neutrino masses

$$m_A = g_A \, M$$

small mass ⇒ small coupling

⇒ A in the bulk and a on the brane:

localized mass

$g_A \sim 1/\sqrt{V_\perp}$

$\Rightarrow m_A \gtrsim M_s^2/M_P \; \simeq \; 10^{-4}\,\text{eV}$

A propagates in part of the bulk

⇒ new submm forces

$g_A \sim 1/\sqrt{V_\perp} \gtrsim M_s/M_P \sim 10^{-16}$

$\Rightarrow \; \gtrsim \; 10^6 - 10^8 \times$ gravity

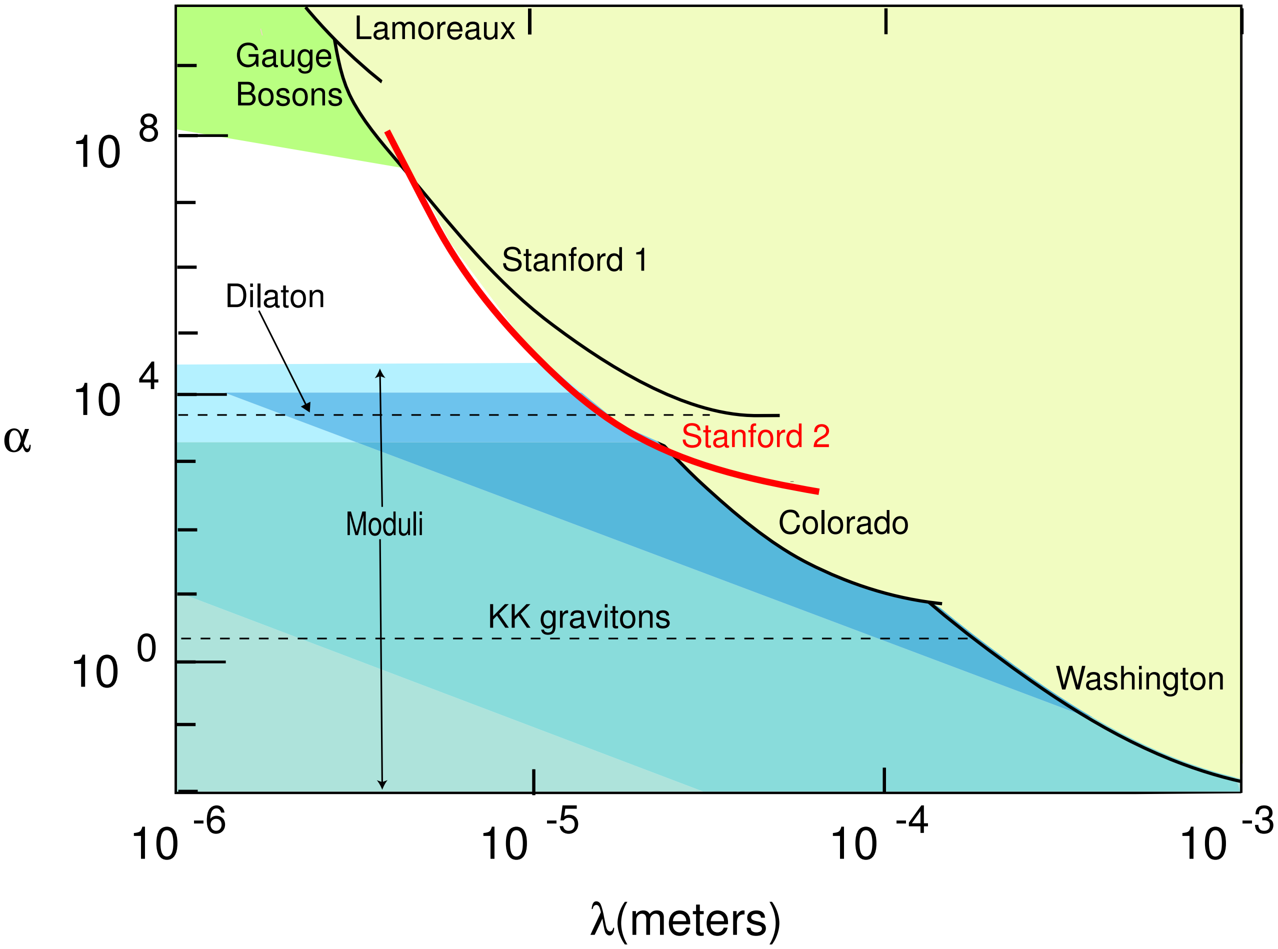
m_{proton}/M_P

supernova ⇒ dim of the bulk ≥ 4

an order of magnitude improvement

on bounds in the range 6-20 μm

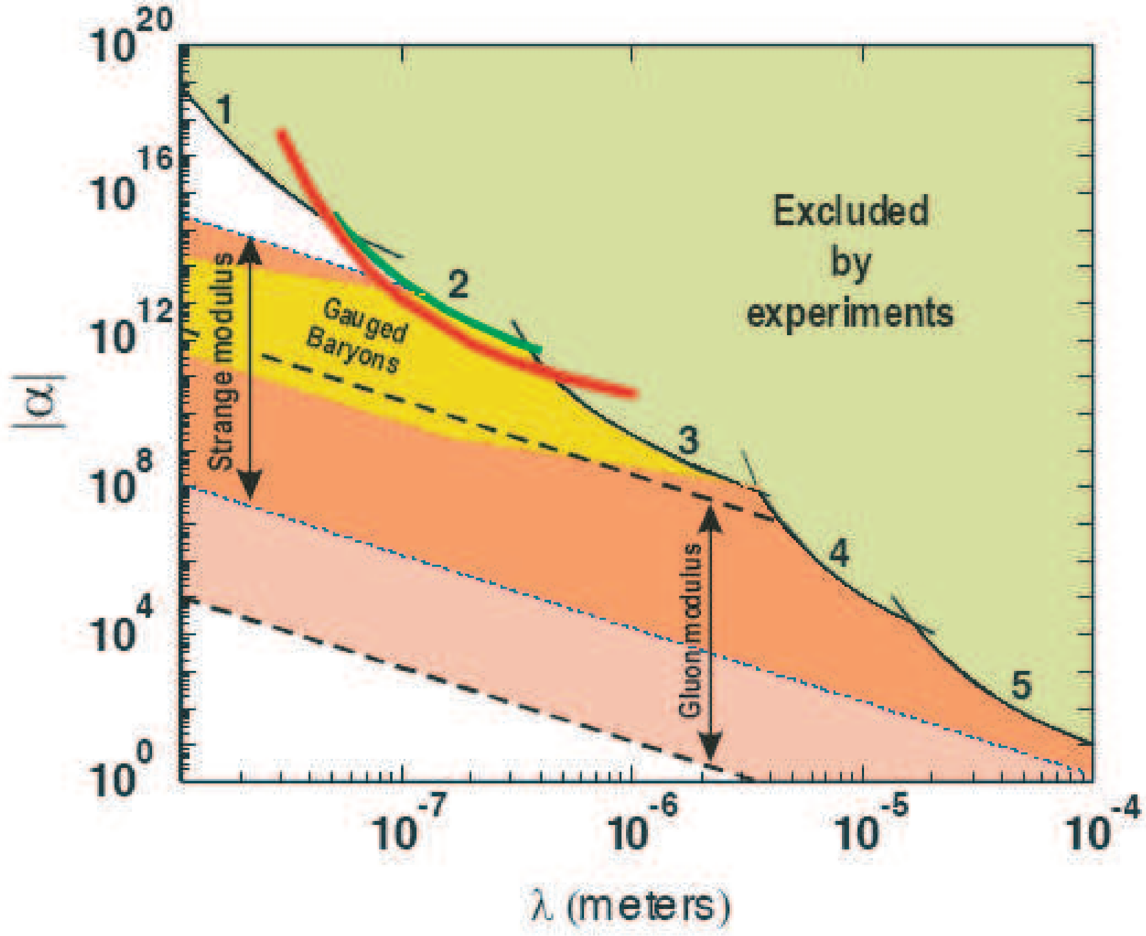
Smullin-Geraci-Weld-Chiaverini-Holmes-Kapitulnik '05



an order of magnitude improvement

on bounds in the range 200 nm

Decca-López-Chan-Fischbach-Krause-Jamell ’05



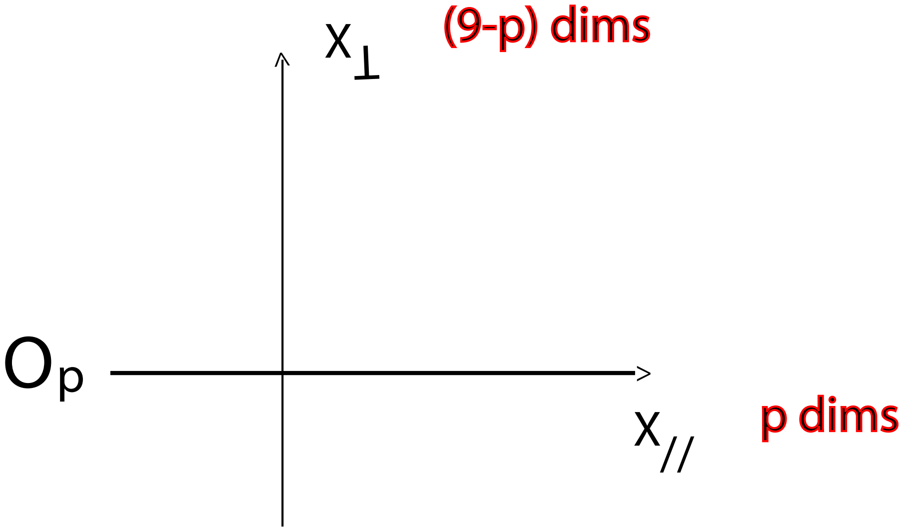
5: Colorado

4: Stanford

3: Lamoureaux

1: Mohideen et al.

Orientifold: (hyper)surface where closed strings change orientation



$X_\perp \to -X_\perp$ p-plane localized at $X_\perp = 0$

$z \to \bar{z}$ worldsheet orientation flip

non-dynamical object with RR charge ⇒

can have negative tension

Brane supersymmetry breaking

I.A.-Dudas-Sagnotti, Aldazabal-Uranga '99

Stable configurations of branes with orientifolds

- absence of tachyons
- bulk susy breaking suppressed by $R_\perp$

	D	D̄	O	Ō
RR charge	$+$	$-$	$-$	$+$
tension	$+$	$+$	$-$	$-$
linear SUSY	Q_e	Q_o	Q_e	Q_o
NL SUSY	Q_o	Q_e		

Model I: DO or D̄Ō

local charge conservation, brane SUSY (locally)

Model II: D̄O or DŌ

brane SUSY breaking (linear), NL SUSY

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

Example: $I = S^1/\mathbb{Z}_2$ with SS SUSY breaking

O8 —— πR —— Ō8

RR charge: -8 +8

- SS SUSY breaking: 16 D9 branes along I

  $\Rightarrow$ $SO(32)$ with fermion mass-shifts

- Model I: 8 D8 branes on O8

  8 D̄8 branes on Ō8

  $\Rightarrow$ $SO(16) \times SO(16)$ ‘SUSY’

- Model II: 8 D̄8 branes on O8

  8 D8 branes on Ō8

  $\Rightarrow$ $SO(16) \times SO(16)$ with fermions in the sym

  $(136, 1) + (1, 136)$ $136 = 135 + 1$ ← goldstino

Model III: D away from O

L + NL SUSY

partial breaking "$N = 2 \to N = 1$"

8 D8 and 8 D̄8 branes in the bulk

O8 $\overline{\qquad\qquad\pi R\qquad\qquad}$ Ō8

RR charge: -8 +8

$\Rightarrow U(8) \times U(8)$

$U(1)$: goldstino multiplet

Origin of EW symmetry breaking?

little hierarchy: $m_W/M_s \lesssim \mathcal{O}(10^{-1})$

string tree-level: $m_W = 0$ or $\mathcal{O}(M_s)$

possible solution: radiative breaking

I.A.-Benakli-Quiros '00

$V = \mu^2 H^\dagger H + \lambda(H^\dagger H)^2$

$\mu^2 = 0$ at tree but becomes < 0 at one loop

non susy vacuum

simplest case: one Higgs from the same brane

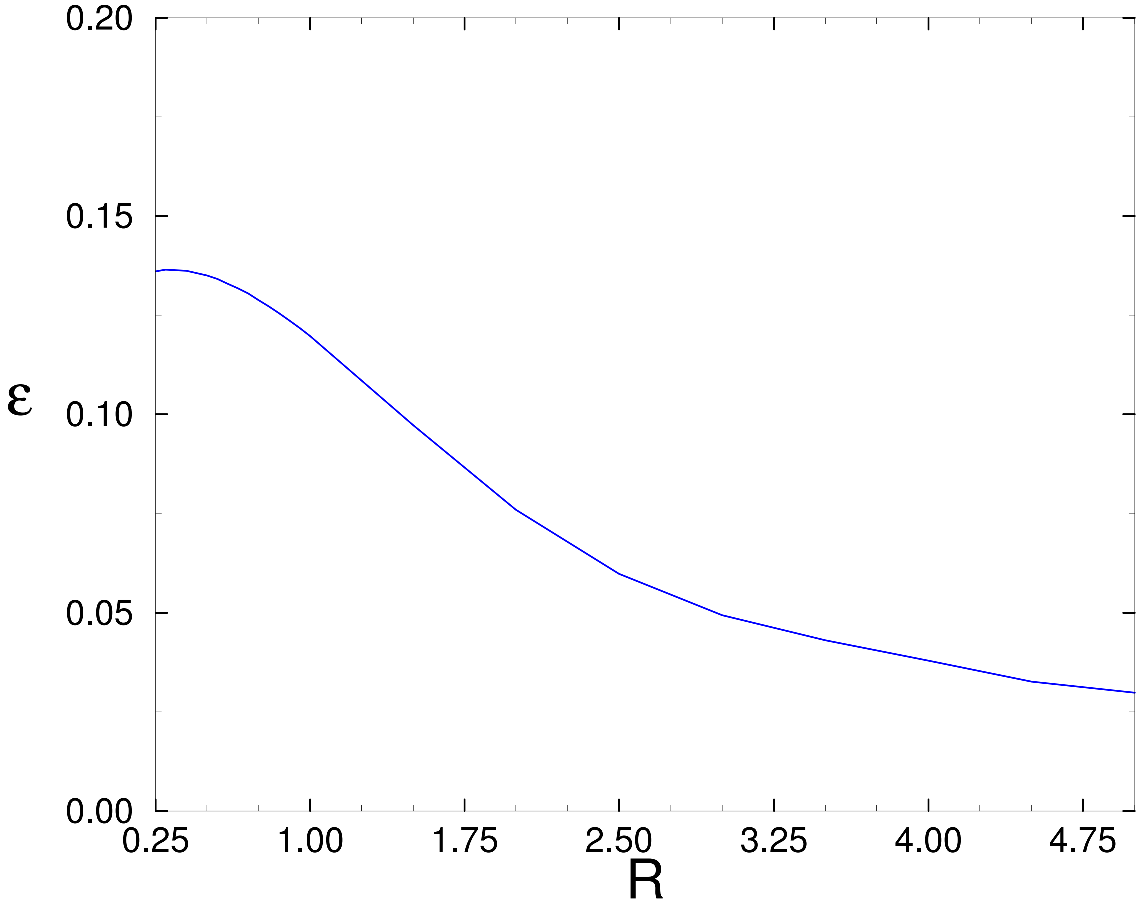
$\Rightarrow$ tree-level V same as susy: $\lambda = \frac{1}{8}(g^2 + g'^2)$

D-terms

$\mu^2 = -g^2 \underset{\nwarrow}{\varepsilon^2} M_s^2 \leftarrow$ effective UV cutoff

loop-factor estimated by a toy model computation

$$\varepsilon^2(R) = \frac{R^3}{2\pi^2}\int_{\underset{\text{IR}}{0}}^{\overset{\text{UV}}{\infty}} dl\, l^{3/2}\, \overset{e^{-\pi l}}{\underset{1}{\frac{\theta_2^4}{16 l^4 \eta^{12}}}} \left(il + \frac{1}{2}\right) \sum_n n^2 e^{-2\pi n^2 R^2 l}$$



$R \to \infty :\ \varepsilon(R) M_s \sim \varepsilon_\infty / R$ $\varepsilon_\infty \simeq 0.008$

UV cutoff: $M_s \to 1/R$

$R \to 0 :\ \varepsilon(R) \simeq 0.14$ large transverse dim

- $M_H = M_Z$ at tree

  same as MSSM for tan $\beta, m_A \to \infty$

- $M_s = M_H/(\sqrt{2}g\varepsilon)$

Low-energy SM radiative corrections

top quark sector

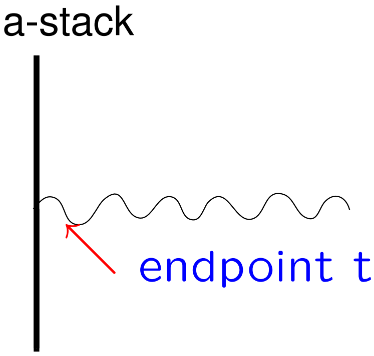
$$M_H \sim 120 \text{ GeV}$$

$\Rightarrow$

$$M_s \sim \text{a few TeV}$$

Generic spectrum

N coincident branes $\Rightarrow U(N)$

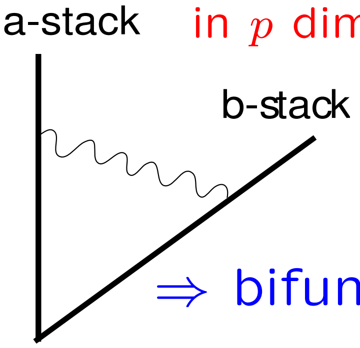


endpoint transformation: $\mathbf{N}_a$ or $\bar{\mathbf{N}}_a$

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

$U(1)$: "baryon" number

- open strings from the same stack $\Rightarrow$ adjoint gauge multiplets of $U(N_a)$
- stretched between two stacks



in p dims

in p' dims

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

in $p \cap p'$ dims

A D-brane embedding of the Standard Model

I.A.-Kiritsis-Tomaras '00

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

- oriented strings ⇒

  need at least 4 brane-stacks

- existence of bulk with large dimensions ⇒

  minimal choice: $\underset{\nearrow}{U(3)} \times \underset{\nwarrow}{U(2)} \times U(1) \times U(1)_{bulk}$

  color branes (g_3) weak branes (g_2)

- also for non-oriented strings

  with Baryon and Lepton number symmetries fermion generation $U(3) \times U(2) \times U(1)$

$Q \quad (\mathbf{3}, \mathbf{2}; 1, w, 0)_{1/6} \qquad w = \pm 1$

$u^c \quad (\bar{\mathbf{3}}, 1; -1, 0, x)_{-2/3} \qquad x = \pm 1, 0$

$d^c \quad (\bar{\mathbf{3}}, 1; -1, 0, y)_{1/3} \qquad y = \pm 1, 0$

$L \quad (\mathbf{1}, \mathbf{2}; 0, 1, z)_{-1/2} \qquad z = \pm 1, 0$

$l^c \quad (\mathbf{1}, 1; 0, 0, 1)_{1}$

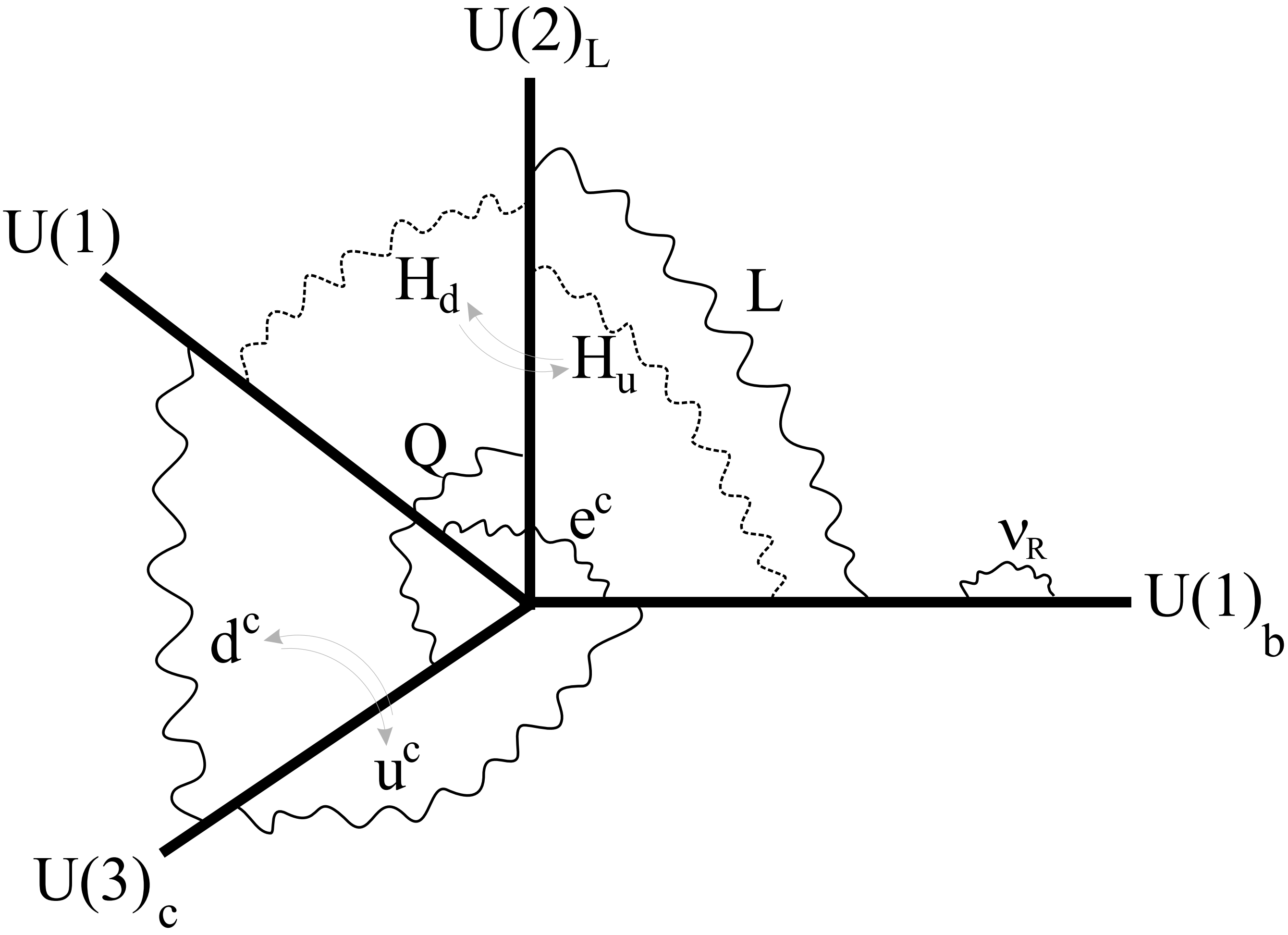
hypercharge $Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3$

$\Rightarrow$ 4 possibilities:

$c_3 = -1/3 \quad c_2 = \pm 1/2 \quad x = -1 \quad y = 0 \quad w = \pm 1 \quad z = -1/0$

$c_3 = 2/3 \quad c_2 = \pm 1/2 \quad x = 0 \quad y = 1 \quad w = \mp 1 \quad z = -1/0$

Standard Model on D-branes



- $g_2^2/g_3^2 = R/l_s \Rightarrow$ KK modes for $SU(2)_L$
- $U(1)^4 \Rightarrow$ hypercharge + B, L, PQ global
- $U(1)$ on top of $U(2)$ or $U(3) \Rightarrow$ prediction for $\sin^2\theta_W$
- ν_R in the bulk $\Rightarrow$ small neutrino masses

The remaining three $U(1)$'s : anomalous

Green-Schwarz anomaly cancellation ⇒

- they become massive (absorb three axions)
- the global symmetries remain in perturbation

- Baryon number ⇒ proton stability

- Lepton number ⇒ protect small neutrino masses

no Lepton number ⇒ $\frac{1}{M_s} LLHH$

⇒ Majorana mass: $\frac{\langle H \rangle^2}{M_s} LL$

$\nearrow$ $\sim$ GeV

- PQ-type symmetry ⇒ electroweak axion

can be explicitly broken by moving slightly away from the orbifold point

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

$$\frac{1}{g_Y^2} = \frac{2c_1^2}{g_1^2} + \frac{4c_2^2}{g_2^2} + \frac{9c_3^2}{g_3^2}$$

$$\sin^2\theta_W = \frac{g_Y^2}{g_2^2+g_Y^2} = \frac{1}{g_2^2/g_Y^2+1}$$

$$= \frac{1}{1+4c_2+2c_1^2 g_2^2/g_1^2+6c_3^2 g_2^2/g_3^2}$$

fermion generation $U(3)\times U(2)\times U(1)$

$$\begin{array}{lll}
Q & (\mathbf{3},\mathbf{2};1,w,0)_{1/6} & w=\pm1 \\
u^c & (\bar{\mathbf{3}},1;-1,0,x)_{-2/3} & x=\pm1,0 \\
d^c & (\bar{\mathbf{3}},1;-1,0,y)_{1/3} & y=\pm1,0 \\
L & (\mathbf{1},\mathbf{2};0,1,z)_{-1/2} & z=\pm1,0 \\
l^c & (\mathbf{1},1;0,0,1)_{1} &
\end{array}$$

hypercharge $Y=c_1Q_1+c_2Q_2+c_3Q_3$

$\Rightarrow$ 4 possibilities:

$c_3=-1/3$ $c_2=\pm1/2$ $x=-1$ $y=0$ $w=\pm1$ $z=-1/0$

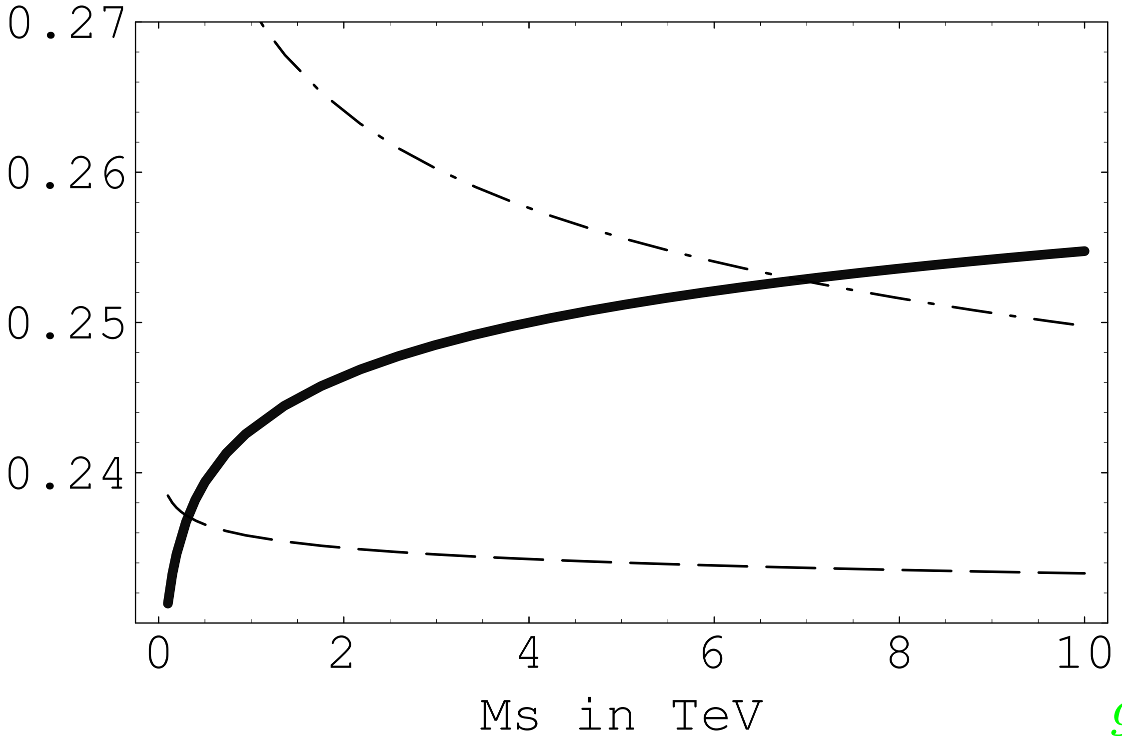
$c_3=2/3$ $c_2=\pm1/2$ $x=0$ $y=1$ $w=\mp1$ $z=-1/0$

$$\sin^2\theta_W=\frac{1}{2+2g_2^2/g_1^2+6c_3^2g_2^2/g_3^2}$$

$$g_1=g_2=g_3\Rightarrow\sin^2\theta_W=\begin{cases}3/14 & c_3=-1/3\\ 3/20 & c_3=2/3\end{cases}$$

$\sin^2\theta_W(M_s)$

$g_1 = g_3 \quad c_3 = 2/3$



$g_1 = g_2$

$c_3 = -1/3$

$\Rightarrow$ correct prediction for $\sin^2\theta_W$

for $M_s \sim$ a few TeV

R-neutrinos: open strings in the bulk $H'L\nu_R$

Arkani Hamed-Dimopoulos-Dvali-March Russell '98

Dienes-Dudas-Gherghetta '98

- $\int d^{4+n}x\ \bar\nu \not\partial \nu \qquad \nu = (\nu_R, \nu_R^c) \ \Rightarrow$

$$R_\perp^n \int d^4x \sum_m \left\{ \bar\nu_{Rm} \not\partial \nu_{Rm} + \bar\nu_{Rm}^c \not\partial \nu_{Rm}^c + \tfrac{m}{R_\perp} \nu_{Rm} \nu_{Rm}^c + c.c. \right\}$$

- $S_{int} = g_s \int d^4x H(x) L(x) \nu_R(x, y = 0)$

$\langle H \rangle = v \ \Rightarrow$ mass-terms: $\frac{g_s v}{R_\perp^{n/2}} \sum_m \nu_L \nu_{Rm}$

$\frac{g_s v}{R_\perp^{n/2}} << \frac{1}{R_\perp} \ \Leftrightarrow \ g_s v << R_\perp^{n/2-1}$ in string units $\Rightarrow$

- $m \neq 0$: masses for KK ν_m unaffected

- $m = 0$: Dirac neutrino masses

$$m_\nu \simeq \frac{g_s v}{R_\perp^{n/2}} \simeq \frac{g_s}{g^2} v \frac{M_s}{M_p}$$

$\simeq 10^{-3} - 10^{-2}$ eV for $M_s \simeq 1 - 10$ TeV

In principle one $\nu_R \Rightarrow$

both solar and atmospheric oscillations

two frequencies: solar $\leftrightarrow m_\nu <<$

atmospheric $\leftrightarrow$ 1st KK excitation

however cannot be made realistic

e.g. KK modes $\rightarrow$ important sterile component

$\Rightarrow$ need to introduce three ν_R^i (at least 2)

explain oscillations in the traditional way

- only from zero modes ν_{R0}^i
- make KK modes heavy

Davoudiasl-Langacker-Perelstein '02

Conclusions

TeV strings and large extra dimensions:

Physical reality or imagination?

Well motivated theoretical framework

with many testable experimental predictions

new resonances, missing energy

Stimulus for micro-gravity experiments

look for new forces at short distances

higher dim graviton, scalars, gauge fields

Internal magnetic fields

- 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 → 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 ⇒ 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

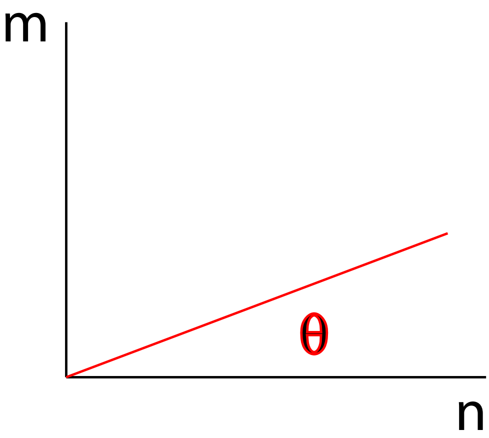
$$H = \frac{m}{n} \frac{1}{R_1 R_2}$$

T-duality: $R_2 \to \alpha'/R_2 \equiv \tilde{R}_2 \Rightarrow$ D8-brane

wrapped around a direction of angle θ in T^2

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

(m, n): wrapping numbers around $(\tilde{R}_2, R_1)$

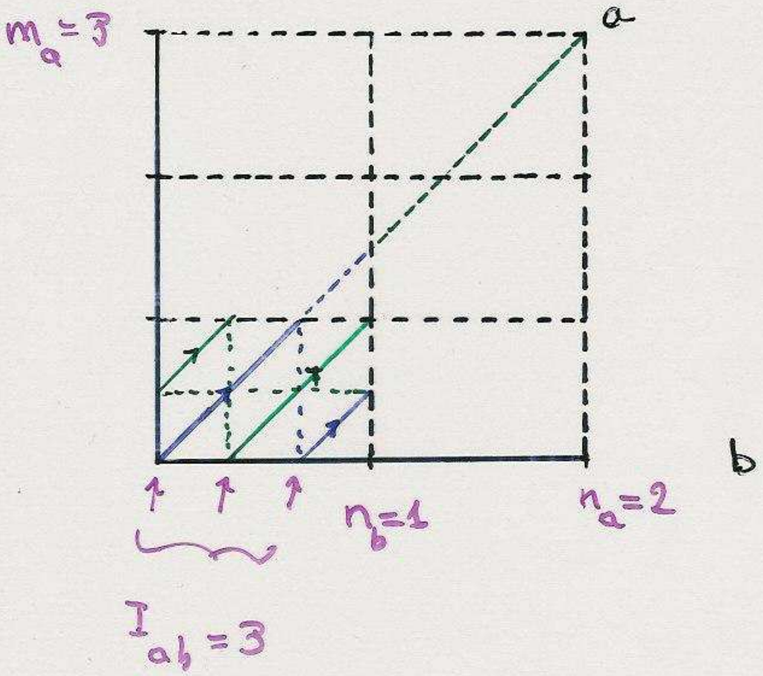


Chirality = intersection number

e.g. $I_{ab} = m_a n_b - m_b n_a$

= intersection nb of branes a, b

ex. $m_b = 0$ $n_b = 1$ $\Rightarrow$ $I_{ab} = m_a$



$(T^2)^3$ 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 ⇔ 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: $\prod_a U(N_a) \leftarrow SU(N_a) \times U(1)_a$

- Neutral strings: adjoint representations

  $\Rightarrow$ massless gauge supermultiplets

- Charged strings $\Rightarrow$ massless chiral fermions

  but in general massive scalars

$\Rightarrow$ Generic spectrum of split SUSY:

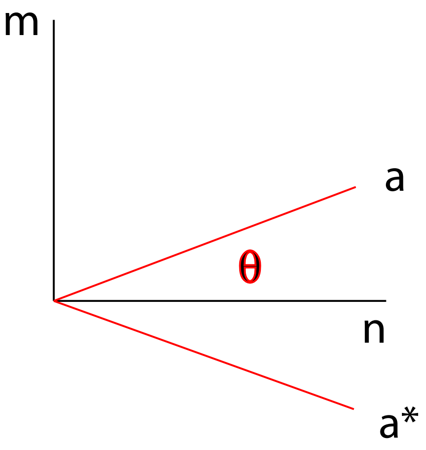
- massless gauginos
- massive squarks and sleptons
- massless Higgs $\Leftrightarrow$ non chiral susy intersection

  two Higgs multiplets

D-brane a: (m, n) ; $n > 0$ anti-brane: $(m, -n)$

Orientifold: $(0, x)$

Miirror brane a^*: $(-m, n)$



multiplicities: nb of intersections in $(1, 1)$

$(N_a, \bar{N}_b)$: $I_{ab} = \prod_I (m_I^a n_I^b - n_I^a m_I^b)$

(N_a, N_b): $I_{ab^*} = \prod_I (m_I^a n_I^b + n_I^a m_I^b)$

same stack: antisymmetric or symmetric

$$I_{aa^*} = \prod_I \left\{ \frac{1}{2}(2m_I^a n_I^a \mp 2m_I^a) \underset{\nearrow}{\pm} 2m_I^a \right\} = \begin{cases} A: \ \frac{1}{2}\left(\prod_I 2m_I^a\right)\left(\prod_J n_J^a + 1\right) \\ S: \ \frac{1}{2}\left(\prod_I 2m_I^a\right)\left(\prod_J n_J^a - 1\right) \end{cases}$$

nb of intersections along $(0, x)$

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

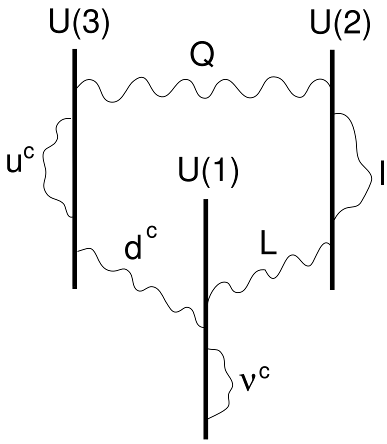
$\Rightarrow\ U(3)\times U(2)\times U(1)$

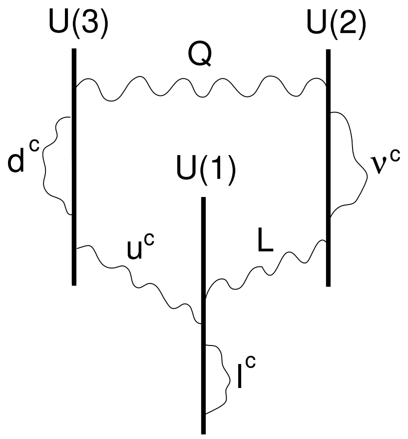
antiquarks u^c, d^c $(\bar{3}, 1)$:

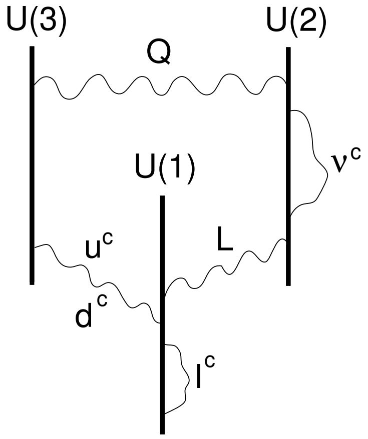
antisymmetric of $U(3)$ or

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

- Higgs can be easily implemented

  massless ⇒ 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

- Model A,B: one combination can be $B - L$

  broken by a SM singlet VEV at high scale

  or survive at low energies

- Model C: Baryon symmetry

- The other/both is/are anomalous

Gaugino masses: protected by R-symmetry

but broken in 4d SUGRA by the gravitino mass

Two possible ways for generating $m_{1/2}$:

(1) via gravity (brane susy) $\Rightarrow$

generate $m_{1/2}$ from $m_{3/2}$

one gravitational loop: 1 handle + 1 boundary

$\Rightarrow m_{1/2} \sim g_s^2 \frac{m_{3/2}^3}{M_s^2}$ 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 '05 gauginos: open strings

$\Rightarrow$ at least one boundary (brane) $h \geq 1$

$N = 2$ superconformal charge:

3/2 units for each (chiral) gaugino

±1 unit for each 2d supercurrent insertion T_F

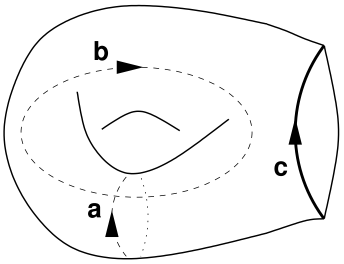
$\Rightarrow$ at least 3 T_F insertions

lowest order (effective genus): $g + h/2 = 3/2$

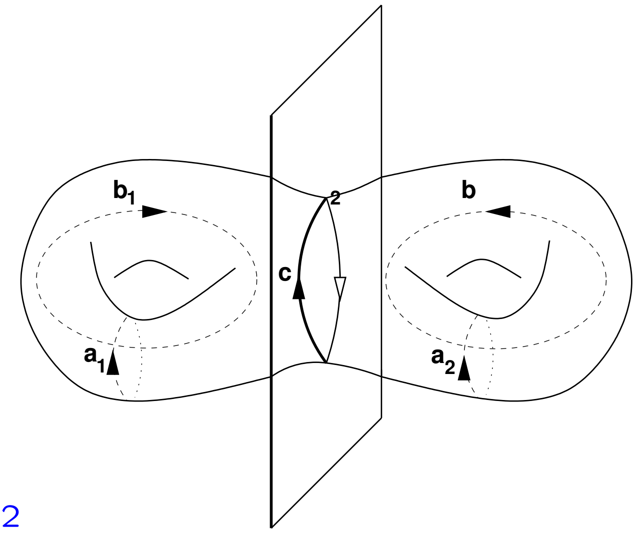
independently of the source of SUSY breaking!

Oriented case

(1) $g = 1$ $h = 1$ from mirror involution of $g = 2$



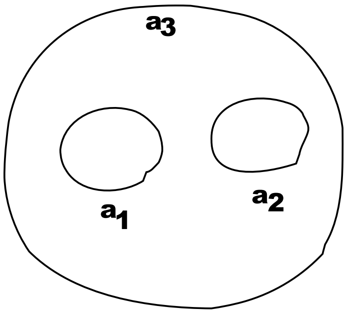
$\longleftarrow$



$a_1 \leftrightarrow a_2$

$b_1 \leftrightarrow -b_2$

(1) $g = 0$ $h = 3$ from mirror involution of $g = 2$



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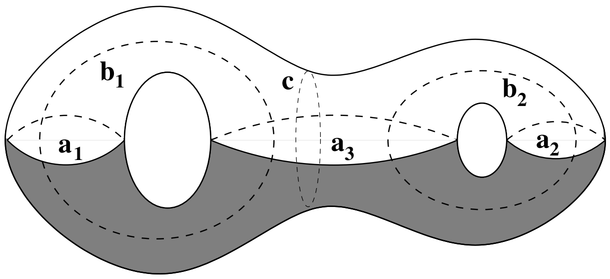


$a_i \leftrightarrow a_i$

$b_i \leftrightarrow -b_i$

Topological partition function F_g $\nwarrow$ genus g

computes $N = 2$ SUSY F-terms

AGNT, BCOV '93

$$F_g \int d^4\theta \; W_{N=2}^{2g} \quad \longrightarrow \quad F_g \, R^2 \, T^{2g-2}$$

F_g: moduli dependent function

Weyl superfield: $W_{N=2} = T + \theta^2 R + \cdots$

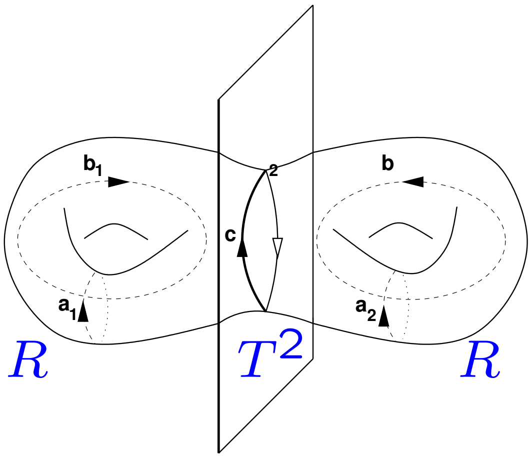
T: graviphoton field strength

R: Riemann tensor

$$F_2 \int d^4\theta \; W^4_{N=2} \quad \rightarrow \quad F_2\, R^2\, T^2$$

- graviphoton vertex T = (gaugino)^2
- graviton vertex = (gauge field)^2

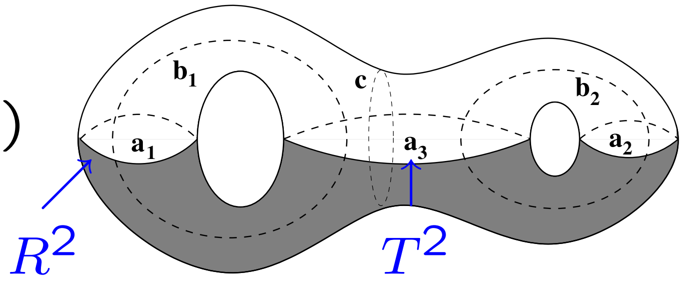
(1)



$\Rightarrow \quad \lambda\lambda\, R$

or SUSY breaking

(2)

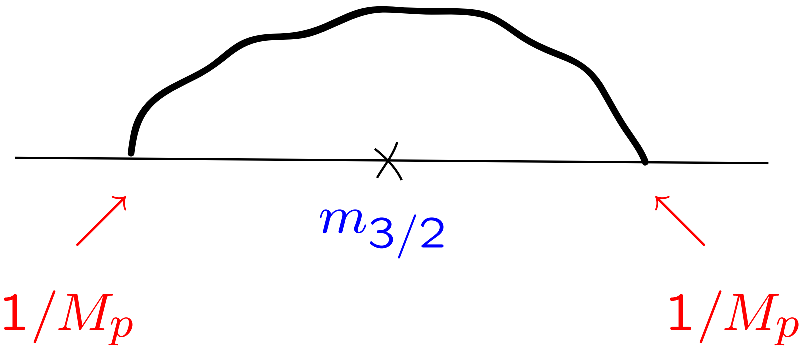


$\Rightarrow \quad \lambda\lambda\, F^2$

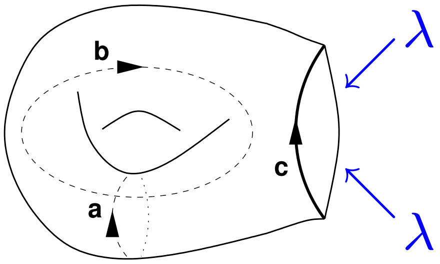
SUSY breaking: $R \rightarrow \langle$gravity auxiliary field$\rangle$

$$F \rightarrow \langle \mathrm{D} \rangle$$

$m_{1/2}$:



$$\sim \frac{m_{3/2}}{M_p^2} \times \begin{cases} \Lambda_{\mathrm{UV}}^2 & \text{if quadr. divergent} \\ m_{3/2}^2 & \text{if convergent} \end{cases}$$



$$\sim g_s^2 \, \frac{m_{3/2}^3}{M_s^2} \qquad g_s \sim g^2$$

but it vanishes for orbifolds

I.A.-Taylor '04

- anomaly mediation:

$$m_{1/2} \sim g^2 m_{3/2} \qquad g^2 \sim g_s$$

- power of g_s does not match

one loop correction always vanishes

by $N = 2$ superconformal charge

- two loops behave $\sim m_{3/2}^3$

- hierarchy between gaugino and scalar masses

however numerics not very good

unless every loop factor $\sim\ 10^{-2}$

Sherk-Schwarz along an interval $\perp$ branes

$\Rightarrow m_{3/2} \sim 1/R$

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

for $M_s \sim M_{\rm GUT} \sim 10^{16}$ GeV

- $m_{1/2} \sim g_s^2 \frac{m_{3/2}^3}{M_s^2} \sim 1$ TeV

if every loop-factor $\sim 10^{-2}$

- $m_0 \gtrsim g_s \frac{m_{3/2}^2}{M_s} \sim 10^8$ GeV

scalar masses induced at one loop

$\Rightarrow$ split supersymmetry framework

heavy scalars, light fermions

Arkani Hamed-Dimopoulos, Giudice-Romanino '04

SUSY breaking by internal magnetic fields

or equivalently branes at angles

Effective QFT description: D-breaking

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

↗

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

R-symmetry broken by string corrections

$\Rightarrow$ higher-dim effective operators:

I.A.-Narain-Taylor ’05

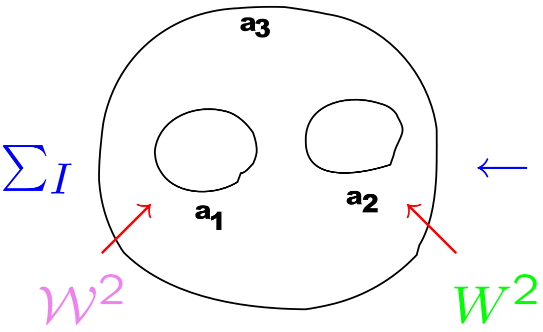
$F_{(0,3)} \int d^2\theta \mathcal{W}^2 \mathrm{Tr} W^2$ $\langle \mathcal{W} \rangle = \theta \langle \mathrm{D} \rangle$

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

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

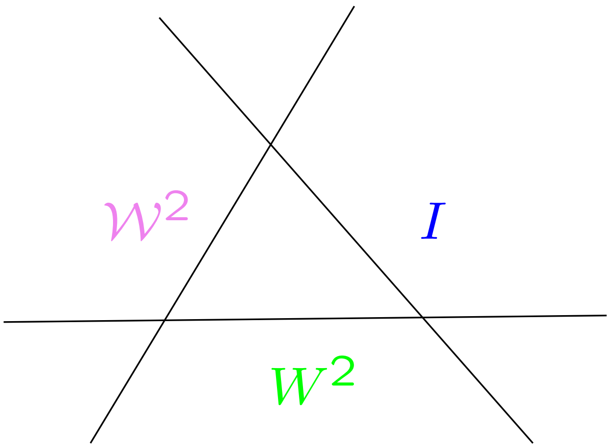
World-sheet with 3 boundaries (2 loops)

Σ_I



$\leftarrow$ I: intermediate brane

T-duality $\Rightarrow$



$\neq 0$: I-brane away from the intersection

of the other two

- as gauge mediation with string scale gaugino masses

- Higgsino mass

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

$$\nearrow$$

$\psi_1 \psi_2$

- 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

in inermediate energy scales $\sim 10^7 - 10^{13}$ GeV

I.A.-Benakli-Delgado-Quirós-Tuckmantel '05

Evading the hierarchy $m_0 >> m_D$:

- SM on a SUSY brane
- gauge mediation with Dirac masses

I.A.-Benakli-Delgado-Quirós in preparation

$\not{\text{SU}}$SY brane with massive hypermultiplets

in its $(N = 2)$ intersection with SM brane

$(M, D) \longrightarrow$ SM $\quad \Rightarrow \quad M_s \to M$

$$D < M < M_s \qquad \Rightarrow \qquad m_D^a = \frac{\alpha_a}{4\pi}\frac{D}{M}$$

- adjoint SM scalars Σ_a: one loop masses

$$m^2_{\Sigma_a} = \frac{\alpha_a}{4\pi}\frac{D^2}{M^2}$$

- squarks and sleptons Q: two loop masses

$$m^2_Q = 2 \sum_a C_a(Q) \left(\frac{\alpha_a}{4\pi}\right)^2 \frac{D^2}{M^2}$$

need $\mathrm{Tr}Y_{\text{hyp}} = 0$ to avoid $m_Q^2 \sim D$ from D_Y^2

$\nearrow$

$D_Y = D_Y^{\text{SM}} + D_Y^{\text{hyp}}$

e.g. messengers in complete $SU(5)$ reps

- Higgs sector: $N = 2$ hyper $(H_1, H_2) \Rightarrow$

$$\begin{aligned} V_H &= m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2(H_1H_2 + h.c.) \\ &+ \frac{1}{8}(g^2+g'^2)(|H_1|^2 - |H_2|^2)^2 + \frac{1}{2}(g^2+g'^2)|H_1H_2|^2 \end{aligned}$$

$\nearrow$ $\nearrow$

$N = 2$ D-term $\Rightarrow$ $N = 1$ D-term $+$ F-term $\Sigma H_1 H_2$

$$m_h = m_Z,\ m_H = m_A,\ m_{H^\pm}^2 = m_A^2 + 2m_W^2$$

$\Rightarrow$

$$g_{Zhh} = g_{Zhh}^{\text{SM}}, \quad g_{ZHH} = 0$$

h behaves as SM Higgs

$\Rightarrow$

H plays no role in EWSB

Conclusions

Gaugino masses from string loops:

High string scale ⇒ hierarchy $m_0 >> m_{1/2}$

1) Majorana masses

- gravity 'mediation' ⇒ $m_{1/2}^2 \sim m_0^3/M_s$
- gauge 'mediation' ⇒ $m_{1/2} \sim m_0^4/M_s^3$

2) Dirac masses ⇒ $m_D \sim m_0^2/M_s$

evading the hierarchy:

$M_s \to M_{\text{hyp}}$, $m_0^2 \to D$ in a SU$\!\!\!/$SY sector

$m_0^{\text{SM}} \sim m_D$ from 2-loops