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Physics of Low-scale string theories

- Motivations:
  - mass hierarchy
  - low scale string framework

    type I with large dimensions
  - susy in the bulk
- Experimental predictions
  - gravity modification at short distances
  - particle accelerators
- U(1) anomalies and masses
- Brane susy breaking

  non-linear susy, radion stabilization
- A minimal embedding of the Standard Model

  $\sin^2\theta_W$, proton stability, neutrino masses

Hierarchy problem

Why gravity is so weak compared to the other 3 known interactions?

Quantum theory: all masses of elementary particles ↗ $M_p \sim 10^{19}$ GeV

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

$\Rightarrow m_{susy} \sim$ TeV

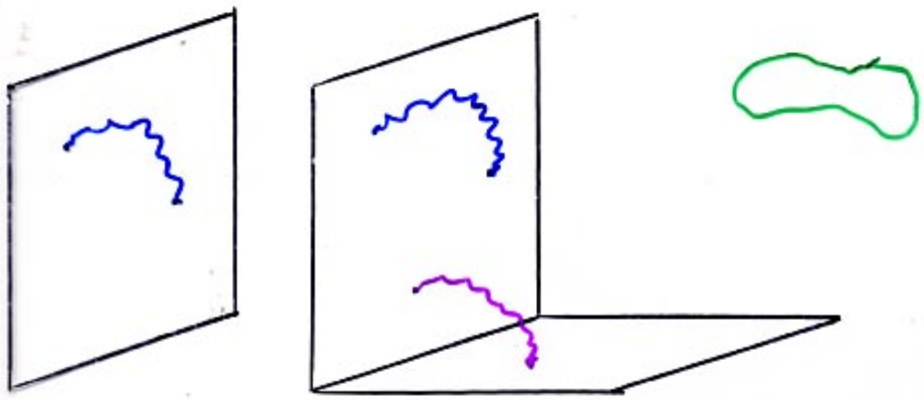
TeV strings: effective ultraviolet cutoff

$M_s \sim$ TeV

I.A. - Arkani Hamed - Dimopoulos - Dvali

Type I strings provide a perturbative framework for model building with low string scale

- gravity : closed strings (bulk)
- gauge interactions : on D-branes



A particularly attractive possibility :

- bulk is susy
- brane susy breaking

Heterotic string :

gauge + gravity interactions appear at tree-level

$$S_H = \int d^{10}x \; \frac{1}{\lambda_H^2}\left(\frac{1}{\ell_H^8} R + \frac{1}{\ell_H^6} F^2 \right) + \dots$$

$$d^{10}x \to d^4x \; V$$

$$\underbrace{V \, \frac{1}{\lambda_H^2} \frac{1}{\ell_H^8}}_{1/\ell_P^2} \qquad\qquad V \, \frac{1}{\lambda_H^2} \frac{1}{\ell_H^6} \sim 1/g^2$$

$$\frac{1}{\ell_P^2} = \frac{1}{g^2} \, 1/\ell_H^2 \quad \Rightarrow \quad M_H = g \, M_P \sim 10^{18} \text{ GeV}$$

$$\frac{1}{g^2} = \frac{1}{\lambda_H^2} \frac{V}{\ell_H^6} \quad \Rightarrow \quad \lambda_H = g \frac{\sqrt{V}}{\ell_H^3} < 1 \quad \Rightarrow \quad V \sim \ell_H^6$$

sphere $\qquad\qquad$ disk

$$S_I = \int d^{10}x \, \frac{1}{\lambda_I^2} \frac{1}{\ell_I^8} R + \int d^{p+1}x \, \frac{1}{\lambda_I} \frac{1}{\ell_I^{p-3}} F^2$$

$$d^4x \, \underbrace{V^{\parallel}_{p-3} \, V^{\perp}_{9-p}}_{1/\ell_P^2} \qquad\qquad d^4x \, \underbrace{V^{\parallel}_{p-3}}_{1/g^2}$$

$$\frac{1}{g^2} = \frac{1}{\lambda_I} \frac{V_{\parallel}}{\ell_I^{p-3}} \Rightarrow \lambda_I = g^2 \frac{V_{\parallel}}{\ell_I^{p-3}} < 1 \Rightarrow V_{\parallel} \sim \ell_I^{p-3}$$

$$\lambda_I \sim g^2$$

$$\frac{1}{\ell_P^2} = \frac{1}{\lambda_I^2} \frac{V_{\perp} V_{\parallel}}{\ell_I^8} \simeq \frac{1}{\lambda_I^2} \frac{V_{\perp}}{\ell_I^{9-p}} \frac{1}{\ell_I^2}$$

weak coupling $\Rightarrow$ longitud dims $\sim$ string size

transverse dims : no constraint

n $\perp$ dims of radius $R_\perp$ $\Rightarrow$

$$M_P^2 = \underbrace{\frac{1}{g^4} M_I^{2+n}}_{M_{P_{(4+n)}}^{2+n}} R_\perp^n$$

Planck mass of 4+n dims

largeness of M_P / M_I $\Rightarrow$ extra-large $R_\perp$

- string coupling : $\lambda_I \simeq g^2$

- gravity strong at $M_{P_{(4+n)}} \sim M_I << M_P$

M_I: TeV, 10^{-16} cm

M_P: 10^{19} GeV, 10^{-33} cm

Extra large transverse dimensions $\Rightarrow$

explain the apparent weakness of gravity

total force = observed force $\times$ volume $\perp$

- total force $\simeq \mathcal{O}(1)$ at 1 TeV

- n dimensions of size $R_\perp$

$n = 1 : R_\perp \simeq 10^8$ km excluded

$n = 2 : R_\perp \simeq .1$ mm (10^{-12} GeV)

possible

$n = 6 : R_\perp \simeq 10^{-13}$ mm (10^{-2} GeV)

- distances $> R_\perp$: gravity 3d

  however for $< R_\perp$: gravity (3+n)d

- strong gravity at 10^{-16} cm $\leftrightarrow$ 10^3 GeV

  10^{30} times stronger than thought previously !

Supernova constraints:

cooling due to graviton production

e.g. $NN \longrightarrow NN + \text{graviton}$

number of gravitons: $\sim (Tr)^n$ $\quad T \gg r^{-1}$

~ 10 MeV

$\Rightarrow$ production rate:

$$P_g \sim \frac{1}{M_P^2} (Tr)^n \sim \frac{T^n}{M_{P(4+n)}^{2+n}}$$

$$P_g < P_{\text{neutrinos}} \underset{n=2}{\Longrightarrow} M_{P(6)} \gtrsim 50 \text{ TeV}$$

$$\Rightarrow M_I \gtrsim 10 \text{ TeV}$$

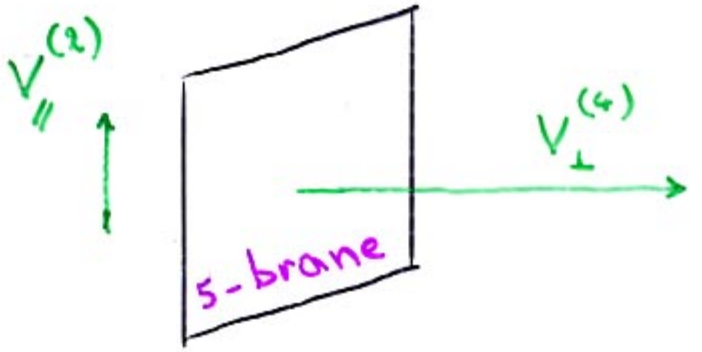
Type II strings

I.A. - Pioline '99

I.A. - Dimopoulos - Giveon '01

Non abelian symmetries : non-perturbative on a 5-brane (NS)

localized at singularities of the internal manifold



$$M_p^2 = \frac{1}{\lambda_{II}^2} \frac{1}{g^2} M_s^{2+4} V_{\perp}^{(4)}$$

New possibility: largeness of $M_p \Rightarrow$ tiny string coupling

all radii $\sim M_s^{-1}$, $\lambda_{II} \simeq 10^{-14}$

- No strong gravity at TeV
- signal: 2 longitudinal (TeV) dims $V_{\parallel}^{(2)}$

  with gauge interactions

similar in Heterotic with small instantons

Benakli - 03

sphere

non-perturbative

$$S_{II} = \int d^{10}x \; \frac{1}{\lambda_{II}^2} \; \frac{1}{\ell_{II}^8} \; R \; + \; \int d^6x \; \frac{1}{\ell_{II}^2} \; F^2$$

$$d^4x \; \underbrace{V_\perp^{(4)} \; V_\parallel^{(2)}}_{1/\ell_p^2} \qquad\qquad d^4x \; \underbrace{V_\parallel^{(2)}}_{1/g^2}$$

$$\frac{1}{g^2} = \frac{V_\parallel^{(2)}}{\ell_{II}^2} \quad \Rightarrow \quad V_\parallel \sim \ell_{II}^2$$

$$\frac{1}{\ell_p^2} = \frac{1}{\lambda_{II}^2} \; \frac{V_\perp^{(4)} \; V_\parallel^{(2)}}{\ell_{II}^8} = \frac{1}{\lambda_{II}^2} \; \frac{1}{g^2} \; \frac{V_\perp^{(4)}}{\ell_{II}^4}$$

Gauge hierarchy

$M_p >> M_Z \Rightarrow$ why large transverse dims ?

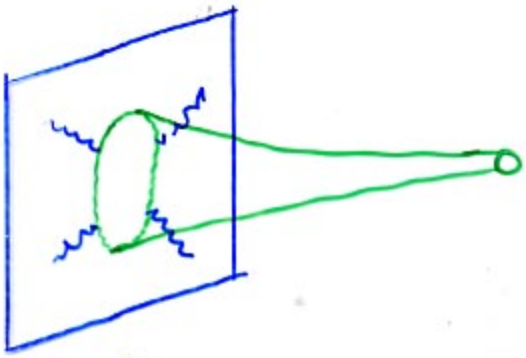
$$r\, M_I \simeq \left(g^2\, M_p / M_I \right)^{2/n} \sim \begin{cases} 10^{15} & n=2 \\ 10^{5} & n=6 \end{cases} \qquad \text{or } \lambda_{II} \simeq 10^{-14}$$

Technical aspect: stability in a non susy vacuum

no large corrections to SM couplings as $rM_I \to \infty$

In general no decoupling if massless bulk fields propagate in less than 2 large transv. dims

I.A.-Bachas '98



IR divergence : emission of massless closed string

UV divergence: open string loop

$d_\perp = 1$: linear IR div $\Rightarrow$ quatratic UV $\quad r \sim M_p^2$

Condition: no bulk propagation in one large dim

or local tadpole cancellation $\Rightarrow$ severe constraints

$d_\perp = 2$: log divergences

can be absorbed into a finite number of parameters:

values of bulk massless fields at the brane position

similar to renormalizable field theory

RGE resum $\Rightarrow$ classical 2d eqs in the transverse space

log dependence $\Rightarrow$ higher derivs irrelevant

$\Rightarrow$ hierarchy could be determined by minim SM eff. potential

$\Rightarrow$ No susy TeV strings:

same protection of hierarchy as softly susy at TeV

Do we need SUSY if $M_{str} \sim$ TeV ?

Type I : non susy string models $\Rightarrow$

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

analog of quadratic div. to Λ in softly broken susy

absence of quadratic sensitivity:

- $\Lambda = 0$ (special models)

- $\Lambda_{brane} \sim M_I^4 \Rightarrow \Lambda_{bulk} \sim M_I^4 / R_\perp^n$

satisfied if approximate susy in the bulk

e.g. susy is broken primordially only on the brane

explicit realization : Brane SUSY breaking

I.A. - Dudas - Sagnotti '99

Aldazabal - Uranga '99

No SUSY in our world (brane)

but it may exist a mm away!

to protect the hierarchy against grav. corrections

Prediction: possible new forces at submm scales

e.g. light scalars:

$$\frac{(\text{TeV})^2}{M_p} \sim 10^{-4}\,\text{eV} = 1\ \text{mm}^{-1}$$

radion - modulus $\equiv \ln R_\perp$

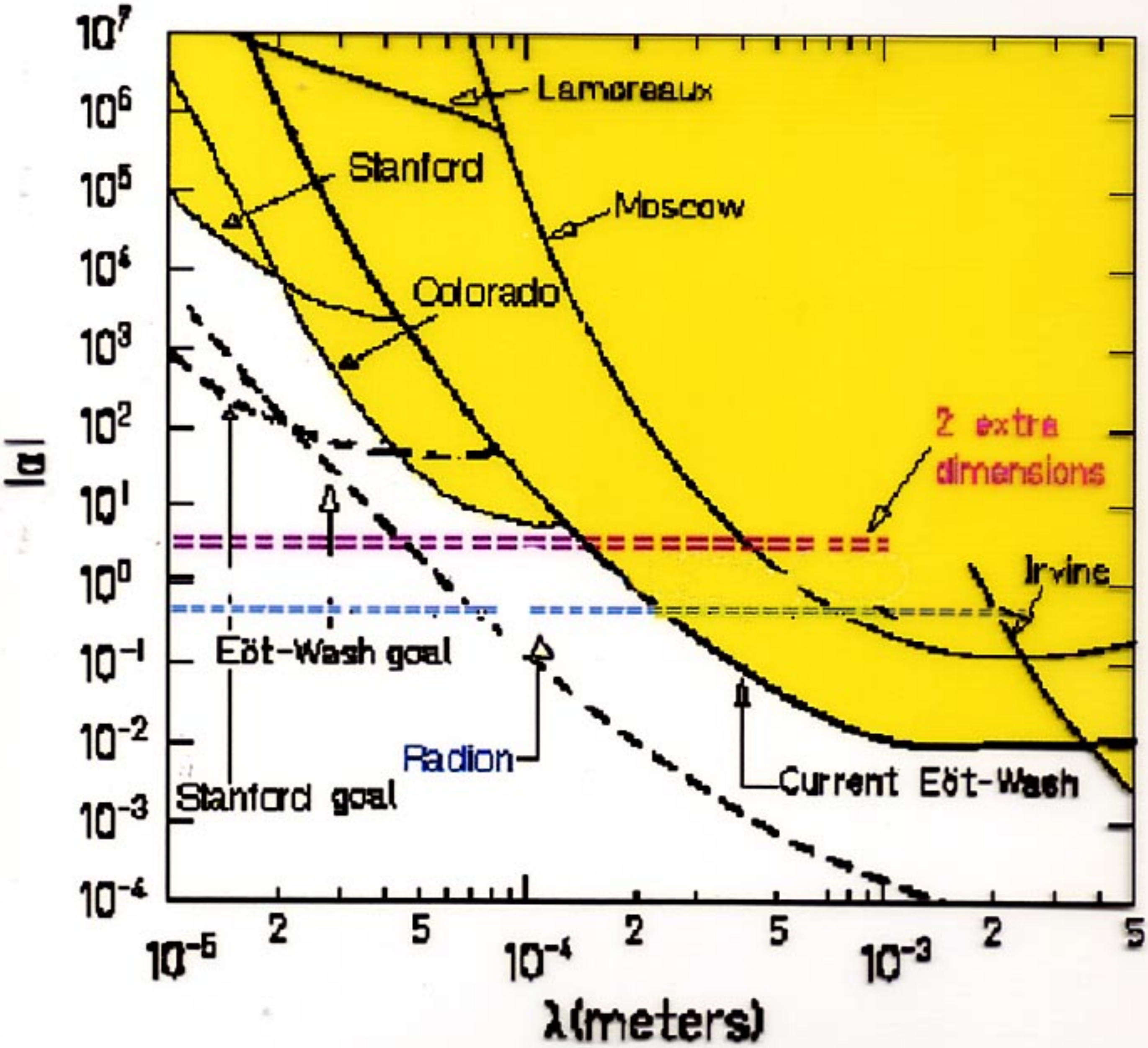
coupling to matter relative to gravity:

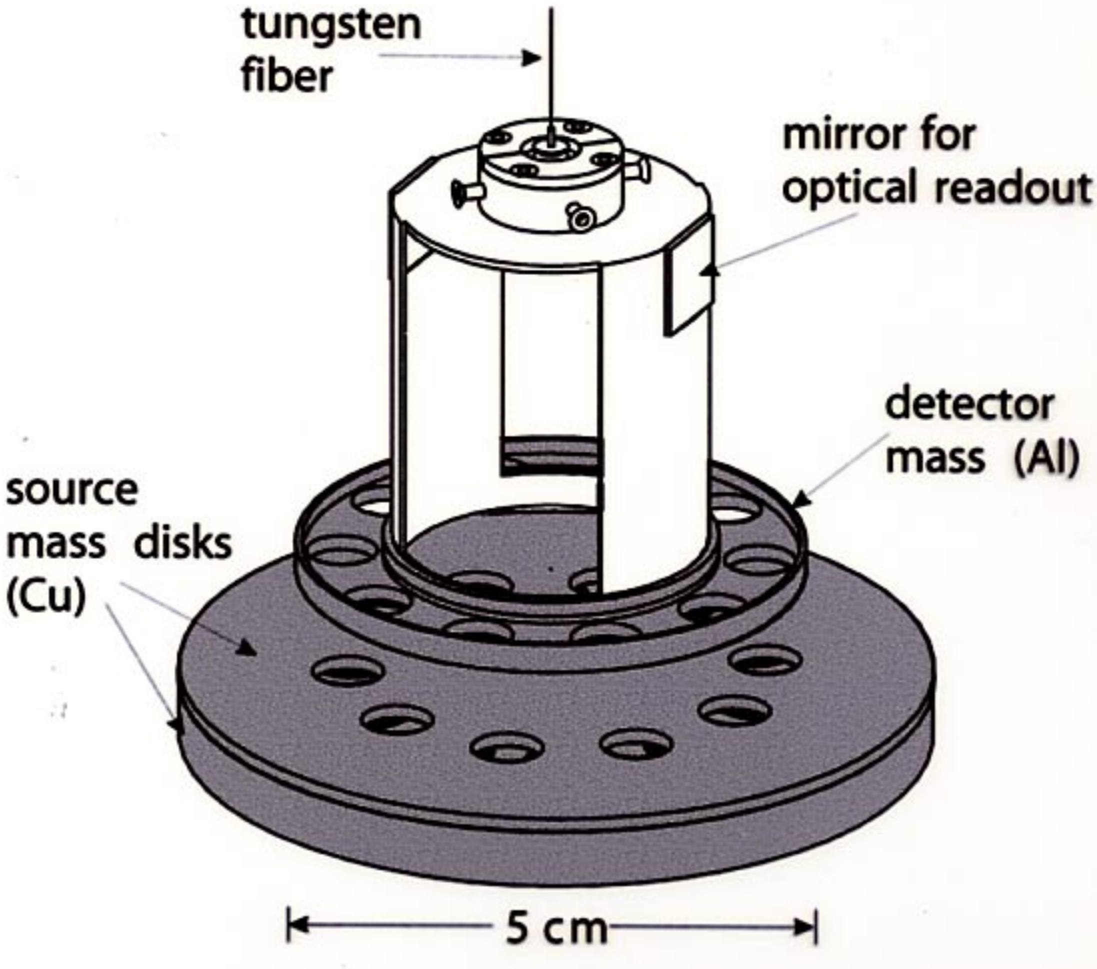
$$\frac{1}{m}\frac{\partial m}{\partial \ln R_\perp} = \sqrt{\frac{n}{n+2}} \sim \mathcal{O}(1)$$

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

I.A. - Benakli - Maillard - Lougier

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





$R_\perp \lesssim 200\ \mu m$ at 95% CL

Hidden submillimeter dimensions

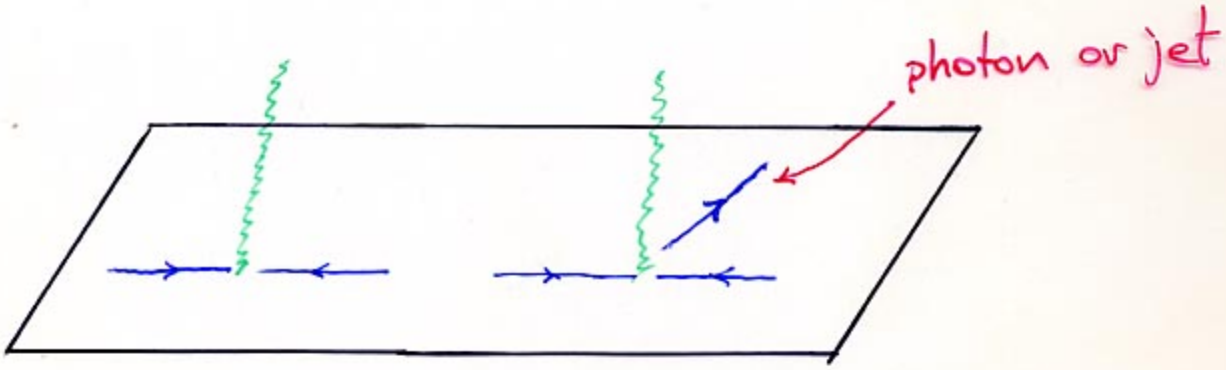
$\Rightarrow$ strong gravity at the TeV

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



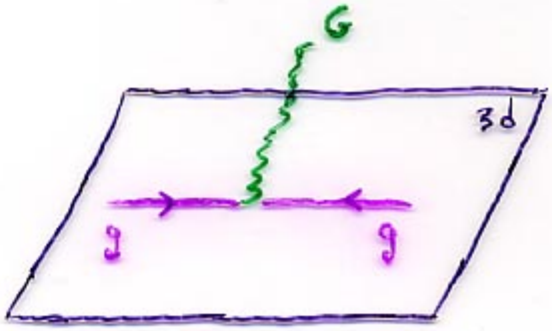
Signal: missing energy

Angular distribution $\Rightarrow$ spin of the graviton

Actual limits from LEP2:

$R_\perp \lesssim .5$ mm $(n = 2)$ – 10^{-10} $(n = 6)$

$gg \longrightarrow G$



$$\sigma(E) \sim \frac{E^p}{M_I^{p+2}} \; \frac{\Gamma\left(1-2E^2/M_I^2\right)^2}{\Gamma\left(1-E^2/M_I^2\right)^4}$$

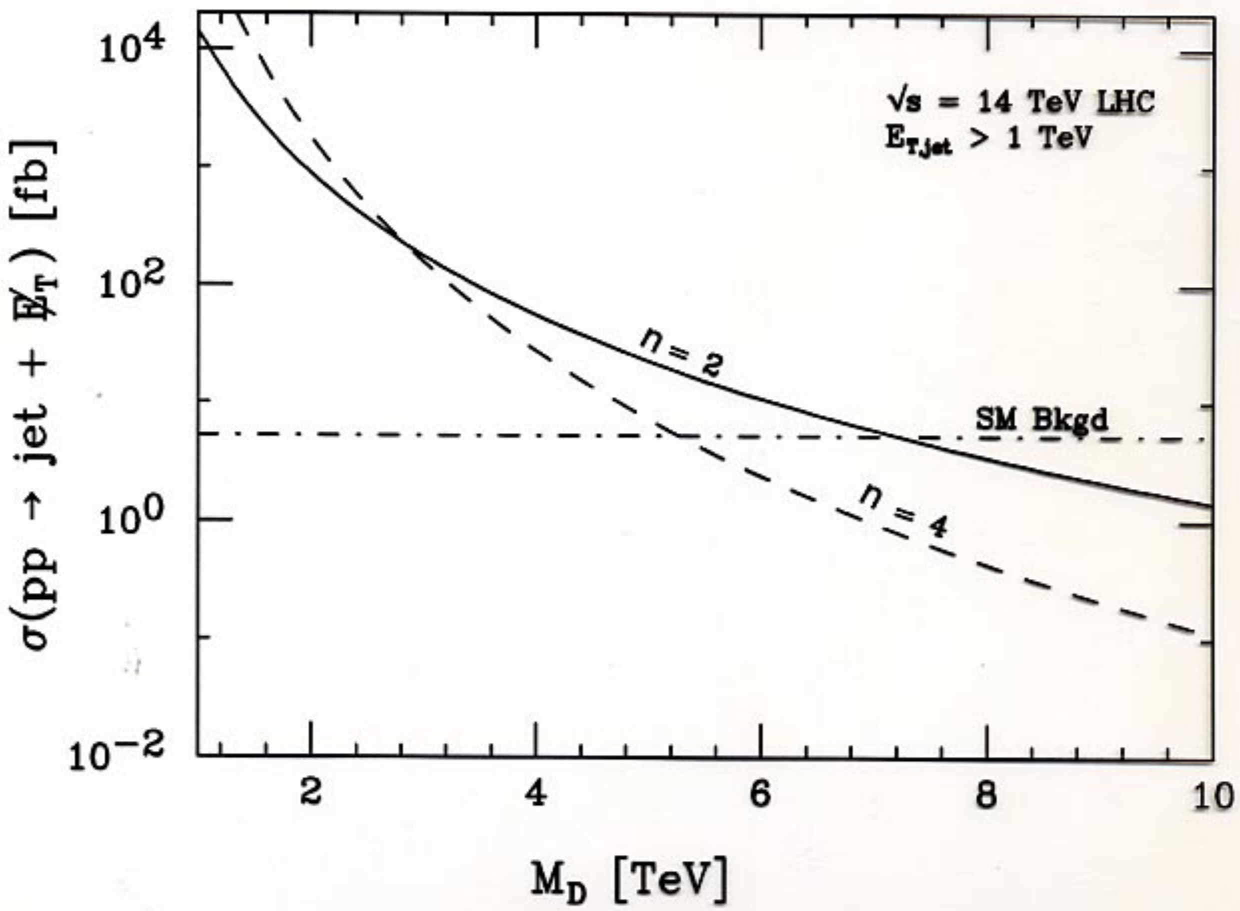
- $E < M_I \Rightarrow \sim E^p / M_I^{p+2}$ gravity in 4+p dims
- $E \sim M_I \Rightarrow$ sequence of poles due to RR resonances
- $E > M_I \Rightarrow$ exp decay due to the UV softness of strings

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

$E < M_I$: reliable computations within eff. field theory

$\Rightarrow$ model independent predictions

Giudice-Rattazzi-Wells '98



no observation $\Rightarrow$

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

- more dimensions $\Rightarrow$ weaker limits

Limits on $R_\perp$ in mm from missing-energy processes

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}
Present non-collider bounds			
SN1987A	3×10^{-4}	1×10^{-8}	6×10^{-10}
COMPTEL	5×10^{-5}	-	-

Experimental predictions

- particle accelerators

- Large TeV dimensions

  seen by gauge interactions

- Extra large hidden dimensions transverse

  $\Rightarrow$ strong gravity

- massive string vibrations

- microgravity experiments

- gravity modifications at short distances

  new submillimeter forces

Large TeV dimensions

longitudinal dimensions: $R^{-1} \lesssim M_{\text{string}} \Rightarrow$

R^{-1} first scale of new physics

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

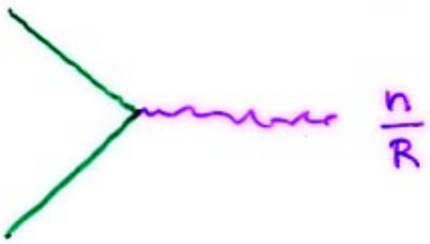
for Standard Model particles

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

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

Localized fermions (on 3-brane intersections)

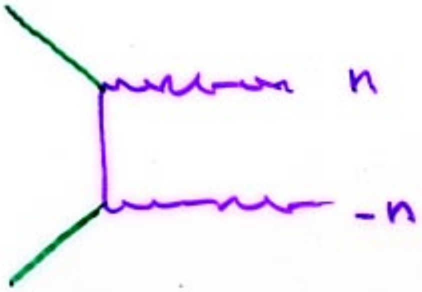
⇒ single production of KK modes



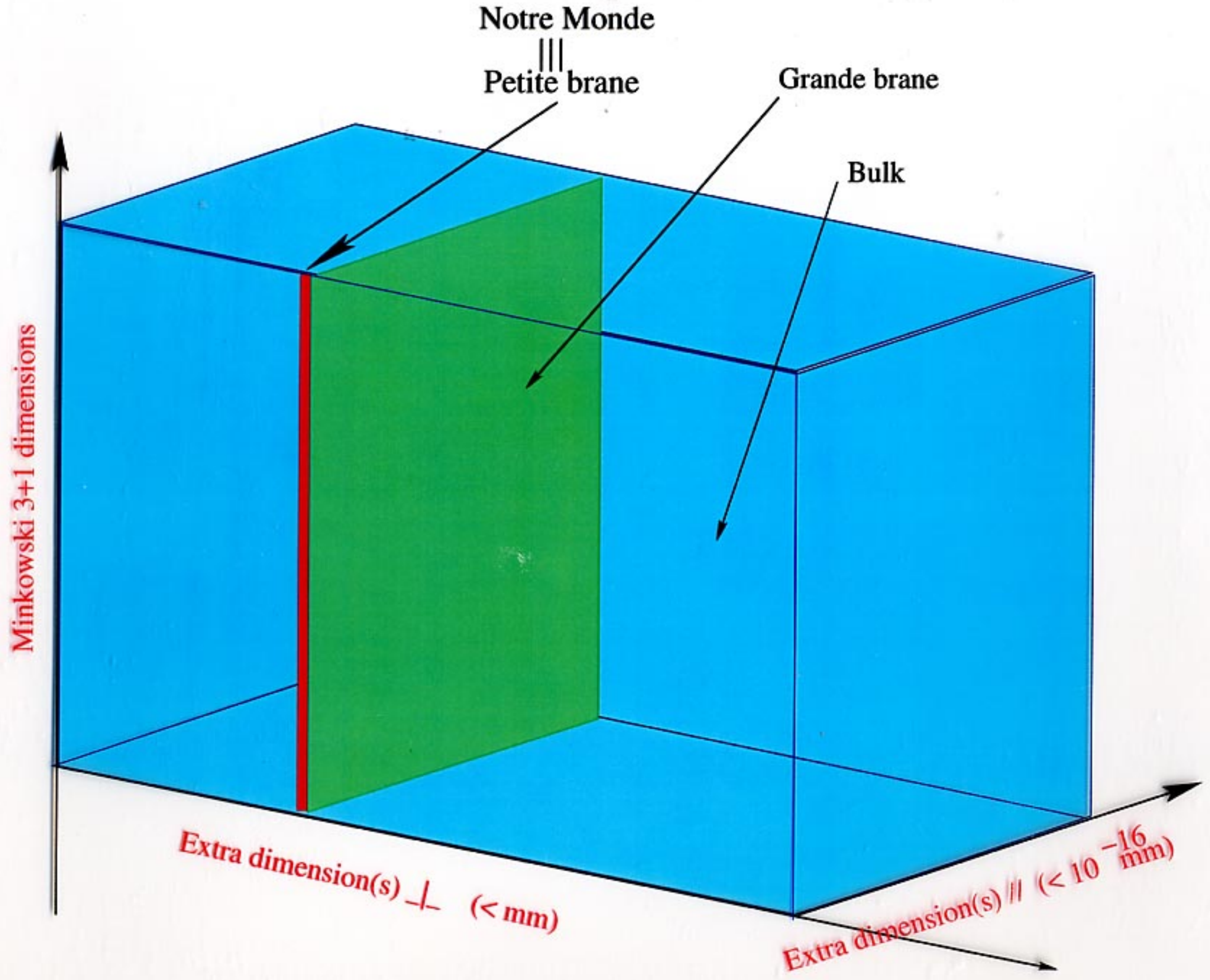
- strong bounds
- new resonances

Otherwise KK momentum conservation

⇒ pair production of KK modes

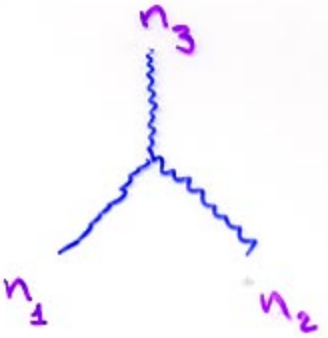


- weak bounds
- no resonances



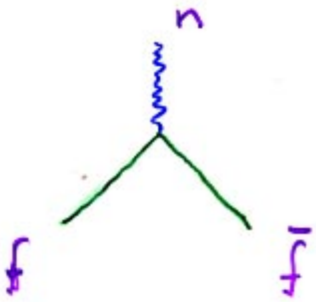
Notre Monde
|||
Petite brane
Grande brane
Bulk
Minkowski 3+1 dimensions
Extra dimension(s) ⊥ (< mm)
Extra dimension(s) // (< 10 $^{-16}$ mm)

Couplings

(a) 

$$= g\, \delta_{n_1+n_2+n_3} \longleftarrow \text{momentum conservation}$$

Fourrier Tranform : $\int dy\, F_{\mu\nu}^2(x,y)$

(b) 

$$= g\, \underset{\delta > 1}{\delta}^{-n^2 \frac{\ell_s^2}{R^2}} \xrightarrow[R \gg \ell_s]{} g$$

FT : $e^{-\frac{y^2}{2\ell_s^2 \ln \delta}} \xrightarrow[\ell_s \to 0]{} \delta(y)$

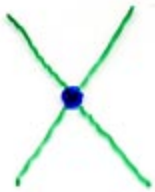
$\Rightarrow$ Gaussian distribution of charge with width

$\sigma = \sqrt{\ln \delta}\, \ell_s \longleftarrow$ "brane thickness"

Experimental constraints

bounds from 4-fermion effective operators (compositeness)

$\sum_{n\neq 0}$ 

$\underset{E \ll R^{-1}}{\simeq}$  $\sim R^2 \sum_{\vec{n}\neq 0} \frac{1}{\vec{n}^2}$

more than 2 dims $\Rightarrow$ regulated sum

$\Rightarrow \sim R^2 (RM_s)^{d-2}$ modulo logs for $d=2$

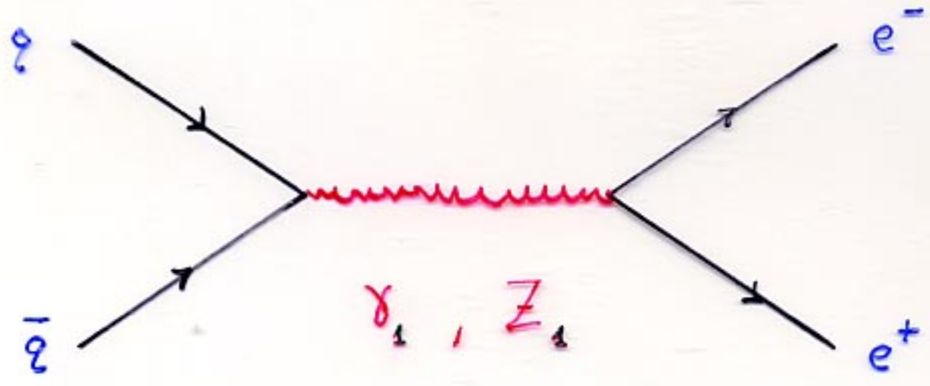
$\Rightarrow R^{-1} \gtrsim$ TeV I.A.-Benakli '94

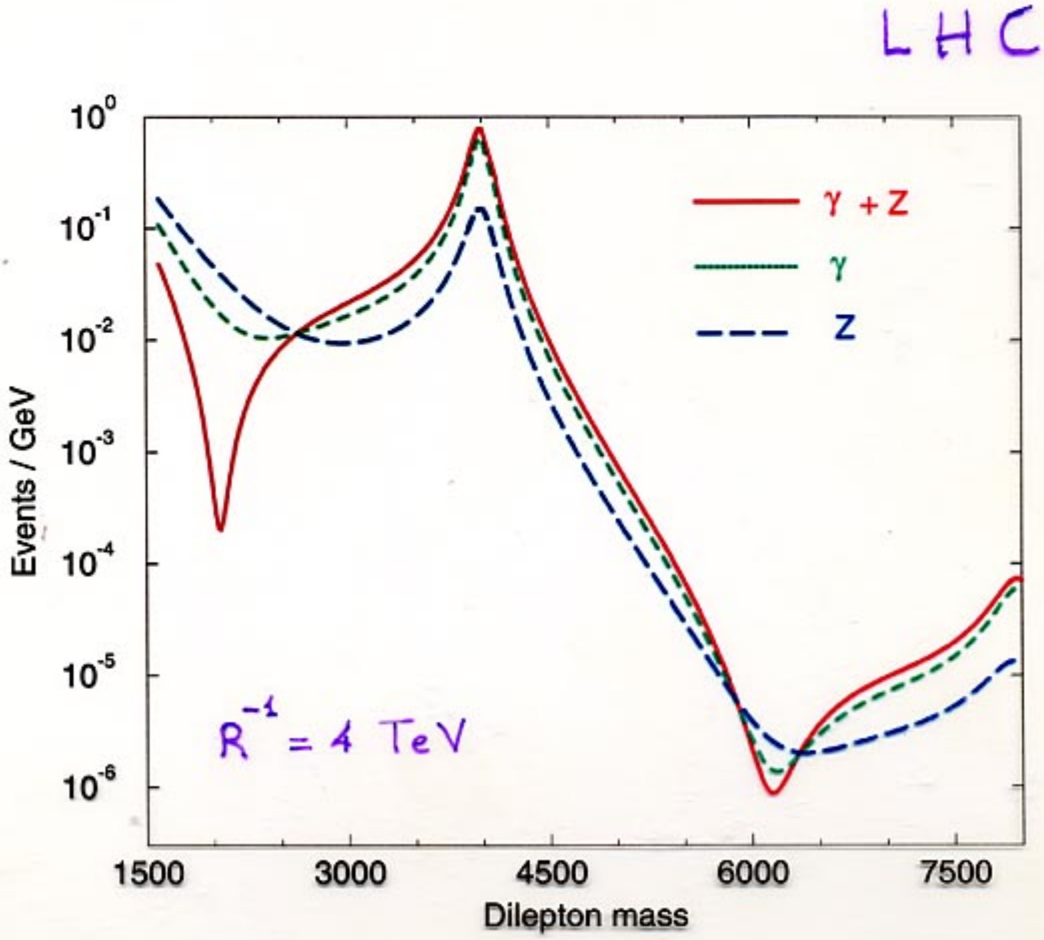
high precision of Z-width + G_F $\Rightarrow R^{-1} \gtrsim 3$ TeV

Nath-Yamaguchi
Masip-Pomarol
Marciano, Strumia '99
Delgado-Pomarol-Quiros

$\Rightarrow$ LHC: production at most one KK resonance $R^{-1} \lesssim 6$ TeV

I.A.-Benakli-Quiros '94, '99
Nath-Yamada-Yamaguchi
Rizzo-Wells '99
I.A.-Accomando-Benakli


q
$\bar{q}$
e^-
e^+
γ_1 , Z_1


LHC
Events / GeV
Dilepton mass
$\gamma + Z$
γ
Z
$R^{-1} = 4$ TeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1500
3000
4500
6000
7500

Universal dimensions

- KK momentum conservation ⇒

  pair production ⇒

  - no resonances

  - weaker limits (300-500 GeV)

- mass splittings from loop effects ⇒

  $(-)^{KK}$ possible symmetry ⇒

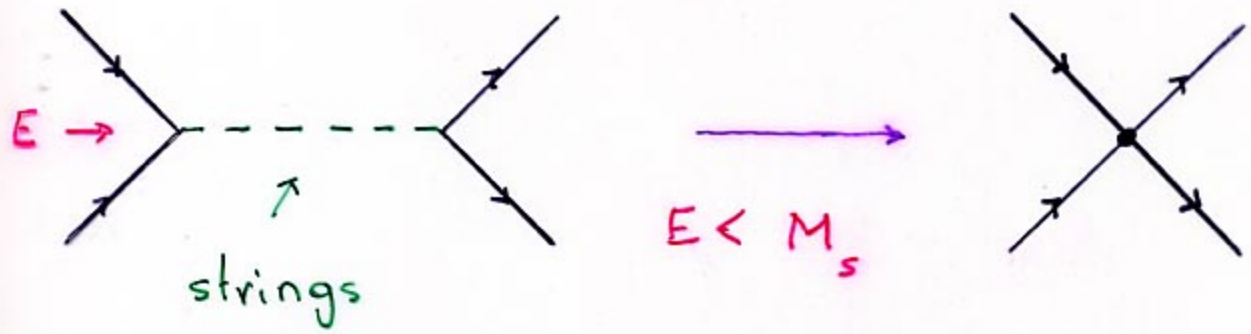
  - similar signals with SUSY

  - lightest KK stable (LKP)

    ⇒ dark matter candidate

Massive string vibrations ⇒ indirect effects

virtual exchanges ⇒ effective interactions



Actual limits: Matter fermions on

branes ⇒ $M_s \gtrsim 500$ GeV

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

Cullen - Perelstein - Peskin

I.A. - Benakli - Laugier

High energies ⇒

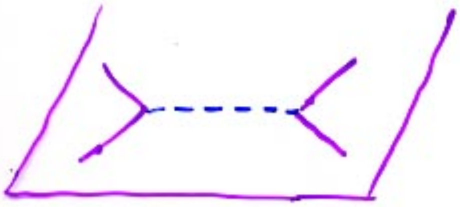
- direct production: string physics
- strong gravity: micro-black hole production?

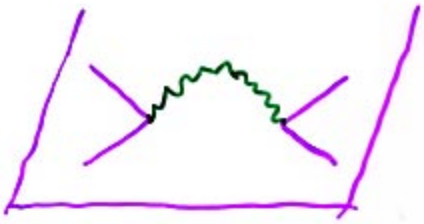
Exchange of massive string modes ⇒

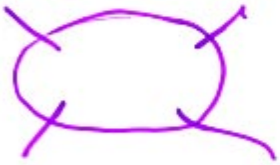
4-fermion effective operators

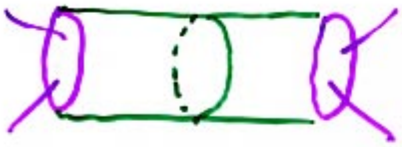
type I string theory : dominant compared to

virtual graviton emission









disk ⇒ g_s 1-loop ⇒ g_s^2

⇒ loop factor enhancement

⇒ probe string physics

I. A. - Accomando - Benakli '99

Cullen - Perelstein - Peskin '00

Matter fermions : open strings ending

- on the same set of branes

$\Rightarrow$ dim - 8 effective operators

$$\frac{g^2}{M_I^4} (\bar{\psi} \partial \psi)^2 \Rightarrow M_I \gtrsim 500 \text{ GeV}$$

Cullen - Perelstein - Peskin

virtual graviton exchange : $\frac{g^4}{M_I^4} (\bar{\psi} \partial \psi)^2$

- on different sets of branes

$\Rightarrow$ dim - 6 eff. operators

$$-\frac{g^2}{M_I^2} (\bar{\psi} \gamma \psi)^2 \Rightarrow M_I \gtrsim 2\text{-}3 \text{ TeV}$$

I.A. - Benakli - Laugier '00

U(1) masses in type I models

I.A. - Kiritsis - Rizos '02

4d U(1) anomalies ⇒ Green-Schwarz mechanism

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

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

cancel the anomaly

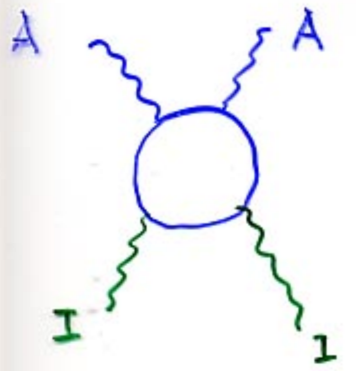
⇒ $U(1)_A$ mass : $M_A = g_A M$

a: Poincaré dual of a 2-form

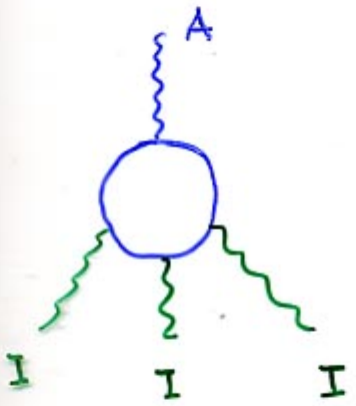
from RR closed string sector

$U(1)_A$ global symmetry remains (in perturbation)

6d U(1) anomalies $\Rightarrow$ a $\begin{cases} \text{2-form } b \\ \text{axion dual to a 4-form} \end{cases}$



$\Rightarrow$ 2-form : $\quad b \wedge \mathrm{tr}\, F_I^2 + (db)^2$



$\Rightarrow$ 0-form : $\quad a\, \mathrm{tr}\, F^3 + (da + MA)^2$

- 2-form $\Rightarrow$ no $U(1)_A$ mass

- 0-form $\Rightarrow$ $U(1)_A$ mass

Compactification to 4d $\Rightarrow$

- no anomaly but still $U(1)_A$ mass
- all k_I must vanish

1-loop string computation in orientifolds

$\Rightarrow$ contact term from the annulus

- $N=4$ sectors $\rightarrow$ 0

- $N=2$ $\Rightarrow$ 6 d masses localized in 4 dims

  non vanishing $\longleftrightarrow$ 6d anomalies

- $N=1$ $\Rightarrow$ 4d masses localized in 6 dims

$$M_A^2 = \frac{1}{\pi^3} \sum_{\substack{N=1 \\ \text{sectors } k}} (\mathrm{Tr}\, \gamma_k \lambda)^2 \, \mathrm{Str}_k \Big[\frac{1}{12} - \underbrace{s^2}_{\text{4d helicity}} \Big]_{\text{closed channel}}$$

$$-\frac{3}{2} N_v + \frac{1}{2} N_c$$

$N=2$ sectors : $\mathrm{Str}[\ ]_{closed} \rightarrow V_2\, \mathrm{Str}[\ ]_{open}$

- Explicit realizations for

  A, a in bulk / brane

- If A in bulk and a in brane :

localized mass

$$m_A \sim 1/\sqrt{V_\perp} \sim \frac{M_s^2}{M_p} \sim 10^{-4}\,\mathrm{eV}$$

$\Rightarrow$ new submm forces

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

$\Rightarrow 10^6 - 10^8 \times$ gravity $\leftarrow \dfrac{m_{proton}}{M_p}$

* supernova $\Rightarrow$ dim of bulk $\geqslant 4$

- all cases : $M_A \lesssim g_s^{1/2} M_s$ up to M_s^2/M_P

  $\Rightarrow$ new effects in accelerators

  production of $U(1)_A$ + possible KK

- Model building : extra conditions for $U(1)_Y$

  to remain massless

  anomaly free in all 6d limits

  e.g. part of non-abelian groups

- Brane SUSY models :

  $D\bar{O}$, $\bar{D}O$: annulus is not affected

  $\Rightarrow$ "SUSY" result remains

  $D\bar{D}$: extra contributions easy to compute

Brane susy breaking in type I theory

Stable non-BPS configurations of

branes - antibranes or branes - antiorientifolds

	RR-charge	tension (NS-charge)	
D	$+$	$+$	
$\bar{D}$	$-$	$+$	
O_-	$-$	$-$	
$\bar{O}_-$	$+$	$-$	
O_+	$+$	$+$	as $D, \bar{D}$
$\bar{O}_+$	$-$	$+$	

$\cancel{susy}$: $D\bar{D}$, $D\bar{O}_\pm$, $\bar{D}O_\pm$

absence of tachyons: $D\bar{D}$ of different type

I.A.-Dudas-Sagnotti '99 e.g. $D9 - \bar{D}5$

or in different positions

Aldazabal - Uranga '99

Simplest model $10D$ IIB/Ω Sugimoto

			RR-charge	tension
* $\Omega = +1$ $\Rightarrow$	16	O_-9	$-$	$-$
	16	$D9$	$+$	$+$

open sector : antisymmetrization $\Rightarrow$ $SO(32)$ susy

* $\Omega = -1$ $\Rightarrow$	16	O_+9	$+$	$+$
	16	$\bar{D}9$	$-$	$+$

open sector: Ω symmetrizes bosons but
antisymmetrizes fermions

$\Rightarrow$ $Sp(32)$ with fermions in the antisym rep

brane susy breaking $\bar{D}O_+$

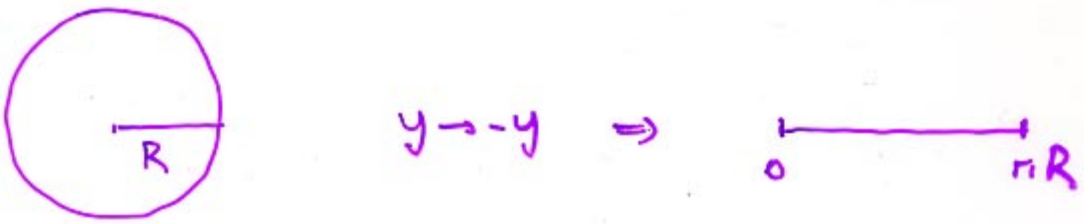
Evading the NS tadpoles:

introduce a small $\not\!\!\text{SUSY}$ in the bulk

by Scherk-Schwarz boundary conditions

I.A. - Benakli - Laugier

- S-S on $S^1/\mathbb{Z}_2$



periodicity under $y \to y + 2\pi R$

bosons: periodic

$\mathbb{Z}_2$ even : $$\phi_e(x^\mu, y) = \sum_n \phi_e^{(n)}(x^\mu) \cos \frac{n}{R} y$$

$\mathbb{Z}_2$ odd : $$\phi_o = \sum_n \phi_o^{(n)}(x^\mu) \sin \frac{n}{R} y$$

fermions : antiperiodic

$\mathbb{Z}_2$-even : $\psi_e = \sum_n \psi_e^{(n)}(x^\mu) \cos \frac{n+1/2}{R} y$

$\mathbb{Z}_2$-odd : $\psi_o = \sum_n \psi_o^{(n)}(x^\mu) \sin \frac{n+1/2}{R} y$

susy parameter : antiperiodic

$$\underset{\text{periodic}}{\delta\phi} = \underset{\text{anti-periodic}}{\psi\eta}$$

· $y=0$: $\eta_o = 0 \Rightarrow$ half of susy remains : η_e

· $y=\pi R$: $\eta_e = 0 \Rightarrow$ " : η_o

No zero mode of $\eta \Rightarrow$

susy is broken globally

	D	$\bar{D}$	O_-	$\bar{O}_-$	O_+	$\bar{O}_+$
RR-charge	+	−	−	+	+	−
NS-NS	+	+	−	−	+	+
SUSY	Q_e	Q_o	Q_e	Q_o	Q_e	Q_o
Non linear	Q_o	Q_e				

Model I : $D\,O_-$ $\bar{D}\,\bar{O}_-$

- local charge conservation
- Brane SUSY (locally)

Model II : $\bar{D}\,O_{\mp}$ $D\,\bar{O}_{\mp}$

- brane SUSY breaking (linear)
- Non linear SUSY

(the other half remains)

Example with 8-branes

- bulk : $S^1/\mathbb{Z}_2$ with SS breaking

$$0 \longmapsto \pi R$$

O_- $\qquad\qquad\qquad$ $\bar{O}_-$

RR charge: -16 $\qquad\qquad$ $+16$

- Model I :

$$\left.\begin{array}{l} 16\ D_8 \text{ on } O_- \\ 16\ \bar{D}_8 \text{ on } \bar{O}_- \end{array}\right\} \Rightarrow SO(16) \times SO(16)$$

"SUSY"

- Model II :

$$\left.\begin{array}{l} 16\ \bar{D}_8 \text{ on } O_- \\ 16\ D_8 \text{ on } \bar{O}_- \end{array}\right\} \Rightarrow SO(16) \times SO(16)$$

with fermions in symmetric reps : $(136, 1) + (1, 136)$

$$136 = 135 + \underset{\substack{\uparrow \\ \text{Goldstino}}}{1}$$

Non-linear susy on the brane

$\Rightarrow$ massless Goldstino χ

Sen, Dudas-Mourad, Pradisi-Riccioni

$$\mathcal{L}_{eff} = -\frac{1}{4V^4}\left(\chi \overleftrightarrow{\partial}_\mu \sigma^\nu \chi\right)\left(f \overleftrightarrow{\partial}_\nu \sigma^\mu f\right) + \frac{2C_f}{V^4}\left(f\partial^\mu \chi\right)\left(f\partial_\mu \chi\right)$$

fixed by susy

model dependent

Brignole-Feruglio-Zwirner

Matter fermions on the same set of branes $\Rightarrow$

- $\frac{V^4}{2} = N \cdot T$ $\leftarrow$ tension $\quad T_{3\text{-brane}} = \frac{M_s^4}{(2\pi)^2 g_s}$

  N: number of branes

- $C_f = \begin{cases} 1 & f,\ \chi \text{ : same internal helicity} \\ 0 & \text{" different "} \end{cases}$

I.A.-Benakli-Laugier

Fixing the radion (for g_s fixed)

2 dimensions of common radius R

$$V_{eff} \underset{R\to\infty}{\simeq} \frac{1}{R^4}\left(\underset{\text{1-loop}}{\underset{\uparrow}{\alpha \ln RM_s}} + \underset{\text{tree}}{\underset{\uparrow}{\beta}}\right)$$

$$\beta = \frac{1}{8\pi^2 g_s}\left(n_D + 8N_0^+ - 8N_0^-\right)$$: total tension

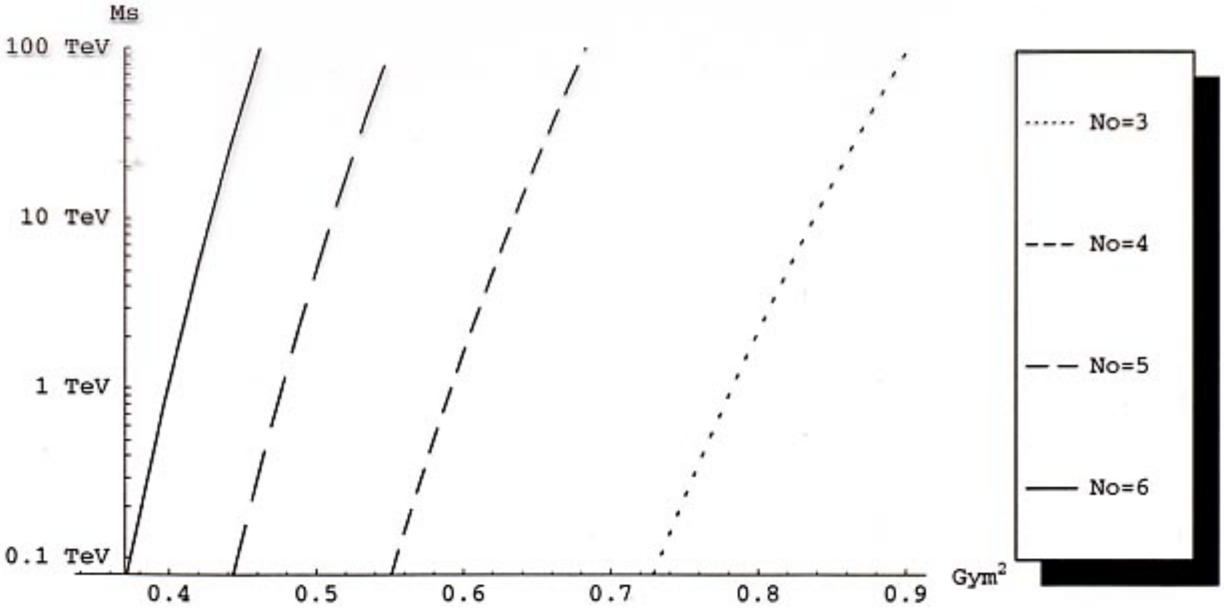
$$\alpha = \frac{1}{\pi^4}\left(n_D^- - n_D^+\right)$$: nb of (fermions - bosons)

$D\bar{O}_+$, $\bar{D}O_+$: Sp groups with antisym fermions

$D\bar{O}_-$, $\bar{D}O_-$: SO groups " sym "

Minimum with $R_0 \gg l_s$: $\alpha < 0$, $\beta > 0$

$$R_0 \sim l_s\, e^{-\beta/\alpha} = e^{\frac{n_D + 8(N_0^+ - N_0^-)}{n_D^+ - n_D^-}\frac{\pi^2}{8g^2}}\, l_s$$


Ms
100 TeV
10 TeV
1 TeV
0.1 TeV
0.4
0.5
0.6
0.7
0.8
0.9
Gym^2
No=3
No=4
No=5
No=6

A D-brane embedding of the Standard Model

I.A. - Kiritsis - Tomaras '00

N coincident branes $\Rightarrow$ $U(N)$

$U(1)$: coupling $= g_N/\sqrt{2N}$

with charge of $\underset{\sim}{N} = 1$

$\Rightarrow$ gauged "baryon" number

$\Rightarrow$ minimal choice : $U(3) \times U(2) \times U(1)$

color branes (g_3) weak branes (g_2) g_1

$$
U(1) \text{ brane with } \begin{cases} U(3) \Rightarrow g_1 = g_3 \\ U(2) \Rightarrow g_1 = g_2 \end{cases}
$$

2 sets of orthogonal branes Dp , Dq

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\uparrow\quad\quad\uparrow$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad U(3)_c\quad U(2)_w$

$\Rightarrow\ p-q=4$

e.g. D3 and D7 or D5 and D5', ... $\Rightarrow$

- just 2 remaining transverse large dims ($\lesssim$ mm)
- $U(1)$ brane on top of $U(3)_c$ or $U(2)_w$
- 2 gauge couplings :

$$\left.\frac{\alpha_3}{\alpha_2}\right|_{M_s} = \frac{V_{\parallel}^{w}}{V_{\parallel}^{c}} > 1 \quad \Rightarrow$$

at least two longitudinal dimensions $\parallel$ w

$$R_{\parallel}^{w} > l_s$$

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

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

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

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

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

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

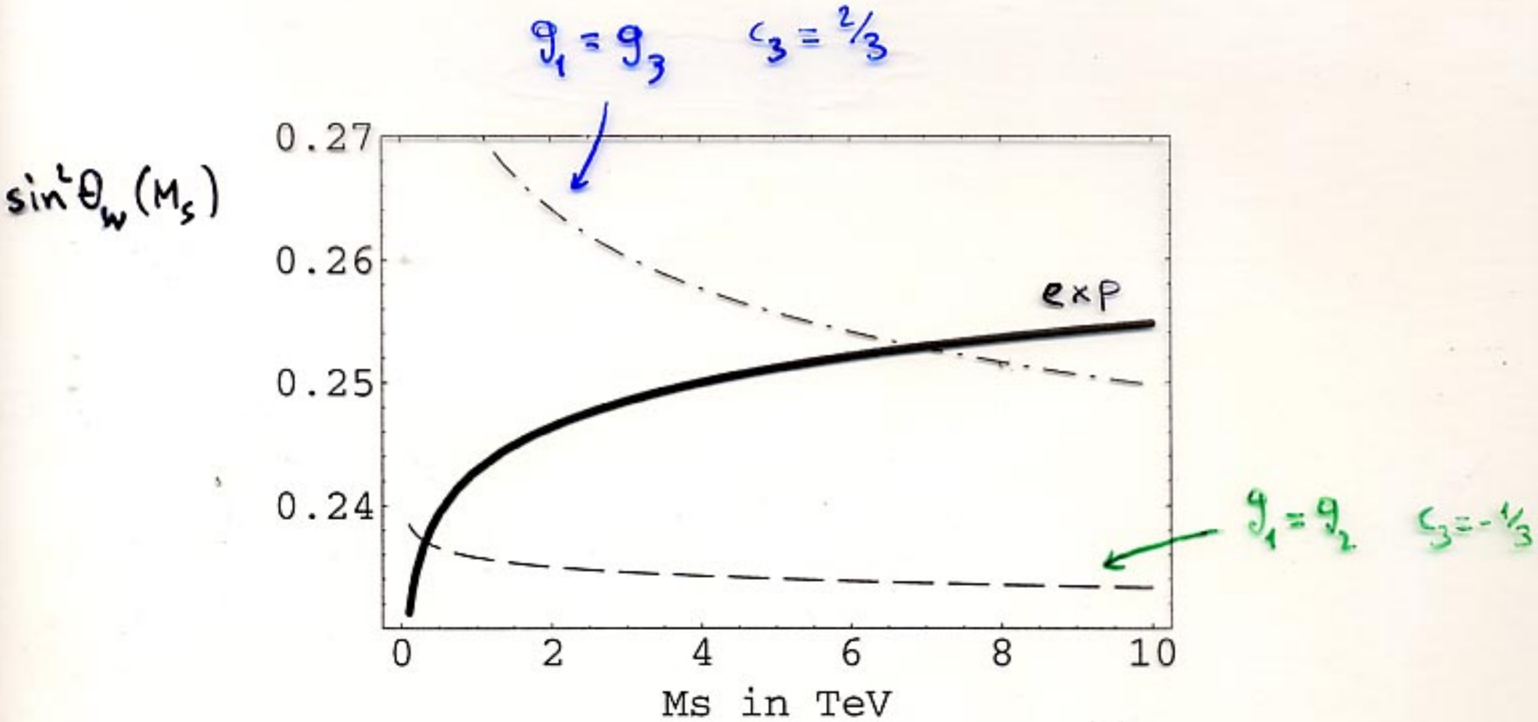
hypercharge $\quad Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \quad \Rightarrow$ 4 possibilities

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

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

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

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



correct prediction for $\sin^2\theta_W$ for $M_s \sim$ few TeV

U(1) with color branes

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

hyperchange $\quad Y = \frac{2}{3} Q_3 - \frac{1}{2} Q_2 + Q_1$

$Q \quad (3, 2 ; 1, 1, 0)$

$u^c \quad (\bar{3}, 1 ; -1, 0, 0)$

$d^c \quad (\bar{3}, 1 ; -1, 0, 1)$

$L \quad (1, 2 ; 0, 1, 0)$

$\ell^c \quad (1, 1 ; 0, 0, 1)$

Higgs: $\quad H \ (1, 2 ; 0, 1, 1) \qquad H' \ (1, 2 ; 0, -1, 0)$

$\Rightarrow \quad H' Q u_c \qquad H^+ L \ell^c \qquad H^+ Q d^c$

- masses to all quarks + leptons $\Rightarrow$ 2 Higgs doublets

- the remaining two $U(1)$'s : anomalous

  Green - Schwarz anomaly cancellation :

  shifting of 2 axions $\Rightarrow$ $U(1)$'s become massive

  $\Rightarrow$ global (perturbative) symmetries :

  • baryon number $\Rightarrow$ proton stability

  • PQ - type symmetry $\Rightarrow$ electroweak axion

  $\nearrow$

  can be explicitly broken by moving slightly

  away from the orbifold point $e^{-m/\lambda}$

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

  Arkani Hamed - Dimopoulos - Dvali - March Russell

  Dienes - Dudas - Gherghetta '98

R-neutrinos in the bulk

$$\int d^{4+p}x \;\; \bar{\nu} \not{\partial} \nu \qquad \nu = (\nu_R , \bar{\nu}_R^c) \quad \Rightarrow$$

$$\int d^4x \,(r M_s)^p \sum_n \left\{ \bar{\nu}_{Rn} \not{\partial} \nu_{Rn} + \bar{\nu}^c_{Rn} \not{\partial} \nu^c_{Rn} + \frac{n}{r} \nu_{Rn} \nu^c_{Rn} + c.c. \right\}$$

$$S_{int} = \lambda \int d^4x \;\; H(x)\, L(x)\, \nu_R(x, \vec{y}=0)$$

$$\langle H \rangle = v \quad \Rightarrow \quad \frac{\lambda v}{\sqrt{(r M_s)^p}} \sum_n \nu_L \nu_{Rn}$$

$$\frac{\lambda v}{(r M_s)^{p/2}} \ll \frac{1}{r} \quad \Leftrightarrow \quad \lambda \frac{v}{M_s} \ll (r M_s)^{\frac{p}{2}-1} \quad \Rightarrow$$

- $n \neq 0$: masses of KK ν_n unaffected

- $n = 0$: Dirac mass for neutrino $\quad m_\nu = \dfrac{\lambda v}{(r M_s)^{p/2}}$

$$M_p = \frac{1}{g^2} M_s^{1+p/2} \, r^{p/2} \quad \Rightarrow$$

$$m_\nu = \frac{\lambda}{g^2} v \frac{M_s}{M_p} \sim 10^{-2} \text{ eV} \quad \text{for } M_s \simeq 10 \text{ TeV}$$

Some open strings have one end in the bulk

$\Rightarrow$ introduce one brane in the bulk : $U(1)_b$

Anomalies $\Rightarrow$ $U(1)_b \rightarrow$ new global symmetry :

Lepton number

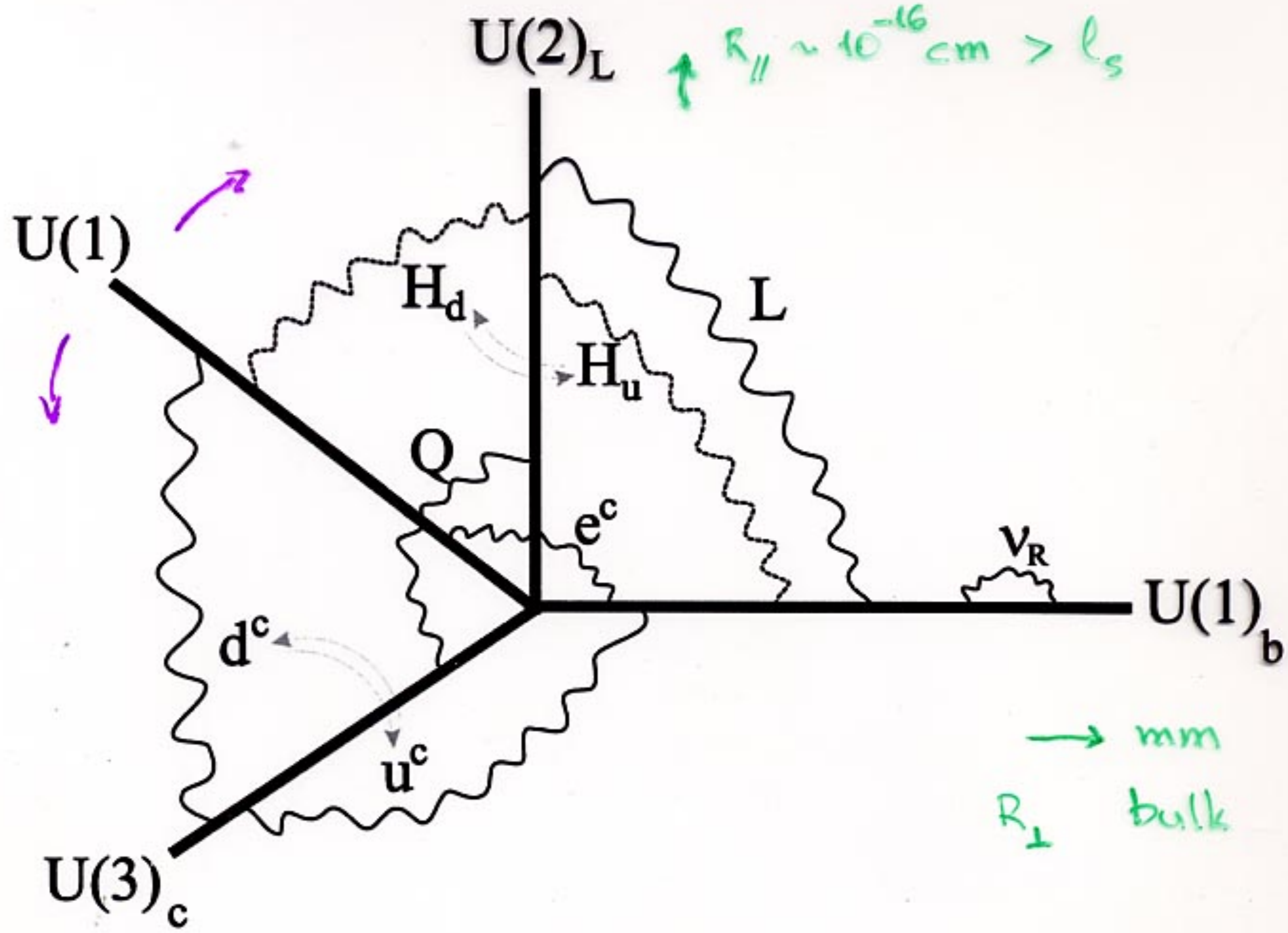
Protect also small neutrino masses :

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

$\Rightarrow$ Majorana mass : $\underbrace{\frac{\langle H \rangle^2}{M_s}}_{\text{GeV}} LL$

I.A. - Kiritsis - Rizos - Tomaras

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

Origin of EW symmetry breaking ?

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

string tree-level : - $m_W = 0$

- $m_W \sim n\, M_s$ $n \gtrsim \mathcal{O}(1)$

- $m_W \sim a \leftarrow$ flat direction

$\Rightarrow$ only possibility : radiative breaking

$$V = \lambda (h^+ h)^2 + \mu^2 (h^+ h)$$

(a) $\mu = 0$ at tree

$\mu^2 < 0$ at one loop non susy vacuum

(b) $\langle h \rangle$ flat at tree

(2 higgses)

lifted radiatively

I.A. - Benakli - Quiros '00

Simplest case: one SM higgs on our brane-world

open string with both ends on the brane $\Rightarrow$

(1) tree-level potential $\equiv$ same as susy

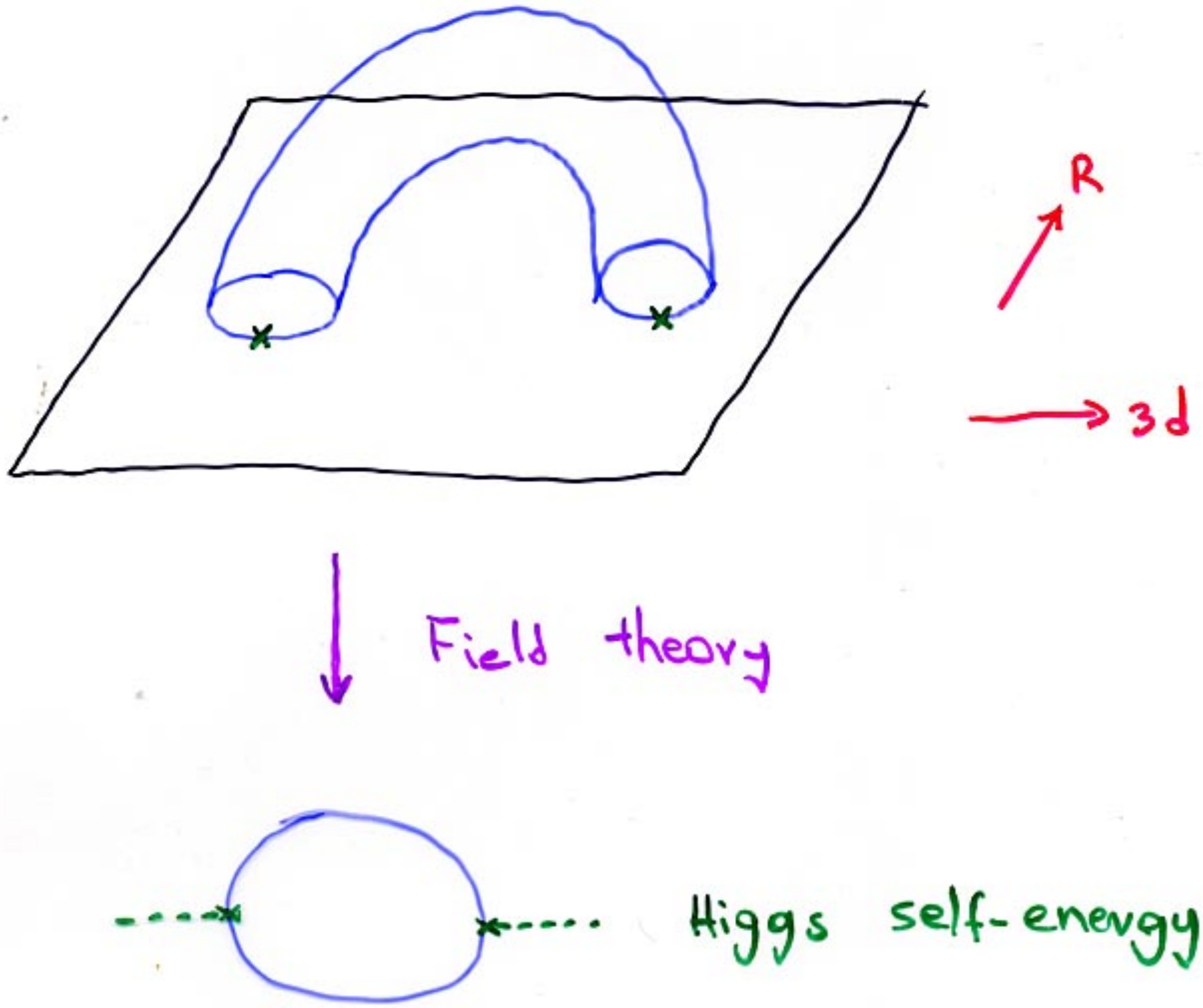
$$\lambda = \frac{1}{8}\left(g^2 + g'^2\right) \qquad \text{D-terms}$$

(2) $$\mu^2 = -\frac{1}{N}\, g^2\, \varepsilon^2\, M_s^2$$

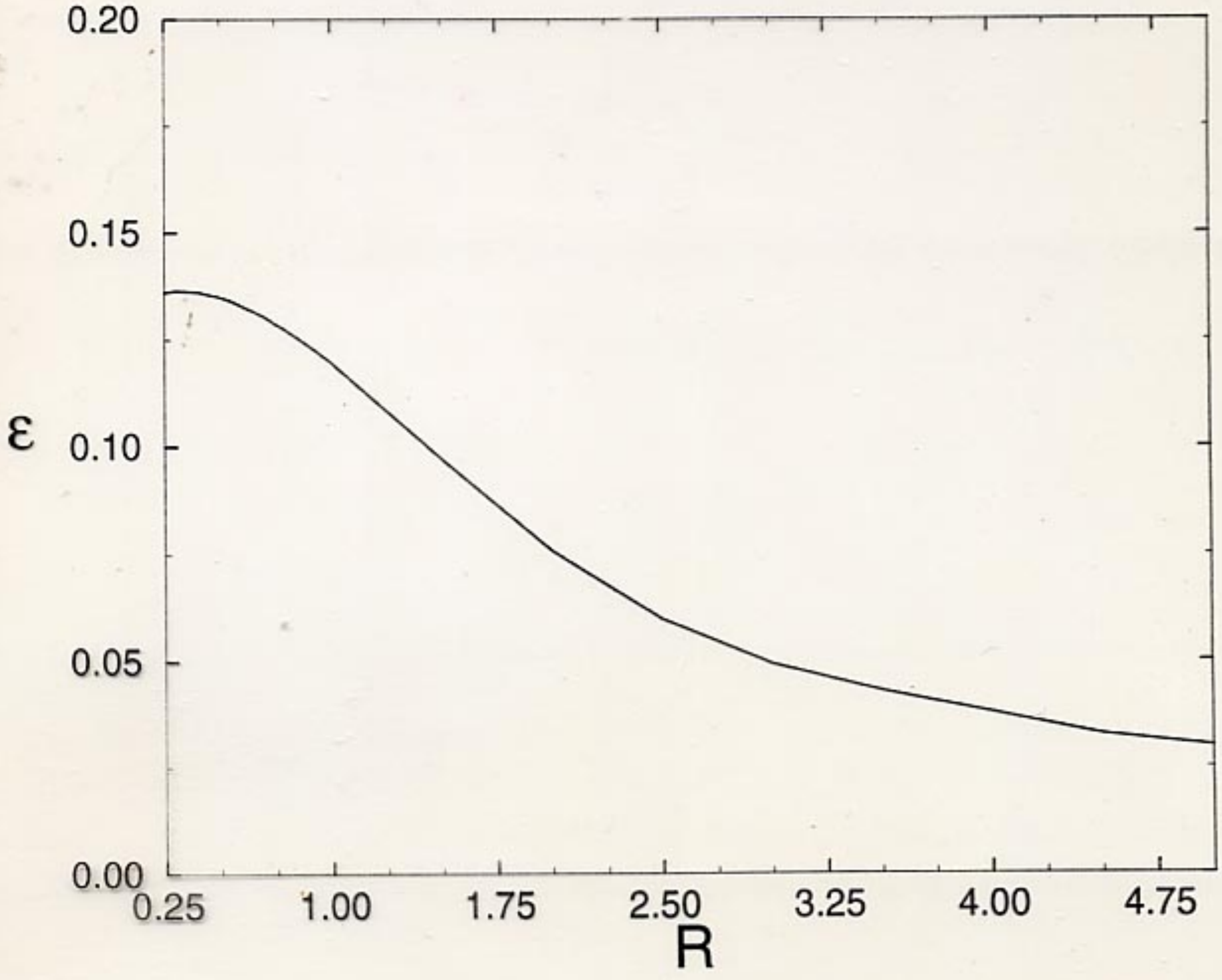
N : order of the orbifold group

ε : estimated by an explicit computation in a toy model

$$\langle h \rangle = \left(0, \, v/\sqrt{2}\right) \quad : \quad v^2 = -\mu^2/\lambda \quad \Rightarrow$$


R
3d
Field theory
Higgs self-energy

$$\varepsilon^2(R) = \frac{R^3}{2\pi^2} \int_0^\infty \frac{d\ell}{(2\ell)^{5/2}} \frac{\theta_2^4}{4\eta^{12}}\left(i\ell + \tfrac{1}{2}\right) \sum_n n^2 e^{-2\pi n^2 R \ell}$$



- $R \to 0$: $\varepsilon(R) \to \varepsilon_0 \simeq 0.14$

- $R \to \infty$: $\varepsilon(R) \sim \dfrac{\varepsilon_\infty}{M_s R}$ $\qquad \varepsilon_\infty \simeq 0.008$

$\Rightarrow$ UV cutoff $\equiv 1/R$

similar to finite temperature $T \sim 1/R$

$\Rightarrow \mu^2 \sim T^2$

(1) $M_h = M_Z$

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

(2) $M_s = \dfrac{M_h \sqrt{N}}{\sqrt{2}\, g\, \varepsilon}$

- Low-energy SM radiative corrections top-quark sector

$\Rightarrow$ $M_h \sim 120$ GeV

$M_s \sim$ a few TeV $\quad \mathcal{O}(1-10)$

- String threshold corrections
  - model dependent
  - can be very important

  e.g. for two large dims in the bulk

  $\ln R_\perp M_s \sim \ln M_P/M_s$

$\Rightarrow$ both M_s and M_h can be increased