I. Antoniadis

Strings 2001

String Physics at Low Energies

→ theoretically viable after '95

New framework for particle physics

alternative to heterotic

Dissociation of string scale M_s from M_p ⇒

- brane world description
- strings in accelerators ?

→ Protection of hierarchy alternative to SUSY :

String scale $M_s \sim$ TeV

Outline

- D-brane / type I realization
  consistent perturbative framework
  for low-scale string models
  - gauge hierarchy
  - Brane SUSY breaking
  - gauge symmetry breaking
  - Standard Model embedding
- NS 5-brane / type II realization
  alternative LST framework

Realizations of TeV strings

Type I $\Rightarrow$ submm dims

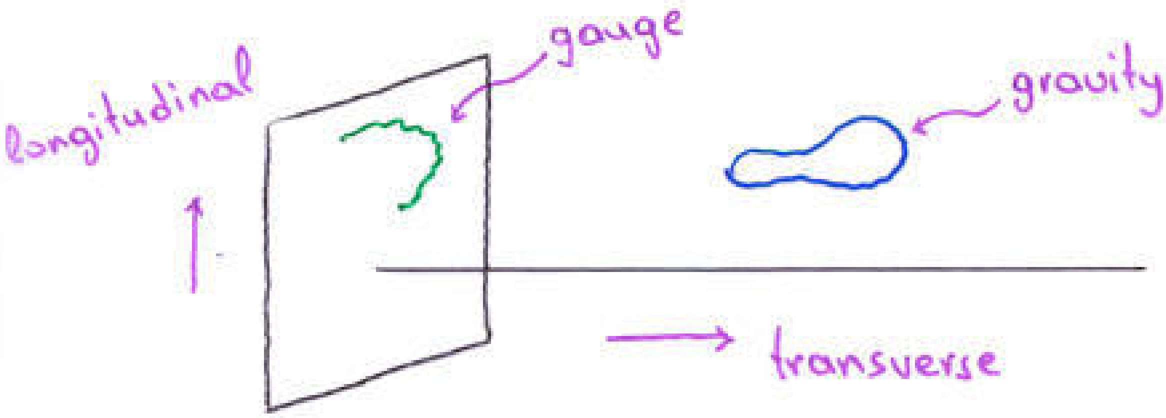
Type II $\Rightarrow$ tiny coupling

strongly coupled Heterotic SO(32) (type I)

$E_8 \times E_8$ (type II)

Type I: closed strings $\rightarrow$ gravity

open strings $\rightarrow$ gauge sector on D-branes



p-brane $\Rightarrow$ p-3 compact dims $\parallel$

$\underbrace{9-p}_{n}$ " " $\perp$

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

transverse dims : no constraint

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

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

$M_{P_{(4+n)}}^{2+n}$ Planck mass of 4+n dims

largeness of M_P / M_I $\Rightarrow$ extra-large r

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

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

M_I: TeV, 10^{-16} cm

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

weak coupling $\Rightarrow$ longitud dims ~ string size

transverse dims : no constraint

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largeness of M_P/M_I $\Rightarrow$ extra-large r

- 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

$M_I \sim 1$ TeV $\Rightarrow$ $n = 2 - 6$: $r \sim$ mm - fm

Gauge hierarchy

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

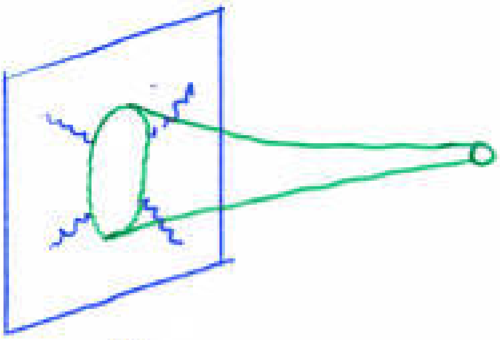
$$r\, M_I \simeq \left(g^2\, M_P / M_I \right)^{2/n} \sim \begin{cases} 10^{15} & n=2 \\ 10^{5} & n=6 \end{cases} \quad \text{or} \quad \lambda_{II} \simeq 10^{-14}$$

Technical aspect: stability in a non susy vacuum

no large corrections to SM couplings as $r M_I \to \infty$

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

I.A.-Bachas '98



$\leftarrow$ IR divergence : emission of massless closed string

$\uparrow$ 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 $\Rightarrow$

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

analog of quadratic div. to Λ in softly broken susy

absence of quadratic sensitivity :

- $\Lambda = 0$ (special models)

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

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 1 mm away!

to protect the gauge hierarchy against gravit. corrections

Prediction: possible new forces at submm scales

e.g. light scalars: $\frac{(\text{TeV})^2}{M_p} \sim 10^{-4}\,\text{eV} = 1\,\text{mm}^{-1}$

modulus $\equiv \ln r$

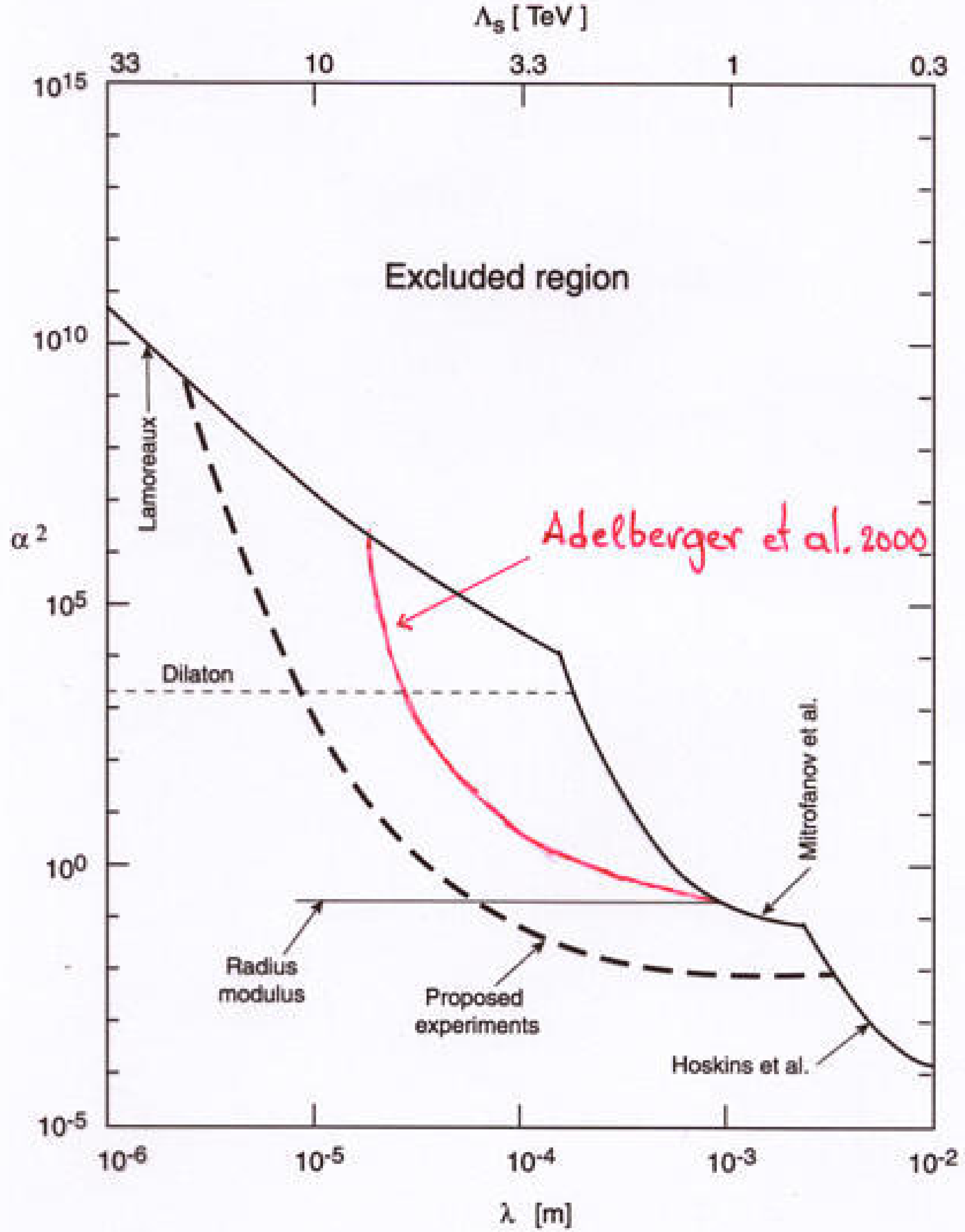
coupling to nucleons relative to gravity:

$$\frac{1}{m_N}\frac{\partial m_N}{\partial \ln r} = \frac{\partial \ln \Lambda_{QCD}}{\partial \ln r} \qquad m_N \sim \Lambda_{QCD} \sim e^{-\frac{1}{b_{QCD}}\frac{2\pi}{\alpha_{QCD}}}$$

$$\sim \frac{\partial}{\partial \ln r}\alpha_{QCD}$$

$O(1)$ in models with log sensitivity in r e.g. $d_\perp = 2$

$\Rightarrow$ can be experimentally tested



Λs [TeV]
33
10
3.3
1
0.3
10^15
10^10
10^5
10^0
10^-5
α ²
Excluded region
Adelberger et al. 2000
Lamoreaux
Dilaton
Mitrofanov et al.
Radius modulus
Proposed experiments
Hoskins et al.
10^-6
10^-5
10^-4
10^-3
10^-2
λ [m]

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 $D, \bar{D}$
$\bar{O}_+$	$-$	$+$	

~~susy~~ : $D\bar{D}$, $D\bar{O}_+$, $\bar{D}O_+$

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 10 D 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 $\bar{D}O_+$

Consistent chiral models:

- RR tadpole cancellations $\Rightarrow$ no anomalies
- No tachyons
- susy is broken on $D\bar{5}$ branes
- NS tadpoles $\Rightarrow$ (tree-level) potential

localized on the (non-susy) branes

explicit toy examples:

- $T^4/\mathbb{Z}_2$: change Ω projection in the twisted sector

17 tensor multiplets

- $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$ with discrete torsion

- add $D9 - D\bar{9}$, $D5 - D\bar{5}$ $\Rightarrow$

general class of interesting models

Aldazabal - Ibanez - Quevedo

I.A. - Angelantonj - D'Appollonio - Dudas - Sagnotti

- tree-level potential $\Rightarrow$ fixing the radii

need branes-antibranes of the same type

ex: $T^4/\mathbb{Z}_2$ $\begin{cases} \text{untwisted sector: } \Omega = +1 \\ \text{twisted sector: } \Omega = \varepsilon = \pm 1 \end{cases}$

SUSY

brane ~~susy~~

tadpole conditions:

$D9: N_+ \qquad \bar{D}9: N_- \qquad D5: D_+ \qquad \bar{D}5: D_-$

$N_+ - N_- = 16 \qquad\qquad D_+ - D_- = 16\,\varepsilon$

$$V_{eff} = e^{-\phi_6} \left\{ (N_+ + N_- - 16)\sqrt{V_4} + \frac{D_+ + D_- - 16\varepsilon}{\sqrt{V_4}} \right\}$$

6D-dilaton

minimization $\Rightarrow$ $V_4 = \dfrac{D_+ + D_- - 16\varepsilon}{N_+ + N_- - 16} = \dfrac{D_-}{N_-}$

- 1-loop potential $\Rightarrow$ fixing the wilson lines

$\leftrightarrow$ branes separation

A toy model

based on $T^4/\mathbb{Z}_2$ orientifold with brane ~~susy~~

I.A. - Benakli - Quiros '99

- 16 non susy anti-D5 branes

all at the origin $\Rightarrow$ $Sp(16) \times Sp(16)$ with

- scalars : $(16, 16)$
- fermions : $(120, 1) + (1, 120) + (16, 16)$

- bulk: gravity + 9-branes

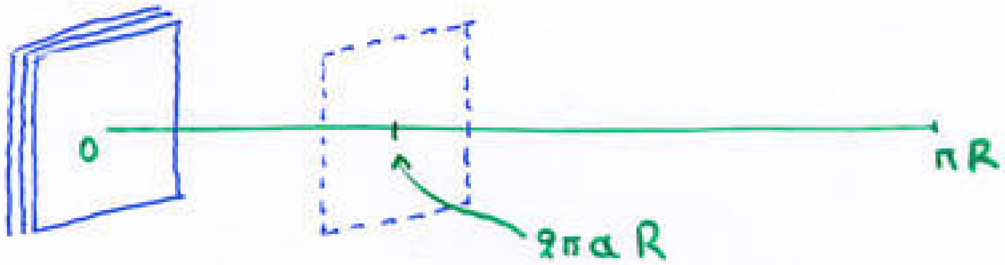
tree-level scalar potential $\equiv$ susy theory

bifundamental hyper-multiplets

$$\Rightarrow V_{tree} = (D\text{-terms})^2$$

flat directions : $\langle a \rangle \neq 0$

$\overline{D5}$ - brane separation from the origin



$$V^{\text{1-loop}}_{eff}(a,R) = \frac{R}{32\pi^4} M_s^4 \int_0^\infty \frac{dl}{(2l)^{5/2}} \frac{\theta_2^4}{4\eta^{12}}\left(il+\tfrac{1}{2}\right) \sum_n \cos 4\pi n a \, e^{-2\pi n^2 R^2 l}$$

$$+ \text{ a-independent}$$

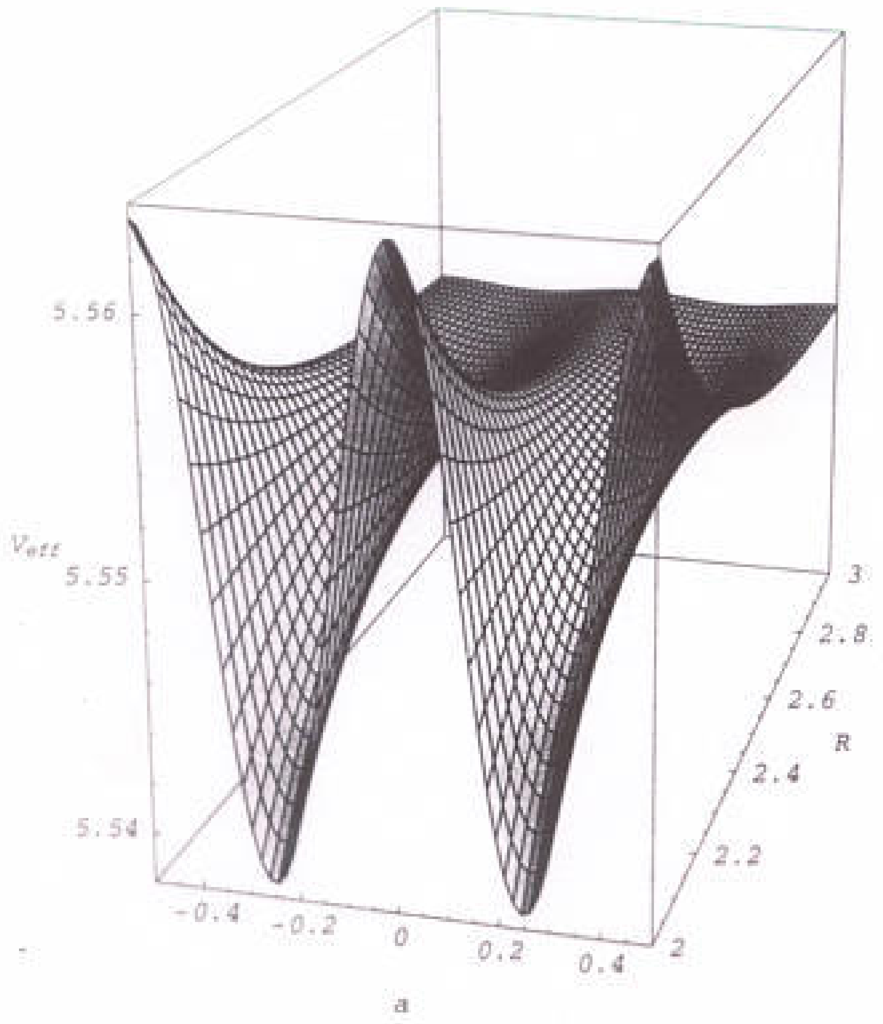
$$V'_{eff} \sim \sin 4\pi n a = 0 \quad \Rightarrow \quad a = 0 \,,\ \tfrac{1}{4}$$

$$V''_{eff}\Big|_{a=0} < 0 \qquad V''_{eff}\Big|_{a=\frac{1}{4}} > 0$$

valid for all $a_I = \frac{1}{4} \Rightarrow$ global minimum

all branes in the midle of the comp. interval

$$Sp(16) \times Sp(16) \to Sp(16)$$



5.56
5.55
5.54
Veff
-0.4
-0.2
0
0.2
0.4
a
2
2.2
2.4
2.6
2.8
3
R

Realistic model: further orbifold projections

$\Rightarrow$ a is projected away but

computation remains valid for charged components

in the case of susy projections

Framework for Standard Model higgs

$\Rightarrow$ radiative EW symmetry breaking

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

- λ given by susy D-terms
- $\mu^2 = -g^2 \varepsilon^2 M_s^2 < 0$ at one loop $\Rightarrow$

- susy prediction for the higgs mass

- $M_s \sim M_W / \varepsilon$

ε: estimated by the previous computation

Expansion around the origin

gauge invariance : $a^2 \longrightarrow \mathrm{Tr}\,\Phi^2$

$$V_{eff} = V_0 + \frac{1}{2}\mu^2\,\mathrm{Tr}\,\Phi^2 + \mathcal{O}(\Phi^4)$$

$$\mu^2 = -\,\varepsilon^2(R)\, g^2\, M_s^2$$

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

Expansion around the origin

gauge invariance : $a^2 \longrightarrow \mathrm{Tr}\, \Phi^2$

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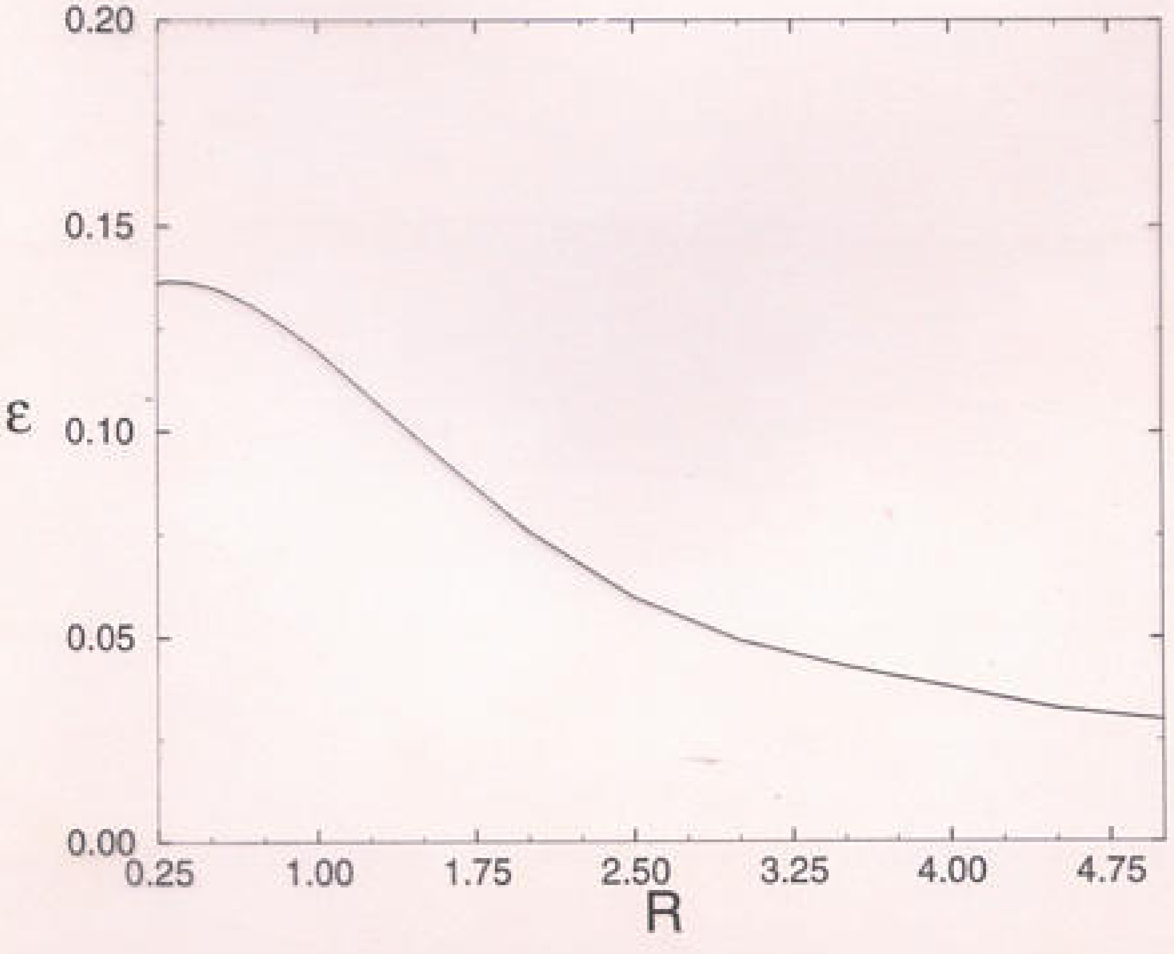


A D-brane embedding of the Standard Model

I.A. - Kiritsis - Tomaras hep-ph/0004214

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

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

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

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

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

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

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

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

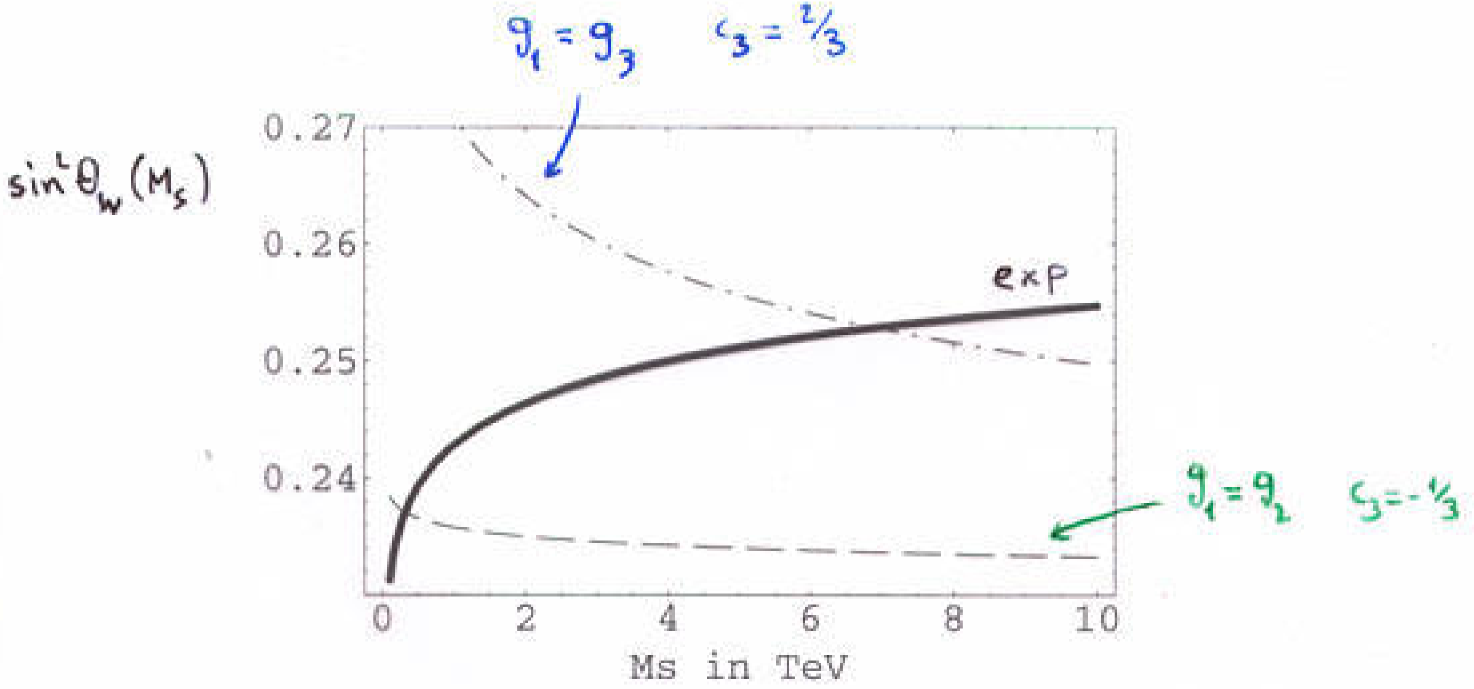
hypercharge $\quad Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow$ 4 possibilities

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

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

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

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



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 $\quad e^{-m/\lambda}$

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

  Arkani Hamed - Dimopoulos - Dvali - March Russell

  Dienes - Dudas - Gherghetta $\quad$ '98

- mixed $U(1)_A$ - non abelian anomalies

$k_i = \mathrm{Tr}\, Q_A T_i^2 \Rightarrow$

$$(\partial a + g_A A)^2 + a \sum_i k_i \,\mathrm{Tr}\, F_i \wedge F_i$$

$$A \to A + \partial\Lambda \qquad a \to a - g_A \Lambda$$

Dine - Seiberg - Witten

- mixed $U(1)_A$ - abelian anomalies

• $k_Y = \mathrm{Tr}\, Q_A Y^2 \Rightarrow$ same as non abelian

• $\xi = \mathrm{Tr}\, Y Q_A^2 \Rightarrow$ Chern - Simons terms:

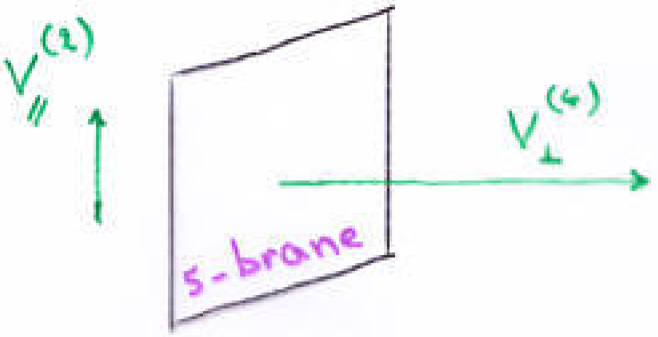
$$\xi \left(- A_Y \wedge \omega_A + a\, F_Y \wedge F_A \right)$$

I.A.-Pioline '99

Type II strings

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

$\lambda_{II} \to 0 \Rightarrow$ Little String Theory at low energies

I.A. - Dimopoulos - Giveon to appear

- Gauge interactions on NS5-branes

$$\text{NS5 on } T^2 \Rightarrow g^2 \sim \begin{cases} 1/R_1 R_2 & \text{type IIB} \\ R_1/R_2 & \text{type IIA} \end{cases}$$

IIB : 0-branes

endpoints of D-strings on NS5's

$T_0 = T_{D1} L \equiv M_W$ L : separation

IIA : "charged" strings

endlines of D2-branes on NS5's

$T_1 = T_{D2} L = M_W / R_1$ ← T-duality from IIB

- Neutral closed little strings

trapped in the vincinity of 5-branes

double scaling limit : $\lambda_{II} \to 0$, $L \to 0$

$$g_{LST} = \frac{\lambda_{II}}{L M_s} = \begin{cases} M_s / M_W & \text{IIB} \\ M_s^2 / T_1 & \text{IIA} \end{cases}$$

IIB : $R_{4,5}^{-1} < M_s$ but $g_{LST} > 1$

IIA : $g_{LST} < 1 \Rightarrow M_s < \sqrt{T_1} < R_{4,5}^{-1}$

$\Rightarrow$ little strings : first signal of new physics!

- stability of hierarchy : automatic
- fixing $\lambda_{II} \sim 0 \Rightarrow$ need $\ln \lambda_{II}$ corrections

to the effective potential

In principle YES if anomalous $U(1)_A$

in a D-brane "hidden" sector

$m_A \sim g_A M_s \quad g_A^2 \sim \lambda_{II} \Rightarrow \ln m_A^2 \sim \ln \lambda_{II}$

- dilaton coupling to matter : ultraweak

$\sim \lambda_{II} / M_p \sim O(1/M_p^2)$

$\Rightarrow$ no exp constraint on its mass

- $\Lambda < O(M_s^4)$

$\Lambda < \Lambda_{exp} \Rightarrow \Lambda = 0$ up to 2 loops

$\Lambda_{3\text{-loops}} \sim \lambda_{II}^4 M_s^4 \sim M_s^8 / M_p^4$