I. Antoniadis

Strings 2000

D-brane physics at low energies

- Motivations
- Realizations of low-scale strings
- Gauge hierarchy
- Brane SUSY breaking
- Gauge coupling unification
- Minimal Standard Model embeddings

At what energies string theory becomes important?

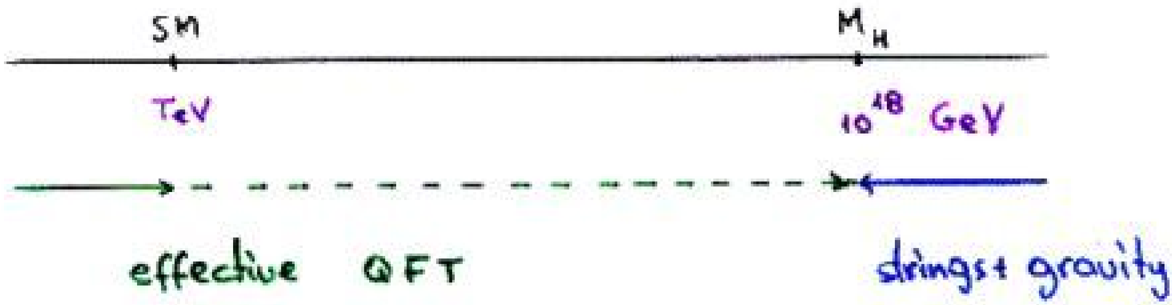
Old view (Heterotic): near $M_P \sim 10^{19}$ GeV $(10^{-33}\,\mathrm{cm})$

$$M_H \sim g\, M_P \simeq 10^{18}\ \mathrm{GeV}$$

$$\lambda_H \sim g\sqrt{V}$$

weak coupling $\lambda_H < 1 \Rightarrow V \sim$ string size

separate physics in 2 regions:



However physical motivations $\Rightarrow$

large volume may be relevant

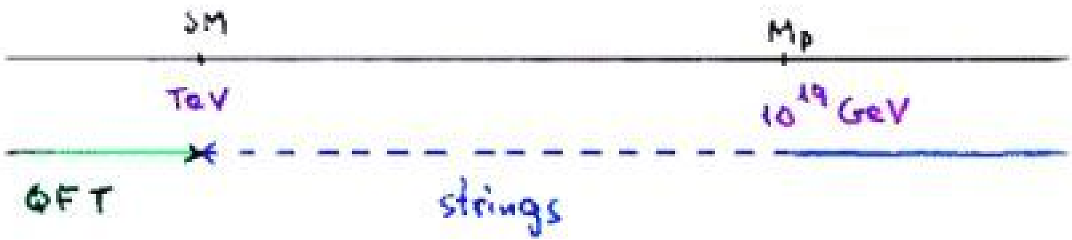
~~SUSY~~ by compactification $\Rightarrow R \sim \mathrm{TeV}^{-1}$ I.A. '90

Recent view : M_s arbitrary parameter   Witten '96

why not at TeV ?   Lykken '97

$M_s \sim$ TeV $\Rightarrow$ nullification of gauge hierarchy

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



- new large dimensions
- low scale quantum gravity   black-holes in accelerators?
- modification of gravitation at (sub)mm
- challenge to re-address most of the "old" problems

Realizations of TeV strings

Type I $\Rightarrow$ submm dims

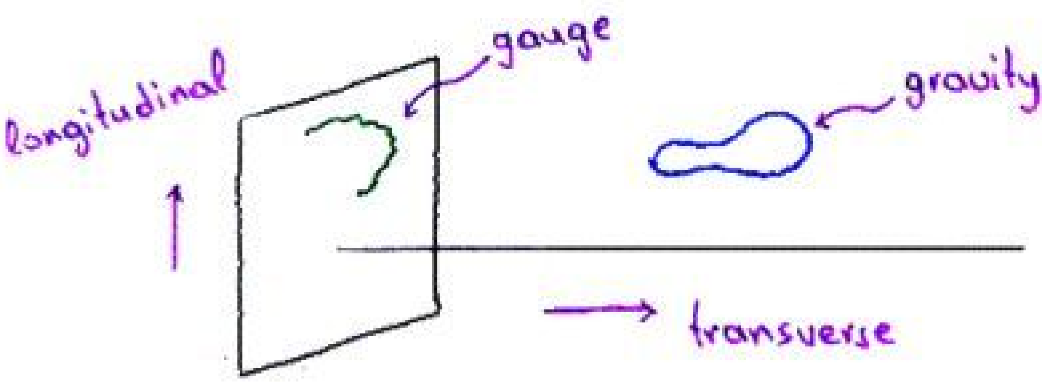
Type II $\Rightarrow$ tiny coupling

strongly coupled Heterotic $SO(32)$ (type I)

$E_8 \times E_8$ (type II)

Type I: closed strings $\to$ gravity

open strings $\to$ 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 $\Rightarrow$

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

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

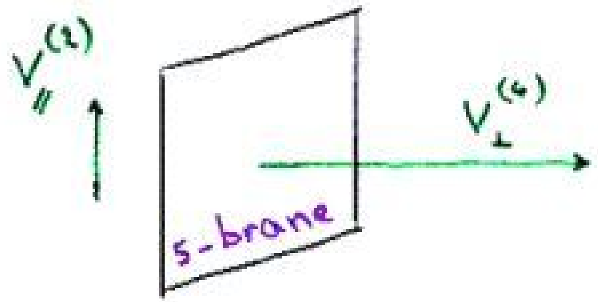
M_P: 10^{19} GeV, 10^{-33} cm

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

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

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

I.A. - Dimopoulos - Giveon in progress

$$\text{NS5 on } T^2 \Rightarrow g^2 \sim \begin{cases} 1/R_1R_2 & \text{type IIA} \\ R_1/R_2 & \text{type IIB} \end{cases}$$

$$R^{-1}_{1,2} < E < M_{II} : \text{6d SCFT} \begin{cases} \text{IIA}: (1,1) \\ \text{IIB}: (2,0) \end{cases}$$

IIB: M_{II} can move up keeping $R^{-1}_{1,2} \sim$ TeV

with fixed g and $\lambda_{II} < 1$

$\Rightarrow$ SCFT: effective theory of tensionless strings

similar in Heterotic with small instantons

Benakli - Oz '99

Gauge hierarchy

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

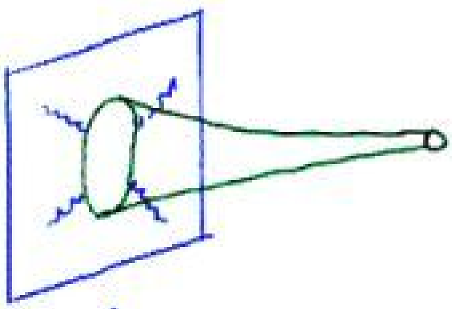
$$r M_I \simeq \left(g^2\, M_P / M_I \right)^{2/n} \sim \begin{cases} 10^{15} & n=2 \\ 10^{5} & n=6 \end{cases} \quad \text{or} \quad \lambda_{II} \simeq 10^{-14}$$

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

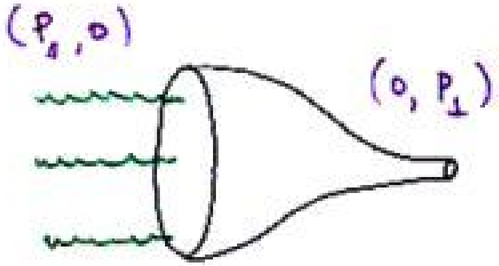
I.A.-Bachas '98



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

$\uparrow$ UV divergence: open string loop

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



cl d : IR divergence

local tadpole of massless closed string

brane: UV divergence

open string loop

$$UV \sim \frac{1}{V_\perp} \sum_{|p_\perp| < M_I} \frac{1}{|p_\perp|^2} F(\vec{p}_\perp)$$

$r^{d_\perp}$

$\ell \sim \frac{1}{|p_\perp|} \gg \ell_I$

$\vec{p}_\perp = \frac{1}{r}(m_1, \ldots, m_{d_\perp})$

$2^{d_\perp}$ orientifolds

global tadpole cancellation $\Rightarrow$ 32 $D(9-d_\perp)$ branes

$$F(\vec{p}_\perp) \sim 32 \prod_{i=1}^{d_\perp} \frac{1+(-)^{m_i}}{2} - 2 \sum_{a=1}^{16} \cos \vec{p}_\perp \vec{x}_a$$

orientifold locations: 0, πr

D-brane locations x_a, $-x_a$

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

Brane susy breaking in type I theory

stable non-BPS configurations of

branes - antibranes or branes - antiorientifolds

	RR-charge	tension
D	+	+
$\bar{D}$	−	+
O_-	−	−
$\bar{O}_-$	+	−
O_+	+	+
$\bar{O}_+$	−	+

$\left.\begin{matrix} O_+ \\ \bar{O}_+ \end{matrix}\right\}$ as $D, \bar{D}$

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

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

e.g. $D9 - \bar{D}5$

or in different positions

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

Brane susy with magnetic fields :

in general tachyons except in special cases

(anti) selfdual internal fields ⇒

D9 acquire D5 ($\bar{D}5$) RR-charge

⇒ new chiral susy (susy) vacua

with reduced rank

I.A. - Angelantonj - Dudas - Sagnotti

$M_6 \times T^2 \times T^2$ with H_1, H_2

Dirac quantization: $q\, H_i\, v_i = k_i \qquad i=1,2$

minimal charge

volume of T^2_i

degeneracy of Landau levels

EFT: for $H_1 \wedge H_2 = 0$

string theory: it can be $\neq 0$

$$T_9 \int_{M_{10}} e^{-\phi} \sqrt{\det\,(1+qF)} + \mu_9 \int_{M_{10}} e^{qF} \wedge C_{10}$$

$(1+q^2H_1)(1+q^2H_2)$

$1+q^2 F_1 \wedge F_2$

$H_1 = \pm H_2$

$$= \underbrace{\int_{M_{10}} T_9\, e^{-\phi} + \mu_9\, C_{10}}_{D9} + \underbrace{\int_{M_6} |k_1 k_2|\, T_5\, e^{-\phi} + k_1 k_2\, \mu_5\, C_6}_{D5}$$

T^4/Z_2: $\quad N = 16 = n + m \qquad D + k_1 k_2\, n = 16$

$k_1 = k_2 = 2 \Rightarrow n=1 \quad D=12 \qquad U(15)_9 \times U(1)_9 \times U(12)_5$

$\vdots \qquad\qquad \vdots$

$n=4 \quad D=0 \qquad U(12)_9 \times U(4)_9$

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:

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

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

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

$\Rightarrow$ can be experimentally tested

Unification : M_s versus M_{GUT} ?

1) accident : 3 different couplings at M_s

2) maintain $g_1 = g_2 = g_3$ at M_s tree-level

all factors of SM on the same collection of branes

explain the difference by :

(a) Power law running Dienes - Dudas - Ghergetta '98

- in energy : $R_{\parallel}^{-1} \longrightarrow M_s$ $\Rightarrow M_{GUT} = M_s$

TeV $\mathcal{O}(10)$ TeV

- in transverse space : $R_{\perp} \longrightarrow l_s$ $\Rightarrow M_{GUT} = R_{\perp} M_s^2$

however power UV sensitivity $\Rightarrow$

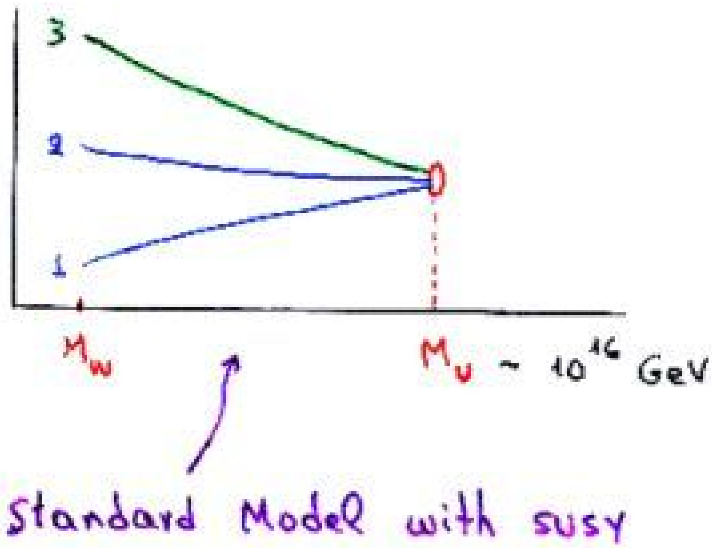
(string) thresholds are important

(b) Log "running" in the bulk for $d_{\perp} = 2$ Bachas '98

I.A. - Bachas - Dudas '99

Arkani Hamed - Dimopoulos - March Russell

Unification



$$\frac{1}{g_a^2} = \underbrace{\frac{1}{g^2} + s_a m}_{\text{tree}} + \underbrace{\sum_{i=1}^{3} \hat{b}_a^i \left(\ln T_i + f(U_i) \right)}_{\text{1-loop}}$$

- $\frac{1}{g^2}$: same collection of branes
- m : twisted (blow-up) moduli

in all examples: anomalous $U(1)$'s $\Rightarrow m=0$

- $T = R_1 R_2 \qquad U = \frac{R_1}{R_2}$ for every torus $i=1,2,3$

$R_1 \sim R_2 \to \infty \quad \Rightarrow \quad b_a \ln R_1 R_2 \qquad d_\perp = 2$

$R_1 \gg R_2 \quad \Rightarrow \quad b_a \, R_1/R_2 \qquad d_\perp = 1$

$f(U) \sim R_1/R_2$

M_s at TeV but gauge coupling unify at a higher scale due to log sensitivity at $d_\perp = 2$

$M_{GUT} = R_\perp M_s^2 \simeq 10^{16}$ GeV for $M_s \sim 10$ TeV $R_\perp \sim$ mm

however in $N=1$ orientifolds logs are controled by $N=2$ β-functions $\Rightarrow$ no concrete example

3) separate one gauge factor

e.g. $SU(2)$ branes $\Rightarrow$ $g_1 = g_3$, g_2

$\Rightarrow$ one prediction : M_s or $\sin^2\theta_W$

I.A. - Kiritsis - Tomaras '00

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) 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

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

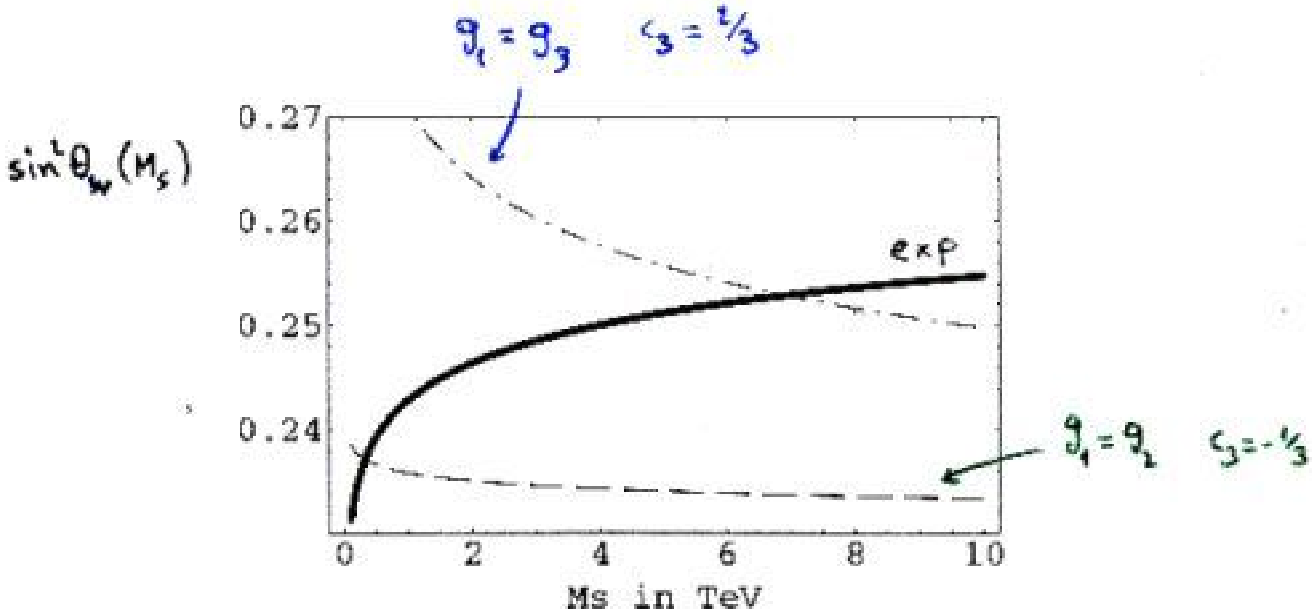
hypercharge $\quad Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3 \Rightarrow$ 4 possibilities

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

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

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

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



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

U(1) with color branes

$3 \times 3 \Big|_{\text{antisym}} = \bar{3}$

$\Rightarrow$ new possibility $\left(c_3 = -\frac{1}{3}\right)$

$2 \times_a 2 = 1$

$u^c \longrightarrow u^{c'} : \ (\bar{3}, 1 \ ; \ 2, 1, 0)$

$\ell^c \longrightarrow \ell^{c'} : \ (1, 1 \ ; \ 0, -2, 0)$

$U(3) \times U(2)$ $\qquad Y = -\frac{1}{3} Q_3 - \frac{1}{2} Q_2$

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

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

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

$$\sin^2\theta_W = \frac{1}{2 + 2g_2^2/3g_3^2} = \frac{3}{8} \text{ for } g_2 = g_3$$

but no Yukawa coupling for u-quark

no automatic baryon $U(1)$

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

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

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 '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:

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