# D-Brane Models

# of Particle Physics

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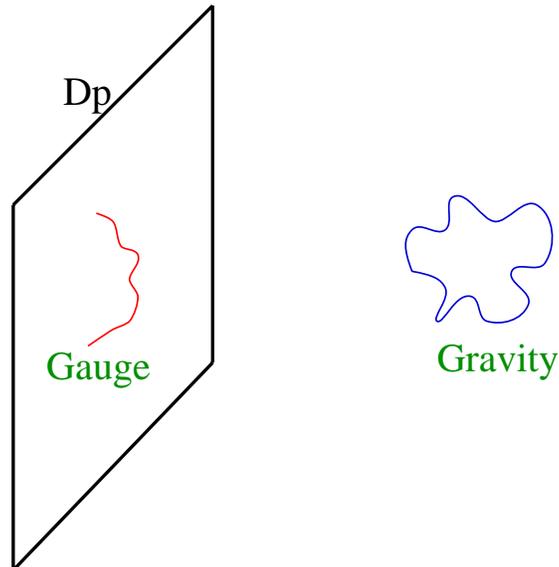
SUSY-2002  Hamburg, June 2002

Dp-branes fundamental (p+1)-dimensional non-perturbative objects in Type II string theory.



Dp

Gauge

Gravity

Open strings $\Longleftrightarrow$ Gauge interactions

Closed strings $\Longleftrightarrow$ Gravity

Standard Model : Most obvious gauge theory to study:

## LOOK FOR A D-BRANE DESCRIPTION OF THE SM

i.e., look for Dp-brane configurations in String Theory with a massless spectrum resembling the SM.

## From a D-brane description of the SM one hopes:

- Unification of gravity and SM interactions

- Construct string realization of brane-world idea (perhaps)

  But also to find new avenues to understand misteries of the SM like:

- Family triplication

- The unreasonable stability of the proton

- Fermion mass hierarchies

- etc.

A crucial requirement on the searched D-brane configuration is that it should lead to

### CHIRAL FERMIONS

D-branes on a smooth space leads to non-chiral theories ($N = 4$ SUSY)

Simplest ways to get chirality in explicit D-brane models:

- D-branes at singularities (e.g., orbifold sing.)

- Intersecting D-branes $\Rightarrow$

- Talk based on:

  L.I. , F. Marchesano and R. Rabadán, hep-th/0105155

  D. Cremades, L.I, F. Marchesano , hep-th/0201205; hep-th/0203160; hep-th/0205074

- Previous related work:

  R. Blumenhagen, L. Görlich, B. Kors, D. Lüst, hep-th/0007024

  G. Aldazabal, S. Franco, L.I., R. Rabadán, A. Uranga, hep-th/0011073 ; hep-ph/0011132

  R. Blumenhagen, B. Körs and D. Lüst , hep-th/0012156

- also:

  R. Blumenhagen, B. Körs, D. Lüst, T. Ott, hep-th/0107138

  M. Cvetic, G. Shiu, A. Uranga, hep-th0107166; hep-th/0107143

  D. Bailin, G. Kraniotis, A. Love, hep-th/0108131

  S. Förste, G. Honecker, R. Schreyer, hep-th/0008250

  G. Honecker, hep-th/0112174; hep-th/0201037

  C. Kokorelis, hep-th/0203187; hep-th/0205147

- brane intersections/fluxes :

  C. Bachas, hep-th/9503030

  M. Berkooz, M. Douglas, R. Leigh, hep-th/9606139

  C. Angelantonj, I. Antoniadis, E. Dudas, A. Sagnotti, hep-th/0007090

## WHY INTERSECTING BRANES?

They have a number of properties present in the SM :

❶ Gauge group: Each stack of $N$ branes carries a $U(N)$ gauge theory.

❷ Chirality: Two intersecting branes present chiral fermions at their intersection, transforming in bifundamental $(N, \bar{M})$ or $(N, M)$.
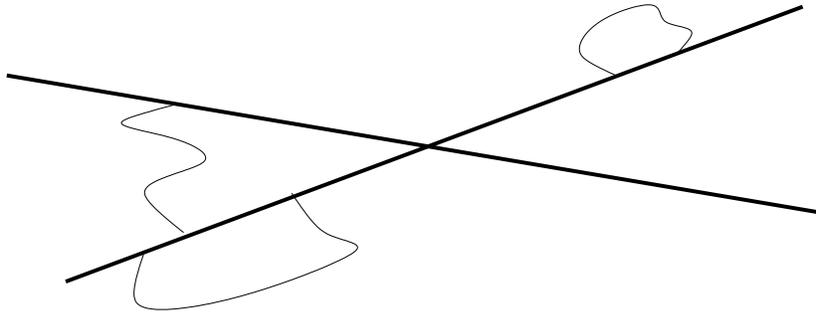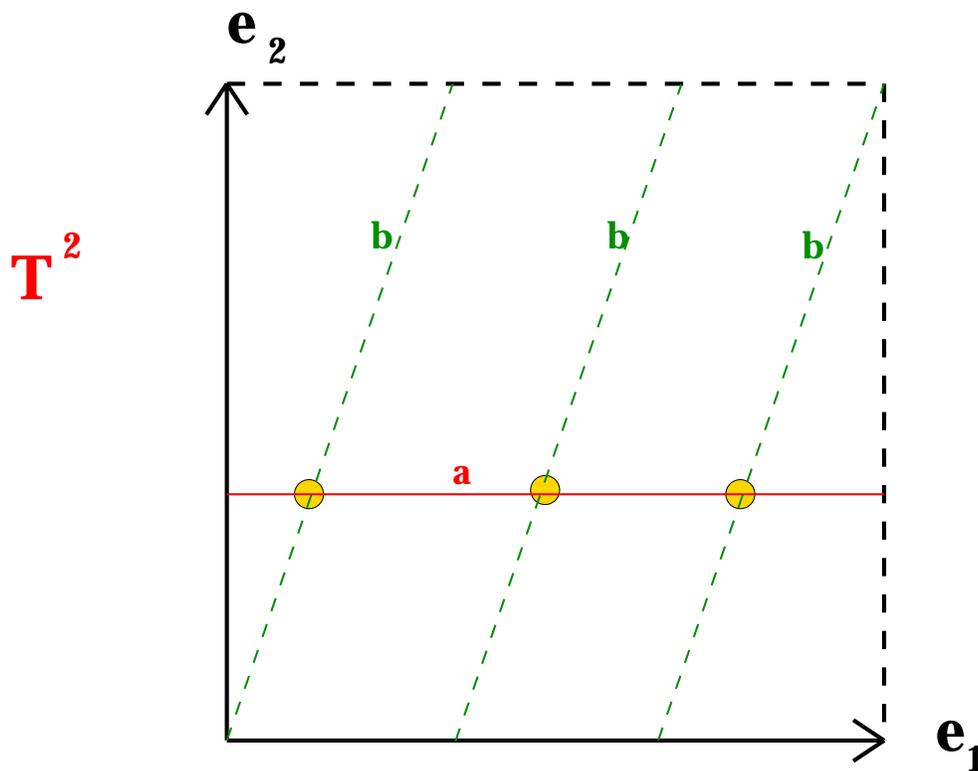
❸ Family replication: Branes at angles wrapping a compact manifold may intersect several times.
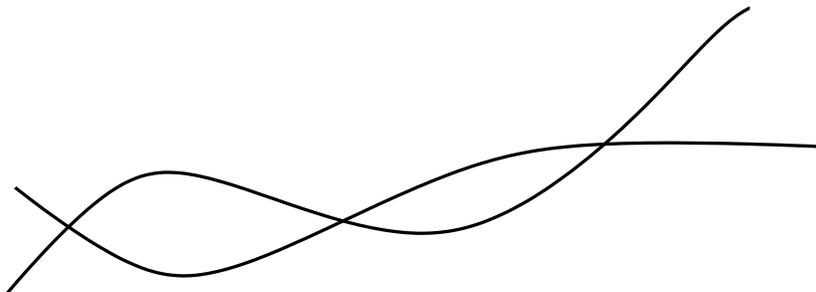
## TRIPLICATION EXAMPLE

- Consider a pair of D4-branes

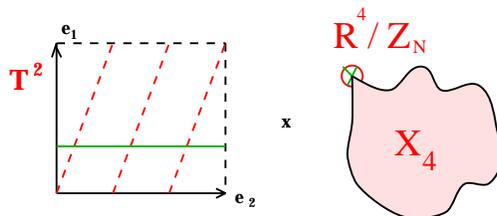- 5-dimensional worldvolume = $M_4 \times C^1$, $C^1$ wrapping a cycle on a 2-torus



'a' and 'b' 4-branes intersect at three points

- wrapping numbers (n,m) = (1,0), (1,3)

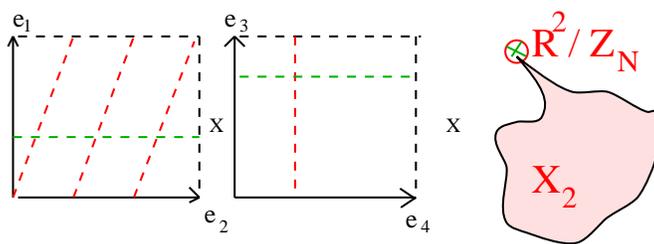# Varieties of Toroidal Intersecting Brane settings

Type II A, B String Theory

❶ D4-branes wrapping 1-cycles on $T^2 \times R^4/\mathbf{Z}_N$



❷ D5-branes wrapping 2-cycles on $T^4 \times R^2/\mathbf{Z}_N$



❸ D6-branes wrapping 3-cycles on $T^6$
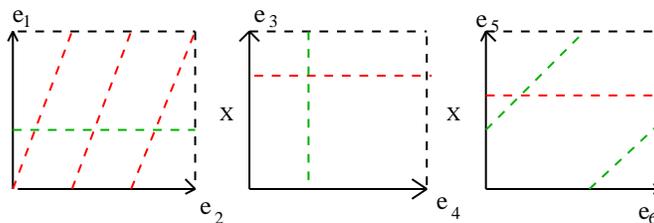
# Minimal Structure of SM D-brane settings

Configuration of 4 stacks of branes:

| stack a | $N_a = 3$ | $SU(3) \times U(1)_a$ | Baryonic brane |
|---------|-----------|-----------------------|----------------|
| stack b | $N_b = 2$ | $SU(2) \times U(1)_b$ | Left brane |
| stack c | $N_c = 1$ | $U(1)_c$ | Right brane |
| stack d | $N_d = 1$ | $U(1)_d$ | Leptonic brane |

## # Generations = # Colours ?

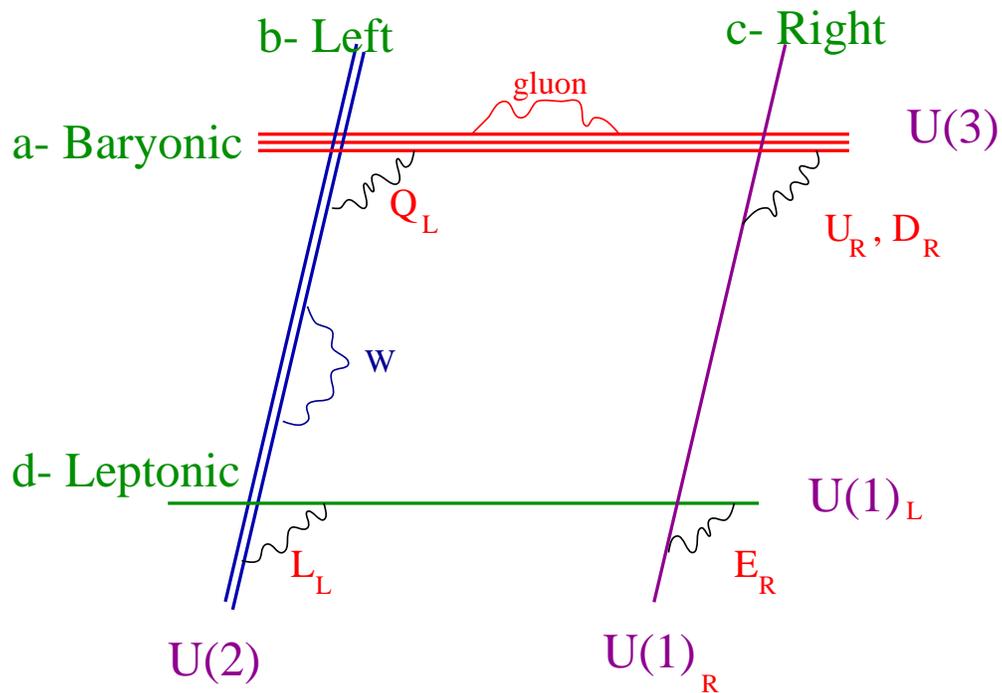- Important constraint in ANY D-brane model with fermions in bifundamentals (comes from RR-tadpole cancellation):

  Number of $N$-plets = Number of $\bar{N}$-plets of $U(N)$

  This is true even for $U(2)$ or $U(1)$.

- Impose Number of $2$-plets = Number of $\bar{2}$-plets of $U(2)$

  Left-handed SM fermions:

  $$3\,Q_L = 3\,(3,2) \longrightarrow 9\ \text{2-plets}$$

  $$3\,L = 3\,(1,\bar{2}) \longrightarrow 3\ \bar{2}\text{-plets}$$

  $\rightarrow$ Minimal SM has 'U(2) anomalies'

  6 extra fermion $SU(2)$ doublets needed to cancel anomalies.

- Simple way to Cancel Anomalies :

  $$2\,(3,2)\ +1\,(3,\bar{2}) \longrightarrow 3\ \text{net}\ \text{2-plets}$$

  $$3\,(1,\bar{2}) \longrightarrow 3\ \text{net}\ \bar{2}\text{-plets}$$

  $\longrightarrow$ U(2) anomalies cancel !!

- this works only because # COLORS = # GENERATIONS

## $(N, M)$ **and** $(N, \bar{M})$ **bifundamentals and orientifolds**

We need $(N, M)$ and $(N, \bar{M})$ bifundamentals to get the minimal fermion spectrum of the SM
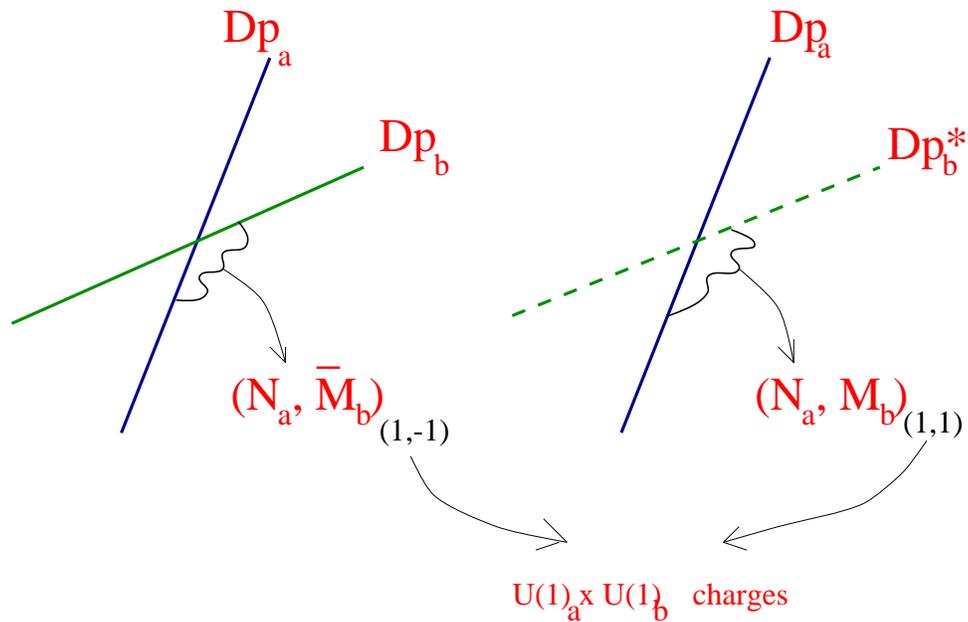
- In string theory they appear in orientifold models:

$$\text{Orientifold} = \text{Type II} \ / \ \Omega\mathcal{R}$$

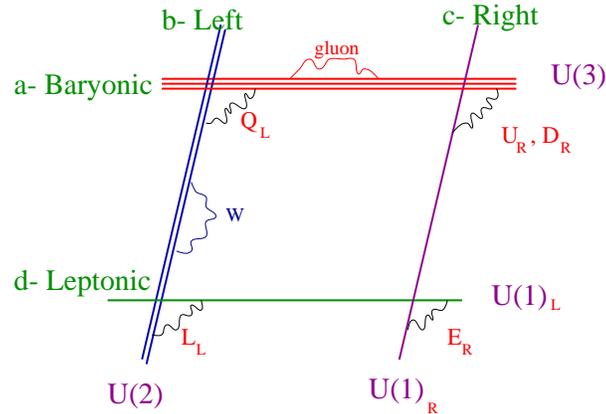$\Omega$ = worldsheet-parity ; $\mathcal{R}$ = some geometrical action (e.g., reflection)

- Under $\Omega\mathcal{R}$ :

Dp-brane $\longleftrightarrow$ Dp*-brane = 'mirror' = $(\Omega\mathcal{R})$Dp

Both brane and mirror need to be present in an orientifold configuration

## Quantum numbers of SM in intersecting brane models



Assuming all fermions come from bifundamentals and imposing $\#N$-plets $=\#\bar{N}$-plets leads to the following model independent unique structure (up to redefinitions):

| Intersection | Matter fields | | $Q_a$ | $Q_b$ | $Q_c$ | $Q_d$ | $Q_Y$ |
|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|
| (ab) | $Q_L$ | $(3,2)$ | 1 | -1 | 0 | 0 | 1/6 |
| (ab*) | $q_L$ | $2(3,2)$ | 1 | 1 | 0 | 0 | 1/6 |
| (ac) | $U_R$ | $3(3,1)$ | -1 | 0 | 1 | 0 | -2/3 |
| (ac*) | $D_R$ | $3(\bar{3},1)$ | -1 | 0 | -1 | 0 | 1/3 |
| (bd*) | $L$ | $3(1,2)$ | 0 | -1 | 0 | -1 | -1/2 |
| (cd) | $N_R$ | $3(1,1)$ | 0 | 0 | 1 | -1 | 0 |
| (cd*) | $E_R$ | $3(1,1)$ | 0 | 0 | -1 | -1 | 1 |

$$SU(3) \times SU(2) \times U(1)_a \times U(1)_b \times U(1)_c \times U(1)_d$$

Where hypercharge is defined as:

$$Q_Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d \qquad (1)$$

(Orthogonal linear combinations will be massive, see below)

Setup: type IIA D6-branes filling $M_4$ and wrapping 3-cycles on $T^6$.

We further assume having a factorized torus and factorizable 3-cycles:

$$T^6 = T^2 \times T^2 \times T^2$$

3-cycle = 1-cycle $\times$ 1-cycle $\times$ 1-cycle
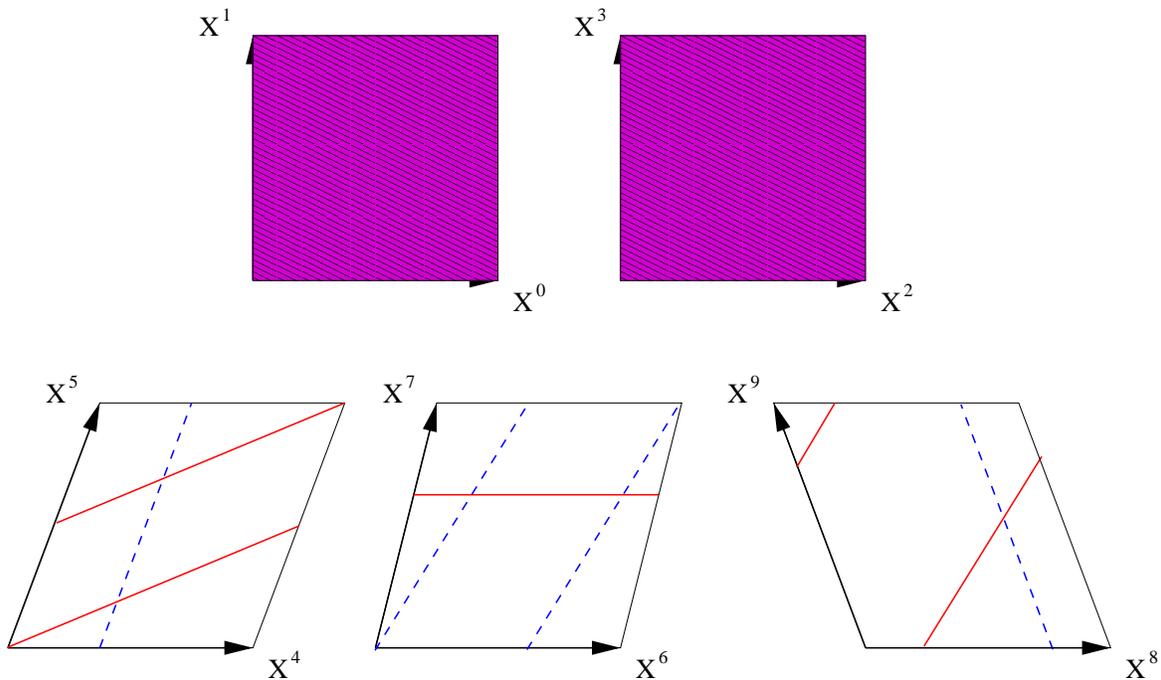


$$[\Pi_a] = (n_a^1, m_a^1) \times (n_a^2, m_a^2) \times (n_a^3, m_a^3)$$

Intersection number: $I_{ab} = I_{ab}^1 \times I_{ab}^2 \times I_{ab}^3$

$$I_{ab}^i = \left( n_a^i m_b^i - m_a^i n_b^i \right)$$

# **ORIENTIFOLD**

Consider the theory

$$\frac{\text{Type IIA on } T^6}{\Omega\mathcal{R}} \quad \overset{T-dual}{\longleftrightarrow} \quad \text{Type I on } \tilde{T}^6 \tag{2}$$

$\Omega$ : Worldsheet parity.

$\mathcal{R} = \mathcal{R}_{(5)}\mathcal{R}_{(7)}\mathcal{R}_{(9)}$

Consequences:

❶ only some tori lattices are allowed by $\Omega\mathcal{R}$ action: square ($b^{(i)} = 0$) or tilted ($b^{(i)} = \frac{1}{2}$).

❷ Mirror branes should be added

For each D6-brane $a$ in our model, we must add its mirror image $a^*$ under $\Omega\mathcal{R}$.

Deffine effective wrapping numbers as

$$(n_a^i, m_a^i)_{\text{eff}} \equiv (n_a^i, m_a^i) + b^{(i)}(0, n_a^i),$$

Then $\Omega\mathcal{R}$ action reduces to

$$\begin{aligned}
\text{D6} - \text{brane } a &\quad \mapsto \quad \text{D6} - \text{brane } a^* \\
(n_a^i, m_a^i) &\qquad\quad (n_a^i, -m_a^i)
\end{aligned} \tag{3}$$

**❸** Fermion spectrum

- $D6_a D6_a$ and $D6_a * D6_a*$ sectors : $U(N)$ $\mathcal{N} = 4$ SYM.
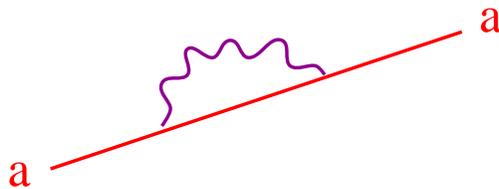


- $D6_a D6_b$ and $D6_a D6_b*$ sector: bifundamental fermion representations $I_{ab}(N_a, \overline{N_b}) + I_{ab*}(N_a, N_b)$
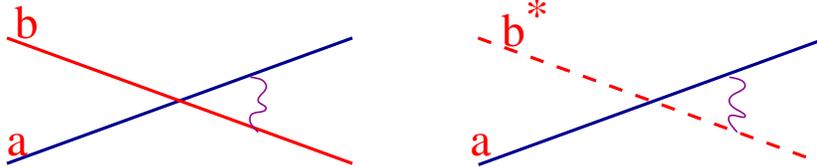


  (asuming each brane does not intersect with its own mirror, which would lead to additional exotic symmetric/antisymmetric fermion fields )

## RR Tadpole Cancellation Conditions

- Consistent compactifications must satisfy RR Tadpole conditions, which imply a vanishing total Charge under certain Ramond-Ramond antisymmetric fields. This automatically ensures non-abelian $SU(N_a)^3$ anomaly cancellation:

$$\sum_c N_c I_{ac} = 0.$$

Notice that, as advertised, in these systems $SU(N)^3$ anomaly cancellation reduces to

# fundamentals = # antifundamentals

- If D6-branes have wrapping numbers $(n_a^1, m_a^1)(n_a^2, m_a^2)(n_a^3, m_a^3)$ the conditions read:

$$
\begin{aligned}
\sum_a N_a \, n_a^1 n_a^2 n_a^3 &= 16 \qquad (4)\\
\sum_a N_a \, n_a^1 m_a^2 m_a^3 &= 0\\
\sum_a N_a \, m_a^1 n_a^2 m_a^3 &= 0\\
\sum_a N_a \, m_a^1 m_a^2 n_a^3 &= 0
\end{aligned}
$$

**SM INTERSECTION NUMBERS**

$$I_{ab} = 1 \; ; I_{ab^*} = 2$$

$$I_{ac} = -3 \; ; I_{ac^*} = -3$$

$$I_{bd} = 0 \; ; I_{bd^*} = -3$$

$$I_{cd} = +3 \; ; I_{cd^*} = -3$$

$$a = U(3)_{baryon} \; ; b = U(2)_{left}$$

$$c = U(1)_{right} \; ; d = U(1)_{lepton}$$

# Getting JUST the SM at intersecting D6-branes

Look for choices of wrapping numbers $(n_a^i, m_a^i)$ yielding the fermion spectrum of the SM that we displayed before:

The general solution is:

| $N_i$ | $(n_i^1, m_i^1)$ | $(n_i^2, m_i^2)$ | $(n_i^3, m_i^3)$ |
|---|---|---|---|
| $N_a = 3$ | $(1/\beta^1, 0)$ | $(n_a^2, \epsilon\beta^2)$ | $(1/\rho, -\tilde{\epsilon}/2)$ |
| $N_b = 2$ | $(n_b^1, \epsilon\tilde{\epsilon}\beta^1)$ | $(1/\beta^2, 0)$ | $(1, -3\rho\tilde{\epsilon}/2)$ |
| $N_c = 1$ | $(n_c^1, 3\rho\epsilon\beta^1)$ | $(1/\beta^2, 0)$ | $(0, 1)$ |
| $N_d = 1$ | $(1/\beta^1, 0)$ | $(n_d^2, \epsilon\beta^2/\rho)$ | $(1, 3\rho\tilde{\epsilon}/2)$ |

Table 1: D6-brane wrapping numbers giving rise to a SM spectrum. The general solutions are parametrized by two phases $\epsilon, \tilde{\epsilon} = \pm 1$, the NS background on the first two tori $\beta^i = 1 - b^i = 1, 1/2$, four integers $n_a^2, n_b^1, n_c^1, n_d^2$ and a parameter $\rho = 1, 1/3$.

Tadpole conditions satisfied if:

$$\frac{3n_a^2}{\rho\beta^1} + \frac{2n_b^1}{\beta^2} + \frac{n_d^2}{\beta^1} = 16 \,. \tag{5}$$

# $U(1)$ **symmetries**

| Intersection | Matter fields | | $Q_a$ | $Q_b$ | $Q_c$ | $Q_d$ | $Q_Y$ |
|---|---|---|---|---|---|---|---|
| (ab) | $Q_L$ | $(3, 2)$ | 1 | -1 | 0 | 0 | 1/6 |
| (ab*) | $q_L$ | $2(3, 2)$ | 1 | 1 | 0 | 0 | 1/6 |
| (ac) | $U_R$ | $3(\bar{3}, 1)$ | -1 | 0 | 1 | 0 | -2/3 |
| (ac*) | $D_R$ | $3(\bar{3}, 1)$ | -1 | 0 | -1 | 0 | 1/3 |
| (bd*) | $L$ | $3(1, 2)$ | 0 | -1 | 0 | -1 | -1/2 |
| (cd) | $N_R$ | $3(1, 1)$ | 0 | 0 | 1 | -1 | 0 |
| (cd*) | $E_R$ | $3(1, 1)$ | 0 | 0 | -1 | -1 | 1 |

$$SU(3) \times SU(2) \times U(1)_a \times U(1)_b \times U(1)_c \times U(1)_d$$

❶ $Q_a$ = 3 B ; $Q_d$ = L ; $Q_c$ = $2I_R$

These known global symmetries of the SM are in fact gauge symmetries !!

❷ Two are anomaly-free :

$$\frac{Q_a}{3} - Q_d = B - L \qquad (6)$$
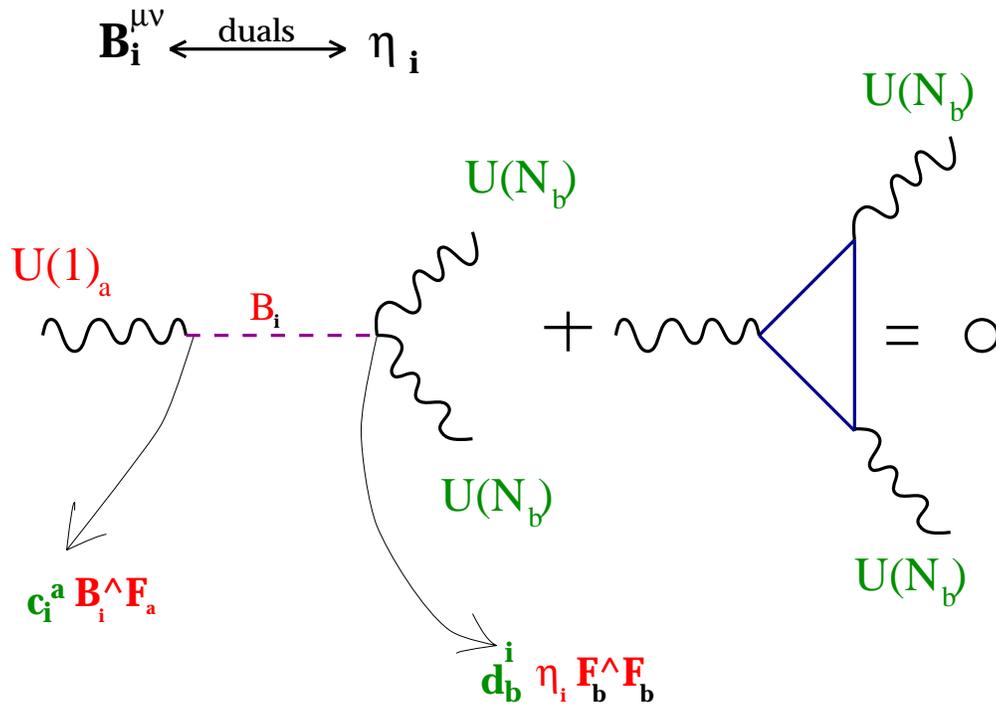$$Q_c = 2I_R$$

with

$$Y = \tfrac{1}{2}(B - L) - I_R$$

❸ Two have triangle anomalies:

$3Q_a + Q_d$ ; $Q_b$

Anomalies are cancelled by a Generalized Green-Schwarz mechanism

**Green-Schwarz mechanism**

$$\mathbf{B_i^{\mu\nu}} \xleftrightarrow{\text{ duals }} \eta_i$$

$c_i^a \, \mathbf{B_i} \wedge \mathbf{F_a}$

$d_b^i \, \eta_i \, \mathbf{F_b} \wedge \mathbf{F_b}$

$$\sum_i c_i^a \, d_b^i \; + \; A_b^a \; = 0$$

- If a $U(1)$ is anomalous it is necessary massive, due to the $B \wedge F_a$ couplings:

$$\epsilon_{\mu\nu\rho\sigma} B^{\mu\nu}(\partial^\rho A^\sigma) = (\partial_\sigma \eta) A^\sigma \; = \; Higgs - like \; coupling$$

- but not the other way round.

- In above orientifold models, there are 4 $D = 4$ RR fields involved, thus at most 4 $U(1)$'s can gain mass.

- Even if the abelian gauge symmetry is lost, the $U(1)$'s remain as perturbative global symmetries.

- In our specific solutions, there are two model-independent anomalous $U(1)$'s, and only one $U(1)$ remains massless:

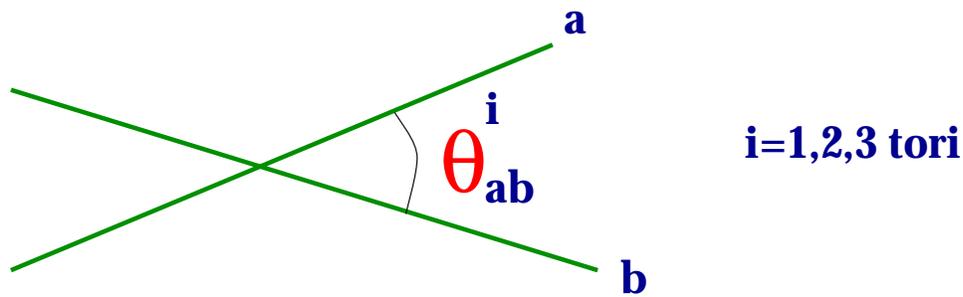$$Q_0 \; = \; n_c^1(Q_a - 3Q_d) \; - \; \frac{3\tilde{\epsilon}\beta^2}{2\beta^1}(n_a^2 + 3\rho n_d^2)Q_c \qquad (7)$$

It coincides with standard hypercharge if:

$$n_c^1 \; = \; \frac{\tilde{\epsilon}\beta^2}{2\beta^1}(n_a^2 + 3\rho n_d^2). \qquad (8)$$

$\Rightarrow$ **Just the SM group and 3 generations**

## Scalars at D6-brane intersections



**i=1,2,3 tori**

- There are three lightest scalars ("squarks/sleptons") at each intersection with masses in string units:

$$M_1^2 = \tfrac{1}{2}(-|\vartheta^1| + |\vartheta^2| + |\vartheta^3|)$$
$$M_2^2 = \tfrac{1}{2}(|\vartheta^1| - |\vartheta^2| + |\vartheta^3|) \tag{9}$$
$$M_3^2 = \tfrac{1}{2}(|\vartheta^1| + |\vartheta^2| - |\vartheta^3|)$$

- For wide ranges of parameters scalars are non-tachyonic

- For particular choices of radi and wrappings $n_a^i, m_a^i$ there is a massless scalar, signaling the presence of $N = 1$ SUSY at THAT intersection

- A fully $N = 1$ SUSY toroidal brane configuration in which all intersections respect the same supersymmetry is not possible (due to RR-tadpole cancellation).

- But one can obtain configurations in which all intersections respect a DIFFERENT $N = 1$ SUSY $\Rightarrow$ Q- SUSY models.
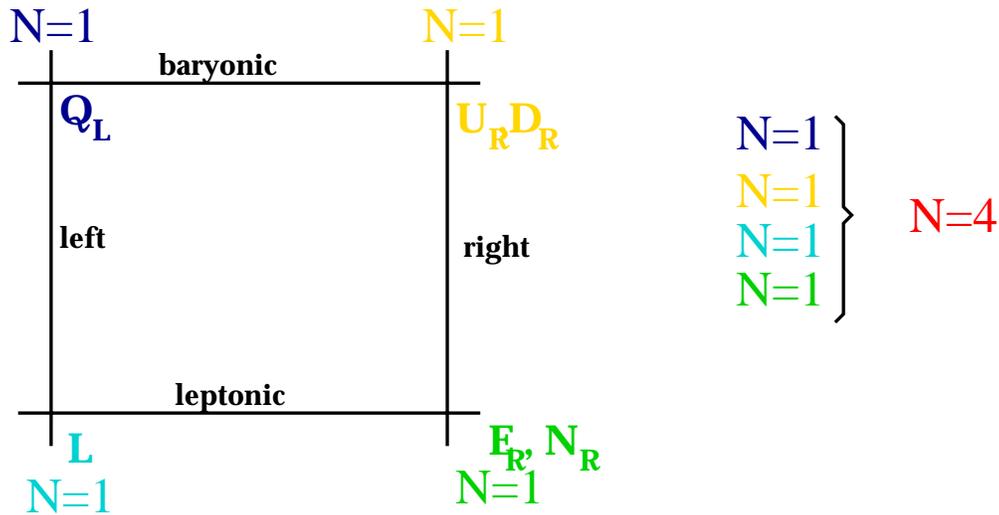
## A SM with different SUSY at each intersection

Consider the particular subset of models with wrapping numbers

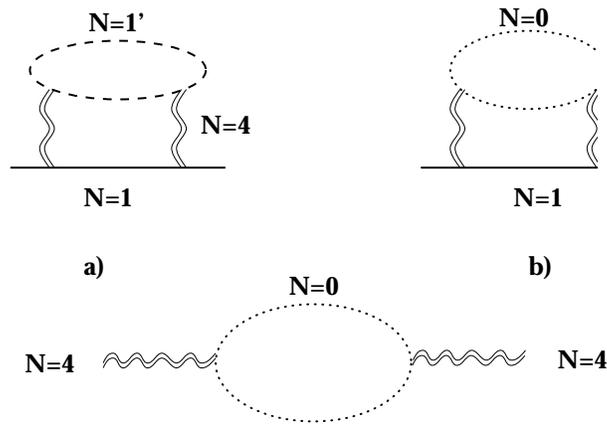| $N_i$ | $(n_i^1, m_i^1)$ | $(n_i^2, m_i^2)$ | $(n_i^3, m_i^3)$ |
|---|---|---|---|
| $N_a = 3$ | $(1, 0)$ | $(n_a^2, \beta^2)$ | $(3, -1/2)$ |
| $N_b = 2$ | $(n_b^1, 1)$ | $(1/\beta^2, 0)$ | $(1, -1/2)$ |
| $N_c = 1$ | $(0, 1)$ | $(1/\beta^2, 0)$ | $(0, 1)$ |
| $N_d = 1$ | $(1, 0)$ | $(n_a^2, 3\beta^2)$ | $(1, 1/2)$ |

and verifying

$$U^1 = \frac{n_b^1}{2} U^3 \; ; \; U^2 = \frac{n_a^2}{6\beta^2} U^3 \; where \; U^i = R_2^i / R_1^i \; , \; i = 1, 2, 3$$

- One can check quarks and leptons have massless SUSY partners
  with respect to 4 different SUSY's:



- Interesting class of theories in which quantum corrections to scalars
  appear only at two loops

- May help in stabalizing a modest hierarchy in between the weak scale and a low string scale $M_s \propto 10 - 100$ Tev

**Getting the chiral spectrum of the MSSM**

- It is also possible to get a D6-brane configuration with the chiral spectrum of the MSSM and quarks, leptons and Higgs multiplets respecting the same $N = 1$ SUSY
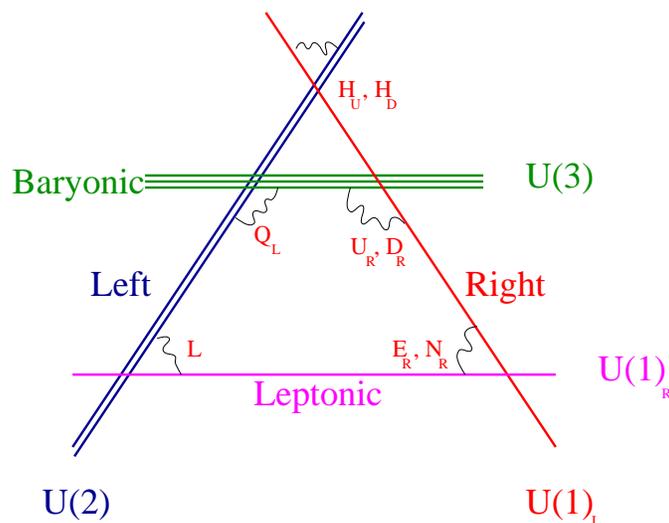
| brane type | $N_i$ | $(n_i^1, m_i^1)$ | $(n_i^2, m_i^2)$ | $(n_i^3, m_i^3)$ |
|---|---|---|---|---|
| $a_2$ | $N_a = 3$ | $(1, 0)$ | $(3, 1)$ | $(3, -1/2)$ |
| $b_2$ | $N_b = 2$ | $(1, 1)$ | $(1, 0)$ | $(1, -1/2)$ |
| $c_2$ | $N_c = 1$ | $(0, 1)$ | $(0, -1)$ | $(2, 0)$ |
| $a_2$' | $N_d = 1$ | $(1, 0)$ | $(3, 1)$ | $(3, -1/2)$ |

Table 2: Wrapping numbers of a three generation SUSY-SM with $\mathcal{N} = 1$ SUSY locally.

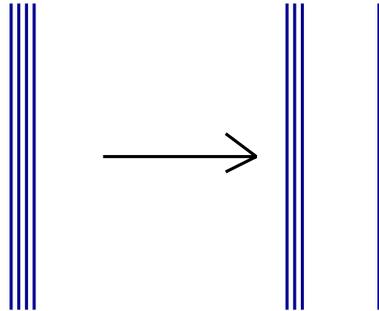| Intersection | Matter fields | | $Q_a$ | $Q_b$ | $Q_c$ | $Q_d$ | $Q_Y$ |
|---|---|---|---|---|---|---|---|
| $ab$ | $Q_L$ | $(3, 2)$ | 1 | -1 | 0 | 0 | 1/6 |
| $ab^*$ | $q_L$ | $2(3, 2)$ | 1 | 1 | 0 | 0 | 1/6 |
| $ac$ | $U_R$ | $3(\bar{3}, 1)$ | -1 | 0 | 1 | 0 | -2/3 |
| $ac^*$ | $D_R$ | $3(\bar{3}, 1)$ | -1 | 0 | -1 | 0 | 1/3 |
| $bd$ | $L$ | $(1, 2)$ | 0 | -1 | 0 | 1 | -1/2 |
| $bd^*$ | $l$ | $2(1, 2)$ | 0 | 1 | 0 | 1 | -1/2 |
| $cd$ | $N_R$ | $3(1, 1)$ | 0 | 0 | 1 | -1 | 0 |
| $cd^*$ | $E_R$ | $3(1, 1)$ | 0 | 0 | -1 | -1 | 1 |
| $bc$ | $H$ | $(1, 2)$ | 0 | -1 | 1 | 0 | -1/2 |
| $bc^*$ | $H$ | $(1, 2)$ | 0 | -1 | -1 | 0 | 1/2 |

Table 3: Chiral spectrum of the SUSY's SM obtained from the above wrapping numbers with $U^1 = U^2 = U^3/2$.

- The model is not fully $N = 1$ SUSY because to cancel RR-tadpoles additional massive $N = 0$ sectors (with no intersection with SM ones) have to be added. Also $N = 4$ gauge sector.

- Due to these additional $N = 0$ sectors the model looks somewhat like a gauge mediated SUSY-breaking model.

- There is an additional $U(1)_{B-L}$.
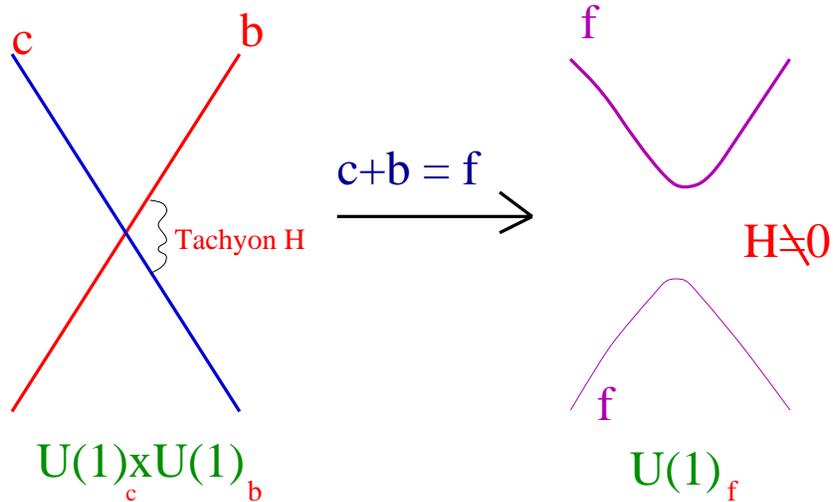
## Higgs mechanism and brane recombination

❶ Brane separation = Adjoint Higgsing Does not lower the rank.
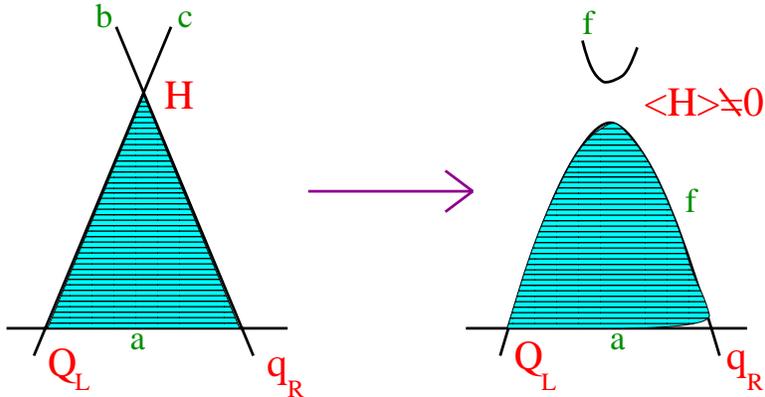
N Dp-branes



$$U(N) \longrightarrow U(N-1) \times U(1)$$

❷ Brane recombination lowers the rank



c        b                        f

$$c + b = f$$

Tachyon H

$H \not= 0$

f

$$U(1)_c \times U(1)_b$$        $$U(1)_f$$

In SM the rank is lowered $\rightarrow$ brane recombination of the branes $b$ and $c(c^*)$ at which intersection the Higgs scalars lie.
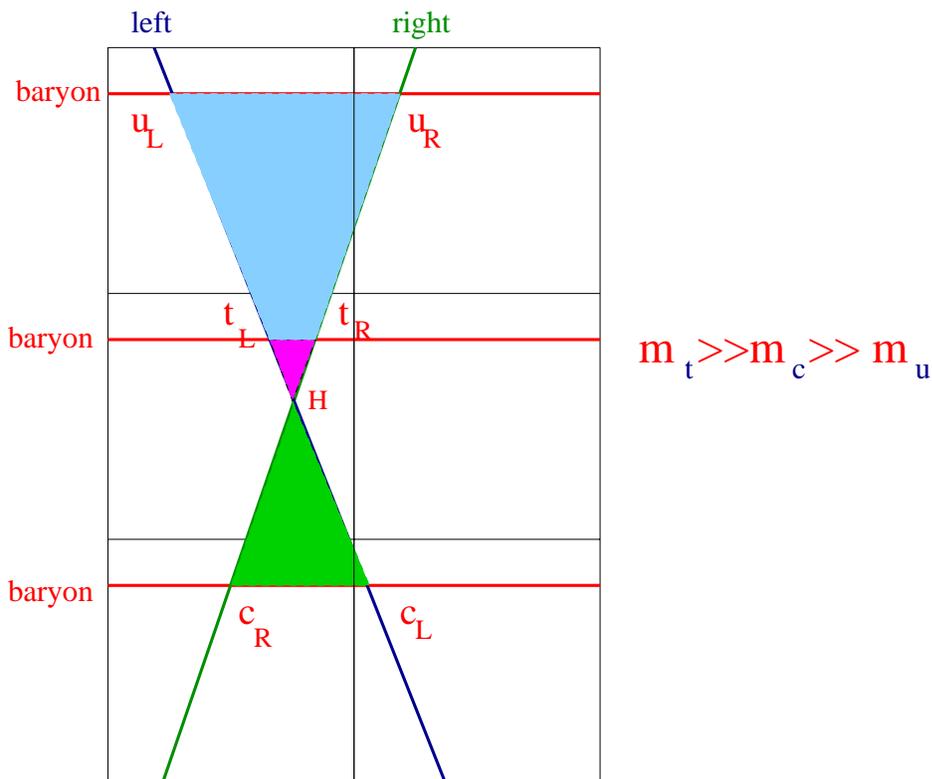
# Hierarchical Yukawa couplings

- Yukawa couplings come from triangular worldsheets



$$Y = \exp(-\text{Area})$$

$$m = \langle H \rangle \exp(-\text{Area})$$

- Different distance to Higgs field gives rise to hierarchical Yukawas ( Aldazabal, Franco, L.I., Rabadán, Uranga , hep-ph/0011132 ).
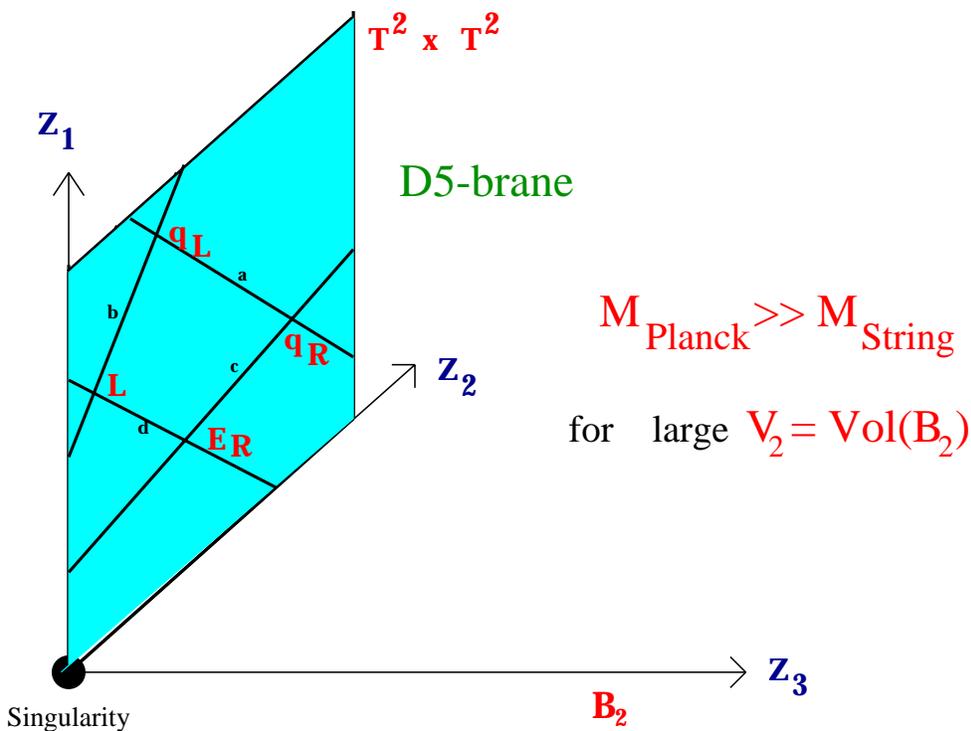


$$m_t \gg m_c \gg m_u$$

Non-SUSY models: To avoid hierarchy problem one should have
$M_s \propto 1$ TeV (Arkani-Hamed,Dimopoulos,Dvali)

❶ D6-branes The A-D-D approach for $M_{Planck} >> M_{string}$ by making transverse volume large not possible: no tori direction transverse to all D6-branes simultaneously. CY? Warping?

❷ D5-branes Analogous intersecting models can be built yielding just the SM fermion spectrum. These are Type IIB compactified on e.g., $T^2 \times T^2 \times (T^2/Z_N)$ with D5-branes wrapping 2-cycles on $T^2 \times T^2$. In this case

$$M_{Planck} = M_{string}^2 \frac{1}{\lambda} \sqrt{V_2}$$



**T$^2$ x T$^2$**

**D5-brane**

$M_{Planck} >> M_{String}$

for   large   $V_2 = Vol(B_2)$

Singularity

## Gauge coupling constants

$$SU(3) \times SU(2) \times U(1)_a \times U(1)_b \times U(1)_c \times U(1)_d$$

- Gauge couplings are not unified :

$$\frac{1}{g_i^2} = \frac{M_s^3}{(2\pi)^4 \lambda} \text{Vol}(\Pi_i) \; ; \; i = a, b, c, d \tag{10}$$

  $\text{Vol}(\Pi_i)$ being the volume each D6-brane is wrapping.

- Thus, e.g., $SU(3)$ interactions are stronger than $SU(2)$ because 'baryonic' branes wrap less volume than 'left' branes

- There are 6 groups but only 4 couplings $\Rightarrow$ There are some relationships :
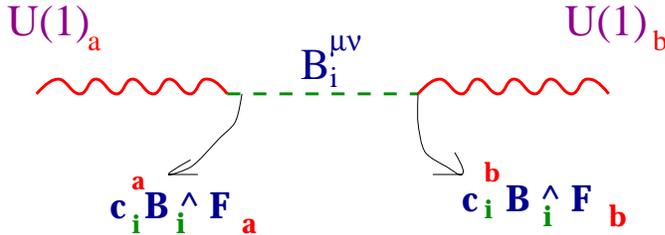
$$g_a^2 = \frac{g_{QCD}^2}{6} \; ; \; g_b^2 = \frac{g_L^2}{4} \; ; \; \frac{1}{g_Y^2} = \frac{1}{36g_a^2} + \frac{1}{4g_c^2} + \frac{1}{4g_d^2}. \tag{11}$$

## TeV-Scale Z' Bosons from D-branes

- There
  is quite a generic structure of extra $U(1)$'s. They are NOT of $E_6$ type:
$$(B - L) \, ; \; I_R \, ; \; (3B + L) \, ; \; Q_b$$

- If $M_s \propto 1 - 10$ TeV , could perhaps be tested at present/future
  accelerators

- Extra $Z$'s get masses by combining with RR string fields $B_i^{\mu\nu}$

$U(1)_a$ $\qquad\qquad\qquad\qquad\qquad$ $U(1)_b$

$B_i^{\mu\nu}$

$c_i^a B_i \wedge F_a$ $\qquad\qquad$ $c_i^b B_i \wedge F_b$

$$M_{ab}^2 \;\; = \;\; \sum_i \; g_a g_b \, c_i^a c_i^b \, M_{string}^2$$

- Four Eigenvalues = $(0, M_2, M_3, M_4)$. In D5, D6-brane models one
  finds typically at least one of them $M_3 < \frac{1}{3} M_{string}$

- Three massive $Z$'s mix with SM $Z^0$ . One can put constraints on
  $M_i$ from the $\rho$-parameter. (D. Ghilencea, L.I., N. Irges, F.Quevedo,
  hep-ph/0205083.)

## Baryon and lepton number violation

- Baryon number is a gauge symmetry. So the proton is automatically stable. (Baryogenesis should take place non-perturbatively).

- Lepton number is also a gauge symmetry. But may be spontaneously broken (e.g. $\tilde{\nu}_R$ vevs.). In the first case only Dirac masses. In the second case Majorana masses of order $M_{string}$ possible.

## CONCLUSIONS

❶ Intersecting D-brane constructions provide for an understanding from the string theory point of view of questions like

- chirality

- family triplication

- proton stability

❷ Certain phenomena of the SM have a geometrical interpretation:

- Hierarchical Yukawas come from the different areas of triangles connecting the Higgs with left and right fermions.

- Different sizes of gauge couplings come from different volumes wrapped by the different branes.

- The SM Higgs mechanism has a geometrical interpretation as brane recombination

❸ We have constructed classes of Intersecting D6 and D5-brane models wrapping toroidal compactifications in (orientifolded) Type II strings.

- The minimal intersecting D-brane SM constructions are obtained from 4 stacks of branes: Baryonic, Leptonic, Left and Right.

- Some classes of $D6$ and $D5$ brane models provide the first explicit string constructions with just the fermions of the SM and gauge group $SU(3) \times SU(2) \times U(1)_Y$.

- The SM intersection numbers are topological in character and may appear in general D-brane configurations wrapping e.g., CY-compactifications.

- It is also possible to find D6-brane configurations with the chiral spectrum of the MSSM, although there is also a massive $N = 0$ sector in these toroidal examples.

- Note that these ideas are not necesarily tied up to a low string scale scenario.

### some homework...

- New configurations of Dp-branes wrapping general cycles of e.g., $CY_3$ and same intersection structure. (see recent R. Blumenhagen, V. Braun, B. Körs, D. Lüst, hep-th/0206038.)

- Stability of configurations. The models discussed are non-SUSY and generically have NS-tadpoles. Look for stabilized vacua (e.g. with antisymmetric tensor fluxes). (Constructing $N = 1$ models is nice but once SUSY is broken stability issues will have to be faced anyhow).

- Phenomenology of $D6$ and $D5$ models :

  - Try to reproduce quark/lepton masses and mixings from hierarchical Yukawas.

  - Study of signatures of three 'canonical' extra $Z$'s.

- ...........