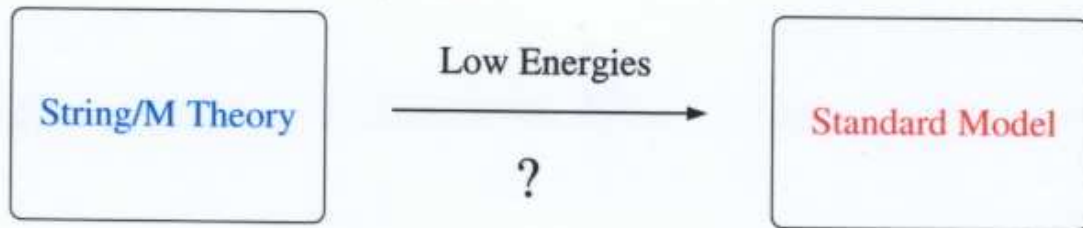


Supersymmetric Standard Model and GUTs from Orientifolds and G_2 Manifolds

- Construction of supersymmetric three-family standard-like model and GUT models from Type IIA orientifolds with intersecting D6-branes;
connection to M-theory on singular G_2 holonomy space
w/ G. Shiu, and A.M. Uranga,
hep-th/0107143,
hep-th/0107166,
hep-th/0111179.
- Derivation of particle physics properties of the models: gauge couplings, Yukawa couplings; hidden sector dynamics
w/ P. Langacker and G. Shiu,
hep-ph/0205252 ,
hep-th/0206115 .



Compactifications $\Rightarrow D = 4, \mathcal{N} = 1$ SUSY string vacua with chiral fermions-quasi realistic features

Pre-second string revolution focus on:

- **Weakly coupled heterotic string:**

models based on orbifold-type constructions and study of their physics implications.

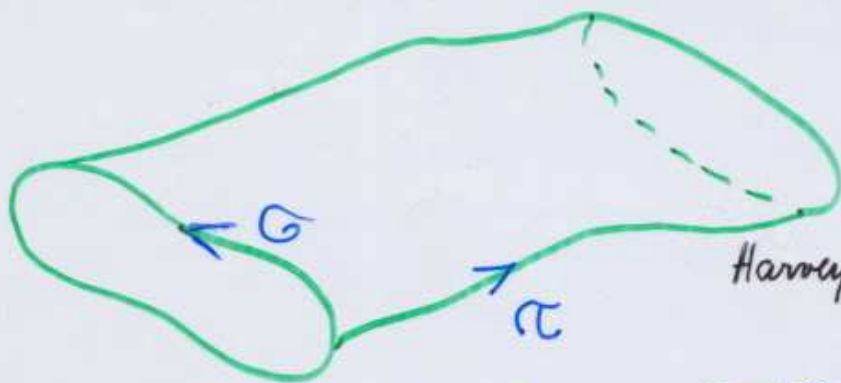
Dixon et al. '85, w/ Dixon '86 blown-up orbifold, Ibáñez et al. Nilles Quevedo '86 ...
Harvey, Vafa & Witten '86-'90, ...;

Study of three-family standard-like models based on the free-worldsheet fermionic models: restabilization of vacuum due to anomalous U(1)-classification of F-flat and D-flat directions and determination of spectrum, Yukawa couplings, low energy implications.

w/G. Cleaver, J.-R. Espinosa, L. Everett, P. Langacker and J. Wang '96-'99

First string revolution

Green & Schwarz
'84



Harvey, Martinec, G

Heterotic
 $E_8 \times E_8$



$(G + \tau)$ - right moving
 $\{X^i, \psi^i\}$ superstring
 $i = 1, \dots, 10$

$(G - \tau)$ - left-moving
 $\{X^I, \chi^I\}$
 $i = 1, \dots, 10$ $I = 1, \dots, 16$
on
 $E_8 \times E_8$

$D = 10$

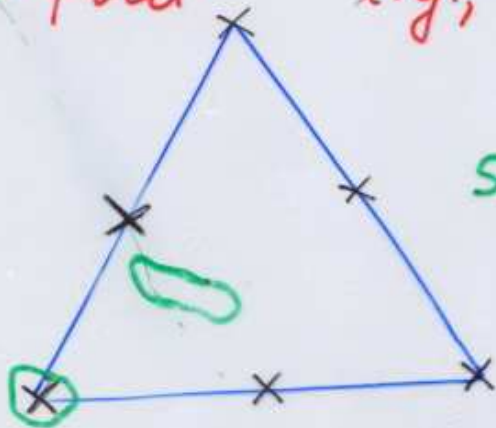


compactify 6-dim

$N = 1$ SUSY $D = 4$

* orbifold

e.g., T^2 / \mathbb{Z}_2



strings free (with nontrivial boundary conditions)



conformal field theory



calculable spectrum & couplings

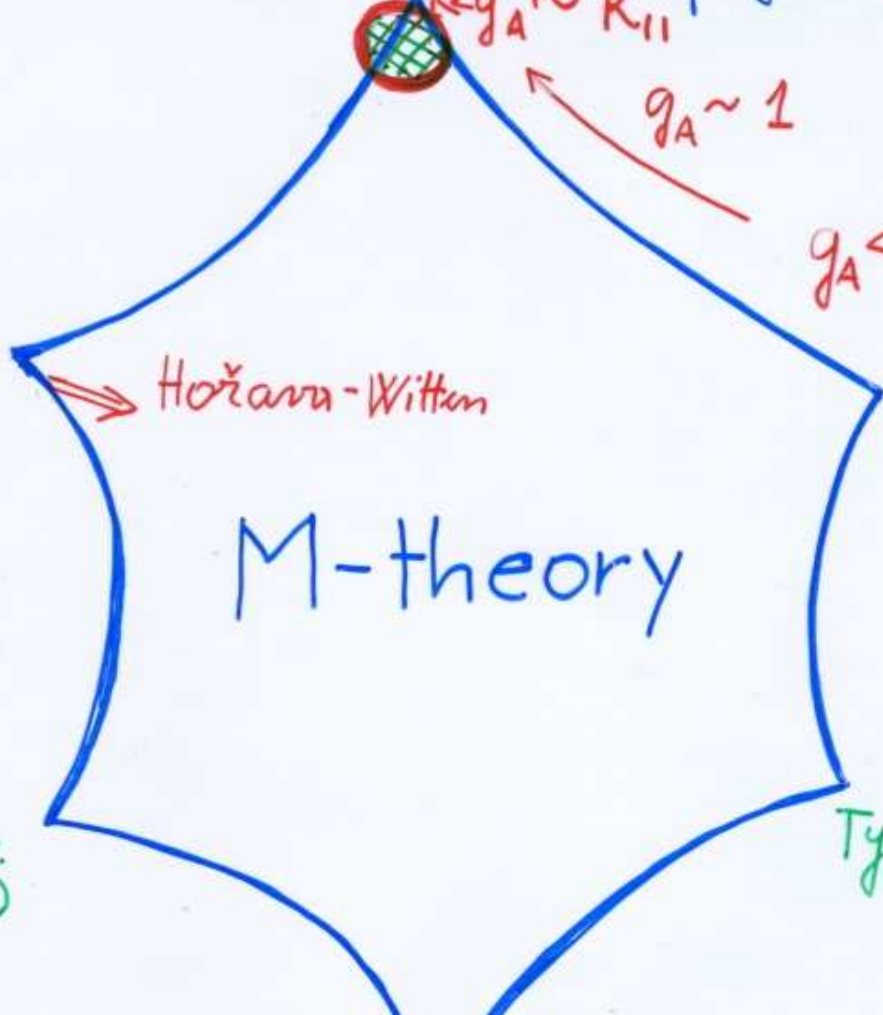
11-dimensional supergravity



$$\ll g_A \sim R_{11}$$

$$g_A \sim 1$$

$$g_A \ll 1$$



Horava-Witten

M-theory

Type IIA

Type IIB

Heterotic
SO(32)



Type I

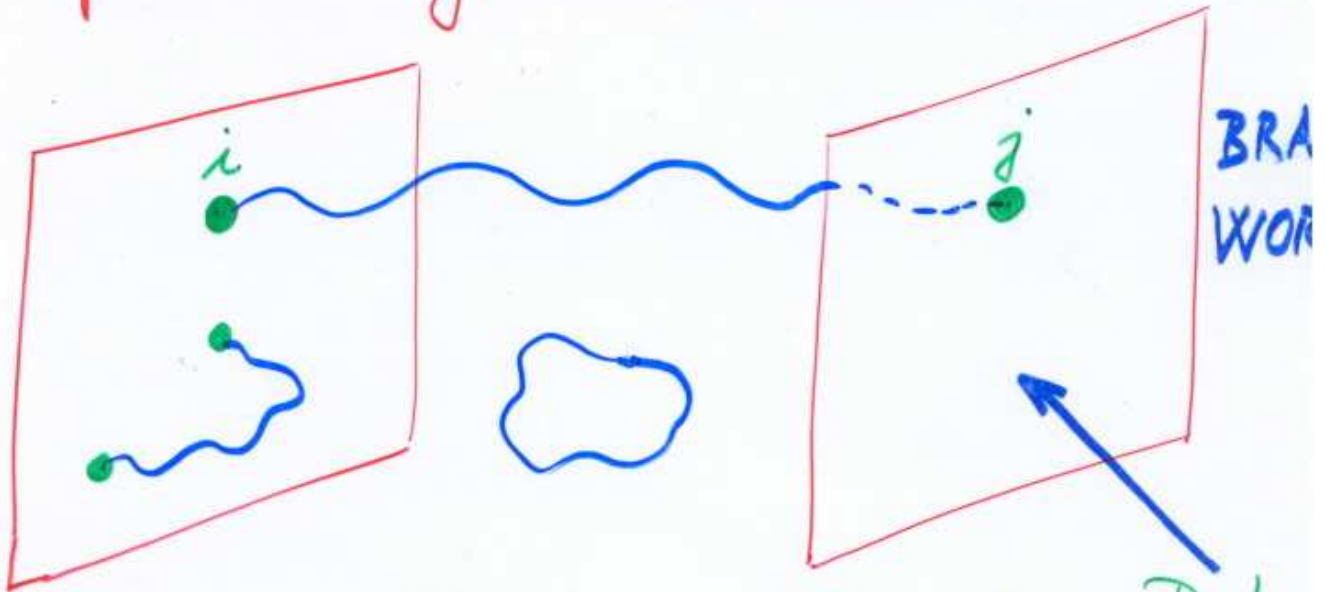


NON-PERTURBATIVE UNIFICATION
(Second string revolution)

Hull & Townsend
'94

Witten '95

Open string solutions



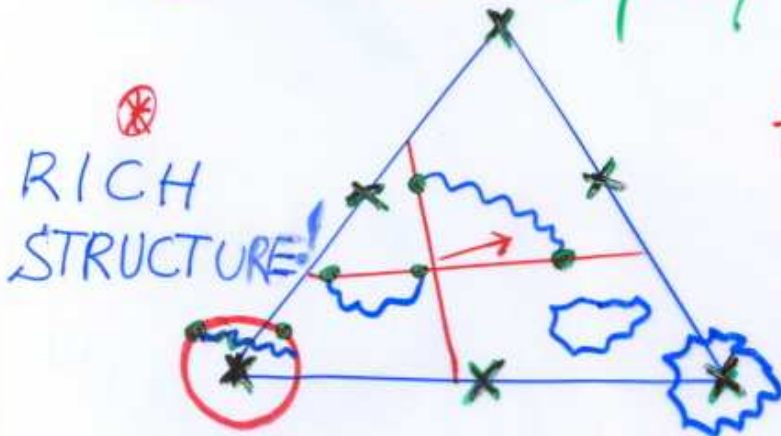
open strings with charges that end on D-branes

in $D=10$

compactified on ORIENTIFOLDS

[orbifolds with world-sheet parity projection
 $X_L(\sigma+\tau) = X_R(\sigma-\tau)$

$D=4$ $N=1$ supersymmetry



free open & closed strings
 w/ non-trivial boundary
 conditions;

CFT techniques

consistent $D=4$ solutions;
 spectrum & couplings CALCULABLE

Disclosure:

1. Focus on orientifold models:
exact conformal field theory techniques
w/ spectrum & couplings calculable
2. $N=1$ supersymmetric constructions:
avoid large quantum corrections,
NS-NS tadpoles $\sim \Lambda^2 \Phi$, tachyon
instabilities...

*

Notable exception:
 Z_3 orientifold w/ D3 branes at orbifold
singularity + D7-branes \subset F-theory
on Calabi-Yau 4-fold

Alvarez-Gaumé, Ibáñez, Quevedo & Urabe
'00

Model Building from Orientifolds-Brief Overview

Four-dimensional $N = 1$ chiral models:

- Type II models on orbifolds (tori moded out by a discrete subgroup of $SU(3)$) with the worldsheet parity Ω projection
→ **ORIENTIFOLDS**.

Original constructions based on symmetric $Z_N \times Z_M$ orientifolds [with branes located at the origin or uniformly distributed]-models with little realistic features; gauge group too large and/or unrealistic chiral spectrum: difficulties with obtaining $U(1)_{\text{hypercharge}}$, $SU(3)_{\text{color}}$, exotics...

Angelantonj, Bianchi, Prodin, Sagnotti and Stanev '96

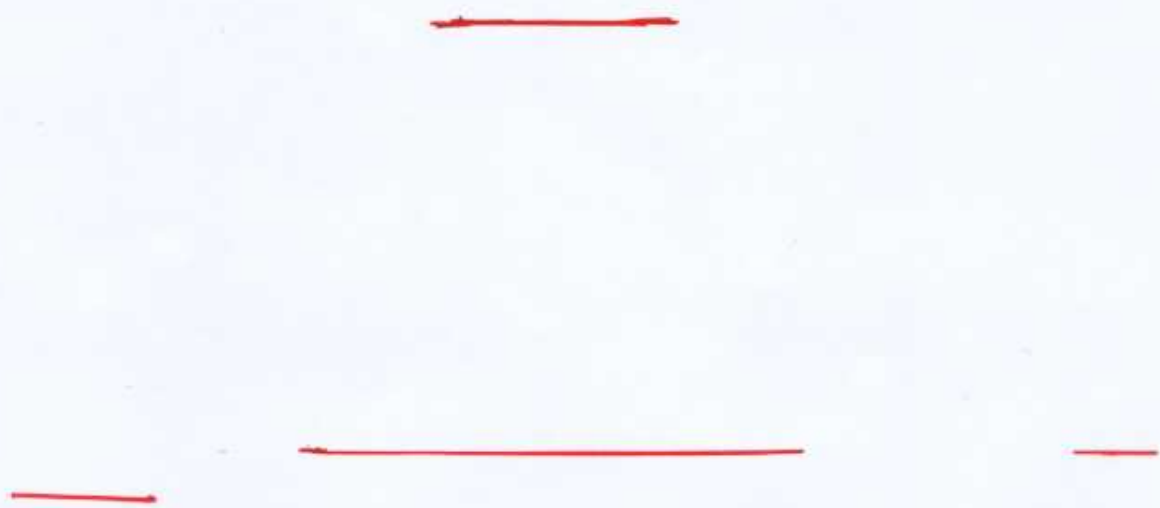
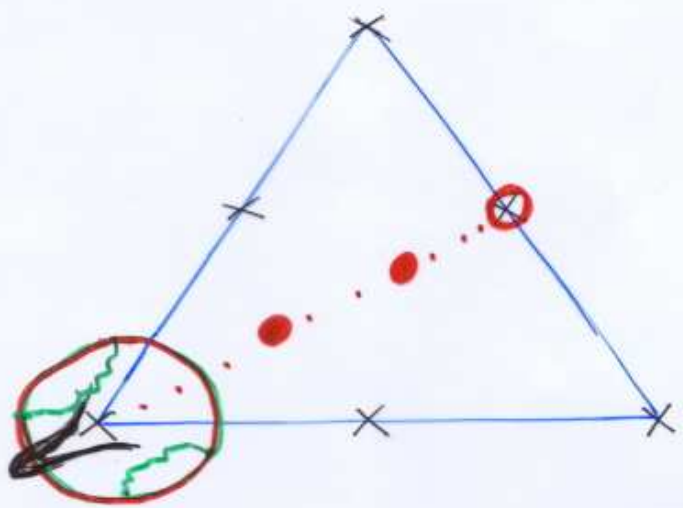
G. Shiu and S.-H. Tye '98

Z. Kakushadze '99

G. Aldazabal, A. Font, L. E. Ibáñez and G. Violero '99

...

w/ Plümacher & Langacker '00



Development of techniques for generalized constructions:

- **Blow-up of orientifold singularities-field theory approach**

B. Greene, M. Douglas and D. Morrison

Application to Z_3 orientifolds:

w/ L. Everett, P. Langacker and J. Wang '00

- Discrete and continuous Wilson lines: in T-dual picture branes moved to different locations on orientifold:

Aldazabal, Font, Ibáñez & Vasiliev '00 ... w/M. Plümacher and J. Wang '00

Application to Z_3 orientifold: string and effective field theory:

w/ P. Langacker '00

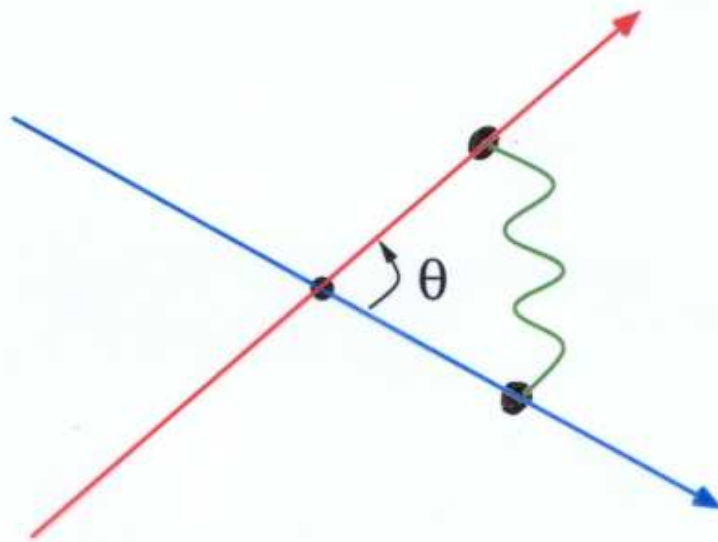
Systematic analysis for Z_6 orientifold-potentially quasi-realistic features: yields left-right symmetric model, but with only two families

w/ A. Uranga and J. Wang '01

- Branes at angles (or in the T-dual picture, branes with flux)

C. Angelantonj, I. Antoniadis, E. Dudas and A. Sagnotti '00

R. Blumenhagen, L. Görlich and B. Kors '01



Chiral fermions at brane intersections. *C. Bachas '95*

M. Berkooz, M. R. Douglas and R. G. Leigh '96

Non-supersymmetric four-dimensional models with branes at angles have been studied extensively recently.

G. Aldazabal, S. Franco, L. E. Ibáñez, R. Rabadán, A. M. Uranga '01

L. E. Ibáñez, F. Marchesano and R. Rabadán '01

R. Blumenhagen, L. Görlich, B. Körs, D. Lüst and T. Ott '00

⋮

The Model Setup

w/Shiu and Uranga

Type IIA orientifold $T^6/\mathbf{Z}_2 \times \mathbf{Z}_2$ orientifold

The two generators θ, ω of $\mathbf{Z}_2 \times \mathbf{Z}_2$ act as

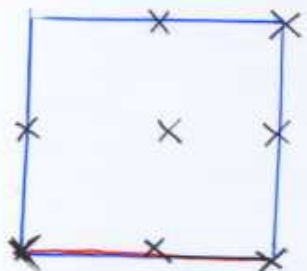
$$\theta : (z_1, z_2, z_3) \rightarrow (-z_1, -z_2, z_3)$$

$$\omega : (z_1, z_2, z_3) \rightarrow (z_1, -z_2, -z_3)$$

where z_i are complex coordinates in T^6 . For simplicity, factorizable $T^6 = T^2 \times T^2 \times T^2$.

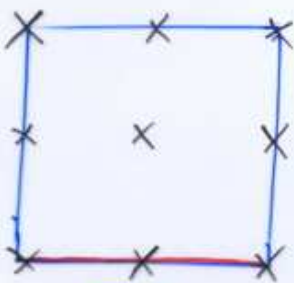
The Type IIA orientifold action ΩR where Ω is world-sheet parity, and R is a reflection symmetry along horizontal axes:

$$R : (z_1, z_2, z_3) \rightarrow (\bar{z}_1, \bar{z}_2, \bar{z}_3)$$



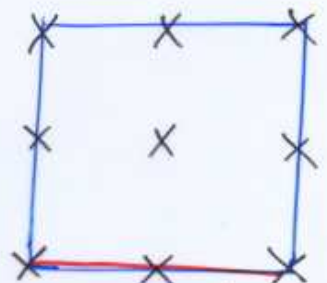
(T^2)

\times



T^2

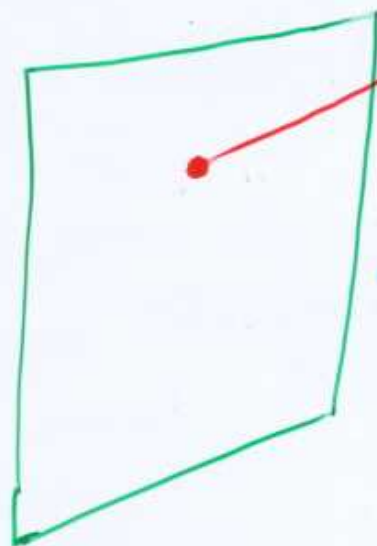
\times



T^2

$)/(\mathbb{Z}_2 \times \mathbb{Z}_2)$

Add D6-branes



extends in 6-dim

3-transverse dim

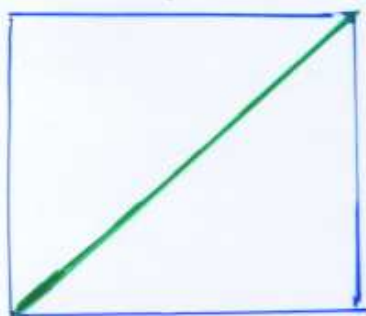
⊗ 3-dimensions - our space

3-dimensions - in compactified space



wrap 3-cycles of T^6

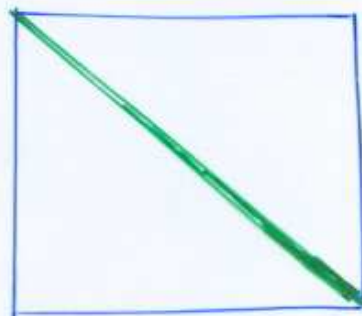
$$\left[\prod_{i=1}^3 (1\text{-cycle}) \text{ on each } T^2 \right]$$



⊗



⊗



(m_a, m_a)

$(1, 1)$

$(1, 0)$

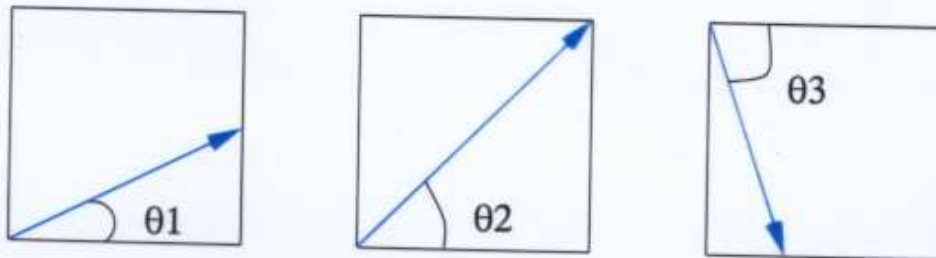
$(1, -1)$

↳ wrapping numbers

Supersymmetric 3-cycles

SUSY requires that D6-branes are related to the O6-planes by an SU(3) rotation:

M. Berkooz, M. R. Douglas and R. G. Leigh



$$\theta_1 + \theta_2 + \theta_3 = 0$$

where

$$\theta_i = \arctan\left(\chi_i \frac{m_i}{n_i}\right)$$

and $\chi_i = (R_2/R_1)_i$ are the complex structure moduli of T^2 .

[Comment: When considering cycles that intersect, they can recombine into a cycle which is homologically identical to the sum of the intersecting cycles-**configurations related to small instanton transitions.**]

Specific model:

consistency

The explicit expression for tadpole cancellation conditions become:

$$\sum_a N_a n_a^1 n_a^2 n_a^3 - 16 = 0$$

$$\sum_a N_a n_a^1 m_a^2 \tilde{m}_a^3 + 8 = 0$$

$$\sum_a N_a m_a^1 n_a^2 \tilde{m}_a^3 + 8 = 0$$

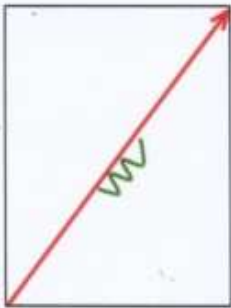
$$\sum_a N_a m_a^1 m_a^2 n_a^3 + 16 = 0$$

To simplify the SUSY conditions, consider angles of the form $(\theta_1, \theta_2, 0)$, $(\theta_1, 0, \theta_3)$ and $(0, \theta_2, \theta_3)$.

$[N_a ; (m_a^i, \tilde{m}_a^i)]$ - brane configuration
 $i=1, 2, 3$

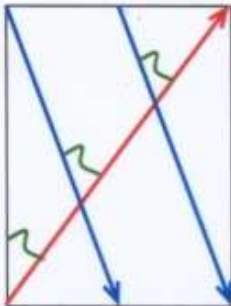
Spectrum - Key ingredient

$$\left. \begin{array}{l} a: N=6 : U(3) \\ b: N=4 : U(2) \end{array} \right\} U(2)_L \times U(3)$$



$$U(N) \xrightarrow{\theta} U(N/2) \times U(N/2) \xrightarrow{\omega} U(N/2)$$

+ 3 Adjoint chiral multiplets

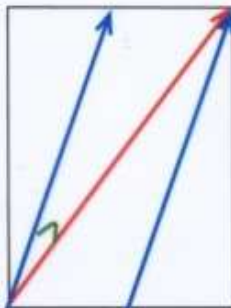


$$I_{ab} = \prod_{i=1}^3 (n_a^i m_b^i - m_a^i n_b^i)$$

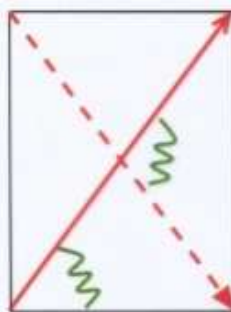
chiral multiplets in $(\square, \bar{\square})$

$$I_{ab} = 3 : 3 \times (\underline{3}, \underline{\bar{2}})$$

(3 copies of left-handed quarks)



I_{ab} , chiral multiplets in (\square, \square)



$$\frac{1}{2} (I_{aa'} - \frac{4}{2k} I_{a,O6}) \quad \square$$

$$\frac{1}{2} (I_{aa'} + \frac{4}{2k} I_{a,O6}) \quad \square$$

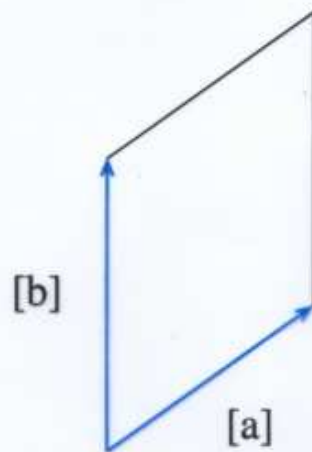
Three-Family Model

The number of chiral families:

$$N_{\text{families}} = I_{ab} + I_{ab'}; \quad I_{ab} = \prod_{i=1}^3 (n_a^i m_b^i - m_a^i n_b^i)$$

For rectangular tori, N_{families} is always EVEN.

The number of families can be odd if, say, one of the tori is tilted.



$$\Omega R [a] = [a] - [b]$$

$$\Omega R [b] = -[b]$$

The wrapping numbers $(n, m) \rightarrow (n, -m - n)$.

It is convenient to define $\tilde{m} = m + \frac{1}{2}n$ so that $\tilde{m} \rightarrow -\tilde{m}$.

and

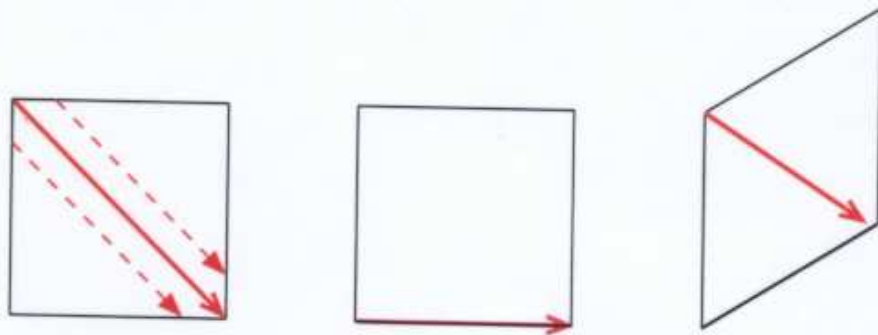
↳ half-integer

$$I_{ab} = \prod_{i=1}^3 (n_a^i \tilde{m}_b^i - \tilde{m}_a^i n_b^i)$$

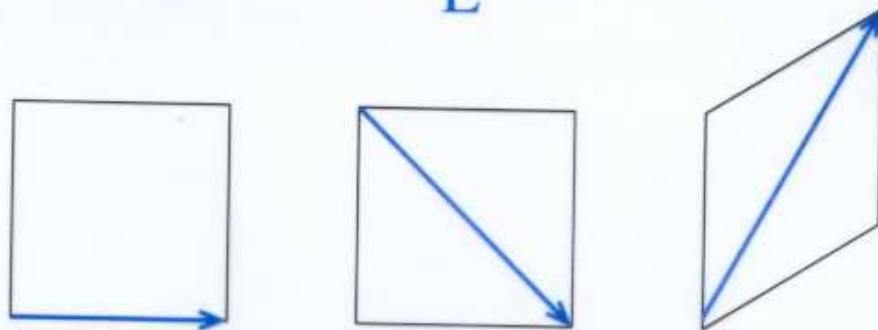
now $N_{families} = I_{ab} + I_{ab'}$ can be ODD.

Building Blocks

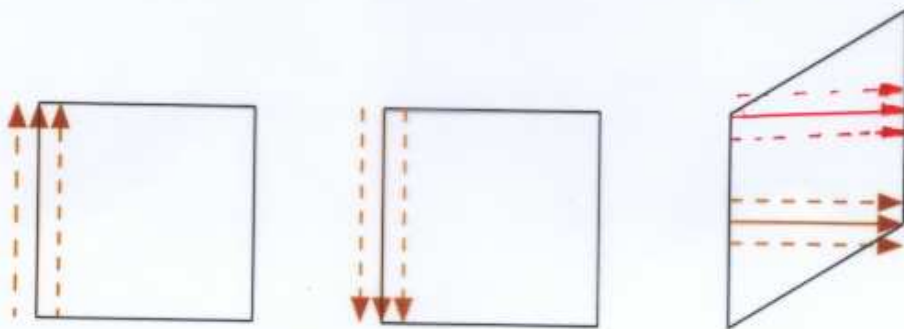
$$N_a=6+2 : U(4) \longrightarrow U(3)_c \times U(1)$$



$$N_b=4 : U(2)_L$$



$$N_c=8 : USp(8) \longrightarrow U(1)_{\delta} \times U(1)_{\delta'}$$



+
Additional D6-branes // w/ orientifold planes -
cancel RR to 4d [hidden sector]

Phenomenology ^{w/ Langacker & Shiu}

Gauge Structure

$$Q_Y = \frac{1}{6} Q_3 + \frac{1}{2} (Q_8 + Q_{8'}) - \frac{1}{2} Q_8$$

$$\text{SUSY: } \chi_1 : \chi_2 : \chi_3 = 1 : 3 : 3$$

$$\chi_a = \begin{pmatrix} R_2^{(a)} \\ R_1^{(a)} \end{pmatrix}$$

S.M. \times $U(1)_{B-L} \times U(1)_{T_R}$ "Hidden"

Sector	$U(3) \times U(2) \times USp(2) \times USp(2) \times USp(4)$	Q_3	Q_1	Q_2	Q_8	Q_8'	Q_Y	$Q_8 - Q_8'$	Field
$A_1 B_1$	$3 \times 2 \times (1, \bar{2}, 1, 1, 1)$	0	0	-1	± 1	0	$\pm \frac{1}{2}$	± 1	H_U, H_D
	$3 \times 2 \times (1, \bar{2}, 1, 1, 1)$	0	0	-1	0	± 1	$\pm \frac{1}{2}$	∓ 1	H_U, H_D
$A_1 C_1$	$2 \times (\bar{3}, 1, 1, 1, 1)$	-1	0	0	± 1	0	$\frac{1}{3}, -\frac{2}{3}$	1, -1	U, D
	$2 \times (\bar{3}, 1, 1, 1, 1)$	-1	0	0	0	± 1	$\frac{1}{3}, -\frac{2}{3}$	-1, 1	U, D
	$2 \times (1, 1, 1, 1, 1)$	0	-1	0	± 1	0	1, 0	1, -1	E, ν_R
	$2 \times (1, 1, 1, 1, 1)$	0	-1	0	0	± 1	1, 0	-1, 1	E, ν_R
$B_1 C_1$	$(3, \bar{2}, 1, 1, 1)$	1	0	-1	0	0	$\frac{1}{6}$	0	Q_L
	$(1, \bar{2}, 1, 1, 1)$	0	1	-1	0	0	$-\frac{1}{2}$	0	L
$B_1 C_2$	$(1, 2, 1, 1, 4)$	0	0	1	0	0	0	0	
$B_2 C_1$	$(3, 1, 2, 1, 1)$	1	0	0	0	0	$\frac{1}{6}$	0	
	$(1, 1, 2, 1, 1)$	0	1	0	0	0	$-\frac{1}{2}$	0	
$B_1 C_1'$	$2 \times (3, 2, 1, 1, 1)$	1	0	1	0	0	$\frac{1}{6}$	0	Q_L
	$2 \times (1, 2, 1, 1, 1)$	0	1	1	0	0	$-\frac{1}{2}$	0	L
$B_1 B_1'$	$2 \times (1, 1, 1, 1, 1)$	0	0	-2	0	0	0	0	
	$2 \times (1, 3, 1, 1, 1)$	0	0	2	0	0	0	0	

12
+
12
3
+
1
no hidden gauge

3 families

TABLE I. Chiral Spectrum of the open string sector in the three-family model. Notice that we have not included the aa sector, even though it is generically present in the model. As explained in the text, the non-chiral pieces in the ab , ab' and aa' sectors are generically not present.

Gauge Couplings:

$$g_{YM_a}^2 = \frac{M_{st} \sqrt{V_6}}{M_{pl} V_{3a}}$$

Volume of 6-torus

Volume of 3-cycle that brane wraps

$$g_{YM_a}^2 = \frac{\sqrt{3} M_{st} \chi^{3/2}}{\sqrt{2} M_{pl} \sqrt{(m_a^{1/2} + m_a^{1/2} \chi^2)(m_a^{1/2} + m_a^{1/2} \chi^2)(m_a^{1/2} + m_a^{1/2} \chi^2)}}$$

$$\frac{R_1^{(2)}}{R_1^{(1)}} = \chi_1 \equiv \chi$$

$$\chi_1 = \chi_2 = \chi_3 = 1:3:2$$

Non-universal!

[but fully determined in terms of χ & M_{st} .!]

$M_{st} \sim M_{pl}$ (branes extend in all directions)

Non-standard gauge coupling relations

- but absolute predictions for given:

$$\alpha, M_s \sim \frac{1}{\sqrt{\alpha'}}$$

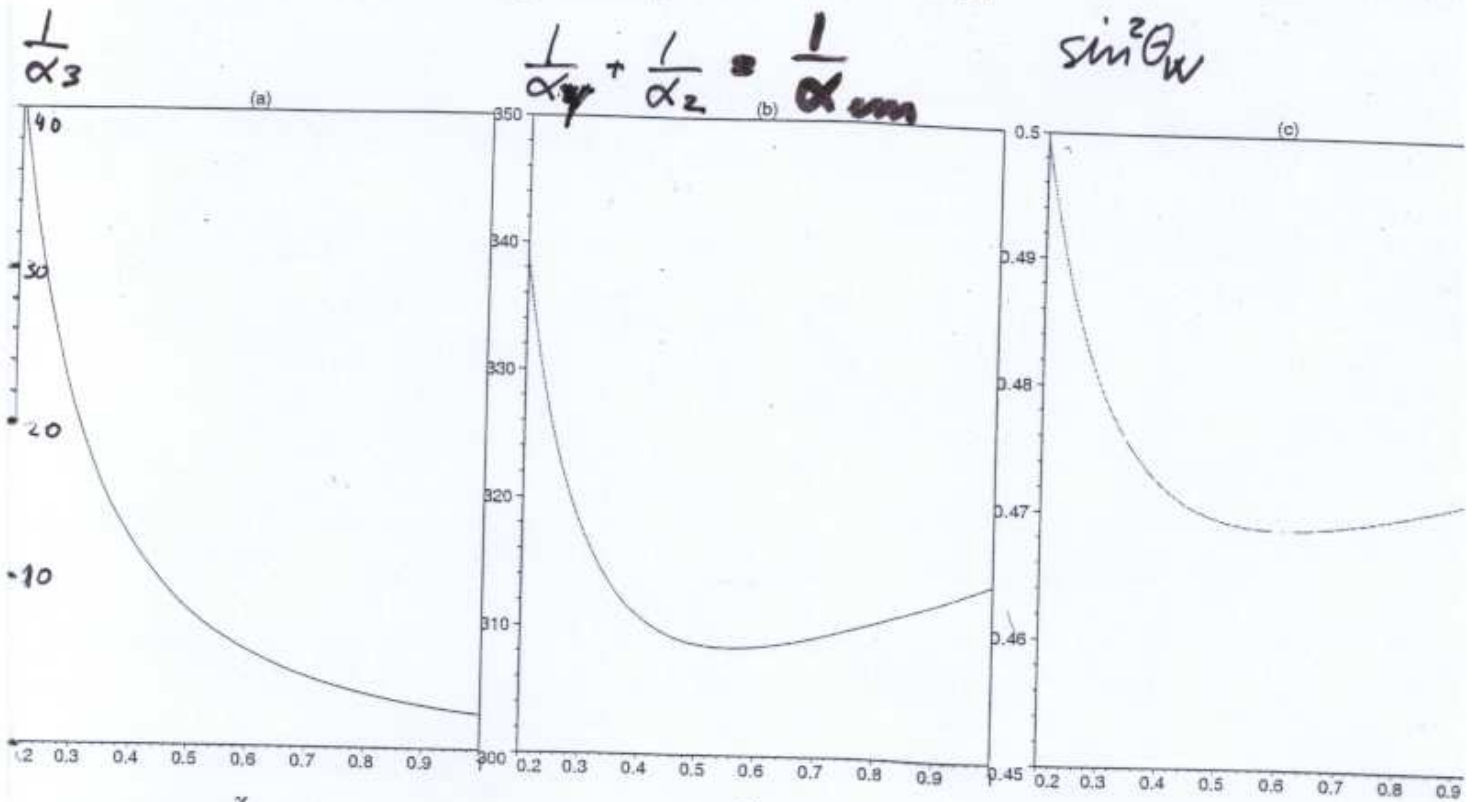
- ordinary sector gives unrealistic
Low Energy predictions for:

$$g_{3c}, g_{2L}, g_Y \quad (\text{exotics})$$

- hidden sector - Asymptotically
 $Sp(2) \times Sp(4)$ free

[dynamical supersymmetry breaking
w/ Langacker
&
Wang

Value of couplings at M_W as a function of χ



1. Predicted values of (a) $1/\alpha_3$, (b) $1/\alpha = 1/\alpha_Y + 1/\alpha_2$, and (c) the weak $\sin^2 \theta_W = \alpha_Y / (\alpha_2 + \alpha_Y)$ at the electroweak scale as a function of χ for $M_P^{(4d)} = M_s$. Options $b_a(\text{int})$ of the states localized at the brane intersections (as well as the gauge coupling running are included). The experimental values are ~ 8.5 , 128 , and 0.23 , respectively.

Susy breaking due to $\langle \lambda \lambda \rangle \neq 0$ in
the hidden sector [novel dependence on
moduli \rightarrow possible to stabilize them]
 $\{S, U_i\}$

work in progress w/ Langacker
Wang

Scales where $Sp(2)_{A,B}$ and $Sp(4)$ become strong as a function of χ .

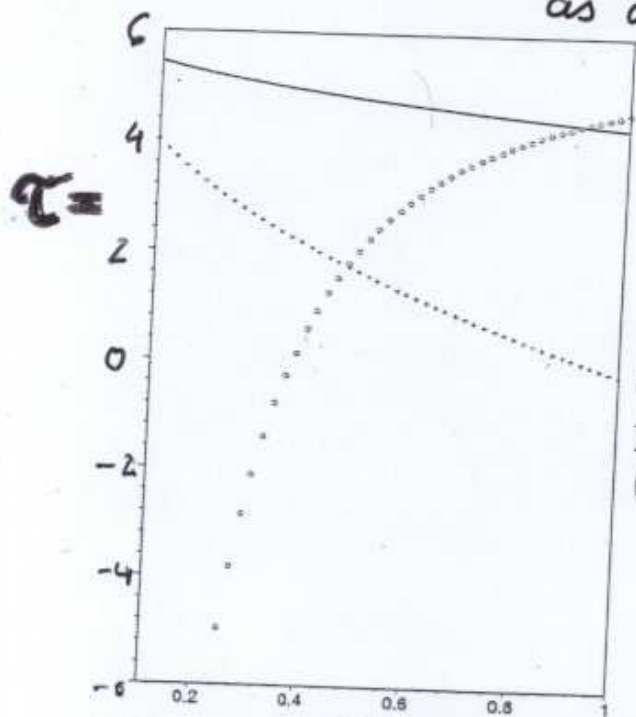


FIG. 2. Scales $\tau = \frac{1}{2\pi} \ln \frac{M}{M_Z}$, where M is the scale at which the Sp group becomes strongly coupled for $M_P^{(4d)} = M_s$. The curves are $Sp(2)$ (solid), $Sp(2)_B$ (circles), $Sp(4)$ (crosses).

$$\chi = \frac{R_2^{(1)}}{R_1^{(1)}}$$

Exotics:

- Fractionally charged:

ϕ $SU(3)_c$ -triplet & $Sp(2)_B$ -doublet $Q_{EM} = \frac{1}{6}$

χ SM-singlet & $Sp(2)_B$ -doublet $Q_{EM} = \dots$

$SU(2)_L$ -doublet & $Sp(4)$ -4-plet $Q_{EM} = \dots$

[May disappear due to strongly coupled dynamics of $Sp(2)_B$ and $Sp(4)$]*

- Adjoint chiral matter (generic problem)

* Bound states (compatible w/ t'Hooft anomaly matching)

$\phi \chi \bar{u} = E_4$
 $\phi \chi \bar{D} = N_4$
 $\phi \chi \bar{E} = U_4$
 $\phi \chi \bar{N} = D_4$

} Quantum nos. of left-handed partners of the 4th family ($\bar{E}, \bar{D}, \bar{N}, \bar{u}$, (exotics))

\uparrow R-element
 \uparrow L-composite

Yukawa Couplings:

Two Q_L^γ $\gamma = i, ii$ ($\gamma = iii$ has NO Yukawa)

Four \bar{u}_k ; \bar{u}'_k $k = I, II$

3 x 4 : $H_{u k}^\alpha$ $H_{u k}^{\alpha'}$ $\alpha = 1, 2, 3$

$$H_{\text{Yukawa}} = \sum_{\alpha=1,2,3} h_{\alpha,\gamma} Q_L^\gamma \left[\sum_{k=I,II} [\bar{u}_k H_k^\alpha + \bar{u}'_k H_k^{\alpha'}] \right]$$

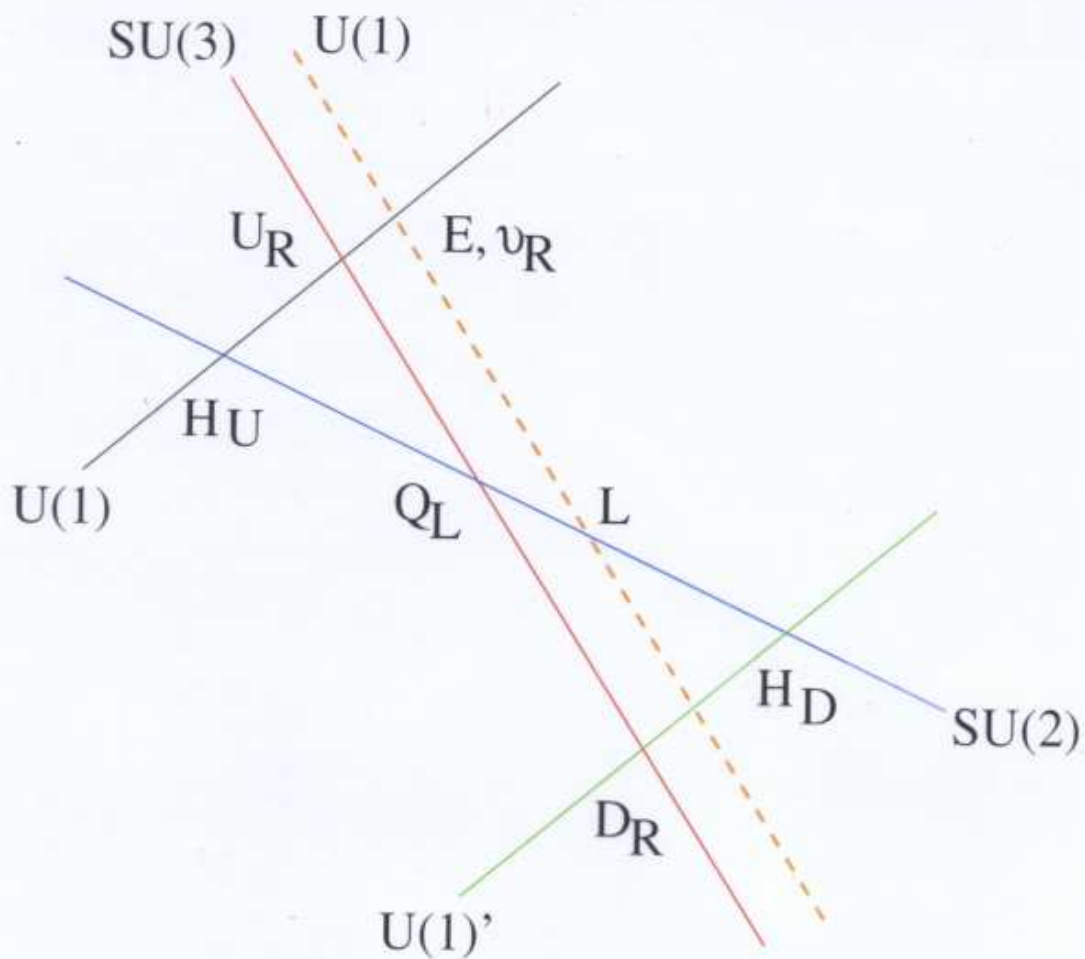
$\gamma = i, ii$

$$h_{\alpha,\gamma} \sim \ell - A_{\alpha,\gamma} / \alpha'$$

Aldazabal, Ibáñez, Rabadan & Uranga
(world-sheet instant)

$A_{\alpha,\gamma}$ = intersection area of (smallest) triangle

Aldarazabal, Ibáñez,
Rabadan & Uranga '00



For the Yukawa couplings not to be negligibly small, the area of the string world-sheet (typically the compactification scale) cannot be much larger than the string length, so internal dimensions should be of the order of the string scale.

There are also generically couplings among aa , ab and ba fields, and among aa fields which are not exponentially suppressed.

Expressions for areas $A_{\alpha, \gamma}$:

$$A_{1,i} = 0$$

$$A_{2,ii} = A_{3,ii} = \frac{1}{12} R_1^{(3)} R_2^{(3)}$$

$$A_{2,i} = A_{3,i} = \frac{1}{3} R_1^{(3)} R_2^{(3)}$$

$$A_{1,ii} = \frac{3}{4} R_1^{(3)} R_2^{(3)}$$

$$h \sim e^{-A/\alpha}$$

Hierarchy in Yukawa couplings:

$$h_{1,i} > h_{2,ii} = h_{3,ii} > h_{2,i} = h_{3,i} > h_{1,i}$$

Up - Down splitting (some degeneracy remains due to $Z_2 \times Z_2$ symm)
 (splitting of $Sp(8)$ branes)
 \downarrow
 $U(1)_8 \times U(1)_8$

Lepton - Quark splitting ($h^{\text{lepton}} < h^{\text{quark}}$)
 (splitting $U(4) \rightarrow U(3)_c \times U(1)$ branes)

$$\gamma = (i, ii) - Q_L$$

$$\alpha = (1, 2, 3) - H$$

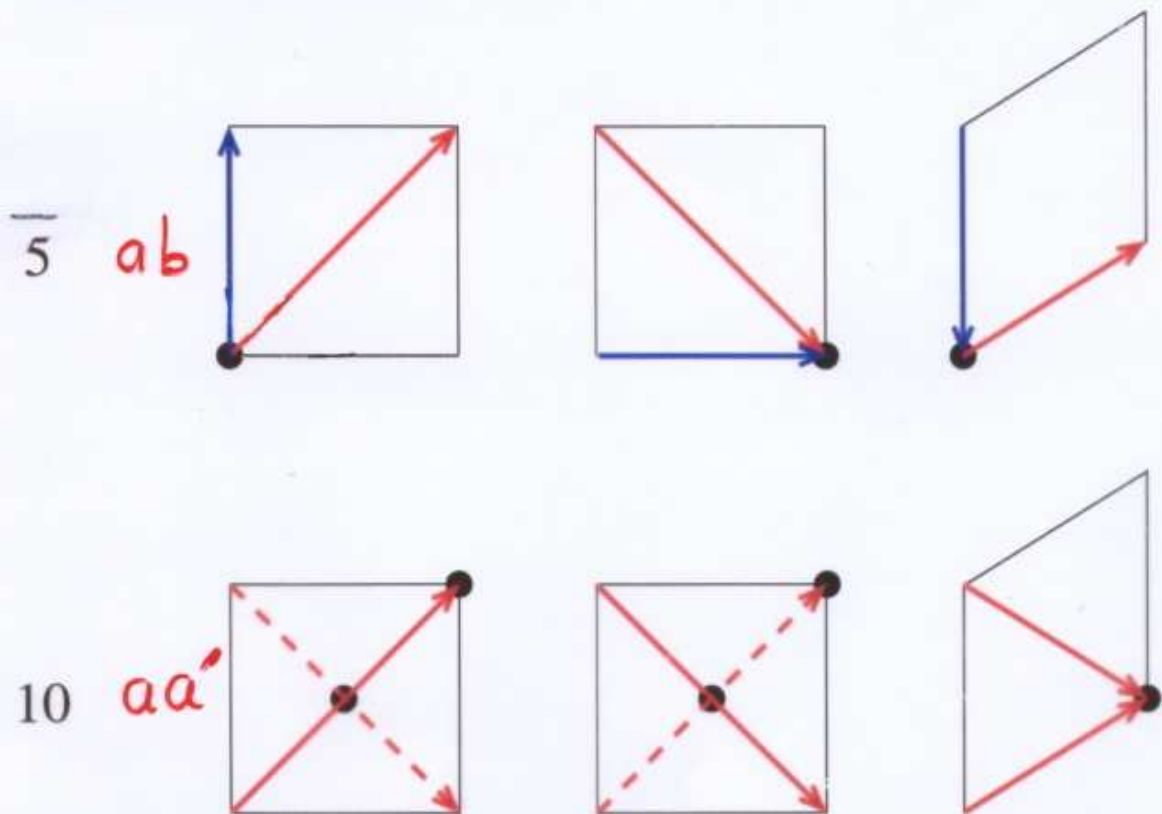
———— $U(3)_C$

..... $U(2)_L$

----- $U(1)_{(8,8')}$

GUT Model

Consider an $SU(5)$ model. Chiral multiplets in the $\mathbf{10}$ representation can come from the intersection of a stack of branes with its orientifold image.



Therefore, all three angles θ_1 , θ_2 and θ_3 are non-zero.

- Adjoint Higgs fields \Rightarrow splitting the $U(5)$ branes:

$$U(5) \rightarrow U(3) \times U(2) \times U(1)$$

- Hypercharge as in conventional GUTs.

An example:

N_a		$(n_a^1, \tilde{m}_a^1) \times (n_a^2, \tilde{m}_a^2) \times (n_a^3, \tilde{m}_a^3)$
$10 + 6$		$(1, 1) \times (1, -1) \times (1, 1/2)$
16		$(0, 1) \times (1, 0) \times (0, -1)$

$$U(5) \times U(3) \times USp(16)$$

$$3(24 + 1, 1, 1) + 3(1, 8 + 1, 1) + 3(1, 1, 119 + 1)$$

$$4(\overline{10}, 1, 1) + (5, 1, 16) + 4(\overline{5}, \overline{3}, 1) + (1, 3, 16) + 4(1, 3, 1)$$

\Rightarrow Four chiral families.

- Search for more realistic GUT Models:

Work in progress: M. Cvetič and I. Papadimitriou

Relation to M-theory

I. Type IIA string + D6-branes
compactified on 6-dim. orientifold
(Calabi-Yau)



⊗ D=4 N=1 SUSY



II. 11-dim supergravity - (low. en.) M-theory
compactified on 7-dim. exceptional G_2 holonomy
space

⊗ I. & II. related? ⇒ YES!
Atiyah, Maldacena & Va

D=11 M-theory compactified on a circle →
D=10 Type IIA theory + D6-branes (Kaluza-Klein
monopole)

D=4 → further compactified on Calabi-Yau space

G_2 holonomy space

w/ Gibbons, Liu &
'01 -

New type of G_2 holonomy spaces:

w/ singularities:

I.

open string

D6-brane



II.

M-theory

co-dimension 4-s

D6-branes - intersecting



codimension 7 singu



Appearance of matter

W/ Shiu,
Uranga '01

Witten
Acharya & W
'02



Further investigation

Summary

- Status: Orientifold construction D=4 N=1 supersymmetric supersymmetric models.
- New supersymmetric orientifold models based on $Z_2 \times Z_2$ orientifold with D6-branes intersecting at angles:
 - – Chiral fermions at brane intersections
 - – Replication of generations \leftrightarrow number of intersections
 - – Hierarchical Yukawa couplings
 - adjoint Higgs fields-geometric interpretation
- Three-family Standard-like and (four-family) GUT models with some phenomenological features that are distinct from the perturbative heterotic string; phenomenological study reveals a number of flaws: exotics, constrained couplings etc.
- Constructions can be interpreted as M theory on G_2 manifolds:
 - Chiral fermions from singularities
 - Global consistency conditions (implemented from tadpole cancellations)