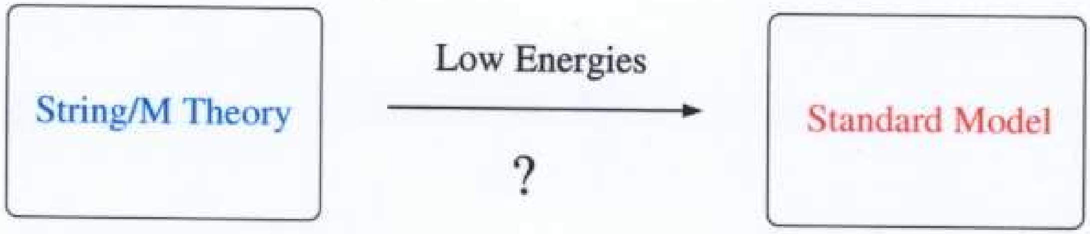
Supersymmetric Standard Model and GUTs from Orientifolds and G_2 Manifolds

- 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

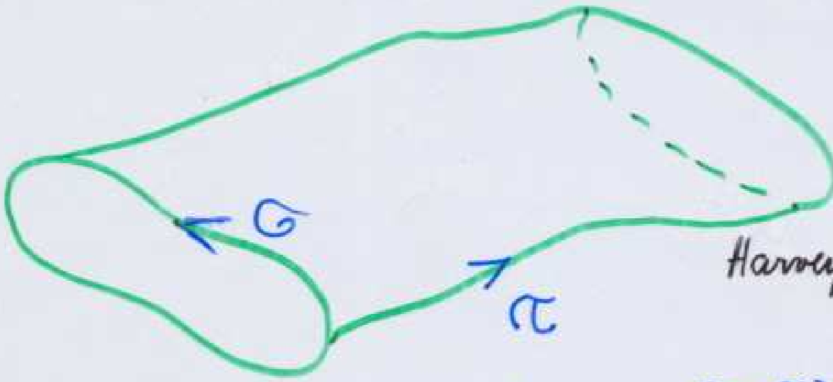
Pre-second string revolution focus on:

- 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. '86-'90,...;
  Harvey, Vafa & Witten
  Nilles Quevedo '86 ...

  Study ofr 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 $E_8 \times E_8$

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

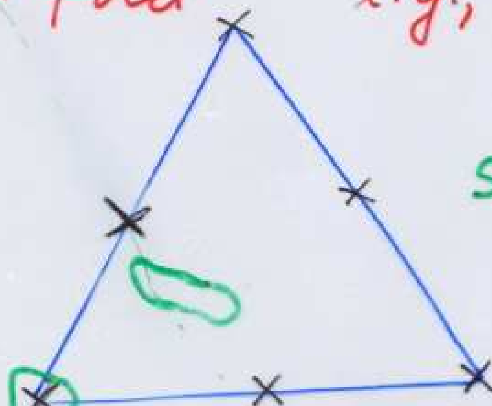
$(\sigma-\tau)$ - left - mov[…]
$\{X^i, X^I\}$
$i=1,\ldots,10$ $I = 1, \ldots 16$ on $E_8 \times E_8$

$D = 10$

↓ compactify 6-dim[…]

$N=1$ SUSY $D=4$

* orbifold e.g., T^2/Z_2



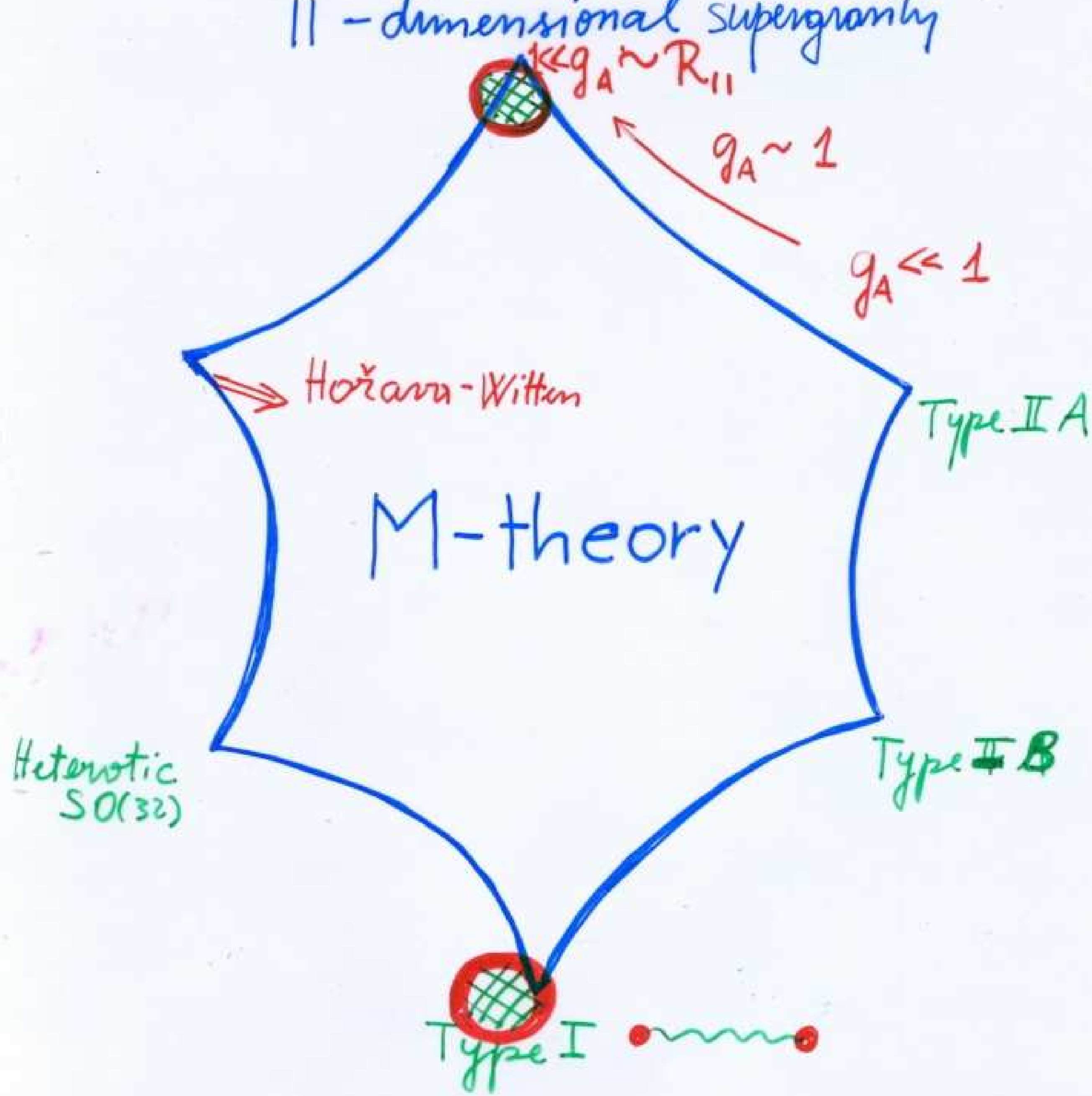
strings free (with nontrivi[…] boundary condi[…]

↓

conformal field theory te[…]

↓

calculable spectrum & couplings



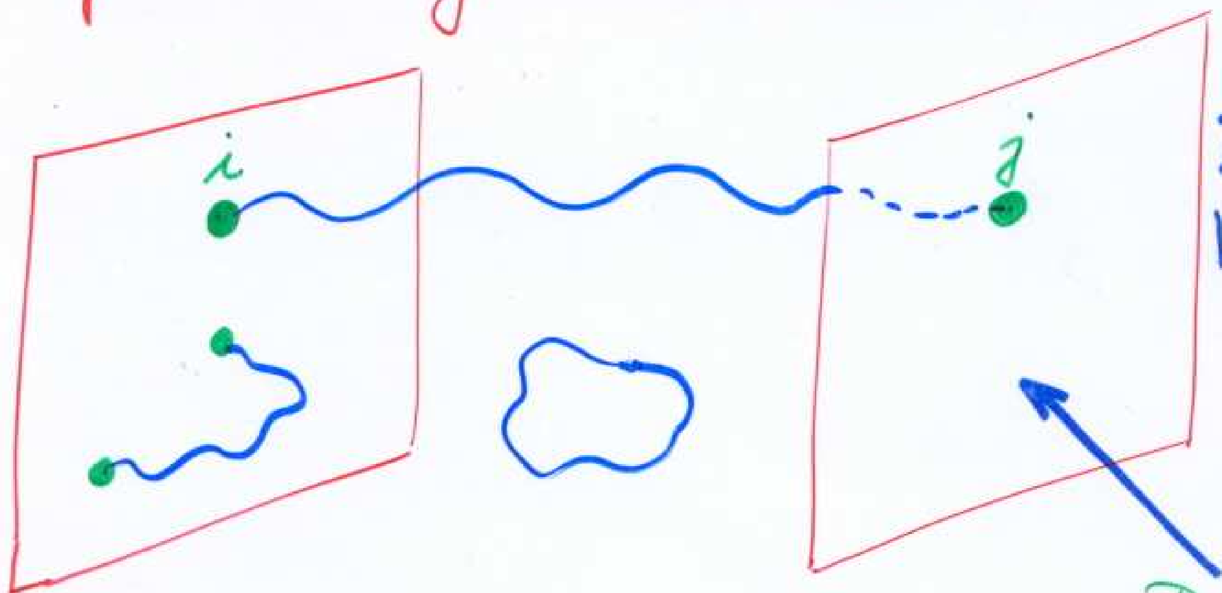
NON-PERTURBATIVE UNIFICATI

(Second string revolutio

Hull & Townsend '94

Witten '95

Open string solutions



BRA
WOR

open strings with charges that end on D-br

in D=10 compactified on ORIENTIFOLDS (*)

[orbifolds with world-sheet parity projecti

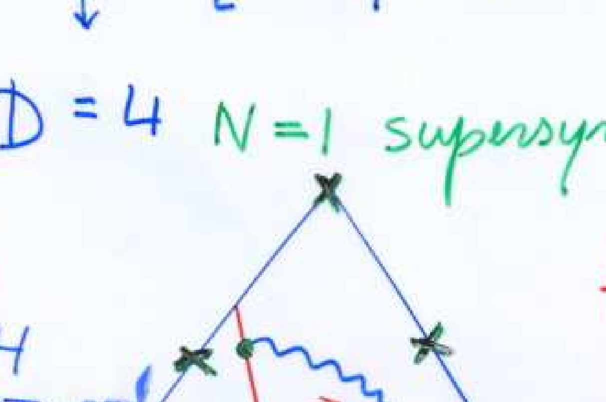
$X_L(\sigma+\tau) = X_R(\sigma-\tau)$

↓

D = 4 N=1 supersymmetry

(*)

RICH STRUCTURE!



free open & closed string
w/ non-trivial boundar
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 $\sim \Lambda e^{\Phi}$, tachyon
instabilities...

*

Notable exception:

Z_3 orientifold w/ D3 branes at orbifol[d]
singularity + D7-branes ⊂ F-theor[y]
on Calabi-Yau 4-fold

Aldazabal, Ibáñez, Quevedo & Uran[ga] '00

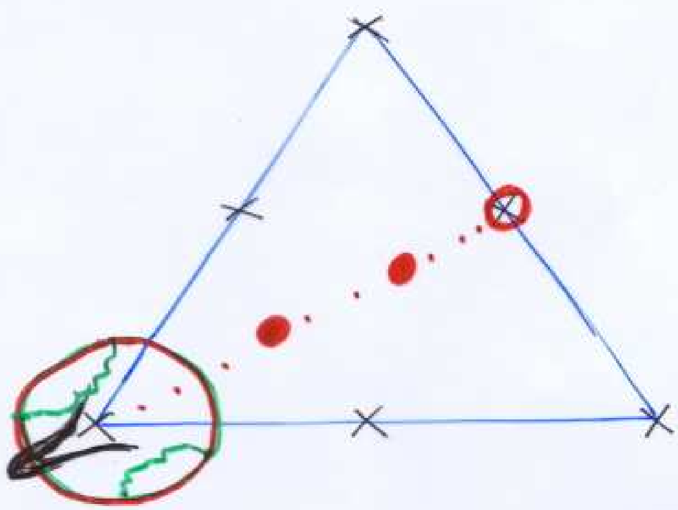
Model Building from Orientifolds-Brief Overview

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 $\mathbf{Z}_N \times \mathbf{Z}_M$ 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 $U(1)_{hypercharge}$, $SU(3)_{color}$, exotics...

Angelantonj, Bianchi, Prodini, 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 continuos Wilson lines: in T-dual picture branes moved to different locations on orientifold:

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

  Application to Z_3 orientifold: string and effective field theory:

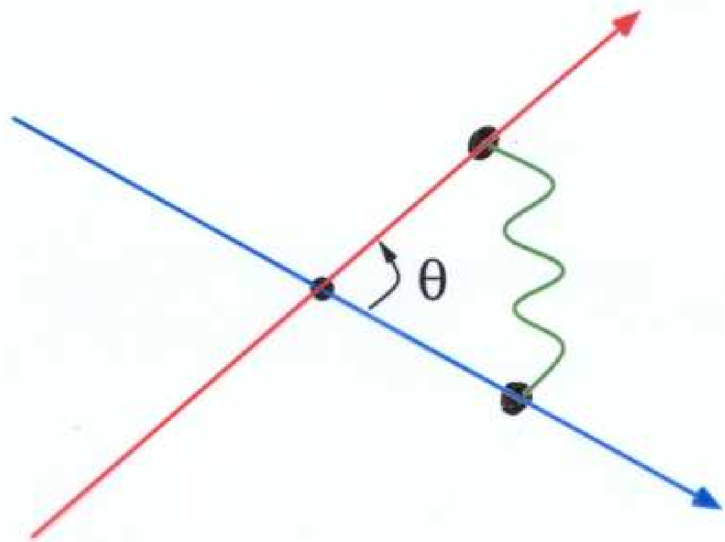
  w/ P. Langacker '00

  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

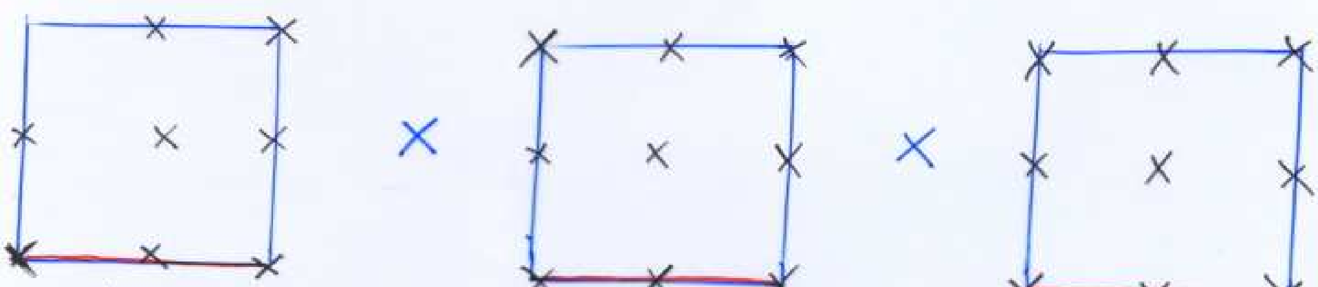
The two generators θ, ω of $\mathbf{Z}_2 \times \mathbf{Z}_2$ act as

$$\theta : \quad (z_1, z_2, z_3) \to (-z_1, -z_2, z_3)$$
$$\omega : \quad (z_1, z_2, z_3) \to (z_1, -z_2, -z_3)$$

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

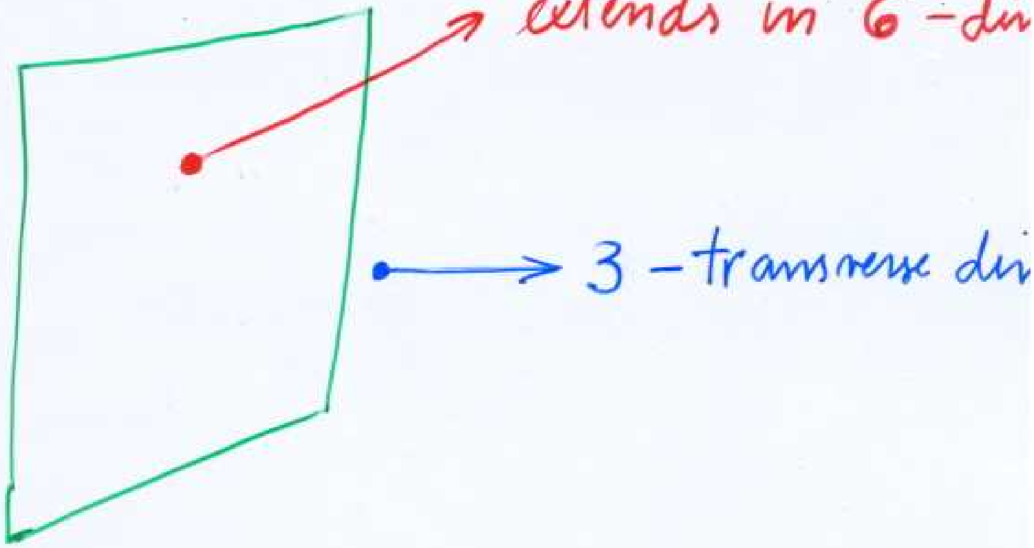
The Type IIA orientifold action ΩR where Ω is world-sheet parity, and R -is a reflection symmetry along horizontal axes:

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



$(T^2 \times T^2 \times T^2)/(Z_2 \times Z$

Add D6-branes



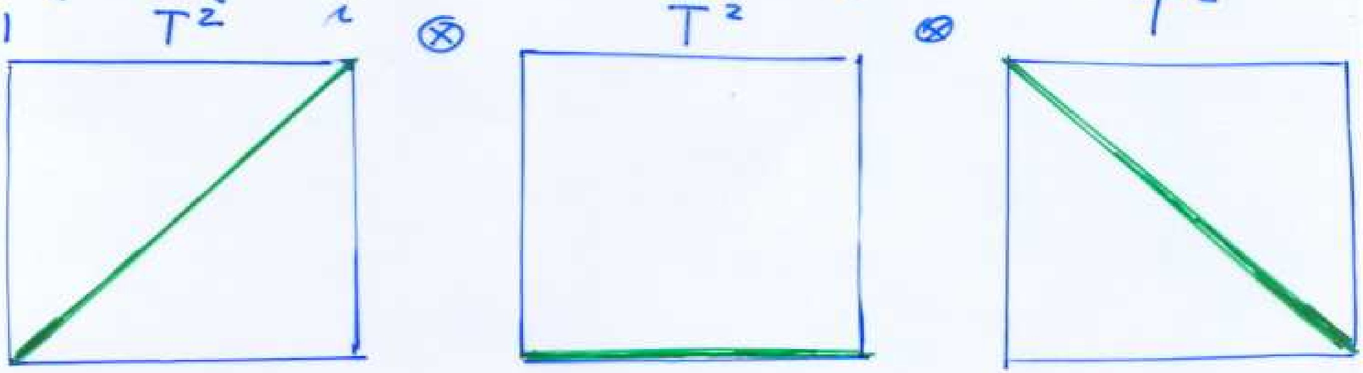
⊛ 3-dimensions – our space

3-dimensions – in compactified space

↓

wrap 3-cycles of T^6

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



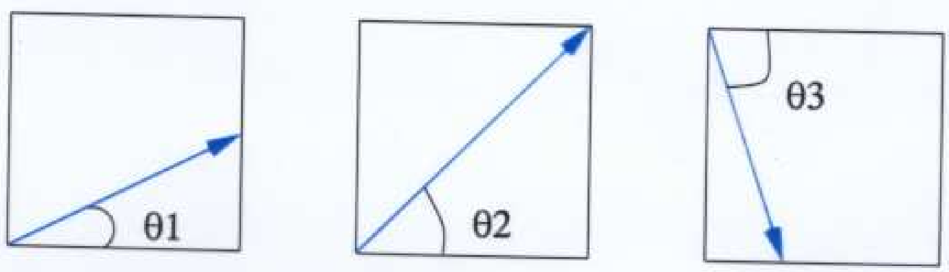
(n_a, m_a) (1, 1) (1, 0) (1, −1)

↳ 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

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

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:

The explicit expression for tadpole cancellation (consistency) conditions become:

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

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

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

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

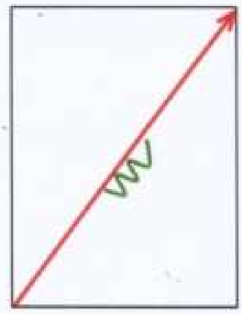
To simplify the SUSY conditions, consider angles of the form $(\theta_1, \theta_2, 0)$, $(\theta_1, 0, \theta_3)$ and $(0, \theta_2, \theta_3)$.

$[N_a ; (n_a^i, m_a^i)]$ - brane configuratio

$i = 1, 2, 3$

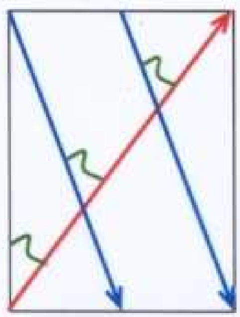
Spectrum – Key ingredient

a: N=6 : U(3)
b: N=4 : U(2)
} $U(2)_L \times U(3$



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

+ 3 Adjoint chiral multiplets

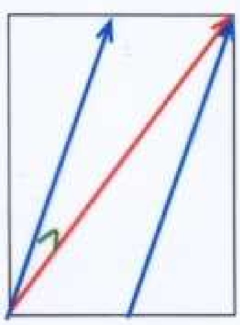


$$I_{ab} = \prod_{i=1}^{3} (n^i_a m^i_b - m^i_a n^i_b)$$

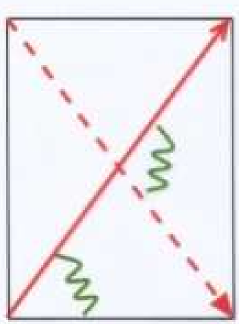
chiral multiplets in $(\square, \bar{\square})$

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

(3 copies of left-handed quark



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



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

$$\frac{1}{2}\left(I_{aa'} + \frac{4}{2^k} I_{a,O6}\right) \ \begin{smallmatrix}\square\\\square\end{smallmatrix}$$

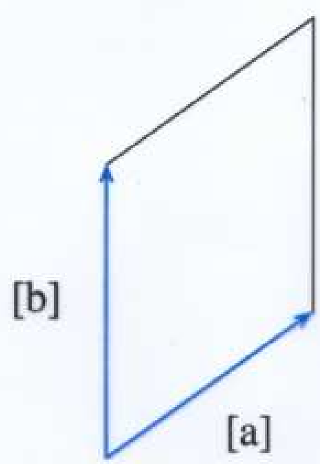
Three-Family Model

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.



ΩR [a] = [a]- [b]

ΩR [b] = - [b]

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

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

↳ half-integer

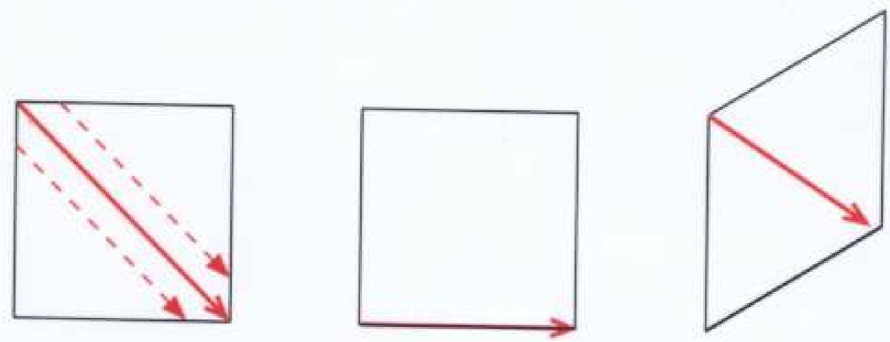
and

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

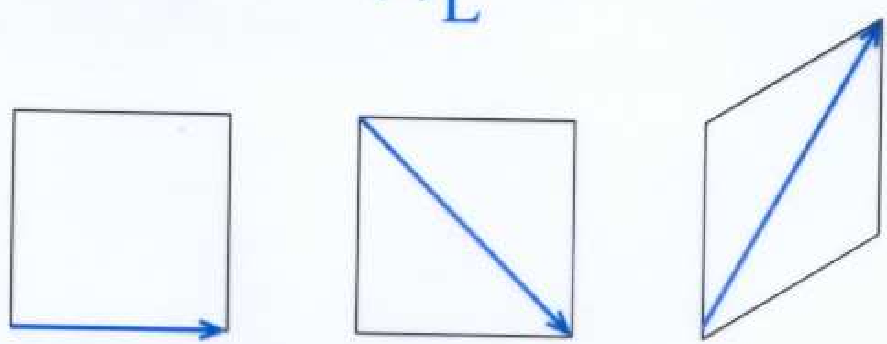
now $N_{families} = I_{ab} + I_{ab'}$ can be ODD.

Building Blocks

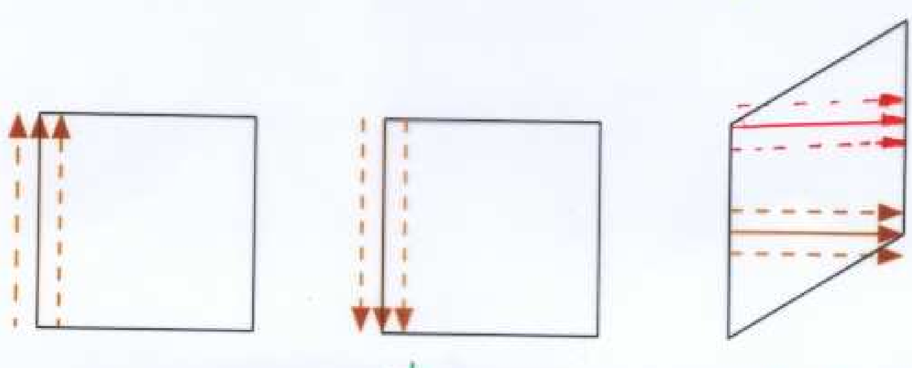
Na=6+2 : U(4) ⟶ $U(3)_c \times U(1)$



Nb=4 : $U(2)_L$



Nc=8 : USp(8) ⟶ $U(1)_8 \times U(1)'_{8'}$



+

Additional D6-branes ∥ w/ orientifold planes -

[hidden sector]

Phenomenology w/ Langacker & Shiu

Gauge Structure

$Q_Y = \frac{1}{6} Q_3 + \frac{1}{2}(Q_8 + Q_{8'}) - \frac{1}{2} Q_1$

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

$\chi_i : \left(\frac{R_2^{(i)}}{R_1^{(i)}} \right.$

S.M. × $U(1)_{B-L}$ × $U(1)_{I_R}$ × "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_1B_1	$3 \times 2 \times (1, \overline{2}, 1, 1, 1)$	0	0	−1	±1	0	$\pm\frac{1}{2}$	±1	H_U, H_D
	$3 \times 2 \times (1, \overline{2}, 1, 1, 1)$	0	0	−1	0	±1	$\pm\frac{1}{2}$	∓1	H_U, H_D
A_1C_1	$2 \times (\overline{3}, 1, 1, 1, 1)$	−1	0	0	±1	0	$\frac{1}{3}, -\frac{2}{3}$	1, −1	U, D
	$2 \times (\overline{3}, 1, 1, 1, 1)$	−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_1C_1	$(3, \overline{2}, 1, 1, 1)$	1	0	−1	0	0	$\frac{1}{6}$	0	Q_L
	$(1, \overline{2}, 1, 1, 1)$	0	1	−1	0	0	$-\frac{1}{2}$	0	L
B_1C_2	$(1, 2, 1, 1, 4)$	0	0	1	0	0	0	0	
B_2C_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	
$B_1C'_1$	$2 \times (3, 2, 1, 1, 1)$	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
$B_1B'_1$	$2 \times (1, 1, 1, 1, 1)$	0	0	−2	0	0	0	0	
	$2 \times (1, 3, 1, 1, 1)$	0	0	2	0	0	0	0	

fractionally charged exotics

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:

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

V_6 ← Volume of 6-torus

V_{3a} ← volume of 3-cycle that brane wraps

$$g_{YM_a}^2 = \frac{\sqrt{3}\,M_{st}\ \chi^{3/2}}{\sqrt{2}\,M_{pe}\sqrt{[(n_a^{(1)2}+m_a^{(1)2}\chi^2)(n_a^{(2)2}+m_a^{(2)2}\chi^2)(n_a^{(3)2}+m_a^{(3)2}\chi^2)]}}$$

↑ Non-universal!

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

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

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

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

Non-standard gauge coupling relatio

- but absolute prediction for given:

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

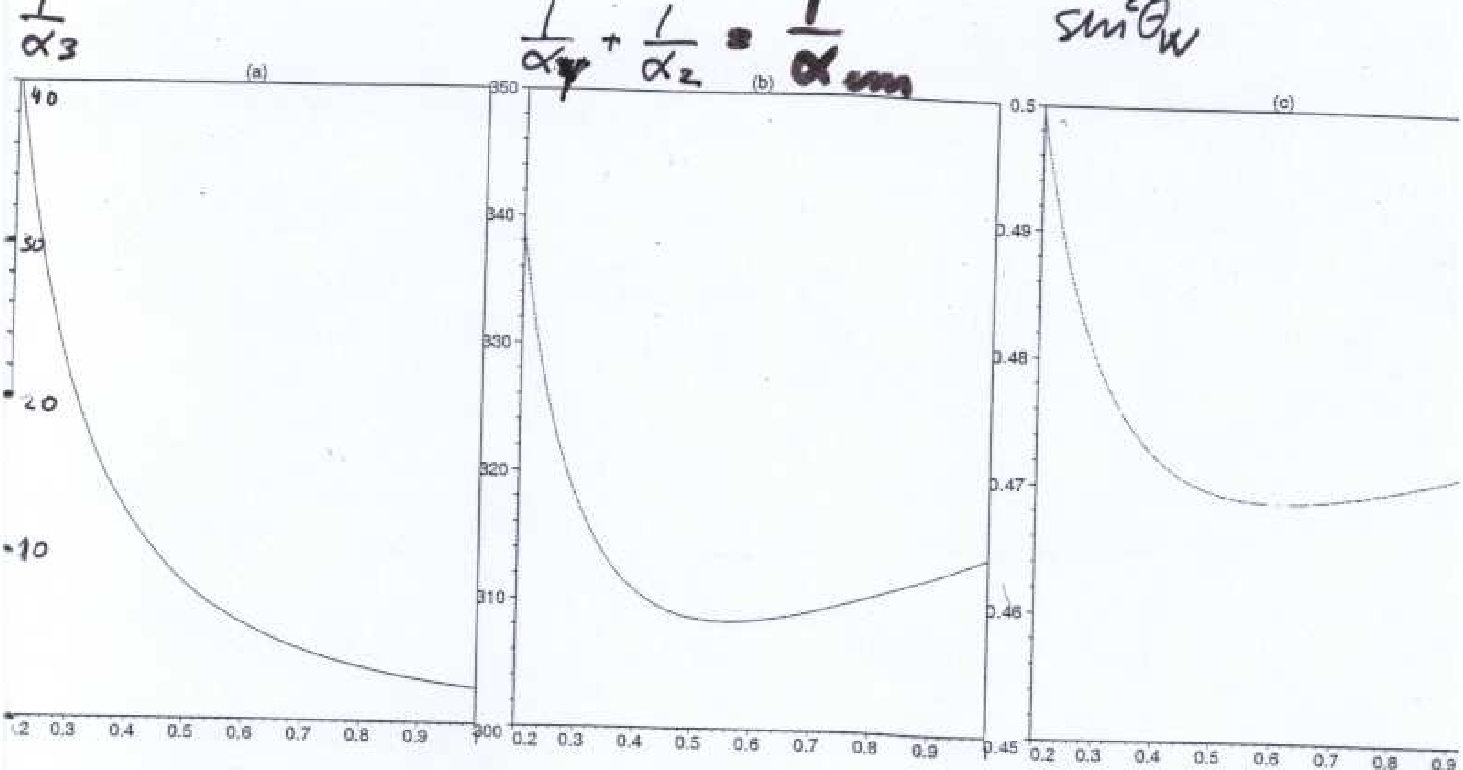
- ordinary sector gives unrealist
Low Energy predictions for:
g_{3_C}, g_{2_L}, g_Y (exotics)

- hidden sector - Asymptotically free
$Sp(2)_1 \times Sp(4)$

[dynamical supersymmetry brea

w/ Langacker & Wang

Value of couplings at M_W as a function of [cut off]



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

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

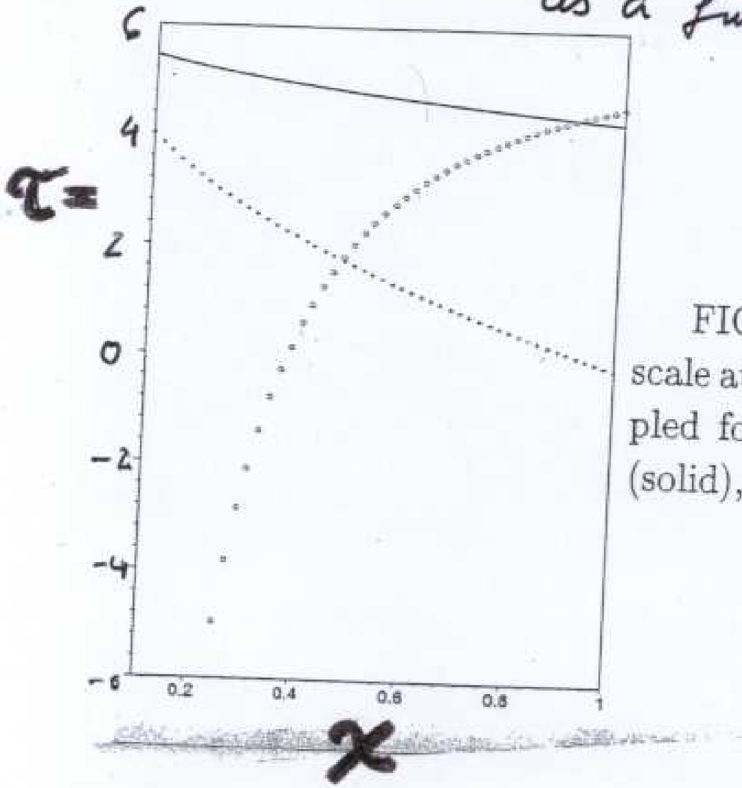


FIG. 2. Scales $\tau = \frac{1}{2\pi}\ln\frac{M}{M_Z}$, where M is t scale at which the Sp group becomes strongly co pled for $M_P^{(4d)} = M_s$. The curves are $Sp(2$ (solid), $Sp(2)_B$ (circles), $Sp(4)$ (crosses).

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

Exotics:

— Fractionally charged:

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

χ SM - singlet & $Sp_B(2)$ - doublet $Q_{EM} = -$

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

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

— Adjoint chiral matter (generic proble

* 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 (exotics) $(\bar{E}, \bar{D}, \bar{N}, \bar{u},$

⇑ L - composite

⇑ R - element

Yukawa Couplings:

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

Four $\bar{u}_K$; $\bar{u}_K'$ $K = I, II$

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

$$\overset{\cup}{H}_{yukawa} = \sum_{\substack{\alpha = 1,2,3 \\ \gamma = i, ii}} h_{\alpha,\gamma}\, Q_L^{\gamma} \Big[\sum_{K = I, II} [\bar{u}_K H_K^{\alpha} + \bar{u}_K' H_K^{\alpha'}] \Big]$$

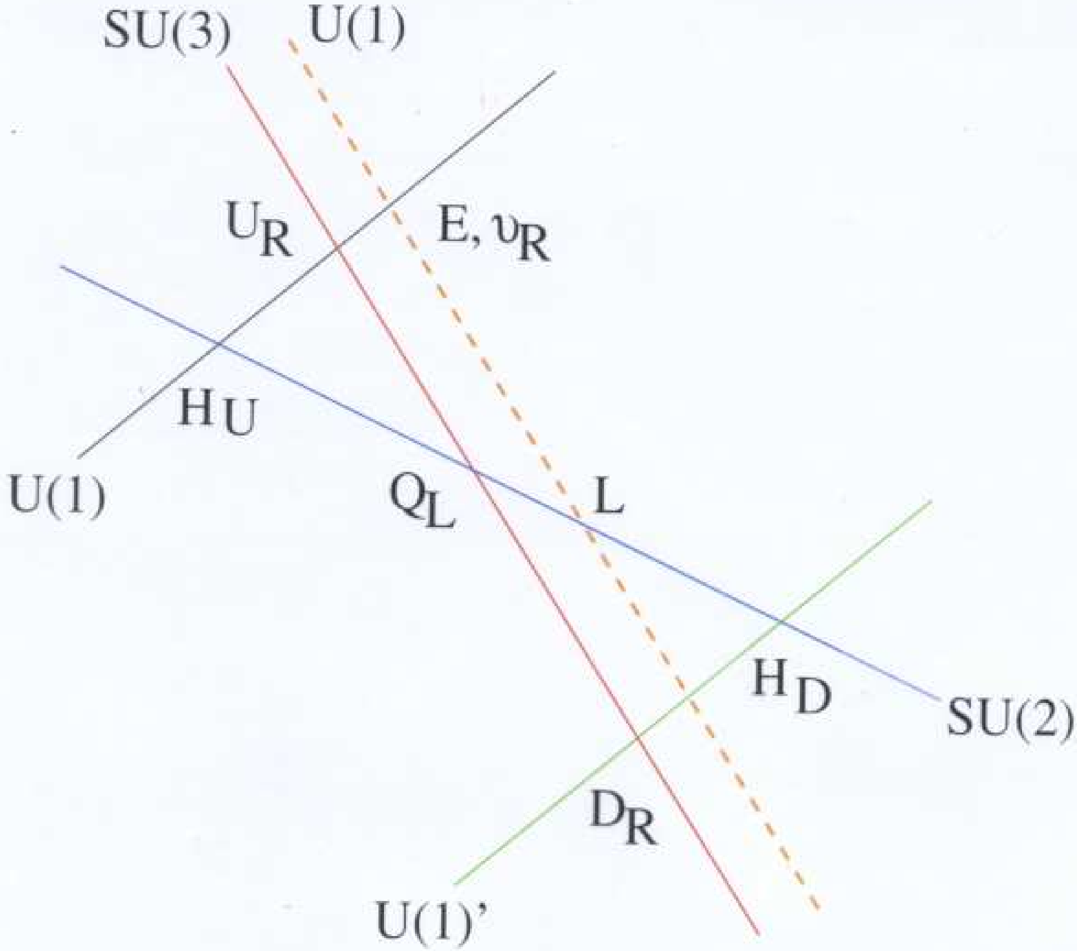
$$h_{\alpha,\gamma} \sim e^{-A_{\alpha,\gamma}/\alpha'}$$

Aldazabal, Ibáñez, Rabadan & Uranga

(world-sheet instan[tons])

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

Aldazabal, 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:

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

Up - Down splitting (some degeneracy remains due to $Z_2 \times Z_2$ symmetry)

(splitting of $Sp(8)$ branes)
$\downarrow$
$U(1)_8 \times U(1)_8$,

Lepton - Quark splitting ($h^{lepton} < h^{quark}$)

(splitting $U(4) \to U(3)_c \times U(1)$ branes)

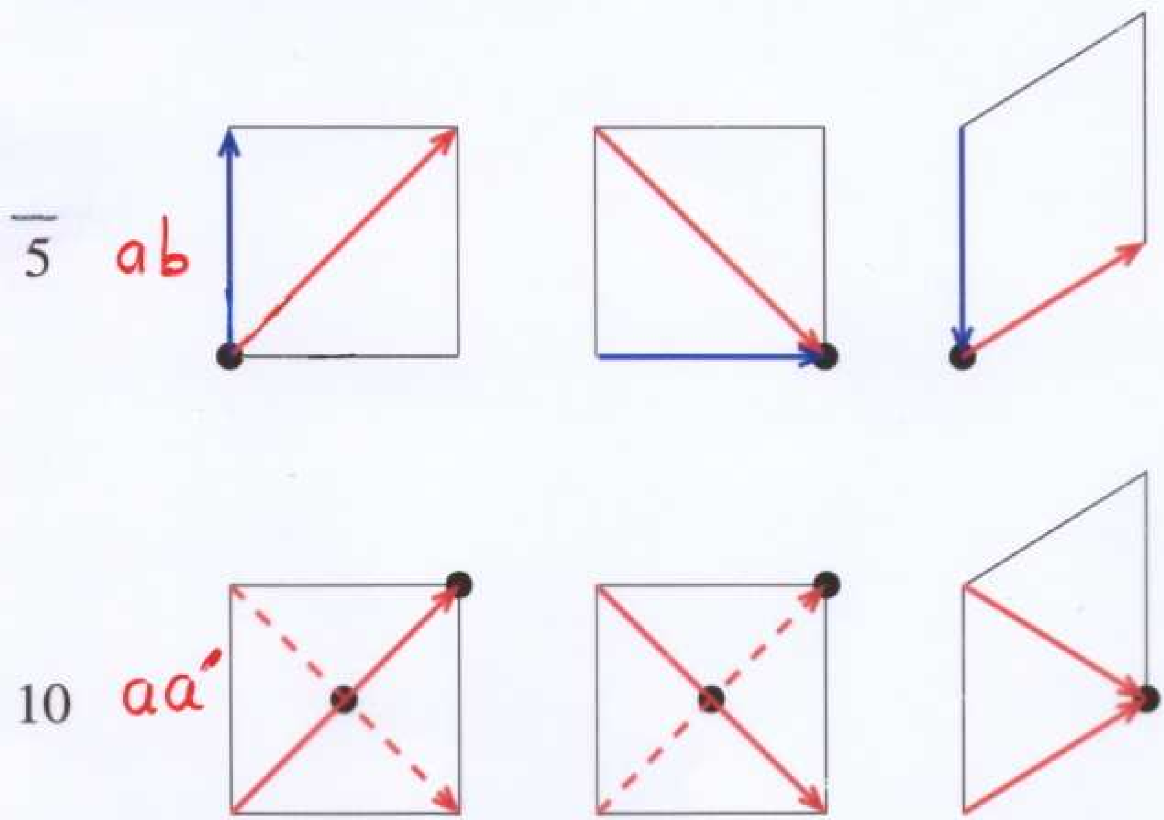
$\gamma = (i, ii)$ – Q_L ——— $U(3)_C$

$\alpha = (1, 2, 3)$ – H · · · · · · $U(2)_L$

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

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 ⇒ splitting the $U(5)$ branes:

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

- 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		$(0,1) \times (1,0) \times (0,-1)$

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

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

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

⇒ 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-the
compactified on 7-dim. exceptional G_2 holono
space

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

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

D=4 → further compactified on Calabi-Yau spa

G_2 holonomy space

w/ Gibbons, Lü &
'01 –

New type of G_2 holonomy spaces:

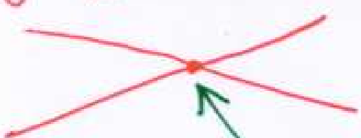
w/ singularities:

I.

open string

D6-brane ⟷ co-dimension 4-si

D6-branes-intersecting ⟷ codimension 7 singu



Appearance of matter

W/ Shiu, Uranga '01

II.

M-theory

Witten

Acharya & W

'0

⇓

Further investigation

Summary

- Status: Orientifold constraction D=4 N=1 supersymmetric supersymmetric models.
- New supersymmetric orientifold models based on $\mathbf{Z_2} \times \mathbf{Z_2}$ 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)