Physics of Type II and Heterotic SM & GUT String Vacua

(a) Spectrum

(b) Couplings

(c) Moduli stabilisation

Type II side [toroidal orientifolds]- summary (a)&(b) [(c)- no time]

new results on SU(5) GUT couplings w/ R. Richter hep-th/060601

Heterotic side [Realistic Calabi-Yau compactification] – NEW

(a) globally consistent MSSM construction Bouchard&Donagi hep-th/0512149

(b) Coupling calculations&implications w/Bouchard&Donagi hep-th/0602096

Type II Side

I.Type IIA - based on toroidal orbifold constructions
w/ intersecting D6-branes;
wealth of 3-family supersymmetric Standard Models & SU(5) GUT Models;

non-Abelian symmetry, chiral matter, family replication & supersymmetry
geometric origin!

Other Type II constructions w/ SM and GUT structure:

Type II rational conformal field theory constructions c.f. Kiritsis's talk
T.Dijkstra,L.Huiszoon&A.Schellekens,hep-th/0403196,0411126
P. Anastasopoulos, T.Dijkstra, E. Kiritsis&A.Schellekens, hep-th/0605226

Local Type IIB SM construction at obifold/orientifold singularity
H. Verlinde&M. Winjholt, hep-th/0508089

[Generalised Magnetised Branes on Tori Antoniadis&Maillard '04-'05]

Gauge degrees of freedom: Dp-branes

extend in (p+1)-dimensions as boundaries of open strings

(i) non-Abelian gauge symmetry

N-coincident D-branes → U(N)

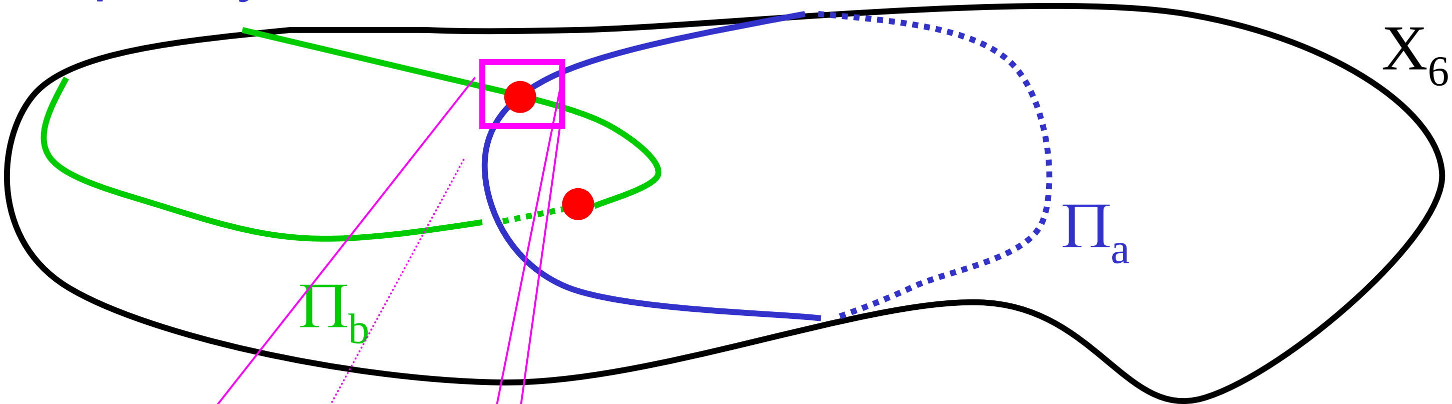
(ii) Appearance of chiral matter → turn to compactification

Specific constructions that produce realistic particle physics:

INTERSECTING D6 branes

Intersecting D6-branes

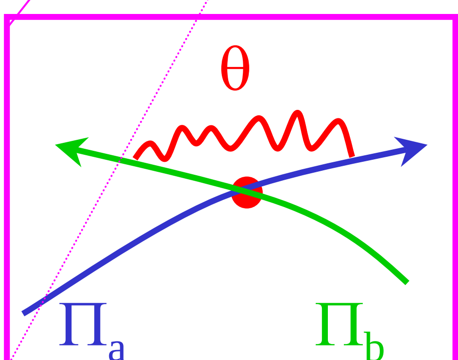
wrap 3-cycles Π



In internal space intersect at points:

Number of intersections $[\Pi_a] \circ [\Pi_b]$ - topological number

Geometric origin of family replications!

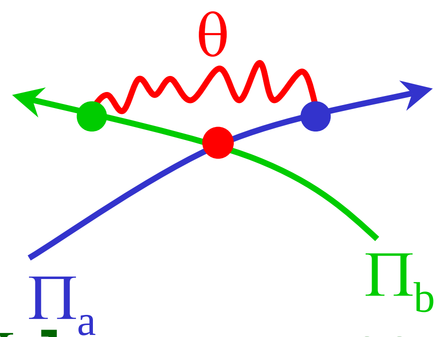


Berkooz, Douglas & Leigh '96

At each intersection-massless 4d fermion ψ

Geometric origin of chirality!

Engineering of Standard Model



N_a- D6-branes wrapping Π_a

N_b- D6-branes wrapping Π_b

$U(N_a) \times U(N_b)$

$\Psi \sim (N_a, \bar{N}_b)$ - bi-fund. ; $[\Pi_a]^\circ[\Pi_b]$ - number of families

$N_a = 3$, $N_b = 2$, $[\Pi_a]^\circ[\Pi_b] = 3$

$U(3)_C \times U(2)_L$

$\Psi \sim (3, 2)$ - 3 copies of left-handed quarks

Blumenhagen, Görlich, Körs & Lüst '00-'01;

Aldazabal,Ibáñez,Rabadan&Uranga'00-'01

Global consistency conditions (D6-brane charge conserv. in internal space)

Antoniadis,Angelantonj,Dudas&Sagnotti'00

& supersymmetry conditions (constraining!)

⬇

Building Blocks of Supersymmetric Standard Model

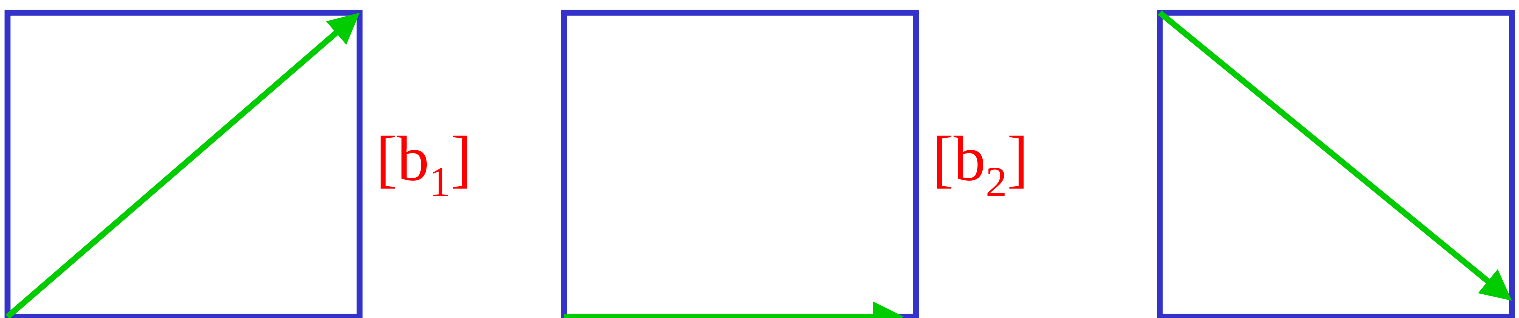
w/ Shiu and Uranga'01

Explicit Constructions

Toroidal Orbifolds & Intersecting D6-branes (CFT techniques)

$T^6/(Z_N \times Z_M)$

$T^6 = T^2 \otimes T^2 \otimes T^2$



$[b_1]$ $[b_2]$ $[b_3]$

$[a_1]$ $[a_2]$ $[a_3]$

$(n_a^i, m_a^i) = (1,1) \quad (1,0) \quad (1,-1)$

$[\Pi_a] = [\Pi_a^1] \otimes [\Pi_a^b] \otimes [\Pi_a^c]$

homology class of 3-cycles

$[\Pi_a^i] = n_a^i [a_i] + m_a^i [b_i]$

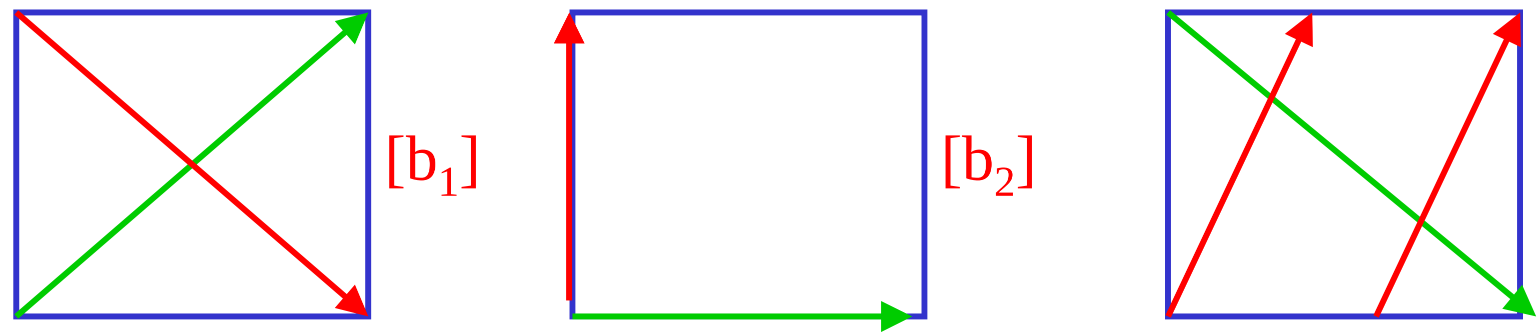
$[N_a, n_a^i, m_a^i]$

Toroidal Orbifolds & Intersecting D6-branes

(CFT techniques)

$$T^6/(Z_N \times Z_M)$$

$T^6 = T^2 \otimes T^2 \otimes T^2$



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$(n_a^i, m_a^i) = \quad (1,1) \quad (1,0) \quad (1,-1)$

$[\Pi_a] = \quad [\Pi_a^1] \otimes [\Pi_a^b] \otimes [\Pi_a^c]$

homology class of 3-cycles

$$[\Pi_a^i] = n_a^i [a_i] + m_a^i [b_i]$$

$$[N_a, n_a^i, m_a^i] \quad [N_b, n_b^i, m_b^i]$$

Intersection number: $I_{ab} = [\Pi_a] \circ [\Pi_b] = \Pi_{i=1}^3 (n_a^i m_b^i - n_b^i m_a^i)$

Global Consistency Conditions

Gimon&Polchinski'98,Sagnotti et al. '90-ies
Blumenhagen, Görlich, Körs & Lüst '00;Aldazabal,Ibáñez,Rabadan&Uranga'00

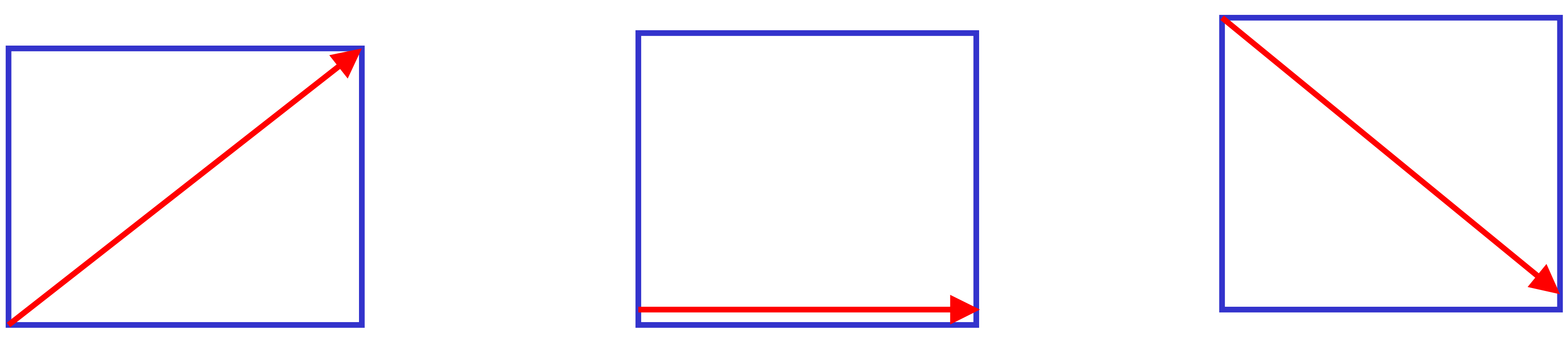
Cancellation of Ramond-Ramond (RR) Tadpoles

Gauss law for D6-charge conservation

$$\mathbf{N}_a \quad [\Pi_a] \quad = \quad 0$$

Not possible to satisfy of CY spaces (``total''tension = charge = 0)

..



Global Consistency Conditions

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Cancellation of Ramond-Ramond (RR) Tadpoles

Gauss law for D6-charge conservation

$$N_a \left([\Pi_a] + [\Pi_{a'}] \right) = -4\, [\Pi_{O6}] \quad *$$

*** Constraints on wrapping numbers**

Not possible to satisfy of CY spaces (``total''tension = charge = 0)

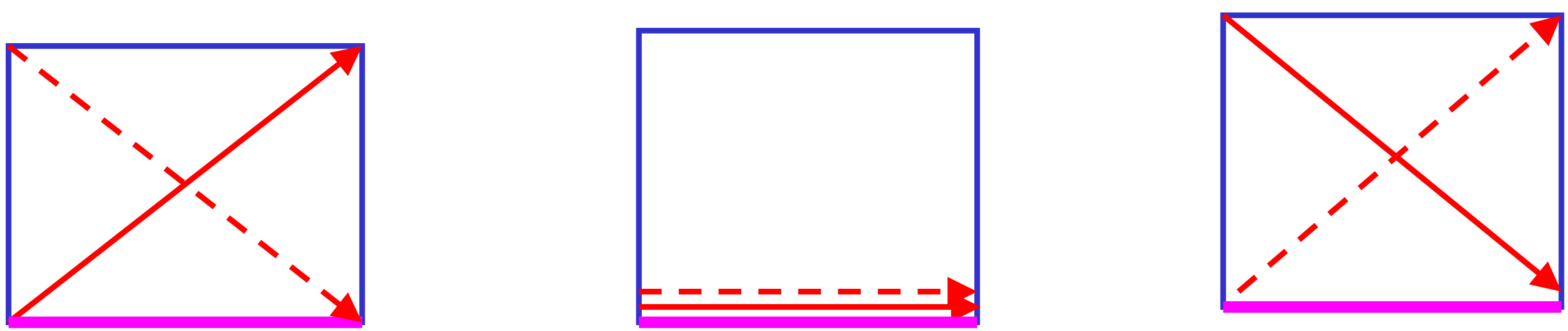
Orientifold planes - fixed planes w/ negative D6- charge

(holomorphic Z_2 involution w/ worldsheet parity projection)

$R \;:\; z_i \to \bar{z}_i$

$\Omega \;:\; \tau, \sigma \to (\tau, -\sigma)$

..



a (n_i , m_i) → a' (n_i , - m_i) - orientifold image

RR-tadpole cancellations

for toroidal orbifolds (example $Z_2 x Z_2$)

w/Shiu&Uranga'01

$$\sum_a N_a \; n_a^1 n_a^2 n_a^3 = 16$$

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

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

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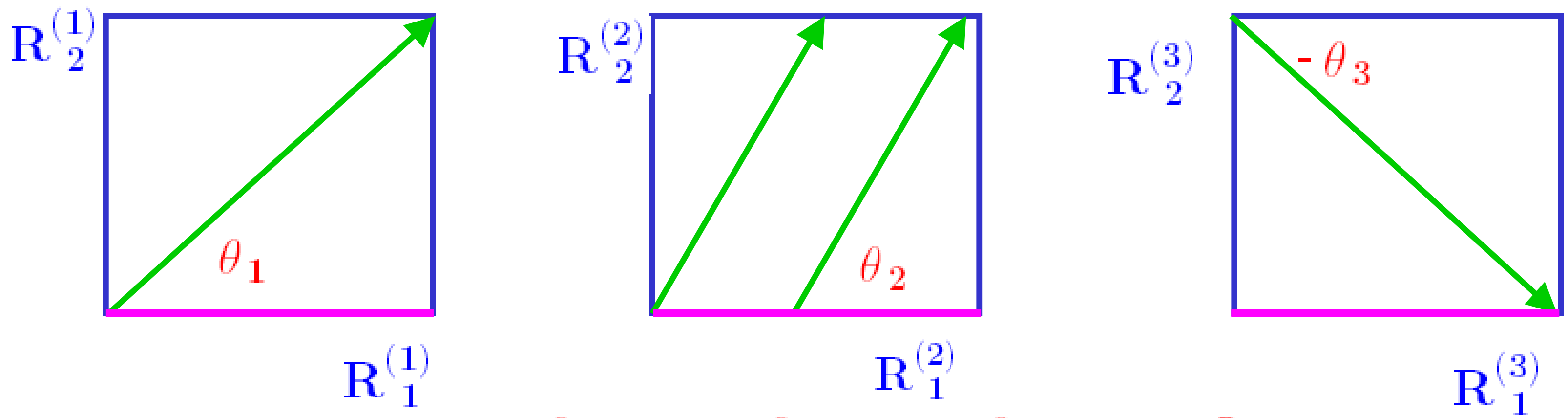
Supersymmetry (toroidal/orbifold example)



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

$$\arctan\left(\frac{m_1}{n_1}\chi_1\right) + \arctan\left(\frac{m_2}{n_2}\chi_2\right) + \arctan\left(\frac{m_3}{n_3}\chi_3\right) = 0$$

Constraints on complex structure moduli- Ui $\sim \chi_i = \frac{R_2^{(i)}}{R_1^{(i)}}$

$\{\theta_i^a\} \neq 0 \quad U(N_a)$

$\{\theta_i^a\} = 0 \quad Sp(N_a)$

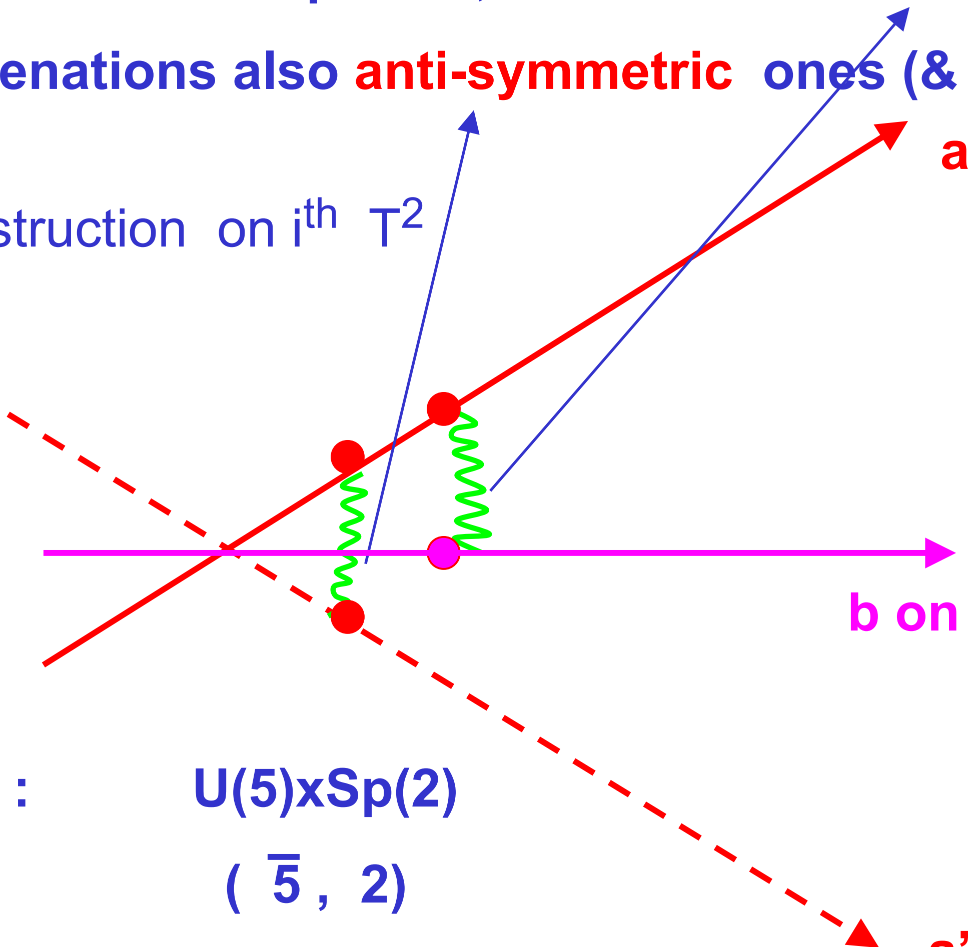
Spectrum on toroidal orientifolds

Sector	**Representation**
$ab + ba$	$I_{ab}\ (\square_a, \overline{\square}_b)$ fermions
$ab' + b'a$	$I_{ab'}\ (\square_a, \square_b)$ fermions
$aa' + a'a$	$\frac{1}{2}(I_{aa'} - \frac{1}{2}I_{a,O})\ \square\!\square$ fermions
	$\frac{1}{2}(I_{aa'} + \frac{1}{2}I_{a,O})\ \begin{smallmatrix}\square\\ \square\end{smallmatrix}$ fermions

New effects on particle spectrum due to Orientifold planes

Due to orientifold planes, in addition to bi-fundamental representations also anti-symmetric ones (& symmetric ones)

E.g. local construction on i^{th} T^2



N_a=5, N_b=2 : **U(5)xSp(2)**

($\bar{5}$, 2)

(10 , 1)

Example of Supersymmetric SU(5) GUT's **w/Shiu&Papadimitriou'03**

i) Supersymmetric Standard Model & SU(5) GUT Constructions

primarily on Z_2xZ_2 orientifolds (CFT techniques)

a) FIRST STANDARD MODEL (1) w/G. Shiu & A. Uranga'01
branes wrap special cycles

b) MORE STANDARD MODELS (4)
branes wrap more general cycles (better models) w/I. Papadimitriou'03

c) SYSYEMATIC CONSTRUCTION OF SU(5) GUT's (order 50)
(3-families on Z_2xZ_2-require 15-plets)
w/I. Papadimitriou & G. Shiu'03

d) SYSTEMATIC SEARCH FOR STANDARD MODELS (11)
based on left-right symmetric models-2 models very close to minimal SM

No time!

w/T.Li&T/Liu'04

e)NEW TECHNICAL DEVELOPMENTS-MORE MODELS (3)
Analysis of brane splittings/electroweak branes || w/ orientifold planes
w/P. Langacker, T. Li & T.Liu'04;Marchesano&Liu'04

f) NEW TECHNICAL DEVELOPMENS (rigid cycles) - MORE MODELS (5)
Branes on rigid cycles w/R.Blumenhagen, F.Marchesano & G.Shiu'05
w/T. Liu,unpublished

g) CONSTRUCTIONS OF FLIPPED SU(5) and GENERALIZED PS CONSTRUCTIONS (2)
C.Chen,G.Kraniotis,V.Mayes,D.Nanopoulos&J.Walker'05…

(e) Other orientifolds:…Z_4 (1) Blumenhagen, Görlich & Ott'03; Z_6 (1) Honecker & Ott '04

(f) Landscape analysis (one in 10^9)Blumenhagen,Gmeiner,Honecker&Lüst,hep-th/0510170

Pedagogical Review: w/R. Blumenhagen, P. Langacker & G. Shiu hep-th/0502005

Three-family SM model w/$SU(2)_L \times SU(2)_R$ directly ($Z_2 \times Z_2$ orbifold)

$\ell^i \equiv 2\, m^i$

III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)^{*} \times Sp(8)]_{hidden}$									
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\square\!\!\!\square}$	b	c	d	d'	2
a	8	$(1,0)\times(1,3)\times(1,-3)$	0	0	3	-3	0	0	0
b	2	$(0,1)\times(1,0)\times(0,-2)$	0	0	-	0	-6	6	0
c	2	$(0,1)\times(0,-1)\times(2,0)$	0	0	-	-	-6	6	0
d	4	$(2,-1)\times(1,3)\times(1,3)$	$\chi_1 = 24\chi_3/(4-9\chi_3^2)$						
2	8	$(1,0)\times(0,-1)\times(0,2)$	$\chi_2 = \frac{1}{2}\chi_3,\ \beta_2^g = -5$						

non-zero Intersections w/hidden sector chiral exotics

wrapping nos. of SM

Cremades,Ibáñez&Marchesano'02

Embedding in $Z_2 \times Z_2$ orbifold-allows for globally consistent construction

w/P.Langacker, T.Li &T.Liu, hep-th/0407178

*"hidden sector" (unitary) branes - necessary for global consistency

(charge conservation)

w/ Langacker, Li &Liu, hep-th/0407178

Four-family Standard Model

Table 2: D6-brane configurations and intersection numbers for the four-family Standard-like model. In the table, χ_i is the complex modulus for the $i-$th torus, and β_i^g is the beta function for the $i-$th Sp group from the $i-$th stack of branes.

$\ell^i \equiv m^i$

I	$[U(4)_C \times Sp(8)_L \times Sp(8)_R]_{observed} \times [U(4) \times Sp(8) \times Sp(8)]_{hidden}$										
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\square\atop\square}$	b	c	d	d'	1	2
a	8	$(1,0)\times(1,1)\times(1,-1)$	0	0	1	-1	0	0	0	0
b	8	$(0,1)\times(1,0)\times(0,-1)$	0	0	-	0	0	0	0	0
c	8	$(0,1)\times(0,-1)\times(1,0)$	0	0	-	-	0	0	0	0
d	8	$(0,1)\times(1,-1)\times(1,-1)$	0	0	-	-	-	0	-1	1
1	8	$(1,0)\times(1,0)\times(1,0)$	$\chi_2=\chi_3=1$							
2	8	$(1,0)\times(0,-1)\times(0,1)$	$\beta_1^g=\beta_2^g=-4$							

no inter-section w/ hidden sector

no chiral exotics!

$Sp(8)_L \times Sp(8)_R$ 1-Higgs (8,8), one-family confining hidden sector

↓ brane splitting ↓ ↓ brane splitting

$U(2)_L \times U(2)_R$ 16- Higgs (2,2), four-families

II. Calculation of couplings (w/ intersecting branes)

a) Yukawa couplings – fermion masses

Cremades, Marchesano& Ibáñez'03 (classical part)

w/I.Papadimitriou'03 (complete CFT calculation)

b) Kähler potential (related to full Yukawa coupling calc.)

Mayr,Lüst,Richter,Stieberger'04

c) Four-point and higher-point functions

Four- Fermi interactions:

FCNC: Antonidias et al.'01, Abel&Owen'03…

SU(5) GUT String Dimension Six operators in proton decay:

10*1010*10 Klebanov&Witten'03

10*1010*10 & $\overline{5*5}$ 10*10 w/R.Richter, he-th/060601

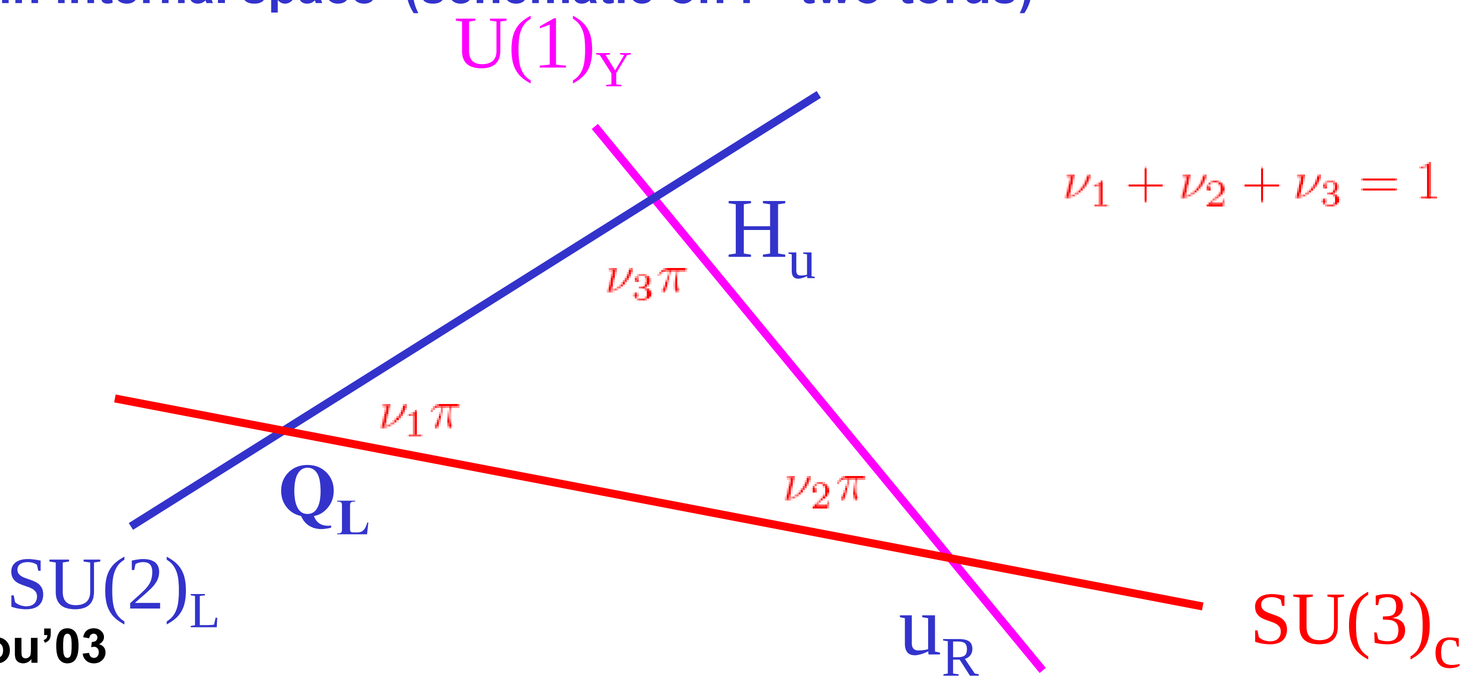
d) Loop corrections: gauge couplings

Stieberger&Lüst'03

Kähler potential Abel&Goodsell'04,'05

Yukawa Couplings

Intersections in internal space (schematic on ith-two-torus)



w/Papadimitriou'03

(Conformal Field Theory Techniques)

$$Y = (2\pi)^{\frac{3}{2}} g_{st} \prod_{i=1}^{3} \left[\frac{\Gamma(1-\nu_1^i)\Gamma(1-\nu_2^i)\Gamma(1-\nu_3^i)}{\Gamma(\nu_1^i)\Gamma(\nu_2^i)\Gamma(\nu_3^I)} \right]^{\frac{1}{4}} \sum_I \exp\left(-\frac{A_I^1 + A_I^2 + A_I^3}{2\pi\alpha'}\right)$$

quantum-Kähler potential

Classical- A_I^i -triangle areas on ith two-torus lattice

Crémades Marchesano &Ibáñez '03 - detailed study

Proton decay via four-Fermi interactions in SU(5) GUT's

w/ R. Richter, hep-th/060601

Local * construction w/ 10 & $\overline{5}$ on top of the same intersection

(maximized effect; applicable to other Calabi-Yau orientifold constructions)

Assume, dim. 5 operators suppressed;

Dim. 6 operators; comparison of STRING effects relative to FIELD THEORY

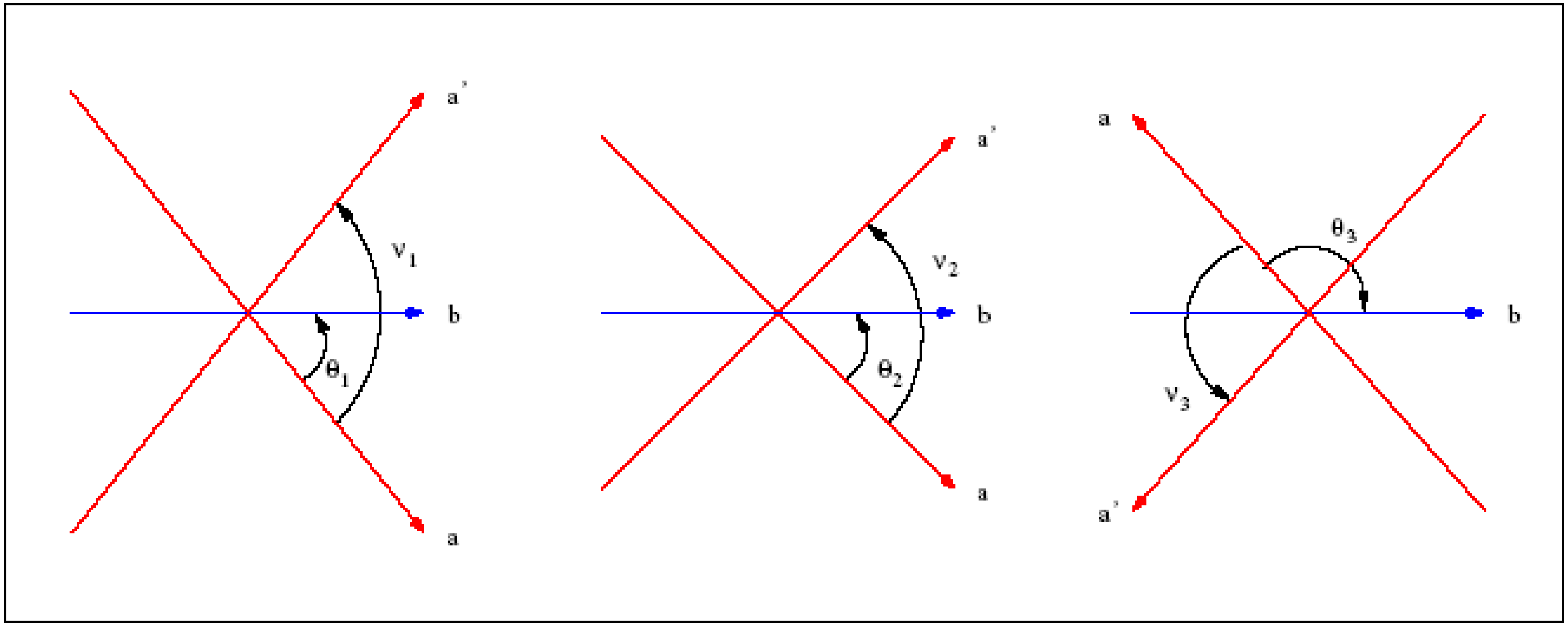


FIG. 1: Intersection angles for the case $-\frac{1}{2} < \theta_1 < 0, -\frac{1}{2} < \theta_2 < 0, \frac{1}{2} < \theta_3 < 1$

Subtle constr. of string vertex opers.(no time!)

* Leading contribution; subleading exp. suppressed by A/α'

$$A_2 = \int \prod_{i=1}^{4} \mathrm{d}z_i \, \langle V^{\bar{5}\,*}_{-\frac{1}{2}}(z_1)\, V^{\bar{5}}_{-\frac{1}{2}}(z_2)\, V^{10\,*}_{-\frac{1}{2}}(z_3) V^{10}_{-\frac{1}{2}}(z_4) \rangle$$

$\overline{5}^*\overline{5}\,10^*10$ String Amplitude

$$= 2\mathrm{i} C_A \, \bar{u}_1 \gamma^\mu u_2 \, \bar{u}_3 \gamma_\mu u_4 (2\pi)^4 \delta^{(4)} \left(\sum_{i=1}^{4} k_i \right)$$

spinors

$$\times \left(Tr(\tilde{\Lambda}_1 \, \Lambda_2 \, \tilde{\Lambda}_3 \, \Lambda_4) K(\theta_1, \theta_2, \theta_3) + Tr(\tilde{\Lambda}_1 \, \Lambda_2 \, \Lambda_4 \, \tilde{\Lambda}_3) T(\theta_1, \theta_2, \theta_3) \right)$$

Chan-Paton

Where: $K(\theta_1, \theta_2, \theta_3) = \int_0^1 \mathrm{d}x \, U(x) \qquad T(\theta_1, \theta_2, \theta_3) = \int_{-\infty}^{0} \mathrm{d}x \, U(x). \qquad C_A = \frac{\pi}{2} g_s \, \alpha'$

Worldsheet coordinate

$$U(x) = x^{-\alpha' s - 1} (1-x)^{-\alpha' u - 1} \left[I\left(-\theta_1, 1+\nu_1, x\right) \, I\left(-\theta_2, 1+\nu_2, x\right) \, I\left(1-\theta_3, 1+\nu_3, x\right) \right]^{-\frac{1}{2}}$$

Mandelstam variables

$$I(x) = \frac{1}{2\pi} \left[B_1(\theta, \nu) \, \overline{G_2}(x) H_1(1-x) + B_2(\theta, \nu) \, G_1(x) \overline{H_2}(1-x) \right] \; ,$$

$$B_1(\theta, \nu) = \frac{\Gamma(\theta)\,\Gamma(1-\nu)}{\Gamma(1+\theta-\nu)} \qquad B_2(\theta, \nu) = \frac{\Gamma(\nu)\,\Gamma(1-\theta)}{\Gamma(1+\nu-\theta)}$$

Gamma functions

$$G_1(x) = {}_2F_1[\theta, 1-\nu, 1; x] \qquad G_2(x) = {}_2F_1[1-\theta, \nu, 1; x]$$

Hypergeometric functions

$$H_1(x) = {}_2F_1[\theta, 1-\nu, 1+\theta-\nu; x] \qquad H_2(x) = {}_2F_1[1-\theta, \nu, 1-\theta+\nu; x] \; .$$

$$\mathbf{A_1} = \int \prod_{i=1}^{4} \mathrm{d}z_i \, \langle V^{10\,*}_{-\frac{1}{2}} \, V^{10}_{-\frac{1}{2}} \, V^{10\,*}_{-\frac{1}{2}} V^{10}_{-\frac{1}{2}} \rangle$$

10*1010*10 String Amplitude

$$= \mathrm{i}C'_A Tr\left(\tilde{\Lambda}_1\Lambda_2\tilde{\Lambda}_3\Lambda_4 + \tilde{\Lambda}_1\Lambda_4\tilde{\Lambda}_3\Lambda_2\right)(2\pi)^4\delta^{(4)}\left(\sum_{i=1}^{4} k_i\right) \bar{u}_1\gamma^\mu u_2 \, \bar{u}_3\gamma_\mu u_4 \, M(\theta_1, \theta_2, \theta_3)$$

$$M(\theta_1, \theta_2, \theta_3) = \int_0^1 \mathrm{d}x \, \frac{x^{-\alpha' s - 1} \, (1-x)^{-\alpha' u - 1}}{L^{\frac{1}{2}}(1+2\theta_1, x) \, L^{\frac{1}{2}}(1+2\theta_2, x) \, L^{\frac{1}{2}}(-1+2\theta_3, x)}$$

$$C'_A = \pi g_s \, \alpha'$$

$$L(x) = \frac{1}{\sin(\pi\,\theta)} \, {}_2F_1[\theta, 1-\theta, 1, x] \, {}_2F_1[\theta, 1-\theta, 1, 1-x]$$

NUMERICAL ANALYSIS

(Field Theory effects. i.e. gauge boson& Higgs exchange subtracted)

$-\frac{1}{2} < \theta_1 < 0$ $-\frac{1}{2} < \theta_2 < 0$ $\frac{1}{2} < \theta_3 < 1$				$\frac{1}{2} < \theta_1 < 1$ $\frac{1}{2} < \theta_2 < 1$ $\frac{1}{2} < \theta_3 < 1$			
θ	K	T	M	θ	K	T	M
-.40	6.5	5.4	10.3	.505	1.5	1.5	2.5
-.42	5.7	5.1	9.4	.51	2.0	2.1	3.5
-.44	4.9	4.6	8.3	.52	2.9	2.9	4.9
-.46	4.0	4.0	6.9	.54	4.0	4.0	6.9
-.48	2.9	2.9	4.9	.56	4.9	4.6	8.3
-.49	2.0	2.1	3.5	.58	5.7	5.1	9.4
-.495	1.5	1.5	2.5	.60	6.5	5.4	10.3

TABLE I: Contribution to K, T and M for different angles θ

$\theta_1 = \theta_2 = \theta$.

Note: $K + T \approx 1.2 \times M$ **(previous estimates K+T < M)**

Comparison with field theory for: $p \to \pi^0 e^+$

Field Theory:

$$\tau_p^{FT} = 1.6 \times 10^{36} years \left(\frac{.04}{\alpha_{GUT}}\right)^2 \left(\frac{M_X}{2 \times 10^{16} GeV}\right)^4$$

String Theory: Subtracting field theory contrib. from A_1&A_2 string amplitudes & relating α' & g_s to α_{GUT} & M_{GUT} (maximized effect) *:

$$\tau_p^{ST} \approx 1.6 \times 10^{36} years \frac{54^2}{L^{4/3}(Q)\, g_s^{2/3}\, ((K+T)^2 + 4M^2)} \left(\frac{.04}{\alpha_{GUT}}\right)^{4/3} \left(\frac{M_{GUT}}{2 \times 10^{16} GeV}\right)^4$$

w/ $M_{GUT} = 2 \times 10^{16} GeV$, $\alpha_{GUT} = 0.04$ & values of K,T,M (from Table):

$$\tau_p^{ST} = (0.5 - 2.1) \times 10^{36} years.$$

Up to factor 3 shorter than FT, n.t.l. beyond sensitivity of future experiments

* w/ $g_s \to 1$ & threshold corrections: $\alpha' = \left(\frac{\alpha_{GUT}\, L(Q)}{(2\pi)^3\, g_s\, M_{GUT}^3}\right)^{2/3}$

[L(Q)-topological invariant of G_2 spaces-Ray Singer index (2-8)

Friedmann&Witten'03]

Features of explicit constructions on toroidal orbifolds

Typically:

(a) more than one Higgs doublet pairs

(b) chiral exotics (due to intersections of observable branes w/ ``hidden'' ones)

(c) couplings: realistic fermion masses ?

string implications for proton decay ?

(d) some combination of toroidal moduli fixed by supersymmetry,

but open-sector brane-splitting and brane-recombination moduli NOT

Strong D-brane dynamics & Supersgravity Fluxes (typeIIB w/magnetized branes)

w/Langacker &Wang'03 Shiu&Marchesano'04; w/Liu,'04,w/Liu&Li'05…

Examples of 3-family SM w/ stabilized all torodial and some brane modul
(phenomenology w/Langacker.Liu&Li (unpublished))

No time

Three-family SM model w/$SU(2)_L$ x $SU(2)_R$ electro-weak sector (Z_2 x Z_2 orbifold)

III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)^{*} \times Sp(8)]_{hidden}$									
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\square\atop\square}$	b	c	d	d'	2	
a	8	$(1,0)\times(1,3)\times(1,-3)$	0	0	3	-3	0	0	0	
b	2	$(0,1)\times(1,0)\times(0,-2)$	0	0	-	0	-6	6	0	
c	2	$(0,1)\times(0,-1)\times(2,0)$	0	0	-	-	-6	6	0	
d	4	$(2,-1)\times(1,3)\times(1,3)$	$\chi_1 = 24\chi_3/(4-9\chi_3^2)$							
2	8	$(1,0)\times(0,-1)\times(0,2)$	$\chi_2 = \frac{1}{2}\chi_3,\ \beta_2^g = -5$							

Non-zero Intersections w/hidden sector- chiral exotics

wrapping nos. of SM

Z_2 x Z_2 orientifold embedding

*U(2)-D9-brane w/ negative D3-charge contribution

Cremades, Ibáñez & Marchesano'03

w/ Langacker, Li & Liu, hep-th/0407178

3-family SM Chiral Flux Vacuum:

U(1) x U(1) & nf=1 flux units

Marchesano & Shiu, hep-th/0408058,0409132

[1= Higgs (2,2); Yukawa couplings give mass to 3rd family; chiral exotics] w/T. Li &T. Liu hep-th/0501041

New Sets of Flux Models

Gauge symmetry: $U(4)_C \times U(2)_L \times U(2)_R \times Sp(2N_1) \times Sp(2N_2) \ldots$

or $(SU(2)_L)$ [under $U(2)_L$]

or $(SU(2)_R)$ [under $U(2)_R$]

``Hidden sector'' [under $Sp(2N_1) \times Sp(2N_2) \ldots$]

SM-sector contains branes whose charge cancels Flux contribution

New representative models (of order 20) of 3- and 4-family Standard Models with up to 3-units of quantized flux.

w/T. Li &T. Liu hep-th/0501041

Table 5: D-brane configurations and intersection numbers for $Model-T_3-1$.

Three -family SM with 3- units of flux (supersymmetric)

$Model-T_3-1$	$[U(4)_C\times U(2)_L\times U(2)_R]_{Observable}$								
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\!\square}$	$n_{\genfrac{}{}{0pt}{}{\square}{\square}}$	b	b'	c	c'	Kähler moduli
a	8	$(1,0)(1,1)(1,-1)$	0	0	-3	1	12	-10	$\chi_3=\chi_2=2\chi_1$
b	4	$(1,1)(2,-1)(1,0)$	-2	2	-	-	6	6	$\chi_3=2\sqrt{10}$
c	4	$(-2,-1)(4,1)(3,1)$	-6	-106	-	-	-	-	

Three -family SM with 2- units of flux

Table 6: D-brane configurations and intersection numbers for $Model-T_2-1$.

$Model-T_2-1$	$[U(4)_C\times U(2)_L\times U(2)_R]_{Observable}\times[Sp(12-4n_f)]_{Hidden}$							
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\!\square}$	$n_{\genfrac{}{}{0pt}{}{\square}{\square}}$	b	b'	c	c'
a	8	$(1,0)(1,1)(1,-1)$	0	0	-3	1	8	-8
b	4	$(2,1)(2,-1)(1,0)$	0	0	-	-	0	4
c	4	$(-2,-1)(3,1)(3,1)$	-44	-64	-	-	-	-
$(D7)_2$	4	$(0,1)(1,0)(0,-1)$	$\chi_3=\chi_2=\chi_1=\sqrt{21}$					

Three -family SM with 1- units of flux

Table 7: D-brane configurations and intersection numbers for $Model-T_1-1$.

$Model-T_1-1$	$[U(4)_C\times Sp(2)_L\times U(2)_R]_{Observable}\times[Sp(8)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\!\square}$	$n_{\genfrac{}{}{0pt}{}{\square}{\square}}$	b	c	c'
a	8	$(1,0)(3,1)(3,-1)$	0	0	-3	3	0
b	2	$(0,1)(0,-1)(2,0)$	0	0	-	16	-
c	4	$(-2,-1)(4,1)(3,1)$	-6	-106	-	-	-
$D3$	8	$(1,0)(1,0)(1,0)$	$\chi_2=\chi_3,\ \frac{12}{\chi_2^2}+\frac{14}{\chi_1\chi_2}$				

More three-family SM's with 1-unit of flux

Table 8: D-brane configurations and intersection numbers for $Model - T_1 - 2$.

$Model - T_1 - 2$	$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable} \times [Sp(8) \times Sp(4)]_{Hidden}$							
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	b	b'	c	c'
a	8	$(1,0)(1,1)(1,-1)$	0	0	-3	1	4	-6
b	4	$(2,1)(2,-1)(1,0)$	0	0	-	-	0	0
c	4	$(-2,-1)(2,1)(3,1)$	-18	-78	-	-	-	-
$D3$	8	$(1,0)(1,0)(1,0)$	$\chi_3 = \chi_2 = \chi_1 = 4$					
$(D7)_2$	8	$(0,1)(1,0)(0,-1)$						

Table 9: D-brane configurations and intersection numbers for $Model - T_1 - 3$.

$Model - T_1 - 3$	$[U(4)_C \times U(2)_L \times Sp(4)_R]_{Observable} \times [Sp(4)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	b	b'	c
a	8	$(-1,-1)(2,1)(2,1)$	-2	-30	3	-5	-4
b	4	$(1,0)(3,1)(1,-1)$	4	-4	-	-	0
c	4	$(1,0)(0,1)(0,-1)$	0	0	-	-	-
$D3$	8	$(1,0)(1,0)(1,0)$	$3\chi_3 = \chi_2,\ \frac{12}{\chi_2^2} + \frac{8}{\chi_1\chi_2} = 1$				

Phenomenology: w/P Langacker,T.Li&T.Liu, unpublished

Models descendants of left-right symmetric (Pati-Salam) Models

(a) Yukawa Couplings:

-Pati-Salam model w/ minimal (MSSM) Higgs sector not viable;
For the specific construction-mass only for the 3rd family.

-Models w/ non-minimal Higgs sector better. However, Yukawa couplings symmetric-a handful of models w/ masses and mixings for 2nd and 3rd family.

(b) Exotics:

-models possess chiral exotics due to SM branes intersecting w/ ``hidden'' sector ones

-new chiral flux constructions w/ mainly right chiral exotics & Yukawa couplings to SM Higgs sector (M~ TeV) –but SM precision constraints

(c) $U(1)_{B-L}$ breaking:

-VEV of right sneutrino-problematic because of R-parity breaking

-$U(1)_{B-L}$ breaking by exotic sneutrinos- but SM precision constraints

Summary –Type II side

(a) Major progress (Type IIA): development of techniques for constructions on toroidal orbifolds w/intersecting D6-branes SPECTRUM & COUPLINGS-geometric; systematic searches

(b) FLUX COMPACTIFICATON w/ SM (Type IIB)
Sizable number of semi-realistic models (on the order of 20 classes)

(c) Models not fully realistic:
typically some exotic matter; couplings not fully realistic;
only open sector& toroidal moduli stabilized
(hierarchy for SUSY breaking fluxes ?)

``Shortcomings'' possibly an artifact of toroidal orbifold constructions

⬇

Foresee progress: Construction on Calabi-Yau threefolds

Heterotic Side

I. Calabi-Yau compactifications- algebraic geometry

holomorphic slope-stable vector bundle constructions

Freedman,Morgan&Witten'97; Donagi'97

Classes of supersymmetric SM-like constructions

Donagi, Ovrut, Pantev&junior collaborators `01-05

New supersymmetric SM-like constructions w/ U(n) bundles

Blumenhagen, Honecker, Weigand'05-'06
(c.f. Blumenhagen's talk)

New results: the only globally consistent construction w/just MSSM spectrum

Massless Spectrum — Bouchard&Donagi, hep-th/0512149

Tri-linear coupling calculation — w/Bouchard&Donagi, hep-th/0602096

II. Orbifold/free-worldsheet fermionic constructions

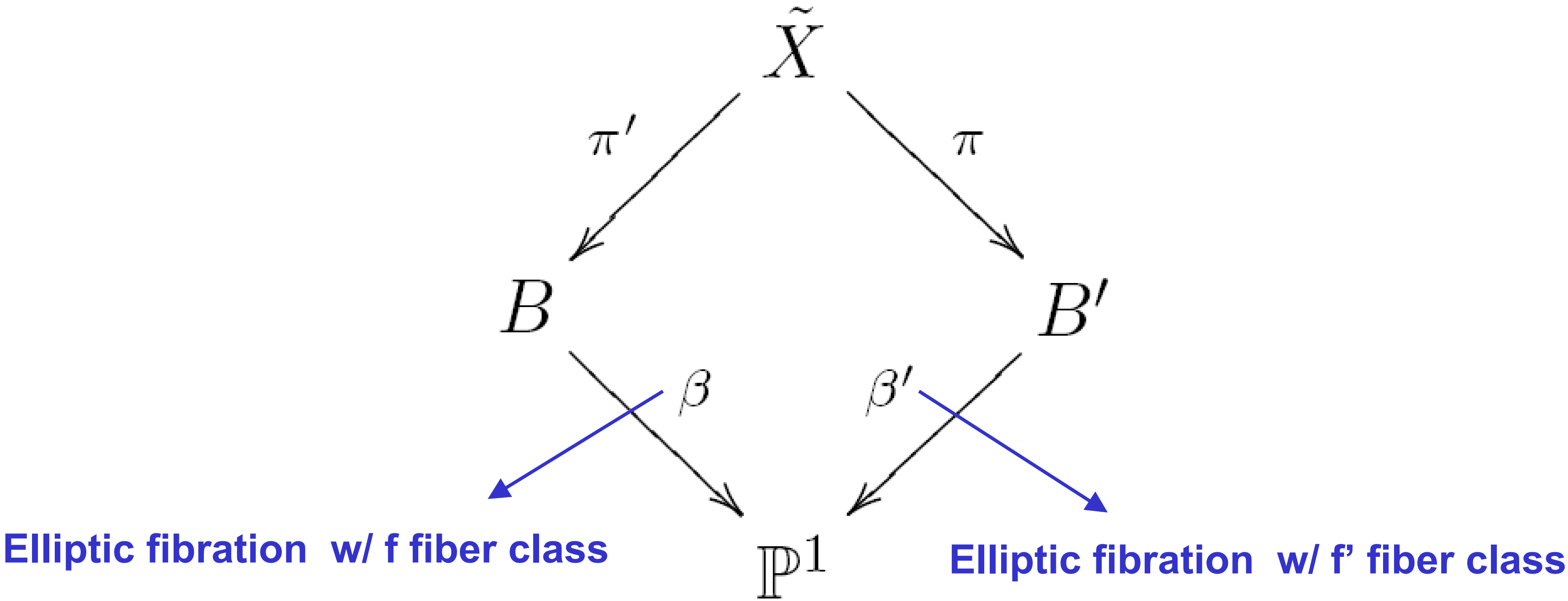
Examples of just MSSM (CFT techniques)

Cleaver,Faraggi&Nanopoulos`01,Buchmüller et al., hep-th/0512326
(c.f. Buchmüller's talk)

No Fluxes!

Summary of the construction:

Calabi-Yau threefold $\tilde{X}$:an elliptic fibration π' over rational elliptic surface B (dP_9)



$\tilde{X}$ - fiber product $B \times_{\mathbb{P}^1} B'$

Free Z_2 action: $\mathbb{Z}_2$ involution $\tau := \tau_B \times_{\mathbb{P}^1} \tau_{B'}$

Donagi,Ovrut,Pantev&Waldram'00

Z_2 invariant **Vector Bundle** $\tilde{V}$ = SU(5) vector bundle of (visible) E_8

with an action of the Z_2 involution

Gauge structure SU(5) → $SU(3)_c \times SU(2)_L \times U(1)_Y$

Implementing Z_2 Wilson line

$\tilde{V}^*$ constructed as an extension:

$$0 \to V_2 \to \tilde{V}^* \to V_3 \to 0$$

rank 2 rank 3

$$V_i = \pi'^* W_i \otimes \pi^* L_i$$

rank i bundles on B line bundles on B'

(Fourier-Mukai transforms)

Donagi'97

Donagi,Ovrut,Pantev&Waldram'00

Spectral cover construction

(Standard Model) Constraints on

Holomorphic vector bundle:

(a) slope-stable ⟺ ∃* solution (Donaldson,Uhlenbeck&Yau)

YES!

(b) SU(5) rather than U(5) bundle: first Chern class $C_1(V)=0$

(c) 3-Chiral Families: third Chern class $C_3(V)=-12$ (Euler Characteristic)

(d) Global consistency (Green Schwarz anomaly cancellation):

second Chern classes: $C_2(T\tilde{X})-C_2(\tilde{V})=[W]$ -effective class

$[W]= 2\, f \times pt + 6\, pt \times f'$ - Yes! (M5-branes wrapping holomorphic 2-cycles)

[or add hidden sector slope-stable bundle U:

$C_2(T\tilde{X})-C_2(\tilde{V})-C_2(U)=0$ (Have not done explicitly)]

Massless spectrum (related to zero modes of Dirac operator on Calabi Yau threefolds) - in terms of cohomology elements:

$$Spec = \bigoplus_{q=1,3} H^q(X, \mathrm{ad}V)$$

Long exact sequences in cohomology

Applied to specific bundle construction: →

MSSM w/ no exotics & n=0,1,2 massless Higgs pairs

[& a number of vector bundle and Calabi Yau moduli]

Multiplicity	Representation	Superfield
$1 = h^3(\tilde{X}, \mathcal{O}_{\tilde{X}})_+$	$(8,1)_0 \oplus (1,3)_0 \oplus (1,1)_0$	$G, W^{\pm}, Z, \gamma$
$3 = h^1(\tilde{X}, \tilde{V}^*)_+$	$(\bar{3},1)_{-4/3} \oplus (1,1)_2$	u, e
$3 = h^1(\tilde{X}, \tilde{V}^*)_-$	$(3,2)_{1/3}$	Q
$0 = h^1(\tilde{X}, \tilde{V})_+$	$(3,1)_{4/3} \oplus (1,1)_{-2}$	exotic
$0 = h^1(\tilde{X}, \tilde{V})_-$	$(\bar{3},2)_{-1/3}$	exotic
$3 = h^1(\tilde{X}, \wedge^2\tilde{V}^*)_+$	$(\bar{3},1)_{2/3}$	d
$3 + n = h^1(\tilde{X}, \wedge^2\tilde{V}^*)_-$	$(1,\bar{2})_{-1}$	$L, \bar{H}$
$0 = h^1(\tilde{X}, \wedge^2\tilde{V})_+$	$(3,1)_{-2/3}$	exotic
$n = h^1(\tilde{X}, \wedge^2\tilde{V})_-$	$(1,2)_1$	H
$62 = h^1(\tilde{X}, \mathrm{ad}\tilde{V})_+$	$(1,1)_0$	ϕ, ν

No exotics

n Higgs pairs

R-handed ν

Table 2: The particle spectrum of the low-energy $SU(3)_C \times SU(2)_L \times U(1)_Y$ theory. Notice that all exotic particles come with 0 multiplicity, and that the spectrum include n copies of Higgs conjugate pairs, where $n = 0, 1, 2$.

+ even ; - odd representation under Z_2 action

Focus on loci in moduli space w/ n=1 and n=2 massless Higgs pairs

Tri-linear superpotential couplings:

$$\lambda_{ijk} \sim \int_X \Omega \wedge \Phi_i \wedge \Phi_j \wedge \Phi_k \,.$$

CY (3,0)-form (0,1)-forms

Classical calculation (triple pairings of co-homology groups):

$$(\mathbf{d}) \quad H^1(\wedge^2\tilde{V}^*)^{(3,3+n)} \times H^1(\wedge^2\tilde{V}^*)^{(3,3+n)} \times H^1(\tilde{V}^*)^{(3,3)} \to H^3(\wedge^5\tilde{V}^*)^{(1,0)} \simeq \mathbb{C},$$

$$(\mathbf{u}) \quad H^1(\tilde{V}^*)_+^{(3,0)} \times H^1(\tilde{V}^*)_-^{(0,3)} \times H^1(\wedge^2\tilde{V})_-^{(0,n)} \to H^3(\mathcal{O})^{(1,0)} \simeq \mathbb{C},$$

$$(\mu) \quad H^1(\mathrm{ad}\tilde{V})_+^{(62,0)} \times H^1(\wedge^2\tilde{V}^*)_-^{(0,3+n)} \times H^1(\wedge^2\tilde{V})_-^{(0,n)} \to H^3(\mathcal{O})^{(1,0)} \simeq \mathbb{C},$$

(d) down-quark, charged lepton couplings, R-parity(Lepton, Baryon)-violating

(u) up-quark couplings

(μ) coupling w/ vector bundle moduli: μ-parameter & neutrino masses

Calculation Involved:

(i) exact spectral sequences, filtration & explicit basis for cohomology elements

(ii) Detailed study of vector bundle moduli space; specifically at n=1,2 loci

(d) Triple Pairing: Down-Sector and R-parity Violating Yukawa Couplings

ZERO! – ranks of cohomology groups- incompatible

$$\lambda_l^{ij} e_i L_j \bar{H} + \lambda_d^{ij} Q_i d_j \bar{H}$$

Charged leptons & down quarks massless

$$\alpha_1^{ijk} L_i L_j e_k + \alpha_2^{ijk} L_i Q_j d_k + \alpha_3^{ijk} u_i d_j d_k$$

R-parity (Lepton & Baryon no.) violating terms ABSENT!

(u) Triple Pairing: Up-Sector Yukawa Couplings

Locus w/ n=1 massless Higgs pair:

$$\lambda_u^{ij} Q_i u_j H \qquad \lambda_u = \begin{pmatrix} a & b & c \\ b & d & e \\ c & e & 0 \end{pmatrix}$$

Symmetric rank 3 matrix -(function of vector bundle moduli on n=1 locus)

Can obtain realistic mass hierarchy

(not quantitative- physical Yukawa couplings depend on Kähler pot.)

Locus w/ n= 2 massless Higgs pairs: two copies of the matrix above

(μ) Triple Pairing: μ-terms and Neutrino Yukawa Couplings

Locus w/ n=1 massless Higgs pair:

Moduli space transverse to n=1 locus 2-dimensional: Φ_1 and Φ_2

Non-zero triple pairing: $\lambda_1 \phi_1 \, H \, \bar{H} \; + \; \lambda_2 \phi_2 \, L \, \bar{H} \, .$

(a) Small deformation transvese to n=1 locus: e.g. $< \Phi_1 > \ll 1$
μ-parameter for the Higgs pair at EW scale (``fine tuning'')

Φ_2- right-handed neutrino & L-lepton doublet ➡ 1 massive neutrino

(b) On n=1 locus, both terms generate masses for 2 neutrinos and

no μ-parameter

Locus w/ n=2 massless Higgs pair: Moduli space transverse to n=1 locus

6-dimensional: Φ_{ij} (i=1,2.3: i=1.2)

Non-zero triple pairing:

$$W = \sum_{i=1}^{3} \sum_{j=1}^{2} \lambda_{ij} \, \phi_{ij} \, L_i \, \bar{H}_j$$

Can generate μ-parameters and/or up to 3 neutrino masses !

Conclusions:

An Heterotic MSSM passed crucial tests at the classical level of couplings:

(a) Up-quark sector: rank 3 matrix –possible realistic mass hierarchy

(b) Down-quark&charged lepton sector -massless

(c) R-parity (L&B) violating couplings –absent (proton stable)

(d) Vector bundle moduli (transverse to n=1,2 massless Higgs pair locus):

Can generate μ-parameters (non-zero VEV's) and/or play a role of right-handed neutrinos with up to 3 Dirac neutrino massive

Further tests at quantum (worldsheet instanton) level:

work in progress w/Bouchard&Donagi

(a) Masses for down-quark&charged lepton sector

Absence of R-parity violating couplings may impose constraints on Vector bundle moduli space

(b) Membrane-instanons-stabilisation/de-stabililisation 11th dimenision

work in progress w/Donagi,Li&Pantev

Is this THE model?

One of a large number with (semi)-realistic features - tip of the iceberg

Expect many more constructions on Calabi Yau threefolds both on Heterotic & Type II side

(employing algebraic geometry & CFT techniques)