Intersecting D-branes, Fluxes and ``Realistic'' Particle Physics

I. Supersymmetric Standard Model constructions w/ D-branes

Recent progress w/ systematic constructions: **w/ I. Papadimitriou '03**

w/ T. Li and T. Liu, hep-th/0403061

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

II. D-branes and Fluxes (moduli stabilization)

Standard-like Models with 3 & 4-chiral families & up-to 3-units of flux

w/ T. Liu hep-th/0409032; w/ T. Li and T. Liu, hep-th/0501041

Phenomenology of flux models **w/P.Langacker,T.Li and T.Liu, to appear**

Pedagogical revicw

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

Outline

- **Constructions w/ intersecting D-branes:**

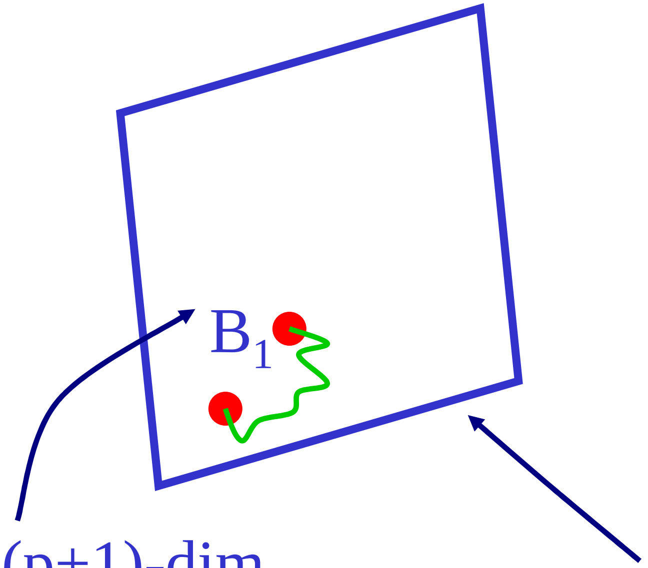
  Geometric origin of non-Abelian gauge symmetry&chirality

  [Standard Model $SU(3)_C \times SU(2)_L \times U(1)_Y$ &

  3-families: $Q_L \sim (\underline{3}, \underline{2}, {}^1/_6)$ –quarks L~ $(\underline{1}, \underline{2}, -1)$ –leptons]
- **Supersymmetric intersecting D-branes on orbifolds:**
  - **explicit constructions of supersymmetric Standard Models (spectrum, couplings)**
  - **systematic constructions**
- **Moduli stabilization – Fluxes**
  - **explicit examples of Standard Models w/ fluxes**
- **Conclusions/outlook**

D-branes & non-Abelian gauge theory

D p-branes



(p+1)-dim
World volume

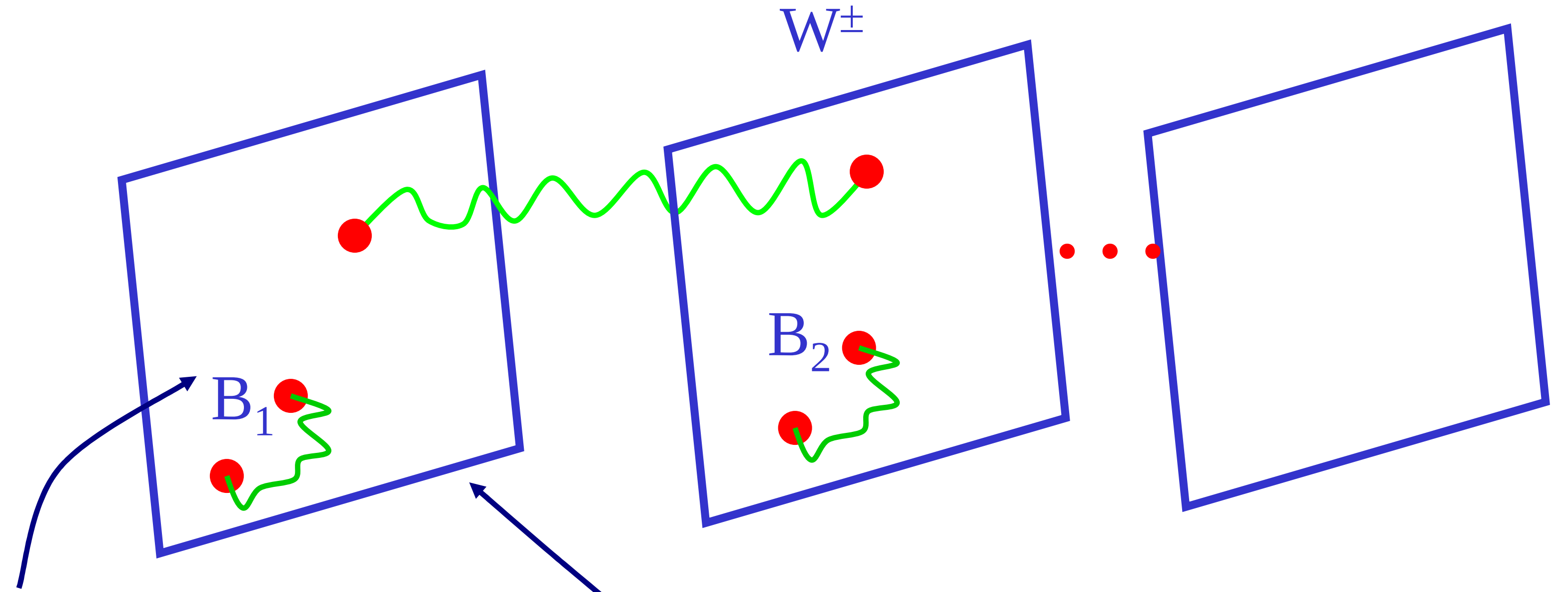
W_{p+1}

(9-p) – dim
transverse

U(1)

D-branes & non-Abelian gauge theory

D p-branes



(p+1)-dim
World volume

(9-p) – dim
transverse

n-coincident D-branes

$$U_1(1) \times U_2(1) \times \ldots U_n(1)$$
$$\downarrow$$
$$U(N)$$

non-Abelian
gauge symmetry

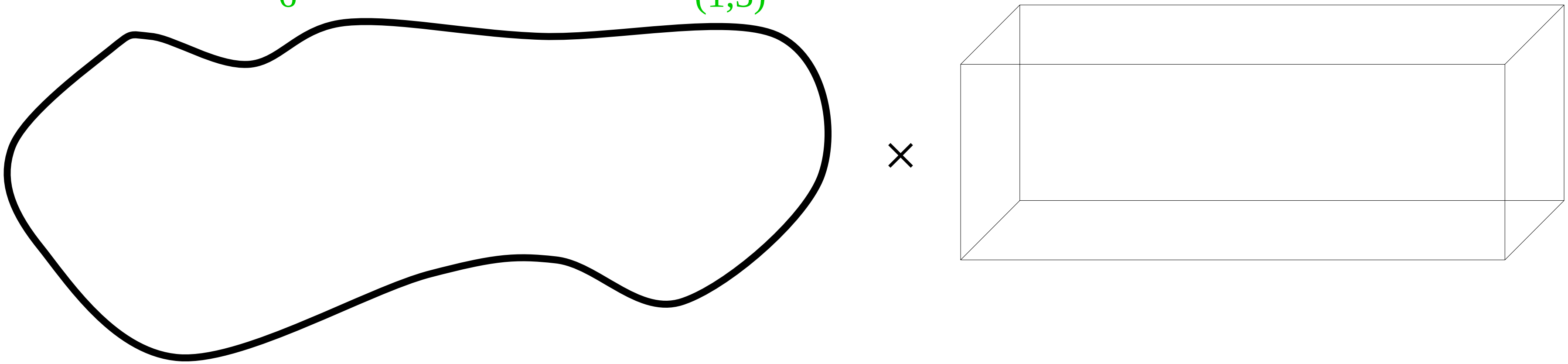
Compactification

D=10 → D=4

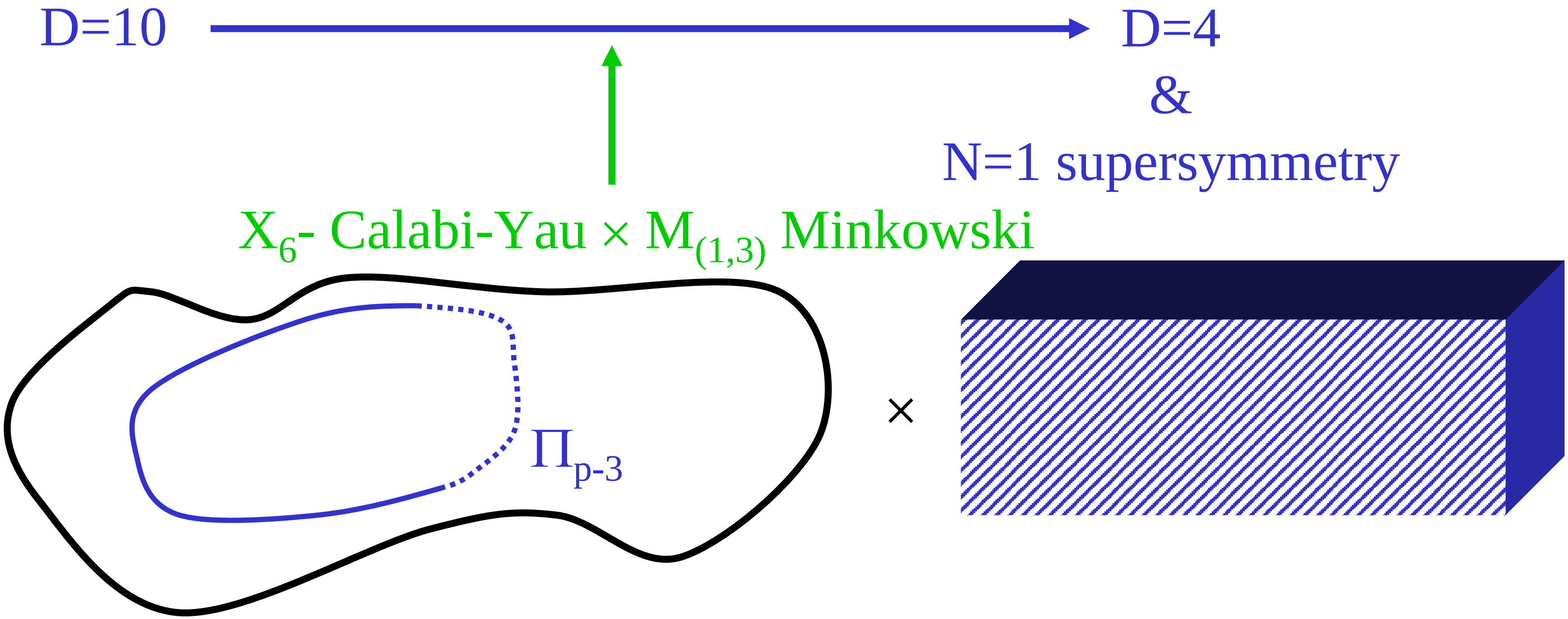
&

N=1 supersymmetry

X_6- Calabi-Yau × $M_{(1,3)}$ Minkowski



Compactification



D=10 → D=4

&

N=1 supersymmetry

X_6- Calabi-Yau × $M_{(1,3)}$ Minkowski

Π_{p-3} ×

D p-branes – $W_{p+1} \equiv \Pi_{p-3} \times M_{(3,1)}$

Wrap – (p-3) cycles of X_6

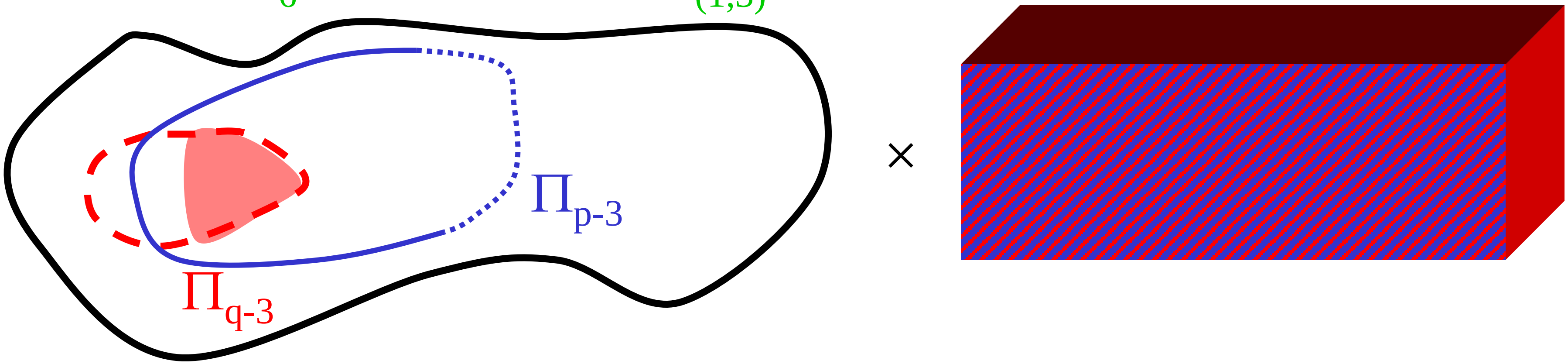
Compactification

D=10 $\xrightarrow{\hspace{6em}}$ D=4

&

N=1 supersymmetry

X_6- Calabi-Yau × $M_{(1,3)}$ Minkowski



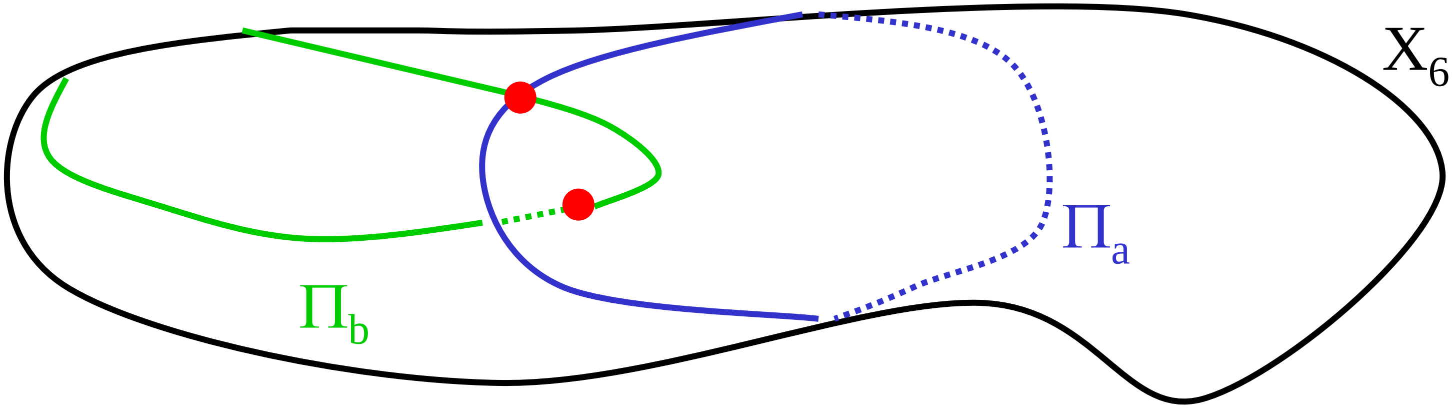
D p-branes – $W_{p+1} \equiv \Pi_{p-3} \times M_{(3,1)}$
Wrap – (p-3) cycles of X_6

D q-branes
Wrap (q-3) cycles

$$\left.\begin{array}{l}\Pi_{q-3} \cap \Pi_{p-3} \\ \Pi_{q-3} \subset \Pi_{p-3}\end{array}\right\} \text{Rich structure}$$

Focus on D6-branes – Realistic Particle Physics

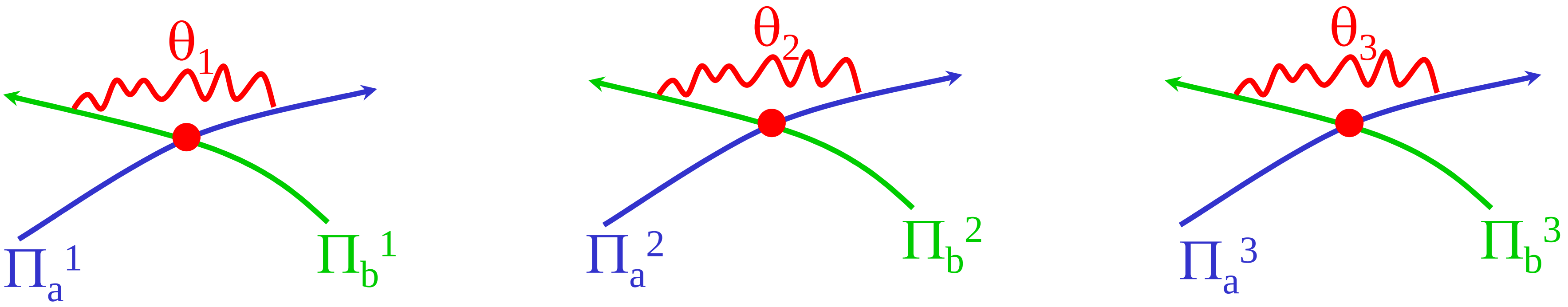
wrap 3-cycles Π



In internal space intersect at points:

$[\Pi_a] \circ [\Pi_b]$ - topological number

$\Pi_a = \Pi_a^1 \otimes \Pi_a^2 \otimes \Pi_a^3$ **– Factorizable 3-cycles**

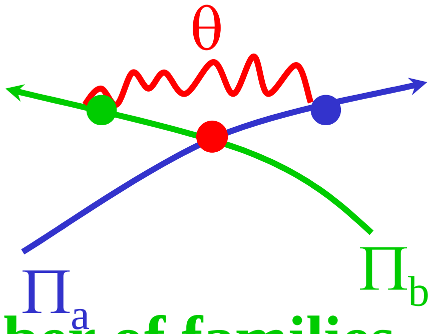


At each intersection – massless 4d fermion ψ!

Geometric origin of chirality!

Berkooz, Douglas & Leigh '96

Engineering of Standard Model



N_a- D6-branes wrapping Π_a

N_b- D6-branes wrapping Π_b

$U(N_a)$ x $U(N_b)$

$\Psi \sim (N_a , \overline{N}_b)$ - $[\Pi_a]°[\Pi_b]$ – number of families

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

$U(3)_C$ x $U(2)_L$

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

&

global consistency conditions & supersymmetry (later)

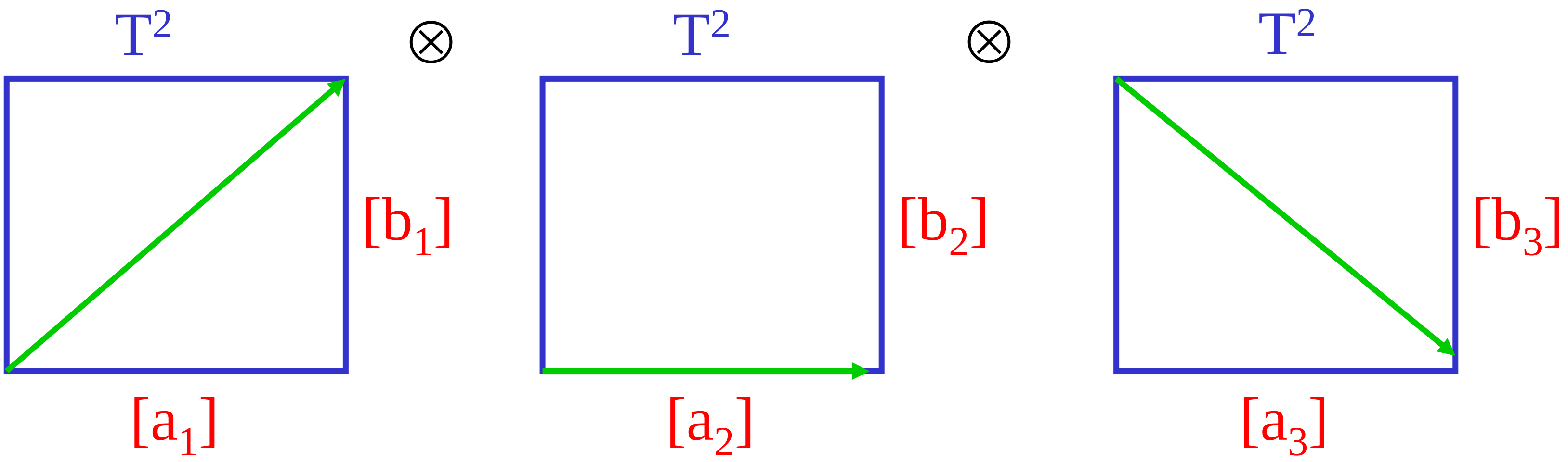
↓

Building Blocks of the Supersymmetric Standard Model

Toroidal/Orbifold compactifications
(calculation of spectrum w/ CFT-techniques)

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

$T^6 =$



$T^2 \otimes T^2 \otimes T^2$

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

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

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

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

homology class of 3-cycles

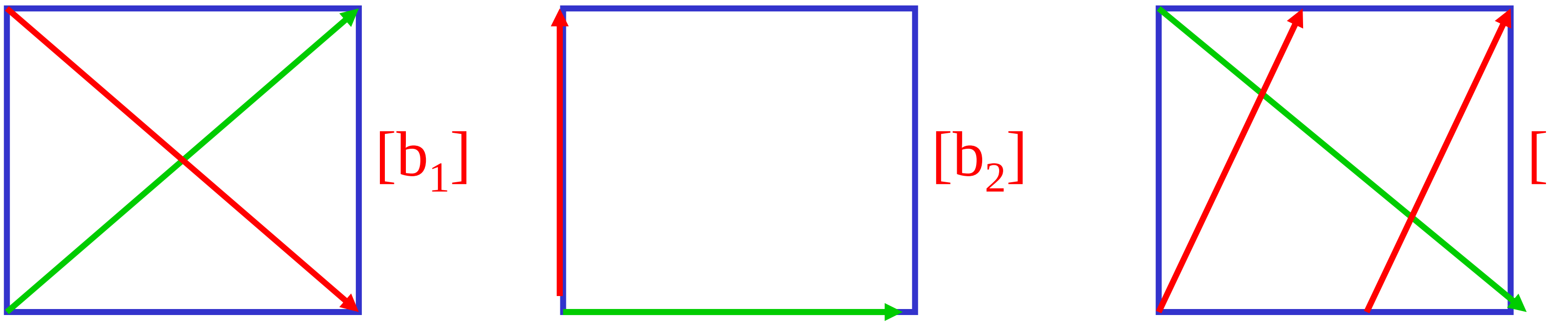
$[\Pi_a^i] = n_a^i [a_i] + m_a^i [b_i]$

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

Toroidal/Orbifold compactifications

CFT-technique

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



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

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

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

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

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

homology class of 3-cycles

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

$[N_a, n_a^{i,} m_a^i]$ $[N_b, n_b^{i,} m_b^i]$

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

Cancellation of Ramond-Ramond (RR) Tadpoles

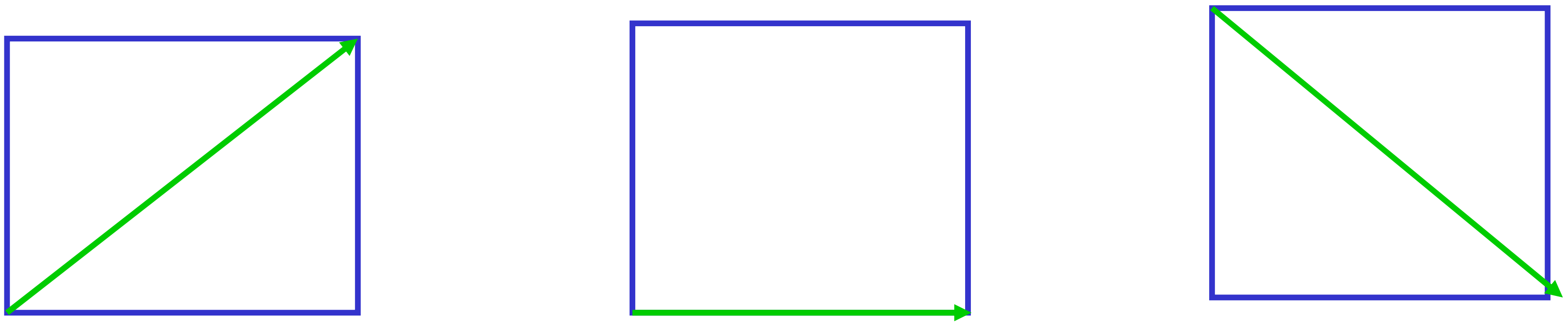
Blumenhagen, Görlich, Körs & Lüst ’00

D6-brane – source for C(7)

eq. for C(7) Gauss law for D6-charge conservation

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

Impossible to satisfy of CY spaces (``total’’tension~charge=0)



Global Consistency Conditions

Cancellation of Ramond-Ramond (RR) Tadpoles

Blumenhagen, Görlich, Körs & Lüst ’00

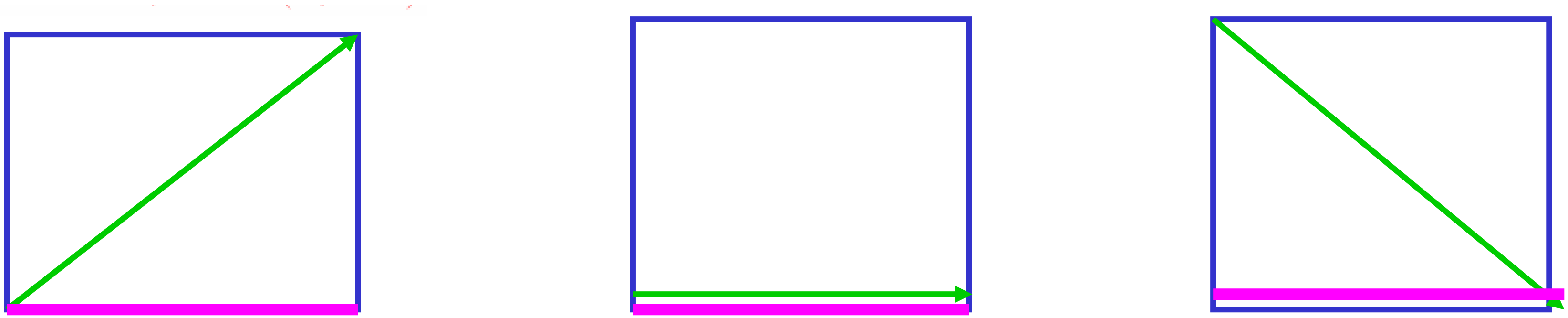
D6-brane – source for $C_{(7)}$

eq. for $C_{(7)}$ Gauss law for D6-charge conservation

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

Impossible to satisfy of CY spaces (``total’’tension = charge = 0)

Orientifold plane - fixed planes w/ negative RR charge



Global Consistency Conditions

Cancellation of Ramond-Ramond (RR) Tadpoles

Blumenhagen, Görlich, Körs & Lüst ’00

D6-brane – source for C(7) - RR potential

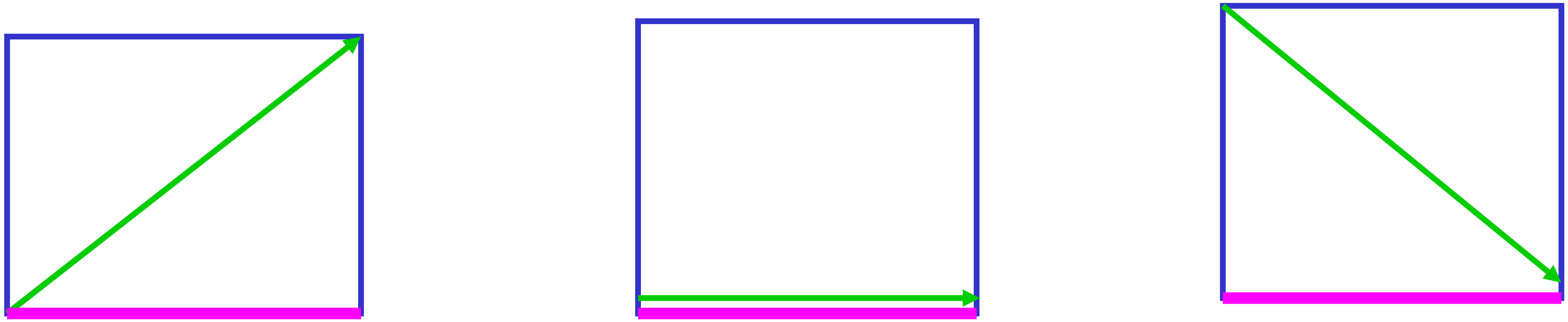
eq. for C(7) Gauss law for D6-charge conservation

$$\mathbf{N}_a \left([\Pi_a] + [\Pi_{a'}] \right) = -4\,[\Pi_{O6}]^{*}$$

* **Constraints on wrapping numbers**

Impossible to satisfy of CY spaces (``total’’tension = charge = 0)

Orientifold plane - fixed planes w/ negative D6- charge



Global consistency conditions

for toroidal/orbifold compactifications

$$
\begin{aligned}
\sum_a N_a \; n_a^1 n_a^2 n_a^3 &= 16 \\
\sum_a N_a \, n_a^1 m_a^2 m_a^3 &= 16 \\
\sum_a N_a \, m_a^1 n_a^2 m_a^3 &= 16 \\
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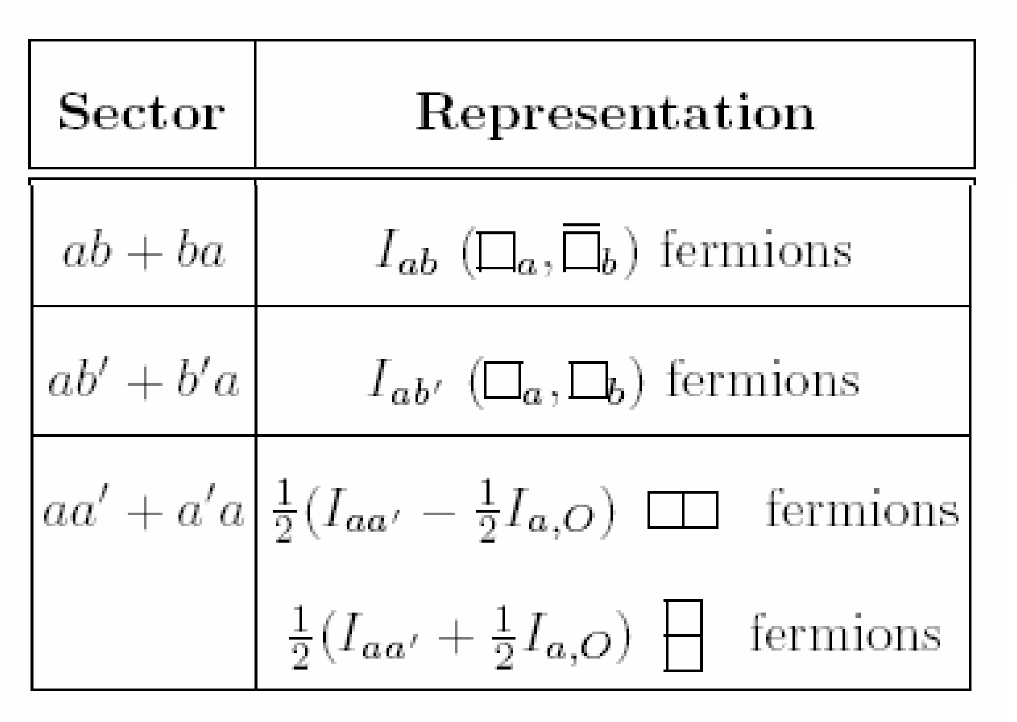
\end{aligned}
$$

Spectrum on toroidal orientifolds



Sector	**Representation**
$ab + ba$	$I_{ab}\ (\Box_a, \overline{\Box}_b)$ fermions
$ab' + b'a$	$I_{ab'}\ (\Box_a, \Box_b)$ fermions
$aa' + a'a$	$\frac{1}{2}(I_{aa'} - \frac{1}{2}I_{a,O})\ \Box\!\Box$ fermions $\frac{1}{2}(I_{aa'} + \frac{1}{2}I_{a,O})\ \begin{array}{c}\Box\\[-4pt]\Box\end{array}$ fermions

Angelantonj, Antoniadis,Dudas&Sagnotti’00

Non-Supersymmetric Standard-like Models (infinitely many)

Blumenhagen, Gorlich, Kors & Lust ’00-01

Aldazabal, Franco, Ibanez, Rabadan & Uranga ’00-’01

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$M_{string} \sim M_{planck}$ large NS-NS tadpole

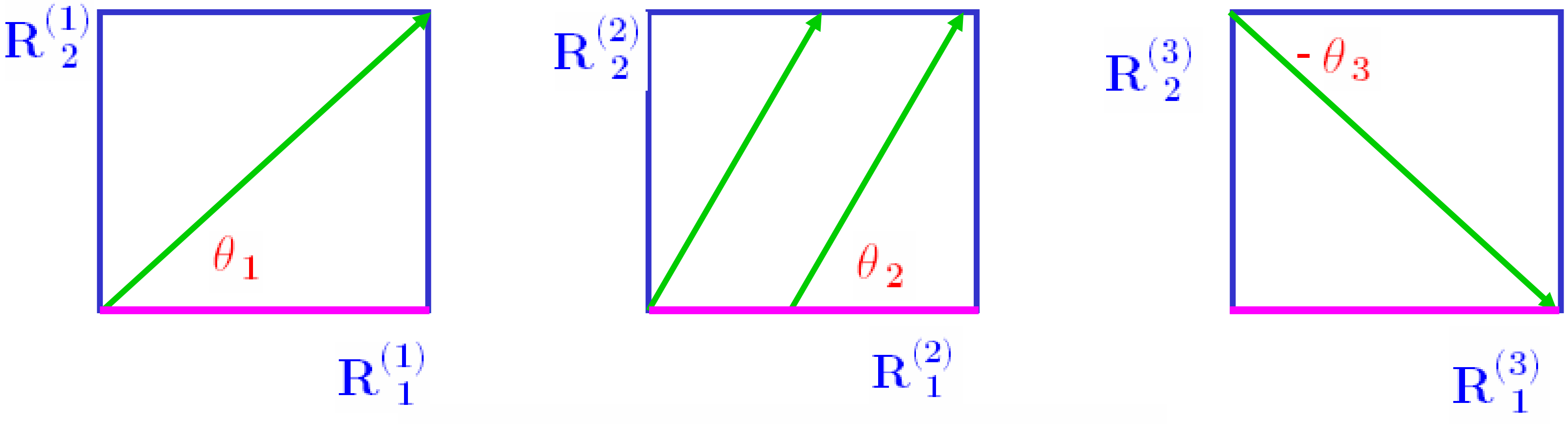
large radiative corrections

↓

Supersymmetric Standard-like Models (constrained)

w/ G. Shiu & A. Uranga ‘01

Supersymmetry (toroidal example)



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

$$\arctan\left(\frac{m_1}{n_1}\chi_1\right) + \arctan\left(\frac{m_1}{n_1}\chi_1\right) + \arctan\left(\frac{m_1}{n_1}\chi_1\right) = 0$$

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

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

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

w/G. Shiu & A. Uranga ’01

Original Model (Z_2 x Z_2 orientifold)

SM x U(1)` x U(1)`` x Sp(2) x Sp(2) x Sp(4)

~ electroweak scale

`` Hidden Sector’’

+ 3-families
- 12 pairs of Higgs doublets
- chiral exotics

(SM branes intersect w/hidden sector)

beta-functions ß < 0

infrared strong dynamics:

gaugino condensation:

SUSY breaking,{S,Ui}- moduli stabilisation

w/P. Langacker and J. Wang ‘03

-3chiral superfields on each set of D-branes-

-brane moduli (due to non-rigid cycles)

[3-adjoints for U(N); 3-antisymmetric rep. for Sp(N)]

`` a blessing’’ and `` a curse’’

Brane splitting-
Gauge symmetry breaking

Flat directions in moduli space

[c.f., work on rigid cycles: **w/R.Blumenhagen,F.Marchesano&G.Shiu,hep-th/0502095]**

Further Developments

(i) Systematic Construction - Z_2 x Z_2 orientifolds:

(a) More Standard-like Models (4)

SM x $U(1)_{B-L-T_{3R}}$ x U(1)' x "Hidden Sector''

Fewer exotics, 8-pairs of Higgs doublets w/I. Papadimitriou'03

(b) Systematic search for left-right symmetric models w/realistic features (11)

Only SM at electroweak scale; 2 models w/ only 2-Higgs doublets;

2-models with $g_{2L}=g_{2R}$; w/T. Li and T. Liu hep-th/0403061

(c) Standard-like Models w/ electroweak $Sp(2f)_L$ x $Sp(2f)_R$ sector (3)

Splitting of branes parallel w/ O6 planes;

f=4-family model w/no chiral exotics, $g_{2L}=g_{2R}$

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

(ii) Other orientifolds

(a) Z_4-orientifold (1) - brane recombination Blumenhagen, Gorlich & Ott'03

(b) Z_4 x Z_2-orientifold (1) - brane recombination Honecker'03

(c) Z_6-orientifold - just SM (1)-Yukawa couplings (?) Honecker & Ott '04

Further Developments

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Building blocks of Pati-Salam Models

$$U(4)_C \text{ x } U(2)_L \text{ x } U(2)_R \quad \text{x} \quad \underbrace{Sp(2n_1) \text{ x } Sp(2n_2) \text{ x } \ldots}$$

3 (4 , 2 , 1)

at least two confining group factors

3 (4 , 1 , 2)

(SUSY breaking, moduli stabilisation)

Symmetry breaking:

$$SU(4)_C \text{ x } SU(2)_L \text{ x } SU(2)_R \quad \text{x} \quad [U(1)_C \text{ x } U(1)_L \text{ x } U(1)_R]$$

brane splitting

brane splitting

(anomalous, $M_{Z'} \sim M_{string}$)

$$SU(3)_C \text{ x } U(1)_{B-L} \qquad U(1)_{T_{3R}}$$

vector pair $D_R = (4,1,2)$

$D_L = (4,2,1)$

D- and F-flat Higgsing

(brane recombination)

$$SU(3)_C \text{ x } SU(2)_L \text{ x } U(1)_Y$$

Just Standard Model!

Brane Splitting | | w/orientifold planes

[f-family SM from $Sp(2f)_L$ x $Sp(2f)_R$ electroweak sector]

Splitting of branes in
one, two, three
toroidal direction

⟷

VEV's to
one, two, three
(antisymm. rep.) moduli

Typical: $Sp(4k) \xrightarrow{\text{one}} Sp(2k) \times Sp(2k)$

$\xrightarrow{\text{two}} Sp(2k)$

$\xrightarrow{\text{three}} U(k)$,

$Sp(4k+2) \rightarrow Sp(2)$ x $Sp(4k)$
not suitable, e.g., 3-families

f=4: $U(4)_C$ x $Sp(8)_L$ x $Sp(8)_R$ $\longrightarrow$ $U(4)_C$ x $U(2)_L$ x $U(2)_R$

$1\ (4,\ 8,\ 1) \longrightarrow 4\ (4,\ 2,\ 1)$

$1\ (\bar{4},\ 1,\ 8) \longrightarrow 4\ (\bar{4},\ 1,\ 2)$

one –family   four-families

f=2: $U(4)_C$ x $Sp(4)_L$ x $Sp(4)_R$ $\longrightarrow$ $U(4)_C$ x $Sp(2)_L$ x $Sp(2)_R$

$1\ (4,\ 4,\ 1) \longrightarrow 2\ (4,\ 2,\ 1)$

$1\ (\bar{4},\ 1,\ 4) \longrightarrow 2\ (\bar{4},\ 1,\ 2)$

one-family   two-families

Chirality change due to splitting from orientifold singularity

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.

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	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	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!

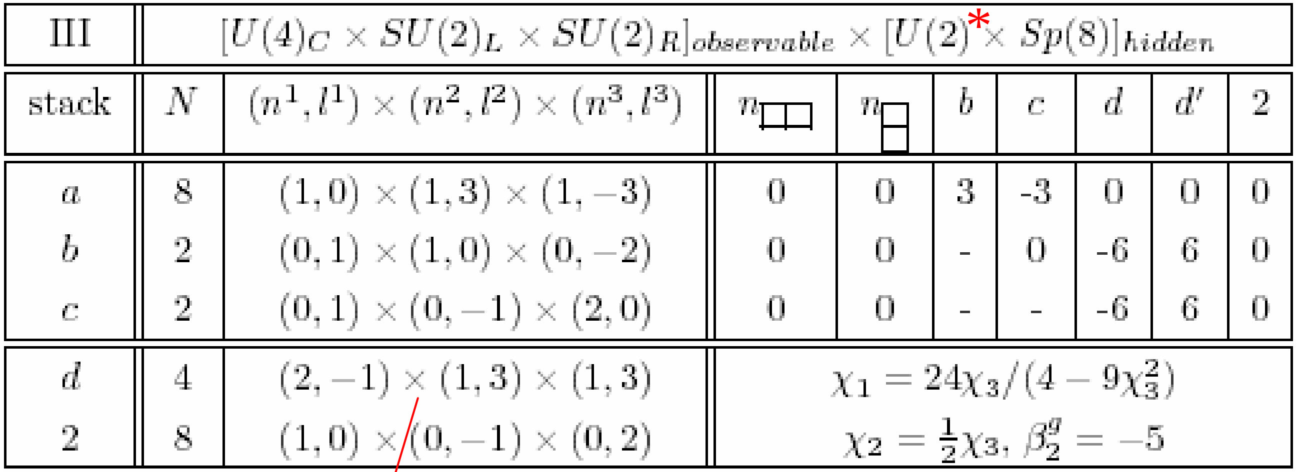
Sp(8)L x Sp(8)R   1-Higgs (8,8),   one-family   confining ``hidden sector

↓ brane splitting ↓ brane splitting ↓

U(2)L x U(2)R   16- Higgs (2,2),   four-families

U(1)L broken at electroweak scale

Three-family SM model w/Sp (2)$_L$ x Sp(2)$_R$ directly (Z$_2$ x Z$_2$ orientifold)



III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)^{*} \times Sp(8)]_{hidden}$									
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\!\square}$	$n_{\substack{\square\\ \square}}$	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-proposed for toroidal orientifold (did not cancel RR-tadpoles)

Cremades, Ibanez & Marchesano'03

Z$_2$ x Z$_2$ orientifold-allows for cancellation of RR-tadpoles

``hidden sector'' unitary symmetry- necessary for RR-tadpole cancellation

*U(2)-no global discrete Witten anomaly (original U(1)-Witten anomaly)

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

[one torus tilted: 2 Higgs (2,2), Yukawa couplings give mass to 2nd and 3rd family]

Moduli Stabilization

I. ``Hidden sector'' strong dynamics (ß < 0)- gaugino condensation

$$f_a = n_a^1 n_a^2 n_a^3 S - m_a^1 n_a^2 n_a^3 U_1 - n_a^1 m_a^2 n_a^3 U_2 - n_a^1 n_a^2 m_a^3 U_3$$

dilaton

complex structure moduli

gauge kin. function

Example of S, U_i-fixed, SUSY broken

w/Langacker&Wang'03

II. Supergravity Fluxes:

Type IIA- less understood; study of superpersymmetry conditions

examples of nearly Kahler spaces and **chiral non-Abelian D-brane sector (no time!)**

w/K. Behrndt hep-th/0308045, 0403049, 0407163

Type IIB- examples of SM with fluxes

Marchesano&Shiu hep-th/0408058,0409132

w/T.Liu/hep-th/0409032, w/T.Li&T.Liu, hep-th/0501041

Fluxes in Massive Type IIA

w/Behrndt hep/0408178

Supersymmetry conditions for general fluxes (w/components in the internal space& warped metric Ansatz):

$$ds_{10}^2 = \exp(A(y))\left[ds_4^2 + \exp(B(y))\left(h_{mn}\,dy^m dy^m\right)\right]$$

AdS4

(i) SU(3) structures: internal space nearly Kahler

unique solution w/ all fluxes turned on; warp factor and dilaton fixed;

Example: coset space $[SU(3)]^3/SU(2) \sim S^3 \times S^3$ allows for non-Abelian chiral intersecting D6-brane sector

(within M-theory c.f., Acharya,Denef, Hofman& Lambert’03)

H3- homology non-trivial;

{(1,0); (0,1); (-1,-1)}-Total homology 0!

Supersymmetric calibrated 3-cycles wrapped by D6-branes without orientifold planes! & orbifolding of $S^3 \times S^3$

U(N) x U(N) x U(N)

$\Psi_1 \sim (N , \bar{N} , 1)$

$\Psi_2 \sim (\bar{N} , 1 , N)$

$\Psi_3 \sim (1 , N , \bar{N})$

Fluxes in Massive Type IIA

w/Behrndt hep/0408178

Supersymmetry conditions for geneal fluxes (w/components in the internal space & Freund-Rubin Ansatz & warped metric Ansatz):

$$ds^2_{10} = \exp(A(y))\left[ds^2_4 + \exp(B(y))\,(h_{mn}\,dy^m\,dy^m)\right]$$

AdS4

(i) SU(3) structures: internal space nearly Kahler

unique solution w/ all fluxes turned on; warp factor and dilaton fixed

Example: **coset space S3 x S3- non-Abelian chiral intersecting D6-brane sector**

(within M-theory c.f., Acharya,Denef, Hofman& Lambert'03)

Minkowski

(ii) SU(2) structures: example of conformally flat internal space

A+iB=F(u+iv); Φ (u,v) & explicit fluxes; (u,v) –coordinates of an internal two-torus

Difficulties in accommodating orientifold/orbifold projection for D-brane sector

Type IIB theory & Fluxes

[D1,D3,D5,D7-branes] **[C(2n) – RR potentials]**

Fluxes better understood: supersymmetry conditions,
back-reaction due to fluxes,
potential for moduli etc.

Gukov,Vafa&Witten'99
Sethi et al. .
Giddings, Kachru&Polchinski'01
.
Kachru, Kallosh,Linde&Trivedi'03
.

rich phenomenologocal studies;
cosmology; landscape etc.

E.g.: **specific flux:** $G_3 = F_3 - \tau H_3$

RR-3form dilaton/axion NS-NS-3form

Supersymmetry: self-dual, primitive (2,1) form

Four-dim **superpotential:** $\mathbf{W} \sim \int \mathbf{\Omega} \wedge \mathbf{G}_{(3)} = \mathrm{f}^{\mathrm{I}}\,\mathrm{p}_{\mathrm{I}}$

complex structure moduli

Type IIA: Intersecting D6-branes

T-duality ($\mathrm{R}_1^{(i)} \rightarrow \frac{\alpha'}{\mathrm{R}_1^{(i)}}$)

Type IIB: Magnetized D9-branes

Cascales&Uranga'03

Blumenhagen,Lust&Taylor'03

$\{\mathrm{N_a}\ ,\ (\mathrm{n_a^i}\ ,\ \mathrm{m_a^i}\ )\ \}$

$$m_a^i \frac{1}{2\pi} \int_{\mathrm{T_i^2}} F_a^i = n_a^i$$

U(1)-D-brane magnetic field

$$Q3_a = N_a n_a^1 n_a^2 n_a^3,$$

$$(Q7_i)_a = N_a n_a^i m_a^j m_a^k,$$

$\mathbf{i} \neq \mathbf{j} \neq \mathbf{k}$

Flux: $G_3 = F_3 - \tau H_3$

$$N_{\rm flux} = \frac{1}{(4\pi^2\alpha')^2} \frac{i}{2\tau_I} \int_{X_6} G_3 \wedge \overline{G}_3$$

Contributes to $\mathrm{Q_{D3}}$ charge

Quantisation conditions: $\mathrm{N_{flux}} = \mathrm{n_f\, N_o}$ $\mathrm{n_f} \in \mathbf{Z}$ $\mathrm{N_o} = 64$

Specific to Z_2 x Z_2 orbifold

Global consistency conditions

For toroidal/orbifold compactifications

$$
\begin{aligned}
\sum_a N_a \; n_a^1 n_a^2 n_a^3 &= 16 \\
\sum_a N_a \, n_a^1 m_a^2 m_a^3 &= 16 \\
\sum_a N_a \, m_a^1 n_a^2 m_a^3 &= 16 \\
\sum_a N_a \, m_a^1 m_a^2 n_a^3 &= 16
\end{aligned}
$$

D-branes & Fluxes (Type IIB)

Global consistency conditions

for toroidal/orbifold compactifications

Q_{D3} $$\sum_a N_a \; n_a^1 n_a^2 n_a^3 = 16 \quad -N_{flux}$$

Q_{D7_1} $$\sum_a N_a \, n_a^1 m_a^2 m_a^3 = 16$$

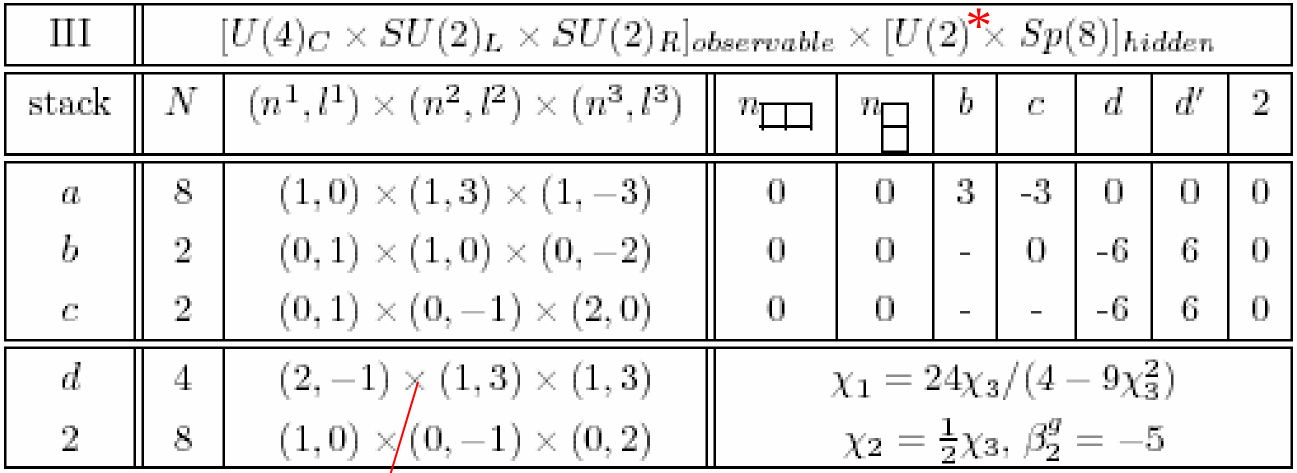
Q_{D7_2} $$\sum_a N_a \, m_a^1 n_a^2 m_a^3 = 16$$

Q_{D7_3} $$\sum_a N_a \, m_a^1 m_a^2 n_a^3 = 16$$

$$N_{flux} = n_f N_o$$

More Constrained !

Three-family SM model w/Sp (2)$_L$ x Sp(2)$_R$ directly (Z$_2$ x Z$_2$ orientifold)



III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)^{*} \times Sp(8)]_{hidden}$								
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\overset{\square}{\square}}$	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-proposed for toroidal orientifold (did not cancel RR-tadpoles)

Cremades, Ibanez & Marchesano'03

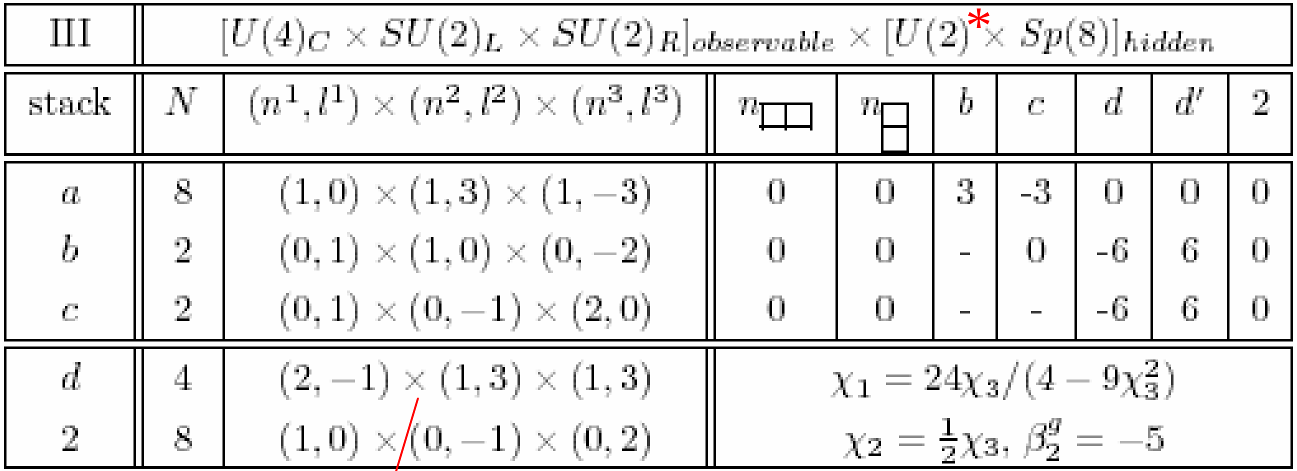
Z$_2$ x Z$_2$ orientifold-allows for cancellation of RR-tadpoles

``hidden sector'' unitary symmetry- necessary for RR-tadpole cancellation

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

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

Three-family SM model w/Sp (2)L x Sp(2)R directly ($Z_2 x Z_2$orientifold) & Fluxes



III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)^{*} \times Sp(8)]_{hidden}$								
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\ \square\end{smallmatrix}}$	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-proposed for toroidal orientifold (did not cancel RR-tadpoles)

Cremades, Ibanez & Marchesano’03

Z_2 x Z_2 orientifold-allows for cancellation of RR-tadpoles

``hidden sector’’ unitary symmetry- necessary for RR-tadpole cancellation

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

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

U(1) x U(1) n_f=1 flux units

Marchesano & Shiu, hep-th/0408058,0409132

[no untilted tori- 1 Higgs (2,2); Yukawa couplings give mass to 3rd family only; chiral exotics]

f-family Standard Model w/$Sp(2f)_L$ x$Sp(2f)_R$ & n_f-units of flux

w/T. Liu hep-th/0409032

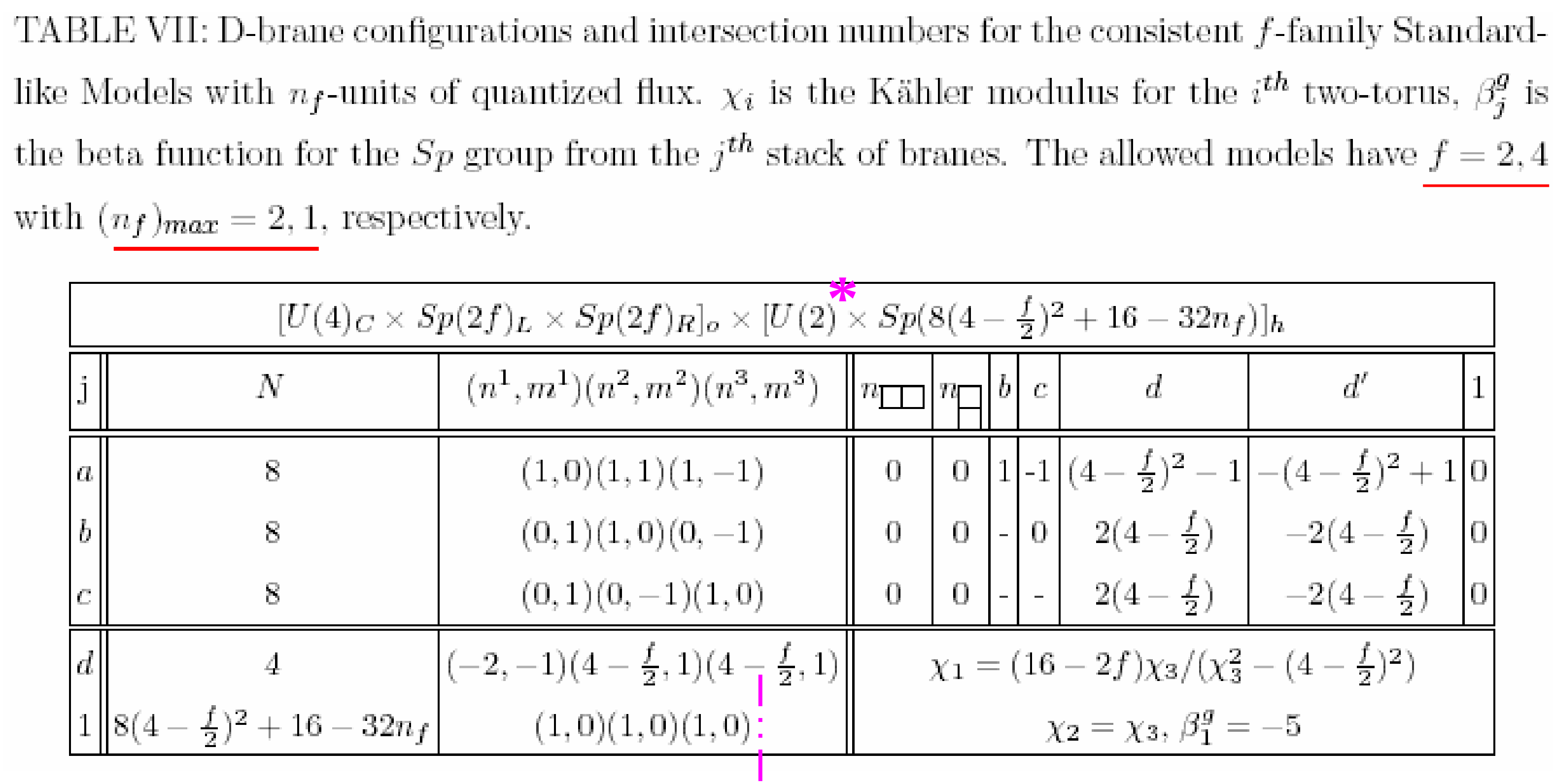


TABLE VII: D-brane configurations and intersection numbers for the consistent f-family Standard-like Models with n_f-units of quantized flux. χ_i is the Kähler modulus for the i^{th} two-torus, β^g_j is the beta function for the Sp group from the j^{th} stack of branes. The allowed models have $f = 2, 4$ with $(n_f)_{max} = 2, 1$, respectively.

$[U(4)_C \times Sp(2f)_L \times Sp(2f)_R]_o \times [U(2)^{*} \times Sp(8(4-\frac{f}{2})^2+16-32n_f)]_h$

j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\\square\end{smallmatrix}}$	b	c	d	d'	1
a	8	$(1,0)(1,1)(1,-1)$	0	0	1	-1	$(4-\frac{f}{2})^2-1$	$-(4-\frac{f}{2})^2+1$	0
b	8	$(0,1)(1,0)(0,-1)$	0	0	-	0	$2(4-\frac{f}{2})$	$-2(4-\frac{f}{2})$	0
c	8	$(0,1)(0,-1)(1,0)$	0	0	-	-	$2(4-\frac{f}{2})$	$-2(4-\frac{f}{2})$	0
d	4	$(-2,-1)(4-\frac{f}{2},1)(4-\frac{f}{2},1)$	$\chi_1 = (16-2f)\chi_3/(\chi_3^2-(4-\frac{f}{2})^2)$						
1	$8(4-\frac{f}{2})^2+16-32n_f$	$(1,0)(1,0)(1,0)$	$\chi_2 = \chi_3,\ \beta^g_1 = -5$						

intersections w/hidden sector chiral exotics

n_f=1, f=4: $Sp(8)_L$ x $Sp(8)_R$ $\xrightarrow{\text{brane splitting}}$ $U(2)_L$ x $U(2)_R$

n_f=2, f=2: $Sp(4)_L$ x $Sp(4)_R$ $\xrightarrow{\text{brane splitting}}$ $Sp(2)_L$ x $Sp(2)_R$

* **U(2)** w/ specific wrapping nos to cancel flux contrib. to Q_{D3} charge

A number of models have all toroidal Kahler moduli fixed due to SUSY constraints OR in some cases the ``hidden sector'' has confining Sp-type gauge symmetry (negative ß function), leading to gaugino condensation:

$$W_{eff} = \frac{\beta_1^g \Lambda^3}{32 e \pi^2} \exp(\frac{8\pi^2}{\beta_1^g} f_W(\frac{V_6}{g_s})) + W_o$$

Kahler modulus   flux contrib. (fixed complex structure moduli)

Kahler modulus - stabilised & SUSY restored (a la KKLT), however since $n_f=1,2,3$ $W_o \sim (M_{string})^3$ and thus the volume size- string size

The other two toroidal Kahler moduli - fixed by SUSY conditions for D-branes

⇓

An explicit chiral SM-like construction w/all toroidal moduli stabilised.

{However, twisted closed sector moduli not stabilised.

D-brane sector moduli: brane splitting moduli (non-chiral)-massive due to flux back-reaction; brane recombination moduli could combine w/ Kahler moduli to form D- and F-flat directions with Kahler moduli-problem!}

SUSY breaking → **anti D3-branes** (a la KKLT) w/T. Li &T. Liu hep-th/0501041

New Sets of Flux Models: D9-branes w/ negative D3 charge part of the Standard Model

Gauge symmetry: $U(4)_C \text{ x } \underset{\substack{\text{or}\\(Sp(2)_L)}}{U(2)_L} \text{ x } \underset{\substack{\text{or}\\(Sp(2)_R)}}{U(2)_R} \text{ x } \underbrace{Sp(2N_1) \text{ x } Sp(2N_2)\ldots}_{\text{``Hidden sector''}}$

SM sector contains D- branes with negative D3-charge

New models (on the order of 20) of three- and four-family Standard Models with up to 3-units of quantized flux.

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

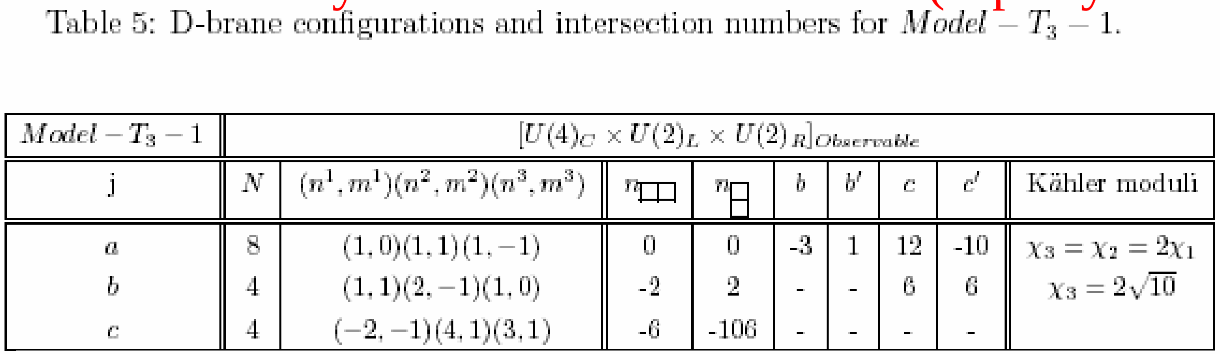


Table 5: D-brane configurations and intersection numbers for $Model - T_3 - 1$.

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

Three -family SM with 2- units of flux

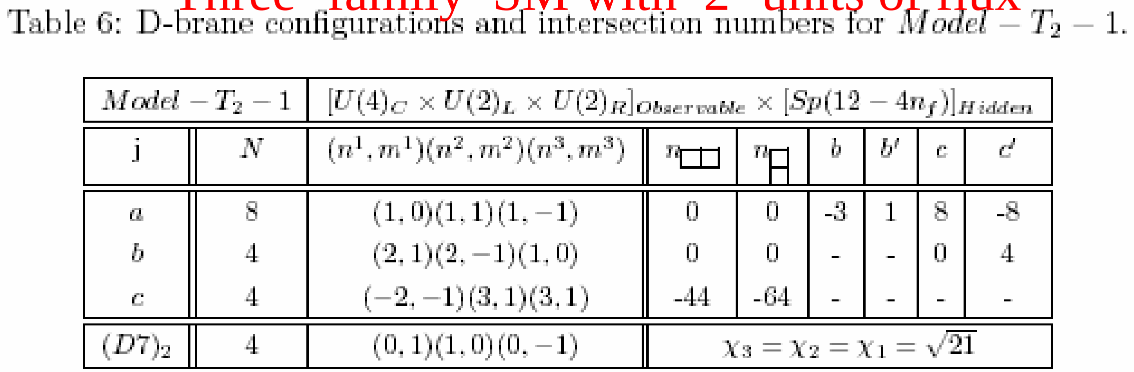


Table 6: D-brane configurations and intersection numbers for $Model - T_2 - 1$.

$Model - T_2 - 1$	$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable} \times [Sp(12-4n_f)]_{Hidden}$							
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	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

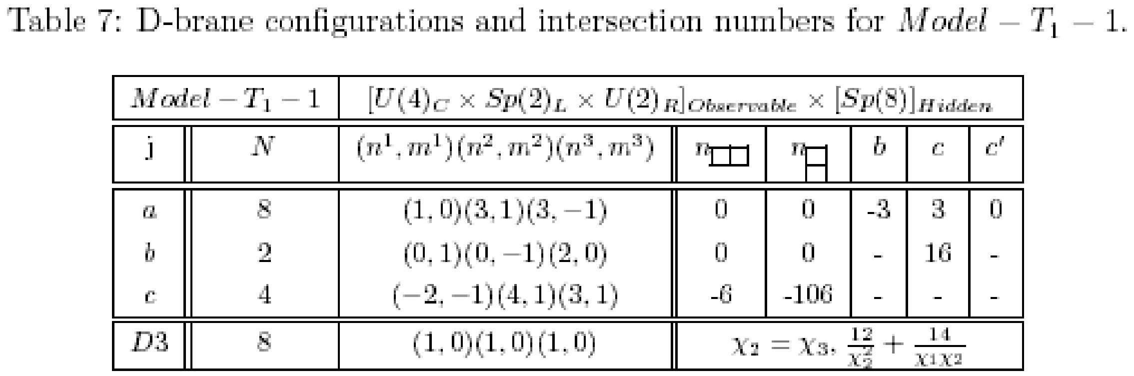


Table 7: D-brane configurations and intersection numbers for $Model - T_1 - 1$.

$Model - T_1 - 1$	$[U(4)_C \times Sp(2)_L \times U(2)_R]_{Observable} \times [Sp(8)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	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

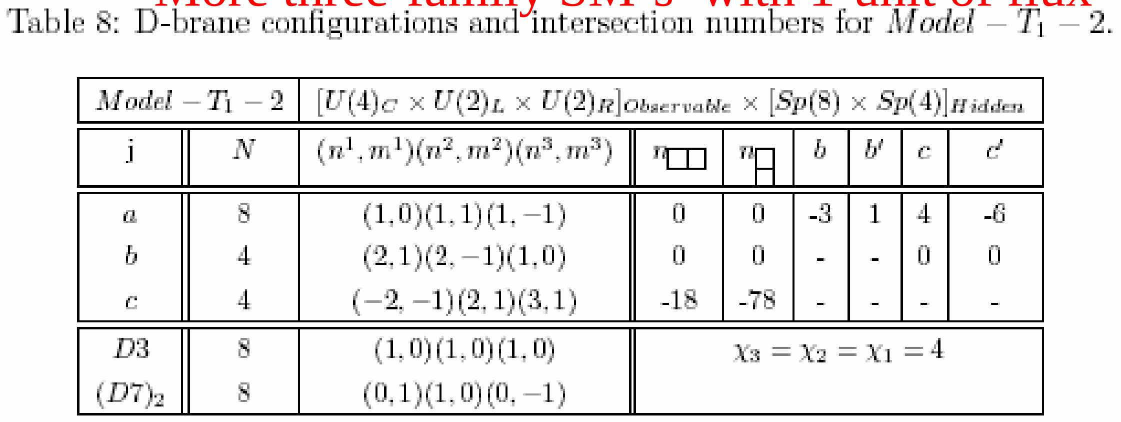


Table 8: D-brane configurations and intersection numbers for $Model - T_1 - 2$.

$Model - T_1 - 2$	$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable} \times [Sp(8) \times Sp(4)]_{Hidden}$							
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	$(0,1)(1,0)(0,-1)$						

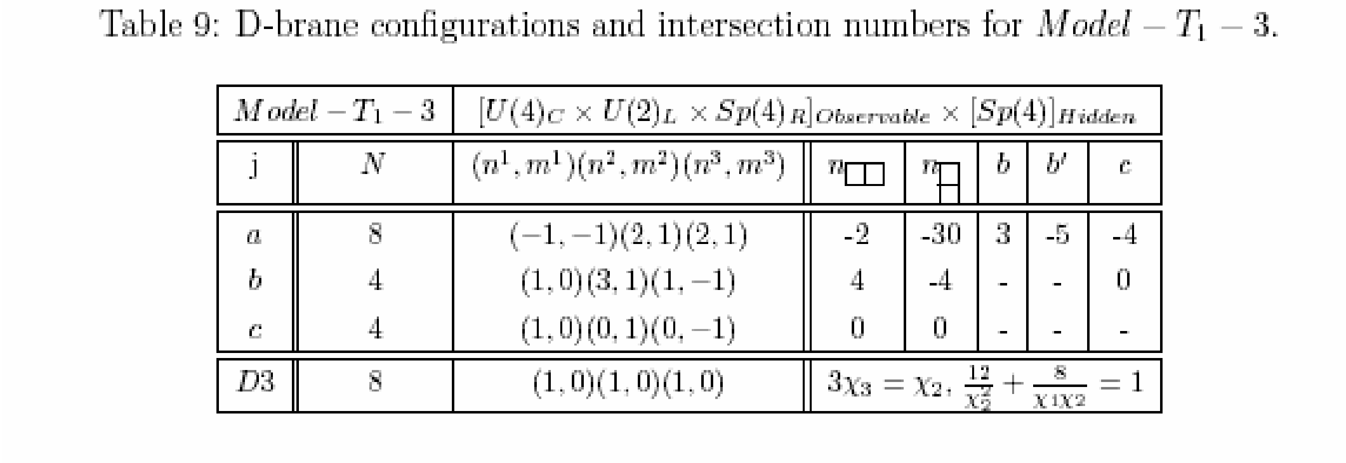


Table 9: D-brane configurations and intersection numbers for $Model - T_1 - 3$.

$Model - T_1 - 3$	$[U(4)_C \times U(2)_L \times Sp(4)_R]_{Observable} \times [Sp(4)]_{Hidden}$						
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	$(1,0)(1,0)(1,0)$	$3\chi_3 = \chi_2, \frac{12}{\chi_2^2} + \frac{8}{\chi_1\chi_2} = 1$				

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

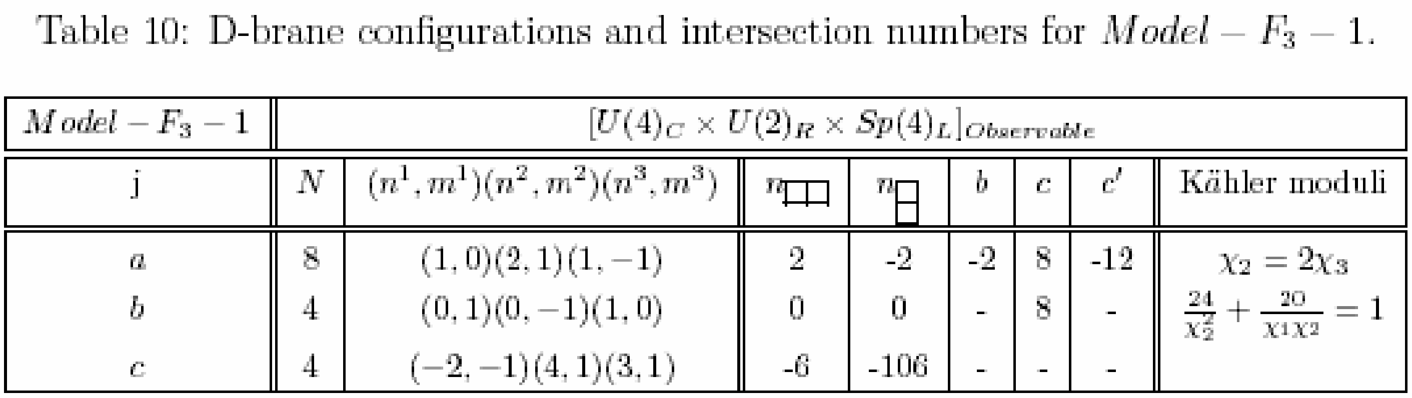
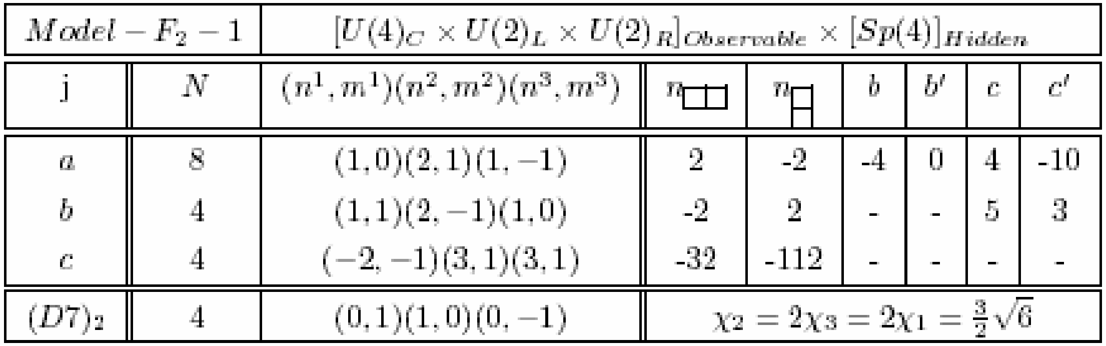


Table 10: D-brane configurations and intersection numbers for $Model - F_3 - 1$.

$Model - F_3 - 1$	$[U(4)_C \times U(2)_R \times Sp(4)_L]_{Observable}$							
j	N	$(n^1, m^1)(n^2, m^2)(n^3, m^3)$	$n_{\Box\!\Box}$	$n_{\substack{\Box\\\Box}}$	b	c	c'	Kähler moduli
a	8	$(1,0)(2,1)(1,-1)$	2	-2	-2	8	-12	$\chi_2 = 2\chi_3$ $\frac{24}{\chi_2^2} + \frac{20}{\chi_1\chi_2} = 1$
b	4	$(0,1)(0,-1)(1,0)$	0	0	-	8	-	
c	4	$(-2,-1)(4,1)(3,1)$	-6	-106	-	-	-	

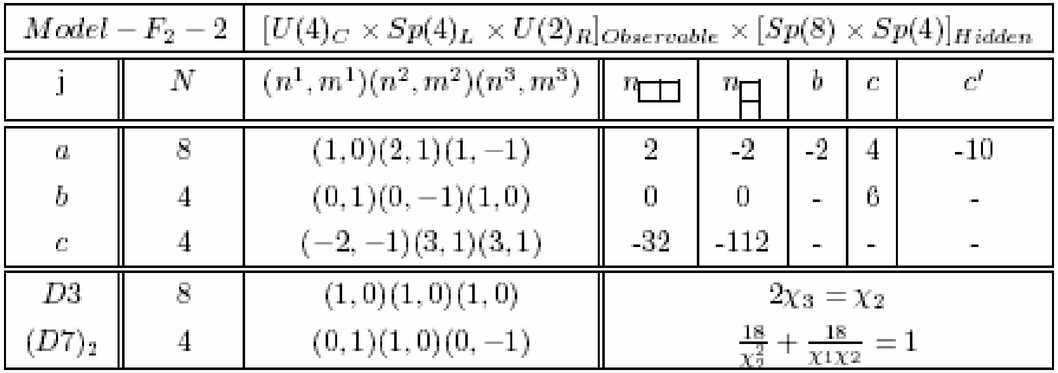
Four-family SM's with 2-units of flux

Table 11: D-brane configurations and intersection numbers for $Model - F_2 - 1$.



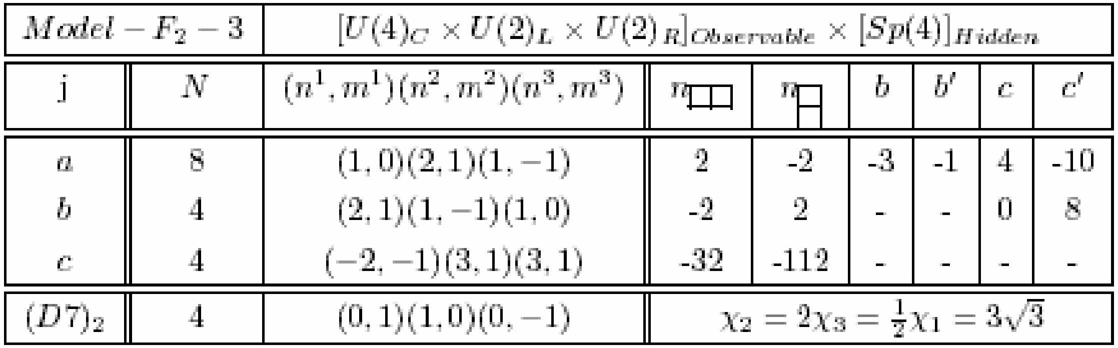
$Model - F_2 - 1$		$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable} \times [Sp(4)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	b	b'	c	c'
a	8	$(1,0)(2,1)(1,-1)$	2	-2	-4	0	4	-10
b	4	$(1,1)(2,-1)(1,0)$	-2	2	-	-	5	3
c	4	$(-2,-1)(3,1)(3,1)$	-32	-112	-	-	-	-
$(D7)_2$	4	$(0,1)(1,0)(0,-1)$	$\chi_2 = 2\chi_3 = 2\chi_1 = \frac{3}{2}\sqrt{6}$					

Table 12: D-brane configurations and intersection numbers for $Model - F_2 - 2$.



$Model - F_2 - 2$		$[U(4)_C \times Sp(4)_L \times U(2)_R]_{Observable} \times [Sp(8) \times Sp(4)]_{Hidden}$					
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	b	c	c'
a	8	$(1,0)(2,1)(1,-1)$	2	-2	-2	4	-10
b	4	$(0,1)(0,-1)(1,0)$	0	0	-	6	-
c	4	$(-2,-1)(3,1)(3,1)$	-32	-112	-	-	-
$D3$ $(D7)_2$	8 4	$(1,0)(1,0)(1,0)$ $(0,1)(1,0)(0,-1)$	$2\chi_3 = \chi_2$ $\frac{18}{\chi_2^2} + \frac{18}{\chi_1\chi_2} = 1$				

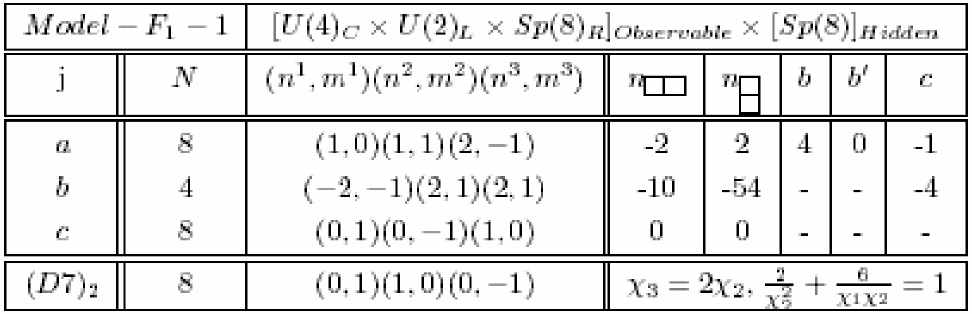
Table 13: D-brane configurations and intersection numbers for $Model - F_2 - 3$.



$Model - F_2 - 3$		$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable} \times [Sp(4)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	b	b'	c	c'
a	8	$(1,0)(2,1)(1,-1)$	2	-2	-3	-1	4	-10
b	4	$(2,1)(1,-1)(1,0)$	-2	2	-	-	0	8
c	4	$(-2,-1)(3,1)(3,1)$	-32	-112	-	-	-	-
$(D7)_2$	4	$(0,1)(1,0)(0,-1)$	$\chi_2 = 2\chi_3 = \frac{1}{2}\chi_1 = 3\sqrt{3}$					

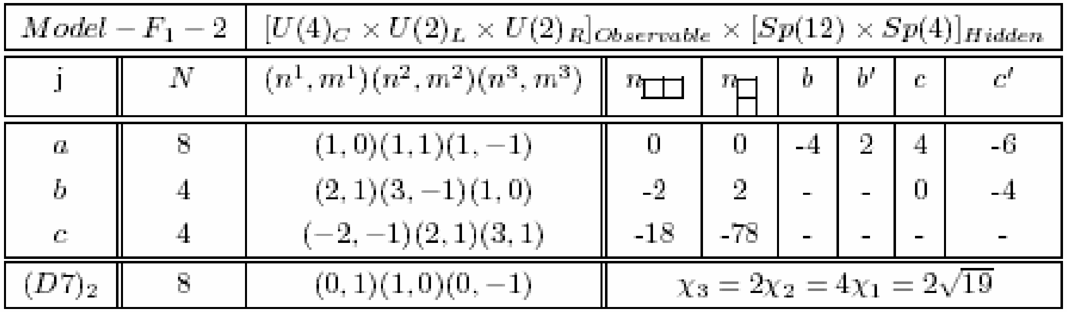
Four- family SM's with 1-unit of flux

Table 14: D-brane configurations and intersection numbers for $Model - F_1 - 1$.



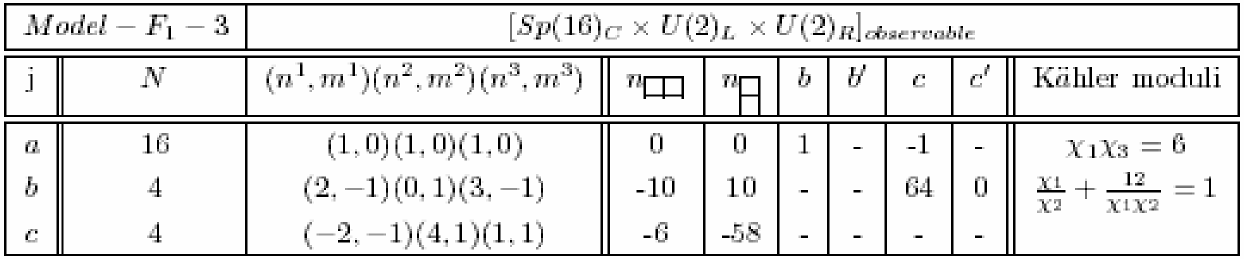
$Model - F_1 - 1$	$[U(4)_C \times U(2)_L \times Sp(8)_R]_{Observable} \times [Sp(8)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\\square\end{smallmatrix}}$	b	b'	c
a	8	$(1,0)(1,1)(2,-1)$	-2	2	4	0	-1
b	4	$(-2,-1)(2,1)(2,1)$	-10	-54	-	-	-4
c	8	$(0,1)(0,-1)(1,0)$	0	0	-	-	-
$(D7)_2$	8	$(0,1)(1,0)(0,-1)$	$\chi_3 = 2\chi_2,\ \frac{2}{\chi_3^2} + \frac{6}{\chi_1\chi_2} = 1$				

Table 15: D-brane configurations and intersection numbers for $Model - F_1 - 2$.



$Model - F_1 - 2$	$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable} \times [Sp(12) \times Sp(4)]_{Hidden}$							
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\\square\end{smallmatrix}}$	b	b'	c	c'
a	8	$(1,0)(1,1)(1,-1)$	0	0	-4	2	4	-6
b	4	$(2,1)(3,-1)(1,0)$	-2	2	-	-	0	-4
c	4	$(-2,-1)(2,1)(3,1)$	-18	-78	-	-	-	-
$(D7)_2$	8	$(0,1)(1,0)(0,-1)$	$\chi_3 = 2\chi_2 = 4\chi_1 = 2\sqrt{19}$					

Table 16: D-brane configurations and intersection numbers for $Model - F_1 - 3$.



$Model - F_1 - 3$	$[Sp(16)_C \times U(2)_L \times U(2)_R]_{observable}$								
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\\square\end{smallmatrix}}$	b	b'	c	c'	Kähler moduli
a	16	$(1,0)(1,0)(1,0)$	0	0	1	-	-1	-	$\chi_1\chi_3 = 6$
b	4	$(2,-1)(0,1)(3,-1)$	-10	10	-	-	64	0	$\frac{\chi_1}{\chi_2} + \frac{12}{\chi_1\chi_2} = 1$
c	4	$(-2,-1)(4,1)(1,1)$	-6	-58	-	-	-	-	

I.Moduli Stabilization:

Toroidal somplex structure moduli-fixed by fluxes.

In some cases all toroidal Kahler moduli fixed by SUSY OR

Examples of two Kahler moduli fixed by SUSY & a hidden sector, w/ negative ß **function,** resulting in gaugino condensation and non-perturbative superpotential:

$$W_{eff} = \frac{\beta_1^g \Lambda^3}{32 e \pi^2} \exp(\frac{8\pi^2}{\beta_1^g} f_W(\frac{V_6}{g_s})) + W_o$$

third Kahler modulus flux contrib.(fixed complex structure moduli)

All toroidal Kahler moduli stabilized & SUSY restored

An explicit chiral SM-like construction w/all toroidal moduli stabilized.

II. Further Phenomenology:

w/P. Langacker, T. Li & T. Liu, to appear

(mainly right) chiral exotics w/ Yukawa couplings to SM Higgs sector (M~ TeV); Higgs sector non-minimal, allowing for quark and lepton masses

III. Analysis of soft SUSY breaking mass terms:

One- and two-units of fluxes (and no hidden sector strong dynamics) break SUSY-

Camara,Ibanez&Uranga, hep-th/0408064; Lust, Reffert&stieberger, hep-th/0410074; Kane,Kumar,Lykken&Wang, hep-th/0411125; . . . . .

Flux SM's with Confining Hidden Sector that stabilizes the left-over Kahler modulus

$Model-F_1-5$		$[U(4)_C \times Sp(8)_L \times U(2)_R]_{Observable} \times [Sp(4) \times Sp(4)]_{Hidden}$					
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\\square\end{smallmatrix}}$	b	c	c'
a	8	$(1,0)(1,1)(1,-1)$	0	0	-1	6	-4
b	8	$(0,1)(0,-1)(1,0)$	0	0	-	3	-
c	4	$(-1,-1)(3,1)(2,1)$	-4	-44	-	-	-
$(D7)_1$	4	$(1,0)(0,1)(0,-1)$	$\chi_2=\chi_3,\ \frac{6}{\chi_3^2}+\frac{5}{\chi_1\chi_3}=1$				
$(D7)_2$	4	$(0,1)(1,0)(0,-1)$	$\beta^g_{(D7)_1}=-3(0),\ \beta^g_{(D7)_2}=-5(-2)$				

Conclusions/Outlook

(i) Overview/status of supersymmetric intersecting D-brane constructions w/realisitic particle physics:

(a) Major progress: development of techniques for consistent constructions on toroidal/orbifold orientifolds (geometric): explicit spectrum & couplings (no time!)

(b) Sizable nos of semi-realistic models (on the order of 20); within Z_2 x Z_2 orientifolds - systematic search (w/ SM, 3 families) leading to construction of (most) classes of models there. Ready for landscape study (???)

(c) `` The devil is in the details!'':

chiral exotics (except a 4-family example)

realistic Higgs sector and/or Yukawa couplings

[geometric w/hierarchy (no time!)]

(ii) Intersecting D-branes and Fluxes

(a) Type IIA: fluxes less explored, but recent progress:
examples of nearly Kahler internal spaces
w/ chiral non-Abelian intersecting D-brane sector

(b) Type IIB: Chiral SM constructions w/fluxes
intersecting D-branes → magnetized D-branes
On the order of 20 SM's with 3- and 4-families and
up to 3-units of quantised flux.
Just scratching the surface!

FULLY REALISTIC CONSTRUCTIONS –at least at the level of spectrum, coupling and all moduli stabilization (???)

TECHNIQUES TO ADDRESS THE LANDSCAPE
OF REALISTIC MODELS (???)