Title: Chiral Flux Compactifications and 'Realistic' Particle Physics

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Abstract:

Chiral Flux Flux Compactifications 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

w/R.Blumenhagen, F.Marchesano and G.Shiu, hep-th/0502095

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

Outline

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

  Geometric origin of non-Abelian gauge symmetry&chirality

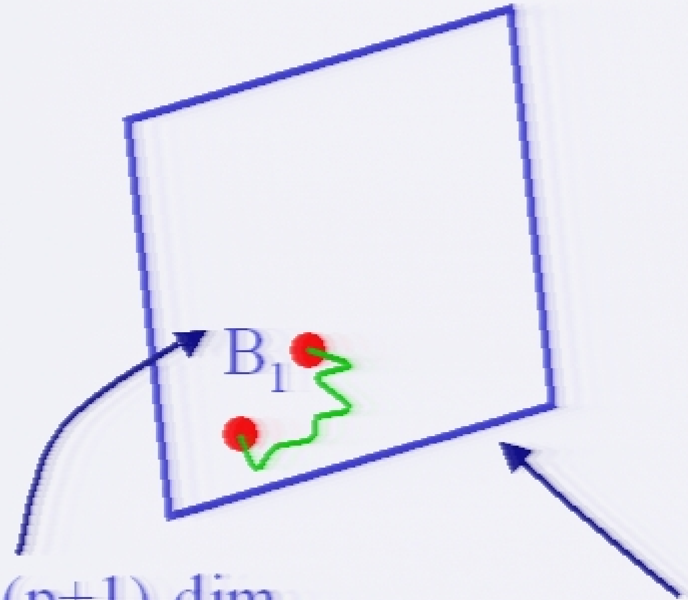
  [Standard Model $SU(3)_C \times SU(2)_L \times U(1)_Y$ &

  3-families: $Q_L \sim (\underline{3}, \underline{2}, {}^{1}/_{6})$ –quarks $L \sim (\underline{1}, \underline{2}, -1)$ –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
  - phenomenology
- **Conclusions/outlook**

D-branes & non-Abelian gauge theory

D p-branes



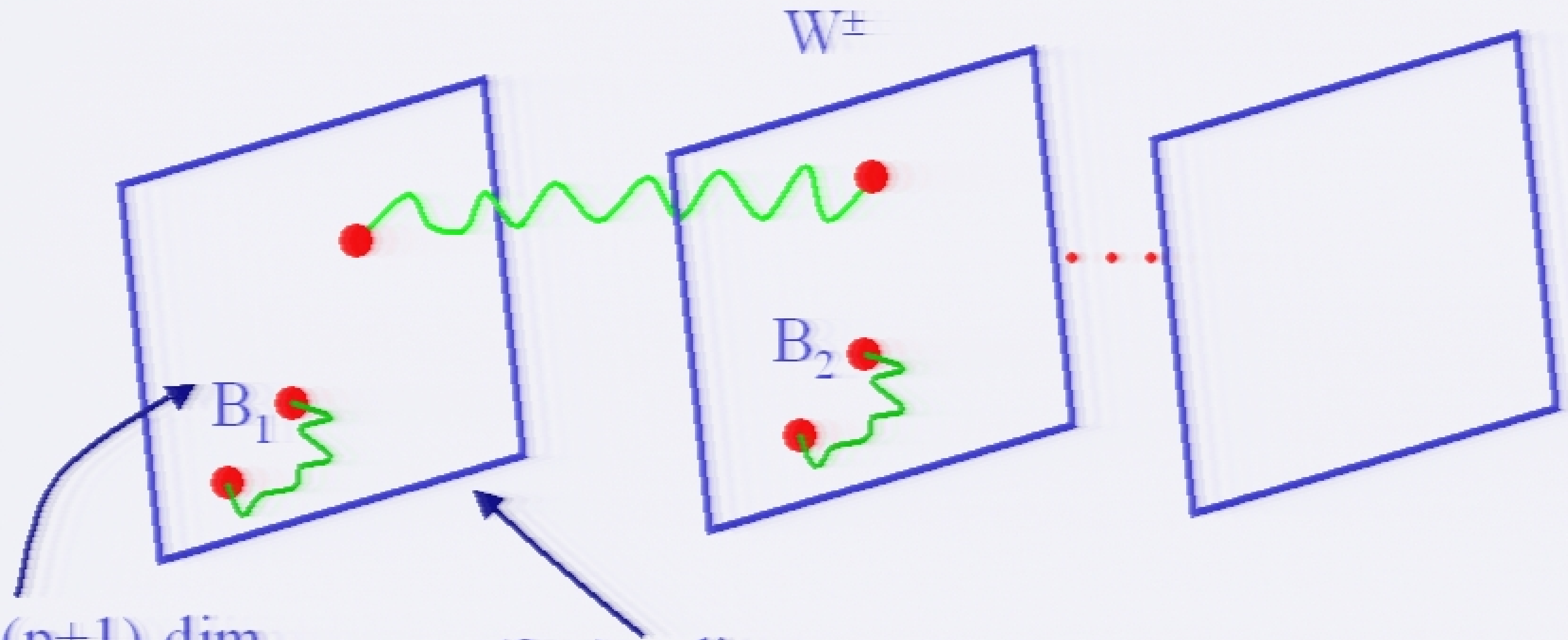
(p+1)-dim
World volume
W_{p+1}

(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

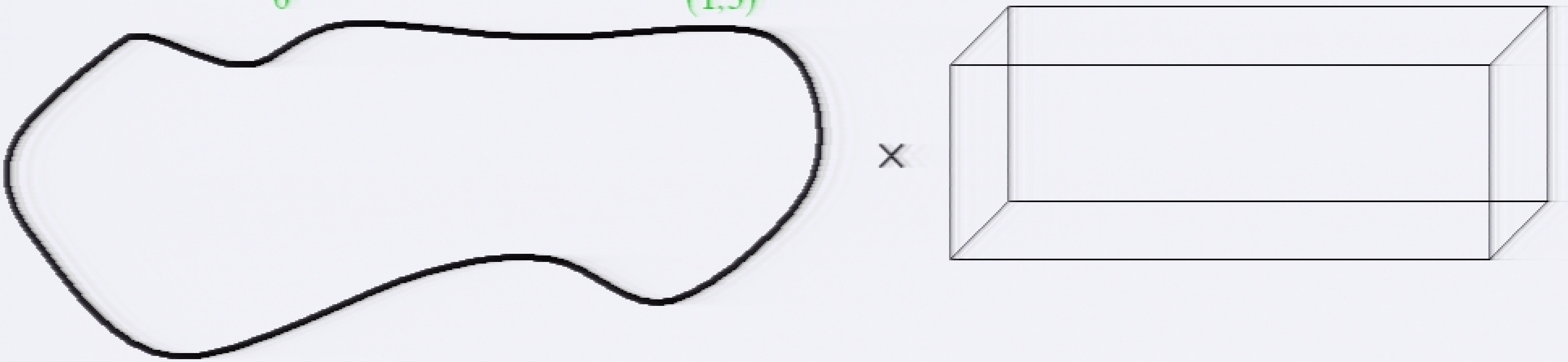
$D=10 \xrightarrow{\hspace{4em}} D=4$

&

$N=1$ supersymmetry

$\uparrow$

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



Compactification

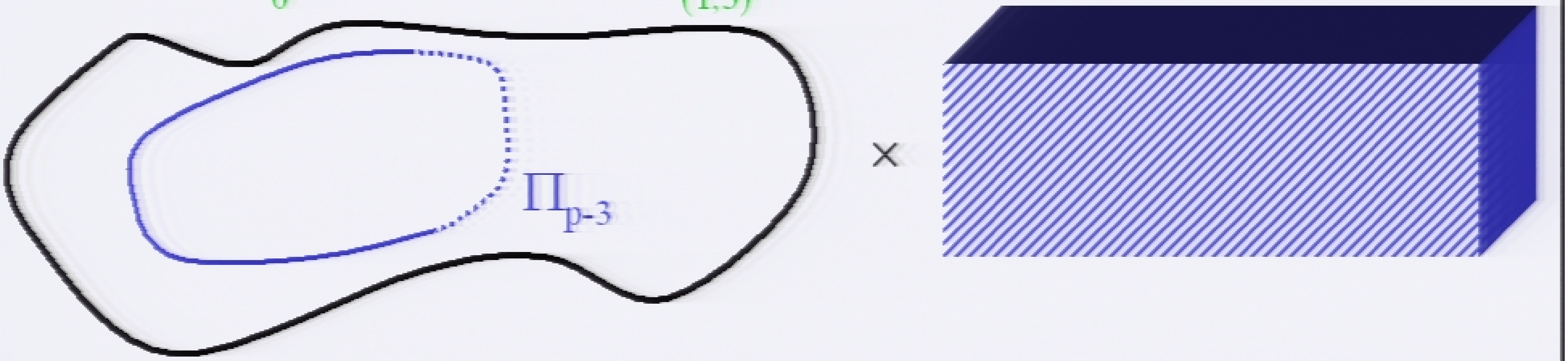
$D=10 \longrightarrow D=4$

&

N=1 supersymmetry

$\uparrow$

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

Compactification

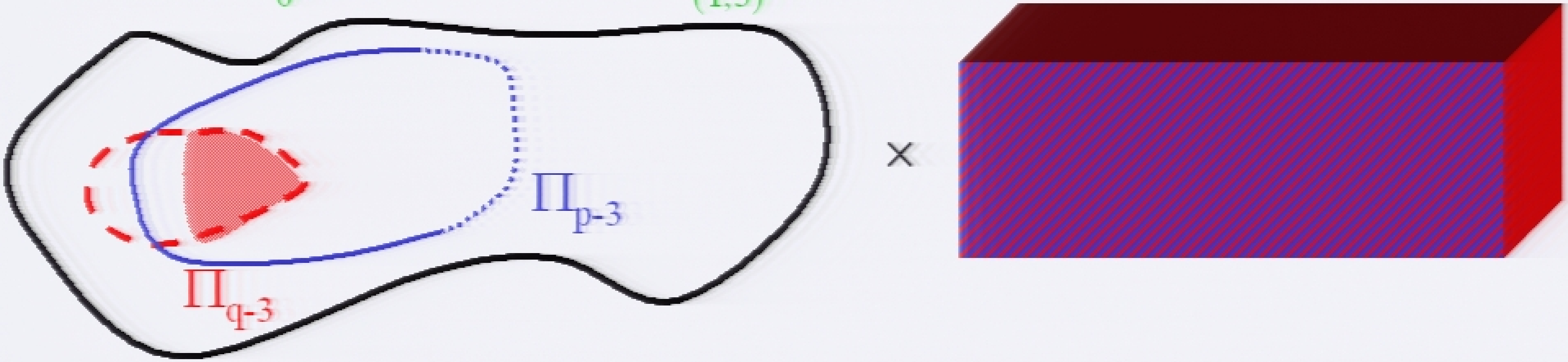
$D=10 \longrightarrow D=4$

&

N=1 supersymmetry

$\uparrow$

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

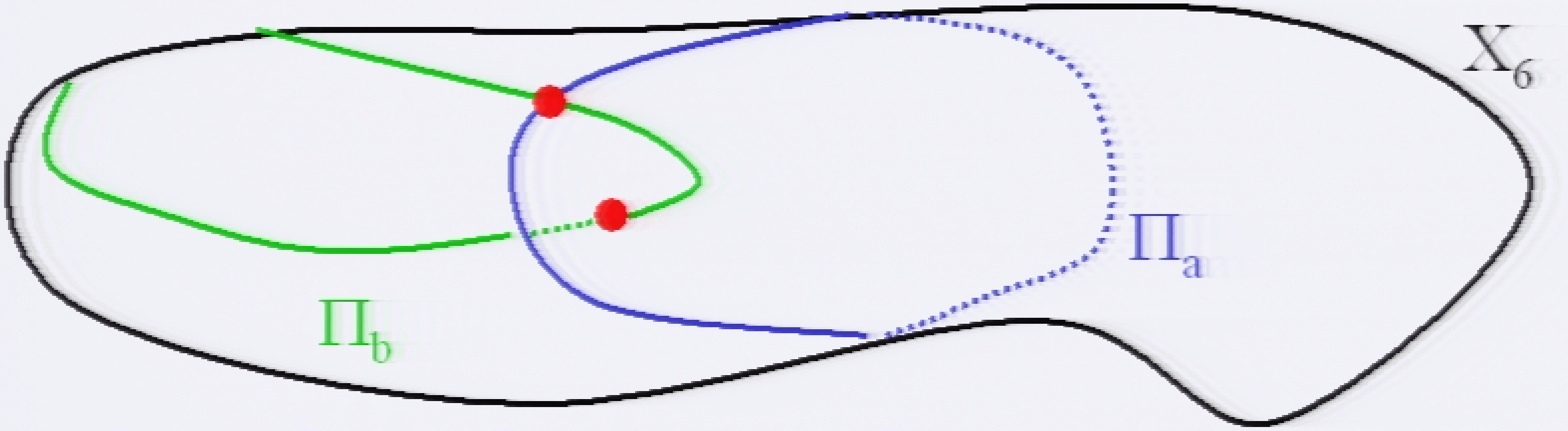
D q-branes

Wrap (q-3) cycles

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

Focus on D6-branes – Realistic Particle Physics

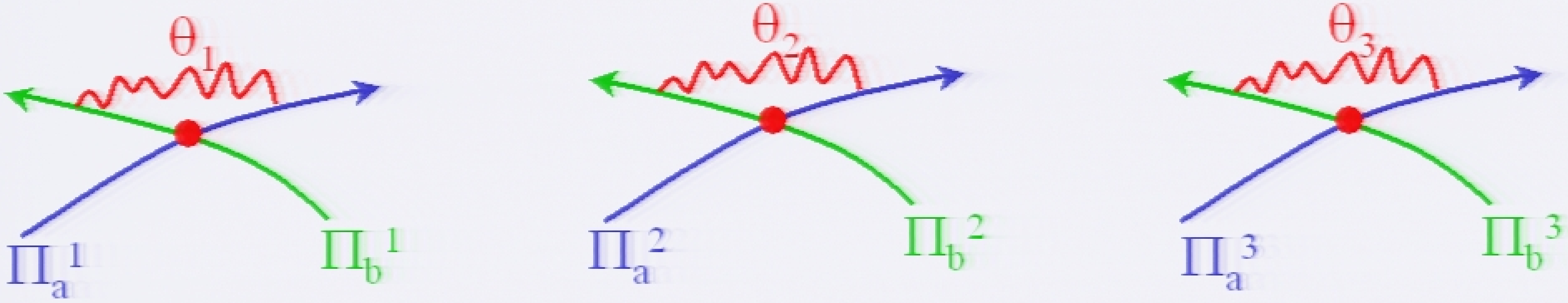
wrap 3-cycles Π



In internal space intersect at points:

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

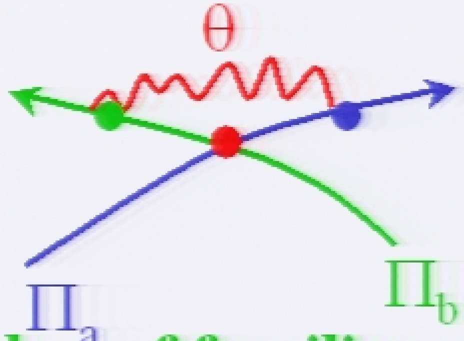
$\Pi_a = \Pi_a^1 \otimes \Pi_a^2 \otimes \Pi_a^3$ – **Factorizable 3-cycles**



At each intersection – massless 4d fermion ψ **Berkooz, Douglas & Leigh '96**

Geometric origin of chirality!

Engineering of Standard Model



N_a- D6-branes wrapping Π_a
N_b- D6-branes wrapping Π_b

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

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

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

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

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

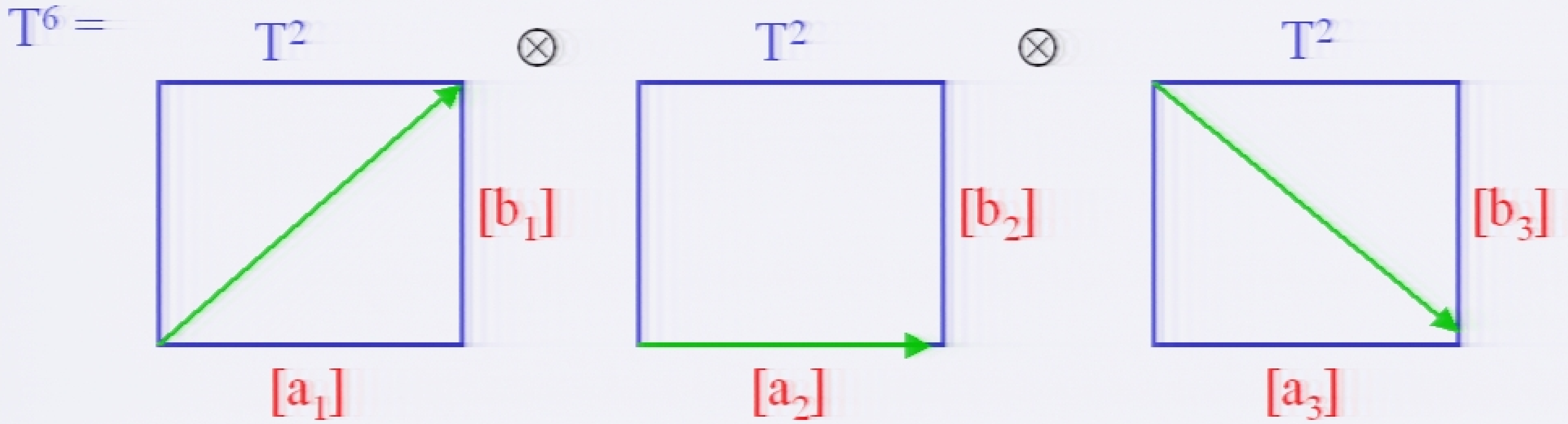
&

global consistency conditions & supersymmetry (later)

↓

Building Blocks of the Supersymmetric Standard Model

Toroidal/Orbifold compactifications
(calculation of spectrum w/ CFT-techniques)
$T^6/(Z_N \times Z_M)$



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

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

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

homology class of 3-cycles

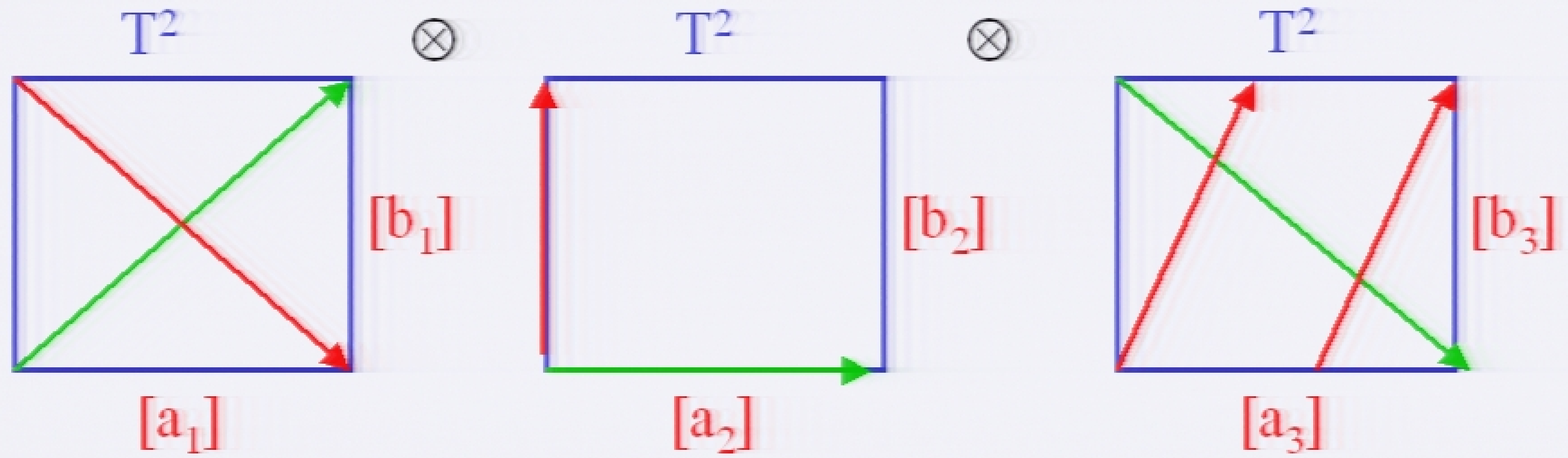
$[\Pi_a^i] = n_a^i [a_i] + m_a^i [b_i]$

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

Toroidal/Orbifold compactifications

$T^6/(Z_N \times Z_M)$ CFT-technique

$T^6 =$



$(n_a^i, m_a^i) =$ (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

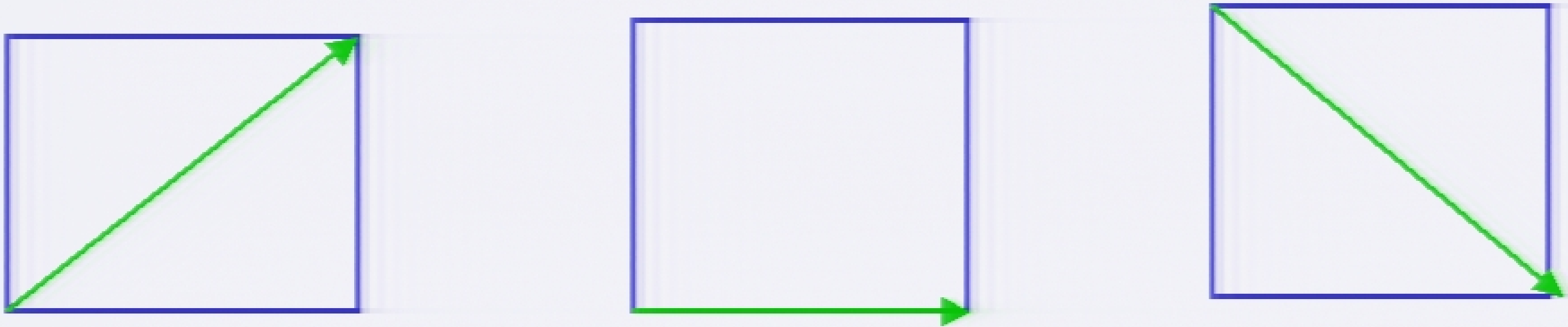
Blumenhagen, Görlich, Körs & Lüst '00

D6-brane – source for $C_{(7)}$

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

$$N_a \qquad [\Pi_a] \qquad\qquad\qquad = \qquad 0$$

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 $C_{(7)}$ - RR potential

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

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

* **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

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

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

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

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K-Theory Constraints

Uranga'01, Marchesano&Shiu'04

For toroidal/orbifold type compactifications of the form:

$$\sum_a N_a m_a^1 m_a^2 m_a^3 = 0 \mod 2\mathbf{Z}$$

$$\sum_a N_a n_a^1 n_a^2 m_a^3 = 0 \mod 2\mathbf{Z}$$

$$\sum_a N_a m_a^1 n_a^2 n_a^3 = 0 \mod 2\mathbf{Z}$$

$$\sum_a N_a n_a^1 m_a^2 n_a^3 = 0 \mod 2\mathbf{Z}$$

[Probe brane (prallel w/ orientifold planes) should not induce chiral spectrum w/ discrete Global (Witten) anomaly]

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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.

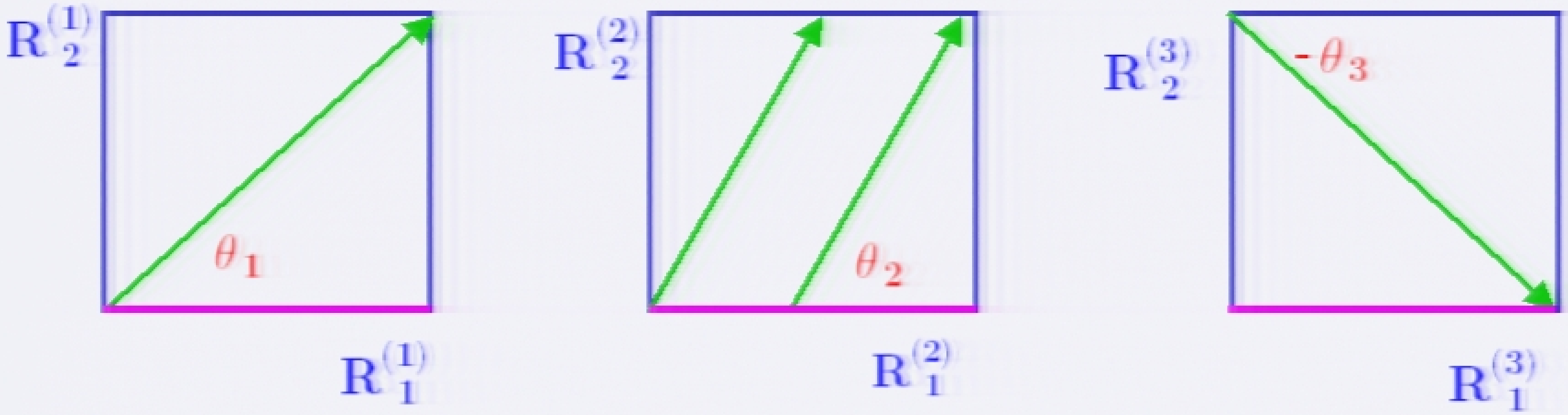
$M_{\text{string}} \sim M_{\text{planck}}$ large NS-NS tadpole
large radiative corrections

↓

Supersymmetric Standard-like Models (constrained)

w/ G. Shiu & A. Uranga '01

Supersymmetry (toroidal example)



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

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

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

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

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

Typical Features of Supersymmetric Models

" Observable sector" x "Hidden Sector"

SM w/ additional U(1)'s x **Sp(2N) x Sp(2M) . . .**

(descendants of Pati-Salam model) (branes || w/ orientifold planes)

\+ 3-families

\- more than one Higgs doublets

\- chiral exotics

(SM branes intersect w/hidden sector)

tyically beta-functions $\beta < 0$

infrared strong dynamics:

gaugino condensation w/

SUSY breaking & moduli stabilization

w/P. Langacker and J. Wang '03

-3chiral superfields on each D-brane set

-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

[* supergravity fluxes (later!)

orientifolds w/ rigid cycles (probably no time)

Status of Constructions

(i) Systematic Construction - $Z_2 \times Z_2$ orientifolds:

(a) Original Construction (1) ; special 3-cycles w/G. Shiu & A. Uranga'01

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

chiral exotics, 12-Higgs pairs

(b) More Standard-like Models (4); special 3-cycles w/I. Papadimitriou'03

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

fewer exotics, 8-pairs of Higgs doublets

(c) Systematic search for left-right symmetric models (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

(d) Standard-like Models w/ electroweak $Sp(2f)_L \times Sp(2f)_R$ 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

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	$(n^1, l^1) \times (n^2, l^2) \times (n^3, l^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\ \square\end{smallmatrix}}$	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 cniral 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)

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

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

Cremades, Ibanez & Marchesano'03

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

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

* "hidden sector" unitary symmetry- necessary for RR-tadpole cancellation

[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, Ui-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

superpotential calculation Derendinger,Kounnas,Petropoulos&Zwirner, hep-th/0411276

Type IIB- examples of SM with fluxes

Marchesano&Shiu hep-th/0408058,0409132

Type IIB theory & Fluxes

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

Fluxes better understood:

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

supersymmetry conditions,
back-reaction due to fluxes
potential for moduli etc.

rich phenomenologocal studies;
cosmology; landscape etc.

E.g.: **specific flux** (w/ mild backreaction-internal space conformal to Calabi Yau):

$$G_3 = F_3 - \tau H_3$$

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

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

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

complex structure moduli

Type IIA: Intersecting D6-branes

↓ T-duality ($R_1^{(i)} \rightarrow \frac{\alpha'}{R_1^{(i)}}$)

Type IIB: Magnetized D9-branes

Cascales&Uranga'03

Blumenhagen,Lust&Taylor'03

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

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

U(1)-D-brane magnetic field

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

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

Flux: $G_3 = F_3 - \tau H_3$

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

Contributes to Q_{D3} charge

Quantization conditions: $N_{\text{flux}} = n_f N_o \quad n_f \in Z \quad N_o = 64$

Specific to $Z_2 \times Z_2$ orbifold

Global consistency conditions

For toroidal/orbifold compactifications

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

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

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

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

D-branes & Fluxes (Type IIB)

Global consistency conditions

for toroidal/orbifold compactifications

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

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 (Z2 x Z2 orientifold)

III	$[U(4)_C \times SU(2)_L \times SU(2)_R]_{observable} \times [U(2)^* \times Sp(8)]_{hidden}$								
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\\square\end{smallmatrix}}$	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

Cremades, Ibanez & Marchesano'03

Z2 x Z2 orientifold embedding-cancellation of RR-tadpoles

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

w/ Langacker, Li & Liu, hep-th/0407178v2

f-family Standard Model w/Sp(2f)$_L$ xSp(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	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	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

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

SM sector contains D- branes with negative D3-charge

New representative models (order of 20) of 3- and 4-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 $Model - T_3 - 1$.

[no confining "hidden sector" -SUSY breaking?]

$Model - T_3 - 1$	$[U(4)_C \times U(2)_L \times U(2)_R]_{Observable}$									
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$	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	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$	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	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\Box\Box}$	$n_{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$	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	$(1,0)(1,0)(1,0)$	[illegible]				

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

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

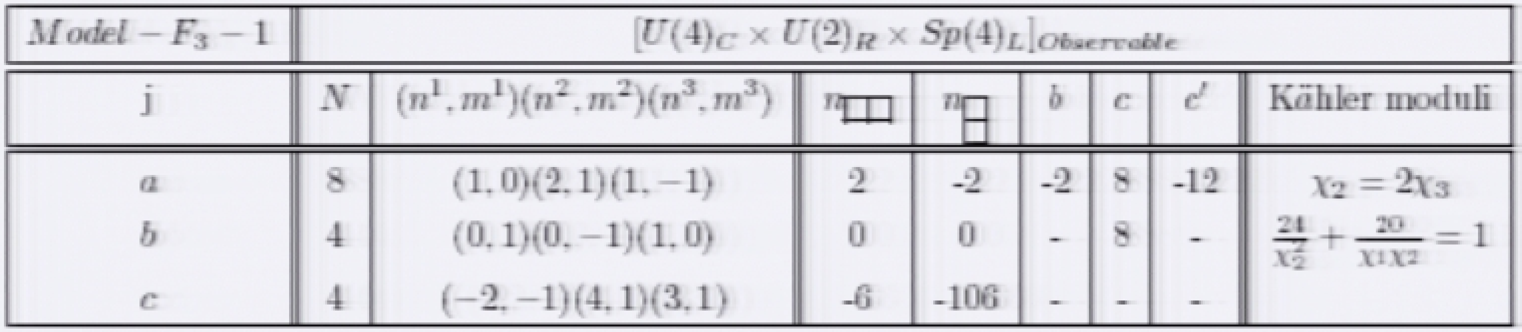
$Model-T_1-2$		$[U(4)_C\times U(2)_L\times U(2)_R]_{Observable}\times[Sp(8)\times Sp(4)]_{Hidden}$						
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	b	b'	c	c'
a	8	$(1,0)(1,1)(1,-1)$	0	0	-3	1	4	-6
b	4	$(2,1)(2,-1)(1,0)$	0	0	-	-	0	0
c	4	$(-2,-1)(2,1)(3,1)$	-18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

[no confining "hidden sector"-SUSY breaking?]



$Model-F_3-1$	$[U(4)_C \times U(2)_R \times Sp(4)_L]_{Observable}$							
j	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	$n_{\square\!\square}$	$n_{\genfrac{}{}{0pt}{}{\square}{\square}}$	b	c	c'	Kähler moduli
a	8	$(1,0)(2,1)(1,-1)$	2	-2	-2	8	-12	$\chi_2 = 2\chi_3$
b	4	$(0,1)(0,-1)(1,0)$	0	0	-	8	-	$\frac{24}{\chi_2^2} + \frac{20}{\chi_1\chi_2} = 1$
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	$(n^1, m^1)(n^2, m^2)(n^3, m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	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	$(n^1, m^1)(n^2, m^2)(n^3, m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	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	-	-	-
$D3$	8	$(1,0)(1,0)(1,0)$	$2\chi_3 = \chi_2$				
$(D7)_2$	4	$(0,1)(1,0)(0,-1)$	$\frac{18}{\chi_3^2} + \frac{18}{\chi_1\chi_2} = 1$				

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	$(n^1, m^1)(n^2, m^2)(n^3, m^3)$	$n_{\square\square}$	$n_{\substack{\square\\\square}}$	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	$(0,1)(1,0)(0,-1)$	$\chi_2 = 2\chi_3 = \frac{1}{\ }\chi_1 = 3\sqrt{2}$					

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	$(n^1, m^1)(n^2, m^2)(n^3, m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	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	$(0, 1)(1, 0)(0, -1)$	$\chi_3 = 2\chi_2, \frac{2}{\chi_2^2} + \frac{6}{\chi_1\chi_2} = 1$				

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	$(n^1, m^1)(n^2, m^2)(n^3, m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	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	$(n^1, m^1)(n^2, m^2)(n^3, m^3)$	$n_{\Box\Box}$	$n_{\substack{\Box\\\Box}}$	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:

(a) Toroidal **complex structure moduli** **U_i** - fixed by fluxes.

(b) In some cases all toroidal **Kahler moduli T_i** - fixed by SUSY

OR

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

$$\mathbf{W_{eff}} = \frac{\beta\Lambda^3}{32e\pi^2}\exp\left(\frac{8\pi^2}{\beta}\mathbf{f(T_i)}\right) + \mathbf{W_o}$$

function of Kahler moduli flux contrib.(fixed complex structure moduli)

All toroidal Kahler moduli stabilized & SUSY restored (à la KKLT)

(c) D-brane splitting moduli-become massive due to flux back-reaction ("curse" lifted)

[However, twisted closed sector moduli not stabilised.;
D-brane recombination moduli-could form flat directions w/Kahler moduli - problem!]

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	$(0,1)(1,0)(0,-1)$	$\beta^g_{(D7)_1} = -3(0),\ \beta^g_{(D7)_2} = -5(-2)$				

Sector w/negative beta functions & Kahler moduli dependent gauge functions

I. Moduli Stabilization:

(a) Toroidal **complex structure moduli U$_i$** - fixed by fluxes.

(b) In some cases all toroidal **Kahler moduli T$_i$** - fixed by SUSY

OR

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

$$\mathbf{W_{eff}} = \frac{\beta\Lambda^3}{32e\pi^2}\exp\left(\frac{8\pi^2}{\beta}\mathbf{f(T_i)}\right) + \mathbf{W_o}$$

function of Kahler moduli   flux contrib.(fixed complex structure moduli)

All toroidal Kahler moduli stabilized & SUSY restored   (à la KKLT)

(c) D-brane splitting moduli-become massive due to flux back-reaction ("curse" lifted)

[However, twisted closed sector moduli not stabilised.;
D-brane recombination moduli-could form flat directions w/Kahler moduli - problem!]

II. Further Phenomenology:

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

(All models descendants of Pati-Salam Models)

(a) Yukawa Couplings:

-Pati-Salam model w/ minimal (MSSM) Higgs sector not viable;
mass matrices and mixings of the SM cannot be realized.
For the specific construction-mass only for the 3rd family.
[Cannot give masses and mixings to 1st &2nd family at the loop level & after SUSY breaking, due to degeneracy of the soft-SUSY breaking mass terms (next page).]

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

(b) Exotics:

-models possess chiral exotics (problem!)

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

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

-VEV of right sneutrino-problematic, due to R-parity breaking resulting in unrealistic neutrino masses!

III. Analysis of soft SUSY breaking mass terms:

Fluxes (and/or hidden sector strong dynamics) break supersymmetry.
Employing full Yukawa Coupling/Kahler potential calculations

w/Papadimitiriou'03

Lust,Mayr,Richter&Stieberger'04;Cremades,Ibanez&Marchesano'04

one can determine soft supesymmetry breaking mass parameters in terms
of F- (and D-) supersymmetry breaking parameters in the closed moduli sector

Camara,Ibanez&Uranga, hep-th/0408064; Lust, Reffert&stieberger, hep-th/0410074; Kane,Kumar,Lykken&Wang, hep-th/0411125; Ibanez&Font, hep-th/0412150 . . . .

For all specific constructions (descendants of Pati-Salam models)
soft mass terms- degenerate among different family species
in the right and left sector & among Leptons and Quarks.
(The soft mass terms are governed by the intersection angles, and are the same for different family species in the right and left sector.)
Problematic for generating masses and mixings at the loop level.

w/Blumenhagen,Marchesano&Shiu, hep-th/0502095

TypeIIA orientifolds w/ rigid cycles

$Z_2 \times Z_2$' orientifold w/torsion (non-commuting Z_2's)

Rigid 3-cycles [D6-branes wrap collapsed 2-spheres at orbifold singularity x circle] - construction of chiral models w/discrete Wilson lines

An example of one 4-family Pati-Salam type model (in Type IIB picture allows for introduction of fluxes)

[related work Dudas et al. hep-th/0502080]

-Systematic search within $Z_2 \times Z_2$' orientifold: w/T.Liu, unpublished

4 additional 4-family Pati-Salam type models (& no 3- family) (in Type IIB picture w/fluxes allowed); different Hidden sector, Higgs sector & exotics

[Also no 3- or 4 family GUT SU(5) models]

Table 3: Model-3

Model-3	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	b	b'	c	c'
a	8	$(1,0)(0,1)(0,-1)$	2	2	-4	0
b	4	$(1,0)(2,-3)(4,1)$	-	-	-10	-10
c	4	$(-3,2)(-2,1)(-4,1)$	-	-	-	-
1	16	$(1,0)(1,0)(1,0)$				
3	8	$(0,1)(1,0)(0,-1)$				

Table 4: Model-4

Original Model

Model-4	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	b	b'	c	c'
a	8	$(1,0)(0,1)(0,-1)$	2	2	-4	0
b	4	$(1,0)(2,-1)(4,1)$	-	-	10	-6
c	4	$(-3,2)(-2,1)(-4,1)$	-	-	-	-
1	16	$(1,0)(1,0)(1,0)$				
2	4	$(1,0)(0,1)(0,-1)$				
3	8	$(0,1)(0,-1)(1,0)$				

Table 5: Model-5

Model-5	N	$(n^1,m^1)(n^2,m^2)(n^3,m^3)$	b	b'	c	c'
a	8	$(1,0)(0,1)(0,-1)$	2	2	-4	0
b	4	$(1,0)(2,-1)(4,3)$	-	-	18	18
c	4	$(-3,2)(-2,1)(-4,1)$	-	-	-	-
1	16	$(1,0)(1,0)(1,0)$				

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

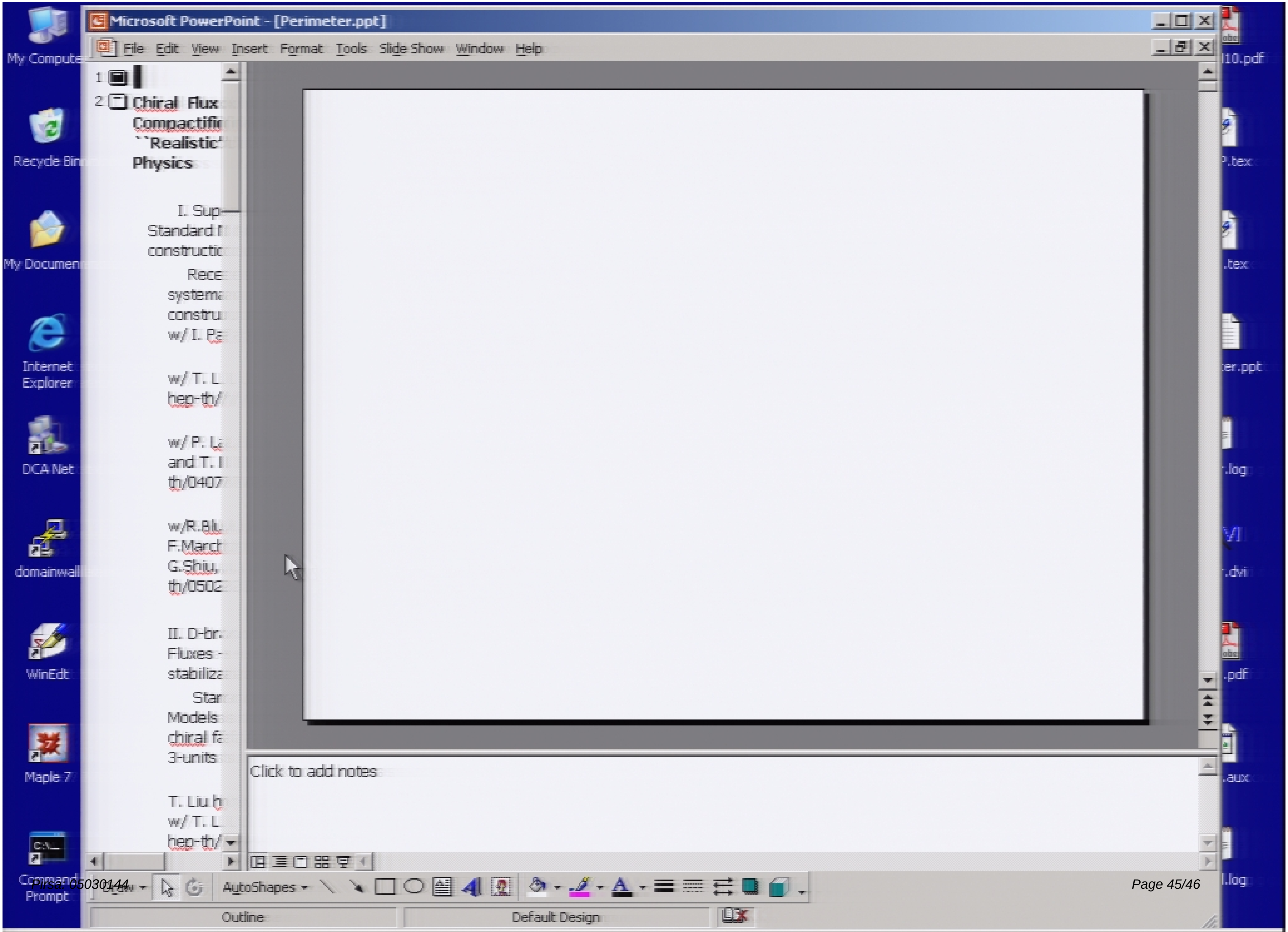
(a) Type IIA: fluxes less explored, but recent progress:
(no time!)

(b) Type IIB: Chiral SM constructions w/fluxes
intersecting D-branes → magnetized D-branes
On the order of 20 representative SM's with
3- &4-families, up to 3-units of quantized 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 (???)



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