String Phenomenology: Hetero vs Intersecting D-brane Models

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1. String phenomenology
2. 4D effective theory
3. Yukawa couplings in string models
4. SUSY breaking
5. Summary

1. String phenomenology

String theory → Phenomenological aspects of
particle physics

String theory → 4D Standard Model (including parameters)

String models (N=1 or 0 SUSY)

Hetero. on CY manifolds, orbifolds
fermionic const., Gepner…

Intersecting D-brane models

Their massless modes

Graviton, Gauge bosons,

Matter fermions, Higgs

Dilaton, Moduli fields

Their action

Gauge couplings, Yukawa couplings,……

Kahler potential (kinetic terms)

← dimensional reduction, CFT calculations

(symmetries, stringy loops)

They depend on VEVs of dilaton and moduli.

→ experimental values of g,

and fermion masses……

Dilaton/moduli potential is perturbatively flat.

How are these moduli stabilized ?

Dilaton/moduli stabilization

It is assumed that some non-perturbative effects generates potential.

V(S,T) → stabilization of S and T

SUSY may break.

→ S-spectra → future experiments

String Cosmology

These moduli fields have important implications on cosmology, inflation,……………………

→ Observation, e.g. WMAP

2. 4D effective field theory

2-1. Heterotic models (on orbifold)

10D heterotic theory → compactify 6D

gauge bosons ← 10D (bulk) modes

(untwisted) matter fields ← 10D (bulk) modes

twisted matter fields ← 4D, 6D modes

on fixed points, torus

"Heterotic brane world"

recent works: T.K., Raby, Zhang, '04

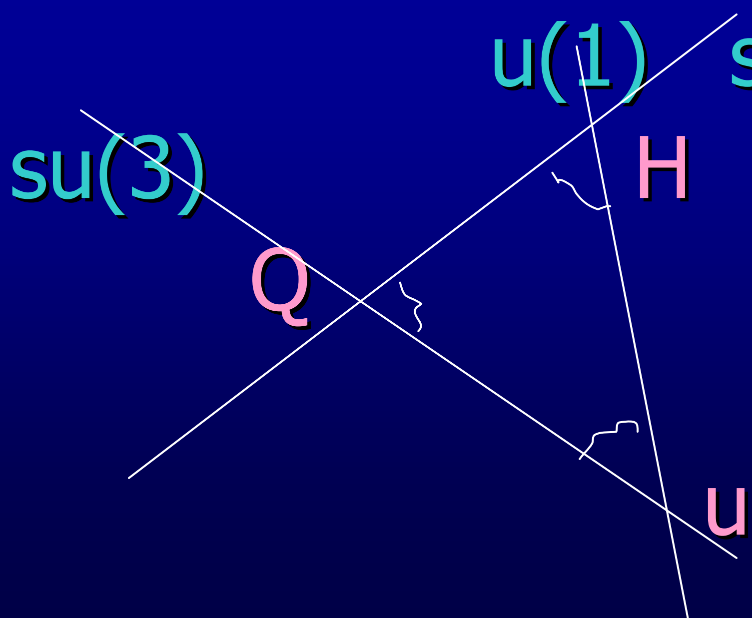
Nilles, et. al. '04

2-2. Intersecting D-brane models (D6 branes on orbifold)

gauge bosons: (p+1) D modes on D-brane

(bi-fundamental)

matter fields: modes localized at intersecting points

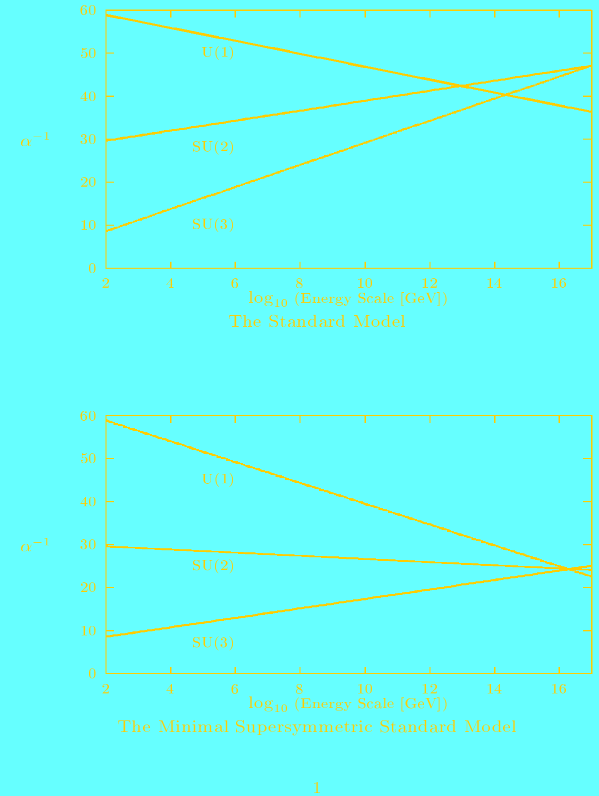


2-3. gauge couplings

Experiments

→ gauge couplings meet at high energy

Unification



Gauge couplings in hetero models

10D E_8 → SU(3) SU(2) U(1)…

gauge couplings are unified (for k=1).

Gauge couplings in intersecting D branes

$$g_a^2 = g_{6D}^2 / V_a$$

Generic model → no prediction on unification

In general, gauge kinetic functions (its moduli-dependence) are different between SU(3), SU(2) and U(1), ………

→ Gauge couplings and gaugino masses

3. Yukawa couplings in string models

The origin of fermion masses and mixing angles is one of important issues in particle physics.

Fermion masses ← Yukawa couplings between
fermions and Higgs fields
e.g. in the Standard Model

O(1) of Yukawa couplings are in a sense natural.

From this viewpoint, how to derive suppressed Yukawa couplings is a key-point in understanding fermion masses.

Quark masses and mixing angles

$$M_t = 174 \quad GeV, \qquad M_b = 4.3 \quad GeV$$
$$M_c = 1.2 \quad GeV, \qquad M_s = 117 \quad MeV$$
$$M_u = 3 \quad MeV, \qquad M_d = 6.8 \quad MeV$$

$$V_{us} = 0.22, \qquad V_{cb} = 0.04, \qquad V_{ub} = 0.004$$

RG effects are not drastic in usual cases except PR-fixed points or superconformal fixed points.

3-1. Yukawa couplings in string models

If fermions and Higgs fields are originated from N=4 or 2 sub-sector, we obtain

$Y = g$ (universal magnitude & diagonal).

In general, Yukawa couplings of string models can be calculated by CFT,

e.g. heterotic models on CY manifolds, orbifolds, Gepner models, fermionic const.

and Intersecting D-brane models.

CFT calculations

→ Universal Yukawa couplings (Y=O(1))

in some models,

and/or diagonal couplings

(allowed by selection rules)

One can not derive realistic mass matrices

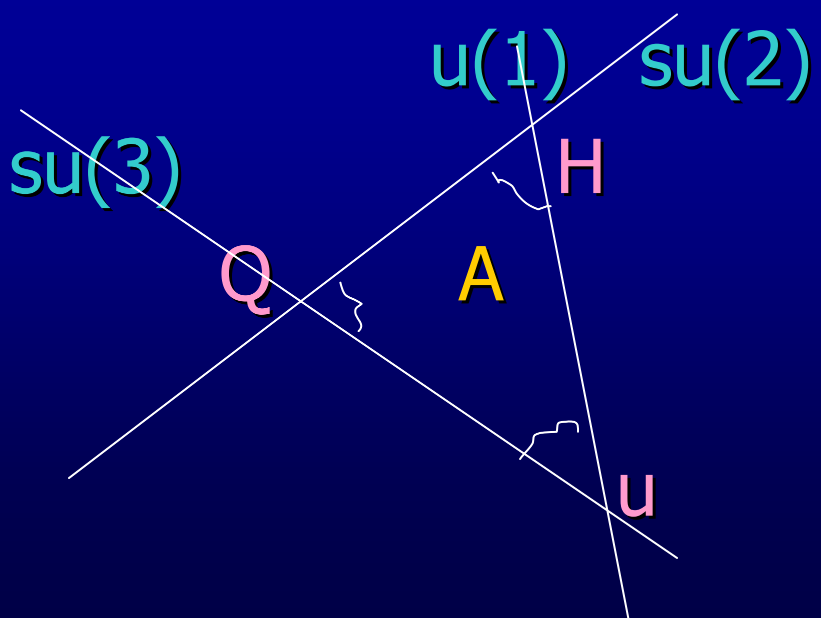
by these structures of Yukawa couplings.

Non-universal (suppressed) and/or moduli-dependent Yukawa couplings

e.g., intersecting D-brane models

hetero. models on orbifolds

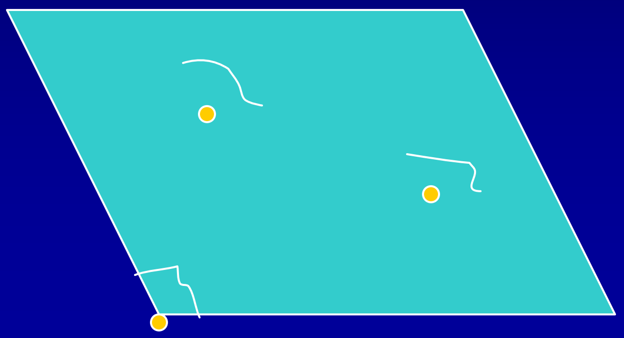
$Y = \exp(-A)$ A: area



3-2. Yukawa in hetero. orbifolds

Orbifold

Dixon, et. al., '85



Fixed points on 2D Z_3 orbifold

(0,0), (2/3,1/3), (1/3,2/3) in su(3) root basis

Twisted strings are associated with these fixed points.

The flavor structure and the selection rule are not so model-dependent compared with intersecting brane models, and these are determined geometrical aspect when we fix orbifold.

2D Z_6 orbifold

Fixed points

T_1 : (0,0)

T_2 : (0,0), (1/3,2/3), (2/3,1/3)

T_3 : (0,0), (0,1/2), (1/2,0), (1/2,1/2)

in G_2 simple root basis

These except (0,0) are not fixed under Z_6 twist, but transformed each other.

Thus, one has to take linear combinations of twisted states corresponding to fixed points, which are not the origin.

Twist eigenstates

T.K., Ohtsubo, '91

$$T_1 :|(0,0)>$$

$$T_2 :|(0,0)>, \qquad |(1/3,2/3)> \pm |(2/3,1/3,)>$$

$$T_3 :|(0,0)>, \qquad |(0,1/2)> + \gamma|(1/2,0)> + \gamma^2|(1/2,1/2)>,$$

$$\gamma = 1, \omega, \omega^2$$

6D orbifold

6D Z_3 orbifold = a product of 3 (2D Z_3)

6D Z_6-I orbifold =

a product of 2 (2D Z_6) and (2D Z_3)

Space group selection rule

Dixon, et. al., '87

Fixed point is denoted by its space group element.

$$(\theta^k, e)$$

$$(\theta^k, e_k)(\theta^l, e_l)(\theta^m, e_m) = (1,0) \qquad up \quad to \quad conjugacy \quad class$$

$$= (1, \sum (1-\theta^k)\Lambda)$$

2D Z_3 $\quad f_k \quad k=0,1,2$

$i + j + k = 0 \mod 3$ diagonal

We can not get non-vanishing mixing angles.

2D Z_6 orbifold

Allowed Yukawa couplings T.K., Ohtsubo, '91

$T_1\ T_2\ T_3$ $T_2\ T_2\ T_2$

The latter is the same as Z_3, that is

we obtain only diagonal couplings.

For the former, only the condition is that

a product of eigenvalues is identity,

that is, off-diagonal elements are allowed.

6D Z_6-I orbifold

Relevant states

$$T_1^{(1)} :|(0,0)> \otimes |(0,0)>$$

$$T_2^{(1)} :|(0,0)> \otimes |(0,0)>$$

$$T_2^{(2)} :|(0,0)> \otimes |(a,b);+1>$$

$$T_2^{(3)} :|(a,b);+1> \otimes |(0,0)>$$

$$T_2^{(4)} :|(a,b);\gamma> \otimes |(a',b');1/\gamma>$$

$$T_3^{(1)} :|(0,0)> \otimes |(0,0)>$$

$$T_3^{(2)} :|(0,0)> \otimes |(a,b);+1>$$

$$T_3^{(3)} :|(a,b);+1> \otimes |(0,0)>$$

$$T_3^{(4)} :|(a,b);\gamma> \otimes |(a',b');1/\gamma>$$

$$a, b, a', b' \neq 0$$

Yukawa couplings on orbifold

CFT calculations → Dixon, et al '87, Hamidi, Vafa, '87,

Burwick, et al '91, Casas, et al '93……

T.K. Lebedev, '03

$\hat{T}_1 \hat{T}_2 \hat{T}_3$ *couplings*

$$Y = \exp[-\sqrt{3}/(4\pi)(f_2 - f_3)^T M (f_2 - f_3)]$$

$$M = \begin{pmatrix} (R_1)^2 & -3(R_1)^2/2 & 0 & 0 \\ -3(R_1)^2/2 & 3(R_1)^2 & 0 & 0 \\ 0 & 0 & (R_2)^2 & -3(R_2)^2/2 \\ 0 & 0 & -3(R_2)^2/2 & 3(R_2)^2 \end{pmatrix}$$

$\hat{T}_2 \hat{T}_2 \hat{T}_2$ *couplings*

$$Y = \exp[-\sqrt{3}/(16\pi)(f_2 - f_3)^T M (f_2 - f_3)]$$

Z_N orbifolds

Z_3, Z_4, Z_6-I, Z_6-II, Z_7, Z_8-I, Z_8-II, Z_{12}-I, Z_{12}-II

We will study Z_6-I orbifold.

Diagonal couplings: Z_3, Z_7

A small number of relevant states:

Z_4, Z_6-II, Z_8-II, Z_{12}-II

One moduli parameter: Z_8-I, Z_{12}-I

Assignments

Ko, T.K., Park, '04

5 types of assignments leading to mixing angles

Since there is a T1 single state, we have to assign fermions with other sectors.

	Q	u	d	H_u	H_d	$possibilities$
$Assignment-1$	$\hat{T}_2$	$\hat{T}_3$	$\hat{T}_3$	$\hat{T}_1$	$\hat{T}_1$	$6\times 6\times 6=216$
$Assignment-2$	$\hat{T}_3$	$\hat{T}_2$	$\hat{T}_2$	$\hat{T}_1$	$\hat{T}_1$	$6\times 6\times 6=216$
$Assignment-3$	$\hat{T}_2$	$\hat{T}_3$	$\hat{T}_2$	$\hat{T}_1$	$\hat{T}_2$	$6^3\times 4=864$
$Assignment-4$	$\hat{T}_2$	$\hat{T}_2$	$\hat{T}_3$	$\hat{T}_2$	$\hat{T}_1$	$6^3\times 4=864$
$Assignment-5$	$\hat{T}_2$	$\hat{T}_2$	$\hat{T}_2$	$\hat{T}_2$	$\hat{T}_2$	$6^3\times 4^2=3456$

Systematical study

We try to fit the mass ratios m_c/m_t, m_s/m_b and mixing angle V_{cb}.

(Cf. Casas, Gomez, Munoz, '92,

where they studied the mass ratios)

We have studied systematically all of possibilities minimizing chi squared varying R_1 and R_2.

$$\chi^2 = \frac{(m_c/m_t - [m_c/m_t]_{\exp})^2}{(\sigma_{mc}/m_t)^2} + \frac{(m_s/m_b - [m_s/m_b]_{\exp})^2}{(\sigma_{ms}/m_b)^2} + \frac{(V_{cb} - [V_{cb}]_{\exp})^2}{(\sigma_{Vcb})^2} + (Y_t - 1)^2$$

Values

We have found examples leading to realistic values.

	m_c / m_t	m_s / m_b	V_{cb}
$Assignment - 1:$	0.004	0.03	0.04
$Assignment - 2:$	0.004	0.03	0.04
$Assignment - 3:$	0.004	0.02	0.04
$Assignment - 4:$	0.004	0.04	0.04
$Assignment - 5:$	0.004	0.03	0.04
$Experiment:$	0.004	0.03	0.04

Forms of Yukawa matrices

We have found examples leading to realistic values.

Assignment-1: hierarchical & democratic

Assignment-2: hierarchical & democratic

Assignment-3: hierarchical form

Assignment-4: hierarchical form

We show some examples.

Assignment 1

$$Q_2, Q_3, \qquad u_2, u_3 \qquad d_2, d_3 \qquad H_u, H_d$$

$$\hat{T}_2^{(2)}, \hat{T}_2^{(4)} \qquad \hat{T}_3^{(3)}, \hat{T}_3^{(2)} \qquad \hat{T}_3^{(1)}, \hat{T}_3^{(3)} \qquad \hat{T}_1, \hat{T}_1$$

$$T_1 = 27.8, \qquad T_2 = 107$$

$$Y_u = \begin{pmatrix} 0.0416 & 0.718 \\ 0.0557 & 0.848 \end{pmatrix} \qquad Y_d = \begin{pmatrix} 0.0313 & 0.0416 \\ 0.0370 & 0.0557 \end{pmatrix}$$

$$m_c / m_t = 0.0038, \qquad m_s / m_b = 0.029, \qquad V_{cb} = 0.041$$

There are several examples leading to similar results.

Assignment 2

$$Q_2, Q_3, \qquad u_2, u_3 \qquad d_2, d_3 \qquad H_u, H_d$$

$$\hat{T}_3^{(2)}, \hat{T}_3^{(4)} \qquad \hat{T}_2^{(3)}, \hat{T}_2^{(2)} \qquad \hat{T}_2^{(1)}, \hat{T}_2^{(3)} \qquad \hat{T}_1, \hat{T}_1$$

$$T_1 = 24.0, \qquad T_2 = 150$$

$$Y_u = \begin{pmatrix} 0.0281 & 0.439 \\ 0.0371 & 0.665 \end{pmatrix} \qquad Y_d = \begin{pmatrix} 0.0199 & 0.0281 \\ 0.0302 & 0.0371 \end{pmatrix}$$

$$m_c / m_t = 0.0038, \qquad m_s / m_b = 0.032, \qquad V_{cb} = 0.041$$

There are several examples leading to similar results.

Assignment 5

$$Q_2, Q_3, \qquad u_2, u_3 \qquad d_2, d_3 \qquad H_u, H_d$$

$$\hat{T}_2^{(2)}, \hat{T}_2^{(4)} \qquad \hat{T}_2^{(2)}, \hat{T}_2^{(4)} \qquad \hat{T}_2^{(3)}, \hat{T}_2^{(2)} \qquad \hat{T}_2^{(4)}, \hat{T}_2^{(4)}$$

$$T_1 = 180, \qquad T_2 = 180$$

$$Y_u = \begin{pmatrix} 0 & 0.0309 \\ 0.0309 & 0.500 \end{pmatrix} \qquad Y_d = \begin{pmatrix} 0.00132 & 0 \\ 0.0214 & 0.0309 \end{pmatrix}$$

$$m_c / m_t = 0.0038, \qquad m_s / m_b = 0.029, \qquad V_{cb} = 0.041$$

Results

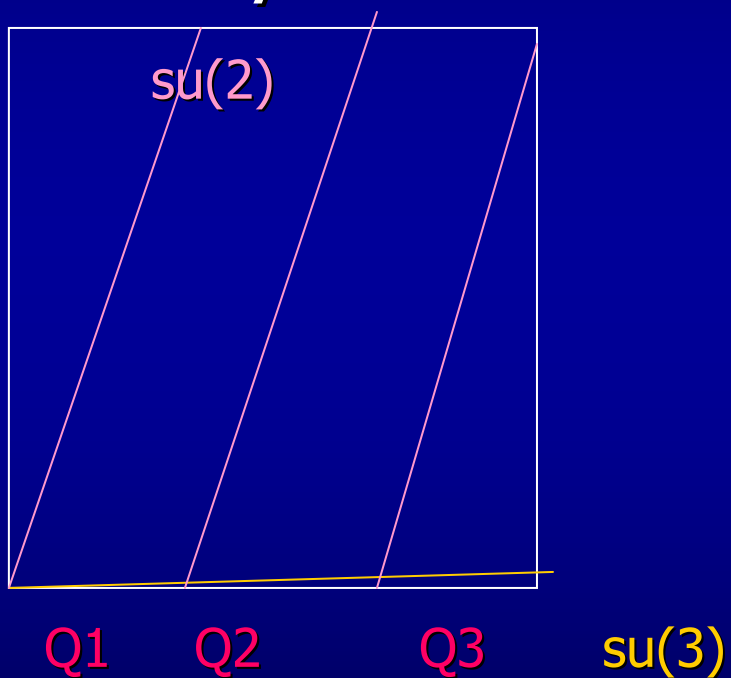
We have found examples leading to a realistic mixing angle as well as mass ratios between the 2nd and 3rd families.

Our results is the first examples to show the possibilities for leading to realistic mixing angles by use of stringy renomalizable couplings with one pair of the up and down Higgs fields.

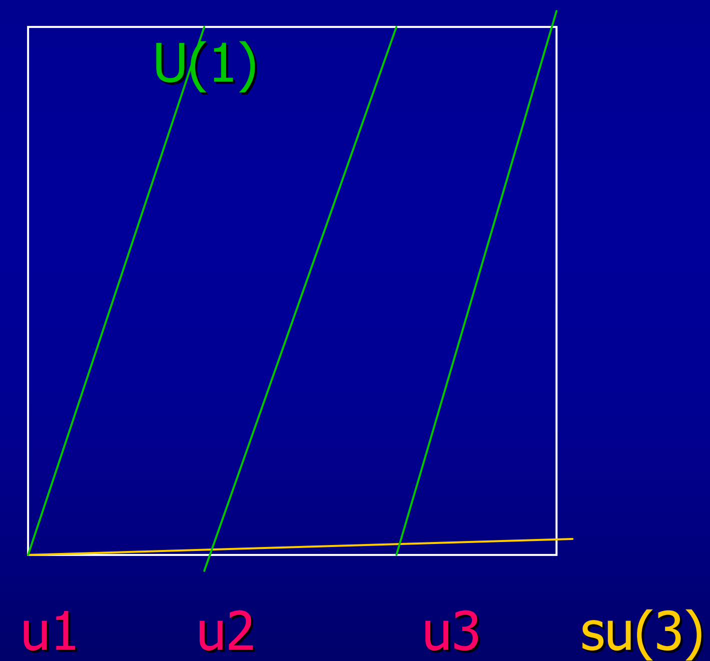
3-3. Yukawa in intersecting D6 models

Flavor structure

Family number = intersection number



1st plane

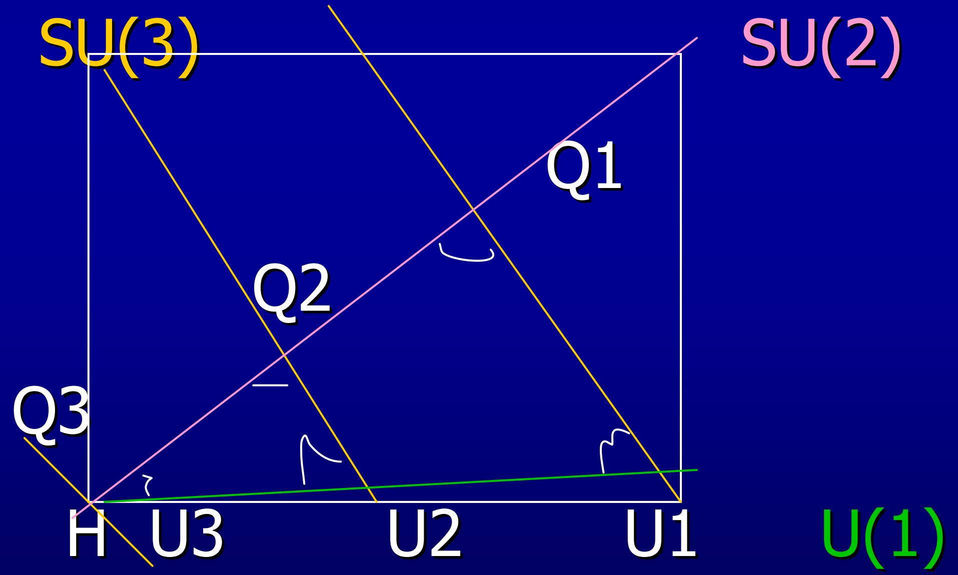


2nd plane

Yukawa in this toy model for 3 families

-> $Y_{ij} = a_i\, b_j$ (rank-one matrix)

Another model for 3 families



Yukawa = diagonal

(almost)

Yukawa matrices in intersecting D-brane models

Those are model-dependent, but most of models, which has been obtained so far, lead to

$$Y_{ij} = a_i b_j$$

This is a rank-one matrix.

One can derive only top mass, but not other light quark masses or mixing angles.

—> Kitazawa, T.K., Maru, Okada, '04

New flavor structure

Flavor number = intersecting number

-> non-realistic Yukawa matrices,

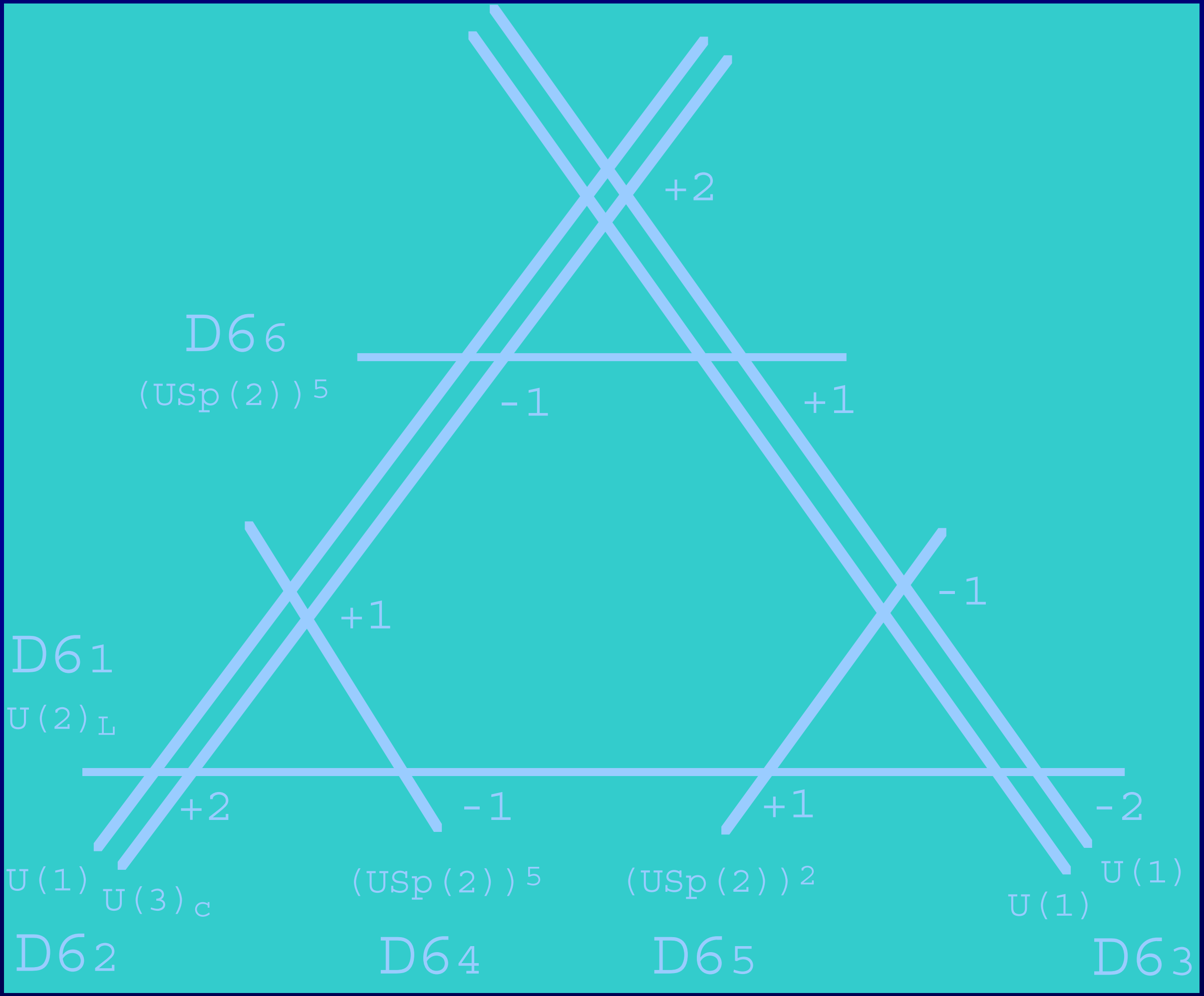
vanishing mixing angles

We need some extensions or

a new type of flavor structure.

Composite model

Kitazawa, '04



(Bi-fundamental) matter

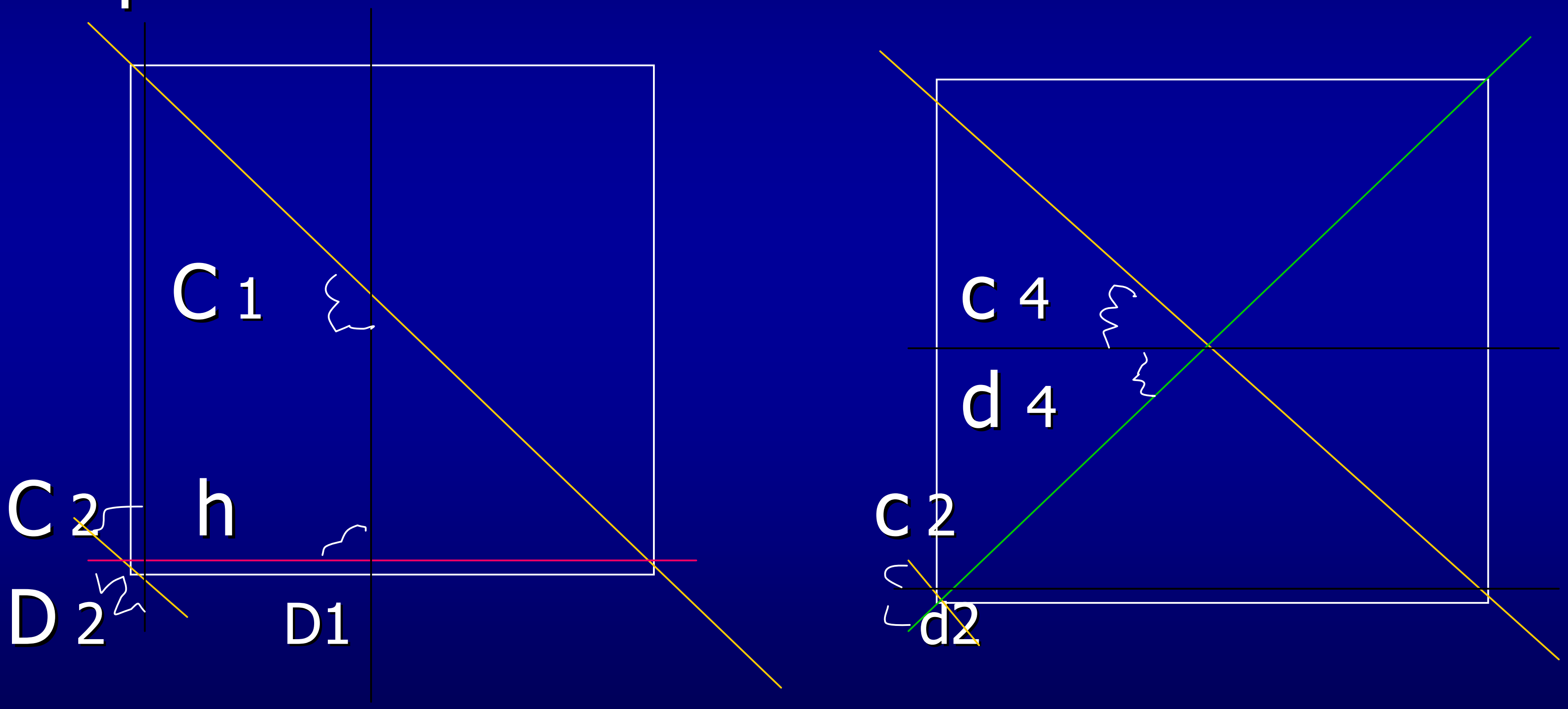
Intersecting number

SU(3)	SU(2)	-2	anti-generation
SU(3)	$Usp(2)_a$	1	C_a
SU(2)	$Usp(2)_a$	1	D_a

$C_a D_a \rightarrow Q_a$

Configuration

3rd plane



Yukawa matrices

Kitazawa, T.K., Maru, Okada '04

$$Y_u = \begin{pmatrix} \varepsilon_1 \varepsilon_2^2 \varepsilon_3 & \varepsilon_2 \varepsilon_3 \\ \varepsilon_1 \varepsilon_2 \varepsilon_3^2 & 1 \end{pmatrix} \qquad Y_d = \begin{pmatrix} \varepsilon_2 \varepsilon_3 & \varepsilon_2 \varepsilon_3 \\ \varepsilon_3^2 & 1 \end{pmatrix}$$

$$m_c / m_t = \varepsilon_1 \varepsilon_2^2 \varepsilon_3, \qquad m_s / m_b = \varepsilon_2 \varepsilon_3, \qquad V_{cb} = \varepsilon_2 \varepsilon_3$$

$$\varepsilon_2 \varepsilon_3 = 10^{-2}, \qquad \varepsilon_1 \varepsilon_2^2 \varepsilon_3 = 10^{-3} \rightarrow realistic$$

4. SUSY breaking

4-1. SUSY breaking in heterotic models

E'_8 → hidden sector

gaugino condensation in hidden sector

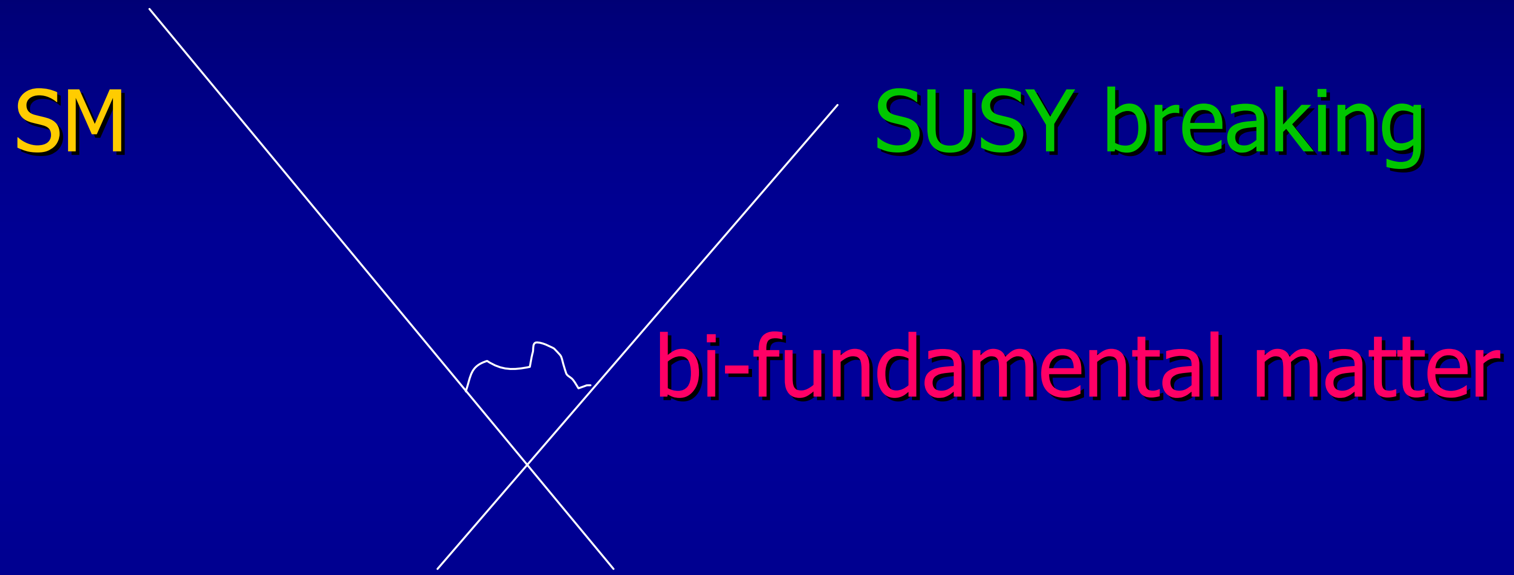
→ SUSY breaking

gravity mediation → visible sector

4-2. extra gauge sector in intersecting brane

There are often matter fields with bi-fundamental rep. between the SM group and extra group.

SUSY breaking in intersecting brane models



Effects from bi-fundamental matter ?

Summary

Many intersecting D-brane models have been constructed.

It is the time to study their phenomenological aspects, e.g. , gauge couplings, Yukawa couplings, ……, SUSY breaking, ……..

Recent topic on moduli stabilization and SUSY breaking is concerned about models with flux.

Summary on Yukawa

We have systematically studied the possibilities for leading to realistic mixing angles in orbifold models.

We have found several examples, and our results are

the first examples in string models.

It is important to extend our analysis into the full 3 family matrices and also the lepton sector.

How to stabilize moduli VEVs at proper values is an important issue.

Yukawa in intersecting brane models

Another possibility for leading to realistic mixing angles is intersecting D-brane models.

So far, there is no explicit model with non-vanishing mixing angles.

New type of flavor structure has been obtained in Kitazawa-san's model.

That can lead to non-vanishing mixing anlges.

Kitazawa, T.K., Maru, Okada, '04