Heterotic Phenomenology

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1. Introduction
2. Heterotic models
3. D-brane models
4. Effective theory (gauge/Yukawa couplings)
5. Moduli stabilization and SUSY breaking
6. Summary

1. Introduction

1-1. Introduction to string phenomenology

Superstring theory : a candidate of unified theory including gravity

Important issue: (if it is really relevant to particle physics)

Superstring → the 4D Standard Model of particle physics including values of parameters （@ low energy）

Problem：

There are innumberable 4D string vacua (models)

← Study on nonperturbative aspects to lift up many vacua and/or to find out a principle leading to a unique vacuum

← Study on particle phenomenological aspects of already known 4D string vacua

String phenomenology

String phenomenology

Which does class of string models lead to realistic aspects of particle physics ？

We do not need to care about string vacua without leading to e.g.

the top quark mass ＝ 174 GeV

the electron mass ＝ 0. 5 MeV,

no matter how many vacua exist.

Let’s study whether we can construct 4D string vacua really relevant to our Nature.

String phenomenology

Superstring : theory around the Planck scale

SUSY ?

GUT ?

? ? ? ? ? Several scenario ? ? ? ? ? ?

Standard Model : we know it up to 100 GeV

Superstring → low energy ? (top-down)

Low energy → underlying theory ? (bottom-up)

Both approaches are necessary to

connect between underlying theory and our Nature.

1-2. Standard Model

Gauge bosons

SU(3)、 SU(2)、 U(1)

parameters: three gauge couplings

Quarks, Leptons 3 families

hierarchical pattern of masses (mixing)

← Yukawa couplings to the Higgs field

Higgs field

the origin of masses

not discovered yet

our purpose "derivation of the SM"

⇒ realize these massless modes and coupling values

Low energy SUSY

Gauge bosons SU(3)、 SU(2)、 U(1)

3 families of Quarks, Leptons

Higgs scalar

their superpartners may appear

Their masses

← Prediction of a specific 4D string model

(with a certain SUSY breaking scenario)

Gauge couplings

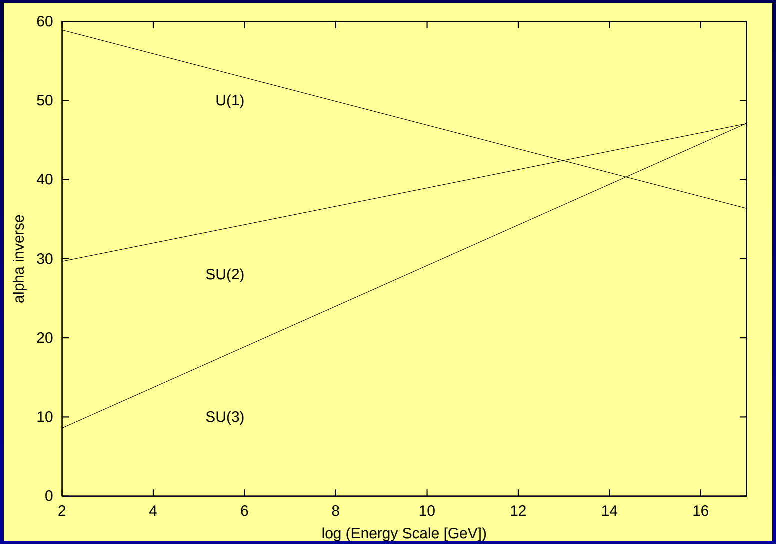
experimental values

RG flow ⇒

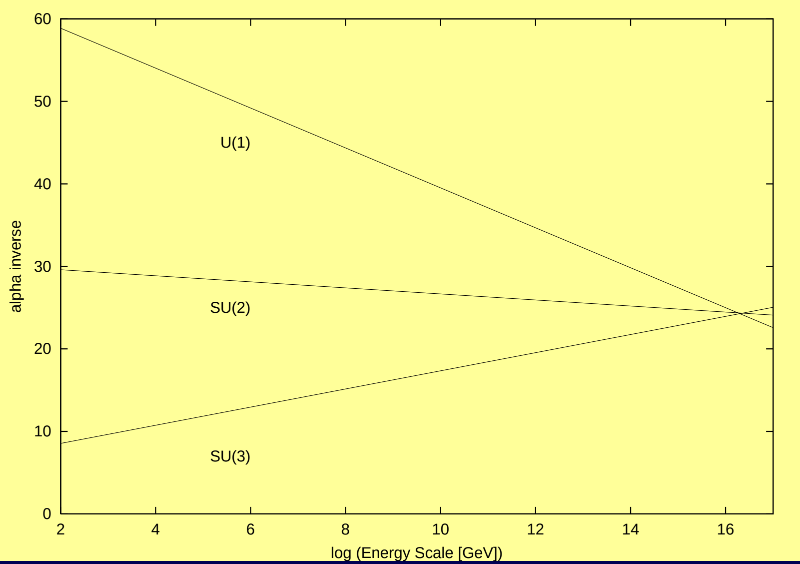
They approach each other

and become similar values

at high energy



In MSSM, they fit each other in a good accuracy



Gauge coupling unification

Quark masses and mixing angles

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

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

These masses are obtained by Yukawa couplings to the Higgs field with VEV, v＝175GeV.

strong Yukawa coupling ⇒ large mass

weak ⇒ small mass

top Yukawa coupling =O(1)

other quarks ← suppressed Yukawa couplings

Lepton masses and mixing angles

$$M_e = 0.5 \quad MeV, \qquad M_\mu = 106 \quad MeV$$

$$M_\tau = 1.8 \quad GeV,$$

mass squared differences and mixing angles consistent with neutrino oscillation

$$\Delta M_{21}^2 = 8 \times 10^{-5} \quad eV^2, \qquad \Delta M_{31}^2 = 2 \times 10^{-3} \quad eV^2$$

$$\sin^2 \theta_{12} = 0.3, \qquad \sin^2 \theta_{23} = 0.5, \qquad \sin^2 \theta_{13} = 0.0,$$

large mixing angles

Cosmological aspects

Cosmological constant (Dark energy)

Dark matter

Inflation

....

1-3. Superstring theory

⇒ predict 6 extra dimensions
in addition to our 4D space-times

Compact space (background)、D-brane configuration、...
← constrained by string theory
(modular invariance, RR-charge cancellation,…)

Once we choose background, all of modes can be investigated in principle (at the perturbative level).

⇒ Massless modes, which appear in low-energy effective field theory, are completely determined.

It is not allowed to add/reduce some modes by hand.

4D string models

4D Chiral theory ⇒ N=0, 1 SUSY

N=0 theory

Tachyonic modes often appear.

instable vacuum

We often start with N=1 theory,

although this is not necessary.

(N=0 theory with tachyonic modes is fine.)

(low energy SUSY ← hierarchy problem)

Several string models

(before D-brane) 1^{st} string revolution

Heterotic models on Calabi-Yau manifold, Orbifolds,

fermionic construction,

Gepner, ...

(after D-brane) 2^{nd} string revolution

Intersecting D-brane models

Magnetized D-branes, ...

Phenomenological aspects

Massless modes ⇒ section 2, 3

gauge bosons (gauge symmetry),
matter fermions, higgs bosons,
moduli fields, ...

Their action ⇒ section 4

gauge couplings, Yukawa couplings, ...
Kahler potential (kinetic terms)
(discrete/flavor) symmetry, ...

moduli stabilization, SUSY breaking, ⇒ section 5

soft SUSY breaking terms, ...

Today's purpose

This is a workshop on heterotic string.

(skipping technical details)

I would like to talk about

which particle phenomenological aspects

can (or not) be understood in heterotic string

models through our current knowledge

on heterotic string

(comparing with other types of string models).

2. Heterotic models

2-1. Heterotic theory

Right-mover: 10D Superstring X, ψ $X \Leftrightarrow \psi$

Left-mover : 26D bosonic string X

10D L-R common dimension

→ space-time dimension

$$X^\mu(\tau,\sigma) = x^\mu + \alpha' p^\mu \tau + (oscillators)$$

The other 16D L-mover

→ gauge part, which is assumed to be compactified on E8 x E8 torus or SO(32) torus

$$X^I(\sigma-\tau) = x^I + (\alpha'/2) p^I (\sigma-\tau) + (oscillators)$$

$$p^I = \underline{(\pm1,\pm1,0,0,0,0,0,0)}(0,0,0,0,0,0,0,0)$$

$$= (\pm1/2,\pm1/2,\ldots\ldots)(0,0,0,0,0,0,0,0)$$

……………………………………………………………

Massless modes of 10D het. theory

graviton, dilaton,

anti-symmetric tensor $\left| p^t = (\underline{\pm 1,0,0,0}) \right\rangle_R \otimes \overline{\alpha^i_{-1}} \left| 0 \right\rangle_L$

gravitino, dilatino $\left| p^t = (\pm 1/2, \pm 1/2, \ldots) \right\rangle_R \otimes \overline{\alpha^i_{-1}} \left| 0 \right\rangle_L$

Gauge bosons $\left| p^t = (\underline{\pm 1,0,0,0}) \right\rangle_R \otimes \left\{ \alpha^I_{-1} \left| 0 \right\rangle_L , \left| (P^I)^2 = 1 \right\rangle_L \right\}$

gaugino $\left| p^t = (\pm 1/2, \pm 1/2, \ldots) \right\rangle_R \otimes \left\{ \alpha^I_{-1} \left| 0 \right\rangle_L , \left| (P^I)^2 = 1 \right\rangle_L \right\}$

→ 10D N=1 supergravity + (E8 x E8) SYM

or SO(32) SYM

no chiral matter

E8 heterotic models

E8 heterotic models are favorable ？

Gauge groups of SM, GUTs are E series.

SM ⇒ SU(5) + (10 + 5) matter ⇒ SO(10) + 16matter

(E3) E4 E5

⇒ E6 + 27matter ⇒ E7 + 56 matter ⇒ E8 + adj.

SO(32) heterotic models

SO(32) gauge group + adj. matter

realistic ?

2-2. Orbifold

Torus compactification 4D N=4 SUSY

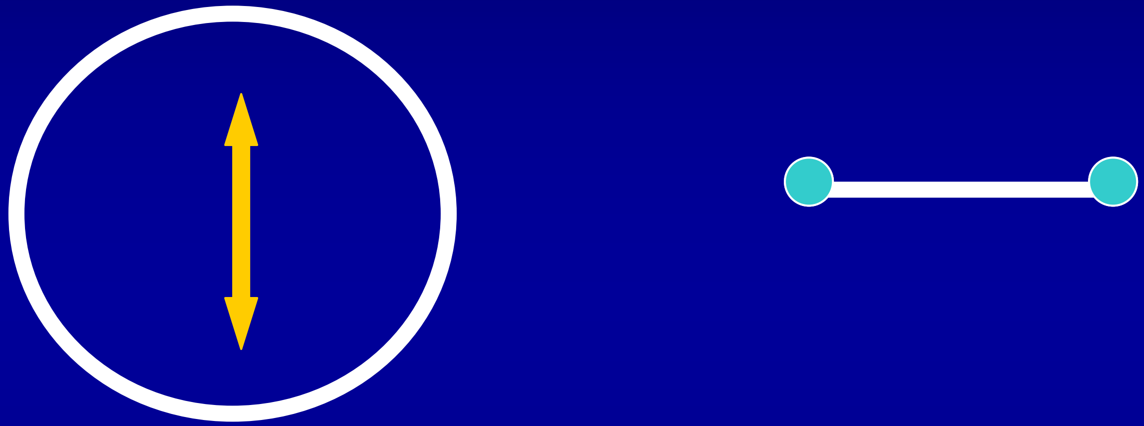
We need compactification leading to chiral theory,
e.g. N=1 theory with chiral matter fields.

Such compactification are
Calabi-Yau, orbifold,……
String on the orbifold background can be solved.

$\Rightarrow$ Any stringy perturbative calculations are possible in principle.

Examples of orbifold

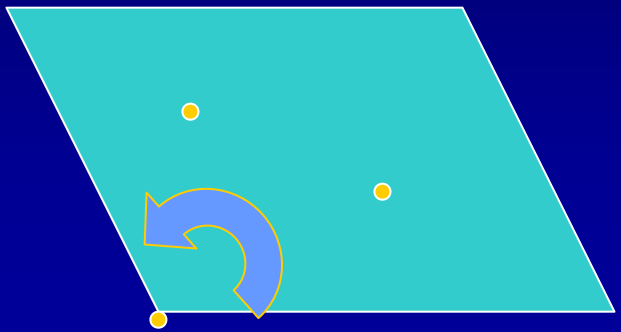
S1/Z2 Orbifold

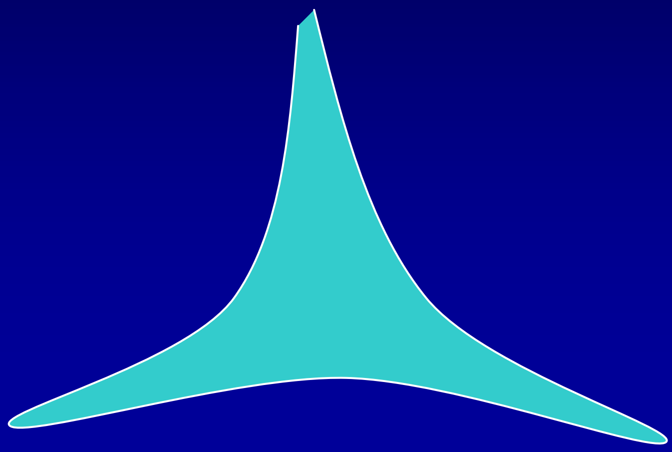


There are two singular points,
which are called fixed points.

Orbifolds

T2/Z3 Orbifold





There are three fixed points on Z3 orbifold

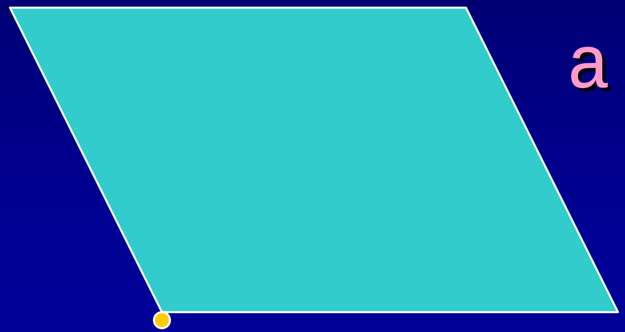
(0,0), (2/3,1/3), (1/3,2/3) su(3) root lattice

Orbifold = D-dim. Torus /twist

Torus = D-dim flat space/ lattice

2D Z6 orbifold and fixed points

First twisted states T1

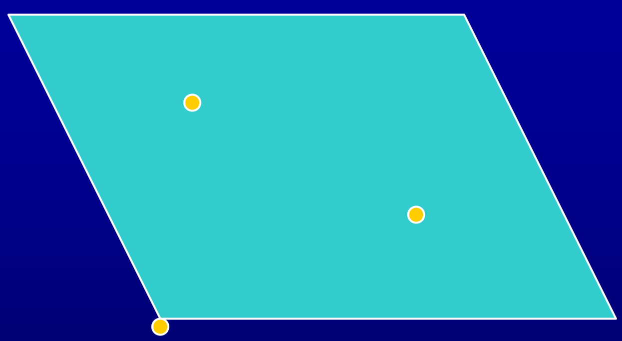


a single fixed point (0,0)

$$(\Theta, 0)$$

$$(1-\Theta)\Lambda = \Lambda$$

Second twisted states T2

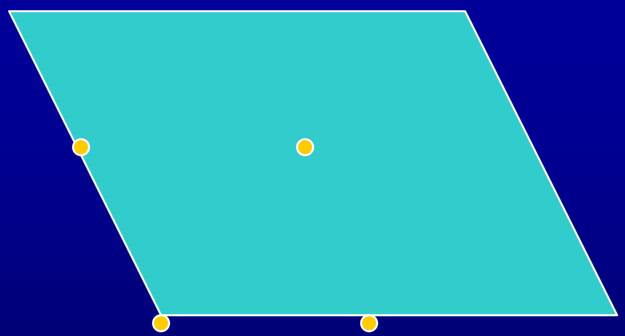


(0,0), (2/3,1/3), (1/3,2/3)

$$(\Theta, ke_1) \qquad k = 0,1,2$$

$$(1-\Theta)\Lambda = \{e_1 - e_2, 3e_1\}$$

third ones T3



(0,0), (1/2,0),(1/2,1/2)(0,1/2)

$$(\Theta, me_1 + ne_2) \qquad m, n = 0,1$$

$$(1-\Theta)\Lambda = \{2e_1, 2e_2\}$$

6D orbifold

Some of 6D orbifolds can be constructed by direct products of 2D orbifolds, e.g.

6D Z_6-II orbifold = a product of Z_6, Z_3 and Z_2

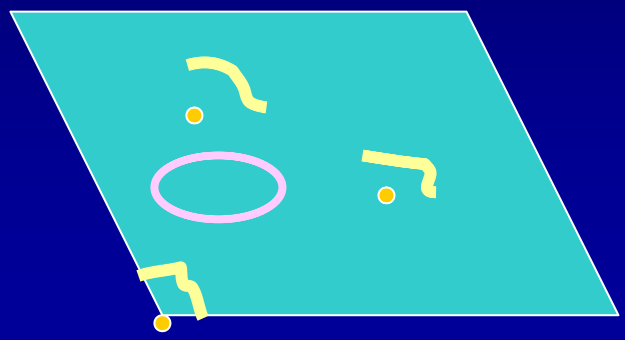
$v=(1, 2, -3)/6$ → D=4 N=1 SUSY

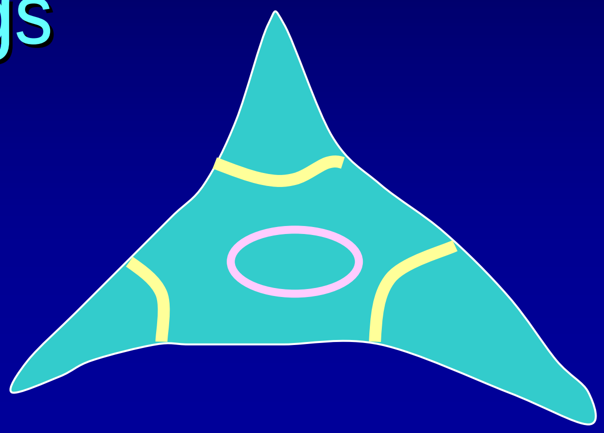
There are other types of orbifolds leading to D=4 N=1 SUSY.

Also, there are orbifolds leading to D=4 N=2 and N=0 SUSY.

Closed strings on orbifold

Untwisted and twisted strings





Twisted strings are associated with fixed points.

"Brane-world" terminology:

untwisted sector   bulk modes

twisted sector   brane (localized) modes

Twisted string

$$X(\sigma=\pi)=\Theta X(\sigma=0)+e$$

→ Center of mass : fixed point

Mode expansions are different from those for periodic boundary condition

oscillator number N

N = integer → integer − 1/M for Z_M

intercept (zero-point energy) also differs

Gauge symmetry breaking

Unbroken E8 is too large

We break the gauge group E8xE8

← (gauge) background fields, Wilson line

Modular invariance

Background fields

⇒ resolve degeneracy of massless spectra

on different fixed points.

Explicit Z6-II model: Pati-Salam

T.K. Raby, Zhang '04

4D massless spectrum

$$6V = (22200000)(11000000)$$

$$3W_3 = (1-1000000)(00200000)$$

$$2W_5 = (10000111)(00000000)$$

Gauge group $SU(4)\times SU(2)\times SU(2)\times SO(10)'\times SU(2)'\times U(1)^5$

Chiral fields

$$U_1 : (4,2,1),\quad U_2 : (1,2,2)\quad U_1 : (4,1,2)+(\bar{4},1,2)$$

$$T_1 : 2(4,2,1)+2(\bar{4},1,2)+4(4,1,1)+4(\bar{4},1,1)+8(1,2,1)+8(1,1,2)+2(1,1,2;1,2)$$

$$T_2 : 2(\bar{4},1,2)+(6,1,1),\quad T_3 : 6(6,1,1)+6(1,2,2),\quad T_4 : (4,1,2)+2(6,1,1)$$

Pati-Salam model with 3 generations + extra fields

All of extra matter fields can become massive

Pati-Salam (GUT) model

Gauge group

SU(4)xSU(2)xSU(2)

⇒ SU(3)xSU(2)xU(1)

Matter fields

(4,2,1)	⇒	(3,2,1)	left-handed quark
		(1,2,1)	left-handed lepton
(4,1,2)	⇒	(3,1,1)	up-sector of r-handed quark
		(3,1,1)	down-sector of r-handed quark
		(1,1,1)	right-handed charged lepton
		(1,1,1)	right-handed neutrino
(1,2,2)	⇒	2x(1,2,1)	up, down sector higgs

Heterotic orbifold as brane world

2D Z2 orbifold

E6 27 (bulk modes)

V2 shift T2/Z2 (V2+W2) shfit

SO(10) SU(6) * SU(2)

unbroken SU(4) * SU(2) * SU(2)

bulk 27 $\Rightarrow$ (4,2,1) + (4*,1,2)+…

SO(10) brane 16 $\Rightarrow$ (4,2,1) + (4*,1,2)

Explicit Z6-II model: MSSM

Buchmuller,et.al. ’06, Lebedev, et. al ‘07

4D massless spectrum

Gauge group $SU(3)\times SU(2)\times U(1)_Y \times G_H$

Chiral fields

3 generations of MSSM + extra fields

All of extra matter fields can become massive along flat directions

There are O(100) models.

Flat directions

realistic massless modes + extra modes
with vector-like rep.

Effective field theory has flat directions.
VEVs of scalar fields along flat directions
$\Rightarrow$ vector-like rep. massive, no extra matter

Such VEVs would correspond to deformation
of orbifolds like blow-up of singular points.

That is CY
(as perturbation around the orbifold limit).

Short summary on massless spectra

Once we choose a background(orbifold, gauge shift, wilson lines), a string model is fixed and its full massless spectrum can be analyzed in principle.

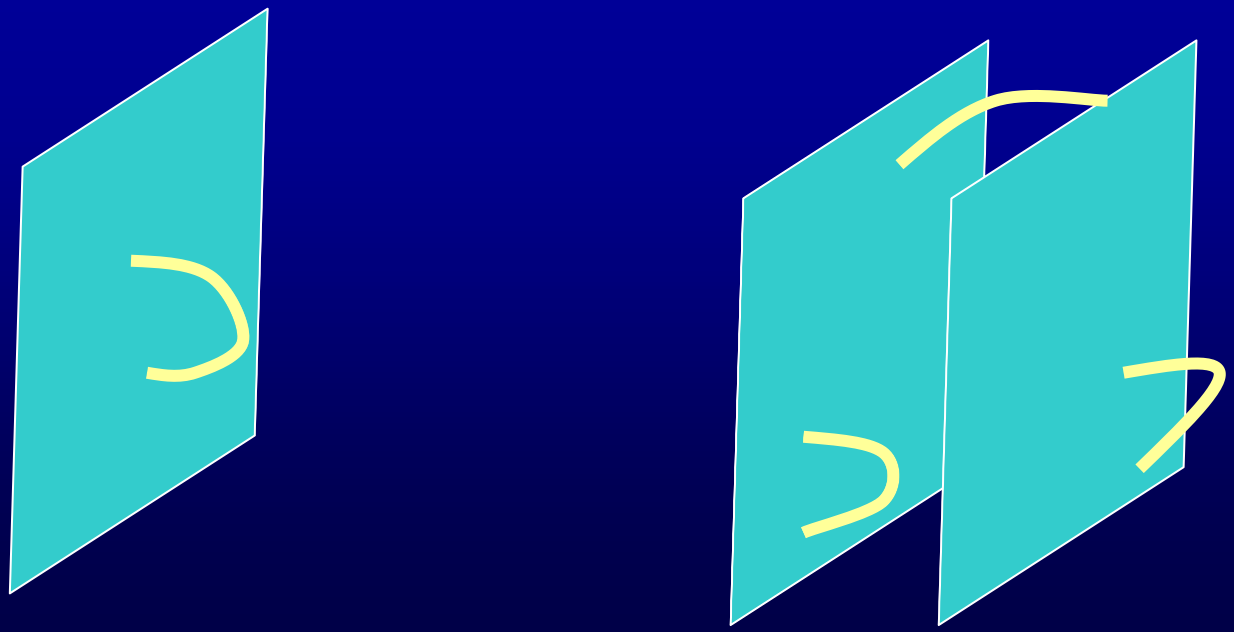
We have 4D string models, whose massless spectra realize the SM gauge group + 3 families（＋extra matter) and its extensions like the Pati-Salam model.

Similar situation for other compactifications

3. Intersecting D-brane models

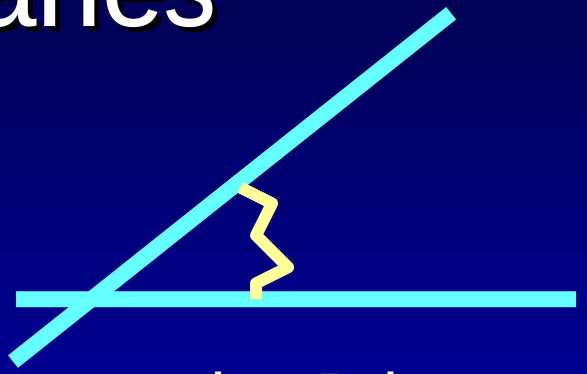
gauge boson: open string, whose two end-points are on the same (set of) D-brane(s)

N parallel D-branes ⇒ U(N) gauge group



Intersecting D-branes

Where is matter fields ?



New modes appear between intersecting D-branes.

They have charges under both gauge groups, i.e. bi-fundamental matter fields.

boundary condition

$$X^2(\sigma = 0) = 0, \quad \partial_\sigma X^1(\sigma = 0) = 0$$

$$X^1(\sigma = \pi)\tan\theta\pi + X^2(\sigma = \pi) = 0,$$

$$\partial_\sigma X^1(\sigma = \pi) - \partial_\sigma X^2(\sigma = \pi)\tan\theta\pi = 0$$

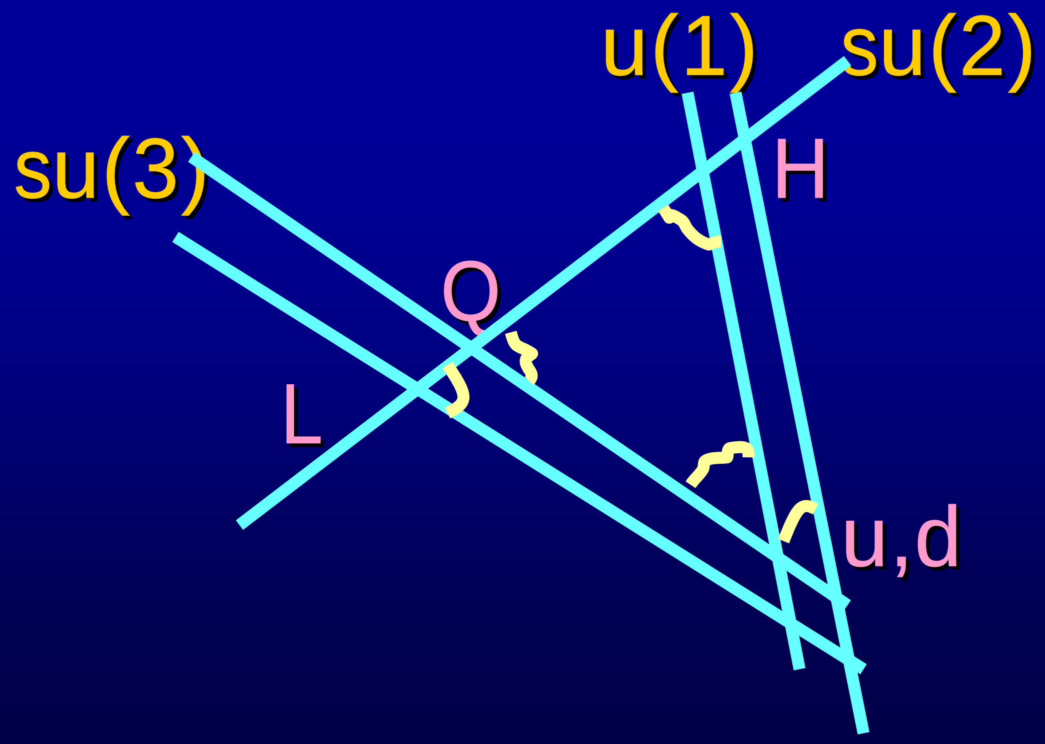
Twisted boundary condition

Toy model (in uncompact space)

gauge bosons : on brane

quarks, leptons, higgs :

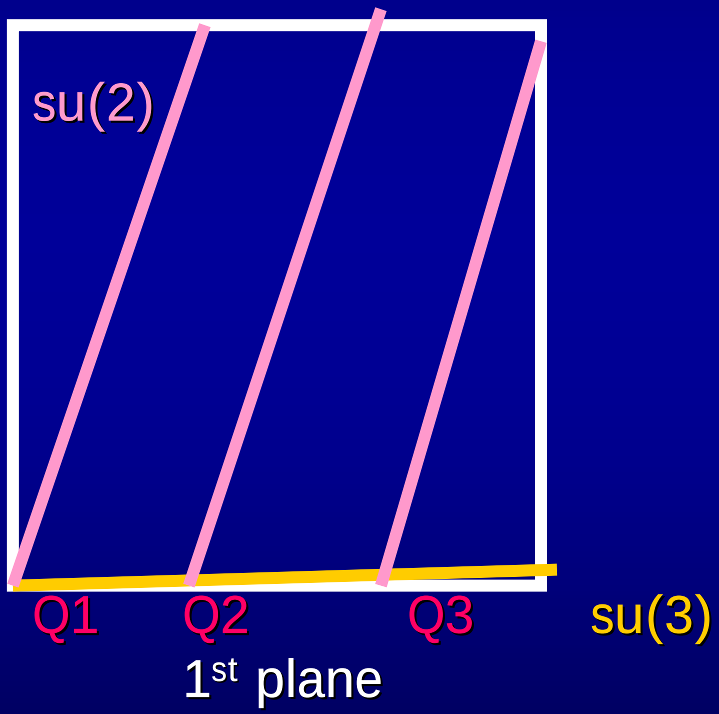
localized at intersecting points

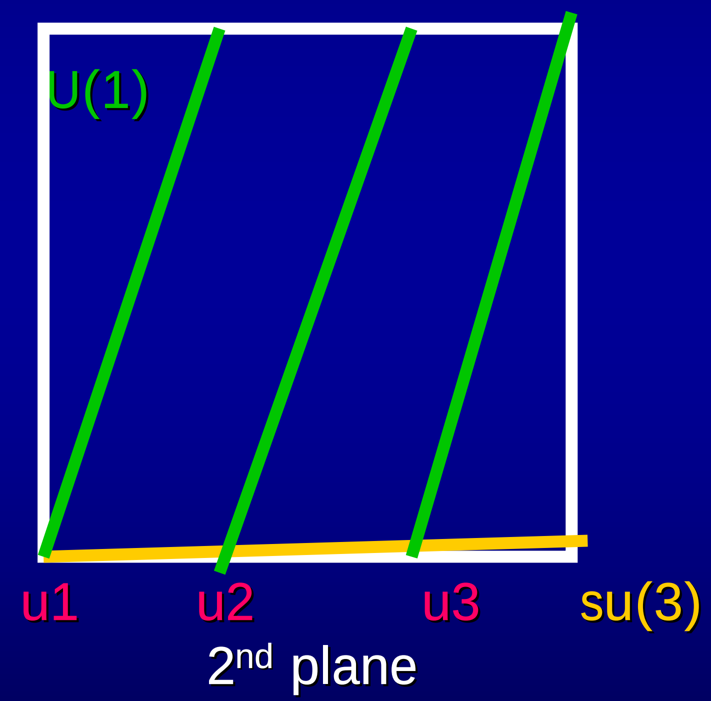


Generation number

compactification

Family number = intersection number





Short summary on massless spectra

We have 4D string models, whose massless spectra realize the SM gauge group + 3 families（＋extra matter) and its extensions like the Pati-Salam model.

Similar situation in other models with D-branes, like magnetized D-brane models

4. Effective theory

Effective theory of massless modes is described by supergravity- coupled gauge theory.

4-1. Gauge coupling

Extra dimensional theory

⇒ dimensional reduction to 4D theory

$$-\left(1/4g_{4+d}^2\right)\int d^4x d^d y \left(F_{MN}\right)^2 = -\left(V/4g_{4+d}^2\right)\int d^4x \left(F_{\mu\nu}\right)^2$$

$$g_4^2 = g_{4+d}^2/V$$

Gauge couplings in 4D depend on volume of compact space as well as dilaton.

Gauge kinetic function

Gauge kinetic function in supergravity

$$1/g_4^2 = \mathrm{Re}[f(\text{moduli})]$$

$$f = V/g_{4+d}^2 + \text{imaginary part}$$

Usually we redefine moduli fields such that gauge kinetic functions are written simply,

e.g. f = S .

heterotic models

Gauge couplings

Gauge sector

10D E8 ⇒ 4D $G_1 * G_2 * \ldots$

(smaller groups)

Gauge couplings at the tree level are unified at the compactification scale for any gauge groups.

$f=S$

Its value is determined by VEV of dilaton/moduli.

D-brane

Dp-brane : (p+1) dimensional extended object

our 4D spacetime

+ (p-3) compact space

For example,

D3-brane : not extend in extra dim. space,

but localize on a point

D6-brane : extend in 3 extra dim. space

D7-brane : extend in 4 extra dim. Space

Gauge sector lives on a set of Dp-branes

Gauge kinetic function

D3/D3 system on T2*T2*T2

Gauge sector on D3

$$-(1/4)\int dx\, e^{-\phi}\left(F_{\mu\nu}\right)^2$$

$$f_{D3} = S = e^{-\phi}$$

Gauge sector on D7(i) extending

on j-th and k-th torus

$$-(1/4)\int dx\, e^{-\phi+2\sigma_j+2\sigma_k}\left(F_{\mu\nu}\right)^2$$

$$f_{D7(i)} = T_i = e^{-\phi+2\sigma_j+2\sigma_k}$$

metric

$$\sum_{i=1,2,3} e^{2\sigma_i}\,|\,dx_i + i dy_i\,|^2$$

Gauge kinetic function

More complicated case

$$f = aS + bT + \cdots$$

Example : Intersecting D-branes

Magnetized D-branes

In general, their compact volumes are different from each other.

The gauge coupling unification is not automatic.

4-2. Yukawa couplings in heterotic orbifold

Yukawa couplings of untwisted matter (bulk fields)

Untwisted sector is originated from 10D modes.

That is, they respect 4D N=4 (10D N=1) SUSY vector multiplet

Yukawa couplings $\leftarrow$ controlled by 4D N=4 SUSY

Certain combinations are allowed: Selection rule

$\Rightarrow$ $Y = g = O(1)$

That fits to the top Yukawa coupling

Yukawa couplings

Yukawa couplings of twisted matter

twisted matter ⇒ localized modes

Extra dimensional field theory

Couplings among local fields are suppressed depending on their distance.

They can explain small Yukawa couplings for light quark/lepton ?

Let’s curry out stringy calculation

(stringy selection rule)

Selection rule for allowed couplings

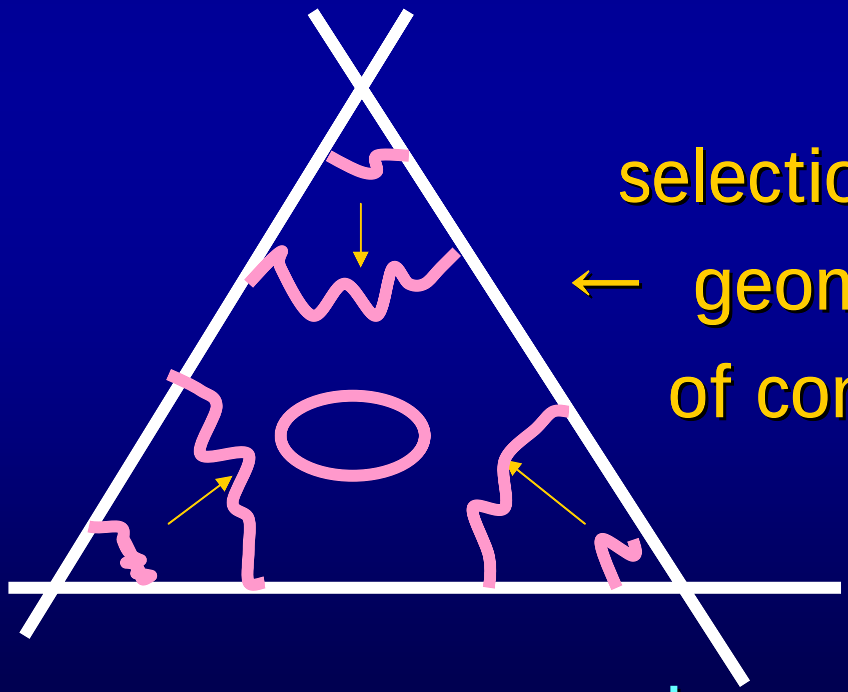
Allowed couplings : gauge invariant

Some selection rules are not understood
by effective field theory.

Stringy selection rule

Coupling selection rule

If three strings can be connected
and it becomes a shrinkable closed string,
their coupling is allowed.

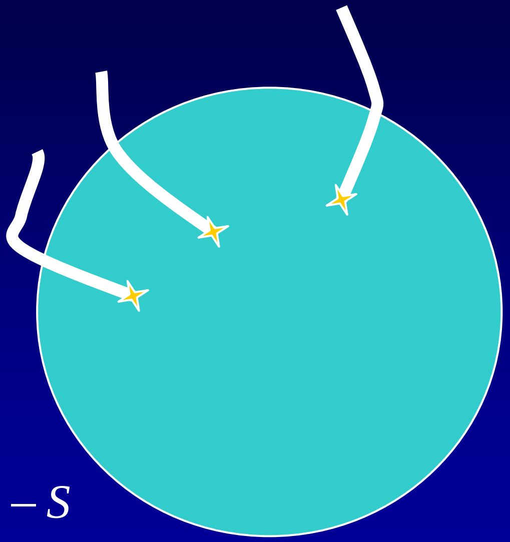


selection rule
← geometrical structure
of compact space

⇒ in general complicated

3-point coupling

Calculate by inserting vertex op.
corresponding to massless modes



$$\langle \sigma_{\Theta}(z_1)\sigma_{\Theta}(z_2)\sigma_{\Theta}(z_3)\rangle = \int dZ e^{-S}$$

$$= \sum_{Z_{cl}} \int dZ_{qu} e^{-S_{cl}-S_{qu}}$$

$$S_{cl} : classial \quad action \approx \quad Area$$

Yukawa couplings are suppressed by the area
that strings sweep to couple.

Those are favorable for light quarks/leptons.

n-point coplings

Choi, T.K. '08

Selection rule $\leftarrow$ gauge invariance

H-momentum conservation

space group selection rule

Coupling strength

calculated by inserting Vertex operators

$$\left\langle \sigma_{\Theta}(z_1)\sigma_{\Theta}(z_2)\cdots\sigma_{\Theta}(z_n)\right\rangle = \sum_{Z_{cl}} \int dZ_{qu} e^{-S_{cl}-S_{qu}}$$

$$S_{cl} : classial \quad action \approx \quad Area$$

Calculations in intersecting D-brane models

are almost the same.

Short summary on effective theory (coupling)

Several couplings are calculable.

← dimensional reduction from

extra dimesion

stringy (non-) perturbative calculation

All couplings are functions depending on moduli (dilaton).

We have to choose proper values of moduli VEVs.

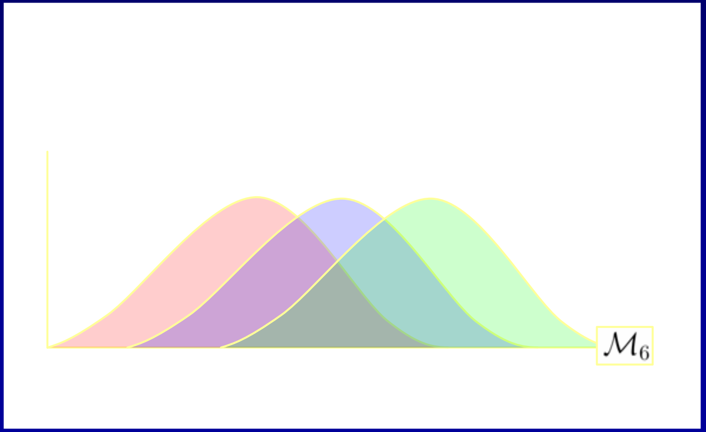
Couplings on CY

Extra dimensional effective field theory

Non-trivial background

→ non-trivial profile

of zero-mode wave function



$$Y_{ijk} = \int dy^{D-4} \psi_L^{i,M_1}(y) \psi_R^{j,M_2}(y) (\psi_H^{k,M_3}(y))^*$$

4D couplings among quasi- localized modes

= overlap integral along extra dimensions

→ suppressed Yukawa couplings

depending on their distance

4-3. More about Yukawa matrices

The number of 6D orbifolds is finite,

Z3,Z4,Z6,……

(crystallographic) space group

For an orbifold all of fixed points, where twisted string is localized, are known,

and its number is finite.

We know selection rules for allowed Yukawa couplings, and their magnitudes.

In principle, it is possible to study systematically which types of Yukawa matrices can appear from 3-point couplings.

Systematical study on Z6-I: Quark sector

Ko, T.K., Park '04

We study systematically all of possible assignments of 2nd and 3rd families to fixed points,

assume one pair of up and down Higgs fields,

examine allowed entries by the selection rule,

try to fit the mass ratios m_c/m_t, m_s/m_b and mixing angle V_{cb} by varying R_1 and R_2.

$$[m_c/m_t]_{\exp} = 0.0038, \qquad [m_s/m_b]_{\exp} = 0.025$$

$$[V_{cb}]_{\exp} = 0.041$$

Assignment 1

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

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

$T_1 = 27.8,$ $T_2 = 107$

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

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

There are several examples leading to similar results.

Assignment 2

$Q_2, Q_{3,}$ $\quad u_2, u_3$ $\quad d_2, d_3$ $\quad H_u, H_d$

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

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

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

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

There are several examples leading to similar results.

Results

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

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.

Results for three families of quarks are not perfectly good.

Systematical study on Z6-I: Lepton sector

Ko, T.K., Park '05

We study systematically all of possible assignments of three families to fixed points,

assume one pair of up and down Higgs fields,

examine allowed entries by the selection rule,

try to fit the lepton mass ratios and

mixing angles by varying R_1 and R_2.

$$[m_e / m_\tau]_{\exp} = 0.000288, \qquad [m_\mu / m_\tau]_{\exp} = 0.0595$$

$$[\Delta m_{31}^2 / \Delta m_{21}^2]_{\exp} = 27, \qquad [\sin^2 \theta_{12}]_{\exp} = 0.30$$

$$[\sin^2 \theta_{23}]_{\exp} = 0.50, \qquad [\sin^2 \theta_{13}]_{\exp} = 0.000$$

Dirac neutrino mass: Assignment 4

$L_1, L_2, L_{3,}$ N_1, N_2, N_3 e_1, e_2, e_3 H_u, H_d

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

$T_1 = 26,\qquad T_2 = 21$

$m_e / m_\tau = 0.0003,\qquad m_\mu / m_\tau = 0.06,\qquad \Delta m_{31}^2 / \Delta m_{21}^2 = 14,$

$\sin^2\theta_{12} = 0.38,\qquad \sin^2\theta_{23} = 0.70,\qquad \sin^2\theta_{13} = 0.000,$

There are several examples leading to similar results、but smaller ratios of neutrino mass difference.

Explicit models

Explicit models have flat directions and several scalar fields develop their VEVs.

Higher dim. Operators $\left(\phi_1 \ldots \phi_n / M^n\right) HQq$ become effective Yukawa couplings after symmetry breaking.

They would lead to suppressed Yukawa couplings

How to control n-point coupling is important.

So far, such analyses have been done model by model.

Non-abelian discrete flavor symm.

Recently, in field-theoretical model building, several types of discrete flavor symmetries have been proposed with showing interesting results,

e.g. S3, D4, A4, S4, Q6, $\Delta(27)$, ……

Neutrino oscillation ⇒ large mixing angles

one Ansatz: tri-bimaximal

$$\begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \end{pmatrix}$$

Discrete flavor symmetries

What is the origin of these discrete non-Abelian flavor symmetries ?

e.g.

S3 : symmetry of equilateral triangle

A4 : symmetry of tetrahedora

……

Extra dimensional compact space could be an origin of discrete non-Abelian flavor symmetries.

S1/Z2

There are two fixed points.

$$(\Theta, me), \qquad m = 0, 1$$

$$(1-\Theta)\Lambda = 2e$$

Θ : Z2 twist

Space group selection rule

$$\prod_{j=1}^{n} (\Theta, m^{(j)}e) = (\Theta^n, \sum_{j=1}^{n} m^{(j)}e) = (1, (1-\Theta)\Lambda)$$

$$n = even, \qquad \sum_{j=1}^{n} m^{(j)} = even$$

D4 Flavor Symmetry

Stringy symmetries require that Lagrangian has the permutation symmetry between 1 and 2, and each coupling is controlled by two Z2 symmetries.

Flavor symmeties: closed algebra S2 U(Z2xZ2)

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \qquad -1 = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \qquad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

D4 elements

$$\pm 1, \qquad \pm \sigma_1, \qquad \pm i\sigma_2, \qquad \pm \sigma_3$$

modes on two fixed points ⇒ doublet

untwisted (bulk) modes ⇒ singlet

Geometry of compact space

→ origin of finite flavor symmetry

Strings on orbifold

Actually, we have constructed explicit string models on the Z6 orbifold, which have D4 flavor symmetries and three generations as D4 singlets and doublets.

T.K., Raby and Zhang, '04

Other flavor symmetries can appear

T.K., Nilles, Ploger, Raby and Ratz, '06

Study on discrete anomalies is also important.

Araki, T.K., Kubo, Ramos-Sanchez, Ratz, Vaudrevange, '08

Discrete anomlies Zn-G-G are universal for all of gauge groups G.

Cf. U(1)-G-G anomalies are universal.

5. Moduli stabilization, SUSY breaking

5-1. Introduction

Superstring theory has several moduli fields including the dilaton.

Moduli correspond to the size and shape of compact space.

VEVs of moduli fields
→ couplings in low-energy effective theory,
e.g. gauge and Yukawa couplings

Thus, it is important to stabilize moduli VEVs at realistic values from the viewpoint of particle physics as well as cosmology

Actually, lots of works have been done so far.

Moduli stabilization and SUSY breaking

Low-energy effective theory = supergravity

Moduli-stabilizing potential may break SUSY.

$$F/M = O(m_{3/2})$$

That would lead to a specific pattern of SUSY breaking terms, i.e. masses of superpartners.

However, moduli stabilization is not clear in heterotic theories such that most of people can agree.

At present, Type IIB would be better in this point.

KKLT scenario

Kachru, Kallosh, Linde, Trivedi, '03

They have proposed a new scenario for moduli stabilization
leading to de Sitter (or Minkowski) vacua,
where all of moduli are stabilized.

Soft SUSY breaking terms

Choi, Falkowski, Nilles, Olechowski, Pokorski '04, CFNO '05

→ a unique patter of soft SUSY breaking terms

Modulus med. and anomaly med. are comparable.

→ Mirage (unification) scale

Mirage Mediation Choi, Jeong, Okumura, '05

→ little SUSY hierarchy (TeV scale mirage mediation)

Choi, Jeong, T.K., Okumura, '05, '06

More about moduli stabilization

a generic KKLT scenario

with moduli-mixing superpotential

$\Rightarrow$ various mirage scale

Abe, Higaki, T.K., ’05

Choi, Jeong, ’06

Choi, Jeong, T.K., Okumura, ‘06

F-term uplifting

Dudas, Papineau, Pokorski, ’06

Abe, Higaki, T.K., Omura, ’06

Kallosh, Linde, ’06

Abe, Higaki, T.K, ‘07

Cosmoligical aspects

Inflation models based on KKLT

Overshooting problem, etc.

However, this is a workshop on heterotic theory.

Summary

We have studied on particle phenomenological aspects on heterotic models to find out a scenario connecting string theory and the particle physics, in particular the Standard Model.

Several issues:
realistic spectra,
flavor structure、moduli stabilization、
SUSY breaking、cosmology、………

Scoreboard at present

Realistic massless spectra

all types of string theories are not bad

We have known already many string models, which have the same content as the MSSM or its extensions.

Gauge coupling unification

heterotic theory is better.

Yukawa matrices

heterotic theory is better, but not perfect.

Moduli stabilizatin

IIB is better, but nobody has considered Moduli stabilization in realistic models.