Dim.-4 Proton Decay and Underlying Gauge Symmetry

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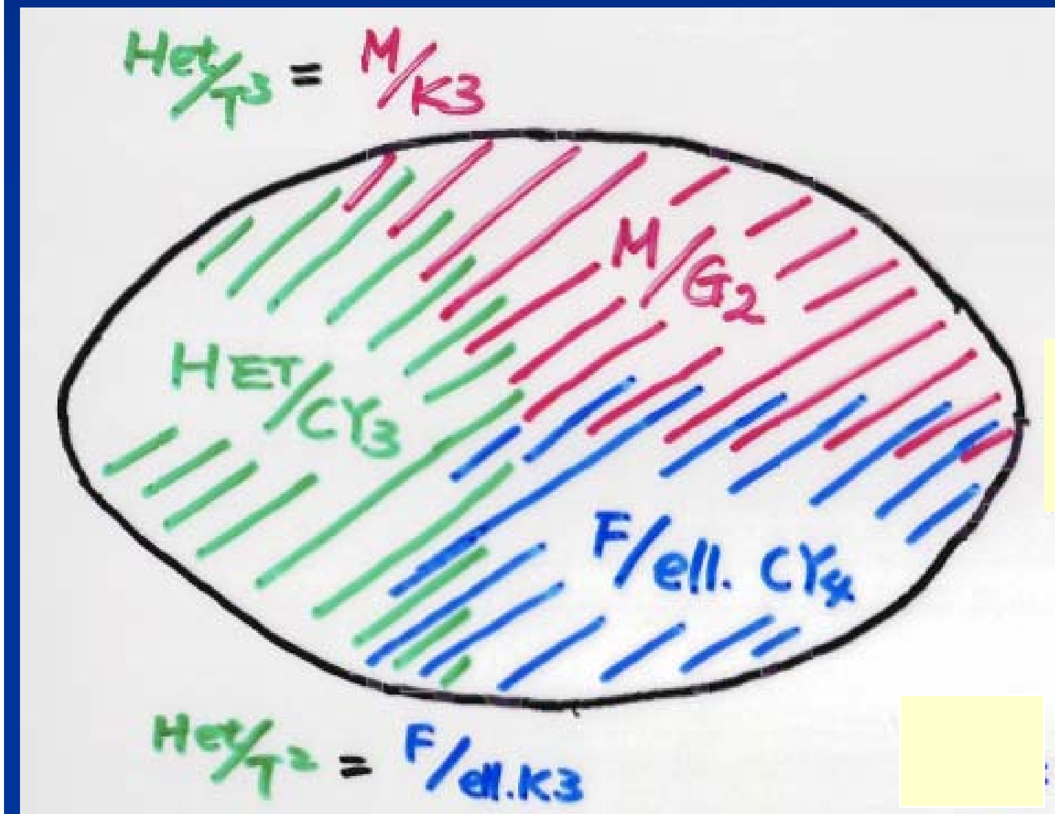
Contents

Introduction

N = 1 Supersymmetric String Landscape



T-dual,
Mirror

String Duality

Het, M, F vacua can have qualitatively similar properties at the 1^{st} order approximation.

Each corner of string moduli space (landscape) requires different mathematical techniques.

But, there is one "common" feature:

- 16 - SUSY YM multiplets of G
- G $\longrightarrow$ H broken by <adj.>
  - vector bundles (Het, Type I, Type IIA, IIB)
  - intersecting branes (Type IIA, IIB)
  - deformation of ADE singularities (M-, F-theory)
- matter chiral multiplets from g/h

G/H '60s

$\pi^\pm, \pi^0$: COORDINATES OF $SU(2)_L \times SU(2)_R / SU(2)_V$

$H = SU(2)_V$ ACTS LINEARLY ON (π^+, π^0, π^-).

FULL $G = SU(2)_L \times SU(2)_R$ SYM. CONTROLS

$$\mathcal{L} = \partial_\mu \pi^a \partial^\mu \pi^a + \cdots$$

$$+ \bar{N} i \gamma^\mu \left(\partial_\mu + \frac{(\partial_\mu \pi^a)\, \pi^b}{F_\pi^2} \tau^c \epsilon_{abc} + \gamma_5 \frac{\partial_\mu \pi^a}{F_\pi} \tau^a \right) N$$

$$+ \cdots$$

Quarks, leptons and Higgs multiplets instead of pions in supersymmetric G/H

Yukawa couplings of quarks and leptons ⟶ G

Determining G

DETERMINATION OF G

ASSUMPTIONS

- ALL YUKAWA COUPLINGS FROM YM INT. OF G.
- Georgi - Glashow $H = SU(5)$.
- $W \ni y_{d,e}\, \bar{5} \cdot 10 \cdot \bar{H}(\bar{5})$ BUT $W \not\ni \bar{5} \cdot 10 \cdot \bar{5}$

  $\bar{5} = (\bar{D}, L)$ AND $\bar{H}(\bar{5}) = (\bar{H}_c, H_d)$

  FROM DIFFERENT IRR. COMPONENTS OF $\mathfrak{g}/\mathfrak{h}$.

POWER OF G + 16 SUSY.

Lykken Poppitz Trivedi '98

$G = SO(11)$ in Type IIB or Type I. $/ \mathbb{C}^3/\mathbb{Z}_3$ or $T^6/\mathbb{Z}_3$.

$H = SU(5)$

$$\begin{bmatrix} \text{adj.} & 10 & 5 \\ \overline{10} & & \bar{5} \\ & & \end{bmatrix}_{11\times 11}$$

3 CHIRAL MULTIPLETS OF $(10 + \bar{5})$

$$W \ni \varepsilon_{abc} \, \mathrm{tr}_{SO(11)\text{-adj.}} \left(\Sigma^a (\partial^b - \Sigma^b) \Sigma^c \right)$$

$\longrightarrow W \ni \bar{5}^a 10^b \bar{5}^c \varepsilon_{abc}$. DIM.-4 p DECAY.

CERTAIN G ARE PREDICTIVE, FALSIFIABLE.

UP-TYPE YUKAWA COUPLINGS

SPECTRUM : $SU(5)_{GUT}$ - 10 FROM $\mathfrak{so}(10)/\mathfrak{su}(5)$.

$SU(5)_{GUT}$ - $\bar{5}$ FROM $\mathfrak{su}(6)/\mathfrak{su}(5)$.

NOT ENOUGH INFO.

UP-TYPE YUKAWA $W \ni 10^{ij}\, 10^{kl}\, H(5)^{m}\, \epsilon_{ijklm}$.

→ NOT JUST SIMPLE 

[NOT IIA. IIB ORIENTIFOLDS. TYPE I.]

$G = E_{6.7.8}$ IN HET. M. F.

$$\mathrm{Res}^{E_6}_{SU(5)\times SU(2)}\, e_6\text{-adj.} = (\text{adj}.1) + (1.\text{adj}.) + \big[(10.2) + (\wedge^2 5.1)\big] + \text{h.c.}$$

$$W \ni \mathrm{tr}_{E_6}\big(\Sigma.[\Sigma'.\Sigma'']\big) \to (10.2)\otimes(10.2)\otimes\overline{(\wedge^2 5.1)}$$

$$\downarrow \qquad \downarrow \qquad \downarrow$$

$$10 \cdot 10 \quad H(5).$$

$e_6 / SU(5)$ CONTAINS $10 + H(5)$, BUT NOT $\bar{5} \,.\, \bar{H}(\bar{5})$.

$$\mathrm{Res}^{E_7}_{SU(5)_{GUT} \times SU(2) \times U(1) \times U(1)} \; e_7\text{-adj.} = (\text{adj.}\,.\,1) + (1\,.\,\text{adj.})$$

$$\left[\begin{array}{l} + \,(5\,.\,1)^{0.6} \\ + \,(\Lambda^2 5\,.\,2)^{1.2} + (\Lambda^4 5\,.\,1)^{2.4} \\ + \,(5\,.\,2)^{1.-4} + (\overline{10}\,.\,1)^{2.2} \\ \qquad\qquad\qquad + \,(1\,.\,2)^{3.0} \end{array}\right] + \text{h.c.}$$

$$W \ni (\Lambda^2 5.2)^{1.2} \otimes (\Lambda^2 5.2)^{1.2} \otimes \overline{(\Lambda^4 5.1)}^{2.4} \longrightarrow 10 \cdot 10 \cdot H(5),$$

$$\overline{(5.2)}^{1.-4} \otimes (\Lambda^2 5.2)^{1.2} \otimes \overline{(5.1)}^{0.6} \longrightarrow \bar{5} \cdot 10 \cdot \bar{H}(\bar{5}), \quad \bar{H}(\bar{5}) \, 10 \, \bar{5}$$

$$\overline{(\Lambda^4 5.1)}^{2.4} \otimes \overline{(5.2)}^{1.-4} \otimes (1.2)^{3.0} \longrightarrow H(5) \cdot \bar{5} \cdot \bar{N}, \quad H \cdot \bar{H} \cdot S$$

$E_7 / SU(5)_{GUT} \times \langle SU(2) \times U(1) \times U(1) \rangle$

IRR. COMPONENTS OF $e_7 / su(5) + su(2)$

CONTAIN 10. $\bar{5}$. $H(5)$. $\bar{H}(\bar{5})$.

SUPER YM INTERACTIONS GENERATE

u. d. e YUKAWA + [ν DIRAC YUKAWA
SH$\bar{H}$.

PROTON DECAY OPERATORS

DIM.-4 $\overline{(5.2)}^{1\text{-}4} \otimes (\wedge^2 5.2)^{1.2} \otimes \overline{(5.2)}^{1\text{-}4}$

DIM.-5 $\overline{(\bar{5}.2)}^{1\text{-}4} \otimes (\wedge^2 5.2)^{1.2\,\otimes 3}$

} NOT INV. UNDER $SU(2) \times U(1)^2$.

$G = E_7$ IS THE MINIMAL CHOICE.

E_8 IS NOT NECESSARY.

THE OTHER POSSIBILITIES

$$E_8 / SU(5)_{GUT} \times \langle SU(2) \times SU(2) \times U(1) \times U(1) \rangle$$

$$E_8 / SU(5)_{GUT} \times \langle SU(2) \times SU(3) \times U(1) \rangle$$

$$E_8 / SU(5)_{GUT} \times \langle SU(4) \times U(1) \rangle$$

STILL. $\bar{5}$ AND $\bar{H}(\bar{5})$ HAVE DIFFERENT ORIGINS

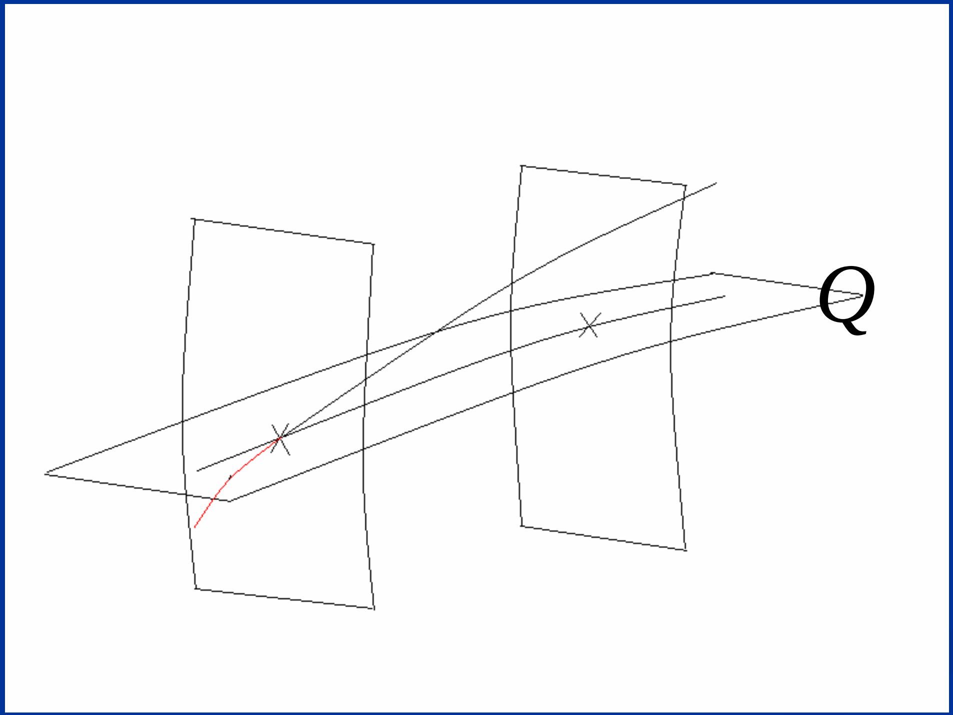
AND DIM-4 PROTON DECAY IS ABSENT.

Up-type Yukawa Matrix in M-theory Vacua

Up-type Yukawa coupling in M-theory vacua

11 D SUGRA / G_2 - holonomy manifold

locally ALE fibration on a compact 3-fold Q



H = SU(5)

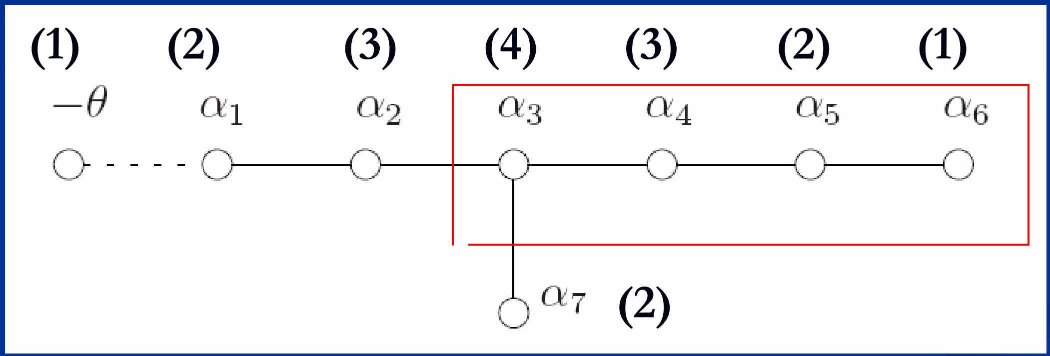
A_4 singular locus $\simeq Q$

Matter chiral multiplets localized at enhanced singularities

Acharya '00
Atiyah Witten '01,
Acharya Witten '01, …

ALE fibre of E_7 or E_8 type

hyper-Kahler quotient of a quiver gauge theory associated with the extended Dynkin diagram



Kronheimer '89
Douglas Moore '96

$$\sum_i n_i \, \alpha_i = 0.$$

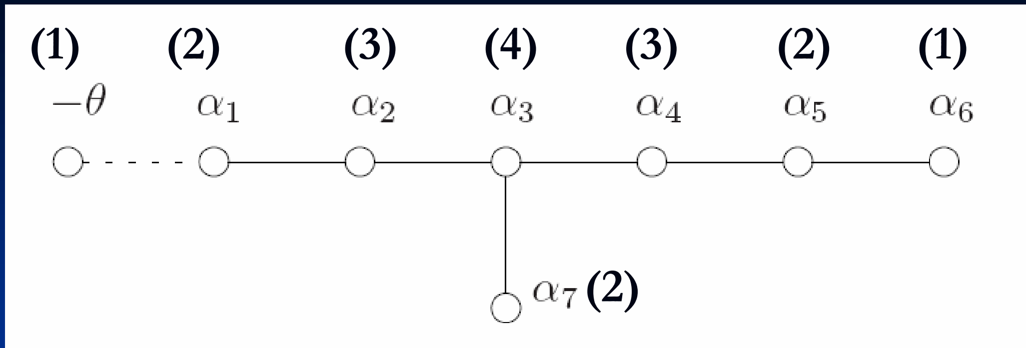
$$\sum n_i \, \zeta_i = 0.$$

r = 7 or 8 independent 2-cycles C_i $\qquad \sum_i n_i \, C_i = 0.$

ζ_i**: size of a 2-cycle**

enhanced A_4 **singulartiy when** $\zeta_{3,4,5,6} = 0.$

[SU(5) N=1 vector multiplet]



Singularity is enhanced where some combination of ζ_i (and C_i) vanishes.

Matter Identification

particles	$\mathbf{10}$	$\bar{\mathbf{5}}$	$H(\mathbf{5})$	$\bar{H}(\bar{\mathbf{5}})$	$\bar{N}$
2-cycles	$-(C_2+C_3+C_7)$, $-(C_1+C_2+C_3+C_7)$	C_2, (C_1+C_2)	$C_1+2C_2+2C_7$ $+3C_3+2C_4+C_5$	C_7	$C_{-\theta}$, $C_{-\theta}+C_1$
singularity	D_5	A_5	A_5	A_5	A_1+A_4

Yukawa interactions from reconnection of M2-branes w/o p decay

$$\mathbf{10}.\mathbf{10}.H(\mathbf{5}) \quad -(C_1+C_2+C_7)-(C_2+C_7)+(C_1+2C_2+C_7)\equiv 0,$$
$$\bar{\mathbf{5}}.\mathbf{10}.\bar{H}(\bar{\mathbf{5}}) \quad C_2[+C_1]-(C_2+C_7[+C_1])+C_7\equiv 0,$$
$$\bar{N}.\bar{\mathbf{5}}.H(\mathbf{5}) \quad C_{-\theta}+(C_1+C_2)+(C_1+2C_2+2C_7)\equiv 0,$$

$$\text{dimension-4}: \quad \bar{\mathbf{5}}.\mathbf{10}.\bar{\mathbf{5}} \quad -(C_2+C_7[+C_1])+2(C_2[+C_1])\not\equiv 0,$$
$$\text{dimension-5}: \quad \mathbf{10}.\mathbf{10}.\mathbf{10}.\bar{\mathbf{5}} \quad -3(C_2+C_7[+C_1])+(C_2[+C_1])\not\equiv 0.$$

$e_6 / SU(5)$ CONTAINS $10 + H(5)$, BUT NOT $\bar{5} \,.\, \bar{H}(\bar{5})$.

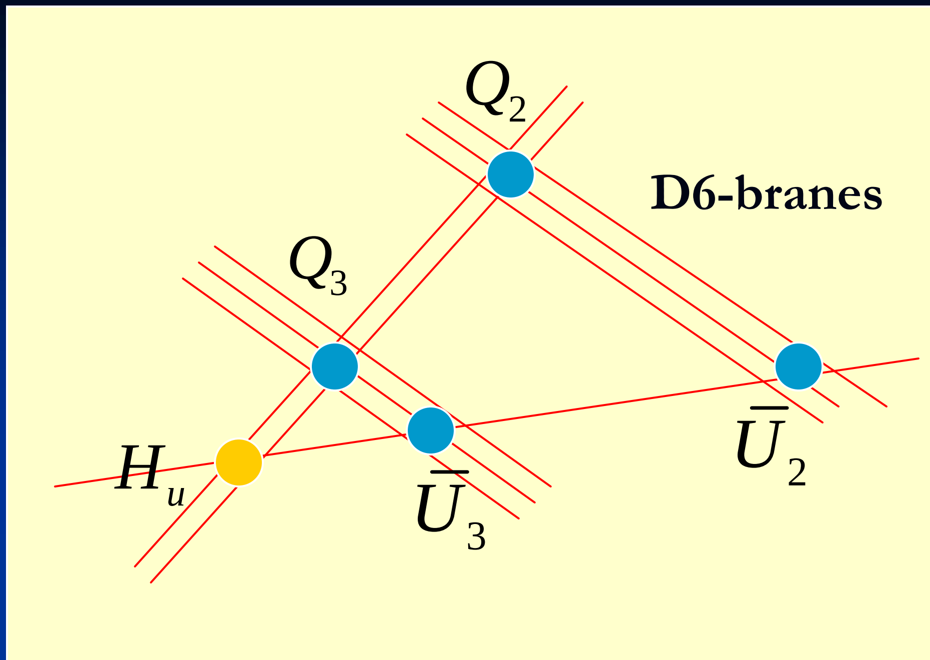
$$\mathrm{Res}^{E_7}_{SU(5)_{GUT} \times SU(2) \times U(1) \times U(1)} \; e_7\text{-adj.} = (\text{adj.}\,.\,1) + (1\,.\,\text{adj.})$$

$$\begin{bmatrix} + (5\,.\,1)^{0.6} \\ + (\Lambda^2 5\,.\,2)^{1.2} + (\Lambda^4 5\,.\,1)^{2.4} \\ + (5\,.\,2)^{1.-4} + (\overline{10}\,\bar{5}\,.\,1)^{2.2} \\ + (1\,.\,2)^{3.0} \end{bmatrix} + \text{h.c.}$$

$$W \ni (\Lambda^2 5.2)^{1.2} \otimes (\Lambda^2 5.2)^{1.2} \otimes \overline{(\Lambda^4 5.1)}^{2.4} \longrightarrow 10 \cdot 10 \cdot H(5),$$

$$\overline{(5.2)}^{1.-4} \otimes (\Lambda^2 5.2)^{1.2} \otimes \overline{(5.1)}^{0.6} \longrightarrow \bar{5} \cdot 10 \cdot \bar{H}(\bar{5}), \quad \bar{H}(\bar{5}) \cdot 10\, \bar{5}$$

$$\overline{(\Lambda^4 5.1)}^{2.4} \otimes \overline{(5.2)}^{1.-4} \otimes (1.2)^{3.0} \longrightarrow H(5) \cdot \bar{5} \cdot \bar{N}, \quad H \cdot \bar{H} \cdot S$$



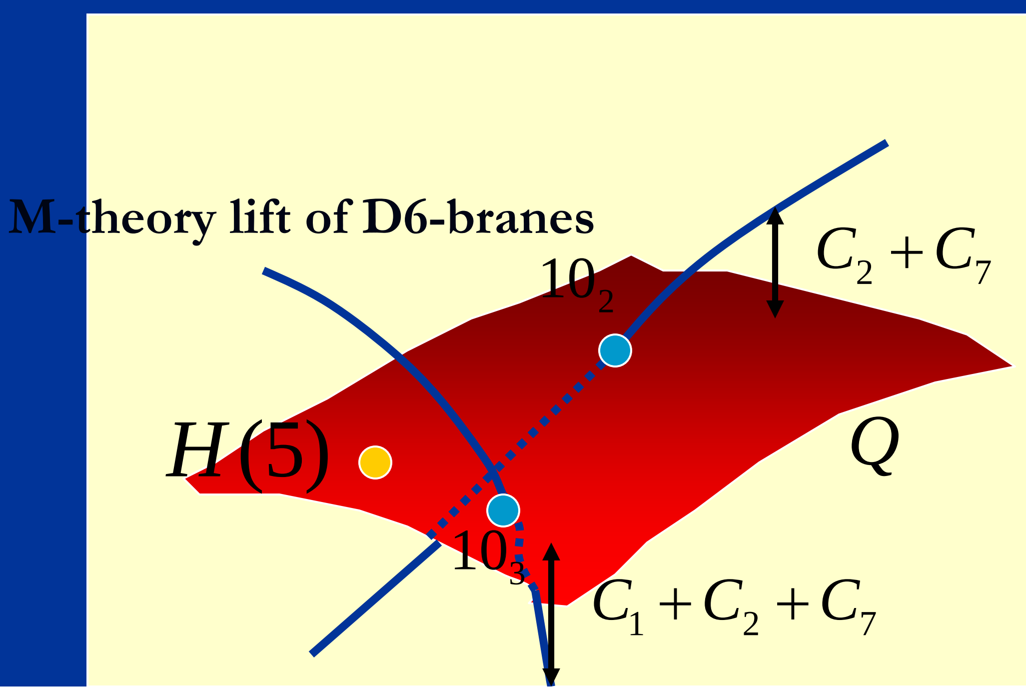
Up-type Yukawa matrix of SUSY Standard Model

$\propto e^{-\text{Area}}$ Cvetic Langacker Shiu '02

$$\propto \begin{pmatrix} 1 & \delta \\ \delta' & \varepsilon \end{pmatrix}.$$

hierarchy: $1 : \delta\delta'$

mixing : $O(\delta), O(\delta')$.



Up-type Yukawa matrix of SU(5) symmetric theories

$10_2 10_3 H(5)$

from minimal volume

$10_3 10_3 H(5), \quad 10_2 10_2 H(5),$

from M2-branes wrapping

Suppressed diagonal entries !

B – L Symmetry Breaking in Heterotic String Vacua

THE OTHER POSSIBILITIES

$$E_8 / SU(5)_{GUT} \times \langle SU(2) \times SU(2) \times U(1) \times U(1) \rangle$$

$$E_8 / SU(5)_{GUT} \times \langle SU(2) \times SU(3) \times U(1) \rangle$$

$$E_8 / SU(5)_{GUT} \times \langle SU(4) \times U(1) \rangle$$

STILL, $\bar{5}$ AND $\bar{H}(\bar{5})$ HAVE DIFFERENT ORIGINS

AND DIM-4 PROTON DECAY IS ABSENT.

G = E_8 ,   SU(5) bdle V ⟶ unbroken SU(5).

$$248 = (\text{adj.}, 1) + (1, \text{adj.}) + [(V, 10) + (\wedge^2 V, \bar{5})] + \text{h.c.}$$

vector bdle moduli

charged matter multiplets

gluons and photons

Dimension-4 proton decay operators do not exist if the vector bundle V is reducible.

$$V_5 = L \oplus U_4, \quad \text{with} \quad L \otimes \det U_4 \simeq \mathcal{O}_Z,$$

$$V_5 = U_3 \oplus U_2, \quad \text{with} \quad \det U_3 \otimes \det U_2 \simeq \mathcal{O}_Z,$$

SU(5) symmetry may be broken down to the Standard Model gauge group via Wilson line or missing partner mechanism.

$$V_5 = L \oplus U_4, \quad \text{with} \quad L \otimes \det U_4 \simeq \mathcal{O}_Z,$$

$10 = (Q, \bar{U}, \bar{E})$ **from** $H^1(Z; U_4)$

no massless modes from $H^1(Z; L)$

V_5

$\bar{5} = (\bar{D}, L)$ **from** $H^1(Z; U_4 \otimes L)$

$\bar{H}(\bar{5})$ **from** $H^1(Z; \wedge^2 U_4)$

$\wedge^2 V_5$

$H(5)$ **is from** $H^1(Z; \overline{\wedge^2 U_4})$

$$\begin{aligned} W \quad \ni \quad & (\mathbf{10}, U_4) \otimes (\mathbf{10}, U_4) \otimes \overline{(\bar{\mathbf{5}}, \wedge^2 U_4)} \longrightarrow \mathbf{10}.\mathbf{10}.H(\mathbf{5}) \\ & + (\bar{\mathbf{5}}, U_4 \otimes L) \otimes (\mathbf{10}, U_4) \otimes (\bar{\mathbf{5}}, \wedge^2 U_4) \longrightarrow \bar{\mathbf{5}} \cdot \mathbf{10} \cdot \bar{H}(\bar{\mathbf{5}}) \\ & + (\bar{\mathbf{5}}, U_4 \otimes L) \otimes (\mathbf{1}, U_4 \otimes L^{-1}) \otimes \overline{(\bar{\mathbf{5}}, \wedge^2 U_4)} \longrightarrow \bar{\mathbf{5}} \cdot \bar{N} \cdot H(\mathbf{5}). \end{aligned}$$

Some of vector bdle moduli adj.(V_5) **are identified w RH-neutrinos.**

$$V_5 = U_3 \oplus U_2, \quad \text{with} \quad \det U_3 \otimes \det U_2 \simeq \mathcal{O}_Z,$$

$10 = (Q, \bar{U}, \bar{E})$ **from** $H^1(Z; U_2)$

no massless modes from $H^1(Z; U_3)$

$\underbrace{\qquad\qquad\qquad}_{V_5}$

$\bar{5} = (\bar{D}, L)$ **from** $H^1(Z; U_3 \otimes U_2)$

$\bar{H}(\bar{5})$ **from** $H^1(Z; \wedge^2 U_3)$

$\underbrace{\qquad\qquad\qquad}_{\wedge^2 V_5}$

$H(5)$ **is from** $H^1(Z; \overline{\wedge^2 U_2})$

Proton decay operators

dim.-4 $\quad \bar{5} \cdot 10 \cdot \bar{5}$ $\quad (U_3 \otimes U_2)^2 \otimes U_2$

dim.-5 $\quad 10.10.10.\bar{5}$ $\quad U_2^3 \otimes (U_3 \otimes U_2)$

in $\wedge^5 V_5$

vanish.

$$V_5 = L \oplus U_4, \quad \text{with} \quad L \otimes \det U_4 \simeq \mathcal{O}_Z,$$

The structure group is SU(4) x U(1), and
the U(1) symmetry is not broken by the bdle configuration.
This is the B – L symmetry; its gauge boson has mass terms
through Green-Schwarz mechanism.

$$\mathcal{L} = \frac{1}{2g_{\rm YM}^2} 2\,{\rm tr}_f(\mathrm{q}_X^2) D_X^2 + D_X \xi_X + D_X q_{X,i} \psi_i^\dagger \psi_i \to V = \frac{1}{2} \frac{g_{\rm YM}^2}{2\,{\rm tr}_f(\mathrm{q}_X^2)} \left(\xi_X + q_{X,i}\psi_i^\dagger\psi_i\right)^2 .$$

$$\xi_X = \frac{10 M_G^2}{32\pi^2} \left[\frac{2\pi l_s^2}{{\rm vol}(Z)} \int c_1(L) \wedge J \wedge J - \frac{g_{\rm YM}^2 e^{2\tilde{\phi}_4}}{2} \int c_1(L) \left(c_2(V_5) - \frac{1}{2} c_2(TZ) \right) \right] .$$

Blumenhagen, Honecker, Weigand '05

Kahler moduli   dilaton

The Fayet—Iliopoulos parameter may not vanish.

If $\xi < 0$,

the D-term condition (equation of motion of the gauge field)

$$\xi - 5\left|\bar{N}\right|^2 + 5\left|\bar{\bar{N}}\right|^2 - \left|10\right|^2 + 3\left|\bar{5}\right|^2 + 2\left|H\right|^2 - 2\left|\bar{H}\right|^2 = 0$$

can be satisfied by $\left\langle \bar{\bar{N}} \right\rangle \neq 0.$

This is equivalent to $0 \to L \to V_5 \to U_4 \to 0.$

more general than the reducible limit.

The B – L gauge boson is Higgsed, and
the mass is typically of the order of Kaluza—Klein scale.

Broken B – L symmetry allows Majorana RH neutrino masses,
and consequently the see-saw mechanism to work.

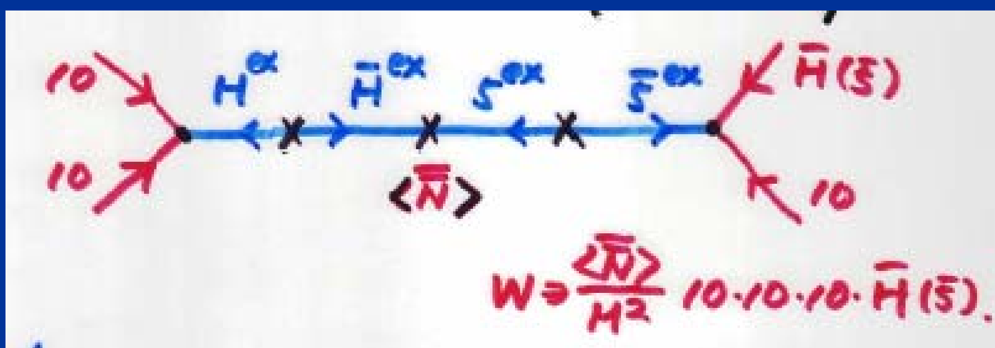
The original motivation, the absence of dim.-4 proton decay, is still maintained even if $\left\langle \bar{\bar{N}} \right\rangle \neq 0$.

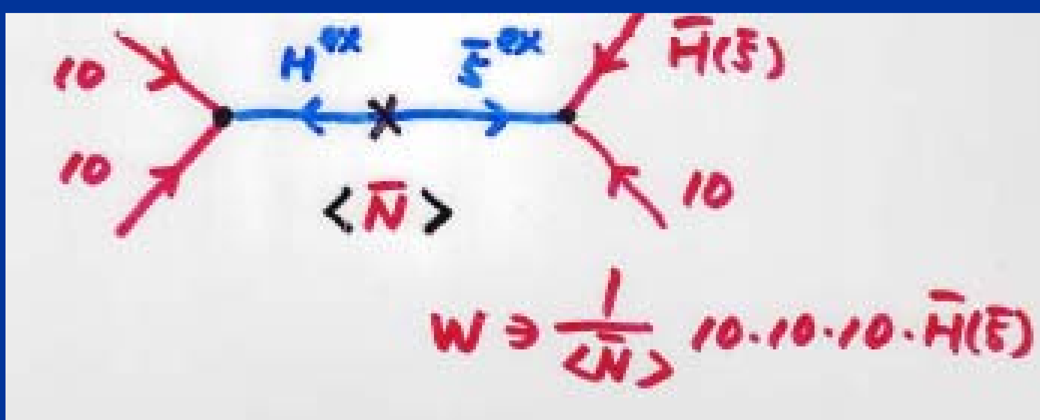
This is because operators of the form $W \neq \overline{5} \cdot 10 \cdot \overline{5} \cdot \bar{\bar{N}}^{n}$ is not allowed by the underlying gauge symmetry E_8 .

LSP Decay

$\langle \overline{\overline{N}} \rangle \neq 0.$ **means that neither R-parity nor matter parity remains unbroken.**

Indeed, after integrating out heavy states, an R-parity violating oprator can be generated (Figure).





The lightest supersymmetry particle (LSP) is not stable. It decays through this operator, and is no longer a good candidate of dark matter.

LSP decay may be seen in future collider experiments.

Axion dark matter

Summary

- Yukawa int. + absence of dim.-4 p decay determines the underlying gauge symmetry: E_7 or E_8.
- In M-theory vacua, diagonal entries of the up-type Yukawa matrix tends to be suppressed.
- The B – L symmetry is spontaneously broken if the Fayet—Iliopoulos parameter is non-zero, allowing Majorana masses of right-handed neutrinos.
- If the sign of the FI parameter is correct, dim.-4 p decay is absent.
- The matter parity or R-parity is not conserved, and the LSP decay may be seen in future experiments.