SECOND LECTURE

CARLOS MUÑOZ

SPECIAL RELATIVITY QUANTUM MECHANICS POINT-LIKE PARTICLES	$\xrightarrow{\text{BASED IN}}$	SPECIAL RELATIVITY QUANTUM MECHANICS ONE-DIMENSIONAL OBJECTS
QFT		STRING THEORY
⇓		⇓
LARGE DEGREE OF ARBITRARINESS		HIGHLY CONSTRAINED

WE ARE FREE TO CHOSE:

- DIMENSION OF SPACETIME
- THE SPIN OF THE PARTICLES
- THE GAUGE GROUP AND ITS RANK
- THE NUMBER OF MATTER FIELDS AND THEIR REPRESENTATIONS
- SCALAR FIELD POTENTIAL
- YUKAWA COUPLINGS
- - - - - - -
- - - - - - -

SO, WHY THE POINT-PARTICLE APPROXIMATION OF ORDINARY QFT IS SO SUCCESSFUL?

BECAUSE PRESENT ACCELERATORS CANNOT RESOLVE

$$\ell < 10^{-16}\ \mathrm{cm}$$

(1) THERE IS ALWAYS A MASSLESS PARTICLE IN THE SPECTRUM WITH $s = 2$ →

GRAVITY

3 THERE ARE NO FREE PARAMETERS

ALL COUPLING CONSTANTS ARE IN FACT NO CONSTANTS

BUT **FIELDS**

THE MEASURED EXPERIMENTAL VALUES OF

$$g_3,\ g_2,\ g_1,\ \lambda_u,\ \lambda_d,\ \lambda_e,\ \ldots$$

CORRESPOND TO THE **VEVs** OF THOSE FIELDS

e.g.

$$g_a \sim \langle S \rangle$$

$\to$ DILATON (ASSOCIATED TO THE GRAVITATIONAL SECTOR)

$$\lambda_i \sim \langle T_j \rangle$$

$\to$ MODULI (RELATED TO THE COMPACT DIMENSIONS)

④ SUPERSTRING THEORY IS ONLY CONSISTENT IN

$$\boxed{D=10} \rightarrow \begin{matrix} 1+9 \\ 4+6 \end{matrix}$$

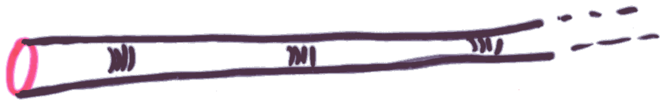
⑤ THERE ARE ONLY **FIVE** DIFFERENT SUPERSTRINGS

TYPE	MASSLESS STATES	SUSY	STRING
I	SO(32) YANG-MILLS + SUGRA	N=1	OPEN + CLOSED
Heterotic	SO(32) YANG-MILLS + SUGRA	N=1	CLOSED
Heterotic	$E_8 \times E_8$ YANG-MILLS + SUGRA	N=1	CLOSED
II A	SUGRA	N=2	CLOSED
II B	SUGRA	N=2	CLOSED

SINCE THE WORLD WE LIVE IS $D=4$, SIX EXTRA SPATIAL DIMENSIONS MUST BE COMPACTIFIED TO BE UNOBSERVABLE

IT IS OF COURSE DIFFICULT TO IMAGINE AN UNIVERSE WITH $R^4 \times M^6$

BUT A SIMPLER MODEL IS PROVIDED BY $R^1 \times S^1$



HETEROTIC $E_8 \otimes E_8$

MASSLESS STATES

D=10, N=1 SUGRA

g_{MN} (graviton)
B_{MN} (antisym. tensor)
ϕ (scalar) — DILATON
ψ_M (gravitino)
λ (spinor)

BOSONS : 35+28+1=64   FERMIONS : 56+8=64

D=10, N=1 SUPER YANG-MILLS

$E_8 \times E_8$ gauge index

A_M^α (gauge bosons) χ^α (gauginos)

GAUGE BOSONS : 2×248   GAUGINOS : 2×248

- THERE ARE AS MANY BOSONS AS FERMIONS : SUPERSYMMETRY
- IT IS ANOMALY FREE
- $E_8 \times E_8 \longrightarrow$ NATURAL HIDDEN SECTOR

COMPACTIFICATION DOWN TO 4 DIMENSIONS

6 EXTRA DIMENSIONS ARE COMPACTIFIED $M_4 \times M_6$ WITH $V_{M_6} \sim (M_P)^{-6}$
$(10^{-33}\,\mathrm{cm})^{+6}$

EACH 10-DIMENSIONAL FIELD LEADS TO AN INFINITE TOWER OF D=4 FIELDS

e.g. FROM A_M ($M \to 0,1,\dots,9$) ONE GETS BOTH

D=4 VECTOR BOSONS $A^\mu(x_\mu; x_n) = \sum_s Y_s(x_n) A_s^\mu(x_\mu)$ ($\mu \to 0,1,2,3$)

D=4 SCALARS $A^m(x_\mu; x_n) = \sum_s Y_s'(x_n) A_s^m(x_\mu)$ ($m \to 4,5,\dots,9$)

- THE MASSLESS FIELDS ($s=0$) IN THE EXPANSION SHOULD GIVE RISE TO THE S.M. PARTICLES
- WHAT PARTICLES ARE LIGHT DEPENDS ON THE PROPERTIES OF M_6

e.g. in $D=5$ with

$0 \leq y \leq 2\pi R$

A MASSLESS SCALAR $\varphi(x_\mu, y)$ HAS THE FOLLOWING K.G. EQUATION:

$$\Box_5 \varphi = 0 \qquad \text{i.e.} \quad \left(\Box_4 + \frac{\partial^2}{\partial y^2}\right)\varphi = 0$$

IMPOSING $\varphi(x_\mu, y=0) = \varphi(x_\mu, y=2\pi R)$

$$\Downarrow$$

$$\varphi(x_\mu, y) = \sum_{n=0}^{\infty} e^{i\frac{ny}{R}} \phi_n(x_\mu)$$

WITH

$$\left(\Box_4 - \frac{n^2}{R^2}\right)\phi_n = 0$$

$$m_n^2 = \frac{n^2}{R^2}$$

$n \neq 0 \longrightarrow$ FIELDS WITH $m_n \sim M_p$ (unobservable)

$n = 0 \longrightarrow$ MASSLESS FIELDS

$\downarrow$

THE PARTICLES THAT WE OBSERVE AT LOW ENERGY

* THE STATES MUST BE INVARIANT UNDER THE DISCRET SYMMETRIES OF THE COMPACT SPACE

IN ORBIFOLDS, WE MUST PROJECT ONTO $S \times G$ INVARIANT STATES

* $g_{MN} \to g_{\mu\nu}\,,\; g_{mn}\;;\qquad s \sim \phi + i\,b$

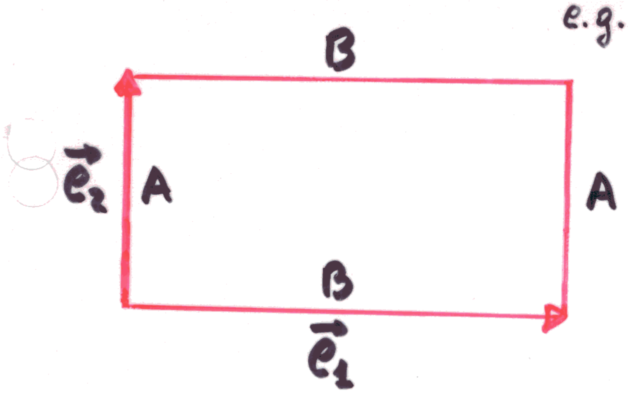
$B_{MN} \to \underset{\displaystyle \downarrow \atop \displaystyle b}{B_{\mu\nu}}\,,\; B_{mn}\;;\qquad T \sim g_{mn} + i\,b_{mn}$

What is String Phenomenology ?

The Search of the Standard Model in String Theory

EXAMPLE OF A 2-DIMENSIONAL COMPACT SPACE : TORUS

e.g. ORTHONORMAL LATTICE



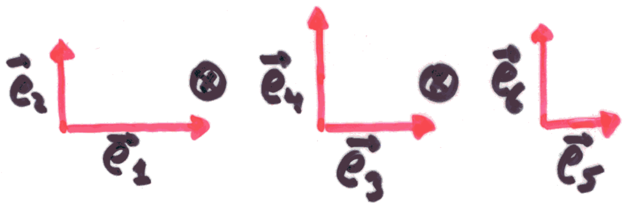
IDENTIFICATION $X = X + \vec{e}_1$

$X = X + \vec{e}_2$

GLUING THE SIDES A AND THE SIDES B

$T_2 = R^2/\Lambda \quad , \Lambda = \{ e_i \ ; \text{ LATTICE VECTORS} \}_{i=1,2}$

e.g. $M_6 = T_2 \otimes T_2 \otimes T_2$



- The compactification of the $E_8 \times E_8$ heterotic superstring on six-dimensional spaces was the starting point for this race

  Calabi-Yau, orbifold, fermionic, ..., 85-86

- It was shown that these compactifications can give rise to four-dimensional standard-like models,

  86-87-88

$\downarrow$

This is interesting: at least we know that something close to the real world can arise from strings

In fact, not any kind of compact space is allowed, only those producing $N=1$ susy, and therefore chirality, are interesting for phenomenology, i.e. those Kähler manifolds with $SU(3)$ holonomy

E.g. a torus produces $N=4$ susy

EXAMPLE:

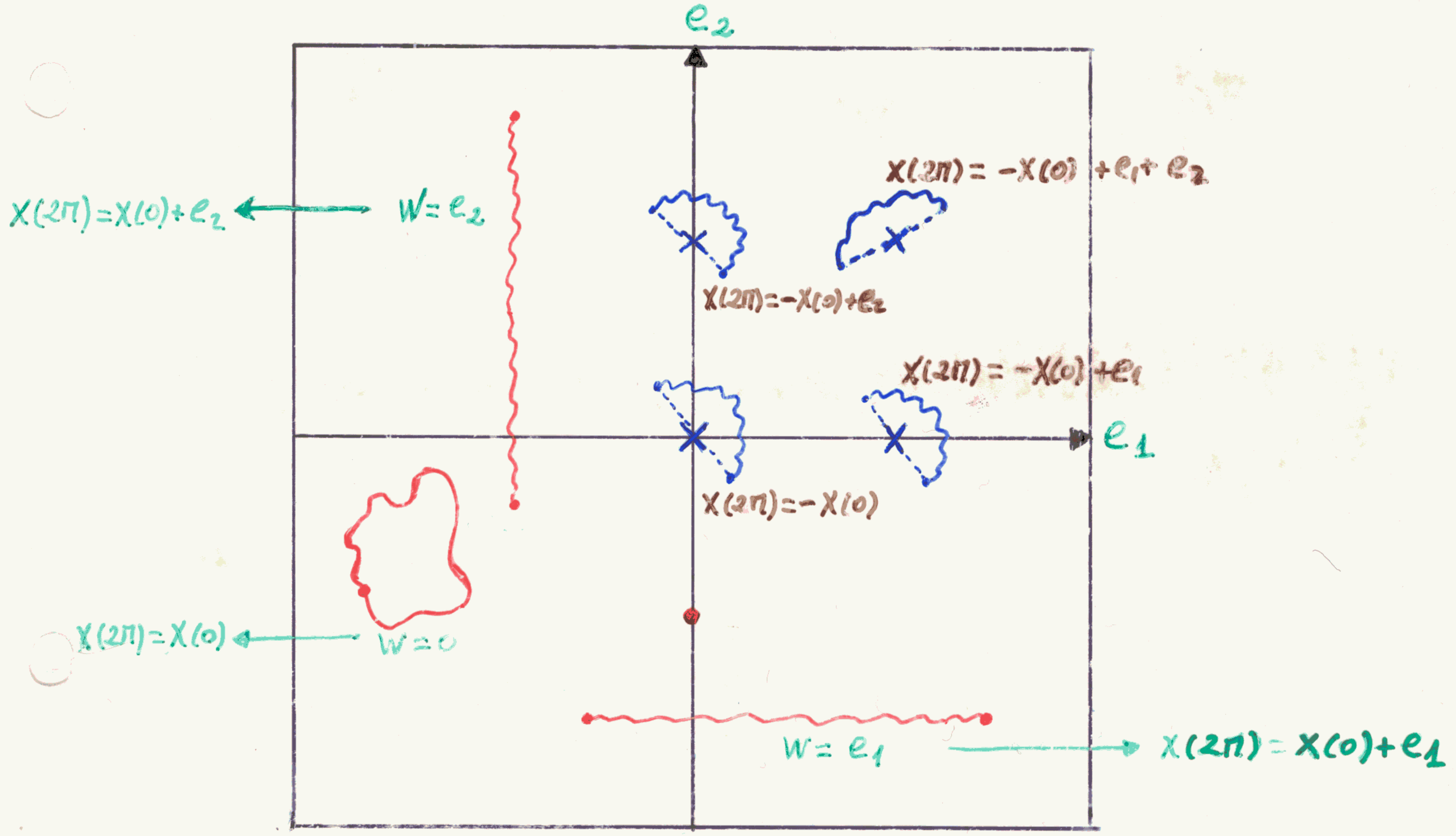
2 - TORUS $\quad T^2 \equiv R^2/\Lambda \quad \Lambda = (e_1, e_2)$

$O^2 \equiv T^2/P \quad [PX = -X]$

FIXED POINTS UNDER P: $\quad x_f = \theta x_f + \sum m_i e_i = -x_f + \sum m_i e_i$

$\Rightarrow \quad x_f = \frac{1}{2} \sum m_i e_i \qquad m_i$ INTEGERS

$m_i = (0,0)$
$(1,0)$
$(0,1)$
$(1,1)$



TWO TYPES OF CLOSED STRINGS:

UNTWISTED $\rightarrow$ $X(\sigma = 2\pi) = X(\sigma = 0) + W$ $\rightarrow$ VECTOR IN THE LATTICE

(THEY ARE CLOSED ON THE TORUS)

$T_1 = R_1^2 = e_i e_i$

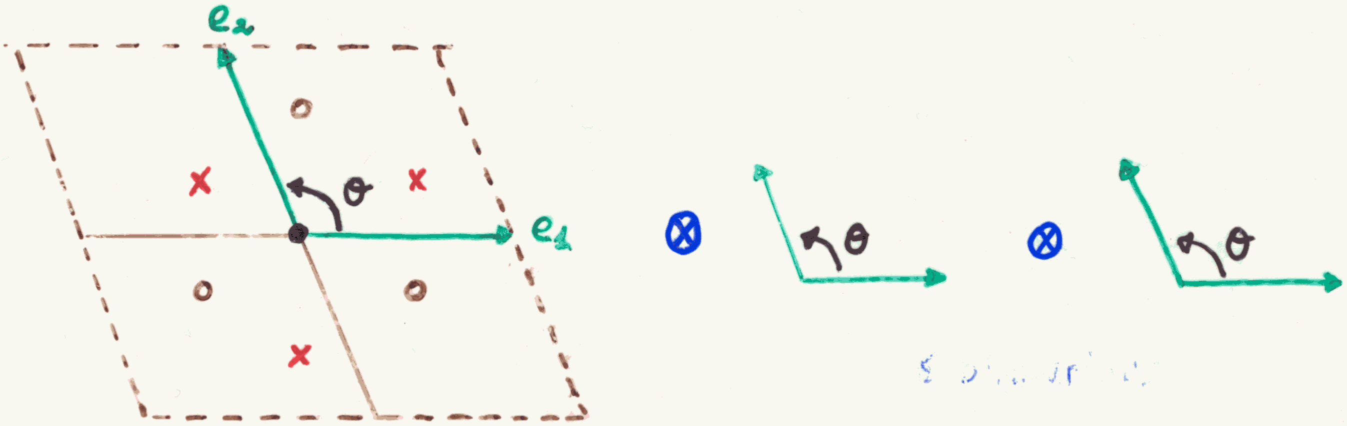
TWISTED $\rightarrow$ $X(\sigma = 2\pi) = \theta X(\sigma = 0) + W$

(THEY ARE CLOSED ON THE ORBIFOLD BUT NOT ON THE TORUS)

ITS CENTER OF MASS COORDINATES CORRESPONDS TO THE POSITION OF THE DIFFERENT FIXED POINTS

Z_3 ORBIFOLD :

$$T^6 \equiv R^6 / (SU(3)^3 \text{ ROOT LATTICE})$$



$$P \equiv (120^\circ \text{ ROTATION}) \otimes (120^\circ \text{ ROTATION}) \otimes (120^\circ \text{ ROTATION}) \equiv \theta \otimes \theta \otimes \theta$$

$$\theta = e^{i\frac{2\pi}{3}}$$

$P^3 = 1$

$$O^6 = T^6 / P$$

FIXED POINTS : $\begin{pmatrix} \circ & \circ & \circ \\ \times \;, & \times \;, & \times \\ \bullet & \bullet & \bullet \end{pmatrix} = 3 \times 3 \times 3 = 27$

D=10 $E_8 \otimes E_8$ HETEROTIC

$\Big\downarrow$ FIELD THEORY LIMIT

D=10 N=1 SUGRA + $E_8 \times E_8$ YANG-MILLS

$\Big\downarrow$ COMPACTIFICATION

D=4 N=1 SUGRA + $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes G_{hidden}$

$\sim 10^{18}$ GeV

COMPACTIFICATION $\Longrightarrow$ SYMMETRY BREAKING

D=10 MINKOWSKI SPACE $\longrightarrow$ D=4 MINKOWSKI $\times$ M_6

$$g_{MN} = \left[\begin{array}{cccc|cccccc} -1 & & & & & & & & & \\ & 1 & & & & & & & & \\ & & 1 & & & & & & & \\ & & & 1 & & & & & & \\ \hline & & & & 1 & & & & & \\ & & & & & 1 & & & & \\ & & & & & & 1 & & & \\ & & & & & & & 1 & & \\ & & & & & & & & 1 & \\ & & & & & & & & & 1 \end{array}\right] \longrightarrow g^{compact}_{MN} = \left[\begin{array}{cccc|c} -1 & & & & \\ & 1 & & & \\ & & 1 & & \\ & & & 1 & \\ \hline & & & & g^{M_6}_{mn} \end{array}\right]$$

$m,n = 4,\dots,9$

CLASSICAL VALUES OF THE FIELDS MUST BE SUCH THAT THE EQUATIONS OF MOTION OF THE D=10 FIELD THEORY ARE OBEYED

THESE ALLOW $\langle A_m \rangle \neq 0$

$m = 4,\dots,9$

$\hookrightarrow$ IN D=4 THIS IS LIKE A VEV OF SCALAR FIELDS

$\downarrow$

SYMMETRY BREAKING

55

It was possible to obtain models, e.g. using orbifolds, with

$$SU(3) \times SU(2) \times U(1)^5 \times G_{hidden}$$

and three generations of particles

(plus extra particles)

And with the following properties:

- One of the $U(1)$'s is usually anomalous
- Combinations of the non-anomalous $U(1)$'s give rise to the physical hypercharge
- The Fayet–Iliopoulos D-term can give rise to the breaking of the extra $U(1)$'s through $<\phi>$

In this way it was possible to construct supersymmetric vacuum states with

- $SU(3) \times SU(2) \times U(1)_Y \times SO(10)_{hidden}$
- with three generations of particles

THE THREE GENERATIONS ARISE BECAUSE

- IN ADDITION TO THE OVERALL FACTOR OF 3 COMING FROM THE RIGHT MOVING PART OF THE UNTWISTED MATTER
- THE TWISTED MATTER COME IN 9 SETS WITH 3 EQUIVALENT SECTORS ON EACH ONE

Let us suppose that the two w.l. correspond to the first and second sublattices

$$\begin{array}{ccl}
\circ & \circ & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right. \\
\circ & \cdot & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right. \\
\circ & \times & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right. \\
\cdot & \circ & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right. \\
\cdot & \cdot & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right. \\
\cdot & \times & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right. \\
\times & \circ & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right. \\
\times & \cdot & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right. \\
\times & \times & \left\{ \begin{array}{c} \circ \\ \cdot \\ \times \end{array} \right.
\end{array}$$

* IN A $\mathbb{Z}_3$ ORBIFOLD (with 2 W.L.)

THERE ARE AUTOMATICALLY $\underline{\underline{3}}$ FAMILIES

* AND IT IS POSSIBLE TO CONSTRUCT MODELS LIKE

$$[SU(3)\otimes SU(2)\otimes U(1)^5]\otimes[SU(2)\otimes SU(2)\otimes U(1)^6]'$$

(IN THIS EXAMPLE THERE ARE 11 U(1) CHARGES)

WITH THE FOLLOWING MATTER CONTENTS

$$3\{(3,2)+(\bar{3},1)+(\bar{3},1)+(1,2)+\mathbb{1}\}$$
$$+\underline{\underline{3}}\{\underline{\underline{4}}\,\underline{\underline{(1,2)}}+6\,(2,1)'+6\,(1,2)'+(2,2)'+\underline{\underline{48}}\,\mathbb{1}\}$$

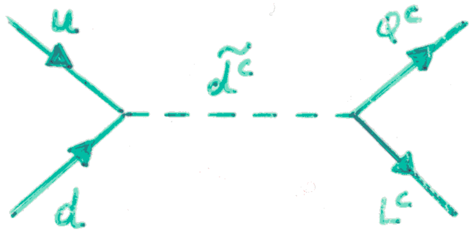
	n_1	n_3	C or C'	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}
	0	0	(2,1)'	-3	-2	-3	-1	-1	-2	0	0	2	2	-2
	0	0	(1,2)'	-3	-2	-3	-1	-1	-2	0	-3	-1	-1	1
	0	0	1	-3	-2	-3	-1	-1	4	0	0	-4	2	-2
	0	0	1	-3	-2	-3	-1	-1	4	0	0	2	-4	-2
	0	0	1	-3	-2	-3	-1	-1	4	0	0	2	2	4
	0	0	1	-3	-2	-3	-1	-1	-2	-6	3	-1	-1	1
	0	0	1	-3	-2	-3	-1	-1	-2	6	3	-1	-1	1
$u^c \rightarrow$	1	0	$(\bar{3},1)$	0	0	0	2	2	4	0	0	0	2	-2
$H_2 \rightarrow$	1	0	(1,2)	3	0	-3	-1	-1	4	0	0	0	2	-2
	1	0	1	-6	0	0	-4	2	4	0	0	0	2	-2
	1	0	1	-6	0	0	2	-4	4	0	0	0	2	-2
	1	0	1	3	-6	3	-1	-1	4	0	0	0	2	-2
	1	0	1	3	6	3	-1	-1	4	0	0	0	2	-2
	-1	0	(2,1)'	0	-4	0	2	2	-2	0	0	-2	2	-2
	-1	0	(1,2)'	0	-4	0	2	2	-2	0	3	1	-1	1
	-1	0	1	0	-4	0	2	2	4	0	0	-2	-4	-2
	-1	0	1	0	-4	0	2	2	4	0	0	-2	2	4
	-1	0	1	0	-4	0	2	2	4	0	0	4	2	-2
	-1	0	1	0	-4	0	2	2	-2	-6	-3	1	-1	1
	-1	0	1	0	-4	0	2	2	-2	6	-3	1	-1	1
	0	1	1	6	4	0	2	0	-4	4	0	2	2	0
	0	1	1	-3	-2	-3	-1	3	-4	4	0	2	2	0
	0	1	1	-3	-2	3	-1	-3	-4	4	0	2	2	0
	0	1	1	6	4	0	2	0	2	-2	-3	-1	-1	3
	0	1	1	-3	-2	-3	-1	3	2	-2	-3	-1	-1	3
	0	1	1	-3	-2	3	-1	-3	2	-2	-3	-1	-1	3
	0	1	1	6	4	0	2	0	2	-2	3	-1	-1	-3
	0	1	1	-3	-2	-3	-1	3	2	-2	3	-1	-1	-3
	0	+1	1	-3	-2	3	-1	-3	2	-2	3	-1	-1	-3
	0	-1	(2,1)'	-3	-2	3	-1	1	0	2	3	-1	-1	-1
	0	-1	(1,2)'	-3	-2	3	-1	1	0	2	0	2	2	2

	n_1	n_3	C or C'	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	Q_{10}	Q_{11}
	0	-1	1	-3	-2	3	-1	1	0	-4	0	-4	2	2
	0	-1	1	-3	-2	3	-1	1	0	-4	0	2	-4	2
	0	-1	1	-3	-2	3	-1	1	0	-4	0	2	2	-4
	0	-1	1	-3	-2	3	-1	1	-6	2	-3	-1	-1	-1
	0	-1	1	-3	-2	3	-1	1	6	2	-3	-1	-1	-1
	1	1	(2,1)'	-6	0	0	2	0	2	4	0	0	2	0
	1	1	(1,2)'	-6	0	0	2	0	-4	-2	0	0	2	0
	1	1	1	-6	0	0	2	0	-4	4	0	0	-4	0
	1	1	1	-6	0	0	2	0	2	-2	-3	-3	-1	-3
	1	1	1	-6	0	0	2	0	2	-2	-3	3	-1	3
	1	1	1	-6	0	0	2	0	2	-2	3	-3	-1	3
	1	1	1	-6	0	0	2	0	2	-2	3	3	-1	-3
$H_1 \rightarrow$	-1	1	(1,2)	0	2	0	2	0	-4	4	0	-2	2	0
$L \rightarrow$	-1	1	(1,2)	0	2	0	2	0	2	-2	-3	1	-1	-3
	-1	1	(1,2)	0	2	0	2	0	2	-2	3	1	-1	3
	-1	1	1	0	-4	0	-4	0	-4	4	0	-2	2	0
	-1	1	1	0	-4	0	-4	0	2	-2	-3	1	-1	-3
$e^c \rightarrow$	-1	1	1	0	-4	0	-4	0	2	-2	3	1	-1	3
$d^c \rightarrow$	1	-1	$(\bar{3},1)$	0	0	0	2	-2	0	-4	0	0	2	2
	1	-1	(1,2)	3	0	3	-1	1	0	-4	0	0	2	2
	1	-1	1	-6	0	0	-4	-2	0	-4	0	0	2	2
	1	-1	1	-6	0	0	2	4	0	-4	0	0	2	2
	1	-1	1	3	-6	-3	-1	1	0	-4	0	0	2	2
	1	-1	1	3	6	-3	-1	1	0	-4	0	0	2	2
	-1	-1	(2,1)'	0	-4	0	2	-2	0	2	-3	1	-1	-1
	-1	-1	(1,2)'	0	-4	0	2	-2	0	2	0	-2	2	2
	-1	-1	1	0	-4	0	2	-2	0	-4	0	-2	-4	2
	-1	-1	1	0	-4	0	2	-2	0	-4	0	-2	2	-4
	-1	-1	1	0	-4	0	2	-2	0	-4	0	4	2	2
	-1	-1	1	0	-4	0	2	-2	-6	2	3	1	-1	-1
	-1	-1	1	0	-4	0	2	-2	6	2	3	1	-1	-1

Table 1

✱ BARYON AND LEPTON NUMBER VIOLATING OPERATORS

$Q_L L d^c \quad , \quad u^c d^c d^c \quad , \quad L L e^c$ → THEY INVOLVE THE STANDARD (SUPERSIM.) PARTICLES SO THEY ARE PRESENT IN ANY REALISTIC MODEL



DANGEROUS !

e.g. SUSY (R-PARITY) RATHER ARTIFICIAL

ALL THESE OPERATORS ARE NATURALLY FORBIDDEN HERE BECAUSE THEY ARE NOT $U(1)$ INVARIANTS

e.g.

$$u^c = (0 \;\; 0 \;\; 0 \;\; 2 \;\; 2 \;\; 4 \;\; 0 \;\; 0 \;\; 0 \;\; 2 \;\; -2)$$

$$d^c = (0 \;\; 0 \;\; 0 \;\; 2 \;\; -2 \;\; 0 \;\; -4 \;\; 0 \;\; 0 \;\; 2 \;\; 2)$$

$$d^c = (0 \;\; 0 \;\; 0 \;\; 2 \;\; -2 \;\; 0 \;\; -4 \;\; 0 \;\; 0 \;\; 2 \;\; 2)$$

* THE FINAL RESULT UNDER $SU(3)\times SU(2)$ IS:

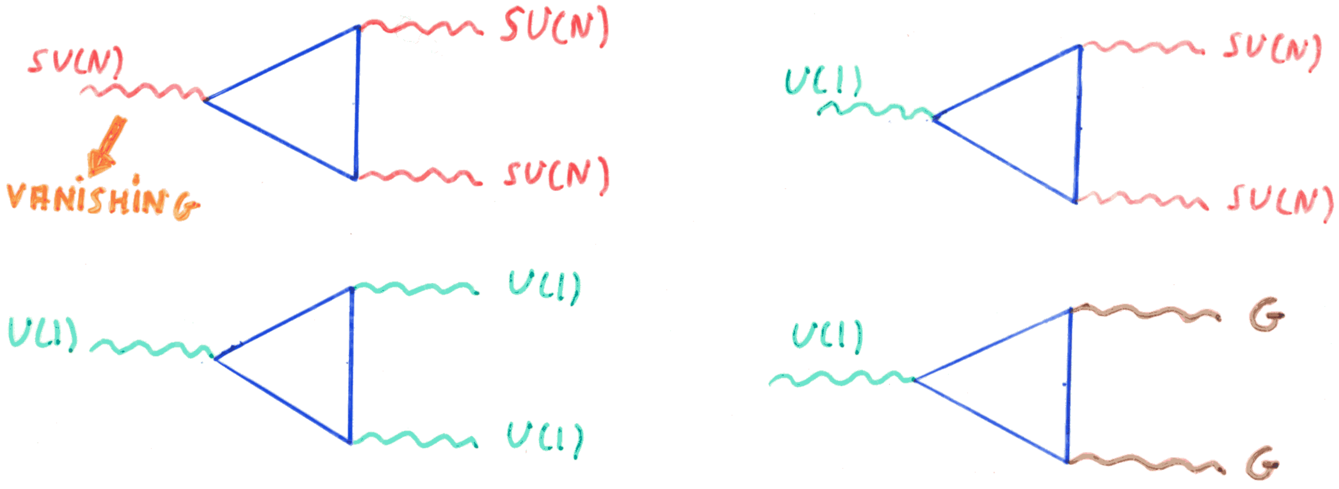
$$3\left\{(3,2)+(\bar{3},1)+(\bar{3},1)+(1,2)+\mathbb{1}\right\}$$

$$+\,3\left\{4\,(1,2)+6(2,1)'+6(1,2)'+(2,2)'+48\,\mathbb{1}\right\}$$

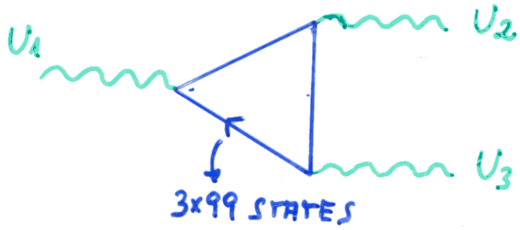
THERE ARE 3×99 STATES

ANOMALY

THERE ARE DIFFERENT TYPES OF ANOMALIES:



* THE 165 DIAGRAMS:



$U_1 \neq U_2 \neq U_3 \neq U_1$

ARE ALSO VANISHING

$$\Rightarrow \quad \partial^\mu J^i_\mu = \frac{g^3}{-32\pi^2}\left\{\sum_j A(i,j,j)\,F^j_{\mu\nu}\,\tilde{F}^{j\mu\nu}\right.$$

$$\left.+\sum_\ell B(i,\ell,\ell)\,G^{(\ell)a}_{\mu\nu}\,\tilde{G}^{(\ell)\mu\nu}_a - C(i)\,R\tilde{R}\right\}$$

$i,j = 1,2,\dots,11$

$\ell = 1,\dots,4$

* THE 176 QUANTITIES $A(i,j,j)$, $B(i,\ell,\ell)$, $C(i)$ ARE:

- FOR THE FIRST $U(1)$:

$$A(1,1,1) = \frac{1}{3}\sum_n \left(Q_1^{(n)}\right)^3 = \boxed{-\sqrt{6}/2}$$

$$A(1,j,j) = \sum_n Q_1^{(n)} \left(Q_j^{(n)}\right)^2 = \boxed{-\sqrt{6}/2} \quad ; \; j \neq 1$$

$$B(1,\ell,\ell) = \sum_m K_m Q_1^{(m)} = \boxed{-\sqrt{6}/2}$$

$$C(1) = \frac{1}{24}\sum_n Q_1^{(n)} = \boxed{-\sqrt{6}/2}$$

$n = 1, 2, \ldots, 3\times 99$ (STATES OF THE MODEL)

$m \equiv$ NON-ABELIAN REPRESENTATION

$K_m \equiv$ INDEX OF THE m-REPRESENTATION

- IN AN ANALOGOUS WAY

$$A(2,j,j) = B(2,\ell,\ell) = C(2) = -3/2$$

$$A(3,j,j) = B(3,\ell,\ell) = C(3) = 0$$

$$A(4,j,j) = B(4,\ell,\ell) = C(4) = \sqrt{2}/2$$

$$A(5,j,j) = B(5,\ell,\ell) = C(5) = 0$$

$$A(6,j,j) = B(6,\ell,\ell) = C(6) = 1/2$$

$$A(7,j,j) = B(7,\ell,\ell) = C(7) = -1/2$$

$$A(8,j,j) = B(8,\ell,\ell) = C(8) = 0$$

$$A(9,j,j) = B(9,\ell,\ell) = C(9) = 0$$

$$A(10,j,j) = B(10,\ell,\ell) = C(10) = \sqrt{2}/2$$

$$A(11,j,j) = B(11,\ell,\ell) = C(11) = 0$$

* SO THERE ARE 5 $U(1)$'s WHICH ARE DIRECTLY NON-ANOMALOUS

$$U_3,\ U_5,\ U_8,\ U_9,\ U_{11}$$

FROM THE OTHER 6 IT IS EASY TO FIND 5 ORTHONORMAL COMBINATIONS WHICH ARE ALSO NON-ANOMALOUS

$$\tilde{U}_1 = \frac{1}{\sqrt{15}}\left(3\,U_1 - \sqrt{6}\,U_2\right)$$

$$\tilde{U}_2 = \frac{1}{\sqrt{2}}\left(U_4 - U_{10}\right)$$

$$\tilde{U}_3 = \frac{1}{\sqrt{2}}\left(U_6 + U_7\right)$$

$$\tilde{U}_4 = \frac{1}{\sqrt{6}}\left\{\sqrt{2}\,(U_6 - U_7) - (U_4 + U_{10})\right\}$$

$$\tilde{U}_5 = \frac{1}{3\sqrt{210}}\left\{15\left[(U_6 - U_7) + \sqrt{2}\,(U_4 + U_{10})\right] + 6\left(\sqrt{6}\,U_1 + 3\,U_2\right)\right\}$$

THEREFORE, FROM THE 11 $U(1)$'s WE ARE LEFT WITH JUST ONE ANOMALOUS COMBINATION:

$$X = \frac{1}{\sqrt{21}}\left\{(U_6 - U_7) + \sqrt{2}\,(U_4 + U_{10}) - (\sqrt{6}\,U_1 + 3\,U_2)\right\}$$

MOREOVER, FOR THIS:

$$\partial^\mu J^X_\mu = \frac{g^3}{-32\pi^2}\left(\frac{\sqrt{21}}{2}\right)\left\{\sum_{j=1}^{11} F^j_{\mu\nu}\tilde{F}^{j\mu\nu} + \sum_{\ell=1}^{4} G^{(\ell)a}_{\mu\nu}\tilde{G}^{(\ell)\mu\nu}_a - R\tilde{R}\right\}$$

( )

IT IS POSSIBLE TO FIND COMBINATIONS OF THE REMAINING $U(1)$'s WHICH GIVE THE CORRECT HYPERCHARGE TO THE STATES

e.g.

$$Y = -\frac{22}{30} U_3 - \frac{3}{2} U_5 + \frac{37}{30} U_8 + \frac{7}{5} U_9 - \frac{\sqrt{105}}{30} \tilde{U}_5$$

ANOMALY CANCELLATION

$$\partial_\mu j^\mu \sim F\tilde{F} - R\tilde{R}$$

$B_{\mu\nu} \sim b$ $\qquad$ $b(F\tilde{F} - R\tilde{R}) \longrightarrow$ FROM 10-DIMENSIONAL GREEN-SCHWARZ TERMS

IT WILL BE ABLE TO ABSORB THE REMAINING ANOMALY BY ASSIGNING A GAUGE TRANSFORMATION TO THE FIELD b:

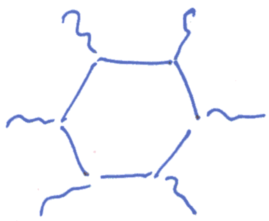
$$b \longrightarrow b + \underset{\operatorname{Tr} Q^{(a)}}{\underset{\wr}{c}}\lambda$$

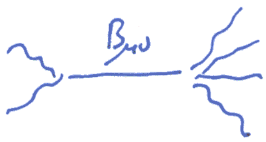
ANOMALY CANCELLATION

$\partial_\mu j^\mu \sim F\tilde{F} - R\tilde{R}$

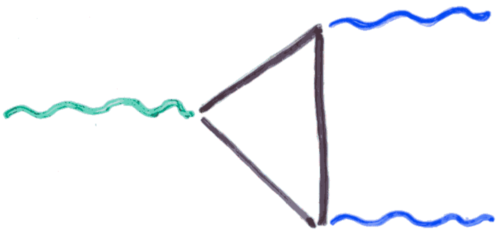
$B_{\mu\nu} \sim b \qquad\qquad b(F\tilde{F} - R\tilde{R})$

$D=10$

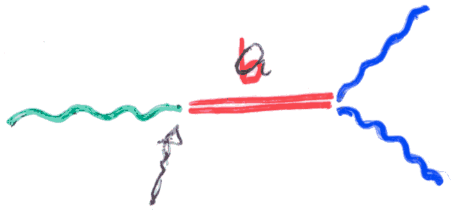




$D=4$



$+$



$\partial_\mu a A^\mu$

a : axion

dual to NS-NS $B_{\mu\nu}$

FAYET-ILIOPOULOS D-TERM IN GLOBAL SUSY

IF THE THEORY IS $U(1)$ INVARIANT WE CAN ADD BY HAND:

$$K \int d^4\theta\, V$$

$$\Downarrow$$

$$V_{scalar} \sim \frac{1}{2} D^2 = \frac{1}{2}\left[g \sum_i A_i^* A_i\right] \longrightarrow V_{scalar} \sim \frac{1}{2} D^2 = \frac{1}{2}\left[K + g \sum_i A_i^* A_i\right]^2$$

NO BROKEN SUSY

$\langle A_i \rangle = 0$

NO BROKEN SUSY

$\langle A_i \rangle \neq 0 \,/\, K + g \sum_i A_i^* A_i = 0$

$\Downarrow$

THE $U(1)$ IS BROKEN:

$g^2 \langle A_i^* \rangle \langle A_i \rangle V_\mu V^\mu$

FAYET-ILIOPOULOS D-TERM IN SUPERSTRINGS

$b \to b + c\lambda$ IN ORDER TO CANCEL THE ANOMALY ; $\quad y = (\phi^{-2} + ib) + \theta \ldots\ldots$

$K = -\lg (y + y^+) + \ldots\ldots$

$y + y^+$ IS NOT INVARIANT UNDER $b \to b + c\lambda$ SO

$y + y^+ \longrightarrow y + y^+ + cV$ WHICH IS INVARIANT

↳ "ANOMALOUS" $U(1)$

THEREFORE $\quad K = -\lg (y + y^+ + cV) + \ldots\ldots$

$$\Downarrow$$

$$V_{scalar} \sim \frac{1}{2} D^2 \sim \left[c + g \sum_i A_i^* A_i\right]$$

A F-I TERM APPEARS IN A NATURAL WAY (NOT BY HAND) IN SUPERSTRINGS, LOWERING THE RANK (IT IS POSSIBLE TO OBTAIN A $SU(3) \times SU(2) \times U(1)$).

THE "ANOMALOUS" $U(1)$ GENERATES A SO-CALLED **FAYET-ILIOPOULOS D-TERM**

$$V_{scalar} \sim \frac{1}{2} D^2 \sim \Big[\underbrace{c_s}_{\mathrm{Tr}\, Q^{(a)} \cdot M_P^2} + \sum_i Q_i^{(a)} \eta_i \eta_i^* \Big]$$

IN ORDER TO PRESERVE SUPERSYMMETRY AT HIGH ENERGIES, SOME SCALARS MUST ACQUIRE LARGE VEVs

WITH VANISHING HYPERCHARGES

$$\langle \eta_i \rangle \sim M_P$$

- AND SINCE THEY ARE GENERICALLY CHARGED UNDER THE EXTRA $U(1)$'s, THE GAUGE SYMMETRY IS BROKEN

$$SU(3) \times SU(2) \times U(1)^n \longrightarrow SU(3) \times SU(2) \times U(1)_Y$$

$$g^2 \langle \eta_i^* \rangle \langle \eta_i \rangle V_\mu V^\mu$$

- IN ADITTION, EXTRA PARTICLES BECOME MASSIVE $\sim M_P$

$\langle \eta \rangle$ 

68

In this way it was possible to construct supersymmetric vacuum states (I,II) where

- $SU(3) \times SU(2) \times U(1)^8 \times SO(10)$
  $\rightarrow SU(3) \times SU(2) \times U(1)_Y \times SO(10)_{hidden}$
  FI

- with three generations of particles.
- baryon and lepton number violating operators absent.

Recently, another model (III) has been analyzed

$SU(3) \times SU(2) \times U(1)^8 \times SU(5) \times SU(2)$

Unfortunately, we cannot claim that one of these models is the Superstring Standard Model, e.g.

- $3\times\{(3,2)+2(\bar{3},1)+(1,2)+1\}+3\times\Big\{(16)'+4[(3,1)+(\bar{3},1)]+12(1,2)+56\cdot 1\Big\}$
  $\rightarrow 3\times\{(3,2)+2(\bar{3},1)+(1,2)+1\}+3\times\Big\{4(1,2)+4\cdot 1+(16)'+11\cdot 1'\Big\}$
  FI

HOWEVER, WE ARE OPTIMISTIC PEOPLE, AND THEREFORE WE ARGUE THAT IF THE STANDARD MODEL ARISES FROM STRINGS, THERE MUST EXIST ONE MODEL WITH

NO EXTRA MATTER

70

But...

Is a model with the gauge group of the Standard Model and three families of quark and leptons, the sought-after Standard Model ?

71

By no means !

THE CORRECT MODEL MUST REPRODUCE ALSO THE RIGHT MASSES FOR QUARKS AND LEPTONS

e.g. the following hierarchies

$$\frac{m_t}{m_u} \sim 10^5 \qquad \frac{m_\tau}{m_e} \sim 10^3$$

YUKAWA COUPLINGS

GIVEN THE COMPACT SPACE ONE CAN COMPUTE ALL COUPLINGS IN 4 DIMENSIONS

D=10

$$\int dx^{10} \sqrt{-g}\, \chi(x_M)\, \gamma^M A_M(x_M)\, \chi(x_M)$$

EXPANSION IN D=4 FIELDS:

$$A_m(x_M) = \sum_s \underbrace{Y'_s(x_n)}_{4,\dots,9}\, \underbrace{\phi_s(x_\mu)}_{0,1,2,3}$$

$$\chi(x_M) = \sum_s Y''_s(x_n)\, \psi_s(x_\mu)$$

"$s=0$" $\to$ FIELDS WHICH SURVIVE AT LOW ENERGY

D=4

$$\mathcal{L}_{\text{YUKAWA}} = g \Big(\underbrace{\int dx^6 \sqrt{-g}\, Y''_0(x_n)\, Y'_0(x_n)\, Y''_0(x_n)}_{\text{YUKAWA COUPLING CONSTANT } \lambda} \Big) \Big(\underbrace{\int dx^4 \sqrt{-g}\, \psi_0(x_\mu)\, \phi_0(x_\mu)\, \psi_0(x_\mu)}_{\text{USUAL YUKAWA COUPLING e.g. QUARK-HIGGS-QUARK}} \Big)$$

$\lambda = \lambda(R_i)$ → SIZE AND SHAPE OF M_6

$R_i^2 \sim \langle T_i \rangle$ GAUGE SINGLET FIELDS (MODULI) ARISING IN THE MASSLESS SECTOR OF THE D=4 SUGRA FROM STRINGS

e.g. $\underbrace{\lambda_e(\langle T_i \rangle) \langle H \rangle}_{m_e} e_L e_R$

The correct model must reproduce also the correct mass hierarchy for quarks and leptons.

$$\frac{m_t}{m_u} \sim 10^5, \qquad \frac{m_\tau}{m_e} \sim 10^3$$

Orbifold spaces have a beautiful mechanism BETWEEN TWISTED-SECTOR FIELDS to generate a mass hierarchy: Yukawa couplings can be computed and they get suppression factors

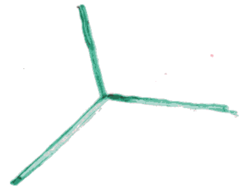
$$\lambda \sim e^{-T_i c^i}; \quad \mathrm{Re}\, T_i \sim R_i^2$$

which depend on the distance between the fixed points to which the relevant fields are attached

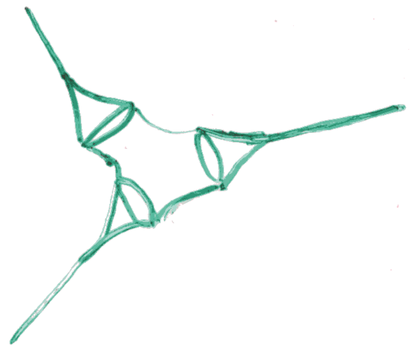
$$\Downarrow$$

one can span five orders of magnitude the Yukawa couplings

STRINGS IN A TORUS OR IN THE UNTWISTED SECTOR OF AN ORBIFOLD SHRINK TO A POINT



HOWEVER IN THE TWISTED SECTOR TO INTERACT THEY NEED TO STRETCH

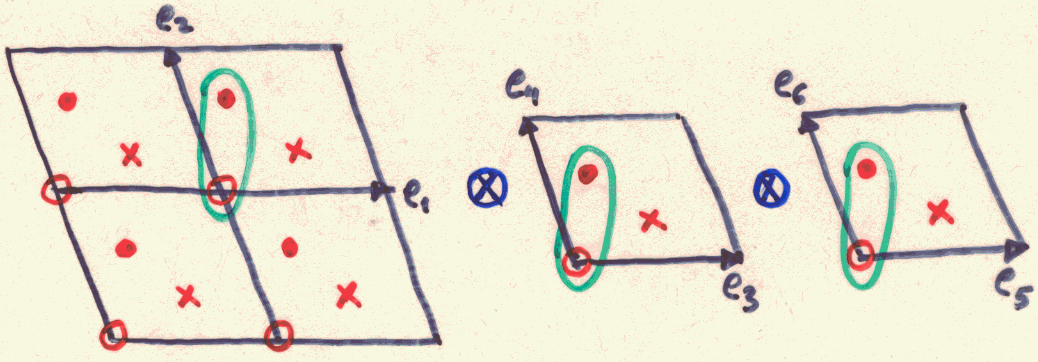


THEY CAN BE INTERPRETED AS (massive) STRINGS STRETCHED BETWEEN THE DIFFERENT FIXED POINTS $\Downarrow$

SUPPRESSION

e.g. $Z_3 = \frac{T^6}{P}$

$T^6 = R^6/(SU(3)^3 \text{ ROOT LATTICE})$



$$\left.\begin{array}{l}\theta = (120^\circ)\otimes(120^\circ)\otimes(120^\circ)\\ P = \{1, \theta, \theta^2\}\end{array}\right\}$$

$$x_{\substack{\circ\\ \times}} = \theta^n x_{\substack{\circ\\ \times}} + \sum_{i=1}^{6} n_i e_i \rightsquigarrow \text{27 FIXED POINTS}$$

THE CENTER OF MASS COORDINATES OF THE STRINGS CORRESPOND TO THE POSITION OF THE DIFFERENT FIXED POINTS

EACH PARTICLE IS ATTACHED TO ONE FIXED POINT

9 INDEPENDENT PARAMETERS (MODULI) DEFINE THE LATTICE $\begin{cases} \text{3 RADII}: R_1, R_3, R_5 \\ \text{6 ANGLES}: \theta_{13}, \theta_{15} \dots \end{cases}$

THE DIFFERENT SUPRESSION FACTORS OF YUKAWA COUPLINGS ARE RELATED TO THE DISTANCES BETWEEN FIXED POINTS

$$h_{123} = g N \sum_{\vec{n}\in \mathbb{Z}^6} \exp\left[-\frac{\sqrt{3}}{8\pi}(\vec{f}_{23}+\vec{n})^T M (\vec{f}_{23}+\vec{n})\right] = N\,\vartheta\begin{bmatrix}\vec{f}_{23}\\ 0\end{bmatrix}[0, \Omega]$$

REPRESENTS THE 6 COMPONENTS OF $(f_2 - f_3)$

JACOBI THETA FUNCTION

with

$$\Omega = i\frac{\sqrt{3}}{8\pi^2}M, \quad N = \sqrt{V_\Lambda}\,\frac{3^{3/4}}{8\pi^3}\frac{\Gamma^6(\frac{2}{3})}{\Gamma^3(\frac{1}{3})}$$

$$\Omega = i\frac{\sqrt{3}}{8\pi^2}\begin{pmatrix} R_1^2 & -\frac{R_1^2}{2} & R_1R_3\alpha_{13} & R_1R_3\alpha_{14} & R_1R_5\alpha_{15} & R_1R_5\alpha_{16} \\ -\frac{R_1^2}{2} & R_1^2 & R_1R_3\alpha_{23} & R_1R_3\alpha_{13} & R_1R_5\alpha_{25} & R_1R_5\alpha_{15} \\ R_1R_3\alpha_{13} & R_1R_3\alpha_{23} & R_3^2 & -\frac{R_3^2}{2} & R_3R_5\alpha_{35} & R_3R_5\alpha_{36} \\ R_1R_3\alpha_{14} & R_1R_3\alpha_{13} & -\frac{R_3^2}{2} & R_3^2 & R_3R_5\alpha_{45} & R_3R_5\alpha_{35} \\ R_1R_5\alpha_{15} & R_1R_5\alpha_{25} & R_3R_5\alpha_{35} & R_3R_5\alpha_{45} & R_5^2 & -\frac{R_5^2}{2} \\ R_1R_5\alpha_{16} & R_1R_5\alpha_{15} & R_3R_5\alpha_{36} & R_3R_5\alpha_{35} & -\frac{R_5^2}{2} & R_5^2 \end{pmatrix}$$

SIZE AND SHAPE OF THE COMPACTIFIED SPACE

$\alpha_{ij} \equiv \cos\theta_{ij}$

$\Rightarrow$ GEOMETRICAL ORIGIN OF THE FAMILY MASS HIERARCHY e.g. CONSIDER THE FOLLOWING ASSIGNMENTS OF FERMIONS TO FIXED POINTS:

Q_t, H_2, t^c	● ● ●	H_1	○ ● ●
Q_c	● ○ ●	b^c	× ● ●
c^c	● × ●	s^c	× × ●

etc...

TAKING INTO ACCOUNT FOR SIMPLICITY JUST THE DOMINANT TERM IN THE SUM (i.e. THE SHORTEST DISTANCE)

$$\mathcal{L}_{YUK} = gN\Big\{ Q_t H_2 t^c + 3e^{-\beta R_1^2} Q_t H_1 b^c + 3e^{-\beta R_3^2} Q_c H_2 c^c + 3e^{-\beta(R_1^2+R_3^2-2R_1R_3\cos\theta_{13})} Q_c H_1 s^c + \dots \Big\}$$

$$\beta \equiv \frac{1}{8\pi\sqrt{3}}$$

FOR APPROPRIATE VALUES OF $R_1, R_3, \theta_{13}, \dots$ THE PHYSICAL MASSES CAN BE FITTED

	m_μ	m_τ	m_s	m_c	m_b	m_t
Exp.	0.1056	1.784	0.199	1.35	5	130
Z_3	0.1055	1.786	0.252	1.35	4.1	125
Z_4	0.1062	1.774	0.173	1.35	4.34	104
$Z_6 - \mathrm{I}$	0.1056	1.785	0.252	1.35	4.04	122
$Z_6 - \mathrm{II}$	1.13	64	5.1	17	8.3	173
Z_7	0.104	1.783	0.466	1.35	5.2	133
$Z_8 - \mathrm{I}$	0.087	2.00	0.280	2.17	6.3	36
$Z_8 - \mathrm{II}$	0.1058	1.82	0.009	0.89	2.47	172
$Z_{12} - \mathrm{I}$	0.103	1.83	0.107	1.40	11	88
$Z_{12} - \mathrm{II}$	0.036	2.15	0.045	1.0	30	24

(78)

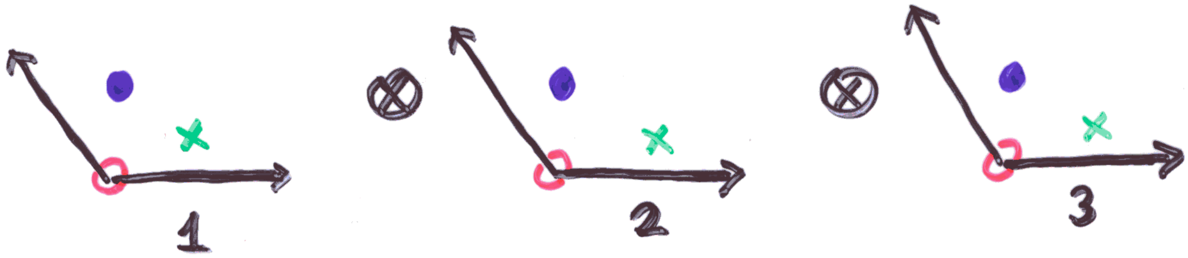
Unfortunately, this is not the end of the story

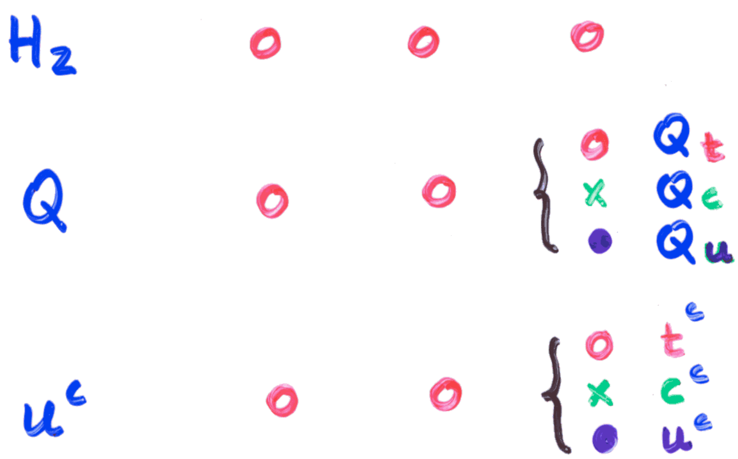
Nature is even more cruel with string phenomenologists:

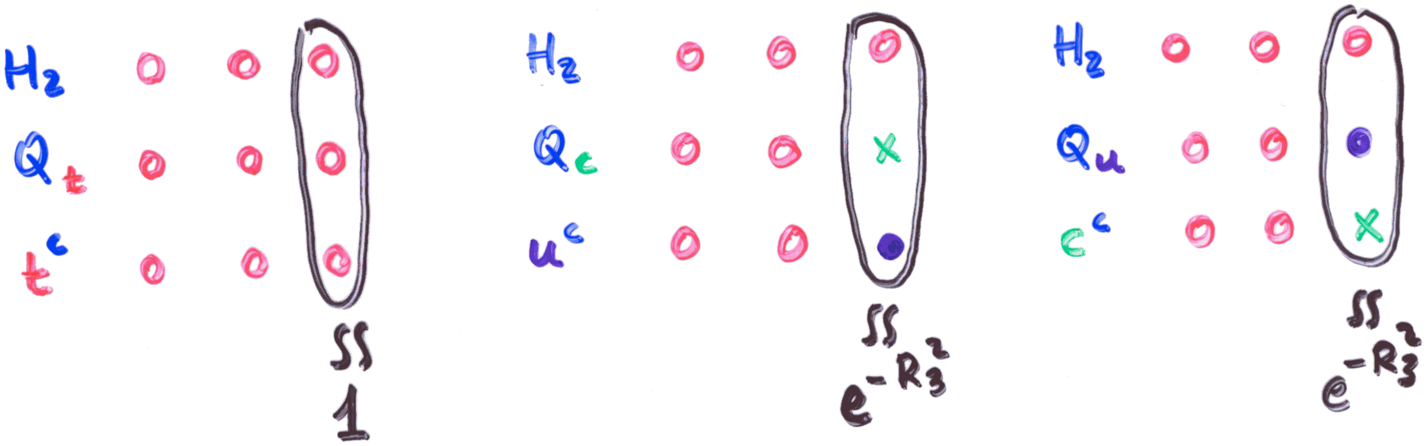
$$\mathcal{M}_{\mathsf{CKM}} = \begin{pmatrix} 0.9745-0.9760 & 0.217-0.224 & 0.0018-0.0045 \\ 0.217-0.224 & 0.9737-0.9753 & 0.036-0.042 \\ 0.004-0.013 & 0.035-0.042 & 0.9991-0.9994 \end{pmatrix}$$

$$\Downarrow$$

$$H_2^0\ \bar{u}_{L\alpha}\lambda_u{}^{\beta\gamma}u_{R\gamma} + H_1^0\ \bar{d}_{L\alpha}\lambda_d{}^{\beta\gamma}d_{R\gamma}$$







AT THE RENORMALIZABLE LEVEL

$$\lambda_{tt} \sim 1 \,, \quad \lambda_{cu} = \lambda_{uc} \sim e^{-R_3^2} \equiv \varepsilon_3$$

$$\to M^u = gN \begin{pmatrix} 0 & v_2 \varepsilon_3 & 0 \\ v_2 \varepsilon_3 & 0 & 0 \\ 0 & 0 & v_2 \end{pmatrix}$$

(80)

Unfortunately, it is extremely difficult to implement this type of mechanisms in a particular model.

Given a model, everything is fixed, and it is not possible to play around

As far as I know, there is no model in the market with all the necessary Yukawa couplings

The main difficulty in string model building resides in how to obtain the weird structure of fermion masses and mixing angles

(82)

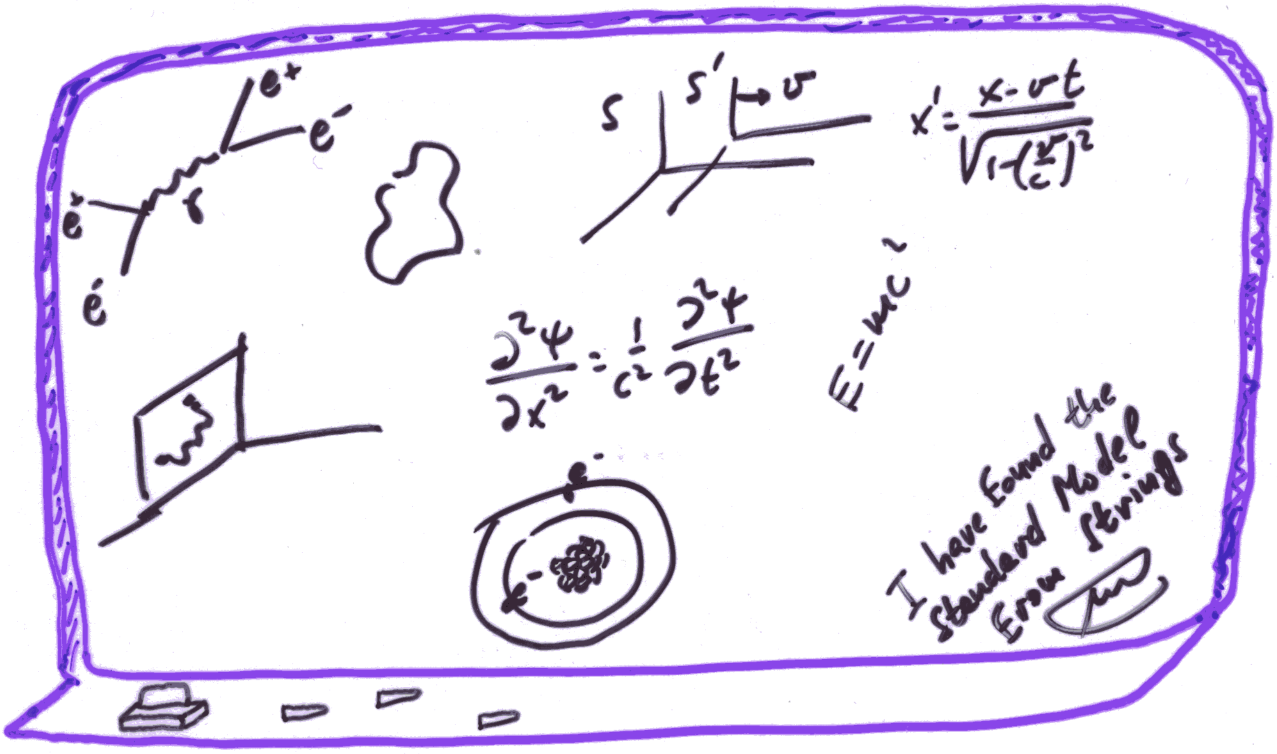
The experimental fact that neutrinos are massive makes this task even more involved:

$$\frac{m_t}{m_u} \sim 10^5, \qquad \frac{m_\tau}{m_e} \sim 10^3, \qquad \frac{m_e}{m_\nu} \gtrsim 10^6$$

$$\mathcal{M}_{\mathsf{CKM}} = \begin{pmatrix} 0.9745 - 0.9760 & 0.217 - 0.224 & 0.0018 - 0.0045 \\ 0.217 - 0.224 & 0.9737 - 0.9753 & 0.036 - 0.042 \\ 0.004 - 0.013 & 0.035 - 0.042 & 0.9991 - 0.9994 \end{pmatrix}$$

$$\mathcal{M}_{\mathsf{MNS}} = \begin{pmatrix} 0.73 - 0.89 & 0.45 - 0.66 & < 0.24 \\ 0.23 - 0.66 & 0.24 - 0.75 & 0.52 - 0.87 \\ 0.06 - 0.57 & 0.40 - 0.82 & 0.48 - 0.85 \end{pmatrix}$$

ALMOST 20 YEARS HAVE GONE BY
SINCE STRING PHENOMENOLOGY STARTED
AND THE STANDARD MODEL HAS NOT BEEN FOUND YET



e^+
e^-
e^-
γ
S
S'
v
$x' = \frac{x - vt}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$
$\frac{\partial^2\psi}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2}$
$E=mc^2$
I have found the Standard Model from strings

(84)

However, since we are optimistic people, we can argue that if the Standard Model arises from strings, there must exist at least one model with

the correct structure for Yukawas

This means:

1) with the necessary Yukawa couplings

$$H_2^0\,\bar{u}_L \lambda_{uu} u_R + H_2^0\,\bar{u}_L \lambda_{uc} c_R + \ldots + H_1^0\,\bar{d}_L \lambda_{db} b_R + \ldots$$

2) with the correct order of magnitude

i.e. on is able to put by hand the values of T_i such that

$$\lambda_t(T_i) \sim 1, \quad \lambda_u(T_i) \sim 10^{-5}, \ldots$$

If, at the end of the day, such a model exists, this would be a great success

85

But then another problem arises:
to compute the explicit values of Yukawas, $\lambda(T_i)$,
we need to know the $< T_i >$

Unfortunately, these are related to the breaking of SUSY, and...

this is one of the biggest problems in strings

It is true that there are candidates for this task, such as gaugino condensation in a hidden sector $W(S, T_i)$, and that we have hidden-sector gauge groups that could condensate

But, again, implementing this mechanism in a particular model is not easy

SUPERSYMMETRY BREAKING

HOW IS SUPERSYMMETRY BROKEN?

THIS IS ONE OF THE TWO **UNSOLVED PROBLEMS** IN SUPERSTRINGS

ALTHOUGH THE SITUATION IS MUCH BETTER THAN IN THE CONTEXT OF PURE SUGRA:

IN SUGRA THEORIES COMING FROM D=4 SUPERSTRINGS
$\boxed{1}$ THERE ARE NATURAL CANDIDATES FOR THE "HIDDEN SECTOR" BREAKING SUSY

$S \quad T_i$

⊛ S, T_i COUPLINGS TO CHARGED MATTER ARE SUPRESSED BY POWERS OF M_p

⊛ THEY ARE GENERICALLY PRESENT IN D=4 MODELS

$\boxed{2}$ K, f ARE CALCULABLE

GIVEN THE COMPACT SPACE ONE CAN DO THE COMPUTATION

$$\mathcal{L}_{D=10}$$

EXPANSION IN D=4 FIELDS

e.g. ORBIFOLD COMPACTIFICATION

$$\mathcal{L}_{D=4} = -\frac{1}{4}\underbrace{\frac{S+\bar{S}}{2}}_{\mathrm{Re}\, f_a} F_a^{\mu\nu} F_{\mu\nu}^a + \underbrace{\frac{3}{(T+\bar{T})^2}}_{\frac{\partial^2 K}{\partial T \partial \bar{T}}} \partial_\mu T \partial_\mu \bar{T} + \underbrace{(T+\bar{T})^{n_\alpha}}_{\frac{\partial^2 K}{\partial Q_\alpha \partial \bar{Q}_\alpha}} \partial_\mu Q_\alpha \partial_\mu \bar{Q}_\alpha$$

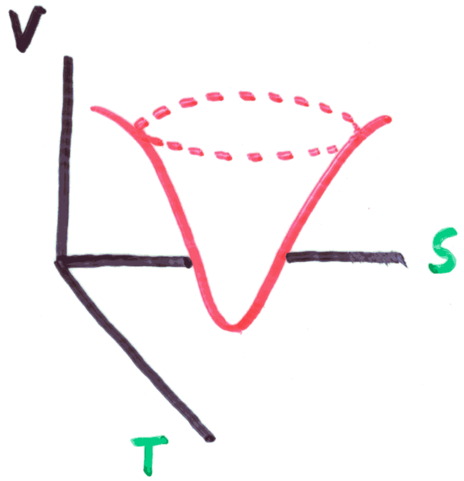
$$f_a = S \qquad K = -3\log(T+\bar{T}) + (T+\bar{T})^{n_\alpha} Q_\alpha \bar{Q}_\alpha$$

ALSO $\quad W = \lambda_{\alpha\beta\gamma}(T)\, Q_\alpha Q_\beta Q_\gamma$

$$V = e^G\left[G_i (G^{-1})^i_j G^j - 3\right] = \frac{1}{(S+\bar{S})(T+\bar{T})^3}\left\{\left|(S+\bar{S})\frac{\partial W}{\partial S} - W\right|^2 + \frac{1}{3}\left|(T+\bar{T})\frac{\partial W}{\partial T} - 3W\right|^2 - 3|W|^2\right\}$$

$$G = K + \log|W|^2$$

ONE WOULD LIKE TO FIND SOMETHING LIKE

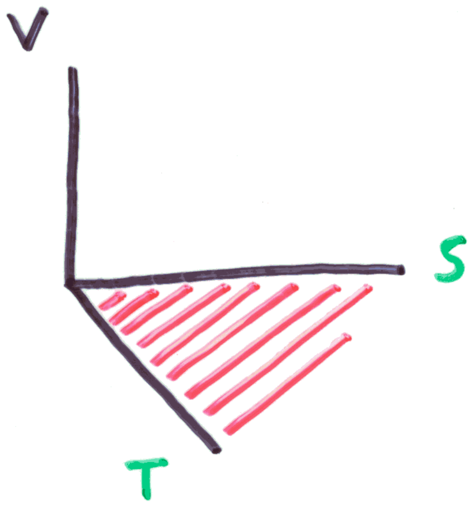


$\langle S \rangle \sim 2$

$\langle T \rangle \sim 1$

UNFORTUNATELY THIS IS NOT THE CASE :

S, T HAVE A FLAT SCALAR POTENTIAL IN STRING PERTURBATION THEORY



$V(S,T) = 0$

EXPECT NON-PERTURBATIVE EFFECTS WILL DETERMINE

$\langle S \rangle \, , \, \langle T \rangle$

ONE INTERESTING POSSIBILITY IS GAUGINO CONDENSATION

GAUGINO CONDENSATION IN SOME HIDDEN GAUGE GROUP

SUGRA $\longrightarrow$ STRINGS

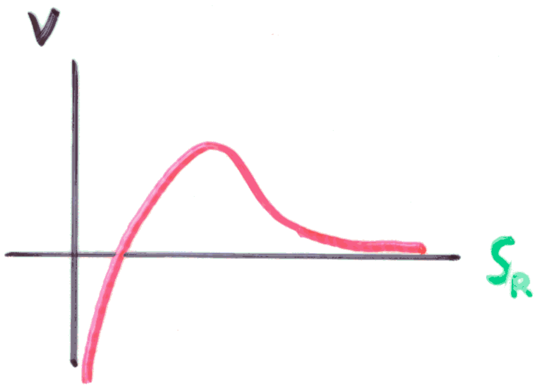
$$W^{np} \sim e^{-\frac{24\pi^2}{b_0 g^2}} \qquad\qquad W^{np} \sim e^{-\frac{24\pi^2}{b_0}S}$$

$$V = \frac{1}{(S+\bar{S})(T+\bar{T})^3}\left\{ \left|(S+\bar{S})\frac{\partial W}{\partial S} - W\right|^2 + \frac{1}{3}\left|(T+\bar{T})\frac{\partial W}{\partial T} - 3W\right|^2 - 3|W|^2 \right\}$$

$$\frac{\partial V}{\partial S} = 0 \Rightarrow (S+\bar{S})\frac{\partial W}{\partial S} - W = 0 \qquad \text{MINIMUM}$$

$$W^{np} \longrightarrow -(S+\bar{S})\frac{24\pi^2}{b_0} - 1 = 0 \qquad (S+\bar{S}) = -\frac{b_0}{24\pi^2} < 0$$

IMPOSSIBLE SINCE $\langle S_R \rangle = \frac{1}{g^2}$



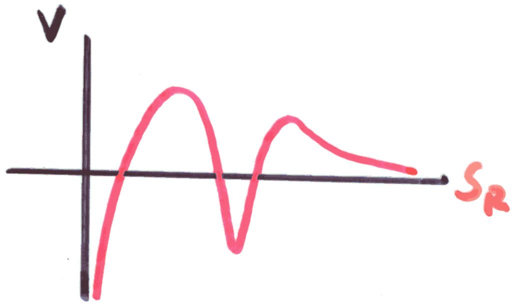
RUNAWAY BEHAVIOUR

SEVERAL WAYS OUT

(*) USUALLY **SEVERAL HIDDEN FACTORS** $\quad G_{\text{HIDDEN}} = \prod_a G_a$

i.e. $E_8 \times E_8 \xrightarrow{\text{COMPACTIFICATION}} SU(3)_c \times SU(2)_L \times U(1)_Y \times [G_1 \times G_2 \times \dots]$

MINIMUM WITH SEVERAL CONDENSATES



$$W^{np} \sim \frac{e^{-\frac{24\pi^2}{b_0} S}}{\eta^6(T)} + \dots \Longrightarrow \begin{array}{ll} G^S = 0 & \langle S_R \rangle \sim 2 \\ G^T \neq 0 & \langle T_R \rangle \sim 1 \end{array}$$

$$\underbrace{S \quad R^2 M_p^2}_{\text{AS DESIRED}} \Longrightarrow R \sim 10^{-33}\ \text{cm}$$

SUSY IS BROKEN

$\tilde{T}$ IS THE GOLDSTINO

$\underbrace{K, f, W}_{\text{AND THE HIDDEN SECTOR}}$ ARE KNOWN $\Longrightarrow$ m, M, A, B CAN BE COMPUTED

e.g. $M \ll m \sim 2$ TeV

(*) GAUGINO CONDENSATION + **S-duality**

↳ THE FORM OF THE CONDENSATE IS MODIFIED

(*) NON-PERTURBATIVE KÄHLER POTENTIAL

PROBLEMS

- WE HAVE TO ASSUME THAT THE DOMINANT NON-PERTURBATIVE EFFECTS IN STRINGS ARE THE FIELD THEORY ONES

- $\langle V \rangle < 0 \longrightarrow m^2 \sim m_{3/2}^2 + \langle V \rangle < 0$

  COSMOLOGICAL CONSTANT PROBLEM IS GENERIC WHEN SUSY IS BROKEN

um

BUT STILL WE CAN LEARN THINGS ABOUT SOFT TERMS WITHOUT KNOWING THE DETAILS OF SUSY BREAKING

i.e. $W^{np}(S,T)$

$$V = e^G \left[(G_S^S)^{-1} |G^S|^2 + (G_T^T)^{-1} |G^T|^2 - 3 \right]$$

$$\left. \begin{aligned} (G_S^S)^{-1/2}\, G^S &= \sqrt{3}\, \sin\theta \\ (G_T^T)^{-1/2}\, G^T &= \sqrt{3}\, \cos\theta \end{aligned} \right| \langle V \rangle = 0$$

$\tilde{h} = \sin\theta\, \tilde{S} + \cos\theta\, \tilde{T}$

fermionic partners of S, T

e.g. $\sin\theta = 1 \rightarrow S$ DOMINANT SOURCE OF SUSY BREAKING

$\sin\theta = 0 \rightarrow T$ DOMINANT SOURCE

DILATON - DOMINATED

THE DILATON HAS UNIVERSAL AND MODEL-INDEPENDENT COUPLINGS

SO IF WE ASSUME $\cos\theta = 0$ THE RESULTS FOR THE SOFT TERMS ARE INDEPENDENT OF THE 4-D STRING CONSIDERED

$W^{np}(S,T)$

$$\boxed{m_\alpha = m_{3/2}}$$

$$\boxed{-A_{\alpha\beta\gamma} = M_a = \sqrt{3}\, m_{3/2}\, e^{-i\gamma_S}}$$

$\Downarrow$

1. SOFT TERMS ARE $\boxed{\text{UNIVERSAL}}$

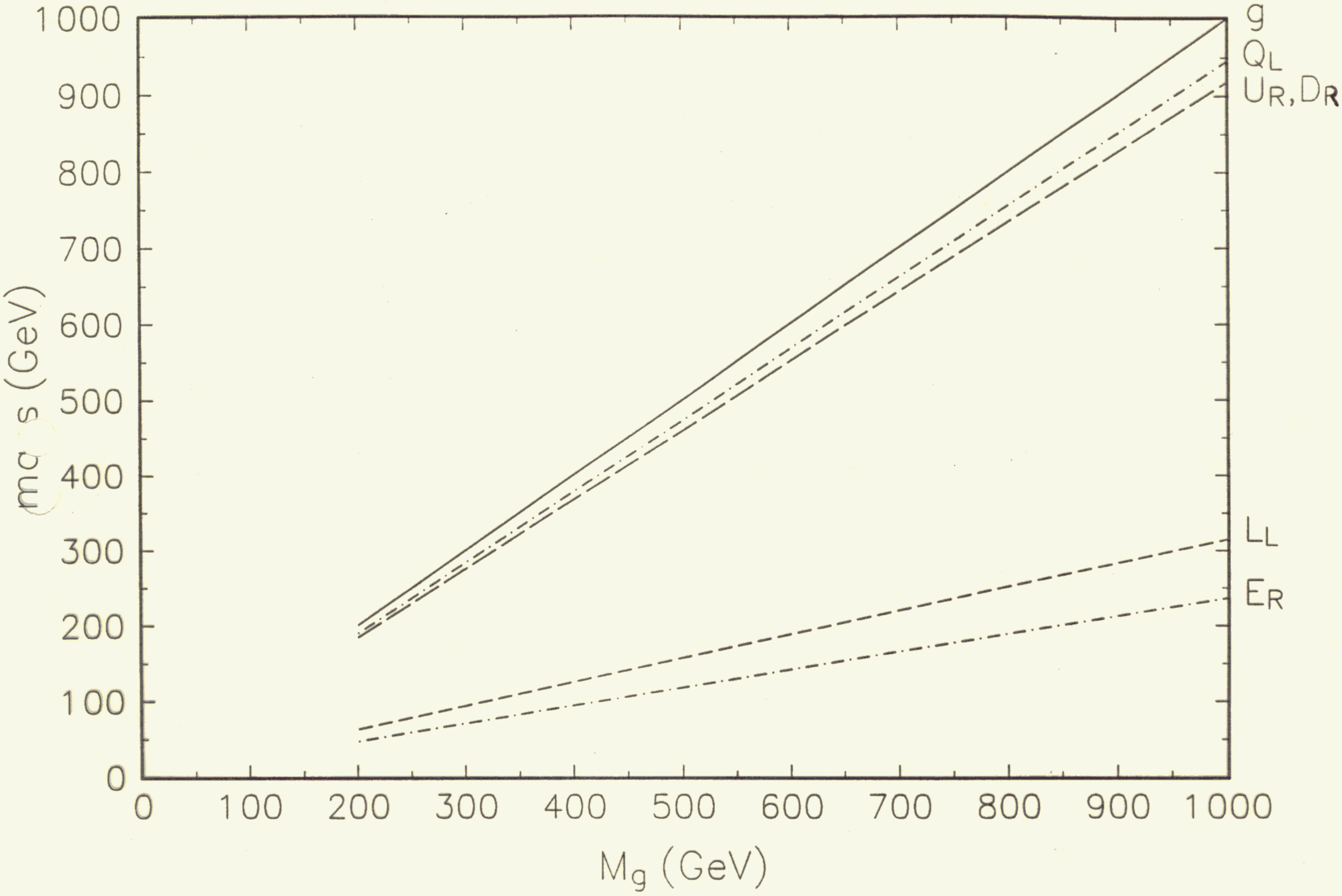
   THIS IS A DESIRABLE PROPERTY NOT ONLY TO REDUCE THE NUMBER OF INDEPENDENT PARAMETERS $33 \rightarrow 1$

   BUT ALSO TO AVOID FCNC

2. SCALARS ARE LIGHTER THAN GAUGINOS $\boxed{m < M}$

   AT LOW-ENERGY
$$\left.\begin{aligned} M^2_{\tilde{g}} &\simeq 9M^2 \\ m^2_{\tilde{q}} &\simeq m^2 + 8M^2 \\ m^2_{\tilde{\ell}} &\simeq m^2 + 0.3M^2 \end{aligned}\right\} \boxed{m_{\tilde{\ell}} \ll m_{\tilde{q}} \simeq M_{\tilde{g}}}$$

ALTHOUGH $\tilde{\ell}$ AND $\tilde{q}$ HAVE THE SAME SOFT MASS, AT LOW-ENERGY $m_{\tilde{\ell}} \ll m_{\tilde{q}}$ BECAUSE OF THE GLUINO CONTRIBUTION TO THE RGES



SQUARK, SLEPTON AND GLUINO MASSES VERSUS GLUINO MASS

$$M_{\tilde{g}} \sim m_{\tilde{q}} \begin{cases} \sim 3\, m_{\tilde{L}_L} \\ \sim 4\, m_{\tilde{E}_R} \end{cases}$$

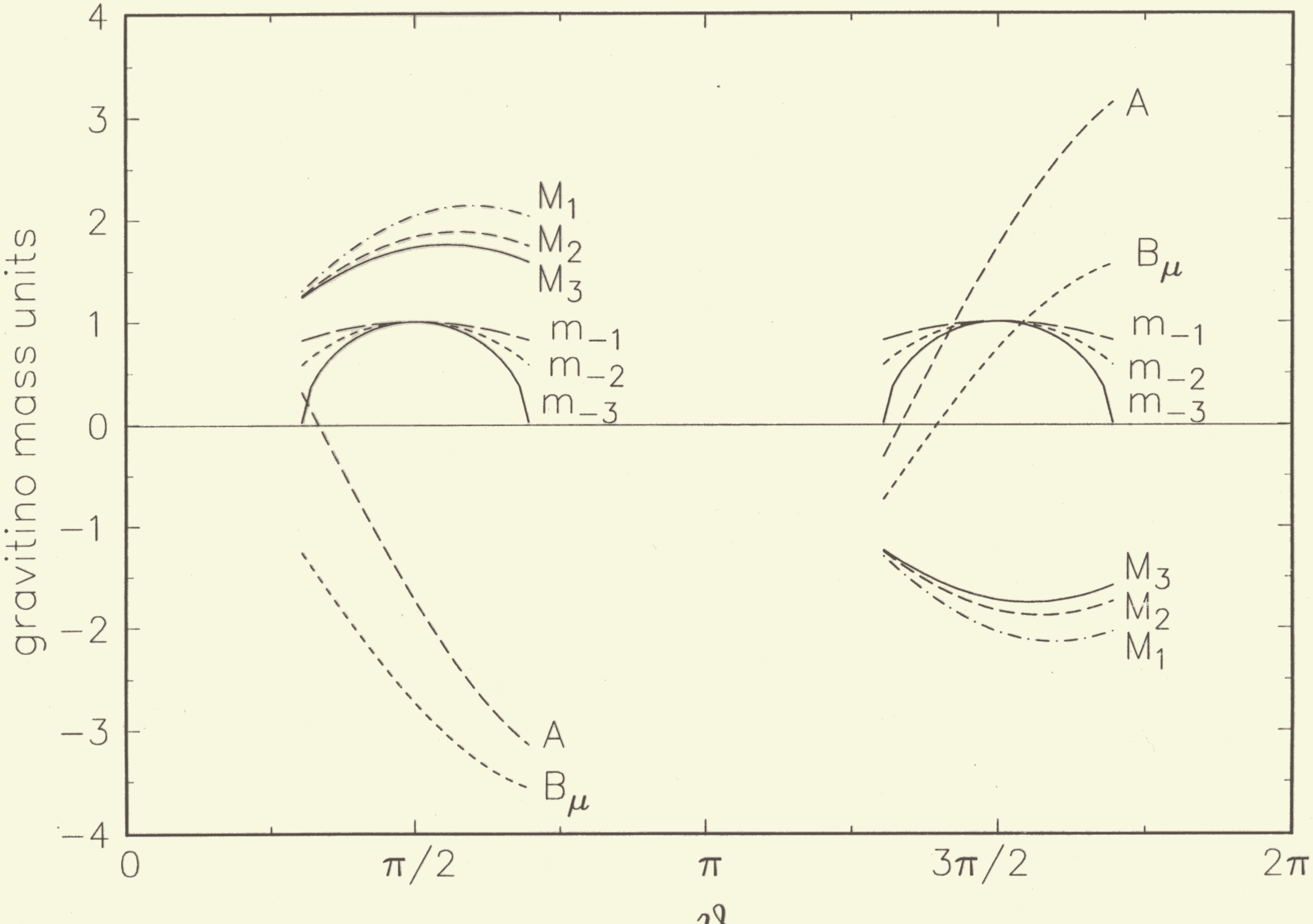
$$M_a = \sqrt{3}\, m_{3/2}$$

$$m_\alpha = m_{3/2}\left(1 + n_\alpha \cos^2\theta\right)$$

$n_\alpha = -1, -2, -3, \ldots$

NON UNIVERSAL

Fig.1b (O–I)



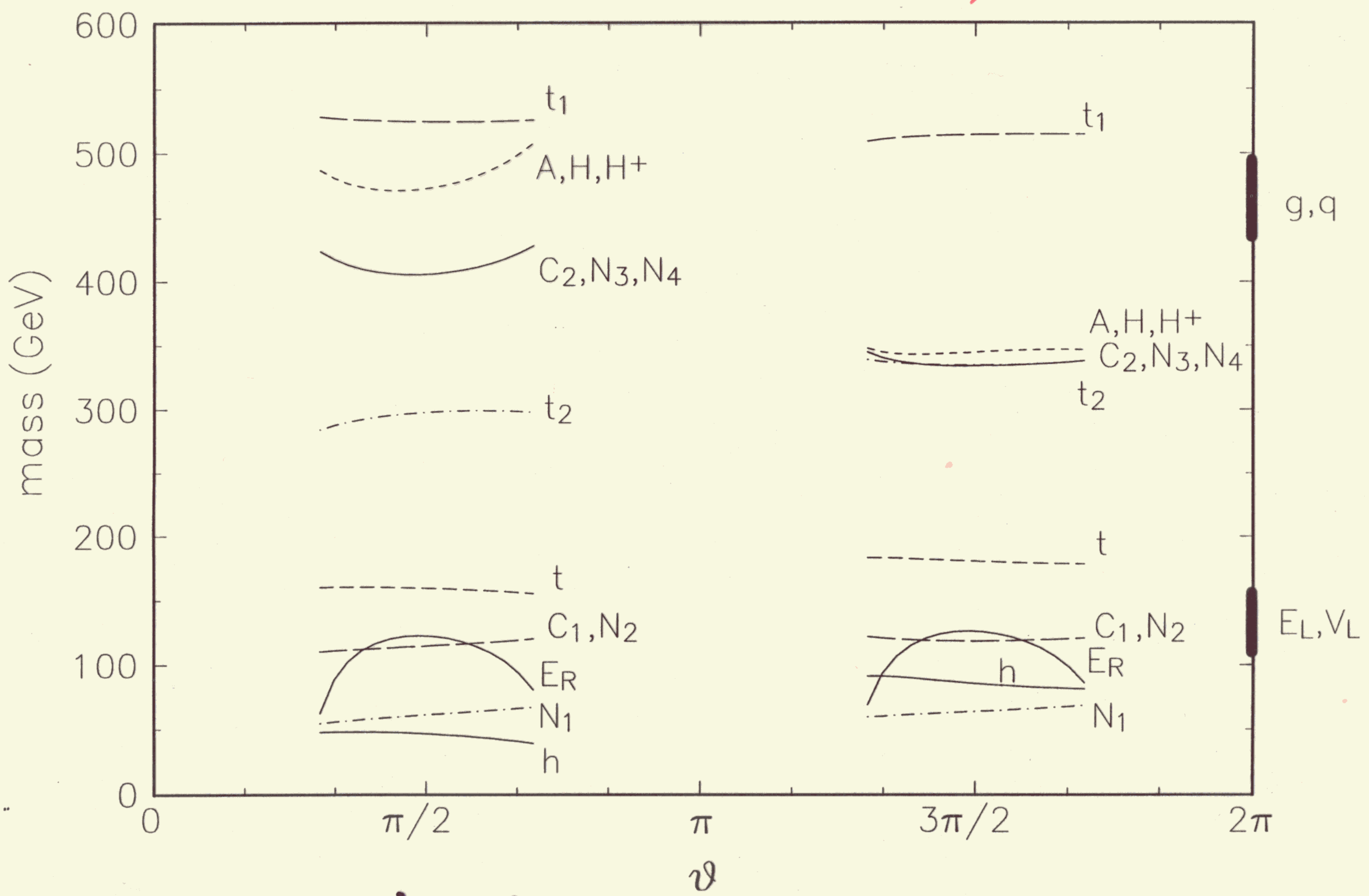
gravitino mass units
4
3
2
1
0
−1
−2
−3
−4
0
π/2
π
3π/2
2π
ϑ
M1
M2
M3
m−1
m−2
m−3
A
Bμ

95

Fig.3b (0–I)

$n_i = -1, -2, -3$

B_μ



$\sin^2\vartheta \geq \frac{2}{3}$

SIMILAR TO THE CASE $n_i = -1$

TO TEST EXPERIMENTALLY SUPERSTRING THEORY IS VERY DIFFICULT

THE NATURAL SCALE OF STRING MODELS IS $\mathcal{O}(10^{17-18}\ \mathrm{GeV})$

THE "NATURAL" SCALE OF PARTICLE ACCELERATORS IS $\mathcal{O}(10^{3}\ \mathrm{GeV})$

PERHAPS, A DETAILED ANALYSIS OF SUSY MASSES (IF SUSY PARTICLES ARE DETECTED!) MIGHT BE AN INDIRECT PROOF

98

Conference Summary

Steven Weinberg*

Theory Group
Department of Physics
University of Texas
Austin, Texas 78712

Talk presented at the XXVI International Conference on High Energy Physics, Dallas, Texas, August, 12, 1992.

- The correct theory underlying the standard model is probably a superstring theory. So far, our best proof consists of asking what else it could be. Superstring theories may be confirmed (and here I'm saying something that Peskin especially wanted me to say) by predictions for the coefficients of soft supersymmetry breaking terms in the supersymmetric standard model. In particular, it has been recently realized that in superstring theories it's typical that the lightest superparticles are gauginos rather than squarks or sleptons.

SUGRA BREAKING
THROUGH e.g. GAUGINO CONDENSATION

$\langle T \rangle \sim R^2$
$\langle S \rangle \sim 1/g^2$

$N=1$ $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ + SOFT TERMS

$m_{3/2} \sim 1\,\mathrm{TeV}$

RADIATIVE BREAKING
OF $SU(2)_L \otimes U(1)_Y$
$\langle H \rangle \neq 0$

$\sim 100\,\mathrm{GeV}$

$SU(3)_c \otimes U(1)_{e.m.}$

$\underbrace{\lambda_e(\langle T \rangle)\langle H \rangle}_{m_e} e_L e_R$

Summarizing: to obtain a connection between (string) theory and present (standard-model) experiments is possible in principle but difficult in practice

What about future experiments (such as LHC) ?

If Nature is SUSY at the weak scale, as many string phenomenologists believe(d), eventually the spectrum of SUSY particles will be measured providing us with a possible connection with the high-energy world of superstrings

This is because in superstring constructions:

- There is a natural hidden sector built in, S, T_i
- $K(S, S^*, T_i, T_i^*)$, $f(S, T_i)$ are known

$$\Downarrow$$

The soft terms, m_α, M_a, ..., can be computed and compared with the experimentally observed SUSY spectrum: 'SOFT' PHENOMENOLOGY

This will not be sufficient to select the (superstring) standard model, but probably will allow us to discard many constructions

[In addition, if experimentalists find some extra particles, this may also help]