

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

STRING PHENOMONOLOGY

Lecture III

H-P. NILLES
University of Bonn
Bonn
GERMANY

METHOD OF REDUCTION AND TRUNCATION

STANDARD EMBEDDING $\text{Tr} F^2 = \text{Tr} R^2$

IDENTIFY $\text{SU}(3)_4$ (Holonomy) $\subset \text{SO}(6)$

WITH $\text{SU}(3)_7$ subgroup of E_8

$$\rightarrow E_8 \times E_8' \longrightarrow E_6 \times \text{SU}(3) \times E_8'$$

$$\begin{array}{ccc} E_8 & & E_6 \times \text{SU}(3) \\ 248 & = & (78, 1) + (27, 3) + (\overline{27}, \overline{3}) + (1, 8) \end{array}$$

$$g_{mn} \stackrel{\wedge}{=} 21 \text{ OF } \text{SO}(6) \quad m = (i, j)$$

$$\rightarrow \textcircled{1} + 8 + 6 + \overline{6} \text{ of } \text{SU}(3)$$

$\rightarrow 5 \text{ FROM ABOVE}$

$$B_{mn} \stackrel{\wedge}{=} 15 \text{ OF } \text{SO}(6)$$

$$\rightarrow \textcircled{1} + 3 + \overline{3} + 8$$

$$\rightarrow \eta$$

$B_{\mu\nu}$ IS PSEUDOSCALAR IN $d=4$

$$(H_{\mu\nu\rho} \epsilon^{\mu\nu\rho\sigma} \stackrel{\wedge}{=} 2^0 \theta) \quad \text{AXION}$$

KEEP ONLY THOSE STATES THAT ARE
SINGLETS UNDER DIAGONAL
SU(3) SUBGROUP OF SU(3)_H × SU(3)_C

EXAMPLE:

$$A = 1 \dots 248$$

$$A_{M=0 \dots 9} \longrightarrow A_{\mu}^A + A_m^A$$

gauge bosons scalars

$$A_{\mu}^A \longrightarrow (78, 1) + \cancel{(27, 3)} + \cancel{(\overline{27}, \overline{3})} + \cancel{(1, 8)}$$

$$A_m^A \longrightarrow (78, 1) + (27, 3) + (\overline{27}, \overline{3}) + (1, 8)$$

$m=6 = 3 + \overline{3}$ $m=i, j$
($i, j = 1, 2, 3$)

KEEP $C^a = A_{\overline{i}}^{a, i}$

WITH $A = (a, i)$ FOR $(27, 3)$

(FAMILY OF E_6 , # defined by topology)

MODULI SECTOR:

$$S = \varphi^{-3/4} \exp(3\sigma) + i\theta$$

$$T = \exp(\sigma) \varphi^{3/4} + i\eta + |C\bar{C}|^2$$

CAN THEN DETERMINE LOW-ENERGY
EFFECTIVE ACTION:

$$\text{Re } F_{\mu\nu} F^{\mu\nu} \longrightarrow \boxed{f = S}$$

$$\boxed{K = -\log(S+\bar{S}) - 3\log(T+\bar{T}-2|C|^2)}$$

SUPERPOTENTIAL COMES FROM:

$$H = \dots \omega^{\text{YM}} \dots = \dots AF - \frac{2}{3} A^3$$

$$\longrightarrow \boxed{W = C^3}$$

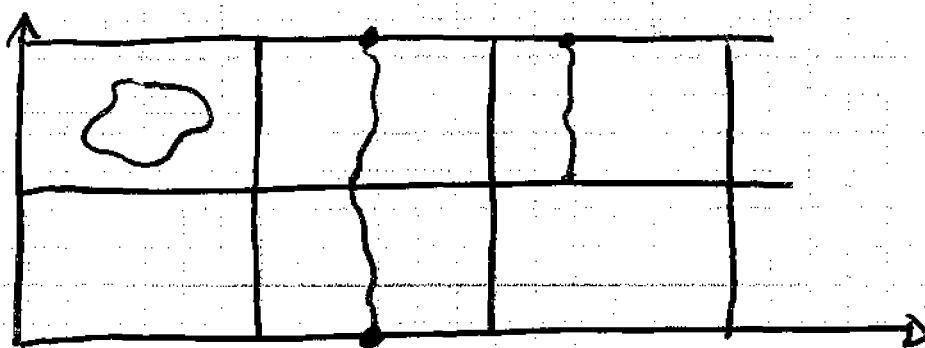
$$V = \frac{1}{ST^3} \left[|W|^2 + \frac{1}{3} T |W'_C|^2 \right] + D\text{-TERMS}$$

SO FAR THE EFFECTIVE FIELD THEORY

STRING: $X_L^M(\tau+\sigma) = X_L^M + P_L^M(\tau+\sigma) +$
+ OSCILLATORS

TORUS COMPACTIFICATION:

IDENTIFY X AND $X + 2\pi R$



WINDING MODES $n > 0$

$$P_R = \frac{m}{2R} - nR \quad P_L = \frac{m}{2R} + nR$$

($n=0, m \in \mathbb{Z}$ KALUZA-KLEIN)
MODES

SYMMETRY $R \leftrightarrow \frac{1}{2R}$

T-DUALITY

T-DUALITY RELATES

$$(E_8 \times E_8)_H \longleftrightarrow SO(32)_H$$

$$\text{TYPE II A} \longleftrightarrow \text{TYPE II B}$$

SYMMETRY OF PERTURBATIVE
STRING THEORY!

IN EFFECTIVE THEORY:

$$K = -3 \log(T + T^*) + \dots$$

$$T \longrightarrow \frac{aT - ib}{icT + d} \quad ad - bc = 1$$

$$K \longrightarrow K + |icT + d|^6$$

$$\longrightarrow W \longrightarrow (icT + d)^{-3} W$$

"MODULAR" FUNCTION OF WEIGHT 3

SUPPOSE $K = -3 \log(T + T^* - |C|^2)$

$$\rightarrow C \rightarrow \frac{C}{iCT+d}$$

$$\Rightarrow W = C^3 \text{ allowed!}$$

IF FIELD D IS INVARIANT
UNDER T-DUALITY $D \rightarrow D$

THEN $W = D^3$ would not
be allowed

$$\text{but } W = \eta(LT)^{-6} D^3$$

→ WORLD SHEET INSTANTON
CONTRIBUTIONS;
SUPPRESSED YUKAWA
COUPLINGS

TORUS $\rightarrow N \geq 4$ SUSY in $d=4$

\rightarrow NONTRIVIAL HOLONOMY

$SO(6) \rightarrow N=0$

$SU(3) \rightarrow N=1$

$SU(2) \rightarrow N=2$

CALABI YAU MANIFOLDS

RICCI FLAT + $SU(3)$ HOLONOMY

$\rightarrow E_6$ WITH MATTER IN

27 DIM. REPRESENTATION

$(\# 27 - \# \bar{27}) \stackrel{!}{=} \frac{1}{2}$ "Euler number"

THERE ARE ALSO SINGLETs

NEED QUITE DETAILED

KNOWLEDGE OF TOPOLOGY....

NOT EASY TO GO BEYOND

STANDARD EMBEDDING

A MORE SIMPLE CONCEPT:

ORBIFOLDS

DISCRETIZED VERSION OF

$SO(3)$ HOLONOMY $Z_3 \subset SO(3)$

(4 of $SO(6) \rightarrow 1 + 3$ OF Z_3)

\rightarrow ONE GRAVITINO LEFT

ORBIFOLDS ARE A GENERALIZATION

OF MANIFOLDS THAT ALLOW

"SINGULARITIES" (FIXED POINTS)

—
HERE WE ARE INTERESTED

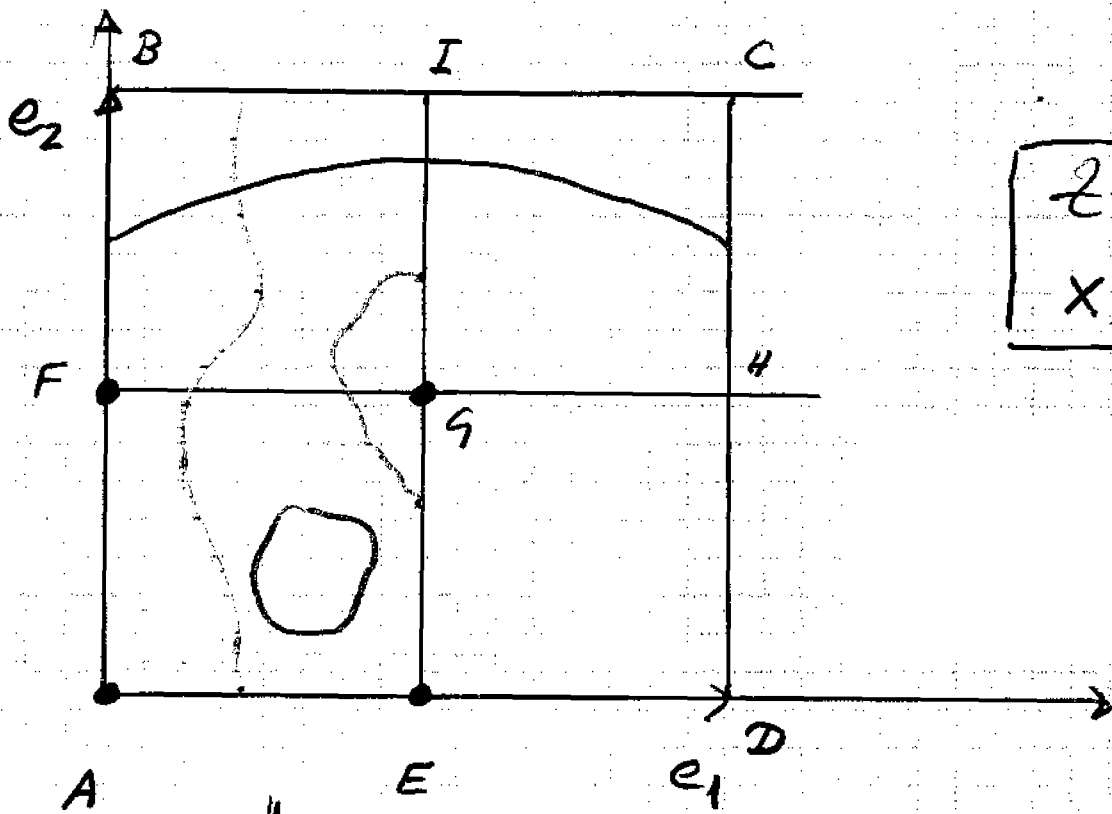
IN "FLAT" ORBIFOLDS

(FLAT EVERYWHERE EXCEPT

AT FIXED POINTS)

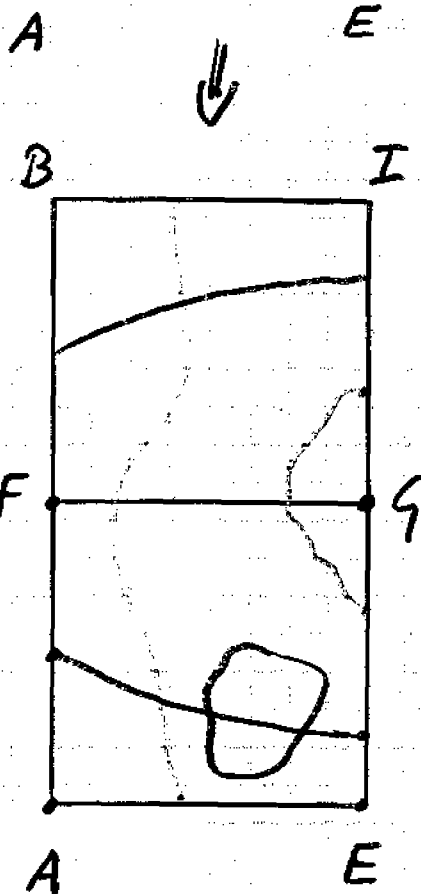
I.E. TWISTED TORI

TOY EXAMPLE (Z_2 in $d=2$)

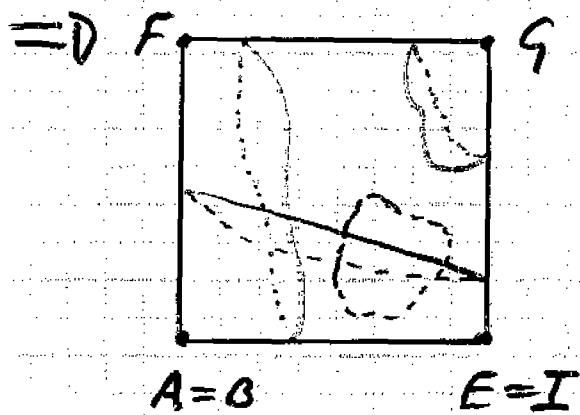


$$Z_2:$$

$$X \rightarrow -X$$



CLOSED
WINDING
WINDING
TWISTED } STRINGS



(TOPOLOGY OF SPHERE)

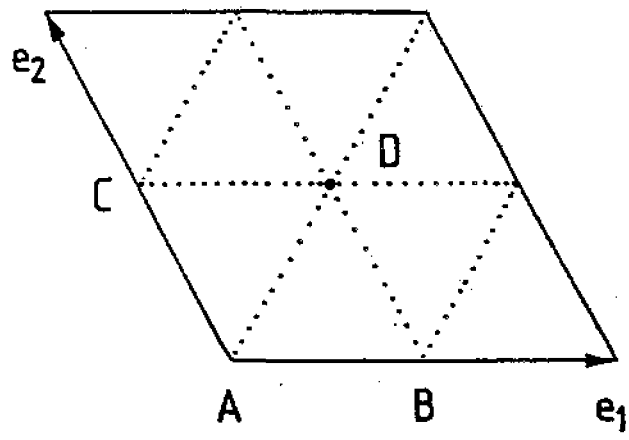


Figure 8

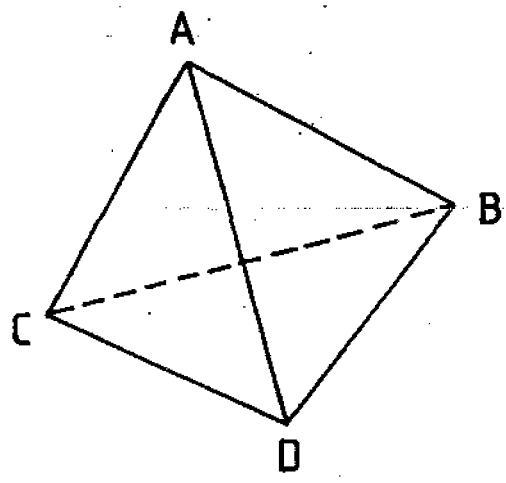


Figure 9

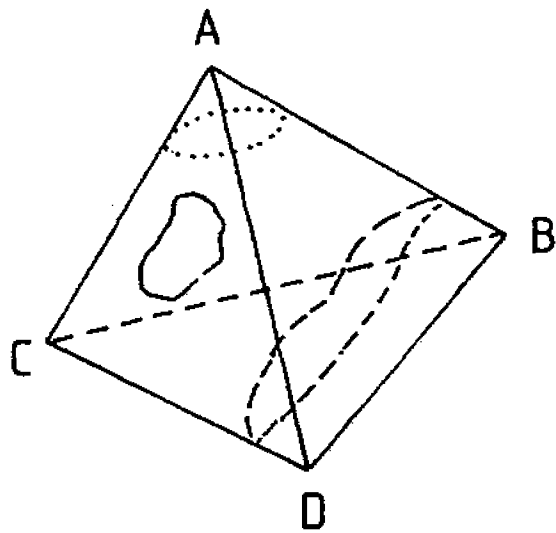
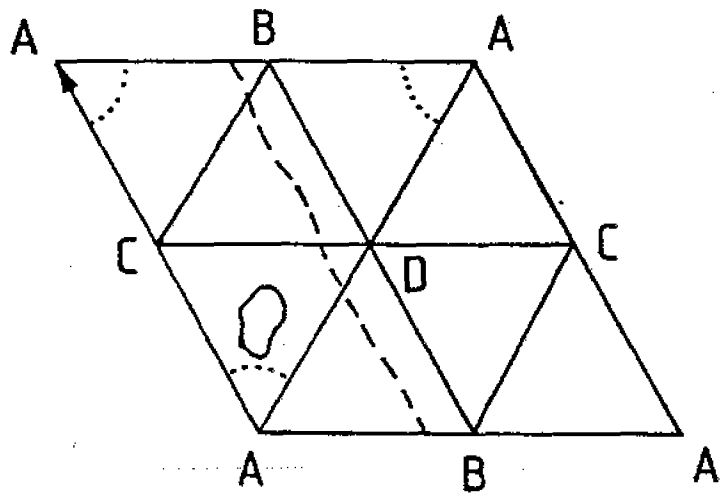


Figure 11

UNTWISTED SECTOR (BULK)

(AS ON TORUS BUT PROJECTION)

TWISTED SECTORS

CHARACTERIZED BY FIXEDPTS.
(BEANES)

SPECTRA CAN BE WORKED
OUT EASILY

GAUGE GROUP USUALLY FROM
UNTWISTED SECTOR ($C E_8 \times E_8$)

MATTER FROM UNTWISTED
OR TWISTED SECTOR

WILSON LINES

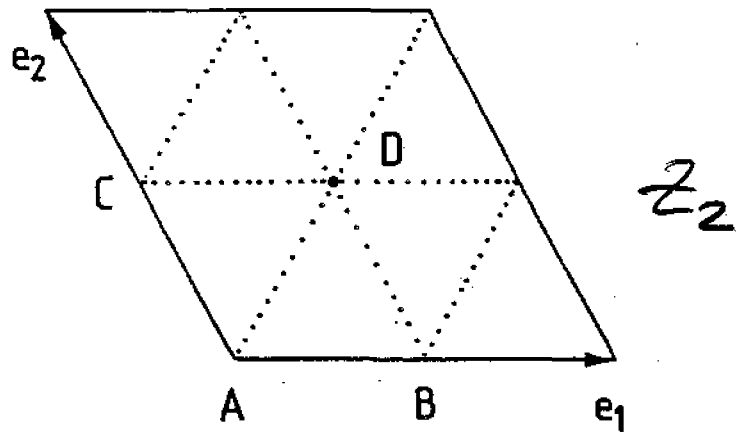


Figure 8

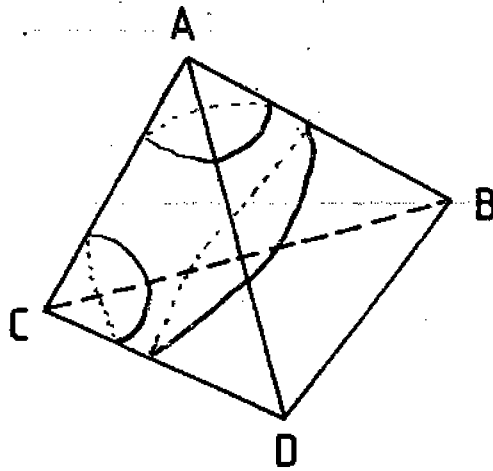


Figure 9

Interactions sometimes
needs "stretching" of string

Yukawa couplings

untwisted sector : C^3

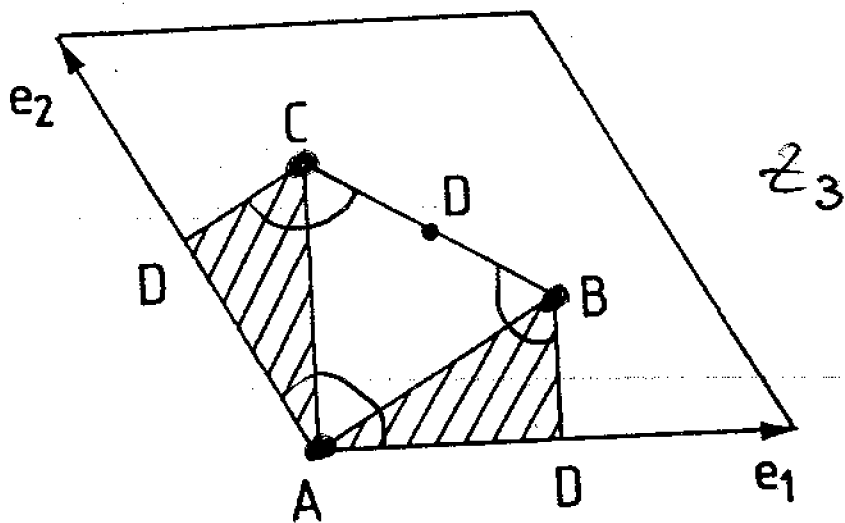
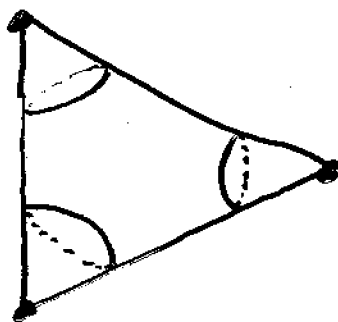


Figure 12

twisted sector : $f(T)D^3$



suppressed
for large T

(world sheet instanton effects)

SPECIFIC CONSTRUCTIONS

* HETEROTIC: ORBIFOLDS
(MOSTLY $E_8 \times E_8$) CALABI YAU
FERMIONIC CONSTR.
COVARIANT LATTICES

* TYPE II ORIENTIFOLDS

(\cong TYPE I ORBIFOLDS)

i.e. OPEN + CLOSED STRINGS

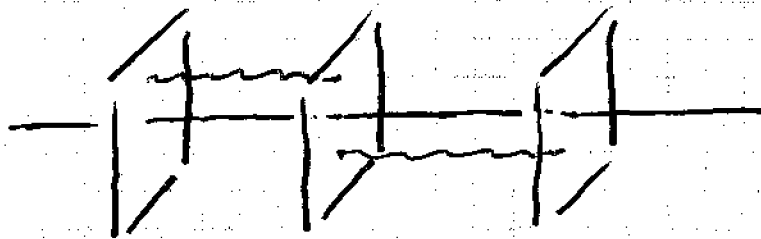
MOSTLY $SO(32)$ FROM 9-BRANES

BUT ALSO 5-BRANES

+ DUALITY TRANSFORMATIONS

* GENERAL BRANE SET-UP

STACKS OF BRANES



$$U(N_1) \times U(N_2) \times U(N_3) \times \dots$$

MATTER IN ADJOINT OR

BIFUNDAMENTAL: LIKE (N_1, \bar{N}_2)

(ALSO BRANES AT ANGLES
OR ANTI-BRANES)

* HORAVA-WITTEN $E_8 \times E_8$

(WITH $d=11$ BULK, 2-BRANES
AND 5-BRANES)

OR COMPACTIFICATION: $d=11 \rightarrow d=4$

(MANIFOLDS OF S_2 -HOLONOMY)

THE SPECTRUM

* CHIRAL SPECTRUM!

* # FAMILIES GIVEN BY

"TOPOLOGICAL" PROPERTIES:

EULER NUMBER, # FIXED POINTS,

COMPACT EXTRA DIMENSIONS,

NUMBER OF COLOURS

* STRUCTURE OF FAMILY

$(\bar{3}, 1); (3, 2); (1, 2); (1, 1)$ OF
 $SU(3) \times SU(2)$

$\bar{5} + 10$ OF $SU(5)$

16 OF $SU(10)$

27 OF E_6

MOST ECONOMIC IS 16 OF $SO(10)$

* EASY TO GET IN HETEROTIC $E_8 \times E_8$
EVEN IF ONLY $SU(3) \times SU(2) \times U(1)$
IS REALIZED IN $d=4$

IN OTHER CONSTRUCTIONS

SPINORS OF $SO(N)$ DO USUALLY
NOT APPEAR

* EMBED IN ADJOINT OF $SO(M)$

TYPE II ORIENTIFOLD

e.g. $SU(12) \times O(8) \subset SO(32)$

WITH FUNDAMENTAL (12)

AND 2-INDEX ANTISYMMETRIC

REPRESENTATION ($\overline{66}$)

→ ECONOMIC DESCRIPTION
OF FAMILY IN $(5 + \overline{10})$

* CRUCIAL IS (3,2)

→ BIFUNDAMENTAL

CAN GET FAMILY, BUT THERE
IS NO EASY RECIPE

USUALLY ONE GETS MORE
THAN NEEDED

* ADDITIONAL U(1)'S

(e.g. $U(3) \times SU(2) \times U(1)^5$)

* MANY "Higgs" DOUBLETS
(μ -PROBLEM)

* Higgs TRIPLETS
(USUALLY NO SPLITTING PROBLEM)

* SINGLETS

NEED DISCRETE SYMMETRIES

HOW TO DISTINGUISH LEPTONS

AND: MIXES : BOTH (1,2)

→ R-PARITY

(OR B, L, M... PARITY)

RELATED, OF COURSE, TO THE

QUESTION OF PROTON

STABILITY, B, L VIOLATION

QUARK-LEPTON "TEXTURES".....

(SO(10) NOT BAD)

IT IS USUALLY NOT TOO

DIFFICULT TO OBTAIN

DISCRETE SYMMETRIES

AXIONS

- * HAVE ALREADY SEEN θ AND η FROM $B_{\mu\nu}$ AND B_{mn}
- * ANOMALOUS U(1)'S IN HETEROTIC ORBIFOLDS AND TYPE II ORIENTIFOLDS
- * GREEN-SCHWARZ MECHANISM RENDERS U(1) GAUGE BOSONS HEAVY
 - REMAINS GLOBAL ANOMALOUS U(1) WITH AXION FOR STRONG CP-PROBLEM (AXION SCALE?)

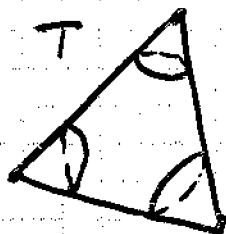
YUKAWA COUPLINGS

* NICE MECHANISM FOR SUPPRESSION:

3rd FAMILY		C^3
2nd	"	$e^{-T} D^3$
1st	"	$e^{-2T} E^3$

AND $e^{-T} \approx \frac{1}{30}$ NEEDED

e^{-T} SUPPRESSION USUALLY UNDERSTOOD GEOMETRICALLY



T DISTANCE
BETWEEN FIXED PTS.

OR AREA OF
WORLD SHEET

* IT IS SOMETIMES DIFFICULT
TO GIVE MASSES TO ALL
QUARKS AND LEPTONS

($U_1 U_2 U_3$ IN UNTWISTED SECTOR)

$$* QH\bar{D} + QH\bar{U} + LH\bar{E} \\ + QL\bar{D} + LLE\bar{E} + \bar{U}\bar{D}\bar{D}$$

CONNECTED TO R-SYMMETRY

$$\rightarrow SO(10): 16_F \times 16_F \times 10_H$$

GIVES DESIRED PATTERN!

$$\rightarrow (\text{ADJOINT})^3 \text{ USUALLY NOT}$$

EG. ORIENTIFOLD $SU(5) \subset SU(12) \times O(2)$

WITH $(\bar{5}, -1)$ AND $(10, 2)$ ALLOWS

$$(10, 2) \times (\bar{5}, -1) \times (\bar{5}, -1)$$

UNIFICATION OF COUPLINGS

DO WE NEED ζ_{UT} -GROUP

* DIFFICULT TO BREAK SPONTANEOUSLY

* SPECTRUM INHERITED FROM ζ_{UT} -GROUP IN $d > 4$

* UNIFICATION BECAUSE OF "UNIQUE" STRING COUPLING

→ * UNIFICATION AT M_{STRING} OR $M_{\text{COMPACTIFICATION}}$

* LOW-ENERGY EXTRAPOLATION LEADS TO $M_{\zeta_{UT}} \sim 10^{16} \text{ GeV}$

HETEROTIC STRING

$$\left. \begin{aligned} g_N &= \frac{e^{2\phi} (\alpha')^4}{64\pi V} \\ \alpha_{\text{GUT}} &= \frac{e^{2\phi} (\alpha')^3}{16\pi V} \end{aligned} \right\} g_N = \frac{\alpha_{\text{GUT}} \alpha'}{4} \quad (*)$$

$$g_N = \frac{k_4^2}{8\pi} = \frac{1}{M_{\text{PLANCK}}^2}$$

$$M_{\text{PLANCK}} = 1.2 \times 10^{19} \text{ GeV}$$

$$\alpha_{\text{GUT}} = \frac{g_{\text{GUT}}^2}{4\pi} \approx \frac{1}{25}$$

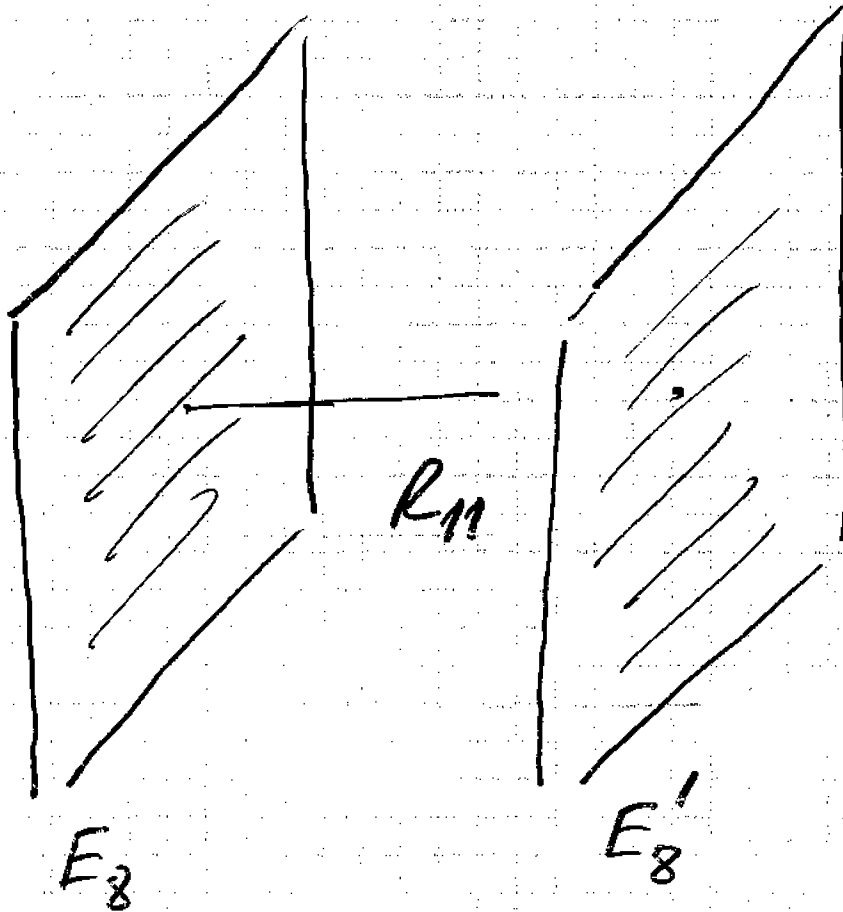
$$M_{\text{STRING}}^2 = T = 1/\alpha'$$

$$(*) \Rightarrow M_{\text{STRING}} = 4 \times 10^{17} \text{ GeV}$$

$$\text{WHILE } M_{\text{GUT}} \approx 2 \times 10^{16} \text{ GeV}$$

$$\rightarrow M_{\text{STRING}} \approx 20 M_{\text{GUT}} \quad ???$$

$E_8 \times E_8$ - M-THEORY



$d=11$ SUSY IN BULK

$E_8 \times E_8$ GAUGE MULTIPLETS ON
RESPECTIVE WALL

WE NOW HAVE ONE MORE
PARAMETER: R_{11}

$$\zeta_N = \frac{k^2}{8\pi V R_{11}} \quad \text{FEELS } R_{11}$$

$$\alpha_{\text{GUT}} = \frac{(4\pi k^2)^{2/3}}{V} \quad \text{DOES NOT DEPEND ON } R_{11}$$

IDENTIFY $V \cong R^6 = (M_{\text{GUT}})^{-6}$

$$M_{\text{GUT}} \approx 3 \times 10^{16} \text{ GeV} \quad \alpha_{\text{GUT}} \approx \frac{1}{25}$$

$$\Rightarrow M_{11} = k^{-2/9} \approx 2 M_{\text{GUT}} \approx 6 \times 10^{16} \text{ GeV}$$

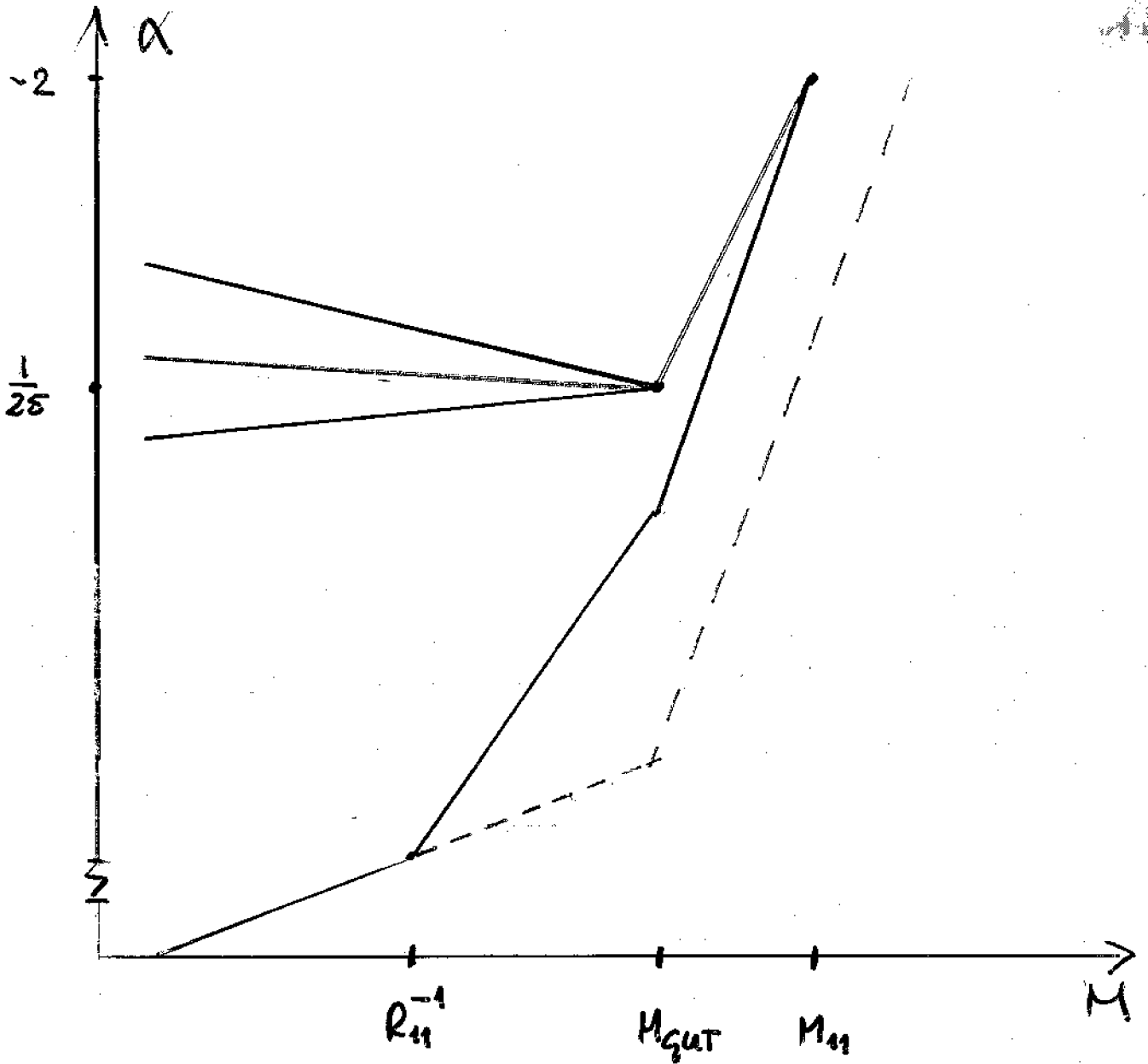
AND ADJUST R_{11} TO FIT M_{PLANCK}

$$\Rightarrow (R_{11})^{-1} \approx \frac{M_{\text{GUT}}}{6} \approx 5 \times 10^{15} \text{ GeV}$$

i.e. $R_{11} \approx 6 R_0$

M_{pl}

3



$$M_{pl} \approx 2 M_{GUT}$$

$$\alpha_{\text{string}}(M_{pl}) \approx \mathcal{O}(1)$$

M_{plank} in $d=4$ "artificially" large

quantum gravity relevant already

at M_{GUT}

→ LARGE EXTRA DIMENSIONS

$$R = \text{Millimeter} !?$$

→ $M_{\text{STRINGS}} \approx \text{TeV} ?$

IN PRINCIPLE POSSIBLE, BUT

THERE REMAIN SOME PROBLEMS

* UNIFICATION OF GAUGE
COUPLING CONSTANTS
AT TEV SCALE

* "STRONG" GRAVITY AT TEV

* PROTON STABILITY

* NEUTRINO MASSES

OTHER DIRECTIONS

* $d=11$ AND M-THEORY ORBIFOLDS
(MANIFOLDS WITH S_2 -HOLONOMY)

* WARPED COMPACTIFICATIONS
(COSMOLOGICAL CONSTANT?)

* "FIELD THEORETIC" ORBIFOLDS
→ BOTTOM-UP APPROACH

* CONSISTENCY CONDITIONS
FROM STRING THEORY
(LOCALIZED ANOMALIES)