united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR.1508 - 28

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 $\mathrm{Tr} F^2 = \mathrm{Tr} R^2$

IDENTIFY $SU(3)_H$ (Holonomy) $\subset SO(6)$

WITH $SU(3)_G$ subgroup of E_8

$$\longrightarrow E_8 \times E_8' \longrightarrow E_6 \times SU(3) \times E_8'$$

$$\underset{E_8}{248} = \underset{E_6 \times SU(3)}{(78,1) + (27,3) + (\overline{27},\overline{3}) + (1,8)}$$

$g_{mn} \hat{=} 21$ OF $SO(6)$ $\quad m = (i, \bar{j})$

$$\longrightarrow \underbrace{1}_{\sigma \text{ FROM ABOVE}} + 8 + 6 + \overline{6} \text{ of } SU(3)$$

$B_{mn} \hat{=} 15$ OF $SO(6)$

$$\longrightarrow \underbrace{1}_{\eta} + 3 + \overline{3} + 8$$

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

$(H_{\mu\nu\rho}\, \epsilon^{\mu\nu\rho\sigma} \hat{=} \partial^\sigma \theta)$ AXION

KEEP ONLY THOSE STATES THAT ARE SINGLETS UNDER DIAGONAL SU(3) SUBGROUP OF $SU(3)_H \times SU(3)_G$

EXAMPLE:

$$A^{A=1\ldots 248}_{M=0\ldots 9} \longrightarrow A^A_\mu + A^A_m$$

gauge bosons SCALARS

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

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

$m = 6 = 3 + \overline{3}$ $\quad m = i, \overline{J}$

$(i, \overline{J} = 1,2,3)$

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

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:

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

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

SUPERPOTENTIAL COMES FROM:

$$H = \cdots \omega^{YM} \cdots = \cdots AF - \tfrac{2}{3}A^3$$

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

$$V = \frac{1}{ST^3}\left[|W|^2 + \frac{1}{3}T\,|W_C'|^2 \right]$$

$+$ D-TERMS

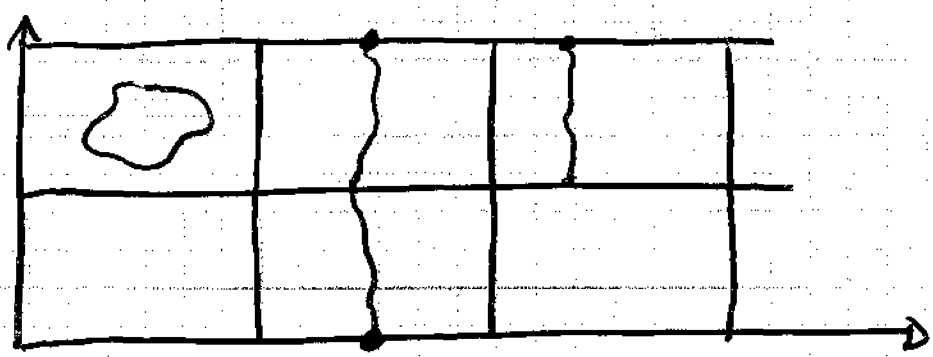
SO FAR THE EFFECTIVE FIELD THEORY

STRING: $X_L^{\mu}(\tau+\sigma) = X_L^{\mu} + p_L^{\mu}(\tau+\sigma) +$

$+$ OSCILLATORS

TORUS COMPACTIFICATION:

IDENTIFY $\underline{X}$ AND $\underline{X + 2\pi R}$



WINDING MODES $n > 0$

$$p_R = \frac{m}{2R} - nR \qquad p_L = \frac{m}{2R} + nR$$

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

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

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:

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

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

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

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

"MODULAR" FUNCTION OF WEIGHT 3

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

$$\longrightarrow \quad C \longrightarrow \frac{C}{icT+d}$$

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

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

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

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

$\longrightarrow$ WORLD SHEET INSTANTON CONTRIBUTIONS; SUPPRESSED YUKAWA COUPLINGS

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

$\to$ NONTRIVIAL HOLONOMY

$SO(6) \to N=0$

$SU(3) \to N=1$

$SU(2) \to N=2$

CALABI YAU MANIFOLDS

RICCI FLAT + $SU(3)$ HOLONOMY

$\to E_6$ with MATTER IN

27 dim. REPRESENTATION

$(\# 27 - \# \overline{27}) \hat{=} \frac{1}{2}$ "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

$SU(3)$ HOLONOMY $\mathbb{Z}_3 \subset SU(3)$

(4 of $SO(6) \to 1 + 3$ OF $\mathbb{Z}_3$)

$\to$ ONE GRAVITINO LEFT

ORBIFOLDS ARE A GENERALIZATION

OF MANIFOLDS THAT ALLOW

"SINGULARITIES" (FIXED POINTS)

HERE WE ARE INTERESTED

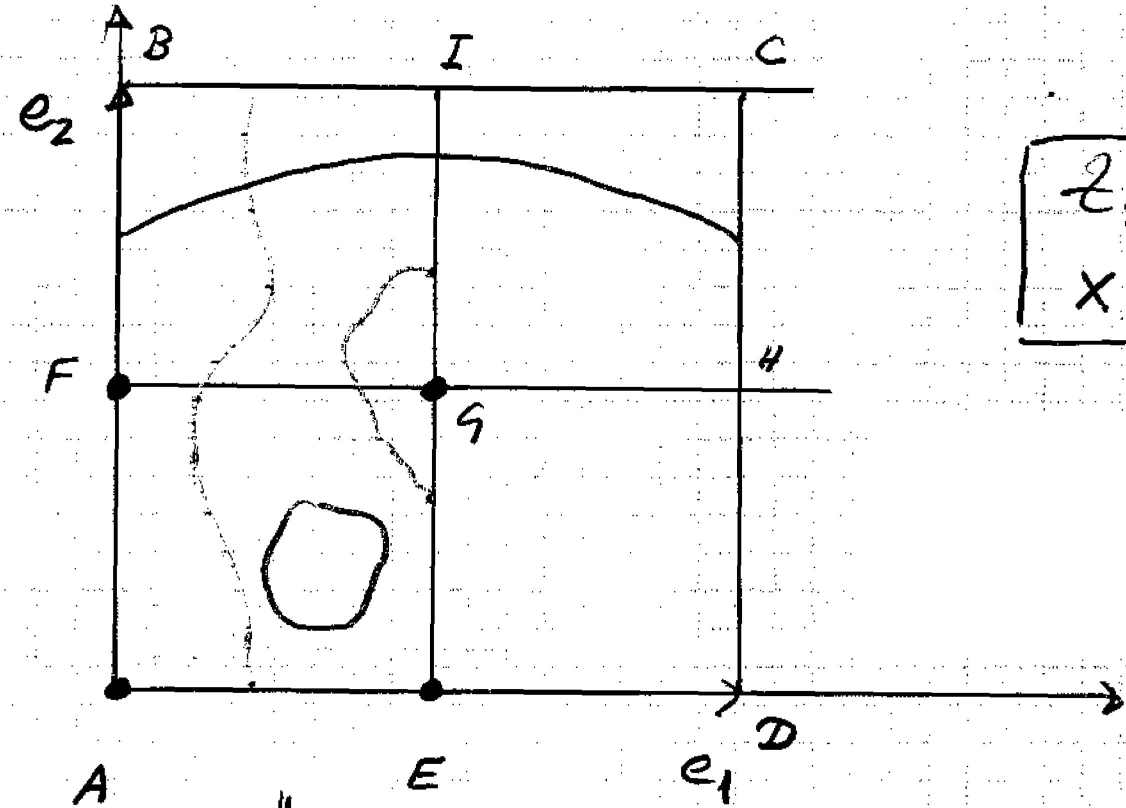
IN "FLAT" ORBIFOLDS

(FLAT EVERYWHERE EXCEPT

AT FIXED POINTS)

I.E. TWISTED TORI

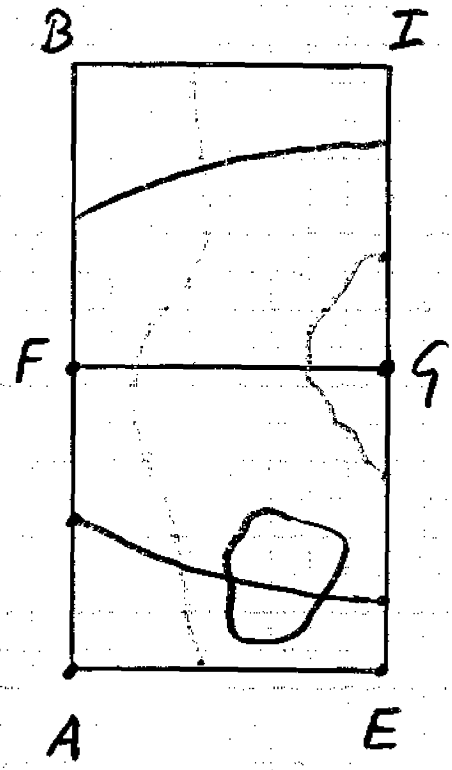
TOY EXAMPLE (Z_2 in $d=2$)



Z_2:

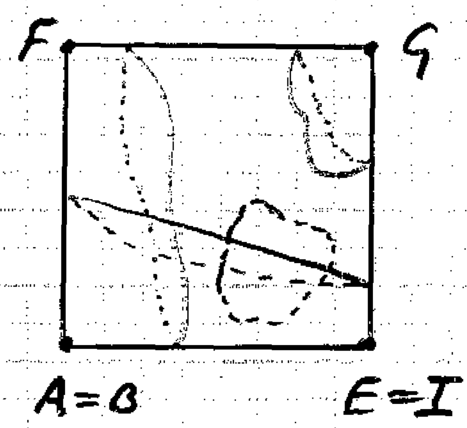
$x \longrightarrow -x$

$\Downarrow$



CLOSED
WINDING
WINDING
TWISTED
} STRING

$\Rightarrow$



(TOPOLOGY OF SPHERE)

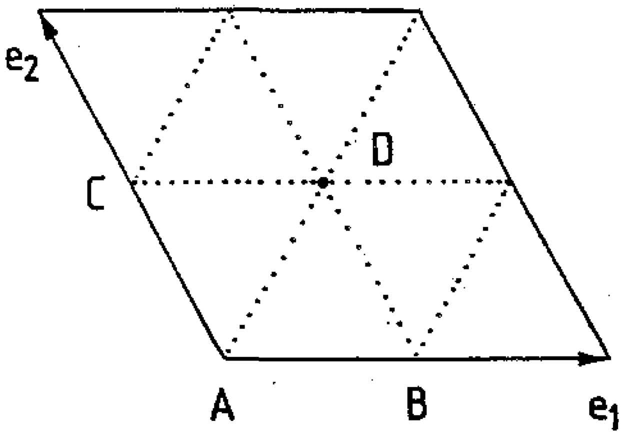


Figure 8

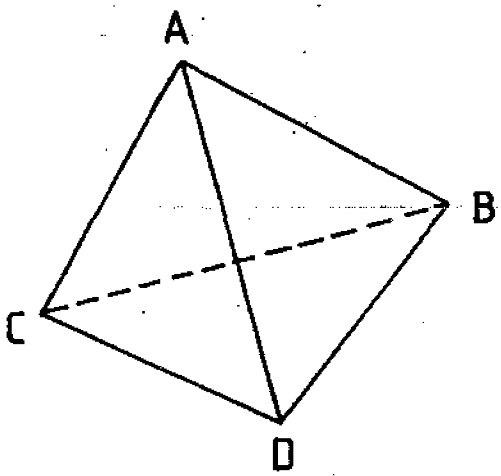


Figure 9

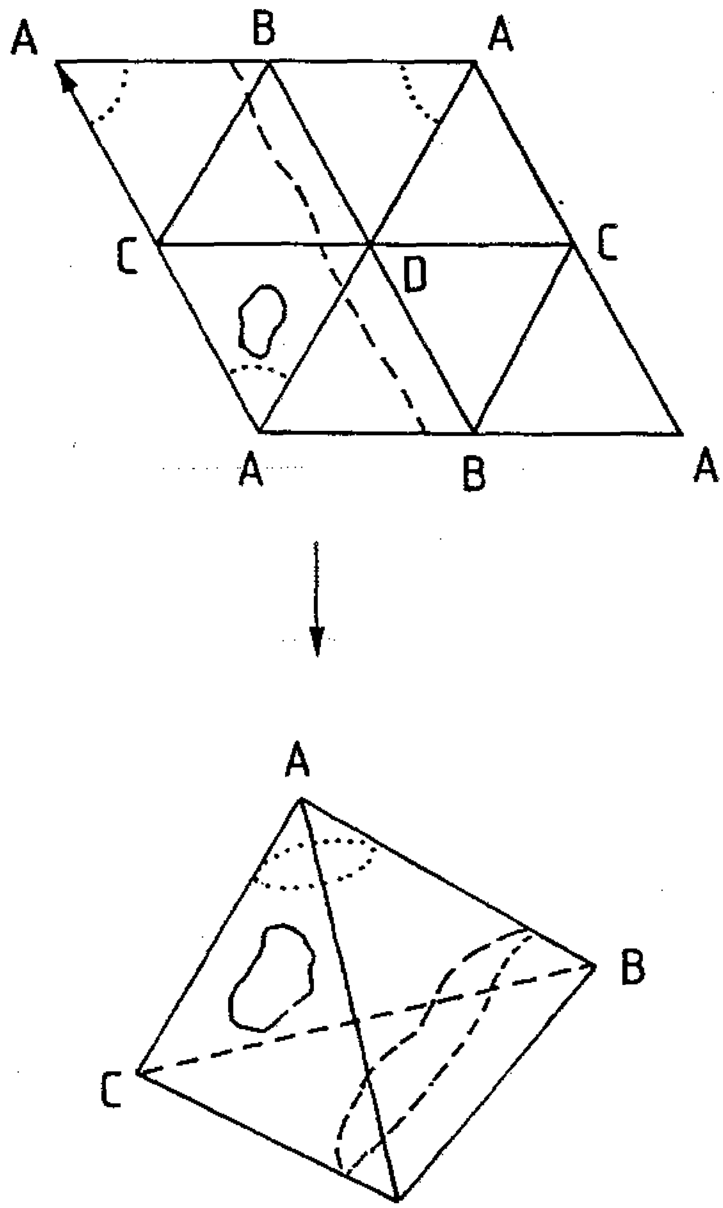


Figure 11

UNTWISTED SECTOR (BULK)

(AS ON TORUS BUT PROJECTION)

TWISTED SECTORS

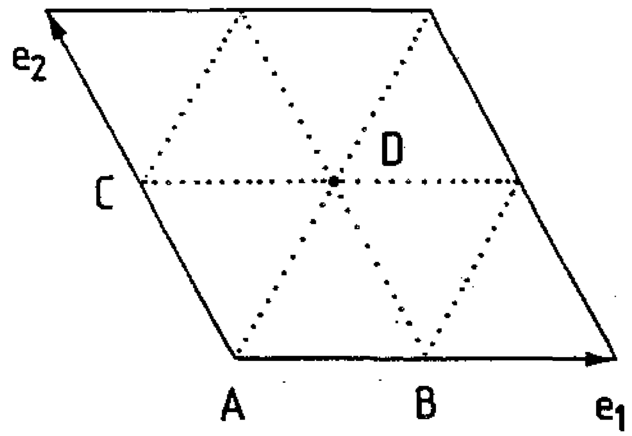
CHARACTERIZED BY FIXED PTS.
(BRANES)

SPECTRA CAN BE WORKED
OUT EASILY

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

MATTER FROM UNTWISTED
OR TWISTED SECTOR

WILSON LINES .....



$\mathbb{Z}_2$

Figure 8

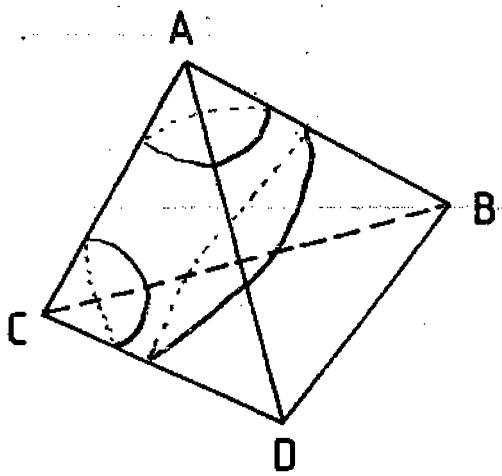


Figure 9

Interactions sometimes
needs "stretching" of string

Yukawa couplings

untwisted sector : C^3

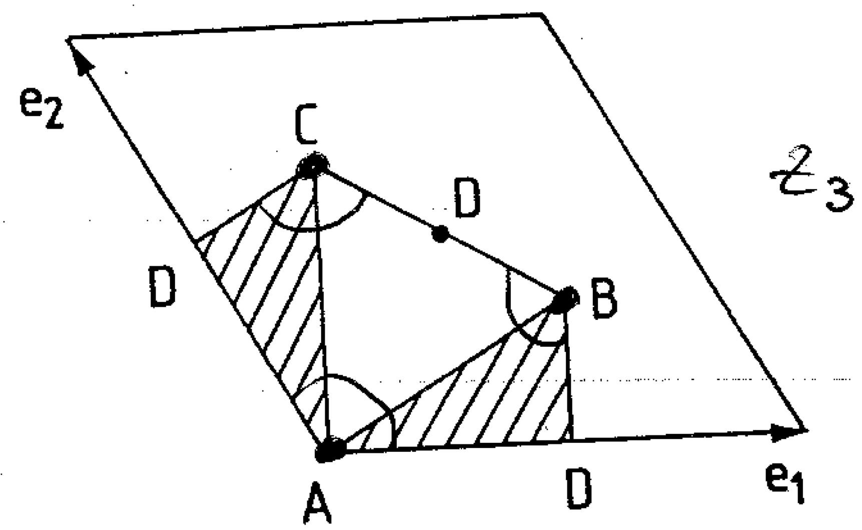
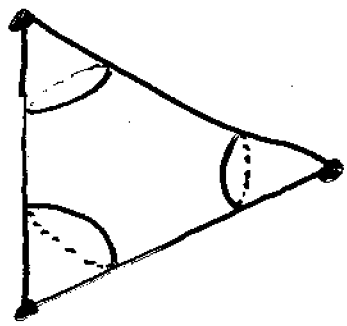


Figure 12

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



suppressed for large T

(world sheet instanton effects)

SPECIFIC CONSTRUCTIONS

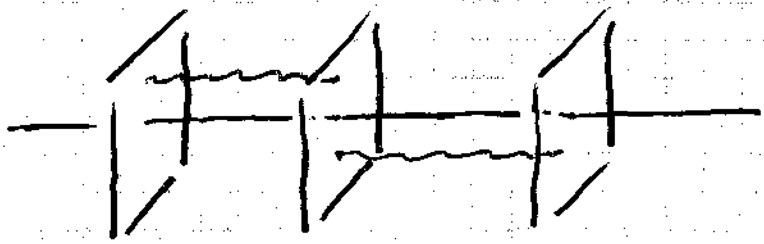
* HETEROTIC: ORBIFOLDS
(MOSTLY $E_8 \times E_8$) CALABI YAU
FERMIONIC CONSTR.
COVARIANT LATTICES

* 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



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

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: $d=11 \to d=4$

(MANIFOLDS OF G_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 $SO(10)$

  27 OF E_6

MOST ECONOMIC IS <u>16</u> 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
<u>SPINORS</u> OF $O(N)$ DO USUALLY
NOT APPEAR

* EMBED IN <u>ADJOINT</u> OF $SO(M)$

TYPE II ORIENTIFOLD

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

WITH FUNDAMENTAL (12)
AND 2-INDEX ANTISYMMETRIC
REPRESENTATION $(\overline{66})$

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

* MANY "HIGGS" DOUBLETS
  (μ-PROBLEM)

* HIGGS TRIPLETS
  (USUALLY NO SPLITTING PROBLEM)

* SINGLETS

NEED DISCRETE SYMMETRIES

HOW TO DISTINGUISH LEPTONS AND HIGGSES : BOTH (1,2)

$\longrightarrow$ 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

  $\rightarrow$ REMAINS GLOBAL ANOMALOUS $U(1)$ WITH AXION FOR STRONG CP – PROBLEM

  (AXION SCALE ?)

YUKAWA COUPLINGS

* NICE MECHANISM FOR SUPPRESSION:

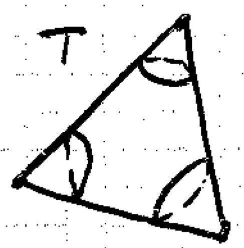
3rd FAMILY $\quad C^3$

2nd $\quad$ " $\quad e^{-T} D^3$

1st $\quad$ " $\quad e^{-2T} E^3$

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

e^{-T} SUPPRESSION USUALLY UNDERSTOOD GEOMETRICALLY



T <u>DISTANCE</u> BETWEEN FIXED PTS.

OR <u>AREA</u> OF WORLD SHEET ....

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

($U_1 U_2 U_3$ IN UNTWISTED SECTOR)

* $Q H \bar{D} + Q \bar{H} \bar{U} + L H \bar{E}$

$+ Q L \bar{D} + L L \bar{E} + \bar{U} \bar{D} \bar{D}$

CONNECTED TO R-SYMMETRY

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

GIVES DESIRED PATTERN!

→ $(\text{ADJOINT})^3$ USUALLY NOT

EG. ORIENTIFOLD $SU(5) \subset SU(12) \times O(8)$

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

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

UNIFICATION OF COUPLINGS

DO WE NEED GUT-GROUP

* DIFFICULT TO BREAK SPONTANEOUSLY

* SPECTRUM INHERITED FROM GUT-GROUP IN $d > 4$

* UNIFICATION BECAUSE OF "UNIQUE" STRING COUPLING

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

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

HETEROTIC STRING

$$G_N = \frac{e^{2\phi}(\alpha')^4}{64\pi V}$$

$$\alpha_{GUT} = \frac{e^{2\phi}(\alpha')^3}{16\pi V}$$

$$\Bigg\} \quad G_N = \frac{\alpha_{GUT}\,\alpha'}{4} \quad (*)$$

$$G_N = \frac{\kappa_4^2}{8\pi} = \frac{1}{M_{PLANCK}^2} \qquad M_{PLANCK} = 1.2 \times 10^{19}\,\mathrm{GeV}$$

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

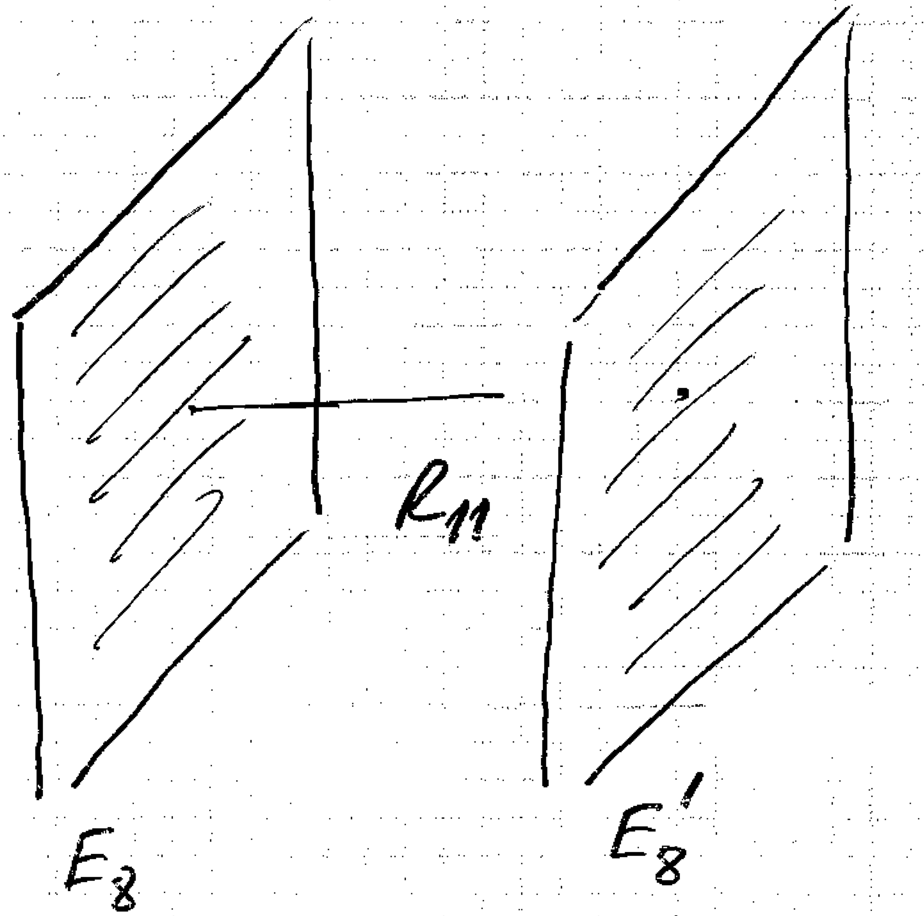
$$M_{STRING}^2 = T = 1/\alpha'$$

$$(*) \Longrightarrow \quad M_{STRING} = 4 \times 10^{17}\,\mathrm{GeV}$$

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

$\rightarrow M_{STRING} \approx 20\, M_{GUT}$???

$E_8 \times E_8$ – M – THEORY



$d = 11$ SUGRA IN BULK

$E_8 \times E_8$ GAUGE MULTIPLETS ON RESPECTIVE WALL

WE NOW HAVE ONE MORE PARAMETER : R_{11}

$$G_N = \frac{\kappa^2}{8\pi V R_{11}} \qquad \text{FEELS } R_{11}$$

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

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

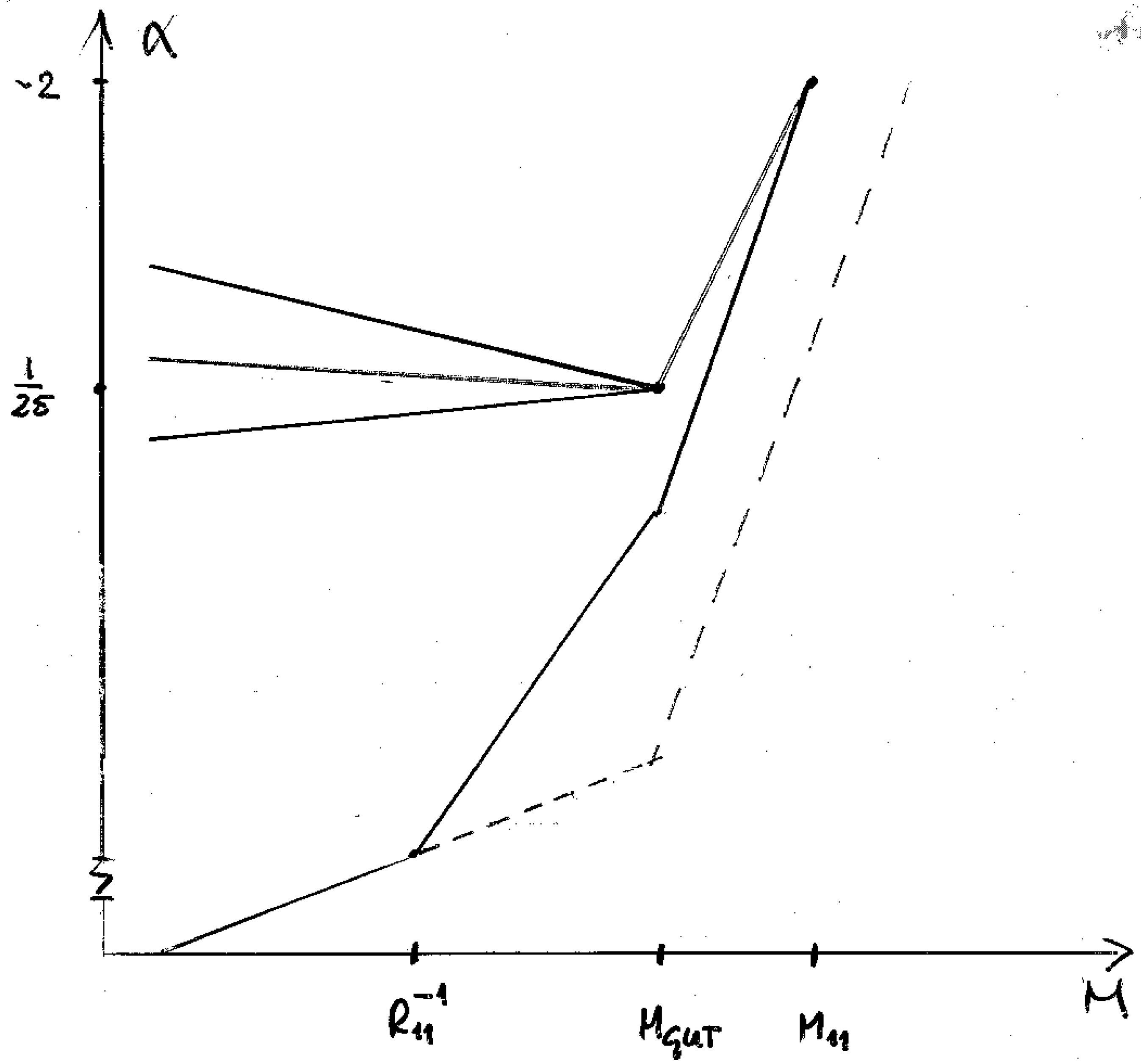
$M_{GUT} \approx 3 \times 10^{16}\ GeV \qquad \alpha_{GUT} \approx \frac{1}{25}$

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

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

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

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



$M_{11} \approx 2\, M_{GUT}$ $\alpha_{string}(M_{11}) \approx O(1)$

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

quantum gravity relevant already at M_{GUT}

→ LARGE EXTRA DIMENSIONS

$R =$ Millimeter !?

→ $M_{STRING} \approx$ 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 G_2-HOLONOMY)

* WARPED COMPACTIFICATIONS
  (COSMOLOGICAL CONSTANT?)

* "FIELD THEORETIC" ORBIFOLDS
  → BOTTOM-UP APPROACH

* CONSISTENCY CONDITIONS
  FROM STRING THEORY
  (LOCALIZED ANOMALIES)