

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

STRING PHENOMONOLOGY

Lecture II

**H-P. NILLES
University of Bonn
Bonn
GERMANY**

SUSY IN $d=4$

CHIRAL MULTIPLETS $\phi_i = (\varphi_i, \psi_i, F_i)$

VECTOR MULTIPLET

$$V \sim (\dots, V^\mu, \lambda, D)$$

POTENTIAL $V = \frac{1}{2} D^2 + \sum_i F_i F_i^*$

SUSY BROKEN

$$\iff \langle F \rangle \text{ OR } \langle D \rangle \neq 0$$

ALGEBRA

$$[\epsilon^\alpha Q_\alpha, \bar{Q}^{\dot{\alpha}} \bar{\epsilon}_{\dot{\alpha}}] \sim \sigma_\mu P^\mu$$

LOCAL SUSY

\Longleftrightarrow SUPERGRAVITY

$$[E(x)Q, \bar{Q} \bar{E}(x)] = E(x) \sigma_\mu \bar{E}(x) P^\mu$$

SPACE-TIME TRANSLATION THAT
DIFFERS FROM POINT TO POINT

GAUGE PARTICLE ψ_μ^α

SPIN $3/2$ "GRAVITINO"

AS PARTNER OF GRAVITON

$$\delta \psi_\mu^\alpha = \partial_\mu E^\alpha(x) \quad \text{AS LOCAL VARIATION}$$

GRAVITY IS "CONSEQUENCE"
OF LOCAL SUSY

SUSY IN $d=4$

Kähler potential $K(\phi^*, \phi)$

$\phi \hat{=} (\varphi, \psi, F)$ is chiral superfield

+ Superspotential $W(\phi)$

describe kinetic terms and
potential of chiral superfields

gauge kinetic function $f_{AB}(\phi)$

(in $f_{AB}(\phi) W_\alpha^A W^{\alpha B}$)

$$[\langle \text{Re } f(\phi) \rangle \hat{=} 1/g^2]$$

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

KINETIC TERMS $\zeta_i^j \partial_\mu \phi^i \partial^\mu \phi_j^*$

KÄHLER METRIC $\zeta_i^j = \frac{\partial^2 \zeta}{\partial \phi^i \partial \phi_j^*}$

POTENTIAL

$$V = e^\zeta \left[\zeta_\kappa (\zeta^{-1})^\kappa_\ell \zeta^\ell - 3 \right]$$

$$+ \frac{1}{2} f_{AB}^{-1} D^A D^B$$

GAUGE KINETIC TERMS

$$f_{AB}(\phi) W^A W^B$$

$$[\text{Re } f(\phi)]^{-1} \sim g^2$$

SUSY BROKEN IF $\langle F \rangle$ OR $\langle D \rangle \neq 0$

SUPERHIGGS EFFECT

$$M_{3/2} \sim \frac{\langle F^2 \rangle}{M_{\text{Planck}}} \quad \text{GRAVITINO MASS}$$

(HIDDEN SECTOR SUPERGRAVITY)

$$V \sim [1/2 F^2 - 3e^G] + \frac{1}{2} f^{-1} D^2$$

$$F_i = \exp(G/2) (\eta^{-1})^j_i \eta_j + \frac{1}{4} \left[\frac{\partial}{\partial \phi_k} f_{AB} \right] (\eta^{-1})^k_i \lambda^\alpha \lambda^\beta + \dots$$

SUSINO CONDENSATE $\langle \lambda \lambda \rangle = \Lambda^3$

BREAKS SUSY IF $\frac{\partial f}{\partial \phi} \neq 0$!

$$\langle F \rangle \sim \frac{\Lambda^3}{M_{\text{Pl}}} \longrightarrow M_{3/2} \equiv \frac{\Lambda^3}{M_{\text{Pl}}^2}$$

SUSY IN $d=11$

$$\frac{1}{2\kappa^2} \int d^{11}x \sqrt{-g} \left[R - \frac{1}{2 \cdot 4!} \zeta^2 \right] -$$

$$- \frac{1}{12\kappa^2} \int C \wedge \zeta \wedge \zeta + \text{FERMIONS}$$

C_{MNO} IS 3-FORM

GAUGE POTENTIAL AND

$\zeta = dC$ IS 4-FORM

FIELD STRENGTH

$d=11$ IS HIGHEST DIMENSION IN

WHICH SUSY POSSIBLE (SPIN ≤ 2)

GAUGE GROUP?

SUSRA IN $d=10$

(ALLOWS ALSO "NORMAL" GAUGE FIELDS)

SUPERGRAVITY MULTIPLY

$$(g_{MN}, \not{D}_{M\alpha}, B_{MN}, \lambda_\alpha, \varphi)$$

$$M, N = (0, \dots, 9), \quad \mu (0, \dots, 3), \quad m (4, \dots, 9)$$

$\alpha = 1, \dots, 8$ is a Majorana-Weyl spinor.

$$\text{GAUGE MULTIPLY } (A_M^A, \chi_\alpha^A)$$

$$A = 1, \dots, 496 \quad (\text{ADJOINT OF } E_8 \times E_8 \text{ OR } SO(32))$$

$$\begin{aligned} \mathcal{L}_{10} = & -\frac{1}{2} R - \frac{i}{2} \not{D}_M \Gamma^{MNP} \not{D}_N \not{D}_P + \\ & + \frac{9}{16} \left(\frac{\partial_m \varphi}{\varphi} \right)^2 + \frac{3}{4} \varphi^{-3/2} H_{MNP} H^{MNP} + \\ & \dots - \frac{1}{4} \varphi^{-3/4} F_{MN} F^{MN} + \dots \end{aligned}$$

$$F_{MN}^A = \frac{1}{2} \partial_{[M} A_{N]}^A + f^{ABC} A_M^B A_N^C$$

($F \hat{=} dA + A^2$)

IS NONABELIAN GAUGE FIELD STRENGTH

ϕ IS CALLED "DILATON"

$$H_{MNP} = \partial_{[M} B_{NP]} + \omega_{MNP}^{YM}$$

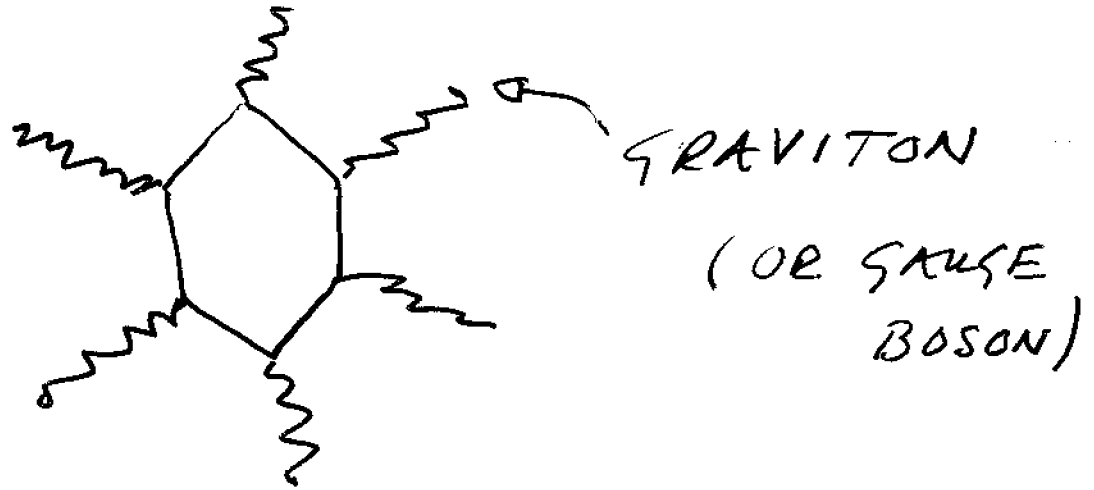
$$\omega^{YM} = \text{Tr} \left(AF - \frac{2}{3} A^3 \right)$$

IS REQUIRED BY SUSY

(CHERN-SIMONS TERM)

→ B_{NP} HAS TO TRANSFORM
NONTRIVIALY UNDER THE
 GAUGE GROUP!

PROBLEM: ANOMALIES



— NEED 496 GAUGE BOSONS

— GAUGE ANOMALIES

STRING OK IF GAUGE

GROUP IS

$SO(32)$

OR $E_8 \times E_8$

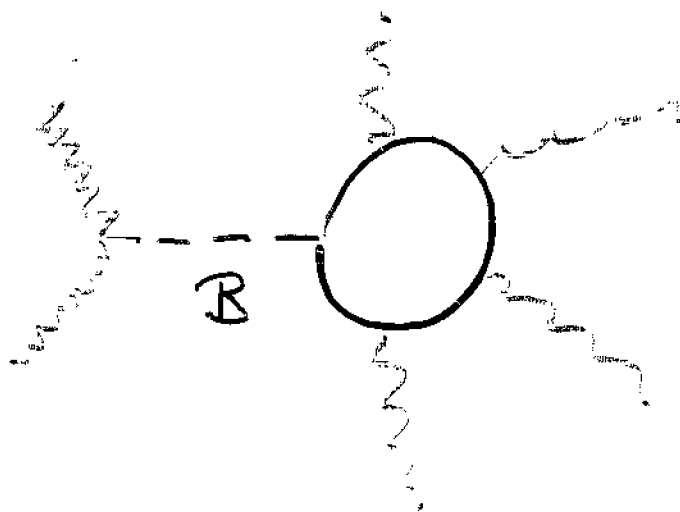
FIELD THEORY PICTURE:

GREEN-SCHWARZ MECHANISM

$$H = dB + \omega^M - \omega^L$$

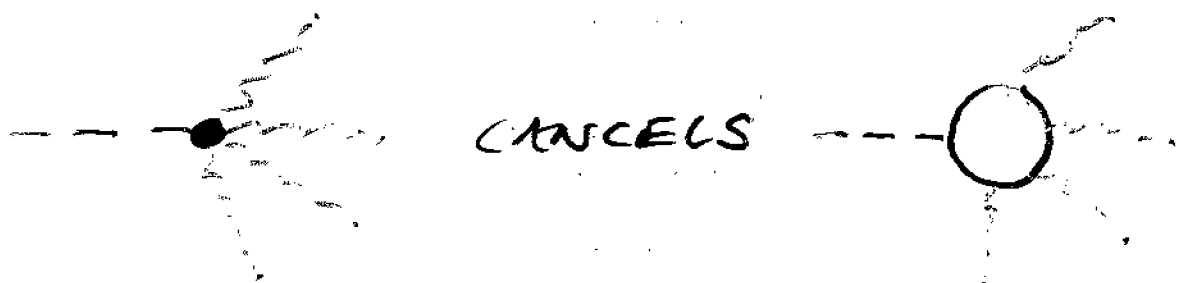
$$\text{where } \omega^L = \text{Tr} \left(\gamma R - \frac{2}{3} \gamma^3 \right)$$

(γ is SPIN CONNECTION)



→ SS - COUNTERTERMS BX_8

$$\text{WITH } X_8 = \frac{1}{8} \text{Tr} F^4 + \frac{1}{4} (\text{Tr} F^2)^2 + \text{Tr} R^4 \dots$$




WHAT IS DIFFERENCE BETWEEN

TYPE I AND HETEROTIC?

(ESPECIALLY FOR $SO(32)$)

TYPE I:  AND

HETEROTIC: ONLY 

TYPE I:
$$L_{eff}^I = e \left[\exp(-2\phi_I) \frac{4}{(\alpha')^4} R + \exp(-\phi_I) \frac{1}{(\alpha')^3} F^2 + \dots \right]$$

HETEROTIC: (UNIVERSAL DILATION)

H:
$$L_{eff}^H = e \cdot \exp(-2\phi_H) \left[\frac{4}{(\alpha')^4} R + \frac{1}{(\alpha')^3} F^2 + \dots \right]$$

THUS HETEROTIC THEORY MAKES

A PREDICTION:

$$S_{\text{NEWTON}} = \frac{e^{2\phi_H} (\alpha')^4}{64\pi}$$

$$\alpha_{\text{GUT}} = \frac{g^2}{4\pi} = \frac{e^{2\phi_H} (\alpha')^3}{16\pi}$$

$$M_{\text{STRINGS}}^2 = 1/\alpha'$$

THUS

$$\boxed{S_N = \frac{\alpha_{\text{GUT}} \alpha'}{4}}$$

IN TYPE I WE WOULD SET

$$S_N = \frac{e^{\phi_I} \alpha_{\text{GUT}} \alpha'}{4}$$

KALUZA-KLEIN COMPACTIFICATION

$d=5$ GRAVITY ON CIRCLE

$$g_{MN} = \begin{pmatrix} g_{\mu\nu} & A_{\mu 5} \\ A_{5\nu} & g_{55} \end{pmatrix}$$

$g_{\mu\nu}$ METRIC IN $d=4$
 $\mu, \nu = 0, 1, 2, 3$

$A_{\mu 5}$ IS U(1) GAUGE BOSON

g_{55} IS SCALAR FIELD

(RADIUS OF 5th DIMENSION,
RADION)

THE ROAD TO $d=4$

$$g_{MN} = \begin{pmatrix} e^{-3\sigma} \hat{g}_{\mu\nu} & \\ \hline & e^{\sigma} g_{mn} \end{pmatrix}$$

IN CASE OF TORUS

$$\int d^6x \sqrt{g_6} = R_c^6 \sim \frac{1}{M_c^6}$$

$\exp(\sigma)$ defines radius of compactification

($\sigma \stackrel{\wedge}{=} \text{"OVERALL RADIUS"}$)

6-TORUS \rightarrow $N=4$ SUSY in $d=4$

$$SO(1,9) \rightarrow SO(1,3) \times SO(6)$$

$$SO(8) \rightarrow SO(2) \times SO(6)$$

$$8_{\text{SPINOR}} \rightarrow (2, 4)$$

$SU(3)$ - HOLONOMY TO OBTAIN
 $N=1$ SUSY IN $d=4$

$$SU(3) \subset SO(6)$$

$$3 + \bar{3} = 6$$

$$1 + 3 = 4 \leftarrow \text{GRAVITINI}$$

COMPACTIFICATION WITH NONTRIVIAL
HOLONOMY REQUIRES VEV OF "RIEMANN"

$$\text{Tr } R^2 \neq 0$$

$$H = dB + \omega^{\text{YM}} - \omega^{\text{L}}$$

$$\rightarrow dH = \text{Tr } F^2 - \text{Tr } R^2$$

$$0 = \int_{C_4} dH = \int_{C_4} (\text{Tr } F^2 - \text{Tr } R^2)$$

$$\Rightarrow \text{Tr } F^2 \neq 0 \quad \text{AND GAUGE GROUP
BROKEN}$$

(LEVEL MATCHING COND.)