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SUPERSYMMETRY AND SUPERGRAVITY

GRAND UNIFICATION

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SUPERSYMMETRY AND SUPERGRAVITY GRAND UNIFICATION

1. INTRODUCTION

For some time, particle theorists have attempted to build models that go beyond the Standard Model. The great success of the S.M. and lack of any experimental evidence of breakdown of the SM, has caused the theoretical analyses to circle around the theoretical insufficiences of the SM. One of the major problems is related to the quadratic divergence in the Higgs mass self energy. Thus in the SM model:

$$m_H^2 = m_0^2 + c\,\frac{\tilde{\alpha}}{4\pi}\,\Lambda^2 \quad ; \quad \Lambda = \text{cutoff},\ \tilde{\alpha} = \text{coupling const.}$$

Thus as Λ increases, m_H^2 increases and since m_H sets the electroweak scale, M_{EW}, then M_{EW} is driven close to the large scale Λ. Alternately, if one choses m_0 to cancel the loop contribution one has a fine tuning problem:

For example: if $\Lambda = M_{GUT} \approx 10^{14}$ GeV, and $m_H \approx M_Z$ then one must fine tune m_0^2 to

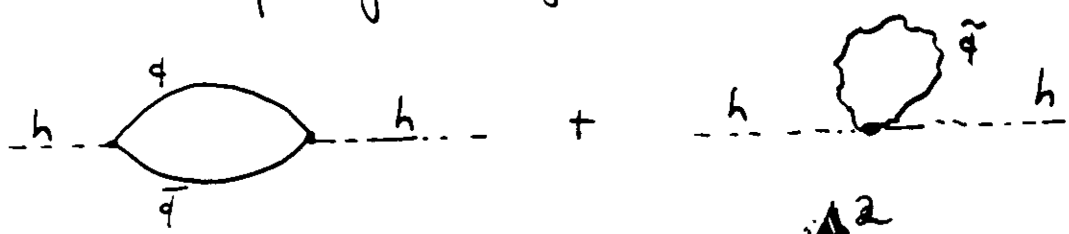
<u>24 decimal places</u>

and trouble already begins for Λ in multi-TeV region.

Two suggestions exist to resolve this problem:

(1) Theories where quadratic divergences cancel:

Supersymmetry – bose-fermi symmetry



q = quark
$\tilde{q}$ = squark

$$\Lambda^2 \longrightarrow (m_{\tilde{q}}^2 - m_q^2) \ln \frac{\Lambda^2}{m_{\tilde{q}}^2}$$

and to avoid fine tuning require

$$m_{\tilde{q}} \lesssim 1 \text{ TeV}$$

(2) Theories where Higgs is a bound state: Here Λ is scale at which Higgs decomposes and need $\Lambda \lesssim 1$ TeV.

(a) Technicolor models – new strong gauge forces at TeV scale

(b) $\langle t\bar{t}\rangle$ Condensate models – $SU(2)\times U(1)$ broken by condensate formed from new forces

(c) Preon models

Last year it was shown that the LEP data was consistent with the combined ideas of supersymmetry and grand unification. This was the first indication that any of these new may have validity.

What we will discuss in these lectures is what additional experimental predictions supersymmetric grand unification to further test the theory. The "minimal" supergravity GUT model turns out to be a highly constrained system and particularly when one includes the constraints of proton decay one can start making strong prediction concerning the masses of the SUSY particles

Subjects To Be Discussed

1) Global SUSY
2) Unification of couplings
3) Supergravity GUT models
4) Radiative breaking of $SU(2) \times U(1)$
5) SUSY mass formulae
6) Proton decay in supergravity GUTS
7) SUSY mass predictions
8) Loop corrections to radiative breaking
9) Fine tuning
10) Quark masses
11) Cosmological constraints

2. GLOBAL SUSY MODELS

We review briefly basic properties of global supersymmetry.

In order to build phenomenologically viable models, one needs two types of SUSY (massless) multiplets:

Vector Multiplet: $J=1$ vector boson, $V_\mu(x)$
$J=\frac{1}{2}$ Majorana gaugino, $\lambda(x)$

Chiral Multiplet: $J=0$ complex scalar, $z(x)$
$J=\frac{1}{2}$ Weyl L-spinor, $\chi(x)$

The vector multiplets account for the gauge particles while the chiral multiplets account for the matter.

Thus for the SM with gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ one has the following particles:

Vector Multiplets

$J=1$	$J=\frac{1}{2}$
g_μ^a, $a=1\ldots8$ gluons	λ^a, $a=1\ldots8$; $SU(3)_c$ gluinos ($\tilde{g}$)
B_μ^α, B_μ^Y, $\alpha=1,2,3$	λ^α, λ^Y, $\alpha=1,2,3$; $SU(2)_L \times U(1)_Y$ gauginos

Chiral Multiplets

$J=\frac{1}{2}$	$J=0$
$\begin{pmatrix} u_{iL} \\ d_{iL} \end{pmatrix}$; u_{iR}, d_{iR} $i=1,2,3$ generation index	$\begin{pmatrix} \tilde{u}_{iL} \\ \hat{d}_{iL} \end{pmatrix}$; $\tilde{u}_{iR}$, $\hat{d}_{iR}$ squarks
$\begin{pmatrix} \nu_{iL} \\ e_{iL} \end{pmatrix}$; e_{iR}	$\begin{pmatrix} \tilde{\nu}_{iL} \\ \tilde{e}_{iL} \end{pmatrix}$; $\tilde{e}_{iR}$ sleptons
$\hat{H}_1 = \begin{pmatrix} \tilde{H}_1^0 \\ \tilde{H}_1^- \end{pmatrix}$; $\tilde{H}_2 = \begin{pmatrix} \tilde{H}_2^+ \\ \tilde{H}_2^0 \end{pmatrix}$ Higgsinos	$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$; $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$ Higgs

Dynamics

SUSY dynamics is governed by gauge interactions and a superpotential W for the Yukawa interactions:

$$W = W(z_a) \quad ; \quad \{z_a\} = \text{scalar fields}$$

<u>Gauge interactions</u>:

Aside from the usual gauge interactions of the vector bosons, there are

(i) Gaugino interactions (λ^i = gauginos)

$$\mathcal{L}_\lambda = -i\sqrt{2}\, g_i \bar{\lambda}^i z_b^+ (T^i)_{ba} \chi^a + h.c.$$

T^i = group generator
g_i = coupling constant
$\{z_a, \chi^a\}$ = chiral multiplet

(ii) D terms in effective potential:

$$V_D = \tfrac{1}{2} g_i^2 D_i D_i^+ \quad ; \quad D_i = z_a^+ (T^i)_{ab} z_b$$

<u>Yukawa</u> <u>interactions</u> (W = superpotential)

(i) Fermi interactions

$$\mathcal{L}_Y = -\frac{1}{2} \sum_{a,b} \left(\overline{\chi^{ac}} \frac{\partial^2 W}{\partial z_a \partial z_b} \chi^b + h.c. \right)$$

$\{z_a, \chi^a\}$ = chiral multiplet

(ii) Bose interactions

$$V_Y = \sum_a \left| \frac{\partial W}{\partial z_a} \right|^2 = F \text{ term}$$

The total effective potential is then

$$V = V_Y + V_D + V_{SB}$$

V_{SB} = SUSY symmetry breaking

For the SM the general form of W is

$$W = W^{(3)} + \mu H_1 H_2$$

with $W^{(3)} = \lambda^{(u)}_{ij} q_i H_2 u^c_j + \lambda^{(d)}_{ij} q_i H_1 d^c_j + \lambda^{(e)}_{ij} l_i H_1 e^c_j$

$q_i = \binom{u_i}{d_i}$; $l_i = \binom{\nu_i}{e_i}$

Thus: $\langle H_2 \rangle \Rightarrow$ u-quark masses

$\langle H_1 \rangle \Rightarrow$ d-quark and lepton masses

$\tan\beta \equiv \langle H_2\rangle / \langle H_1\rangle$

After $SU(2)\times U(1)$ breaking:

(i) Higgsino and $SU(2)\times U(1)$ gauginos mix to form:

Charginos (Winos): 2 charged spin $\frac{1}{2}$ (Dirac) spinors

$$\tilde{W}_i \; ; \; i = 1,2$$

Neutralinos (Zinos): 4 neutral spin ½ Majorana spinors

$$\tilde{Z}_i \; ; \; i = 1,2,3,4$$

and we will label states such that $m_i < m_j$ for $i<j$.

(ii) $W^\pm$ and Z^0 grow mass leaving 3 neutral and 1 charged Higgs:

h^0, H^0	CP even
A^0	CP odd
$H^\pm$	charged

where h^0 resembles most the SM Higgs.

Thus there are 31 new SUSY particles:

12	+ 9	+ 2	+ 4	+ 1	+ 3	= 31
squarks	sleptons	Winos	Zinos	gluino	Higgs	

3. MSSM

In order to proceed further, one needs to know what the symmetry breaking terms are:

$$V_{SB} = ?$$

In global supersymmetry no physically acceptable way of producing spontaneous breaking of supersymmetry is known. One can, on purely phenomenological grounds, add in symmetry breaking terms that are "soft breaking" i.e. break supersymmetry but still maintain the cancellation of the quadratic divergences. The general form of V_{SB} that is soft breaking is

$$V_{SB} = m^2_{ab}\, z_a^* z_b + \left[A^{(u)}_{ij} \lambda^{(u)}_{ij} q_i H_2 u^c_j + A^{(d)}_{ij} \lambda^{(d)}_{ij} q_i H_1 d^c_j + A^{(e)}_{ij} \lambda^{(e)}_{ij} l_i H_1 e^c_j + B\mu H_1 H_2 + h.c. \right] + \tilde{m}_i \bar{\lambda}^i \lambda^i$$

where

m^2_{ab} = scalar mass matrix

$A^{(u)}_{ij}$, $A^{(d)}_{ij}$, $A^{(e)}_{ij}$, B = Polonyi constants

$\tilde{m}_i$ = gaugino Majorana masses

For an $SU(3) \times SU(2) \times U(1)$ invariant theory V_{SB} depends on 137 parameters (or eve 87 soft breaking parameters if one assumes all the parameters real)! While many can be eliminated on phenomenological grounds a theory of this type clearly has no predictive value. Instead what is adopted is the "Minimal Supersymmetric Standard Model" - MSSM defined as follows:

(i) Particle content: supersymmetrized Standard Model (no "exotic" extra particles)

(ii) All squarks (except perhaps t-squarks) degenerate
All sleptons degenerate

(iii) Gaugino masses $\tilde{m}_i$, $i=1,2,3$ for $U(1)_Y$, $SU(2)_L$, $SU(3)_C$ scale by coupling constants

$$\tilde{m}_1 : \tilde{m}_2 : \tilde{m}_3 = \alpha_1 : \alpha_2 : \alpha_3$$

(iv) Polonyi terms diagonal

The assumptions reduce the number of free parameters but appear somewhat arbitrary. We will see, however, that the MSSM is an approximation to low energy limit of supergravity GUT models.

Experimental Bounds on SUSY Masses

All the phenomenological analysis of data leading to limits on SUSY particle masses have been done within framework of MSSM. Current bounds are following

Gluino: $m_{\tilde{g}} \gtrsim 130$ GeV [CDF; Baer et al]

Squark: $m_{\tilde{q}} \gtrsim 150$ GeV [CDF; Baer et al]

except for lightest t-squark $\tilde{t}_1$:

$m_{\tilde{t}_1} > 45$ GeV [LEP]

Sleptons: $m_{\tilde{e}}, m_{\tilde{\mu}}, m_{\tilde{\tau}} > 45$ GeV [LEP]

$m_{\tilde{\nu}} > 32$ GeV [LEP]

Charginos: $m_{\tilde{W}_1} > 45$ GeV [LEP]

Neutralinos: $m_{\tilde{Z}_1} > 20$ GeV

$m_{\tilde{Z}_2} > 45$ GeV; $\tan\beta > 3$ [LEP]

$\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$

Higgs (SUSY): $m_h > 43$ GeV

$m_A > 20-44$ GeV

$m_{H^\pm} > 42$ GeV [LEP]

The bound on the t-quark mass is

$m_t \gtrsim 90$ GeV [CDF]

A detailed fit to all data assuming SM gives

$m_t = 130^{+25}_{-28}$ GeV for $m_{Higgs} = M_Z$

1.4 GeV $< m_H < 160$ GeV, 68% CL, $m_t = 130$ GeV [Ellis, Fogli, Lisi]

An important question is how much further will searches for SUSY particles be able to go in near future:

LEP 2: m_h up to ≈ 95 GeV

$m_{\tilde{W}_1}$ up to ≈ 100 GeV

Tevatron: $m_{\tilde{q}}$ up to ≈ 200 GeV

$m_{\tilde{t}_1}$ up to ≈ 100 GeV

$m_{\tilde{W}_1}$ up to ≈ 70 GeV

(with data sample of 100 pb^{-1})

4. UNIFICATION OF COUPLINGS

We briefly review analyses of LEP data [Langacker, Ellis et al, Amaldi et al.] indicating grand unification of gauge coupling constants.

The coupling constants α_1, α_2 and α_3 have now been reasonably well determined at electroweak scale M_Z:

$$\alpha_1(M_Z) \equiv \tfrac{5}{3}\alpha_Y = 0.016887 \pm 0.000040$$

$$\alpha_2(M_Z) = 0.03322 \pm 0.00025$$

$$\alpha_3(M_Z) = 0.113 \pm 0.005$$

(Only the value of $\alpha_3(M_Z)$ has some doubt.)

Using the 2-loop RG eqns. can determine $\alpha_i(\mu)$ at scale μ to see whether they intersect at $\mu = M_G$ the GUT scale:

$$\mu \frac{d}{d\mu}\alpha_i(\mu) = \frac{1}{2\pi}\left[b_i + \frac{1}{4\pi}\sum_j b_{ij}\,\alpha_j(\mu)\right]\alpha_i^2(\mu)$$

$$b_i = \begin{pmatrix} 0 \\ -22/3 \\ -11 \end{pmatrix} + N_{Fam}\begin{pmatrix} 4/3 \\ 4/3 \\ 4/3 \end{pmatrix} + N_{Higgs}\begin{pmatrix} 1/10 \\ 1/6 \\ 0 \end{pmatrix}; \quad SM$$

$$b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_{Fam}\begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_{Higgs}\begin{pmatrix} 3/10 \\ 1/2 \\ 0 \end{pmatrix}; \quad SUSY$$

and known expressions for b_{ij}.

Experiment	$\alpha_3(M_Z)$
ALEPH	0.125 ± 0.005
DELPHI	0.113 ± 0.007
L3	0.125 ± 0.009
OPAL	0.123 ± 0.006
J/Ψ	0.108 ± 0.005
Υ	0.109 ± 0.005
Deep Inelastic	0.109 ± 0.005

For SM, grand unification fails by over 7 std. For SUSY case with 2 Higgs doublets, grand unification occurs. If one makes approximation that all SUSY particles have common mass M_S then for 2 Higgs doublets:

$$M_G = 10^{16.1 \pm 0.3}\,\mathrm{GeV}; \quad \alpha_G^{-1} = 25.7 \pm 1.7\ ; \quad M_S = 10^{2.5 \pm 1}\,\mathrm{GeV}$$

[Amaldi et al]

errors coming mainly from α_3. Further the errors in M_G and M_S are anti-correllated:

$$M_G \cong 10^{16.1}\,\mathrm{GeV}\left[\,10^{2.5}/M_S\,(\mathrm{GeV})\right]^{0.3}$$

Finally only 2 Higgs doublets leads to acceptable theory (e.g. 4 doublets has too small M_G and hence too large p-decay).

Standard (Non-SUSY) SU(5)
1 Higgs doublet

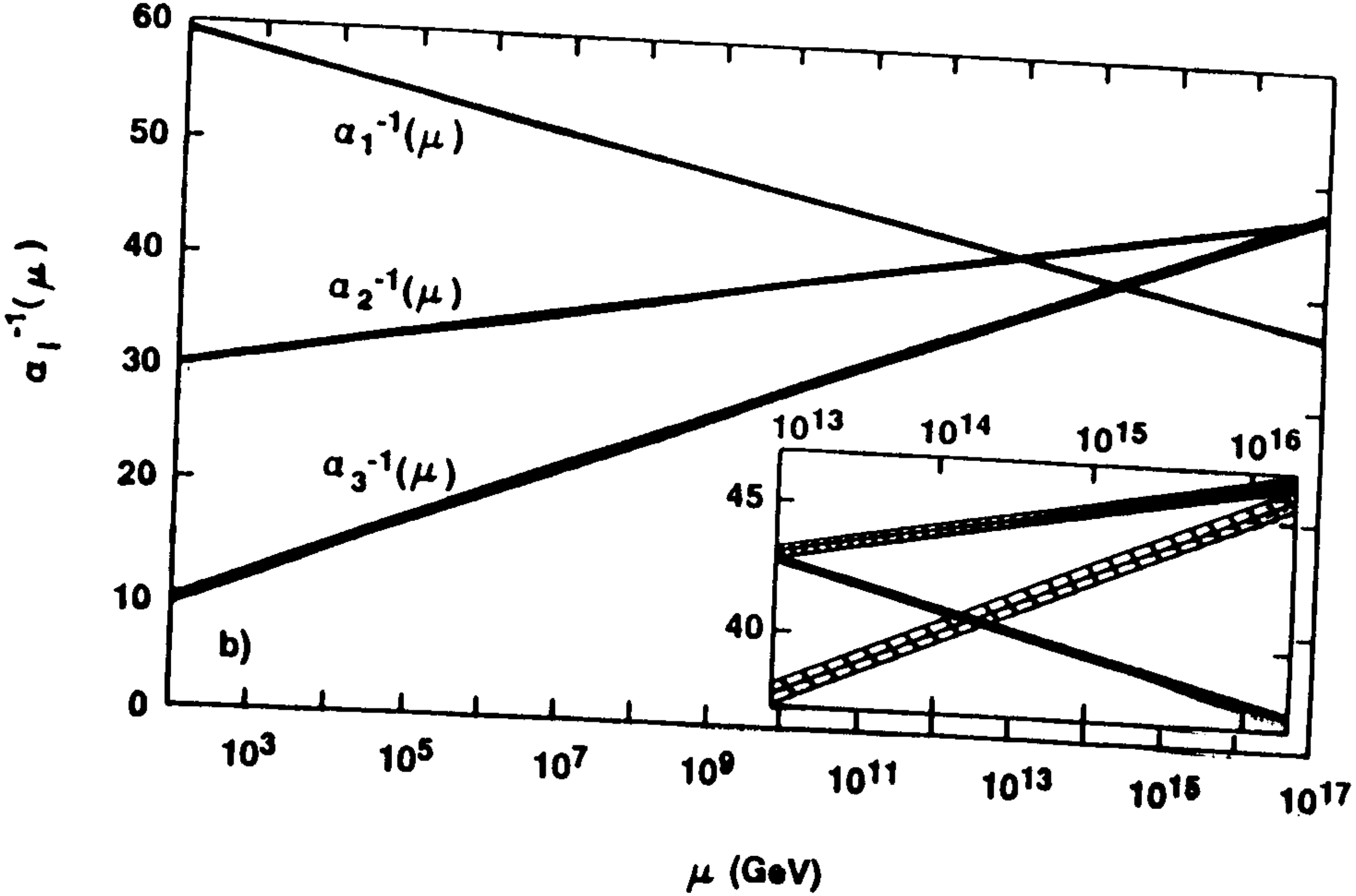
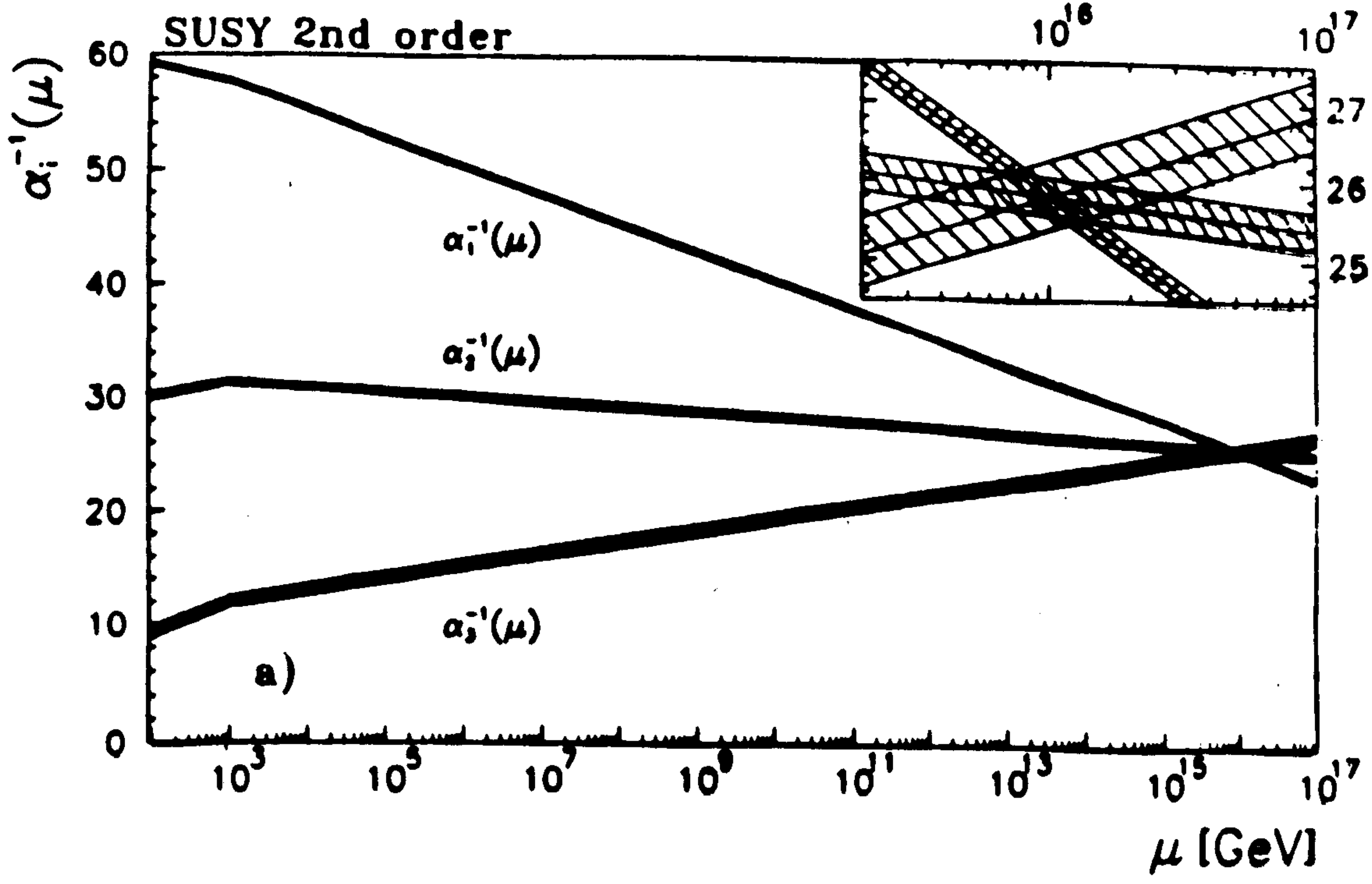


Figure 1

Amaldi et al

1 Pair of Higgs Doublets



Amaldi et al

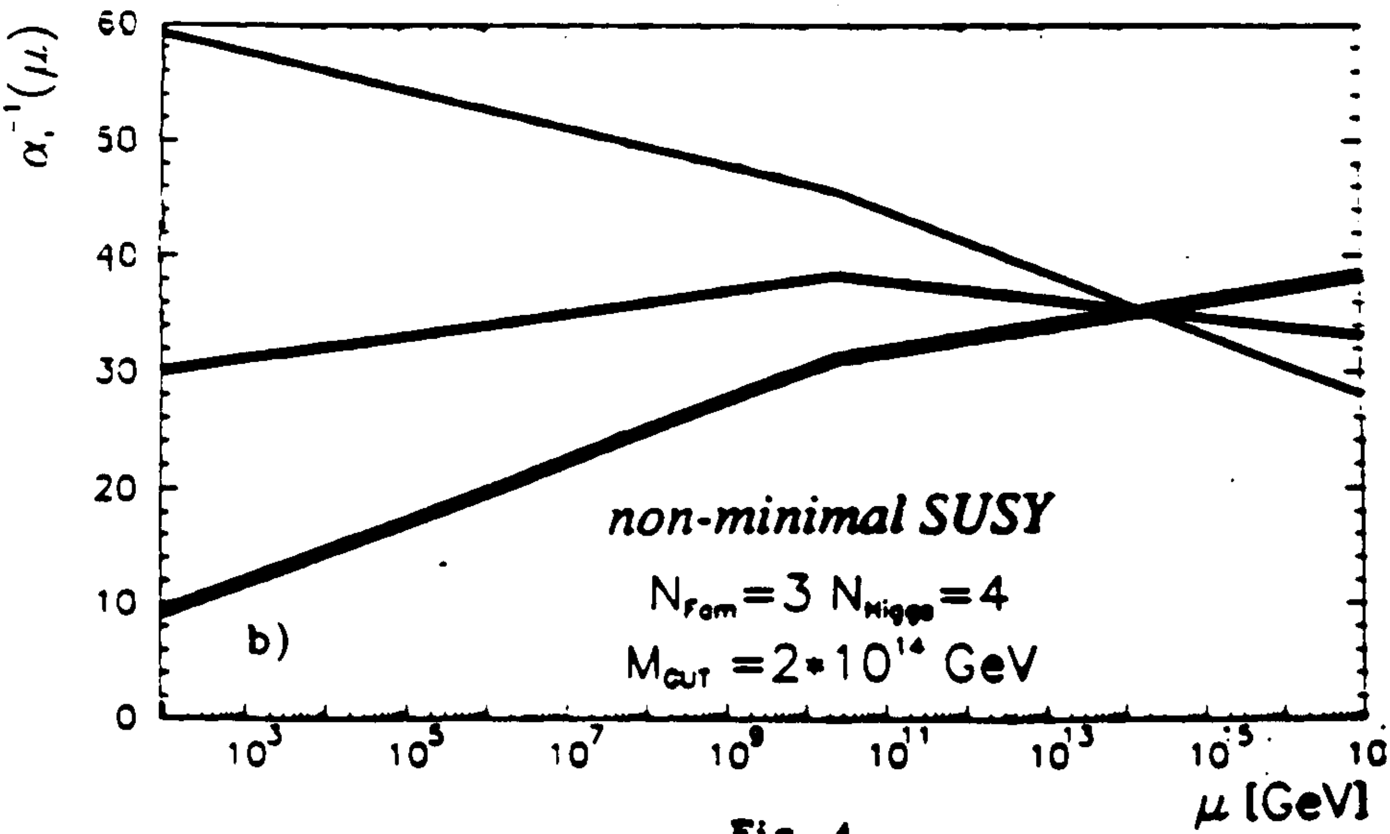


Fig. 4

Amaldi et al

Comments:

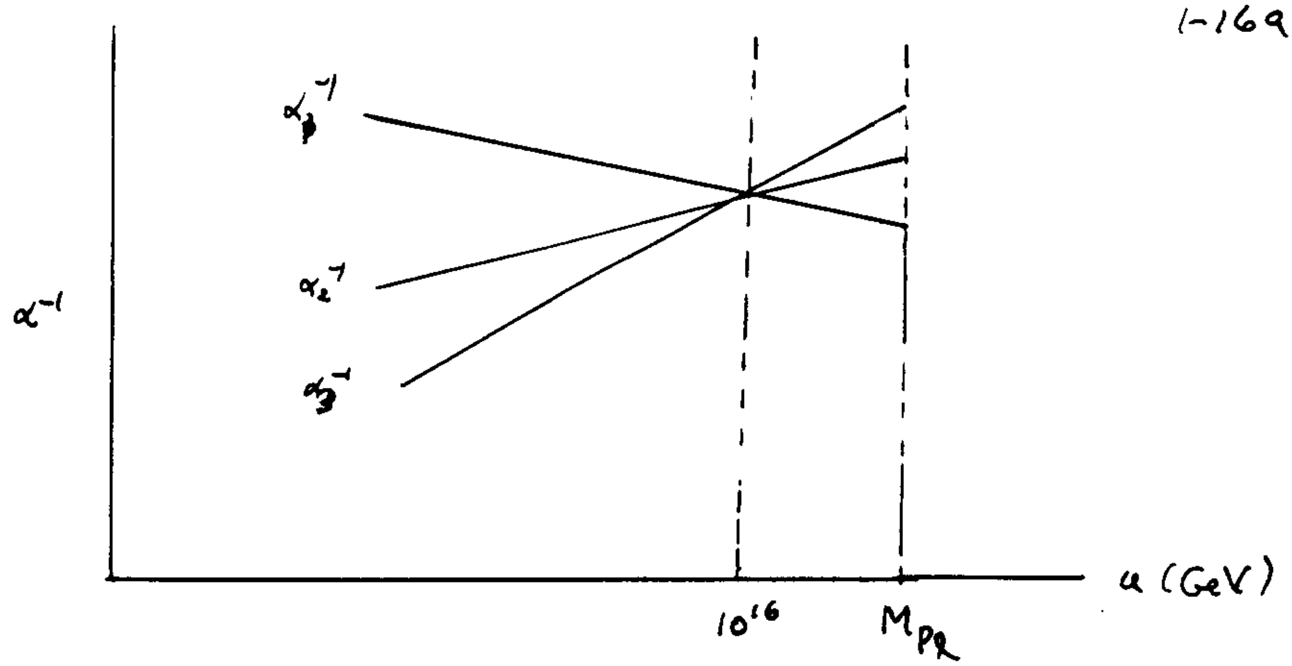
(1) All SUSY particles not degenerate at single mass M_S, and one should take into account mass splitting. Further, if one believes result implies grand unification, there are similar thresholds in vacinity of M_G which can modify results. Those questions cannot be treated within framework of global SUSY at low energy, as this has no theory of SUSY breaking (which produces SUSY mass spectrum) nor of GUT physis. Will discuss later how to deal with this in framework of supergravity GUTs. However, appears to be only 1 std. effects.

(2) Models have been proposed without supersymmetry that achieve grand unification [Langacker and Luo; Amaldi, de Boer, Frampton, Fürstenau, Liu; M.K. Gaillard]. However, these models are often less predictive (extra intermediate thresholds adjusted

to fit data) but more serious they still have the terrible problem of fine tuning to 25 decimal places.

(3) The natural unification scale for string theory is $M_{Pl} = 2.4 \times 10^{18}$ which is much higher. Thus string theory has a problem. Possible explanation is that string theory populates the dessert with additional "exotic" particles which delay unification. Examples of this have been suggested for flipped $SU(5)$ case [Ellis, Lopez, Nanopoulos] and conceivable that the E_6 singlets will do same for Calabi-Yau strings [J. Wu]. However, one again loses predictiveness as one has to adjust the additional thresholds to achieve grand unification.

An alternate suggestion is to assume there are no thresholds before the Planck scale, and that the meeting of the three coupling constants is accidental



Then if there are sufficient strong thresholds at M_{Pl} (as might be in orbifold compactifications) unification might be achieved by threshold effects there [Ibañez, Lüst, Ross]. However, no models that can do this have been found.

5. Supergravity GUTS

[Chamseddine, R.A., Nath; Ibañez]

In order to have a theory where supersymmetry breaks spontaneously, necessary to promote global SUSY to local symmetry i.e. supergravity. Only $N=1$ supergravity interacts with chiral matter. The $N=1$ supergravity interacting with chiral and vector multiplet matter has a Lagrangian which depends on 3 functions:

$W(z_i)$ = superpotential; $\{z_i\}$ = scalar fields

$d(z_i, z_i^*)$ = Kahler potential;

$f_{\alpha\beta}(z_i, z_i^*)$ = gauge kinetic fnc; α, β = gauge indices

Actually d and W enter in a single combination:

$$\mathcal{G} = -\kappa^2 d - \ln[\kappa^6 W W^*] \; ; \qquad \kappa = \frac{1}{M_{Pl}}$$

$$M_{Pl} = 2.4 \times 10^{18}\ \text{GeV}$$

Kahler metric is defined

$$g_{ij} \equiv d_{,ij^*} = \frac{\partial^2 d}{\partial z_i \partial z_j^*} \Longrightarrow \delta_{ij} \text{ for } d = z_i z_i^*$$

The Lagrangian is very complicated but there are three important terms:

(1) Effective Potential

$$V = \frac{1}{\kappa^4} e^{-\mathcal{G}} \left[-\mathcal{G}^{-1}_{ij^*} \mathcal{G}_{,i} \mathcal{G}^*_{,j} - 3 \right]$$

$$+ \underbrace{\frac{g^2}{2} (\mathrm{Re}\, f^{-1}_{\alpha\beta}) D_\alpha D_\beta}_{V_D} \qquad ; \; D_\alpha = -\frac{1}{\kappa^2} \mathcal{G}_{,i} (T^\alpha)_{ij} z_j$$

or

$$V = e^{\kappa d} \left[d^{-1}_{ij^*} \underbrace{\left(\frac{\partial W}{\partial z_i} + \kappa^2 d_{,i} W \right) \left(\frac{\partial W}{\partial z_j}^* + \kappa^2 d^*_{,j} W^* \right)}_{\left| \frac{\partial W}{\partial z} \right|^2 + \cdots} - 3\kappa^2 |W|^2 \right]$$

$$+ V_D \qquad \Big\} \; -\frac{1}{\kappa^2} \mathcal{G}_{,i} \sim d_{,i} \sim z_i^*$$

(2) Gauge Kinetic Term

$$-\frac{1}{4} \mathrm{Re}\, f_{\alpha\beta} F^\alpha_{\mu\nu} F^\beta_{\mu\nu} \qquad ; \qquad f_{\alpha\beta} = \delta_{\alpha\beta} (1 + \kappa z_i + \cdots) + \cdots$$

(3) Gluino Mass Term

$$\frac{1}{4} e^{-\mathcal{G}/2} \underbrace{(\mathcal{G}^{-1})_{ij^*} \mathcal{G}_{,j^*} f^*_{\alpha\beta,i}}_{\sim m_{1/2}} \bar{\lambda}^\alpha \lambda^\beta$$

Supersymmetry Breaking

Since V is no longer positive-definite, (as in global SUSY) spontaneous breaking of supersymmetry is possible by a super Higgs mechanism.

Let $\{z_i\} = \underbrace{\{z_a\}}_{\text{matter}} + \underbrace{z}_{\text{superHiggs}}$

The basic point is to do the breaking without destroying the gauge hierarchy. Require

(i) z be gauge singlet

(ii) $\mathcal{W}(z_i) = W(z_a) + W_h(z)$

z represents the "hidden sector" since it can interact with the matter fields only gravitationally. Simple choices, e.g

$$W_h = m^2(z+B) \qquad \text{[Polonyi]}$$

will cause z to grow a VEV when V is minimized:

$$\langle z \rangle = O(\tfrac{1}{\kappa}) = O(M_{Pl})$$

i.e supersymmetry breaks at the Planck scale.

From the gluino term generate a mass;

$$m_{1/2} \sim \langle \mathcal{G}_{,z} f^*_{\alpha\beta,z} \rangle \sim \langle \frac{\partial W_h}{\partial z} \kappa \rangle \; ; \; f_{\alpha\beta} = \delta_{\alpha\beta}(1+\kappa z + \cdots)$$

It turns out the spontaneous breaking of supersymmetry generates $SU(2) \times U(1)$ breaking and this sets the scale of $m_{1/2}$;

$$m_{1/2} = O(M_{EW})$$

(e.g. $\kappa m^2 = O(M_{EW})$ for Polonyi example).

The superHiggs mechanism is the simplest way supersymmetry can be broken in supergravity theory. An alternate procedure is to use non-perturbative effects in the hidden sector:

Assume hidden sector has its own gauge interactions (which are gauge singlet with respect to physical sector) which become sufficiently strong so that a gaugino condensate forms:

$$\langle \lambda_h \lambda_h \rangle \neq 0 \qquad \text{[Nilles]}$$

Then gravitino grows mass (signally supersymmetry breaking) of size

$$m_{3/2} \sim \kappa^2 \langle \lambda_h \lambda_h \rangle \qquad m_{3/2} = \text{gravitino mass}$$

Explicit calculations in this model are difficult (non-perturbative effects) but general effects <u>same</u> <u>as in</u> <u>superHiggs</u> <u>mechanism</u>.

[Note: hidden sectors of this type occur in <u>string</u> <u>theory</u>.]

GUT Group Breaking and Effective Theory

As one proceeds from M_{Pl} to M_G, the GUT group G breaks to the S.M. group:

$$G \rightarrow SU(3)\times SU(2)\times U(1) \quad \text{at } M_G$$

and some of the z_a grow VEV and become superheavy:

$$\langle z_A\rangle = O(M_G)\,;\quad M_{z_A} = O(M_G)$$

One may now integrate out all the superheavy matter fields z_A and eliminate superHiggs field to obtain an effective $SU(3)\times SU(2)\times U(1)$ theory at GUT scale [Hall, Lykken, Weinberg; R.A., Chamseddine, Nath]:

$$W^{eff} = W^{(3)} + W^{(2)} \quad , W^{(3)} = \text{cubic terms}$$
$$W^{(2)} = \text{quadratic terms}$$

$$V^{eff} = \left\{ \sum \left| \frac{\partial W^{eff}}{\partial z_a}\right|^2 + V_D \right\} + [m_0^2\, z_a z_a^* + (A_0 W^{(3)} + B_0 W^{(2)} + h.c.)]$$

$$\mathcal{L}_{\lambda}^{mass} = [- m_{1/2}\, \bar{\lambda}^{\alpha} \lambda^{\alpha}]$$

where

$\{z_a\}$ = remaining light matter (quarks, leptons and Higgs)

$$m_{1/2}, m_0, A_0, B_0 = O(M_{EW})$$

$m_{1/2}, m_0, A_0, B_0$ are fncs. of W_h and thus, a priori are arbitrary. They govern the soft breaking of supersymmetry generated by the superHiggs effect (or alternately the condensate of the hidden sector).

Example - SU(5) Model

Superpotential of form

$$W = \underbrace{W_Y}_{\text{Yukawa}} + \underbrace{W_G}_{\text{GUT}} + \underbrace{W_h(z)}_{\text{Hidden}}$$

where Yukawa part is

$$W_Y = \lambda^1_{ij}\, \epsilon_{xyzwu} H_1^x M_i^{yz} M_j^{wu} + \lambda^2_{ij}\, \bar{H}_{2x} \bar{M}_{iy} M_j^{xy}$$

$M_i^{xy} = 10$, $\bar{M}_{iy} = \bar{5}$ matter

$H_1^x = 5$, $\bar{H}_{2x} = \bar{5}$ Higgs

$x, y \ldots = 1 \cdots 5$ SU(5) index

$i, j = 1, 2, 3$ generation index

$H_1^x = (H_1^a, H_1^\alpha)$; $\bar{H}_{2x} = (H_{2a}, H_{2\alpha})$

The GUT part is [originally proposed by Dimopoulos, Georgi ; Sakai in global SUSY]:

$$W_G = \lambda_1 \left[\tfrac{1}{3} \mathrm{Tr}\,\Sigma^3 + \tfrac{1}{2} M\, \mathrm{Tr}\,\Sigma^2 \right] + \lambda_2 \bar{H}_{2x} (\Sigma^x_y + 3M' \delta^x_y) H_1^y$$

$$\Sigma^x_y = 24 \quad ; \quad M' = M + \mu_0 / 3\lambda_2$$

$$\mu_0 \ll M$$

The basic point of choice $M' \cong M$ is to make sure the Higgs doublets remain light while the Higgs triplets H_1^a, $\bar{H}_{2a}$ have superheavy mass $O(M \simeq M_G)$. There are ways of doing this without just imposing it (which is still all right because of the SUSY no-renormalization theorem i.e. it will be maintained by loop corrections). One is "missing partner mechanism" [Grinstein; Masiero et al] where structure of W_G doesn't have a partner for Higgs doublets to form superheavy mass due to group theory content of representations. A second mechanism [Inoue et al; Anselm and Johansen; Barbieri et al] introduces a larger global symmetry in W_G (e.g. $SU(6)$) where the Higgs doublets become psuedo-Goldstone bosons when the global symmetry, and hence remains light.