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SMR.762 - 31

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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MULTI-TeV PHYSICS

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Please note: These are preliminary notes intended for internal distribution only.

MULTI - TeV PHYSICS

G. ROSS

Trieste June 96.

S.M. → ?

Top Down

Bottom Up

- Strings
- Guts
- SUSY
- Technicolour
- $t\bar{t}$ condensate ...

• NIGHTMARE SCENARIO :

S.M. $\quad \overset{\checkmark}{q}, \overset{\checkmark}{\ell}, \overset{\checkmark}{W^{\pm}}, \overset{\checkmark}{Z}, \overset{\checkmark}{G}, \overset{\checkmark}{\gamma}, \overset{?}{H}$

$m_H \gtrsim 1\,\mathrm{TeV}$?

⇨ "No - lose theorem"[†] $\quad W_L^{+} \sim \partial_L H^{+}$ etc

For $m_H^2 \gg s \gg M_W^2$, get universal W_L, Z_L scattering given, in lowest order, by Weinberg $\pi\pi$ low-energy amplitudes with $F_\pi = 93\,\mathrm{MeV}$ replaced by $v = 250\,\mathrm{GeV}$.

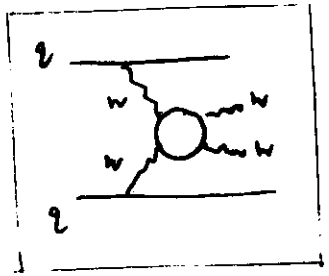
$$M(W_L^+ W_L^- \to Z_L Z_L) = \frac{g^2 s}{4 \rho M_W^2}$$

violates tree unitarity at 1-2 TeV.

ρ = 1 expt $\left(\rho = \left(\frac{M_W}{M_Z \cos\theta_W}\right)^2\right)$

Estimates using various unitarization procedures of enhanced WW, ZZ production at LHC show small ZZ enhancement $M_{ZZ} = O(1\,\mathrm{TeV})$

... difficult to disentangle from background.



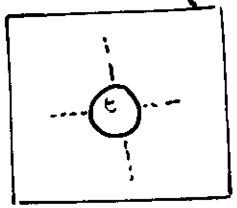
(†)

> "No-lose corollary"† $\lambda |H|^4$, $h_t \bar{t}_L t_R H^0$

$g(\mu)$, $\lambda(\mu)$, $h_t(\mu) < \infty$ for $\mu \in [m_H, \Lambda]$

In perturbation theory Landau singularities thought to signal problems for the full theory (eg $\lambda\phi^4$ triviality)

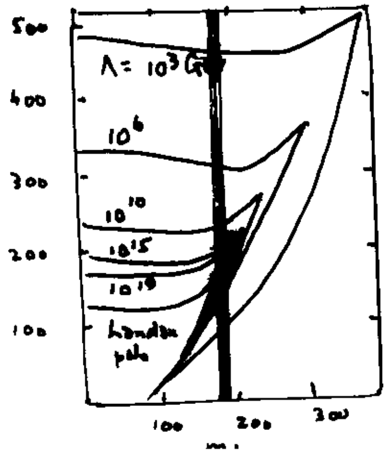
$$\underset{\text{Tree}+1\text{loop}}{V(H)} = -\mu^2 |H|^2 + \frac{a}{16\pi^2 v^2} |H|^4 \ln\left(\frac{|H|^2}{M^2}\right), \qquad a = \boxed{3\sum_V M_V^4 - 4m_t^4 + m_H^4}$$



μ, M fix M_H and v.

Vacuum stability constraints

Putting these constraints together :-



➡ New physics
... but what is it?

☺†

Bottom-Up Motivation.

Much of the SM can be constructed starting from the assumption it is an effective field theory descending from physics at some high scale, M.

$$\mathcal{L}(\phi_{light}, \phi_{heavy}) \xRightarrow[\text{HEAVY MODES}]{\text{INTEGRATE OUT}} \mathcal{L}^{eff}(\phi_{light}) = \sum_n a_n O_n^{d_n} \left(\frac{1}{M}\right)^{d_n - 4}$$

local combination of light fields

$$\boxed{\text{cf} \quad \frac{G_F}{\sqrt{2}} [\bar{\mu} \gamma_\mu \nu][\bar{\nu} \gamma^\mu e]}$$

↗ Low dimension ($d_n \leq 4$) terms dominate for $E \ll M$

... **Renormalisable** scalar + fermion theory

$$\mathcal{L}^{eff} \sim \phi^4, \ \bar{\psi}\psi\phi, \ \underset{?}{M^2\phi^2}, \ \underset{?}{M\bar{\psi}\psi}$$

↗ Light fields must have low dimension terms absent.

ii) Light fermions - If $\mathcal{L}$ has a chiral symmetry light fermions are possible :

$$\psi_L \to e^{i\alpha}\psi_L \;,\quad \psi_R \to \psi_R \qquad \cancel{M\bar{\psi}\psi = M(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)}$$

ii) Light bosons - If $\mathcal{L}$ has a local gauge symmetry light gauge bosons are possible :

$$A_\mu \to A_\mu + \partial_\mu \Lambda \quad - \quad \cancel{M^2 A_\mu A^\mu}$$

iii) EFFECTIVE THEORY MUST BE RENORMALISABLE LOCAL GAUGE FIELD THEORY

$$A^\mu \left[a\bar{\psi}_L\gamma_\mu\psi_L + b\bar{\psi}_R\gamma_\mu\psi_R \right]$$

massive ψ, ξ

UNBROKEN

MASSLESS GAUGE BOSONS	- VECTOR COUPLING. ($a=b$)
MASSIVE GAUGE BOSONS	- CHIRAL COUPLING. ($a\neq b$)

$m\bar{\psi}_L\psi_R$

$\langle H \rangle$

SPONTANEOUS SYMMETRY BREAKING.

$\sim M_Z$

⇨ Light scalars - If $\mathcal{L}$ has a spontaneously broken global symmetry light Goldstone bosons

$$\phi \to \phi + a \qquad \cancel{M^2\phi^2}$$

... BUT ϕ CANNOT CARRY GAUGE QUANTUM NUMBERS, OTHERWISE $M'^2\phi^2$ TERM ALLOWED $M' \sim gM$

iv) The only possible symmetry protecting light Higgs bosons is SUPERSYMMETRY (+ CHIRAL SYMMETRY)

$$Q_\alpha \to \begin{pmatrix} \psi \\ \phi \end{pmatrix} \quad \begin{matrix} J=\frac{1}{2} \\ J=0 \end{matrix}$$

$$m_\psi \bar{\psi}\psi + m_\phi^2 \phi^\dagger\phi \quad : \quad m_\phi \Rightarrow m_\phi = m_\psi$$

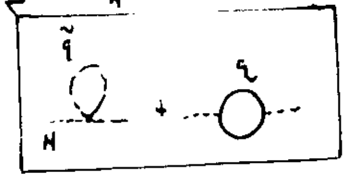
THIS REQUIRES A STAGE OF SUPERSYMMETRIC UNIFICATION

Summary :

2 ways to solve the Gauge Hierarchy Problem.

i) Low-Energy Supersymmetry.

$\delta m_H^2 = \alpha \Lambda_{SUSY}^2 \Rightarrow \boxed{\Lambda_{SUSY}^2 \lesssim \frac{m_H^2}{\alpha}}$



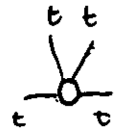
ii) Composite Higgs

form factor, e^{-a^2/Λ_c^2}

$$\boxed{M_H^2, M_W^2 \sim \alpha \Lambda_c^2 << M_{Planck}^2, \eta_x^2}$$

Composite Models

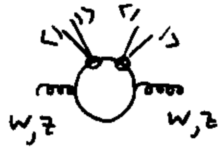
- $t\bar{t}$ condensate



: $\frac{1}{\Lambda_c^2}(\bar{t}t)^2 \Rightarrow \langle \bar{t}t\rangle \neq 0.$

Extreme example of dynamical symmetry breaking ... reduces to S.M. with Higgs at scales below Λ_c

- Precision Tests * ($\sim$ SM)
- m_t *



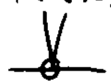
$$M_W^2 = \frac{g_2^2}{2} \frac{N_c}{(4\pi)^2} m_t^2 \ln\left[\frac{\Lambda_c}{m_t^2}\right]$$

$$\boxed{\Lambda_c > 10^{10}\text{ GeV},\ m_t = 230 \pm 20\text{ GeV},\ m_H \sim 1.2 m_t}$$

Bardeen, Hill, Lind

I.R. Fixed point

$\Rightarrow$ need to reduce Λ_c to 1 TeV to avoid fine tuning and to get m_t correct -- spoils calculability



- $\frac{m_{q_i}}{m_{q_j}}$ *

$= \frac{\lambda_{ij}}{\Lambda^2}\langle \bar{t}t\rangle$

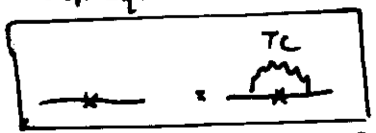
- TECHNICOLOUR AND EXTENDED TECHNICOLOUR

⇨ Add technifermions bound by new $(SU(N_f))$ interaction becoming strong at Λ_{TC}.

$\begin{pmatrix} U \\ D \end{pmatrix}$ Techniquarks

$\begin{pmatrix} N \\ E \end{pmatrix}$ Technileptons.

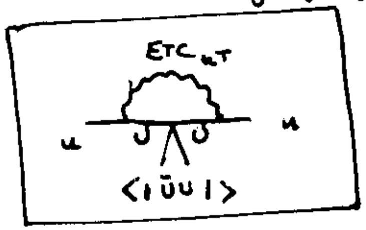
Gap eq.:



$\Rightarrow \langle \bar{U}U \rangle = \langle \bar{D}D \rangle = \ldots \approx \Lambda_{TC}^3$

TECHNICONDENSATE GIVES M_W, M_Z ✓

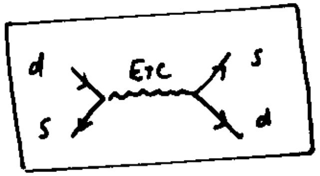
⇨ FERMION MASSES : Add ETC gauge group coupling light to heavy



$$m_u \sim \frac{g^2}{4\pi^2} \frac{\langle \bar{U}U \rangle}{M^2_{ETC\,uT}} \qquad \langle \bar{U}U \rangle \nearrow \Lambda_{TC}^3$$

etc.

⇨ FCNC :



$$\sim \frac{g^2}{M^2_{ETC}} \qquad M_{ETC} \gtrsim 1000\,\text{TeV} \cdot \sin\theta_c \cos\theta_c$$

TO RECONCILE QUARK MASS WITH ABSENCE OF FCNC REQUIRES

POSTULATE TC NOT QCD-Like "WALKING TECHNICOLOUR"

- PRECISION TESTS * (??)

New technifermions contribute to $S, T, \; R = \dfrac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$:

$\dagger$
$$T \sim 0.18\, N_{TC} \left(\frac{\Delta m^2}{M_Z^2}\right)$$
$$S \sim 0.4 N_{TC} \left[1 - \tfrac{1}{?} \ln \frac{m_N}{m_E}\right]$$
$$\Delta R \sim 0.04 \left(\frac{1\,\text{TeV}}{M_{ETC}}\right)^2$$

➡ SIMPLE MODELS RULED OUT

?? ~ STRONG INTERACTION EFFECTS (UNCALCULABLE) }† Not included
~ NEW (LIGHT) STATES, MAJORANA ν's, Z^0_{ETC} ...

- m_t ? * ?

$$\frac{m_{q_i}}{m_W} = \frac{\Lambda^2_{TC}}{\Lambda^2_{ETC_i}}, \quad \Lambda_{ETC_i} > \Lambda_{TC}$$

? ... need combination of $T\bar{T}$, $t\bar{t}$ condensates or non-QCD-like behaviour.

- $\dfrac{m_{q_i}}{M_W}$, $i \neq t$ *

➧ COMPARED TO SUSY, COMPOSITE MODEL BUILDERS ARE SWIMMING AGAINST THE TIDE!

TECHNICOLOUR SURVIVAL KIT : Appelquist Terning

- WALKING TC NEEDED TO ENHANCE QUARK MASSES WITHOUT FCNC.

- STRONG WEAK ISOSPIN SPLITTING IN (LIGHT) TECHNILEPTON SECTOR

$\begin{pmatrix} U \\ D \end{pmatrix}$ – DEGENERATE

$\begin{pmatrix} N \\ E \end{pmatrix}$ 50–150 GeV
150 GeV.

- STRONGLY SPLIT TECHNILEPTONS

$$SU(8)_L \times SU(8)_R \times U(1)_V \longrightarrow SU(6)_L \times SU(6)_R \times \cdots$$

$$\theta^\alpha_a = \bar{Q}\gamma_5 \lambda_a t^a Q \qquad \Theta_a = \bar{Q}\gamma_5\lambda_a Q$$

$$\rho^t = \bar{Q}\gamma_5 t^t Q \qquad + \cdots$$

$$50\,\text{GeV} < M_{\rho^\pm} < 150\,\text{GeV}.$$

$$250\,\text{GeV} < M_{\theta^\alpha_a} < 500\,\text{GeV}.$$

⇨ IF TC/ETC CORRECT ∃ VAST ZOO OF STRONGLY INTERACTING STATES IN TEV REGION

- SUPERSYMMETRY.

$M_H, M_W, m_{q_i}, m_{\ell_i} = 0$ due to SUSY (+ chiral symmetry)

➡ $M^2_{H,W} = \alpha M^2_{susy}$, M_{susy} SUPERSYMMETRY BREAKING SCALE.

$$\boxed{M_H, M_W \ll M_{Planck}, M_X \text{ if } M_{susy} \ll M_{Planck}, M_X.}$$

⇛ NEW SUSY STATES (MSSM) $\tilde{q}, \tilde{\ell}, \tilde{g}, \tilde{W}, \tilde{H}_{1,2} \lesssim \frac{M_W}{\sqrt{\alpha}} \lesssim \underline{1\text{ TeV}}$

2 Higgs doublets needed †

- PRECISION TESTS * (~ SM)

$M_{susy} \to \infty$, MSSM → SM with LIGHT Higgs $m_h^0 < 146$ GeV.

Espinosa, Quiros
Kane, Kolda, Wells
...

- m_t *

I.R.F.P. : $\boxed{m_t^\varphi \sim 200 \sin\beta}$

$\tan\beta = \frac{v_1}{v_2}$ †

- $\frac{m_{q_i}}{m_{q_j}}$ etc. ? (NOT DETERMINED BY SUSY ALONE!)

[redacted]

N=1 SUPERSYMMETRY

MULTIPLET STRUCTURE : $(N=1) \times SU(3)_c \times SU(2)_L \times U(1)_Y$.

$\boxed{\text{GAUGE BOSONS} + \text{GAUGINOS}}$ VECTOR SSM.

QUARKS + SQUARKS, LEPTONS + SLEPTONS

$$+ \; 3 \times \left\{ \begin{pmatrix} q_L \\ \tilde{q}_L \end{pmatrix} + \begin{pmatrix} Q_L \\ \tilde{Q}_L \end{pmatrix} + \begin{pmatrix} L_L \\ \tilde{l}_L \end{pmatrix} + \begin{pmatrix} E_L^c \\ \tilde{E}_L^c \end{pmatrix} \right\}$$

Higgsinos + Higgs bosons — CHIRAL SSM.

$$+ \begin{pmatrix} \tilde{H}_1 \\ H_1 \end{pmatrix} + \begin{pmatrix} \tilde{H}_2 \\ H_2 \end{pmatrix}$$

$(1, 2, \tfrac{1}{2})$ $\qquad$ $(1, 2, -\tfrac{1}{2})$

TWO HIGGS DOUBLETS NEEDED TO CANCEL HIGGSINO ANOMALY

$\boxed{\text{Discrete symmetries} : Z_2 \text{ "}R_p\text{"}, \; Z_3 \ldots \text{ "}\mu\text{"}}$

COUPLINGS : $D \leq 4$ TERMS CONSISTENT WITH

GAUGE SYMMETRIES.

$$[\Phi_i^\dagger \Phi_i]_D \rightarrow \boxed{\bar{q}_L \not{D} q_L + |D_\mu \tilde{q}_L|^2 + \text{"ino" interactions} + \text{"D" terms}}$$

$\frac{g_2^2 + g_1^2}{8} [|H_1|^2 - |H_2|^2]^2 \ldots$

$$h_{ij} [q_i H_2 u_j^c]_F \rightarrow h_{ij} (\bar{u}\, \bar{d})_i \begin{pmatrix} H_2^0 \\ -H_2^- \end{pmatrix} u_j + h_{ij} (\bar{u}\, \bar{d})_i \begin{pmatrix} \tilde{H}_2^0 \\ -\tilde{H}_2^- \end{pmatrix} \tilde{u}_j + \text{"F" terms}$$

up quark mass terms. $\quad + h_{ij} (\tilde{u}\, \tilde{d})_i \begin{pmatrix} \tilde{H}_2^0 \\ -\tilde{H}_2^- \end{pmatrix} u_j$

$\mu [H_1 H_2]_F$

$h'_{ij} [q_i H_1 d_j^c]$ $\quad h''_{ij} [L_i H_1 E_j^c]$ $\rightarrow$ down quark + lepton masses.

m_t: FIXED POINT STRUCTURE

$$\frac{dh_t}{dt} = \frac{h_t}{8\pi^2} \left(-\frac{8}{3} g_3^2 - \frac{3}{2} g_2^2 - \frac{13}{30} g_1^2 + 3 h_t^2 \right)$$

$\frac{h_t^2}{4\pi}$ $\qquad \frac{16}{3b_3} + 1$

$$\boxed{\frac{Y_t(t)}{\alpha_3(t)} = \left(\frac{Y_t}{\alpha_3} \right)^* \left[1 + \left(\frac{\alpha_3(t)}{\alpha_3(0)} \right)^{\beta} \left(\frac{Y_t}{\alpha_3} \right)^* \left(\frac{\alpha_3(0)}{Y_t(0)} - \left(\frac{\alpha_3}{Y_t} \right)^* \right) \right]}$$

$$\frac{d \ln (h_t / g_3)}{dt} = \frac{1}{8\pi^2} \left(-\frac{8}{3} g_3^2 + 3 h_t^2 - \frac{b_3}{2} g_3^2 \right) = 0$$

$$\left(\frac{h_t^2}{g_3^2} \right)^* = \frac{8 b_3}{\ldots}$$

$(1, (3\bar{3})) \left[\begin{smallmatrix} H_1 & H_2 & L \\ E^c & \nu_R & \end{smallmatrix} \right]$ $\quad (u\,d)_L \; H_1 \; u_R$ $\quad l_\beta^\alpha \leftarrow SU(3)_R$

- If $\quad Y_t(0) \gg \alpha_3(0)$ $\qquad$ (eg. $t\bar{t}$ condensate)† $\quad$ Hill.

$$\frac{Y_t(t)}{\alpha_3(t)} \simeq \left(\frac{Y_t}{\alpha_3} \right)^* \left[1 - \left(\frac{\alpha_3(t)}{\alpha_3(0)} \right)^{\beta} \right]$$

$$\boxed{m_t = 230 \pm 20 \text{ GeV.}}^\dagger \qquad (\Lambda = 10^{16} \text{ GeV})$$

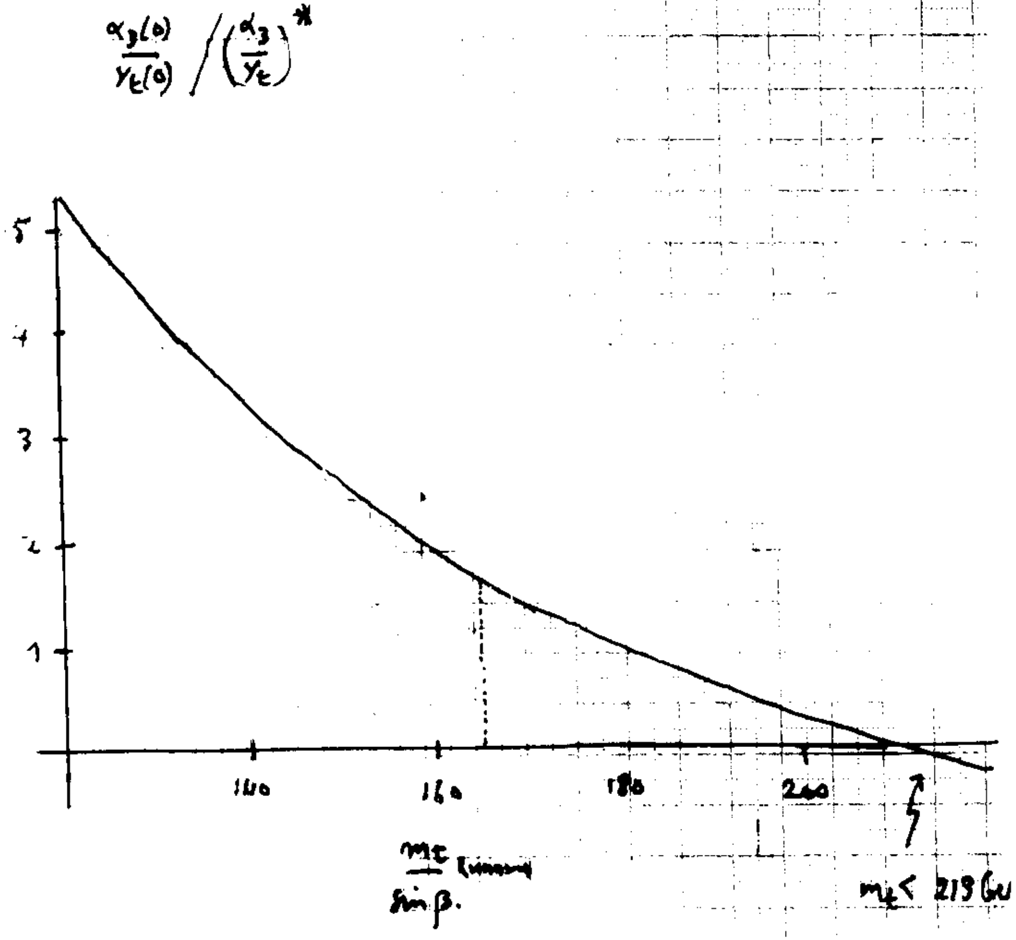
- If $\quad m_t < m_t$ $\quad$ QUASI FIXED PT $\Rightarrow Y_t(0)$ in perturbative domain .... ~~expectations~~ from strings.

$SU(3)^3 \rightarrow h_t$ $\quad h_t = h_b = \ldots$

$$\boxed{h_t^2(0) = O(1)\, g_t^2(0)\, f(T, u)}$$

$\frac{1}{T^{3/2}}$ untwisted orbifold. $T \geq 1$.

Consolidated : Can diverge at singular pts. of manifold.



- <u>PARAMETER COUNT.</u>

g_1, g_2, g_3

$M_W, \underline{M_H}$

$$\boxed{\frac{(g_2^2+g_1^2)}{8}\left[|H_1|^2-|H_2|^2\right]^2}$$

Known in SUSY.

m_{l_i}, m_{q_i}

$\theta_i \quad \delta$

θ_{QCD}

$$\boxed{\begin{array}{ll} \tilde{\theta}_i & \tilde{\delta}_i \\ \tilde{m}_i, & \tilde{\mu}, \ldots \end{array}}$$

SOFT <u>SUSY BREAKING</u> TERMS

NEED FURTHER UNIFICATION TO RELATE PARAMETERS...

GRAND UNIFICATION, SUPERSTRINGS.

ONLY MAKES SENSE IN SUSY THEORIES

	GUTs	4-D STRINGS
GAUGE GROUP	• $SU(5) \supset SU(3) \times SU(2) \times U(1)$ $g_i \to g_{GUT}$	• $G \times G'$ "Hidden" sector (SUSY BREAKING) "Visible" sector
MATTER	• $\bar{5} + 10 \sim 1$ generation $\to SO(10) \quad 16 = (1 + \bar{5} + 10)$	• DEFINITE MULTIPLET STRUCTURES - EVEN WITHOUT GUT eg "LEVEL-1" 4-D MODELS : SU(3) : 3, 1 REPS ONLY. SU(2) : 2, 1
FAMILY STRUCTURE	• ? larger gauge structure ... not very convincing	• DEFINITE FAMILY STRUCTURE ... 3 GENERATION EXAMPLES KNOWN.
MASS HIERARCHY	• $M_\gamma, M_g = 0$ ✓ $M_W, M_H \neq 0 \sim M_X$? ⇨ SUSY GUTS	• (N=1) SUSY CAN PERSIST FROM SUPERSTRING TO LOW ENERGY. (NO NEED FOR COLOURED HIGGS CHANGING CONDENSATION)
LOW ENERGY STRUCTURE	• (N=1) SUSY $\cancel{B}$? $\cancel{L}$? ⇨ DISCRETE SYMMETRIES NEEDED	• (N=1) SUSY $\cancel{B}$? $\cancel{L}$? DISCRETE SYMMETRIES PREDICTED (GAUGE)
PARAMETERS	• $g_i \to g_{GUT}$ $m_b = m_\tau$ etc. Higgs sector ? MANY	• IN PRINCIPLE ALL PREDICTED ... SINGLE PARAMETER ~ M...

$SU(5) \quad \supset \quad SU(3) \times SU(2) \times U(1)$

$$\psi_{\bar{5}} = \begin{bmatrix} d^c \\ d^c \\ d^c \\ e^- \\ \nu_e \end{bmatrix}_L = (\bar{3}, 1) + (1, 2)$$

$$\chi^{10} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & u^c & u^c & u & d \\ -u^c & 0 & u^c & u & d \\ u^c & -u^c & 0 & u & d \\ u & u & u & 0 & e^+ \\ d & d & d & e^+ & 0 \end{bmatrix}_L \quad \ldots \quad a_{jk} = \frac{1}{\sqrt{2}}\left(a_j a_k - a_k a_j\right)$$

$\bar{5} \times \bar{5} = \bar{15} + 10$

• $SU(5) \xrightarrow{\langle \Sigma_{24}^A \rangle} SU(3) \times SU(2) \times U(1) \xrightarrow{\langle H_5 \rangle} SU(3) \times U(1)$

• $\sin^2 \theta_W = \dfrac{\mathrm{Tr}(T_{3L}^2)}{\mathrm{Tr}(Q^2)} = \dfrac{3}{8}$

• $\mathcal{L}_Y = h \, \bar{\psi}^p_{\bar{5}R} \, \chi^{10}_{p,q\,L} \, H^q_5 \quad \Rightarrow \quad m_e = m_d = h \langle H^5_5 \rangle$

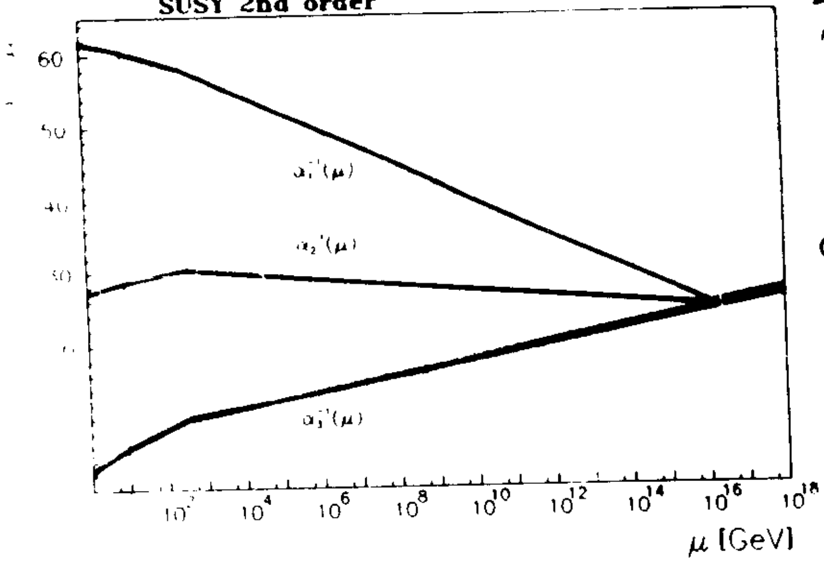
$\left(\mathcal{L}'_Y = h' \, \bar{\psi}^p_R \, H^{sq}_p \, \chi_{sq\,L} \quad \Rightarrow \quad m_q = 3 m_e \right)$

H : 45.

EVIDENCE OF SUPERSYMMETRY · 20 Amaldi, de Boer, ; Furstenau; see also Ellis, Kelley, Nanopoulos; Langacker Luo.

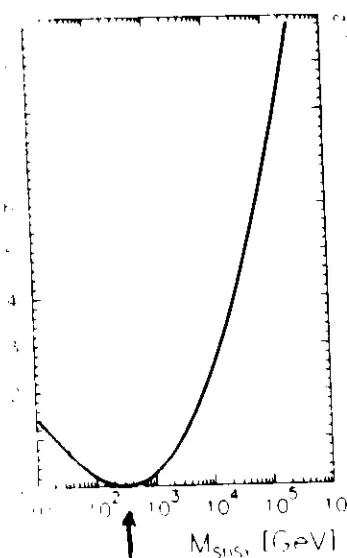
$$\alpha_i^{-1}(\mu) = \alpha_{GU}^{-1}(\mu) + \frac{b_i}{4\pi}\ln\left(\frac{M_X^2}{\mu^2}\right) + \cdots$$

SUSY 2nd order

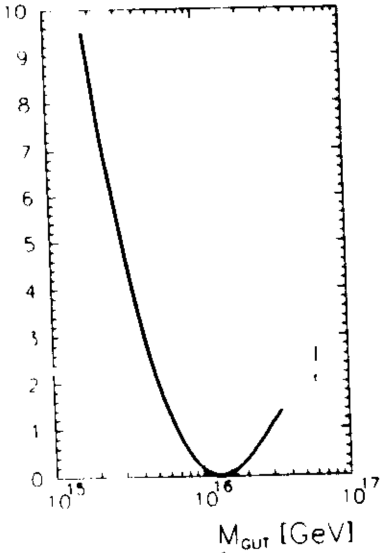


Roberts Ross.

(Ibanez Ross; Dimopoulos Georgi)



$M_{susy} = 10^{2.5 \pm 1.0}$



$10^{16.1 \pm 0.3}$

- **GAUGE GROUP** $G \times G'$

Rank ≤ 22 ie $\{SU(11)\}^2 \times N=4$

Hidden sector: $E_8, \ldots$

Visible sector: $\rightsquigarrow$ GUT : E_6, $SU(5)\times U(1), \ldots$

$\rightsquigarrow$ NON GUT : $SU(3)^3$, $SU(3)\times SU(2)\times U(1), \ldots$

… no unification

But $g_i(M_X) = g$ maintained (Kaplunovsky, + ..)

(SU(5) normalisation)

$$\Rightarrow \boxed{\alpha_i^{-1}(\mu) = k_i\,\alpha^{-1} + \frac{b_i}{4\pi}\ln\left(\frac{M_{SU}^2}{\mu^2}\right)}$$

KAC-MOODY LEVEL

$k_i = 1$ USUAL

(k_i arbitrary ? Ibanez)

INCLUDES STRING THRESHOLD CORRECTIONS … MASSIVE STRING STATES.

$M_{SU} = 3.10^{17}\,\mathrm{GeV} \times f$

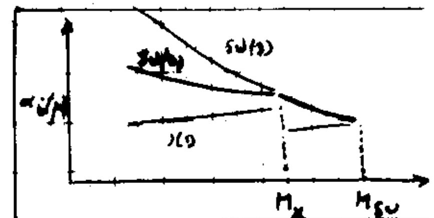
?? eg.

$\rightsquigarrow$ "Flipped" $SU(5)\times U(1)$: $f \simeq 2$ (Antoniadis et al).

$M_{SU} \sim 7.10^{17}$ GeV … TOO HIGH

BECAUSE $SU(5)\times U(1) \xrightarrow{M_X} SU(3)\times SU(2)\times U(1)_Y$

TOO HIGH



$\Rightarrow$ NEED ADDITIONAL HEAVIES : eg $Q = \left(3, 2, \tfrac{1}{6}\right) + 1\,\mathrm{of}\,\{D^c, U^c, E^c\}$: 10^{13} GeV

Dimopoulos Raby Wilczek

$\rightsquigarrow$ Orbifolds : typically $f \gtrsim 1$ … TOO HIGH ($f \sim \frac{1}{10}$ just possible but..) (Ibanez + ..)

$\Rightarrow$ SOME UNIFICATION eg $[SU(3)]^3$ OR NEW HEAVIES

- GAUGE COUPLING THRESHOLD EFFECTS

↗ CORRECTIONS TO g_i HAVE BEEN CALCULATED FOR LOOPS CONTAINING MASSIVE MOMENTUM AND WINDING STATES.

$$\frac{1}{g_a^2(\mu)} = \frac{k_a}{g^2_{string}} + \frac{b_a}{16\pi^2}\log\frac{M_{string}}{\mu^2}$$
$$- \frac{1}{16\pi^2}\sum_{i=1}^{3}\left(b'^{i}_{a} - k_a\delta_{GS}\right)\log\left(T+\bar{T}\right) \cdot |\eta(T_i)^{\dagger}|^4 .$$

(Note ... structure of argument of log may be understood from modular group

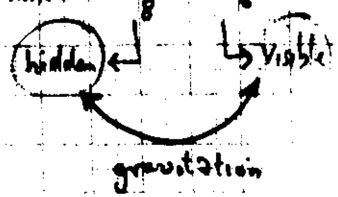
Λ_{GUT} must be made modular invariant.

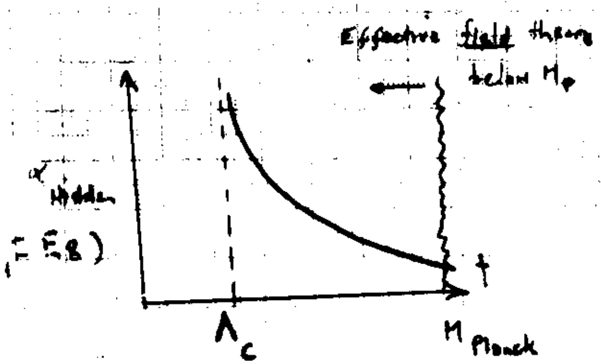
$$\Lambda^2_{GUT} \to \frac{1}{\langle \mathrm{Re}\,S\ \mathrm{Re}\,T\rangle\, |\eta(T)|^4} \quad)$$

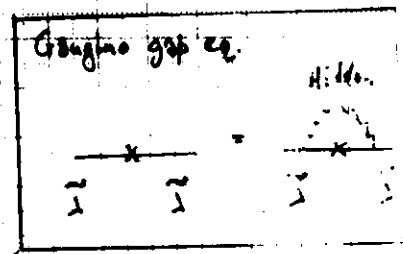
† Dedekind function $\eta(T) = e^{-\pi T/12}\prod_{n=1}^{\infty}\left(1-e^{-2\pi n T}\right)$

THE ORIGIN OF THE MASS HIERARCHY : GAUGINO CONDENSATION?

- HIDDEN SECTOR : eg HETEROTIC STRING $E_8 \times E_8$







· GAUGINO CONDENSATION

$$\langle 0|\vec{\lambda}\bar{\lambda}|0\rangle = \Lambda_c^3 \approx M^3_{Planck}\exp\left(-\frac{3}{2b_0 g^2}\right)$$

IN LOCAL SUSY, GAP EQUATION SOLUTION FAVOURS SUPERSYMMETRY BREAKING GAUGINO CONDENSATE.

Ibanez, Nilles, Ferrara, Girardello, Dine .., Kounnas, Gaillard, de la Macorra, G.R.., Casas, Munoz

SUSY BREAKING SCALE $\boxed{m^2_{3/2} = \frac{\langle 0|\bar{\lambda}\bar{\lambda}|0\rangle^2}{4 S_r T_r^3} \cdot \frac{\Lambda_c^6}{4 S_r T_r^3}}$

S_r, T_r moduli ... †FINE STRUCTURE CONST $\boxed{g^2 = \frac{1}{S_r}}$

+ COMPACTIFICATION RADIUS $\boxed{R_c^2 = T}$

HIERARCHY DETERMINED BY S.

//

EVIDENCE OF SUPERSYMMETRY + UNIFICATION

$2\cdot10^{16}$ GeV

1. Unification of gauge couplings ⇨ $\left\{\frac{g_i}{g_j}\right\}, M_X$ ✓

$g_i \to g_u$

2. Unification of masses ⇨ $\tilde m_i^2, (g_u)$

M_W ?

$\tilde m_i^2 \longrightarrow m_{3/2}^2$

$$V_H = m_{H_1}^2|H_1^0|^2 + m_{H_2}^2|H_2^0|^2 + m_3^2 H_1^0 H_2^0$$

$$+ \underbrace{\frac{g_2^2+g_1^2}{8}}_{\text{KNOWN IN SUSY.}}\left(|H_1^0|^2 - |H_2^0|^2\right)^2 + \text{squark, slepton terms}$$

Electroweak breaking if m_H^2 -ve !

... M_W predicted in terms of $\mu, m_0, M_{1/2}, m_t$

+ $SU(3)\times SU(2)\times U(1) \longrightarrow SU(3)\times U(1)_{em}$ ✓

Ibanez, Ross; Alvarez-Gaume..; Claudson, Wise; Inoue et al

3. $M_X \longrightarrow \tau_p$?

4. Unification of Yukawa couplings? ⇨ m_{q_i}, m_{ℓ_i}; θ_c, δ

RENORMALISATION GROUP EQUATIONS ... CONTINUED.

top Yukawa coupling

$$\frac{dh}{dt} = \frac{h}{8\pi^2}\left(-\frac{8}{3}g_3^2 - \frac{3}{2}g_2^2 - \frac{13}{30}g_1^2 + 3h^2\right)$$

$$\frac{d\tilde m_Q^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{16}{3}M_3^2 g_3^2 - 3M_2^2 g_2^2 - \frac{1}{15}M_1^2 g_1^2 + \delta_{a3}h^2 F_t\right)$$

$$\frac{d\tilde m^2_{u_a^c}}{dt} = \frac{1}{8\pi^2}\left(-\frac{16}{3}M_3^2 g_3^2 - \frac{16}{15}M_1^2 g_1^2 + \delta_{a3}2h^2 F_t\right)$$

$$\frac{d\tilde m^2_{d_a^c}}{dt} = \frac{1}{8\pi^2}\left(-\frac{16}{3}M_3^2 g_3^2 - \frac{4}{15}M_1^2 g_1^2\right)$$

$$\frac{d\tilde m^2_{L_a}}{dt} = \frac{1}{8\pi^2}\left(-3M_2^2 g_2^2 - \frac{3}{5}M_1^2 g_1^2\right)$$

$$\frac{d\tilde m^2_{e_a^c}}{dt} = \frac{1}{8\pi^2}\left(-\frac{12}{5}M_1^2 g_1^2\right)$$

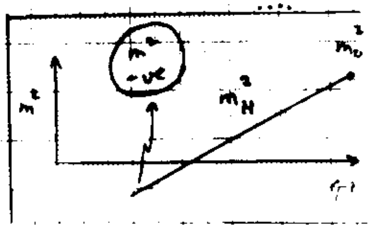
$$\frac{dm^2_{H_2}}{dt} = \frac{1}{8\pi^2}\left(-3M_2^2 g_2^2 - \frac{3}{5}M_1^2 g_1^2 + \delta_{a3}3h^2 F_t\right) \quad †$$

$$\frac{dm^2_{H_1}}{dt} = \frac{1}{8\pi^2}\left(-3M_2^2 g_2^2 - \frac{3}{5}M_1^2 g_1^2\right)$$

Ibanez, Ross; Alvarez-Gaume..; Polchinski, Wise; Inoue et al; Ibanez, Lopez; Ellis et al ....

$$F_t = m^2_{\tilde Q_3} + \tilde m^2_{u_3^c} + m_H^2 + A_t^2$$

† ACTS AS TRIGGER FOR ELECTROWEAK BREAKING



$$\frac{dh_b}{dt} = \frac{h_b}{8\pi^2}\left(-\frac{8}{3}g_3^2 - \frac{3}{2}g_2^2 - \frac{7}{18}g_1^2 + \frac{1}{2}h_t^2 + 3h_b^2\right)$$

$$\frac{d\mu}{dt} = \frac{\mu}{8\pi^2}\left(-\frac{3}{2}g_2^2 - \frac{1}{2}g_1^2 + \frac{3}{2}h_t^2 + \frac{3}{2}h_b^2\right)$$

$$\frac{dA_t}{dt} = \frac{1}{8\pi^2}\left(\frac{16}{3}g_3^2M_3 + 3g_2^2M_2 + \frac{13}{9}g_1^2M_1 + 6h_t^2A_t + h_b^2A_b\right)$$

$$\frac{dA_b}{dt} = \frac{1}{8\pi^2}\left(\frac{16}{3}g_3^2M_3 + 3g_2^2M_2 + \frac{7}{9}g_1^2M_1 + h_t^2A_t + 6h_b^2A_b\right)$$

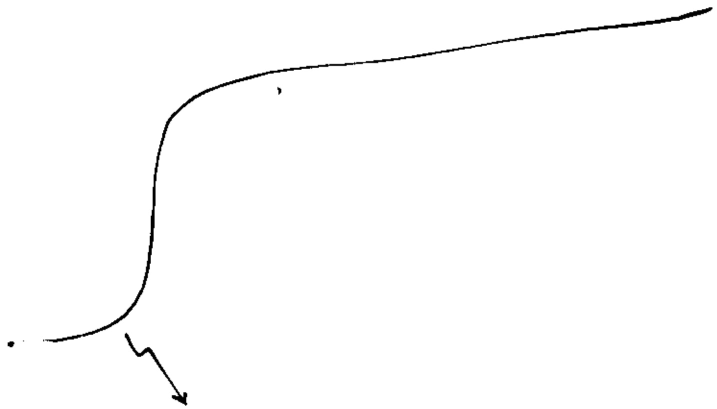
$$\frac{dB}{dt} = \frac{1}{8\pi^2}\left(3g_2^2M_2 + g_1^2M_1 + 3h_t^2A_t + 3h_b^2A_b\right)$$

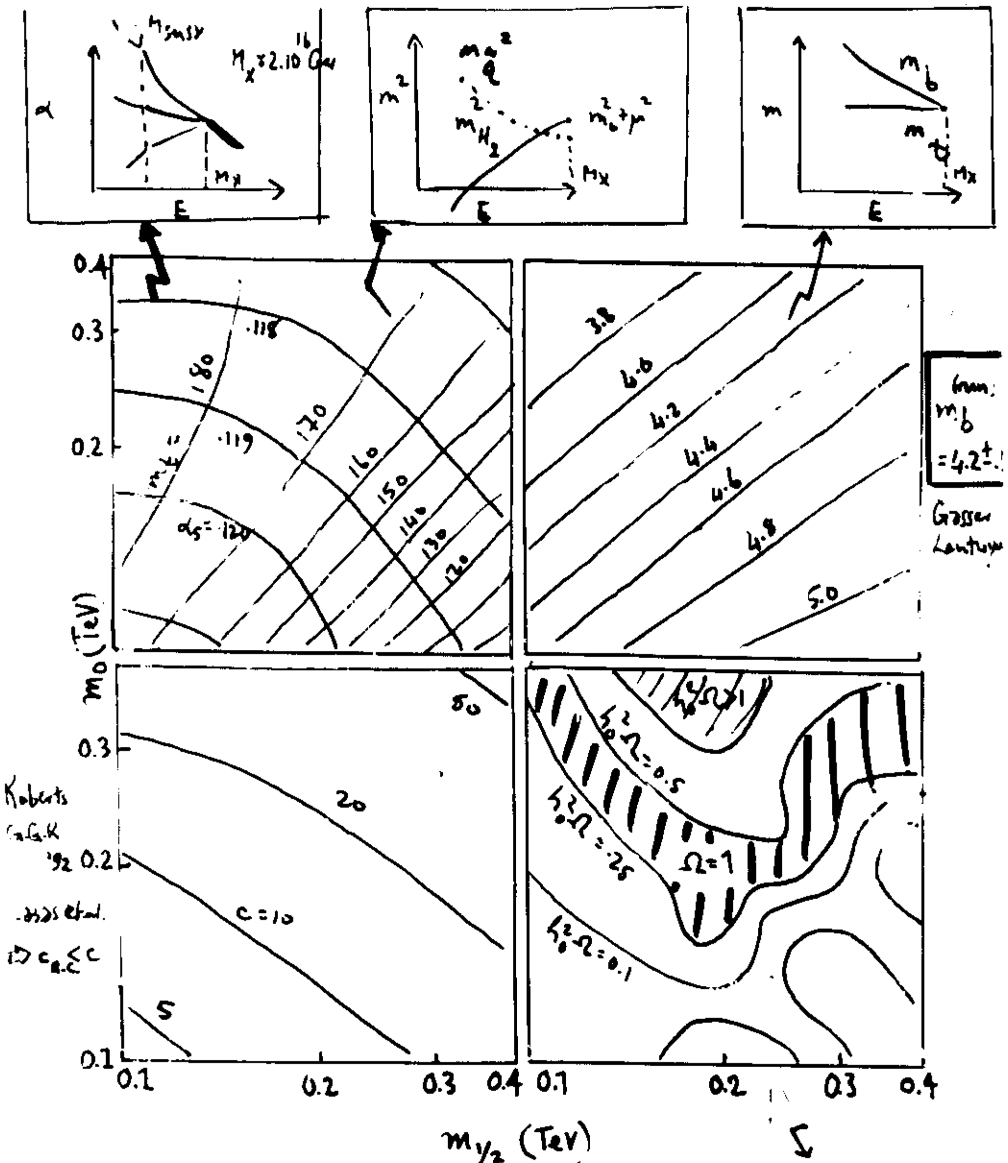
$$\left(\frac{dh_t}{dt} = \frac{h_t}{8\pi^2}\left(-\frac{3}{2}g_2^2 - \frac{3}{2}g_1^2 + \frac{3}{2}h_t^2 + 2h_b^2\right)\right)$$

+ two loop corrns. for $\frac{m_b}{m_t}$

$$M_i(t) = M\,\frac{g_i^2(t)}{g_i^2(0)}$$

$$— = \frac{m_{H_2}^2}{|m_{H_2}|}$$





Roberts
GGK
'92
Gasser et al.
$c_{n.c.} < c$

Gasser
Leutwyler

talk by G. Kane

Amaldi, de Boer, Fürstenau,
Ellis et al.
Langacker, Luo
Roberts GGR
Dreer et al.
Anselmo et al.

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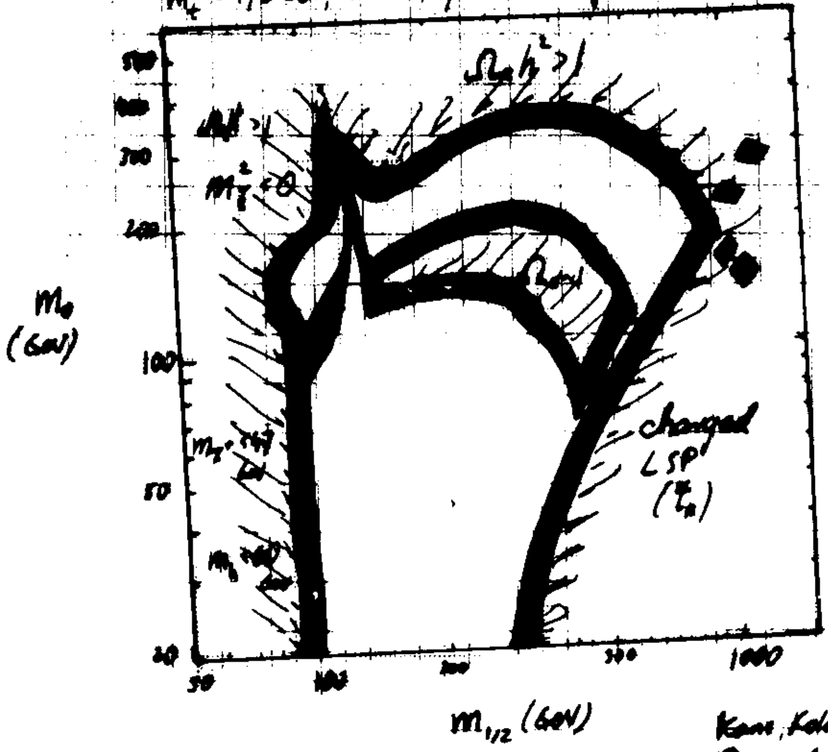
Typical case
(always true for $\tan\beta \lesssim 5$)
In general we do not
assume b-τ unification

$M_t^{pole} = 170$ GeV, $A_0 = 0$, $\mu < 0$ $\tan\beta = 2.1$ ($m_b = m_\tau$ unification √)



Kane, Kolda
Roszkowski Wells

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SUMMARY.

Higgs	Composite $t\bar{t}$	Composite $T\bar{T}$ $(+t\bar{t})$	Elementary SUSY.
$\frac{m_{H,W}}{M_X}$	✓	✓	✓
PRECISION TESTS	✓	× ?	✓
m_t	× ?	× ?	✓
m_{q_i}/m_{q_j}	× ?	✓	?
m_H	?	?	"LIGHT"

SUSY UNIFICATION ?

$g_i \to g_u(M_X)$ ✓

$M_W\ (m_t)$ ✓

$\frac{m_b}{m_\tau} \to 1\ (M_X)$ ✓

$\frac{m_t}{m_b} \xrightarrow{?} 1\ (M_X)$ ✓

$\Omega_{\tilde{N}} \sim 1$ ✓

m_{h^0} bounded

$M_X = 2.10^{16}$ GeV

$M_{SUSY} \lesssim 1$ TeV.

$h_b = h_\tau \stackrel{?}{=} h_t$

.. SO(10) or Superstring?

FURTHER UNIFICATION ? ... TEXTURE ZEROS SUGGEST THERE IS

IMPLICATION FOR PHYSICS IN MULTI-TEV REGION

COMPOSITE THEORIES.

COMPLETE SPECTRA OF STATES ASSOCIATED WITH NEW CONFINING INTERACTION (cf QCD). , $M \sim$ TeV

... LIGHTEST P.G.B. ASSOCIATED WITH APPROXIMATE GLOBAL SYMMETRIES. , $M \ll$ TeV.

SUPERSYMMETRY

SUPERSYMMETRIC "ZOO" OF NEW STATES. USING UNIFICATION CONSTRAINTS THE SPECTRUM IS VERY TIGHTLY CONSTRAINED.

EXOTICA MOTIVATED BY GUTS, STRINGS.

- NEW GAUGE BOSONS
- NEW MATTER STATES
- CRYPTONS.

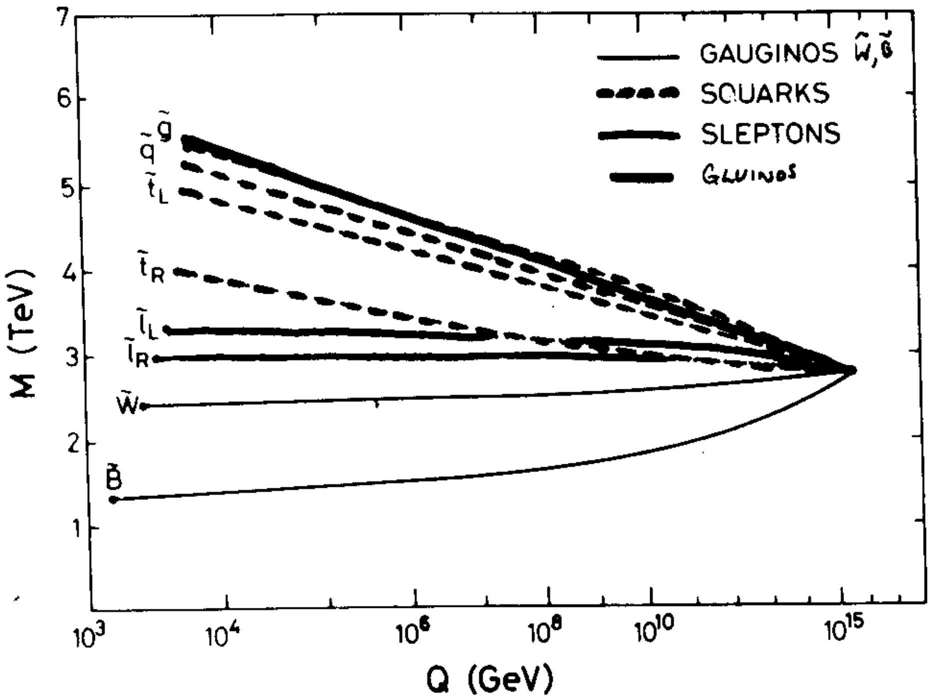


Fig. 2

$m_0 = m_{1/2} = \mu_0 = 2.8$ TeV

SUPERSTRING EXOTICA.

• NEW GAUGE BOSONS ? CAN HAVE LARGER GAUGE GR

$SU(5)\times U(1)$, $(E_8)\times E_6$ .... $SO(44)$

$\xrightarrow{\text{S.S.B.}}$ $SU(3)\times SU(2) + U(1)$ + NEW RIGHT CHARGED OR NEUTR

CURRENTS ?

CALABI-YAU

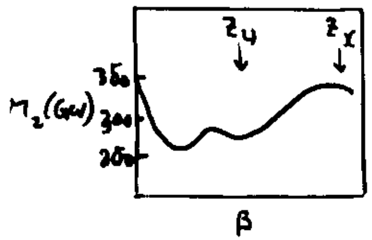
MOST ANALYSES HAVE CONCENTRATED ON $E_6 \rightarrow SU(3)\times SU(2)\times U(1)$

$$Z_1^m = Z_1^0 \cos\theta + Z_2^0 \sin\theta$$
$$Z_2^m = -Z_1^0 \sin\theta + Z_2^0 \cos\theta$$

S.M. Z

$$Z_\psi^0 \cos\beta + Z_\chi^0 \sin\beta$$

$$E_6 \rightarrow SO(10)\times U(1)_\psi \rightarrow SU(5)\times U(1)_\chi \times U(1)_\psi$$



del Aguila
Masip
Moreno
Quiros
...

.... BUT THERE ARE, IN GENERAL, MANY MORE POSSIBLE N.C.

EXTENSIONS [RANK 22 ... $E_8\times E_6\times U(1)^8$]