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SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

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SUPERSYMMETRY AND UNIFICATION

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

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Supersymmetry and Unification

1. The framework defined
2. Experimental "evidence"
3. The most outstanding theoretical problems
4. Discovering supersymmetry

Hints of a deeper structure

More symmetry ⇔ less divergences

QED, SM, ...

(Isn't renormalizability enough?
m_H, NR operators)

$\boxed{\text{Supersymmetry}}$

gravity included in a unified picture

$$\delta\varphi = \bar{\epsilon}\psi$$
$$\delta\psi = (\partial_\mu\varphi)\gamma_\mu\epsilon$$

local supersymmetry
$\Updownarrow$
supergravity
(superstrings)

The Grand Unification Pattern

$$\left\{ \binom{u}{d}_L, u_R, d_R, \binom{\nu}{e}_L, e_R, \nu_R \right\} \equiv \text{SO(10) spinor}$$

(charge quantized, no anomaly, ...)

Why $M_G \ggg M_W$?

$\boxed{\text{Because the world is almost supersymmetric}}$

$$m_S/M_G \approx M_W/M_G \lll 1$$

Table 2. Standard Model fits of all LEP and of all LEP+SLD data for fixed Higgs mass.

	$m_H = 65$GeV	$m_H = 1$TeV
LEP	m_t(GeV) = 146 ± 13.5	m_t(GeV) = 181 ± 12
LEP + SLD	m_t(GeV) = 138 ± 11	m_t(GeV) = [illegible]
	$\alpha_s(M_Z) = 0.123 \pm 0.0044$	$\alpha_s(M_Z) = 0.127 \pm$ [illegible]

The light Higgs fit has a slightly better χ^2 ($\Delta\chi^2 = 3.5$). Most significant is the separation, in the two fits, between the central values of m_t, especially if this separation is compared with the theoretical error, $\Delta m_t^{th} \approx 6 \div 8$GeV, this is estimated to affect the determination of m_t from a pure $t-\bar{t}$ cross section measurement at the Tevatron 4]. This comparison may become a relevant source of information on the Higgs mass in a not too distant future. To this end, a more complete information is contained in the isoplot of the χ^2 in the m_t, m_H plane, given in Fig. 1, for $\alpha_s(M_Z) = 0.118 \pm 0.007$, and using all e^+-e^- data (LEP + SLD).

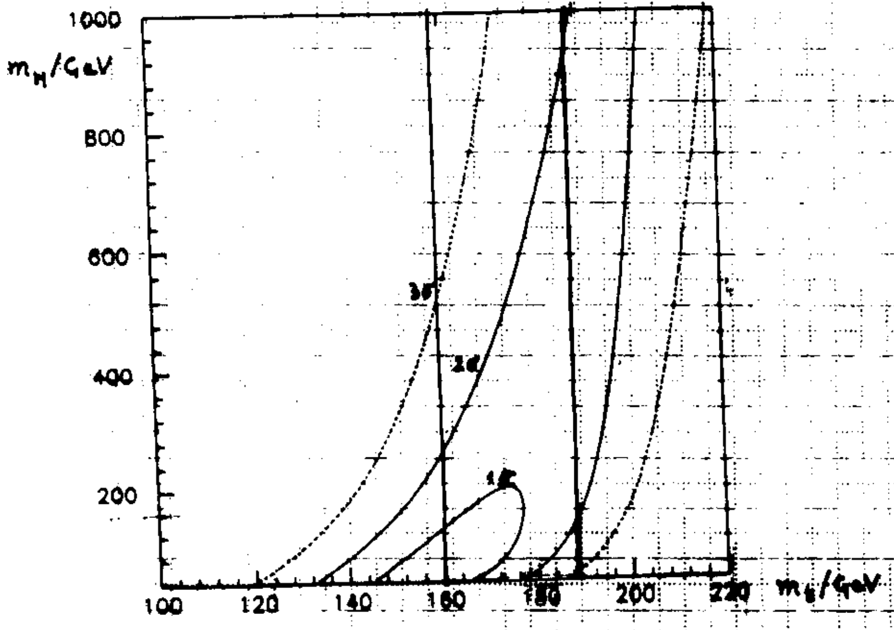


Figure 1. Isoplot of the χ^2 of the SM fit of all e^+-e^- data (LEP + SLD), with $\alpha_s(M_Z) = 0.118 \pm 0.007$. The lines give constant values of the χ^2 ($\chi^2 = \chi^2_{min} + 1^2, 2^2, 3^2$ respectively)

The framework defined

1. the SM is literally correct even in the symmetry breaking sector (the Higgs exists)

2. the strong and electroweak interactions are manifestations of a unique force, at a scale $M \simeq 10^{16}$ GeV, which is supersymmetric to a high degree of precision, of order $M_W/M \approx 10^{-14}$ (the paradigm of supersymmetric GUTs)

Experimental "evidence"

1. Electroweak precision tests
2. Unification of couplings

Non Standard Analysis of Electroweak Precision Tests

Altarelli, B

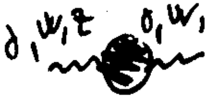
A, B, Caravaglios

$$\hat{O}_i = \hat{O}_i^0 (1 + a_{ij}\epsilon_j) \qquad j = 1, 2, 3, b$$

"Born approximation + QED rad. corr.

"genuine" electroweak rad. corr.

- Isolate different sectors of special physical significance:
  - Higgs sector ...
  - Z, $b\bar{b}$ coupling ...
  - ...



- Do not restrict analysis to SM only
- Never specify m_t

Electroweak precision tests

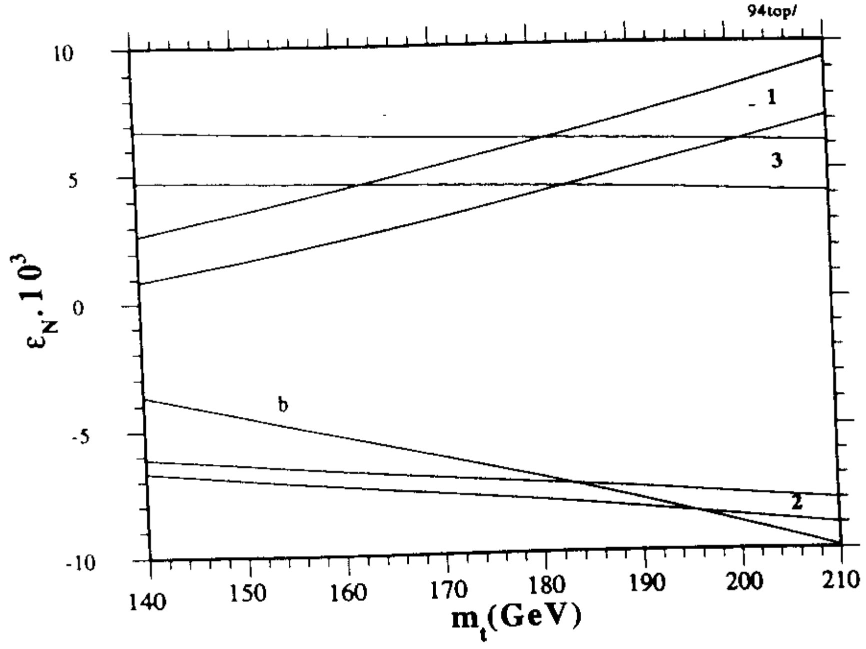
20/3/94

LEP

	MARSEILLE	LATHUILE-MORIOND '94
mZ(GeV)	91.187 ± 0.007	91.1899 ± 0.0044
ΓT(MeV)	2489 ± 7	2497.1± 3.8
R=Γh/Γl	20.76± 0.05	20.795± 0.04
$\sigma_h = 12\pi\Gamma_e\Gamma_h/m_Z^2\Gamma_T^2$ (nb)	41.56± 0.14	41.51± 0.12
Γl(MeV)	83.79 ± 0.28	83.98± 0.18
Γh(MeV)	1740± 6	1746± 4
Γb(MeV)	383 ± 6	385.5± 3.4
Rbh=Γb/Γh	0.220 ±0.0027	0.2210±0.0019
A_{FB}^{l}	0.0158 ± 0.0018	0.0170 ± 0.0016
A_{pol}^{τ}	0.139 ± 0.014	0.150 ± 0.010
A^{e}	0.130 ± 0.025	0.120 ± 0.012
A_{FB}^{b}	0.098 ± 0.006	0.0970± 0.0045
A_{FB}^{c}	0.075 ± 0.015	0.072± 0.011
gv/ga(all asymmetries -LEP)	0.0712±0.0028	0.0711 ±0.0020
ALR (SLD)	0.100±0.044	0.1668±0.0079
gv/ga(all asymmetries-LEP+SLD)		0.0737 ±0.0018
mW/mZ (UA2+CDF)	0.8798 ± 0.0028	0.8814 ± 0.0021
Rneutrino=σNC/σCC	0.312 ±0.003	
APV(Cs) QW	-71.04 ± 1.81	

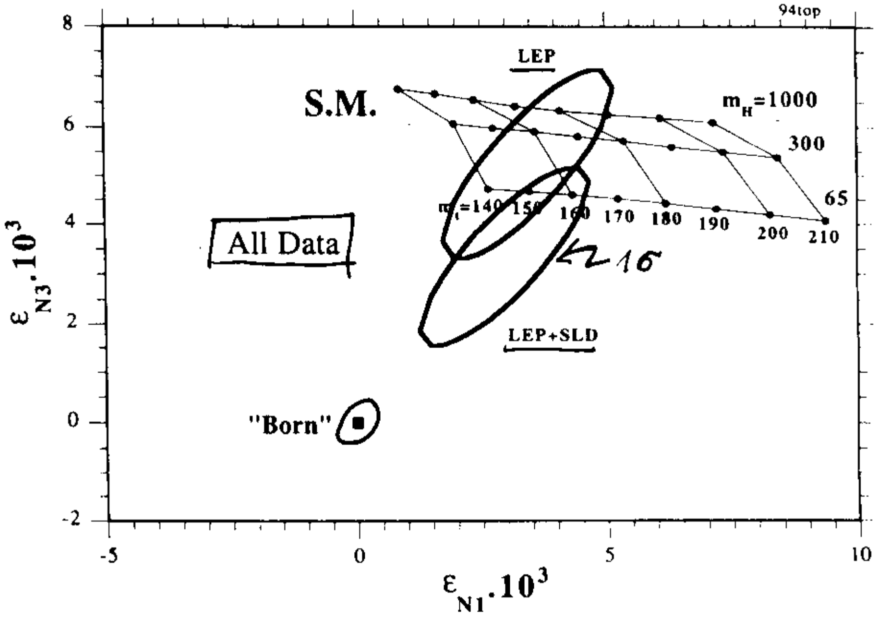
Also : $\alpha_s(m_Z)$ =0.119± 0.005

$\epsilon_1, \epsilon_2, \epsilon_3, \epsilon_b$
in the Standard Model



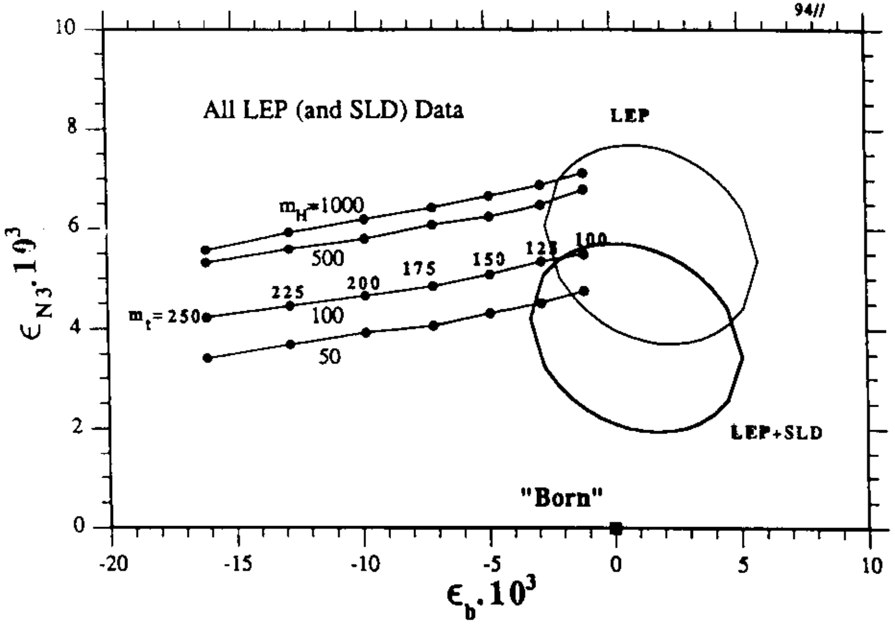
Typical size of ϵ_i's in "Higgs-less" models
(current literature)
$\epsilon_i \approx 1 \div 3\%$

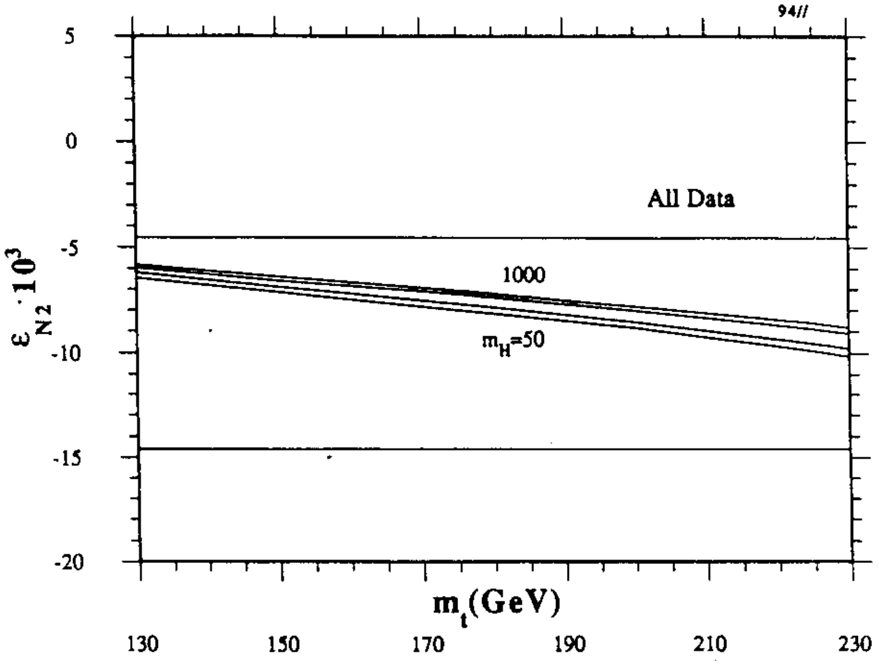
ϵ_3 versus ϵ_1



. Deviations from "Born" seen for the first time

. As expected in SM


94//
All LEP (and SLD) Data
LEP
m_H=1000
500
m_t=250
225
200
175
150
125
100
100
50
LEP+SLD
"Born"
ε_N3·10^3
10
8
6
4
2
0
-20
-15
-10
-5
0
5
10
ε_b·10^3


94//
All Data
1000
m_H=50
ε_N2·10^3
5
0
-5
-10
-15
-20
m_t(GeV)
130
150
170
190
210
230

$$\mathcal{L}^{eff}_{VB} = -\frac{1}{2} W^{+}_{\mu\nu} W^{-}_{\mu\nu} - \frac{1}{4}(1-e_2) W^{3}_{\mu\nu} W^{3}_{\mu\nu}$$

$$-\frac{1}{4} B_{\mu\nu} B_{\mu\nu} + \frac{1}{2}\frac{s}{c} e_3 B_{\mu\nu} W^{3}_{\mu\nu}$$

$$+\frac{1}{2} M_Z^2 Z_\mu^2 + M_Z^2 c^2 (1+e_1) W^{+}_{\mu} W^{-}_{\mu}$$

$$\mathcal{L}^{eff}_{eq}(Z \to b\bar{b}) = \frac{g}{2c} e_B Z_\mu \bar{b}_L \gamma_\mu b_L$$

$$\epsilon_1 = e_1 + \dots \leftarrow (\Pi'', \delta g_{V,A}, \delta G)$$

$$\epsilon_2 = e_2 + \dots$$

$$\epsilon_3 = e_3 + \dots$$

$$\epsilon_b = e_b + \dots$$

$$e_1 \propto T$$

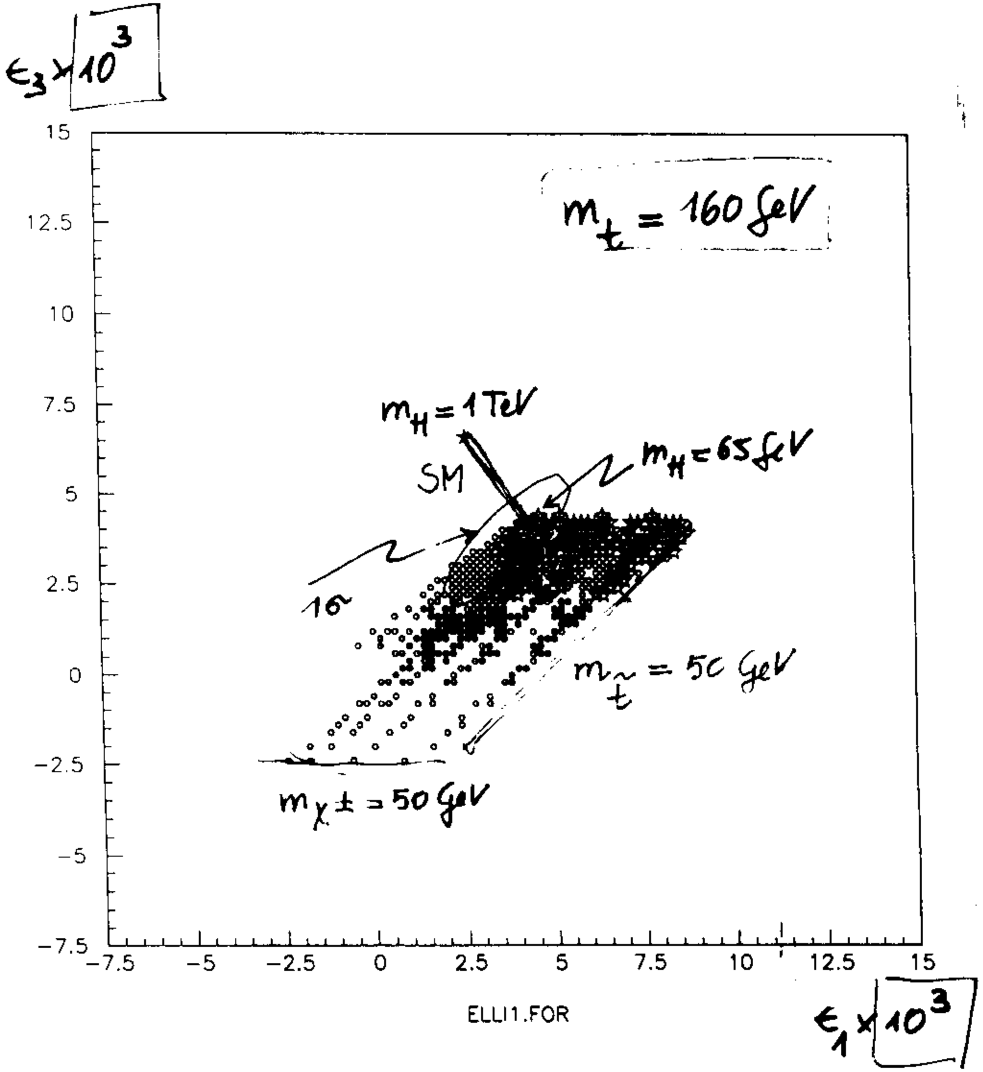
$$e_3 \propto S$$

Summary on ϵ's

	Defining variables	All data	
$\epsilon_1 \times 10^{-3}$	4.8 ± 2.2	3.0 ± 1.7	$\Leftarrow$
ϵ_2	-7.0 ± 5.3	$-9.5 \pm \underline{5.0}$	(ΔM_W)
ϵ_3	3.5 ± 3.0	3.4 ± 1.8	$\Leftarrow$
ϵ_b	5.05 ± 4.8	$\underline{\underline{1.3 \pm 4.1}}$	$(\Delta\alpha_s) \swarrow$

The expected deviations in the SM from Born seen for the first time

Minimal Supersymmetric Standard Model



"TECHNICOLOUR" AND ALL THAT
("HIGGS-LESS" THEORIES)

$\boxed{\epsilon_1 = ?}$ (top-bottom mass difference)

$\epsilon_1(exp) = (3.0 \pm 1.7)\,10^{-3}$

$\boxed{\epsilon_3 = (20 \div 35)\,10^{-3}}$ (QCD-like, $N_{TC} = 4$, 1 TC-family)

Peskin, Takeuchi

$\epsilon_3(exp) = (3.4 \pm 1.8)\,10^{-3}$

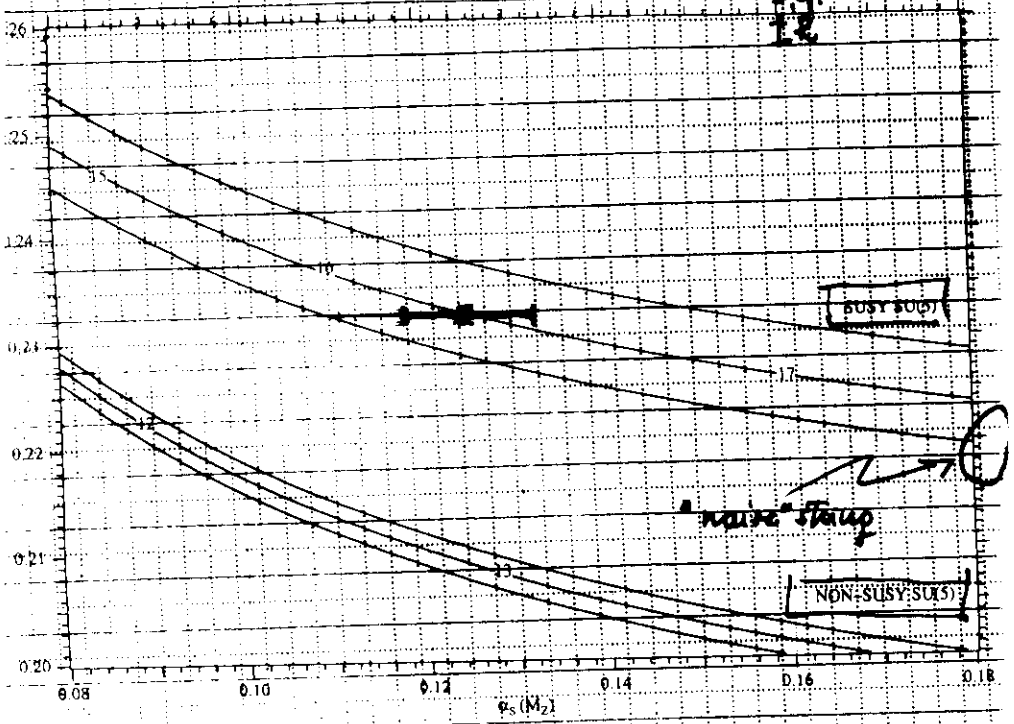
$\boxed{\epsilon_b = -(20 \div 30)\,10^{-3}}$ (extended technicolour)

Chivukula et al

$\epsilon_b(exp) = (1.3 \pm 4.1)\,10^{-3}$

UNIFICATION OF COUPLINGS

DRW. 1991
PG.
12



- Error dominated by theoretical uncertainties
  (my own 'estimate')

- $(\alpha_G, M) \xrightarrow{\alpha_{exp}}$ one parameter relation between $\sin^2\theta_W$ and α_S

as opposed to

$(\alpha_G, M, M_I) \rightarrow (\alpha, \sin^2\theta_W, \alpha_s)_{exp}$

IS THERE A GRAND UNIFIED SUPERSYMMETRIC STANDARD MODEL?

- * correct vacuum

  $G \to SU(3) \times SU(2) \times U(1) \to SU(3) \times U(1)_{em}$

- * No fast proton decay : "doublet-triplet splitting"

- * Flavour simplicity at high energy

Not quite! A highly rewarding task:

neutrino masses,

τ_{proton},

threshold effects, ...

The most outstanding theoretical problems

1. Supersymmetry breaking
2. Finding a "consistent" GUT
3. The flavour problem

* Soft breaking terms ↔ Strings

* GUTs ↔ Strings

$$\frac{1}{\alpha_i(M_Z)} = k_i \frac{1}{\alpha_G(M_X)} + b_i \lg \frac{M_X}{M_Z} + \Delta_i$$

$$M_X \simeq g\, 10^{18}\ \text{GeV}$$

Need significant Δ_i. If $\Delta_i = c b_i \Rightarrow M_X \to M$

$$\underline{\Delta_i \neq c b_i}$$

* The flavour problem

up → down ⇐

bottom → up

↳ "Textures"

$$M_{ij} = \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon^2 \\ \epsilon^2 & \epsilon & \epsilon \\ 1 & \epsilon & 1 \end{pmatrix}$$

An example

BDS

motivated by strings (?)

$$G = SO(10)_1 \times SO(10)_2 \times SO(10)_3 \qquad (\subset SO(32))$$

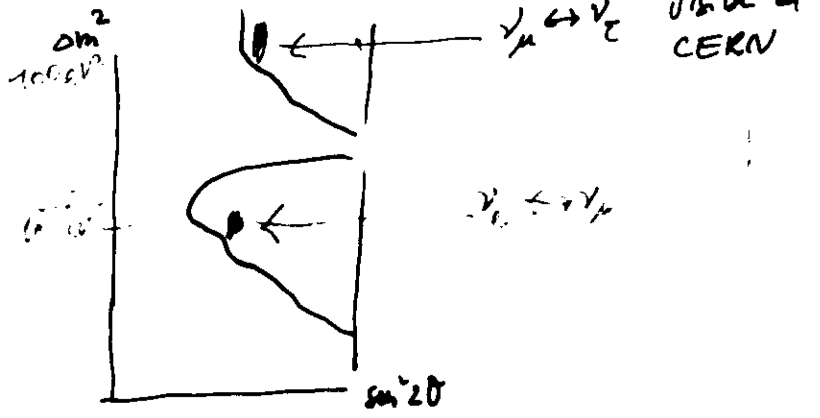
family index $i = 1,2,3$

invariant under P_{ij}

$$m_{\nu_\tau} = \boxed{\frac{M_{Pl}}{\langle \nu_R \rangle^2}}\, m_t^2(GUT) \lesssim 100\,eV \quad \Big\} \ \mathrm{sen}\,2\theta_{\tau\mu} \boxed{\simeq} 0.1$$

$$m_{\nu_\mu} = m_{\nu_\tau}\left(\frac{m_c}{m_t}\right)^2_{GUT} \lesssim 3\cdot 10^{-3}\,eV \quad \Big\} \ \mathrm{sen}\,2\theta_{\mu e} \boxed{\simeq} 0.1$$

$$m_{\nu_e} \simeq m_{\nu_\mu}\left(\frac{m_u}{m_c}\right)^2_{GUT} \lesssim 10^{-7}\,eV$$

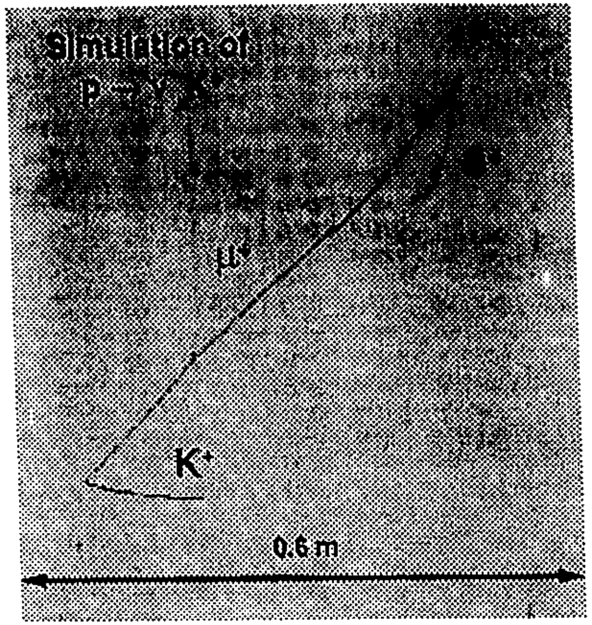


DISCOVERING SUPERSYMMETRY

Find	Sufficient	Almost sufficient	Necessary
One (more) superpartner below 1 TeV	X		X
p → Kν	X		
WIMP dark matter		X	
A light Higgs		X	X

(EVERY BOX REQUIRING AN
ELEMENT OF JUDGEMENT!
IS ALWAYS)

(ICARUS)



$\tau(p \to \nu K) \gtrsim 10^{32}$ y.s Kamiokande

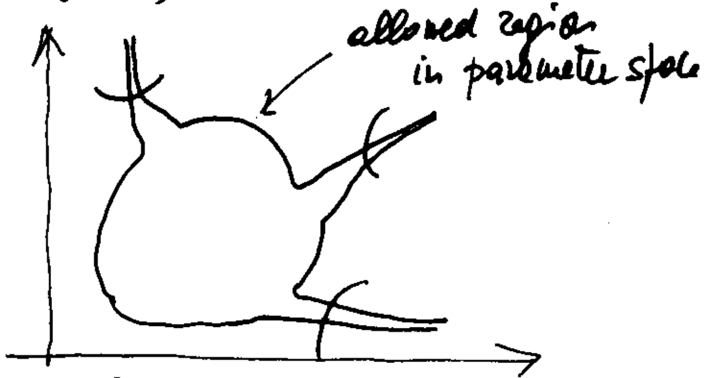
Bounds on supersymmetric particle masses

B.G.

MSSM $a_i = (\mu, M, m, A, B)$ λ, γ

$$M_Z^2 = f_\mu \mu^2 + f_M M^2 + f_m m^2$$

$$f_i(g; g_t; A, B)$$



$\forall_i$ $$\frac{\Delta M_Z^2}{M_Z^2} \lesssim \frac{1}{\delta}\frac{\Delta a_i}{a_i}$$

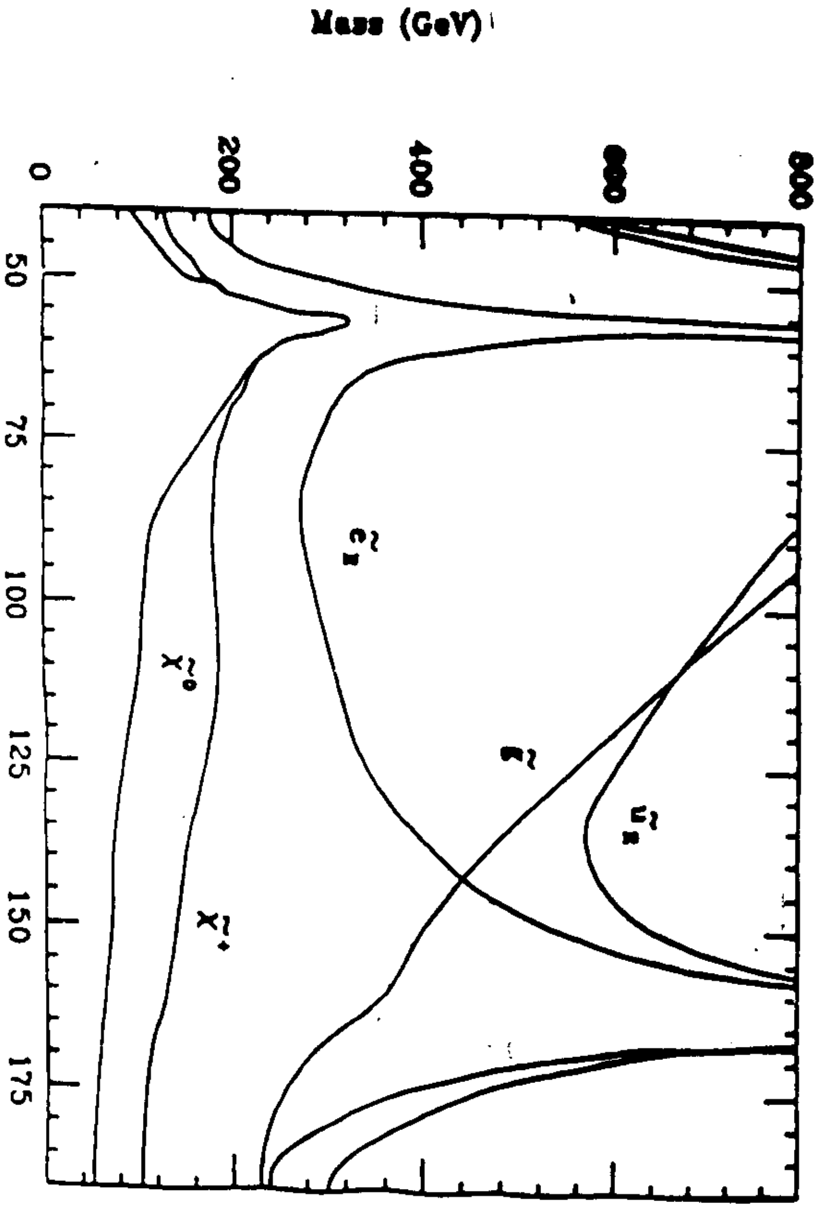
$\delta = 10\%$

$m_{\chi_1} \lesssim 100$ GeV

$m_{\chi_1^\pm} \lesssim 200$ GeV

$m_{\tilde\ell} \lesssim 300$ GeV

$m_{\tilde q}, m_{\tilde g} \lesssim 700$ GeV

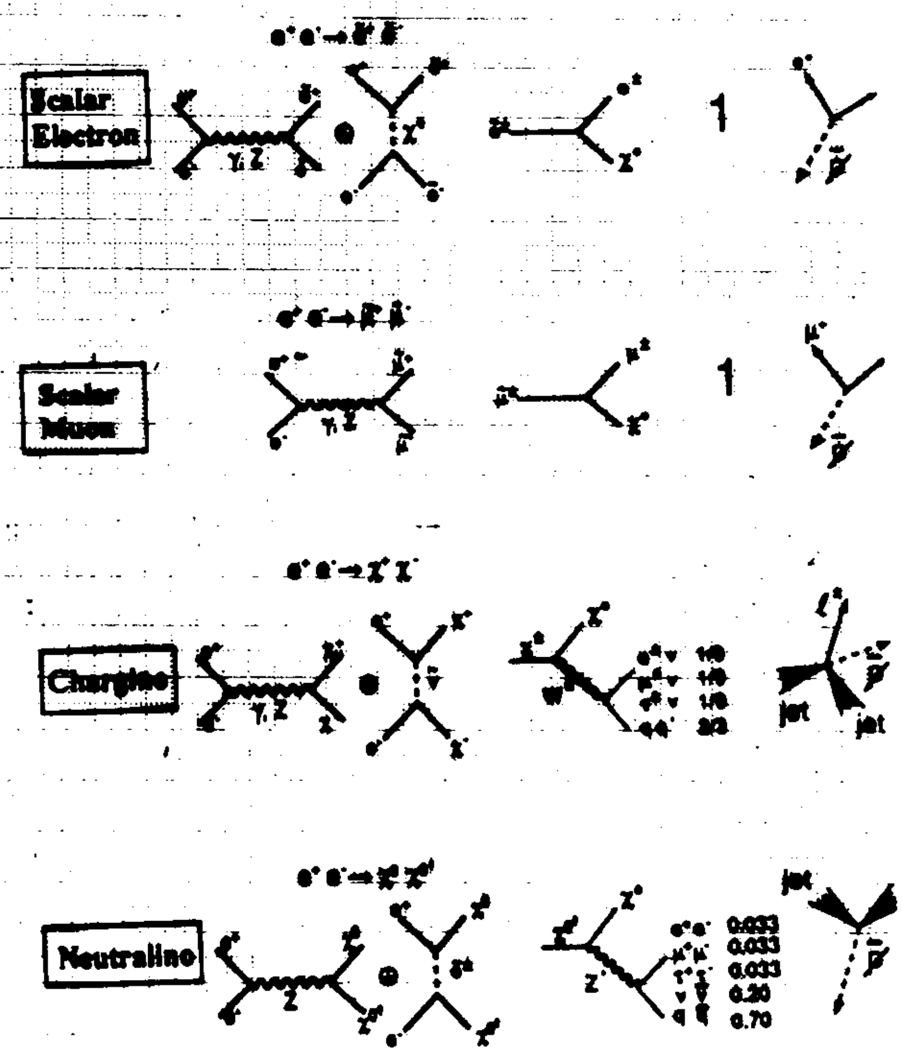


NATURALNESS UPPER BOUNDS
ON SUPERSYMMETRIC
PARTICLES

B. Giudice

SUSY PARTICLE SIGNATURES

LEP II

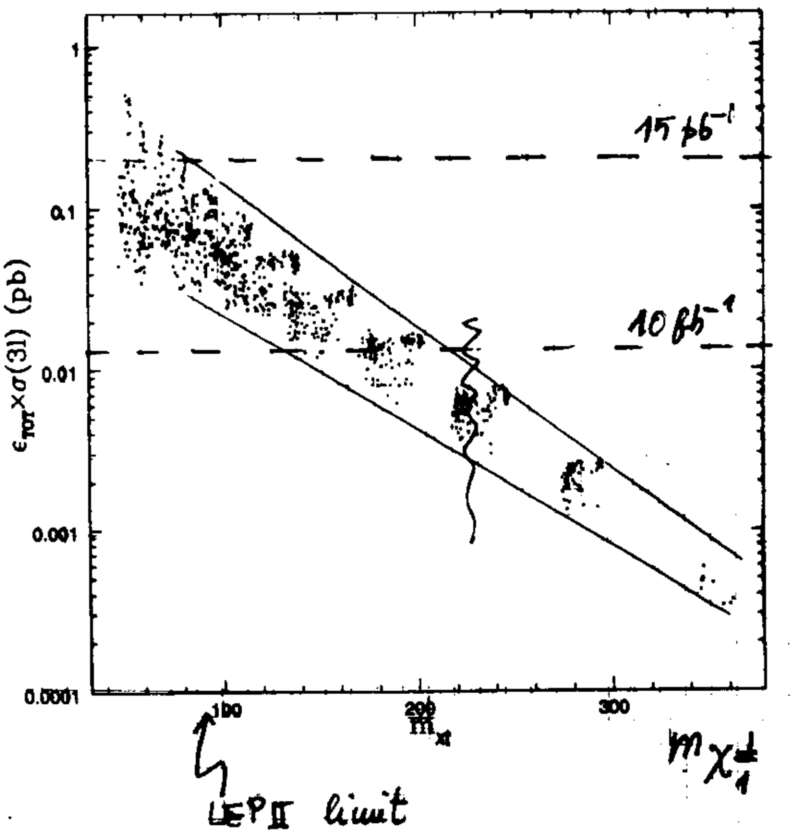


SUSY PARTICLE	PRODUCTION	DECAY	BR	SIGNATU
Scalar Electron	$e^+e^- \to \tilde{e}^+\tilde{e}^-$	$\tilde{e}^\pm \to e^\pm \chi^0$	1	
Scalar Muon	$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$	$\tilde{\mu}^\pm \to \mu^\pm \chi^0$	1	
Chargino	$e^+e^- \to \chi^+\chi^-$	$e^\pm\nu$ $\mu^\pm\nu$ $\tau^\pm\nu$ $q\bar{q}'$	1/9 1/9 1/9 2/3	
Neutralino	$e^+e^- \to \chi^0\chi^{0\prime}$	e^+e^- $\mu^+\mu^-$ $\tau^+\tau^-$ $\nu\bar{\nu}$ $q\bar{q}$	0.033 0.033 0.033 0.20 0.70	

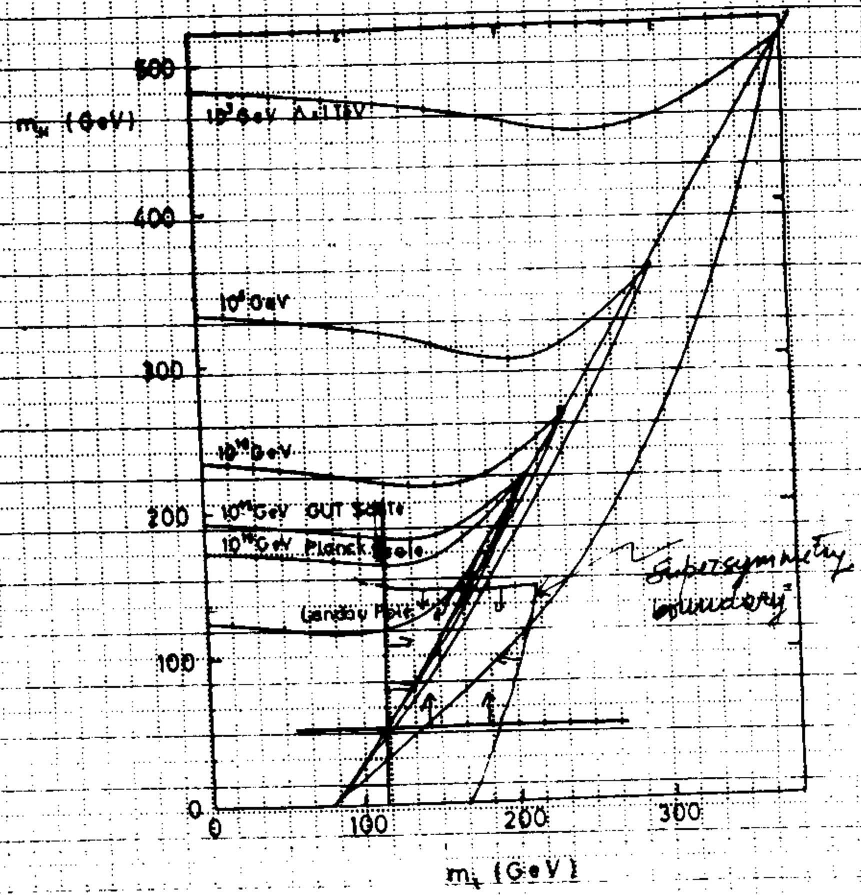
$$p\bar{p} \rightarrow \chi^{+}\chi^{-} \rightarrow 3\ell^{+} + \ldots$$

$$\sqrt{s} = 2\,\mathrm{TeV}$$

Kane et al



Finding the top and the Higgs



Arbitrary supersymmetry

⊕

$\underline{\Lambda = 10^{16}\,\text{GeV}}$ (conform with SM)

$\lambda^{\text{eff}} = \alpha g^2 + \beta\lambda \quad \alpha,\beta < 1$

Quiros
Kane et al

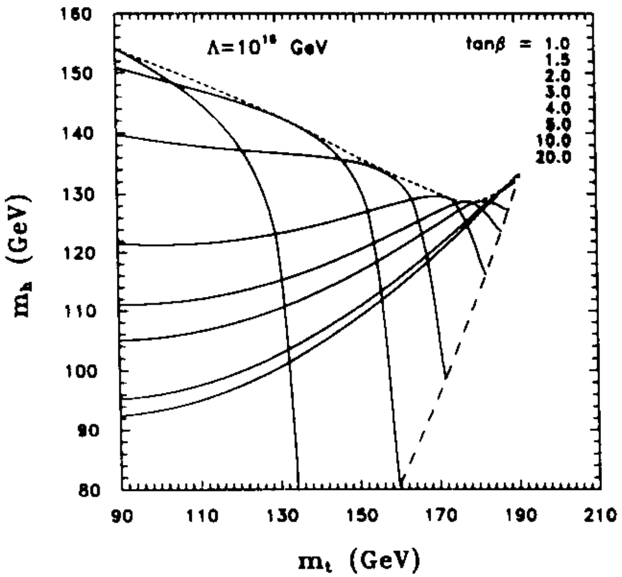


Fig. 4

$m_h < 155$ GeV

$m_t = 140$ GeV → $\tan\beta > 1.1$ $\quad m_h < 140$ GeV

Supersymmetry with Higgs doublets only

$V = \lambda\varphi^4 + \ldots$ $\quad \boxed{\lambda = g^2}$ $\quad m_H \simeq g v$

$W = \cancel{H_{1/2} H_{1/2} H_{1/2}}$

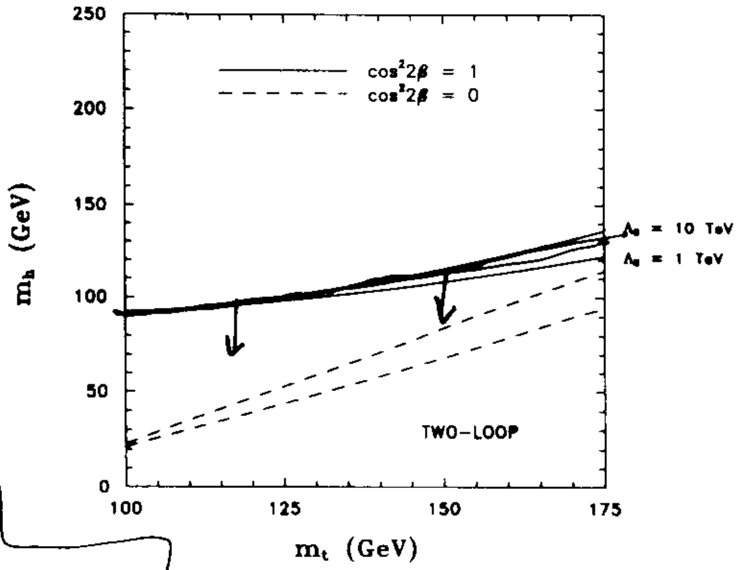


Fig. 1

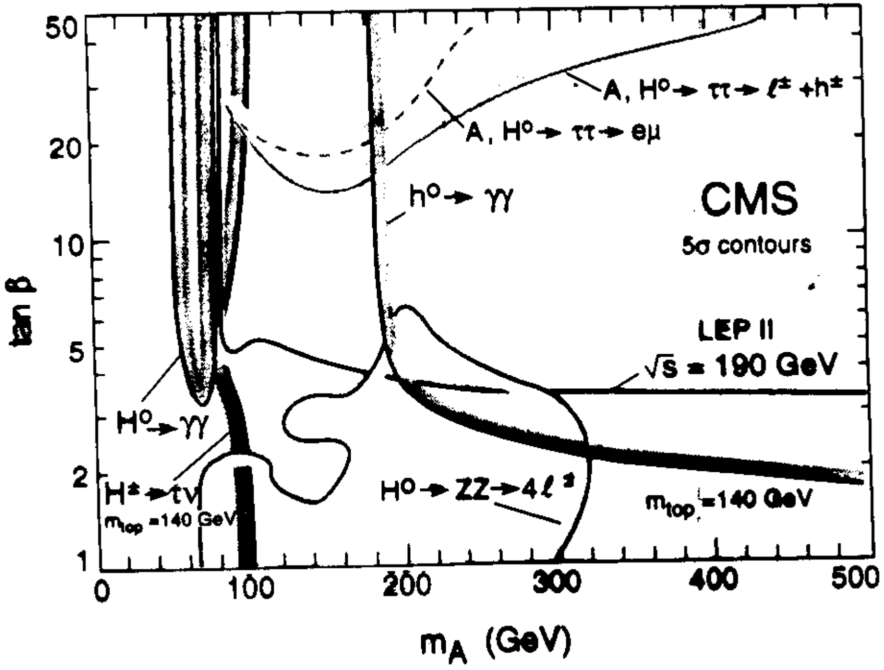
no problem
from the convergence
of the expansion

Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels

K. Z.

$h^0 \to \gamma\gamma$; $H^0 \to \gamma\gamma$, $H^0 \to ZZ \to 4\ell^\pm$ for 10^5 pb^{-1}

$H^\pm \to \tau\nu$; $A, H \to \tau\tau \to \ell\ell'$ or ℓh for 10^4 pb^{-1}



	LEP II	Tevatron upgraded	LHC
χ $\chi^\pm$ $\tilde{e}$ $\tilde{\mu}$	$m \lesssim \frac{\sqrt{s}}{2} - 5$ GeV	?	$m \lesssim 150 \div 300$ GeV
$\tilde{g}$ $\tilde{q}$	—	?	$m \lesssim 800 \div 1000$ GeV
h	$m \leq \sqrt{s} - 100$ GeV	?	~any m

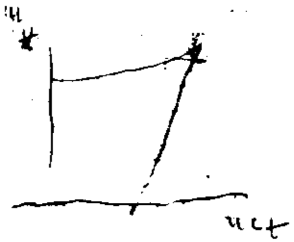
A top-Higgs correlation

1. Fixed point behaviour of g_t :

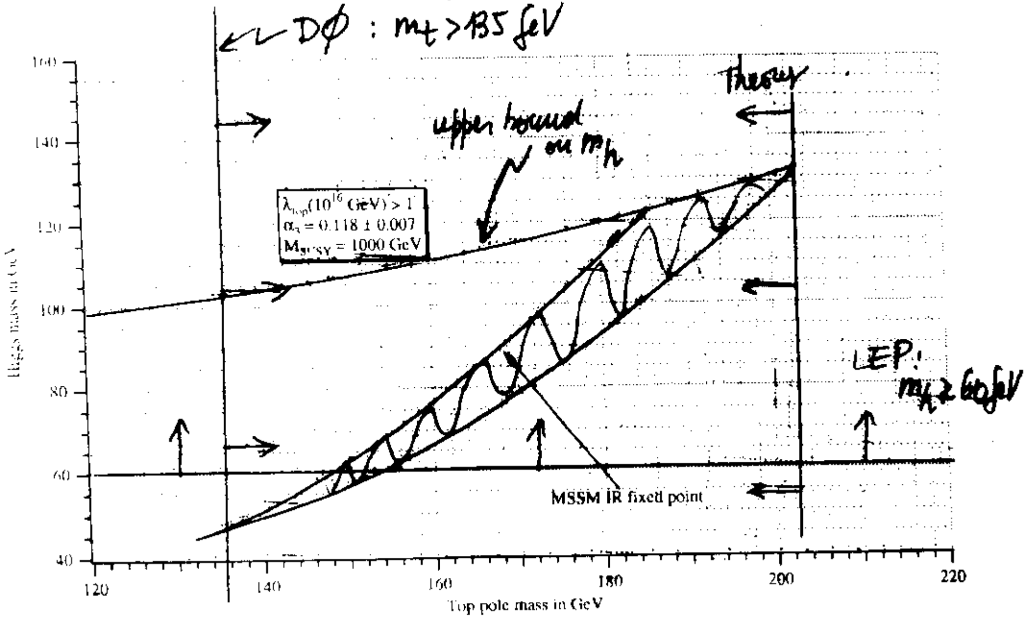
$$SM \;:\; \underline{m_t \gtrsim 230\ GeV} \quad (M \simeq 10^{15} \div 10^{19}\ GeV)$$
$$(m_H \gtrsim 260\ GeV)$$

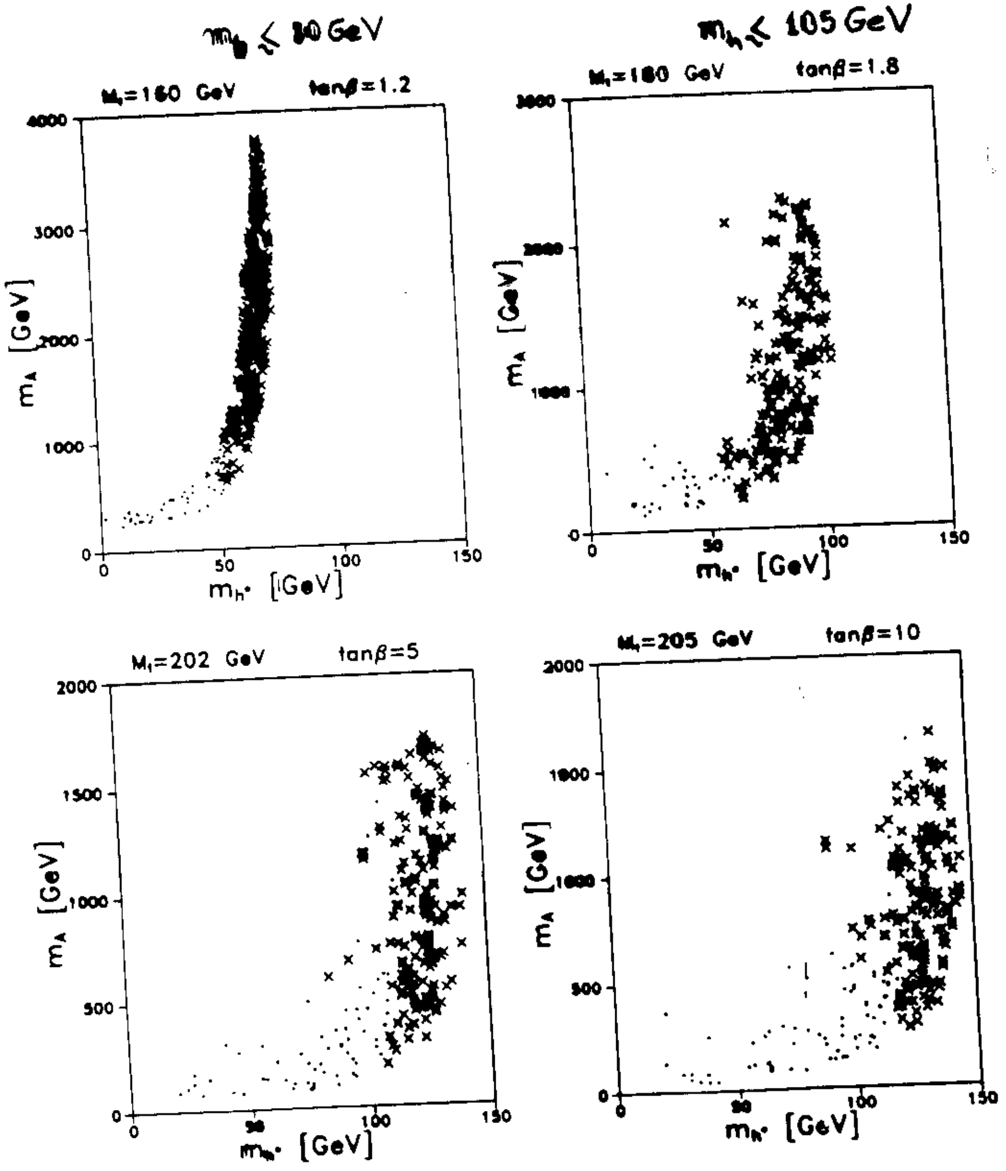
2. $\underline{m_b/m_\tau\big|_M = 1}$

$$SM \;:\; \underline{m_t \lesssim 90\ GeV}$$



$\boxed{\text{MSSM}}$





POKORSKI ET AL.

CONCLUSIONS

1. Since first theoretical proposals of SGUTs experiments have (slowly) moved in the <u>expected</u> (foreseen) direction
2. Overall picture not yet at hand, but...
3. Clear discovery potentials

WHEN (IF) FIRST SEEN ...

y_t "infrared" fixed point → Pendleton, Ross
Hill (in SM)
...
...

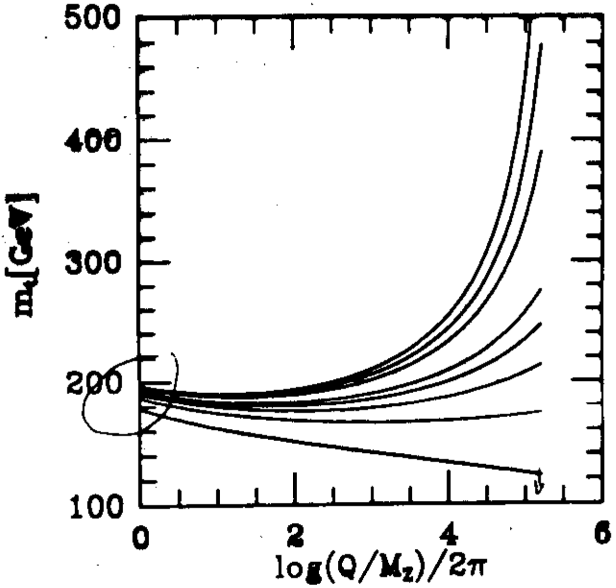


Fig. 1

Dimopoulos et al
Barger et al
Langacker, Polonsky
Polonsky et al
Carena, Wagner

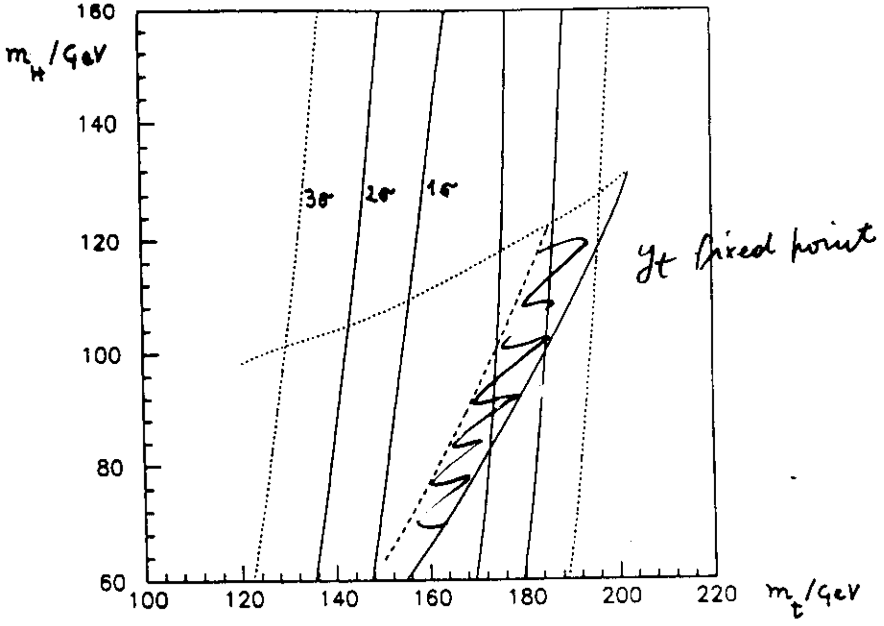


Figure 7. The same as in figure 6, compared with the isoplot of the χ^2 from the precision tests, as in figure 1.

ACKNOWLEDGEMENTS

I have greatly benefited from the collaboration on these matters with G. Altarelli and F. Caravaglios. I am also grateful to D. Bardin, O. Nicrosini and G. Passarino for providing tables of the various observables in the Standard Model, using their programmes ZFITTER and TOPAZ0. Finally, it is a pleasure for me to thank Giorgio Bellettini and Mario Greco for their organisation of the Conference.

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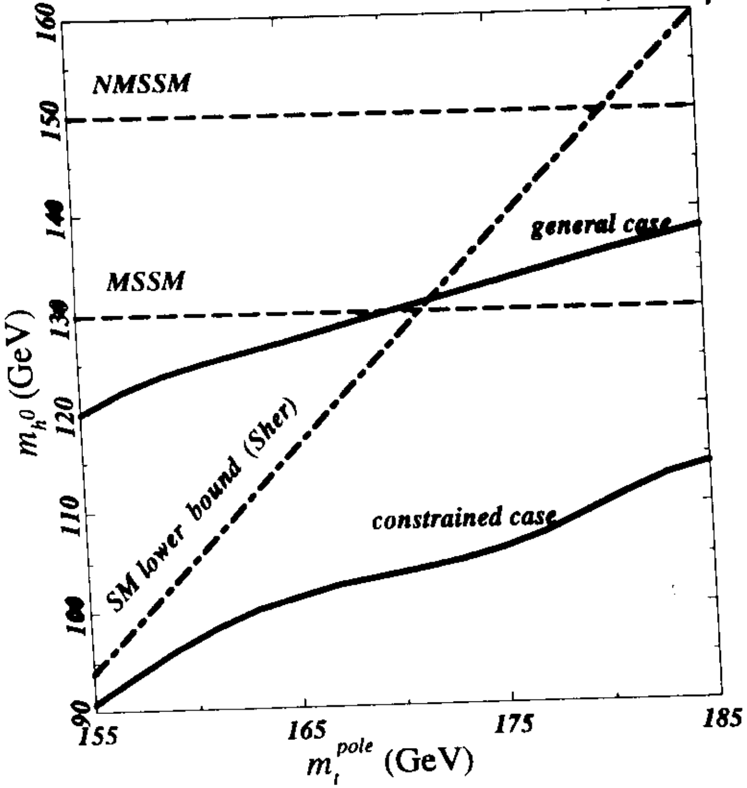
Polonsky


NMSSM
MSSM
general case
constrained case
SM lower bound (Sher)
m_{h^0} (GeV)
90
100
110
120
130
140
150
160
155
165
175
185
m_t^{pole} (GeV)