

LEPTS, 28 Aprile 2000

## **VERSO IL DOPO LEP**

**G. Altarelli**

- Cosa ci ha insegnato LEP
- Il quadro generale della fisica delle particelle
- Conseguenze per la ricerca dell'Higgs e della Nuova Fisica

## THE CONTEXT:

AT PRESENT IN PARTICLE PHYSICS  
THERE IS A STANDARD MODEL

**AND**

A STANDARD WAY BEYOND THE  
STANDARD MODEL:

STANDARD MODEL  
+ SUPERSYMMETRY  
+ GRAND UNIFICATION  
+ STRING THEORY

ALL ACCELERATOR EXPERIMENTS  
STRONGLY SUPPORT THE STANDARD  
MODEL :

NO SIGNIFICANT DEVIATIONS ARE  
OBSERVED FOR

$$E \leq 100 - 1000 \text{ GeV}$$

OR

$$r \geq 10^{-16} - 10^{-17} \text{ cm}$$

OR WE CAN FOLLOW THE HISTORY OF  
THE UNIVERSE DOWN TO

$$t \geq 10^{-10} - 10^{-12} \text{ s}$$

FROM THE BIG BANG

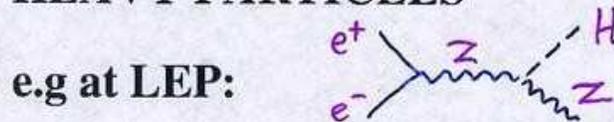
$$(t(\text{s})) = [1 \text{ MeV}/kT]^2, \text{ where}$$

t=time,  
T= temperature)

- THE STANDARD MODEL WORKS VERY WELL

- WHY NOT FIND THE HIGGS AND DECLARE PARTICLE PHYSICS SOLVED?

**FIRST OF ALL YOU HAVE TO FIND IT!**  
**DIFFICULT: IT ONLY COUPLES TO HEAVY PARTICLES**



→ **BECAUSE OF BOTH :**

**CONCEPTUAL PROBLEMS:**

- MAINLY THE HIERARCHY PROBLEM

**AND EXPERIMENTAL CLUES:**

- COUPLING UNIFICATION
- NEUTRINO MASSES
- DARK MATTER
- BARYOGENESIS

## CONCEPTUAL PROBLEMS OF SM

MOST CLEARLY:

- NO QUANTUM GRAVITY ( $M_{\text{Pl}} \sim 10^{19}$  GeV)
- BUT A DIRECT EXTRAPOLATION OF SM LEADS DIRECTLY TO GUT's ( $M_{\text{GUT}} \sim 10^{15-16}$  GeV)

$M_{\text{GUT}}$  CLOSE TO  $M_{\text{Pl}}$

SUGGESTS UNIFICATION WITH GRAVITY  
(SUPERSTRING THEORIES)

POSES THE PROBLEM OF RELATION OF PHYSICS AT  $M_{\text{W}}$  AND AT  $M_{\text{GUT}} - M_{\text{Pl}}$

CAN THE SM BE VALID UP TO  $M_{\text{GUT}} - M_{\text{Pl}}$ ??

**IT LOOKS VERY UNPLAUSIBLE!!**

MOST OF THE CONCEPTUAL PROBLEMS  
OF SM CAN BE POSTPONED TO  $M_{\text{pl}}$ :  
(e.g TO THE SUPERSTRING "TOE")

- PROLIFERATION OF PARAMETERS
- FERMION SPECTRUM (FAMILIES,  
MASSES, MIXINGS)
- ORIGIN OF P, C, CP NON  
CONSERVATION
- .....

BUT THIS PROBLEM **NEEDS** A SOLUTION  
AT TeV ENERGIES:

## THE HIERARCHY PROBLEM

$M_{\text{W}}/M_{\text{pl}} \sim 10^{-17}$  very unnatural in SM !!

**THE HIERARCHY PROBLEM HAS TO  
DO WITH THE E-W SYMMETRY  
BREAKING SECTOR OF THE THEORY**

## THE HIERARCHY PROBLEM



- ASSUME "THE DESERT"
- A "TOE" AT  $\Lambda \sim M_{\text{GUT}} \sim M_{\text{Pl}}$
- A LOW ENERGY EFFECTIVE THEORY AT  $O(1\text{TeV})$

IN THIS CONTEXT RENORMALISABILITY APPEARS AS A NECESSARY CONDITION FOR INSENSITIVITY TO LARGE MOMENTA OF  $O(\Lambda)$ .

NOT ONLY A SELF CONSISTENT AND PREDICTIVE LOW ENERGY THEORY MUST BE RENORMALISABLE

BUT BEING  $\Lambda$  SO LARGE

THE DEPENDENCE ON  $\Lambda$  OF COUPLINGS AND MASSES MUST BE REASONABLE

With New Physics at  $M_{\text{GUT}} - M_{\text{Pl}}$  the renorm.ble SM/MSSM is only an effective theory

After integration of heavy d.o.f.:

$$\mathcal{L} = \underbrace{o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4 + \dots}_{\text{Ren. part}} + \underbrace{o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6 + \dots}_{\text{Non Ren. Part}}$$

$\mathcal{L}_i$ : Operator of dim  $i$

In absence of symmetries or selection rules:  $c_i \mathcal{L}_i$

$\rightarrow o(\Lambda^{4-i}) \mathcal{L}_i$

$\mathcal{L}_2$ : Boson masses ( $\phi^2$ ). In SM Higgs sector  
**NOT PROTECTED**:  $c_2 \sim O(\Lambda^2)$

$\mathcal{L}_3$ : Fermion masses ( $\bar{\psi}\psi$ ). In SM **PROTECTED**  
by chiral symmetry,  $SU(2) \otimes U(1)$ :  $\Lambda \rightarrow m \log \Lambda$

$\mathcal{L}_4$ : renorm.ble interactions e.g.  $\bar{\psi}\gamma^\mu\psi A_\mu$

$\mathcal{L}_{i>4}$ : nonrenorm.ble interactions: suppressed  
e.g.  $c/\Lambda^2 \bar{\psi}\gamma^\mu\psi \bar{\psi}\gamma_\mu\psi$

$\Lambda$  : SCALE OF NEW PHYSICS  
BEYOND THE S.M.

$$\delta p^2 \sim \Lambda^2$$

$$\Lambda \gg m_W, m_Z$$

THE S.M. IS O.K. UP TO NOW

$$\Lambda \sim (\text{few times } G_F^{-1/2}) \sim O(1\text{TeV})$$

FOR A NATURAL EXPLANATION  
OF THE FERM SCALE

FOR EXAMPLE:

BROKEN SUPERSYMMETRY

$$\Lambda \sim m_{\text{SUSY PARTNERS}}$$

[FOR EXACT SUPERSYMMETRY

BOSONS  $\sim$  FERMIONS  $\Rightarrow$

$\Rightarrow$  NATURAL CANCELLATION OF  $\delta p^2$ ]

# THE HIERARCHY PROBLEM

FUNDAM. H?

COMPOSITE H?

DISREGARD??

Susy

NEW VERY STRONG FORCES

VERY EXOTIC!  
QUANTUM GRAVITY AT FEW TeV  
EXTRA COMPACTIFIED DIMENSIONS

TC  
or  
 $\bar{E}E$  CONDENSATE  
or  
TOP COLOR

GUT'S OK

PROBLEMS WITH GUT'S COSMOLOGY

SUPPORTED BY LEP

DISFAVOURD BY LEP

CAVEAT: THE COSMOLOGICAL CONSTANT  
A GIGANTIC UNRESOLVED UNNATURALITY

## SUSY NEAR THE WEAK SCALE

- Many theorists consider SUSY as established at MPI.

- Why not try to use it also at low energy to fix the SM problems.

- SUSY near the weak scale can:
  - Solve the hierarchy problem
  - Explain EW symm. breaking from  $m_t$  large
  - Readjust coupling unification
  - Provide cold dark matter

.....

- Perfectly compatible with LEP
  - Evidence for a rather light Higgs in the pert. region is hint for SUSY

- Possibly viable models exists: MSSM
  - Softly broken with gravity mediation
  - or with gauge messengers
  - or with anomaly mediation

.....

- Maximally rewarding for theorists
  - Degrees of freedom identified
  - Hamiltonian specified
  - Theory formulated, finite and computable up to MPI

PRECISE LEP DATA CONFIRM WHAT ALREADY KNOWN FROM  $p$  DECAY,  $\sin^2 \theta_W$ :

STANDARD ONE-SCALE GUTS FAIL

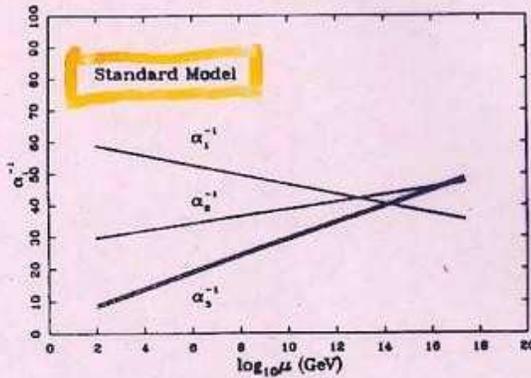
SUPERSYMMETRIC GUTS O.K.

P DECAY:

SUSY GUTS:

$M_{GUT} \uparrow \approx 10^{16} \text{ GeV}$

DOMINANT  
P DECAY  
FROM  
HIGGS  
SECTOR



↑  
MOST  
IMPORTANT  
PHEN.  
HINT  
FOR  
SUSY!

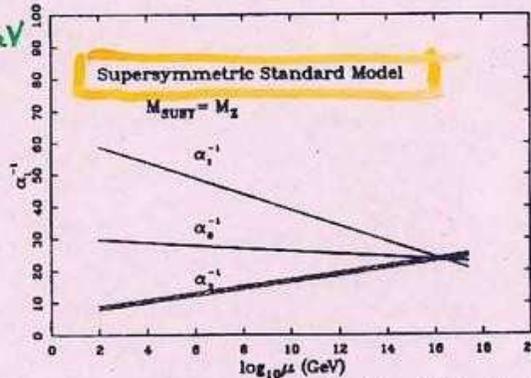


Figure 8: Running coupling in (a) the standard model and (b) in the minimal supersymmetric extension of the standard model (MSSM) with two Higgs doublets for  $M_{SUSY} = M_Z$ . The corresponding figure for  $M_{SUSY} = 1 \text{ TeV}$  is almost identical. It is seen that the couplings unify at  $\approx 10^{16} \text{ GeV}$  in the MSSM.

## GUTS: SUSY VS NON SUSY

FROM  $\alpha(m_Z)$ ,  $\sin^2 \theta_W$   
UNIFICATION OF COUPLINGS  
PREDICTS  $\alpha_s(m_Z)$

NON SUSY GUTS: (ONE SCALE)

$$\alpha_s(m_Z) = 0.073 \pm 0.002$$

SUSY GUTS

(Langacker,  
Polonsky)

$$\alpha_s(m_Z) = 0.130 \pm 0.010$$

ERROR WOULD BE SOMEWHAT LARGER  
DUE TO THRESHOLDS AT GUT SCALE

NON-SUSY GUTS EXCLUDED

SUSY GUTS PREFER LARGE  $\alpha_s(m_Z)$

PRESENT EXP. WORLD AVERAGE

$$\alpha_s(m_Z) = 0.119 \pm 0.003$$

BY NOW GUT'S ARE PART OF OUR CULTURE IN PARTICLE PHYSICS

IT IS OUR #1 PRIORITY IN BEYOND THE SM !!

- UNITY OF FORCES
- UNITY OF  $g$  AND  $e$
- CHARGE QUANTISATION  $Q_d = -\frac{1}{3} \Rightarrow N_{\text{colors}}$
- $B, X \Rightarrow$  BARYOGENESIS  
V MASSES
- (REALLY) ASYMPTOTIC FREEDOM  
 $\Rightarrow$  SOLUTION TO LANDAU POLES (QED etc)
- UNDERSTANDING FAMILY Q. NUMBERS  
e.g.  $SO(10)$ : A WHOLE FAMILY IN 16  
.....

**BUT:**

$$\mathcal{L}_{SM} = \mathcal{L}_{SYMM} + \mathcal{L}_{HIGGS}$$



GUT'S



HIERARCHY  
PROBLEM

$$\mathcal{L}_{SM} = \mathcal{L}_{SYMM} + \mathcal{L}_{HIGGS}$$

UNTESTED



GUT's

$$M_{GUT} \approx M_{Pl}$$



HIERARCHY PROBLEM

CONFIRMED BY  $\nu$  MASSES

⊥

BARYOGENESIS VIA LEPTOGENESIS



SUSY GUT's

- UNIF. OF  $\alpha_i(M_{cut})$
- NO CLASH WITH P-DECAY UNOBSERVED
- ..... ??



SUSY

NEUTRALINOS AS OPTIMAL DARK MATTER CANDIDATES

## EXP. HINTS FROM THE SKY/COSMOLOGY

### $\nu$ OSCILLATIONS

SOLAR  $\nu$ 's

ATMOSPHERIC  $\nu$ 's

(+ LOS ALAMOS)

BY NOW DIFFICULT  
TO IMAGINE THAT  
ALL GO AWAY  
OR EXPLAINED AWAY



$\nu$  MASSES

{ A WINDOW ON MGUT  
NEW INPUT FOR FERMION MASSES

### DARK MATTER

COLD (PERHAPS SOME HOT)

NON-BARYON D.M. NEEDED

OPTIONAL!

HOT: COULD BE  $\nu$ 's :  $m_\nu \sim$  FEW eV

COLD: **MISSING!**

AXIONS

susy  $\Rightarrow$  NEUTRALINOS

.....

### BARYOGENESIS

IN S.M.

1) NOT ENOUGH  $\mathcal{CP}$

2) NEED  $m_H \leq 80$  GeV

BEYOND:

AT THE WEAK SCALE: MSSM?

**EXCLUDED**

NEAR  $M_{GUT}$ : LEPTOGENESIS?

$$\Delta m_{\text{atm}}^2 \sim 3.5 \cdot 10^{-3} \text{ eV}^2$$

IF  $m_3^2 \gg m_2^2 \gg m_1^2$       THREE  
LARGELY SPLIT  
LIGHT  $\nu$ 'S

$$m_3 \sim \frac{v^2}{M} \sim \sqrt{\Delta m_{\text{atm}}^2} \quad v \sim m_t \sim 200 \text{ GeV}$$

$$\rightarrow M \sim \frac{v^2}{\sqrt{\Delta m_{\text{atm}}^2}} \sim 10^{15} \text{ GeV}$$

TANTALIZING CLOSE TO  $M_{\text{GUT}}$

$\nu$  MASSES : A WINDOW ON  
PHYSICS AT  $M_{\text{GUT}}$

## **GREAT EXP. PROGRESS IN LEP ERA!**

In '89 LEP and SLC started, CDF presented the first results.

**FROM MY TALK AT LP'89 (Stanford):**

$M_Z=91120\pm 160$  MeV (MarkII,CDF)  
 $M_t=130\pm 50$  GeV (from all EW data)  
 $\text{Sin}^2\theta_{\text{weff}}=0.2330\pm 0.0023$  "  
 $M_H\geq 3-4$  GeV !!  
 $\alpha_s(m_Z)=0.11\pm 0.01$

**NOW MORE THAN 10 YEARS LATER**

~16 Million Z+ t discovered at Tevatron+.....+LEP2

$M_Z=911871\pm 21$  MeV  
 $M_t=174.3\pm 5.1$  GeV  
 $\text{Sin}^2\theta_{\text{weff}}=0.23149\pm 0.00017$   
 $M_H\geq 106$  GeV  
 $\alpha_s(m_Z)=0.119\pm 0.003$

ALSO:  $N_\nu=2.9835\pm 0.0083$   
 $m_w=80419\pm 38$  MeV

**BUT NO SIGNIFICANT DEVIATIONS  
FROM THE SM WERE FOUND!!**

Quantity	Data (March 2000)	Pull
$m_Z$ (GeV)	91.1871(21)	0.1
$\Gamma_Z$ (GeV)	2.4944(24)	-0.6
$\sigma_h$ (nb)	41.544(37)	1.7
$R_h$	20.768(24)	1.2
$R_b$	0.21642(73)	0.85
$R_c$	0.1674(38)	-1.3
$A_{FB}^l$	0.01701(95)	0.8
$A_\tau$	0.1425(44)	-1.2
$A_e$	0.1483(51)	0.1
$A_{FB}^b$	0.0988(20)	-2.3
$A_{FB}^c$	0.0692(37)	-1.3
$A_b$ (SLD direct)	0.911(25)	-1.0
$A_c$ (SLD direct)	0.630(26)	-1.5
$\sin^2 \theta_{eff}$ (LEP-combined)	0.23192(23)	2.1
$ALR \rightarrow \sin^2 \theta_{eff}$	0.23096(26)	-1.9
$m_W$ (GeV) (LEP2+p $\bar{p}$ )	80.419(38)	0.1
$1 - \frac{m_W^2}{m_Z^2}$ ( $\nu N$ )	0.2255(21)	1.2
$Q_W$ (Atomic PV in Cs)	-72.06(44)	2.5
$m_t$ (GeV)	174.3(5.1)	0.1

# ELECTROWEAK THEORY

$$\mathcal{L} = \mathcal{L}_{\text{SYMM}} + \mathcal{L}_{\text{HIGGS}}$$

$$\mathcal{L}_{\text{SYMM}} = -\frac{1}{4} \left[ \partial_\mu W_\nu^A - \partial_\nu W_\mu^A - ig \epsilon_{ABC} W_\mu^B W_\nu^C \right]^2 +$$

↑ LEP 2, Tevatron, LHC

$$-\frac{1}{4} \left[ \partial_\mu B_\nu - \partial_\nu B_\mu \right]^2 +$$

$$+ \bar{\Psi} \gamma_\mu i (\partial^\mu - ig \tilde{W}^\mu - ig' \tilde{B}^\mu) \Psi$$

↑ WELL TESTED (ESP. AT LEP 1)

$\left\{ \begin{array}{l} \tilde{W}_\mu = \sum_A \epsilon^A W_\mu^A \\ \tilde{B}_\mu = B_\mu \frac{\gamma}{2} \end{array} \right.$

$$\mathcal{L}_{\text{HIGGS}} = \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 +$$

$$\left[ (\partial_\mu - ig \tilde{W}_\mu - ig' \tilde{B}_\mu) \phi \right]^2 +$$

$$+ \bar{\Psi} \Gamma \Psi \phi$$

$$m_H \gtrsim 105 \text{ GeV}$$

LEP 2

NO EXPERIMENTAL CHECK

A CHALLENGE FOR LEP 2, LHC, NLC

ONLY HINT :

$$m_W^2 = m_Z^2 \cos^2 \theta_W$$

AS FOR DOUBLET HIGGS

# EXPERIMENTS PROVE THAT ALL COUPLINGS ARE SYMMETRIC

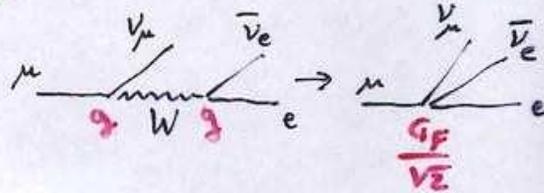
## BASIC TREE LEVEL RELATIONS

ALL CORRECTED BY  
COMPUTABLE  $f(m_i^2, \ln m_i)$   
RADIATIVE EFFECTS

•  $g \sin \theta_W = e$

•  $g'/g = \tan \theta_W$

•  $\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}$

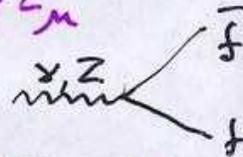


### Z COUPLINGS

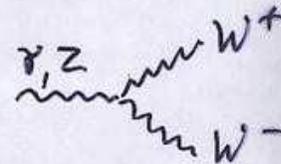
•  $\frac{g}{2\cos\theta_W} \bar{f} \gamma^\mu (g_V^f - g_A^f \gamma^5) f Z_\mu$

$f = u, c, t$   
 $d, s, b$   
 $e, \mu, \tau$   
 $\nu$ 's

$$\left\{ \begin{array}{l} g_A^f = \pm 1/2 \\ g_V^f / g_A^f = 1 - 4|Q^f| \sin^2 \theta_W \end{array} \right.$$



•  $\frac{g_{WW\gamma}}{g_{WWZ}} = \tan \theta_W$



YET THE SYMMETRY IS BADLY  
BROKEN IN THE MASSES

GAUGE SYMMETRY PREDICTS

ALL GAUGE BOSONS  
ALL FERMIONS } MASSLESS

BUT  $M_W, M_Z \neq 0$

[  $M_Z \approx M_{\text{MOLYBDENUM ATOM}} \approx 97 \text{ NUCLEONS}$  ]

ALSO, FOR EXAMPLE,  $m_t \neq m_b \neq 0$

NO REMNANT OF EVEN  
GLOBAL SU(2) SYMMETRY



SPONTANEOUS SYMMETRY

BREAKING :

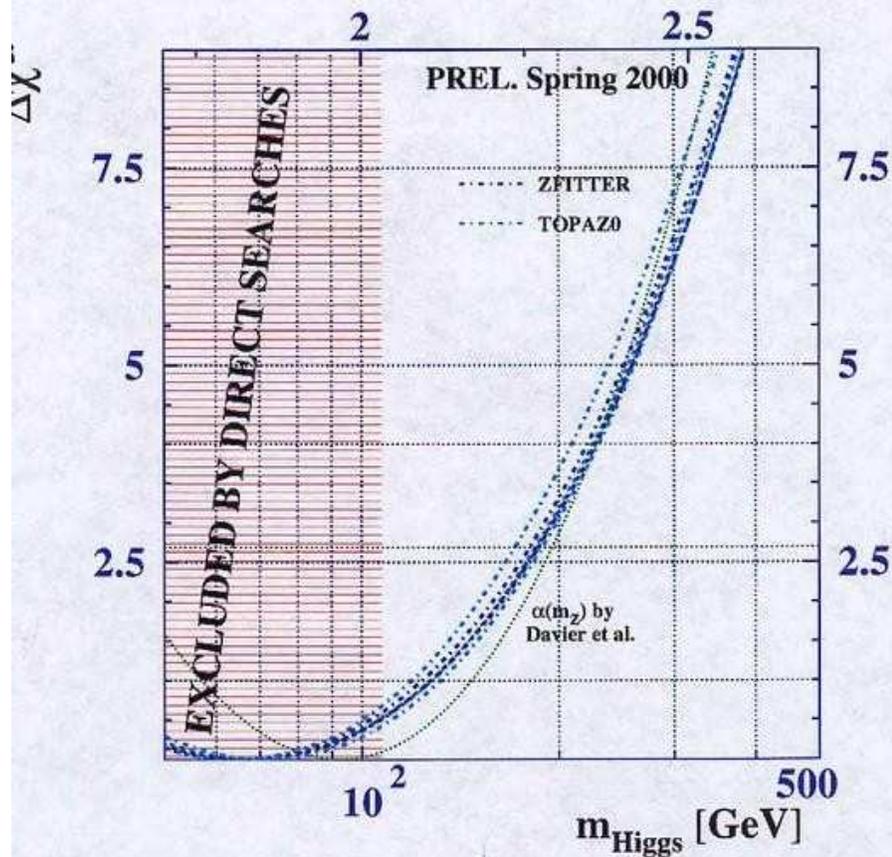
{ CURRENTS, CHARGES CONSERVED  
SPECTRUM NON SYMMETRIC

SSB IN GAUGE TH.  $\Rightarrow$  HIGGS MECHANISM

STRONG INDICATION FROM THE DATA  
FOR A LIGHT HIGGS

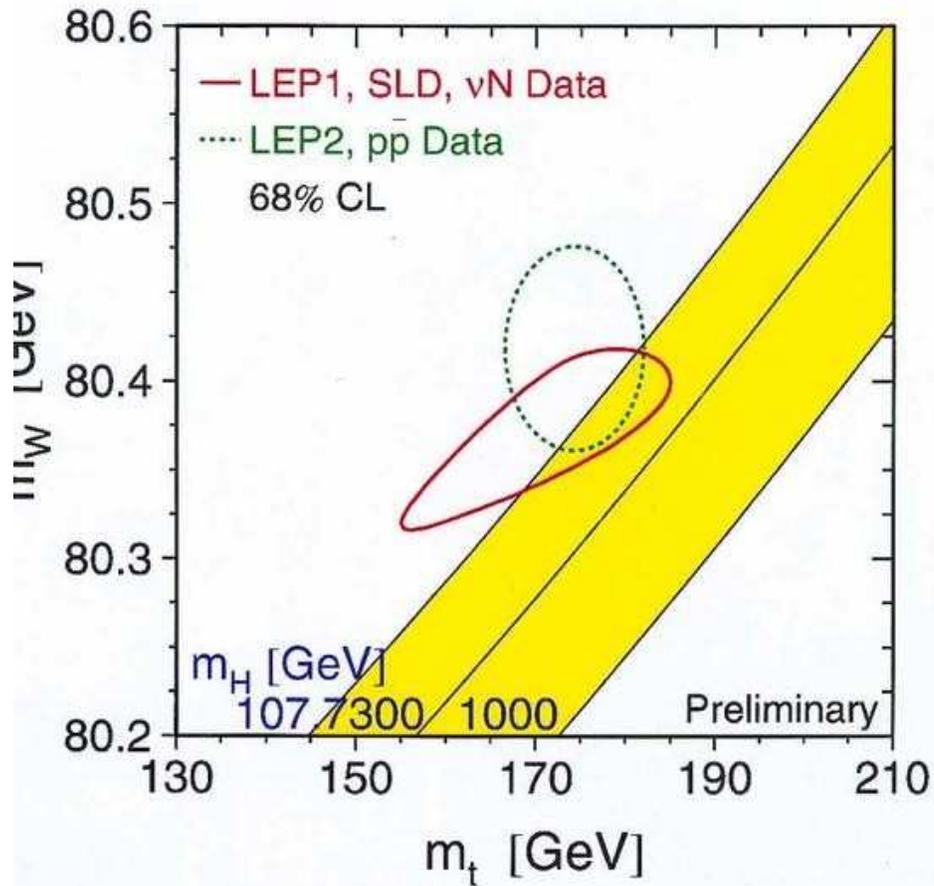
$$m_H \lesssim 200 \text{ GeV} \quad \underline{\underline{IF}} \quad \text{SM TRUE}$$

BY ADDING NEW PHYSICS THIS  
BOUND CAN BE EVADED [BUT SOME  
CONSPIRACY  
NEEDED!]

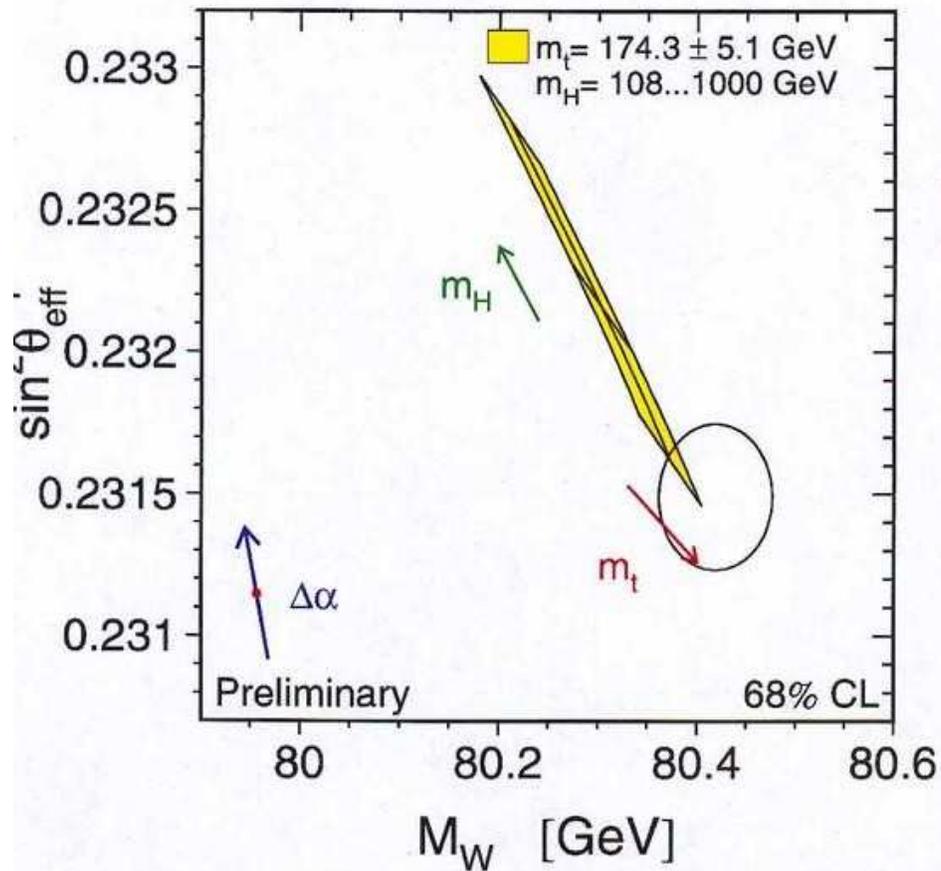


FOR EXAMPLE :

EXP. VALUES OF  $m_W, m_t \Rightarrow$   
 $\Rightarrow m_H$  LIGHT



$m_W, \sin^2 \theta_{\text{eff}} \Rightarrow m_H \text{ light}$



There are two fully developed, consistent and predictive models that explain all LEP data:

## The SM and the MSSM

We do not believe that the SM is the full effective low energy theory, while the MSSM could be (may be it is only a toy model).

### IMPORTANT RESULT:

FOR PRECISION EW TESTS  
IF ALL S-PARTNERS ARE HEAVY ENOUGH THE

MSSM ---->SM[With  $m_H$  light 0(100 GeV)]

Barbieri, Frigeni, Caravaglios

GIVEN PRESENT LIMITS ON  
S-PARTNERS ONLY SMALL DEVIATIONS  
FROM SM ARE POSSIBLE

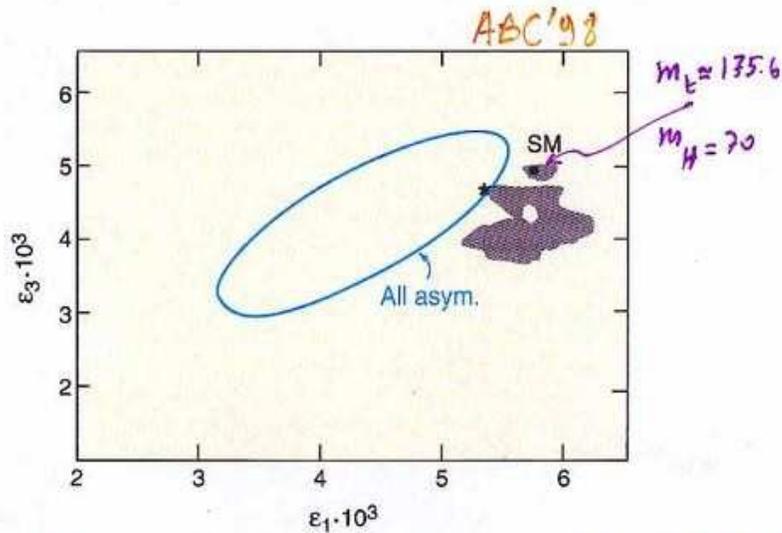
## MSSM : SCATTER PLOT

$$t_g \beta = 1.5 - 2.5$$

$$m_{\tilde{t}} = 100 - 500 \text{ GeV}$$

$$m_{\tilde{g}} = 1 \text{ TeV}, \quad m_{\tilde{t}} \text{ LARGE } (\delta R_2 \approx 0)$$

$$-200 \lesssim \mu \lesssim 200, \quad 0 < M < 250 \text{ GeV}$$



BEST REGION (\*):  $m_{\chi_1^+} \sim 90 - 105 \text{ GeV}$

$$t_g \beta \sim 1.5$$

$$m_{\chi_1^0} \approx 58.72 \text{ GeV}$$

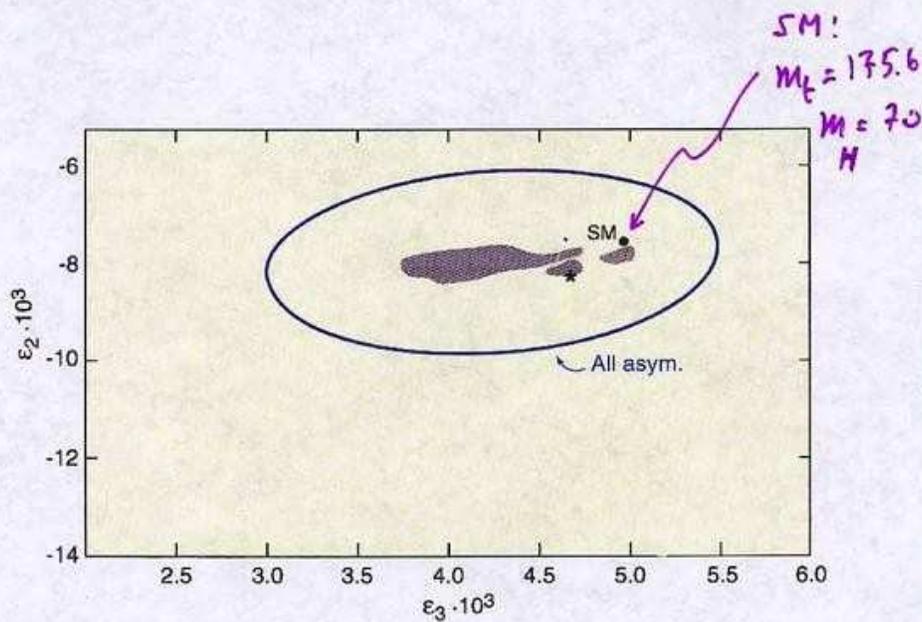
$$m_{\tilde{e}} \sim 100 \text{ GeV}$$

$$m_{\chi_2^0} \approx 129 - 147 \text{ GeV}$$

$$m_{\tilde{g}} \sim 1 \text{ TeV} \\ (\tilde{E} \text{ heavy})$$

PRESENT LIMITS ON SUSY  $\Rightarrow$

$\Rightarrow$  VERY SMALL IMPROVEMENTS  
ARE ONLY POSSIBLE!



ALL EXPERIMENTAL SUCCESSES  
OF SM ARE ALSO SHARED  
BY ITS SUSY EXTENSION  
(POSSIBLE BECAUSE  $m_H^{\text{exp}}$  LIGHT)

## STATUS OF HIGGS SEARCH

### STANDARD MODEL HIGGS:

*m<sub>h</sub> | b max*  
Theoretical limits: If SM valid up to  $\Lambda$  then:

$$\Lambda \sim M_{\text{GUT}} - M_{\text{Pl}} \rightarrow 135 \leq m_H \leq 180 \text{ GeV}$$

$$\Lambda \sim 1 \text{ TeV} \rightarrow m_H \leq 500 - 800 \text{ GeV}$$

Experimental limits

$$m_H \geq 107 \text{ GeV}$$

### MINIMAL SUSY HIGGS: h, A, H

Theoretical limit:

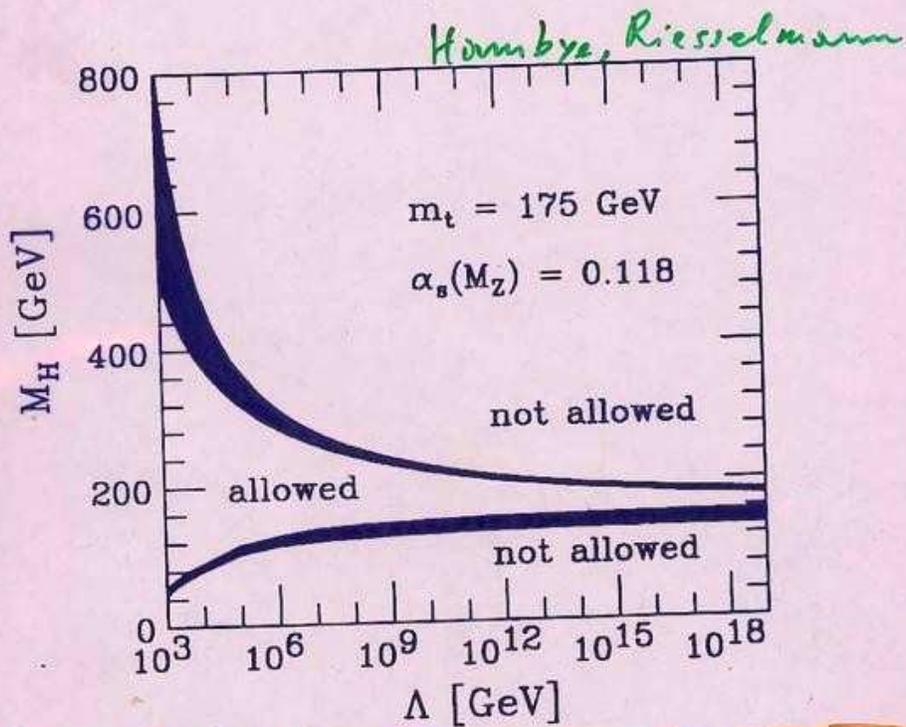
$$m_h \leq 130 \text{ GeV} \text{ (at large } \tan\beta)$$

Experimental limit:

$$m_{h,A} \geq 88 \text{ GeV}$$

Actually  $m_{h,A} \geq 80 \text{ GeV}$  if CP viol. phases are allowed. Kane, Wang

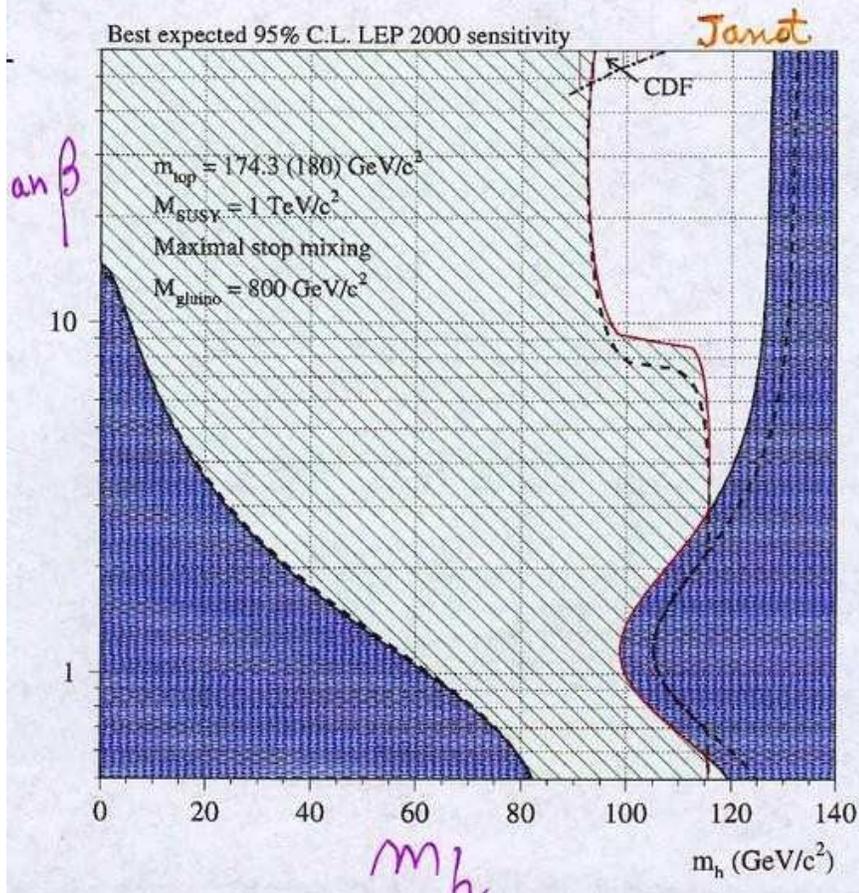
SUMMARY OF LIMITS ON  $M_H$   
IN S.M. AS FUNCTION OF  $\Lambda$



$\Lambda = M_{pl} \sim 10^{19} \text{ GeV} \quad 135 \lesssim M_H \lesssim 180 \text{ GeV}$

$\Lambda \sim 1 \text{ TeV} \quad M_H \lesssim 0.5 - 0.8 \text{ TeV}$

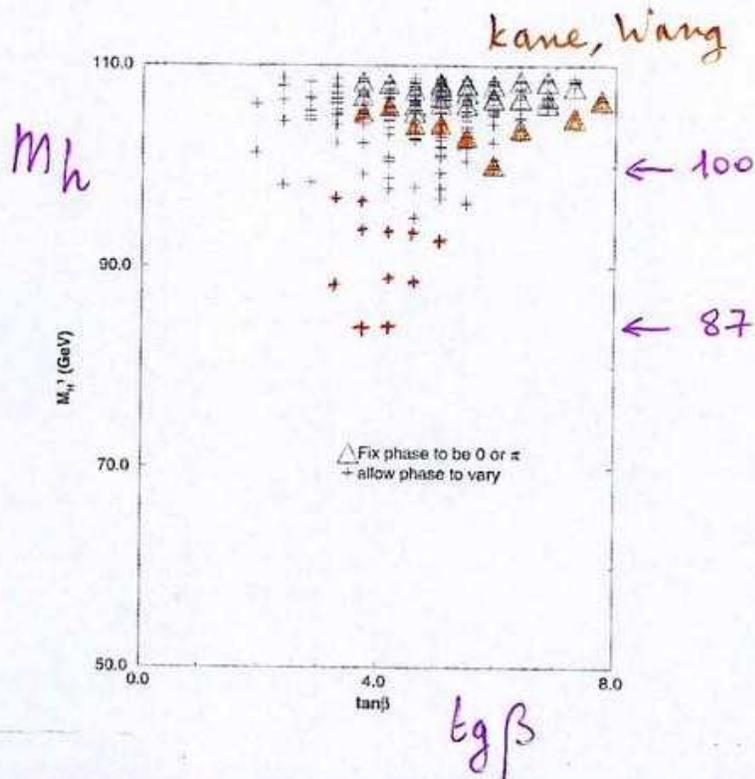
$m_h$  LIMITS FROM LEP AFTER  
2000 RUN (IF NOT SEEN)



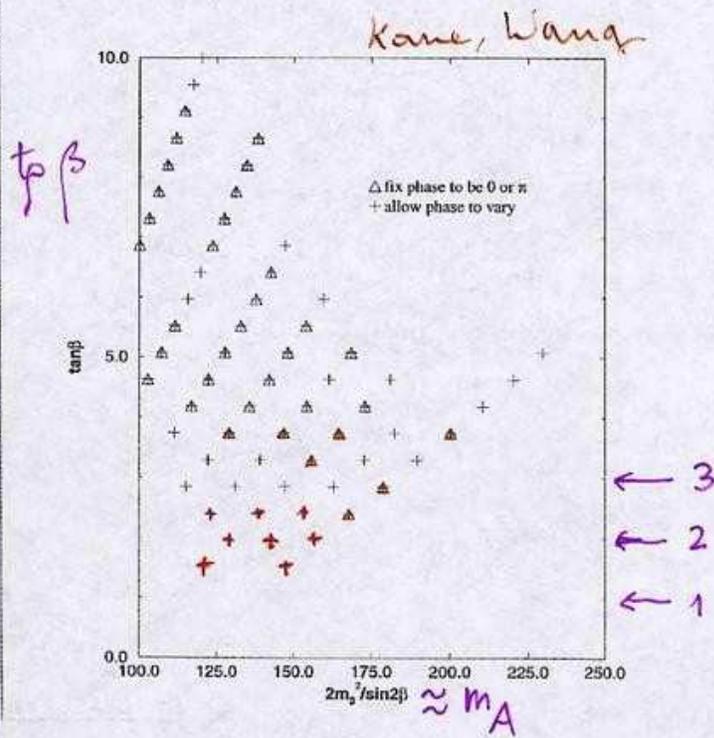
THE LEP LIMIT ON  $M_h$  IS WEAKENED  
 IF ~~CP~~ PHASES ARE KEPT IN  
 THE HIGGS POTENTIAL

e.g.  $\mu \rightarrow e^{i\phi_\mu} |\mu|$

[USUALLY  $\phi_\mu = 0, \pi$  ONLY WAS  
 ASSUMED]



PHASES MAKE EXCLUSION OF  
SMALL  $\tan\beta$  VALUES MORE  
DIFFICULT.



**SM HIGGS:** Data indicate  $m_H \leq 200 \text{ GeV}$

**A VERY IMPORTANT RESULT:**

- Supports the SM/MSSM case of a fundamental Higgs vs compositeness
- Suggests that the Higgs and/or New Physics are around the corner

**HOWEVER WE CANNOT EXCLUDE THAT THERE IS A CONSPIRACY:**

**THERE COULD BE NEW PHYSICS AT A SCALE  $\Lambda$  THAT MAKES THE SM BOUND INVALID SUCH THAT  $M_H$  AND/OR  $\Lambda$  ARE LARGE**

Recently many papers have discussed this rather obvious point.

In SM at 1-loop dependence on  $m_H$  is logarithmic

The most sensitive quantities are  $\epsilon_1$  and  $\epsilon_3$

$$\left\{ \begin{array}{l} \epsilon_1 \sim - \underbrace{\frac{3G_F m_W^2}{4\pi^2 \sqrt{2}} \tan^2 \theta_W}_{-1.2 \cdot 10^{-3}} \left[ \text{Log} \frac{m_H}{m_Z} + f_1 \right] + \dots \\ \epsilon_3 \sim + \underbrace{\frac{G_F m_W^2}{12\pi^2 \sqrt{2}}}_{0.45 \cdot 10^{-3}} \left[ \text{Log} \frac{m_H}{m_Z} + f_3 \right] + \dots \end{array} \right.$$

$f_{1,3}$  are slowly varying and constant at large  $m_H$

**DATA:  $\text{Log}_{10}[m_H(\text{GeV})] \sim 1.88 \pm 0.29$**

Just in the narrow window  
allowed in the SM

$$107 \leq M_H \leq 500-800 \text{ GeV}$$

or in the MSSM:  $M_h \leq 130 \text{ GeV}$

**This is a very impressive test:  
 $f_{1,3}$  are exactly as predicted in the SM!**

Assume there is no Higgs. Then the theory is no more renormalisable.

$$\text{Log} m_H \text{ ----> Log } \Lambda$$

$\Lambda$  is the scale of the new physics that replaces the Higgs.

The same coefficients appear in front of the logs, but the finite terms are modified  $f_{1,3} \text{ --->} c_{1,3}$ .

$$\epsilon_1 \sim - \frac{3G_F m_W^2}{4\pi^2 \sqrt{2}} \epsilon g^2 Q_W \left[ \log \frac{\Lambda}{m_Z} + c_1 \right] + \dots$$
$$\epsilon_3 \sim + \frac{G_F m_W^2}{12\pi^2 \sqrt{2}} \left[ \log \frac{\Lambda}{m_Z} + c_3 \right] + \dots$$

**IF  $c_{1,3}$  ARE BOTH NEGATIVE AND OF SUITABLE SIZE  $\Lambda$  CAN BE LARGER THAN THE BOUND.**

Bagger, Falk, Swartz  
Kniehl, Sirlin

Suppose we have the Higgs but New Physics is added that modifies the bound on  $m_H$ .

Typically this adds to the Lagrangian effective operators of higher dimension ( $\text{dim} \geq 6$ ): contact terms suppressed by  $o(1/\Lambda^2)$

$$\epsilon_{1,3} \sim 10^{-3} \text{Log}(m_H/m_Z) + \dots + o(m_Z^2/\Lambda^2)$$

Clearly for  $o(m_Z^2/\Lambda^2) \sim 10^{-3} m_H$  is changed by a factor 2-3.

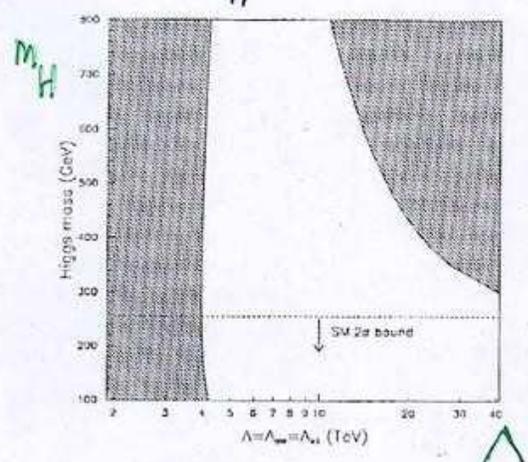
Hall, Kolda// Barbieri, Strumia// Chivukula, Evans, Hoelbling// Kolda, Murayama

Of course the additional terms must obey all constraints from theoretical criteria and from the whole set of experimental precision EW tests.

ADDING NEW PHYSICS TO MODIFY THE BOUNDS ON  $m_H$

$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{NEW}$  HIGHER DIM. EFF. OPERATORS

$\mathcal{L}_{NEW} \approx \frac{1}{\Lambda_{WB}^2} H^\dagger \overleftrightarrow{\partial}_\mu H \vec{W}^{\mu\nu} B_{\mu\nu} +$   
POWER SUPPRESSED  $\frac{1}{\Lambda_H^2} (H^\dagger D^\mu H)(D_\mu H^\dagger H) + \dots$  MANY MORE



ONE CAN INCREASE ALLOWED  $m_H$

Hall, Kolda

BUT IS UNLIKELY : NEEDS CONSPIRACY

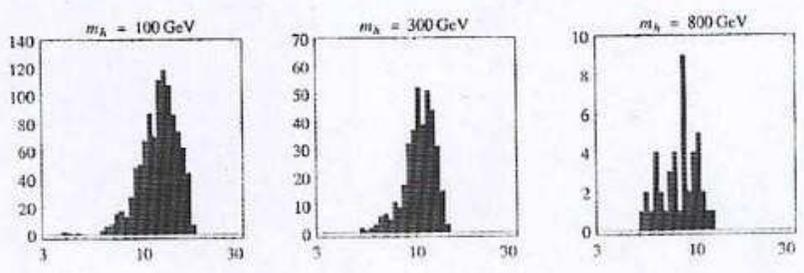


Figure 2. Distribution of the limits on  $\Lambda/\text{TeV}$ , at 95% C.L., for the set of 1021 "theories" defined in the text.

Barbieri, Strumia

Barbieri, Strumia

INDEPENDENT  
FLAVOUR SINGLET  
DIM 6  
CONTACT TERMS

Dimension 6 operators

$O_{WB}$	$= (H^\dagger \tau^a H) W_{\mu\nu}^a B_{\mu\nu}$	} Bosonic
$O_H$	$=  H^\dagger D_\mu H ^2$	
$O_{LL}$	$= \frac{1}{2} (\bar{L} \gamma_\mu \tau^a L)^2$	
$O'_{HL}$	$= i(H^\dagger D_\mu \tau^a H) (\bar{L} \gamma_\mu \tau^a L)$	
$O'_{HQ}$	$= i(H^\dagger D_\mu \tau^a H) (\bar{Q} \gamma_\mu \tau^a Q)$	
$O_{HL}$	$= i(H^\dagger D_\mu H) (\bar{L} \gamma_\mu L)$	
$O_{HQ}$	$= i(H^\dagger D_\mu H) (\bar{Q} \gamma_\mu Q)$	
$O_{HE}$	$= i(H^\dagger D_\mu H) (\bar{E} \gamma_\mu E)$	
$O_{HU}$	$= i(H^\dagger D_\mu H) (\bar{U} \gamma_\mu U)$	
$O_{HD}$	$= i(H^\dagger D_\mu H) (\bar{D} \gamma_\mu D)$	

ONLY THE BOSONIC OPERATORS CAN FIT AT LARGE  $m_H$

$\pm 1$  MEANS THE SIGN IN FRONT OF  $\pm \frac{1}{\Lambda^2} O_6$

$m_h$	100 GeV		300 GeV		800 GeV	
	-1	+1	-1	+1	-1	+1
$O_{WB}$	10	9.7	6.9	—	6.0	—
$O_H$	5.5	4.5	3.7	—	3.2	—
$O_{LL}$	8.1	5.9	6.3	—	—	—
$O'_{HL}$	8.8	8.3	6.6	—	—	—
$O'_{HQ}$	6.6	6.9	—	—	—	—
$O_{HL}$	7.6	8.9	—	—	—	—
$O_{HQ}$	5.7	3.5	—	3.7	—	—
$O_{HE}$	8.8	7.2	—	7.1	—	—
$O_{HU}$	2.4	3.3	—	—	—	—
$O_{HD}$	2.2	2.5	—	—	—	—

—: NO FIT POSSIBLE

$m_H, \Lambda$  PLANE ALLOWED BY  
 DATA +  
 TRIVIALITY + VACUUM STABILITY +  
 NATURALITY (HIERARCHY)

THE WEDGE IS FOR  $m_H \approx$  VEVSMAH  
 VALUE  
 i.e. WHEN 1-LOOP COEFF OF  $\Lambda^2$   
 VANISHES.

Murayama, Kolda

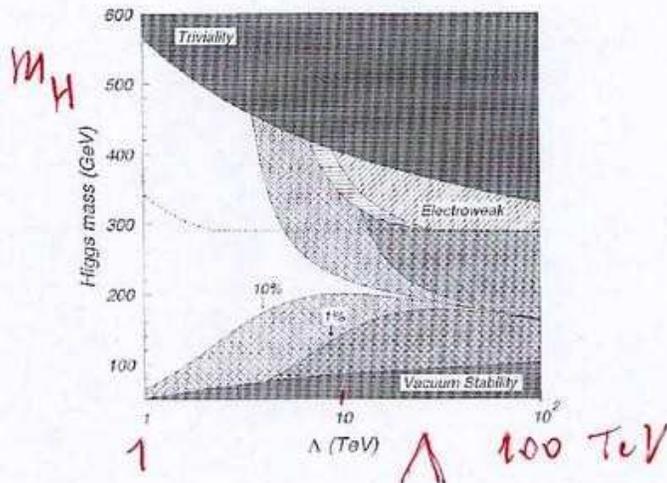


Figure 2: Plot in the  $m_H - \Lambda$  plane showing the canonical constraints from Figure 1 as well as the tuning contours. The darkly hatched region marked "1%" represents tunings of greater than 1 part in 100; the "10%" region means greater than 1 part in 10. The empty region is consistent with all constraints and has less than 1 part in 10 finetuning.

FITTING THE DATA IN TERMS OF  
 $\Delta T \propto \Delta E_1$  AND  $M_H$   
 + TRIVIALITY BOUND

Chivukula et al

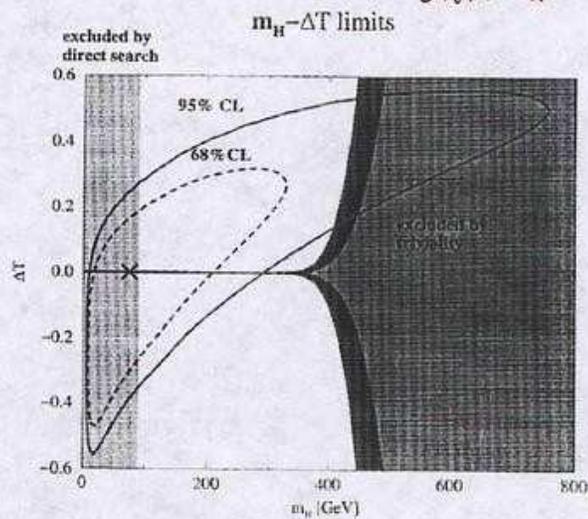


Figure 1: 68% and 95% CL bounds in the  $(m_H, \Delta T)$  plane allowed by a fit to precision electroweak data [30]. The best fit "standard model" value is shown by the cross on the  $\Delta T = 0$  line. The light region to the right is excluded by eqn. 1.3 for  $b_*^2 = 4\pi^2$ . The dark region denotes the additional area excluded for  $b_*^2 = 4\pi^2$ . The positive branches of the curves bounding these regions are lower bounds for  $\Delta T$  in the top-saw and composite higgs models described in the text. Any  $(m_H, \Delta T)$  with positive  $\Delta T$  and to the left of the appropriate triviality curve can be realized in the corresponding model.

IN GUT-EXTENDED MSSM THE  $SU(2) \otimes U(1)$  BREAKING IS NATURALLY AND AUTOMATICALLY GENERATED BY  $M_F$  LARGE

RECALL: IN S.M.

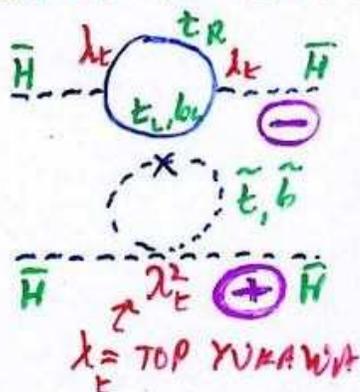
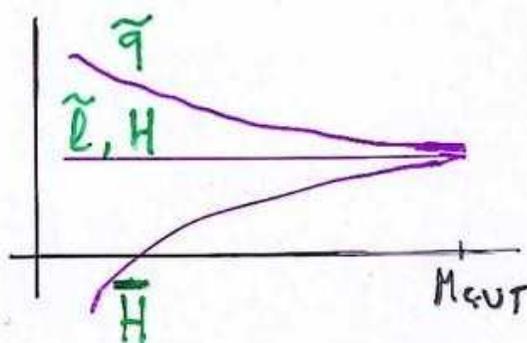
$$V(\phi) = \frac{\mu^2}{2} \phi^2 + \frac{\lambda}{4} \phi^4 \quad (\lambda > 0 \text{ BY POSITIVITY AT } \phi \neq 0)$$

$$\frac{\partial V}{\partial \phi} = \phi [\mu^2 + \lambda \phi^2] = 0$$

A NON TRIVIAL SOLUTION NEEDS  $\mu^2 < 0$

$$\phi \equiv v = \sqrt{-\mu^2/\lambda}$$

SIMILAR BUT MORE COMPLICATED IN MSSM



CORRECT E-W BREAKING LEADS TO CONSTRAINTS ON MSSM PARAMETERS (MORE IF NO FINE-TUNING)

$$M_2^2 \approx C_1 M_{1/2}^2 + C_2 M_0^2 + C_3 A^2 + C_4 \mu^2$$

$$C_i = C_i(M_t, g_i) \text{ COMPUTABLE}$$

IF  $M_{1/2}^2, M_0^2, A^2, \mu^2 \gg M_2^2 \Rightarrow$

$\Rightarrow$  FINE TUNING OF  $C_i$

VARIOUS NO FINETUNING  
CRITERIA ANALYSED:

TYPICALLY NO MORE  
THAN FACTOR TEN

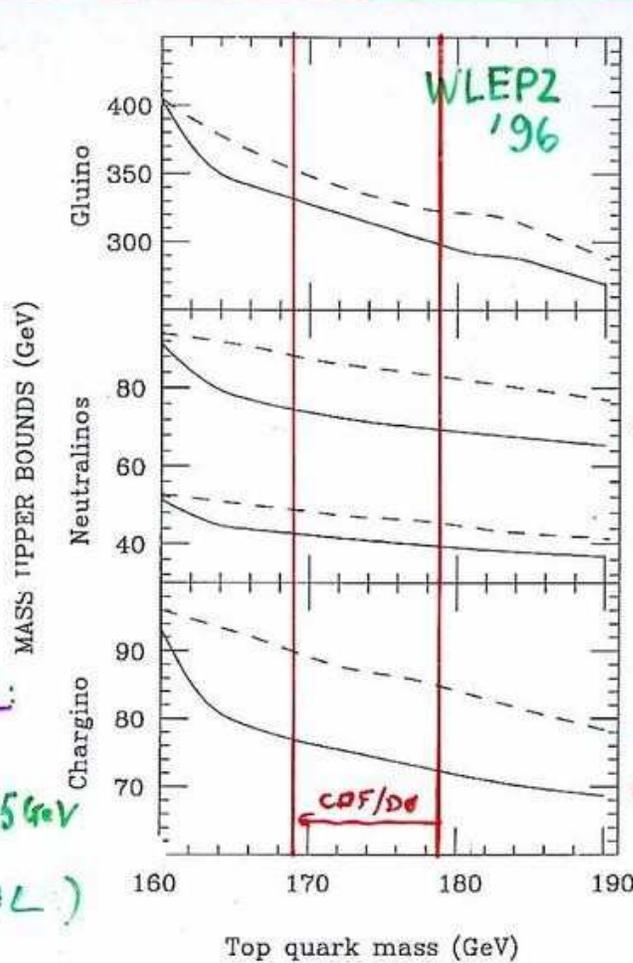
FINE TUNING ALLOWED

Ellis et al '86  
Barbieri, Giudice  
Roberts, Ross  
Arnowitt, Nath  
Nonopoulos  
de Carlos, Casas  
Berger, Berger, Ohmura

### Recent Analyses:

Chankowski, Ellis, Pokorski '97  
Barbieri, Strumia '98  
Kane, King '98  
Giusti, Romalis, Strumia '98  
Chankowski, Ellis, Olechowski, Pokorski '98

# BOUNDS FROM NO FINE TUNING



BY FACTOR OF 10  
 $\tilde{g}$

GOES LIKE  $\sqrt{f}$   
 NOW  $\chi$  20-30 NEEDED

$\chi^\pm$

RECALL:  
 LEP2  
 $m_{\chi^\pm} \geq 95 \text{ GeV}$   
 TYPICAL)

- : UNIVERSAL BOUNDARY COND'S AT GUT SCALE (FOR SCALARS & GAUGINOS)
- - - - - : UNIVERSALITY DROPPED BUT ONLY FOR SCALARS

LOOP CORRECTIONS HELP: Arnowitt, Nath '92  
Barger et al '94

LESS THAN FACTOR 10 FINE TUNING

$$\Rightarrow m_h \sim 90 - 112 \text{ GeV (LEP2)}$$

Barbieri, Strumia '98

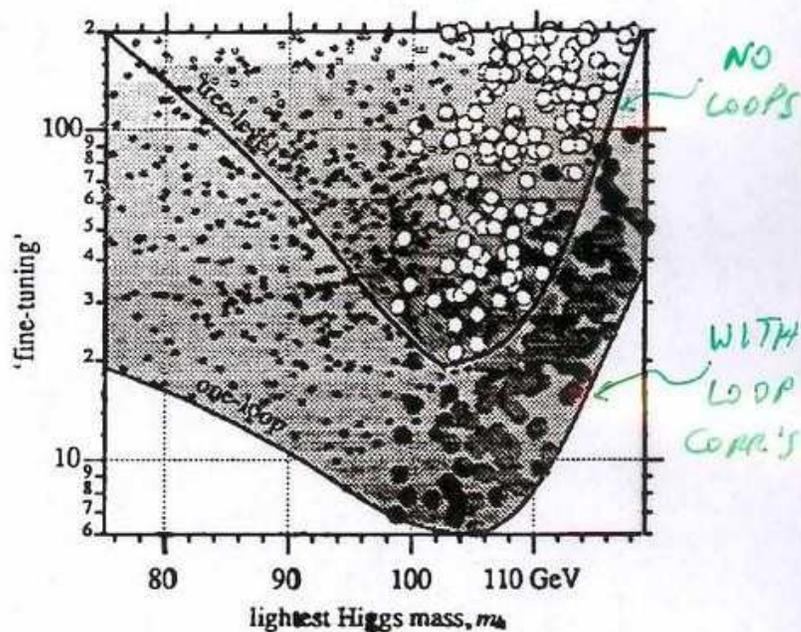


Figure 3: Scatter plot of the fine-tuning as function of  $m_h$ . In the empty  $\circ$  (filled  $\bullet$ ) points the FT is computed as in CEP (as here). Small points have  $\tan \beta < 4$ , bigger points have  $\tan \beta > 4$ .

REMOVING GAUGINO DEGENERACY  
AT  $M_{cut}$  IMPROVES NATURALNESS

$$m_{\tilde{g}} < m_{\tilde{W}, \tilde{B}}$$

$\chi^\pm, \chi^0$  CAN BE MADE HEAVIER  
WITHOUT INCREASING FINE TUNING  
BY MAKING  $m_{\tilde{W}, \tilde{B}} \uparrow$  AT FIXED  $m_{\tilde{g}}$

Kane, King '98

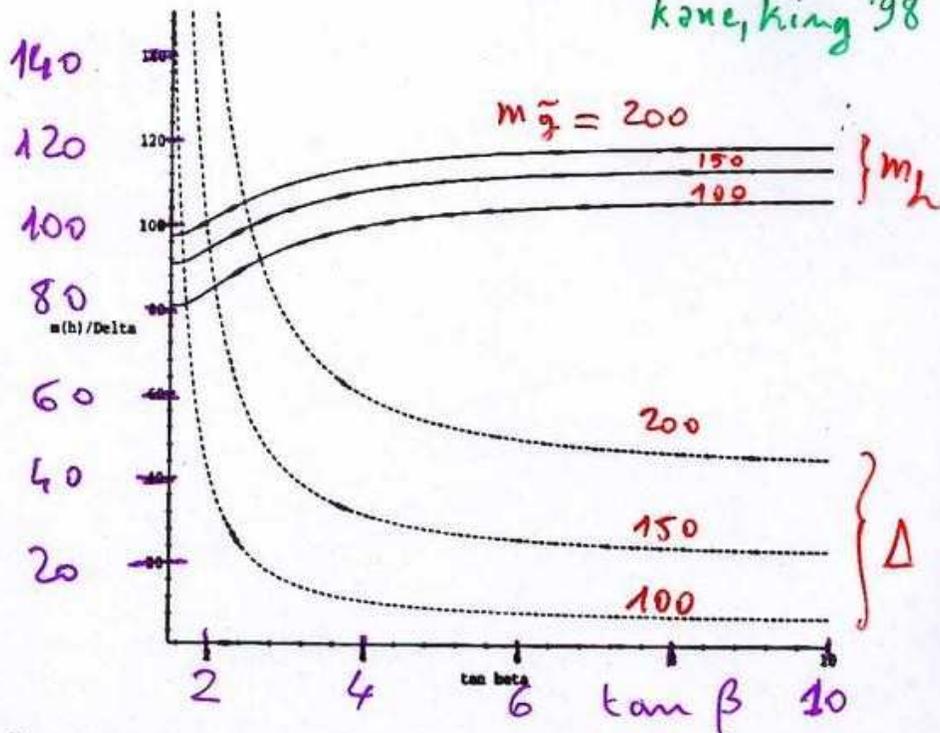


Figure 1: The Higgs mass  $m_h$  (in GeV) (solid) and fine-tuning parameter  $\Delta_{\mu(t)}$  (dashed) as a function of  $\tan \beta$ . The upper to lower curves correspond to  $M_3(0) = 200, 150, 100$  GeV. Apart from the gluino mass we use universal parameters  $m_0 = 100$  GeV,  $M_{1,2}(0) = 200$  GeV in each case. Note the large decrease in the measure of fine-tuning as  $M_3(0)$  decreases.

Giusti, Romanino, Strumia 98

SAMPLING WITH DENSITY  $\propto$  NATURALNESS

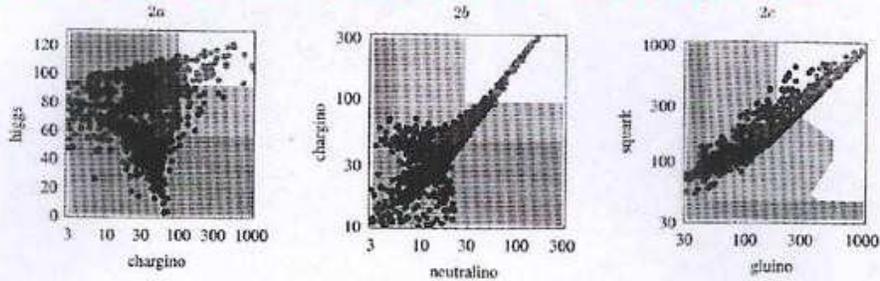


Figure 2: Scatter plot with sampling density proportional to the naturalness probability. The area shaded in light gray (dark gray) in fig.s 2a,b correspond to regions of each plane excluded at LEP2 (at LEP1), while the area shaded in light gray in fig. 2c has been excluded at Tevatron. The dark gray (black) points correspond to sampling spectra excluded at LEP2 (at LEP1). Only the light gray points in the unshaded area satisfy all the accelerator bounds. Points with unbroken electroweak symmetry are not included in this analysis.

MINIMAL SUSGA : SITUATION SERIOUS!!

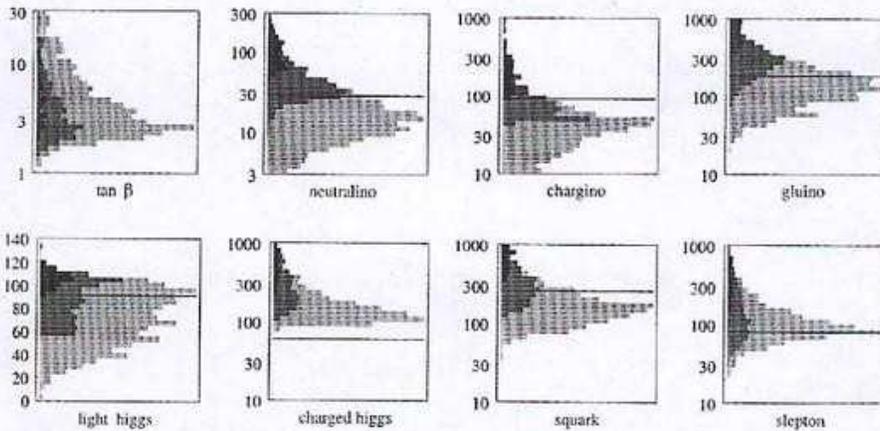


Figure 3: Naturalness distribution of sparticle masses in minimal supergravity. Allowed spectra contribute only with the small tails in dark gray. The remaining 95% of the various bell-shaped distributions is given by points excluded at LEP2 (in medium gray) or at LEP1 (in light gray). On the vertical axes on each plot the particle masses in GeV are reported ( $\tan \beta$  in the first plot). With 'squark' and 'slepton' we mean the lightest squark and slepton excluding the third generation ones, that have weaker accelerator bounds.

NATURALNESS IN GAUGE MEDIATED SUSY BREAKING: WORSE!

THE LAST 2 YEARS OF LEP (199-'00)  
ARE BEING EXTREMELY CONSTRAINING  
FOR THE MSSM

PARTICULARLY IMPORTANT REGIONS  
OF PARAMETER SPACE AND  
SIMPLE MODELS CAN BE EXCLUDED

EXAMPLE:

SUGRA BOUNDARY CONDITIONS  
+  $b-\tau$  YUKAWA UNIFICATION  
( $m_b(\text{GUT}) = m_\tau(\text{GUT})$ )

$\Rightarrow$  EITHER  $\tan\beta \sim 1-3$   
OR  $\tan\beta \sim 30-50$

THE SMALL  $\tan\beta$  SOLUTION  
IS IN DANGER !!

Langacker, Polonsky  
Caruana, Pokorski, Wagner  
Barger et al  
DeBoer, Chret, Karkov

SMALL  $\tan \beta$

LARGE  $\tan \beta$

de Baer

$M_t = 175 \pm 5 \text{ GeV}$

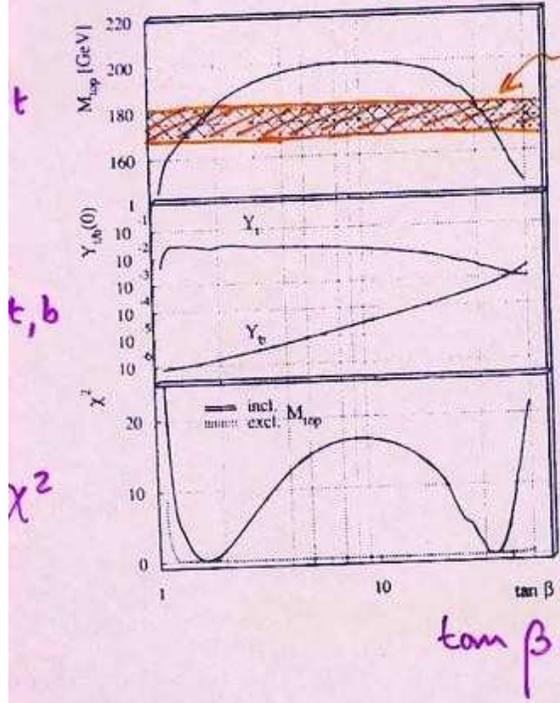


Figure 6: The top quark mass as function of  $\tan \beta$  (top). The middle part shows the corresponding values of the Yukawa couplings at the GUT scale and the lower part the  $\chi^2$  values. For  $\tan \beta < 20$  the Yukawa coupling of the b-quark  $Y_b$  is small compared to  $Y_t$ , in which case the top quark mass is given by the infrared fixed point solution of  $Y_t$ . For large values of  $\tan \beta$   $Y_t$  is reduced by the negative corrections from  $Y_b$  and  $Y_\tau$ , which were assumed to have common values at the GUT scale ( $b-\tau$  unification). If the top constraint ( $m_t = 175 \pm 6$ , horizontal band) is not applied, all values of  $\tan \beta$  are allowed (thin dotted lines at the bottom), but if the top mass is constrained to the experimental value, only the regions around  $\tan \beta \approx 1.7$  and  $\tan \beta \approx 35$  are allowed.

Caroniu, Chankowski,  
Pokorski, Wagner '98

$\tan\beta$

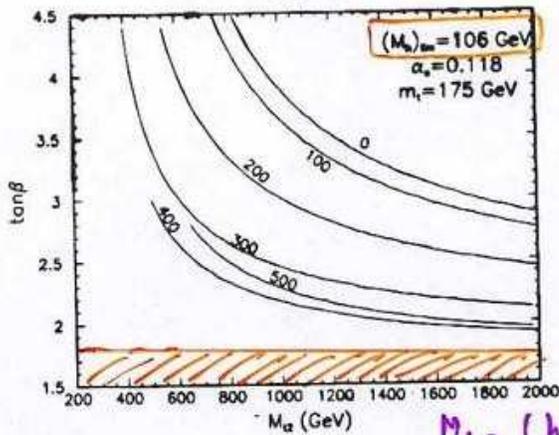
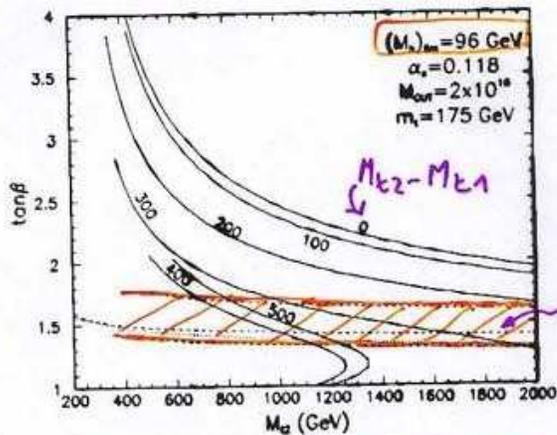


Figure 3: The same as Fig. 1, but for lower bounds on the Higgs boson mass of 96 GeV and 106 GeV.

## CONCLUSION

Still no evidence of New Physics at LEP2,  
Tevatron, Hera...

LEP2 has already excluded SUSY near the  
corner (a bit frustrating):

typical	$m_{\chi^+} \geq 100 \text{ GeV}$
limits	$m_{eR} \geq 95 \text{ GeV}$
now	$m_t \geq 90 \text{ GeV}$

The Higgs search continues at LEP2 in  
2000 at  $2E \leq 206 \text{ GeV}$ .

Reach: **SM:  $m_H \leq 115 \text{ GeV}$**

**MSSM:  $m_h \leq 95 \text{ GeV}$**

**For conceptual reasons we remain  
confident on nearby New Physics**