Nouvelles Physiques

1 - Cadre général :

comment briser la symétrie électrofaible

2 - La supersymétrie :

supestition ou superchérie ?

3 - Les masses et les oscillations des neutrinos

la première percée au-delà du Modèle St^{d}

4 - Le grand au-delà :

vers la grande unification et les supercordes

1 - Cadre Général

1.1 - Le Modèle Standard et ses Problèmes

1.2 - Le Mechanisme de Higgs
et contraintes sur la masse du boson H

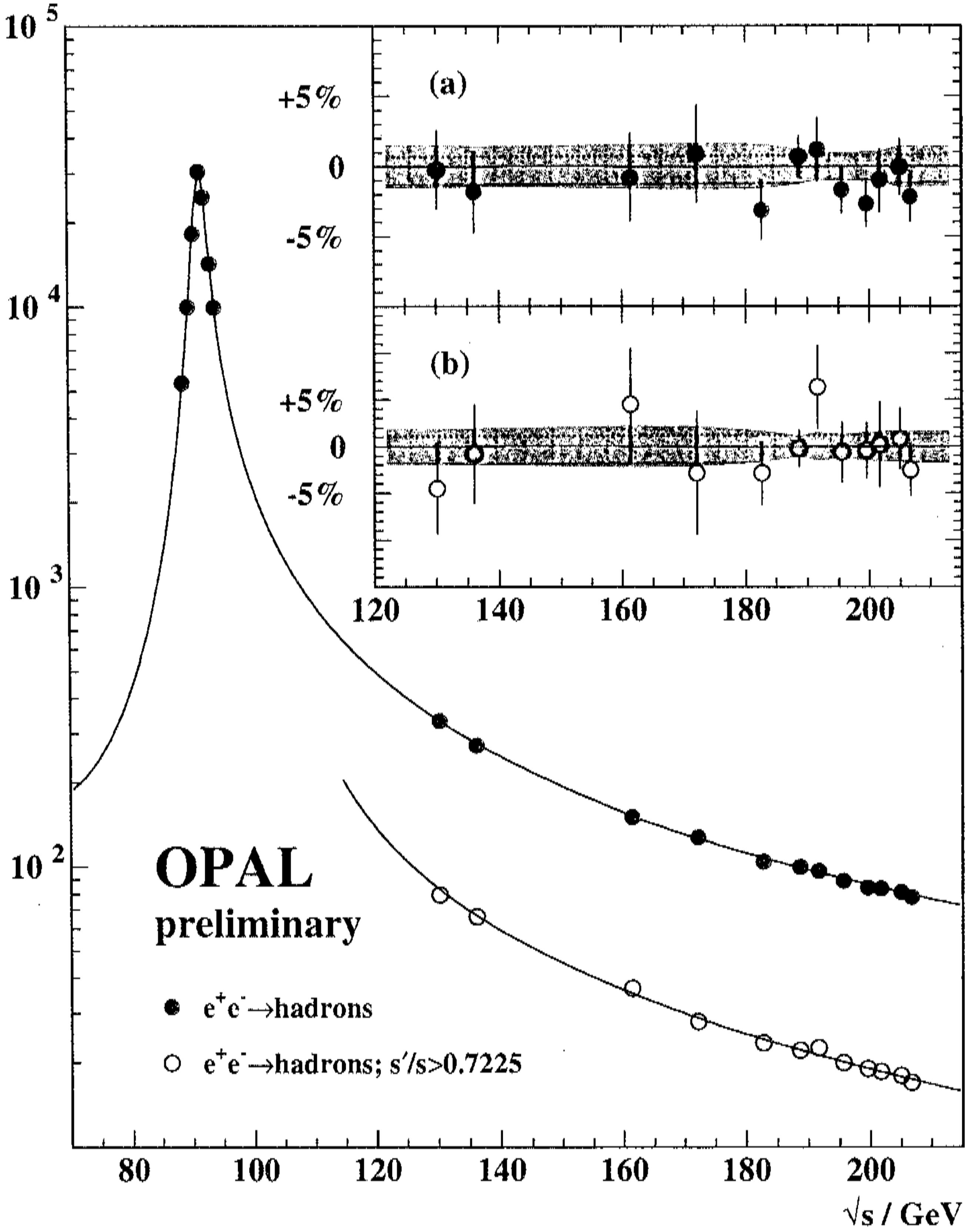
1.3 - Le vide électrofaible
champ de Higgs composé, ou ...?

1.4 - À la recherche du Higgs perdu
chez les accélérateurs de l'avenir

The Standard Model of Particle Physics

- Three generations of fermions make up matter 6 quarks, electron + two heavier siblings, 3 neutrinos
- Four fundamental forces between them electromagnetic, strong, weak, gravity
- All carried by messenger particles photon, gluons, W & Z, graviton (?)
- Massless: photon, gluon, graviton
- Massive: quarks, electrons, W & Z Why ? How ?

Tests of the Standard Model @ LEP



Defects of the Standard Model

it agrees with all confirmed accelerator data

But

is theoretically very unsatisfactory:

no explanations for particle quantum #'s

Q, I, Y, C

contains ≥ 19 arbitrary parameters

3 gauge couplings g_3, g_2, g_1

① CP-violating vacuum angle $\textcircled{\theta_3}$

untidy gauge structure: 3 independent groups

6 quark masses $m_{u,d,s,c,b,t}$

3 charged-lepton masses $m_{e,\mu,\tau}$

3 "Cabibbo" weak mixing angles α, β, γ

① CP-violating Kobayashi-Maskawa phase $\textcircled{\delta}$

arbitrary Yukawa couplings

1 W mass m_W

1 Higgs mass m_H

$\overline{19}$ Higgs potential

as if that was not enough...

3	neutrino masses	$m_{1,2,3}$
3	neutrino mixing angles	$\theta_{1,2,3}$
③	CP-violating phases	$\boxed{\delta_\nu}$

without even talking about mechanism for ν mass generation: more Higgs? heavy ν_R?...

and do not forget gravity:

1	Newton's constant	$G_N = 1/m_P^2$
1	Cosmological "constant"	Λ

↖ is it? or $\Lambda(t)$?

also keep in mind:

$\geqslant 1$	inflation parameter	m_I

not Standard Model: $\frac{\delta T}{T} \propto \left(\frac{m_I}{m_P}\right)^2$

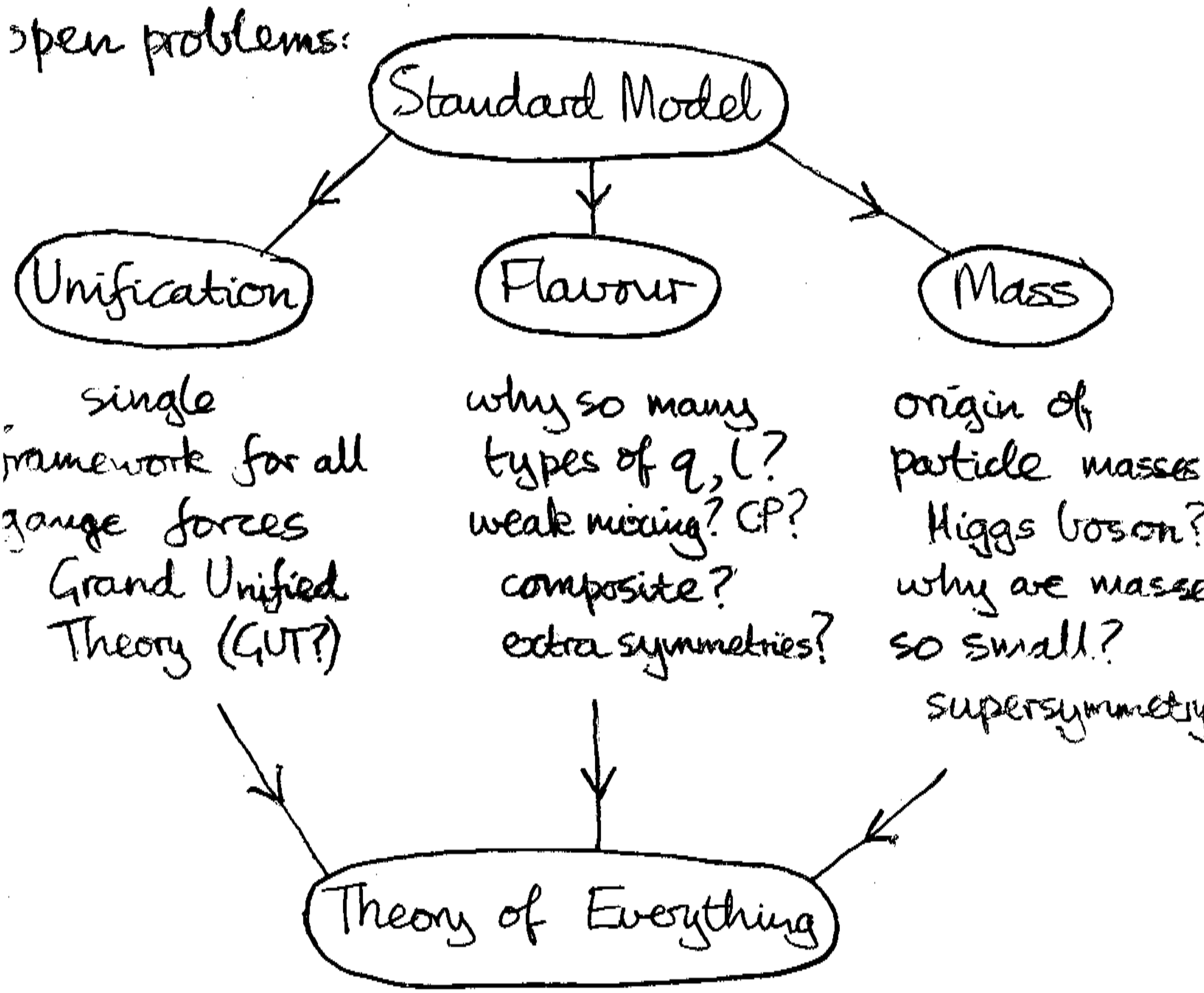
$\simeq 10^{-5} \gg (m_W/m_P)^2$

$\boxed{\geqslant 1}$	parameter for baryon asymmetry	$\boxed{n_B/n_\gamma}$

not Standard Model: $m_H > 70$ GeV

Roadmap to physics
Beyond the Standard Model

open problems:



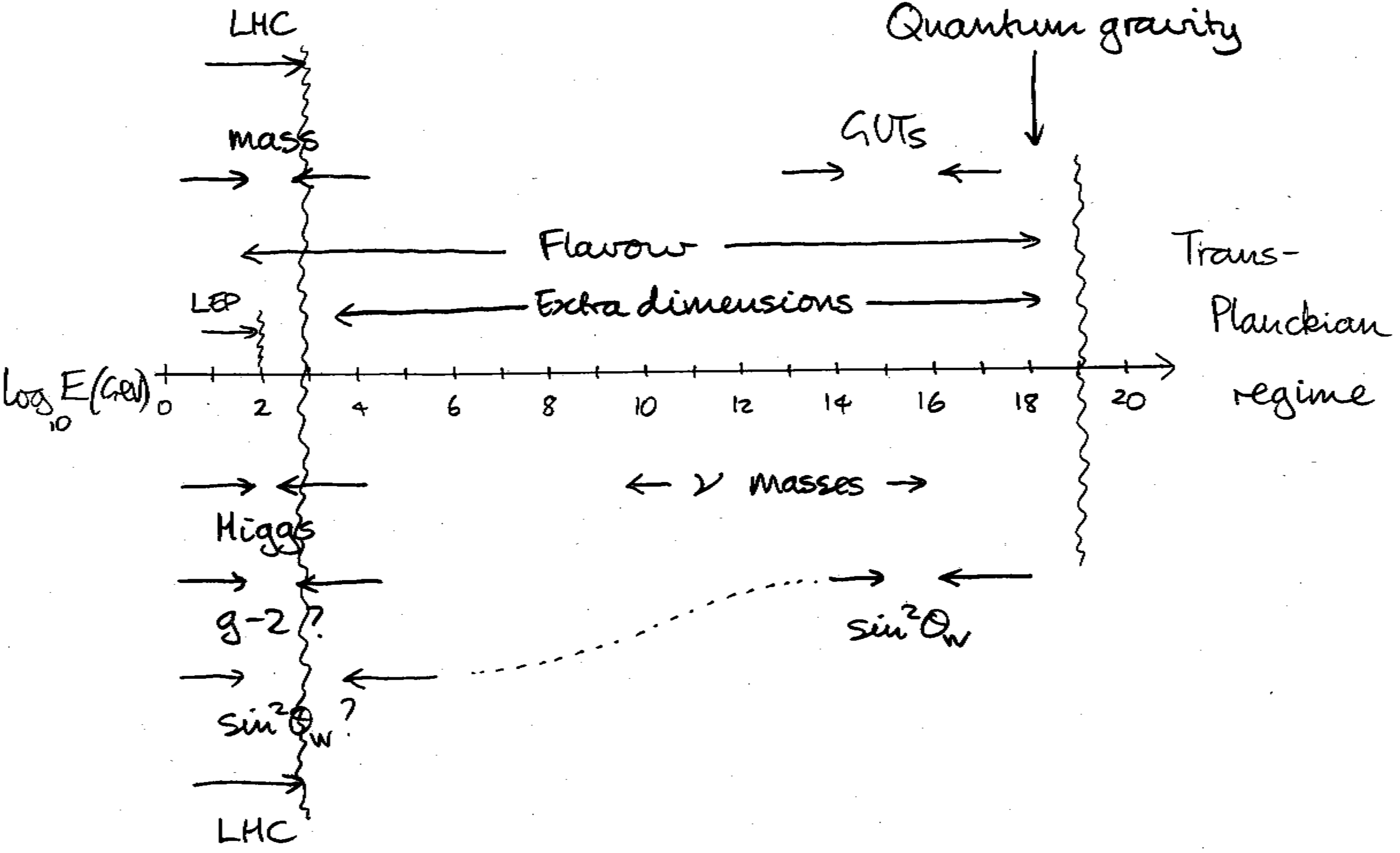
single
framework for all
gauge forces
Grand Unified
Theory (GUT?)

why so many
types of q, l?
weak mixing? CP?
composite?
extra symmetries?

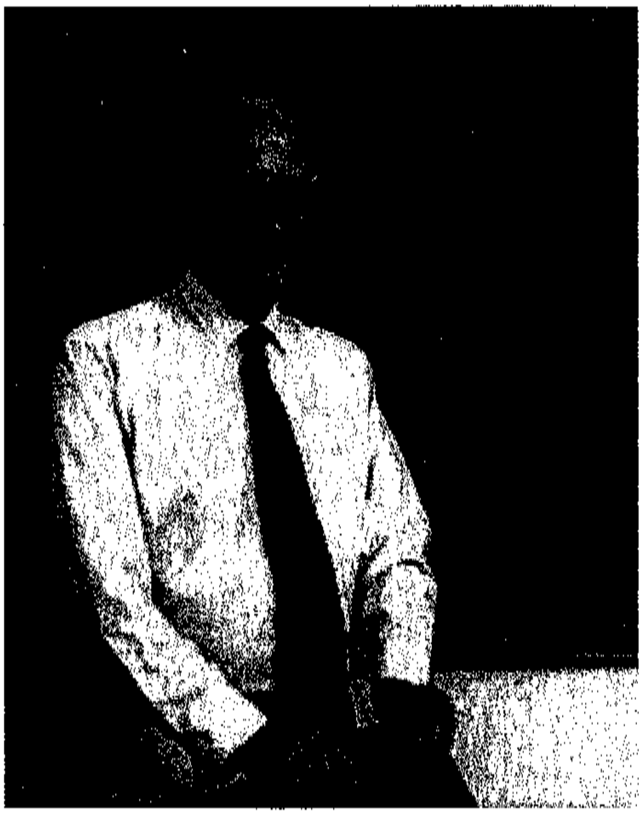
origin of
particle masses
Higgs boson?
why are masse
so small?
supersymmetr

include gravity
reconcile it with quantum mechanics
origin of space-time
why 4 dimensions?
⋮
superstring?
M theory?

Where will New Physics Appear?



Higgs in ground state



Mechanism for mass generation

Higgs-Brout-Englert scalar field:

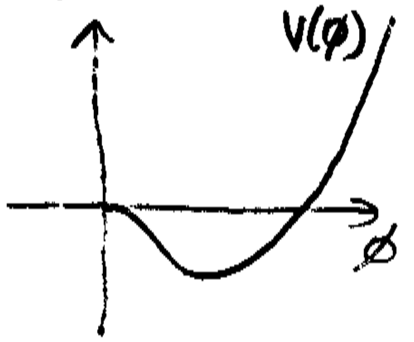
$$\mathcal{L}_\phi = -|D_\mu \phi|^2$$

↖ doublet of SU(2)? elementary?

with effective potential:

$$\mathcal{L}_V = -V(\phi): \quad V(\phi) = -\mu^2 \phi^\dagger \phi + \frac{\lambda}{2}(\phi^\dagger \phi)^2$$

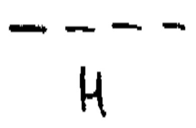
unstable at origin ↗

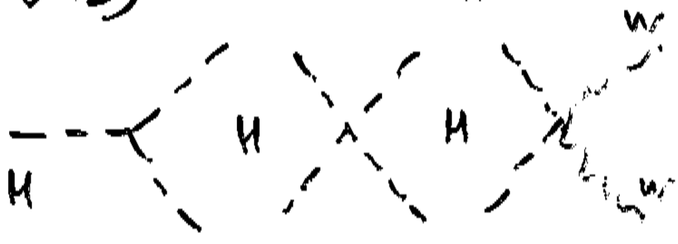


⇒ spontaneous symmetry breaking

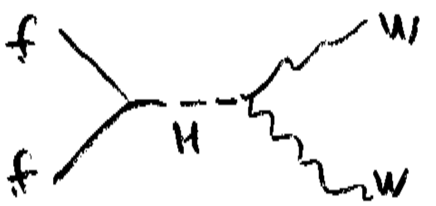
vacuum expectation value:

$$\langle 0|\phi|0\rangle = \langle 0|\phi^\dagger|0\rangle = v\begin{pmatrix}0\\ 1/\sqrt{2}\end{pmatrix} : \quad v^2 = \mu^2/2\lambda$$





only consistent mechanism: required for renorm^n



cancellation

fermion masses

$$\mathcal{L}_m = -\lambda_f \bar{f}_L \phi f_R + \text{herm. conj.}$$

the missing link ...

The Higgs Boson

massless gauge boson: e.g. γ, g

2 polarization states: $\rightarrow \quad \leftarrow \quad \pm 1$

massive gauge boson: e.g. $W^\pm$, Z^0

3 polarization states: $\rightarrow \quad \cdot \quad \leftarrow \quad 0, \pm 1$

Need supplementary spin-0 field

with non-zero isospin: $m_{W^\pm, Z^0} \neq 0$

Minimal choice:

complex doublet with $I = \frac{1}{2}$: $\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \begin{pmatrix} \bar{H}^0 \\ H^- \end{pmatrix}$

 4 degrees of freedom

$-$ 3 eaten by $W^\pm, Z^0$

$=$ 1 physical Higgs boson

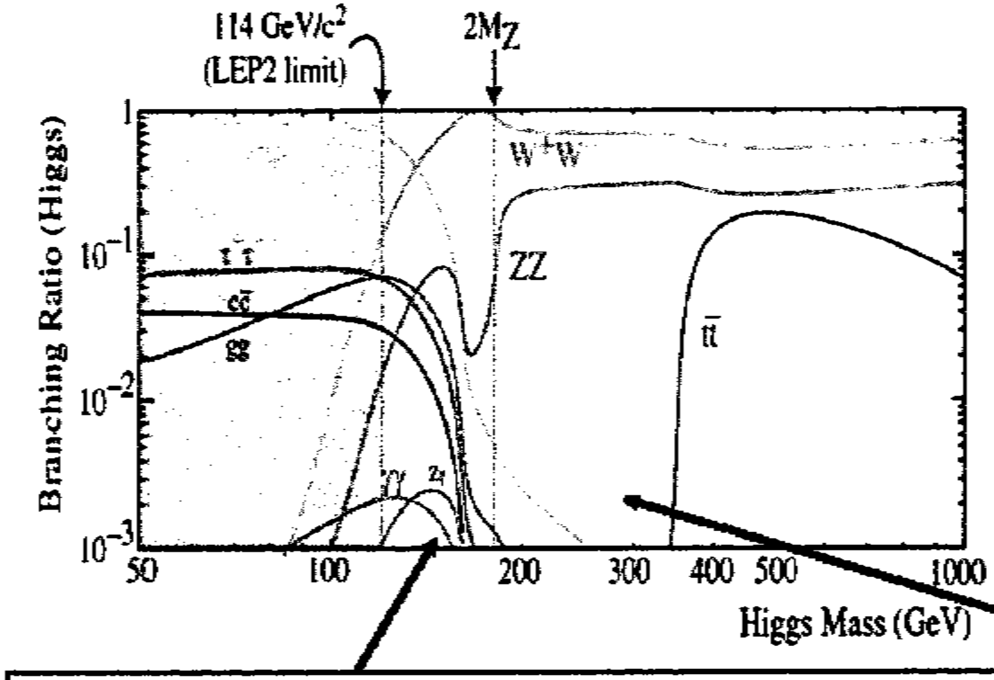
Mass free parameter: $m_H^2 = 2\mu^2$

Couplings completely determined: $g_{Hf\bar{f}} = \frac{m_f}{v}$

Predictable production, decay

e.g. $e^+e^- \to Z + H$ (J.E. + Gaillard + Nanopoulos : 1975

Most Important Higgs Decays



Dominant BR for m_H<2m_Z:
σ (H → bb) ≈ 20 pb;
σ (bb) ≈ 500 μb
for m(H) = 120 GeV
→ no hope to trigger
or extract fully
hadronic final states
→ **look for final**
states with ℓ, γ
(ℓ = e,μ)

Low mass region: m(H) < 2 m_Z :
H → γγ : small BR, but best resolution
H → bb : good BR, poor resolution → ttH, WH
H → ZZ* → 4ℓ
H → WW* → ℓνℓν or ℓνjj : via VBF
H → ττ : via VBF

m(H) > 2 m_Z :
H → ZZ → 4ℓ
qqH → ZZ → ℓℓνν *
qqH → ZZ → ℓℓjj *
qqH → WW → ℓνjj *
* for m_H > 300 GeV
forward jet tag

Most complicated/relevant/interesting region?

Sensitivity to unseen particles

Veltma

at one loop

$$M_W^2 \sin^2\Theta_W = M_Z^2 \cos^2\Theta_W \sin^2\Theta_W = \frac{\pi\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

top quark

not renormalizable

⇑

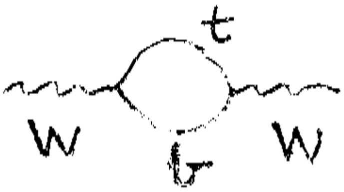
without it, gauge structure lost

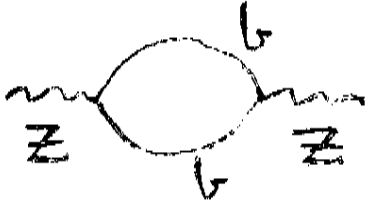
measure of electoweak isospin breaking

$$\begin{pmatrix} t \\ b \end{pmatrix}$$

$$\propto (m_t^2 - m_b^2)$$

seen via vacuum polarization (oblique) diagra





$$\Delta r \ni \frac{3G_\mu}{8\pi^2\sqrt{2}} m_t^2$$ for $m_t \gg m$

Higgs boson

theory { with / without } spontaneous symmetry breaking

both renormalizable @!!

Veltman screening theorem

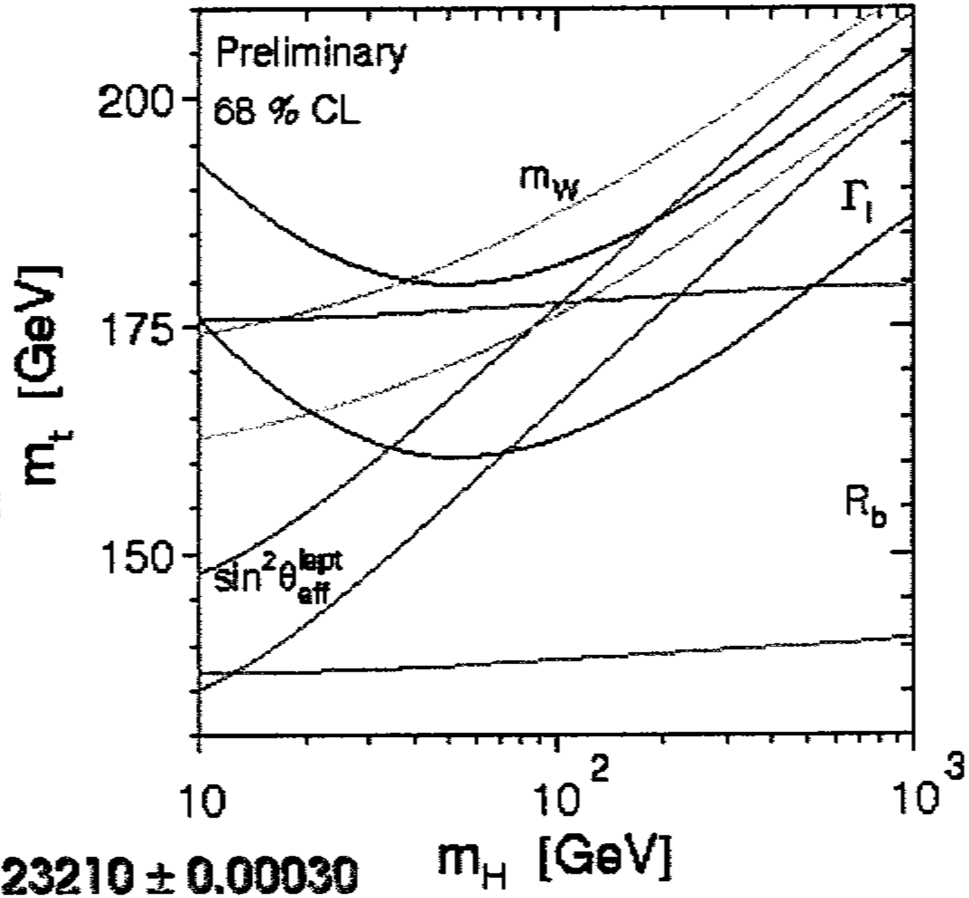
$$\Delta \sim \ln\left(\overset{\text{physic}}{m_H^2} \Big/ \underset{\text{unphysical "eaten}}{m_Z^2}\right)$$

$$\Delta r \ni \frac{\sqrt{2}\,G_\mu}{16\pi^2} m_W^2 \left\{ \frac{11}{3} \ln m_H^2 / m_W^2 - \cdots \right\}$$

Consistency with the SM

All the high Q^2 measurements are fitted as a function of:

$O(\alpha, G_\mu, m_Z, \alpha_s, m_{Higgs}, m_{top})$



Changes w.r.t. summer 03:

-New measurement of m_{top} at TeVatron:

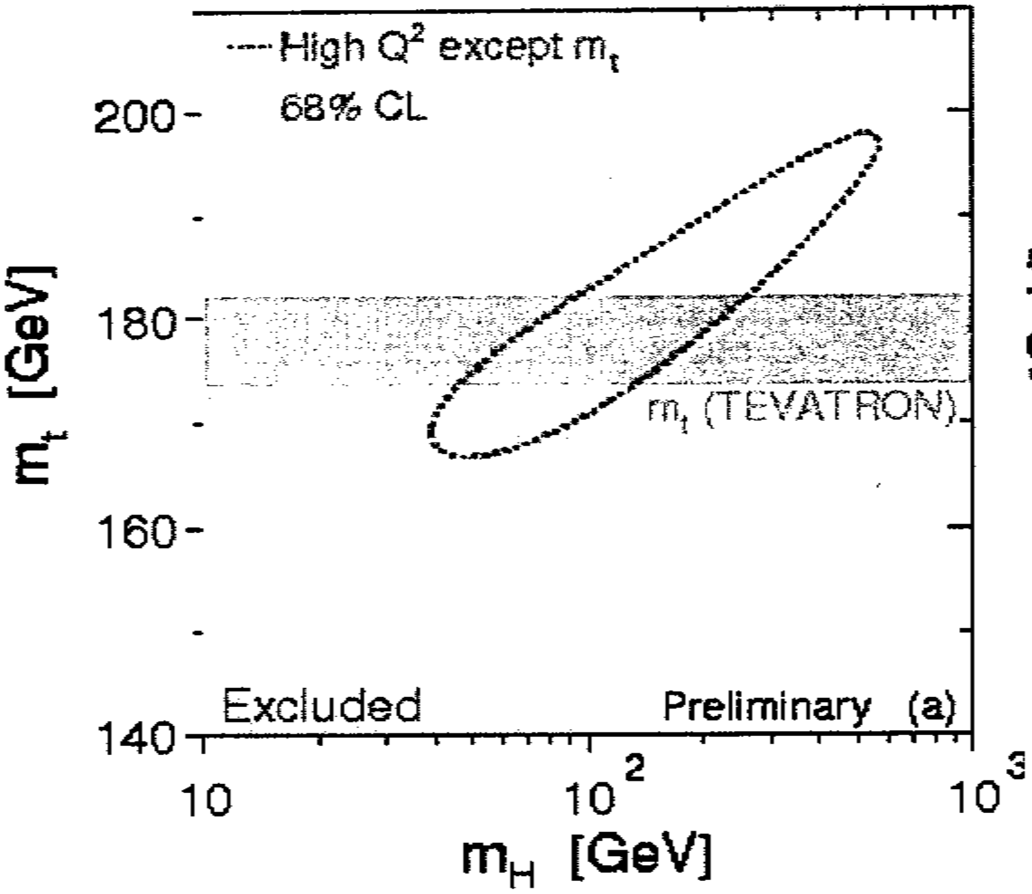
m_{top} = 174±5.1 GeV ⇨ 178.0 ± 4.3 GeV

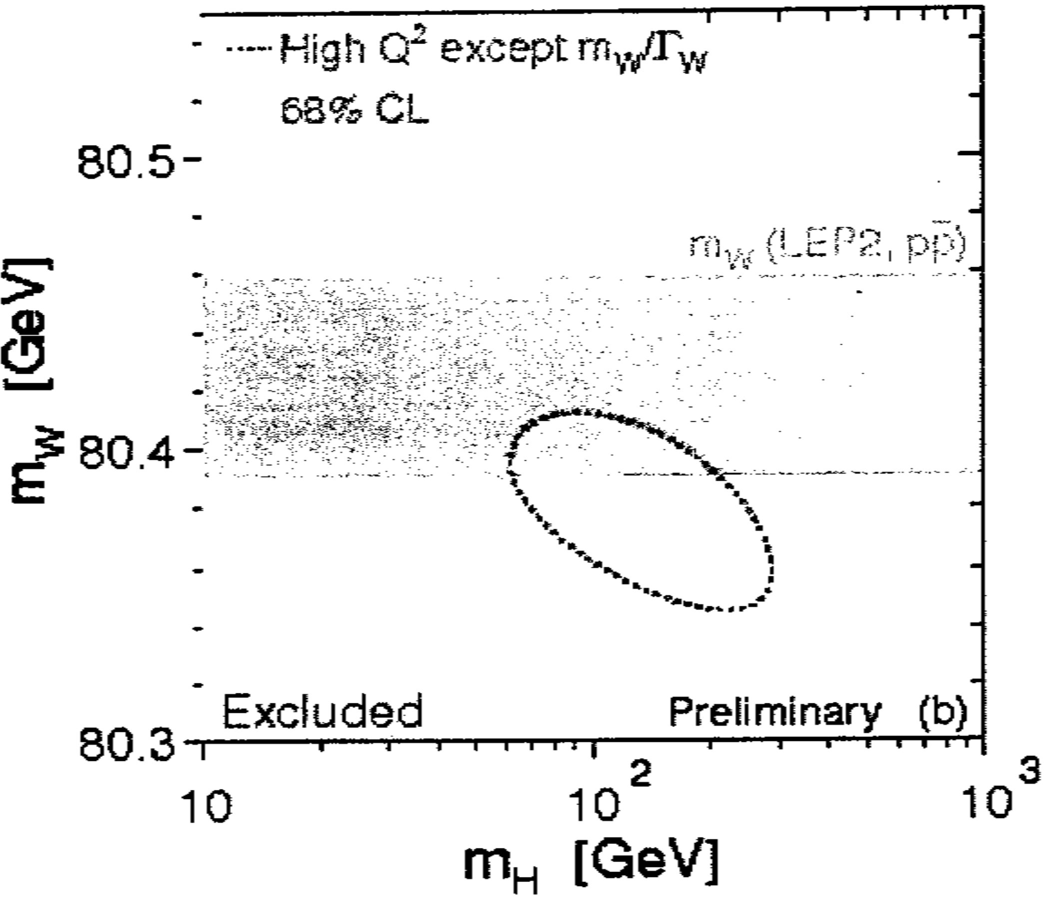
-New HF average from LEP:

$\sin^2\theta_{eff}$(b-asym) = 0.23212±0.00029 ⇨ 0.23210 ± 0.00030

-New version of ZFITTER v6.4 with two loop corrections to Mw and $\sin^2\theta_{eff}$

Consistency with the SM





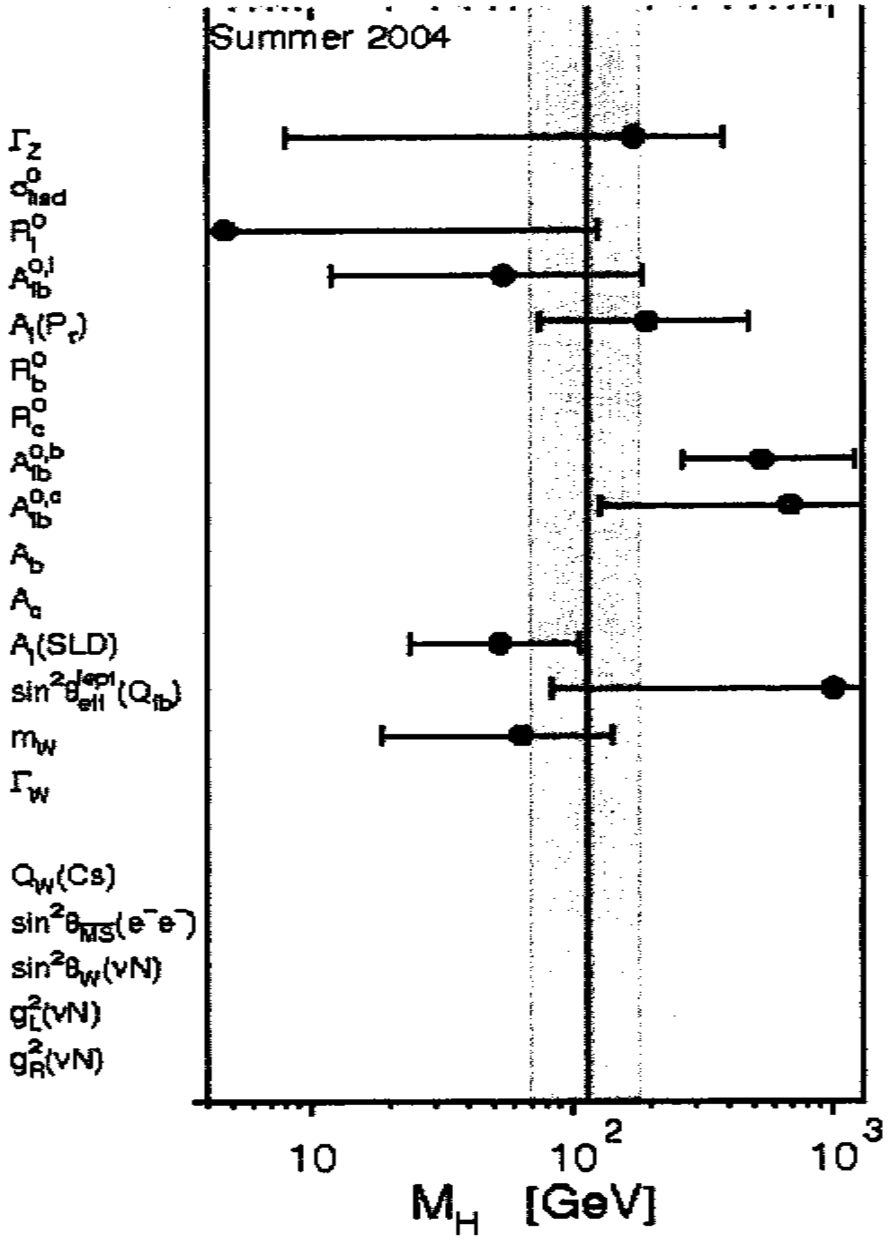
m_{top} (fit) = 179 ± 10 GeV
(χ^2/dof = 15.8/12)

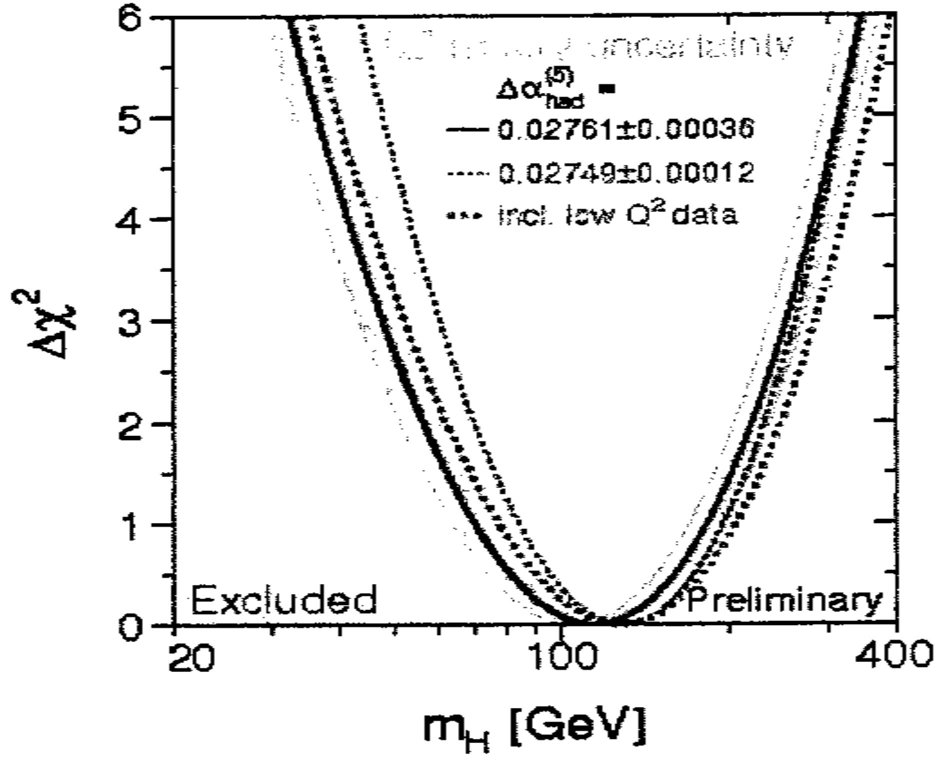
m_{top} (exp) = 178.0 ± 4.3 GeV

m_W (fit) = 80.379 ± 0.023 GeV
(χ^2/dof = 14.1/11)

m_W (exp) = 80.425 ± 0.034 GeV

Constraints on m_{Higgs}





$\log(m_{Higgs}) = 2.06 \pm 0.21$

$m_{Higgs} = 114^{+69}_{-45}$ GeV

$m_{Higgs} < 260$ GeV @95% c.l.

$m_{Higgs} > 114$ GeV @95% c.l.

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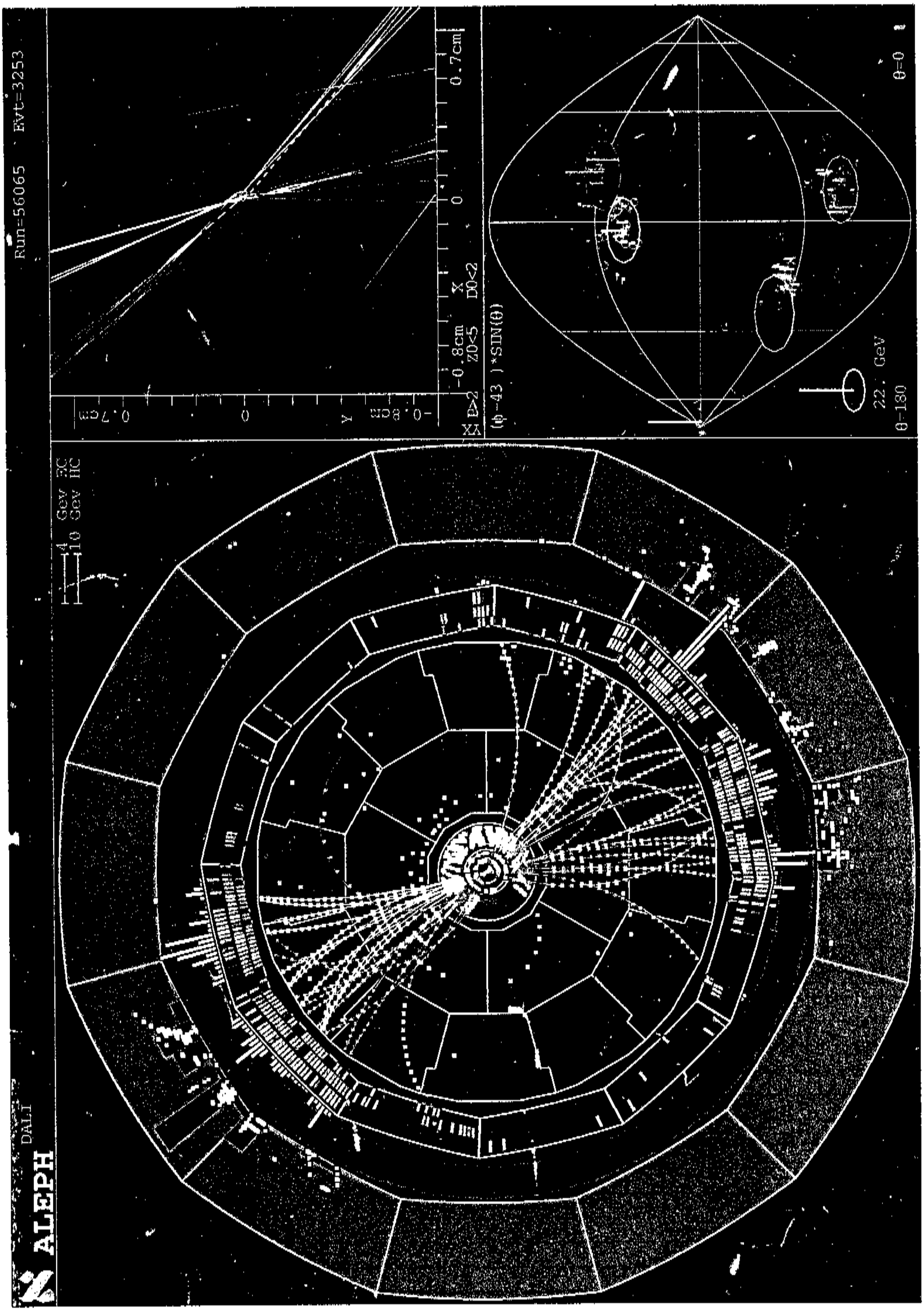


Summary of LEP Higgs Search

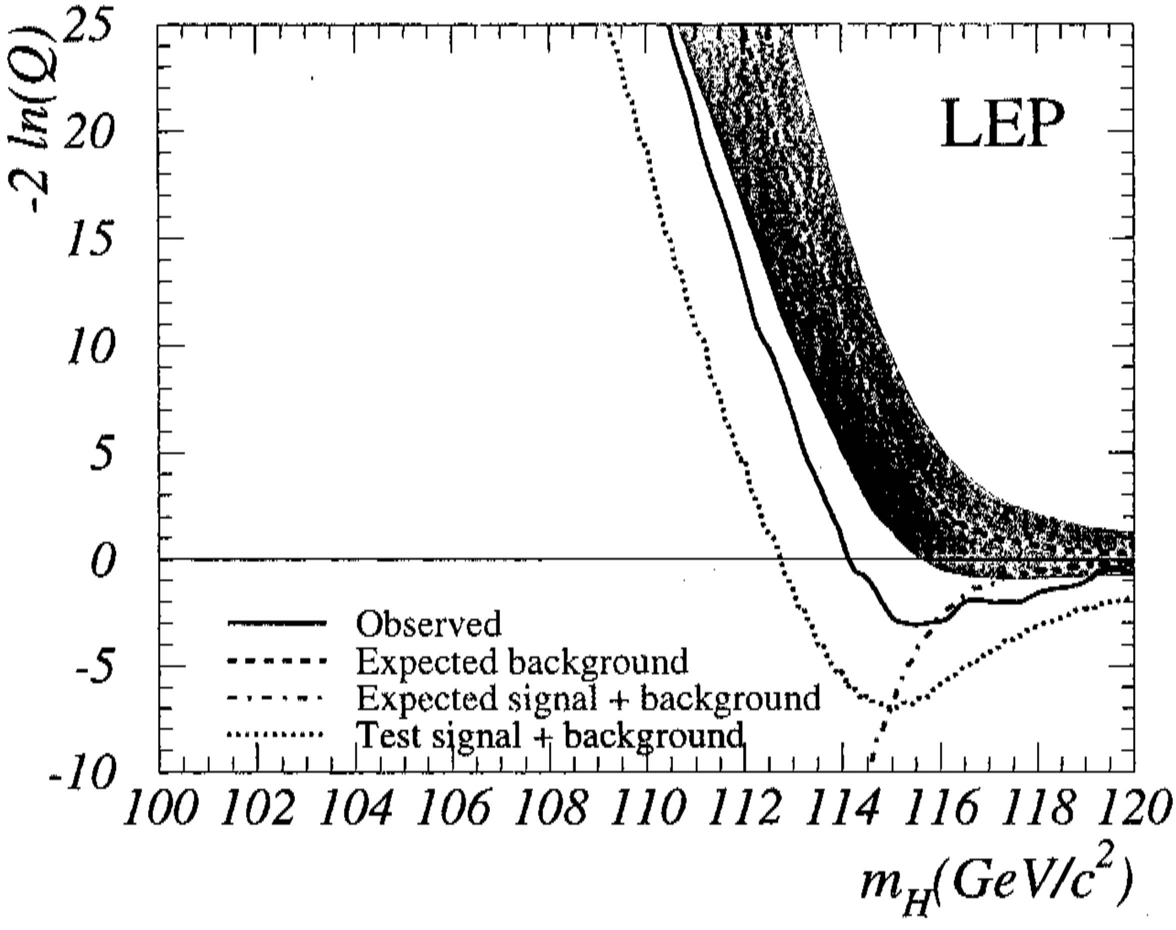


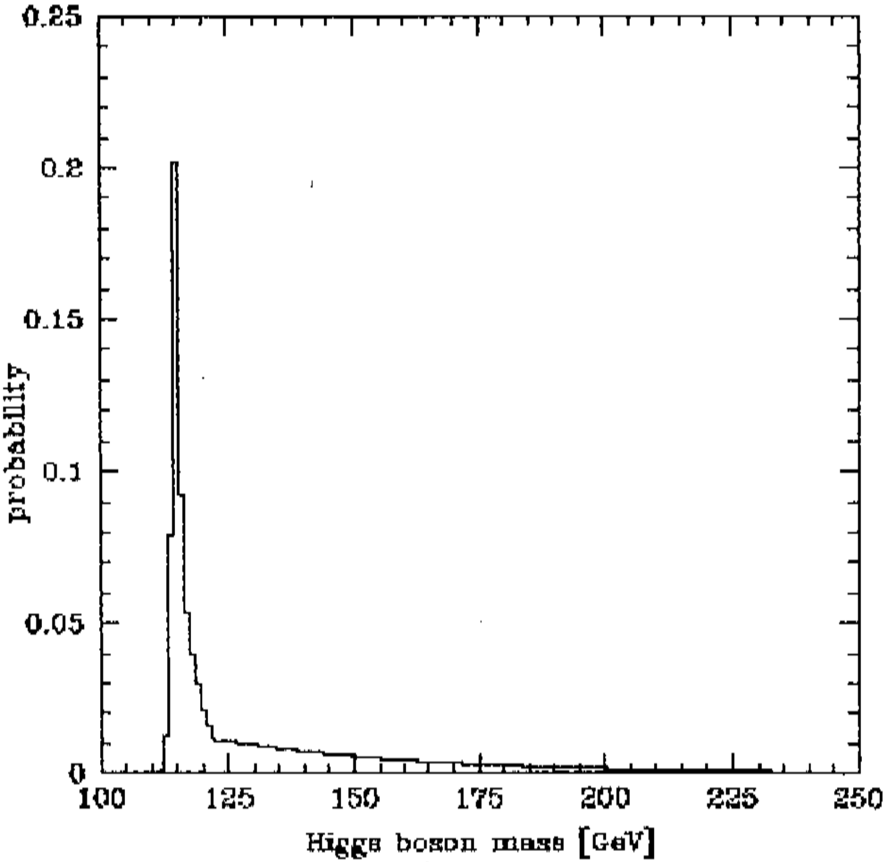
Figure 1: Observed and expected behaviour of the likelihood ratio $-2 \ln Q$ as a function of the test-mass m_H, obtained by combining the data of all four experiments. The solid line represents the observation; the dashed/dash-dotted lines show the median background/signal+background expectations. The dark/light shaded bands around the background expectation represent the ±1/±2 standard deviation spread of the background expectation obtained from a large number of background experiments. The dotted line is the result of a test where the signal from a 115 GeV Higgs boson has been added to the background and propagated through the likelihood ratio calculation.

(LEP Higgs WG

Probability Distribution for Higgs Mass

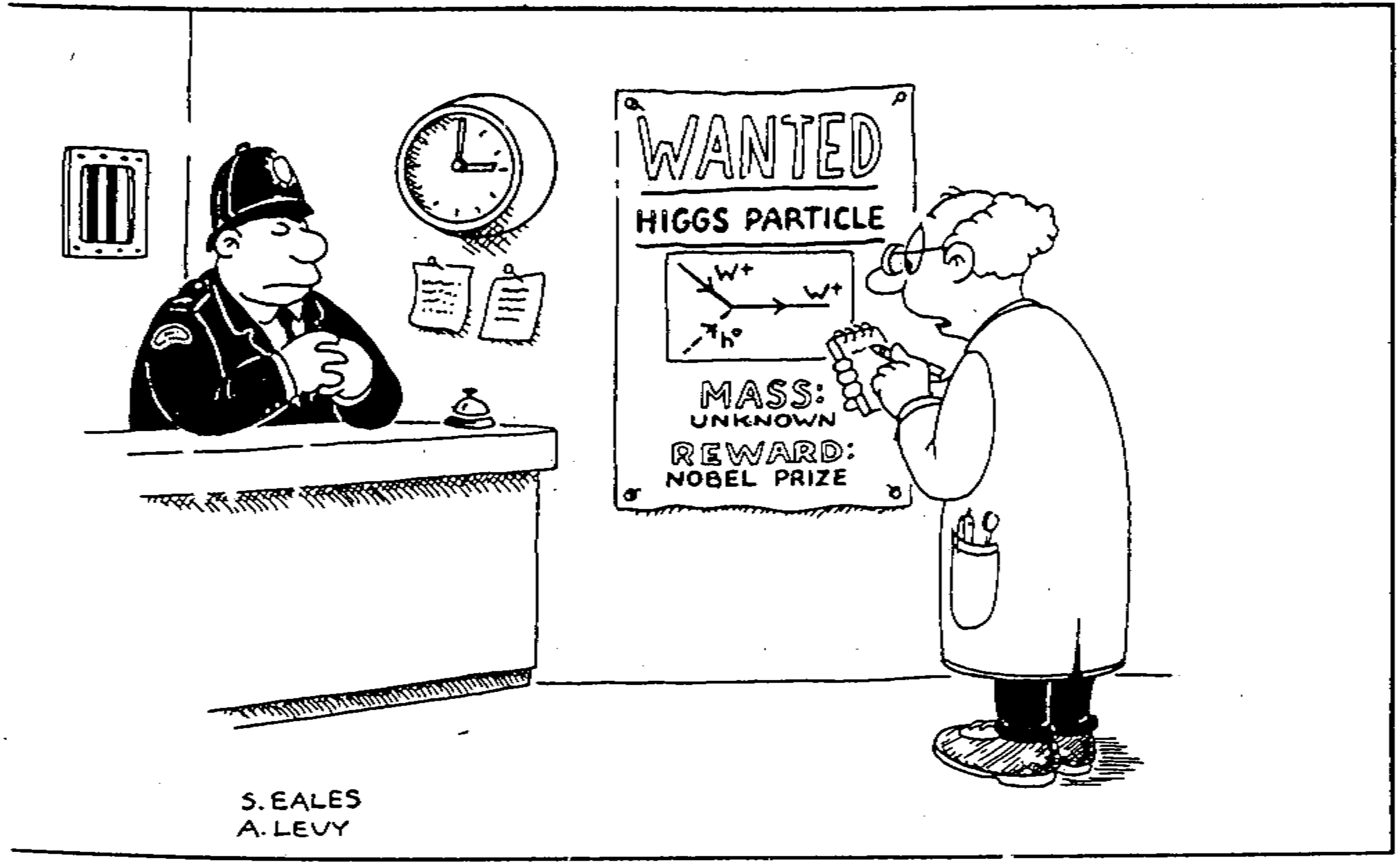
combining precision measurements

⊕ direct limits



Standard Model

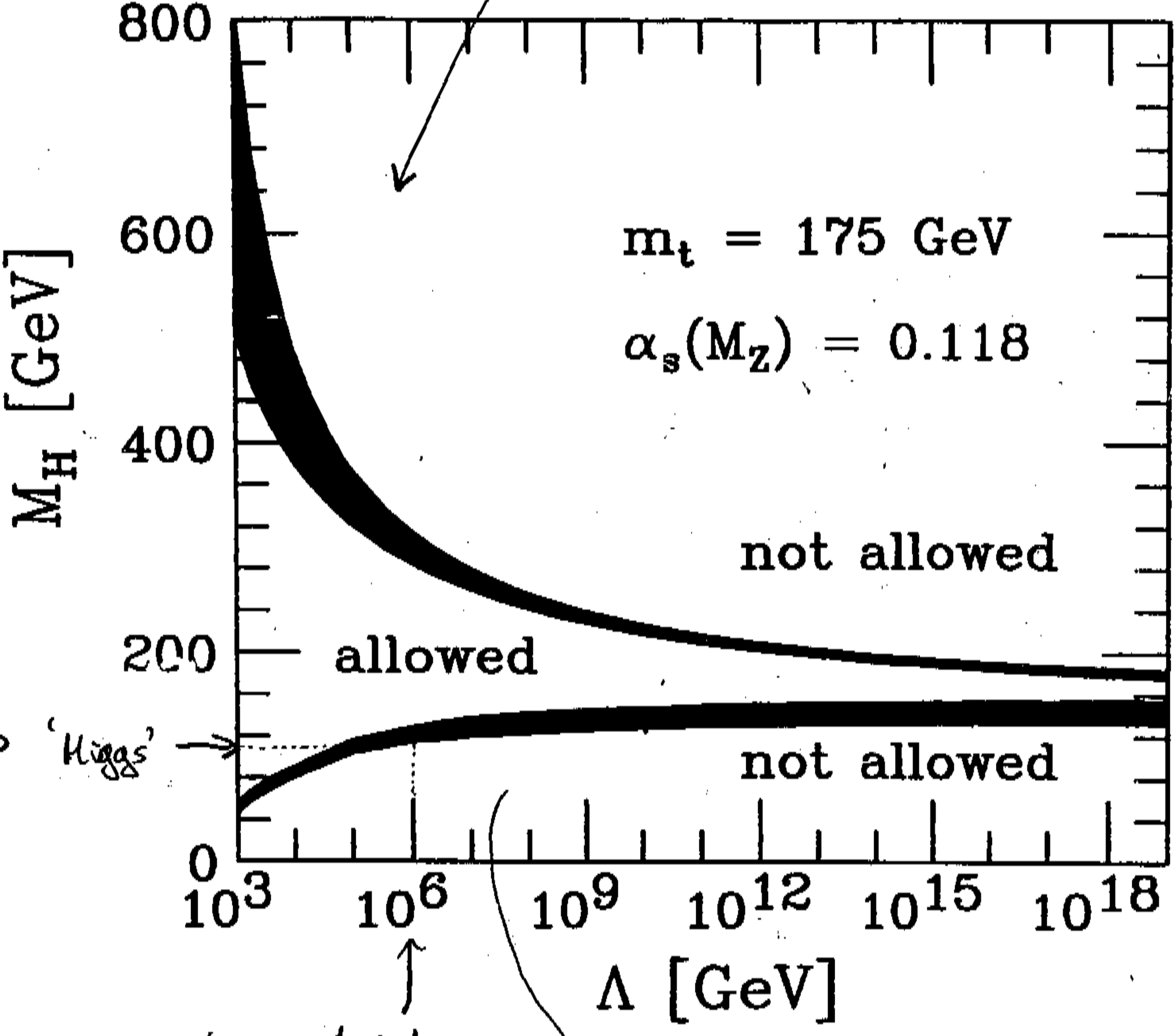
(Erler:
hep-ph/001015



S. EALES
A. LEVY

Limitations of the Standard Model

couplings blow up! (Scylla)



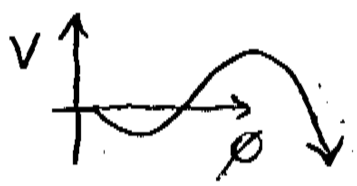
LEP 'Higgs' →

scale by which
new physics
must appear!

(Hambye +
Riesselmann

potential
unstable!

(Altarelli + Isidori

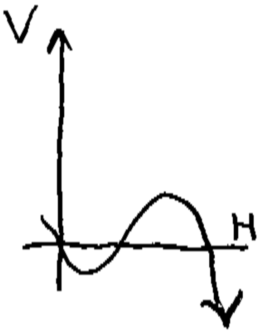


(charybdis)

It Quacks like Supersymmetry

To avoid vacuum collapse (Charybdis

must introduce new bosons



$\lambda_{22} |H|^2 |\phi|^2$

↖ N_I isomultiplets I

RGE solutions very sensitive to λ_{22}

danger of non-perturbative blow-up (Scylla

↙

can only be avoided by coupling to fermions, ...

to survive up to $m_p \sim 10^{19}$ GeV

couplings must be finely tuned

↗

automatic within supersymmetry

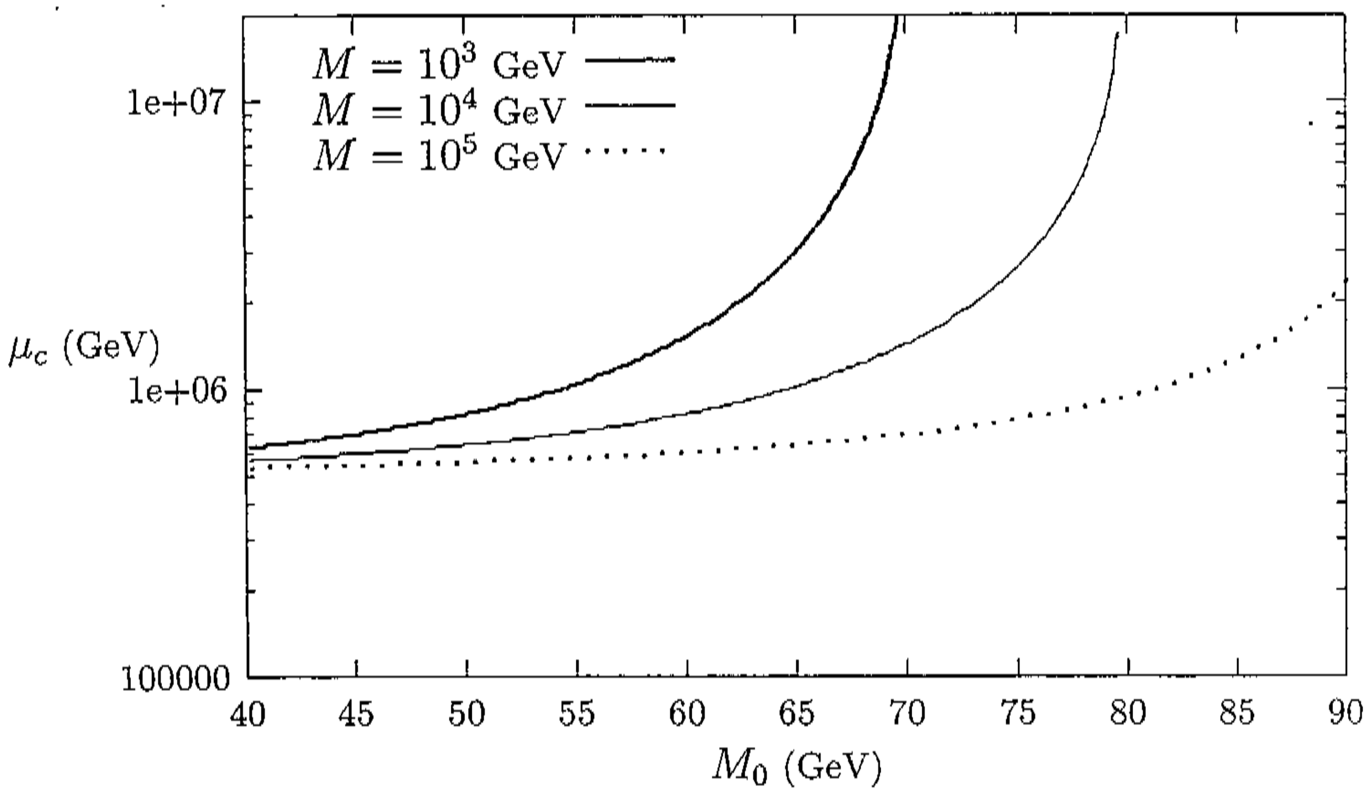
(J.E. + D. Ross:
hep-ph/0012067

Introducing new bosons

$$M^2 |\phi|^2 + \lambda_{22} |H|^2 |\phi|^2 \quad : \quad M_0^2 = \lambda_{22} v^2$$

can postpone collapse of potential

if $M \lesssim 10^5$ GeV



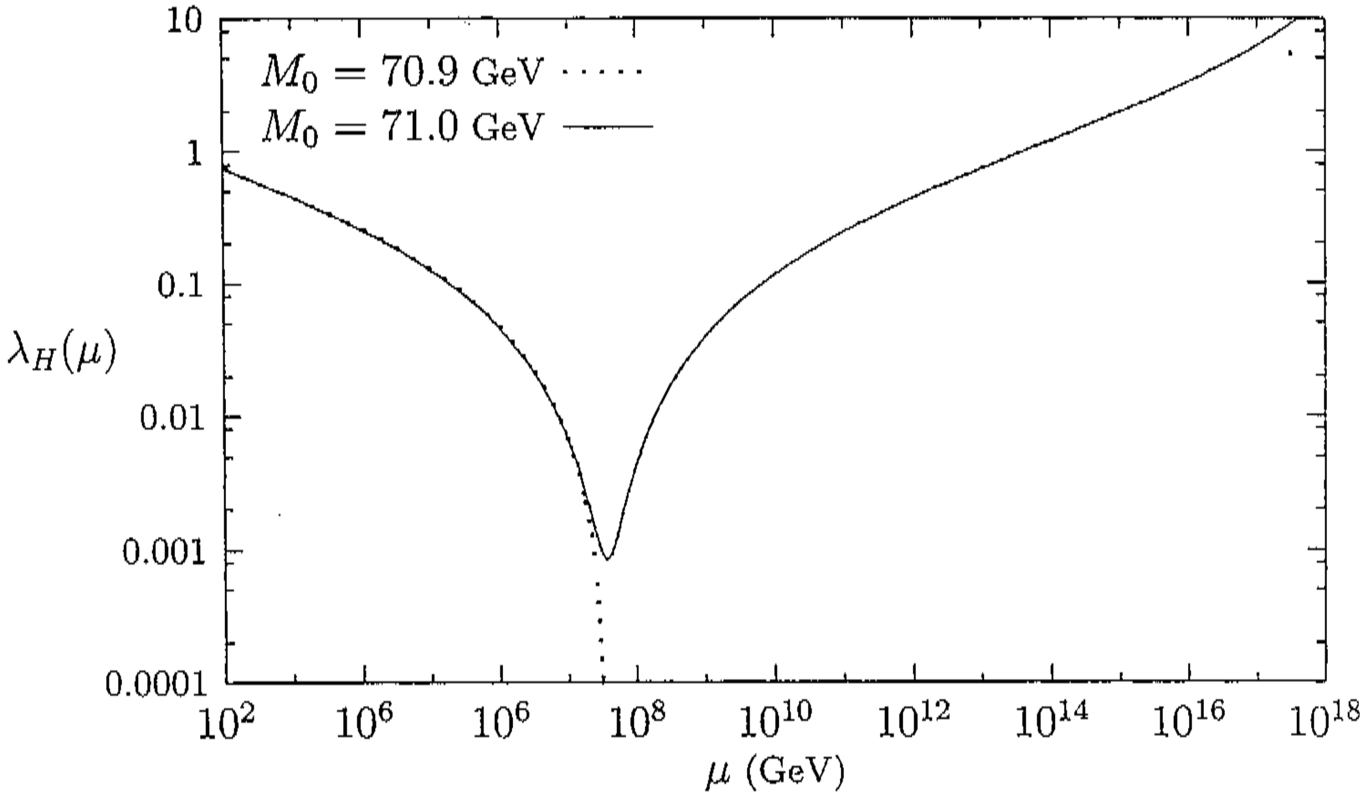
(J.E. + D. Ross: hep-ph/0012067

New physics must be fine-tuned

to steer between

potential collapse

blow-up of couplings

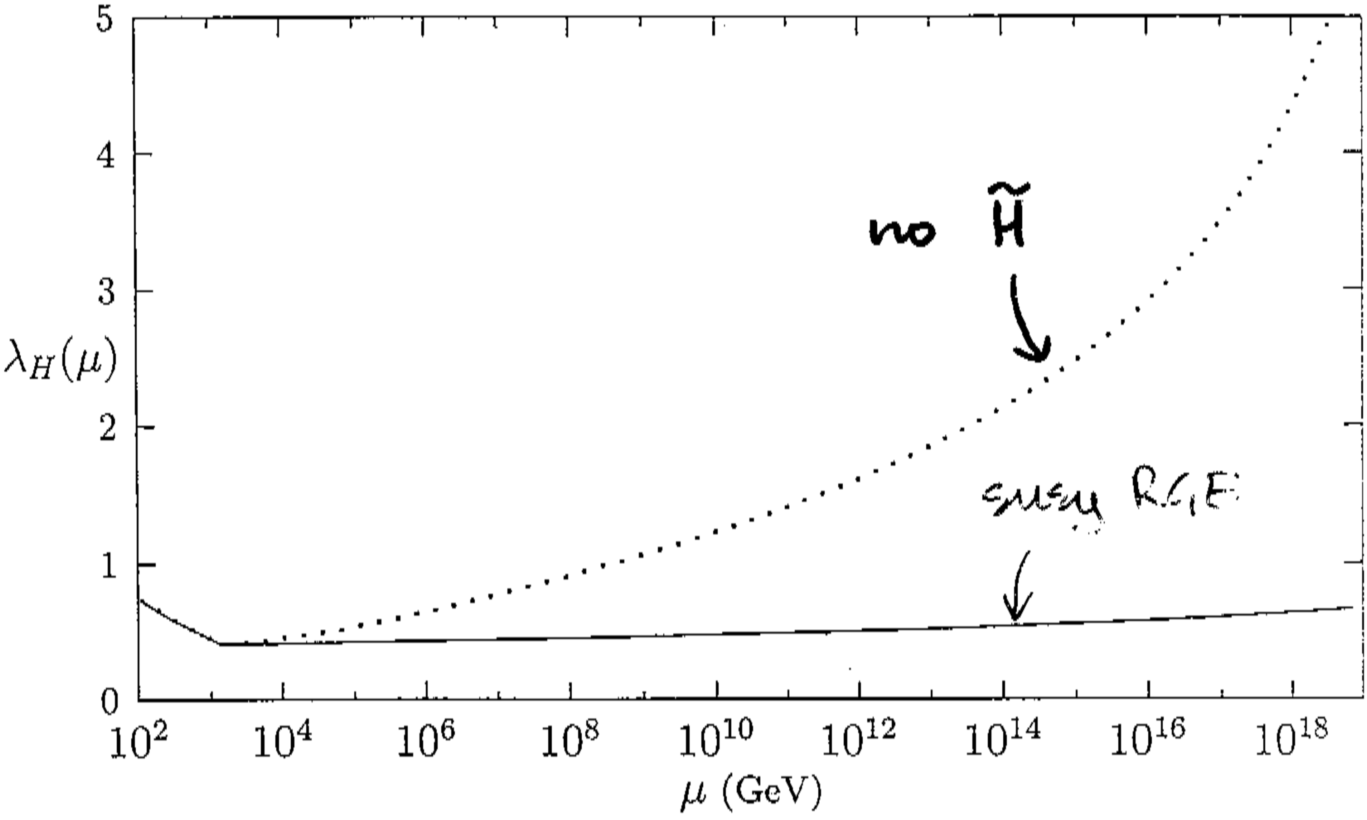


(J.E. + D.Ross –
hep-ph/0012067

Fine-tuning quacks like supersymmetry

need relation: $\lambda_H \Leftrightarrow \lambda_t, g$

natural in susy with $\tilde{t}, \tilde{H}$



(J.F. + D. Ross -
hep-ph/0012067

3- The Electroweak Vacuum

Generating particle masses requires breaking gauge symmetry:

$$m_{W,Z} \neq 0 \iff \langle 0 | X_{I,I_3} | 0 \rangle \neq 0$$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \simeq 1 \Longleftarrow I = \tfrac{1}{2}$$

$$m_f \neq 0 \iff \langle 0 | X_{\frac{1}{2}, \pm\frac{1}{2}} | 0 \rangle \neq 0$$

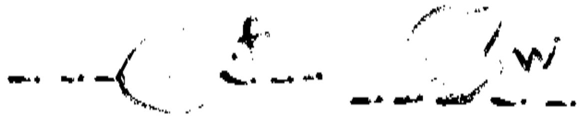
[illegible] $I = 0$

What is X ?

Elementary ?

Higgs boson: $\langle 0 | H^0 | 0 \rangle \neq 0$

problems with loops:



$\delta m^2_H = \mathcal{O}\left(\frac{\alpha}{\pi}\right) \Lambda^2$

cut-off scale

Supersymmetry ?

$\Lambda \lesssim \tilde{m} < 1$ TeV

Composite ?

$\bar{F}F$ condensate: $\langle 0 | \bar{F}F | 0 \rangle \neq 0$

cf QCD: $\langle 0 | \bar{q}q | 0 \rangle \neq 0$

superconductivity

$\bar{t}t$ condensate ?

wanted $m_t \approx$ [illegible]

Technicolour ?

minimal model

× [illegible] ≥ 5

Technicolour

composite Higgs à la QCD:

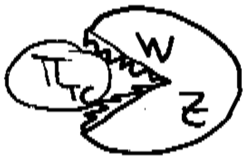
$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \implies \langle 0|\bar{Q}_L Q_R|0\rangle \neq 0$$

breaks isospin: $I = \frac{1}{2}$ new strong interactions:

$$\Lambda_{QCD} < 1\ \text{GeV} \implies \Lambda_{TC} \sim 1\ \text{TeV}$$

$$f_\pi \sim 100\ \text{MeV} \implies m_W = \frac{g}{2} F_\pi \Leftarrow \sim 250\ \text{GeV}$$

cf QCD: 3 massless technipions



1 massive scalar $\not\simeq$ "heavy Higgs"
~ TeV

Single TC doublet not enough:

anomalies, give fermion masses, ...

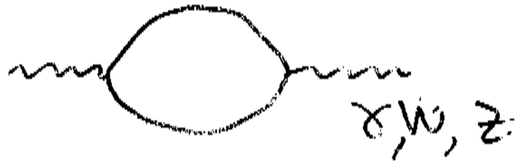
Single Technigeneration Model:

$$\begin{pmatrix} \nu \\ l \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_{1,2,3} \qquad \begin{pmatrix} N \\ L \end{pmatrix}_{1,\ldots,N_{TC}} \begin{pmatrix} U \\ D \end{pmatrix}_{\substack{1,\ldots,N_{TC} \\ 1,2,3}}$$

study models as functions of (N_{TC}, N_{TF})

technicolours, techniflavours

General Parametrization of Radiative Corrections



1-loop: no vertices

Electroweak observables given by 3 combinations of vacuum polarizations:

e.g. $T \equiv \epsilon_1/\alpha \equiv \Delta\rho/\alpha$

(Altarelli + Barbieri + Caravaglios

(Peskin + Takeuchi

measures isopin breaking:

$$\Delta\rho = \frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{\Pi_{WW}(0)}{M_W^2} - 2\tan\theta_W \frac{\Pi_{\gamma Z}(0)}{M_Z^2}$$

$$T = \frac{3}{16\pi}\frac{1}{\sin^2\theta_W\cos^2\theta_W}\left(\frac{m_t^2}{M_Z^2}\right) - \frac{3}{16\pi\cos^2\theta_W}\ln\left(\frac{M_H^2}{M_Z^2}\right) + \cdots$$

also $$S \equiv \frac{4\sin^2\theta_W}{\alpha}\epsilon_3 = \frac{1}{12\pi}\ln\left(M_H^2/M_Z^2\right) + \cdots$$

$$U \equiv -\frac{4\sin^2\theta_W}{\alpha}\epsilon_2$$

use data to constrain $\epsilon_{1,2,3}$ (S, T, U)

and extensions of Standard Model with:

- same gauge group: $SU(2)\times U(1)$
- extra matter particles: e.g. technicolour

Beware of vertices, 2-Loop effects, ...

can parametrize $Z\to\bar{b}b$ vertex by ϵ_b

omparison with TC

problem!

problem!

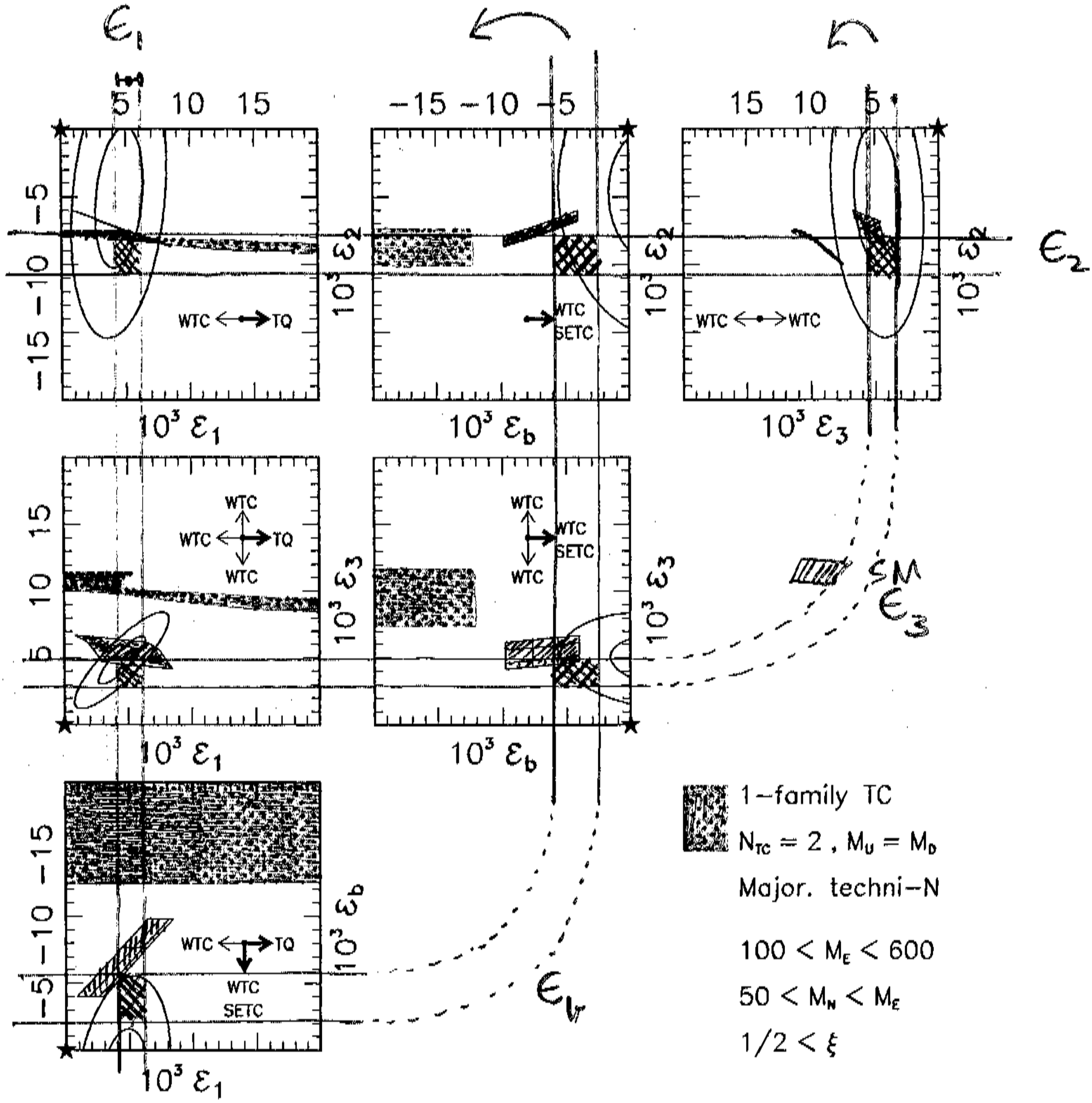


Fig. 3

(J.E.+Fogli+Lisi:95

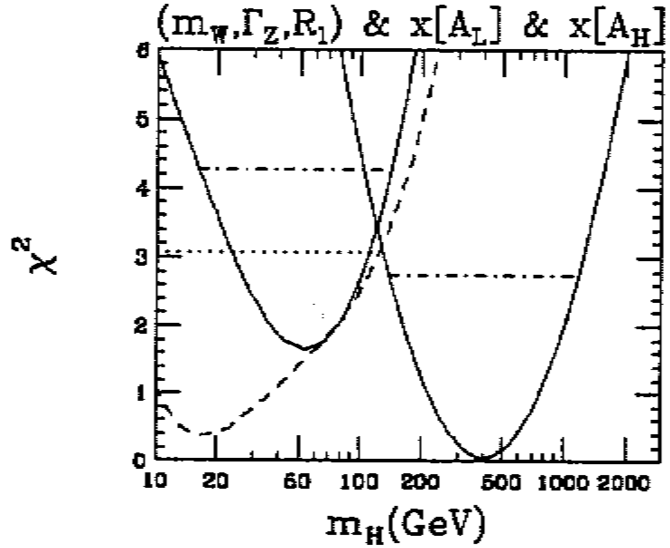
(Altarelli+Caravaglios+
Giudice+Gambino
+Ridolfi:01

Theorists getting Cold Feet

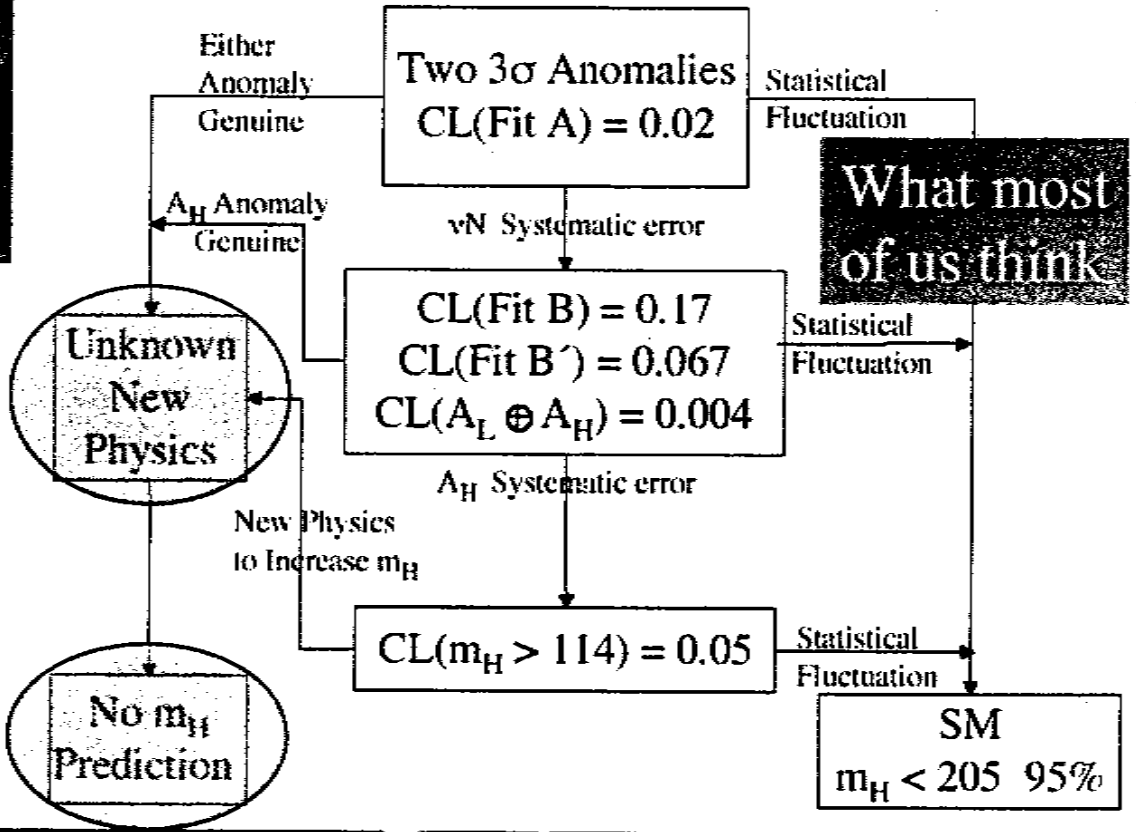
- Interpretation of EW data?
  consistency of measurements? Discard some?
- Higgs + higher-dimensional operators?
  corridors to higher Higgs masses?
- Little Higgs models
  extra `Top', gauge bosons, `Higgses'
- Higgsless models
  strong WW scattering, extra D?

Heretical Interpretation of EW Data

Do all the data
tell the same story?



What attitude towards LEP, NuTeV?



Two 3σ Anomalies
CL(Fit A) = 0.02

Either Anomaly Genuine

Statistical Fluctuation

νN Systematic error

A_H Anomaly Genuine

CL(Fit B) = 0.17
CL(Fit B´) = 0.067
CL($A_L \oplus A_H$) = 0.004

Statistical Fluctuation

A_H Systematic error

What most of us think

Unknown New Physics

New Physics to Increase m_H

CL($m_H > 114$) = 0.05

Statistical Fluctuation

No m_H Prediction

SM
$m_H < 205$ 95%

Higgs + Higher-Order Operators

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^p} \mathcal{O}_i^{(4+p)}$$

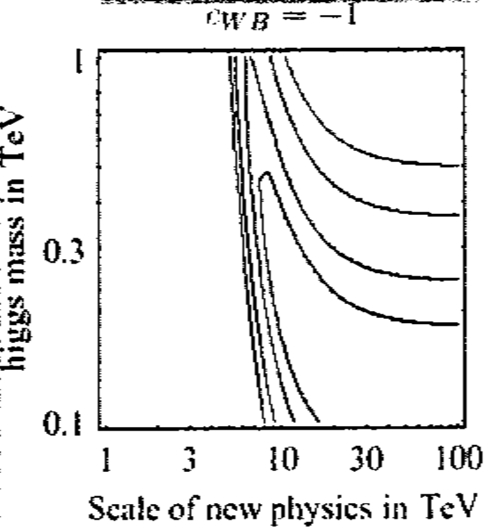
Precision EW data suggest they are small: why?

Dimension six operator	$c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB} = (H^+ \sigma^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.0	13
$\mathcal{O}_H = \lvert H^+ D_\mu H)\rvert^2$	4.2	7.0
$\mathcal{O}_{LL} = \frac{1}{2}(\bar{L}\gamma_\mu \sigma^a L)^2$	8.2	8.8
$\mathcal{O}_{HL} = i(H^+ D_\mu H)(\bar{L}\gamma_\mu L)$	14	8.0

95% lower bounds on Λ/TeV

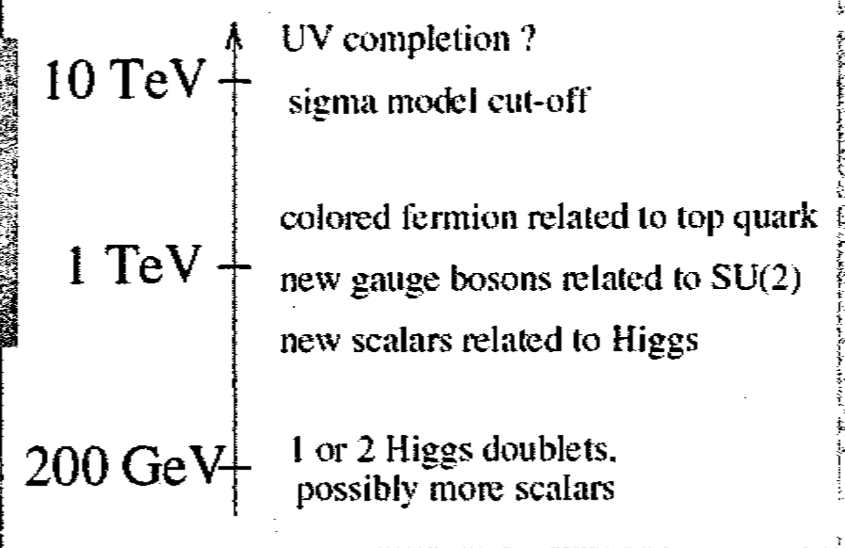
But conspiracies are possible: m_H could be large, even if believe EW data …?

Corridor to heavy Higgs?



Do not discard possibility of heavy Higgs

Generic Little Higgs Spectrum



UV completion ?

sigma model cut-off

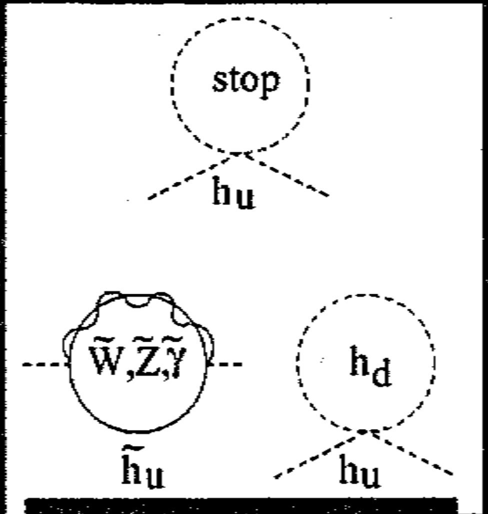
colored fermion related to top quark

new gauge bosons related to SU(2)

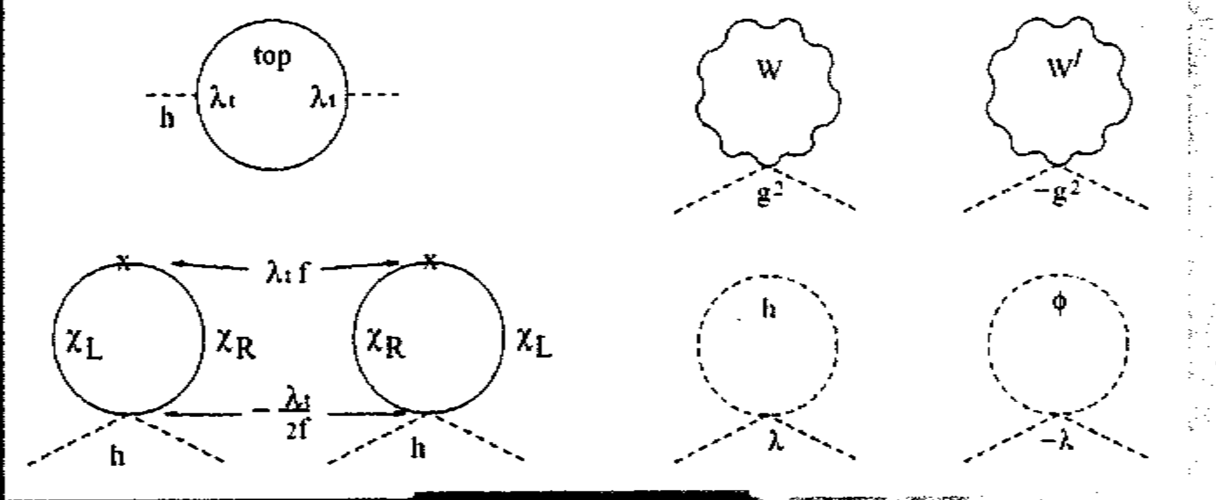
new scalars related to Higgs

1 or 2 Higgs doublets.
possibly more scalars

Loop cancellation mechanisms



Supersymmetry



Little Higgs

Little Higgs Models

- Embed SM in larger gauge group
- Higgs as pseudo-Goldstone boson
- Cancel top loop

$$\delta m^2_{H,top}(SM) \sim (115GeV)^2(\frac{\Lambda}{400GeV})^2$$

with new heavy T quark $m_T > 2\lambda_t f \sim 2f$ $f > 1$ TeV

$$\delta m^2_{H,top}(LH) \sim \frac{6G_F m_t^2}{\sqrt{2}\pi^2} m_T^2 log\frac{\Lambda}{m_T} \gtrsim 1.2f^2$$

- New gauge bosons, Higgses
- Higgs light, other new physics heavy

$M_T < 2$ TeV (m_h / 200 GeV)

$M_{W'} < 6$ TeV (m_h / 200 GeV)

$M_{H++} < 10$ TeV

Not as complete as susy: more physics > 10 TeV

Higgsless Models

- Four-dimensional versions:

  Strong WW scattering @ TeV, incompatible with precision data?

- Break EW symmetry by boundary conditions in extra dimension:

  delay strong WW scattering to ~ 10 TeV?

  Kaluza-Klein modes: $m_{KK} > 300$ GeV?

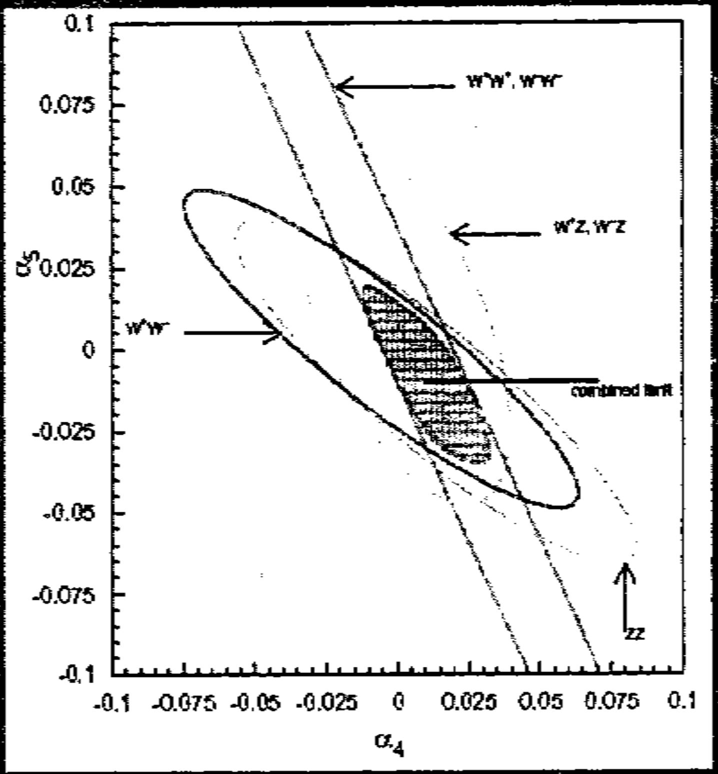
  compatibility with precision data?

- Warped extra dimension + brane kinetic terms?

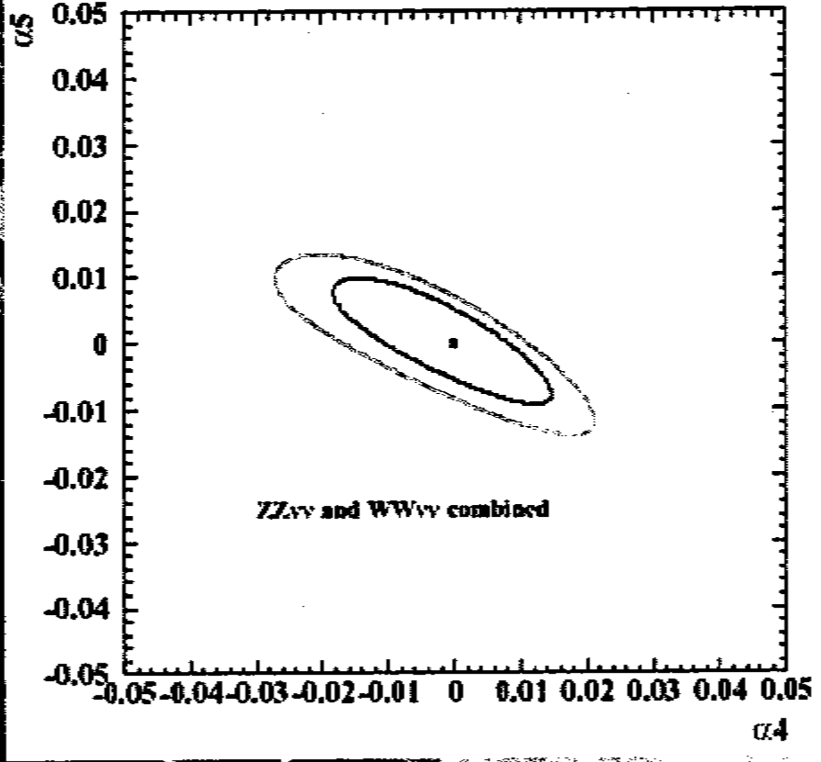
Lightest KK mode @ 300 GeV, strong WW @ 6-7 TeV

Sensitivity to Strong WW scattering

@ LHC



@ 800 GeV LC



-Where do we go from here?

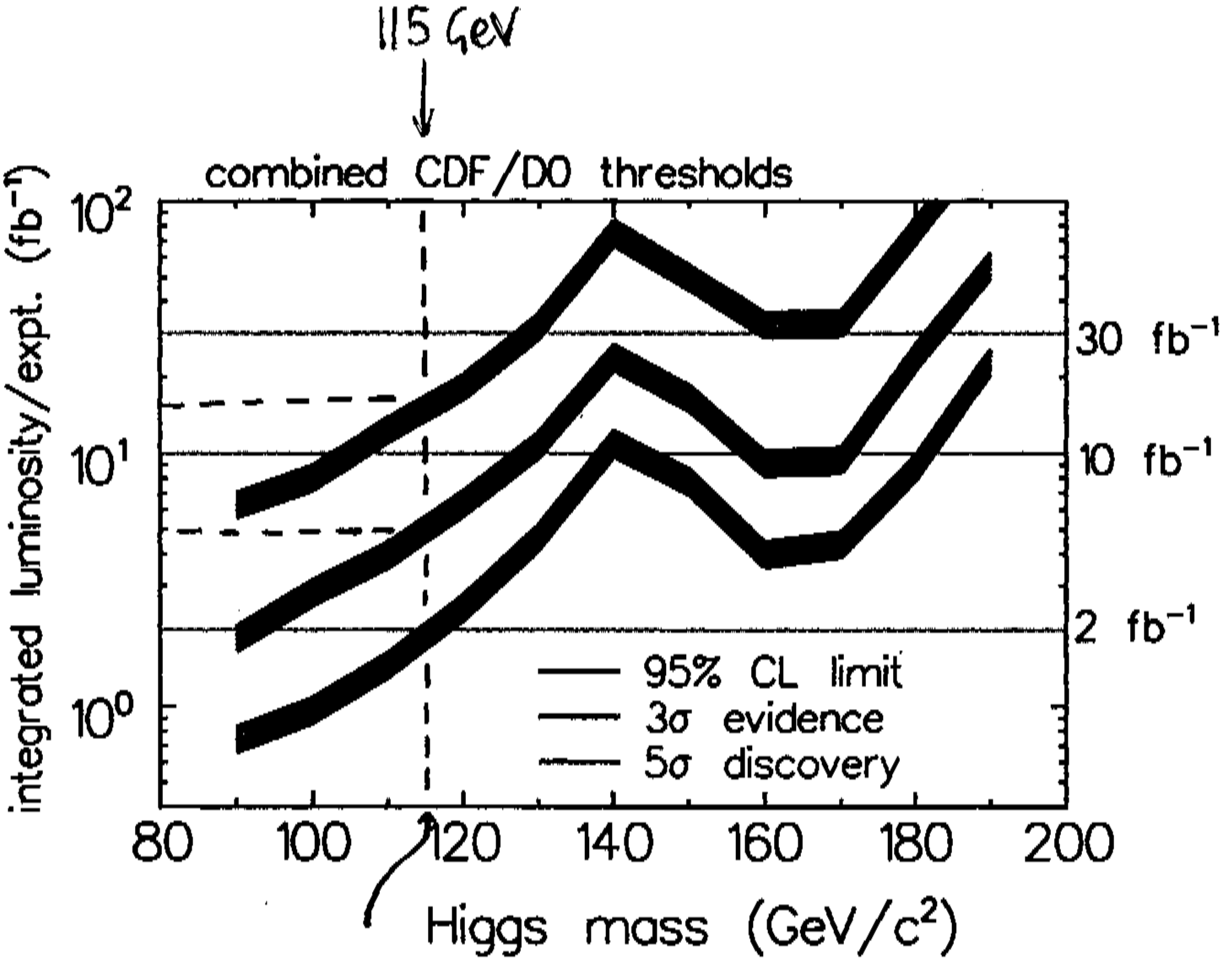
7- Prospects for Higgs Discovery

Tevatron will have chance if m_H = 115GeV
if heavier?

not before 2007 ?

LHC will discover it @ any mass
will observe 2 or 3 decay modes
measure mass to ~ 1%
cover MSSM parameter space
↘ several times?
new analysis including LEP, universality, cosmology
measure MSSM parameters?

Prospects for the Tevatron Collider



$5\,fb^{-1}$ needed to duplicate LEP 'signal'

$15\,fb^{-1}$ needed for 5σ discovery

(Tevatron Higgs Working
Group