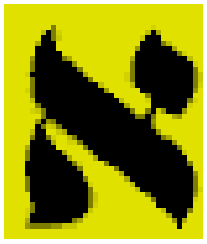
Higgs Bosons in the SM and the MSSM Searches at LEP

P. Igo-Kemenes

Heidelberg / CERN

Topical Seminar on the Legacy of LEP and SLC

Siena, Oct 8-11, 2001



†

The Legacy

- **SM Higgs boson** ... $m_{\mathrm{H}} > 114.1$ **GeV**
  Indication (2.1σ) **at** $m_{\mathrm{H}} \approx 115.6$ **GeV**
- **MSSM Higgs bosons**
  $m_{\mathrm{h}} > 91.0$ **GeV** , $m_{\mathrm{A}} > 91.9$ **GeV**
  $\tan\beta = v_2/v_1$: $0.5 - 2.4$ **unlikely**

Higgs mechanism / Higgs bosons

... a <u>model</u> to provide mass to gauge bosons and fermions without conflicting with the principle of gauge invariance

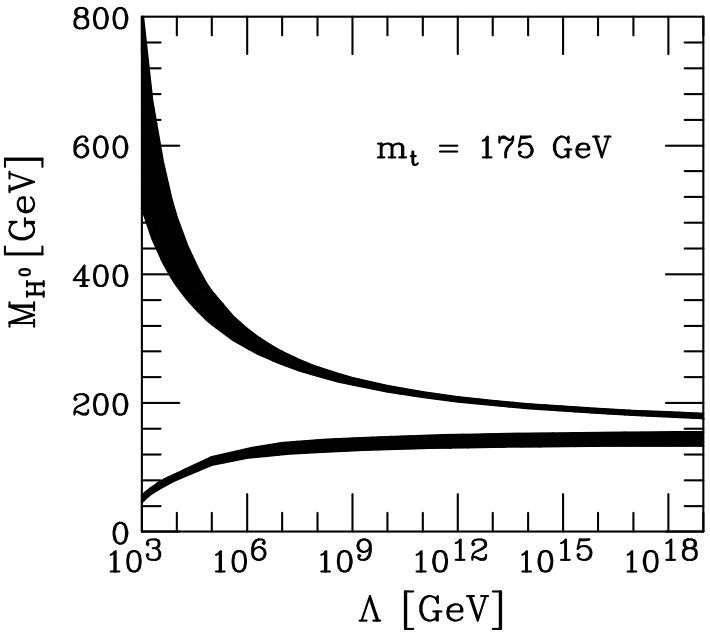
Standard model	Minimal SUSY extension
One complex scalar field doublet ϕ $< \phi >= v \approx 246$ GeV	Two field doublets ... ϕ_1, ϕ_2 $v^2 = v_1^2 + v_2^2\,, \;\; v_2/v_1 = tan\beta$
4 degrees of freedom • $M_{W^+}, M_{W^-}, M_{Z^0}$ • One physical Higgs boson $\mathrm{H^0}$	8 degrees of freedom • $M_{W^+}, M_{W^-}, M_{Z^0}$ • $\mathrm{h^0, H^0, A^0, H^+, H^-}$ *(mixing α)*
m_{H} fixes all couplings ... to fermions : $\sim m_f$ ... to vector bosons : $\sim m_V^2$	• Tree level : 2 parameters e.g. $(\alpha, \tan\beta)$ or $(m_{\mathrm{A}}, \tan\beta)$ • Loop level : Many soft SUSY breaking parameters Unification at Λ_{GUT} ... $m_0, m_{1/2}, \mu, A_t$

Proof ... detection of a Higgs particle

Higgs boson masses

Standard model

m_{H} **is a free parameter ... theory suggests ...**



- **Upper bound:** *perturbability* **up to scale** Λ
- **Lower bound: from** *vacuum stability* **up to** Λ

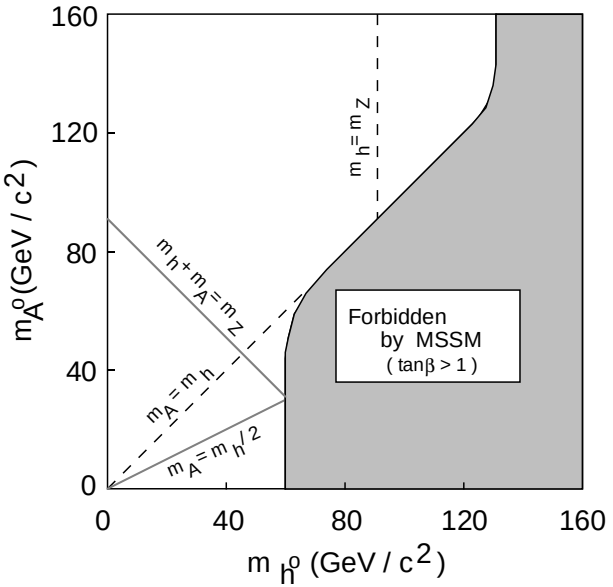
  Consistency of the SM up to Λ_{GUT} **...**

  $\Rightarrow \; 130 \lesssim m_{\mathrm{H}} \lesssim 190$ **GeV**

Minimal SUSY (MSSM)

- *Tree level* **...** $m_{\mathrm{h}} < M_Z$, $m_{\mathrm{h}} < m_{\mathrm{A}}$

  $m_{\mathrm{H}} > M_Z$, $m_{H^\pm} > M_W$



- *One loop* **...** *Ellis, Ridolfi, Zwirner, ... (1991)*

  $\sim m_t^4$, $\sim \log\,(m_{\tilde{t}}/m_t)^2$

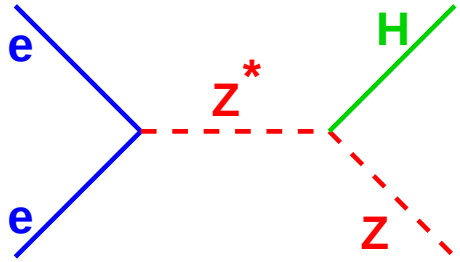
  Two-loop ... *Carena, Wagner, Hollik, Weiglein ...*

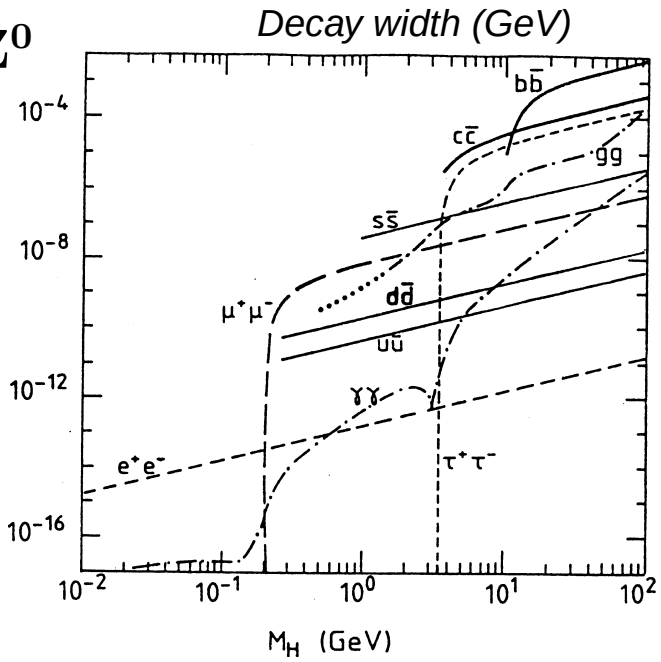
  $m_{\mathrm{h}} < 135$ **GeV**

Higgs Production / Decay

Standard Model

"Higgs-strahlung" ... $e^+e^- \to H^0Z^0$





LEP1 : final-state Z^0 is virtuel

LEP2 : final-state Z^0 is real

MSSM

$e^+e^- \to h^0Z^0$ ... $\sigma_{hZ} = \sin^2(\beta-\alpha)\ \ \sigma_{SM}$

$e^+e^- \to h^0A^0$ ... $\sigma_{hA} = \cos^2(\beta-\alpha)\ \ \bar{\lambda}\ \sigma_{SM}$

Complementarity !

Couplings ... relative to SM

	"Up" fermions	"Down" fermions	Vector bosons
h^0	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H^0	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A^0	$1/\tan\beta$	$\tan\beta$	0

Searches for lowest-mass Higgs

Searches prior to LEP

P.J. Franzini et al., in CERN-89/08-V2

- Muonic x-rays (^{24}Mg, ^{28}Si)
- $0^+ \rightarrow 0^+$ nuclear transition
- π^+, K^0, B^0 decays
- $\Upsilon \rightarrow \mathrm{H}^0\gamma$ decays

Theoretical "loopholes"

QCD corrections

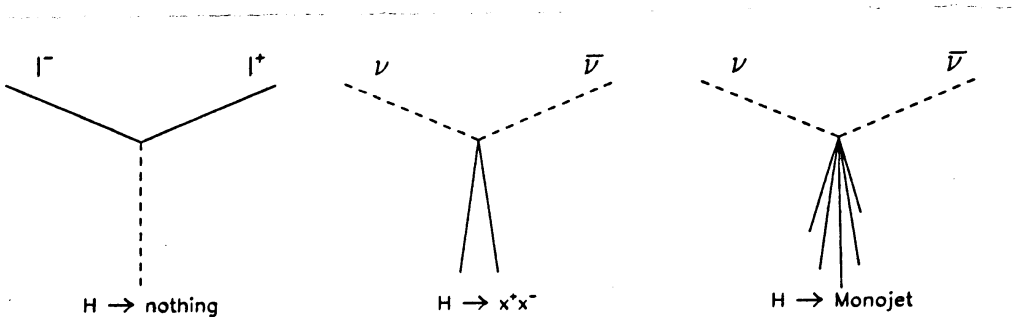
Higgs final states ... uncertain

$\Rightarrow$ **No compelling mass limits**

Early searches at LEP1 ... aiming at model-independence

Special topologies ... $\mathrm{Z}^0\mathrm{H}^0$ ... low-mass kinematics

- **Minimal assumptions for Higgs final states**
- **Including** *invisible* **decays**
- **and** *very long lifetimes* **(at lowest masses)**
- **Complementarity ...**



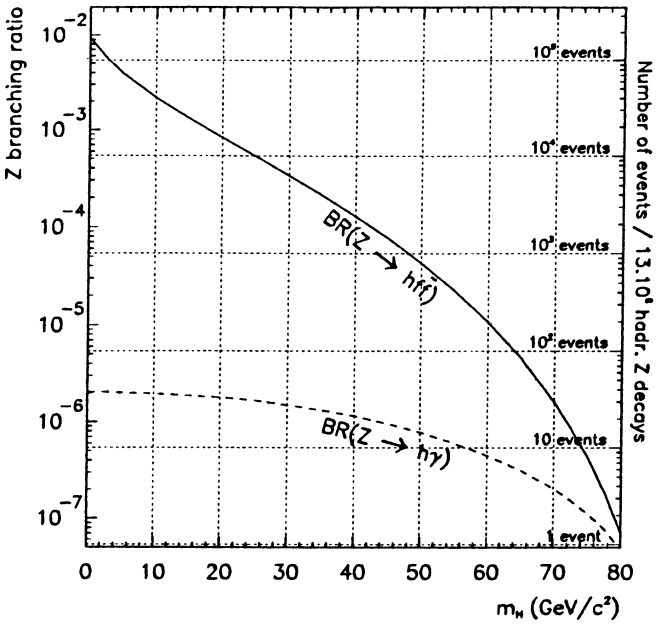
ALEPH, DELPHI, L3, OPAL ... *(end of 1990)*

$\Rightarrow$ $0 \leq m_H \lesssim 20$ GeV

definitively excluded

LEP1 searches (SM, $m_H \gtrsim 15$ GeV)

1989 - 1994 : A+D+L+O ... 13 Millions hadronic Z^0 decays



m_H=10 GeV

50,000 Z^0H^0 events

$S/B \approx 2 \times 10^{-3}$

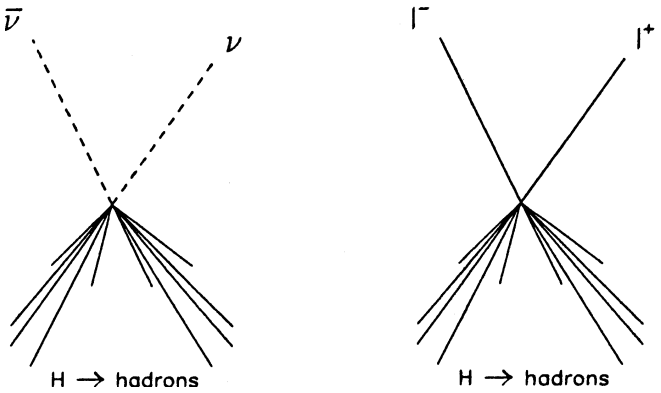
m_H=65 GeV

60 Z^0H^0 events expected

$S/B \approx 4 \times 10^{-6}$

Useful final states ... $(Z^0 \to e^+e^-, \mu^+\mu^-, \nu\bar{\nu})\, H^0$ ... **25 %**

$(Z^0 \to q\bar{q}, \tau^+\tau^-)\, H^0$ *... high background*



m_H=65 GeV

$\Rightarrow$ **15 signal events**

in 13 millions $Z^0 \to had$ *!*

Analysis procedures ... increasing sophistication

- **Cut-based kinematic selection**
- **Likelihood analyses and Neural networks**

  $\Rightarrow$ **More efficient S / B discrimination**

Progress in simulation tools for precise background estimate and description of detector properties ...

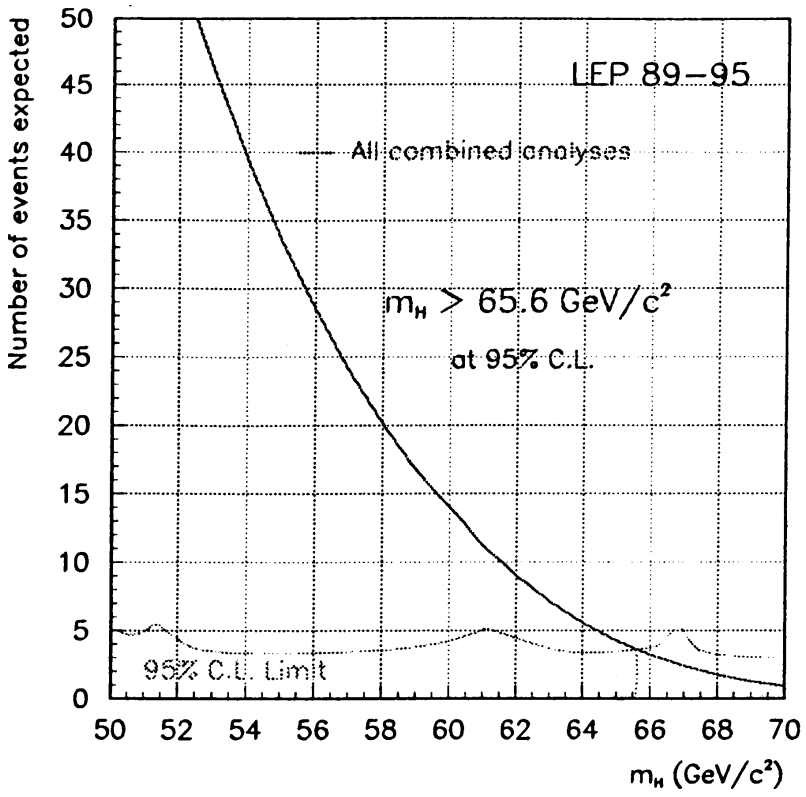
LEP1 ...final results (SM Higgs)

	Lower mass bound (95% c.l.)
ALEPH	63.9 GeV
DELPHI	55.4 GeV
L3	60.2 GeV
OPAL	59.6 GeV

A+D+L+O $\Rightarrow$ ADLO

($Z^0 \to \nu\bar{\nu}$) H^0 channel ... 4 events (6.0 expected , $e^+e^- \to b\bar{b}$)

($Z^0 \to \ell^+\ell^-$) H^0 channel ... 9 events (14.6 exp., $e^+e^- \to \ell^+\ell^- q\bar{q}$)



ADLO *(1995)*

$m_H > 65.6$ GeV

(95% c.l.)

P. Janot, Nucl. Phys. B(Proc. Suppl.)38 (1995) 264

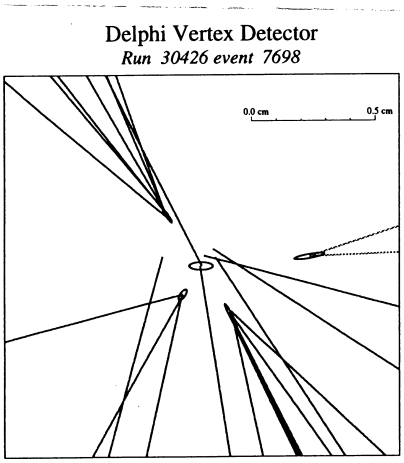
LEP1 ...final results (MSSM Higgs)

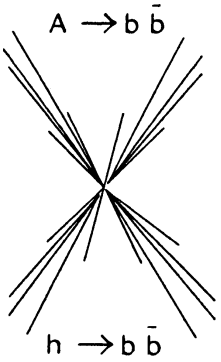
$Z^0 \to h^0 Z^{0*}$ ... **SM searches reinterpreted for MSSM couplings**

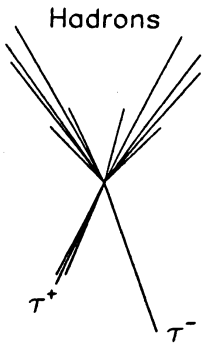
$Z^0 \to h^0 A^0$ ... **A new set of topological searches**

- **Tagging b-jets**

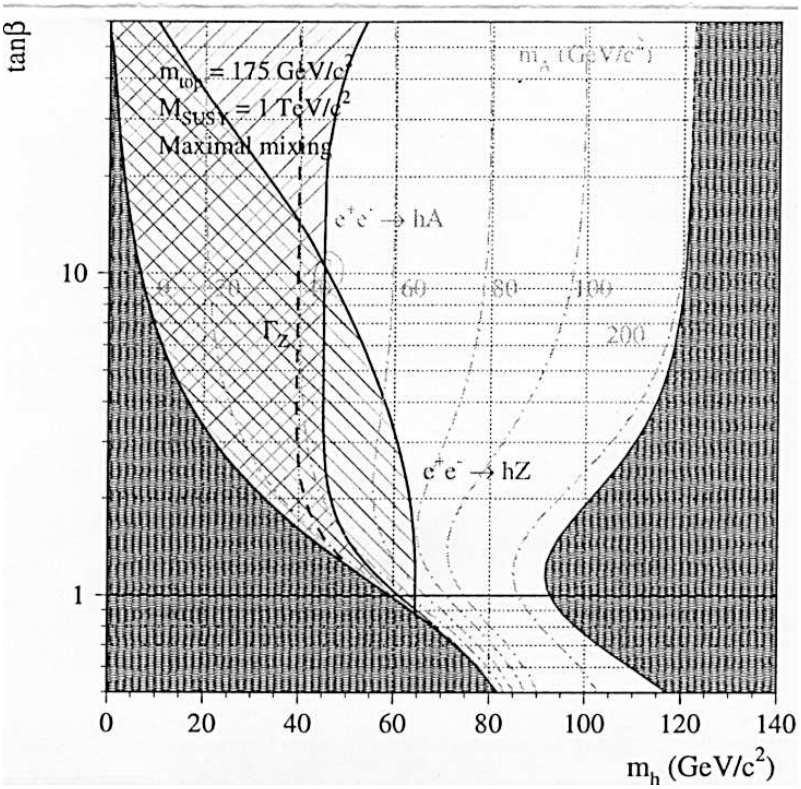
(secondary vertices in Si-μVtx detectors)







ADLO exclusion

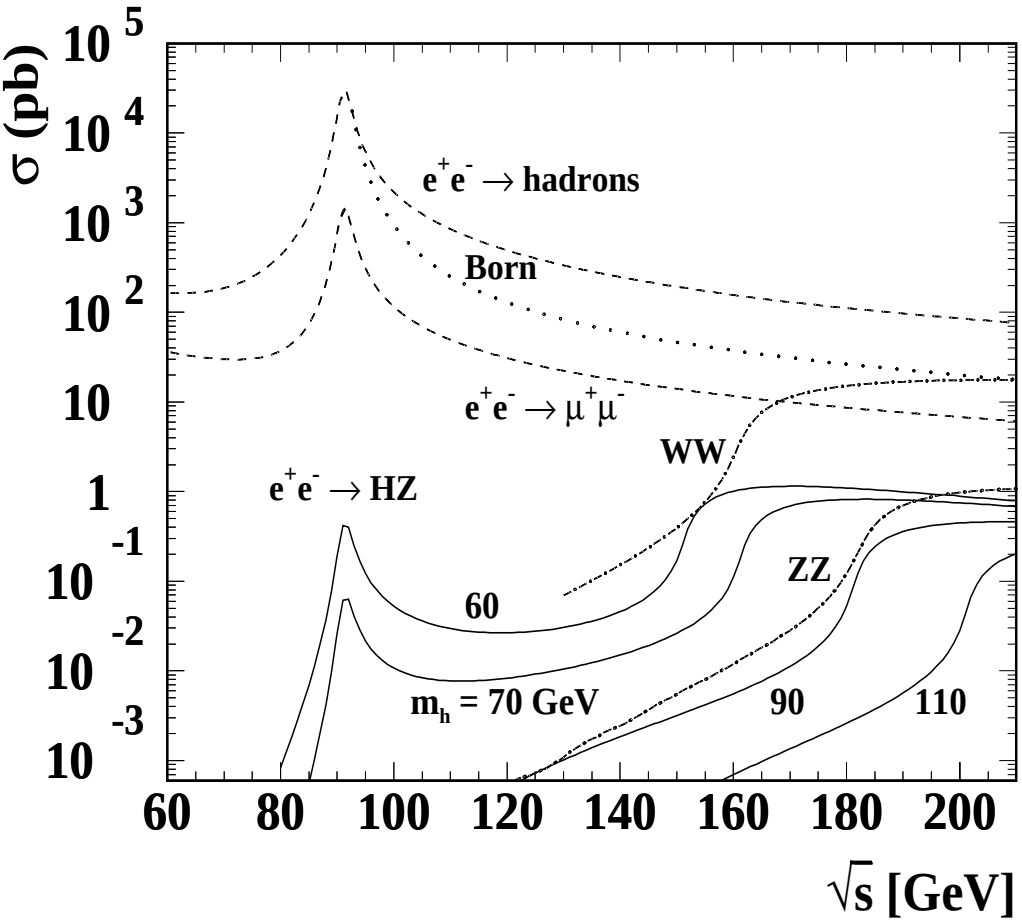


ADLO **(95% c.l.)**

$m_h, m_A \gtrsim 45$ **GeV**

No constraint on $\tan\beta$

LEP 2 Search Environment

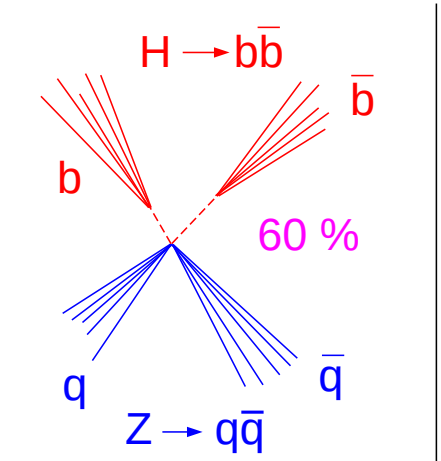


- *1995 - 2000 ... LEP2* ... $\sqrt{s} \sim 135 - 208$ GeV
  $\sqrt{s} \gtrsim 189$ GeV ... $\int L \approx 2500\ \mathrm{pb}^{-1}$
  $\sqrt{s} \gtrsim 206$ GeV ... $\int L \approx 550\ \mathrm{pb}^{-1}$
- $S/B \sim 10^{-2} - 10^{-3}$ ... more favourable than at LEP1
- *Background : complexity* ... $\mathrm{e^+e^-} \to \mathrm{q\bar{q}}$, W^+W^- ,$\mathrm{Z^0Z^0}$
  Kinematic properties similar ($m_{\mathrm{H}} \sim M_W \sim M_Z$)
  But ... $\mathrm{Z^0}$ is real $\Leftarrow$ Constrained kinematic fits
  Sophisticated b-jet tagging algorithms
  Si$-\mu$Vtx detectors ... upgraded geom. coverage, redundancy

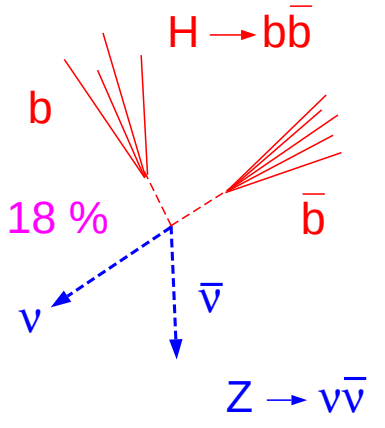
All $\mathrm{H^0Z^0}$ *final states are exploited at LEP2 !*

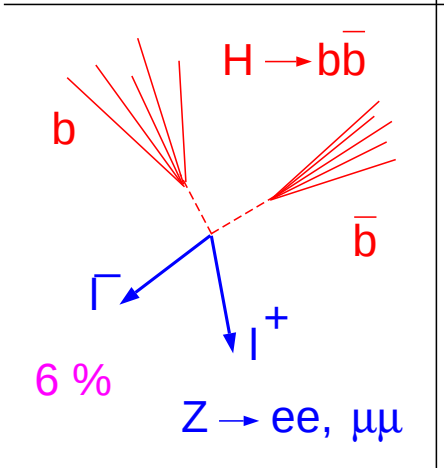
Main $e^+e^- \to H^0Z^0$ final states

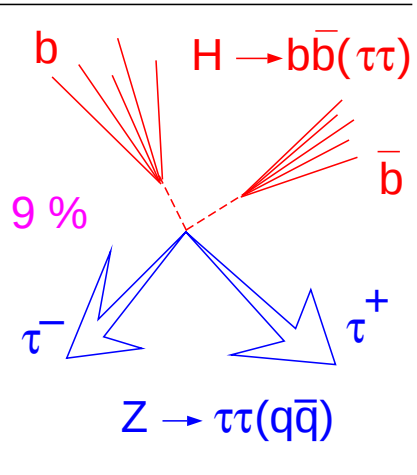
"Four-jet"



"Missing-E"







"Leptonic"

"Tau channels"

LEP2

All four channels exploited

- $\gtrsim$ **90% of H^0Z^0 cross-section**

Example **... $\sqrt{s}$ = 206 GeV**

m_H (GeV)	H^0Z^0
110	75 events
115	15 events

- *ADLO sensibility* $\Rightarrow$ *kin. limit*

$$m_H^{max} \approx \sqrt{s} - M_Z$$
$$\approx 208 - 91 = 117 \text{ GeV}$$

Statistical combination : A+D+L+O $\Rightarrow$ ADLO

(Developed by LEP-Higgs working group)

- **AIM** ... highest overall sensitivity ... by adding all "channels"

  SM : $\approx 10\ \sqrt{s}\ \times 4$ decay channels $\times 4$ exp'ts $\approx$ **160 channels**

  MSSM : $\oplus\ \mathrm{e^+e^-}\rightarrow\mathrm{h^0A^0}$ ... similar number

- **INPUTS** ... provided by the experiments ... binned in

  $\Rightarrow$ Reconstructed Higgs mass M_H^{rec}

  $\Rightarrow$ Global discriminating variable $\mathcal{G}$ ... *(LH or ANN)*

  composed of b-tag, kinematics, other discriminating properties ...

In each bin i ...

Bkgd. estimate (MC) b_i

Signal estimate (MC) $s_i(m_H)$

... for test-mass m_H

Nbr of candidates N_i

$\Uparrow$ $\mathcal{G}$		
	$s_i(m_H)/b_i$	
		$M_H^{rec}\ \Rightarrow$

Candidate "weights" ... $s_i(m_H)/b_i$ ... detailed MC simulation

$\sqrt{s}$, $\int \mathcal{L}$, ϵ_{sig} , ϵ_{bkgd} , *resolution (tails) , syst. errors*

The origin ... *channel* ... **of candidates is irrelevant**

- **LIKELIHOOD TEST** ... $sig + bkgd \iff bkgd$

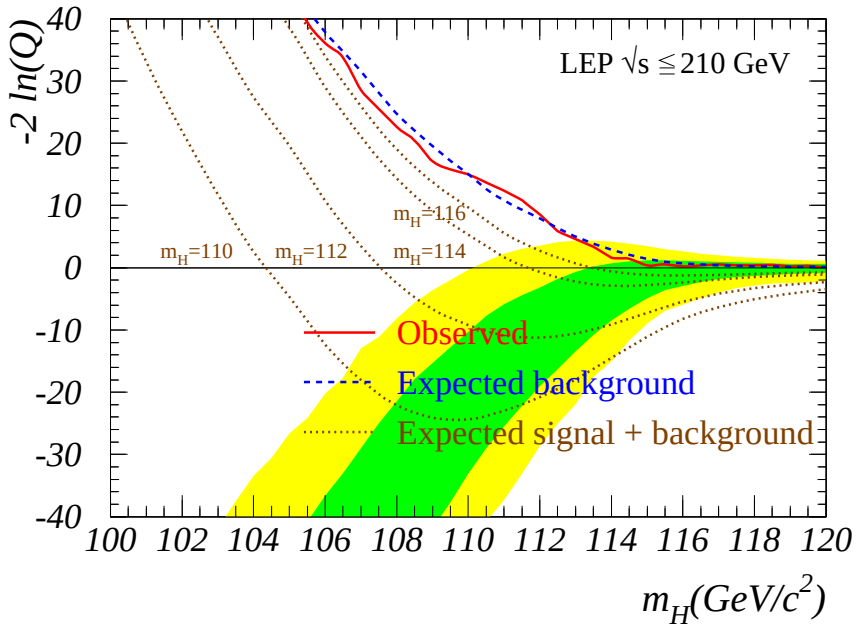
  Test-statistic ... $Q = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b}$ ... to rank the candidates

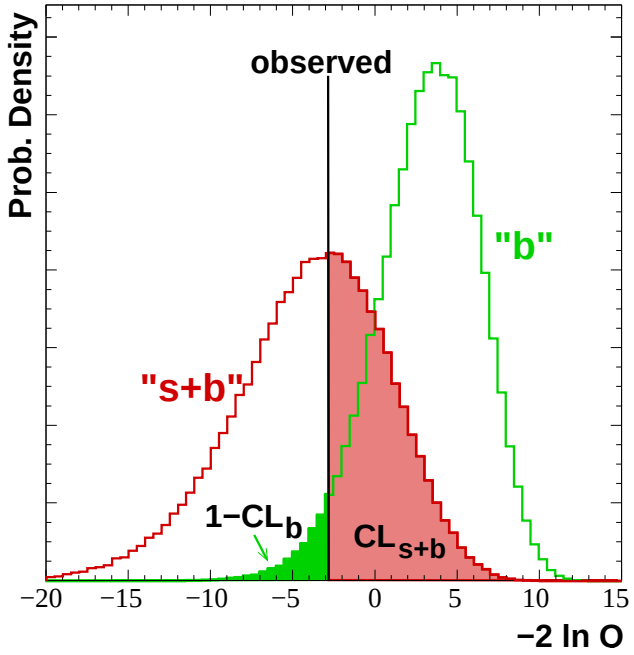
$$\ln Q(m_H) = -s_{tot} + \sum_i N_i \ln[1 + s_i(m_H)/b_i]$$

$\Uparrow$

Candidate "weights" ... additive

For illustration ... *Osaka, July 2000*





As a function of test-mass m_H *...*

Observed likelihood

Expectation for b **... and for** $s+b$

... and stat. $\pm 1\sigma$ **and** $\pm 2\sigma$ **bands**

Slice ... at fixed test-mass m_H *...*

Prob. dens. funct's for b **and** $s+b$ **... integrals**

$1-CL_b$ **... compatibility with bkgd hyp.**

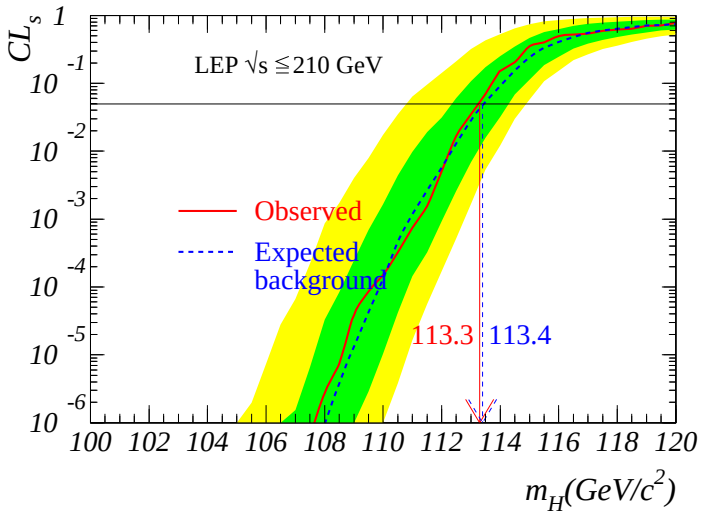
2.7×10^{-3} ... 3σ *"evidence"*

5.7×10^{-7} ... 5σ *"discovery"*

CL_{s+b} **... signal hyp.** $\Rightarrow$ *Mass limit*

Recent LEP History

- **Osaka, July 2000 ... ADLO: NO HIGGS !**



Data mainly from 1998-99

$\oplus\ 120pb^{-1}$ @ $\sqrt{s}\approx$ 206 GeV

Mass limit @ 95% CL

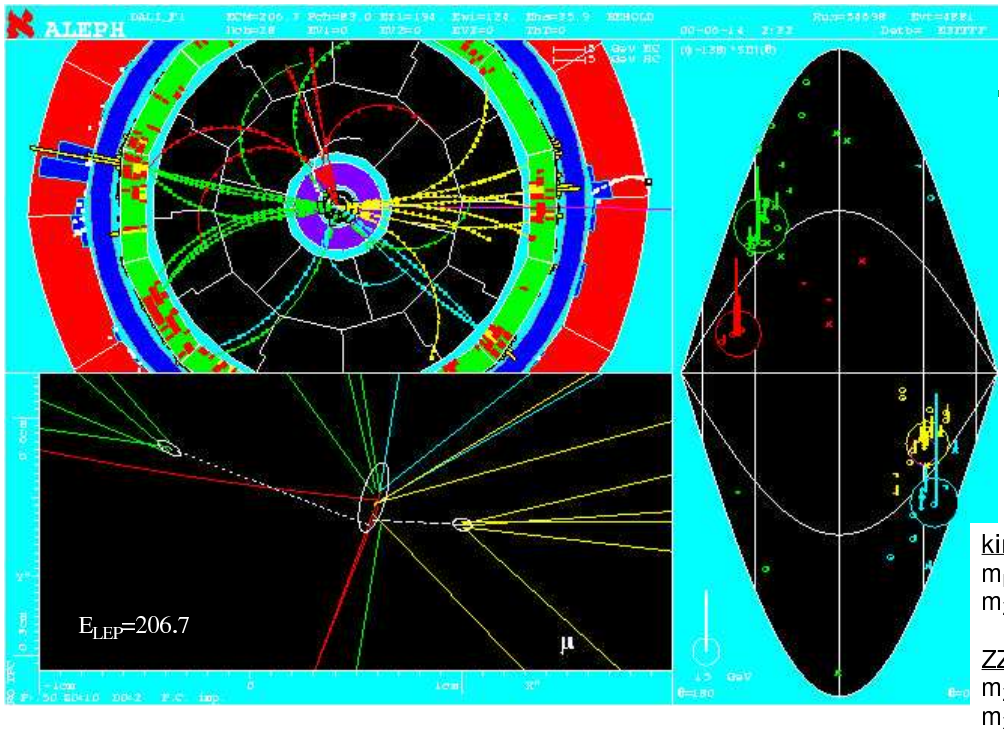
$m_H > 113.3$ GeV

LEP ... "Discovery mode" *(Higgs, SUSY) ...* **until shutdown (***beg. October***)**

- **!! SURPRISE !! ... end of August ... ALEPH "excess" ... 3.9σ**

  Essentially from three "4-jet" candidates @ $\sqrt{s}\approx$ 206 GeV

  $m_H \approx 114$ Gev



2 b cand.

HZ hyp.
m_H=114 GeV
–3 GeV

NN = 0.996

jet b-tag:
Z
1 0.14
2 0.01
H
3 0.99
4 0.99

kin. mass fit
m_H=112.4GeV
m_Z=93.3GeV

ZZ hyp.
m_Z=102 GeV
m_Z=91.7GeV

- **Sept 5, Report to LEPC ...** **304 pb^{-1}@$E_{cm} > 206$ GeV**

  ALEPH: 3.9σ ... DLO: No excess $\Rightarrow$ ADLO: 2.6σ

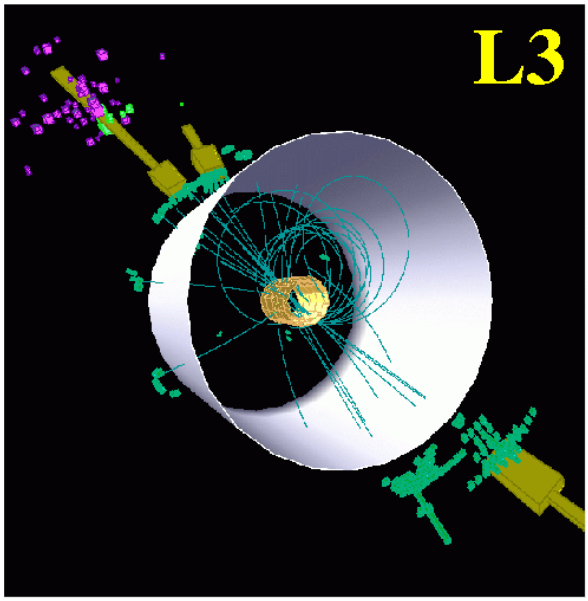
  ADLO... *(revisited ... Nov 3 ...)* 2.2σ

  $\Rightarrow$ **Continue LEP for one more month ...** **" to see the trend ..."**

- **Nov 3, Report to LEPC ...** **488 pb^{-1} @$E_{cm} > 206$ GeV**

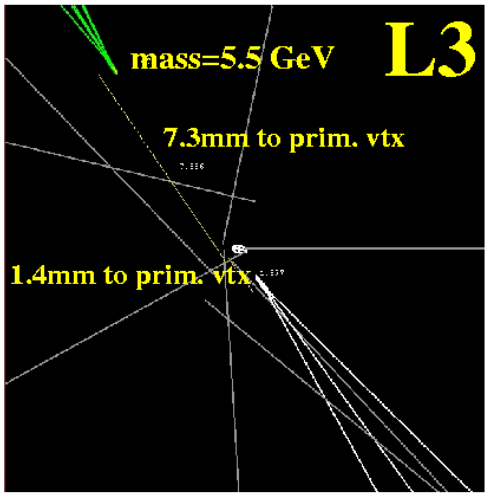
  L3 ... Strong candidate in "E-miss" channel

most significant Hνν candidate



measured H mass=114.4 GeV
H mass resolution ~3 GeV

Secondary vtx's view



P. Igo-Kemenes - Heidelberg - Nov. 28, 2000

ADLO ... 2.2σ $\Rightarrow$ 2.9σ **...** *Trend positive !*

$\Rightarrow$ **Request to continue LEP for another year ...**

Perspective ... $2.9\sigma \rightarrow (5.3 \pm 0.5)\sigma$

Request not retained ... Comm. of Council, Nov 17

Current Status: SM Higgs

- **Since November 2000 ... All LEP data included**

  Integrated luminosities (ADLO)

  $E_{cm} \gtrsim 189$ **GeV ... 2465** pb^{-1}

  $E_{cm} \gtrsim 206$ **GeV .... 542** pb^{-1}

- **LEP Higgs workshop ...** *Evian, May 2001*

  Analysis procedures revisited

- **Changes within the experiments**

  Recalibration of detector parameters ... *b-tag ... Si−μVtx*

  Improvements in selections ... better sensitivity

  Revision of procedures for extra- and interpolations

  Study of resolution functions close to $\mathrm{H^0Z^0}$ **kin. lim.**

  Revision of backgrounds and systematic errors

  Better Monte Carlo statistics over the whole phase-space

- **Publications ... Phys. Lett. B**

  Aleph, Delphi, Opal ... preliminary *L3 ... final*

(Values quoted for $m_H = 115$ *GeV)*

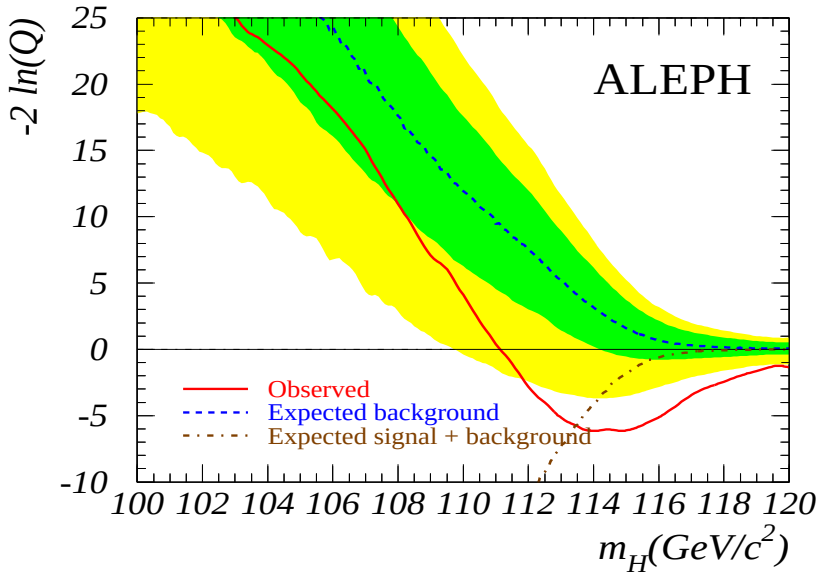
ALEPH	$1-CL_b$	
Nov 2000	6.5×10^{-4}	3.4σ
Phys. Lett.	2.7×10^{-3}	3.0σ

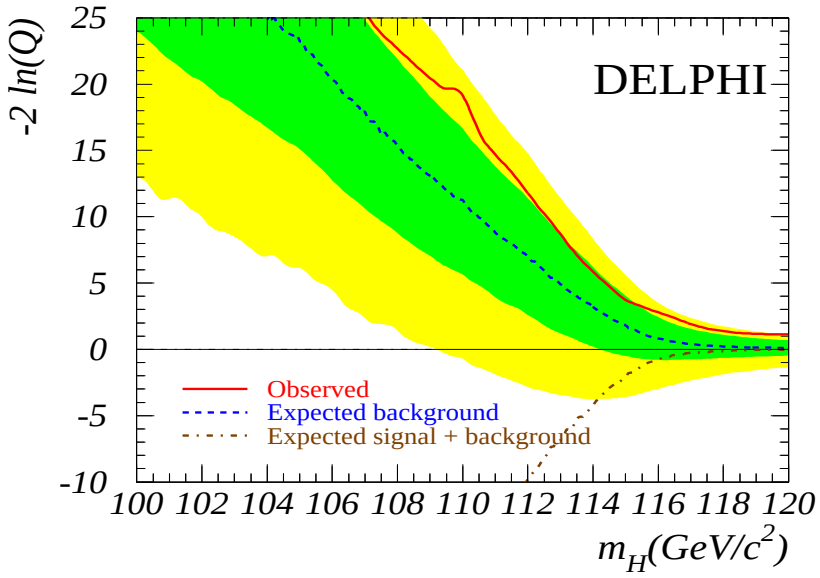
DELPHI	$1-CL_b$	
Nov 2000	0.68	bkgd-like
Phys. Lett.	0.77	bkgd-like

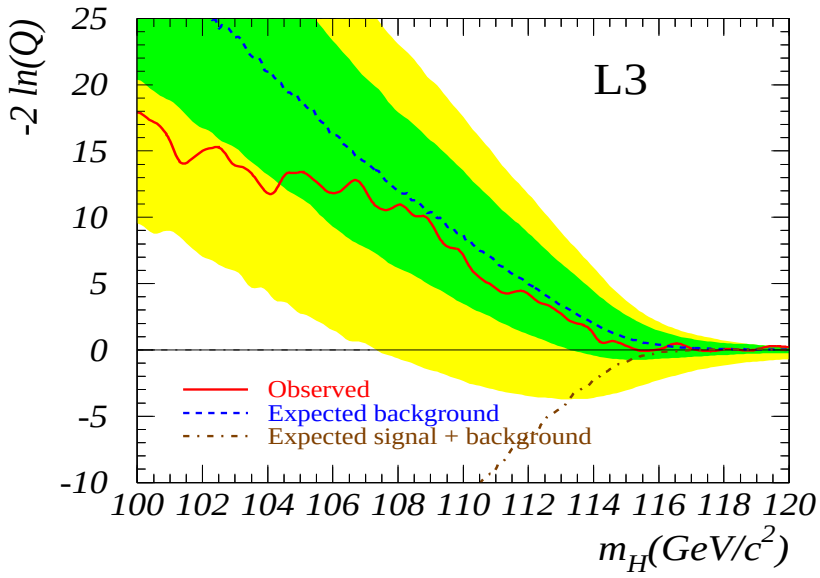
L3	$1-CL_b$	
Nov 2000	6.8×10^{-2}	1.8σ
Phys. Lett.	0.32	bkgd-like

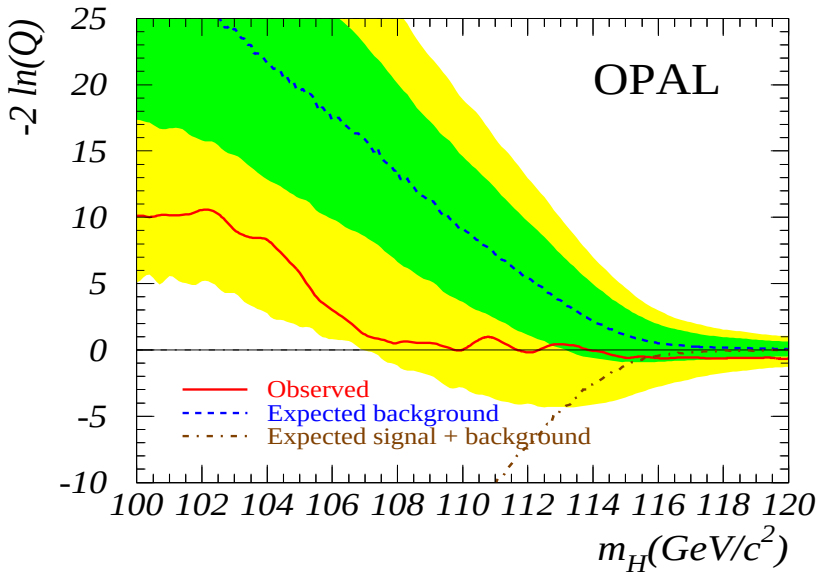
OPAL	$1-CL_b$	
Nov 2000	1.9×10^{-1}	1.3σ
Phys. Lett.	2.0×10^{-1}	1.3σ

$-2\ln(Q)$ ... by Experiment

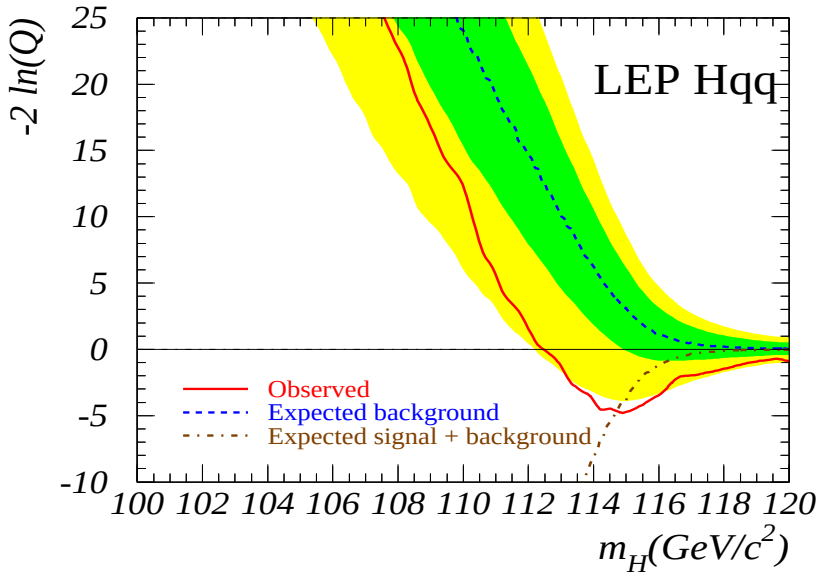


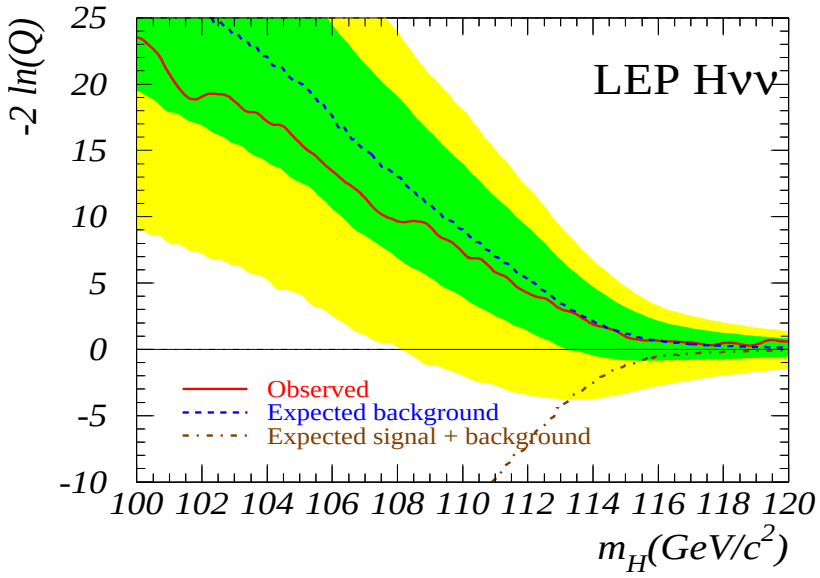


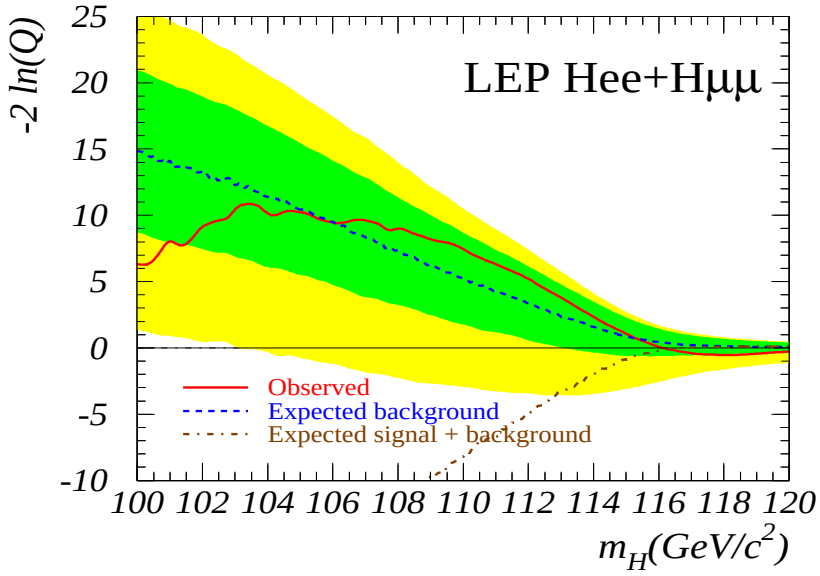


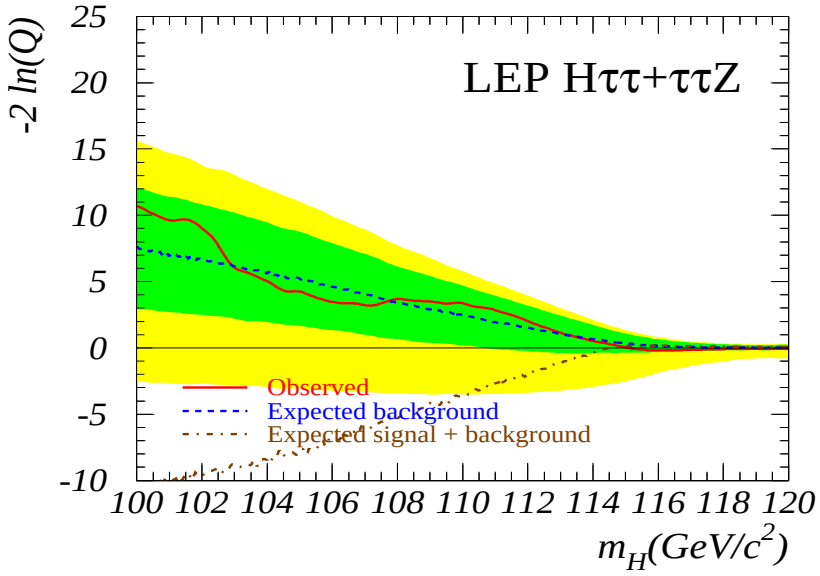


$-2\ln(Q)$ ... by Final State





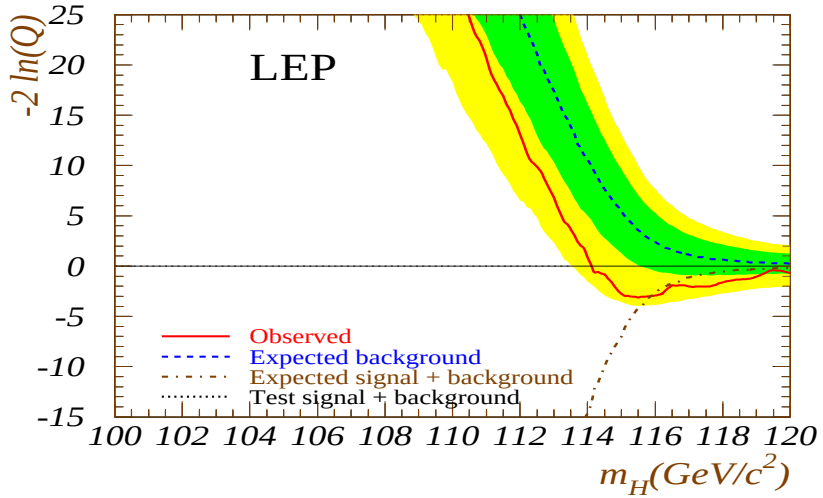




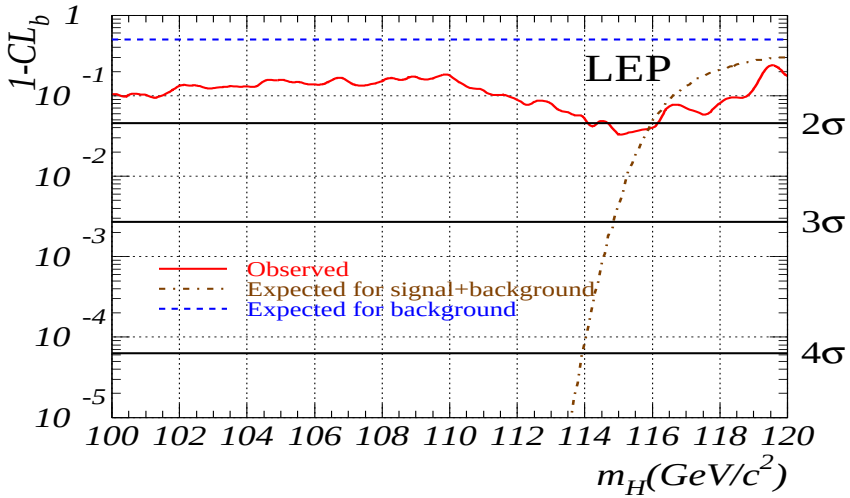
ADLO ... Current Combined Results ... SM Higgs

LHWG Note/2001-03 , CERN-EP/2001-055 (July'01)

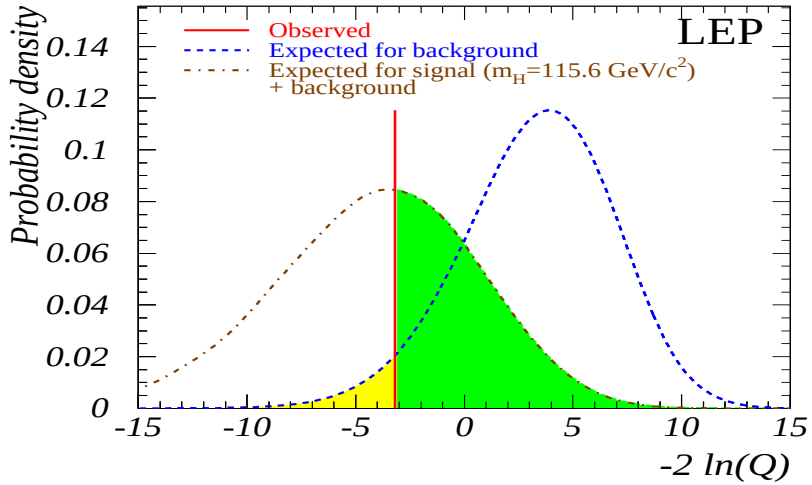
Minimum ... at $m_H = 115.6$ GeV



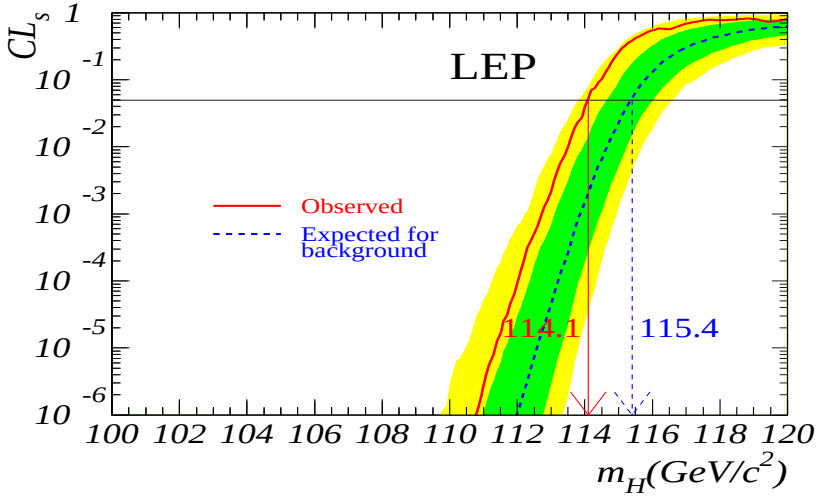
@115.6 GeV ... Significance $\approx 2.1\sigma$



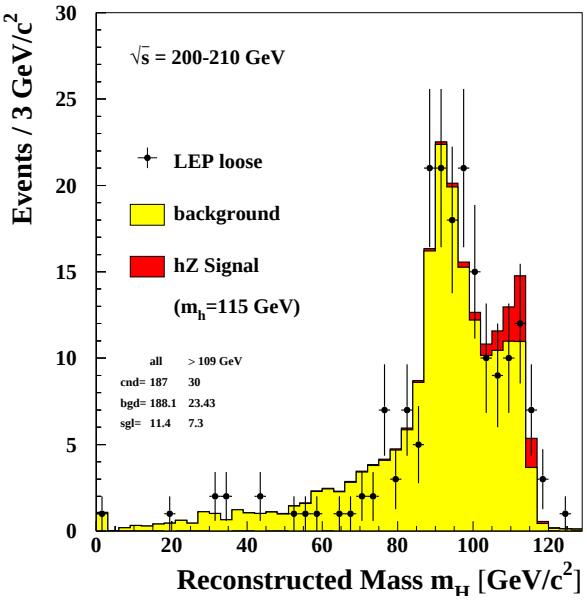
@115.6 GeV ... $1 - CL_b = 3.4\%$



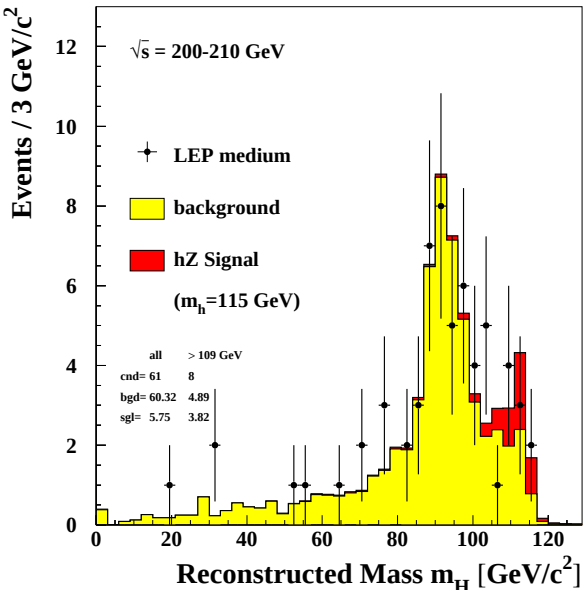
$m_H > 114.1$ GeV (at 95% CL)



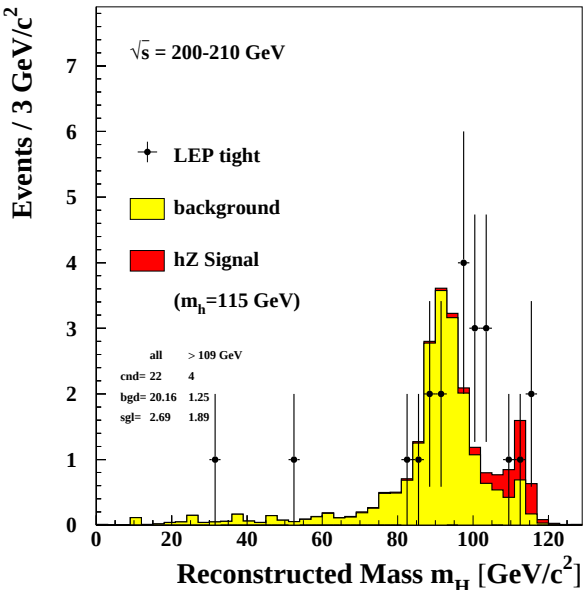
ADLO ... Reconstructed Mass



Loose selection



Medium selection



Tight selection

For $m_H = 115.6$ GeV

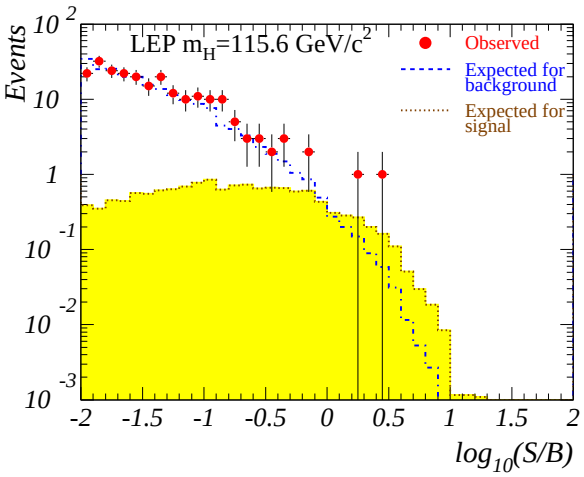
	Exp. sig.	Exp. bgd	Data
Loose	11.4	188.1	187
Medium	5.75	60.32	61
Tight	2.69	20.16	22

Distributions of event "weights"

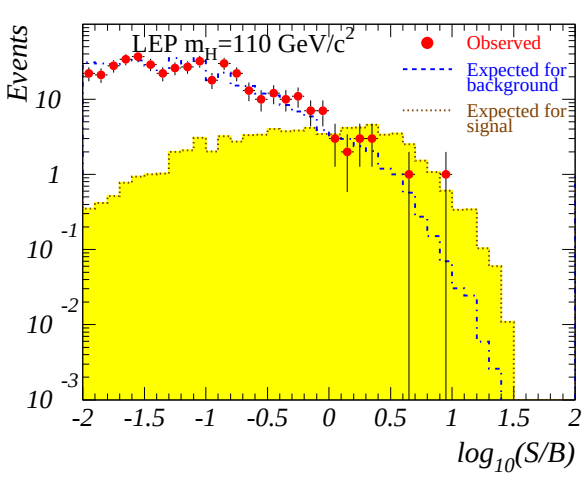
$$-2 \ln Q \sim \Sigma_i \ln(1 + s_i/b_i)$$

"Background"-like or "Signal+background"-like ?

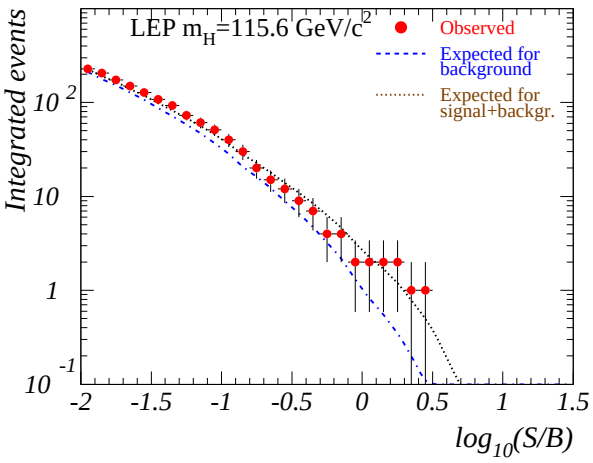
$m_H = 115.6$ GeV



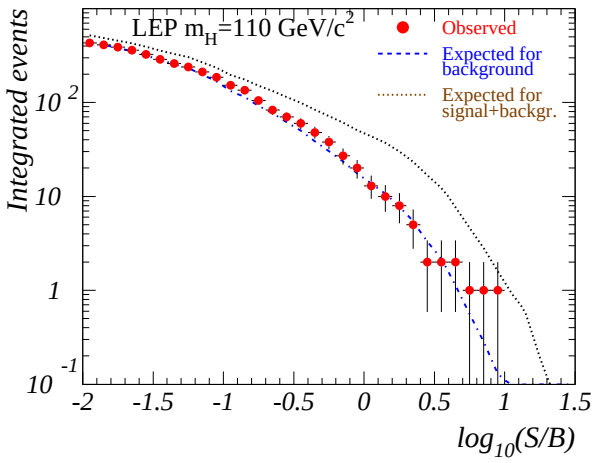
$m_H = 110$ GeV



Integrals from "right" to "left"



$m_H = 115.6$ GeV



$m_H = 110$ GeV

Current Status: MSSM Higgs

ADLO : LHWG Note / 2001-04 (July '01)

"Benchmark" parameter scenarios

Carena, Heinemeyer, Wagner, Weiglein hep-ph/9912223

m_A , $\tan\beta$ ... **basic MSSM parameters** ... **scanned**

M_{SUSY} ... **sfermion mass parameter** ... **1 TeV**

M_2 ... **gaugino mass parameter** ... **200 GeV**

μ ... **Higgs mass parameter** ... **$-$200 GeV**

A_t ... **Trilinear Higgs-squark coupling**

Squark mixing parameter $X_t \equiv A_t - \mu/\tan\beta$

m_{top} ... **Top mass** ... **174.3 GeV**

$m_{\tilde{g}}$ ... **Gluino mass** ... **800 GeV**

- **"No mixing" scenario** ... $X_t = 0$
- **"m_h-max" scenario** ... $X_t = 2M_{SUSY}$

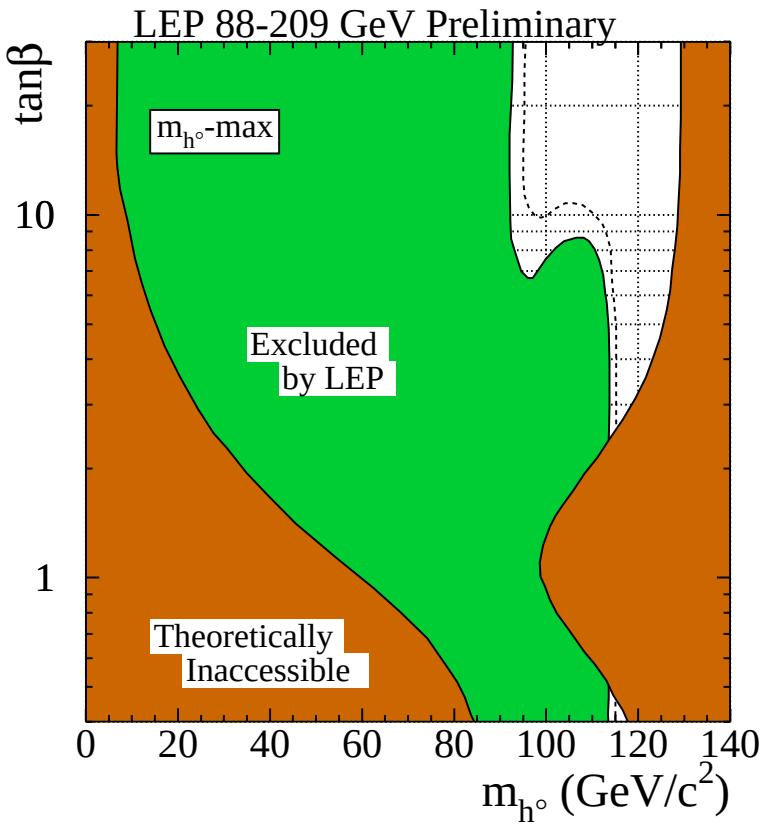
  maximizes the range of m_h

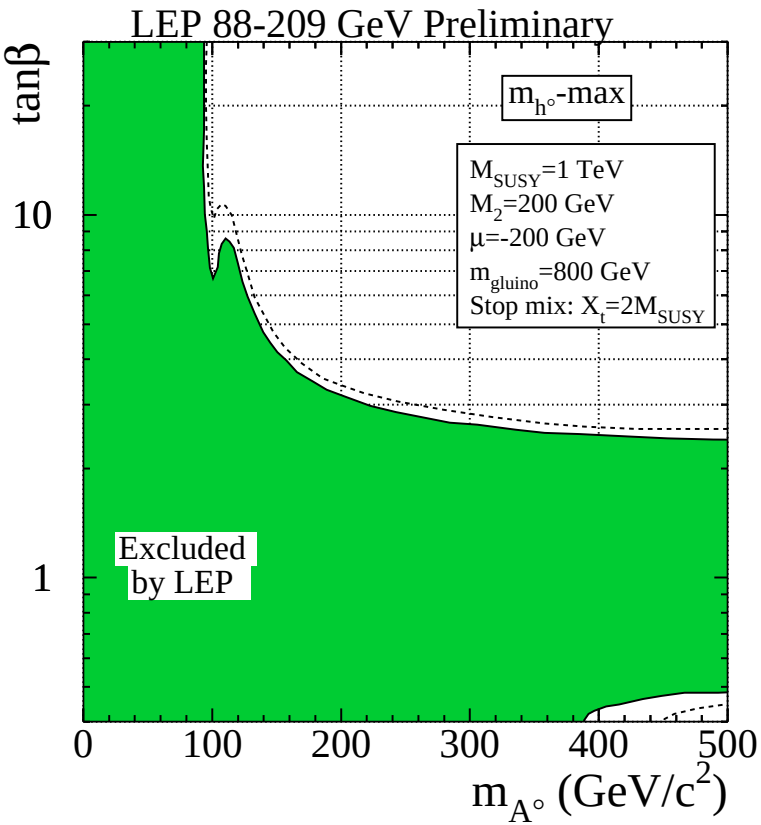
  $\Rightarrow$ **Conservative exclusion limits**

ADLO ... *combined results shown here in two projections*

(m_h , $\tan\beta$) (m_A , $\tan\beta$)

MSSM "m_h-max" Scenario



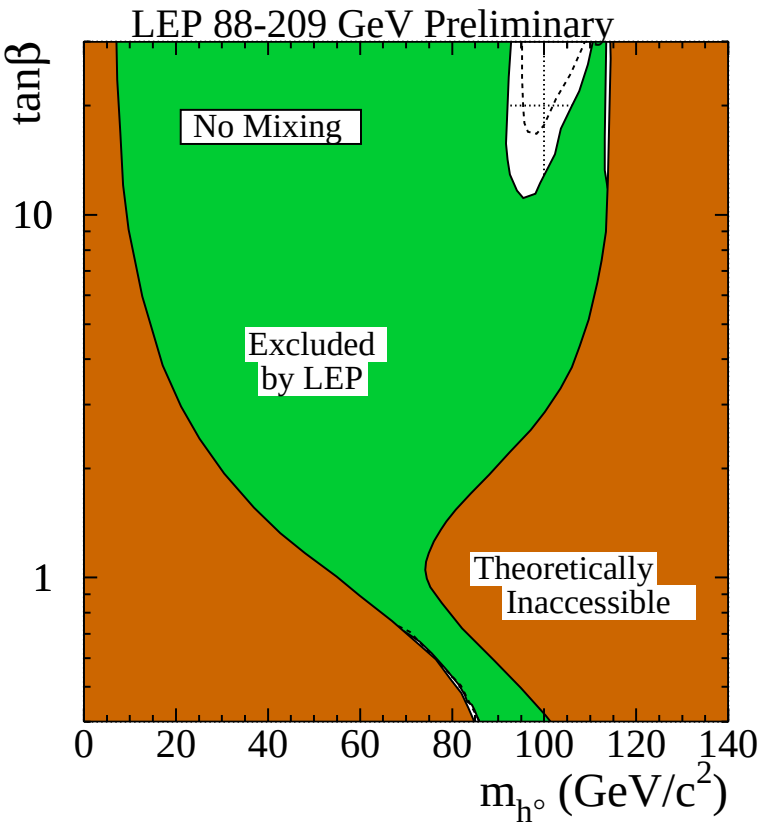


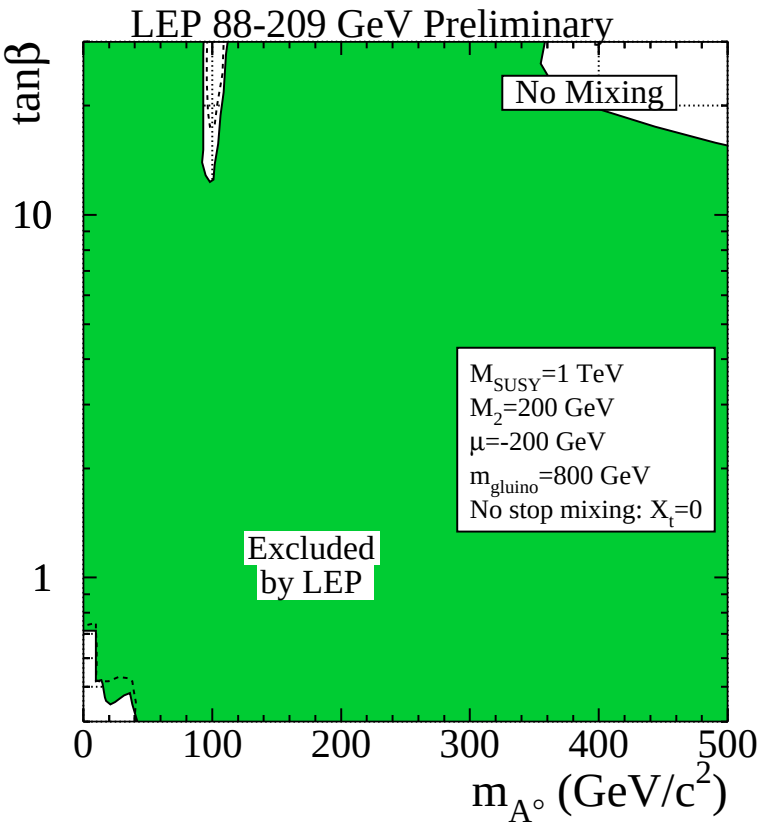
$m_h > 91.0$ GeV

$m_A > 91.9$ GeV @ 95% c.l.

$0.5 \lesssim \tan\beta \lesssim 2.4$ (m_{top} =174.3 GeV)

MSSM "No mixing" Scenario

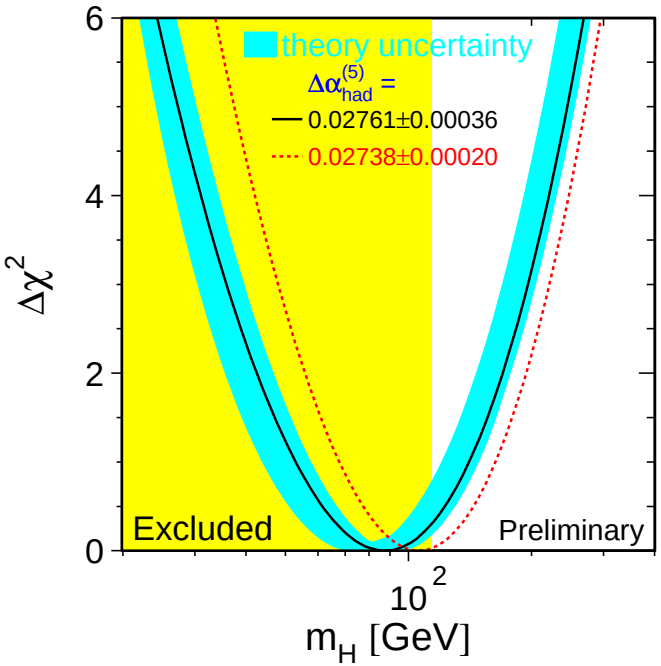




... *almost entirely excluded*

The Legacy

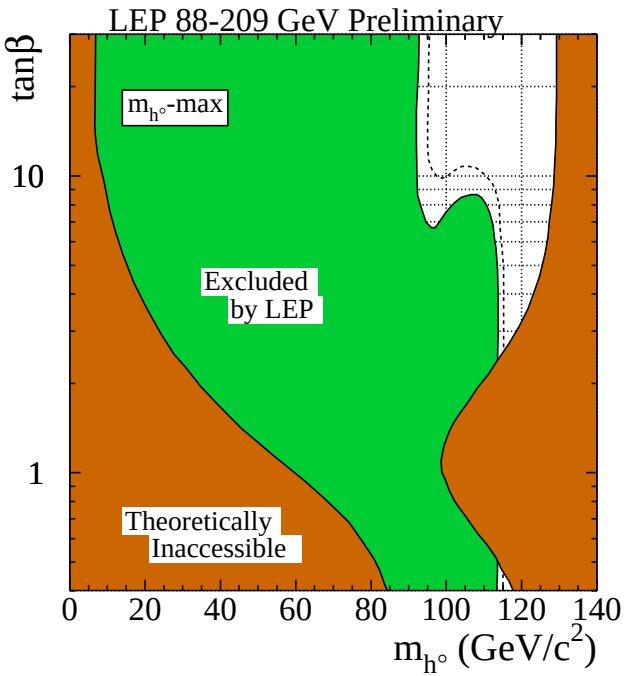
Standard Model ...



SM fits ... $m_H \lesssim$ 200 GeV

Searches ... $m_H >$ 114.1 GeV

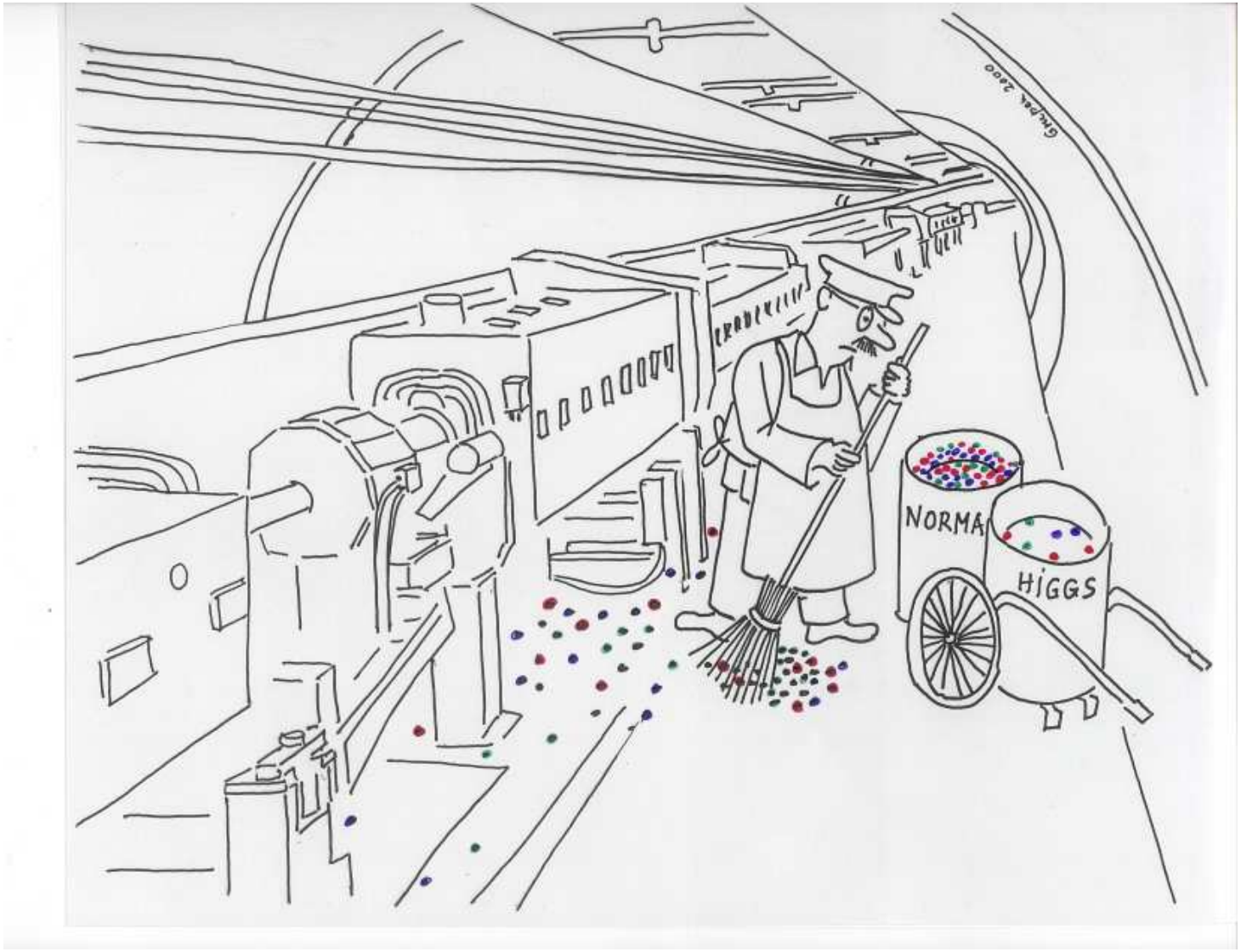
In the MSSM ...



Theory ... $m_h \lesssim$ 135 GeV

Searches ... $m_h >$ 91 GeV

$\Rightarrow$ A "hint" for a signal at 115 GeV $\Leftarrow$


NORMA
HIGGS