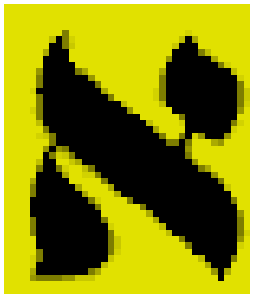
Higgs Bosons in the SM and the MSSM
Searches at LEP



P. Igo-Kemenes

Heidelberg / CERN

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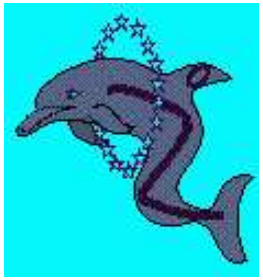
The LEP Legacy



- **SM Higgs boson** ... *Final results*

  $m_{\mathrm{H}} > 114.4$ **GeV @ 95% c.l.**

  Small "hint" $(< 2\sigma)$ **at** $m_{\mathrm{H}} \approx 116$ **GeV**

- **MSSM Higgs bosons** ... *Preliminary*

  $m_{\mathrm{h}} > 91.0$ **GeV ,** $m_{\mathrm{A}} > 91.9$ **GeV**

  $\tan\beta = v_2/v_1$ **:** $0.5 - 2.4$ **unlikely**

  New ! ... **Scenarios with CP-violation**

Higgs mechanism / Higgs bosons

Model to provide mass to gauge bosons and fermions

without conflicting with the principle of gauge invariance

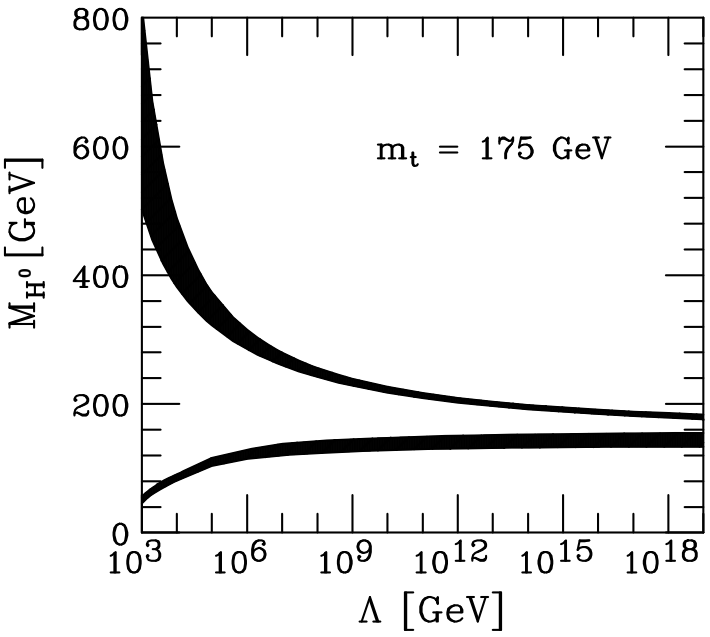
Standard model	Minimal SUSY extension
One complex scalar field doublet ϕ $< \phi >= v \approx 246$ GeV	Two field doublets ... ϕ_1, ϕ_2 $v^2 = v_1^2 + v_2^2$, v_2/v_1 = $\tan\beta$
4 degrees of freedom • $M_{W^+}, M_{W^-}, M_{Z^0}$ • One physical Higgs boson H^0 mass not specified	8 degrees of freedom • $M_{W^+}, M_{W^-}, M_{Z^0}$ • h^0, H^0, A^0, H^+, H^- ... *CP conserving* $H^0{}_1, H^0{}_2, H^0{}_3, H^+, H^-$ ... *CP violating*
m_H fixes all couplings ... to fermions : $\sim m_f$ ... to vector bosons : $\sim m_V^2$	• Tree level : 2 parameters e.g. $(m_A, \tan\beta)$ ... or ... $(m_{H^\pm}, \tan\beta)$ • Loop level : Many soft SUSY breaking parameters Unification at $\Lambda_{GUT} \Rightarrow m_0, m_{1/2}, \mu, A_t$

Proof ... detection of a Higgs particle !

Higgs boson masses

Standard model

m_{H} ... *Theory suggests ...*



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

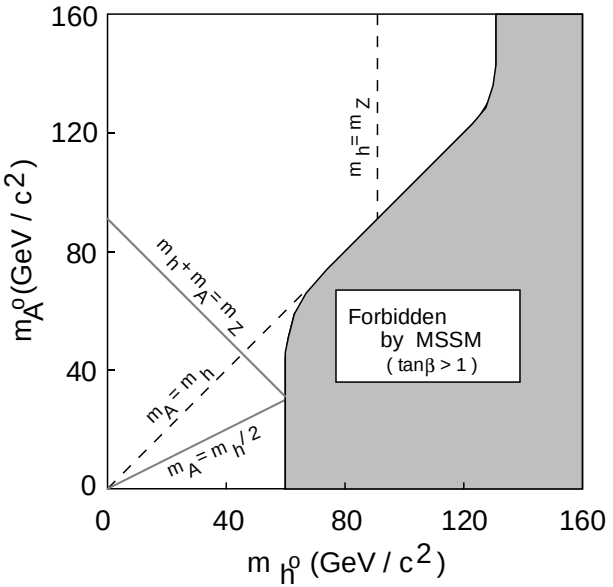
  Consistency of the SM up to Λ_{GUT} **...**

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

  $m_{\mathrm{h}} \lesssim 130$ **GeV**

Higgs searches at LEP

- **LEP1 phase ... 1989 - 1994**

  Searches ... in the decay of the Z boson ... $e^+e^- \longrightarrow Z \longrightarrow Z^*H$

  A+D+L+O ... 17×10^6 **Z decays analysed**

  $\Rightarrow$ **SM Higgs ... mass > 65 GeV** *(95% c.l.)*

  $\Rightarrow$ **MSSM Higgs h and A** *(CP conserving)* **... mass > 45 GeV** *(95% c.l.)*

- **LEP2 phase ... 1995 - 2000**

  E_{cm} **... 135, 161, 171, 183, ... 189 - 209 GeV ...** $e^+e^- \longrightarrow Z^* \longrightarrow ZH$

  Integrated luminosity ... (A+D+L+O) ... 2.46 fb^{-1} ... $E_{cm} >$ **189 GeV**

  ... 0.55 fb^{-1} ... $E_{cm} >$ **206 GeV**

  Year 2000 *(last year of LEP)* **optimised for the SM Higgs search**

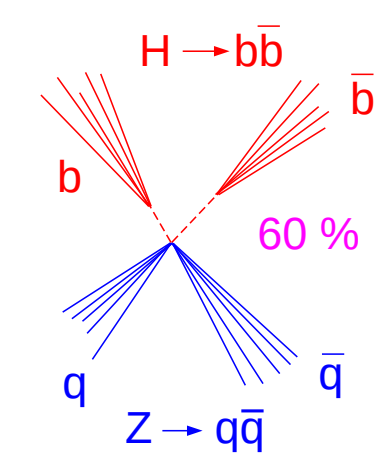
$\Rightarrow$ **SM Higgs ...** *final LEP-combined results*

$\Rightarrow$ **MSSM Higgs ... CP conserving** *preliminary LEP-combined results*

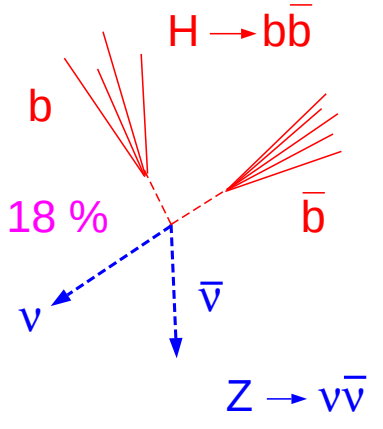
CP violating *OPAL ... pioneering*

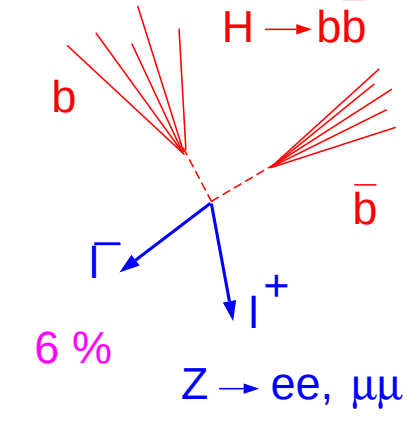
Searches for the Standard Model Higgs boson

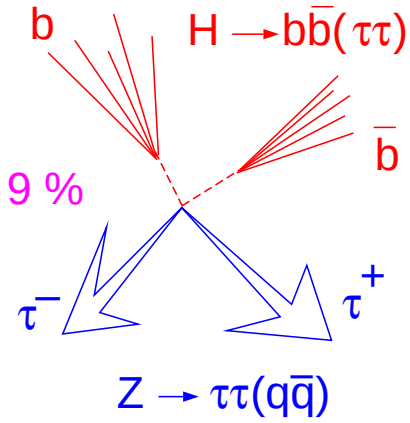
"Four-Jet"



"Missing energy"







"Leptonic"

"Tau lepton"

$e^+e^- \longrightarrow H\,Z$

Main sources of background ...

$e^+e^- \longrightarrow q\bar{q}\,(\gamma, g)$, W^+W^-, Z^0Z^0

(3-4 orders of magnitude above the signal)

- **Kinematics selection** (e.g. m_H^{rec})
- **b-tag ... Si-μVtx Detectors**

ALEPH, DELPHI, L3, OPAL ...

Combine all decay channels

and all E_{cm} data sets...

LEP Higgs working group ...

A+D+L+O $\Rightarrow$ LEP data combined

$\Rightarrow$ Increased (range of) sensitivity

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

(LEP Higgs working group)

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

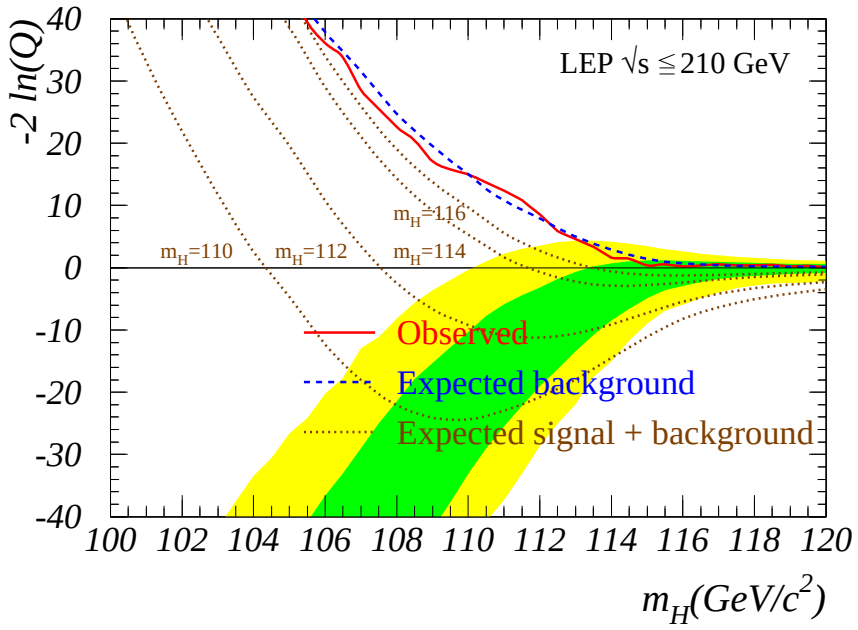
  Test-statistic ... $Q = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b}$ **... to rank the candidates**

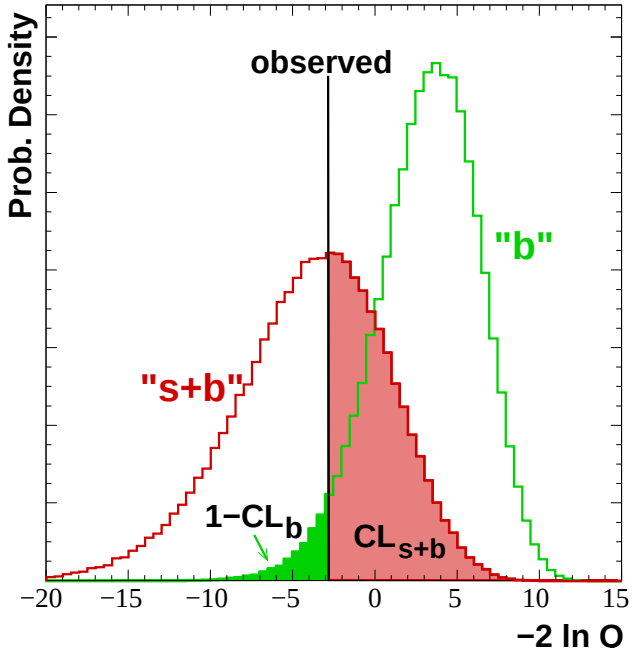
$$-2 \ln Q(m_H) = 2s_{tot} - 2 \sum_i N_i \ln[1 + s_i(m_H)/b_i]$$

$\Uparrow$

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"*

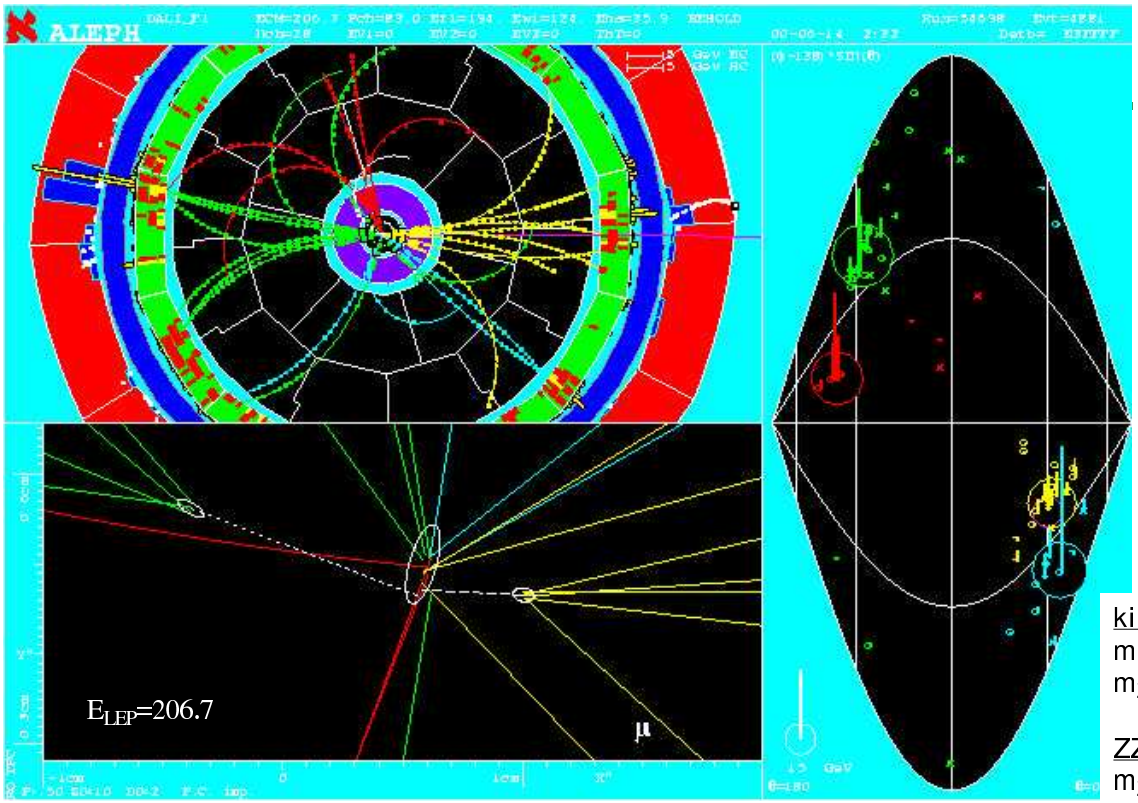
5.7×10^{-7} ... 5σ *"discovery"*

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

The last three months of LEP running

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

  Three "4-jet" events ($E_{cm} \gtrsim 206$ GeV) ... $m_H^{rec} \approx 114$ 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

16

- **LEP shutdown ... postponed ... until Nov 2 ...**

  to increase statistics at highest energies ($E_{cm} > 206$ GeV)

  ALEPH (no new high-weight candidates): $3.9\sigma \rightarrow 3.4\sigma$

  L3: Candidate in the "missing energy" channel

  ADLO: 2.9σ

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

  Perspective ... $2.9\sigma \rightarrow (5.3 \pm 0.5)\sigma$ ... if the signal was real

- **Nov 17 ... decision ... not to continue LEP**

  The shutdow of Nov. 2, 2000 was indeed final !

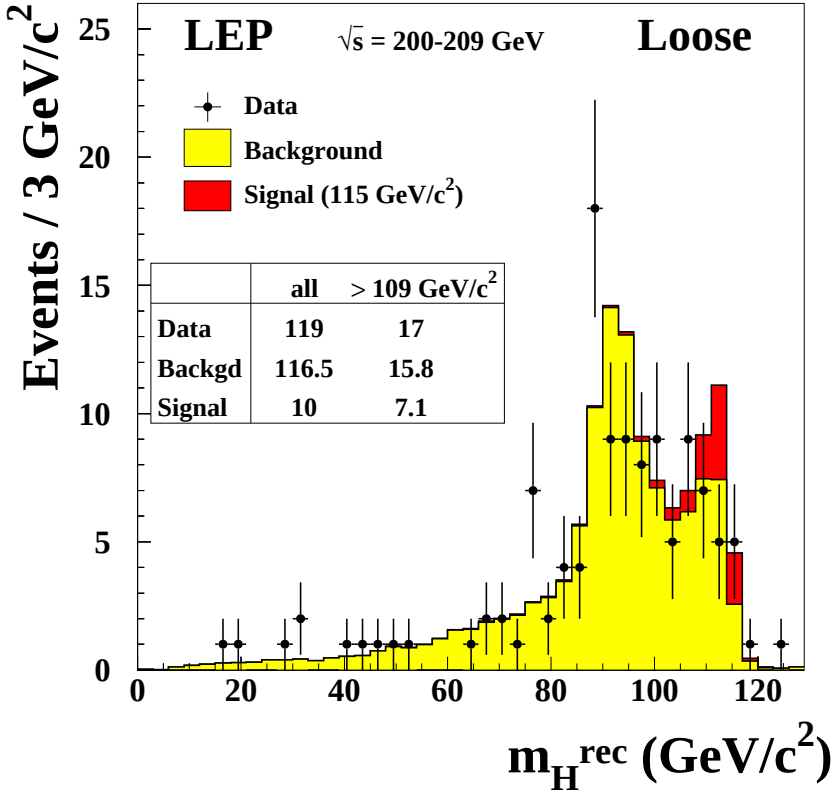
Since Nov 2000 ...

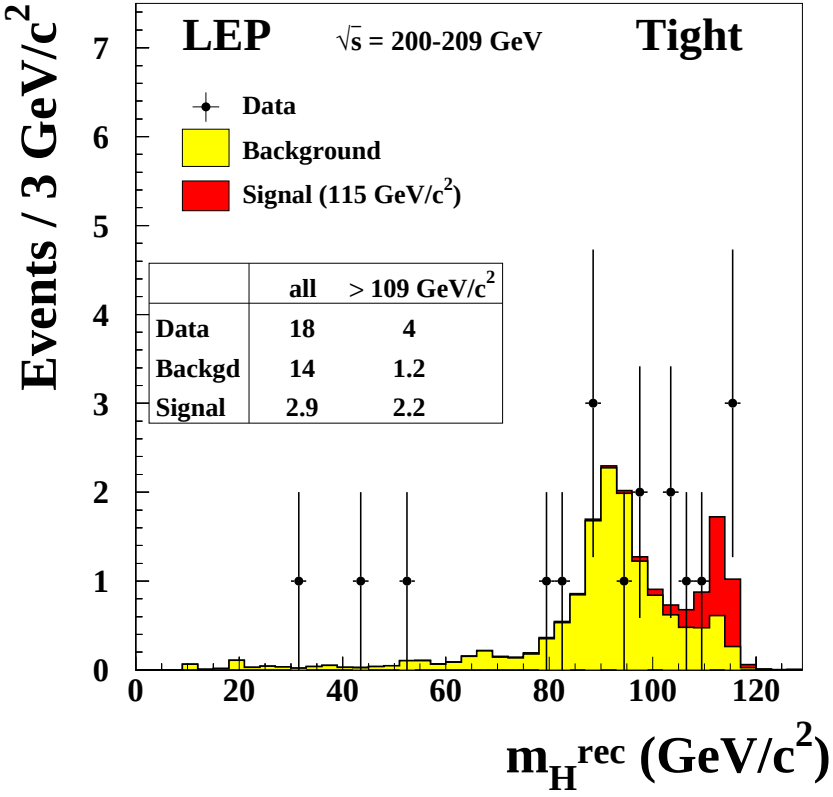
many changes within the experiments

- **Recalibration of detector parameters ... and E_{cm}**
- **Better Monte Carlo statistics over the whole phase-space**
- **Improvements in selections ... better sensitivity**
- **Revision of technicalities (extra- and interpolations)**
- **Study of resolution functions close to HZ kin. limit**
- **Revision of backgrounds**
- **Reassessment of systematic errors**

Final results published ... and ... combined

- **Reconstructed Higgs Mass ...** *(LEP combined)*



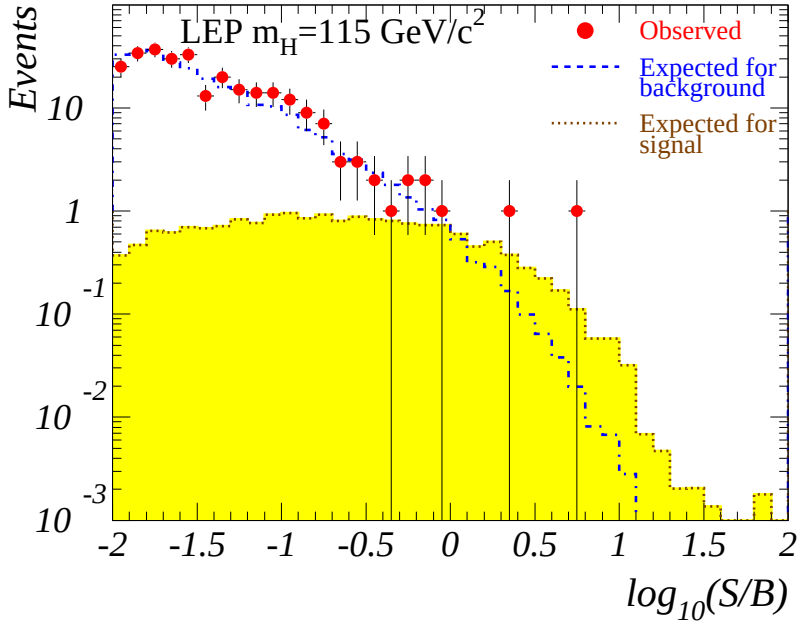


- **Distributions of event "weights"**

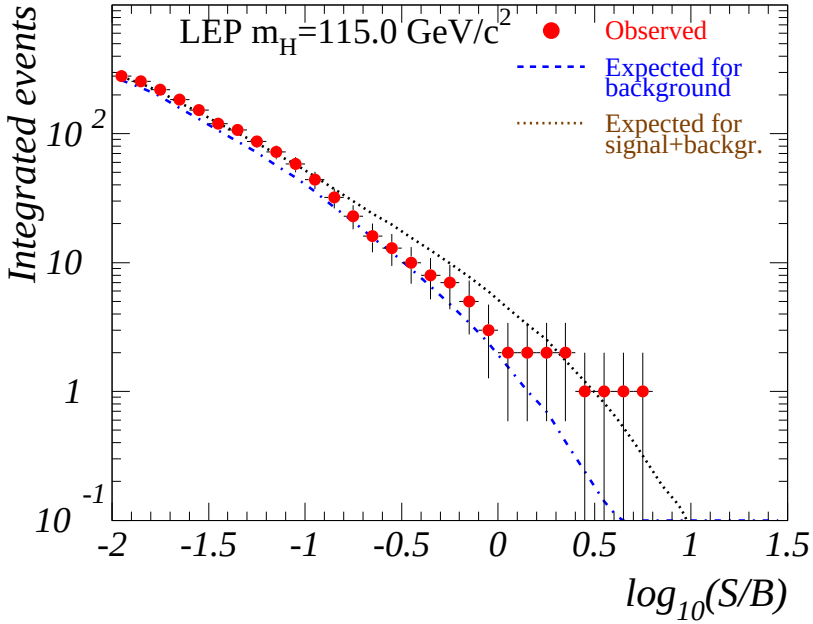
$$-2 \ln Q \sim \Sigma_i \ln(1 + s_i/b_i)$$

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

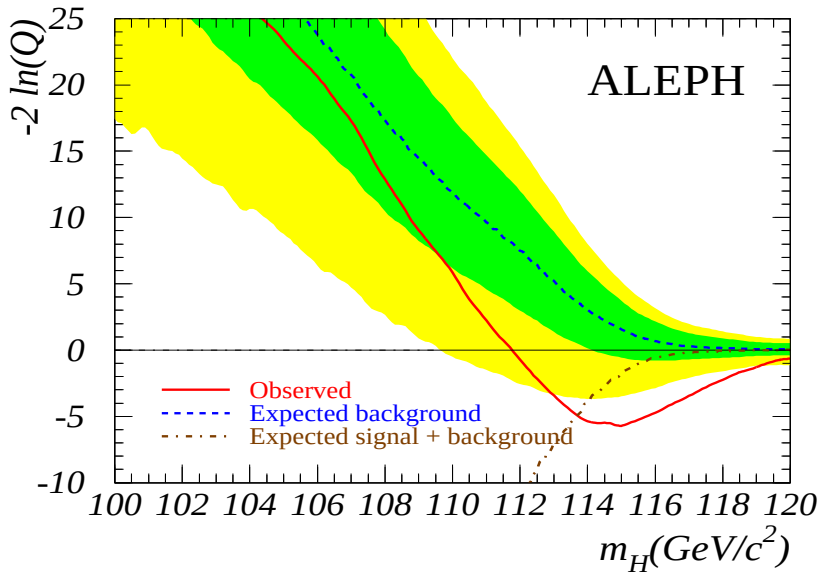
$m_H = 115$ GeV

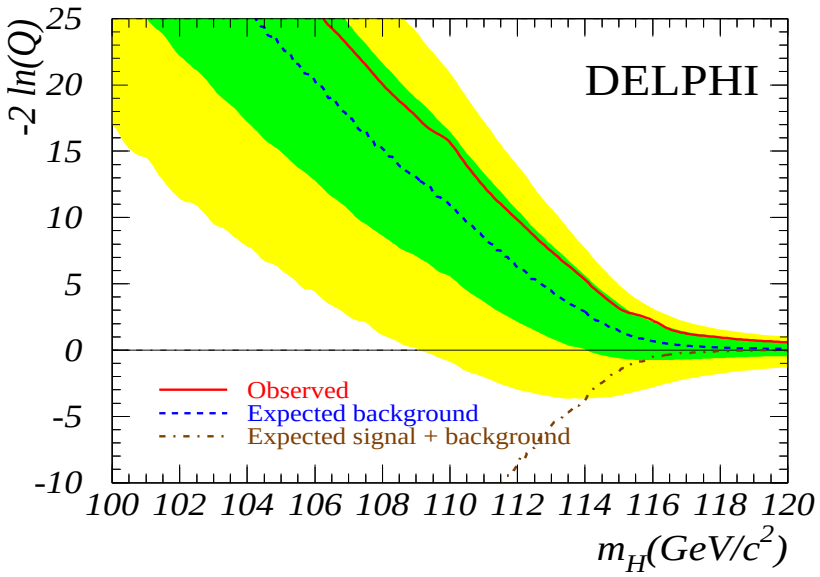


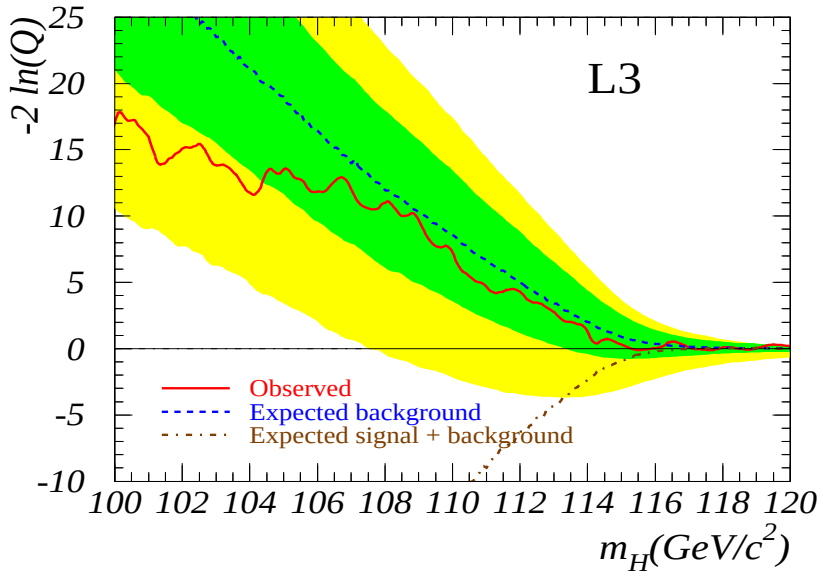
Integral from "right" to "left"

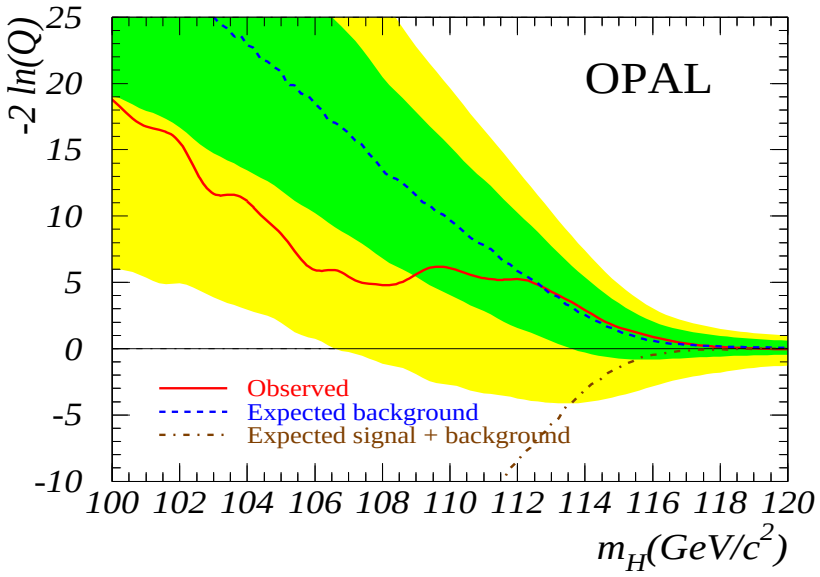


- **Test-statistic $-2\ln Q$ ... by Experiment**

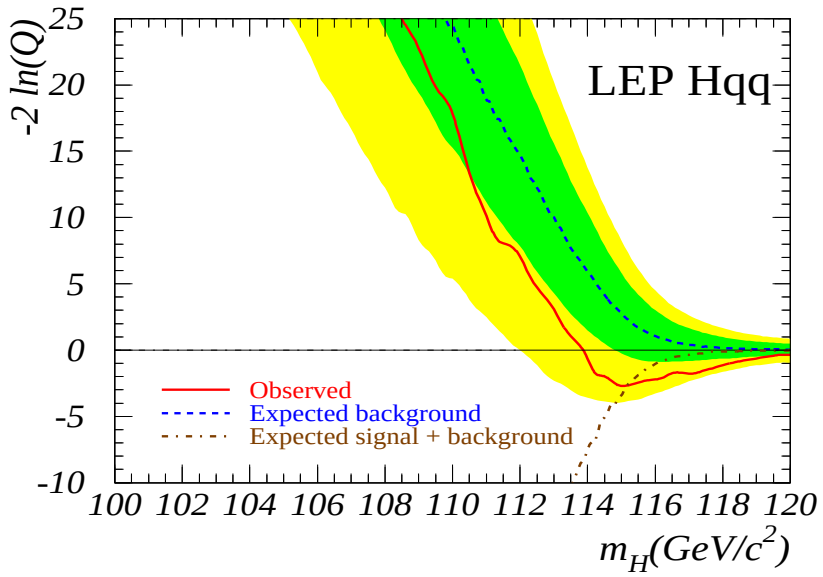


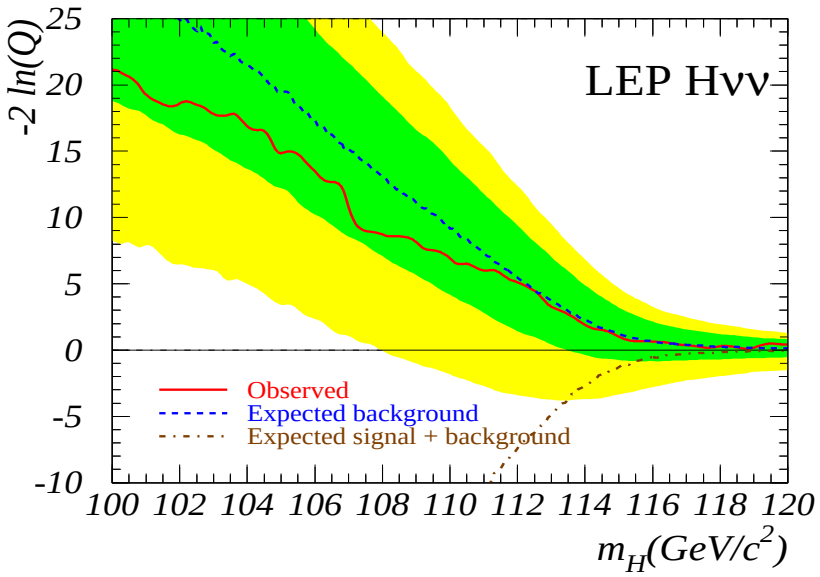


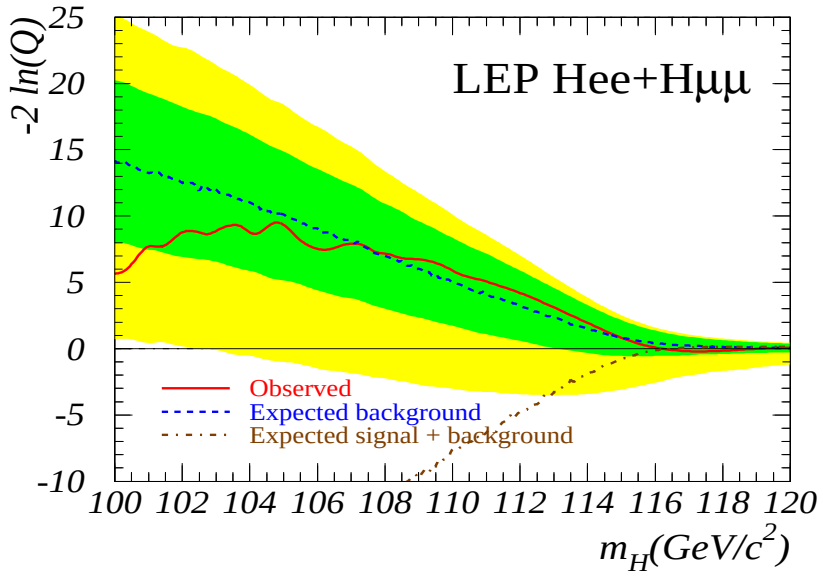


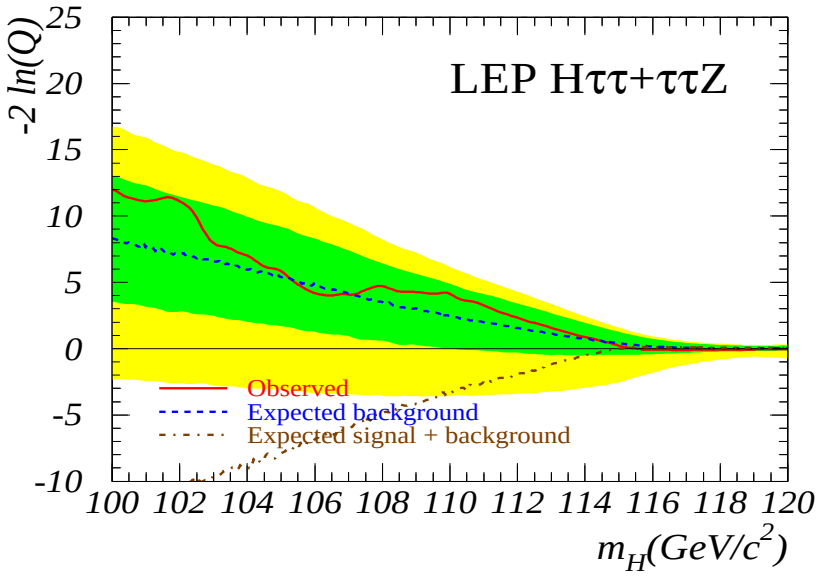


- $-2\ln(Q)$ **by Final State ...** *(LEP combined)*

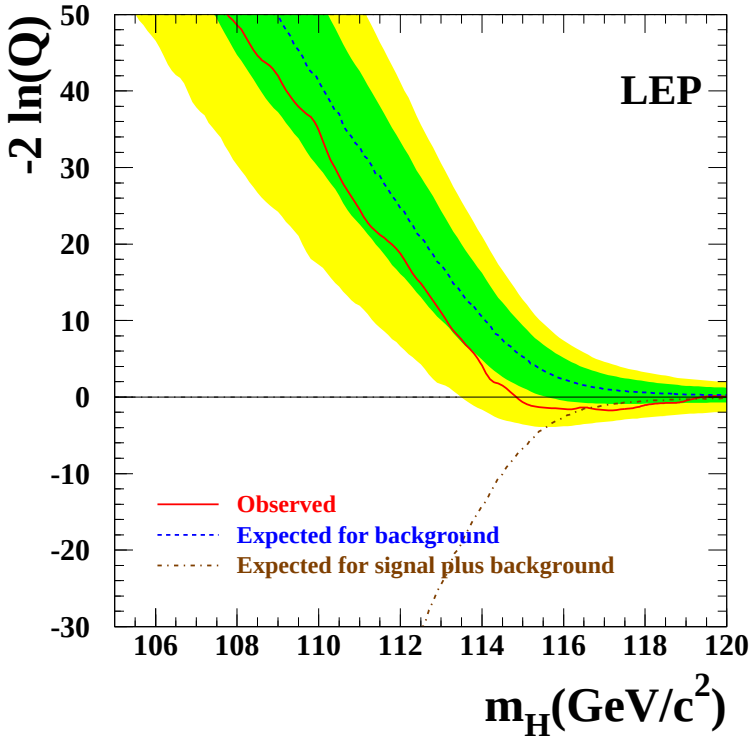




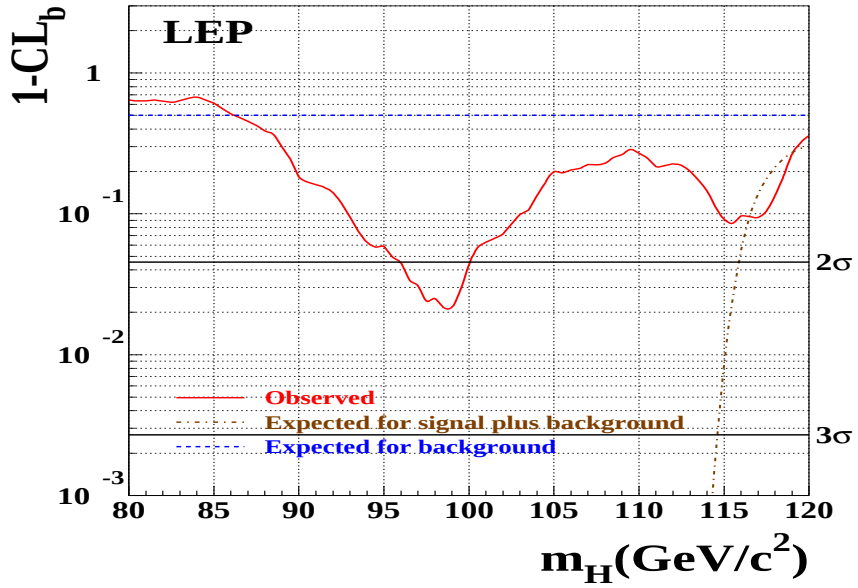




- $-2\ln(Q)$ ... *(LEP combined)*



- $1 - CL_b$ ... *(LEP combined)*



(1) **Region ...** $m_H \approx 98$ **GeV**

Excess ... incompatible with SM rate... *(* $\approx 2.2\sigma$ *)*

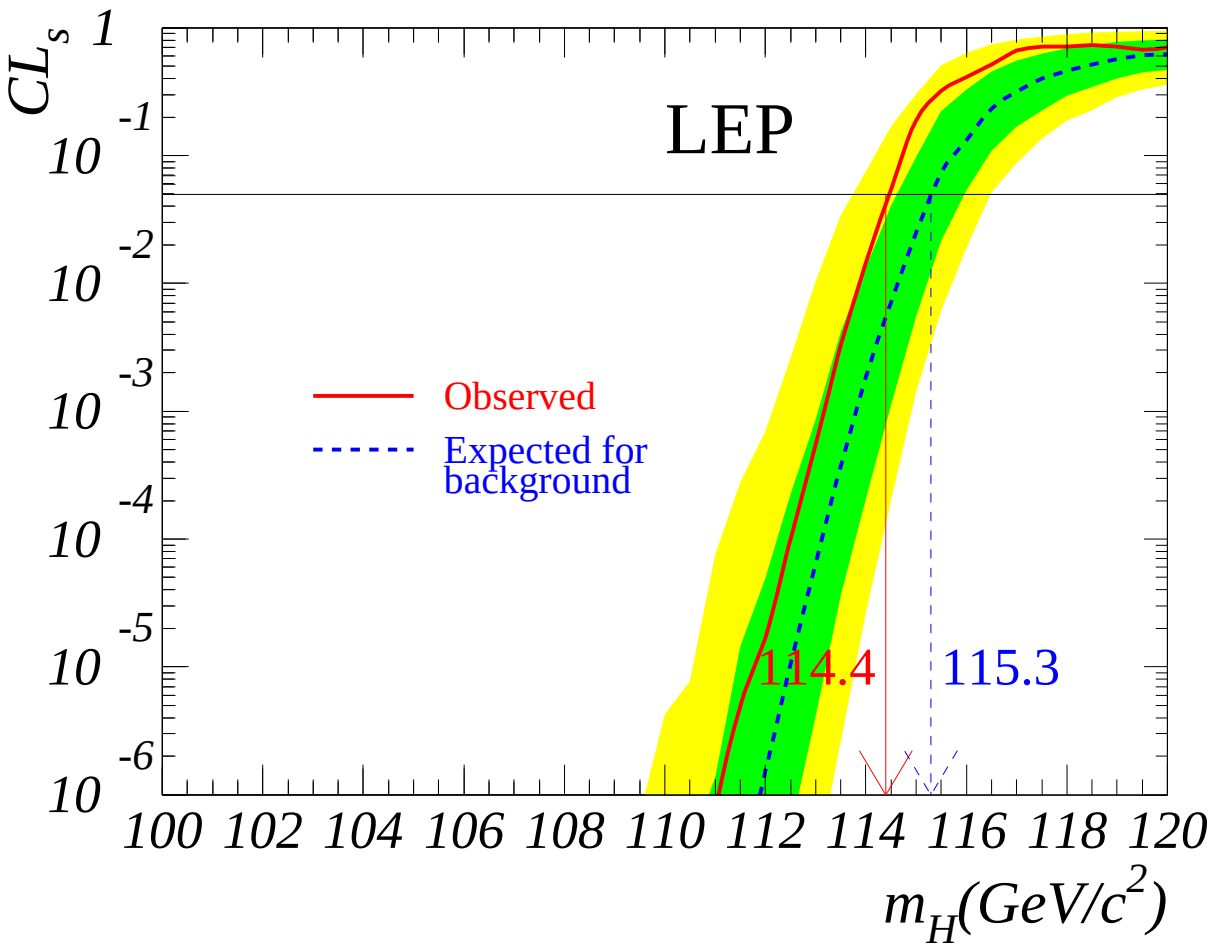
(2) **Region ...** $m_H \gtrsim 115$ **GeV**

$1 - CL_b \approx$ **9%** *(* $\approx 1.7\sigma$ *)*

$CL_{s+b} \approx$ **37%**

Final results ... SM Higgs ... *(LEP combined)*

LHWG Note/2002-01 (July'02)

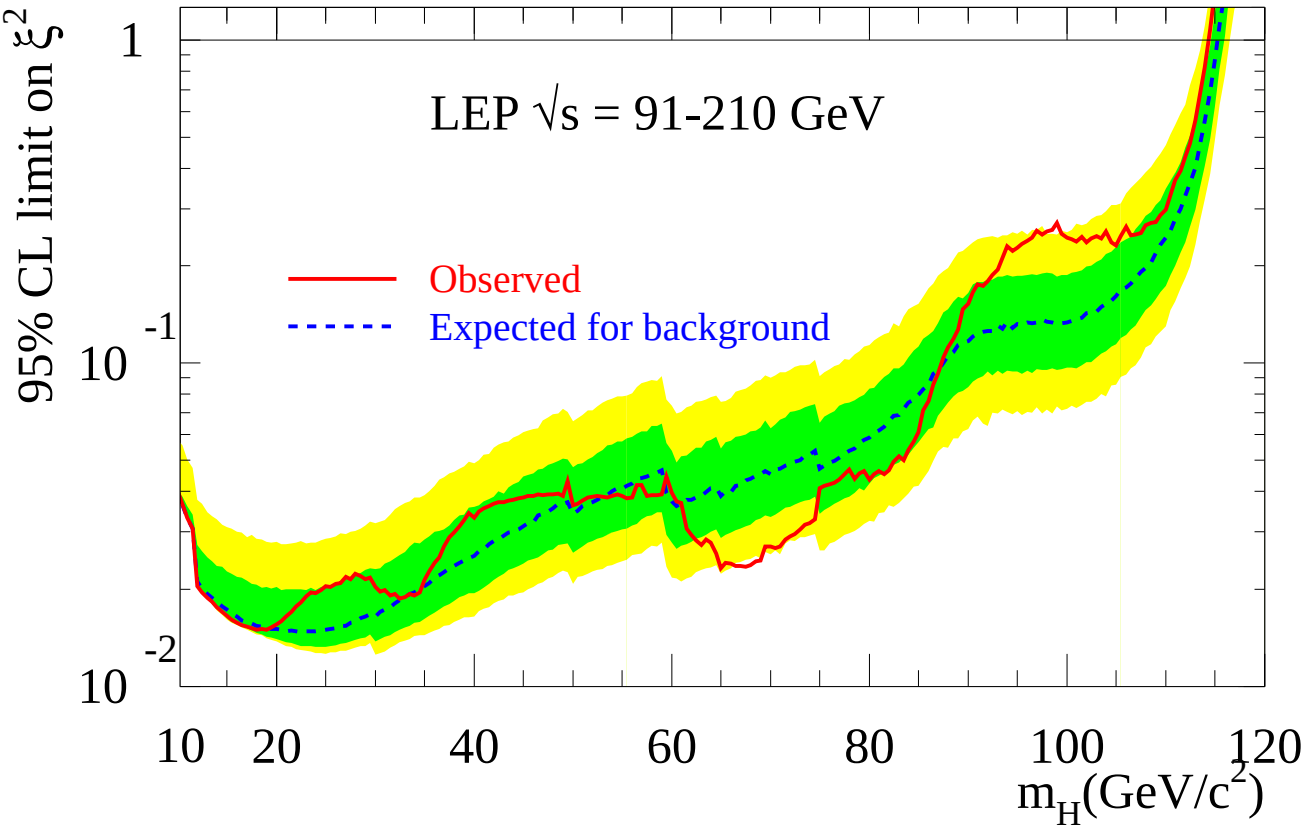


$m_H > 114.4$ **GeV** *(95% c.l.)*

(Expected limit : $\mathbf{115.3}$ *GeV)*

Limits on the Higgs - Z coupling ... *(LEP combined)*

LHWG Note/2002-01 (July'02)



$$\xi^2 = (g_{HZZ}/g^{SM}_{HZZ})^2$$

for Higgs decays ... like in the Standard Model

MSSM Higgs searches: Current status

A. CP conserving scenarios ... *LHWG Note / 2001-04*

Two search channels ...

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

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

Complementarity !

"Benchmark" parameter scans ...

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

$\tan\beta$	=	0.4 – 40	ratio of Higgs v.e.v. ... *scanned*
m_{A^0}	=	0 – 500 GeV	CP-odd Higgs mass ... *scanned*
μ	=	-200 GeV	Higgs doublet mixing
m_{SUSY}	=	1 TeV	SUSY breaking scale
m_2	=	200 GeV	SU(2) gaugino mass matrix parameter
m_{top}	=	174.3 GeV	top quark mass
$\lvert m_{\tilde{g}} \rvert$	=	800 GeV	gluino mass

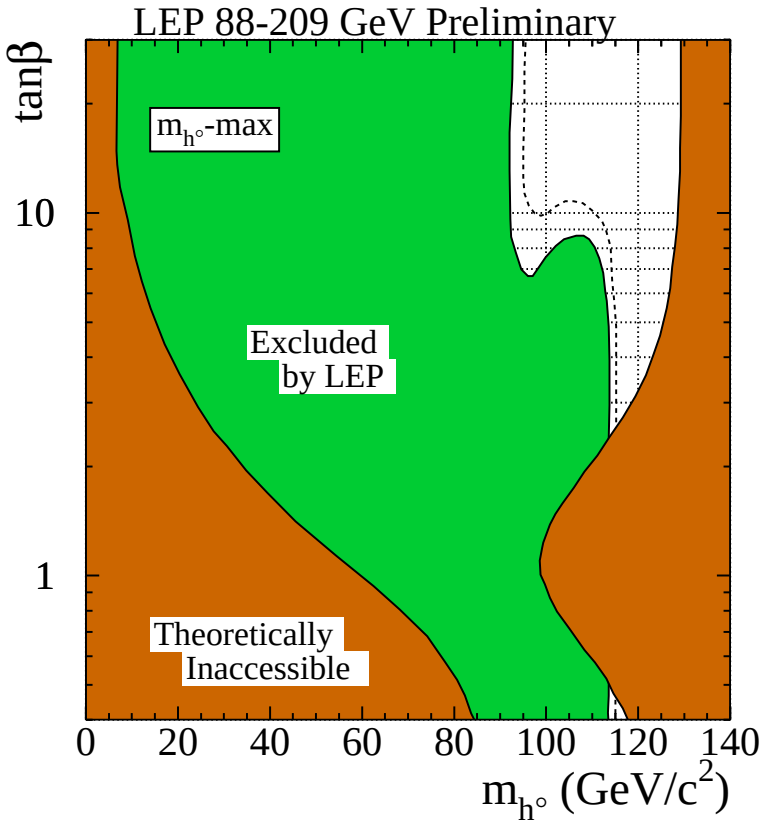
Squark mixing parameter $X_t \equiv A_t - \mu / \tan\beta$

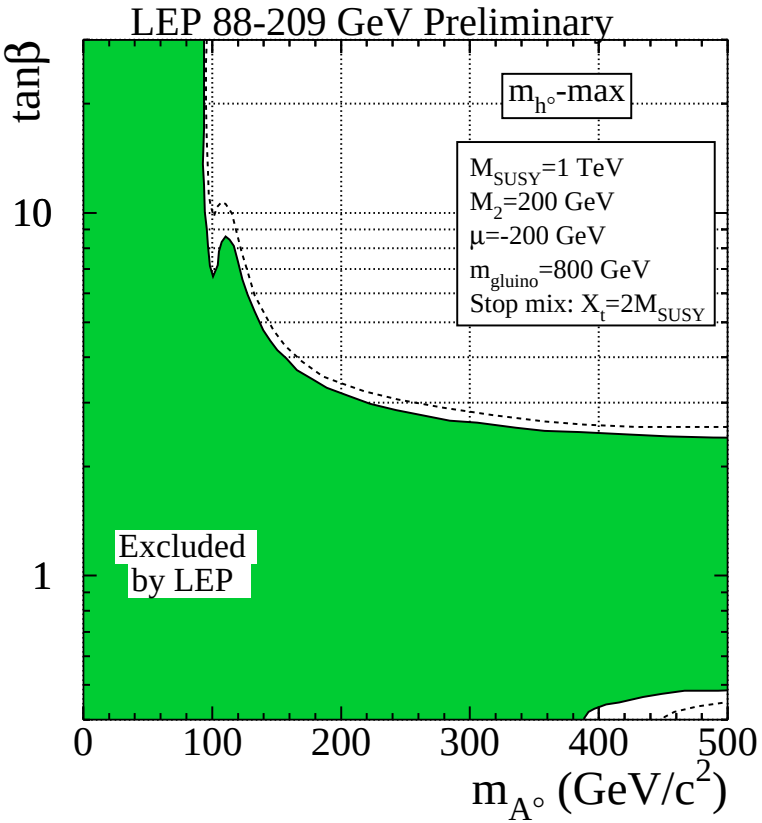
(A_t ... trilinear Higgs-squark coupling)

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

ADLO ... *combined results*

MSSM "m_h-max" Scenario



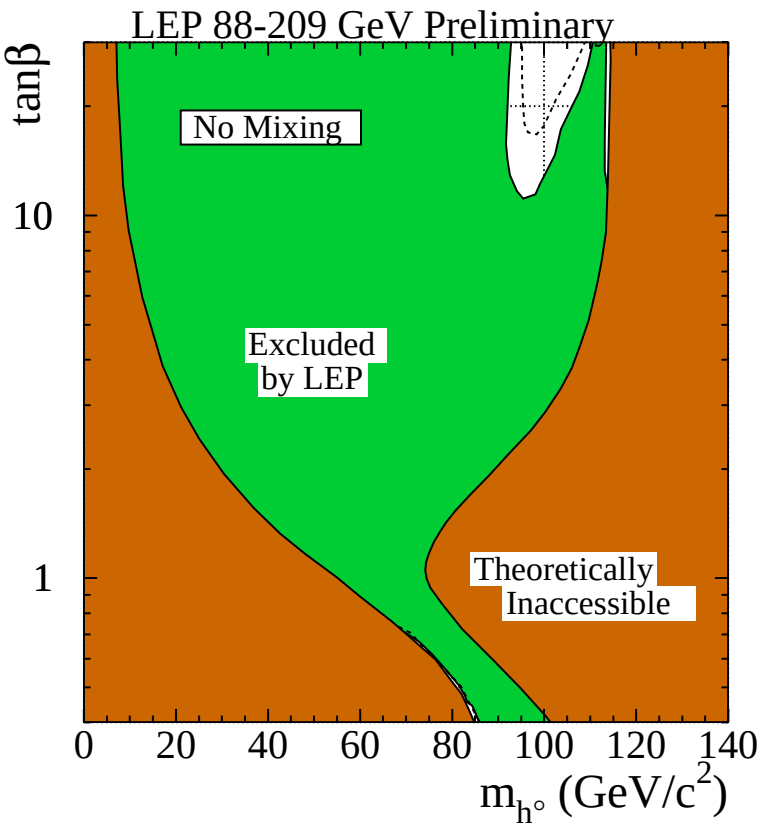


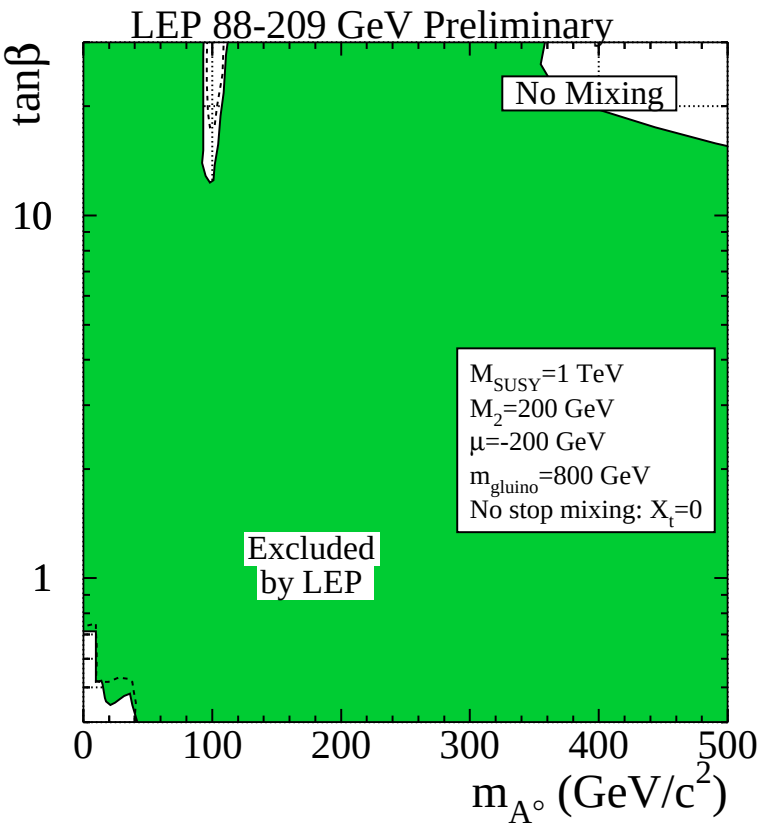
$m_h > 91.0$ GeV

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

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

MSSM "No mixing" Scenario





⇑

OPAL : CERN-EP/2002-058

... Almost entirely excluded

B. CP violating MSSM scenario

Appealing ! **Cosmic matter/antimatter asymmetry**

Can be introduced, e.g., by rad. corr. $\mathcal{O}(1)$ to the (CP-invariant) Higgs potential, mainly 3^d generation squarks

Carena, Ellis, Pilaftsis, Wagner ...

Phys. Lett. B495 (2000) 155, Nucl. Phys. B586 (2000) 93

MSSM Higgs spectrum ..... $\mathbf{H^0}_1, \mathbf{H^0}_2, \mathbf{H^0}_3, \quad \mathbf{H^+}, \mathbf{H^-}$

Neutral mass eigenstates are CP even/odd mixtures

Off-diagonal elements to the mass matrix ...

$$\mathcal{M}^2_{ij} \sim \frac{m^4_{top}}{v^2} \times \frac{Im(\mu A_t)}{m^2_{SUSY}}$$

Large deviations w.r.t. CP conserving scenarios ...

for m_{SUSY} small and $Im(\mu A_t)$ and m_{top} large

Production ... $\mathbf{e^+e^- \to H^0}_i\mathbf{Z} \quad (i = 1,2,3)$ ... *($\mathbf{hZ}$ - like)*

$\mathbf{e^+e^- \to H^0}_i\mathbf{H^0}_j \quad (i \neq j)$ ... *($\mathbf{hA}$ - like)*

Decay ... similar to CP conserving scenario

$\mathbf{H^0}_1 \to \mathbf{b\bar{b}}\,,\ \tau^+\tau^-$

$\mathbf{H^0}_2 \to \mathbf{H^0}_1\mathbf{H^0}_1$ ... *($\mathbf{h \to AA}$ - like)*

The signal is spread over more final states than in the CP conserving MSSM; the sharing of rates depends on two CP-violating phases ... of A_t and $m_{\tilde{g}}$

$\Rightarrow$ *Experimentally more challenging*

CP violating "benchmark" scenario CPX ...

Maximizing the changes w.r.t. CP conserving MSSM

$\tan\beta$	=	0.4 – 40	ratio of Higgs v.e.v. ... *scanned*
m_{H^+}	=	0 – 1 TeV	charged Higgs mass ... *scanned*
μ	=	2 TeV	Higgs doublet mixing ... *large*
m_{SUSY}	=	500 GeV	SUSY breaking scale $= m_{\tilde{q}}$ ... *small*
m_2	=	200 GeV	SU(2) gaugino mass matrix parameter
$\lvert A_q\rvert$	=	1 TeV	strength of trilinear coupling ... *large*
$\arg(A_q)$	=	90^0	phase of $A_q \Rightarrow$ *max CP-violation*
$\lvert m_{\tilde{\mathrm{g}}}\rvert$	=	1 TeV	gluino mass
$\arg(m_{\tilde{\mathrm{g}}})$	=	90^0	phase of $m_{\tilde{\mathrm{g}}} \Rightarrow$ *max CP-violation*

OPAL search ... *Physics Note PN505 (July 2002)*

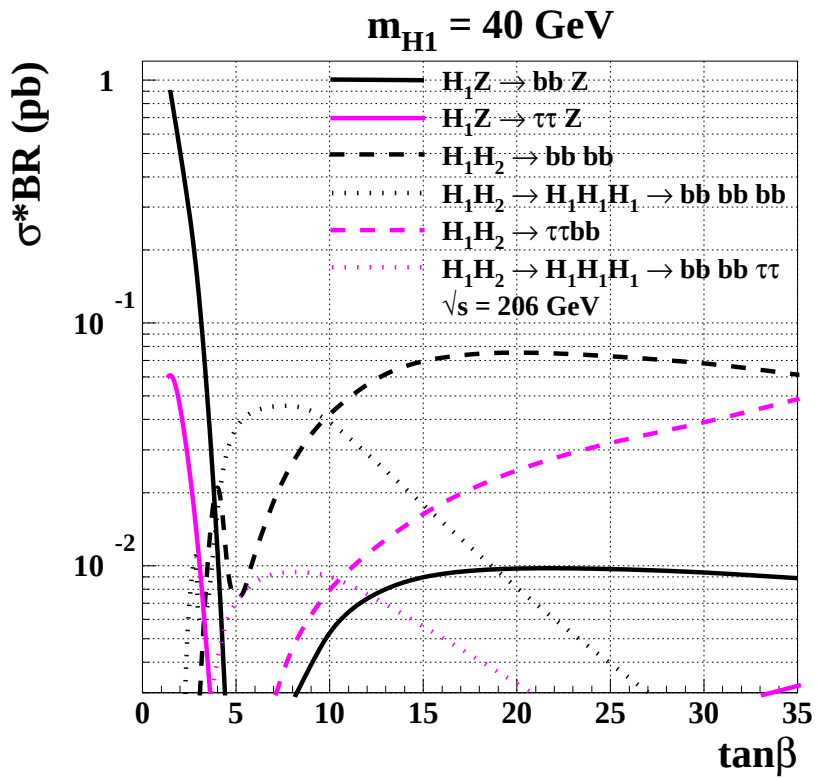
LEP1 and all LEP2 data included

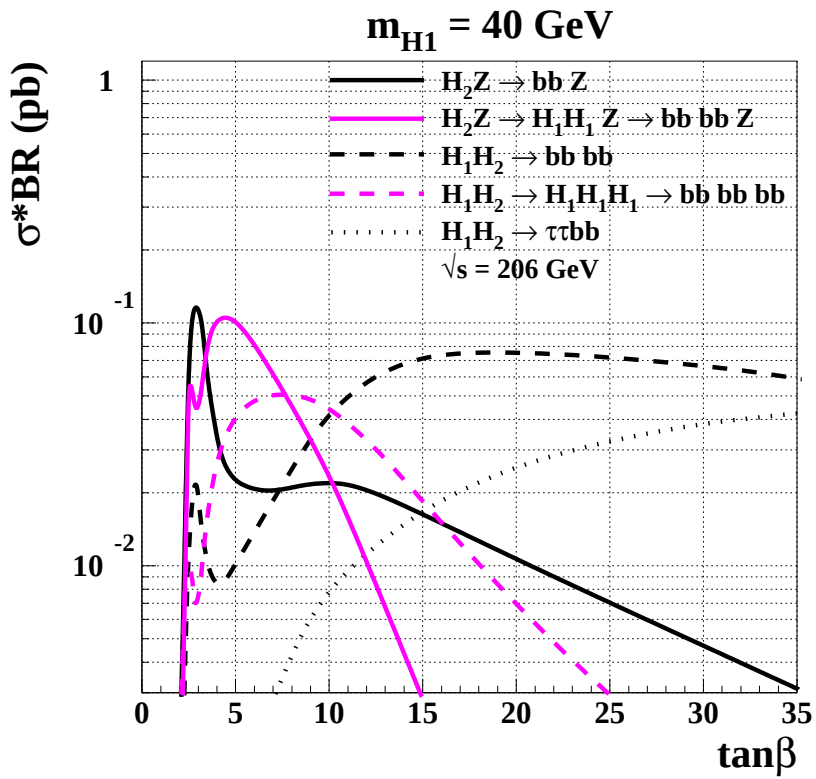
"Standard" hZ and hA searches ... adapted

CPX scenario $\bigoplus$ Phases varied between 0^0 and 90^0

$\bigoplus$ m_{top} varied within exp. errors

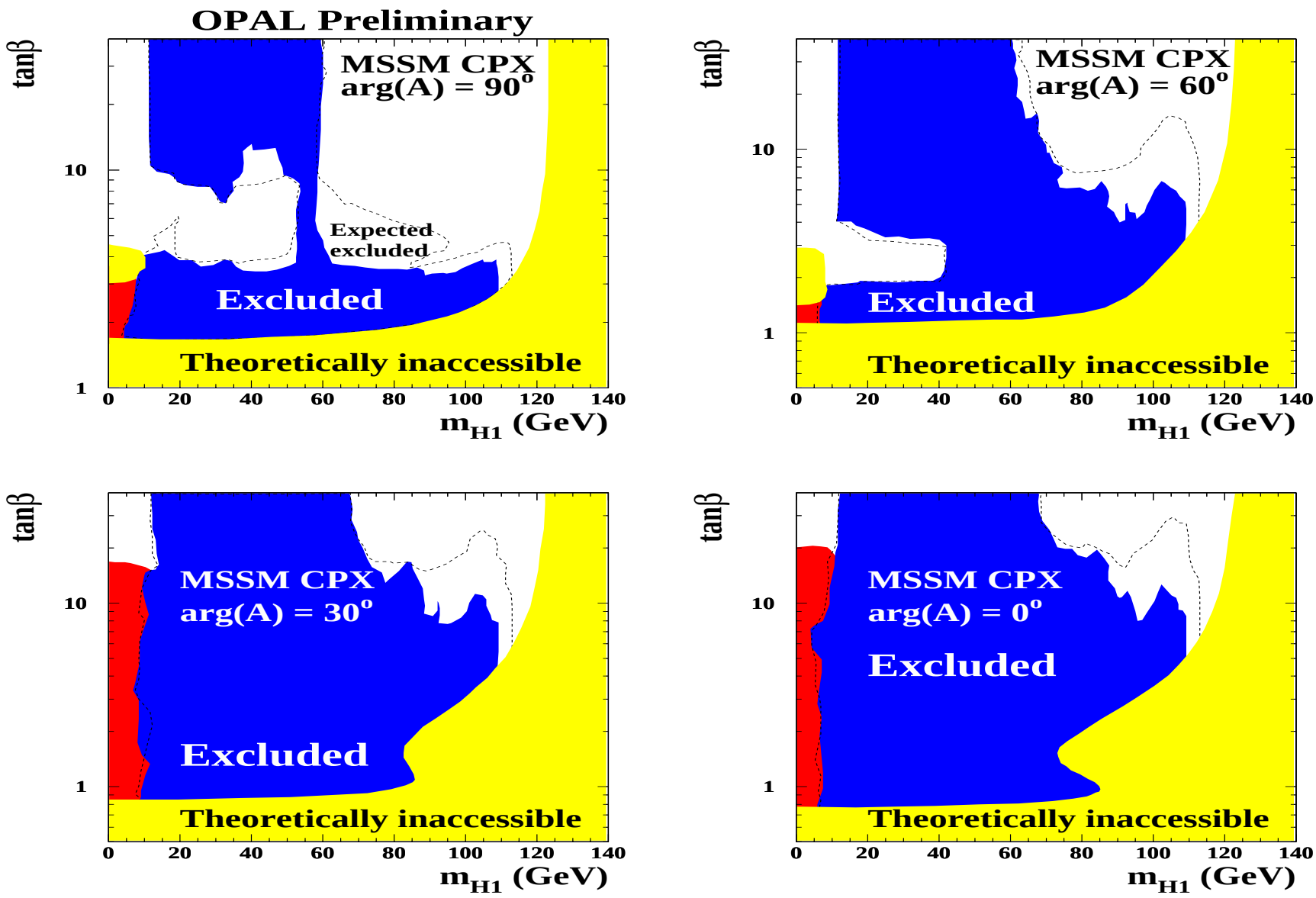
CPX scenario: Single channel rates



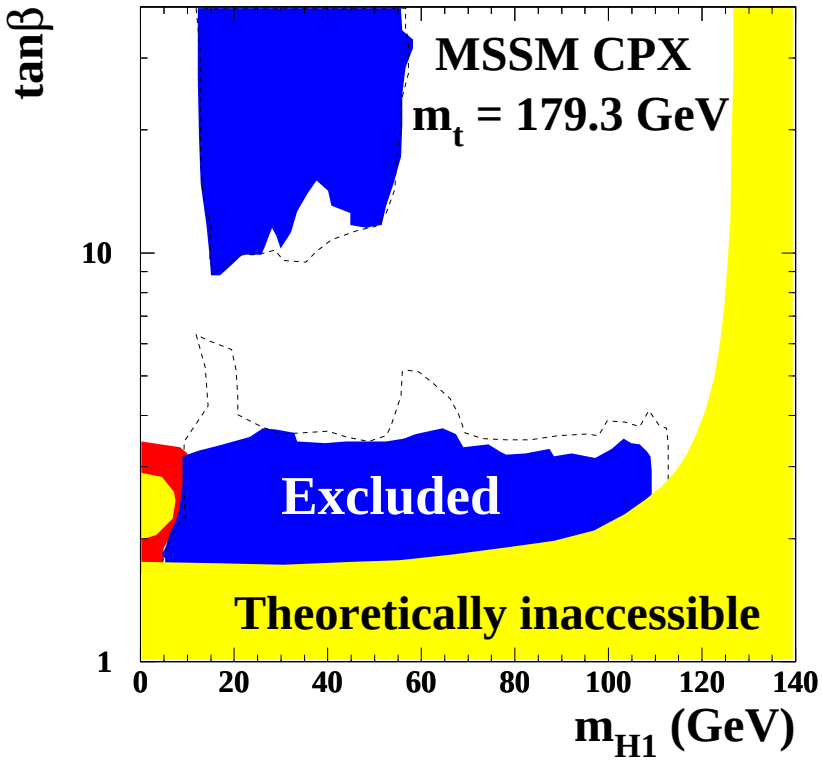


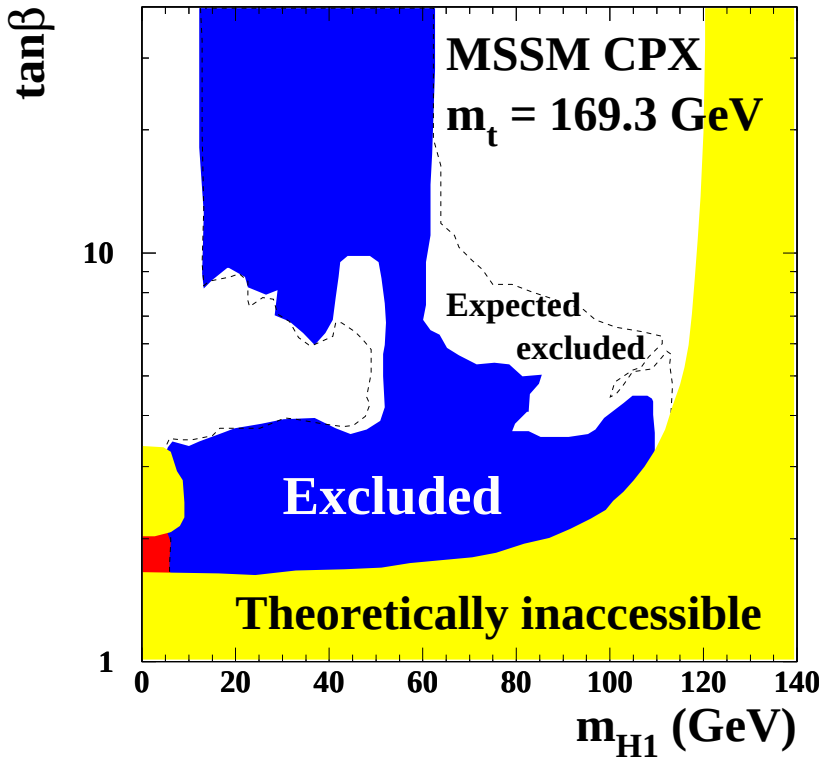
- **Weak region ...** $4 \lesssim \tan\beta \lesssim 10$
- **Rate dispersed into many channels**

OPAL CPX scan (Preliminary)



Dependence on the Top mass ...





Results ...

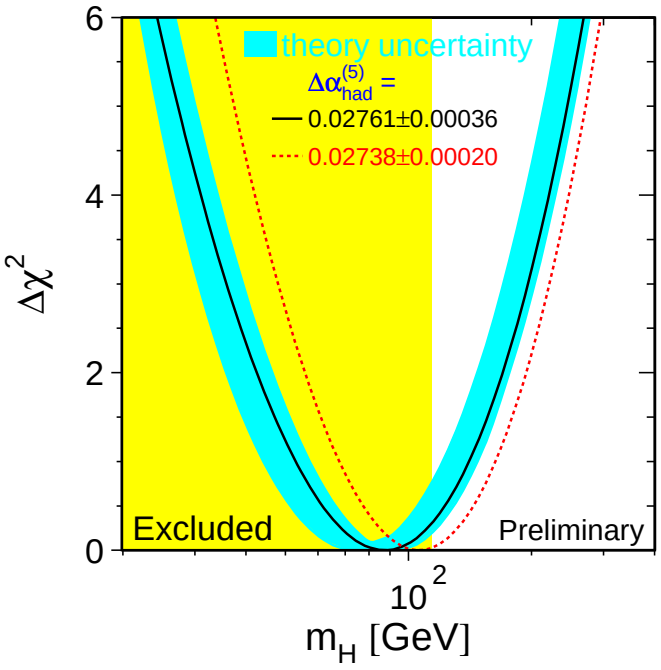
- $\tan\beta \gtrsim 2$ **(95% c.l.)**
- **No absolute limit on the lightest Higgs** H^0_1

Outlook ... **OPAL ... improved sensitivity ... soon to be published**

OPAL $\oplus$ others (?) ... combined $\Rightarrow$ Better sensitivity !

After LEP: a constrained situation

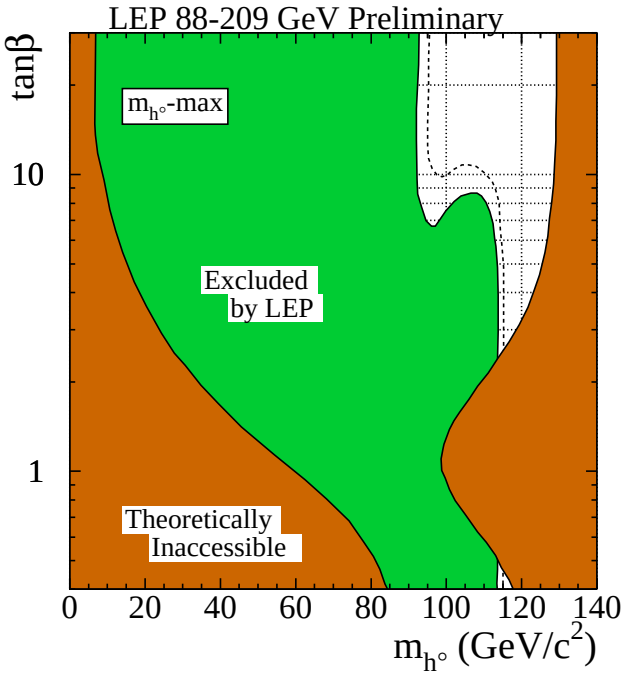
Standard Model ...



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

Searches ... $m_H >$ 114.4 GeV

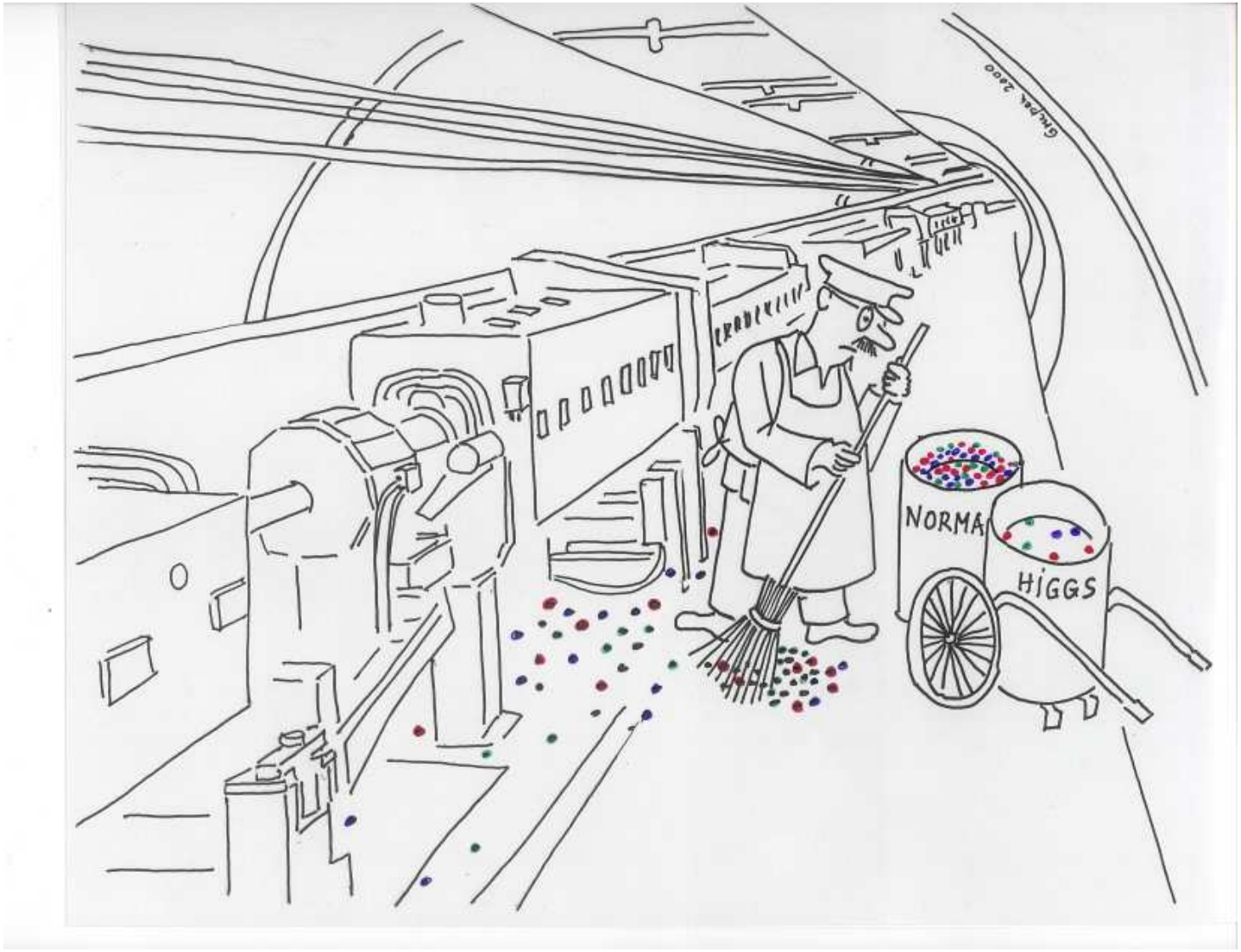
In the MSSM ... (CP conserved)



Theory ... $m_h \lesssim$ 130 GeV

Searches ... $m_h >$ 91 GeV

⇒ Small "hints" for possible signals ⇐


NORMA
HIGGS