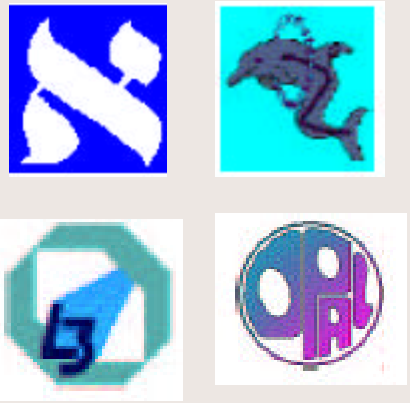
Beyond the Standard Model Neutral Higgs Searches at LEP

Daniel Zer-Zion

University of California Riverside

On Behalf of the LEP Experiments



LEP-Higgs-WG

Outlook

- **hZZ Coupling limits**
- **Two Higgs Doublet Models**
- **Fermiophobic Higgs**
- **CP-conserving MSSM**
- **CP-violating MSSM**
- **Anomalous Couplings**

ICHEP04 16-22 August 2004 Beijing China

Standard Model-Like searches (95 % CL)

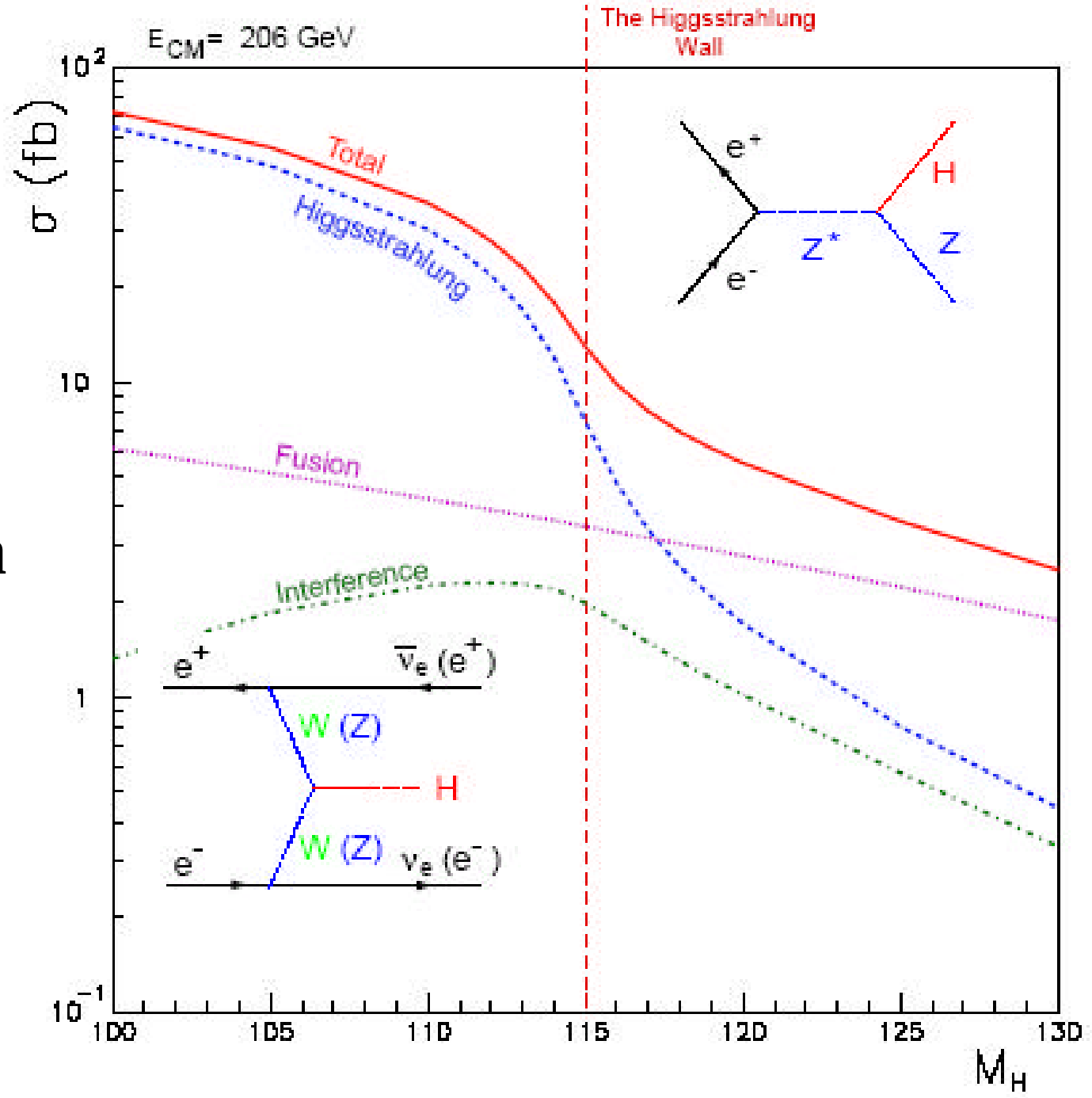
a) m_H should be larger than 114.4 GeV

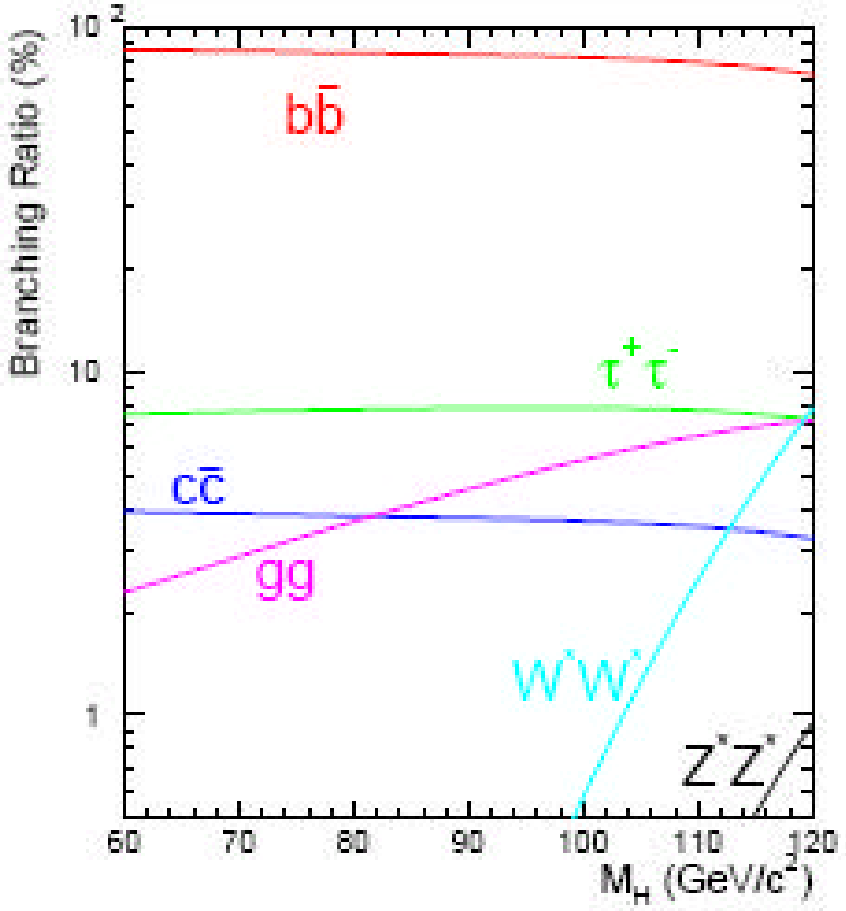
b) non-SM couplings with b- and tau-decays in the final state strongly bounded

ICHEP04 Contribution:

LEP Higgs Working Group (12-0122)

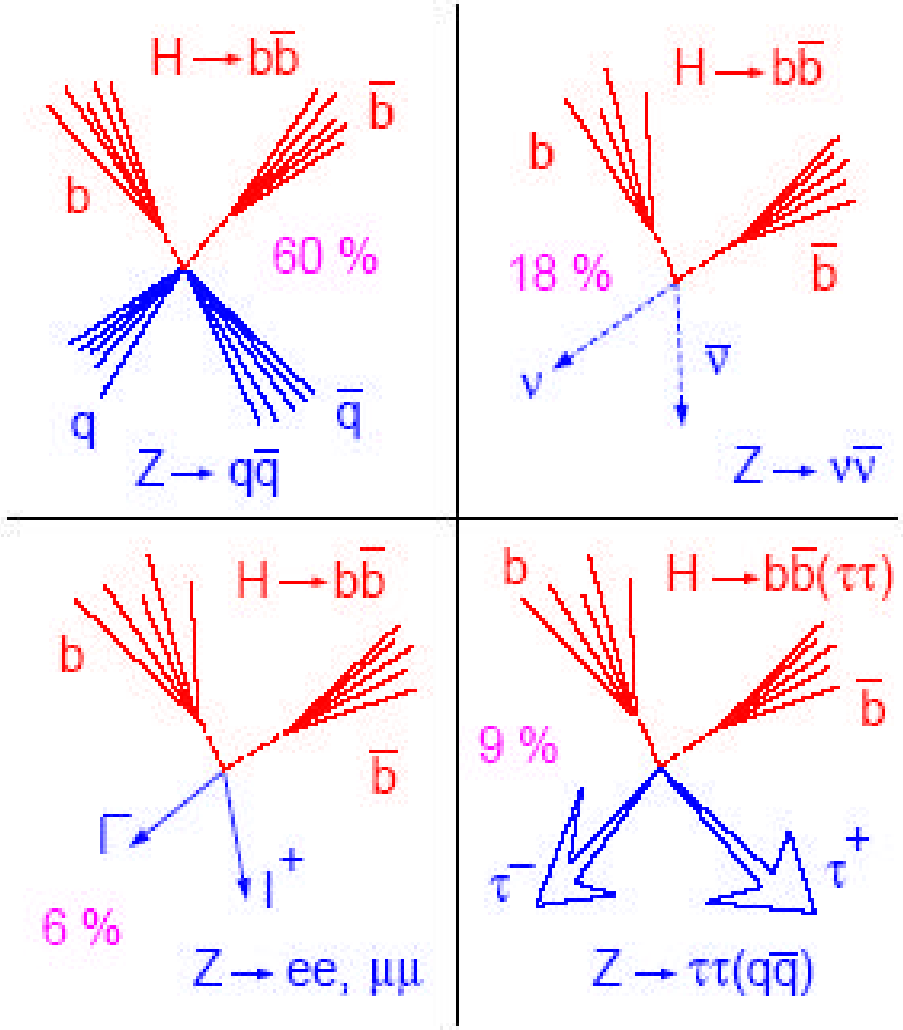
SM Higgs Production at LEP



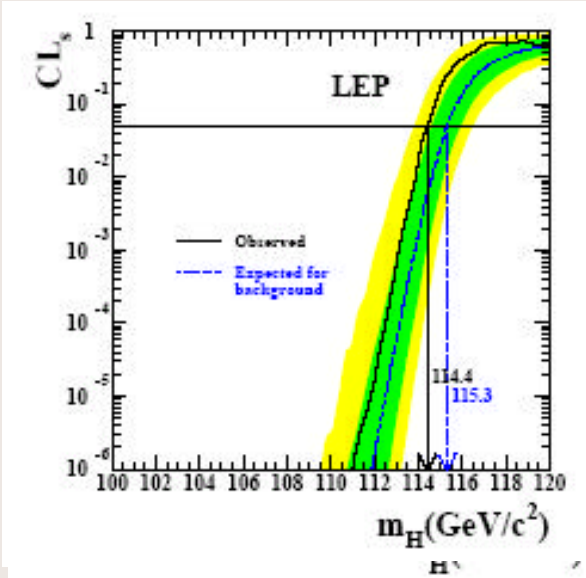


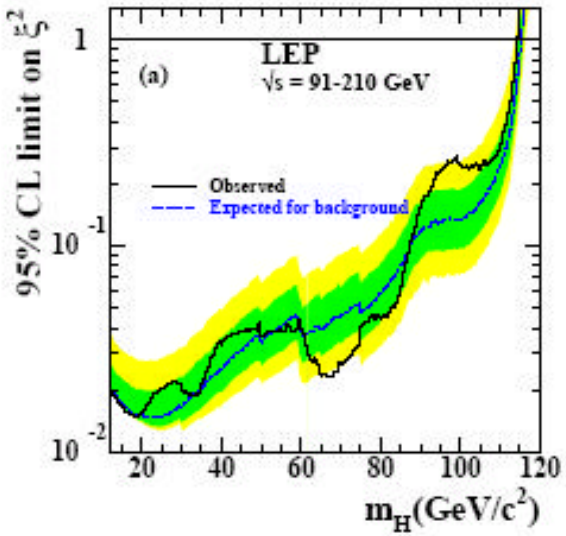
SM Higgs Decays at LEP

SM final state topologies

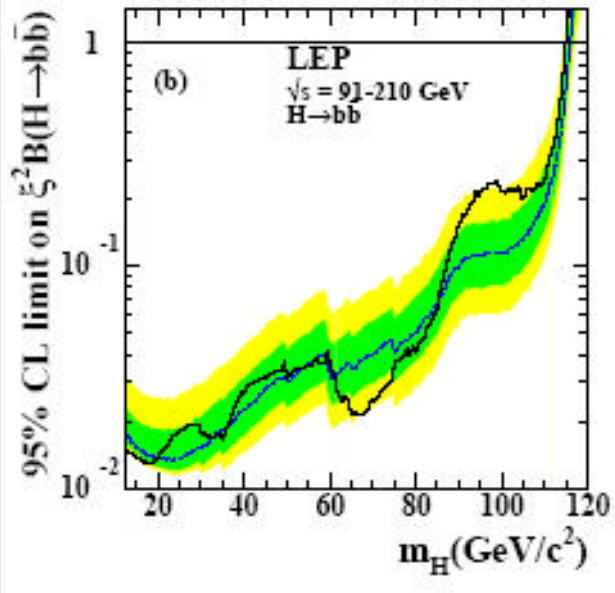


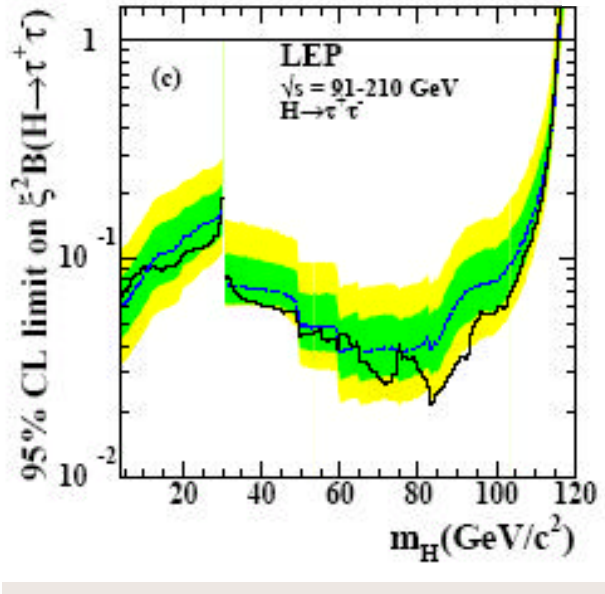
LEP Combination: Bounds for the Higgs boson mass (114.4 GeV) and couplings ($\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$)





a) SM BR's
b) Limits on ξ^2 BR($H \to b\bar{b}$)
c) Limits on ξ^2 BR($H \to \tau^+\tau^-$)





Flavour independent searches

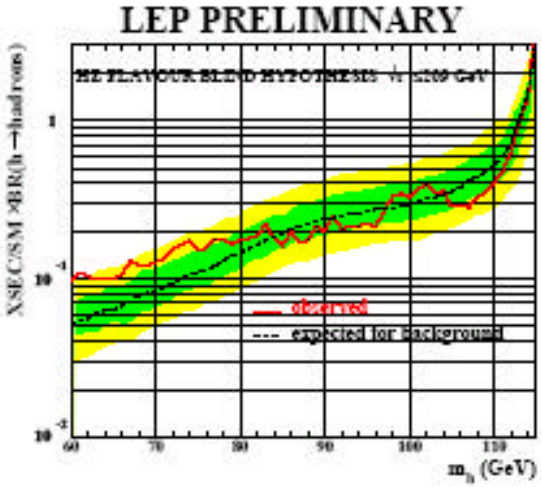
Assuming BR(h->hadrons) = 100 %
the mass of a Higgs boson produced with SM cross-section is bounded to be larger than 112.9 GeV

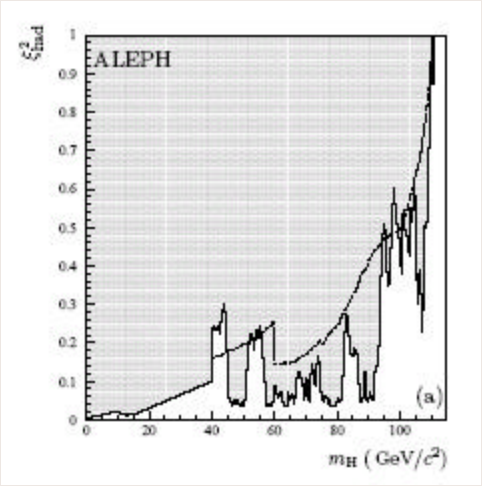
ICHEP04 Contributions: DELPHI (12-0732)
L3 (12-0198), OPAL (12-0463)

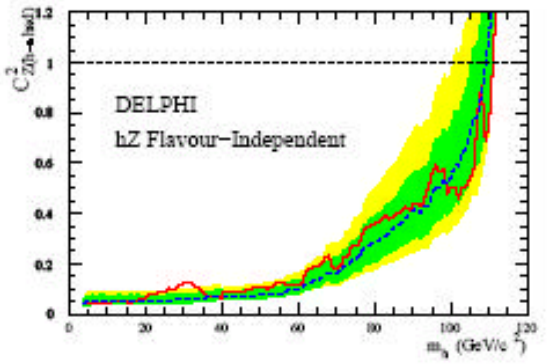
The HZZ coupling limits
95 % CL limit on

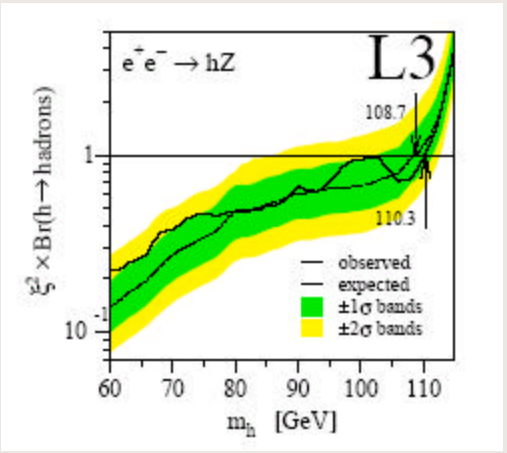
$$\xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$$

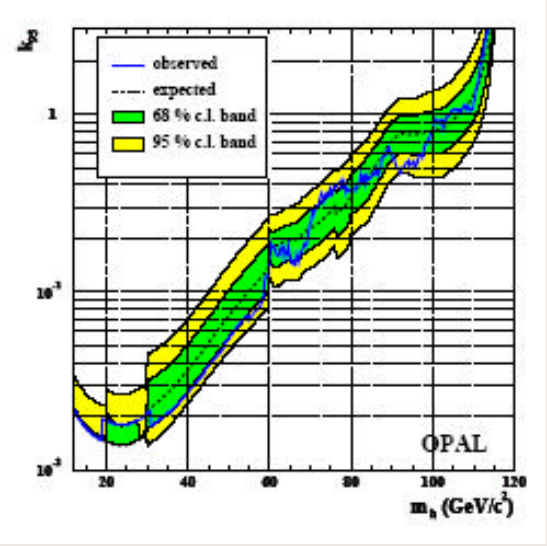
Flavour blind searches: Higgs boson decays to down type fermions are suppressed; BR(H->hadrons) = 100 %











A 110.6 GeV
D 110.6 GeV
L 110.3 GeV
O 104.0 GeV
LEP 112.9 GeV

Two Higgs Doublet Models

a) Large regions of the parameter space of 2HDM(II) excluded

b) Topological searches with specific final states

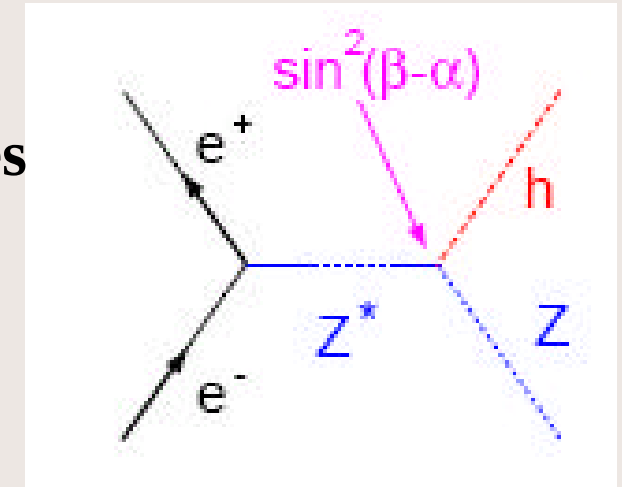
ICHEP04 Contributions: DELPHI (12-0732, 12-0736), L3 (12-0198), OPAL (12-0466)

Two Higgs Doublet Models (2HDM)

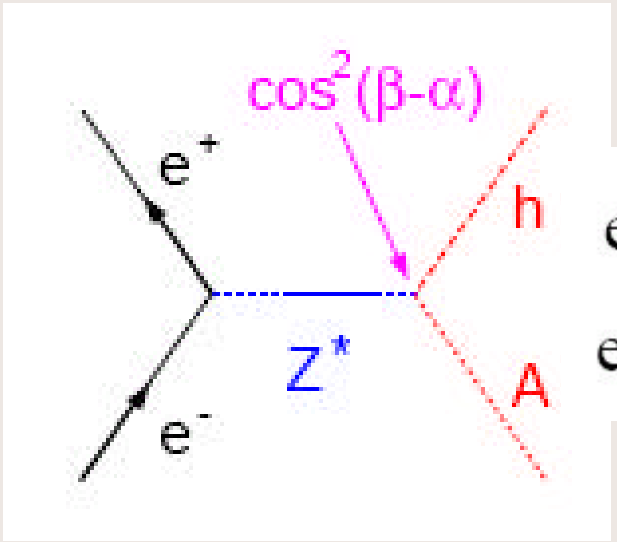
Simplest extension of SM with 2 complex scalar field doublets, in total 5 physical scalar Higgses:

- **CP even scalars: h, H**
- **CP odd scalar: A**
- **Two charged scalars: $H^{\pm}$**

6 Free parameters: 2 angles, 4 masses



Two production processes:



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

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

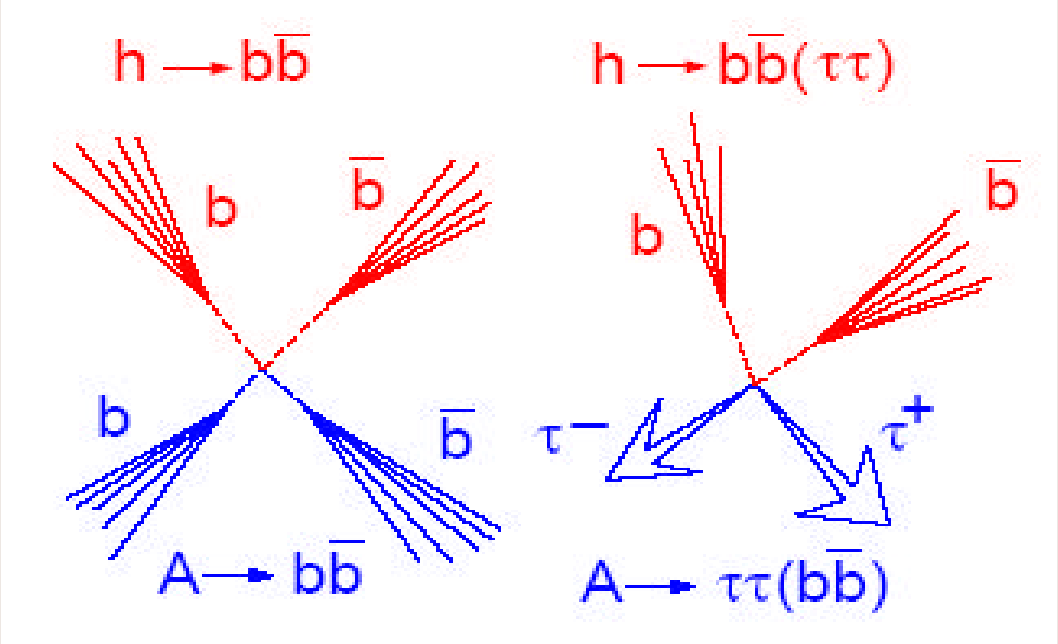
$\bar{\lambda}$ **: kinematic factor**

The type of 2HDM is determined by the couplings of the Higgs doublets to fermions:

- **Type I: quarks and leptons only couple to the 2nd Higgs doublet**
- **Type II: 1st Higgs doublet couples only to down-type fermions, 2nd Higgs doublet couples only to up-type fermions**

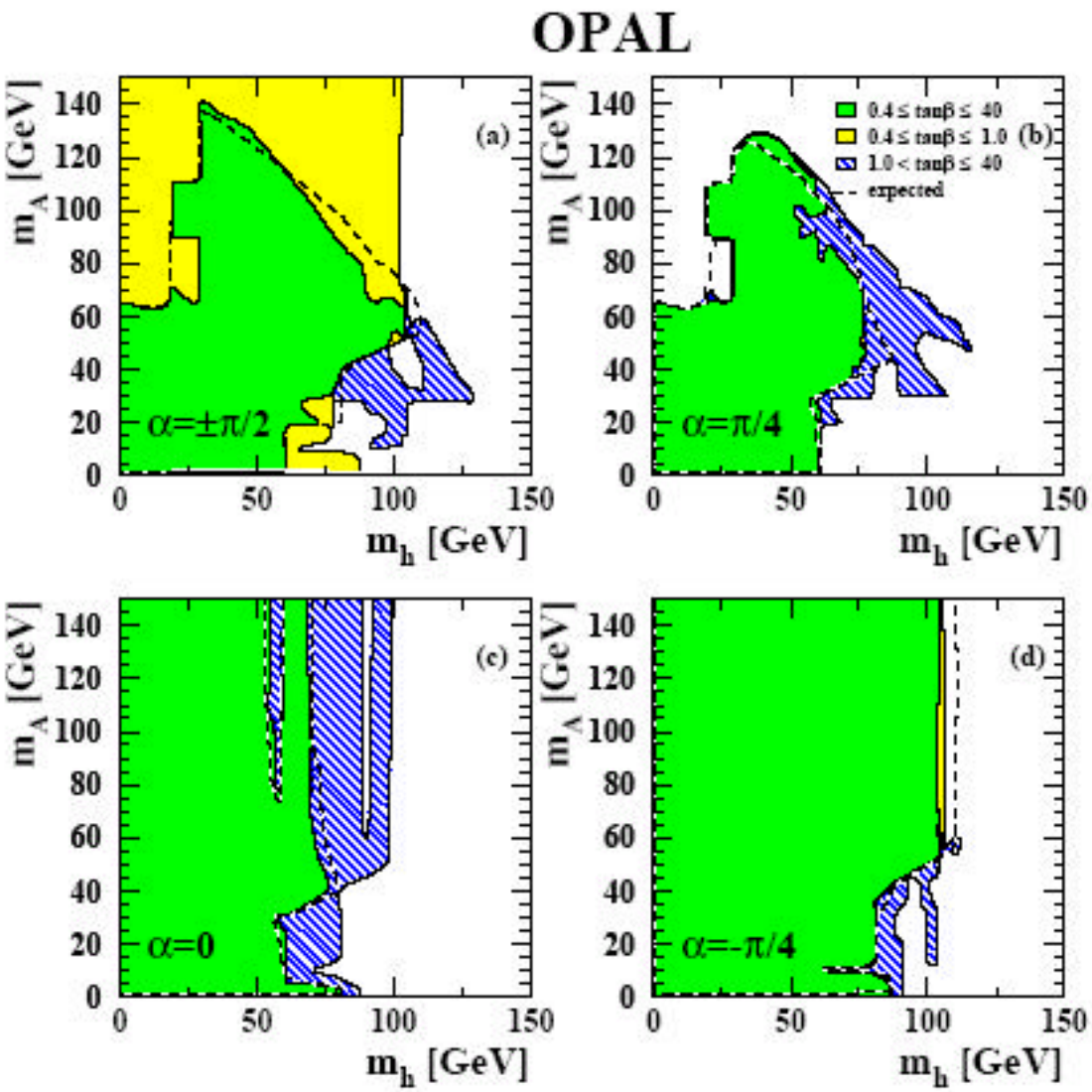
$$h^0 c\bar{c} \sim \frac{\cos\alpha}{\sin\beta} \qquad h^0 b\bar{b} \sim \frac{\sin\alpha}{\cos\beta} \qquad A^0 c\bar{c} \sim \cot\beta \qquad A^0 b\bar{b} \sim \tan\beta$$

New phenomena, in addition to hZ SM-like



$1 \leq m_h \leq 130$ GeV 3 GeV $\leq m_A \leq 2$ TeV

$0.4 \leq \tan\beta \leq 40$ $\alpha = \pm\pi/2,\ \pm\pi/4,\ 0$



$h^0Z^0 \rightarrow$

$b\bar{b}q\bar{q}$, $b\bar{b}\nu\bar{\nu}$, $b\bar{b}e^+e^-$,

$b\bar{b}\mu^+\mu^-$, $b\bar{b}\tau^+\tau^-$

$q\bar{q}q\bar{q}$, $q\bar{q}\nu\bar{\nu}$, $q\bar{q}e^+e^-$,

$q\bar{q}\mu^+\mu^-$, $q\bar{q}\tau^+\tau^-$

$h^0A^0 \rightarrow$

$q\bar{q}\tau^+\tau^-$

$b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$

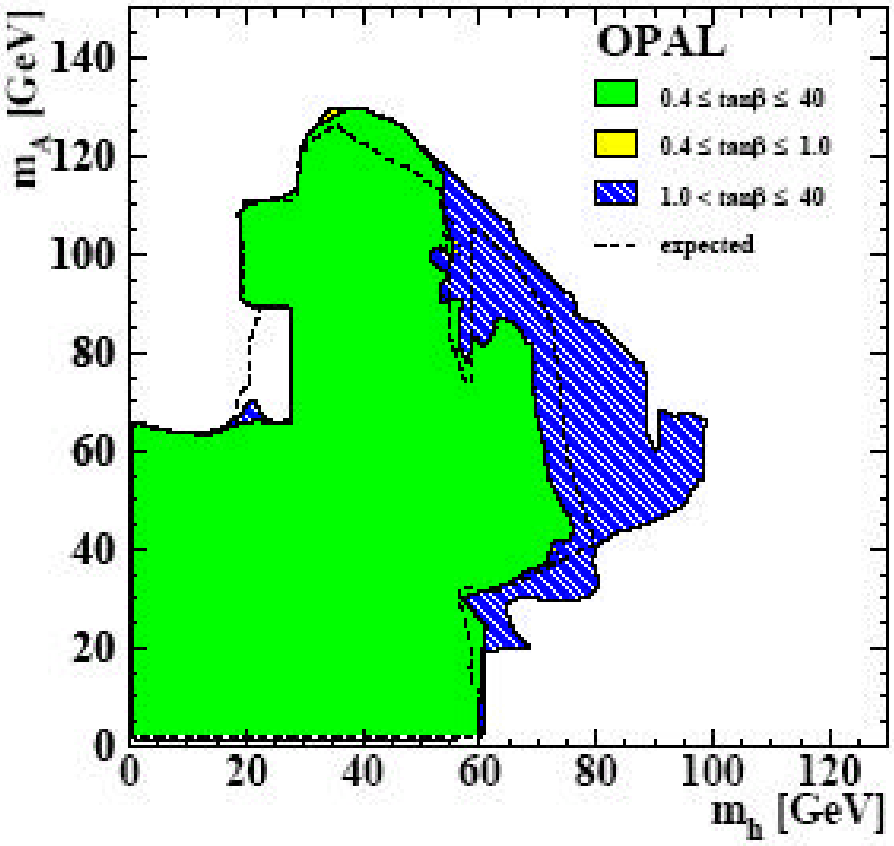
$q\bar{q}q\bar{q}$

$h^0A^0 \rightarrow (A^0A^0)A^0$

$h^0Z^0 \rightarrow (A^0A^0)Z^0$

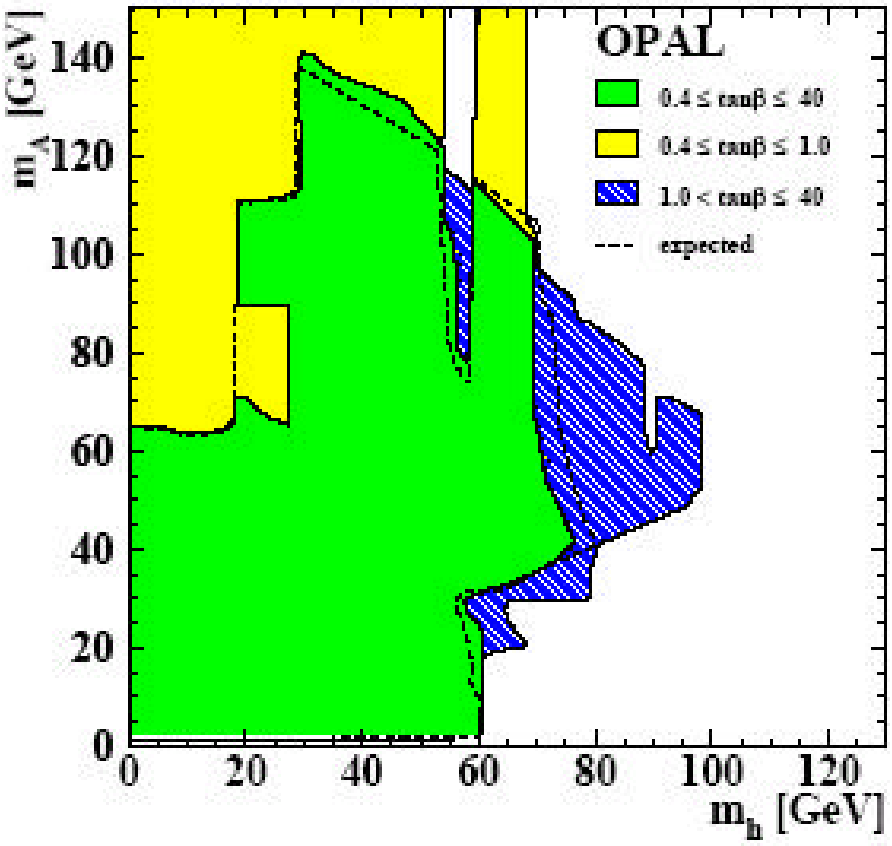
General 2HDM(II)

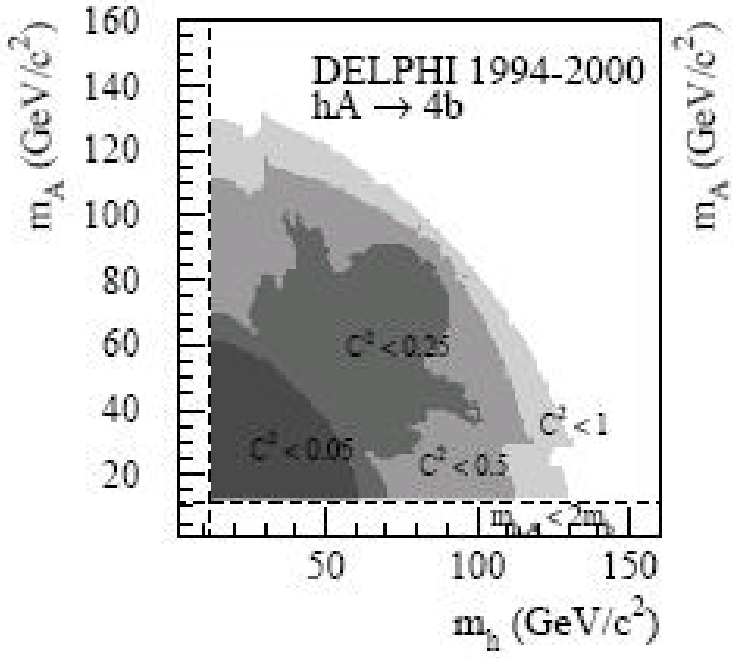
$$-\pi/2 \leq \alpha \leq \pi/2$$

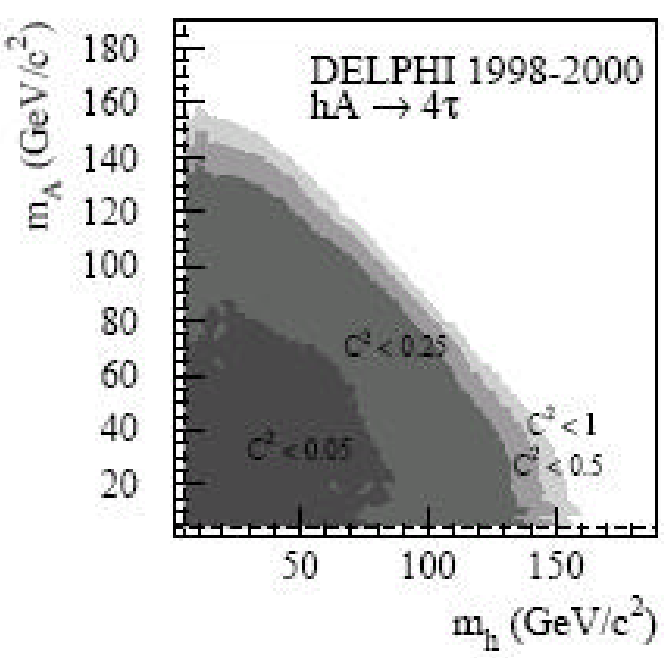


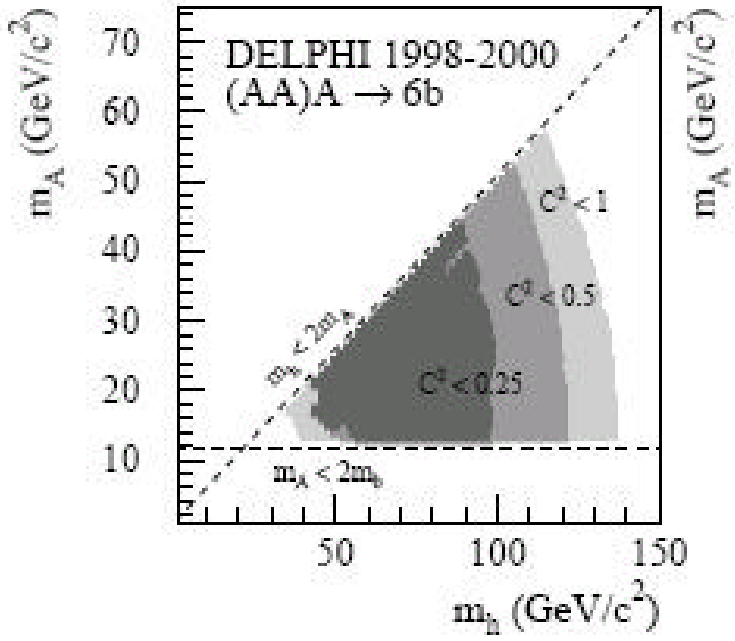
MSSM-like

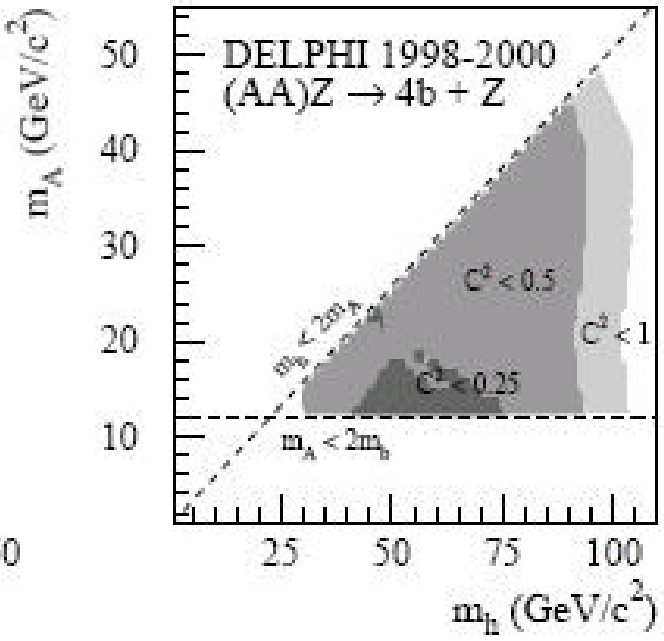
$$-\pi/2 \leq \alpha \leq 0$$







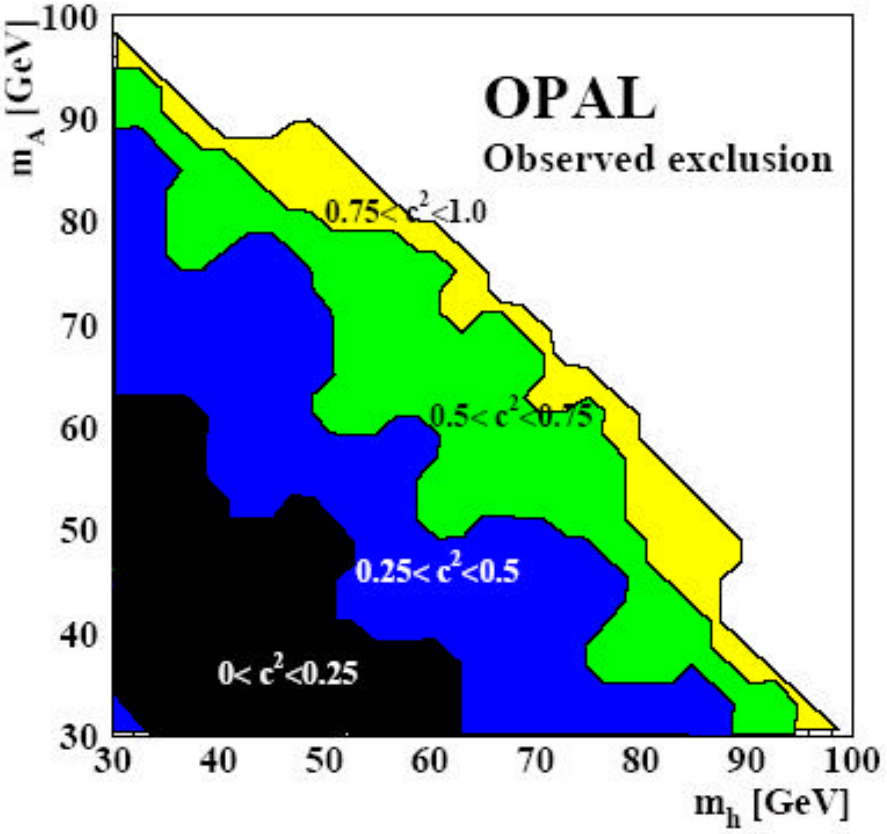




Topological searches

New limits by DELPHI assuming 100 % BR into specific final states

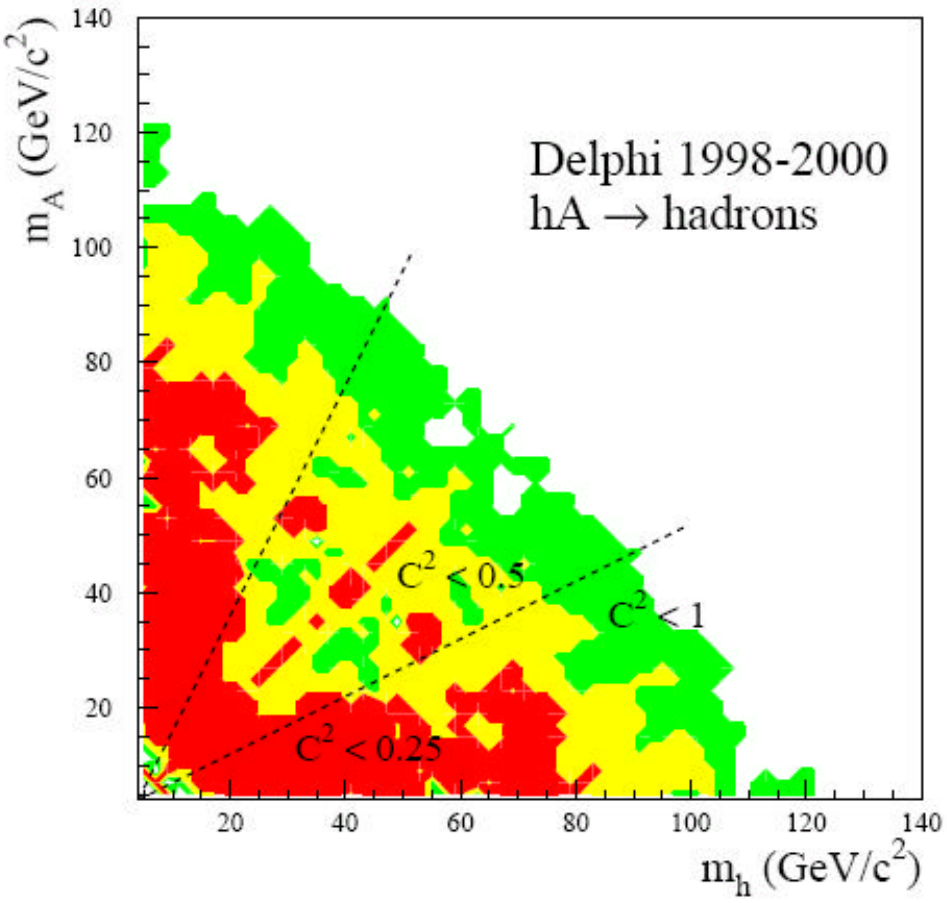
hA->hadrons cross-section limits by DELPHI and OPAL



$m_h \sim m_A < 70$ GeV

$m_h + m_A < 140$ GeV

Excluded at 95 % CL



Fermiophobic models

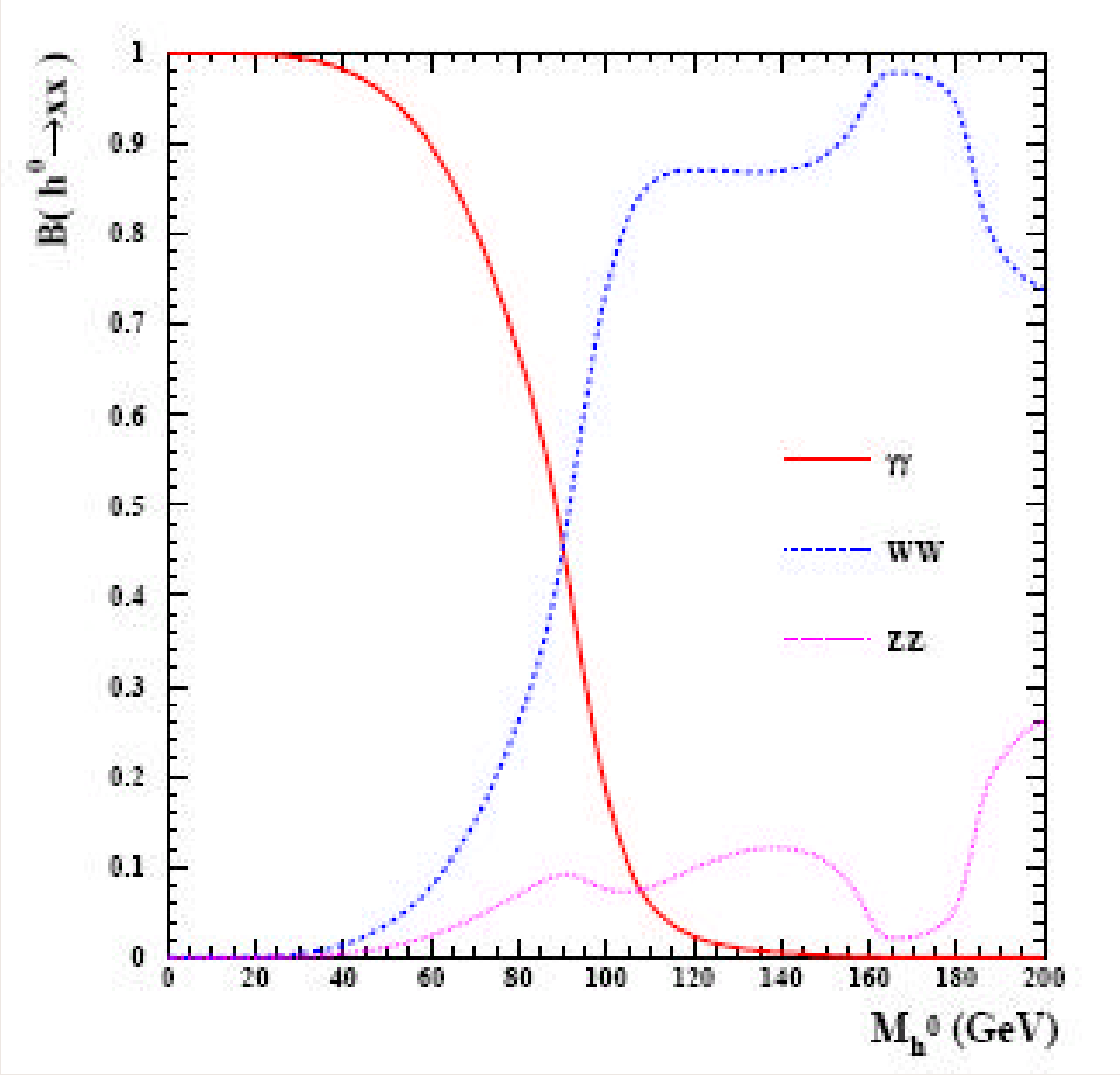
a) Mass limits at around 109 GeV in the benchmark fermiophobic model for the 2 photons final state

b) 2HDM(I) Fermiophobic excluded at large (m_h, m_A) domains

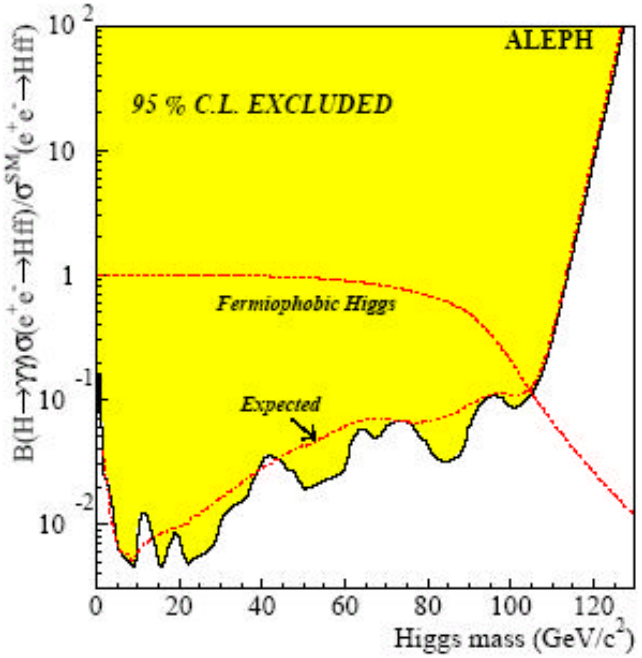
c) H->WW* (ZZ*) fermiophobic excluded in the mass region (83.7,104.6) GeV

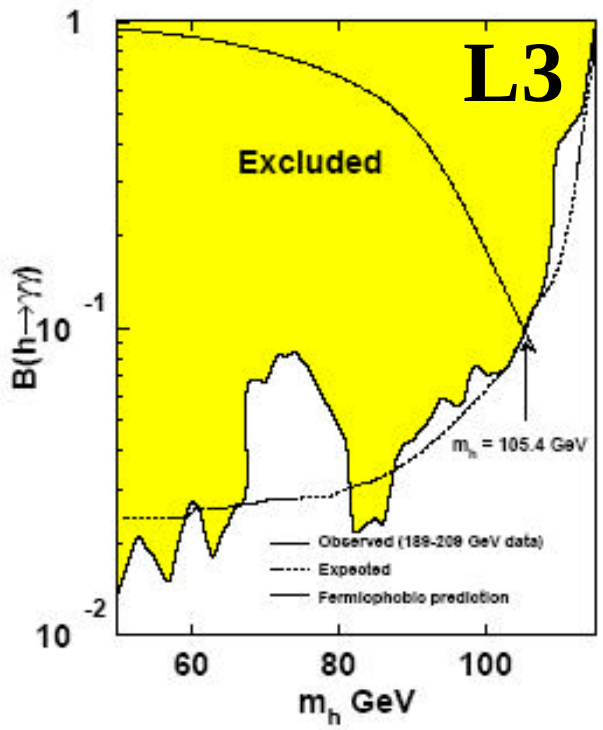
ICHEP04 Contributions: DELPHI (12-0736), L3 (12 0197)

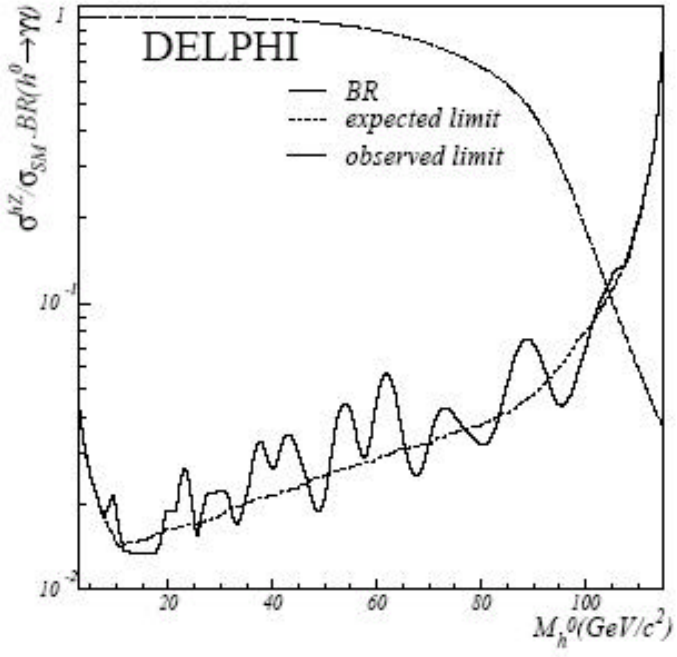
Fermiophobic Higgs searches:

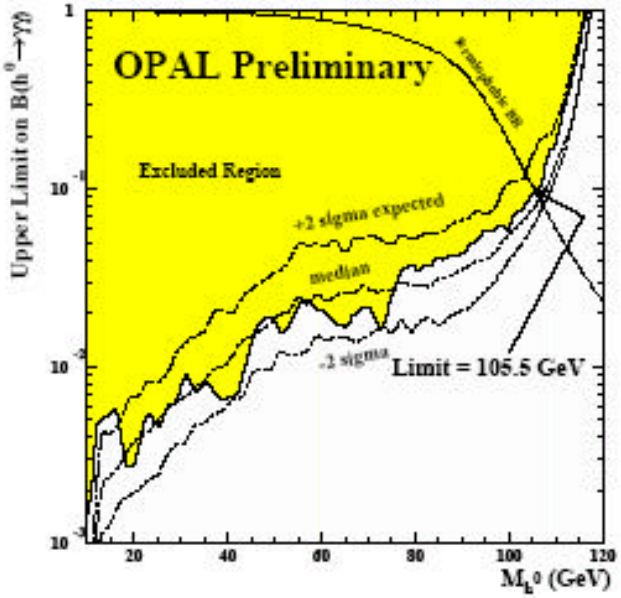


Benchmark: HZ-SM production cross-section with all direct decays into fermions removed









Mass limits:

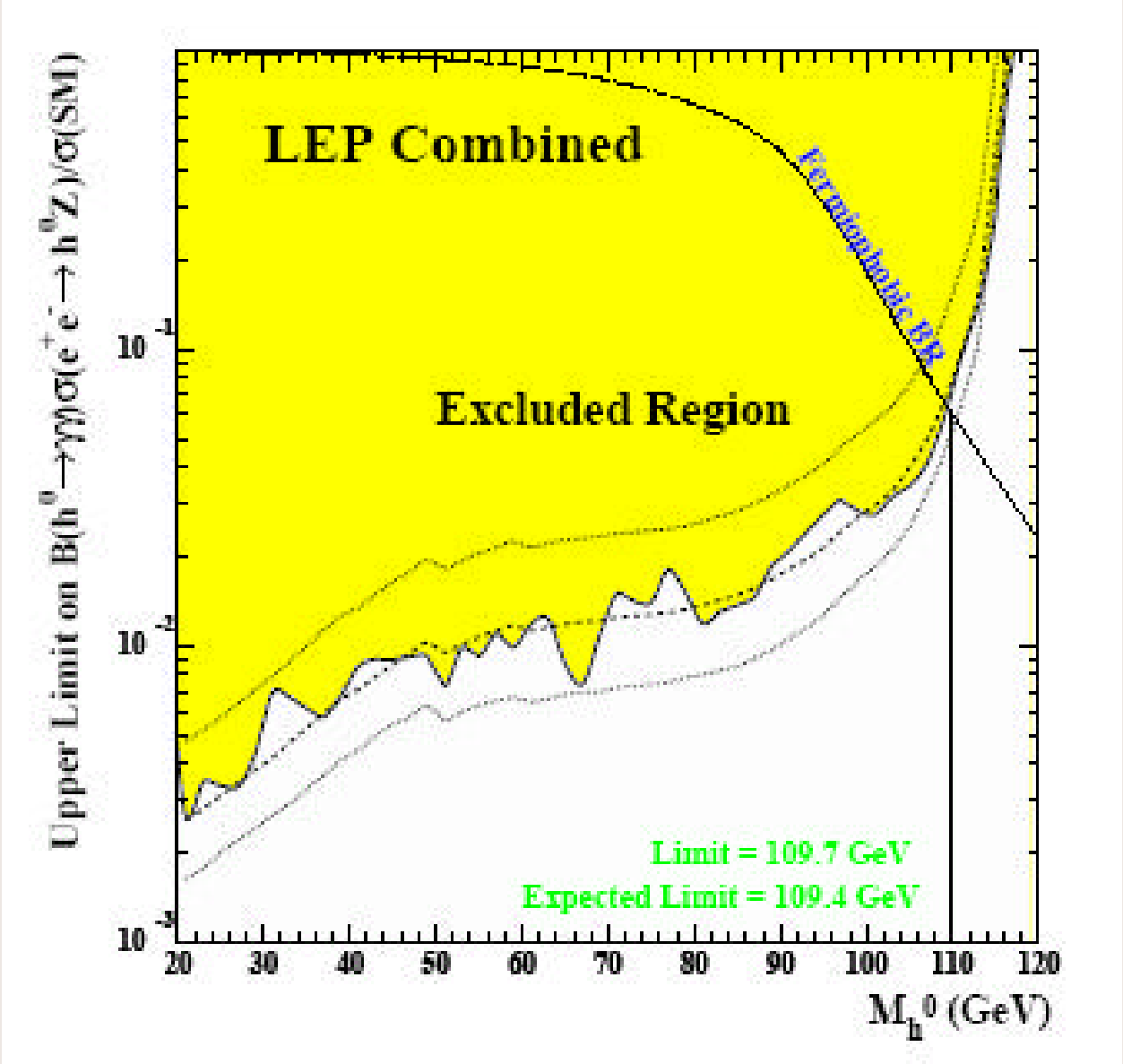
A 105.4 GeV

D 104.1 GeV

L 105.4 GeV

O 105.5 GeV

LEP fermiophobic limit: 109.7 (109.4) GeV



Fermiophobic 2HDM

2HDM(I): $hf\bar{f} \sim \cos\alpha$

If $\alpha = \pi/2$, $hf\bar{f}$ couplings vanish

and h^0 becomes fermiophobic

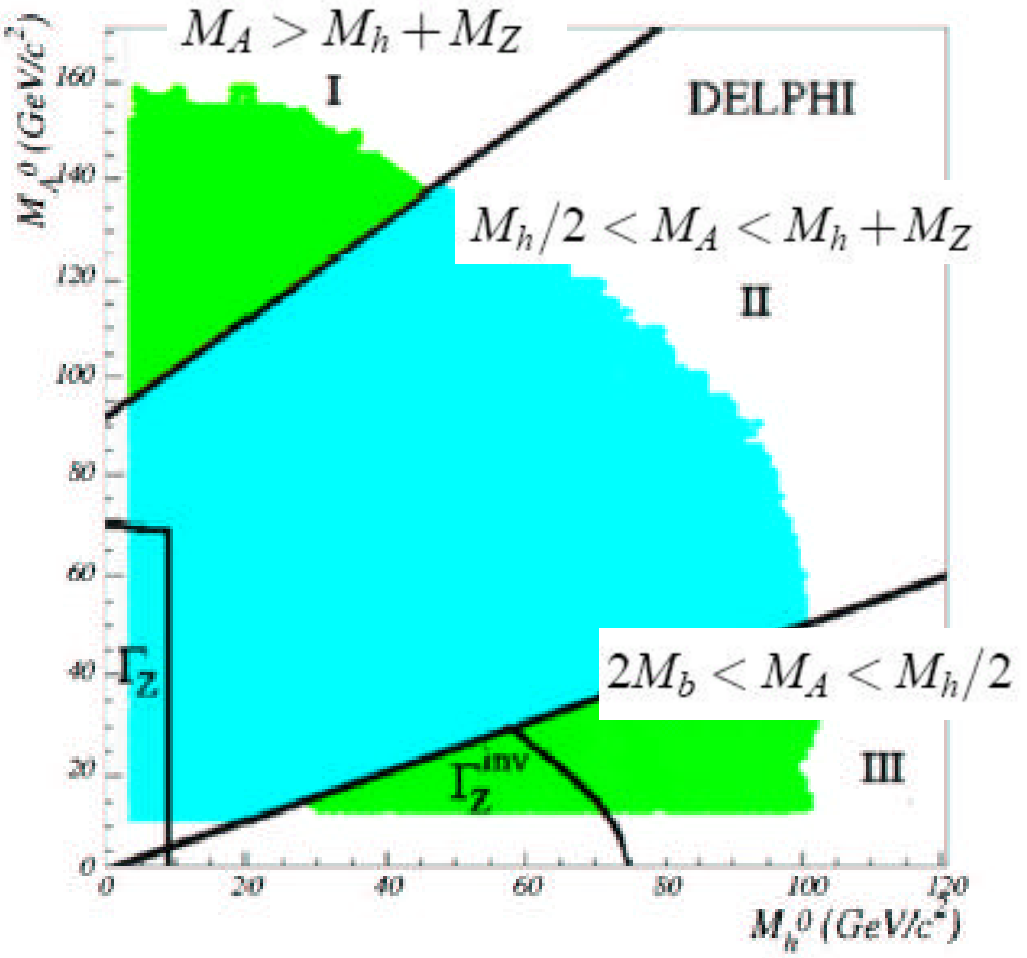
$h^0 \to \gamma\gamma$, $A^0 \to b\bar{b}$

or $A^0 \to h^0 Z^0 \to \gamma\gamma Z^0$

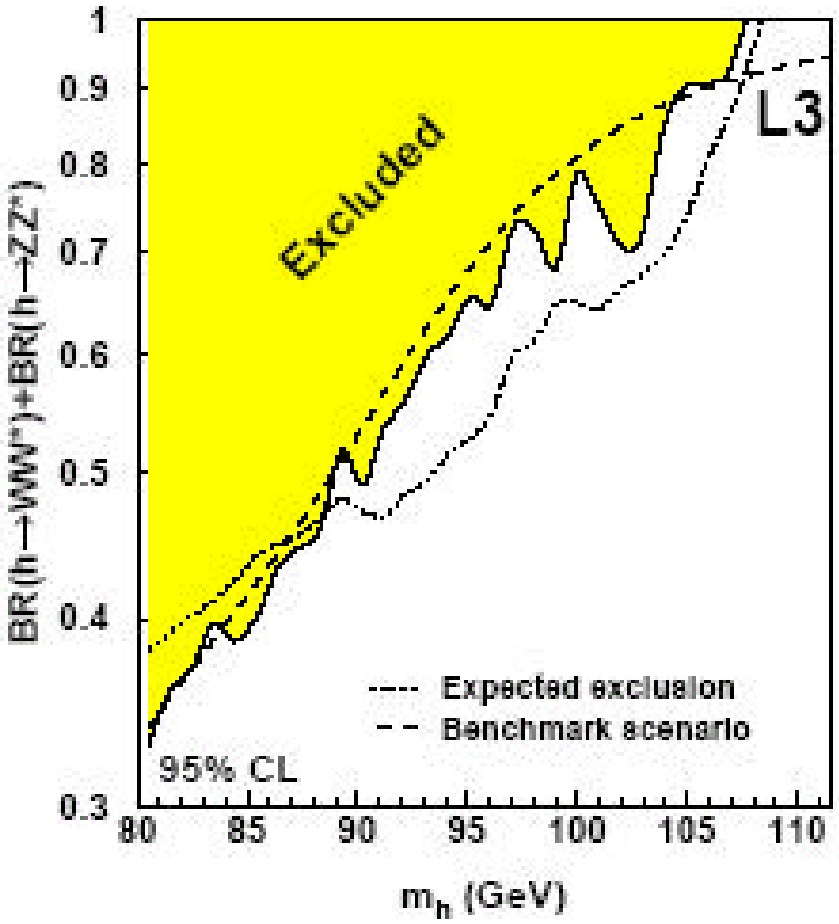
$h^0 A^0 \to \gamma\gamma b\bar{b}$, $h^0 A^0 \to \gamma\gamma\gamma\gamma Z^0$

Combined with

$h^0 Z^0 \to \gamma\gamma Z^0$



Fermiophobic H->WW*(ZZ*) by L3



Fermiophobic benchmark:

BR(H->WW*)+BR(H->ZZ*) given by HDECAY, SM cross section with fermionic decays switched off
Excl. Limit 95 % CL 83.7 < m_h < 104.6 GeV

If BR(H->WW*)+BR(H->ZZ*) =1 then m_h < 108.1 GeV Excl. at 95 % CL

MSSM (LEP Combination)

a) CP- Conserving

b) CP-Violating

ICHEP04 Contributions: DELPHI (12-0144), OPAL (12-0461), LEP-Higgs-WG (12-0122)

The MSSM framework at LEP

- Interpretation in a constrained MSSM
- At tree level, 2 parameters describe the Higgs sector
- Additional parameters enter at the level of radiative corrections:

M_{susy} : Energy scale of SUSY breaking, it is a common mass for all sfermions at the EW scale

M_2 : Common gaugino mass at EW scale

μ : strength of the supersymmetric Higgs mixing

A: a common trilinear Higgs-squark coupling

$m_{\tilde{g}}$: gluino mass

X_t , X_b : stop and sbottom mixing parameters

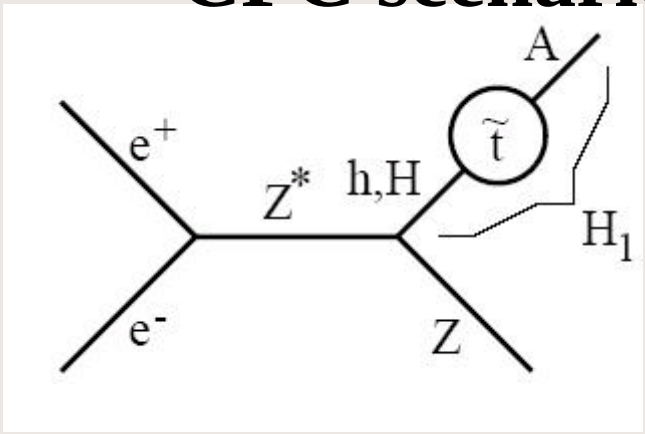
MSSM Benchmark CPC scans

1) **no-mixing: $X_t = 0$, relatively restricted MSSM parameter space**
2) **mh-max: designed to maximise the upper bound of mh for every $\tan\beta$**
3) ***large-μ*** **: detection a priori difficult**

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

MSSM Benchmark CPV scan (new)

4) CPX: designed to give large deviations from CPC scenarios



$$\sigma_{H_i Z} = g^2_{H_i ZZ}\, \sigma^{SM}_{HZ}$$

$$\sigma_{H_i H_j} = g^2_{H_i H_j Z}\, \bar{\lambda}\, \sigma^{SM}_{HZ}$$

$$g_{H_i ZZ} = \cos\beta O_{1i} + \sin\beta O_{2i}$$

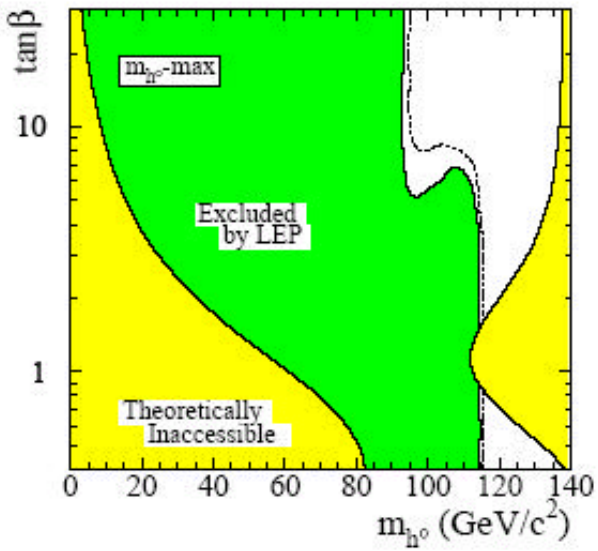
$$g_{H_i H_j Z} = O_{3i}(\cos\beta O_{2j} - \sin\beta O_{1j}) - O_{3j}(\cos\beta O_{2i} - \sin\beta O_{1i})$$

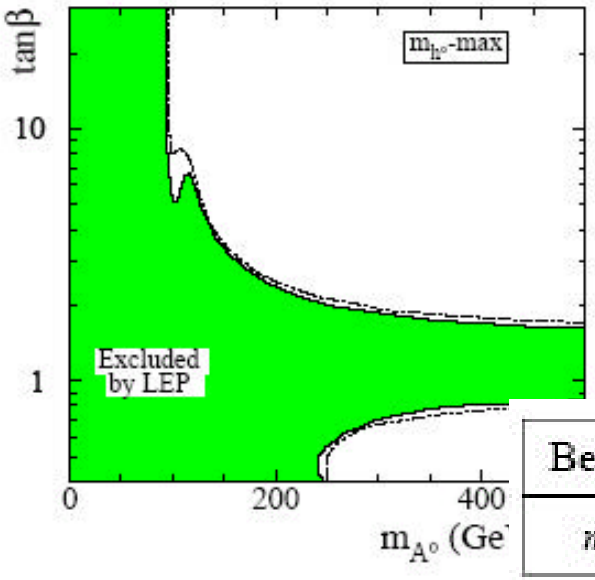
$$O^2_{ij} \propto \frac{m_t^4}{v^2} \frac{\mathrm{Im}(\mu A)}{32\pi^2 M^2_{SUSY}}$$

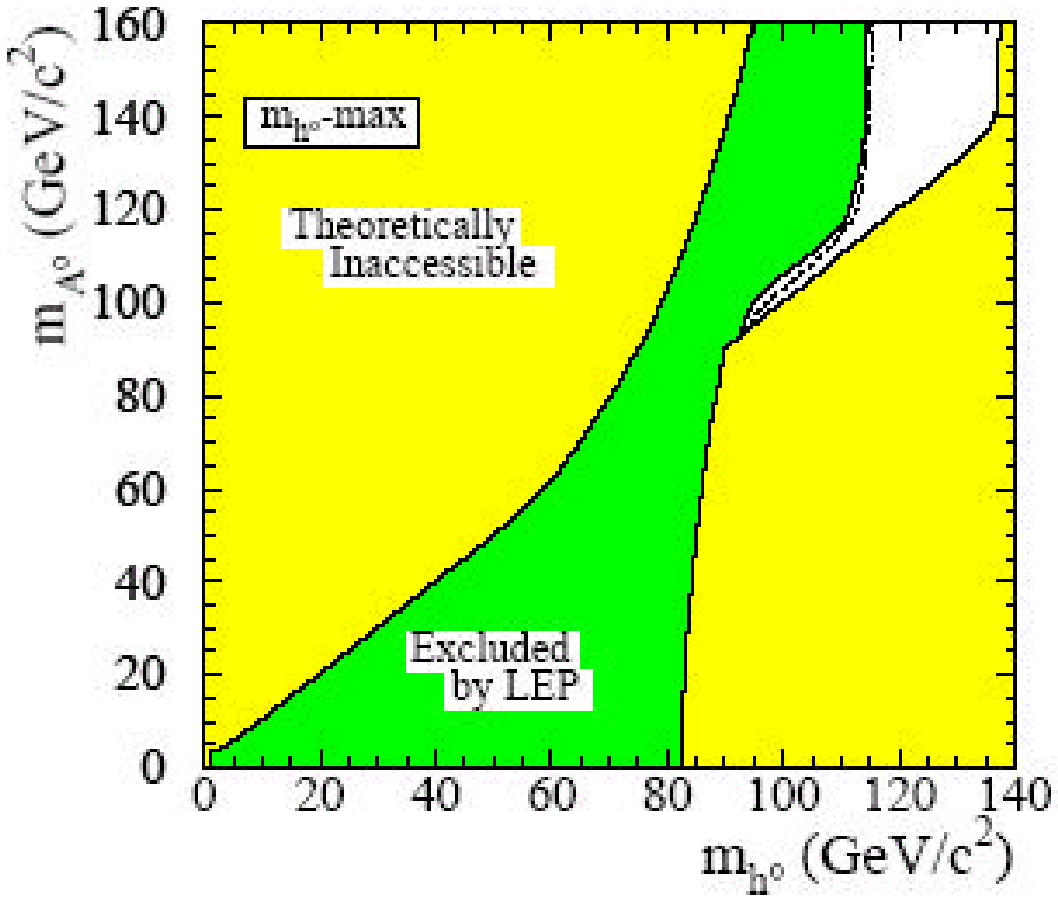
Carena, Ellis, Pilaftsis, Wagner
Phys. Lett. B495 (2000) 155

Benchmark parameters				
	no-mixing	m_h-*max*	*large-*μ	*CPX*
Parameters varied in the scan				
$\tan\beta$	0.4-40	0.4-40	1-50	0.6-40
m_A [GeV]	4-1000	4-1000	4-400	-
$m_{H^\pm}$ [GeV]	-	-	-	4-1000
Fixed Parameters				
M_{SUSY} [GeV]	1000	1000	400	500
M_2 [GeV]	200	200	400	200
μ [GeV]	-200	-200	1000	2000
$m_{\tilde{g}}$ [GeV]	800	800	200	1000
X_t [GeV]	0	$\sqrt{6}M_{SUSY}$	-300	$A-\mu\cot\beta$
A [GeV]	$X_t+\mu\cot\beta$	$X_t+\mu\cot\beta$	$X_t+\mu\cot\beta$	1000
arg A, arg $m_{\tilde{g}}$	-	-	-	90°

LEP MSSM Exclusions at 95 % CL for the m_h –max benchmark scenario (m_t = 179.3 GeV)

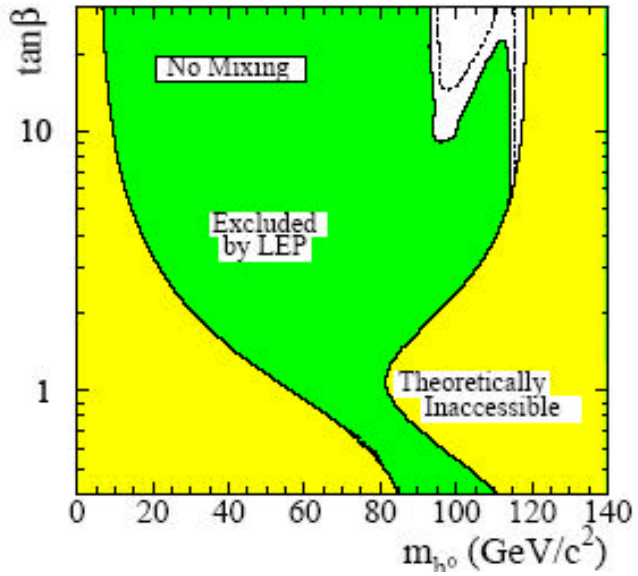


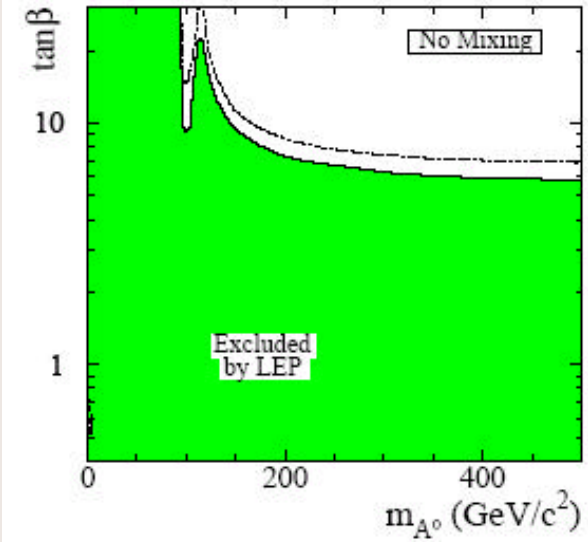


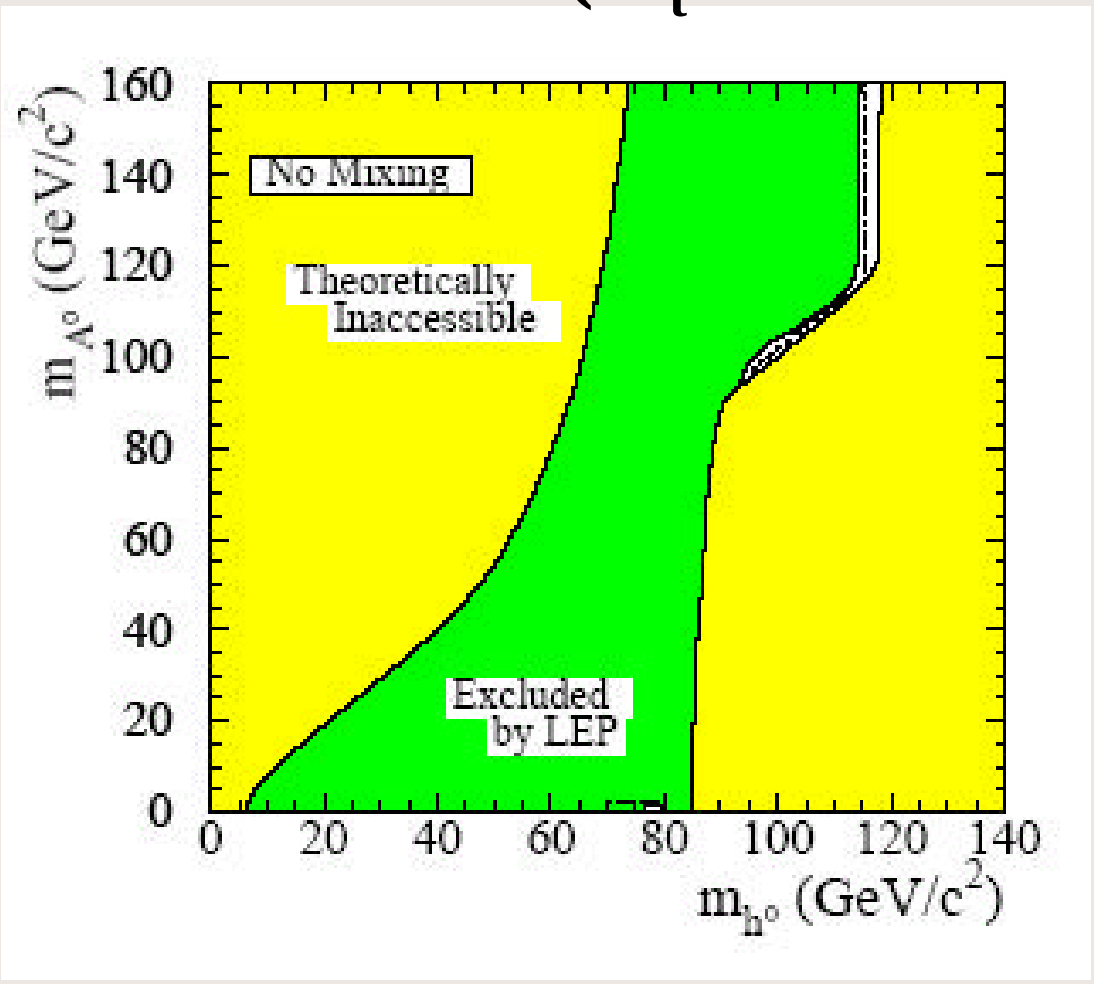


Benchmark	m_h limit (GeV)	m_A limit (GeV)	Excluded tan β range
m_h-*max*	92.9	93.4	$0.9 < \tan\beta < 1.5$

LEP MSSM Exclusions at 95 % CL for the no-mixing benchmark scenario (m_t = 179.3 GeV)

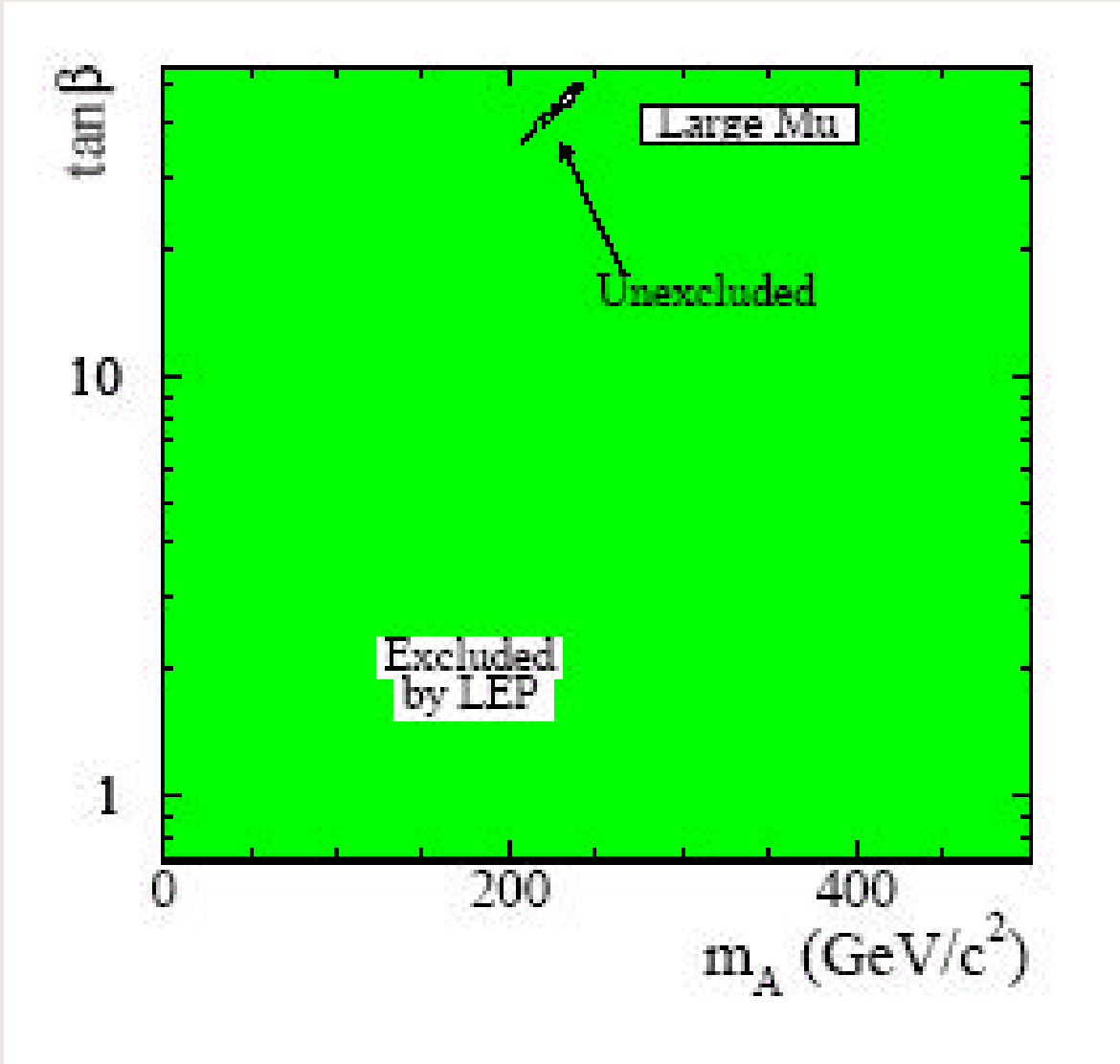




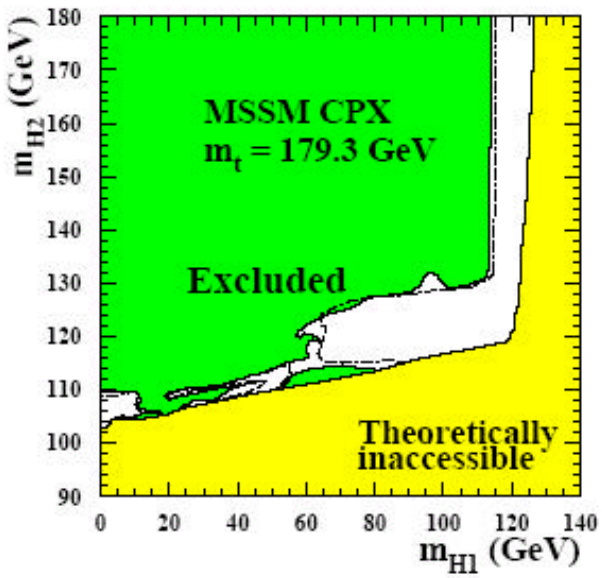


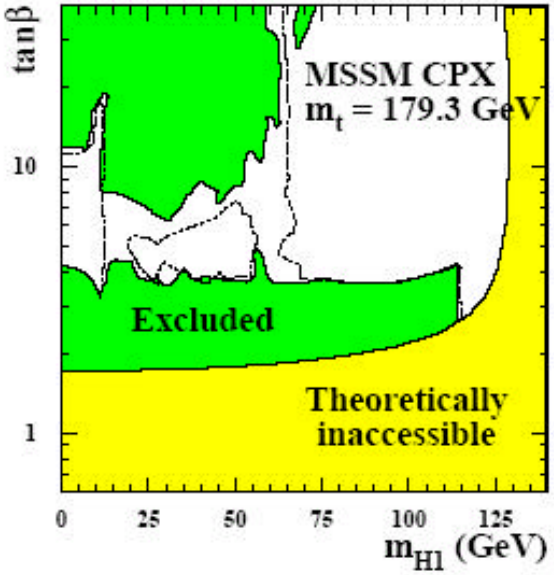
Benchmark	m_h limit (GeV)	m_A limit (GeV)	Excluded tan β range
no-mixing	93.3	93.3	$0.4 < \tan\beta < 5.6$

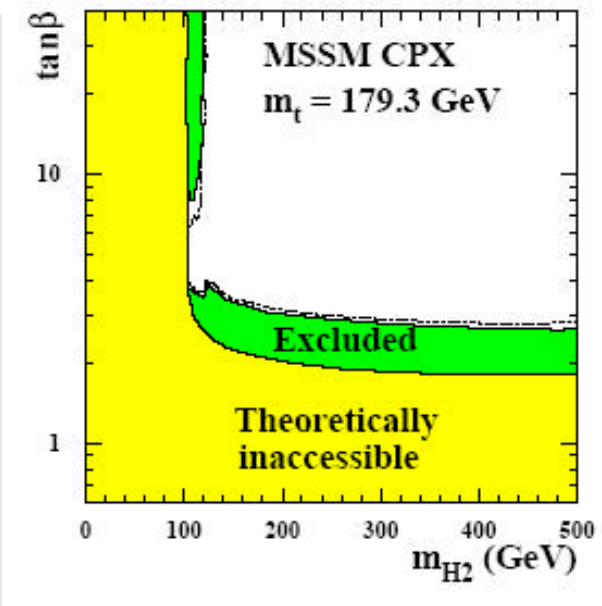
LEP MSSM Exclusions at 95 % CL for the *large-μ* benchmark scenario (m_t = 179.3 GeV)

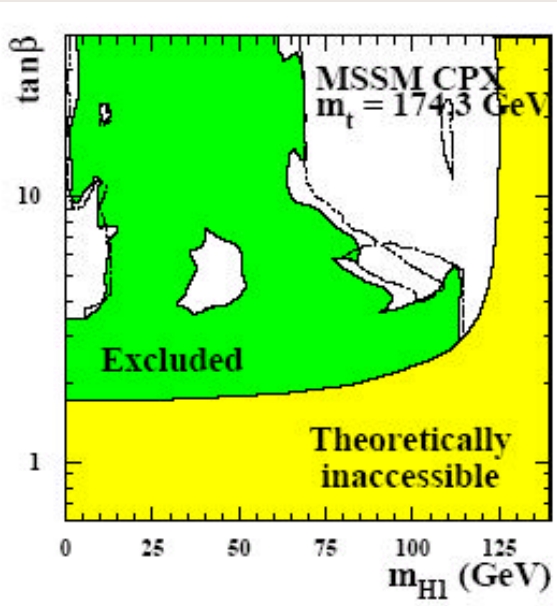


LEP Exclusions at 95 % CL for the CPX scenario









Search for anomalous couplings by L3

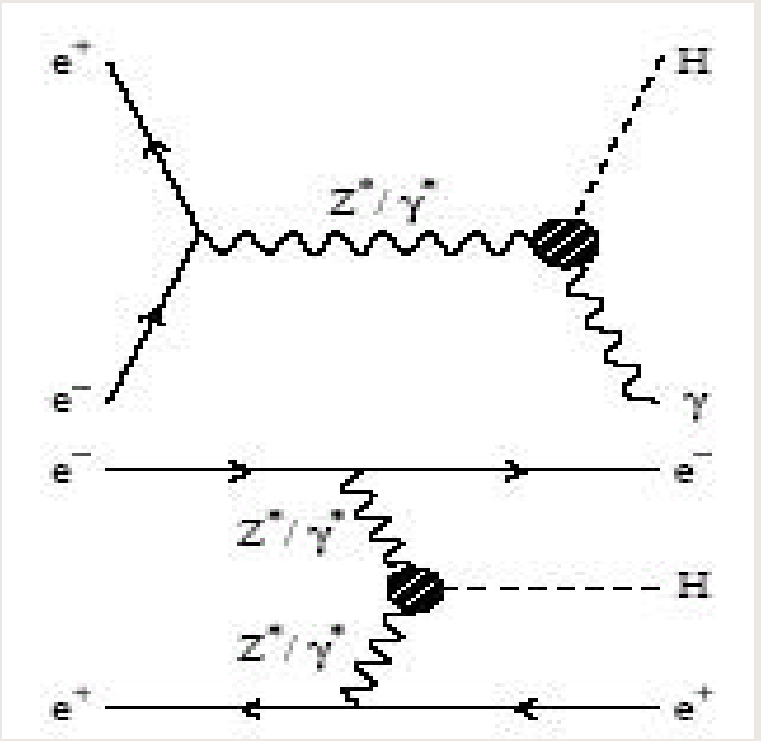
Large regions excluded in the parameter space

ICHEP04 Contribution: L3 (12-0194)

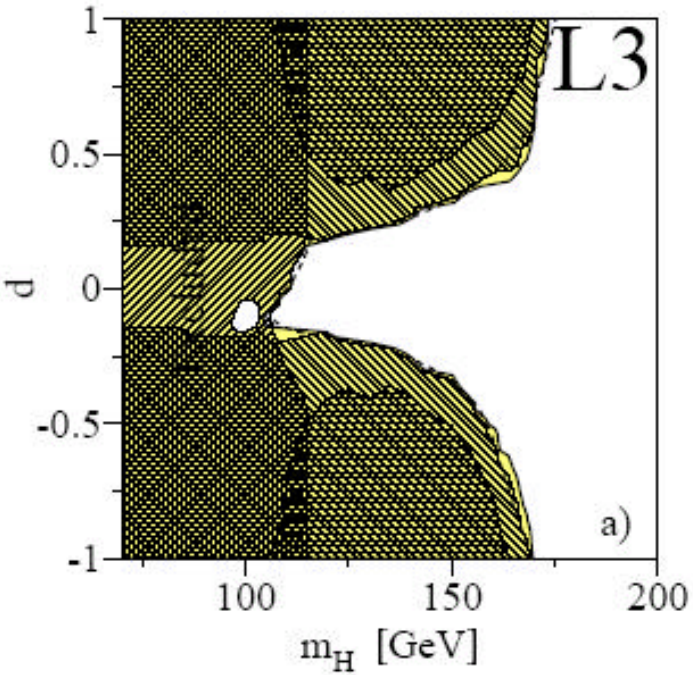
Search for anomalous couplings by L3

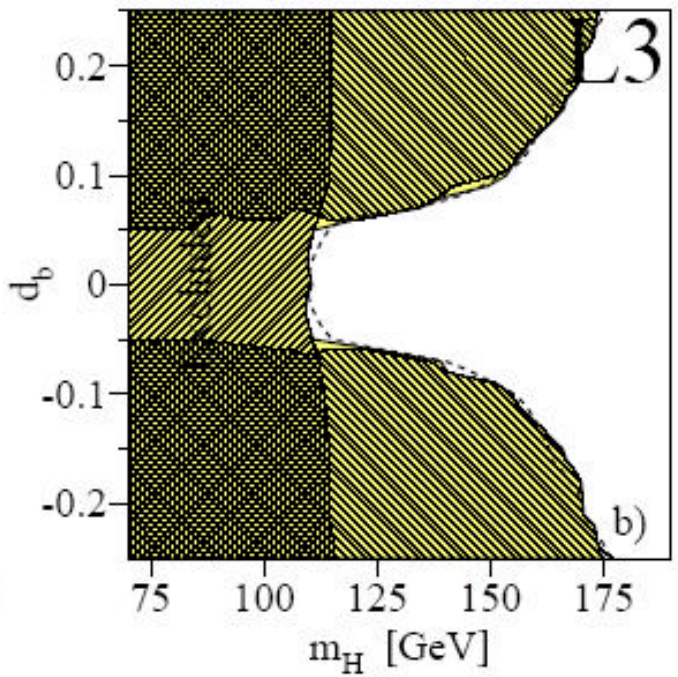
SM Expanded via a linear SU(2) x U(1) representation to higher orders where new interactions become possible

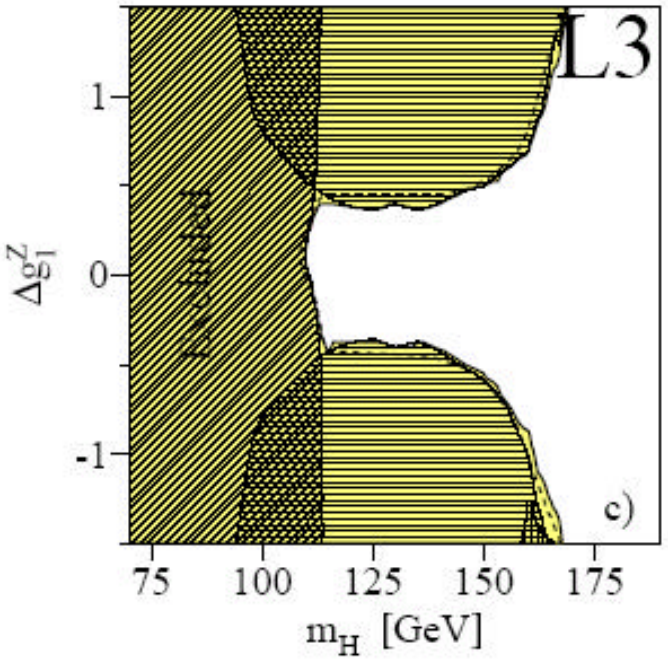
$$\mathcal{L}_{\rm eff} = g_{\rm H\gamma\gamma}\,{\rm HA}_{\mu\nu}{\rm A}^{\mu\nu} + g^{(1)}_{\rm HZ_\gamma}\,{\rm A}_{\mu\nu}{\rm Z}^{\mu}\partial^{\nu}{\rm H} + g^{(2)}_{\rm HZ_\gamma}\,{\rm HA}_{\mu\nu}{\rm Z}^{\mu\nu} + g^{(1)}_{\rm HZZ}\,{\rm Z}_{\mu\nu}{\rm Z}^{\mu}\partial^{\nu}{\rm H} + g^{(2)}_{\rm HZZ}\,{\rm HZ}_{\mu\nu}{\rm Z}^{\mu\nu} + g^{(3)}_{\rm HZZ}\,{\rm HZ}_{\mu}{\rm Z}^{\mu} + g^{(1)}_{\rm HWW}\,({\rm W}^{+}_{\mu\nu}{\rm W}^{\mu}_{-}\partial^{\nu}{\rm H} + h.c.) + g^{(2)}_{\rm HWW}\,{\rm HW}^{+}_{\mu\nu}{\rm W}^{\mu\nu}_{-},$$

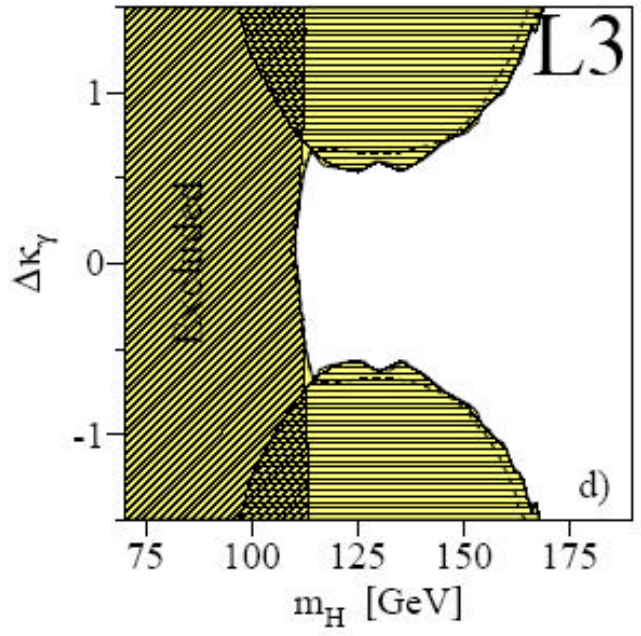


$$\begin{aligned}
g_{\rm H\gamma\gamma} &= \frac{g}{2m_{\rm W}}\left(d\sin^2\theta_W + d_B\cos^2\theta_W\right)\\
g^{(1)}_{\rm HZ_\gamma} &= \frac{g}{m_{\rm W}}\left(\Delta g_1^{\rm Z}\sin 2\theta_W - \Delta\kappa_\gamma\tan\theta_W\right)\\
g^{(2)}_{\rm HZ_\gamma} &= \frac{g}{2m_{\rm W}}\sin 2\theta_W\ \left(d - d_B\right)\\
g^{(1)}_{\rm HZZ} &= \frac{g}{m_{\rm W}}\left(\Delta g_1^{\rm Z}\cos 2\theta_W + \Delta\kappa_\gamma\tan^2\theta_W\right)\\
g^{(2)}_{\rm HZZ} &= \frac{g}{2m_{\rm W}}\left(d\cos^2\theta_W + d_B\sin^2\theta_W\right)\\
g^{(3)}_{\rm HZZ} &= \frac{g\ m_{\rm W}}{2\ \cos^2\theta_W}\delta_{\rm Z}\\
g^{(1)}_{\rm HWW} &= \frac{g\ m_{\rm W}}{m_{\rm Z}^2}\Delta g_1^{\rm Z}\\
g^{(2)}_{\rm HWW} &= \frac{g}{m_{\rm W}}\frac{d}{\cos 2\theta_W},
\end{aligned}$$









Exclusion (95% CL):

Combined

Expected limit

$ee \to \gamma\gamma\gamma$, $ee\gamma\gamma$

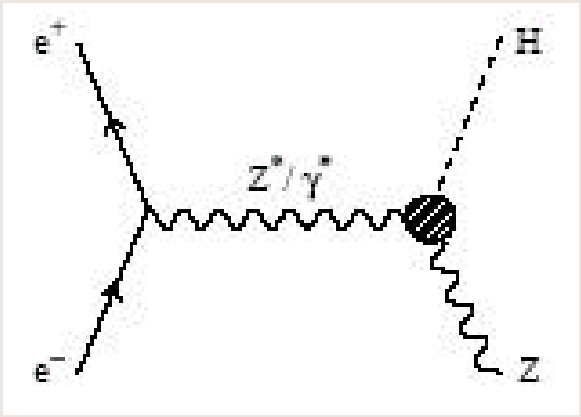
$ee \to Z\gamma\gamma$

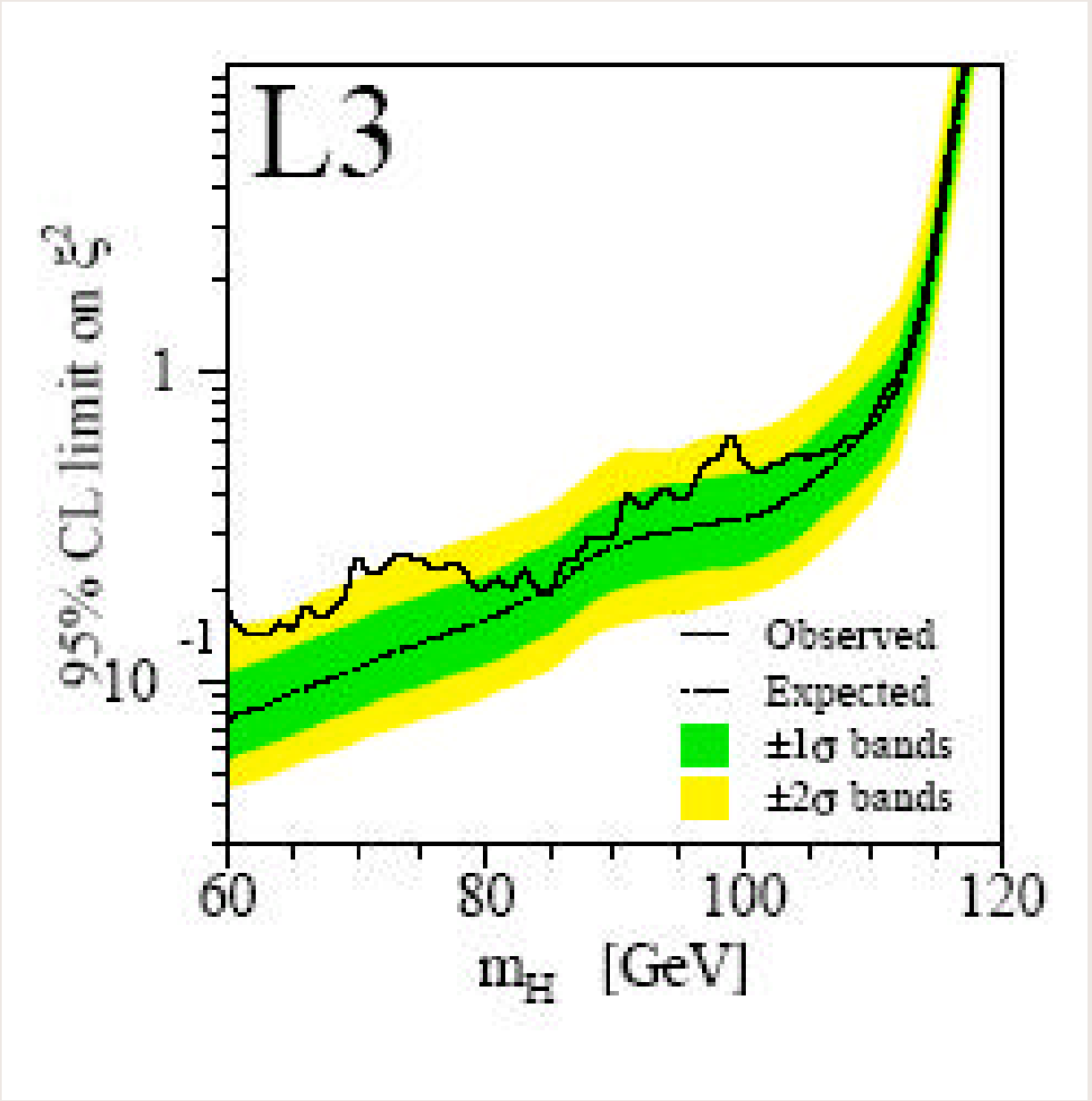
$ee \to HZ$

$ee \to WW^{(*)}\gamma$

Limits on a global rescaling factor of all Higgs couplings

$$\xi^2 = (1+\delta_Z)^2$$





Summary

SM-Like searches (95 % CL):

- m_H should be larger than 114.4 GeV
- non-SM couplings with b- and tau-decays in the final state strongly bounded

Flavour independent searches:

- Assuming BR(h->hadrons) = 100 % the mass of a Higgs boson produced with SM cross-section is bounded to be larger than 112.9 GeV

2HDM(II):

- Large regions of the parameter space excluded
- Topological searches exclude hA->hadrons, hA->4b, hA->4tau, hA->(AA)A->6b, 4b+Z in large (m_h, m_A) domains

Fermiophobic models:

- Mass limits at 109 GeV in the benchmark model with 2 photons in the final state
- 2HDM(I) Fermiophobic excluded at large (m_h, m_A) domains
- H->WW* (ZZ*) fermiophobic excluded in the mass region (83.7,104.6) GeV

MSSM:

- CP-Conserving and CP-Violating scans over benchmark scenarios exclude large regions of the parameter space of the models considered

Anomalous couplings:

- large regions excluded in the parameter space