Searches for Higgs Bosons Beyond (MS)SM at LEP

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Have we missed the Higgs boson because our models are too restricted ?

Introduction to Non-(MS)SM Higgs Boson Searches at LEP

no SM Higgs boson found *(all LEP)*

→ add SUSY → benchmark MSSM — **no MSSM Higgs boson found** *(all LEP)*

→ extend parameter space → general 2HDM — **wide area of parameter space excluded** *(all LEP)*

→ decays to down-type fermions suppressed ? — **perform flavor-blind search** *(all LEP)*

→ decays to fermions suppressed ? — **search for fermiophobic Higgs boson** *(all LEP)*

→ decays to visible particles suppressed ? — **search for invisible Higgs boson** *(all LEP)*

→ consider higher order SM — **search for anomalous couplings** *(L3)*

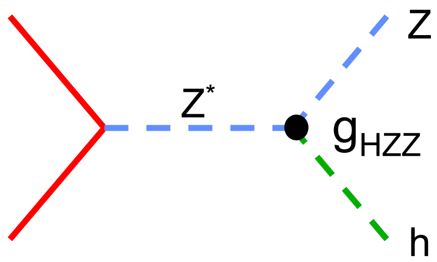
→ Higgs sector CP violating ? — **search for CPV Higgs bosons** *(OPAL)*

→ Higgs triplet model? — **search for doubly charged Higgs bosons** *(DELPHI, OPAL)*

→ something more exotic? — **perform mode-independent search** *(OPAL)*

The combined SM Higgs boson searches at LEP have been reinterpreted.

LEP Model Independent Results



What is the upper bound on the production cross section permitted by the data ?

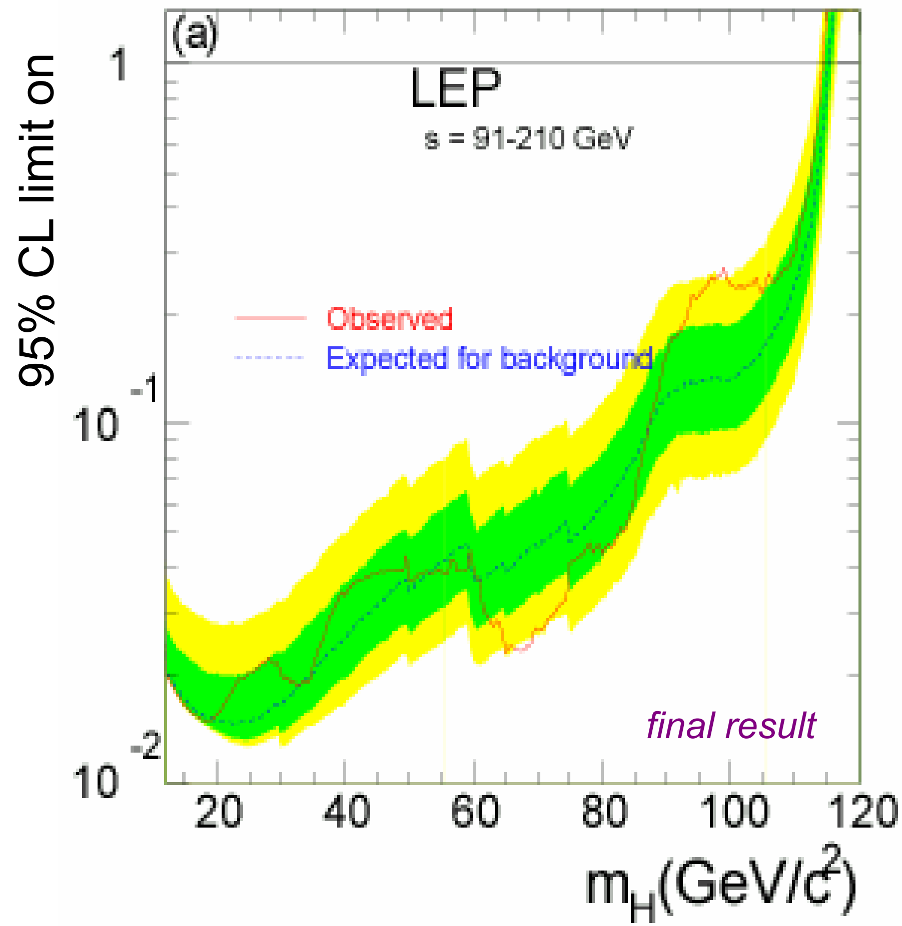
Evaluation of LEP combined result, based on 2461 pb^{-1} of LEP1+2 data, in terms of max. (95% CL)

$$\xi^2 = \left(\frac{g_{HZZ}}{g^{SM}_{HZZ}} \right)^2$$

allows for model-independent interpretation

Here: assume SM Higgs decays

In progress: limits for $h \to b\bar{b}$
and $h \to \tau^+\tau^-$ exclusively.



Flavor blind searches of all LEP experiments have been combined.

LEP Flavor Independent Results

For specific MSSM or 2HDM(II) parameter choices the Higgs boson decay to down type fermions can be suppressed. Decays to cc or gluons (via top-loops) may become dominant.

→ Reduce model dependence by not exploiting the flavor information

Search channels are the same as in (MS)SM

→ Adopt the (MS)SM analyses, without b-tagging,

Use dedicated analyses for 4Jet-channel, focusing on boson masses

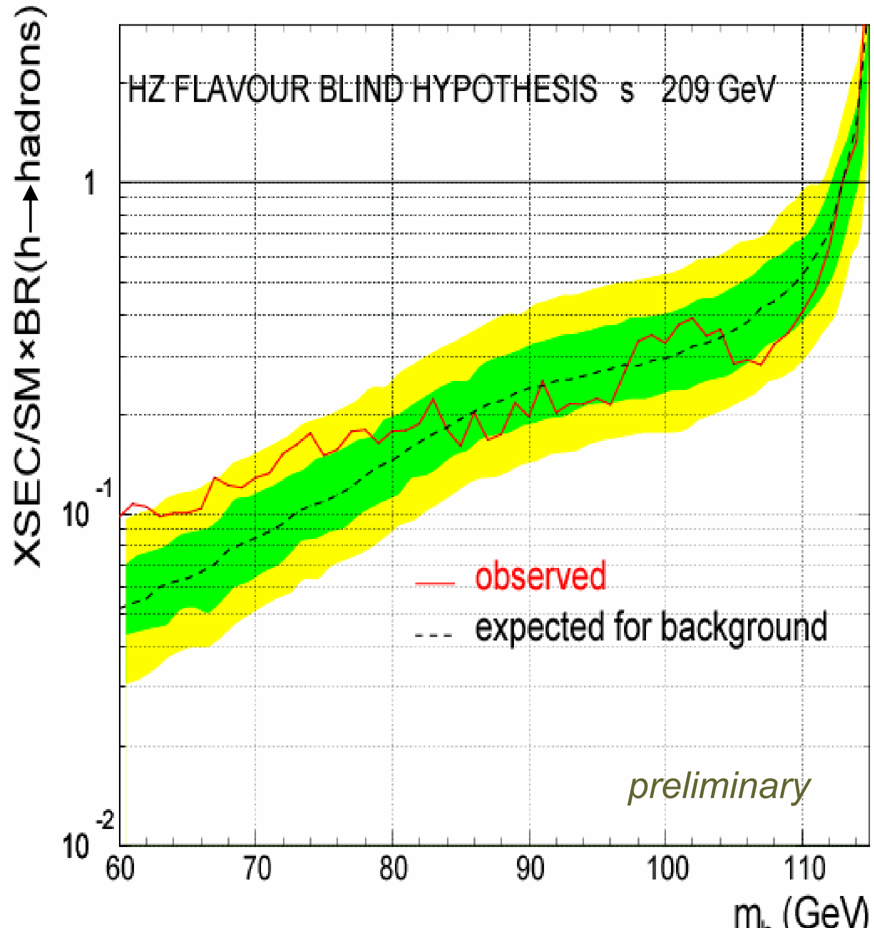
Results are given as 95% CL limit on

$$\frac{\sigma}{\sigma_{SM}} \times \mathrm{Br}(h \to ...)$$

observed limit:
m_h > 112.9 GeV

expected limit:
m_h > 113.0 GeV

new (final) combination in progress



All collaborations have searched for di-photon Higgs decays.

Fermiophobic Higgs Boson Search at ALEPH and LEP

$h \rightarrow \gamma\gamma$ can be enhanced by
- appropriate mixing in 2HDM
- anomalous couplings (see below)
- additional particles (light SUSY partners) entering loops

benchmark fermiophobic Higgs boson:
decays like SM, but fermions switched off

example: ALEPH's global analysis:

→ select events with two isolated energetic photons

→ classify events according to charged multiplicity of jets

n_{ch}	$\nu\bar{\nu}$	l^+l^-	$\tau^+\tau^-$	$q\bar{q}$
0	⊗	○		
2		⊗	⊗	
3–4		○	⊗	
≥5			●	⊗

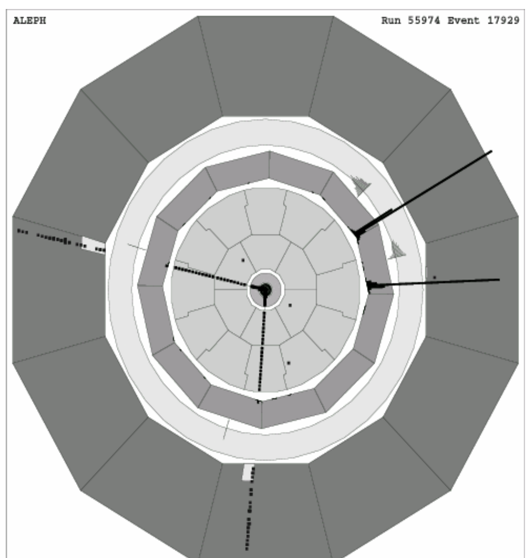
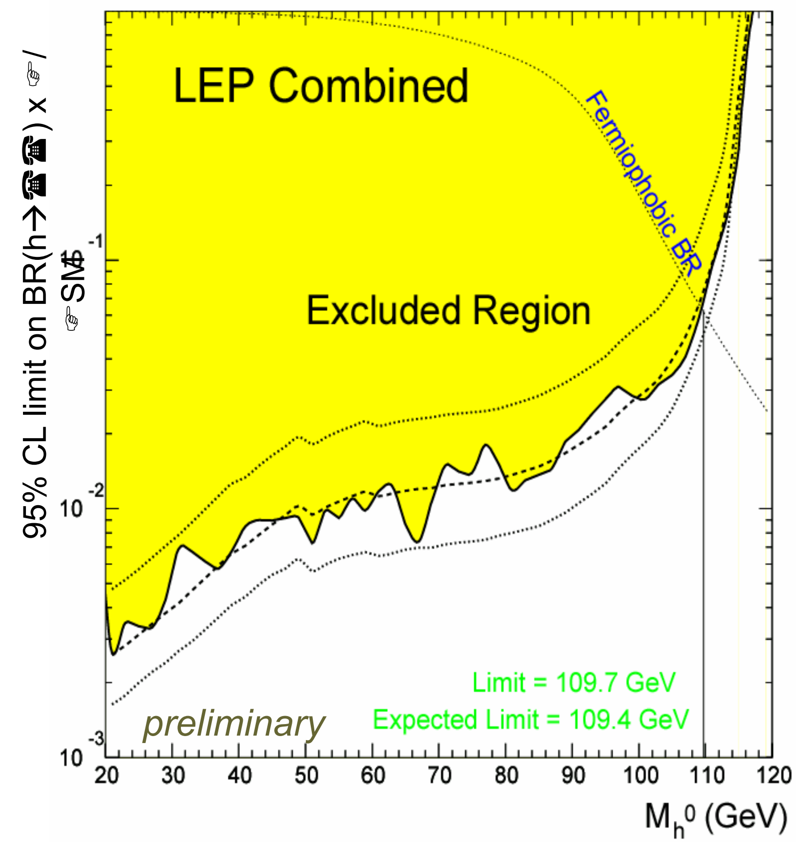
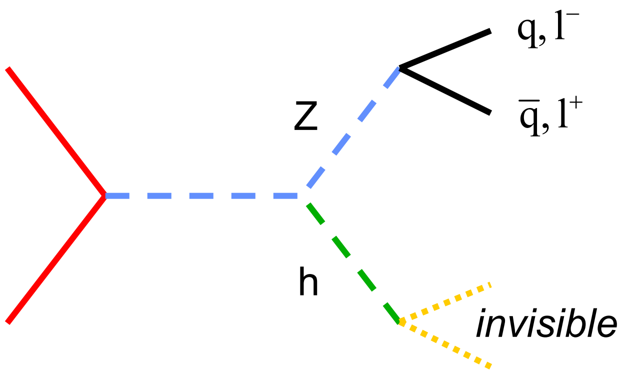


Figure 2: The candidate event observed in 2000.



For SM cross-section the mass limit for an invisible Higgs boson is 114.3 GeV.

LEP Combination of Invisible Higgs Boson Searches

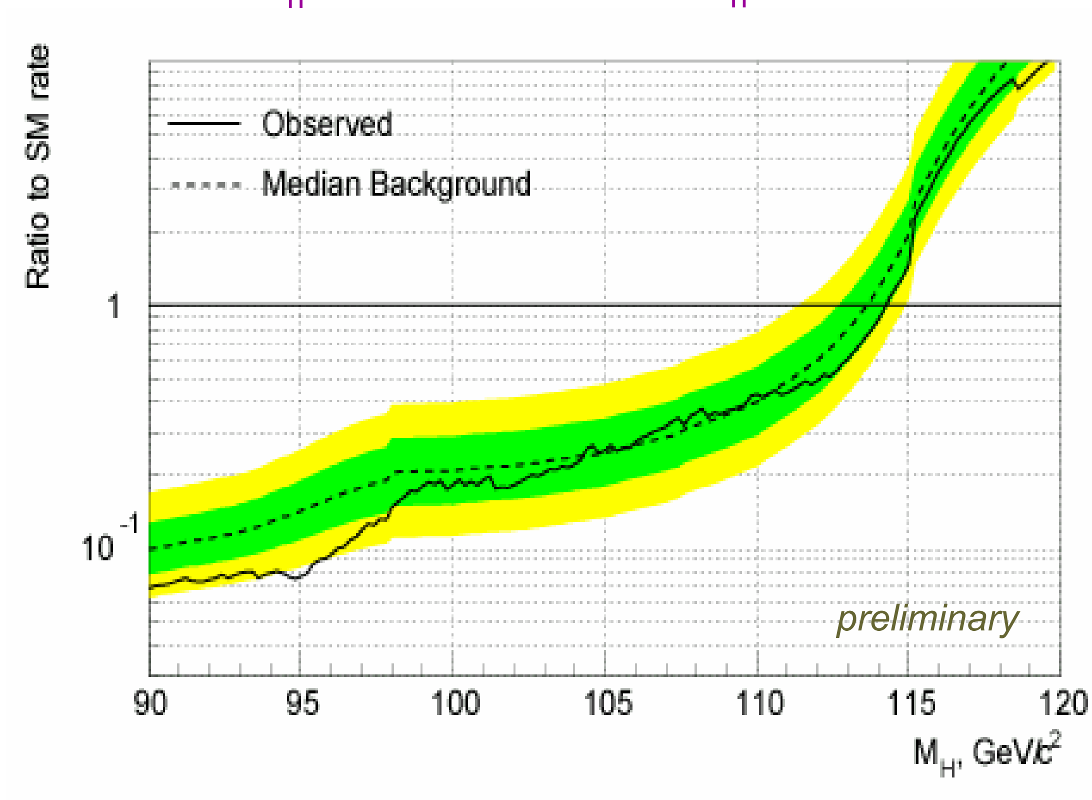


might be **LSP**, if light enough, or **Majoron**

search for events with
2 acoplanar jets
and missing energy

observed limit: $m_h > 114.3$ GeV

expected limit: $m_h > 113.6$ GeV



exclusion curve for $\sigma(hZ)$ / $\sigma_{SM}(HZ)$

L3 has searched for anomalous couplings.

Introduction to Anomalous Couplings

The Standard Model can be extended via a linear representation of the SU(2)xU(1) symmetry breaking mechanism.

→ The lowest order corresponds to the Standard Model.

→ Higher orders enable new interactions between Higgs and gauge bosons.

Parameterize them as:

$$g_{H\gamma\gamma} = \frac{g}{2m_W}\left(d\sin^2\theta_W + d_B\cos^2\theta_W\right)$$

$$g^{(1)}_{HZ\gamma} = \frac{g}{m_W}\left(\Delta g_1^Z \sin 2\theta_W - \Delta\kappa_\gamma \tan\theta_W\right)$$

$$g^{(2)}_{HZ\gamma} = \frac{g}{2m_W}\sin 2\theta_W\left(d - d_B\right)$$

$$g^{(1)}_{HZZ} = \frac{g}{m_W}\left(\Delta g_1^Z \cos 2\theta_W + \Delta\kappa_\gamma \tan^2\theta_W\right)$$

$$g^{(2)}_{HZZ} = \frac{g}{2m_W}\left(d\cos^2\theta_W + d_B\sin^2\theta_W\right)$$

$$g^{(3)}_{HZZ} = \frac{g\cdot m_W}{2\cos^2\theta_W}\delta_Z$$

$$g^{(1)}_{HWW} = \frac{g\cdot m_W}{m_Z^2}\Delta g_1^Z$$

$$g^{(2)}_{HWW} = \frac{g\cdot d}{m_W\cos 2\theta_W}$$

⇨ 5 anomalous couplings:

$$d, d_B, \Delta g_1^Z, \Delta\kappa_\gamma, \delta_Z$$

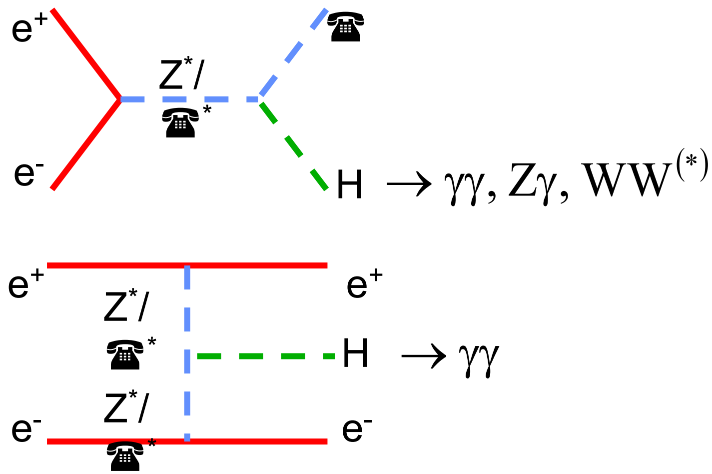
not severely constrained by electroweak measurements

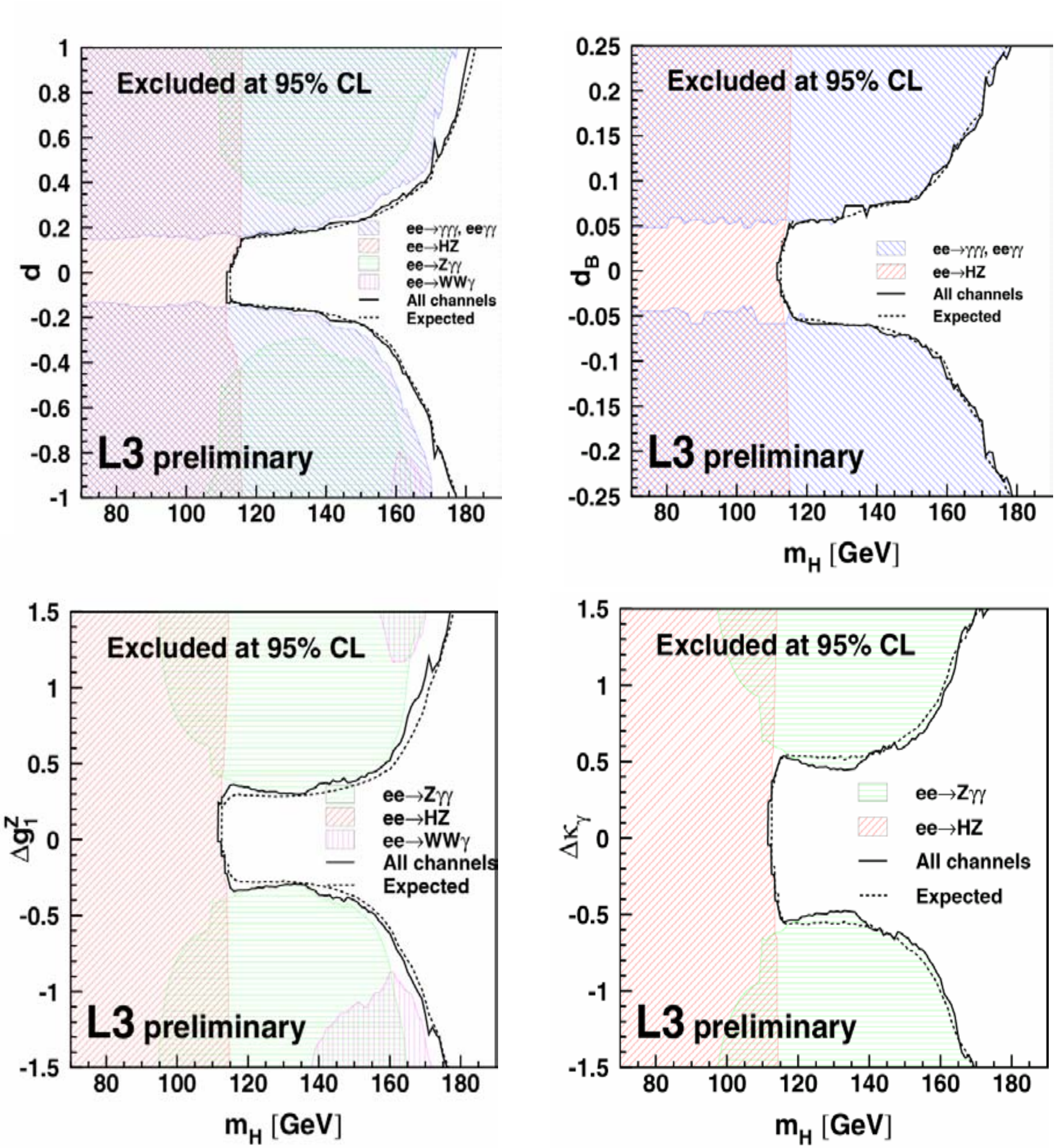
$$1+\delta_Z = \xi$$

global scaling factor of all Higgs couplings, set limit by reinterpreting SM analysis (see LEP combined result)

The search was done for the H☎ and He^+e^- modes.

Limits on Anomalous Couplings





calculate σxBR

by setting one coupling,

assuming all other couplings =0

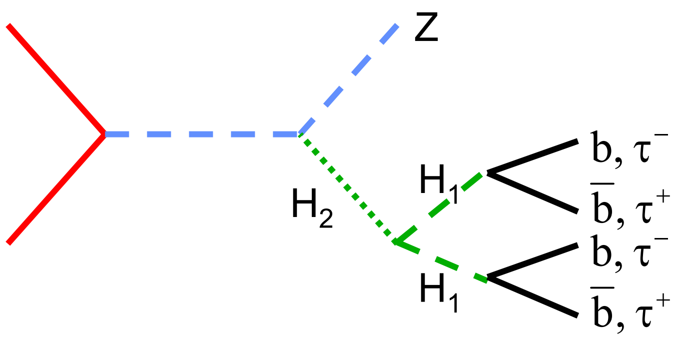
OPAL is searching for Higgs bosons in a CP violating MSSM.

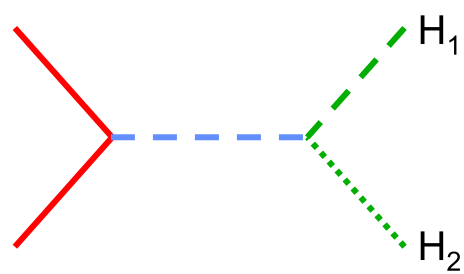
Introduction to OPAL CPV-MSSM Analysis

In MSSM Higgs sector: all parameter phases set to zero → $(H_1,H_2,H_3) = (h,H,A)$

CP violating phases in sector of soft SUSY breaking would allow for CPV in Higgs sector
→ MSSM would provide enough CPV to explain cosmic baryon asymmetry

Higgs production like in MSSM, but all H_1, H_2, (H_3) can be produced





$$m_{SUSY} = 500\,\text{GeV}$$
$$m_2 = 200\,\text{GeV}$$
$$\mu = 2\,\text{GeV}$$
$$|A_q| = 1\,\text{TeV}$$
$$\arg(A_q) = 90^\circ$$
$$|m_{\tilde{g}}| = 1\,\text{TeV}$$
$$\arg(m_{\tilde{g}}) = 90^\circ$$

define CP violating benchmark scenario (CPX)
in accordance with neutron electric dipole measurements
yielding maximum dissimilarities with CP conserving MSSM

measure for dissimilarities:

$$M_{ij}^2 \propto \frac{m_t^2}{\upsilon^2}\,\frac{\Im(\mu A_t)}{32\pi^2 m_{SUSY}^2}$$

scan parameters:

$$\tan\beta = 0.4\ldots 40$$
$$m_{H^+} = 0\ldots 1\,\text{TeV}$$

There are 5 different search regions.

CPV Higgs Boson Search Channels at OPAL

	tanβ<4	4< tanβ<10	tanβ>10
m_{H1}<12 GeV	SM-like no dedicated analysis	$H_2 \rightarrow H_1H_1 \rightarrow 4b$ H_2Z and fusion	H_1H_2 pair production $H_1 \rightarrow$☺☺
12<m_{H1}<50 GeV	SM-like no dedicated analysis	$H_2 \rightarrow H_1H_1 \rightarrow 4b$ H_2Z and fusion	$H_1H_2 \rightarrow 4b$ pair production
m_{H1}>50 GeV	SM-like no dedicated analysis	$H_2 \rightarrow bb$ SM-like	$H_1H_2 \rightarrow 4b$ pair production

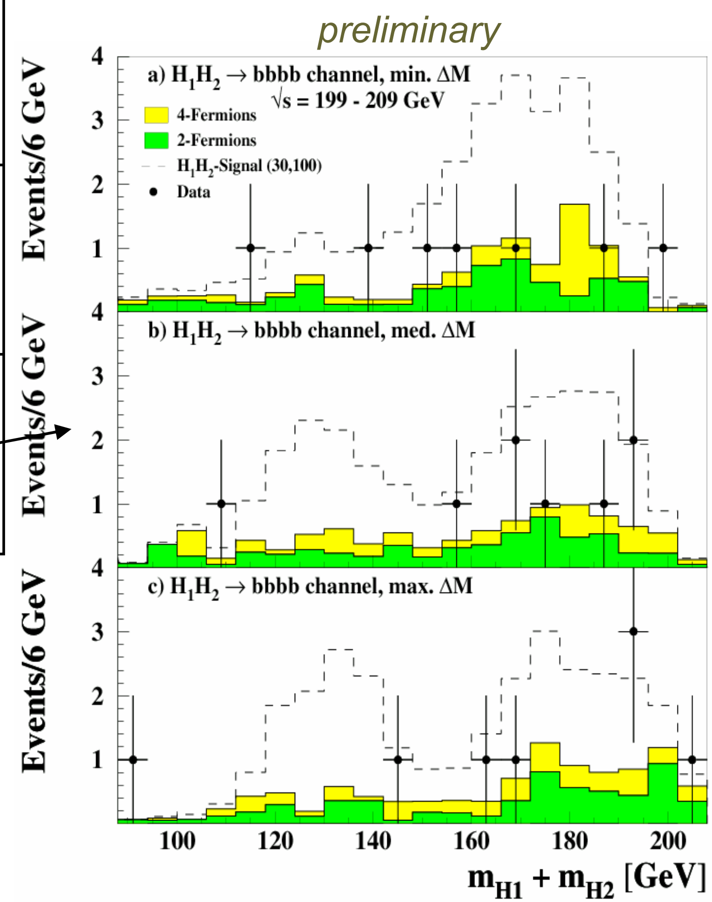
4-Jet + missing Energy and 6-Jet channels,

calculate signal expectation by

L x σ x BR x ε

adopt $Ah \rightarrow 4b$ analysis for low Δm, extend for high Δm

reconstructed H_1+H_2 mass sum for different jet pairings

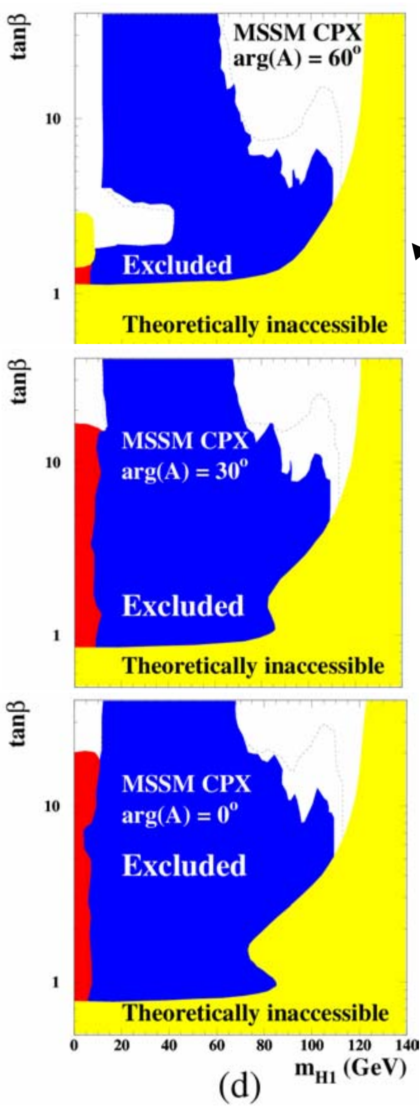


$$(m_{H_1}, m_{H_2}) = (30{,}100)\ \text{GeV}$$

Low tanβ are excluded in the CP violating benchmark scenario.

OPAL CPV Higgs Results

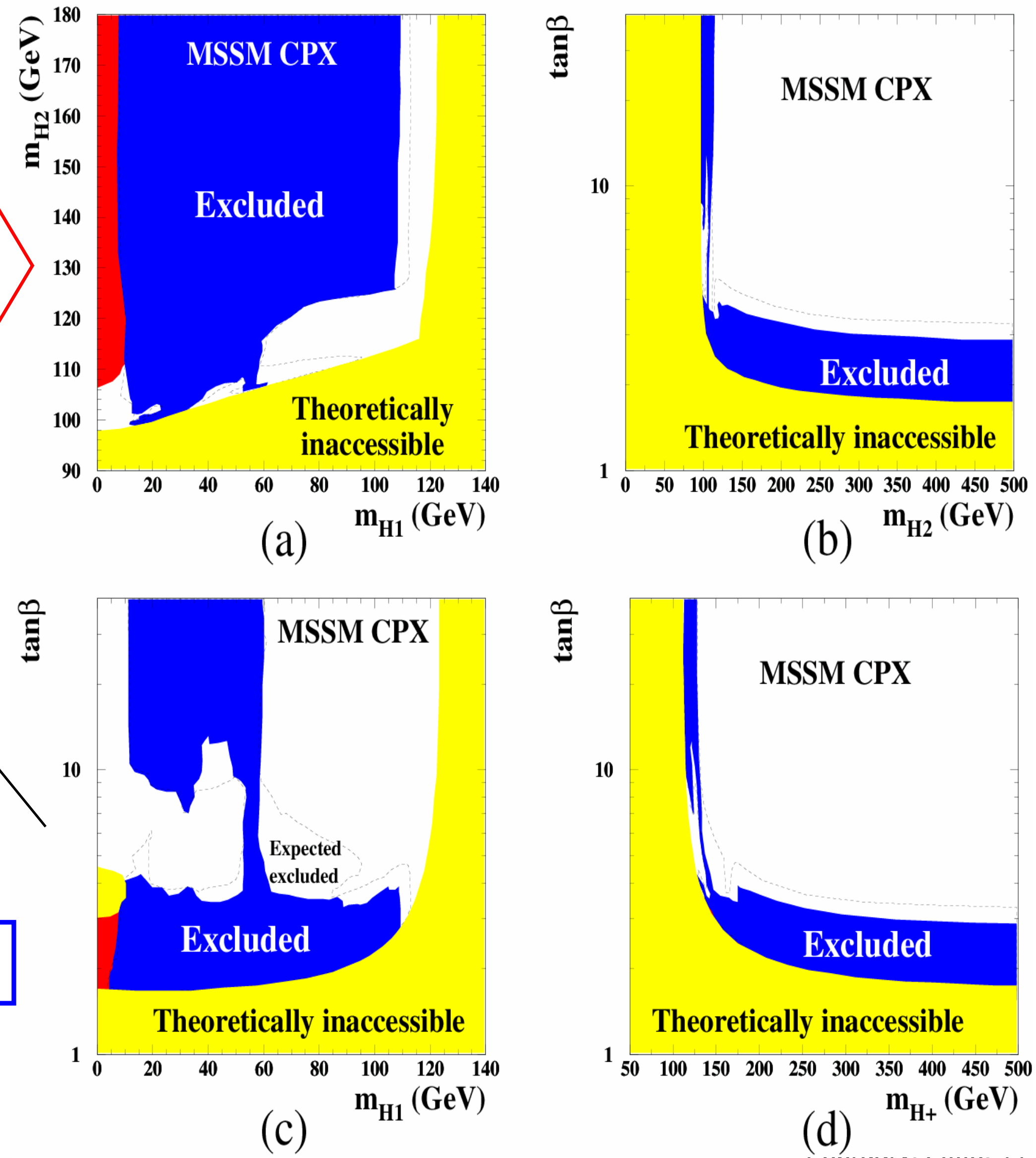
all plots preliminary



red area excluded by Z width constraints or decay-mode independent searches

turn down CP violation

tanβ > 2.9

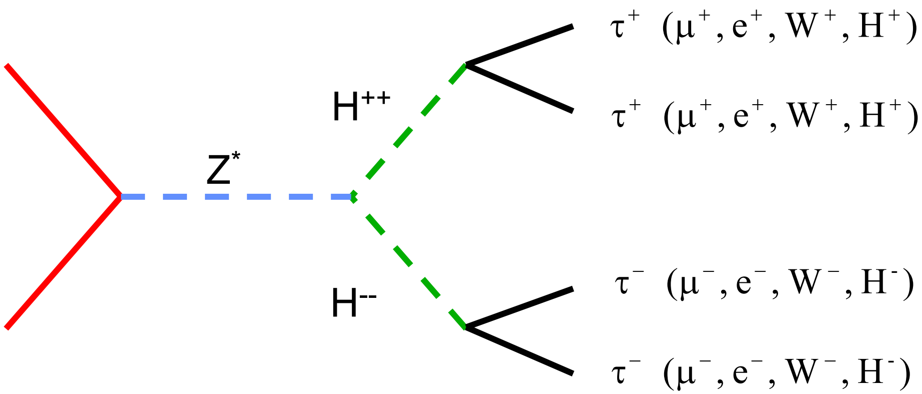


DELPHI has searched for doubly charged Higgs bosons.

Doubly Charged Higgs Boson Search at DELPHI

$H^{\pm\pm}$ appear in left-right symmetric and Higgs triplet models.

heavy 🖫$_R$ with see-saw mechanism can lead to $H^{\pm\pm}$ with accessible mass



Yukawa coupling $h_{☺☺}$ is free parameter

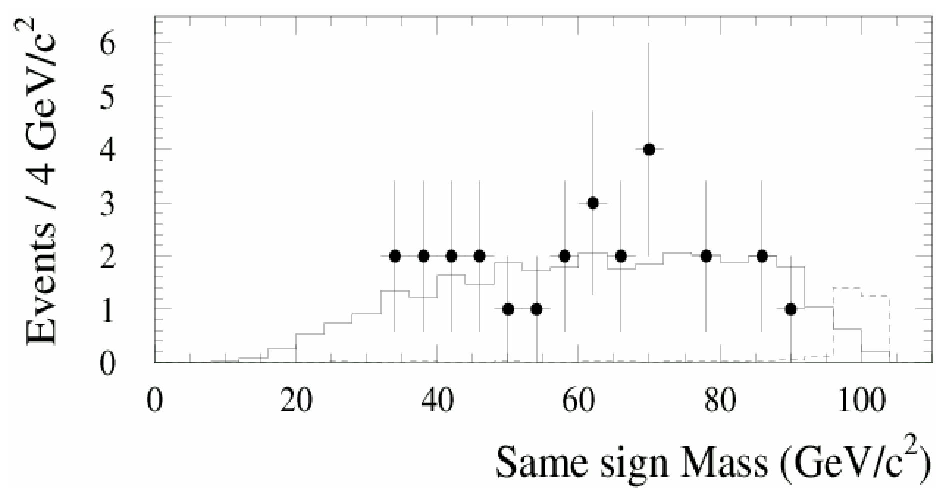
$h_{☺☺} > 10^{-7}$ s : decay close to IP

$h_{☺☺} < 10^{-7}$ s : decay inside detector or beyond

search for: 4 narrow low-multiplicity jets

2 tracks from IP with secondary vertices or kinks

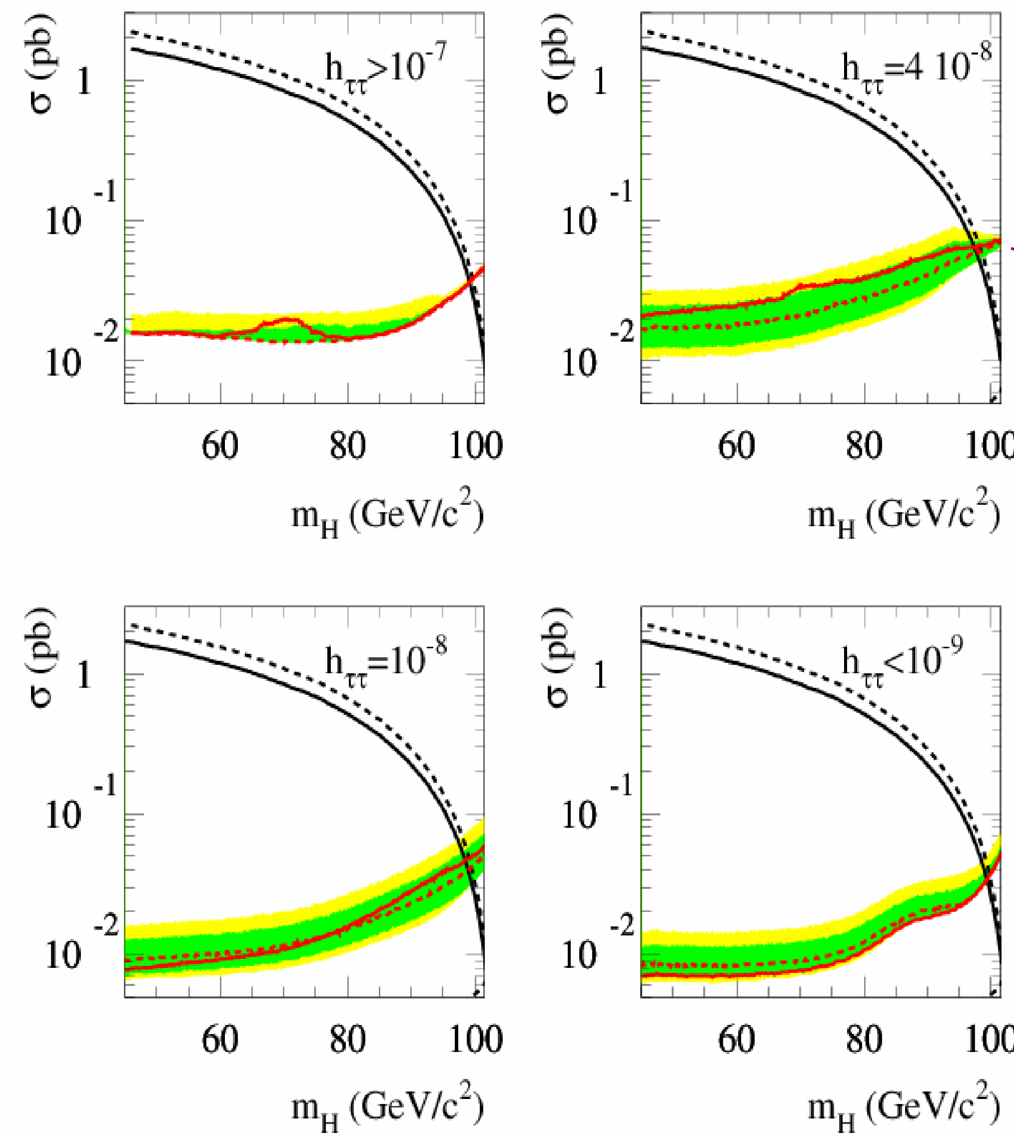
2 stable heavy massive particles (use SUSY analysis)



A similar analysis and a search for single production of $H^{\pm\pm}$ was done by OPAL.

The lower mass limit for $H^{\pm\pm}$ in LR-symmetric models is ~100 GeV.

DELPHI Results for the Doubly Charged Higgs Boson



$H_L^{\pm\pm}$ (dashed line)

$H_R^{\pm\pm}$ (solid line)

lowest observed limit :

$m_{H_R^{\pm\pm}} > 97.3$ GeV

exp. : 97.6 GeV

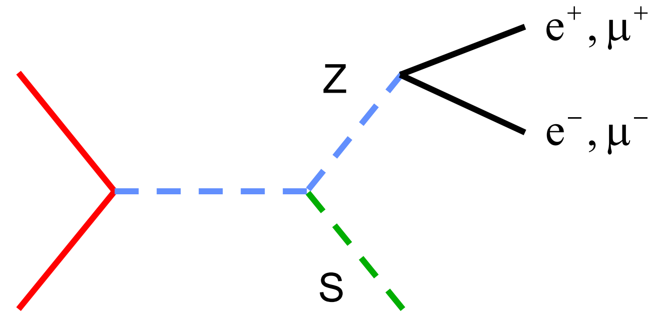
final results

OPAL has created a mode-independent analysis.

Mode Independent Scalar Boson Search by OPAL

topological search for new neutral scalar S in SZ production

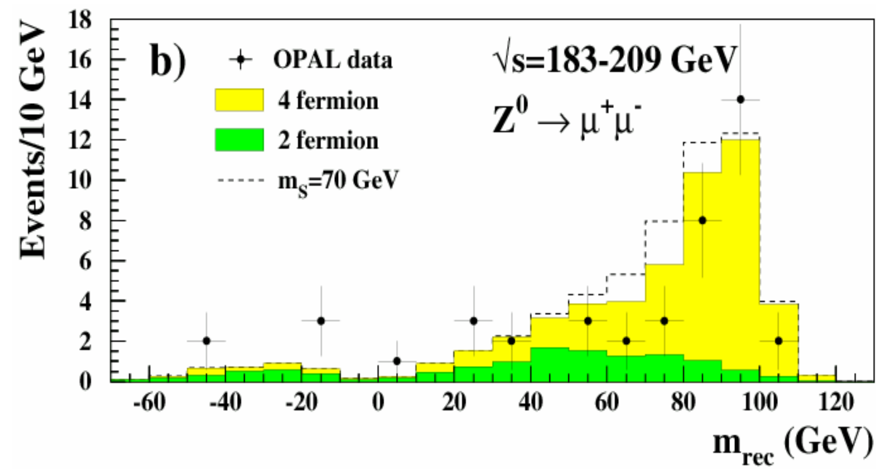
study recoil mass spectrum in Z→e^+e^- or 💻$^+$💻$^-$ events
(smaller background, clear identification than Z→qq)



sensitive to all combinations of S-decay particles
including invisibly and non-decaying S

give 95% CL limits on $k = \frac{\sigma_{SZ}}{\sigma_{HZ}^{SM}(m_H = m_S)}$

limits not only on single mass peak, but also on
continuous distribution
→ Uniform Higgs, Stealthy Higgs models



identify leptons with standard ID and E/p, dE/dx

require charge pair, isolation, Z-mass

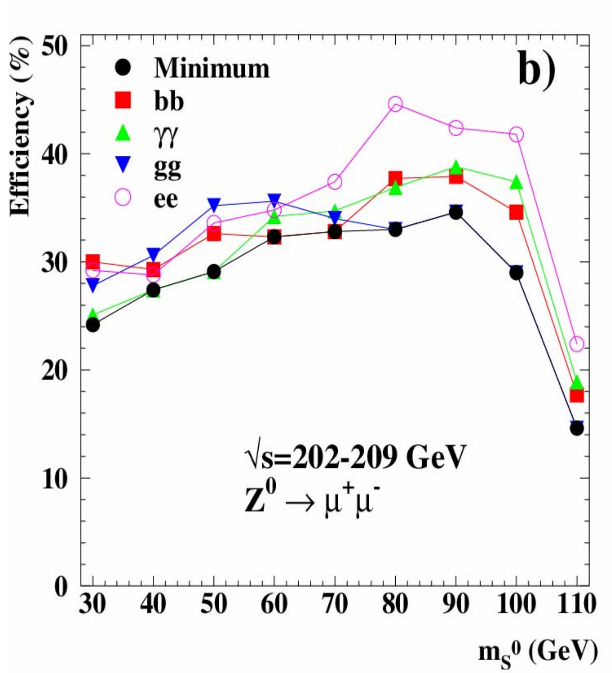
reduce background from radiative Z-decays, 2 photon, semileptonic b-decays

→ removal of photons and electrons suppresses SZ→n☎🖫🖫 and ee🖫🖫

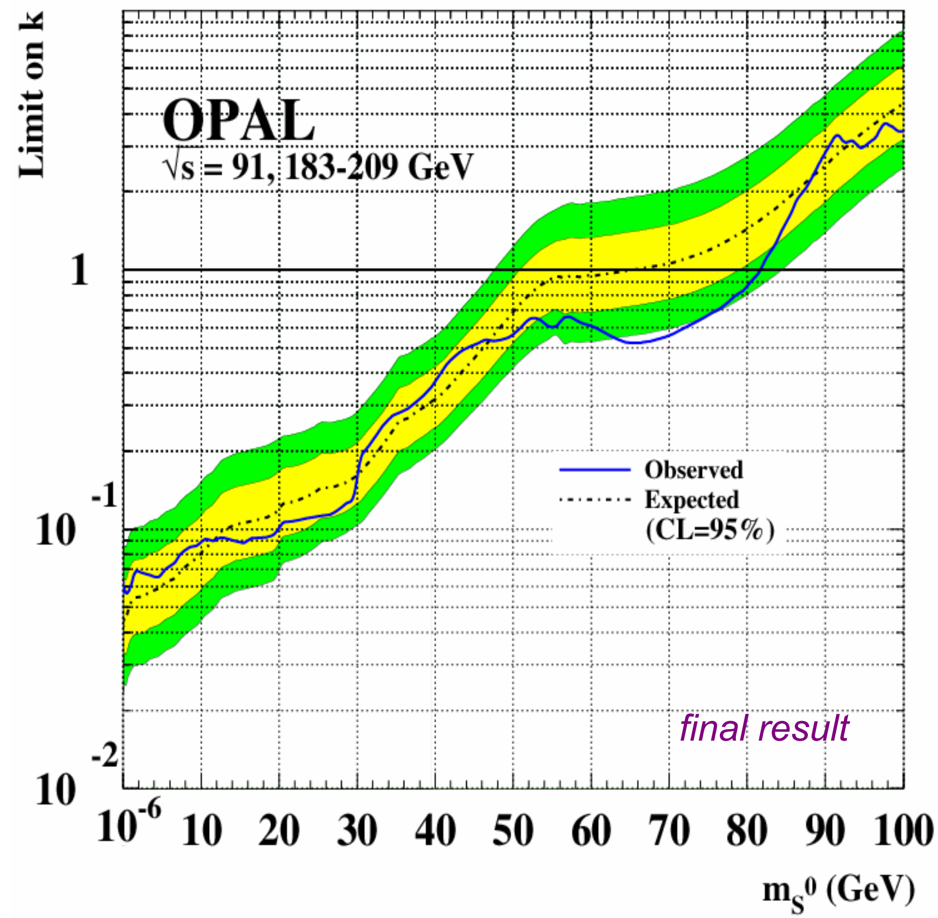
→ dedicated analyses necessary to remain mode-independent

If the unknown boson had SM cross section, its mass limit would be 81 GeV.

OPAL Results of Mode Independent Neutral Scalar Search



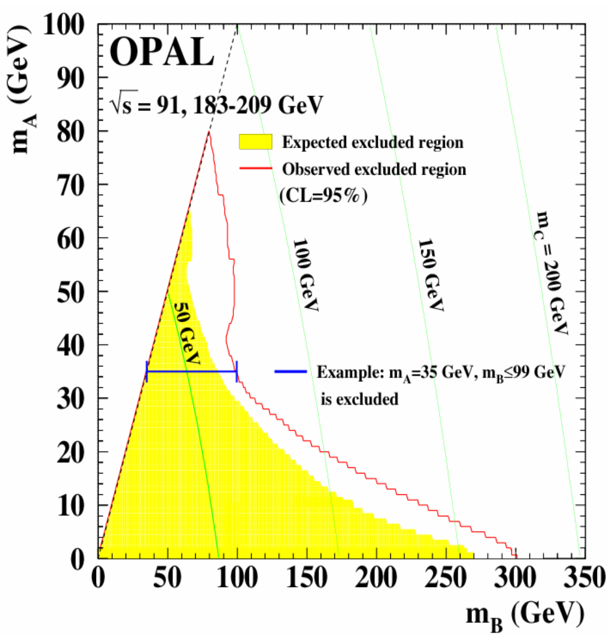
efficiency for various decay modes and resulting minimum, taken for limit calculation



Limits on models with continuous mass spectra have been calculated.

OPAL Results for Uniform and Stealthy Higgs Models

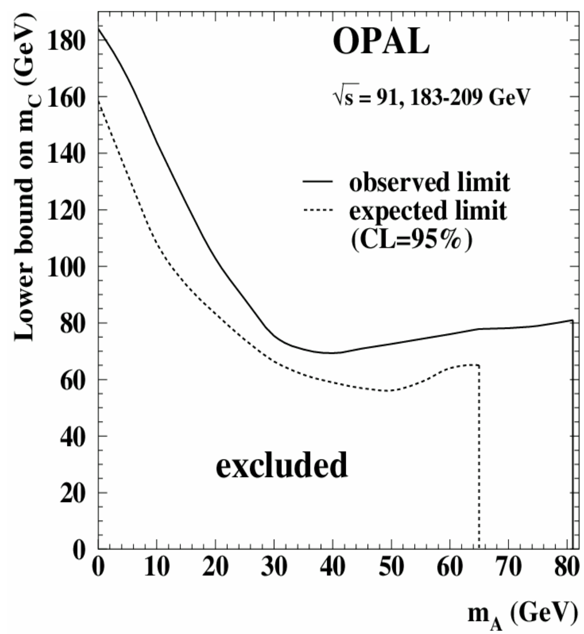
Uniform Higgs: coupling



$$\tilde{K}(m) = \begin{cases} \frac{1}{m_B - m_A} & \text{for } m_A < m < m_B \\ 0 & \text{else} \end{cases}$$

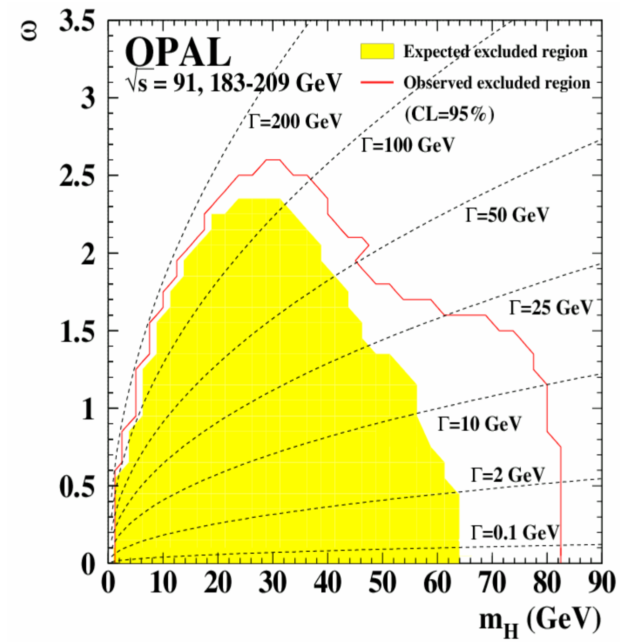
exclude point (m_A, m_B) if 95% CL limit of $\int \tilde{K}(m) \cdot dm$ is less than 1

Uniform Higgs: mass scale



for each m_A find max. excluded m_B,
exclude $m_C = \int \tilde{K}(m) \cdot m \cdot dm$

Stealthy Higgs



add N singlets of $SU(3) \times SU(2) \times U(1)$
$\Rightarrow$ phions, interacting with H only
for $N \to \infty$:

$$\Gamma_H(m_H) = \Gamma_H^{SM}(m_H) + \frac{\omega^2 \upsilon^2}{32 \pi m_H}$$

Conclusions

1. No evidence for a Higgs boson beyond SM or MSSM was found.
2. Lower mass bounds for Higgs bosons with SM cross-section decaying into hadrons, photons, or invisible particles are between 100 and 115 GeV.
3. Similar limits are valid in the presence of anomalous couplings.
4. In a CP violating MSSM, $\tan\beta$ is greater than 2.9, but no mass limits independent on $\tan\beta$ can be set at present.
5. Doubly charged Higgs bosons in left-right symmetric models are heavier than 97 GeV.
6. A scalar boson with SM cross-section is heavier than 81 GeV, regardless of its decay.