

# Higgs Beyond the Standard Model at LEP2

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Representing the  
LEP Collaborations

- Introduction
- NEW Higgs Searches up to  $\sqrt{s} = 209$  GeV
  - Fermiophobic
  - Flavour-Independent
  - General Scan
  - MSSM
  - Invisible
- Summary

All results are preliminary and limits are at the 95% CL.

# Introduction

## Two-Higgs Doublet Models (2HDM)

	Type I	Type II
$\phi_1$	Does not couple to fermions	Couples to “up”-type fermions
$\phi_2$	Is the SM Higgs	Couples to “down”-type fermions
Models	Fermiophobic	Flavour-Independent Model-Independent (General Scan) MSSM

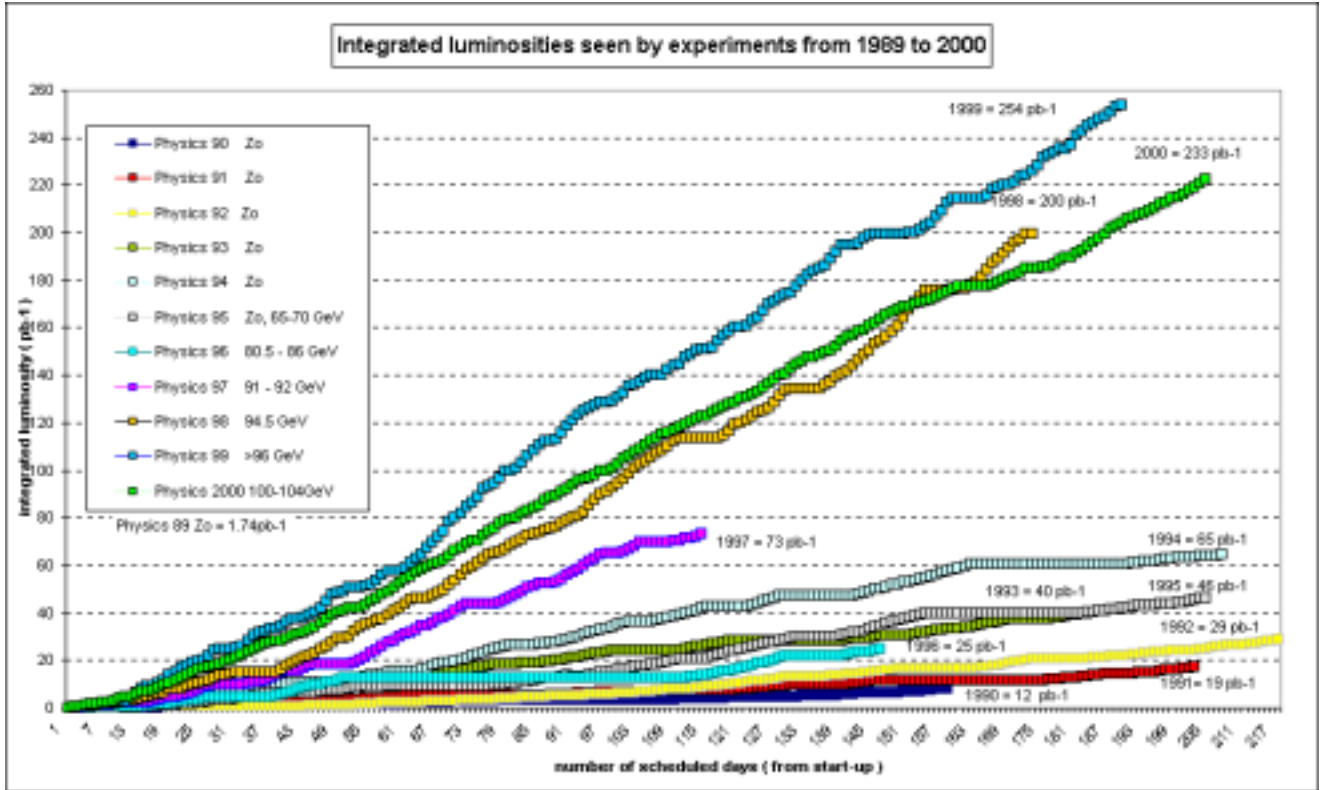
- To give mass to SUSY particles, extend the SM to two Higgs doublets.
- To avoid FCNC, fermions of a given charge must couple to at most one doublet.

## Parameters of 2HDM's

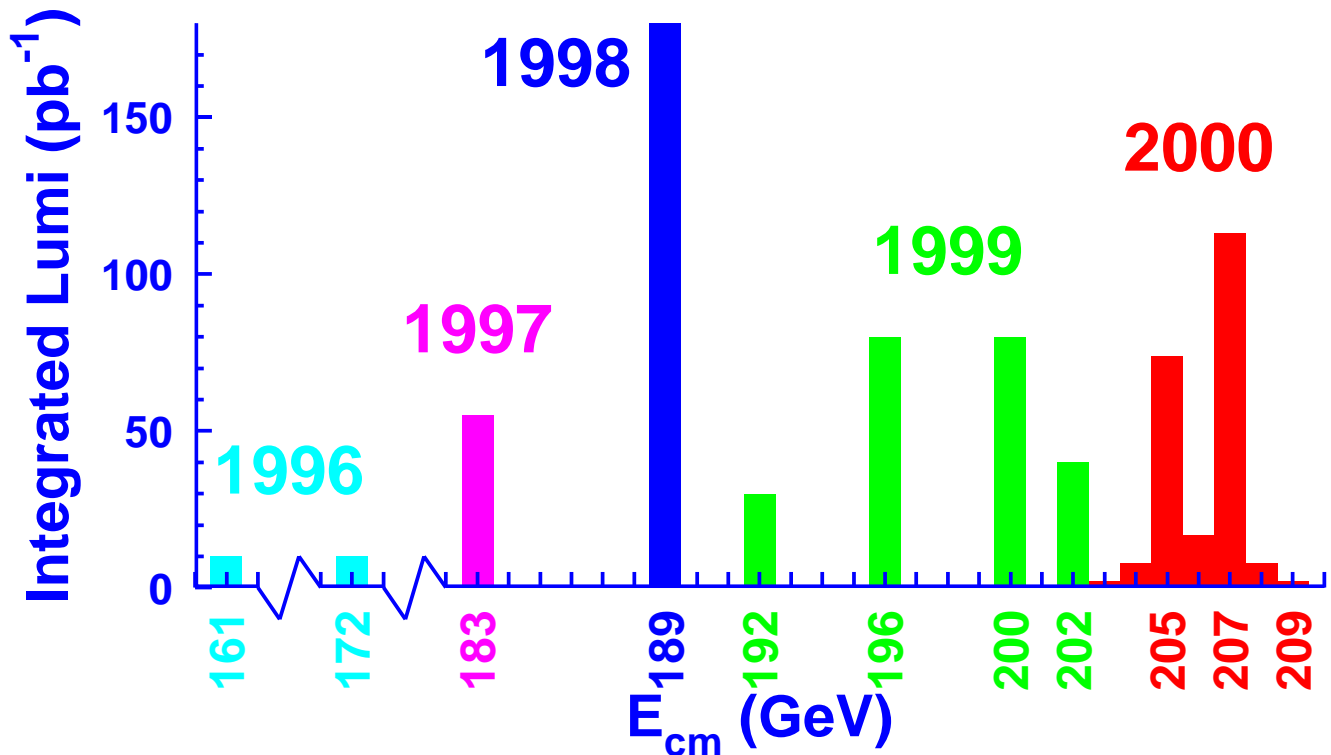
Six Free Parameters, assuming no CP-violation:

- $m_{h^0}$  mass of CP-even Higgs
- $m_{H^0}$  mass of CP-even Higgs,  $m_{h^0} < m_{H^0}$
- $m_{A^0}$  mass of CP-odd Higgs,  $m_{A^0} < m_{H^0}$
- $m_{H^\pm}$  mass of Charged Higgs
- $\alpha$  mixing angle between  $h^0$  and  $H^0$
- $\tan \beta$  ratio of vacuum expectation values  $v_2/v_1$

# LEP Performance



Over 200 pb<sup>-1</sup> at  $\sqrt{s} \approx 206$  GeV per experiment

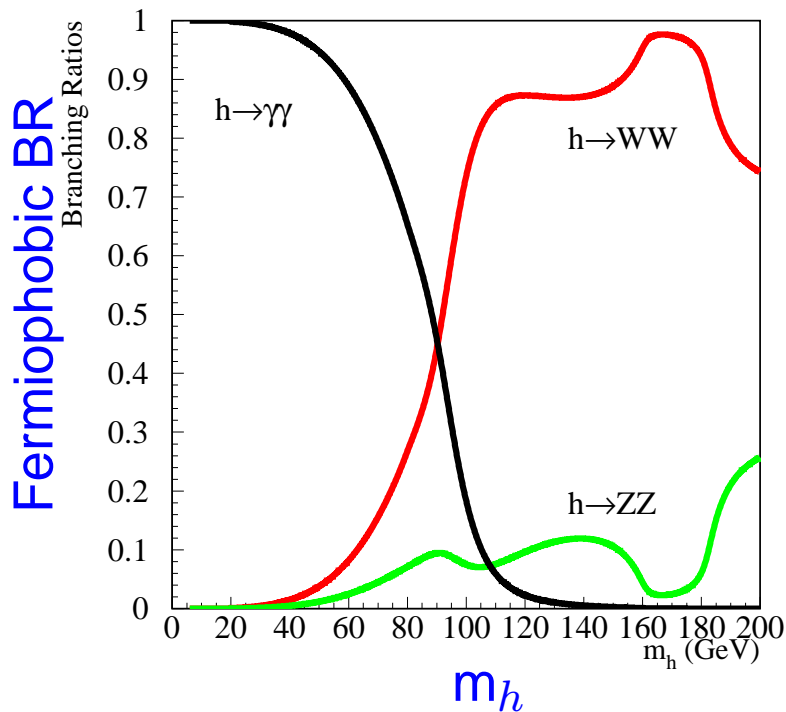


# (1) Fermiophobic Higgs

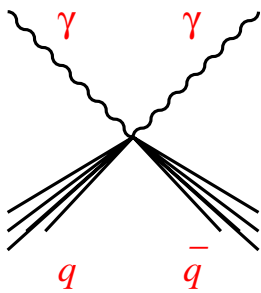
In SM,  $\text{BR}(h^0 \rightarrow \gamma\gamma) = 10^{-3}$  for  $m_h^0 = 90$  GeV.

For a 2HDM(I), if  $\cos \alpha = 0$ , then  $h^0$  and  $H^0$  do not mix, coupling to fermions switched off

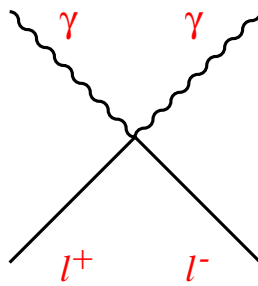
→ Fermiophobic Higgs.



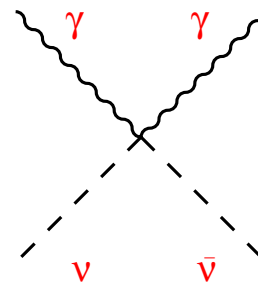
Signal: Two photons +  $m_{recoil} \approx m_Z$



Hadronic  
 $\approx 70\%$

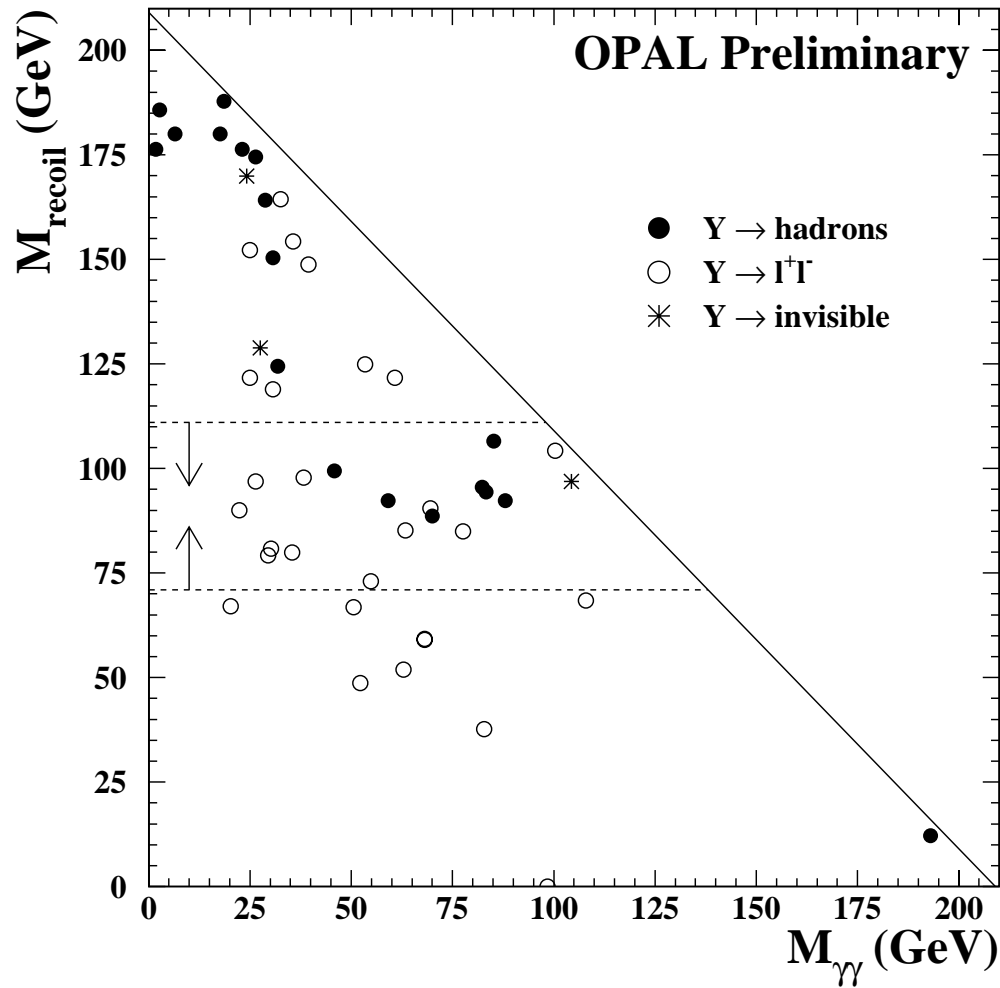


Leptonic  
 $\approx 20\%$

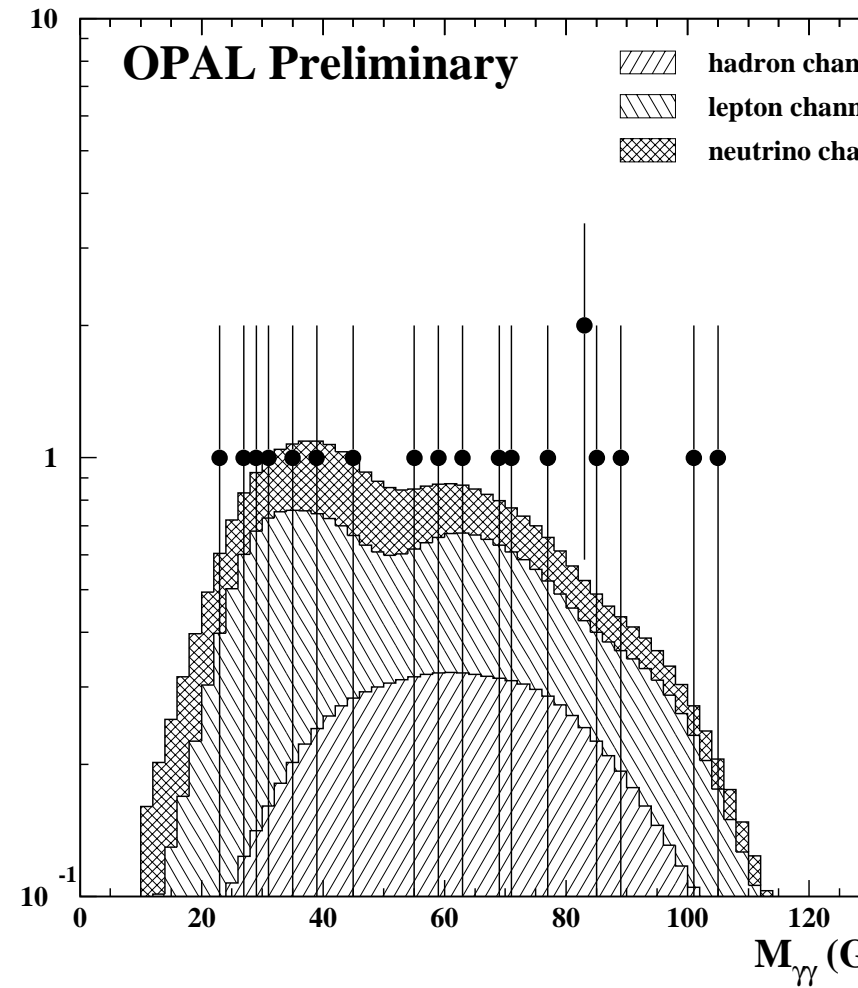


Neutrino  
 $\approx 10\%$

# Fermiophobic Higgs Results from 2000 Data

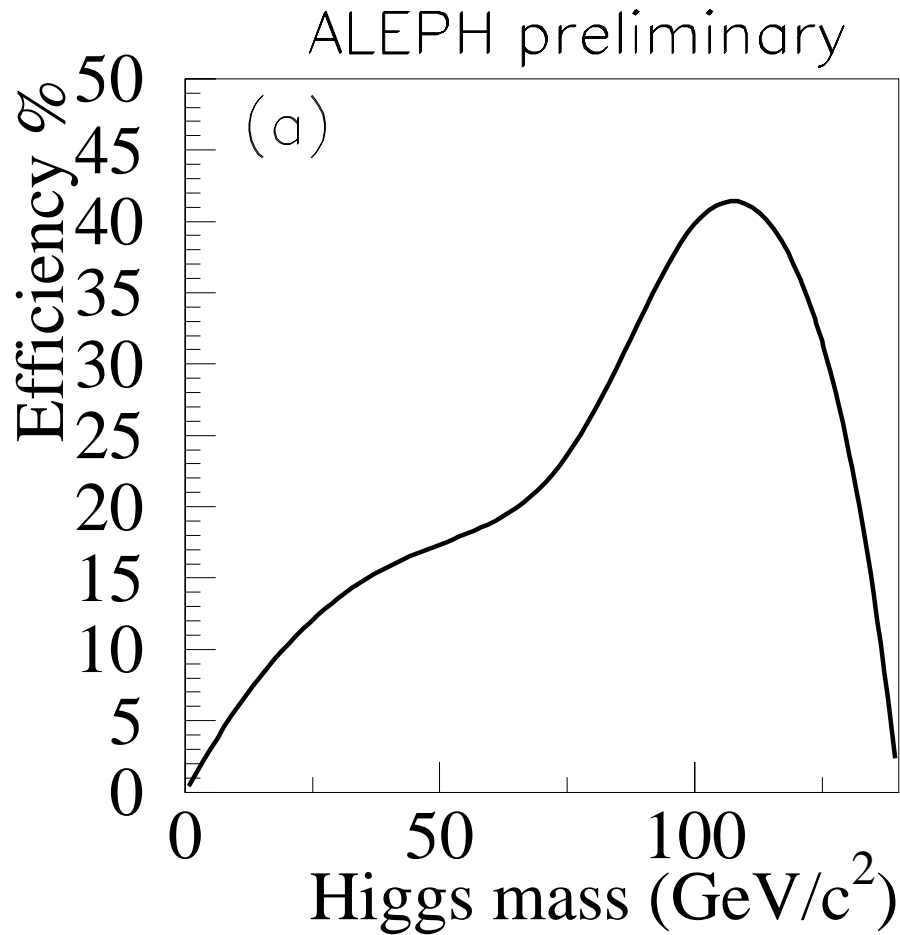


Apply cut on  $m_{\text{recoil}}$

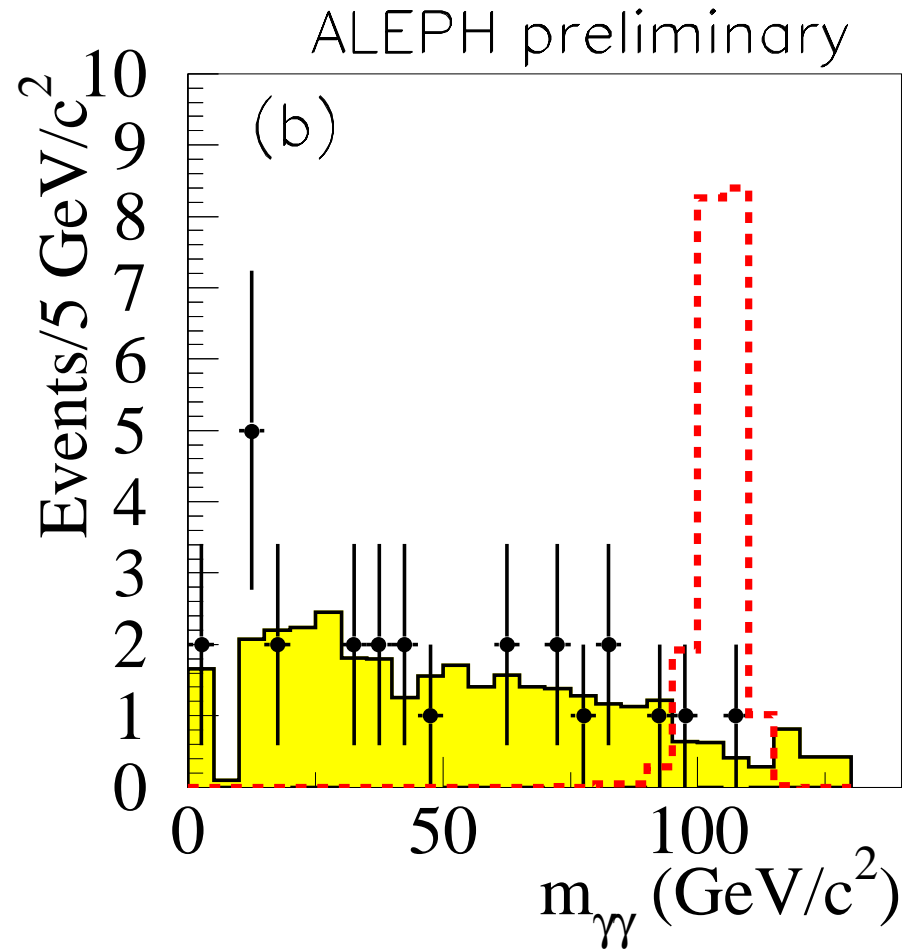


$N_{\text{obs}} = 29, N_{\text{exp}} = 24.2 \pm 2.1$

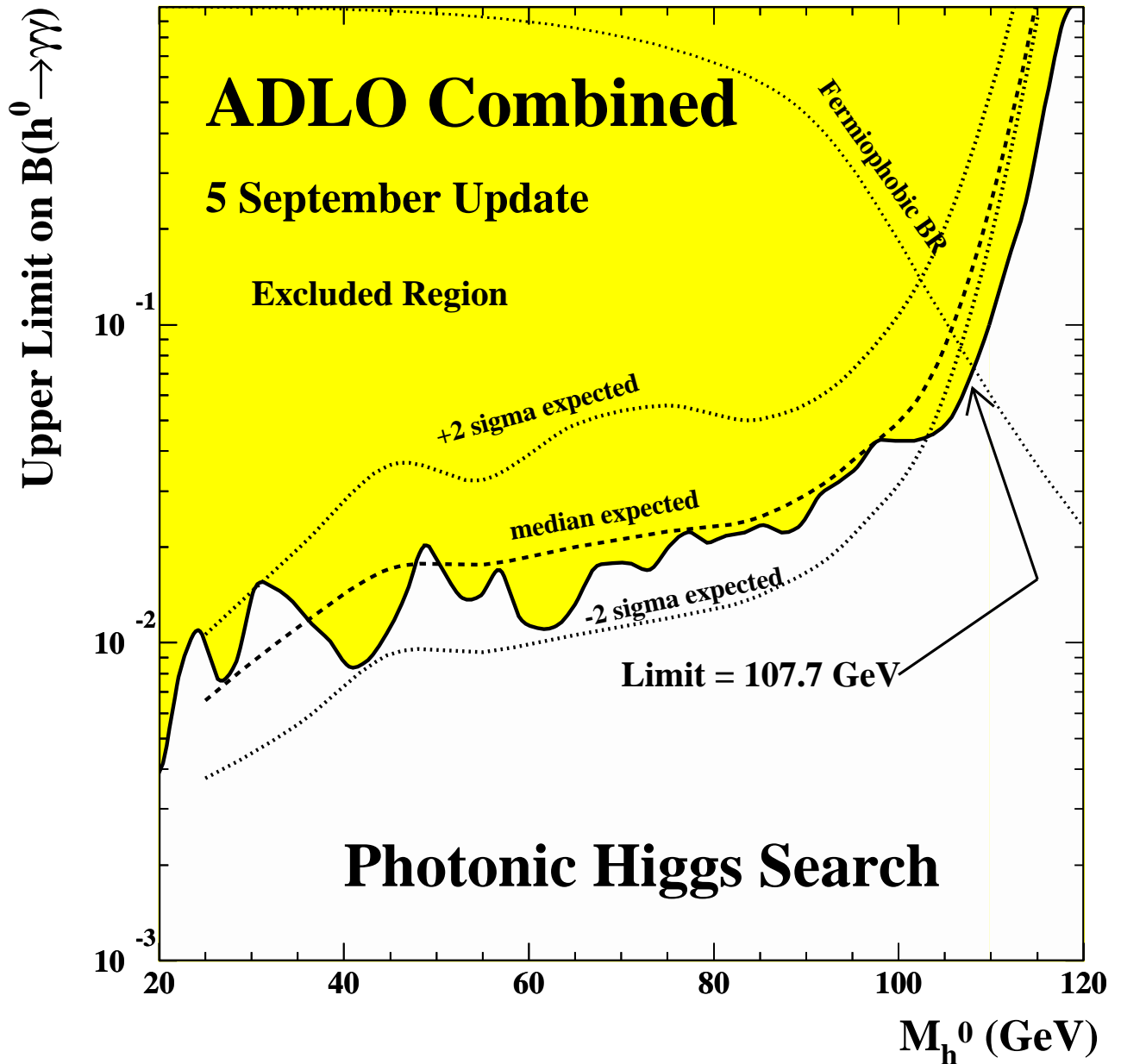
# Fermiophobic Higgs Results from 1991-2000 Data



Efficiency at  $\sqrt{s} = 206 \text{ GeV}$

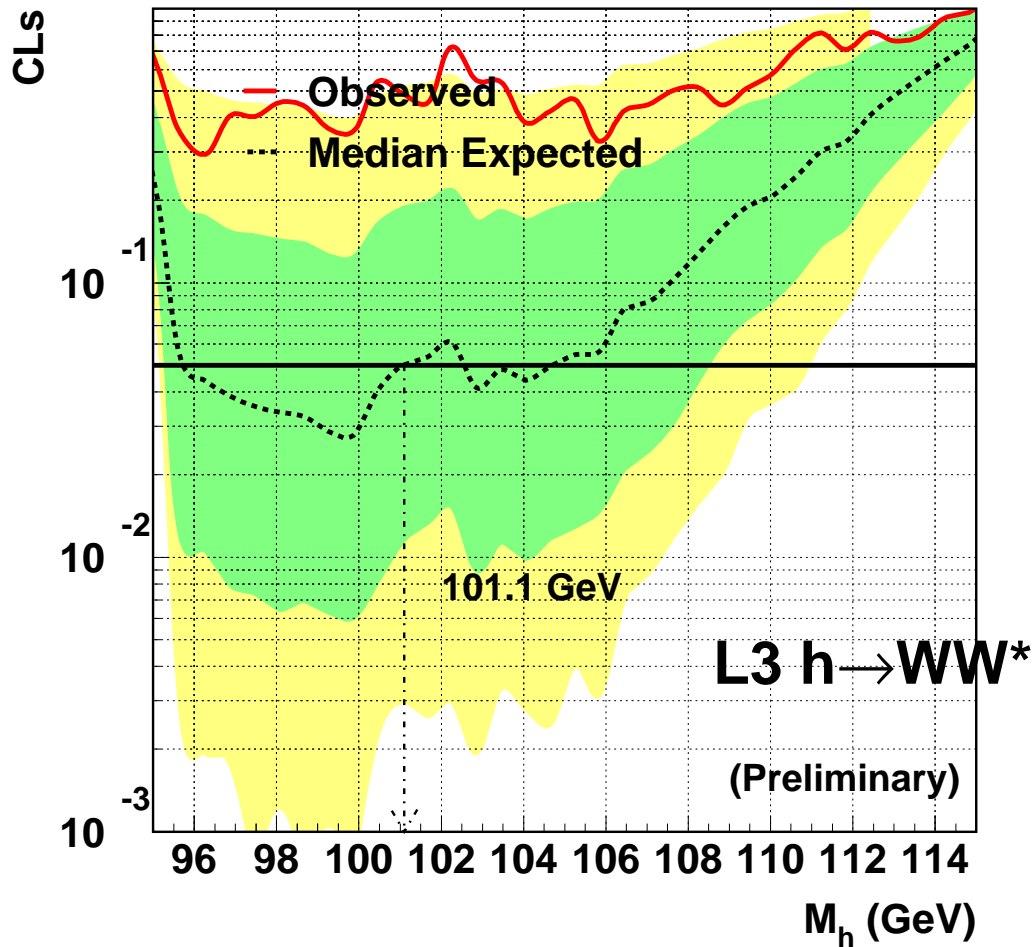


# Fermiophobic Higgs: LEP Combined

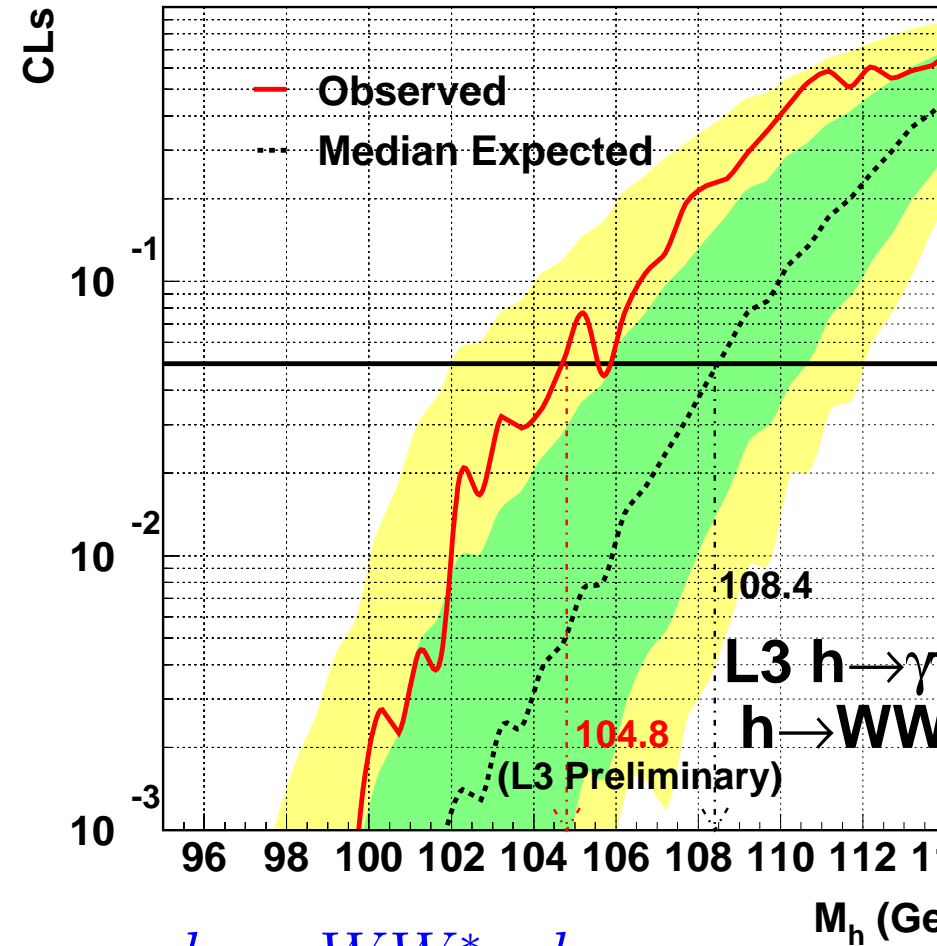


Mass Limit for  $h^0 \rightarrow \gamma\gamma$ : **107.7 GeV (obs)**  
 with  $BR(h^0 \rightarrow f\bar{f}) = 0$  **105.8 GeV (expected)**

# NEW: Inclusion of $h^0 \rightarrow WW^*$ Decays



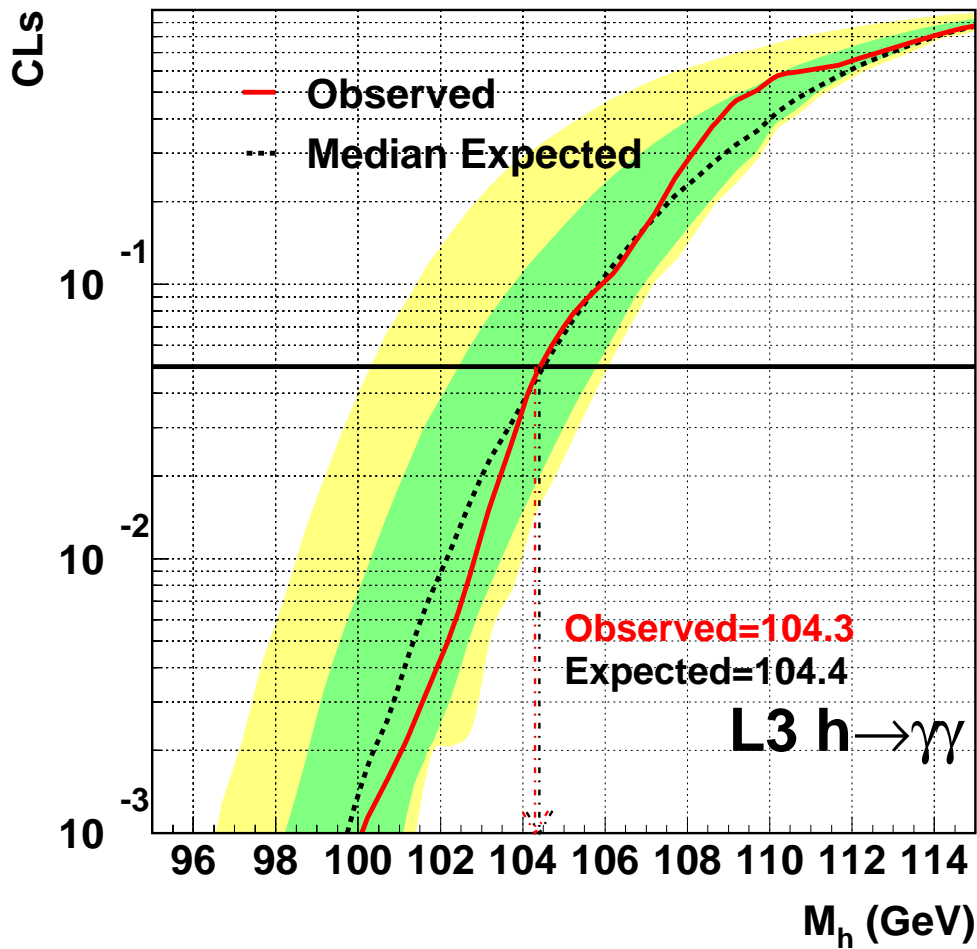
$$h \rightarrow WW^*$$



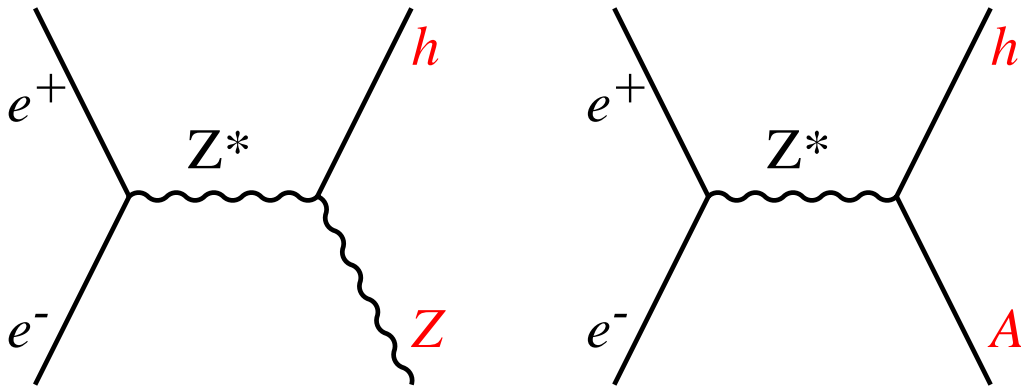
$$h \rightarrow WW^* + h \rightarrow \gamma\gamma$$

Topologies:  $hZ \rightarrow (\nu\nu)qqqq, (\nu\nu)qq\ell\nu, (qq)qqqq, (qq)qq\ell\nu$

# Fermiophobic Higgs: L3 Photonic Decays Only



## (2) Flavour-Independent Higgs Searches



Higgs-strahlung, Higgs Pair Production

- Production: Tree level cross-sections:

$$\sigma_{hz} = \sin^2(\beta - \alpha) \sigma_{HZ}^{\text{SM}}$$

$$\sigma_{hA} = \cos^2(\beta - \alpha) \bar{\lambda} \sigma_{HZ}^{\text{SM}}$$

- Decay: Tree Level Higgs couplings wrt. SM:

$$h^0 c\bar{c} : \cos\alpha / \sin\beta$$

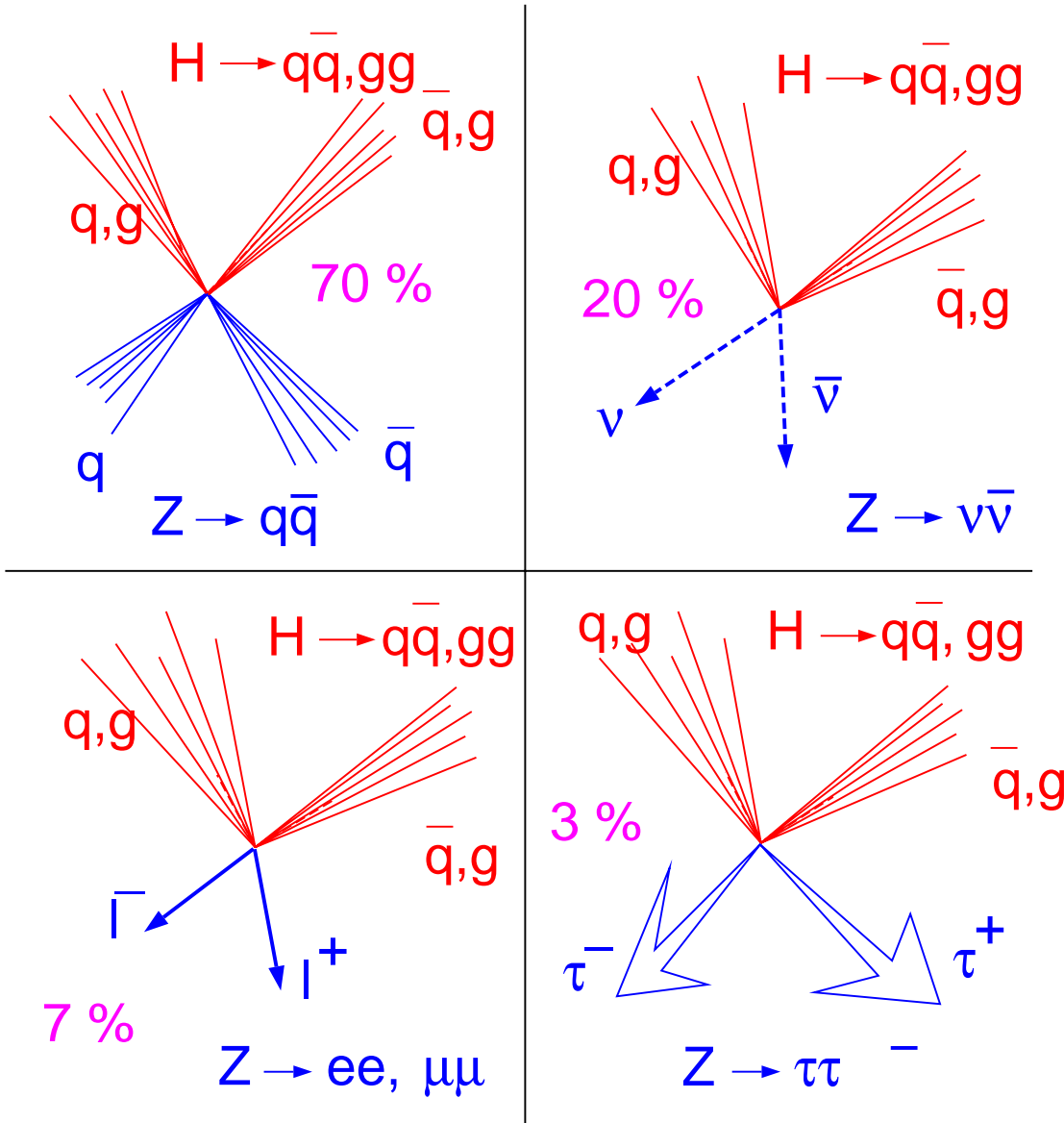
$$h^0 b\bar{b} : -\sin\alpha / \cos\beta$$

$$A^0 c\bar{c} : \cot\beta$$

$$A^0 b\bar{b} : \tan\beta$$

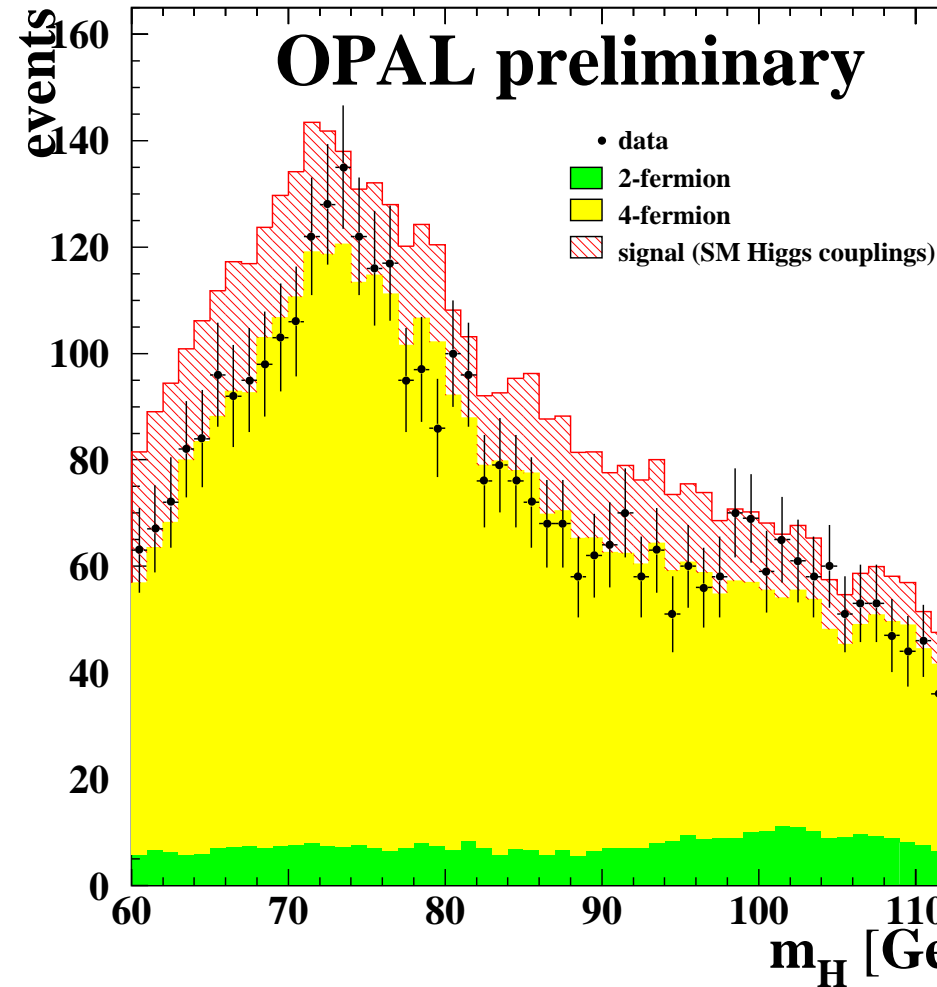
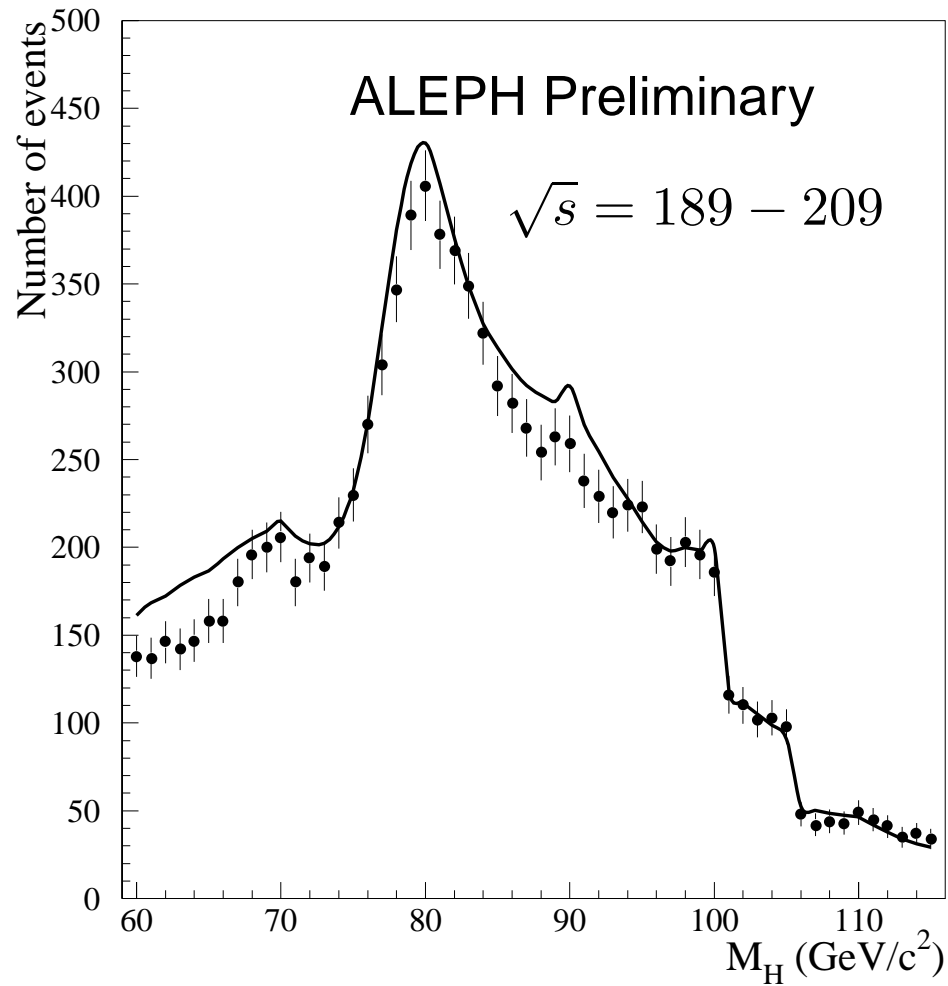
# Flavour-Independent Higgs Searches

In the 2HDM(II), for certain values of  $\alpha$  and  $\tan(\beta)$ ,  $\text{BR}(h^0 \rightarrow b\bar{b}, \tau^+\tau^-)$  can be suppressed, leaving  $c\bar{c}$ ,  $gg$  decays dominant.



Channels: 4-jet, Missing Energy, Leptonic, Tau

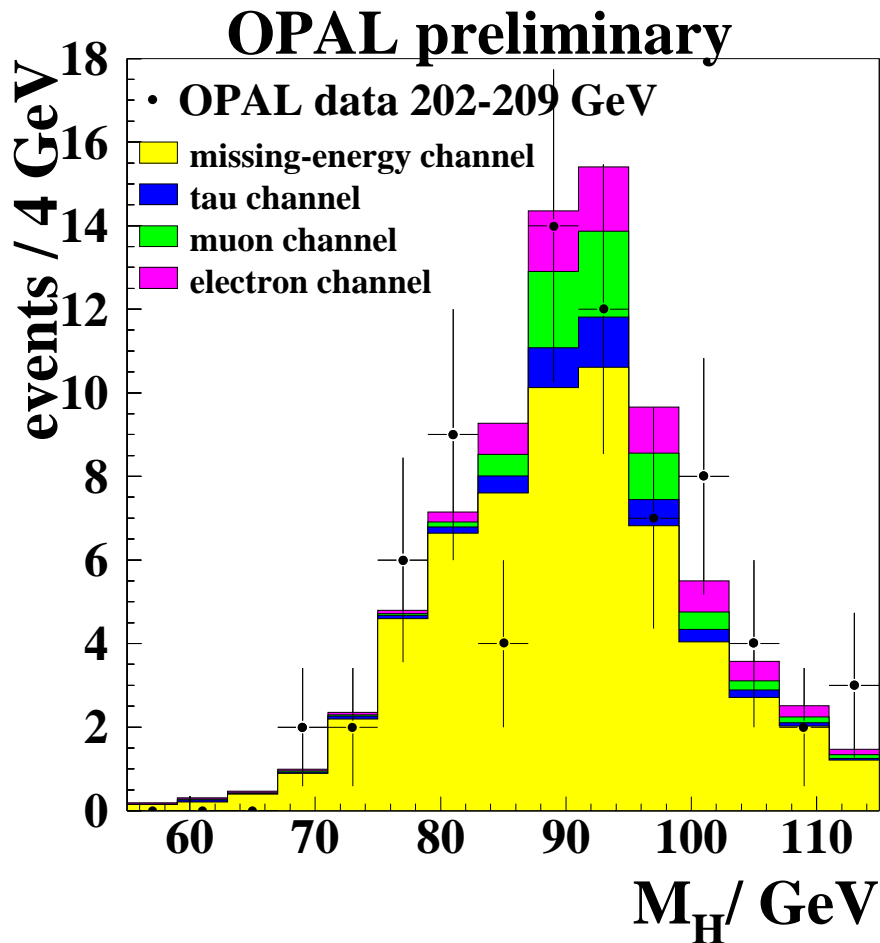
# Flavour-Independent Higgs Results: 4-Jet Channel



4-jet mass spectra in data compared to SM background.

# Other Channels for Flavour-Independent Higgs Searches

No excesses observed in other channels:

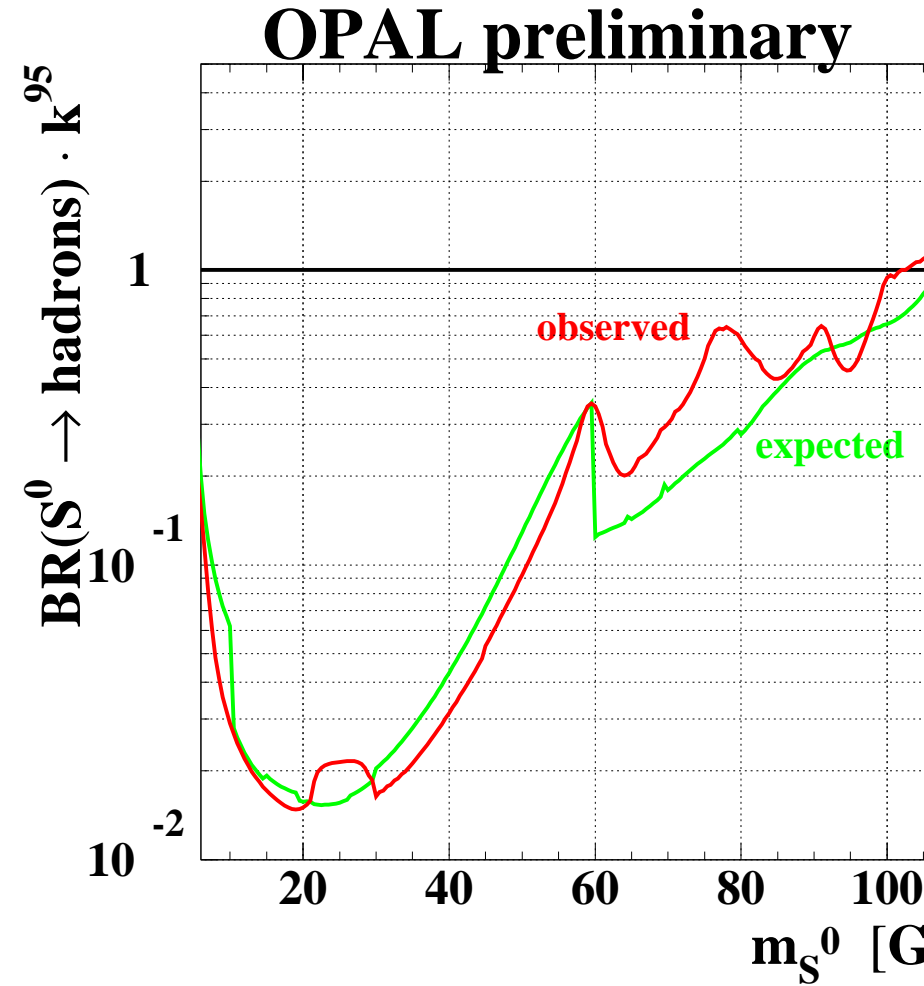
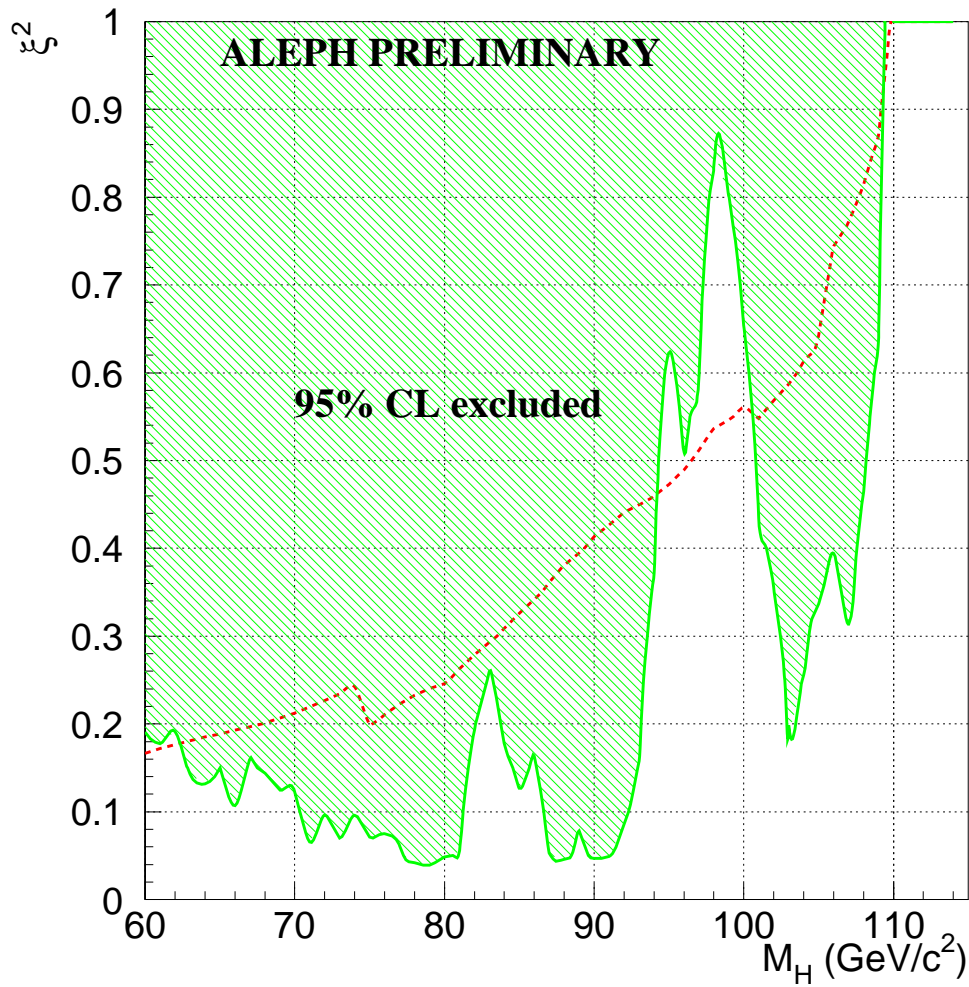


Mass Limits from Flavour-Independent Searches:

	Observed	Expected
ALEPH	109.4 GeV	109.8 GeV
OPAL	101.8 GeV	107.3 GeV

Valid for SM cross-section and 100% hadronic BR.

# Decay-Mode-Independent 2HDM(II) Higgs Searches

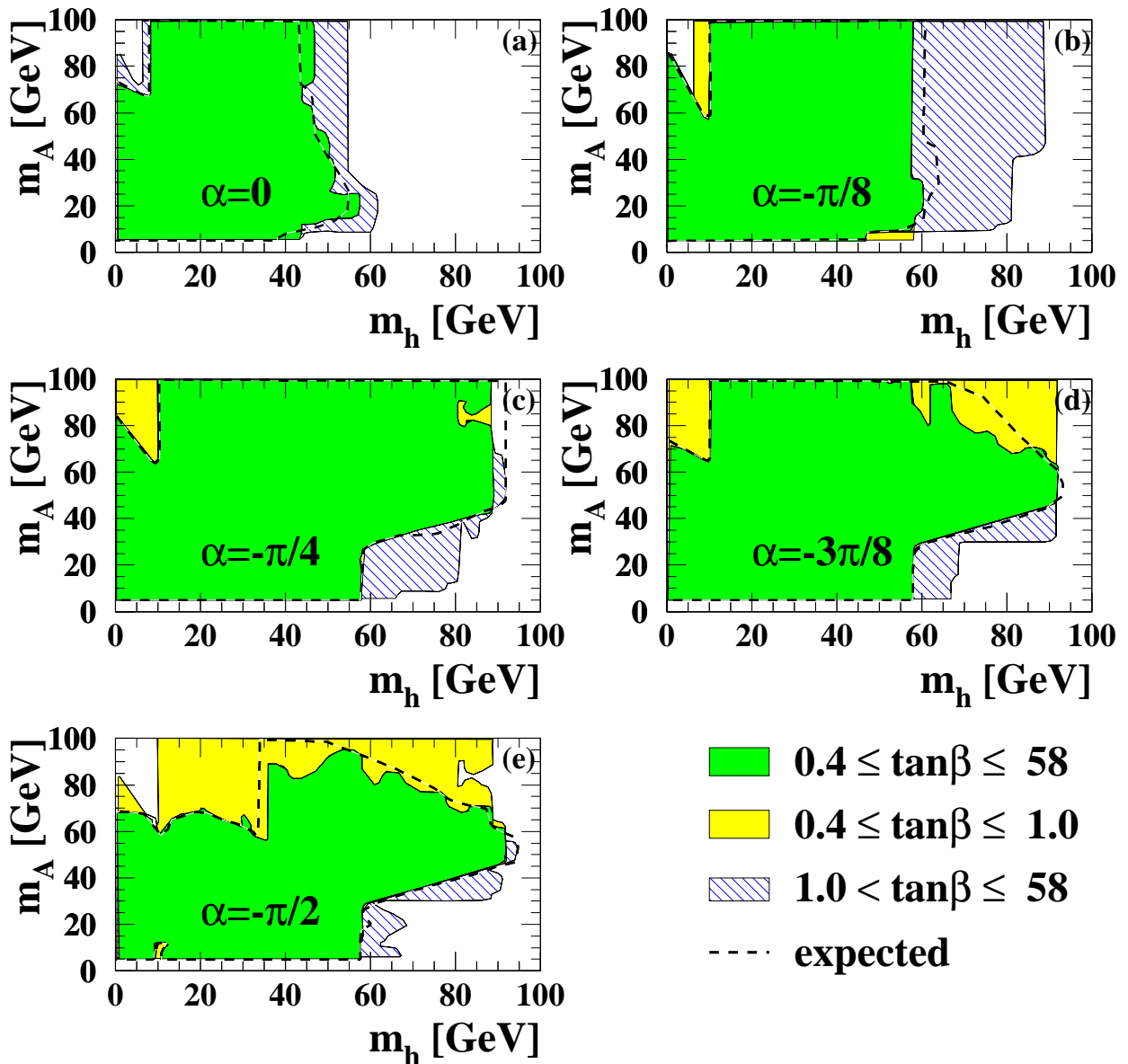


Limits including branching ratio into hadrons.

# Flavour-Independent 2HDM(II) Exclusion Regions

Scan over range of masses,  $\tan \beta$  and  $\alpha$ , extract limits.

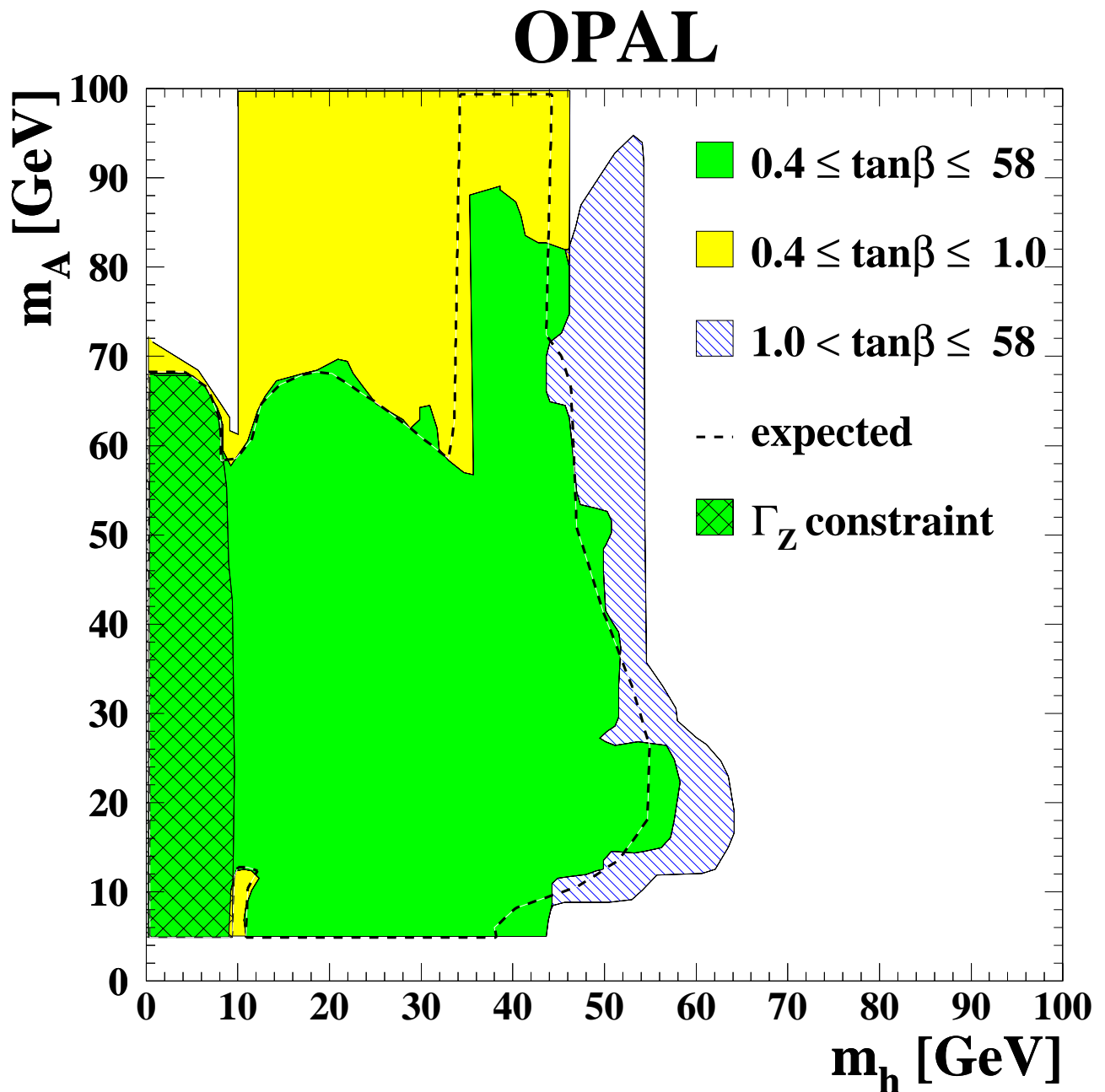
## OPAL



A point  $(m_h, m_A, \alpha)$  is excluded at 95%CL if it is excluded for all values of  $\tan \beta$ .

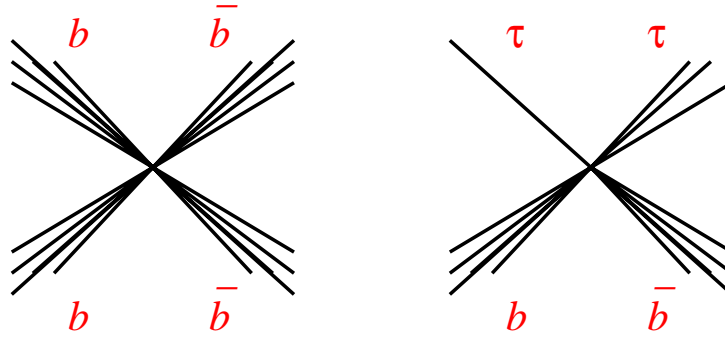
# Flavour-Independent 2HDM(II) Exclusion Regions

Complete scan over  $-\pi/2 < \alpha < 0$ :

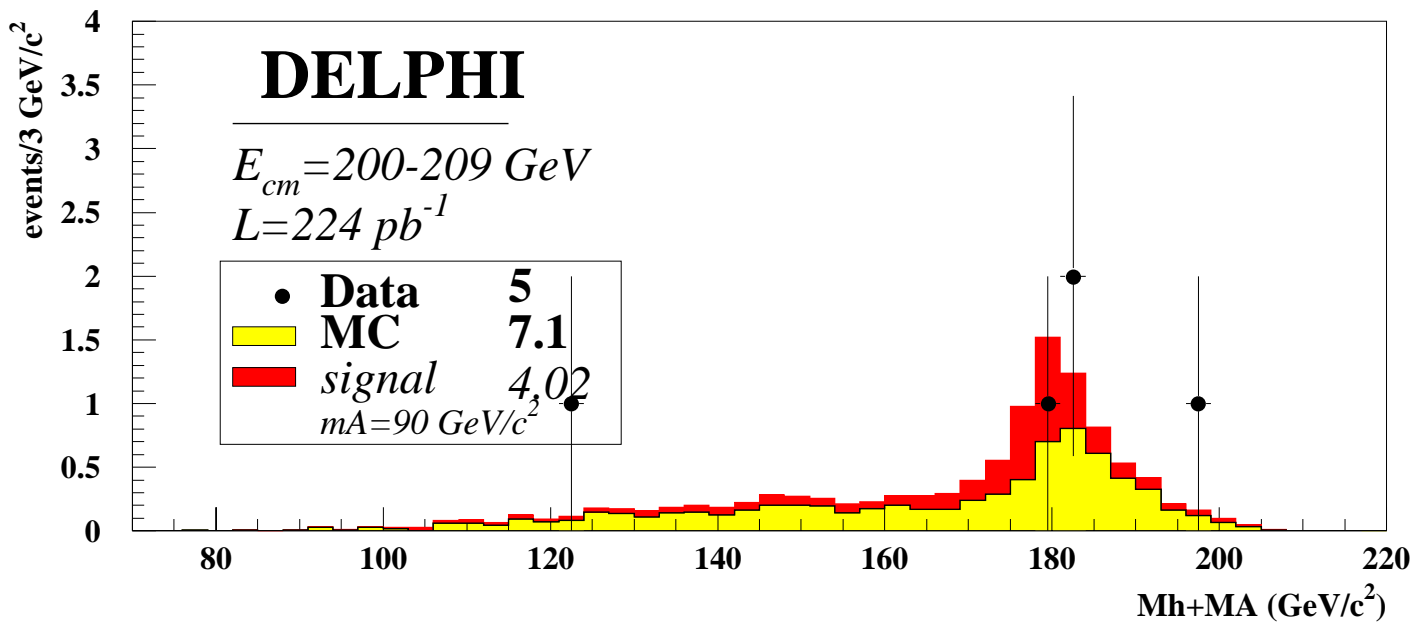


# MSSM Higgs Searches

- In MSSM  $m_{h^0} < 135$  GeV
- Search for  $h^0 Z$  (SM) and  $h^0 A^0$  production:



- Largest cross-section for  $m_{h^0} \approx m_{A^0}$ , so plot reconstructed  $m_{h^0} + m_{A^0}$ .

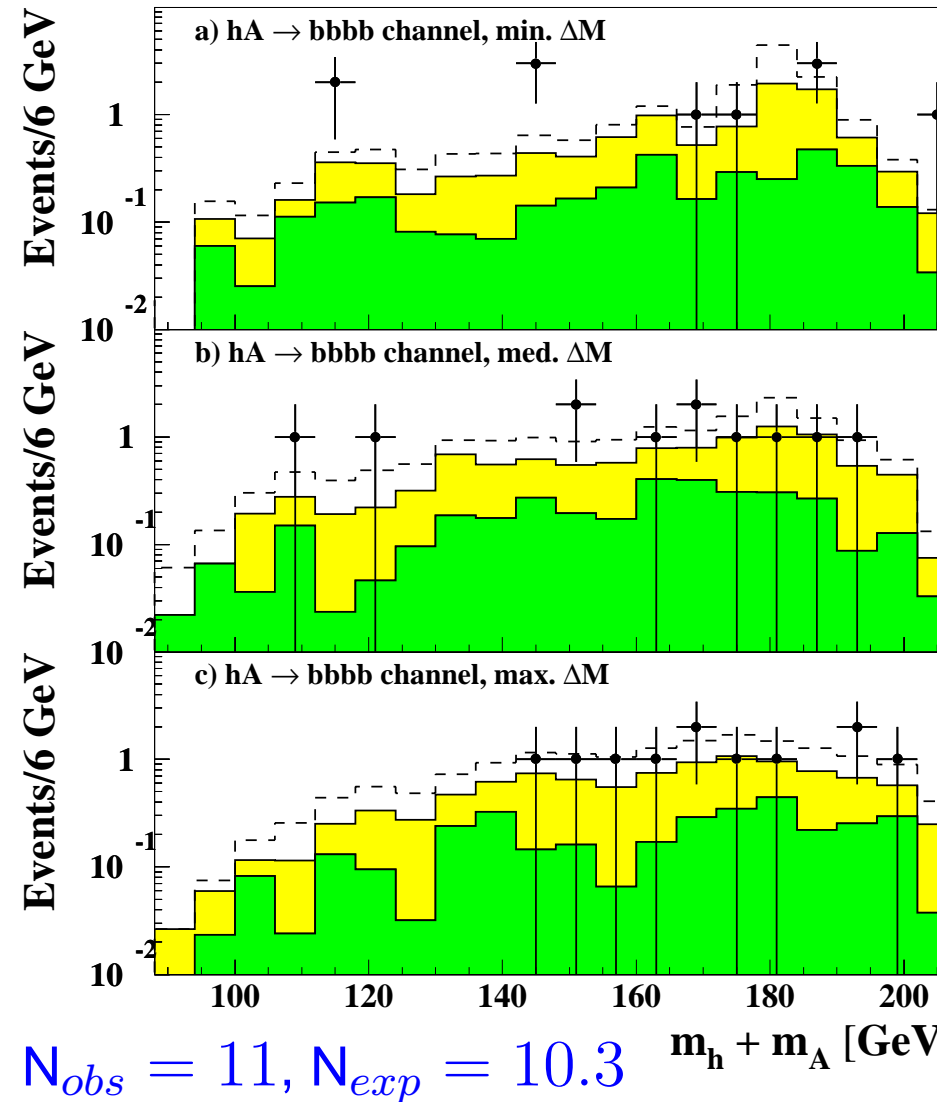
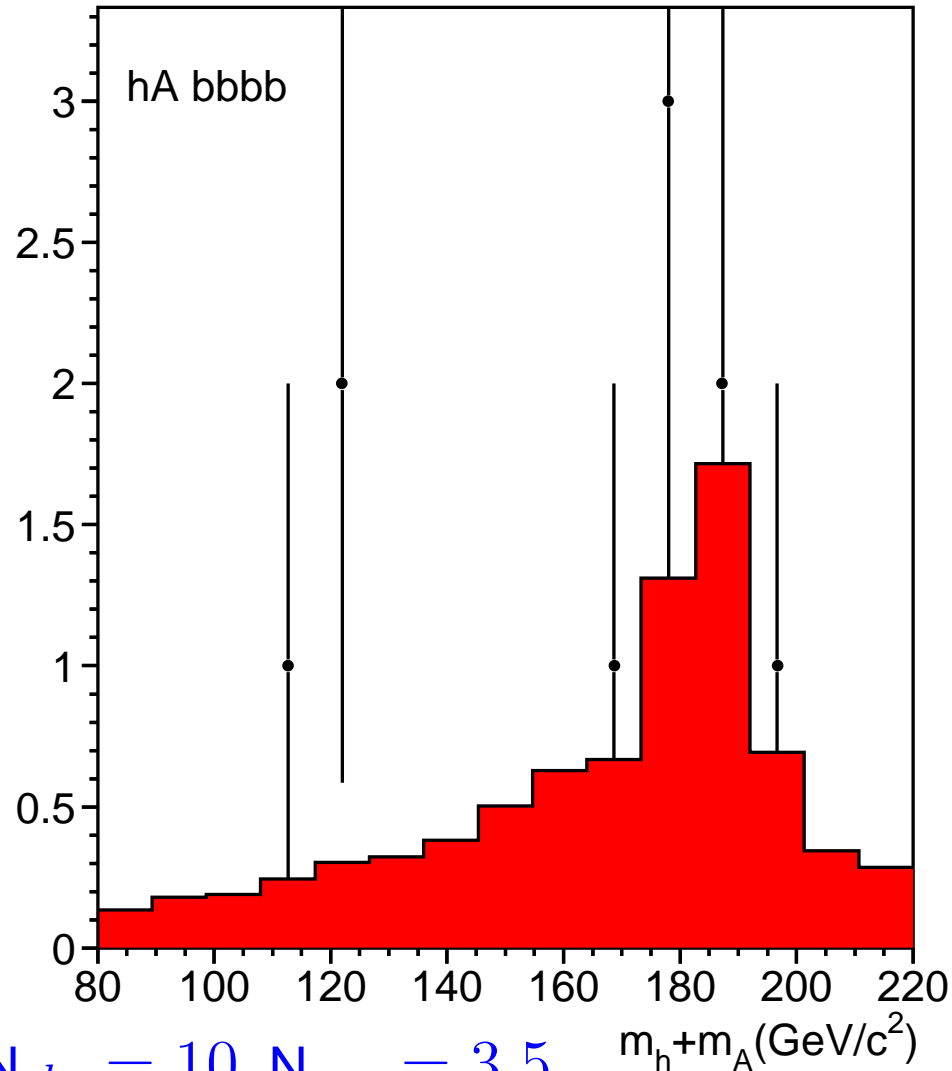


Combined  $A^0 h^0 \rightarrow b\bar{b}b\bar{b} + A^0 h^0 \rightarrow b\bar{b}\tau\tau$

# MSSM Searches: $A^0 H^0 \rightarrow b\bar{b}b\bar{b}$ at $\sqrt{s} \approx 206$ GeV

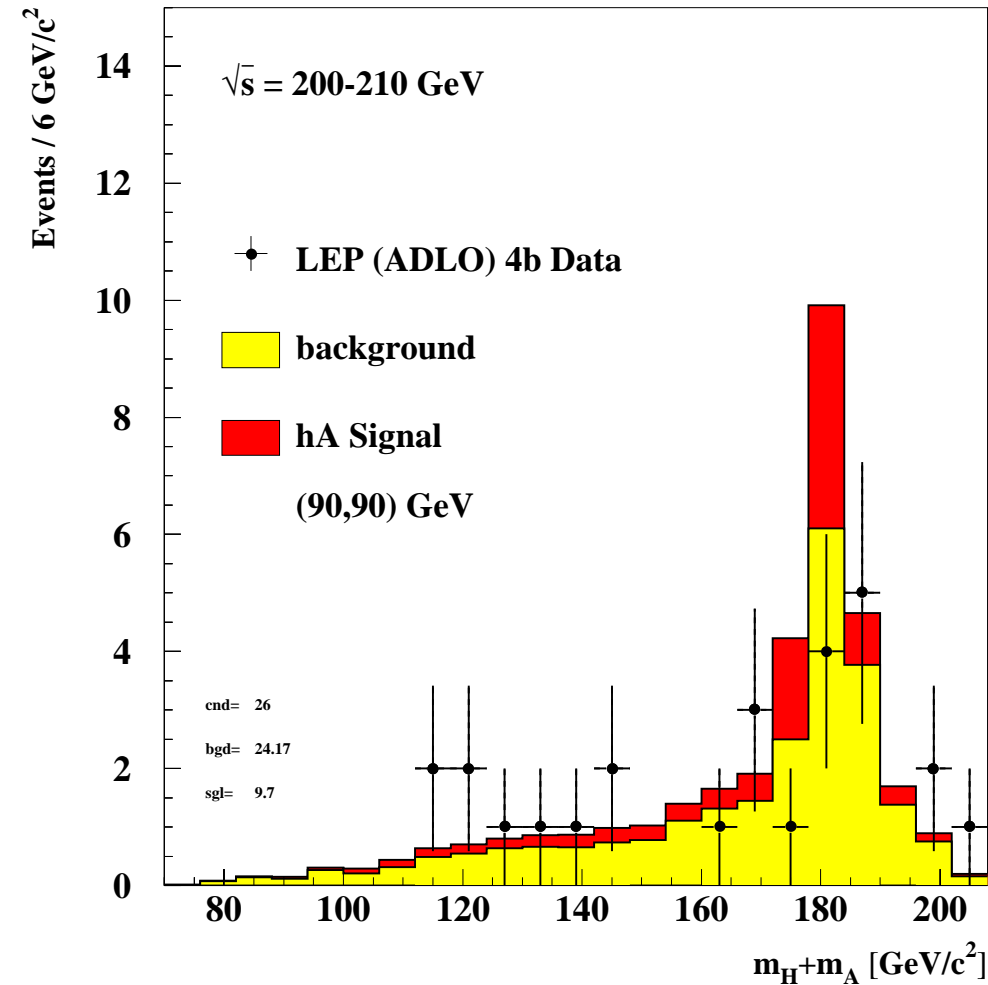
## OPAL preliminary

ALEPH Preliminary



# LEP Combined MSSM Searches at $\sqrt{s} = 200 - 210$ GeV

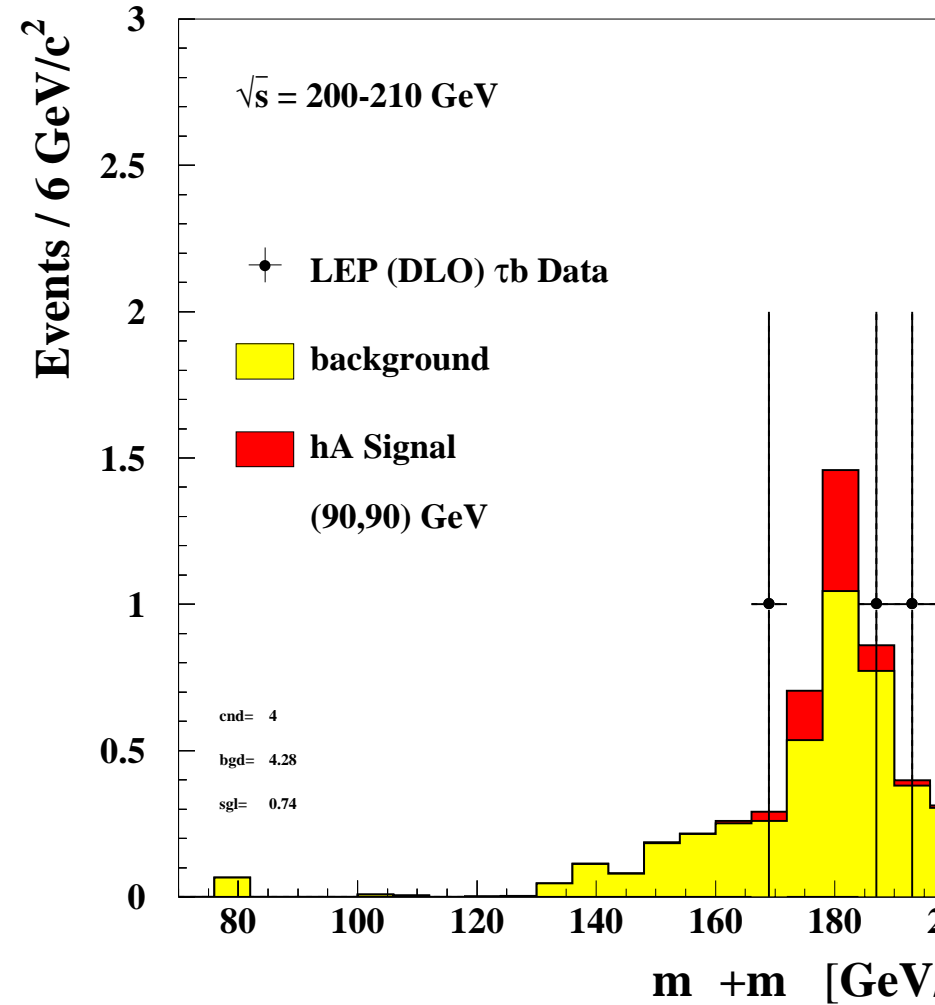
$$A^0 h^0 \rightarrow b\bar{b}b\bar{b}$$



$$N_{obs} = 26, N_{exp} = 24.17$$

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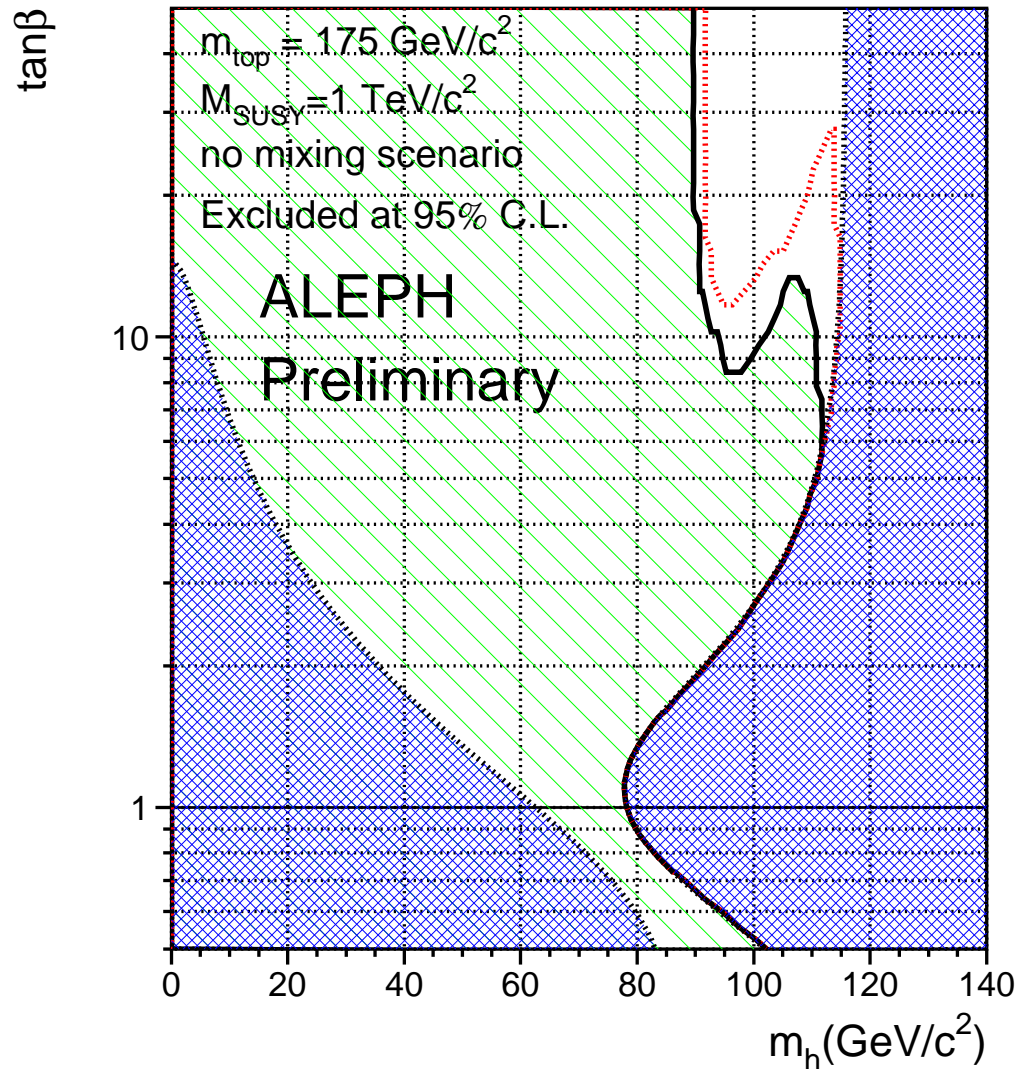
$$A^0 h^0 \rightarrow b\bar{b}\tau\tau$$



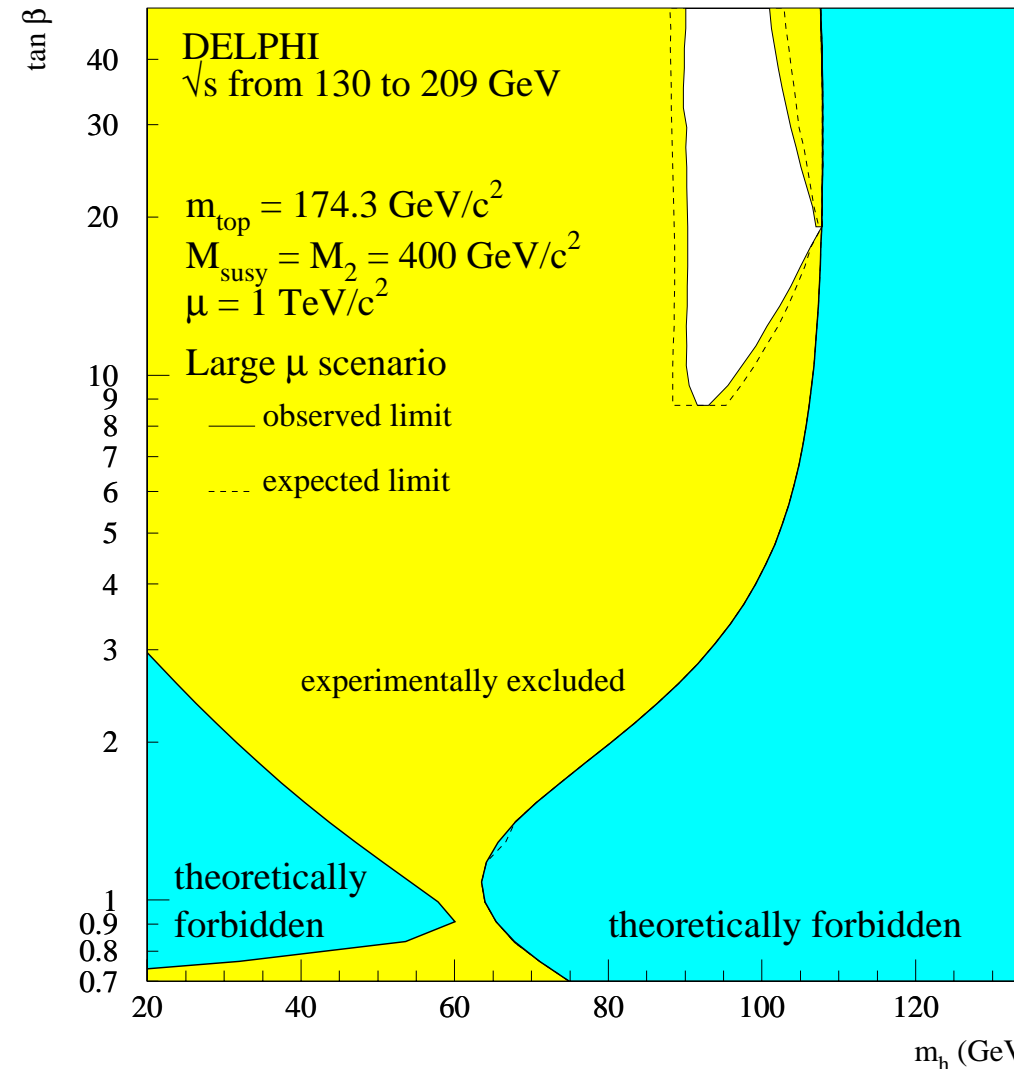
$$N_{obs} = 4, N_{exp} = 4.28$$

Moriond Electroweak March 2001

# MSSM Higgs Scans

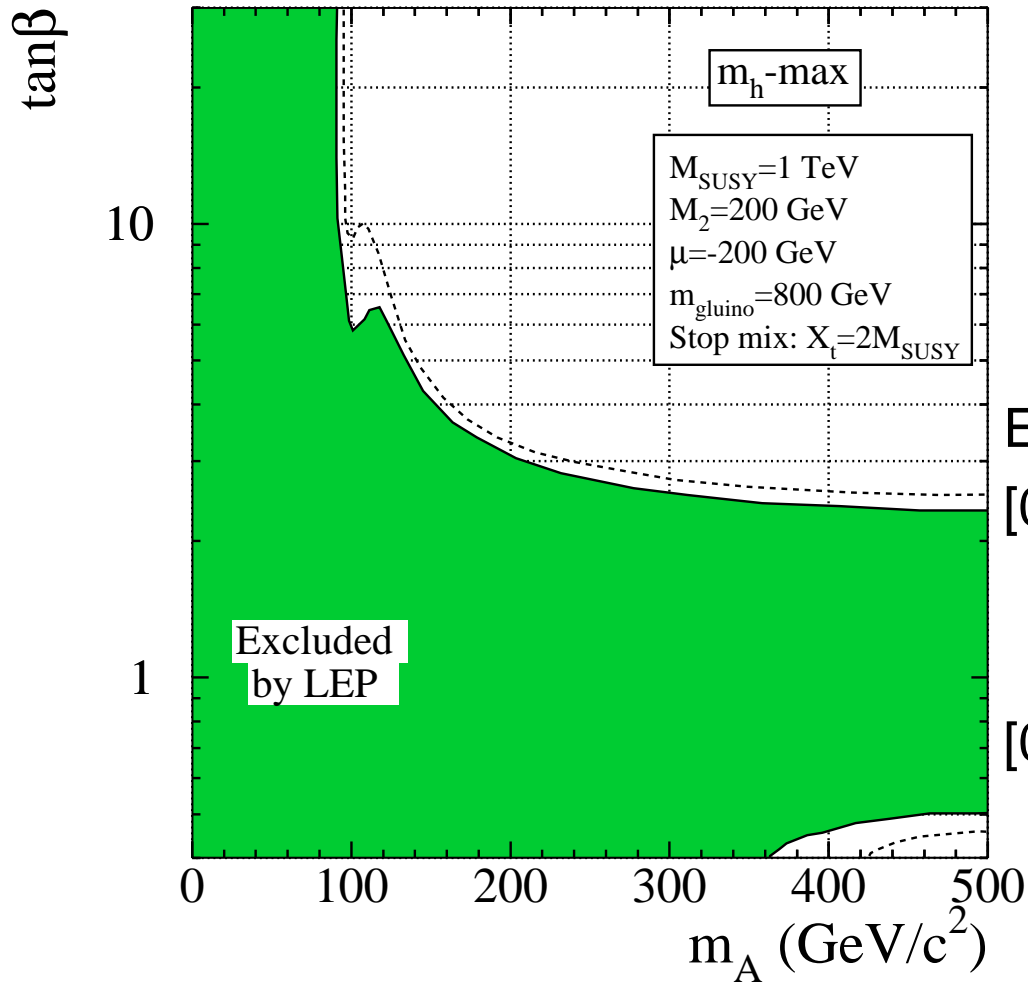


No stop mixing

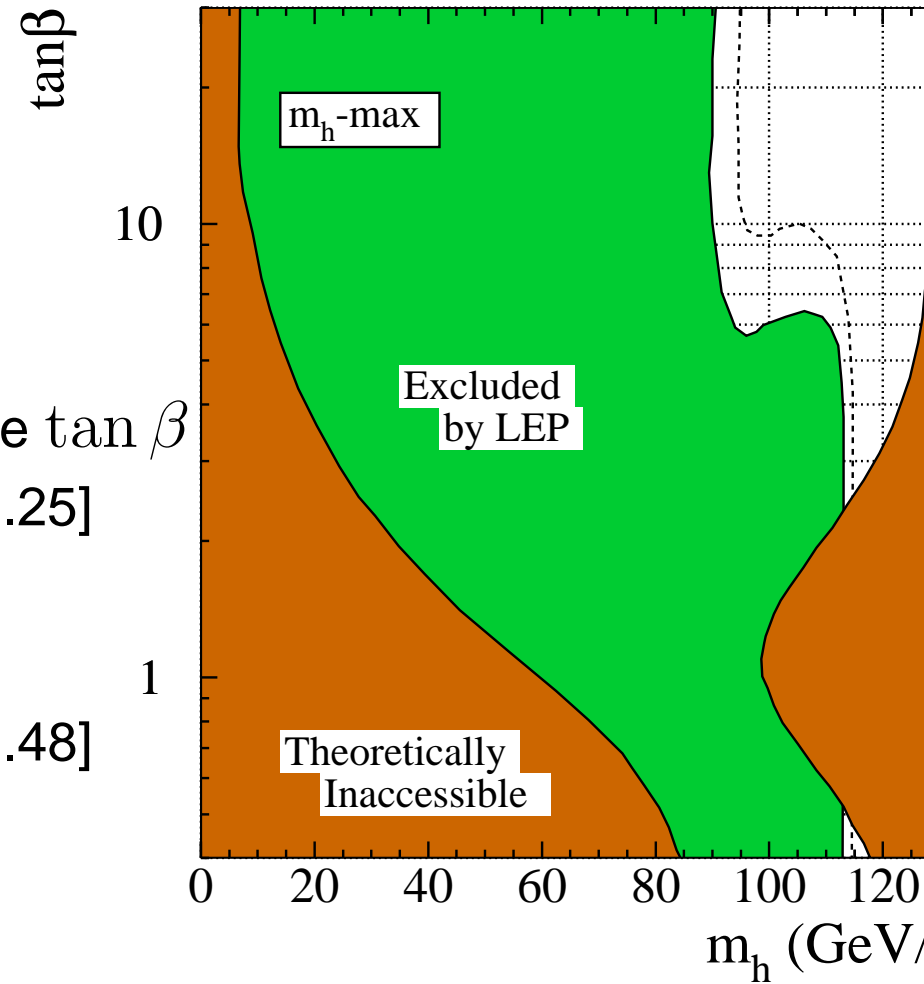


Large  $\mu$  scenario

# LEP Combined MSSM Higgs Results

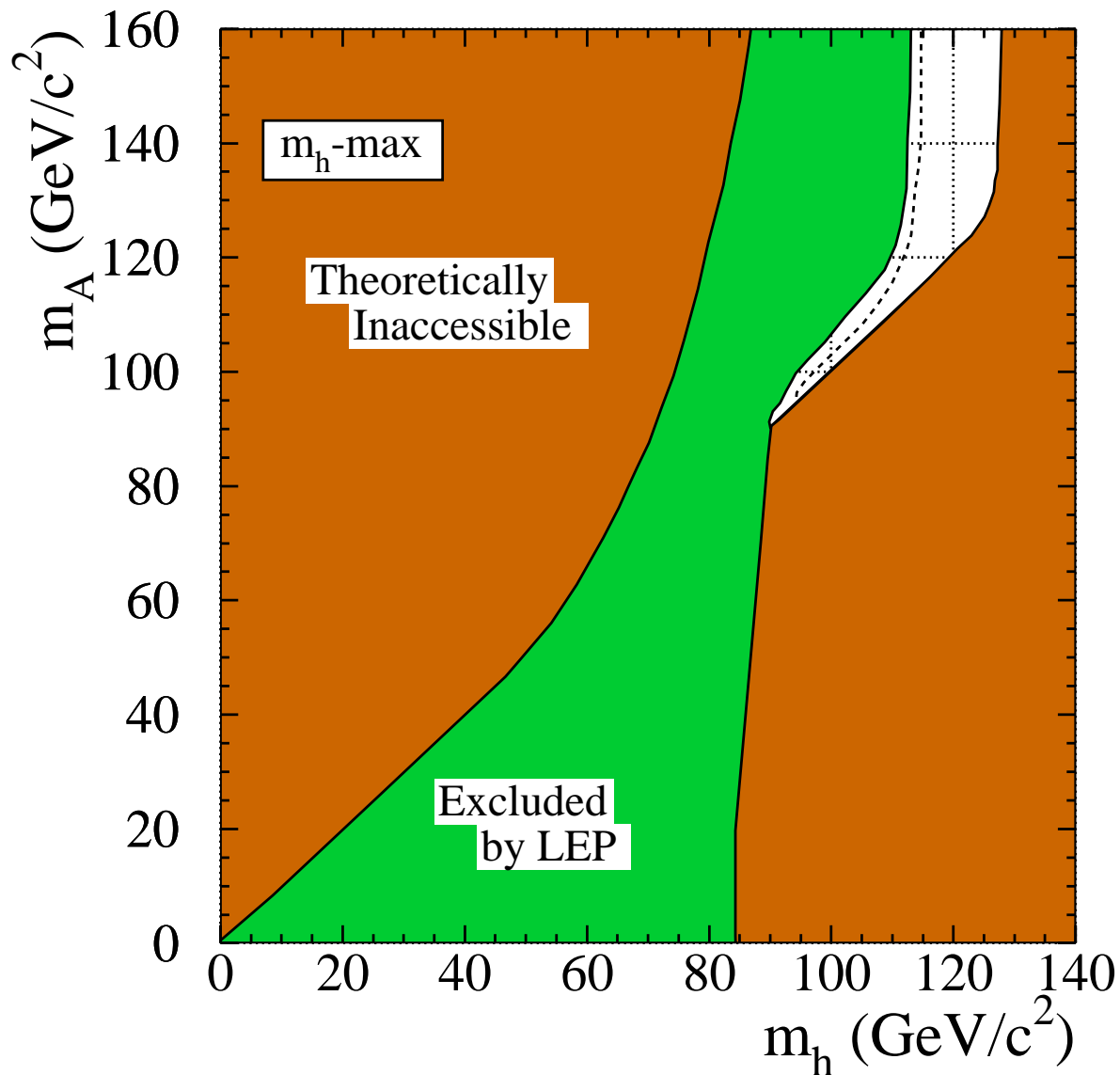


$$m_A > 90.5 \text{ (obs)} \quad 94.1 \text{ (exp)} \text{ GeV}$$

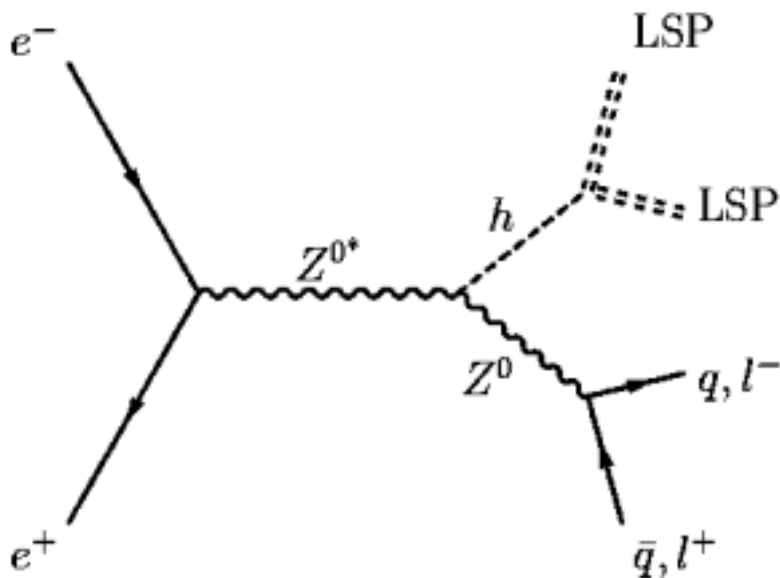


$$m_h > 89.9 \text{ (obs)} \quad 93.8 \text{ (exp)} \text{ GeV}$$

# LEP Combined MSSM Higgs Results

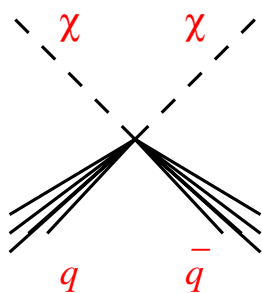


# Invisible Higgs Searches

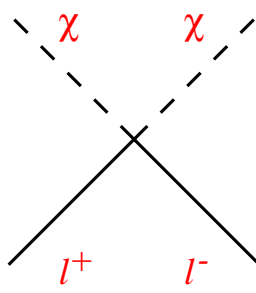


- In the MSSM the Higgs can decay into a pair of undetected LSP's.
- Other models allow for Higgs decays into stable weakly-interacting particles.

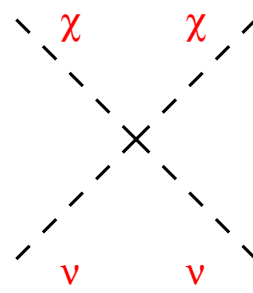
## Signal Topologies:



Hadronic  
 $\approx 70\%$



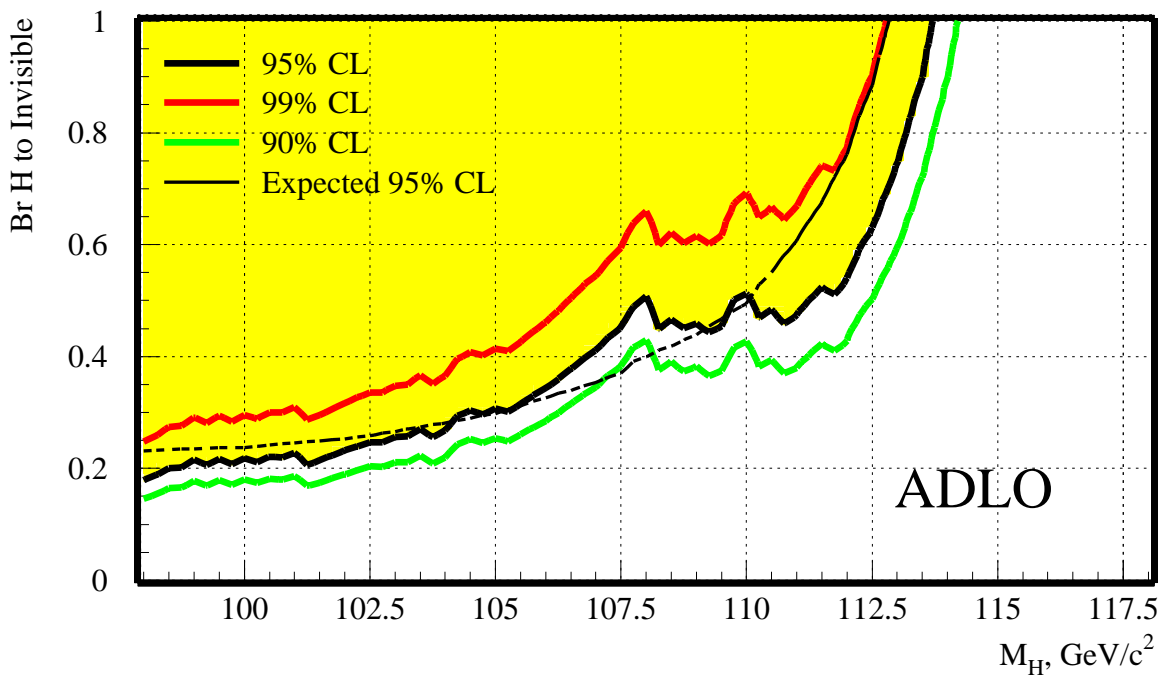
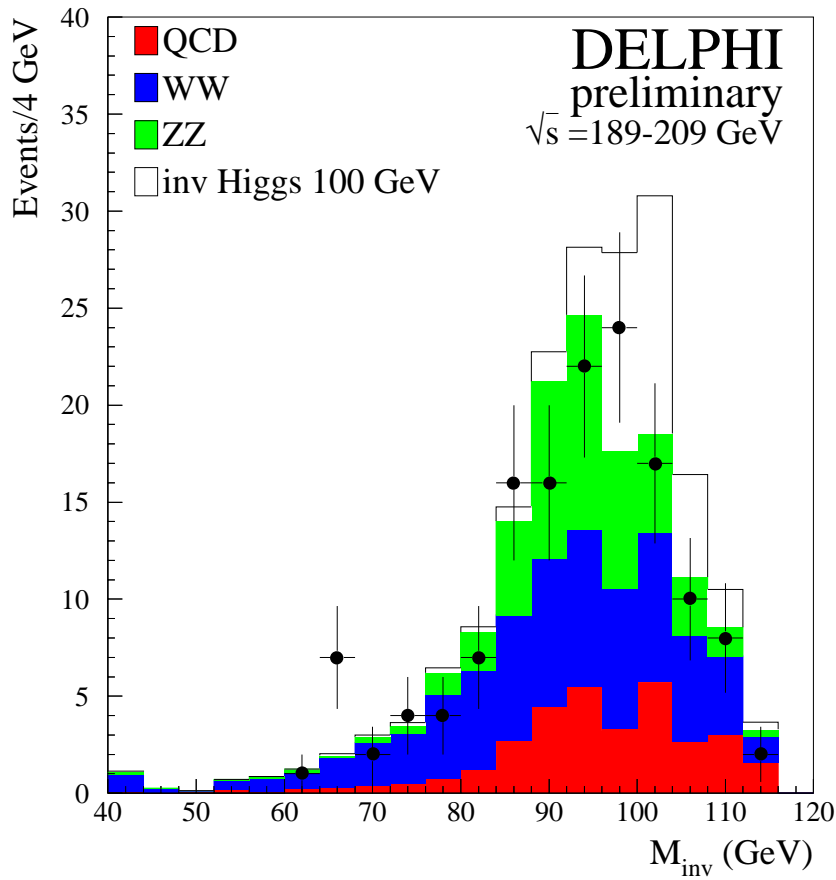
Leptonic  
 $\approx 7\%$



Not Searched for

# Results of Invisible Higgs Searches

Hadronic Channel:



LEP combined: excluded below 113.7 GeV.

## Summary of Non-SM Higgs Searches at LEP2

$H^0 \rightarrow \gamma\gamma$	$m_{H^0} > 107.7 \text{ GeV}$
$H^0 \rightarrow \text{flavour-indep}$	$m_{H^0} > 102 - 109 \text{ GeV}$
$m_{h^0}, m_{A^0}, \alpha, \tan \beta$	2HDM General Scan
$h^0$	$m_{h^0} > 89.9 \text{ GeV (} m_h\text{-max)}$
$A^0$	$m_{A^0} > 90.5 \text{ GeV (} m_h\text{-max)}$
$H^0 \rightarrow \chi\chi \text{ (invis)}$	$m_{H^0} > 113.7 \text{ GeV}$

## Outlook

- Thanks to the ALEPH, DELPHI, L3, and OPAL collaborations for providing results, apologies for any topics left out.
- ALEPH: [http://alephwww.cern.ch/ALPUB/oldconf/oldconf\\_01.html](http://alephwww.cern.ch/ALPUB/oldconf/oldconf_01.html)
- DELPHI:  
[http://delphiwww.cern.ch/teams/searches/moriond2001/higgs\\_plots](http://delphiwww.cern.ch/teams/searches/moriond2001/higgs_plots)
- L3: <http://l3www.cern.ch/conferences/Moriond2001/>
- OPAL: <http://opalinfo.cern.ch/opal/doc/physnote/index2001.html>
- The Future... A search on Yahoo! for “Higgs” beyond the Standard Model yields the following Web site...

