Beyond SM Higgs Searches at LEP

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for the LEP Collaborations

- **Neutral Higgses in the MSSM**
- **Neutral Higgses in 2HDM**
- **Charged Higgs**
- **Higgs and Photons**
- **Invisibly Decaying Higgs**
- **Conclusions**

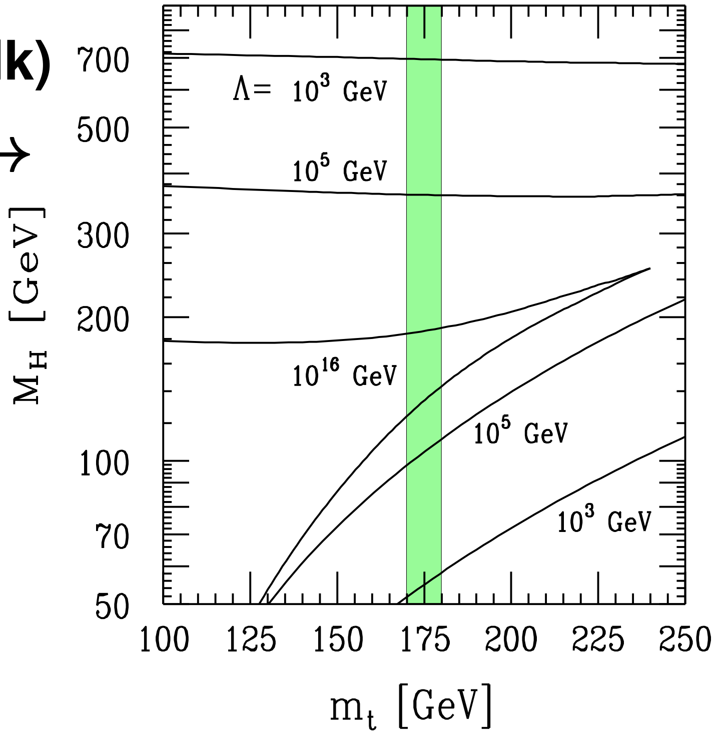
Thanks to all LEP Collaborations and the LEP Higgs Working Group

for providing information, plots and help!

Introduction

No SM-Higgs yet... (prev. talk)

o.k., that must be heavy... $\longrightarrow$



$\longrightarrow$ **Search for non-SM Higgses**

Most obvious extensions:

(1) 2 Higgs Doublets $\longrightarrow$ more than one Higgs

specific case: **MSSM**

$\longrightarrow$ masses,cross-sections,branching ratios known,

for a given MSSM parameter set $\longrightarrow$ good testability

(2) Higgs bosons with different decay modes

(photons,invisible decays)

The Higgs Sector in the MSSM

In any Two-Higgs-Doublet Model:

5 physical Higgs Bosons

2 CP-even neutral Higgses	$\mathrm{h}^0, \mathrm{H}^0$	$m_\mathrm{h} < m_\mathrm{H}$
1 CP-odd neutral Higgs	A^0	
2 charged Higgses	$\mathrm{H}^\pm$	
Free parameters:	$\tan\beta = v_2/v_1$	(VEV ratio)
	α	(mixing angle of h,H)

MSSM tree-level mass relations:

$$m_\mathrm{h} < m_\mathrm{Z} < m_\mathrm{H}$$

$$m_{\mathrm{W}^\pm} < m_{\mathrm{H}^\pm}$$

Significantly changed by radiative corrections:

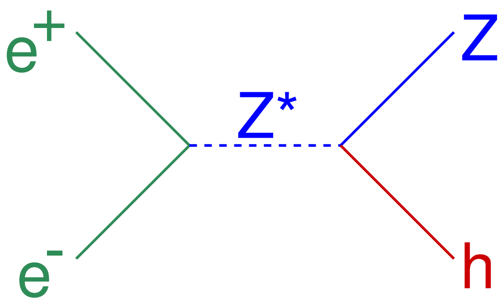
$$\Delta m_\mathrm{h}^2 \sim \frac{m_\mathrm{top}^4}{m_\mathrm{W}^2} \times (\log \frac{m_{\tilde{\mathrm{t}}_1}^2 m_{\tilde{\mathrm{t}}_2}^2}{m_\mathrm{top}^4} + ...)$$

strong dependence on m_top and $m_{\tilde{\mathrm{t}}}$ $\rightarrow$ depend on mixing parameters A_t and μ ($+$ soft SUSY breaking parameters)

still: $m_\mathrm{h} \lesssim$ 130 GeV

for any MSSM parameter choice

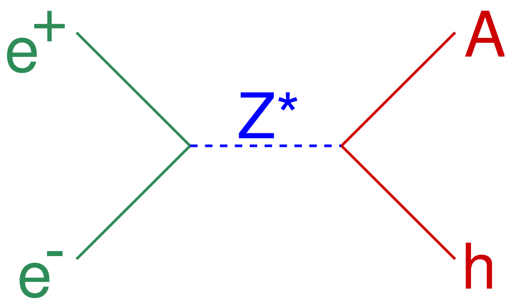
Production and Decay of Neutral Higgses at LEP



"Higgsstrahlung"

$$\sigma = \sin^2(\beta - \alpha)\, \sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$

- largest at small $\tan\beta \approx 1.4$
- SM topologies
- $\rightarrow$ recycle SM searches

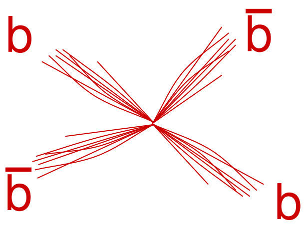


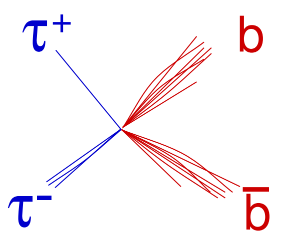
"Pair Production"

$$\sigma = \cos^2(\beta - \alpha)\, \bar{\lambda} \sigma^{\mathrm{SM}}_{\nu\bar{\nu}}$$

- largest at $\tan\beta > 15$
- typically $m_{\mathrm{A}} \approx m_{\mathrm{h}}$
- new topologies
- $\rightarrow$ dedicated searches:

$\mathrm{Ah} \rightarrow \mathrm{b\bar{b}b\bar{b}}$, $\mathrm{Ah} \rightarrow \tau^+\tau^-\mathrm{b\bar{b}}$





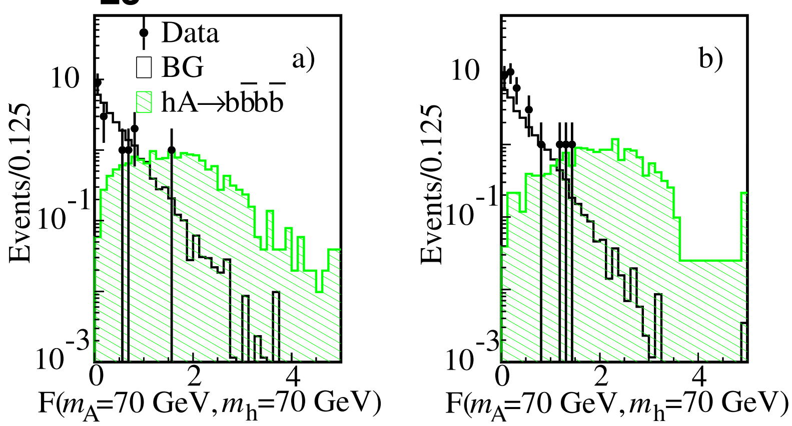
further complications:

- $\mathrm{h} \rightarrow \mathrm{AA}$ is possible
  leading to $\mathrm{q\bar{q}b\bar{b}b\bar{b}}$, $\mathrm{b\bar{b}b\bar{b}b\bar{b}}$, $\mathrm{b\bar{b}b\bar{b}}\tau^+\tau^-$,...
- $\mathrm{h} \rightarrow \tilde{\chi}^0\tilde{\chi}^0$ (invisible Higgs)
- for some parameter configurations
  heavy H is within reach

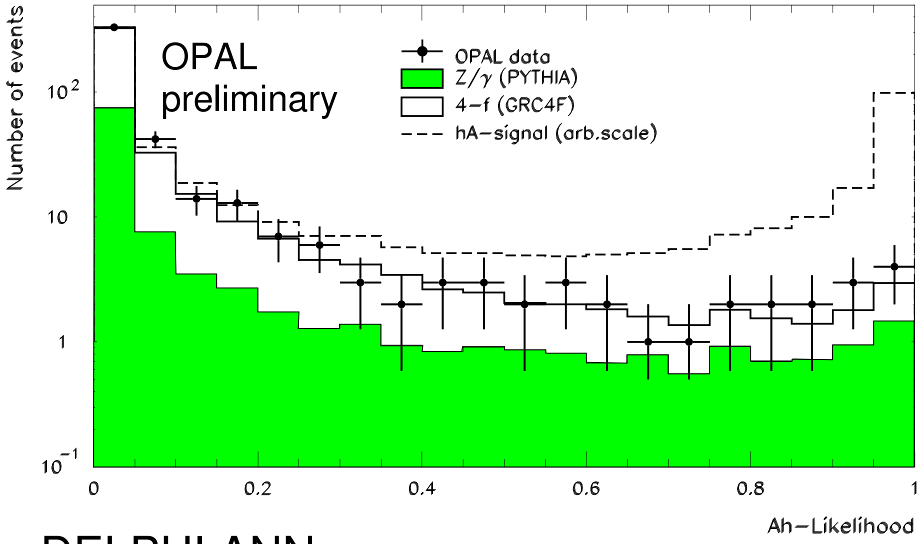
The hA $\rightarrow$ $b\bar{b}b\bar{b}$ - Channel

All analyses have a high level sophistication:

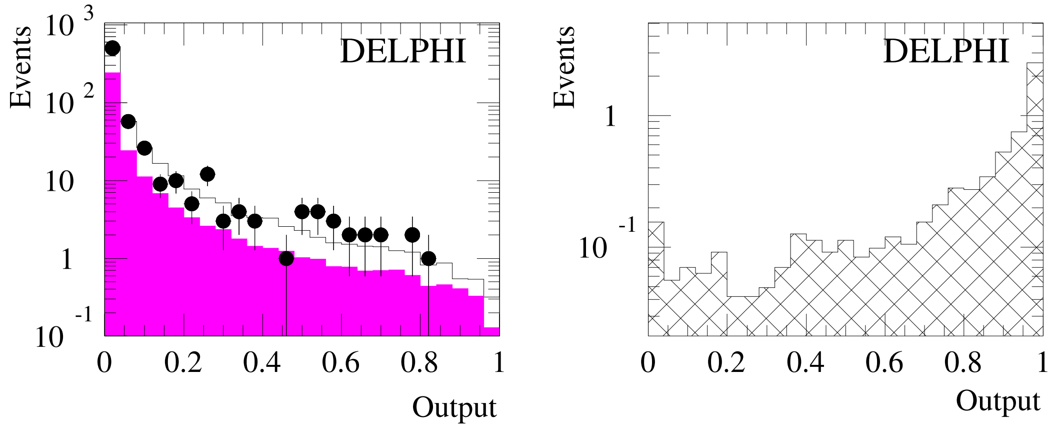
L3 Discriminant variable for hA→bbbb



OPAL likelihood

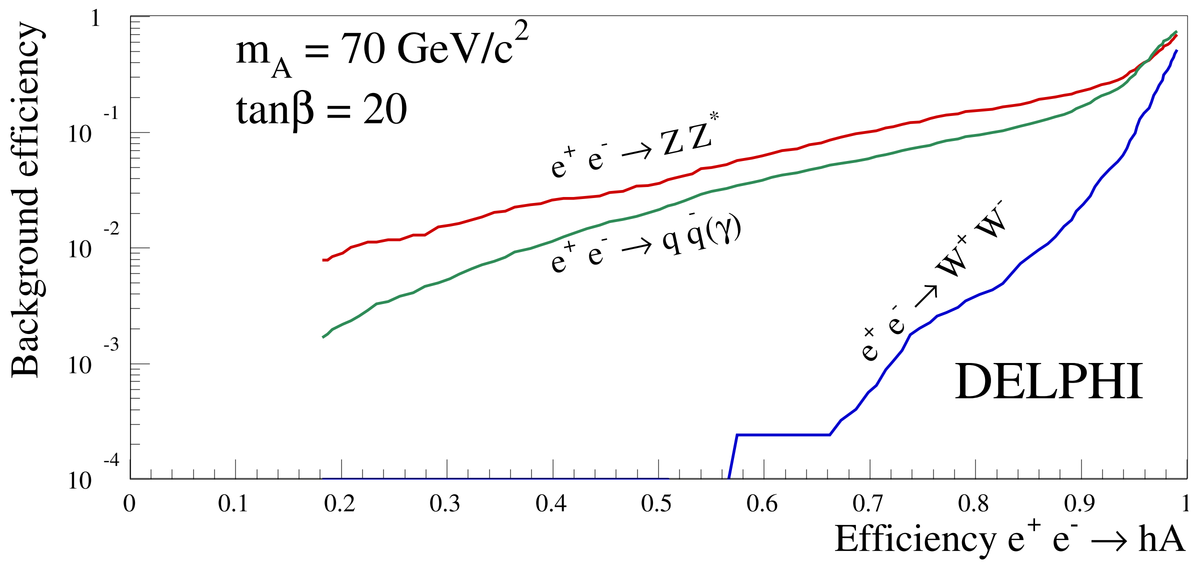


DELPHI ANN



The hA $\rightarrow$ $b\bar{b}b\bar{b}$ - Channel

B-tagging is the essential tool:



Performance of the analyses:

typical signal efficiency: 50-60%

typical remaining background: 30-60 fb

total (ADLO) candidates at 183 GeV: 11

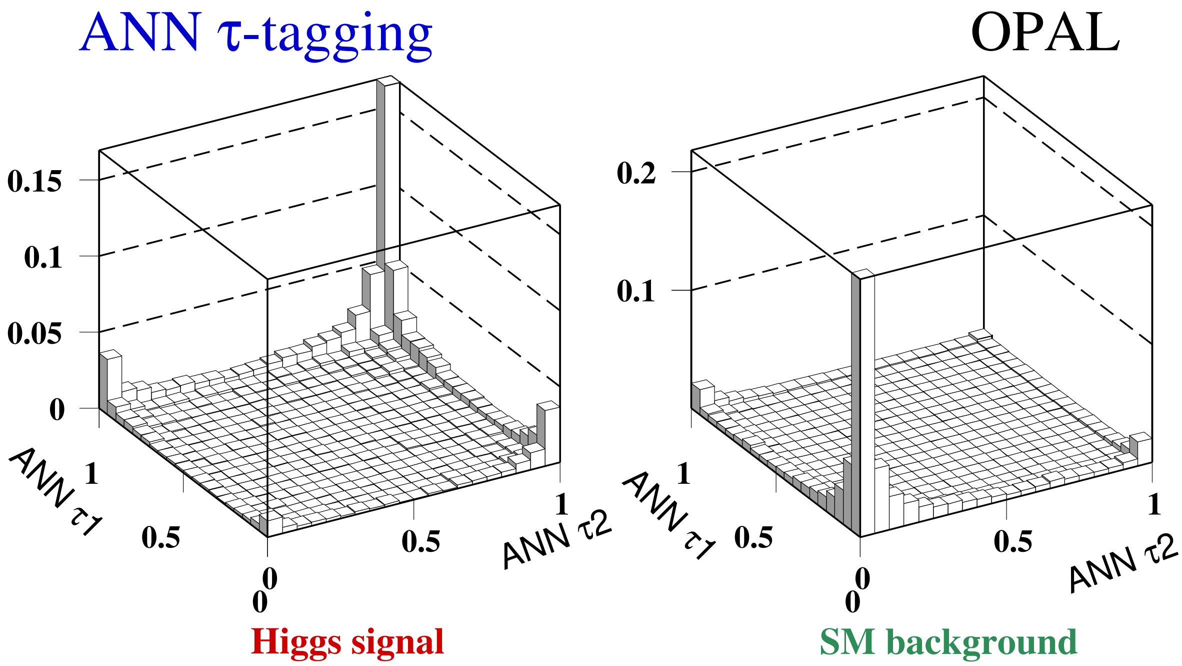
total (ADLO) exp. background at 183 GeV: 11.2
(count only events with discriminant $>$ 1 for L3)

total (ADO) candidates at 189 GeV: 7

total (ADO) exp. background at 189 GeV: 4.6
(L3 has also no excess at 189 GeV)

The hA $\rightarrow \mathrm{b\bar{b}}\tau\tau$ - Channel

Recent improvements in τ-tagging:



Performance of the analyses:

typical signal efficiency: 25-45%

typical remaining background: 2-20 fb

total (ADLO) candidates at 183 GeV: 3

total (ADLO) exp. background at 183 GeV: 2.5
(count only events with discriminant $>$ 0.2 for L3)

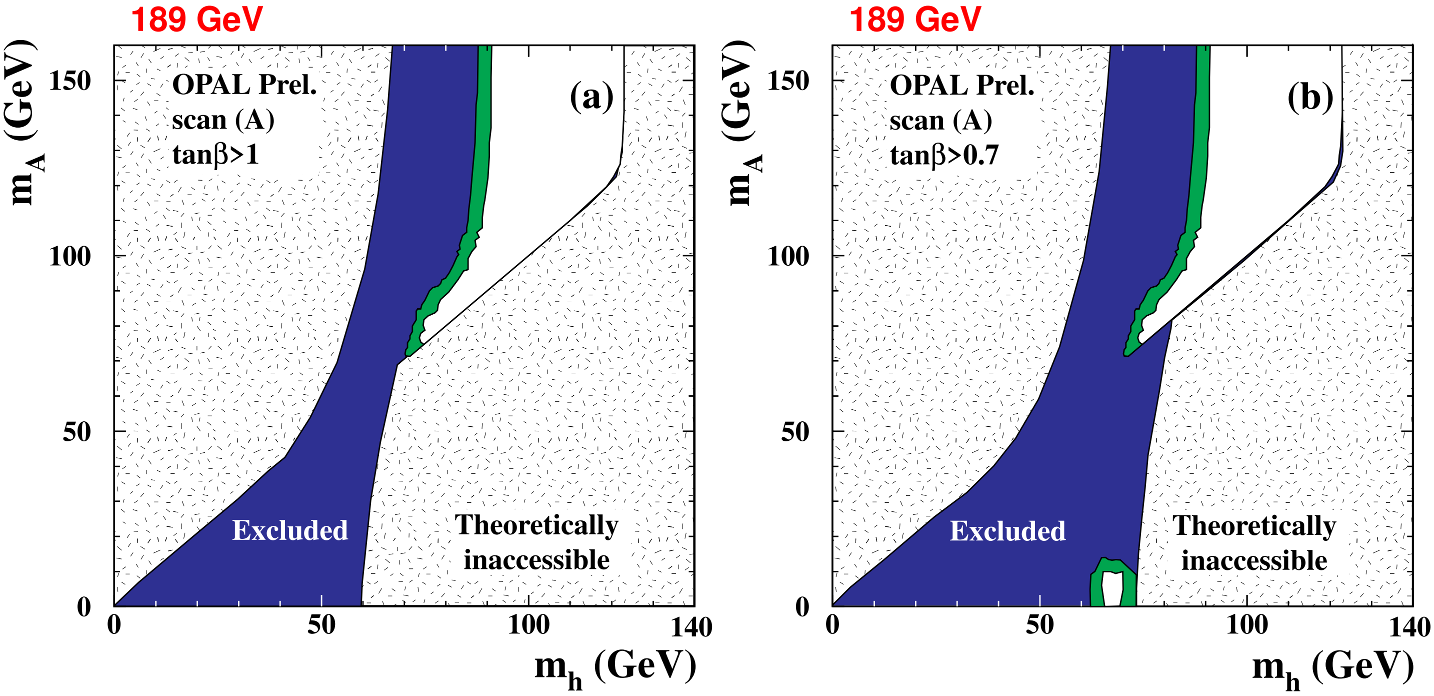
total (ADO) candidates at 189 GeV: 0

total (ADO) exp. background at 189 GeV: 1.4
(L3 has also no excess at 189 GeV)

Interpretation of MSSM Higgs Searches

"Benchmark" Scan:

- soft SUSY breaking masses fixed at 1 TeV
- minimal or maximal $\tilde{t}$-mixing
- $m_{\rm top}$ fixed at 175 GeV



Mass limits at 95% CL for $\tan\beta \geq 1$

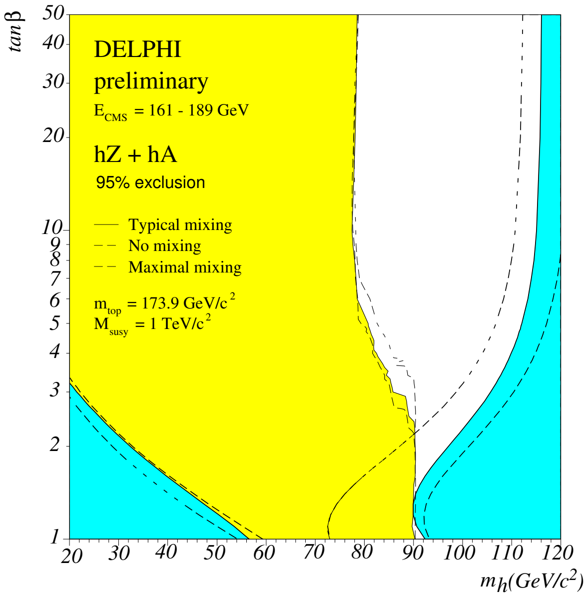
	183 GeV		189 GeV	
	$m_{\rm h}$	$m_{\rm A}$	$m_{\rm h}$	$m_{\rm A}$
ALEPH	72.2	76.1	79.7 *	79.7 *
DELPHI	74.4	75.3	77.5	78.3
L3	70.7	71.0	74 **	74 **
OPAL	70.5	72.0	73.5	74.5

* from hA search only

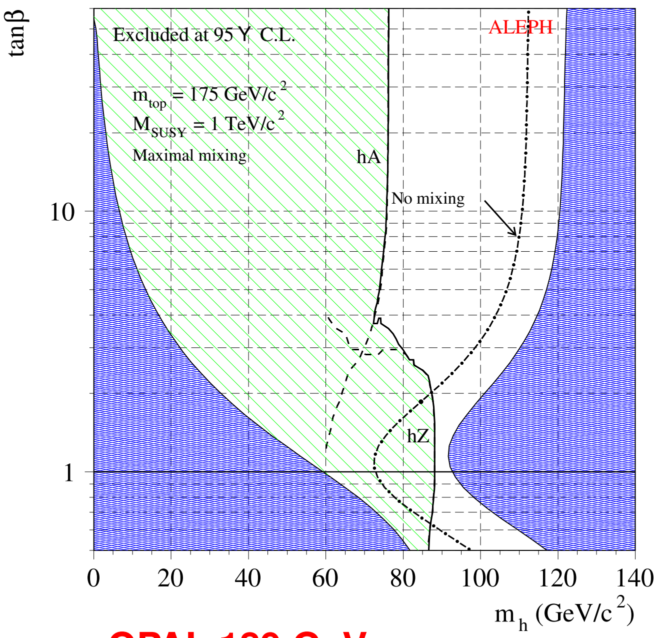
** from low $\tan\beta$ search only

"Benchmark" Scan: Another "View"

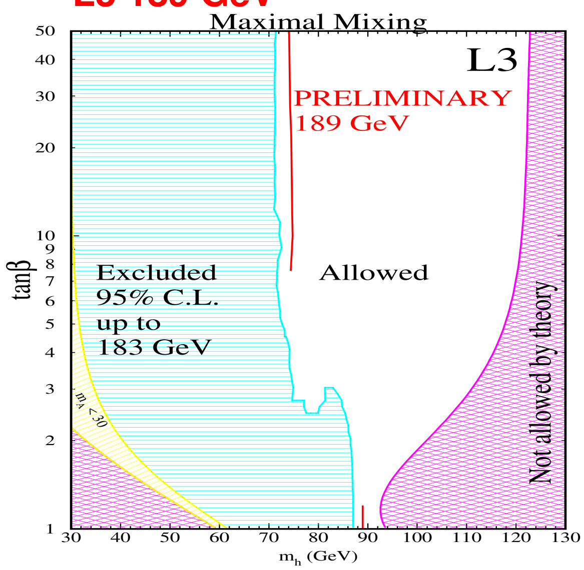
DELPHI 189 GeV



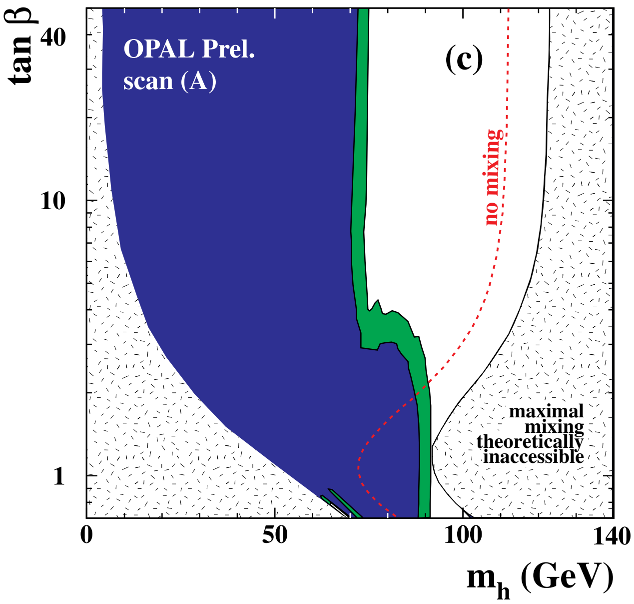
ALEPH 183 GeV



L3 189 GeV



OPAL 189 GeV



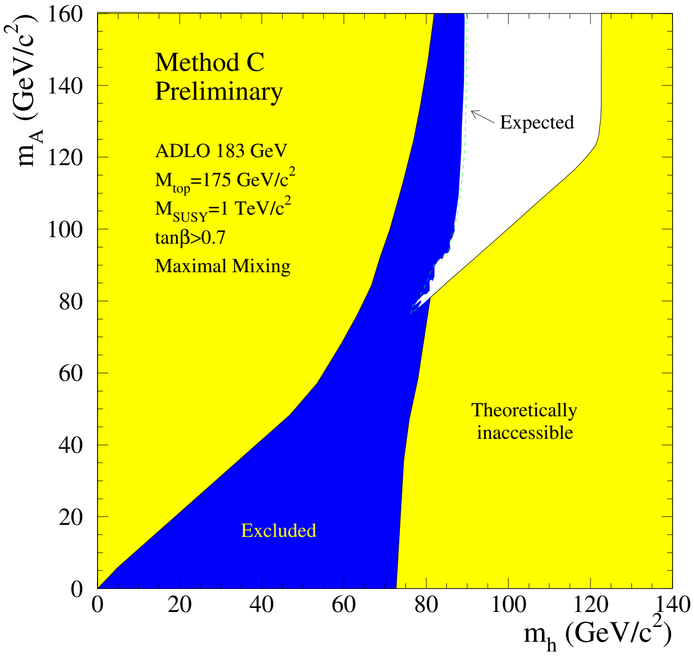
All experiments start to exclude a range in $\tan\beta$ around 1 for no $\tilde{t}$-mixing and m_{top} = 175 GeV
However, no exclusion for maximal mixing and/or m_{top} = 185 GeV

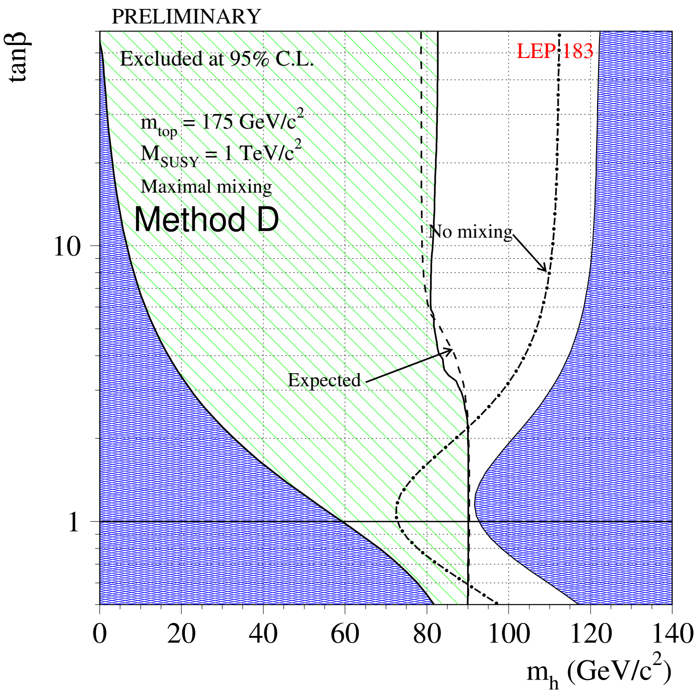
low-$\tan\beta$ infra-red fixed-point solution (soon) in trouble...?

LEP-wide Combination

Absolute limits on m_{h} and m_{A} (at large $\tan\beta$) are well below the kinematic limit $\longrightarrow$ more luminosity helps!

LEP Higgs Working Group has performed the first prel. combination of MSSM neutral Higgs searches with data from all experiments up to 183 GeV for this conference:





$$\boxed{m_{\mathrm{h}} > 77\ \text{GeV},\ m_{\mathrm{A}} > 78\ \text{GeV}}$$

95% CL

$$\boxed{\tan\beta < 0.8 \text{ or } \tan\beta > 2.1}$$

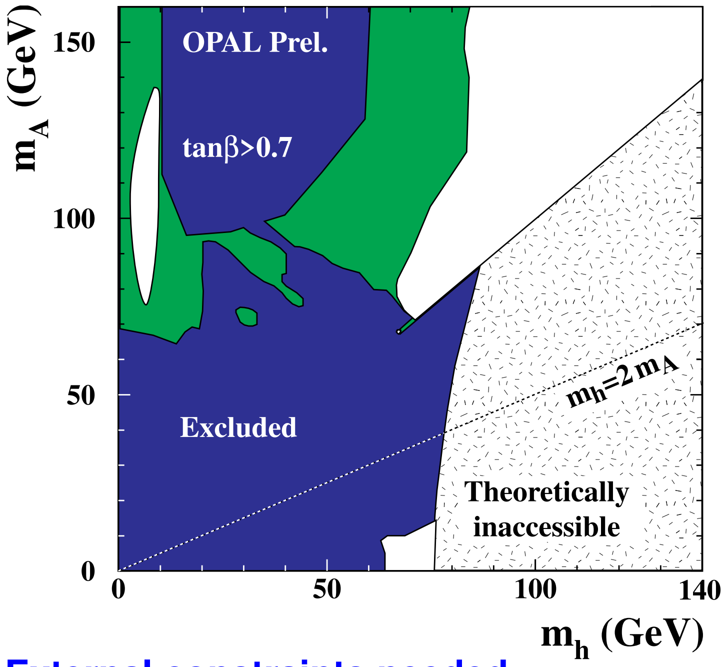
for no mixing, $m_{\mathrm{top}} = 175$ GeV

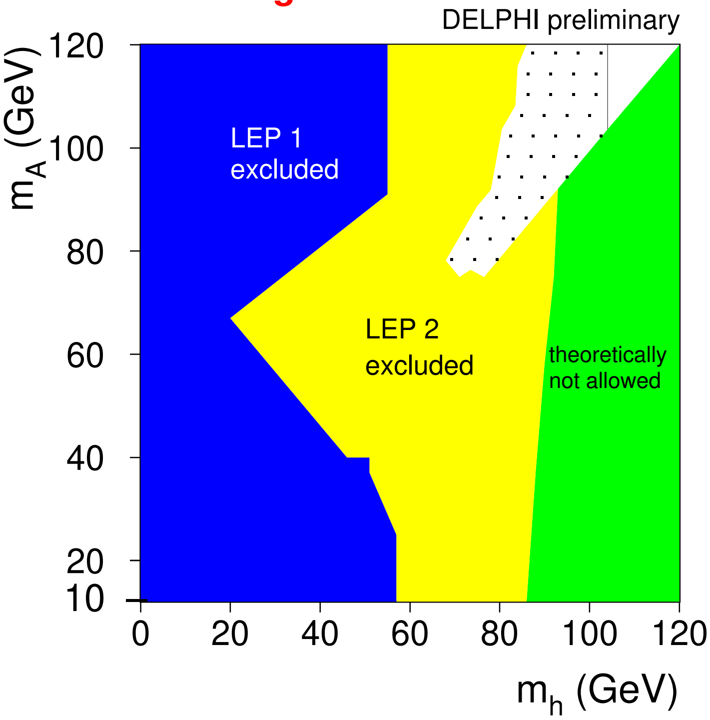
95% CL

Beyond the "Benchmark": General MSSM Scans

OPAL,DELPHI and ALEPH have performed a more thorough examination of the MSSM parameter space

Do the "benchmark" limits hold when mixing parameters and SUSY masses are no longer fixed?





External constraints needed:

- **Protection against Charge+Color breaking minima (OPAL, green area)**
- **Constraints from $\mathrm{b} \rightarrow \mathrm{s}\gamma$ and $\Delta\rho$ (DELPHI)**
- **Constraints from direct $\tilde{\chi}^0$- and $\tilde{\mathrm{t}}$-searches (DELPHI,OPAL,ALEPH)**

What do we learn?

- **All experiments found, that some "pathological??" parameter sets for m_h lower than the "benchmark" limits are unexcludable.**
- **They are typically at simultaneously large $|A_t|$ and $|\mu|$, with small $\sin^2(\beta-\alpha)$ (tiny hZ prod.) and heavy A (no hA prod.)**

Conclusions from the experiments:

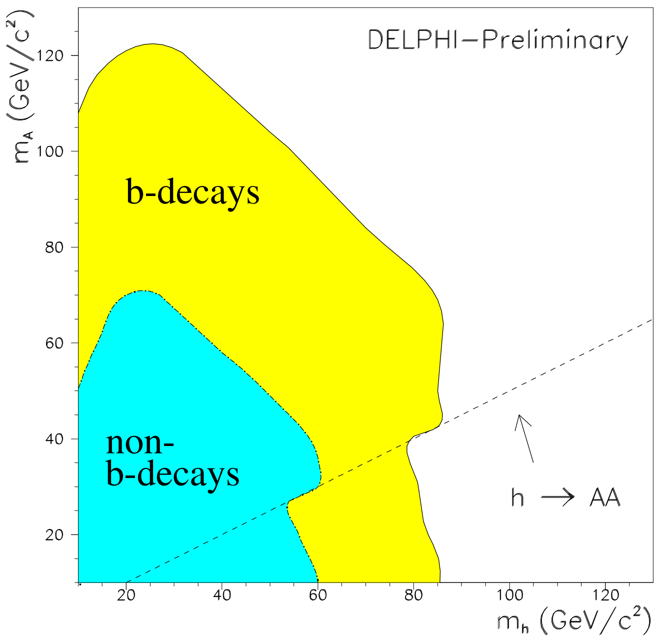
DELPHI,OPAL: absolute mass limits are lowered by 5-10 GeV w.r.t. benchmark.

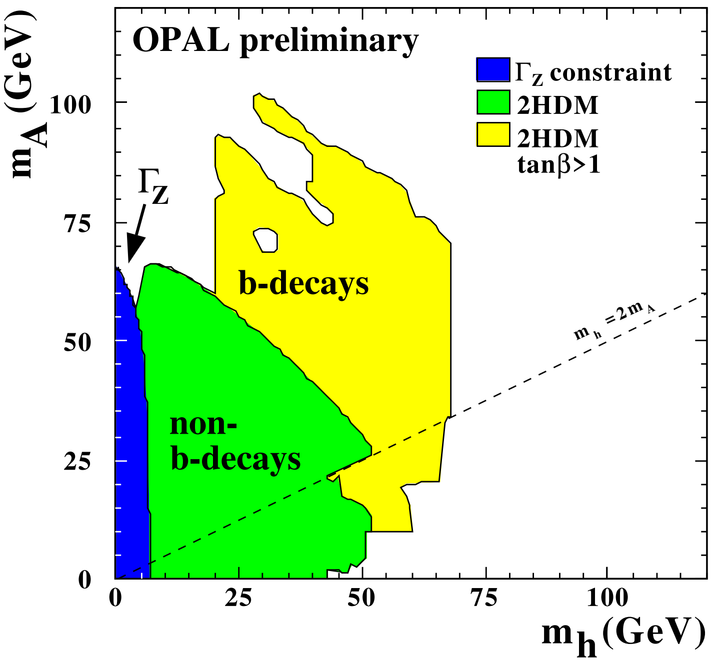
ALEPH: For 99.99% (99.9%) of explored param. sets benchmark limits remain valid at low (high) $\tan\beta$

Two-Higgs-Doublet Models

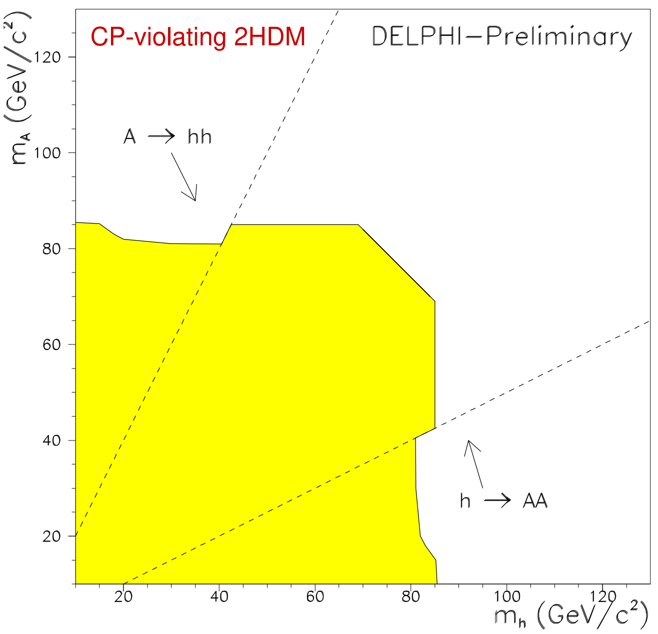
Searches for h^0Z^0 and h^0A^0 production can be interpreted in general Two-Higgs-Doublet Models (2HDM):

$$\sigma_{hZ} = \sin^2(\beta-\alpha)\,\sigma^{SM}_{HZ} \qquad \sigma_{hA} = \cos^2(\beta-\alpha)\,\bar{\lambda}\,\sigma^{SM}_{\nu\bar{\nu}}$$





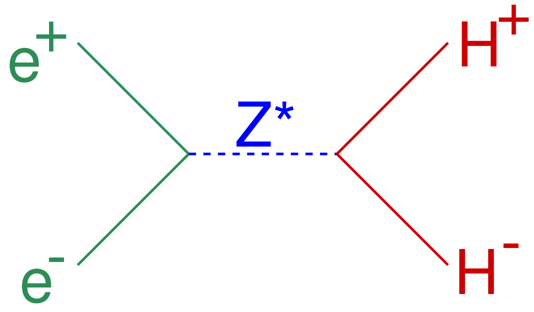
CP-violating model with hZ-, Ah- and ZA-coupling:



Assumption:

$$C^2_{hZ} + C^2_{Ah} + C^2_{AZ} = 1$$

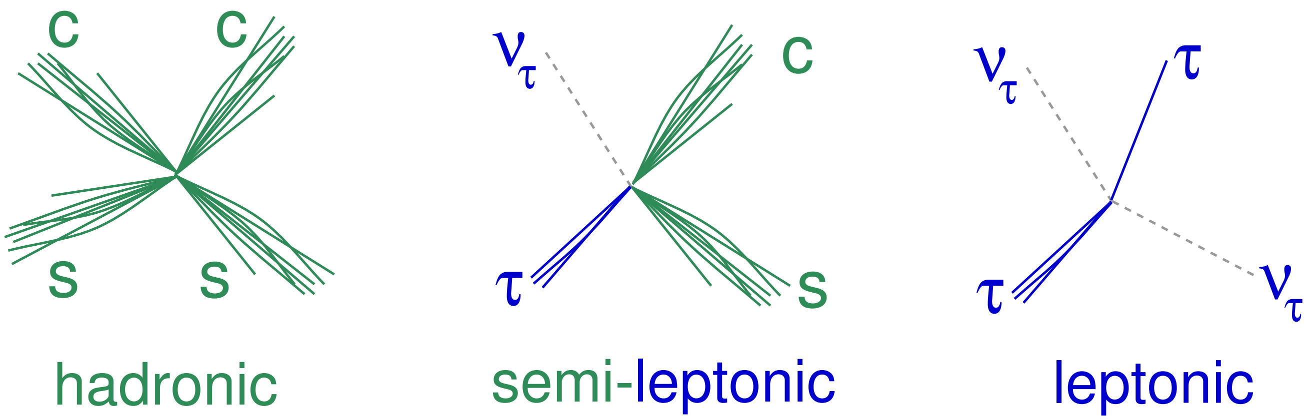
Charged Higgs



Why search for it ?

- in the MSSM at tree-level: $m_{\mathrm{H}^\pm} > m_{\mathrm{W}^\pm}$ $\longrightarrow$ not (yet?) accessible at LEP2
- rad. corrections sometimes yield $m_{\mathrm{H}^\pm} < m_{\mathrm{W}^\pm}$
- relevant mostly at $\tan\beta < 1$
- some models exist which predict light $\mathrm{H}^\pm$

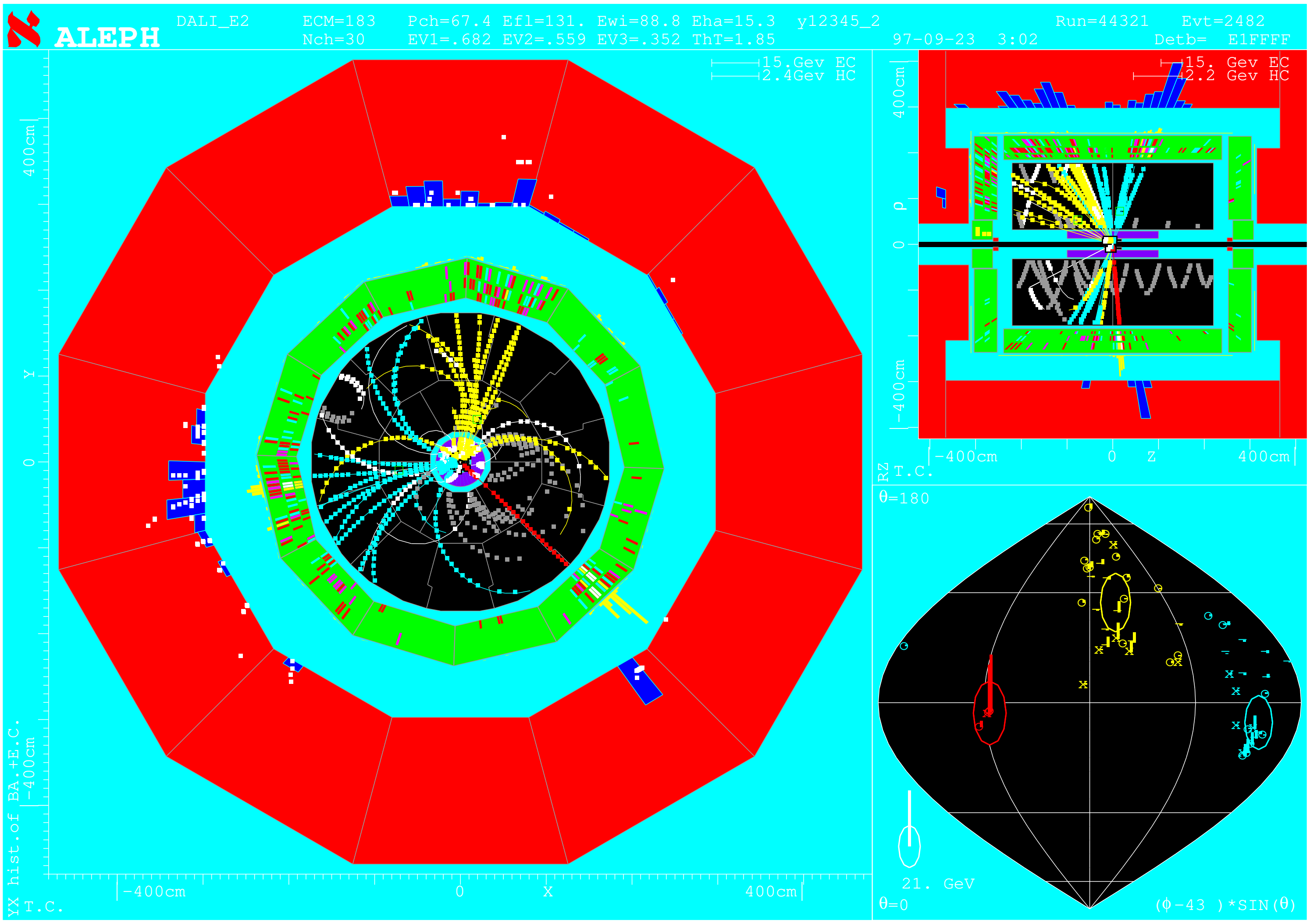
Final states:



Experimentally challenging

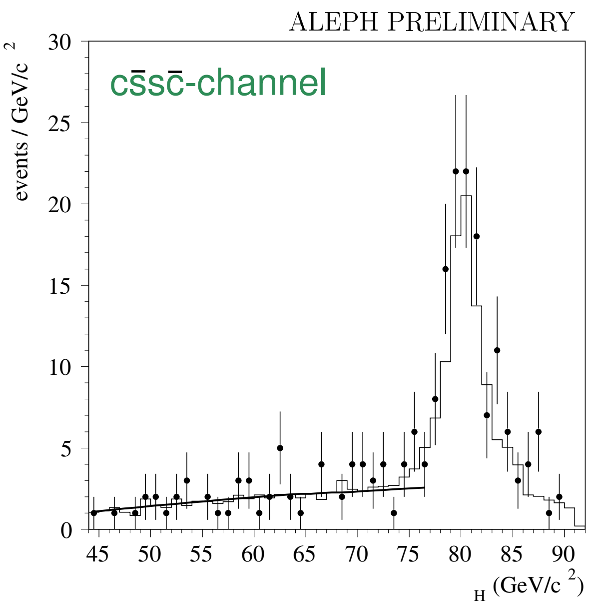
W-pair pair production is very hard to suppress

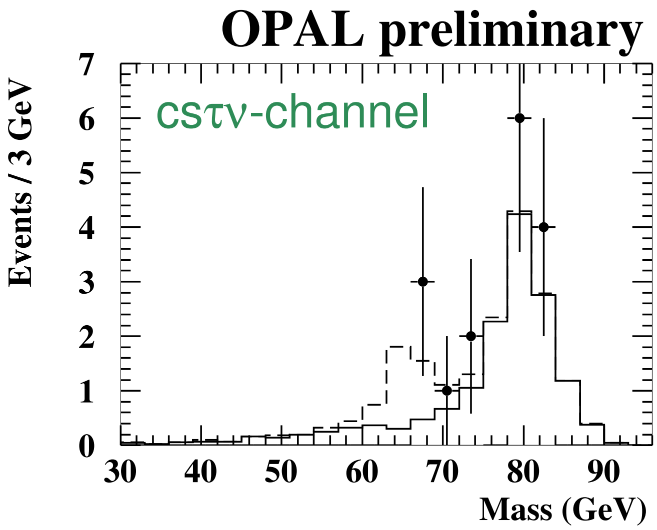
Charged Higgs: a Candidate

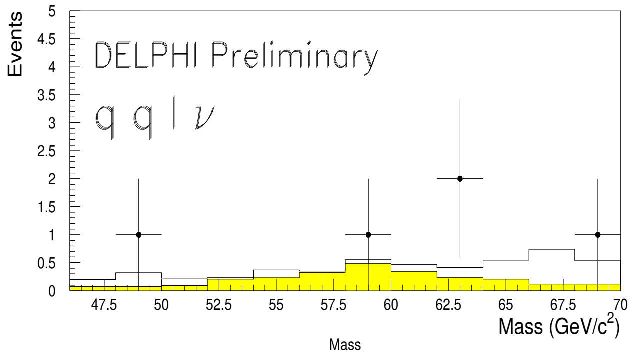


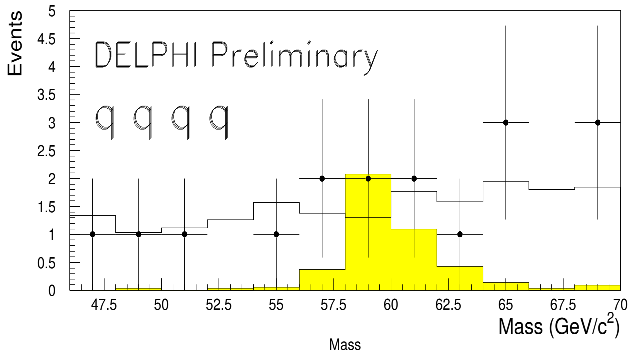
Charged Higgs: Mass Distributions

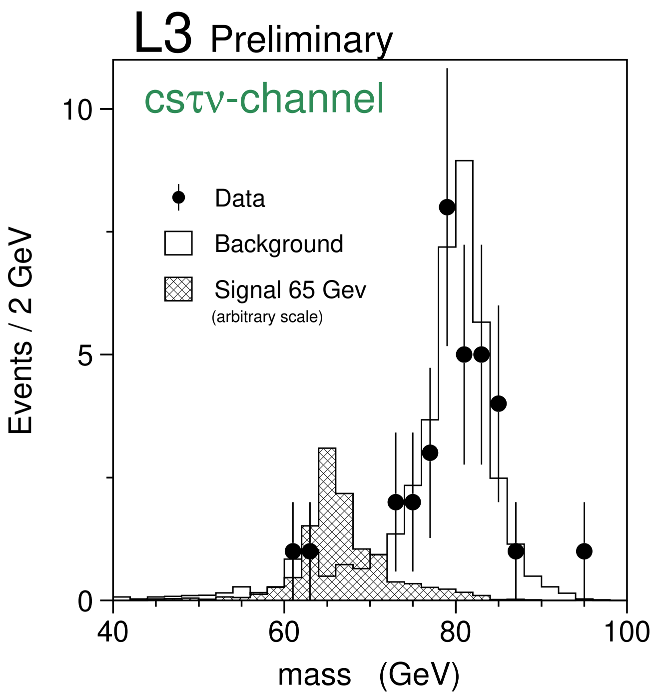
183 GeV results:





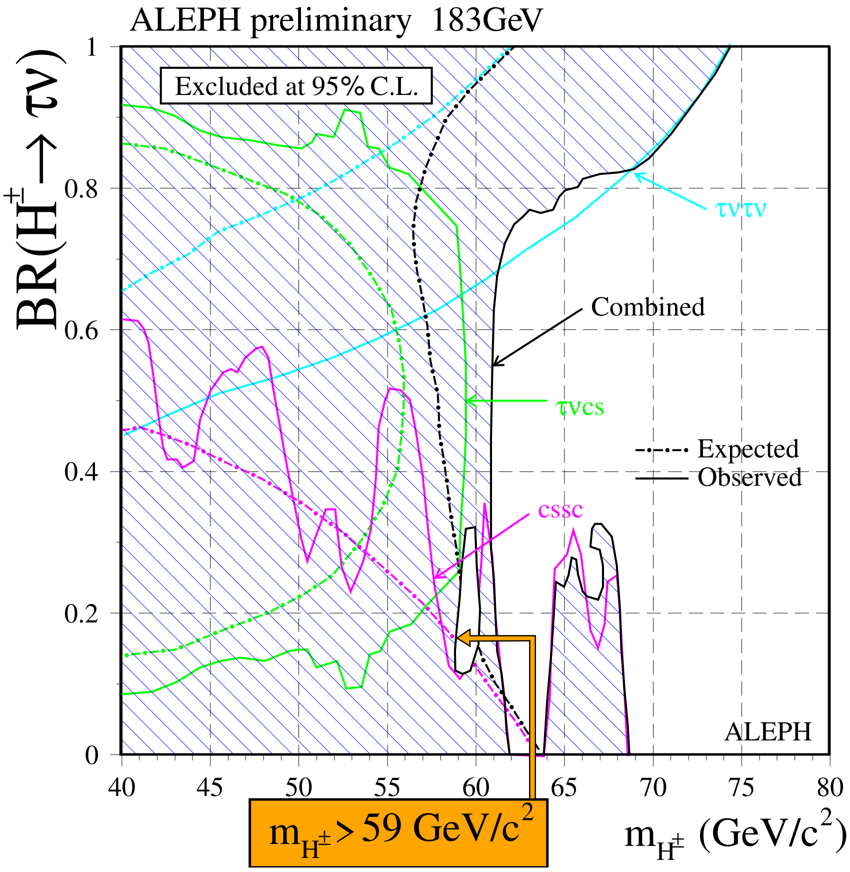






Charged Higgs: Mass Limits

All 4 experiments have updated results,example:



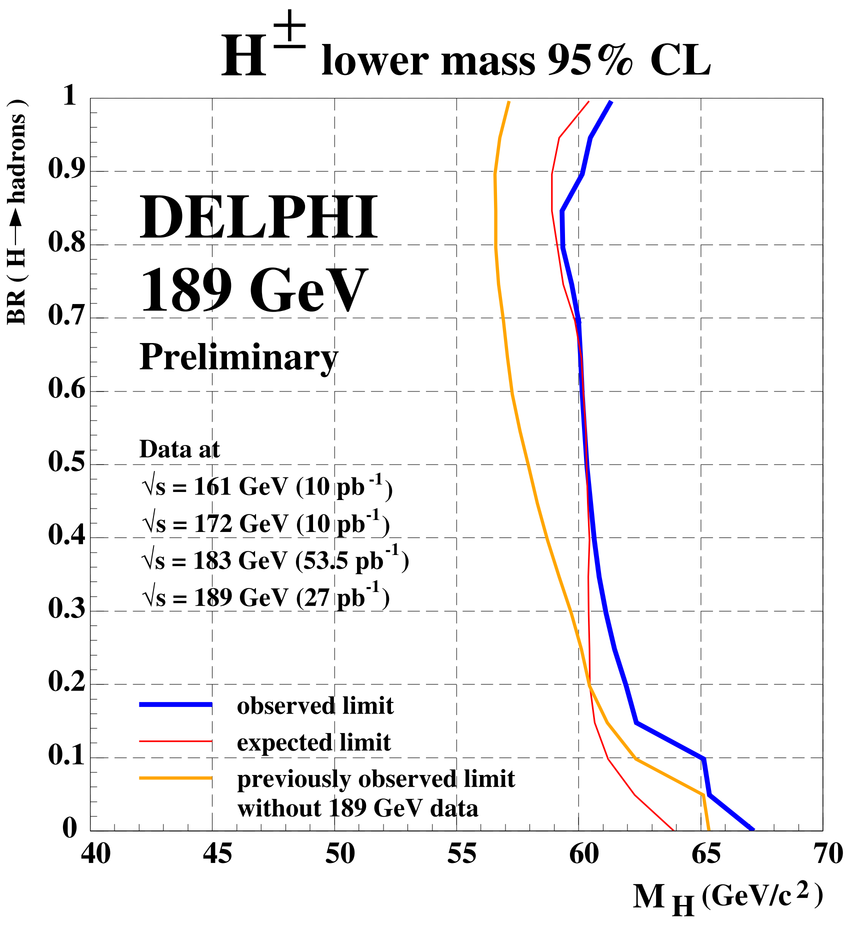
ALEPH	$m_{\mathrm{H}^\pm} > 59$ GeV	
L3:	$m_{\mathrm{H}^\pm} > 57$ GeV	all at 95% CL
DELPHI	$m_{\mathrm{H}^\pm} > 56.5$ GeV	183 GeV
OPAL	$m_{\mathrm{H}^\pm} > 56$ GeV	

independent of $\mathrm{BR}(\mathrm{H}^\pm \to \tau\nu_\tau)$

assuming $\mathrm{BR}(\mathrm{H}^\pm \to \tau\nu_\tau) + \mathrm{BR}(\mathrm{H}^\pm \to \mathrm{q\bar{q}'}) = 1$

Charged Higgs: 189 GeV Update

Delphi has already updated with 189 GeV data:



DELPHI $m_{\mathrm{H}^\pm} > 59.2$ **GeV** at 95% CL

independent of BR $(\mathrm{H}^\pm \to \tau\nu_\tau)$

assuming $\mathrm{BR}(\mathrm{H}^\pm \to \tau\nu_\tau) + \mathrm{BR}(\mathrm{H}^\pm \to \mathrm{q\bar{q}'}) = 1$

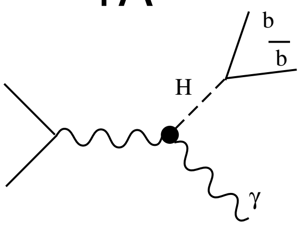
Higgs and Photons

in the SM: no Higgs-Photon coupling but beyond SM
there might be effective HZγ- and Hγγ-couplings.

"fermiophobic Higgses"→large B(H→γγ) for $m_H \lesssim 100$ GeV

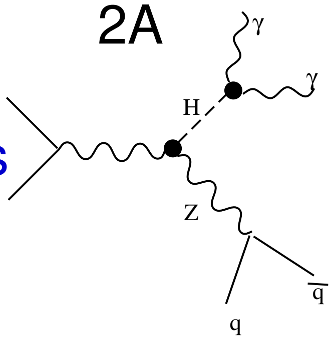
1A

1 photon

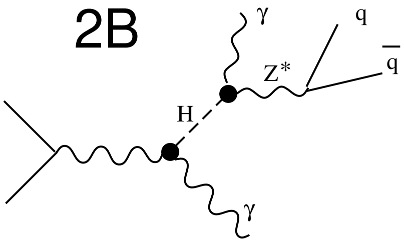


2A

2 photons

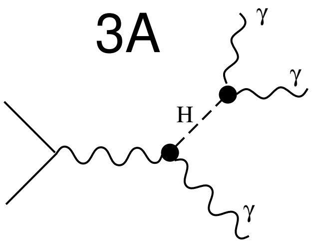


2B



3A

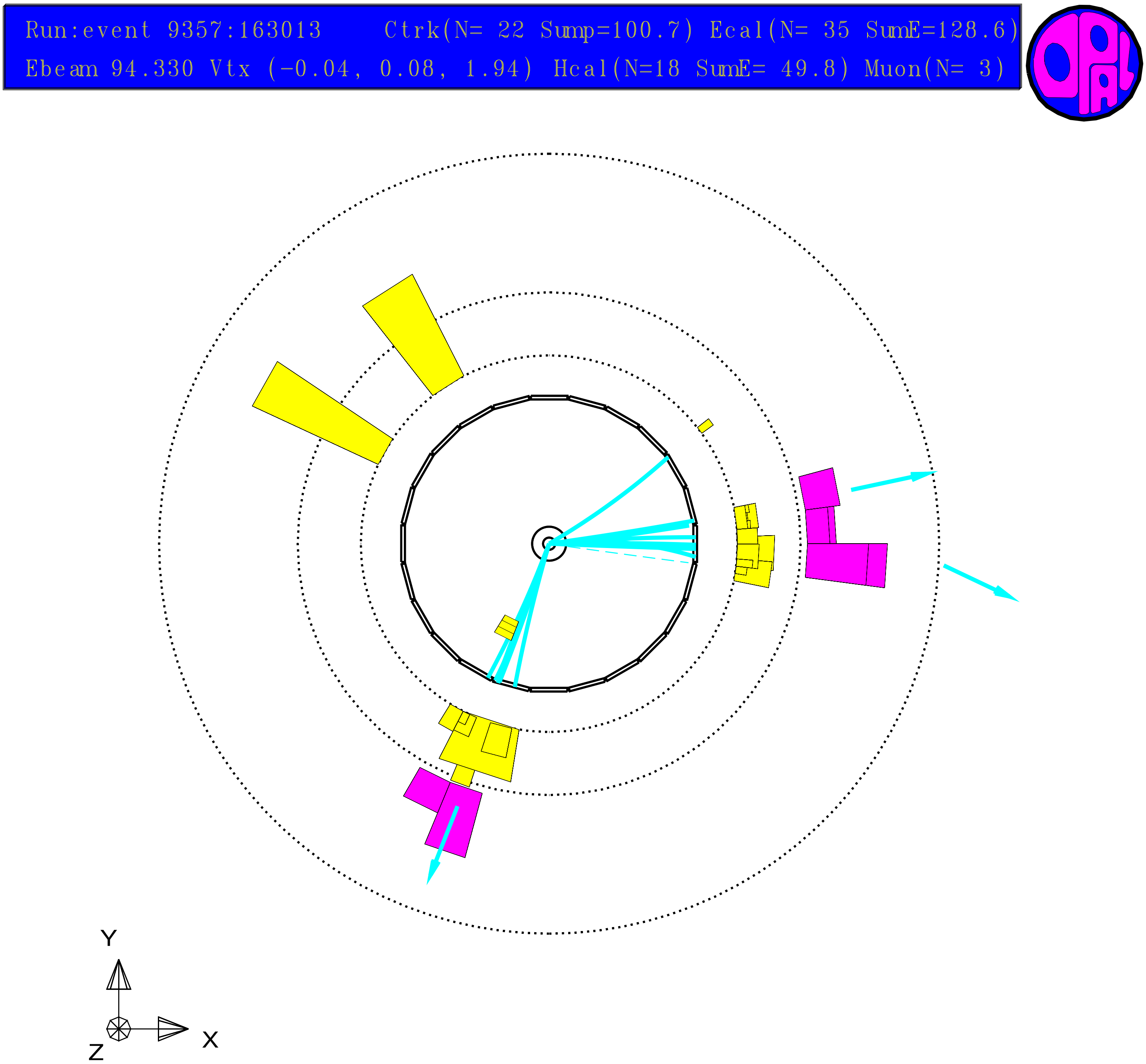
3 photons



DELPHI: search for 1A,2A,2B,3A
interpretatation in terms of anomalous couplings

OPAL: search for 2A for all Z-decays + "hA→γγf$\bar{f}$"

Higgs and Photons: a Candidate



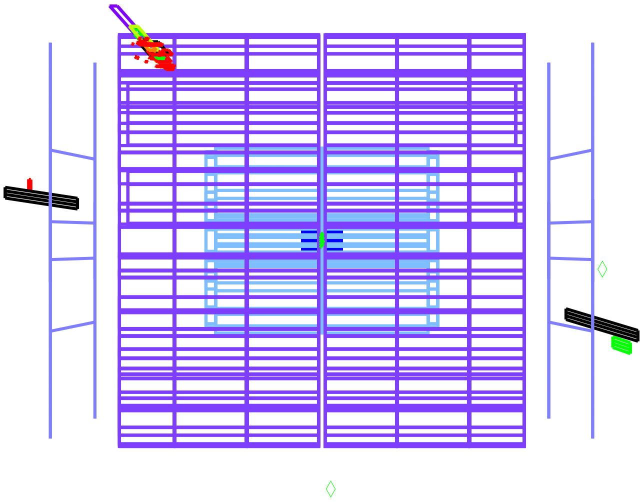
$$m_{\gamma\gamma} = 57.6 \pm 2.1 \text{ GeV}$$

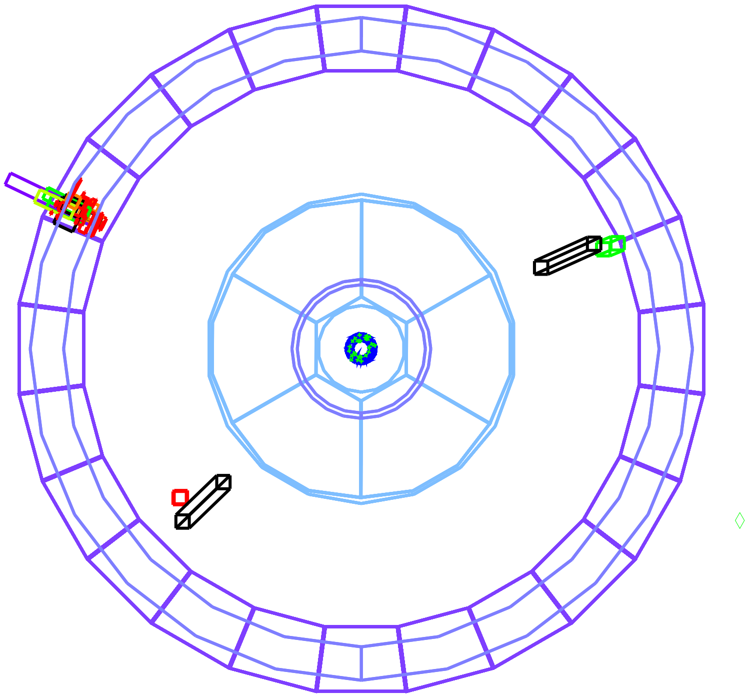
$$m_{\text{hadr}} = 77.4 \pm 5.2 \text{ GeV}$$

Higgs and Photons: Another Candidate

DELPHI

183 GeV





$$m_{\gamma\gamma} = \textbf{163 GeV}$$

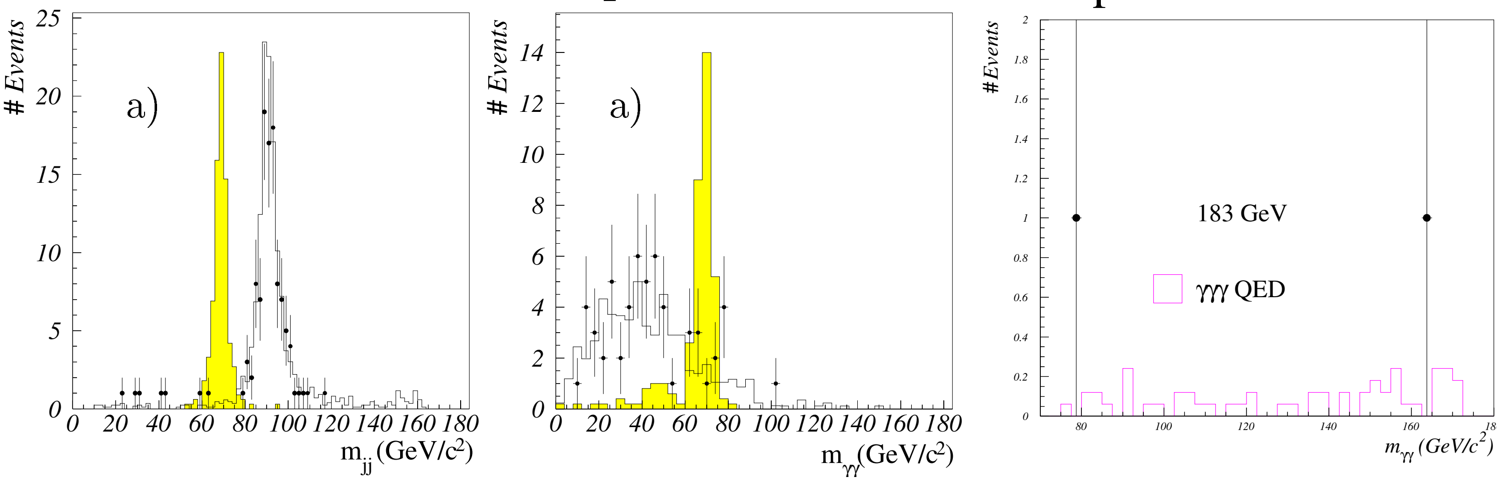
$$m_{\gamma\gamma} = \textbf{78 GeV}$$

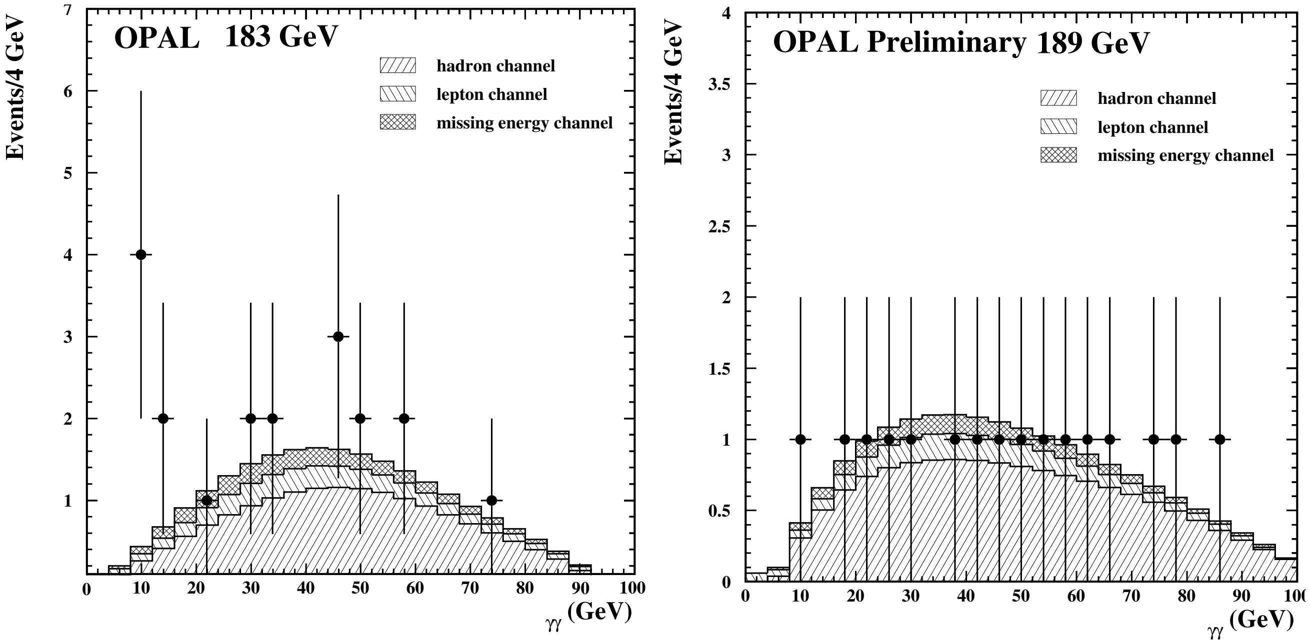
$$m_{\gamma\gamma} = \textbf{29 GeV}$$

Higgs and Photons

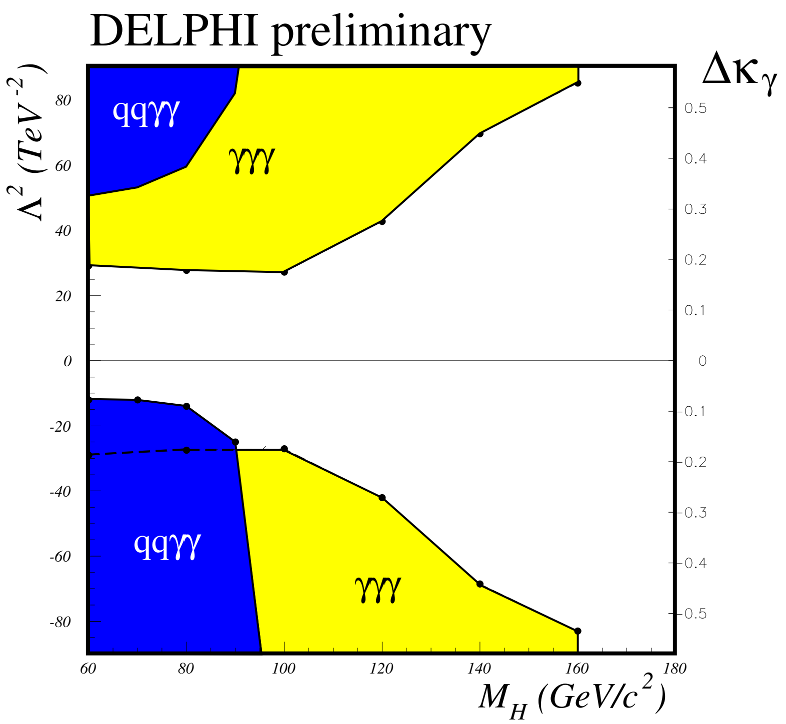
DELPHI Preliminary - 183 GeV

1 photon | 2 photons | 3 photons

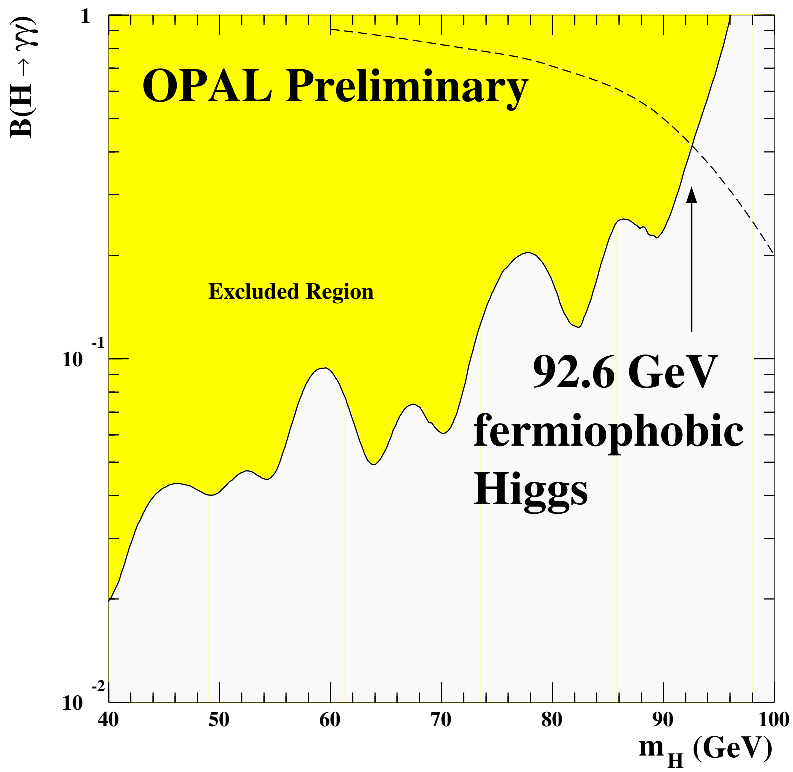




Higgs and Photons

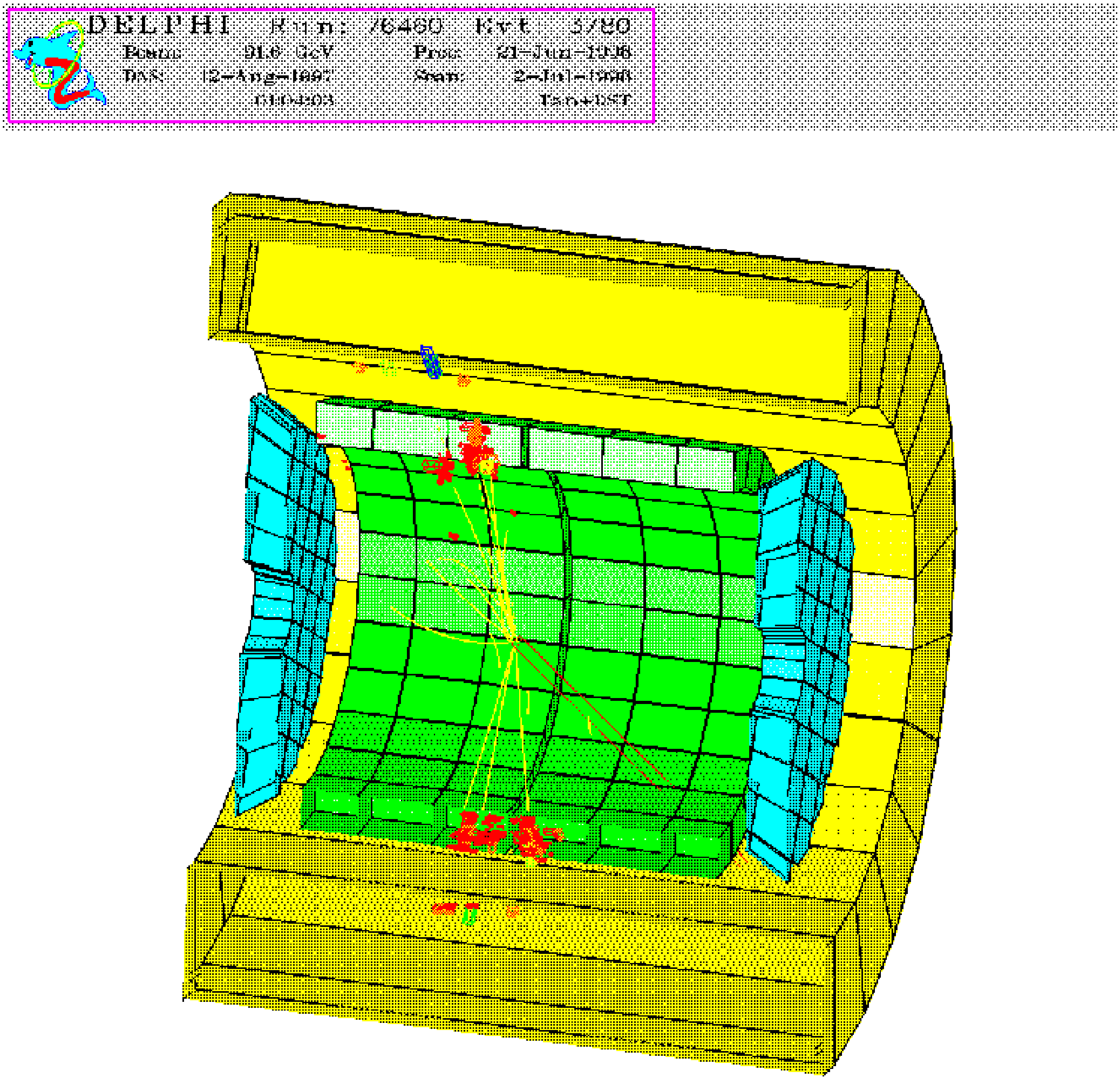


limits on
anomalous couplings
assuming they are
all equal



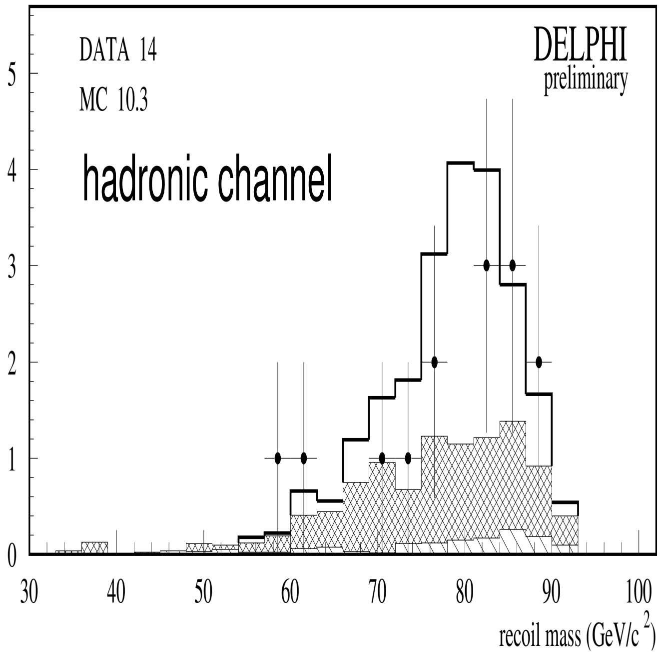
limit on BR(H$\longrightarrow \gamma\gamma$)
assuming SM production

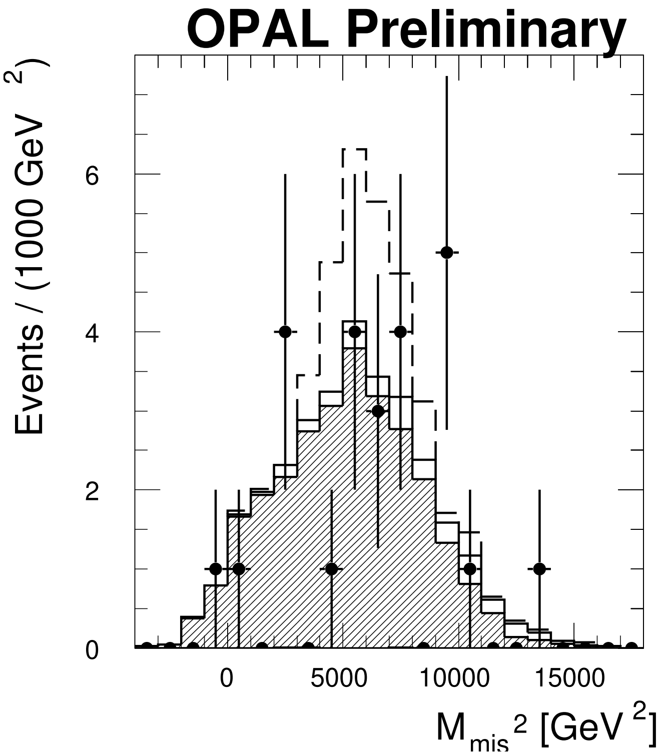
Invisible Higgs: a Candidate

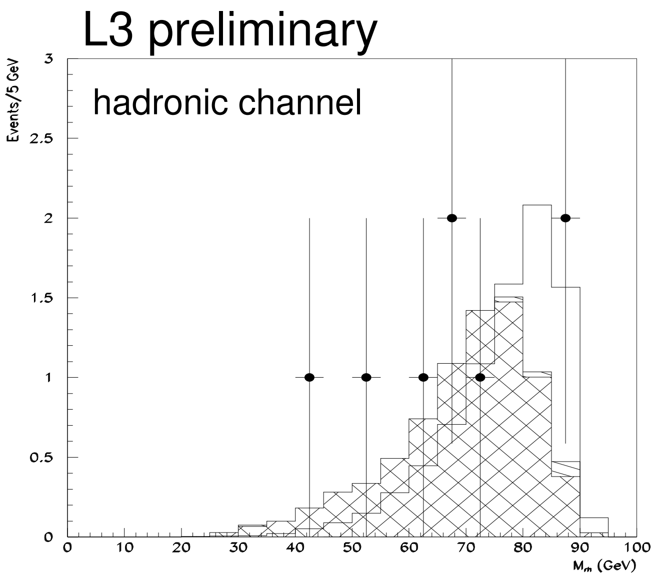


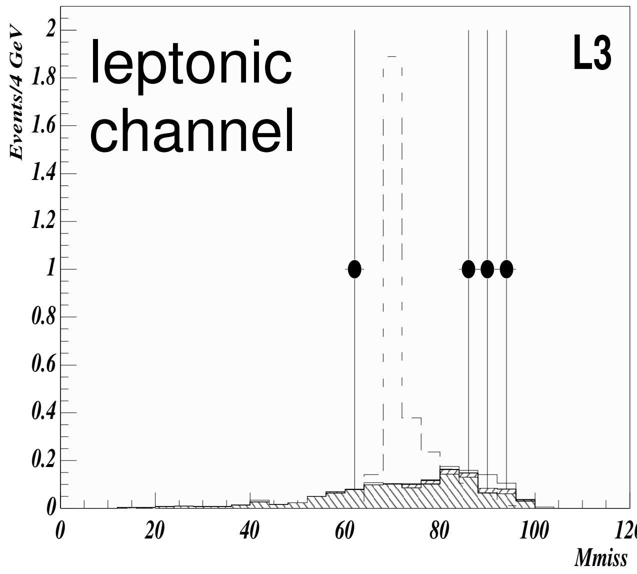
$$m_{\rm vis} = 90.3\,\rm GeV \quad m_{\rm inv} = 87.8\,\rm GeV$$

Invisible Higgs: Mass Distributions



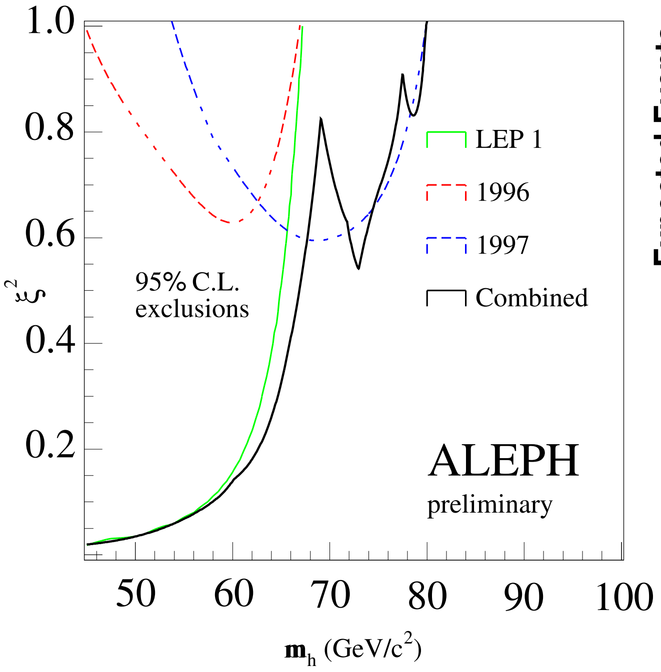


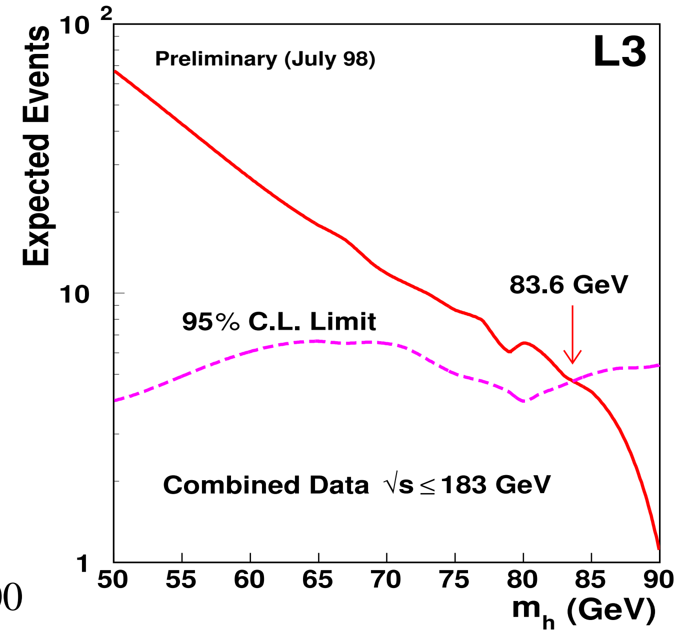


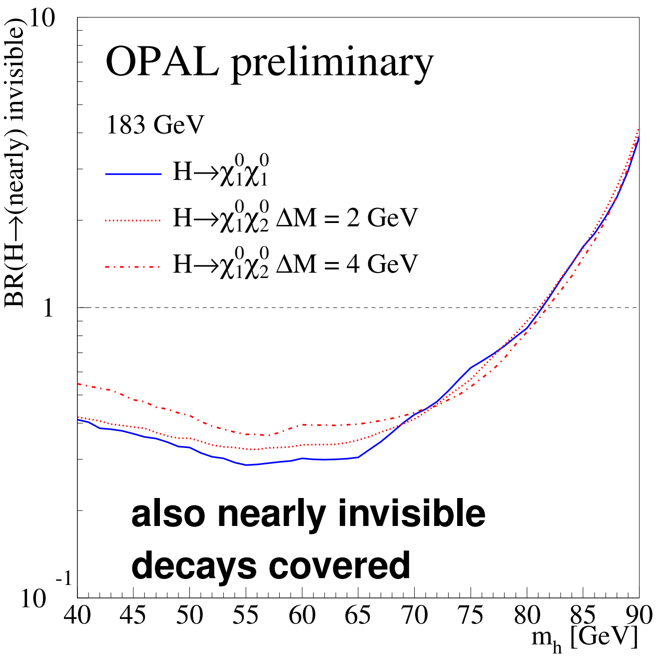


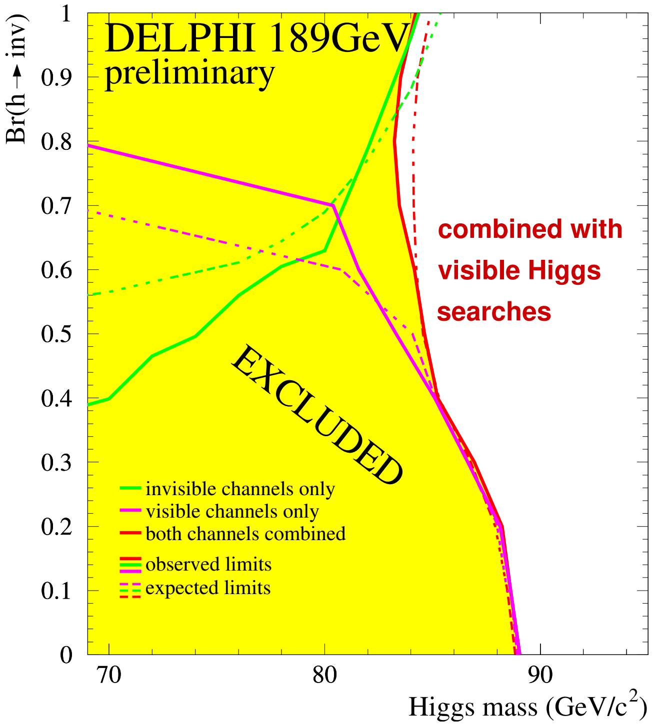
ALEPH: use b-tagging in hadronic channel → very low background

Invisible Higgs: Limits









Mass limits	**ALEPH**	**80 GeV**	**L3**	**83.6 GeV**
	DELPHI	**84.3 GeV (189 GeV)**	**OPAL**	**81 GeV**

all at 95% CL and for SM-production and BR ($H \to$ invisible) $= 1$

Summary/Conclusion

- The four LEP experiments presented new searches for non-SM Higgs bosons
- The searches are sensitive to basically any possible Higgs final state (fermions,photons,invisible decays)
- No signal has been observed $\longrightarrow$ new mass limits:

MSSM "Benchmark": $m_\mathrm{h} > 77$ GeV
$m_\mathrm{A} > 78$ GeV
$m_{\mathrm{H}^\pm} > 59$ GeV

LEP-combined
beginning to be
superseded by 189 GeV data

- Only a small part in MSSM parameter space is left for low $\tan\beta$-solution
- Limits are lower for general MSSM scan
- Much more data to come:

the LEP Higgs searchers are ready
to become Higgs finders...