Higgs Results from LEP2

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January 24, 2002
WIN '02

No Higgs?

In December, 2001, New Scientist wrote:

"The legendary particle that physicists thought explained why matter has mass probably does not exist"

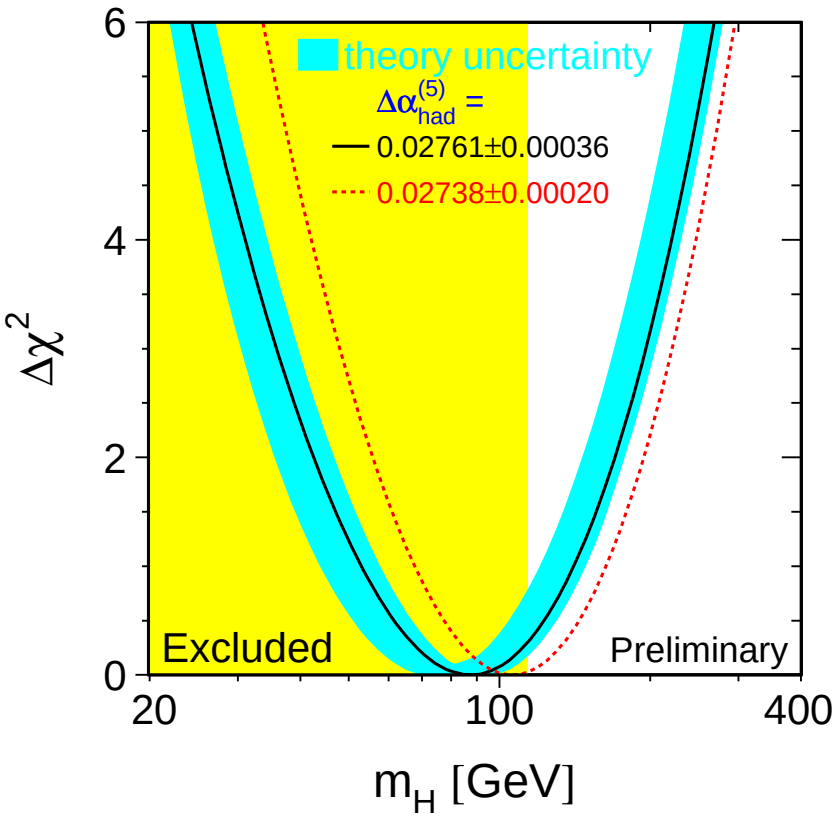
This prompted a Times article claiming:

"... the whole investigation has been a wild goose chase."

Has LEP demonstrated that the Higgs does not exist??

Electroweak Predictions

New Scientist's claim was based on the LEP Electroweak Working Group fit



$m_H = 88^{+53}_{-35}$ GeV From EW fit

Direct Search Limit: $m_H > 114.1$ GeV

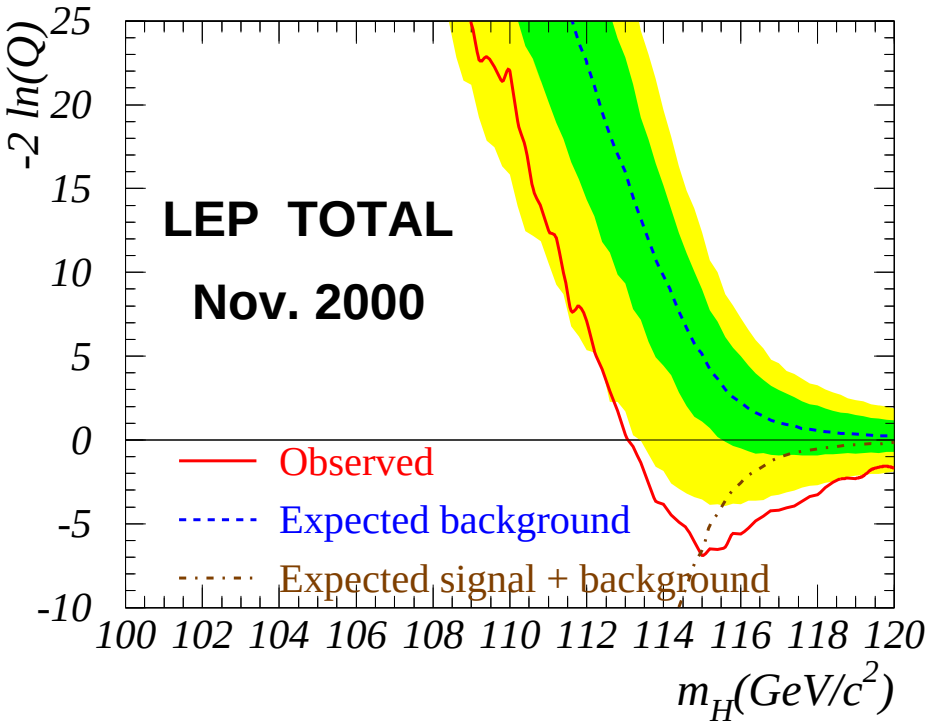
BUT

EW fit upper limit: $m_H < 196$ GeV

Still some room for a Higgs boson!

Direct Searches

Additionally, in November 2000, LEP reported a 2.9 sigma excess in the Higgs search



The data was consistent with the presence of a Higgs boson of mass 115 GeV

How does this lead to claim that there is no Higgs?

Take a closer look at the Higgs search

LEP

For the last several years,
the Large Electron-Positron Accelerator (LEP)
outside Geneva, Switzerland has been
used to search for the Higgs boson.

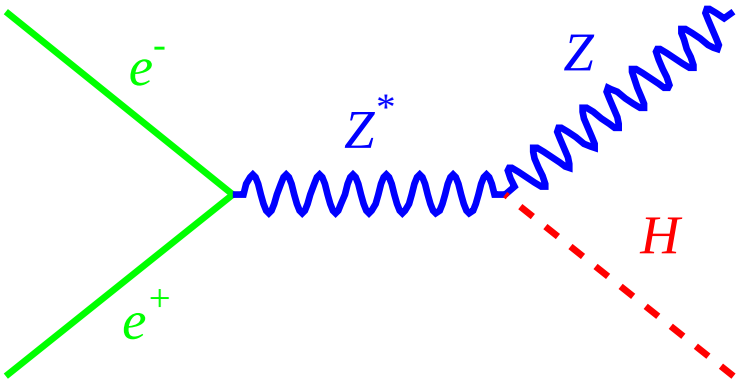
LEP has been run with steadily increasing collision energy, and thus Higgs mass sensitivity, since 1996.

Year	Energy (GeV)	Lower Limit (GeV/c^2)
< 1995	91.2	65
1996	161-172	78
1997	183	90
1998	189	95
1999	192-202	108
2000	202-208	???

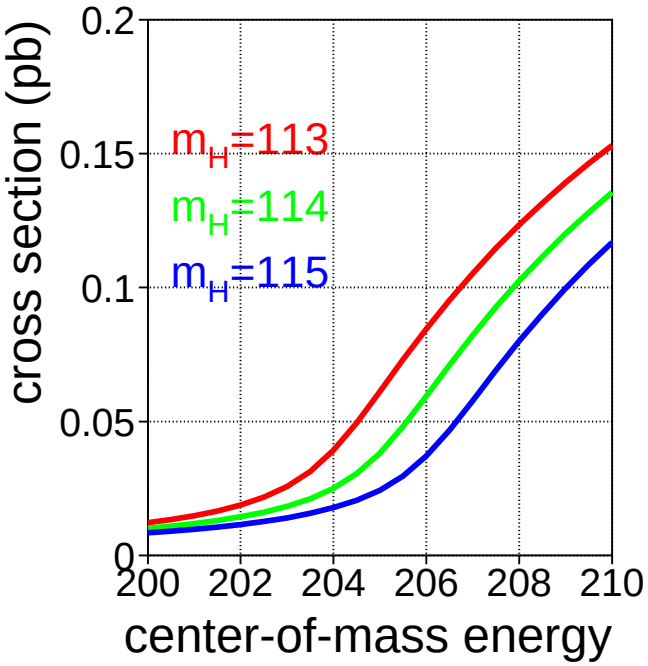
After 11 very successful years of operation,
LEP was shut down in November 2000.

Higgs Production

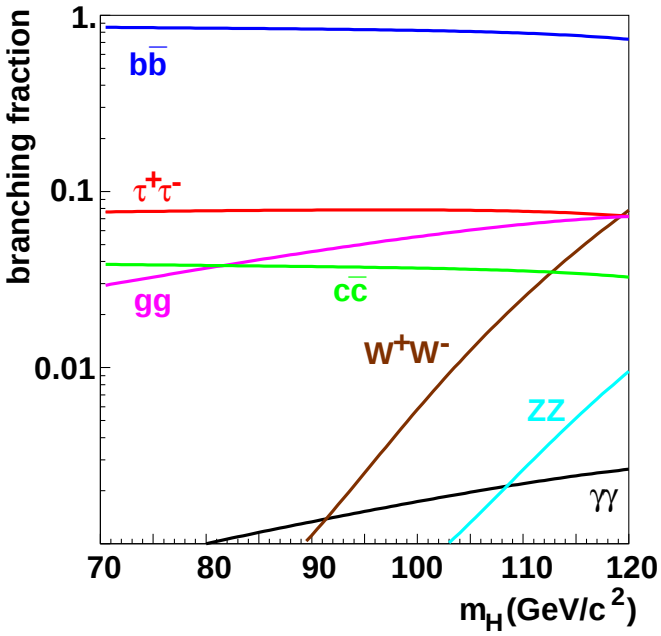
At LEP, Higgs is predominantly produced via the Higgs-strahlung process



Because of need to produce Z Bosons, Higgs production is limited to $\sqrt{s} - m_Z$



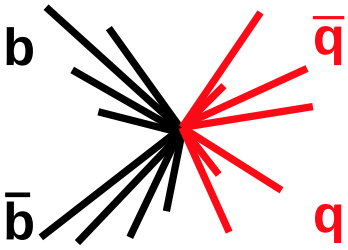
Topologies



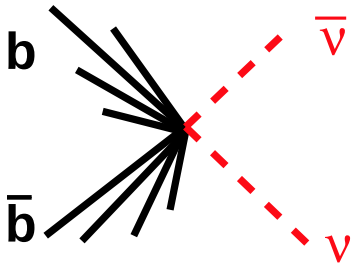
In the LEP range, the Higgs decays predominantly to $b\bar{b}$ and $\tau^+\tau^-$

When decays of the Z are considered, several different topologies are possible

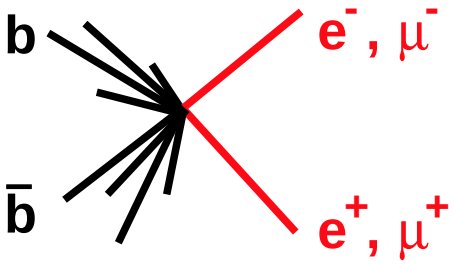
Four Jet (65%)



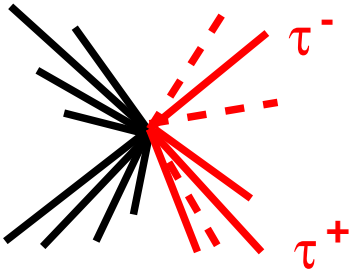
Missing Energy (20%)



"Leptons" (7%)

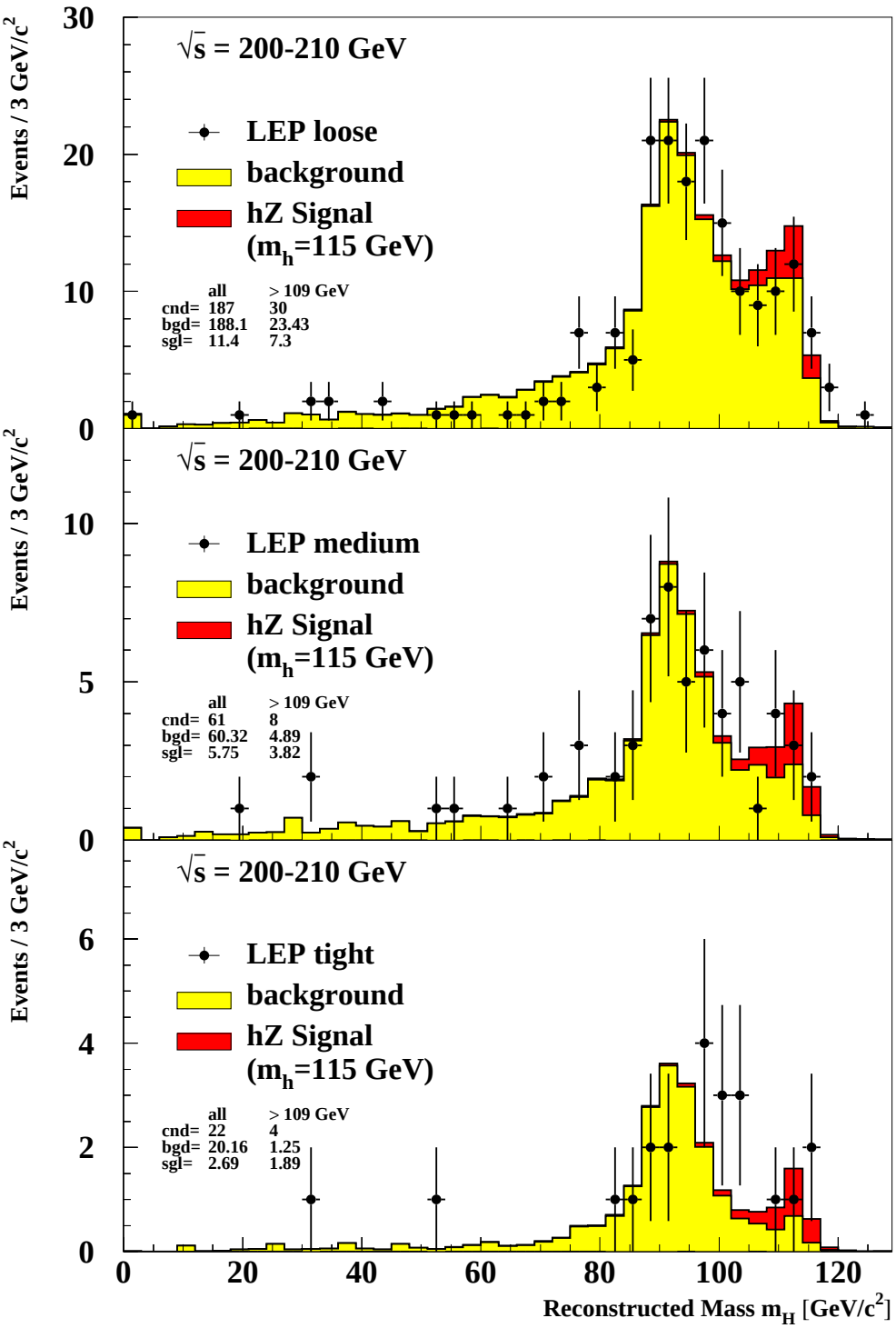


Taus (9%)



Events Selected

Applying the analyses to LEP data collected in 2000,



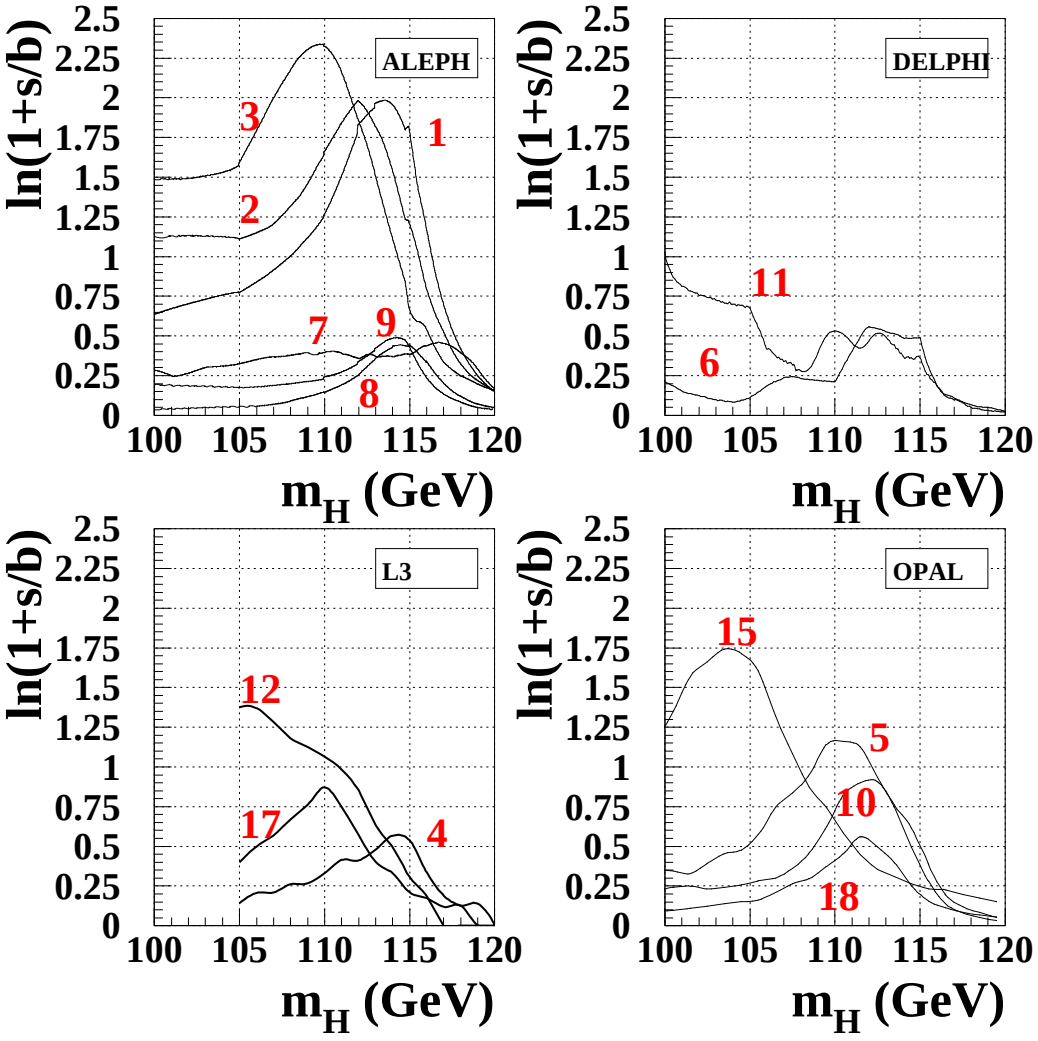
Likelihood Ratio

Interpretation of data is not simple event counting

Instead, a Likelihood Ratio is constructed:

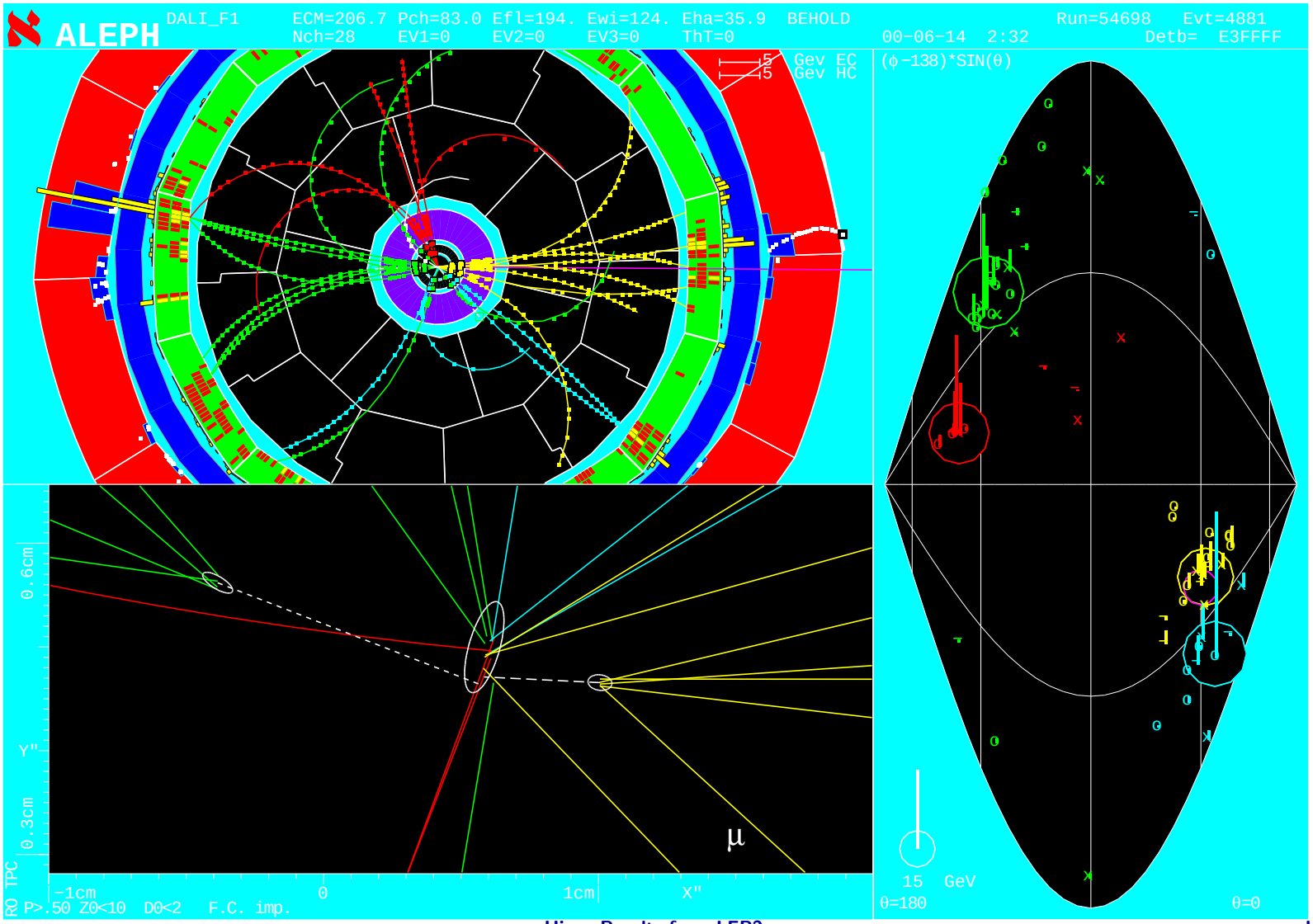
$$\ln Q = \ln \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)} = -s + \sum (1 + \frac{s f_s(m_i)}{b f_b(m_i)})$$

This is a sum of event weights:



Excess primarily from a few high weight candidates

ALEPH bbqq Candidate – $m_H = 114.3$ GeV



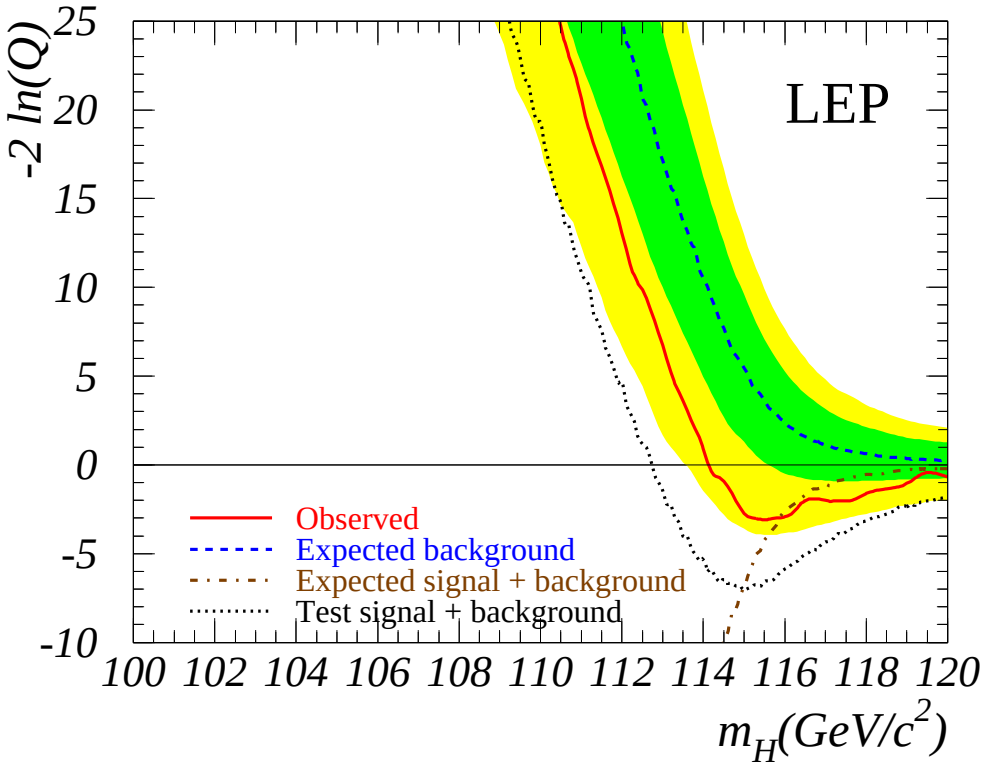
Summer 2001 Update

In July 2001, LEP updated the Higgs combination

All data now included

ALEPH and L3 included improved treatment of very high weight candidates

L3 final result, including reanalysis of Four Jet and Missing Energy channels

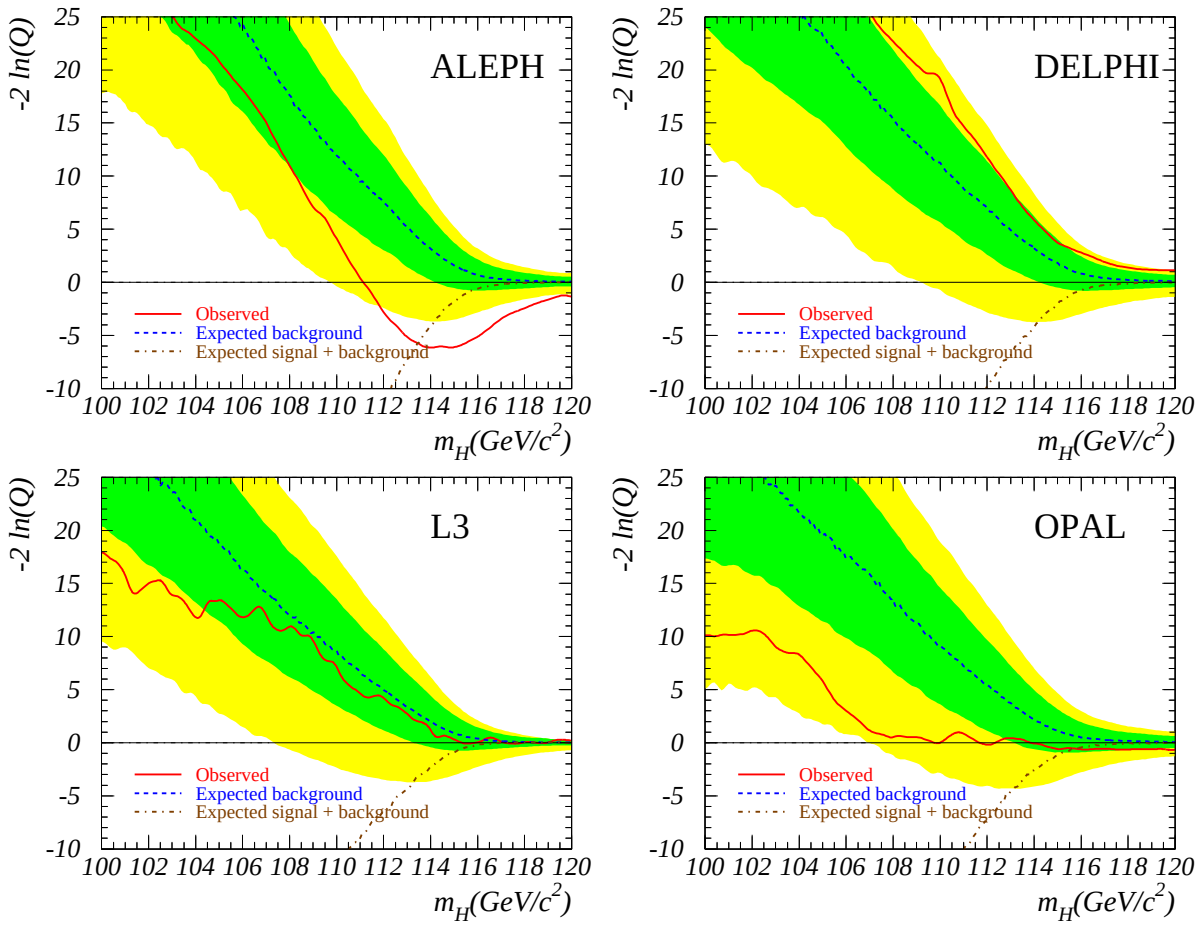


Minimum shifted from

-6.9 @ 115 GeV $\Rightarrow$ -3.2 @ 115.6 GeV

Result by Experiment

Excess comes predominantly from ALEPH data

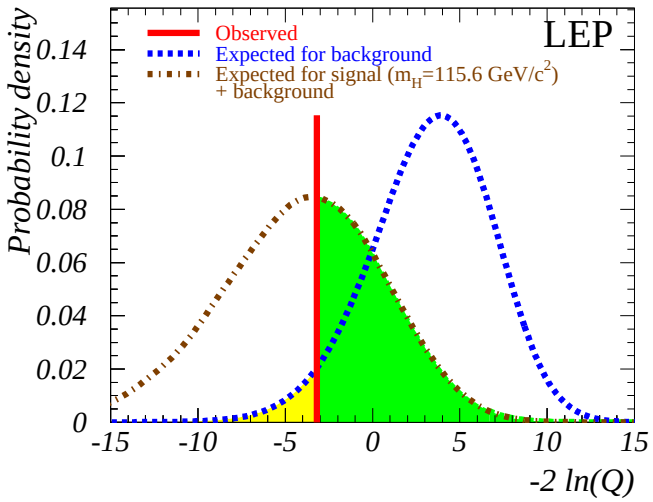


At 115.6 GeV:

Experiment	$-2\ln Q$
ALEPH	-5.59
DELPHI	$+3.14$
L3	-0.26
OPAL	-0.48

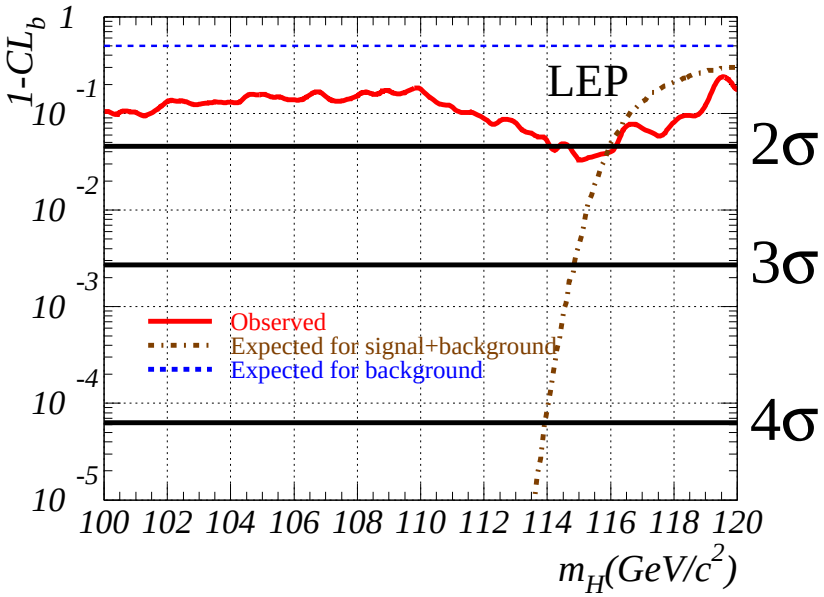
Significance

Large numbers of simulated experiments are generated for each Higgs signal mass



At 115.6 GeV: signal+background and background-only

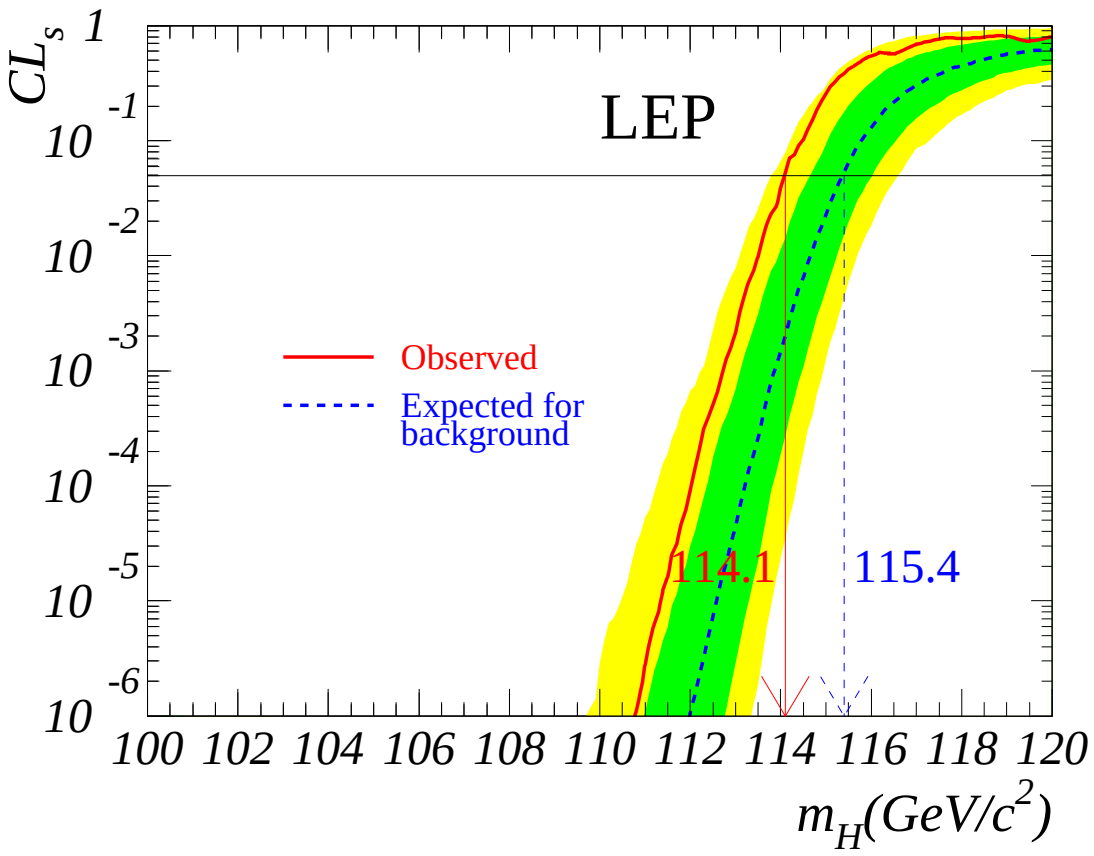
Integrating over the log-likelihood ratio distribution for background-only



At 115.6 GeV, observed log-likelihood corresponds to 2.1σ Excess

Higgs Limit

We can also set a lower limit on the Higgs mass



Higgs masses below 114.1 GeV/c^2
are excluded at the 95% confidence level
(with a limit of 115.4 GeV/c^2 expected)

Recent Developments

In December, ALEPH released their final results

Result incorporated:

Final detector alignment
Improved LEP energy calibration
Increased simulation statistics
Beam background rejection

Preliminary ALEPH results confirmed

2.82σ excess seen near $m_H = 115$ GeV

(was 2.96σ from ALEPH in November 2000)

Final Result of L3 was included in July combination

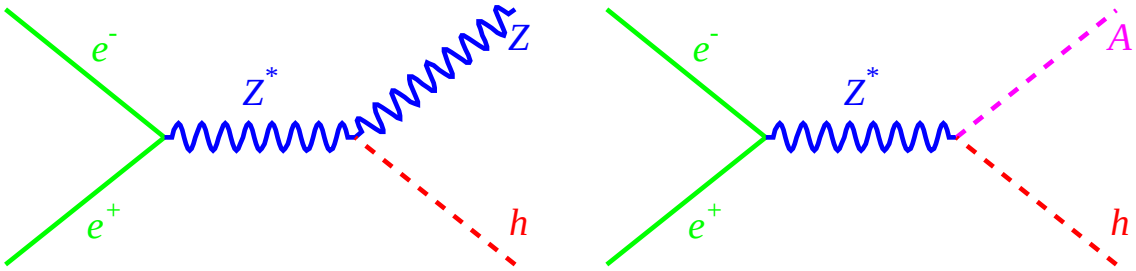
Results of DELPHI and OPAL are
expected to be finalized soon

A final LEP combination should follow
shortly thereafter

MSSM Higgs

In addition to the Standard Model Higgs, there are a large number of other Higgs models which have been examined at LEP

For example, in the MSSM, Higgs is produced either through Higgs-strahlung as in the SM or through associated pair production



These processes are complementary:

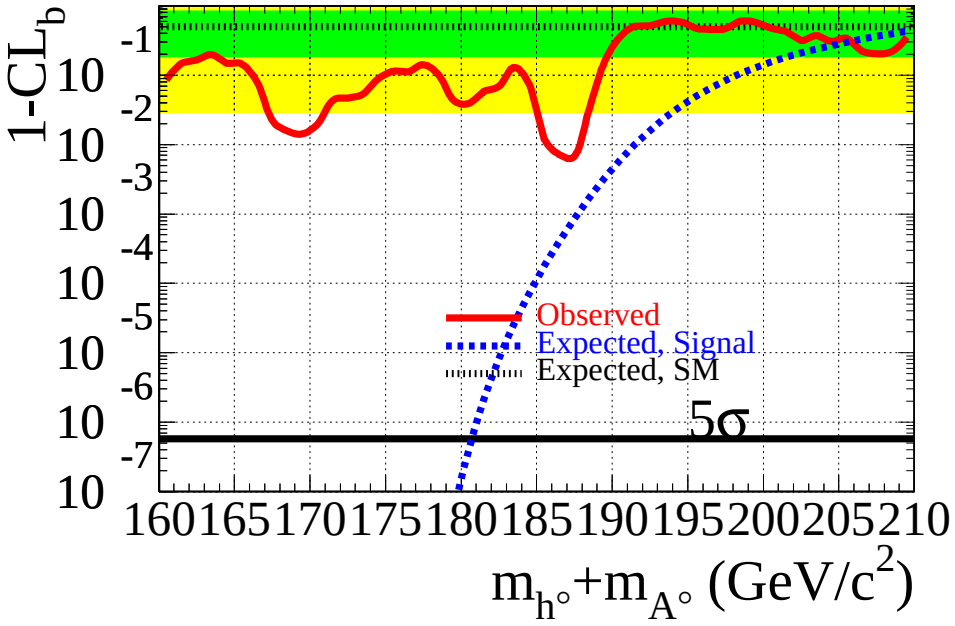
$$\sigma_{hZ} = \sigma_{HZ} \times sin^2(\beta - \alpha)$$

$$\sigma_{hA} \propto \sigma_{HZ} \times cos^2(\beta - \alpha)$$

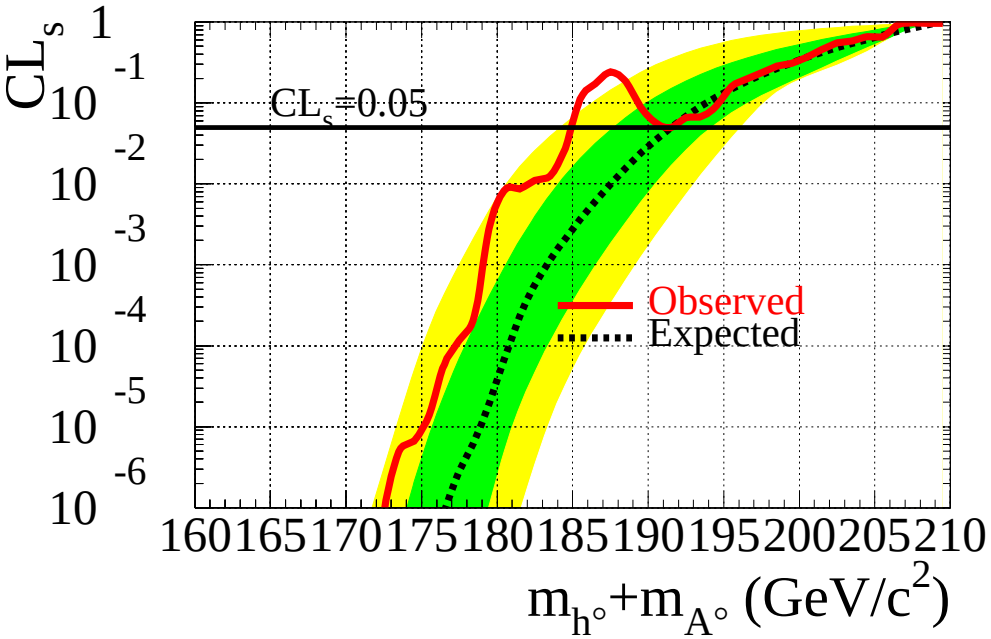
hA Results

Looking for the production of hA only

LEP 88-209 GeV Preliminary

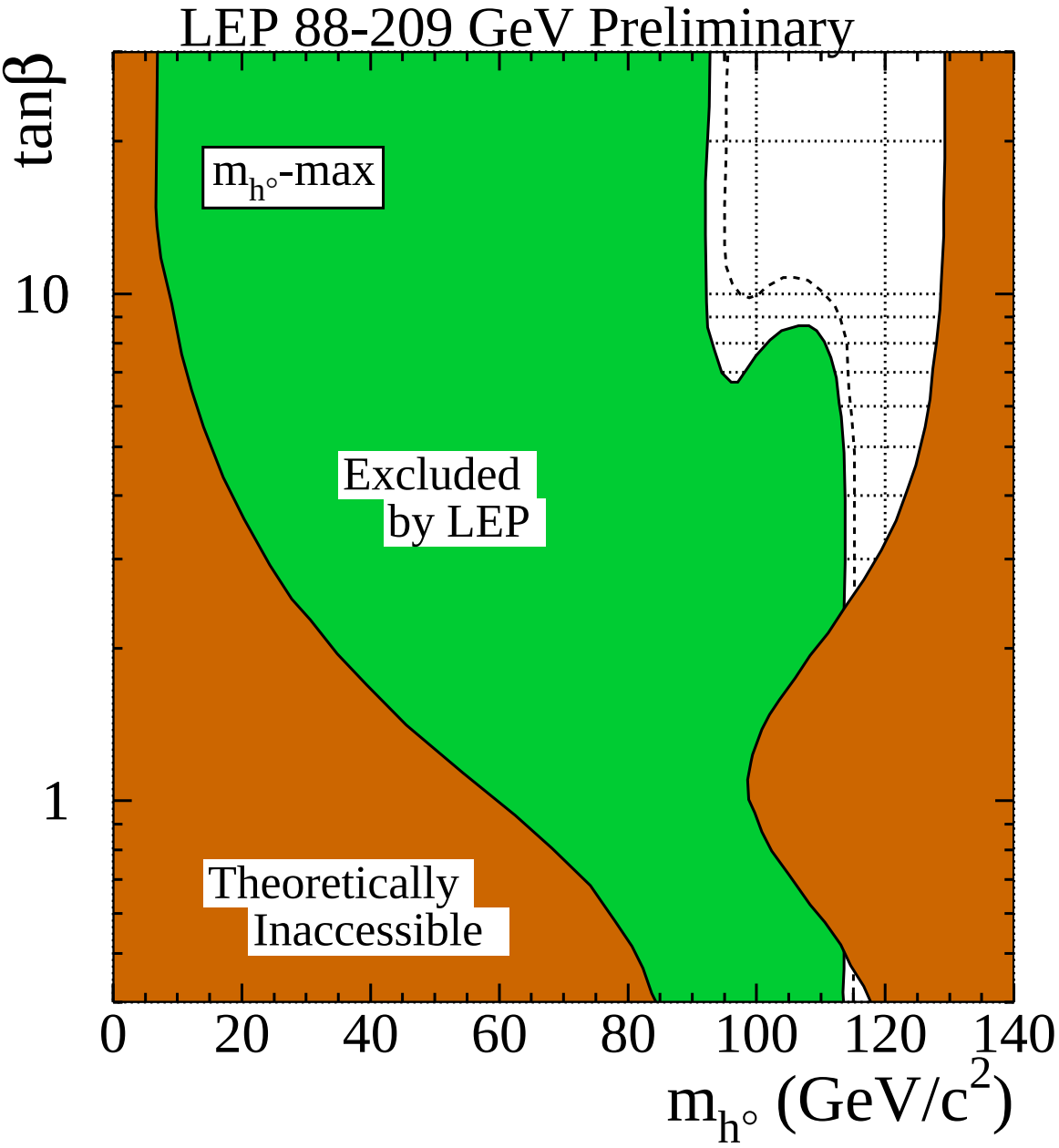


An excess near $m_h + m_A = 187$ GeV causes limit to be ≈ 7 GeV below expected



MSSM Exclusion

In the conservative max-m_h benchmark



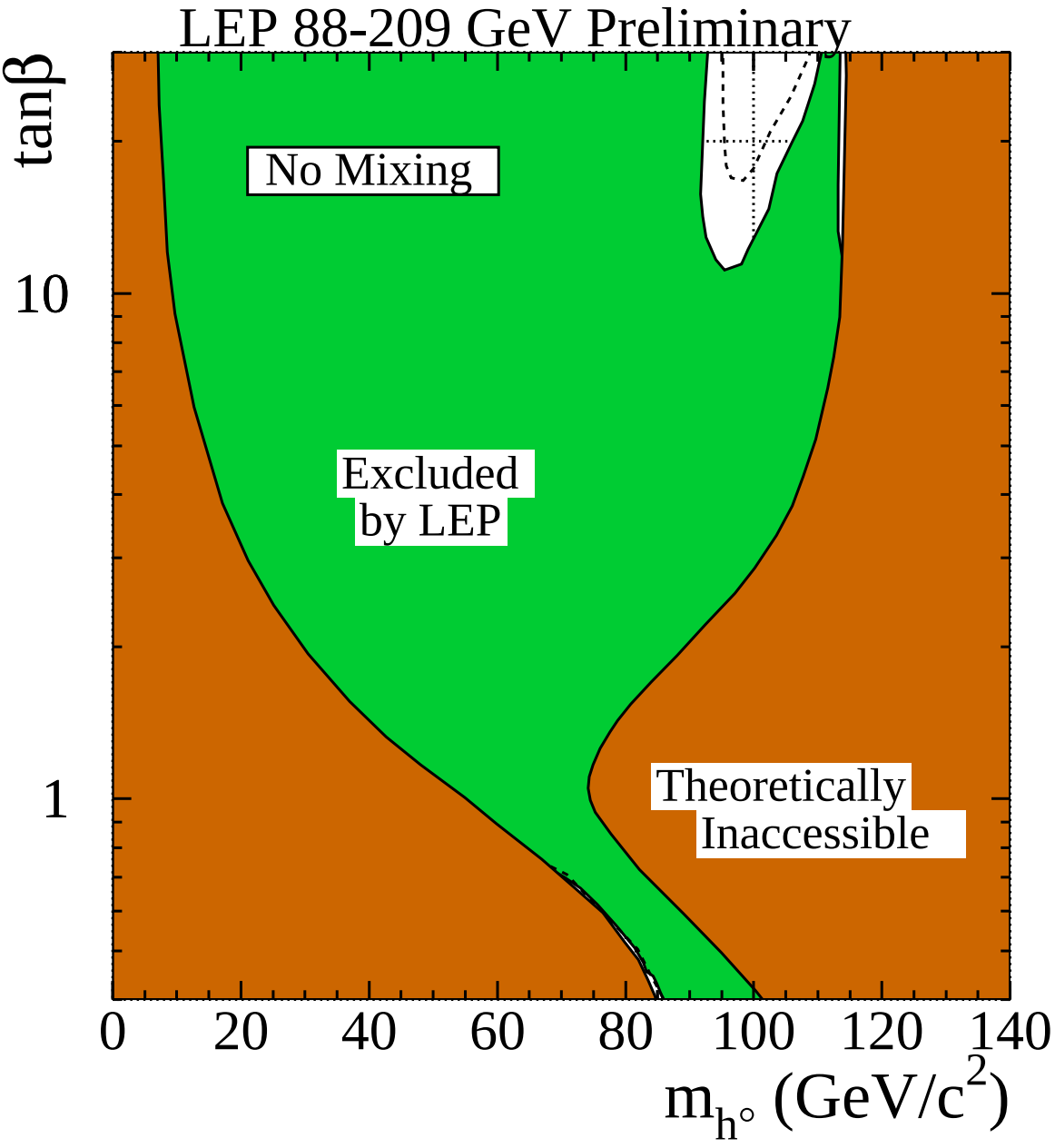
$m_h > 91.0$ GeV ($m_h > 94.6$ GeV expected)

$m_A > 91.9$ GeV ($m_A > 95.0$ GeV expected)

$0.5 < \tan\beta < 2.4$ Excluded

MSSM Exclusion

In the no mixing benchmark scenario



$m_h > 91.5$ GeV ($m_h > 95.0$ GeV expected)

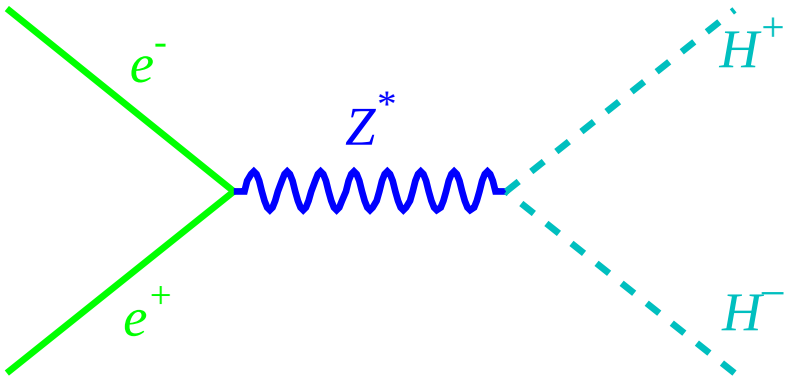
$m_A > 92.2$ GeV ($m_A > 95.3$ GeV expected)

$0.7 < \tan\beta < 10.5$ Excluded

Charged Higgs

In the MSSM, the Charged Higgs is usually too heavy to be produced at LEP

However, light Charged Higgs can be produced in general 2 Higgs Doublet models

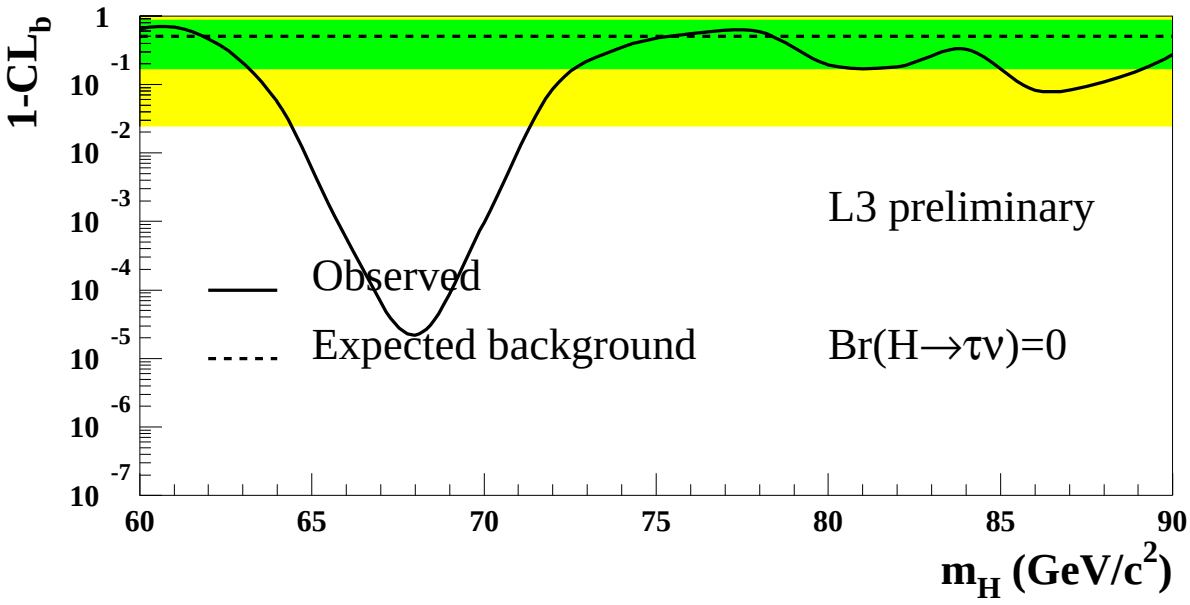


It is assumed that the Charged Higgs decays only to $c\bar{s}$ or $\tau^+\nu$

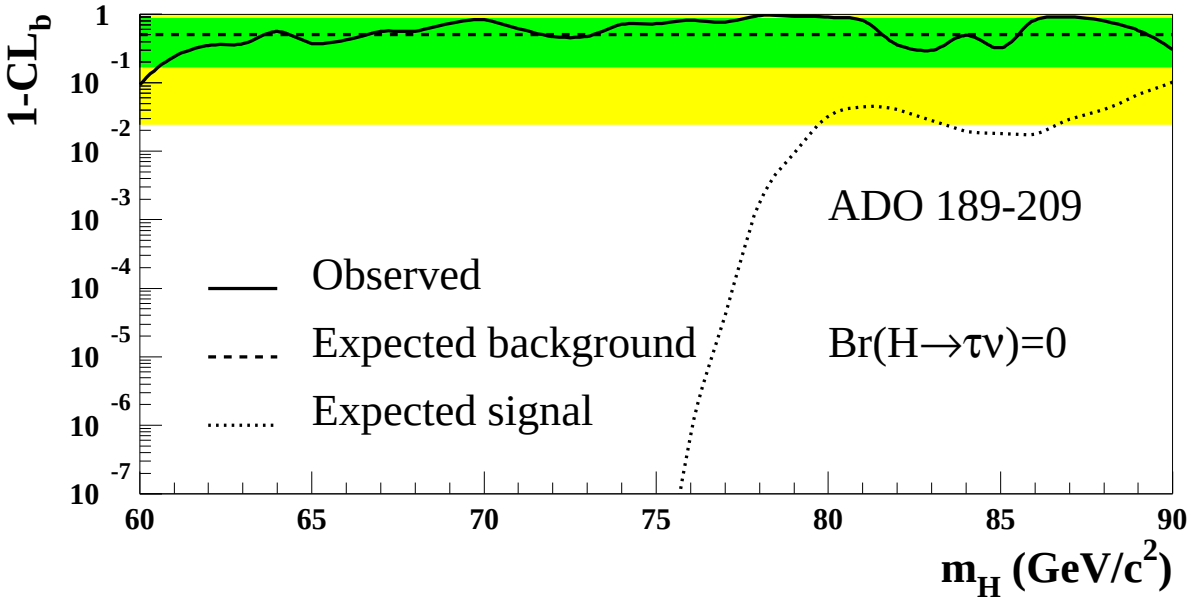
The branching ratio is left free, and the search is performed over a range of m_{H^+} and $\mathrm{BR}(H^+ \rightarrow \tau^+\nu)$

L3 Excess

L3 sees a large ($\approx 4\sigma$) excess in
$H^+H^- \to c\bar{s}\bar{c}s$ at $m_{H^+} = 68$ GeV

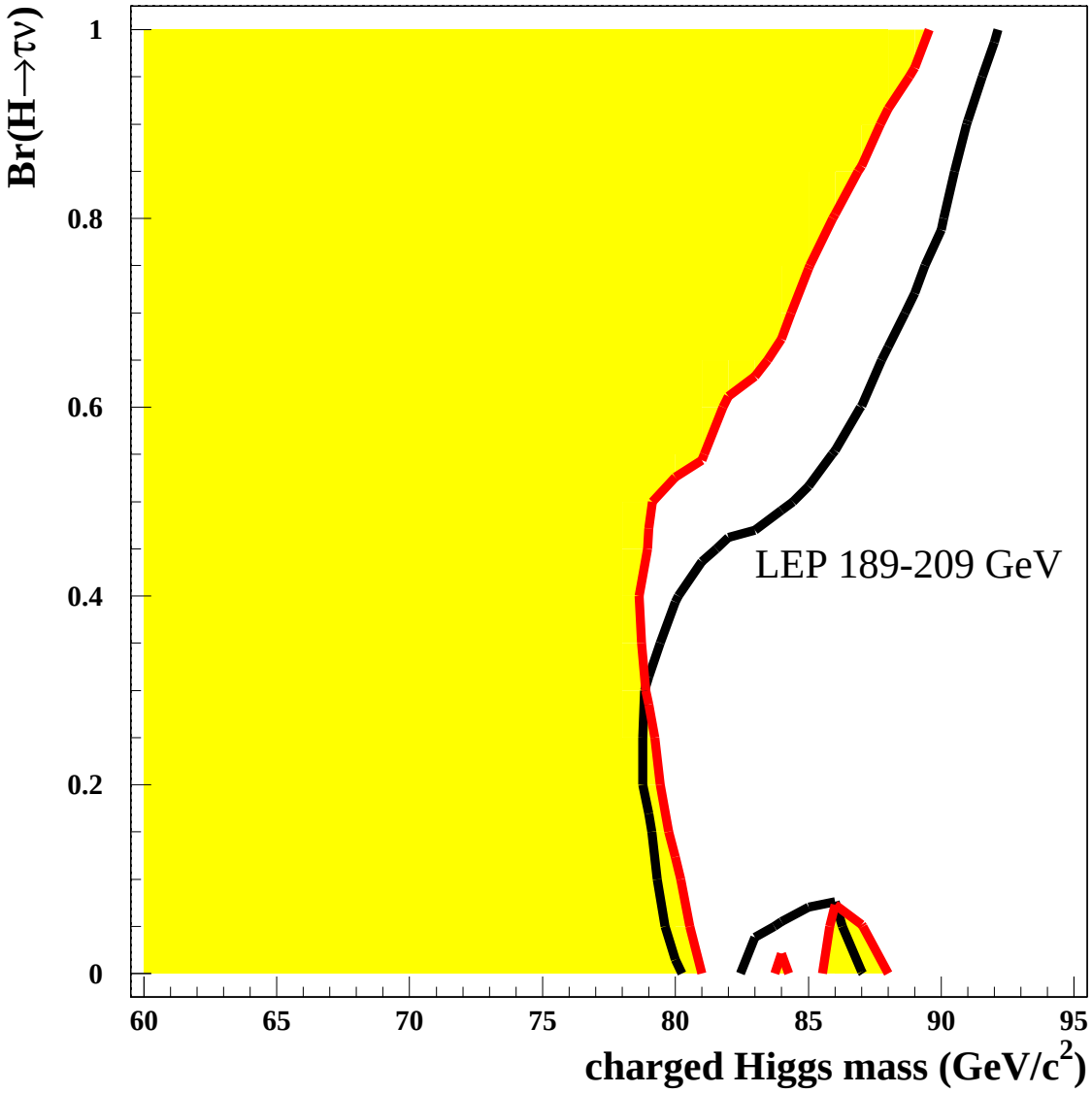


Other experiments see no excess



When combined, excess reduced below 2σ
and region is easily excluded.

Charged Higgs Exclusion

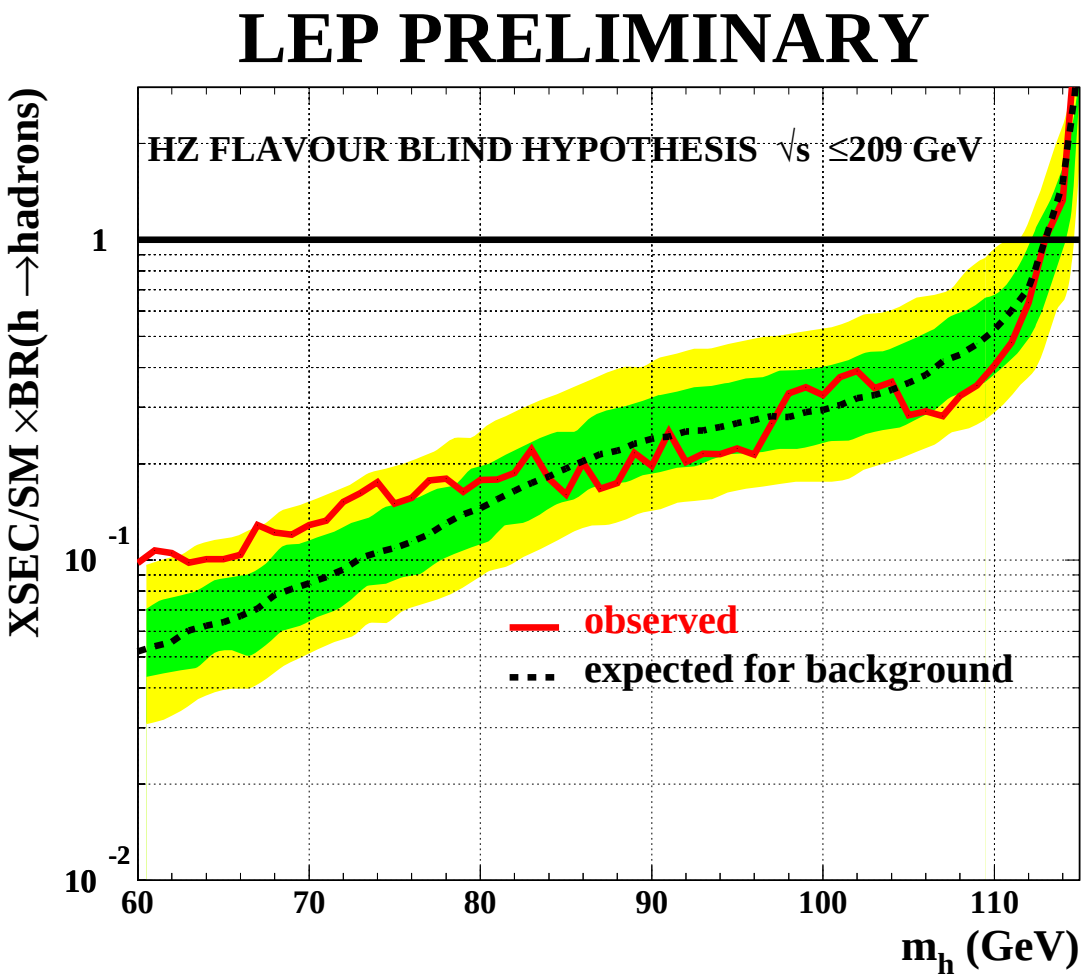


BR($H^+ \to \tau^+ \nu$)	Observed Limit	Expected Limit
0	81.0	80.2
1	89.6	92.1
Any	78.6	78.8

Flavor Independent Decays

In 2 Higgs Doublet Models,
the Higgs coupling to $b\bar{b}$ can be suppressed

Higgs with then decay to light quarks or gluons

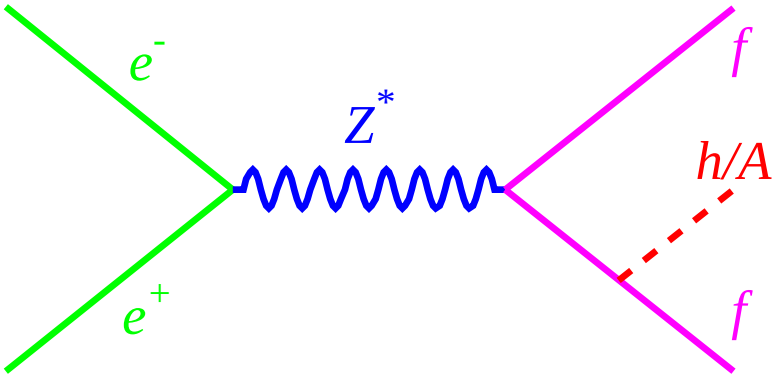


For $\sigma/\sigma_{SM} \times BR(h \rightarrow hadrons) = 1$,

$m_h > 112.9$ GeV ($m_h > 113.0$ GeV expected)

Yukawa production

Another production process possible in 2HDM's is Yukawa production



Cross section for this process can be large

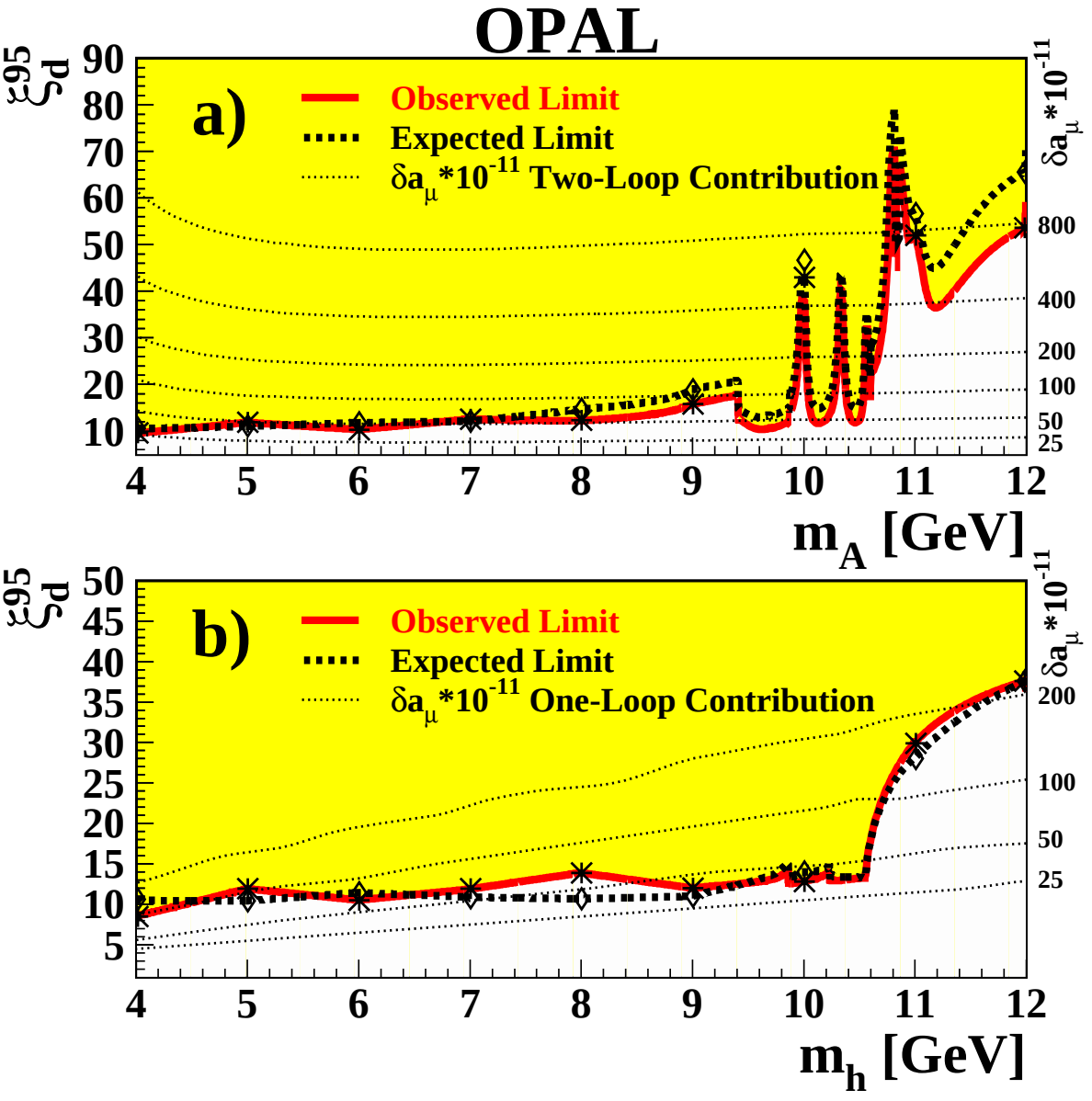
For $f = b$ or τ:

$$\sigma_{Yukawa,h} \propto \sin^2\alpha / \cos^2\beta \equiv (\xi_d^h)^2$$
$$\sigma_{Yukawa,A} \propto \tan^2\beta \equiv (\xi_d^A)^2$$

Yukawa production

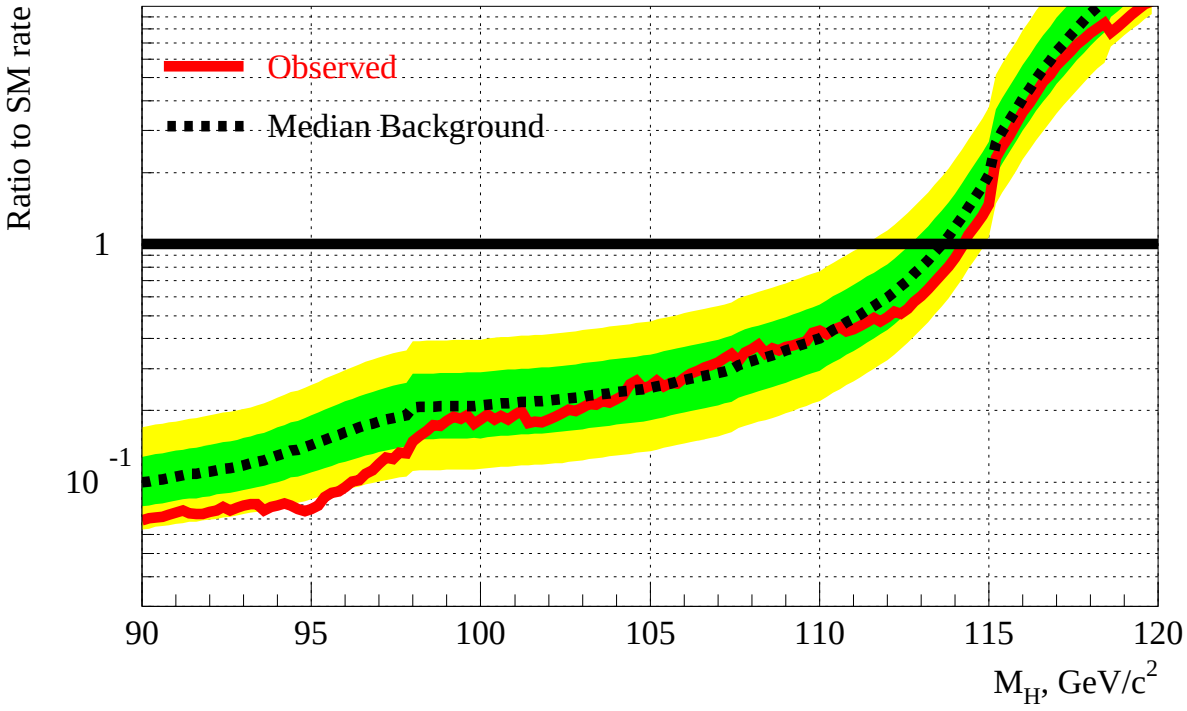
Loop diagrams involving h or A in such a scenario could explain the recent (g-2) measurement

$$a_\mu(exp) - a_\mu(SM) = 430 \pm 160 \times 10^{-11}$$



Invisible Higgs

In some models (e.g $H \rightarrow$ neutralinos),
the decay products of the Higgs will be invisible



LEP sets a 95% CL limit of

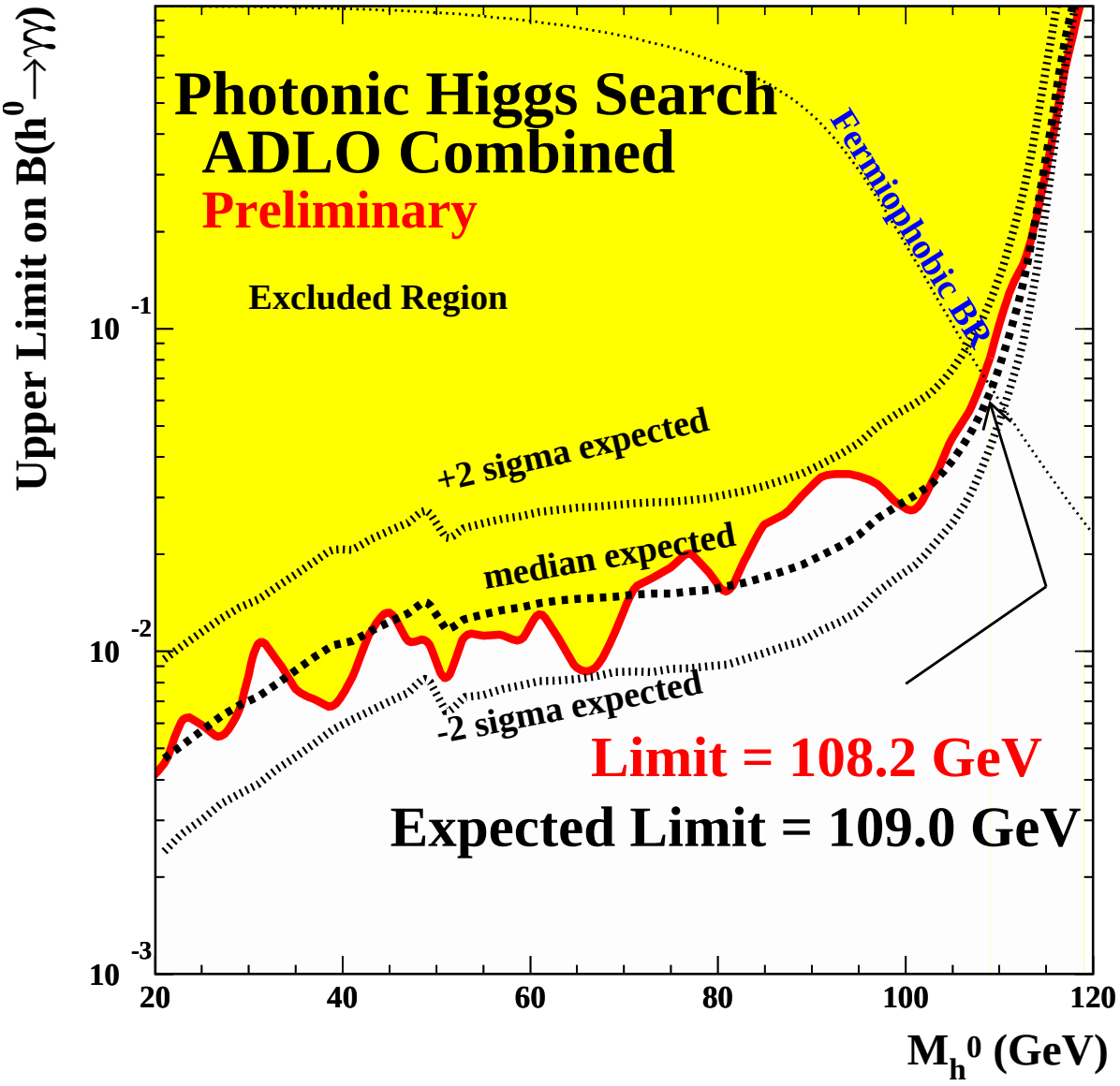
$m_H > 114.4$ GeV

($m_H > 113.6$ GeV expected)

Fermiophobic Higgs

Although $H \rightarrow \gamma\gamma$ has a very low branching ratio in the Standard Model

In some models the process is significantly enhanced



Conclusion

Rumors of the death of the Higgs
have been greatly exaggerated

In the Standard Model:

EW fit: $m_H < 196$ GeV
Direct Search: $m_H > 114.1$ GeV
2.1σ excess at 115.6 GeV

In the MSSM:

Max–m_h
$m_h > 91.0$ GeV
$m_A > 91.9$ GeV
$\tan\beta$ excluded:
0.5-2.4

No Mixing
$m_h > 91.5$ GeV
$m_A > 92.2$ GeV
$\tan\beta$ excluded:
0.7-10.5

Other Higgs Models:

Charged Higgs	$m_{H^+} > 78.6$ GeV
Flavor Independent	$m_h > 112.9$ GeV
Invisible Higgs	$m_H > 114.4$ GeV
Fermiophobic	$m_h > 108.2$ GeV