Higgs boson searches at LEP

On behalf of the
LEP Higgs working group

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LEP Physics Jamboree
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Higgs search results:

- Standard Model
- MSSM
- charged, $H^{\pm}$
- invisible
- fermiophobic
- flavour independent (NEW)

Y2K data now included
PRELIMINARY
RESULTS

Standard Model Higgs

- previous LEP combination presented at the LEPC on Nov. 3, 2000.

What has changed in the meantime?

- ALEPH, DELPHI, L3 and OPAL published their first findings in Nov.–Dec. 2000

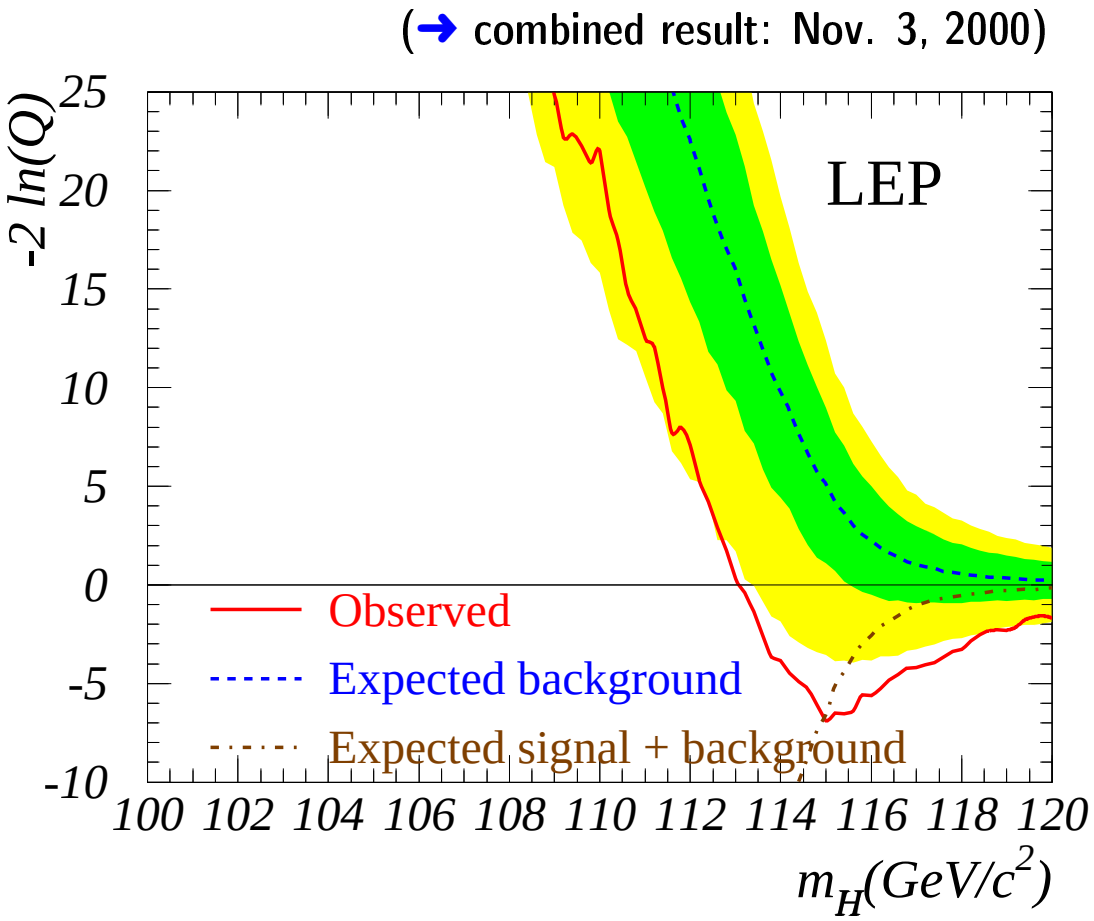
- L3 has already submitted its final results (Phys. Lett. B, June 2001)

The combined results presented in this talk reflect the latest published results from A, D, L and O (red).

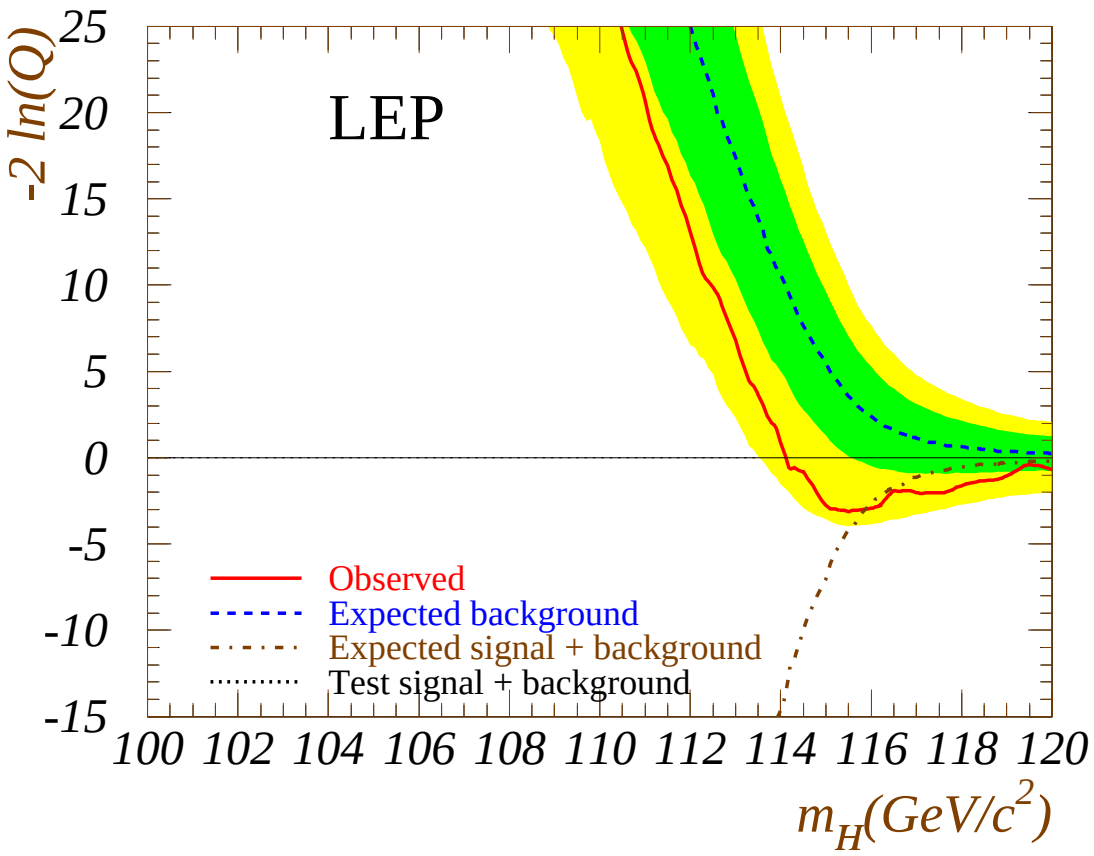
Likelihood ratio, Q

$$Q = \frac{L_{s+b}}{L_b} = \frac{P(n_{obs}; s+b) \times (S(\vec{x}_i) + B(\vec{x}_i))}{P(n_{obs}; b) \times B(\vec{x}_i)}$$

$$-2 \ln Q(m_h) = 2 s_{tot} - 2 \sum_i^{n_{obs}} \ln(1 + \frac{s_i}{b_i})$$



Combined likelihood ratio, Q



—— observed

- - - median expected background

· · · median expected background + $m_h = 115$ GeV

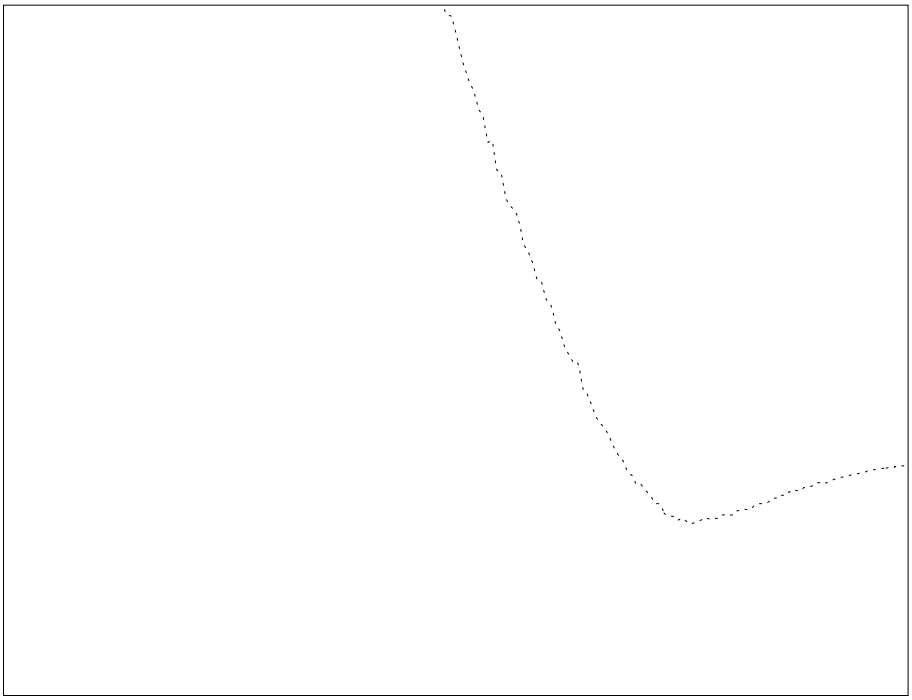
➜ maximum likelihood ratio at:

$$m_h = 115.6 \text{ GeV}$$

➜ probability of background fluctuation at $\approx 2\ \sigma$ level

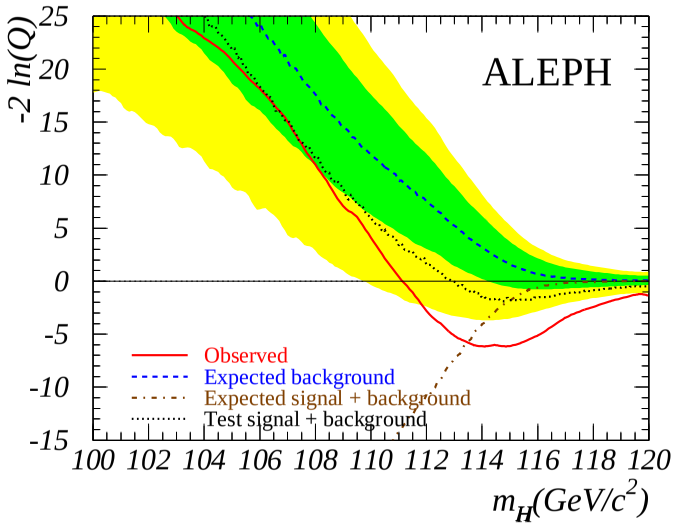
"Tail test"

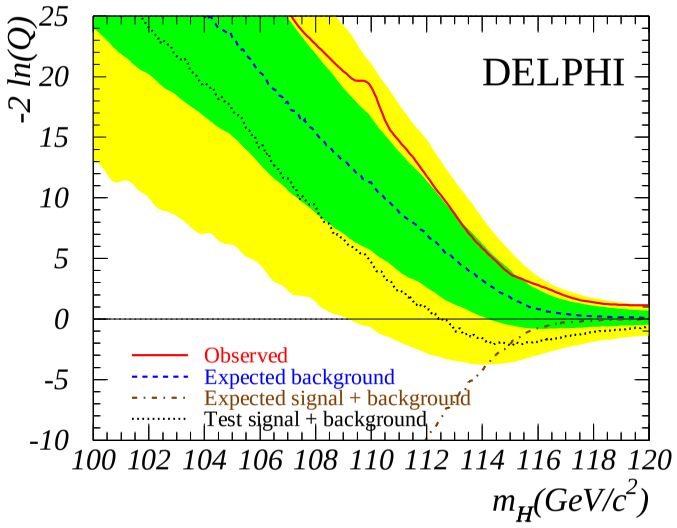
Expected log likelihood ratio curve
for m_{h} =115 GeV

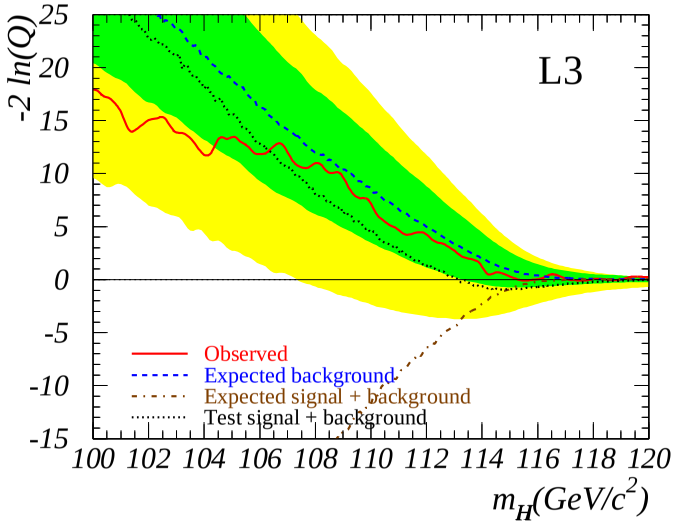


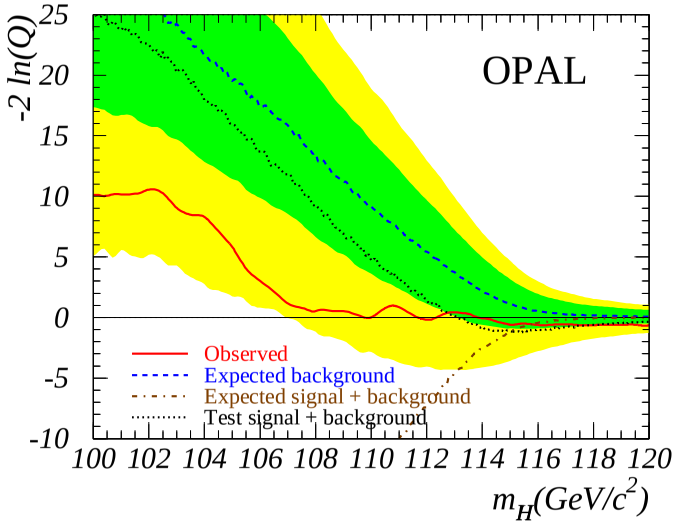
(✗ ...not yet available for m_{h} =115.6 GeV)

A,D,L,O Likelihood ratios









Changes to likelihood ratio @ m_{h} =115 GeV

$$-2\ln Q(m_{\mathrm{h}}) = 2s_{\mathrm{tot}} - 2\sum_{i}^{\mathrm{n_{obs}}} \ln(1+\frac{s_i}{b_i})$$

	Nov. 3, 2000	July 10, 2001	Δ	Comments
ALEPH	-7.61	-6.13	+1.5	+ 10.2 pb^{-1} ■: 2D correlation
DELPHI	+3.01	+3.64	+0.6	+12.5 pb^{-1} ▲
L3	-1.71	+0.36	+2.1	+16.5 pb^{-1} ■ ● ●
OPAL	-0.59	-0.74	-0.25	+16 pb^{-1} ($\mathrm{hq\bar{q}}$ cand.) ■●▲◆: bgd. ↗ 5%
Total	-6.90	-2.87	+4.0	+55.2 pb^{-1} data

Improved sensitivity / understanding in channel
4-jets (■), $\not{E}$(●), leptonic (▲) and tau (◆) channels.

Comparison with previous combination

Comparison at 115 GeV:

- log likelihood ratio: $-2\ln Q$
- significance of observed excess

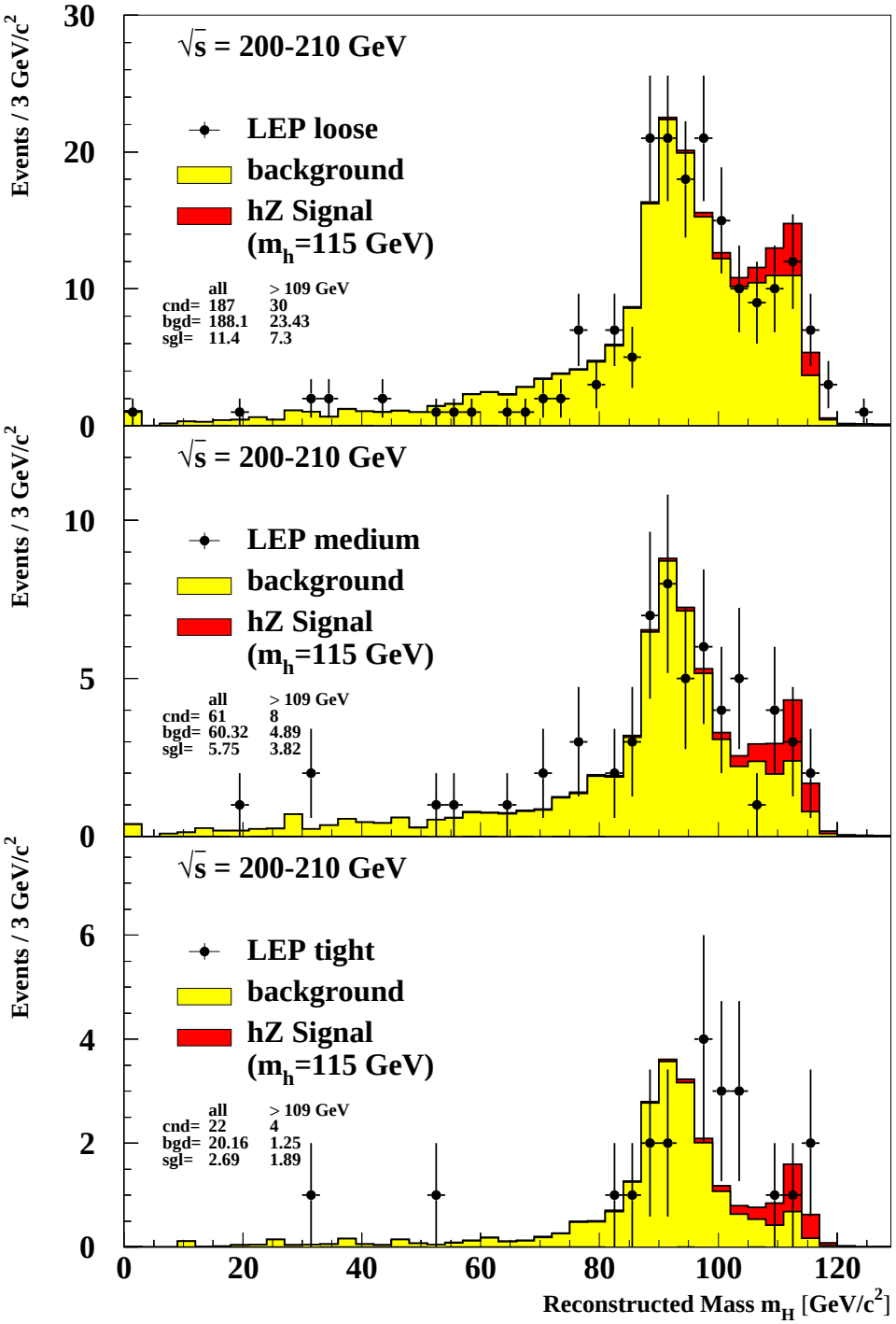
Channel	Nov. 3, 2000		July 10, 2001	
	$-2\ln Q$	σ	$-2\ln Q$	σ
$hq\bar{q}$	-5.15	2.58	-4.70	2.45
$h\nu\bar{\nu}$	-2.27	1.93	+0.81	0.86
he^+e^-, $h\mu^+\mu^-$	+0.55	0.39	+1.04	0.15
$hZ \longrightarrow \tau^+\tau^- q\bar{q}$, $b\bar{b}\tau^+\tau^-$	-0.03	0.77	-0.03	0.77

Largest changes are in missing energy channel and, to a lesser extent in four-jet channel.

Candidate weights @ m_{h} =115 GeV

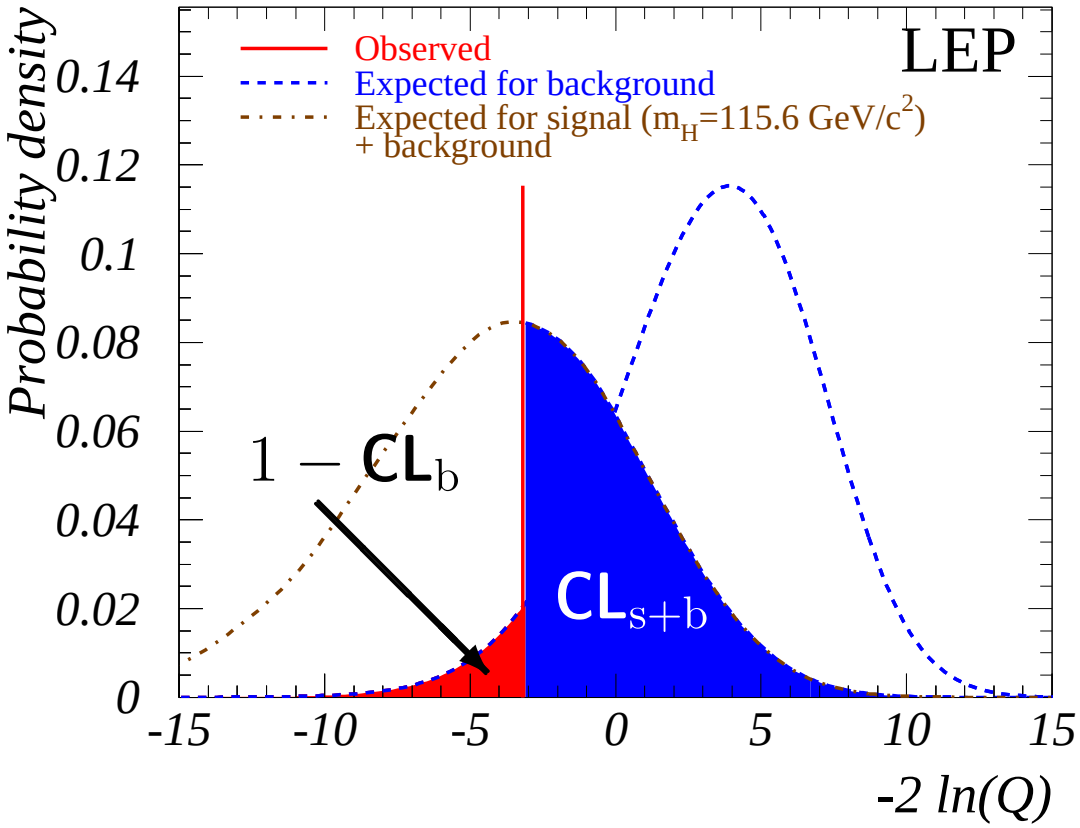
	Expt	E_{cm}	Channel	M_H^{rec} (GeV)	$\ln(1+s/b)$ @115 GeV
1	A	206.7	4-jet	114.3	1.73
2	A	206.7	4-jet	112.9	1.21
3	A	206.5	4-jet	110.0	0.64
4	L	206.4	E-miss	115.0	0.53
5	O	206.6	4-jet	110.7	0.53
6	D	206.7	4-jet	114.3	0.49
7	A	205.0	Lept	118.1	0.47
8	A	208.1	Tau	115.4	0.41
9	A	206.5	4-jet	114.5	0.40
10	O	205.4	4-jet	112.6	0.40
11	D	206.7	4-jet	97.2	0.36
12	L	206.4	4-jet	108.3	0.31
13	A	206.5	4-jet	114.4	0.27
14	A	207.6	4-jet	103.0	0.26
15	O	205.4	E-miss	104.0	0.25
16	A	206.5	4-jet	110.2	0.22
17	L	206.4	E-miss	110.1	0.21
18	O	206.4	E-miss	112.1	0.20
19	D	206.7	4-jet	110.1	0.20
20	L	206.4	E-miss	110.1	0.18

Reconstructed mass distributions



LEP combined result

Observation vs. simulated experiments for b-only, b+s(m_h =115.6 GeV)



Compatibility with

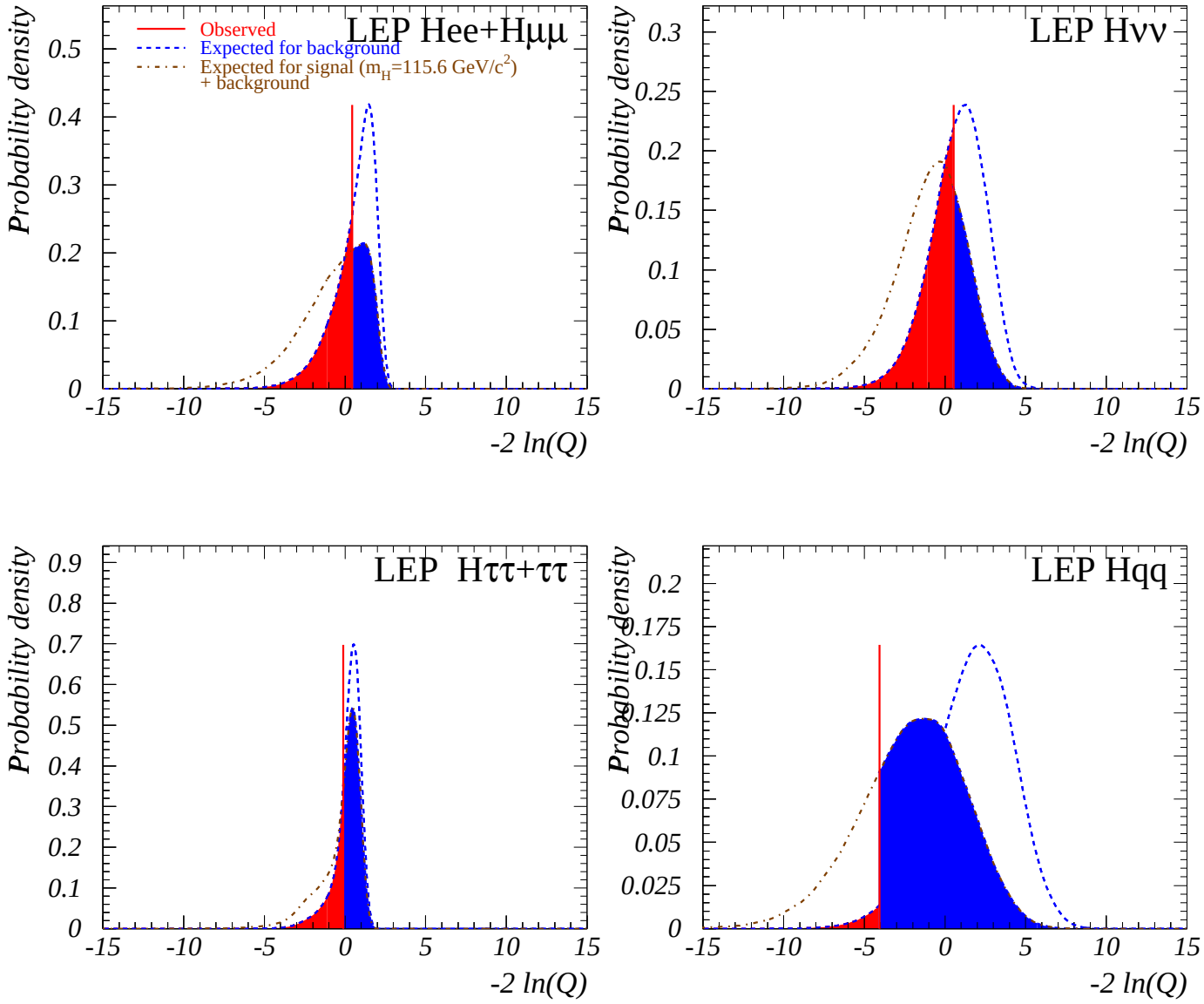
➜ background, $1 - CL_b = 3.5\%$

➜ background + $m_h = 115.6$ GeV, $CL_{s+b} = 43.5\%$

Observation vs. simulated experiments

b-only, b+s(m_h =115.6 GeV)

by search topology:



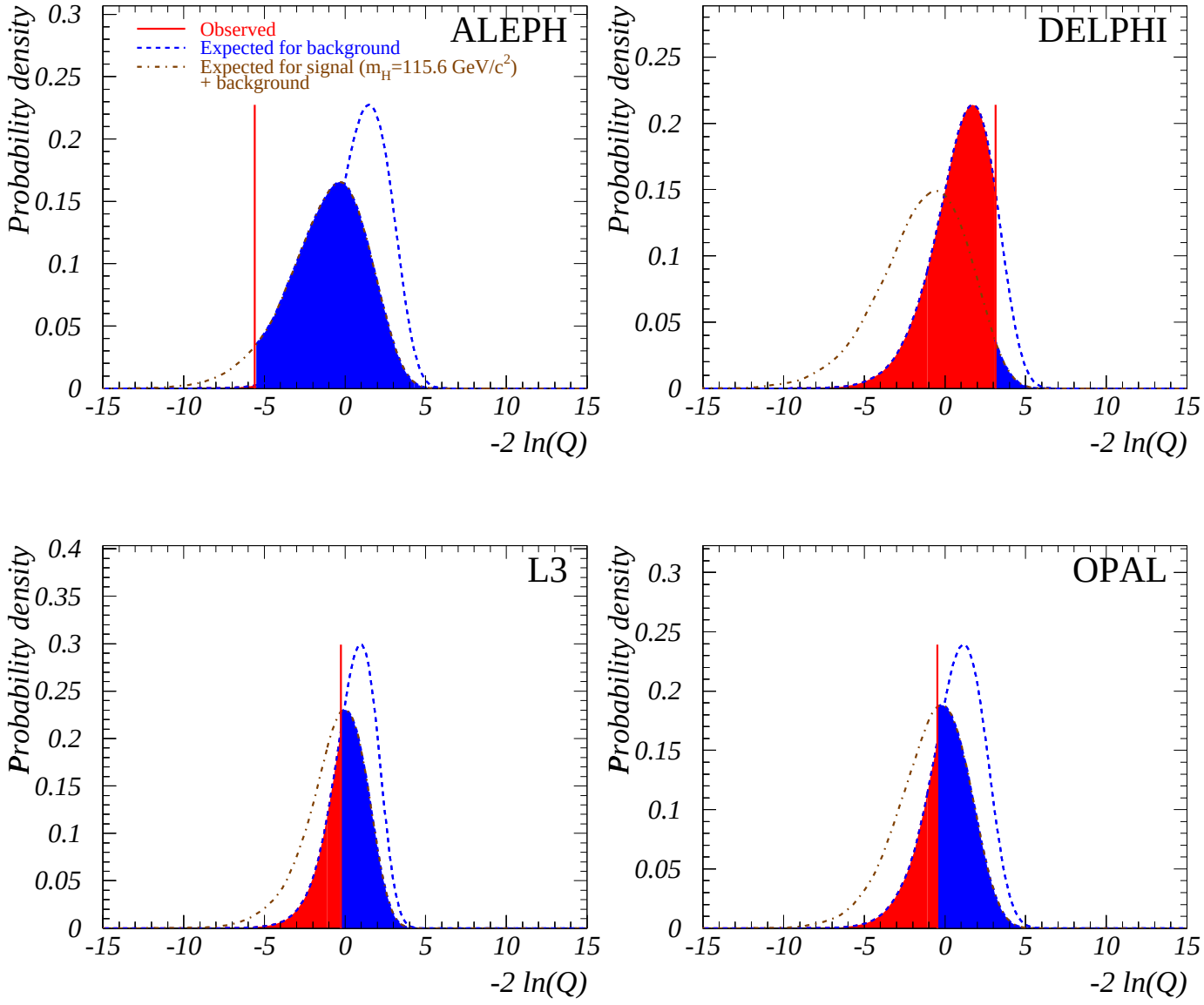
➜ separation of curves:

$\propto$ sensitivity to m_h =115.6 GeV hypothesis

Observation vs. simulated experiments

b-only, b+s(m_h =115.6 GeV)

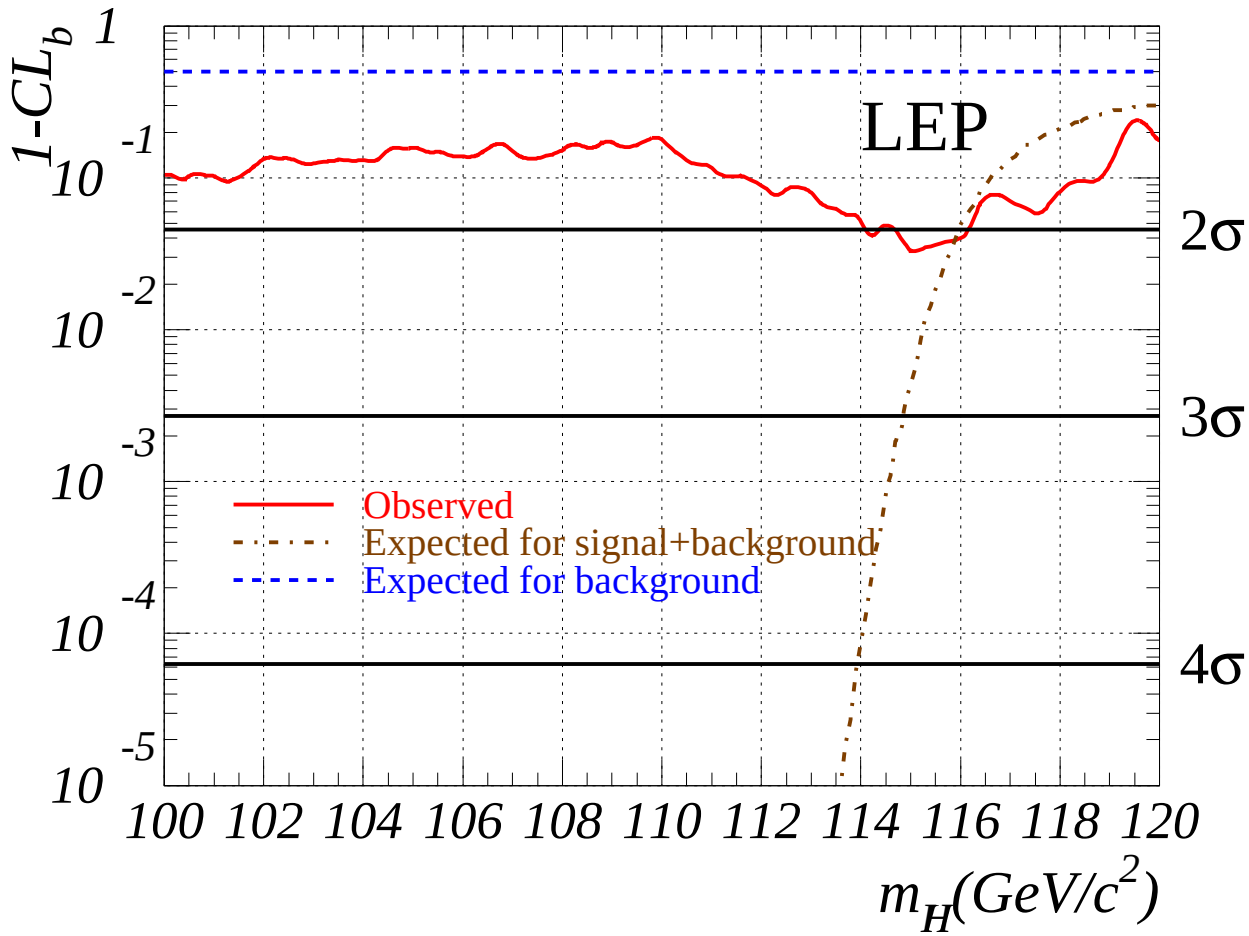
by experiment:



➜ separation of curves:

$\propto$ sensitivity to m_h =115.6 GeV hypothesis

Background fluctuation probability:1-CL$_b$



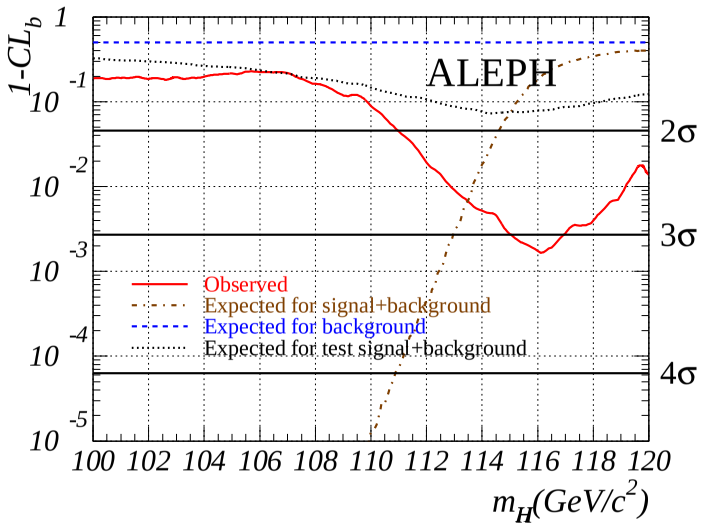
- **background fluctuation probability**

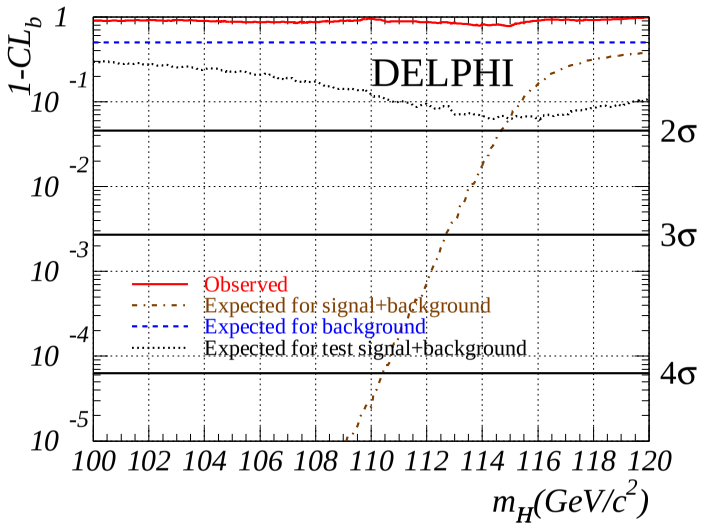
at m_h =115.6 GeV: $1 - CL_b = 3.5\%$

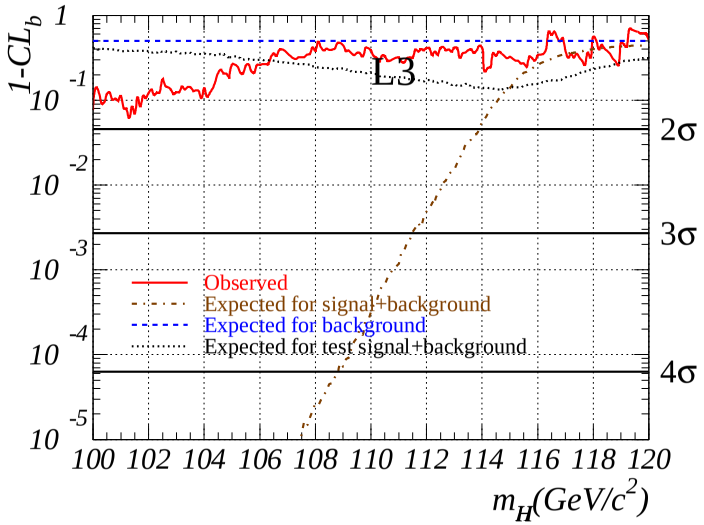
- **at the 95% C.L.:**

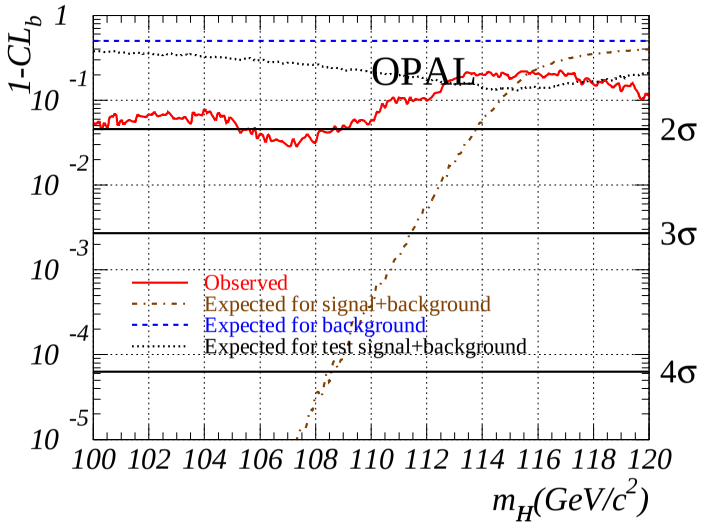
$$m_h > 114.1 \text{ (115.4 exp.) GeV}$$

A,D,L,O 1-CL$_b$

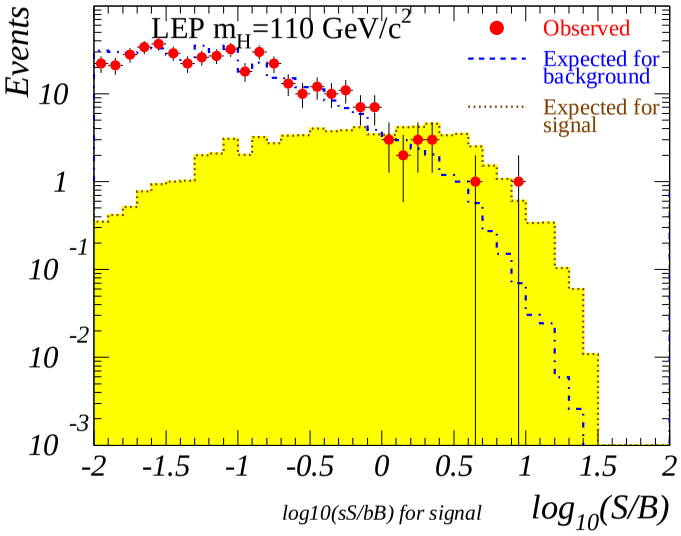

ALEPH
1-CL$_b$
Observed
Expected for signal+background
Expected for background
Expected for test signal+background
2σ
3σ
4σ
m_H(GeV/c^2)

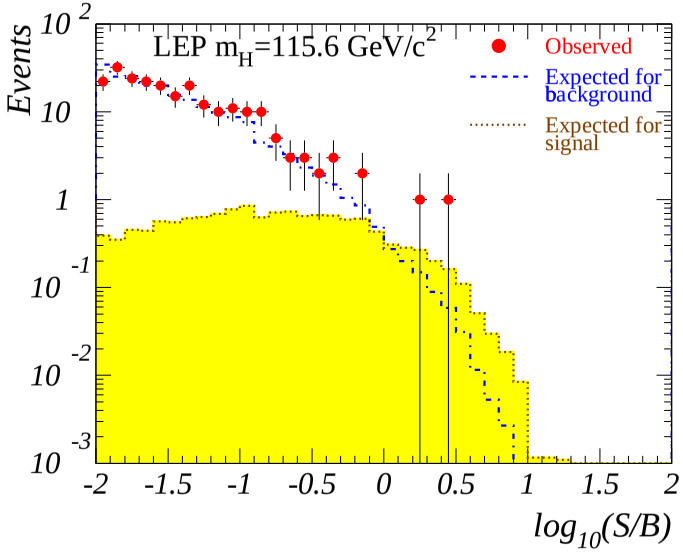

DELPHI
1-CL$_b$
Observed
Expected for signal+background
Expected for background
Expected for test signal+background
2σ
3σ
4σ
m_H(GeV/c^2)

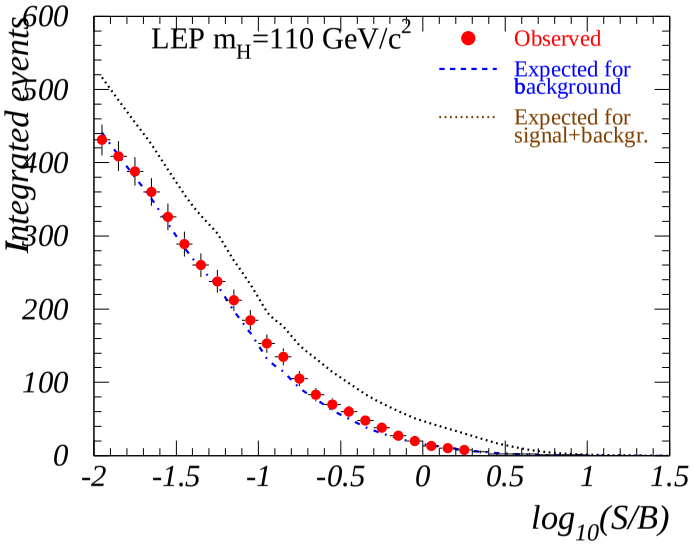

L3
1-CL$_b$
Observed
Expected for signal+background
Expected for background
Expected for test signal+background
2σ
3σ
4σ
m_H(GeV/c^2)

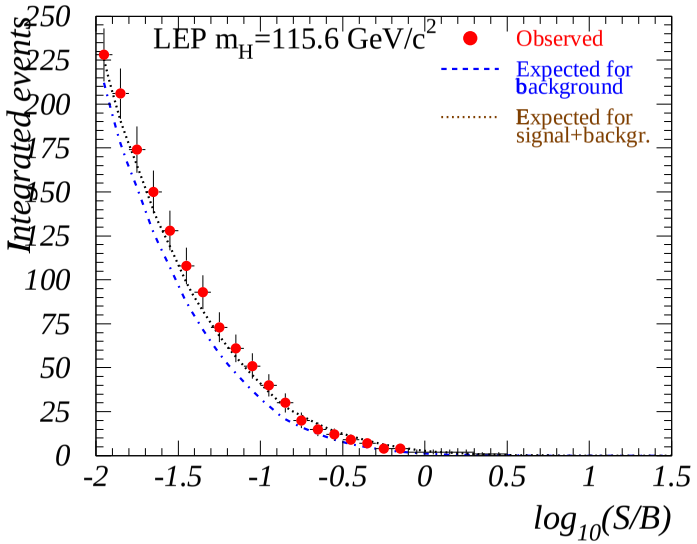

OPAL
1-CL$_b$
Observed
Expected for signal+background
Expected for background
Expected for test signal+background
2σ
3σ
4σ
m_H(GeV/c^2)

Event weight distributions: 110 / 115.6 GeV









Standard Model Higgs boson

- current LEP-combined result corresponds to 2.1σ excess over the background
- maximum likelihood occurs at

$$m_{\mathsf{h}} = 115.6 \text{ GeV}$$

- at the 95% CL:

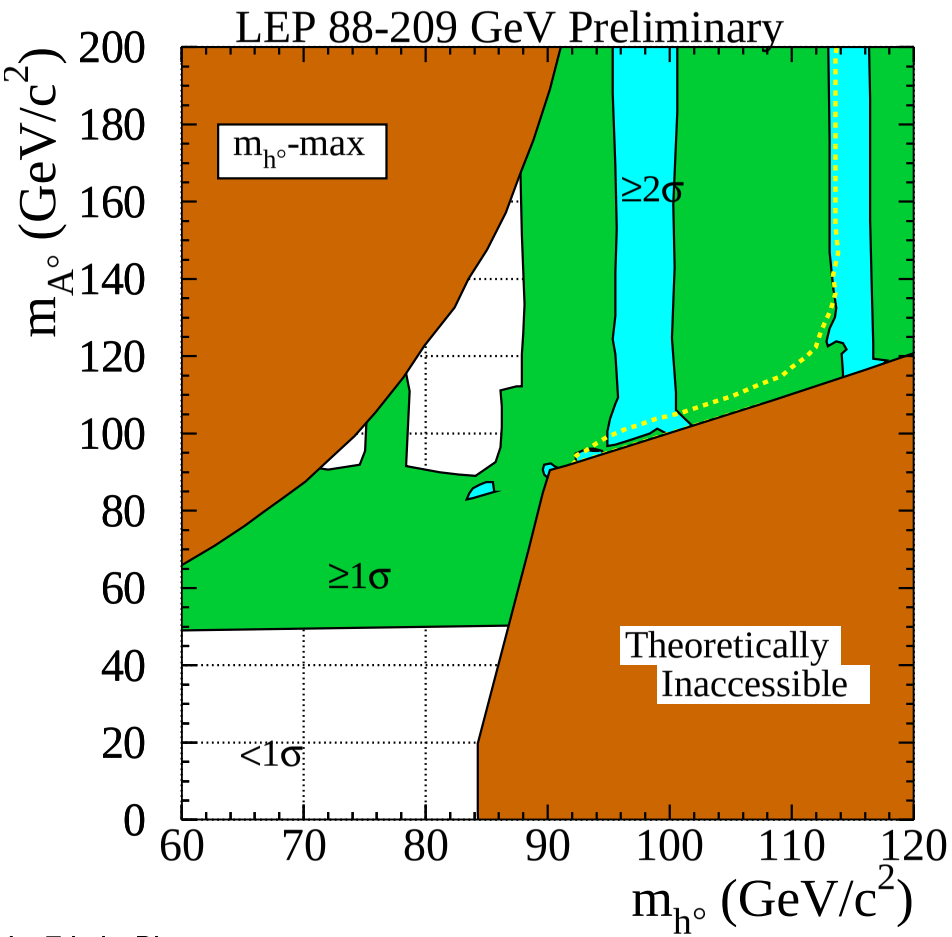
$$m_{\mathsf{h}} > 114.1 \text{ (115.4 exp.) GeV}$$

- 3 out of 4 experiments still have to publish their final results:

➜ Final combined results to appear towards the end of 2001.

MSSM: m_h-max benchmark

$1 - \mathrm{CL_b}$ in (m_h, m_A):



➜ $e^+e^- \to hA$ searches:

$\sim 2\sigma$ excess for

$(m_h, m_A) \approx$ (83,83), (93,93) G

➜ $e^+e^- \to hZ$ searches:

$\geq 2\sigma$ excess for

$m_h = 97$ & 115 GeV

excluded at 95% CL (- - -):

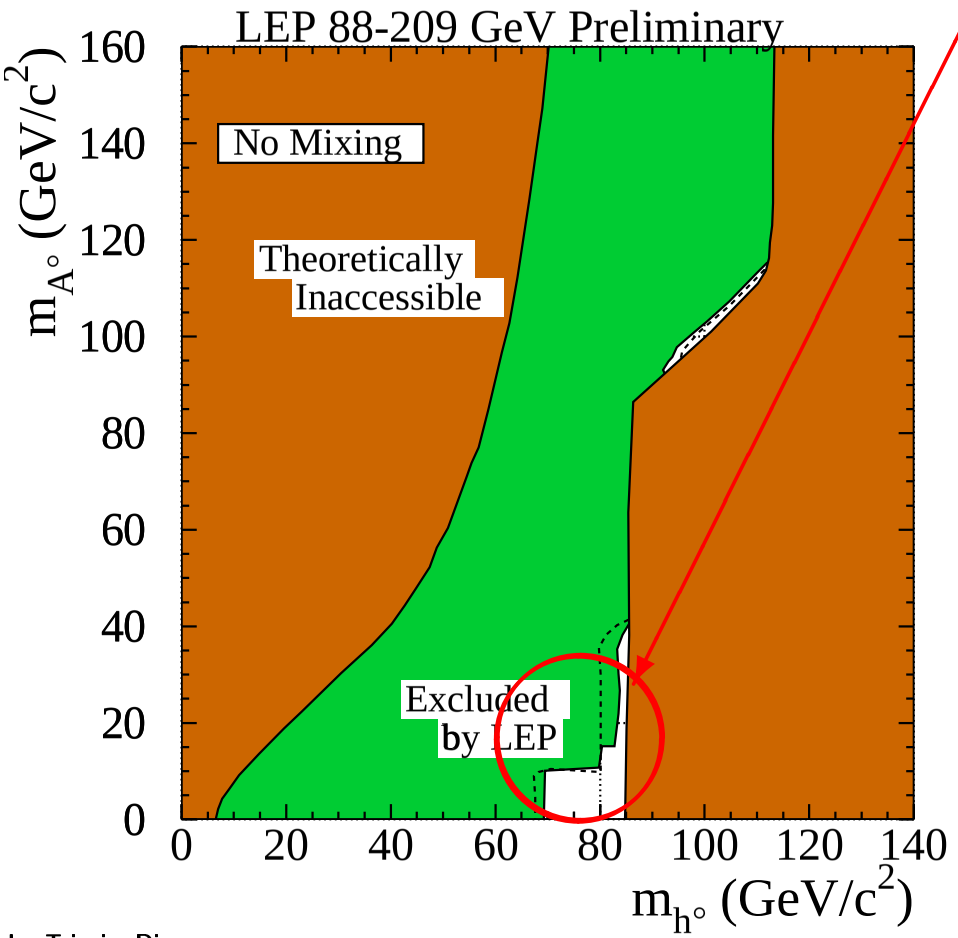
$m_h < 91.0$ (95.0 exp.) GeV

$m_A < 91.9$ (94.6 exp.) GeV

$0.5 < \tan\beta < 2.4$

MSSM: no-mixing benchmark

(m_h, m_A) 95% CL exclusion:



- $e^+e^- \to hZ \to AAZ$, but no $A \to b\bar{b}$!

  occurs for

  $\tan\beta < 0.7$ & $m_{H^\pm} < 74$ GeV

- Use $H^\pm$ direct searches to exclude this .

  ... but: $B(H^\pm \to W^\pm A) \neq 0$

  $\Rightarrow$ under investigation

excluded at 95% CL (for $\tan\beta > 0.7$):

$m_h < 91.5$ (95.0 exp.) GeV

$m_A < 92.2$ (95.3 exp.) GeV

$0.7 < \tan\beta < 10.5$

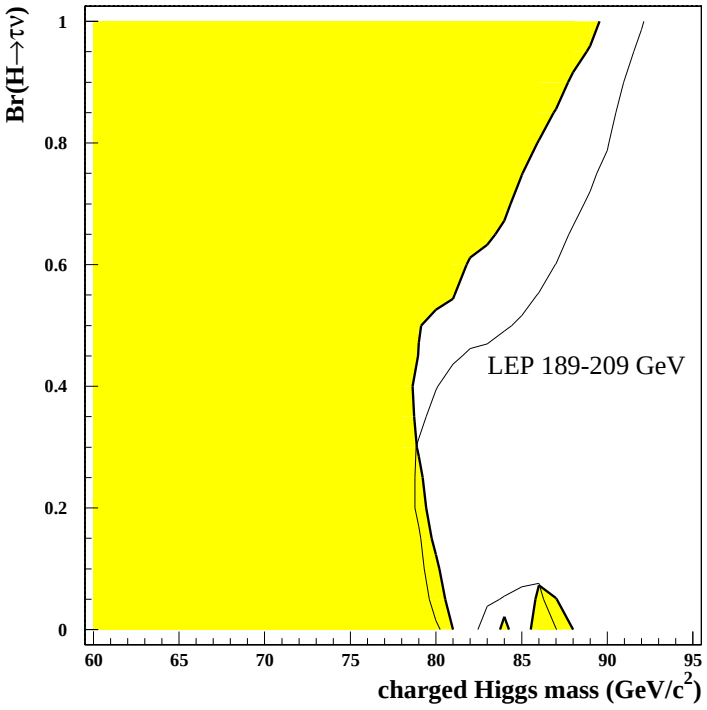
Charged Higgs, $H^{\pm}$

Assume $B(H^+ \to c\bar{s}) + B(H^+ \to \tau^+\nu) \doteq 1$

➜ $e^+e^- \to H^+H^- \to c\bar{s}s\bar{c},\ c\bar{s}\tau^-\bar{\nu},\ \tau^+\nu\tau^-\bar{\nu}$

- L3 observe a large excess in the 4-jets channel

➜ compatibility with ALEPH, DELPHI, OPAL is being investigated.



LEP combined search excludes (95%CL)

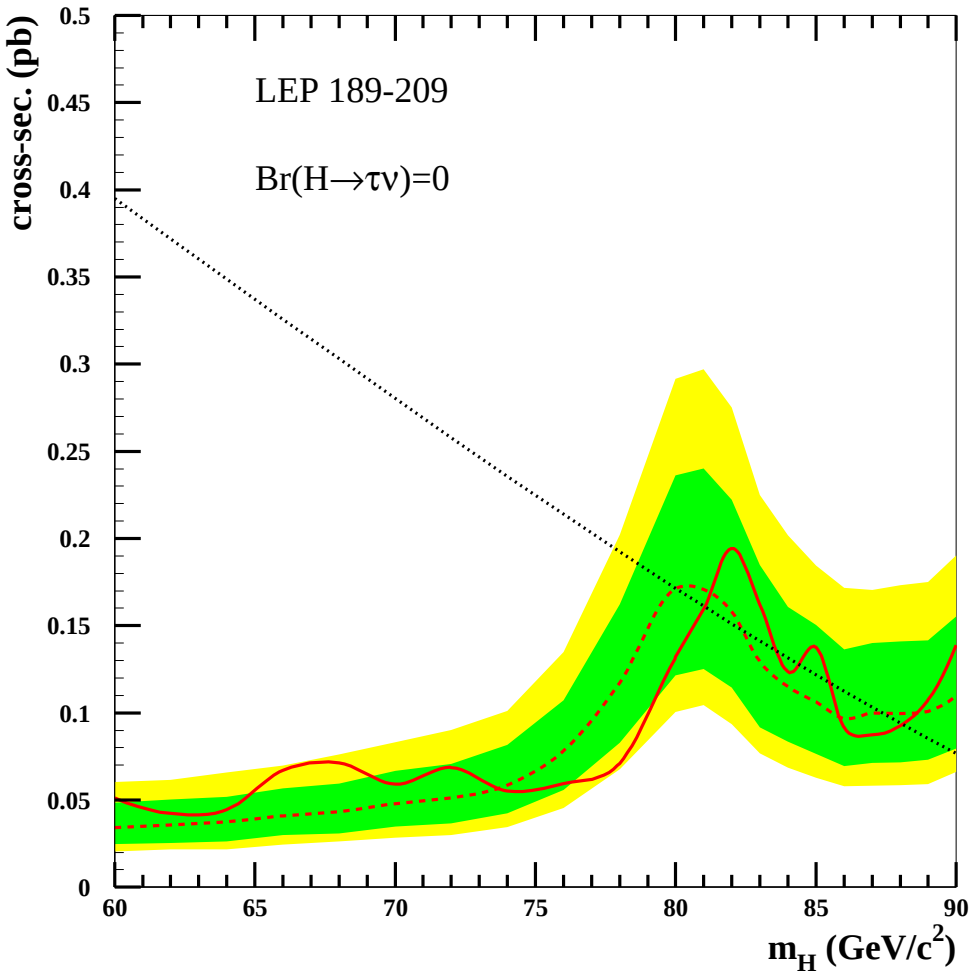
$m_{H^{\pm}} < 78.6$ (78.8 exp.) GeV

for any $B(H^+ \to \tau^+\nu)$

Cross-section limits, $H^{\pm}$

Upper bound on production cross-section,

for $B(H^+ \to \tau^+\nu = 0)$:



$\cdots$ predicted cross-section for $\sqrt{s} = 206$ GeV

Invisible Higgs

e.g., $\mathrm{h} \to \chi\chi$ **(**$\chi =$ **LSP)**

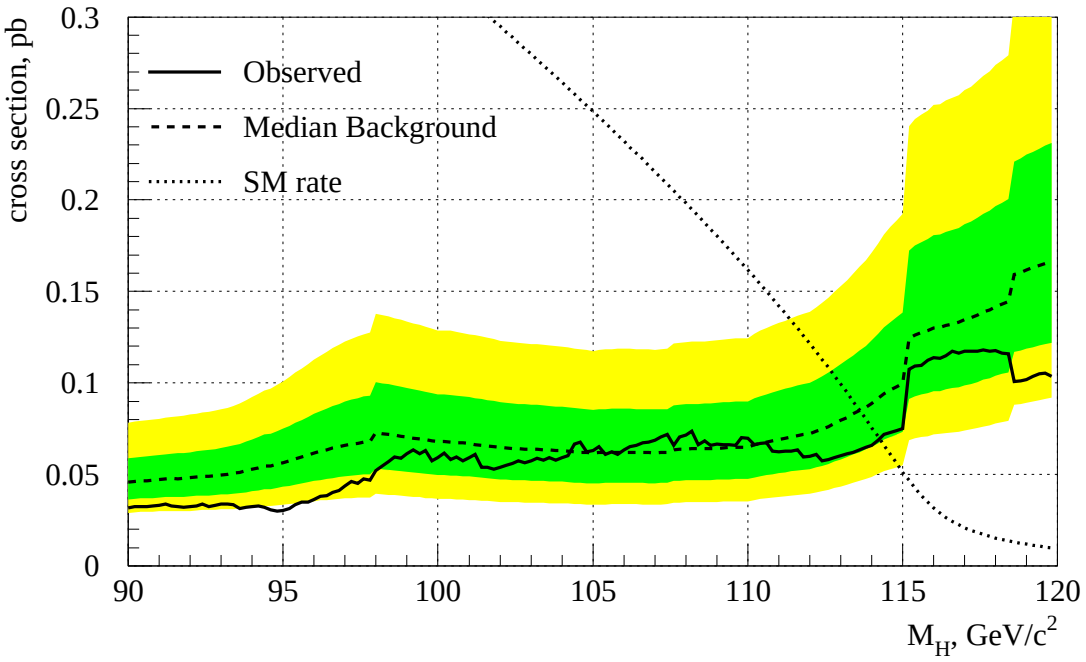
Search for $\mathrm{h} \to \mathrm{inv.}$ + $\mathrm{Z} \to \mathrm{q\bar{q}},\ \ell^+\ell^-$**:**

- **acoplanar jets / leptons**

  - $m_{\mathrm{h}} >$ **114.4 (113.5 exp.) GeV**

Upper bound on production cross-section:

(for SM Higgs σ**, and B(**$\mathrm{h} \to \mathrm{inv.}$**)=100%)**

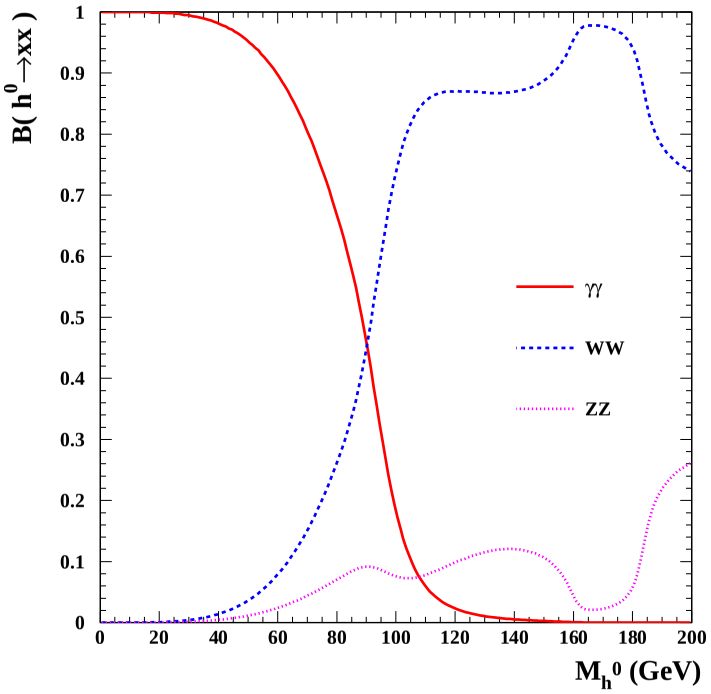


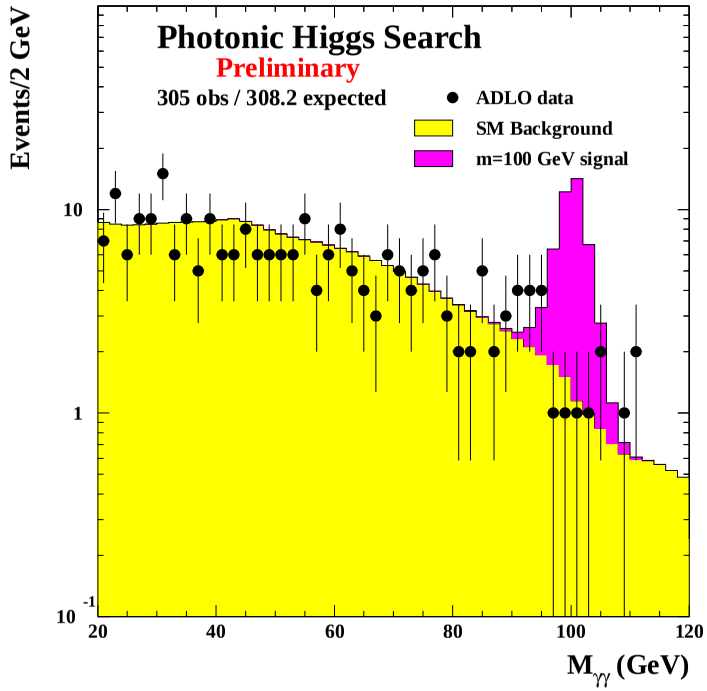
$\cdots$ **predicted cross-section for** $\sqrt{s} = 206$ **GeV**

Fermiophobic Higgs

h ✗→ $f\bar{f}$; ✓ h → $\gamma\gamma$, W^+W^-, ZZ

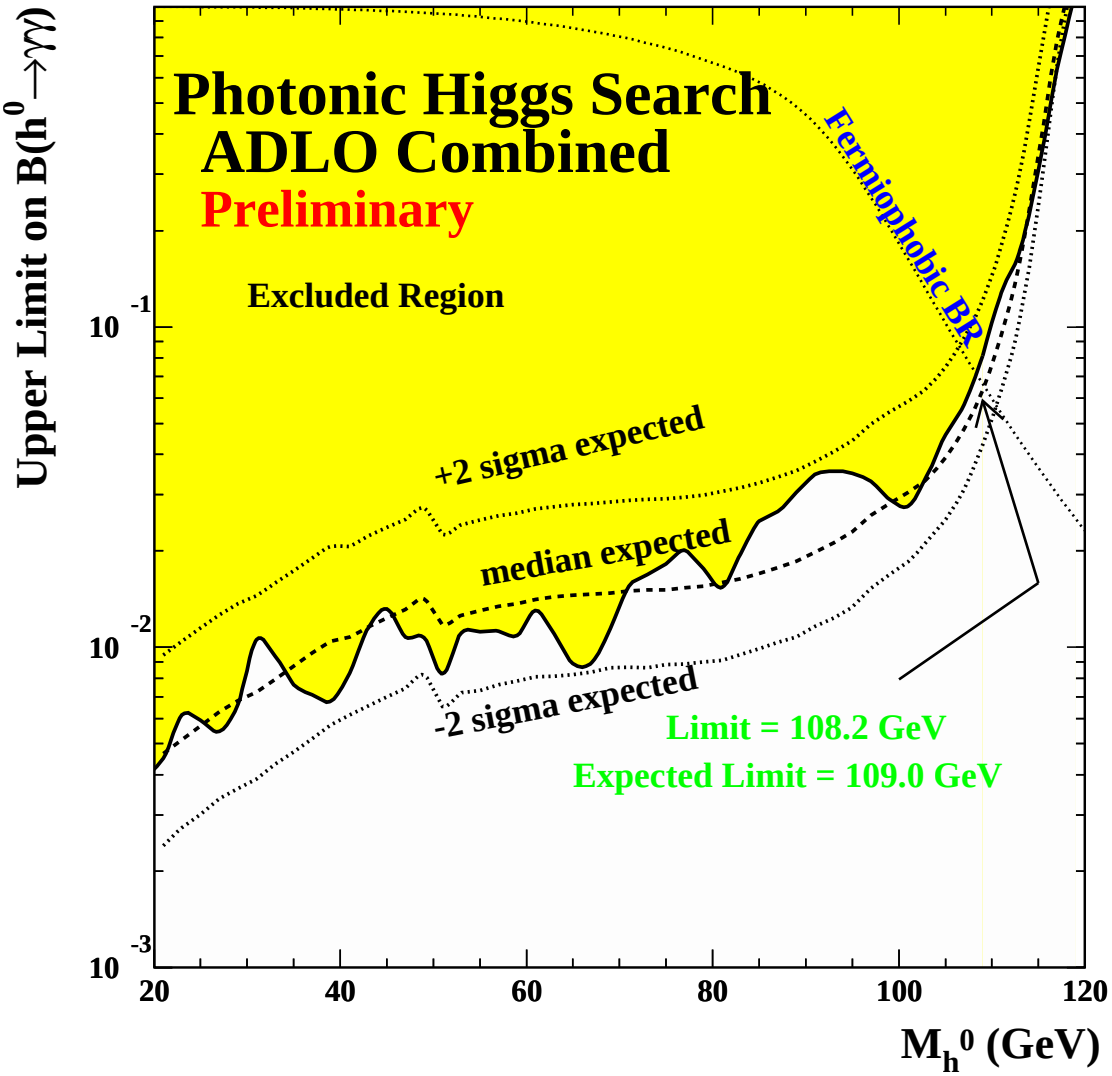
➜ <u>benchmark:</u> SM Higgs production rate





➜ only h → $\gamma\gamma$ searches included in this combined result

Fermiophobic Higgs



at the 95% CL:

- $m_{\mathrm{h}} > 108.2$ (109.0 exp.) GeV
- $\mathrm{B}(\mathrm{h} \to \gamma\gamma) < 6\%$

Flavour-blind Higgs searches

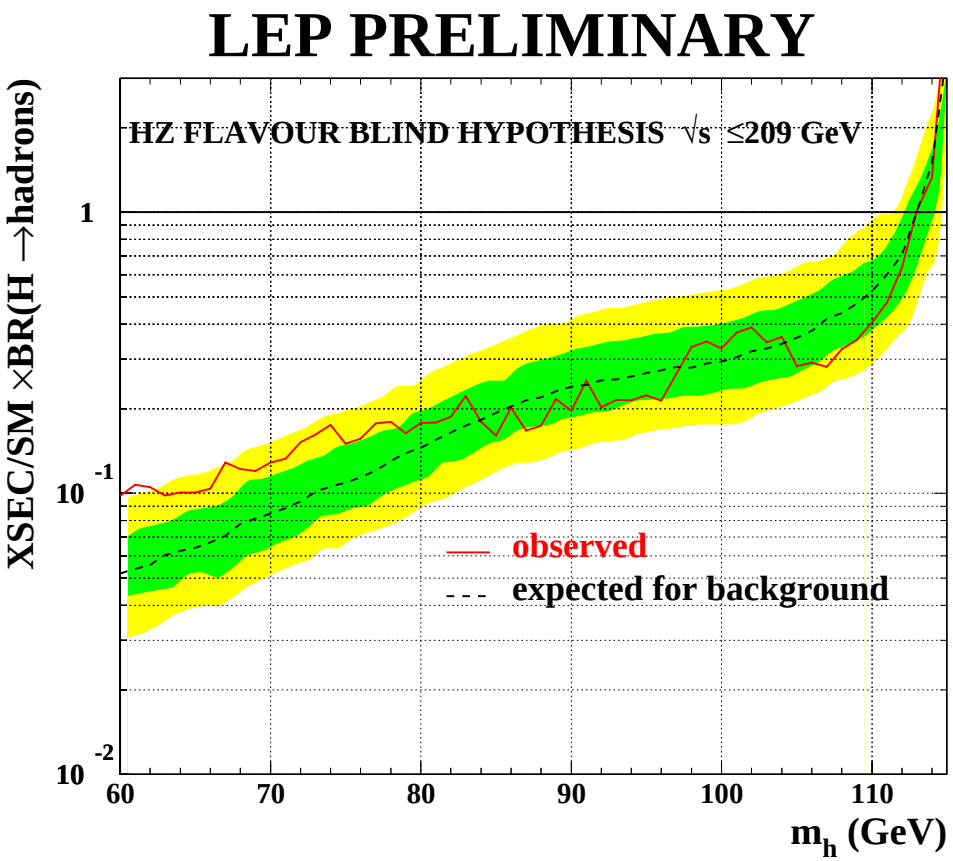
➜ $h \to q\bar{q}, gg$

dedicated searches, not relying on b-tagging:

- improved sensitivity if supressed $h \to b\bar{b}$
- less model-dependent search results

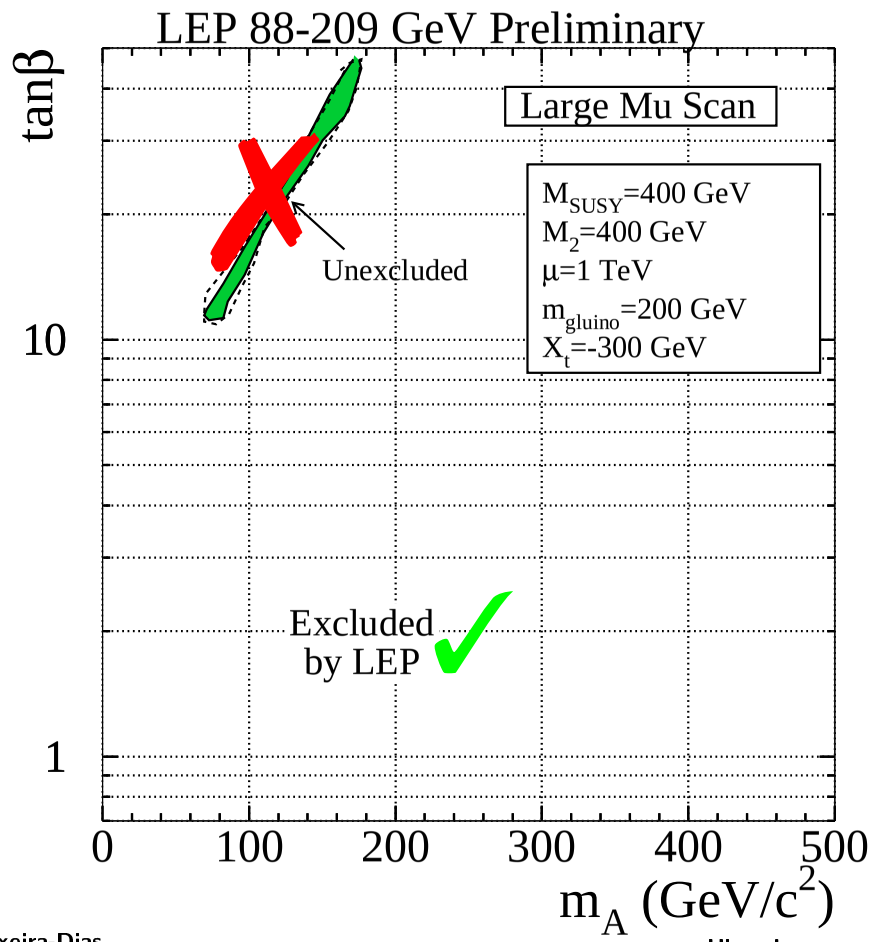
For SM Higgs σ and B(h $\to$hadrons)=100%:

- $m_h >$ 112.9 (113.0 exp.) GeV



MSSM: large-μ benchmark

$(m_h, \tan\beta)$ **plane:**



➜ **scenario designed to**

suppress $h \to b\bar{b}$

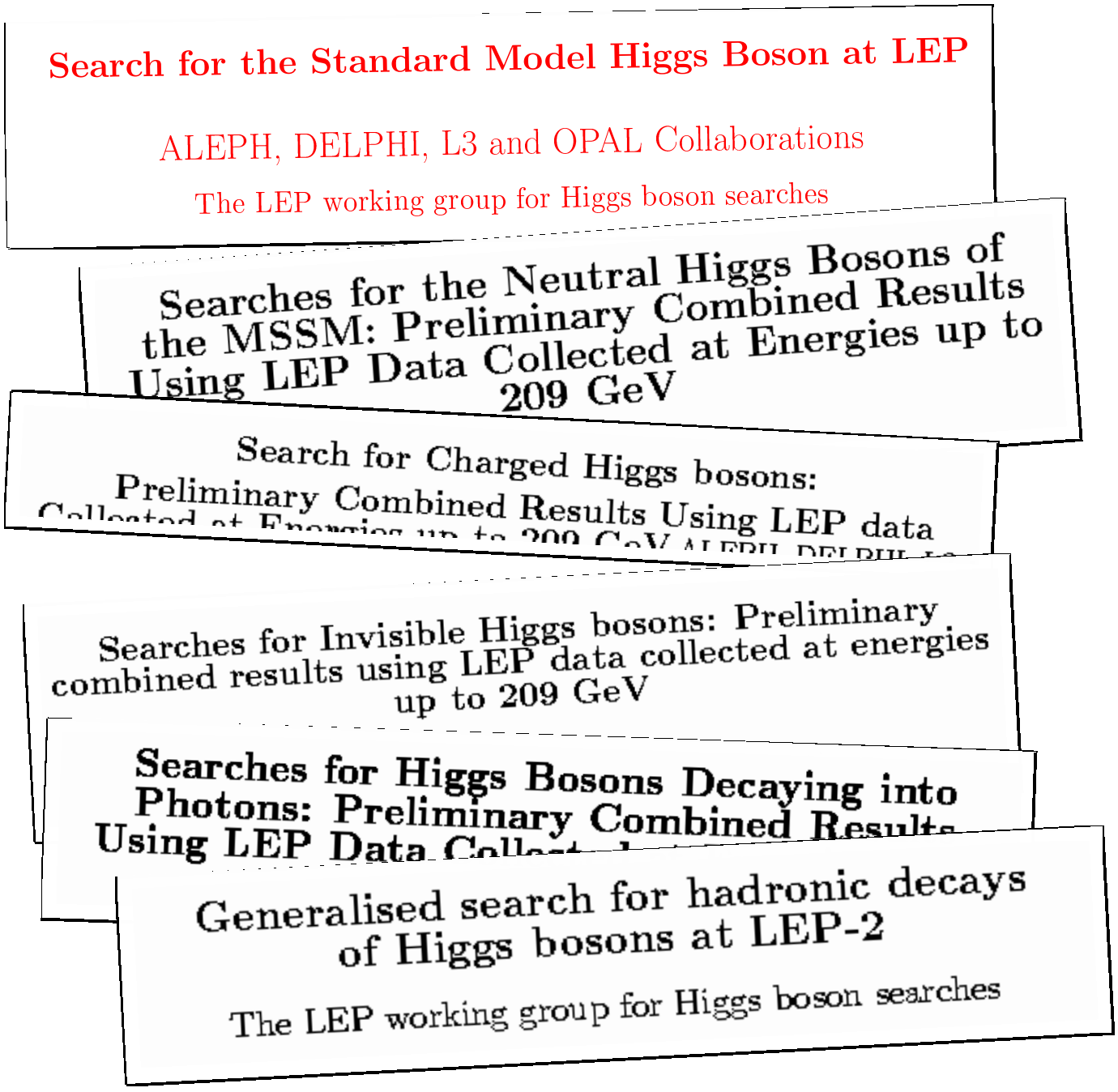
➜ **previous exclusion (at right) based only on** $h \to b\bar{b}$, $\tau^+\tau^-$

➜ **new flavour-independent search**

$\Rightarrow$ **cover** $h \to c\bar{c}$ **&** $h \to gg$

➜ **All points excluded @ 95% CL**

LEP Higgs WG notes



➜ will be available from

http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html