ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2005. Т. 36. ВЫП. 1

УДК 539.12

HIGHLIGHTS OF HIGGS PHYSICS AT LEP

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Final results from the combined data of the four LEP experiments ALEPH, DELPHI, L3, and OPAL on Standard Model (SM) Higgs boson searches are presented. New preliminary results of searches in extended SM are reviewed.

Дан окончательный обзор результатов поиска бозона Хиггса в Стандартной модели на основе совместных данных четырех экспериментов на LEP: ALEPH, DELPHI, L3 и OPAL. Обсуждаются также предварительные результаты поиска бозонов Хиггса в различных расширениях Стандартной модели.

INTRODUCTION

The LEP experiments took data between August 1989 and November 2000 at centre-of-mass energies first around the Z resonance (LEP-1) and later up to 209 GeV (LEP-2). In 2000, most data was taken around 206 GeV. The LEP accelerator operated very successfully and a total luminosity of $\mathcal{L} = 2461$ pb^{-1} was accumulated at LEP-2 energies. Data-taking ended on 3 November 2000, although some data excess was observed in searches for the SM Higgs boson with 115 GeV mass. In this report several different research lines are addressed: 1) the Standard Model Higgs boson: candidates, confidence levels, mass limit, coupling limits; 2) the Minimal Supersymmetric extension of the SM (MSSM): dedicated searches, three-neutral-Higgs-boson hypothesis, benchmark and general scan mass limits; 3) CP-violating models; 4) invisible Higgs boson decays; 5) flavour-independent hadronic Higgs boson decays; 6) neutral Higgs bosons in the general 2-doublet Higgs model; 7) Yukawa Higgs boson processes $b\bar{b}h$ and $b\bar{b}A$; 8) singly-charged Higgs bosons; 9) doubly-charged Higgs bosons; 10) fermiophobic Higgs boson decays $h{\rightarrow}WW, ZZ, \gamma\gamma$.

The results from Standard Model Higgs boson searches are final [1], and the results of searches in extended models are mostly preliminary [2]. Limits are given at 95% CL.

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1. STANDARD MODEL HIGGS BOSON

Figure 1 shows that the observed SM excess is less than 2σ for combined LEP data, and the final candidates are listed in Table 1. The excess is reduced compared to previous reports. A short summary of the development of the data excess was given previously [3].

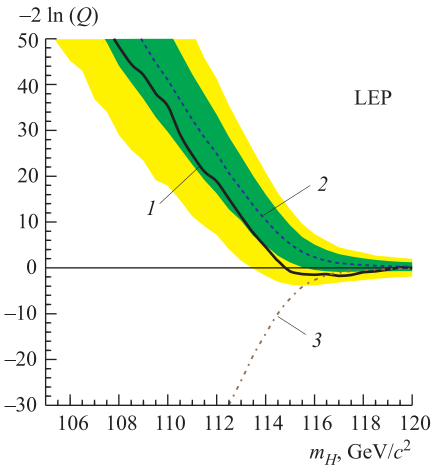

Fig. 1. SM Higgs boson: test statistics for the likelihood ratio $Q = \mathcal{L}_{\rm signal+backgr}/\mathcal{L}_{\rm backgr}$. The 1σ- and 2σ-error bands are indicated (shaded area): *1* — observed; *2* — expected for background; *3* — expected for signal plus background

Table 1. **Final candidates. The signal s and background b estimates are used to construct an event weight** $\ln(1+s/b)$

Experiment	$\sqrt{s}$, GeV	Final state topology	$m_H^{\rm rec}$, GeV	$\ln(1+s/b)$ at 115 GeV
ALEPH	206.6	Four-jet	114.1	1.76
ALEPH	206.6	Four-jet	114.4	1.44
ALEPH	206.4	Four-jet	109.9	0.59
L3	206.4	Missing E.	115.0	0.53
ALEPH	205.1	Leptonic	117.3	0.49
ALEPH	208.0	Tau	115.2	0.45
OPAL	206.4	Four-jet	111.2	0.43
ALEPH	206.4	Four-jet	114.4	0.41
L3	206.4	Four-jet	108.3	0.30
DELPHI	206.6	Four-jet	110.7	0.28
ALEPH	207.4	Four-jet	102.8	0.27
DELPHI	206.6	Four-jet	97.4	0.23
OPAL	201.5	Missing E.	108.2	0.22
L3	206.4	Missing E.	110.1	0.21
ALEPH	206.5	Four-jet	114.2	0.19
DELPHI	206.6	Four-jet	108.2	0.19
L3	206.6	Four-jet	109.6	0.18

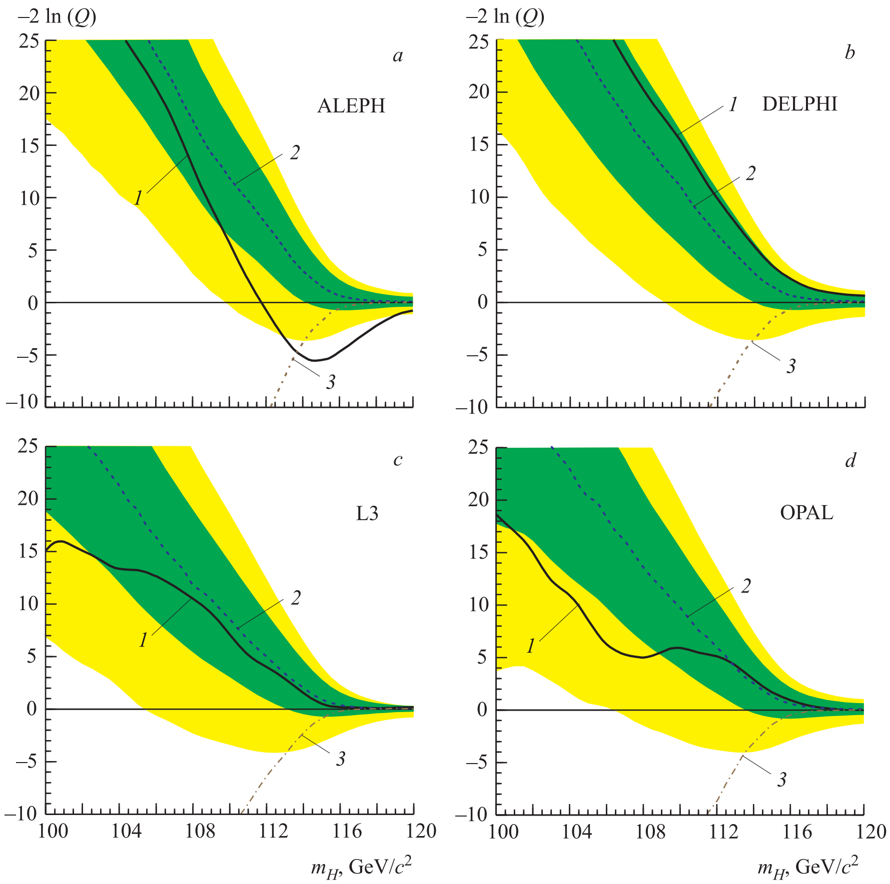

Fig. 2. SM Higgs boson: test statistics for each experiment. As described in Fig. 1, *1* — data; *2*, *3* — expectation for background and for signal plus background

Figure 2 shows the test statistics for each experiment separately.

Figure 3 shows the test statistics for the four-jet channel and all other search channels combined.

Figure 4 shows the significance of the SM candidates as listed in Fig. 1 for each experiment separately as a function of the Higgs boson mass.

Figure 5 shows the significance of the candidate events for a 110 and 115 GeV Higgs boson hypothesis.

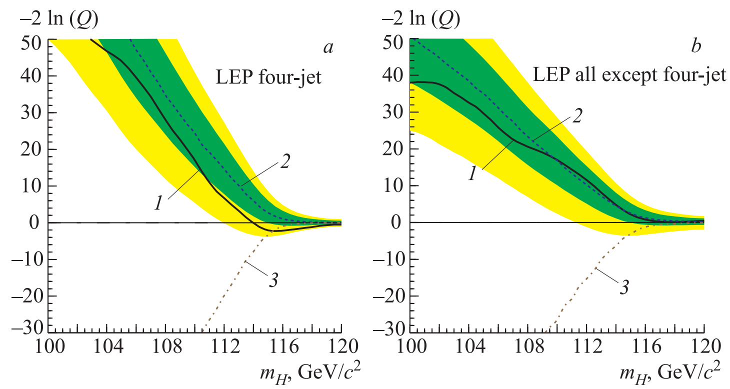

Fig. 3. SM Higgs boson: test statistics for the four-jet channel (*a*) and all other search channels combined (*b*). As described in Fig. 1, *1* — data; *2, 3* — expectation for background and for signal plus background

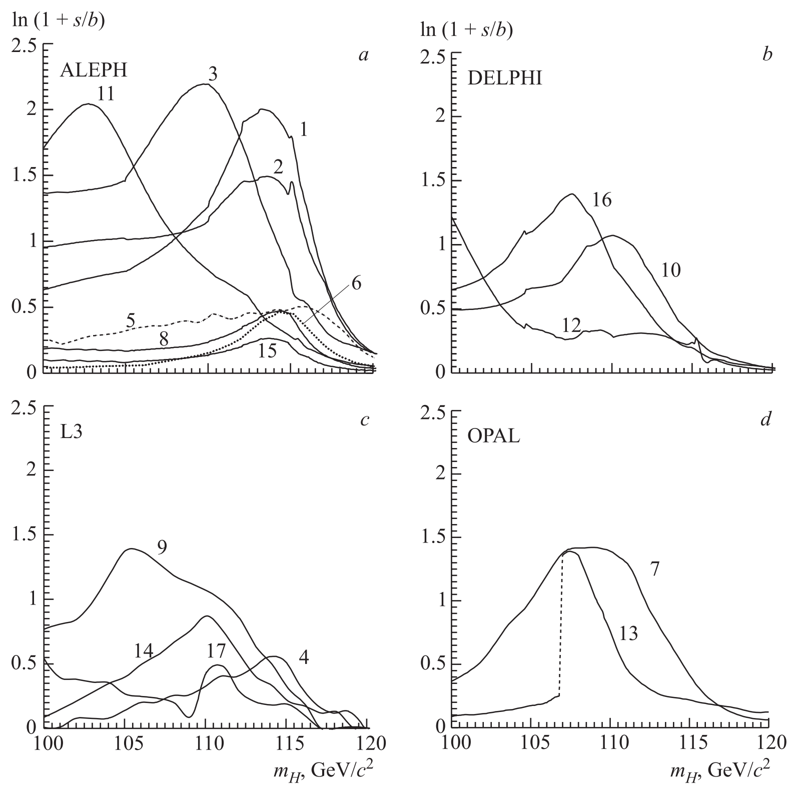

Fig. 4. SM Higgs boson: significance of candidates as a function of the Higgs boson mass

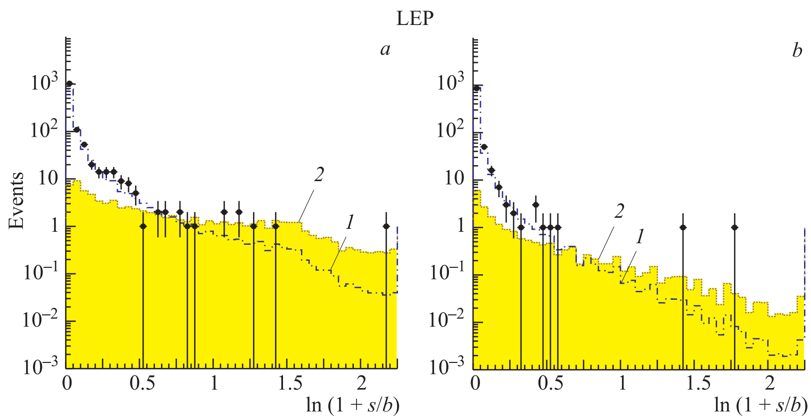

Fig. 5. SM Higgs boson: significance of candidate events for a 110 GeV (*a*) and 115 GeV (*b*) Higgs boson hypothesis. ● — observed; *1* — expected for background; *2* — expected for signal

Figure 6 shows the reconstructed mass of the Higgs boson candidates with loose and tight selection cuts for a 115 GeV Higgs boson hypothesis.

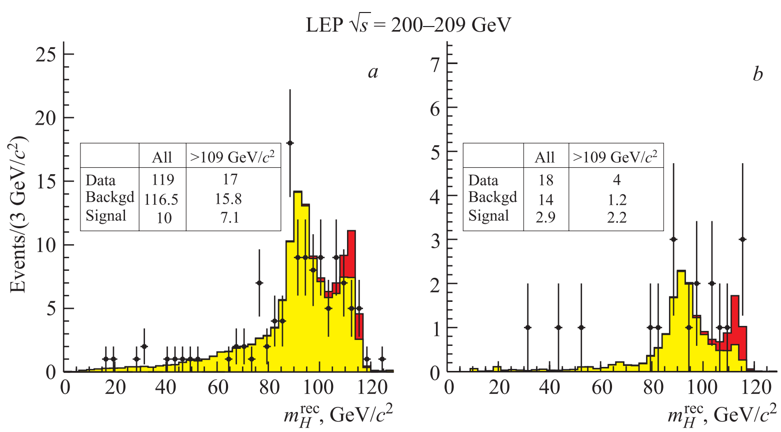

Fig. 6. SM Higgs boson: reconstructed mass of Higgs boson candidates for loose (*a*) and tight (*b*) selection cuts. ● — data; grey area — background; black — signal (115 GeV/c^2)

Figure 7 shows the confidence levels for background-only hypotheses for each experiment separately.

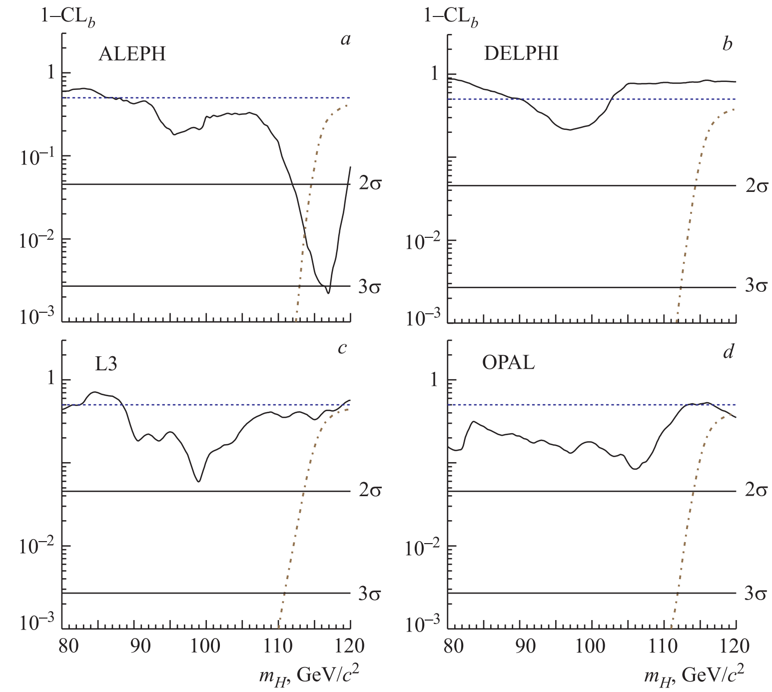

Fig. 7. SM Higgs boson: confidence levels for background-only hypotheses for each experiment. The value $1-\mathrm{CL}_b$ expresses the incompatibility of the observation with the background-only hypothesis

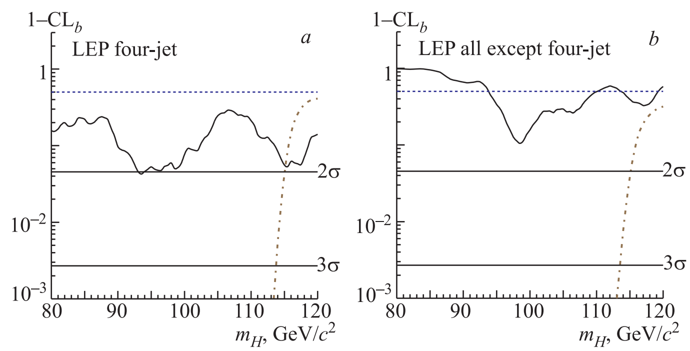

Fig. 8. SM Higgs boson: a small data excess at 98 GeV in the four-jet (*a*) and also in all other channels combined (*b*). In addition, a small excess at 115 GeV in the four-jet channel is observed

Figure 8 shows a small data excess at 98 GeV in the four-jet channel and also in all other channels combined. In addition, a small excess at 115 GeV in the four-jet channel is observed.

Figure 9 shows the probability densities of the test statistics $-2\ln Q$ for background-only and signal-plus-background hypotheses for a 115 GeV Higgs boson, and the observed value of $-2\ln Q$.

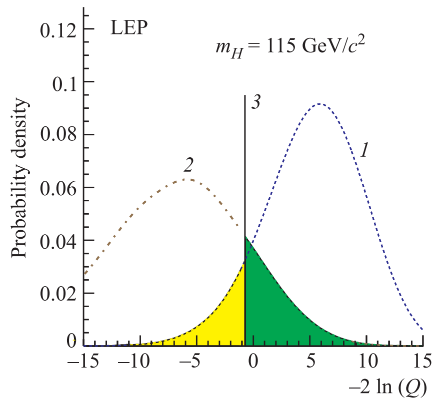

Fig. 9. SM Higgs boson: probability densities of the test statistics $-2\ln\,Q$ for background-only (*1*) and signal-plus-background hypotheses (*2*), and the observed value of $-2\ln\,Q$ (*3*)

Figure 10 shows the SM mass limit, and coupling limits assuming the Higgs boson decays with SM branching fractions and a SM production rate reduced by the factor $\xi^2 = (g_{HZZ}/g_{HZZ}^{\rm SM})^2$.

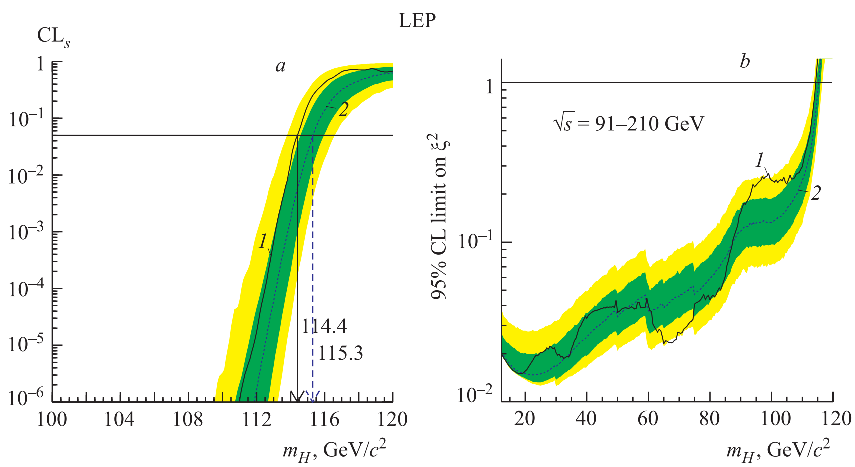

Fig. 10. SM Higgs boson. *a*) Mass limit; *b*) coupling limits assuming the Higgs boson decays with SM branching fractions and a SM production rate reduced by the factor $\xi^2 = (g_{HZZ}/g_{HZZ}^{\rm SM})^2$. *1* — observed; *2* — expected for background

Figure 11 shows coupling limits for b-quark and τ-lepton decay modes.

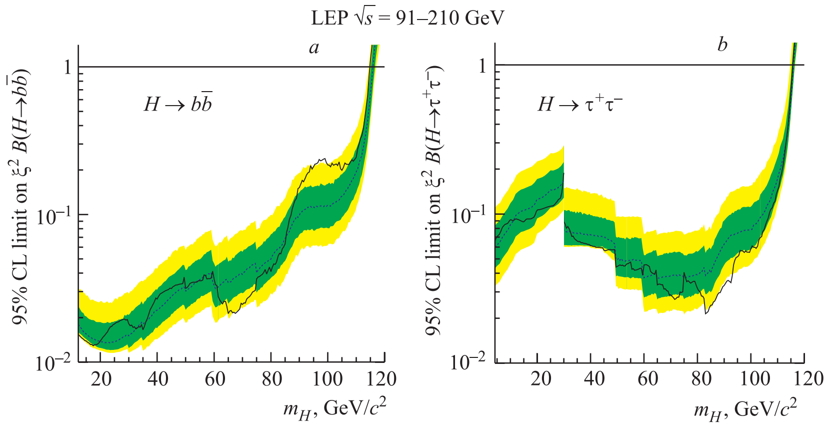

Fig. 11. SM Higgs boson: coupling limits for b-quark (a) and τ-lepton decay modes (b)

2. MINIMAL SUPERSYMMETRIC EXTENSION OF THE SM (MSSM)

Figure 12, a shows a previously small unexcluded mass region for light A masses in the no-mixing scalar top benchmark scenario. This region is mostly excluded by new dedicated searches for a light A boson (Fig. 12, b).

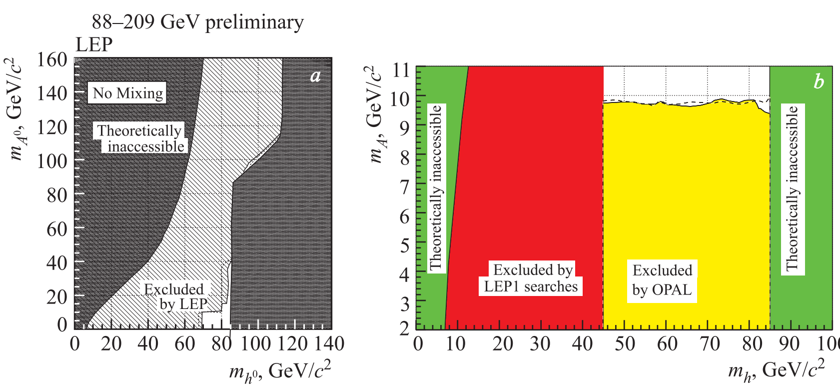

Fig. 12. MSSM. a) Unexcluded mass region for a light A boson in the no-mixing scalar top benchmark scenario; b) excluded mass region by dedicated searches for a light A boson

Figure 13 shows mass limits for the maximum h-mass benchmark scenario, including results from dedicated searches for the reaction $h \to AA$.

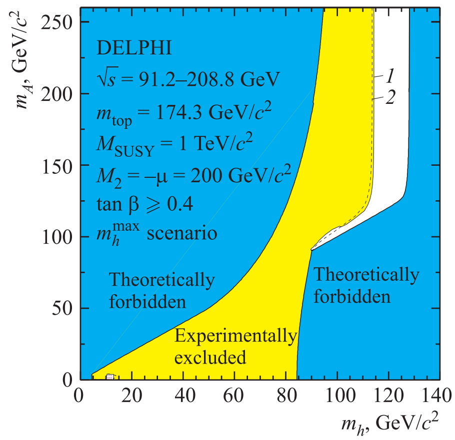

Fig. 13. MSSM: excluded mass region for the maximum h-mass benchmark scenario, including results from dedicated searches for $h \rightarrow AA$. *1* — observed limit; *2* — expected limit

The hypothesis of three-neutral-Higgs-boson production, via hZ, HZ, and hA is compatible with the data excess seen in Fig. 14. For the reported MSSM parameters [4] reduced hZ production near 100 GeV and HZ production near 115 GeV is compatible with the data (Fig. 14, *a*). For $m_h \approx m_A$, hA production is also compatible with the data (Fig. 14, *b*).

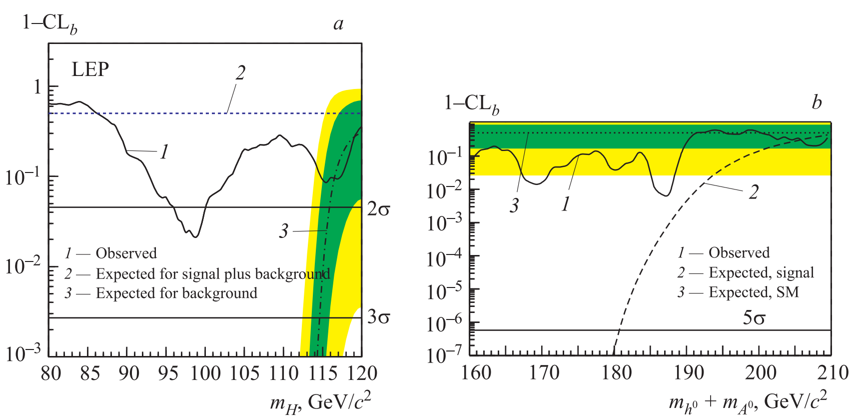

Fig. 14. MSSM. *a*) Small data excess at 99 and 116 GeV in hZ/HZ searches. *b*) Small data excess at $m_h + m_A = 187$ GeV in hA searches

Mass limits in the MSSM depend on invisibly-decaying Higgs boson searches, in particular for general MSSM parameter scans as shown in Fig. 15.

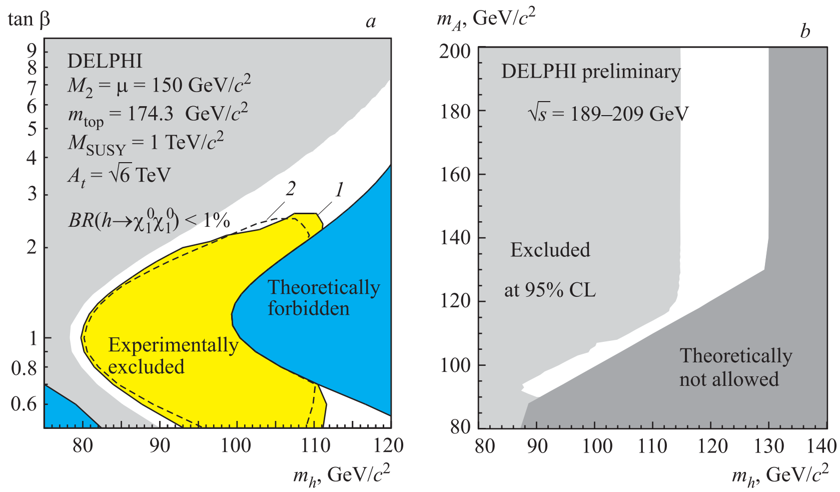

Fig. 15. MSSM. *a*) Mass limits from searches for invisibly-decaying Higgs bosons: *1* — observed limit; *2* — expected limit. *b*) Mass limits from a general MSSM parameter scan

3. CP-VIOLATING MODELS

Instead of h, H, and A, the Higgs bosons are named H_1, H_2, and H_3. The reactions $e^+e^-\to H_2Z\to b\bar{b}\nu\bar{\nu}$ and $e^+e^-\to H_2Z\to H_1H_1Z\to b\bar{b}b\bar{b}\nu\bar{\nu}$ are searched for. No indication of these processes is observed in the data as shown in Fig. 16.

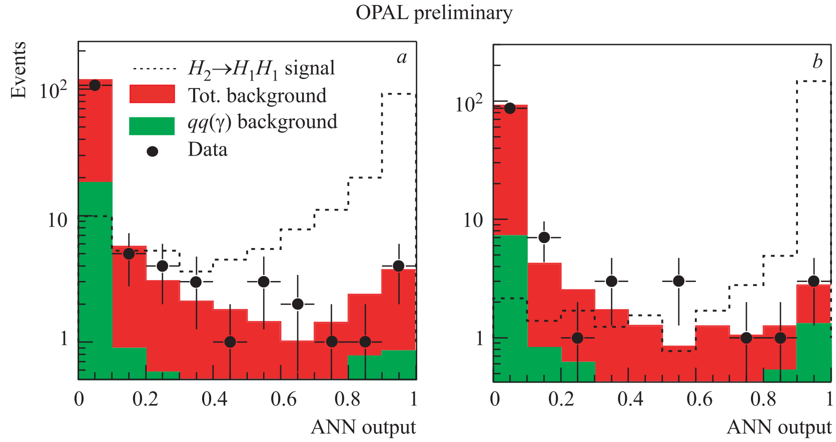

Fig. 16. CP-violation models. Artificial Neural Network (ANN) output distributions for the reactions $e^+e^- \to H_2Z \to b\bar{b}\nu\bar{\nu}$ and $e^+e^- \to H_2Z \to H_1H_1Z \to b\bar{b}b\bar{b}\nu\bar{\nu}$ for different data subsamples. No indication of a signal is observed

Figure 17 from another study shows that a variation in CP mixing reduces the MSSM mass limits significantly.

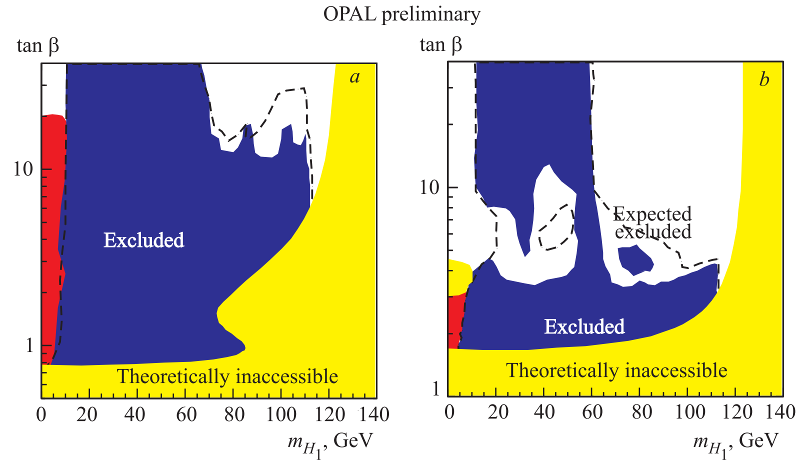

Fig. 17. CP-violation models. *a*) Mass limits with no CP-mixing (arg $(A) = 0°$); *b*) mass limits with full CP-mixing (arg $(A) = 90°$)

4. INVISIBLE HIGGS BOSON DECAYS

No indication of invisibly-decaying Higgs bosons is observed as shown in Fig. 18. Figure 19, *a* shows mass limits for SM and invisible Higgs boson decays

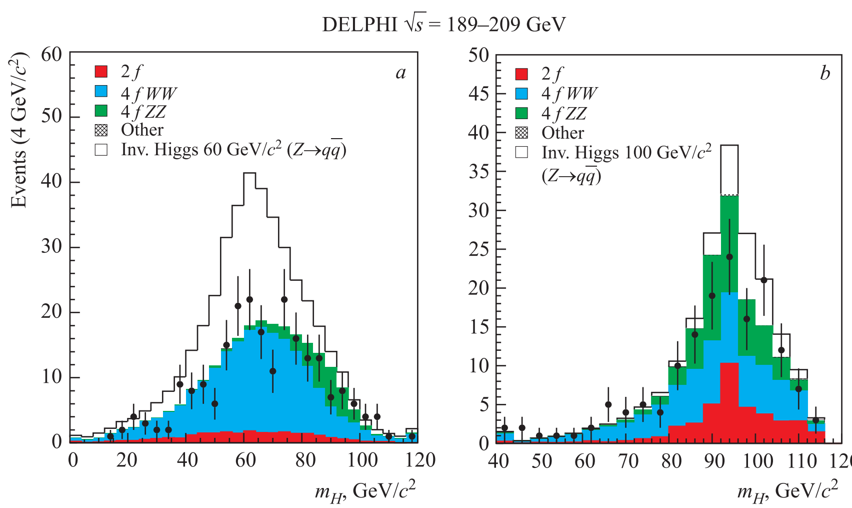

Fig. 18. No indication of invisibly-decaying Higgs bosons is observed in searches optimized in low- and high-mass regions

combined. Figure 19, b shows the mass limits in Majoron models with an extra complex singlet, $H/S \to JJ$, where J escapes undetected.

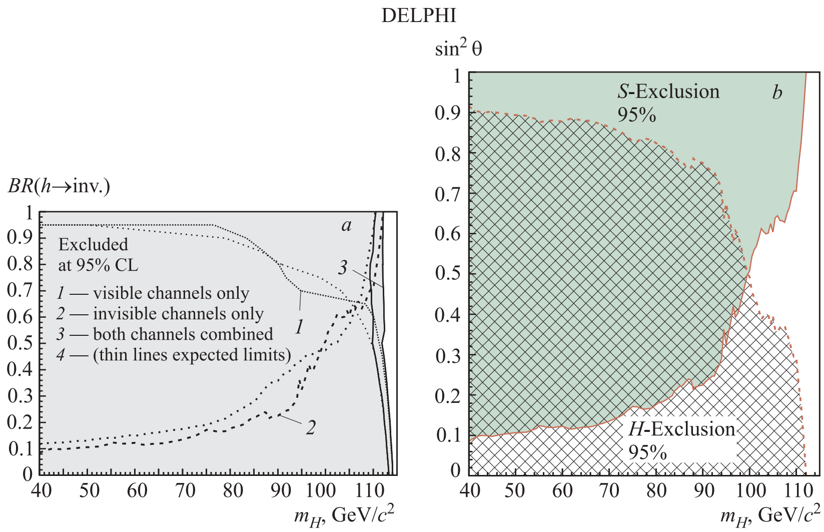

Fig. 19. a) Mass limits for SM and invisible Higgs boson decays combined. b) Mass limits in Majoron models with an extra complex singlet, $H/S \to JJ$, where J escapes undetected. $\sin\theta$ is the H/S mixing angle

5. FLAVOUR-INDEPENDENT HADRONIC HIGGS BOSON DECAYS

Figure 20 shows no indication of a signal for the process $hZ \to q\bar{q}\ell^+\ell^-$ above the background $ZZ \to q\bar{q}\ell^+\ell^-$. In addition, the expected signal efficiencies are

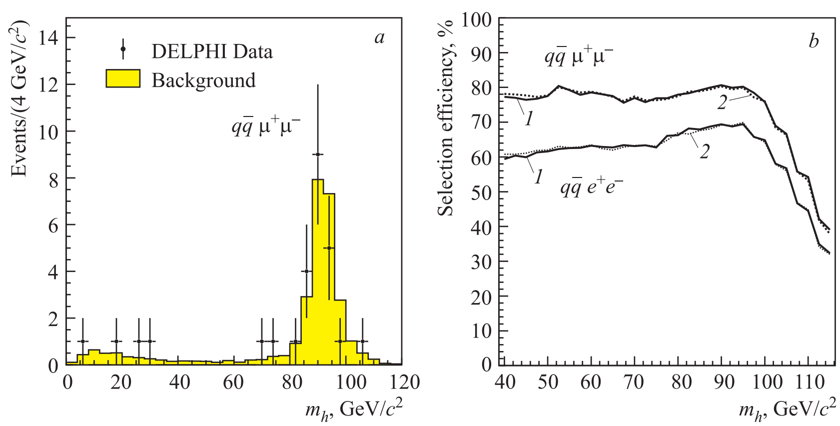

Fig. 20. a) No indication of a signal for the process $hZ \to q\bar{q}\ell^+\ell^-$ above the background $ZZ \to q\bar{q}\ell^+\ell^-$. b) Expected signal efficiencies: *1* — $hZ(h \to s\bar{s})$; *2* — $hZ(h \to gg)$

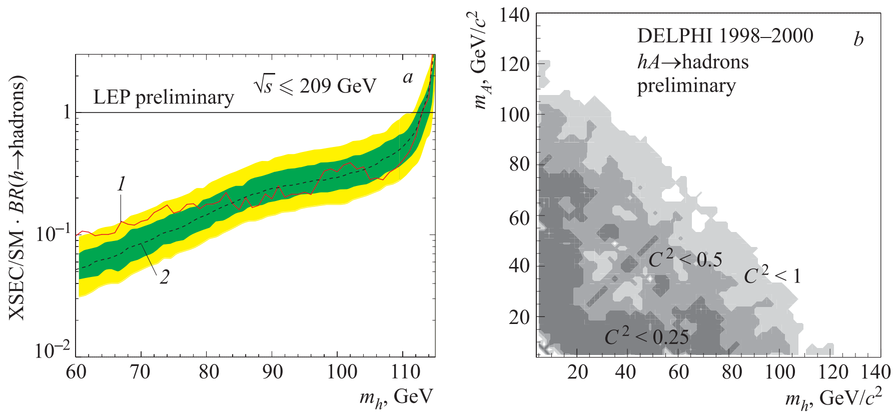

Fig. 21. Flavour-independent limits from searches for hadronic hZ and hA decays. No b-tagging requirement is applied. C^2 is the reduction factor on the maximum production cross section. *1* — observed; *2* — expected for background

shown. Flavour-independent limits from searches for hadronic hZ and hA decays are shown in Fig. 21.

6. NEUTRAL HIGGS BOSONS IN THE GENERAL 2-DOUBLET HIGGS MODEL (2DHM)

Figure 22 shows mass limits from dedicated searches for hA production and from a parameter scan. The scan combines searches with b-tagging and flavour-independent searches.

7. YUKAWA HIGGS BOSON PROCESSES $b\bar{b}h$ and $b\bar{b}A$

Figure 23 shows mass limits from searches for the Yukawa processes $e^+e^- \to b\bar{b} \to b\bar{b}h,\ b\bar{b}A$.

8. SINGLY-CHARGED HIGGS BOSONS

Figure 24 shows mass limits from searches for $e^+e^- \to H^+H^- \to c\bar{s}\bar{c}s$, $cs\tau\nu$, $\tau^+\nu\tau^-\bar{\nu}$. The decay $H^\pm \to W^\pm A$ could be dominant and limits from searches for the process are shown in Fig. 25.

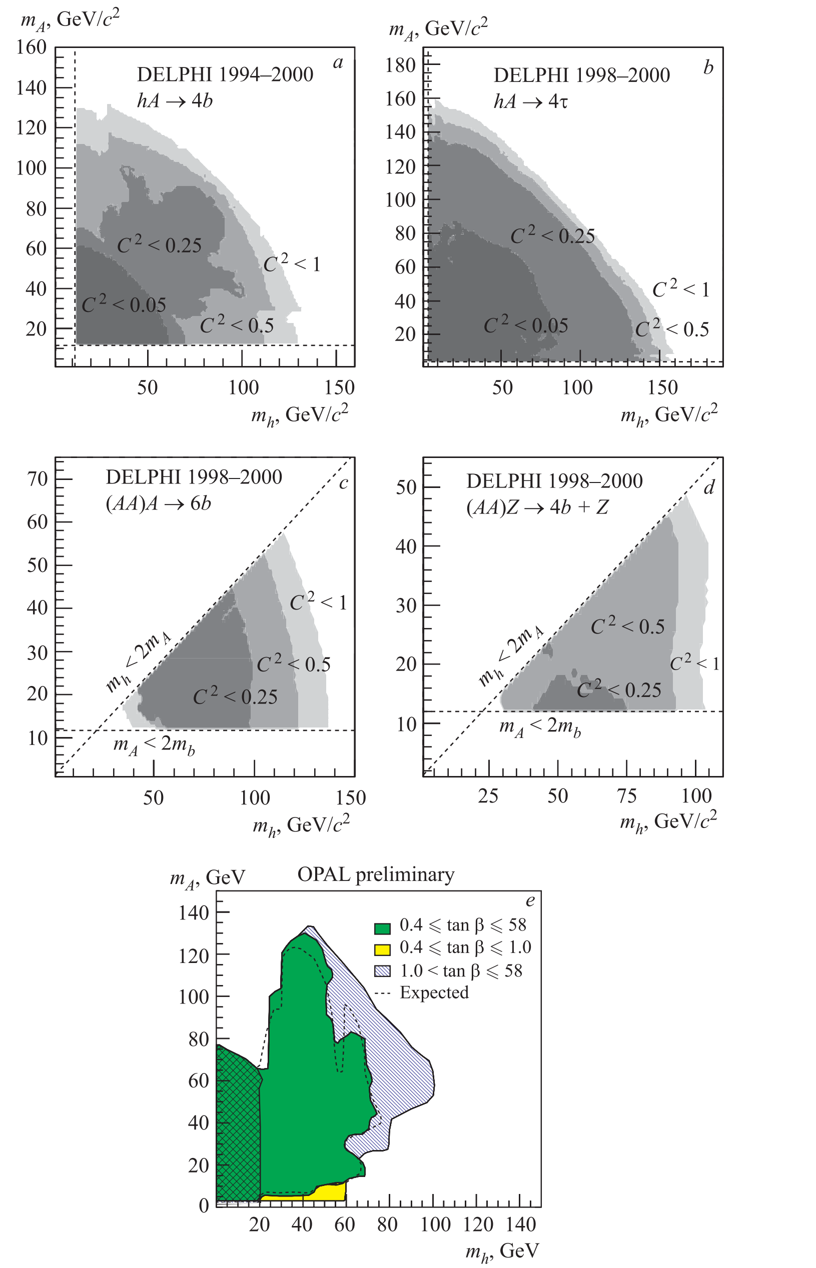

Fig. 22. 2DHM. a, c) Mass limits from dedicated searches for hA production. C^2 is the reduction factor on the maximum production cross section. b, d) Mass limits from a general 2DHM parameter scan

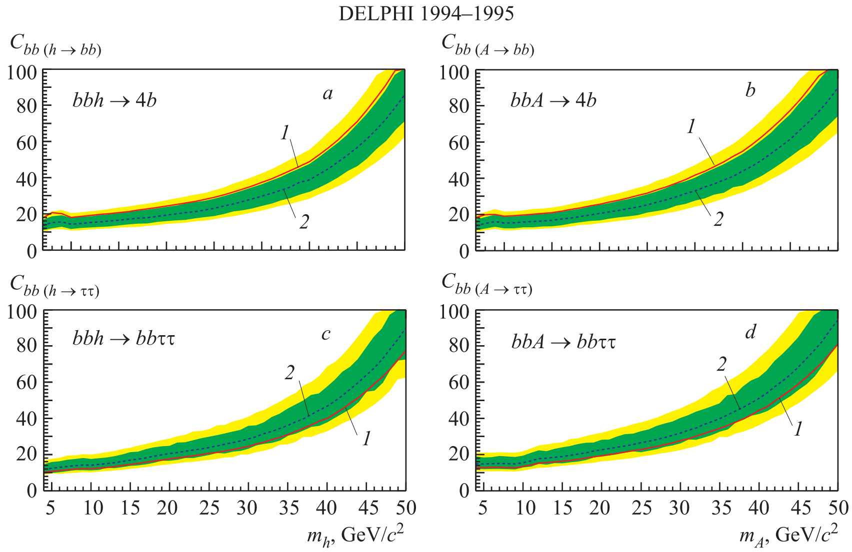

Fig. 23. Observed (*1*) and expected (*2*) mass limits from searches for the Yukawa processes $e^+e^- \to b\bar{b} \to b\bar{b}h,\ b\bar{b}A$. The C factors include vertex enhancement factors and decay branching fractions

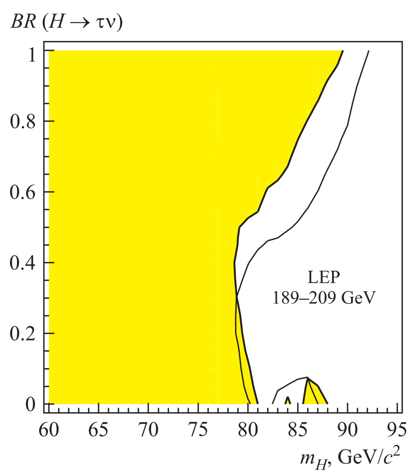

Fig. 24. Excluded mass region (shaded area) from searches for $e^+e^- \to H^+H^- \to c\bar{s}\bar{c}s$, $cs\tau\nu$ and $\tau^+\nu\tau^-\bar{\nu}$. The thin line shows the expected limit

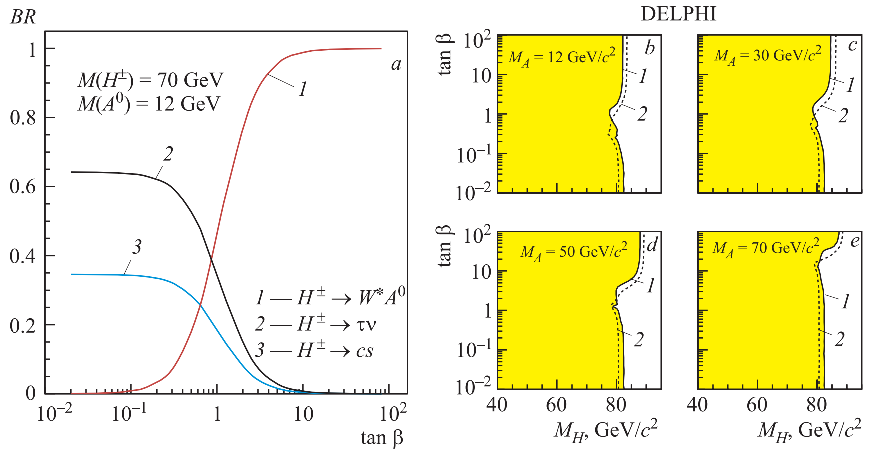

Fig. 25. *a*) $H^{\pm} \to W^{\pm} A$ decays could be dominant for light A boson masses. *b–e*) Excluded mass region (shaded area) from searches for this process. *1* — observed; *2* — expected

9. DOUBLY-CHARGED HIGGS BOSONS

The process $e^+e^- \to H^{++}H^{--} \to \tau^+\tau^+\tau^-\tau^-$ can lead to decays at the primary interaction point ($h_{\tau\tau} \geqslant 10^{-7}$) [5, 6], a secondary vertex, or stable massive particle signatures. Figure 26 shows no indication of a signal in the data. Limits on the production cross section are given in Fig. 27.

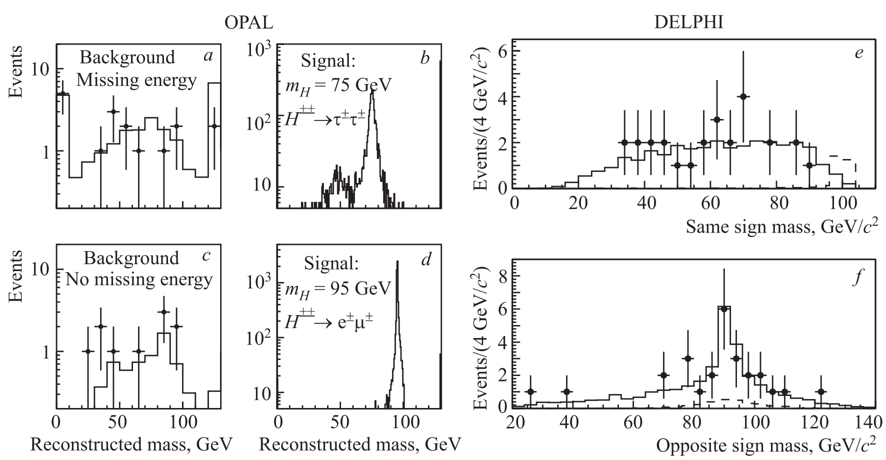

Fig. 26. No indication of $e^+e^- \to H^{++}H^{--} \to \tau^+\tau^+\tau^-\tau^-$ is observed in the data

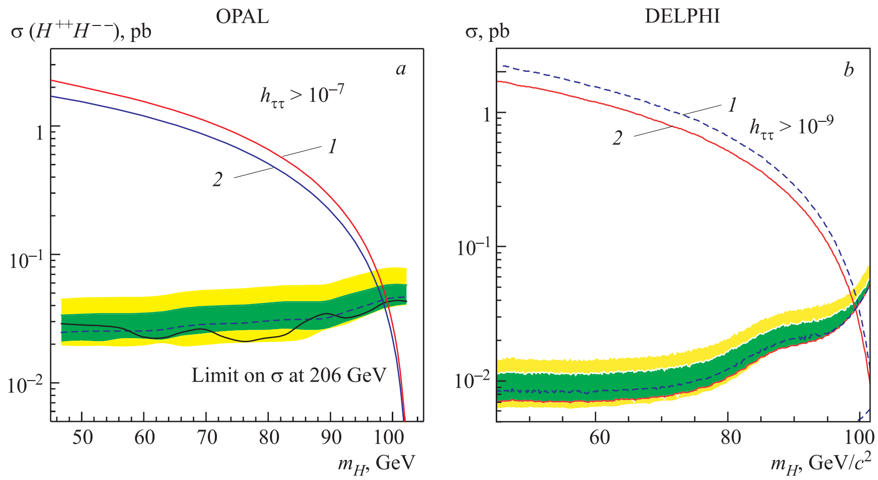

Fig. 27. Limits on the $e^+e^- \to H^{++}H^{--}$ production cross section are set as a function of the doubly-charged Higgs boson mass. *1* — σ_L; *2* — σ_R

10. FERMIOPHOBIC HIGGS BOSON DECAYS: $h \to WW, ZZ, \gamma\gamma$

If Higgs boson decays into fermions are suppressed, $h \to WW$, ZZ, $\gamma\gamma$ decays could be dominant. Mass limits from dedicated searches are shown in Fig. 28.

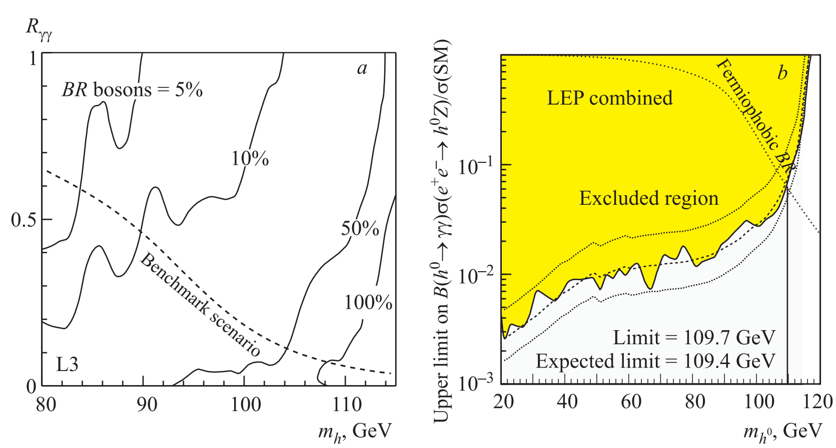

Fig. 28. *a*) Mass limits as defined in Ref. 7 from $h \to WW, ZZ, \gamma\gamma$ searches. *b*) Mass limits from $h \to \gamma\gamma$ combined results

CONCLUSIONS

Immense progress over a period of 14 years has been made at LEP in searches for Higgs bosons and much knowledge has been gained in preparation for new searches. No signal has been observed and various stringent limits are set as summarized in Table 2.

Table 2. **Summary of Higgs boson mass limits at 95% CL**

Search	Experiment	Limit
Standard Model	LEP	$m_H^{\rm SM} > 114.4$ GeV
Reduced rate and SM decay		$\xi^2 > 0.05 : m_H > 85$ GeV
		$\xi^2 > 0.3 : m_H > 110$ GeV
Reduced rate and $b\bar{b}$ decay		$\xi^2 > 0.04 : m_H > 80$ GeV
		$\xi^2 > 0.25 : m_H > 110$ GeV
Reduced rate and $\tau^+\tau^-$ decay		$\xi^2 > 0.2 : m_H > 113$ GeV
MSSM (no scalar top mixing)	LEP	Almost entirely excluded
General MSSM scan	DELPHI	$m_h > 87$ GeV, $m_A > 90$ GeV
CP-violating	OPAL	Strongly reduced limits
Visible/invisible Higgs decays	DELPHI	$m_H > 111.8$ GeV
Majoron model (max. mixing)		$m_{H,S} > 112.1$ GeV
Flavour-ind. hadronic decay	LEP	$hZ \to q\bar{q} : m_H > 112.9$ GeV
(for $\sigma_{\max}$)	DELPHI	$hA \to q\bar{q}q\bar{q} : m_h + m_A > 110$ GeV
2DHM	DELPHI	$b\bar{b}b\bar{b} : m_h + m_A > 150$ GeV
(for $\sigma_{\max}$)		$\tau^+\tau^-\tau^+\tau^- : m_h + m_A > 160$ GeV
		$(AA)A \to 6b : m_h + m_A > 150$ GeV
		$(AA)Z \to 4b\ Z : m_h > 90$ GeV
General 2DHM scan	OPAL	$\tan\beta > 1 : m_h \approx m_A > 85$ GeV
Yukawa process	DELPHI	$C > 40 : m_{h,A} > 40$ GeV
Singly-charged Higgs bosons	LEP	$m_{H^\pm} > 78.6$ GeV
W$^\pm$A decay mode	DELPHI	$m_{H^\pm} > 76.7$ GeV
Doubly-charged Higgs bosons	DELPHI/OPAL	$m_{H^{++}} > 99$ GeV
Fermiophobic $H \to WW, ZZ, \gamma\gamma$	L3	$m_H > 108.3$ GeV
$H \to \gamma\gamma$	LEP	$m_H > 109.7$ GeV

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