Searches for Higgs Bosons Beyond the Standard Model

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(On behalf of the LEP Collaborations)

Outline

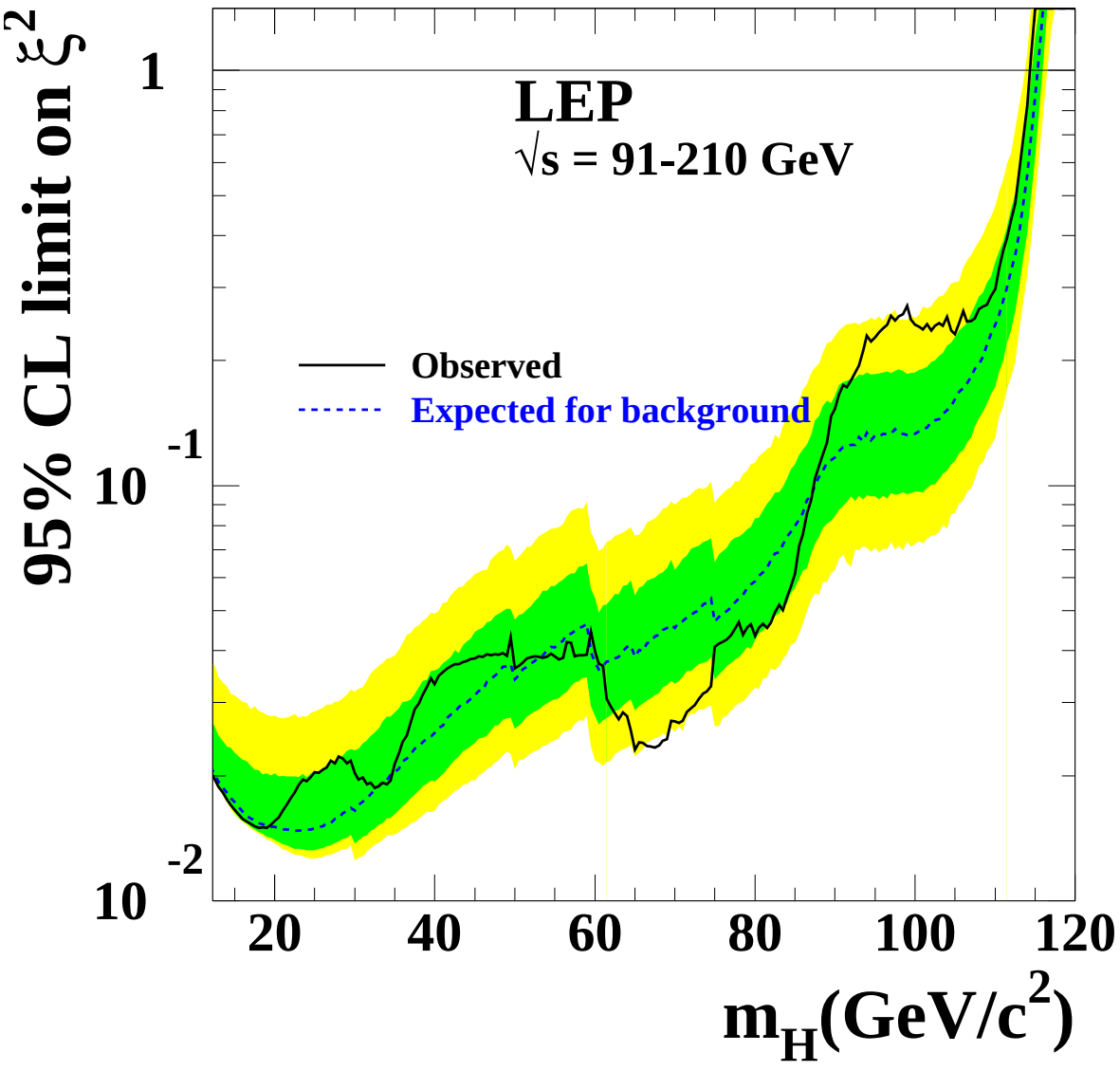
- Introduction
- HZZ Couplings
- Anomalous Couplings
- Minimal Supersymmetric Extension of the SM (MSSM): Dedicated Searches, Three-Higgs-Boson Hypothesis, Benchmark and General Scan Mass Limit
- CP-Violating Models
- Invisible Higgs Boson Decays
- Flavor-Independent Hadronic Decays
- Yukawa Process
- Singly and Doubly-Charged Higgs Bosons
- Fermiophobic Higgs Boson Decays ($\rightarrow$ dedicated talk)
- Conclusions

Introduction

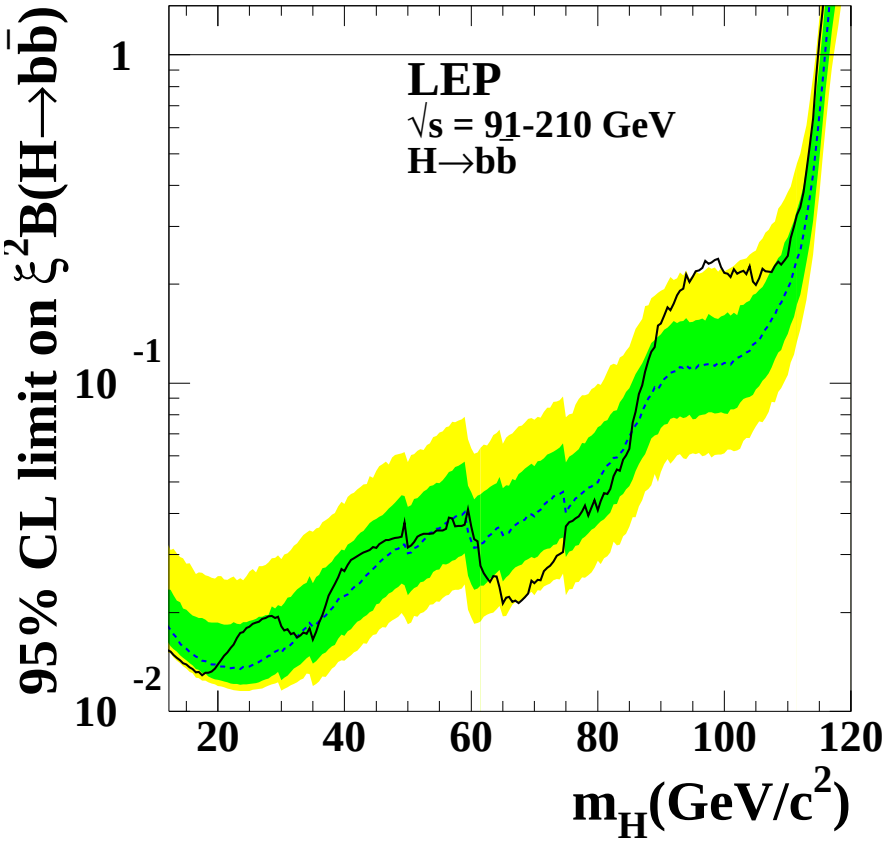
LEP experiments are finalizing their analyses for non-Standard-Model Higgs boson searches.

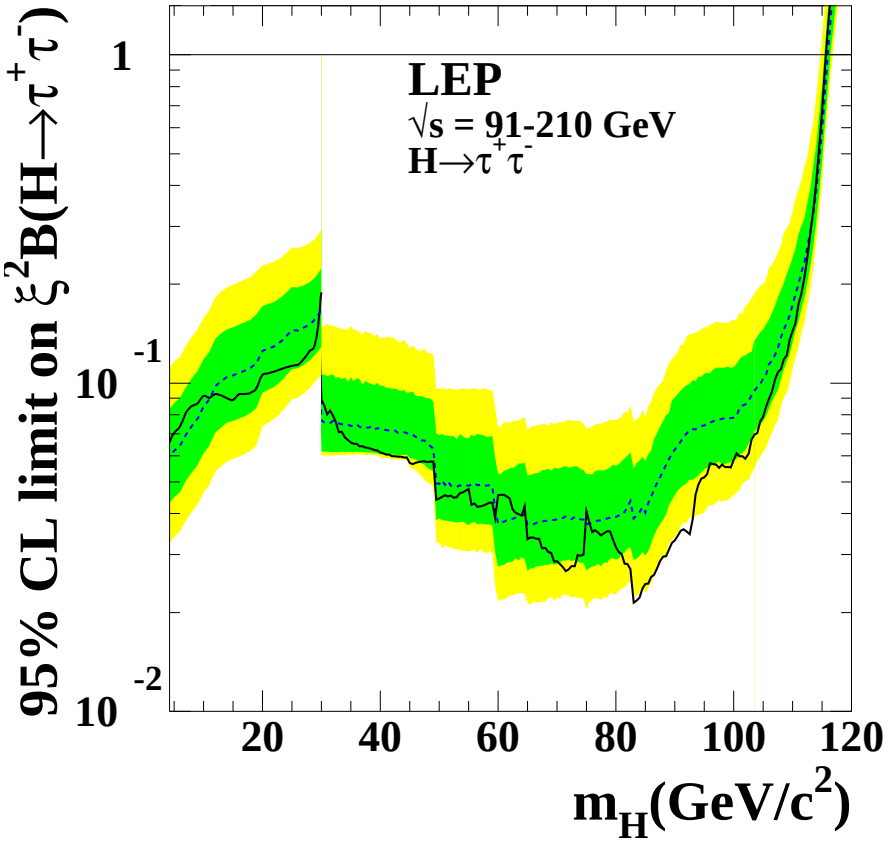
- Still very active and final results in sight: some results are *preliminary*.
- Accelerator: Very successful. Larger luminosity ($\mathcal{L} = 2461$ pb^{-1}) and higher energy (≤ 209 GeV) than anticipated.
- Data-taking ended November 3, 2000, although some data excess was observed.

$\xi^2 = (g_{\mathrm{HZZ}}/g^{\mathrm{SM}}_{\mathrm{HZZ}})^2$ Coupling Limit: SM-like Decays

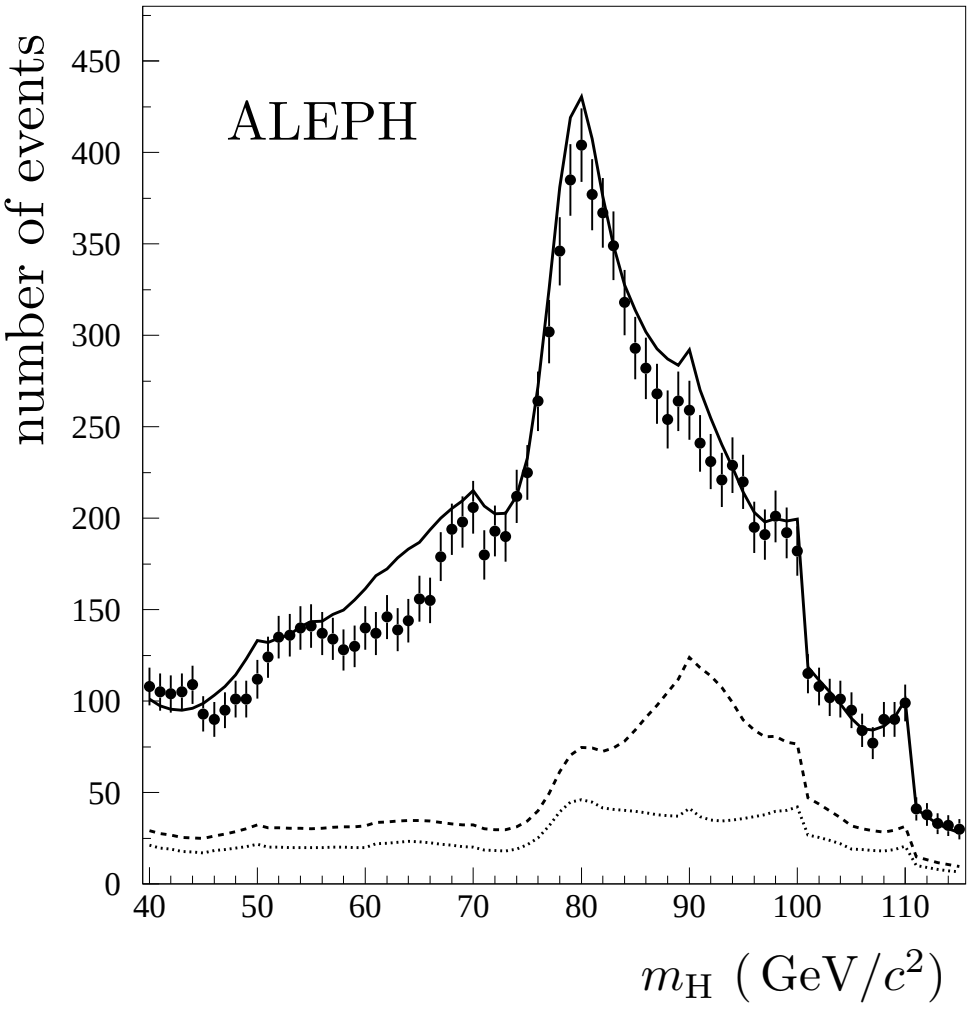


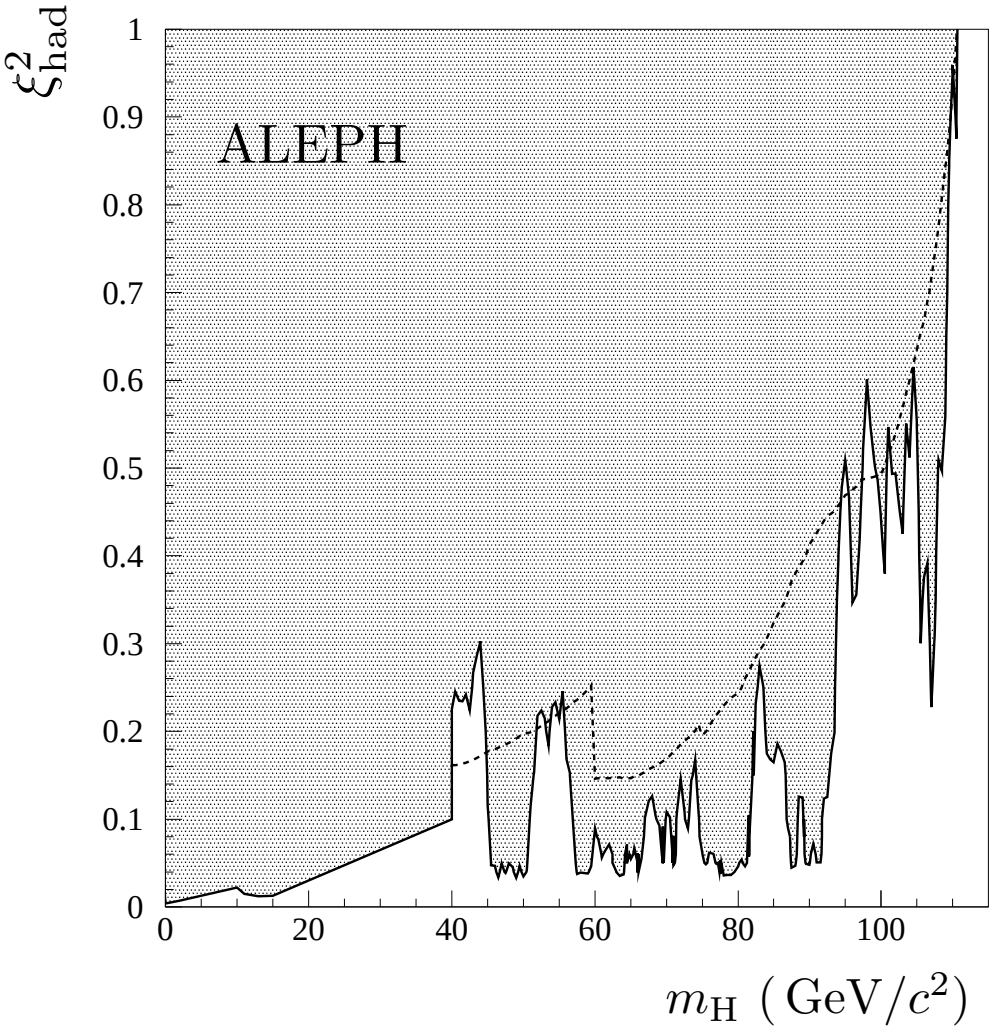
Coupling Limit: b-quark and τ-lepton Decay Mode





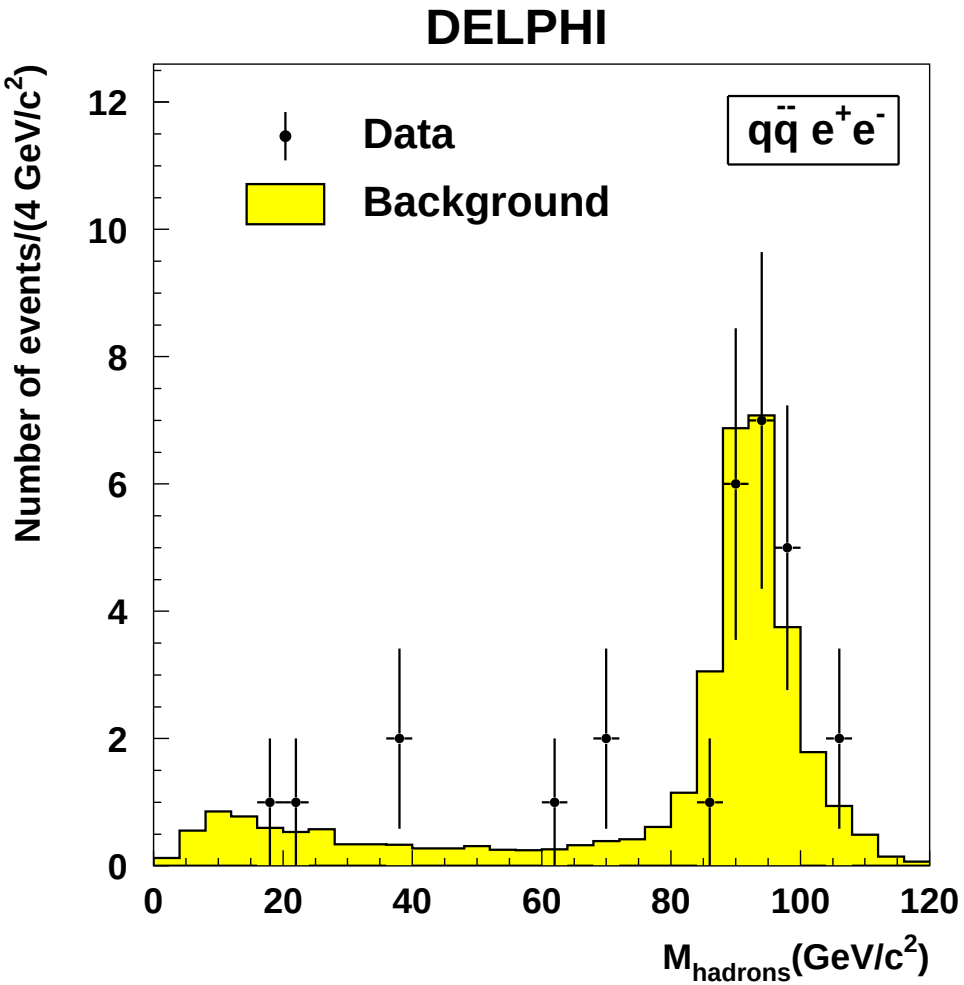
Coupling Limit: Hadronic Decay Mode

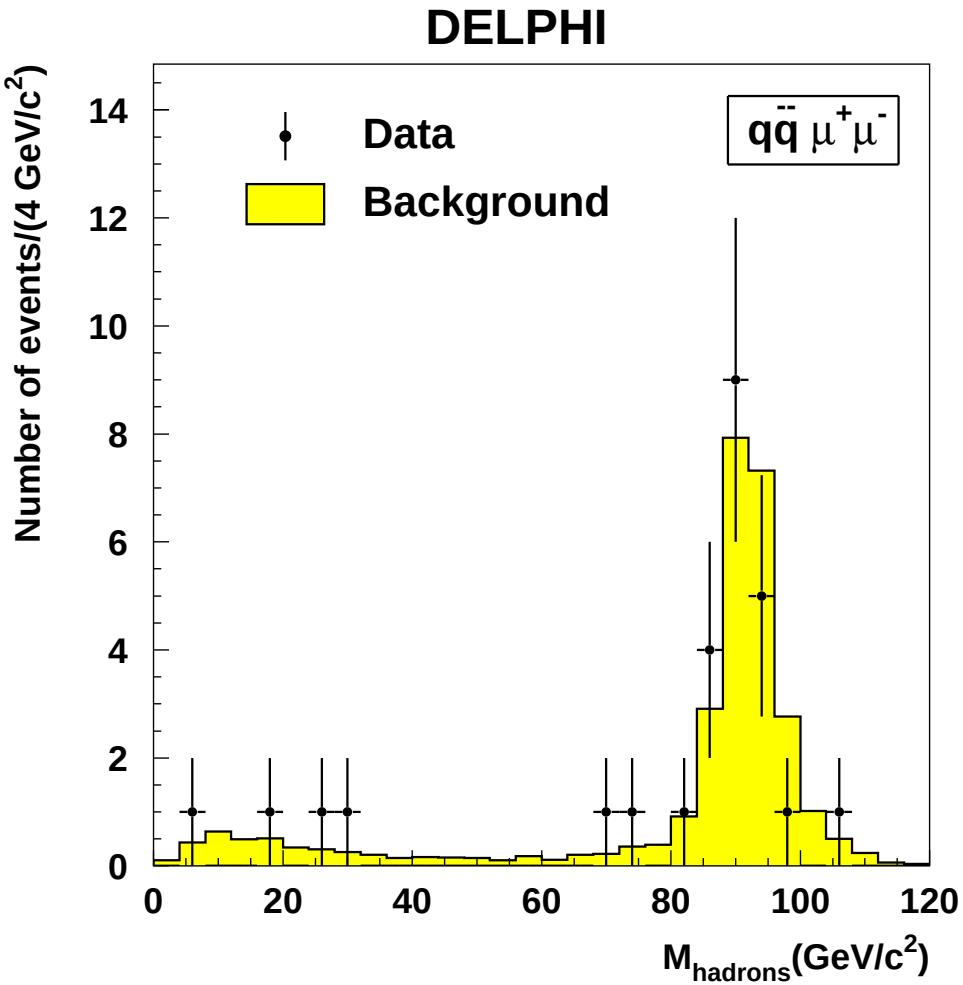




Flavor-Independent Hadronic hZ Searches

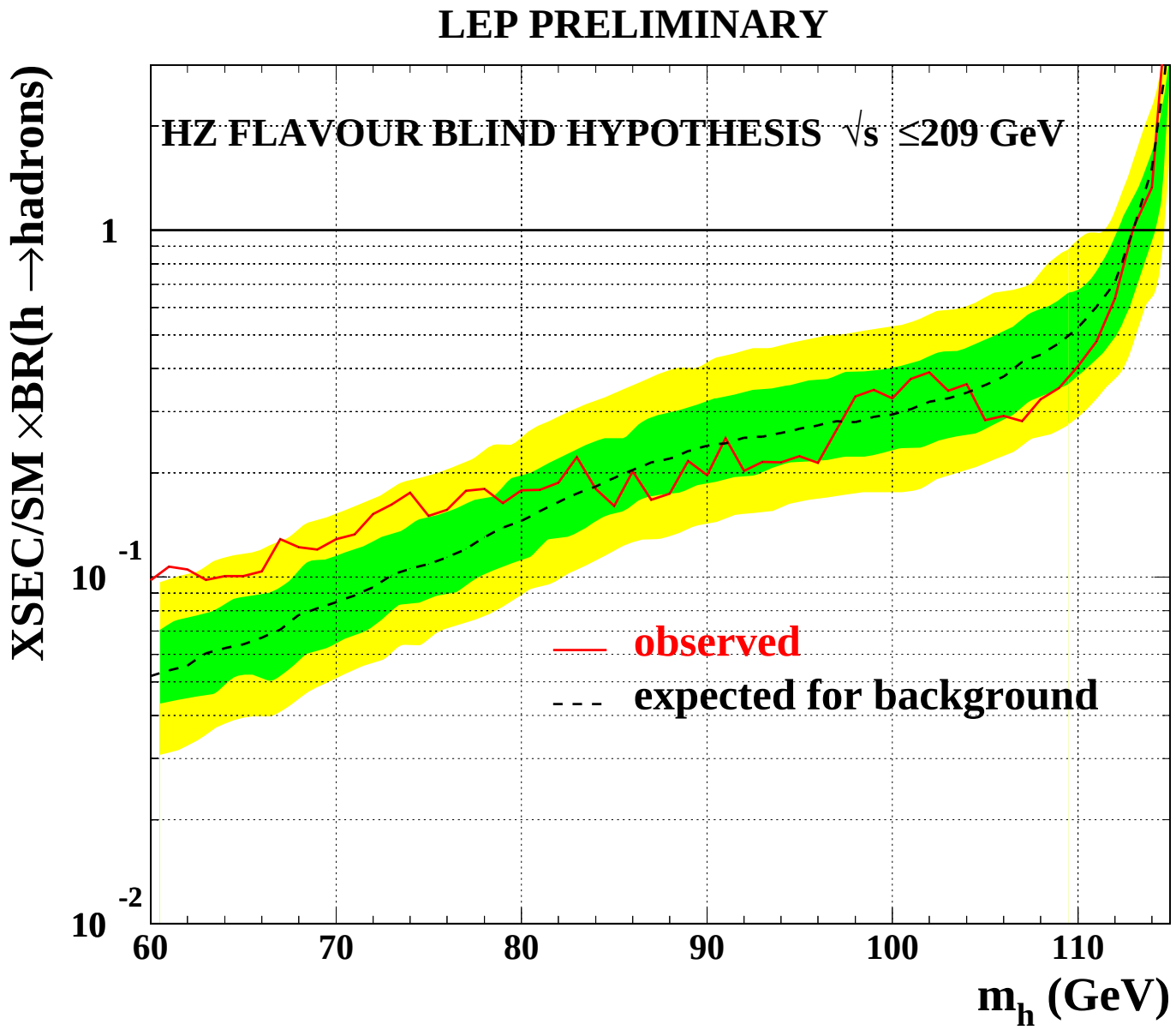
$hZ \to q\bar{q}l^+l^-$. $ZZ \to q\bar{q}l^+l^-$ background. Efficiency $\approx 65\%$ (e^+e^-) and 75% $(\mu^+\mu^-)$





Flavor-Independent Hadronic hZ Limits

No b-tagging requirement.



Anomalous Couplings

$$g_{\mathrm{H}\gamma\gamma} = \frac{g}{2m_{\mathrm{W}}}\left(d\sin^2\theta_W + d_B\cos^2\theta_W\right) \quad (1)$$

$$g^{(1)}_{\mathrm{HZ}\gamma} = \frac{g}{m_{\mathrm{W}}}\left(\Delta g_1^{\mathrm{Z}}\sin 2\theta_W - \Delta\kappa_\gamma\tan\theta_W\right) \quad (2)$$

$$g^{(2)}_{\mathrm{HZ}\gamma} = \frac{g}{2m_{\mathrm{W}}}\sin 2\theta_W\ \ (d - d_B) \quad (3)$$

$$g^{(1)}_{\mathrm{HZZ}} = \frac{g}{m_{\mathrm{W}}}\left(\Delta g_1^{\mathrm{Z}}\cos 2\theta_W + \Delta\kappa_\gamma\tan^2\theta_W\right) \quad (4)$$

$$g^{(2)}_{\mathrm{HZZ}} = \frac{g}{2m_{\mathrm{W}}}\left(d\cos^2\theta_W + d_B\sin^2\theta_W\right) \quad (5)$$

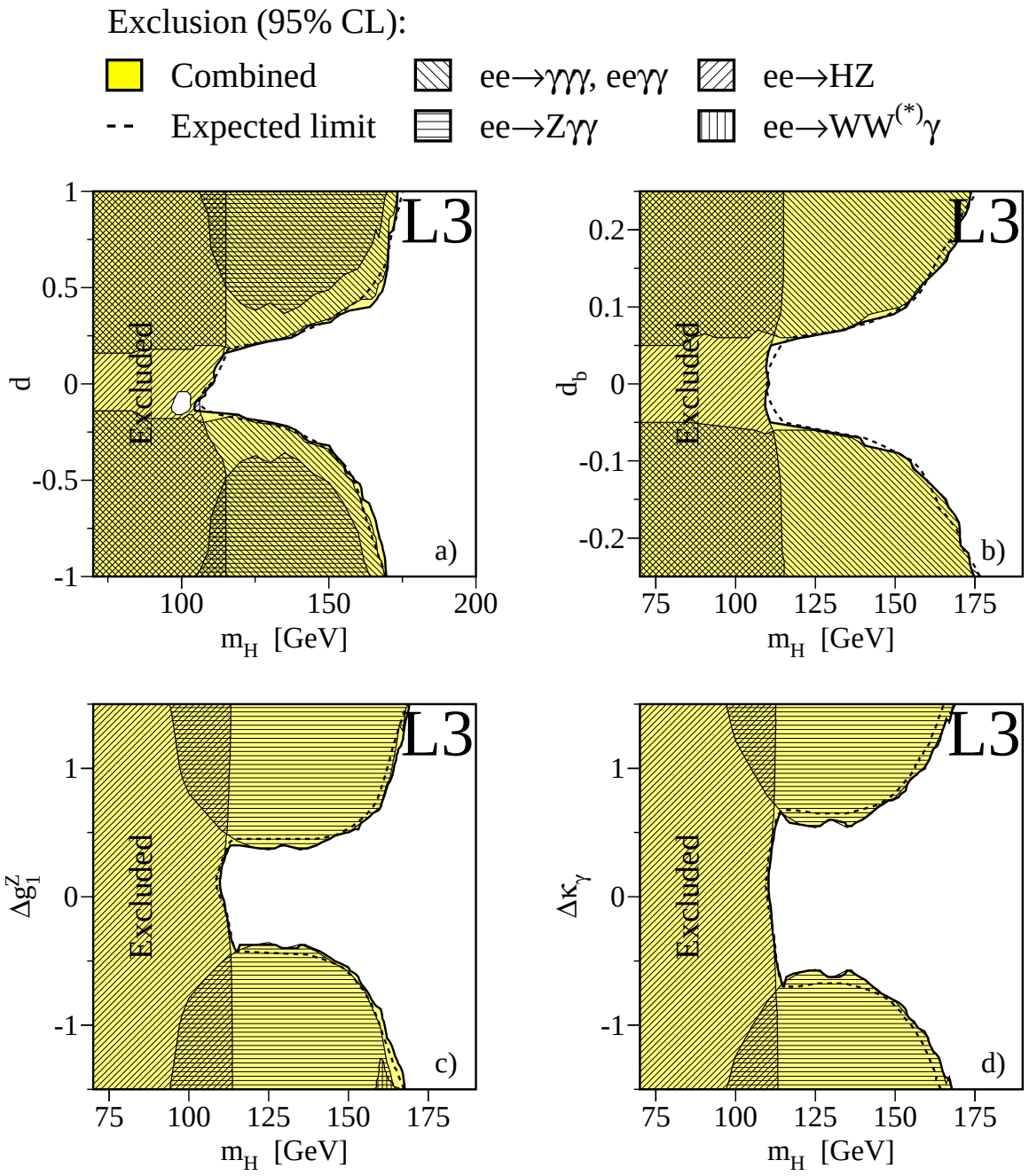
$$g^{(3)}_{\mathrm{HZZ}} = \frac{g\ m_{\mathrm{W}}}{2\ \cos^2\theta_W}\delta_{\mathrm{Z}}, \quad \xi^2 = (1+\delta_{\mathrm{Z}})^2 \quad (6)$$

$$g^{(1)}_{\mathrm{HWW}} = \frac{g\ m_{\mathrm{W}}}{m_{\mathrm{Z}}^2}\Delta g_1^{\mathrm{Z}} \quad (7)$$

$$g^{(2)}_{\mathrm{HWW}} = \frac{g}{m_{\mathrm{W}}}\frac{d}{\cos 2\theta_W} \quad (8)$$

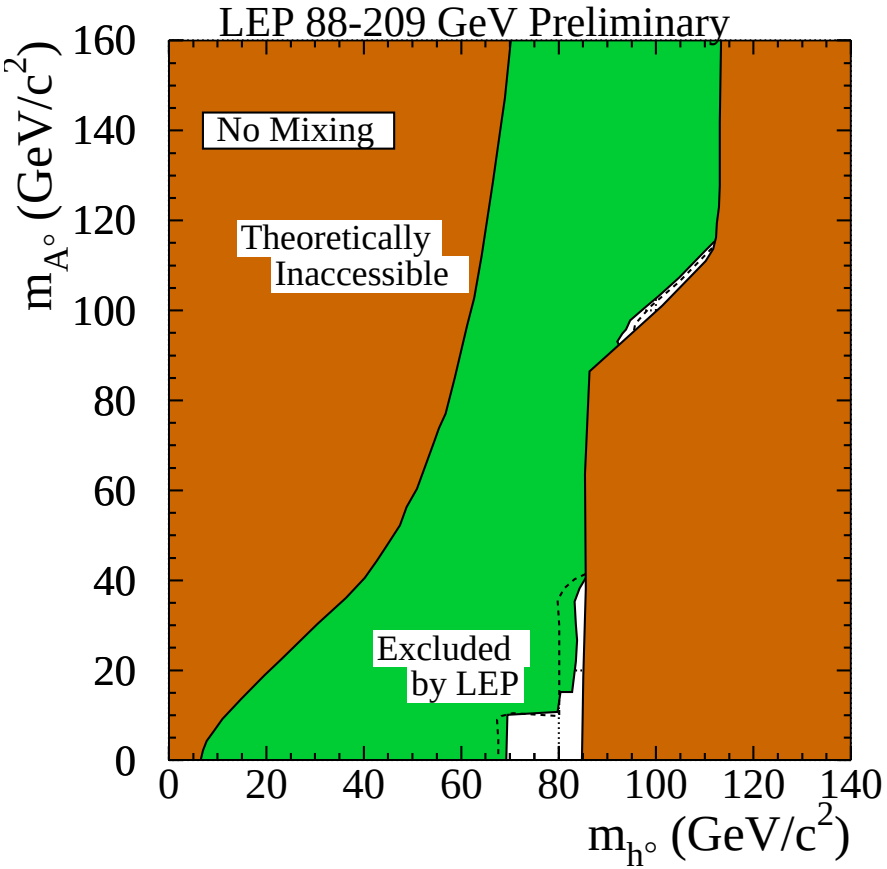
Parameters: $d,\ d_B,\ \Delta g_1^{\mathrm{Z}},\ \Delta\kappa_\gamma$

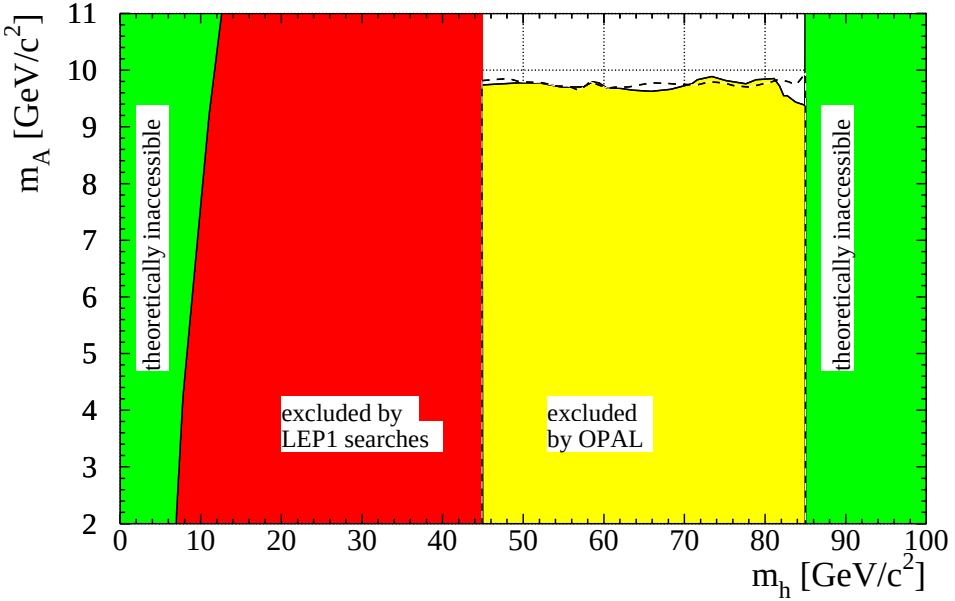
Anomalous Couplings: Parameter Limits



MSSM: Dedicated Low m_{A} Searches

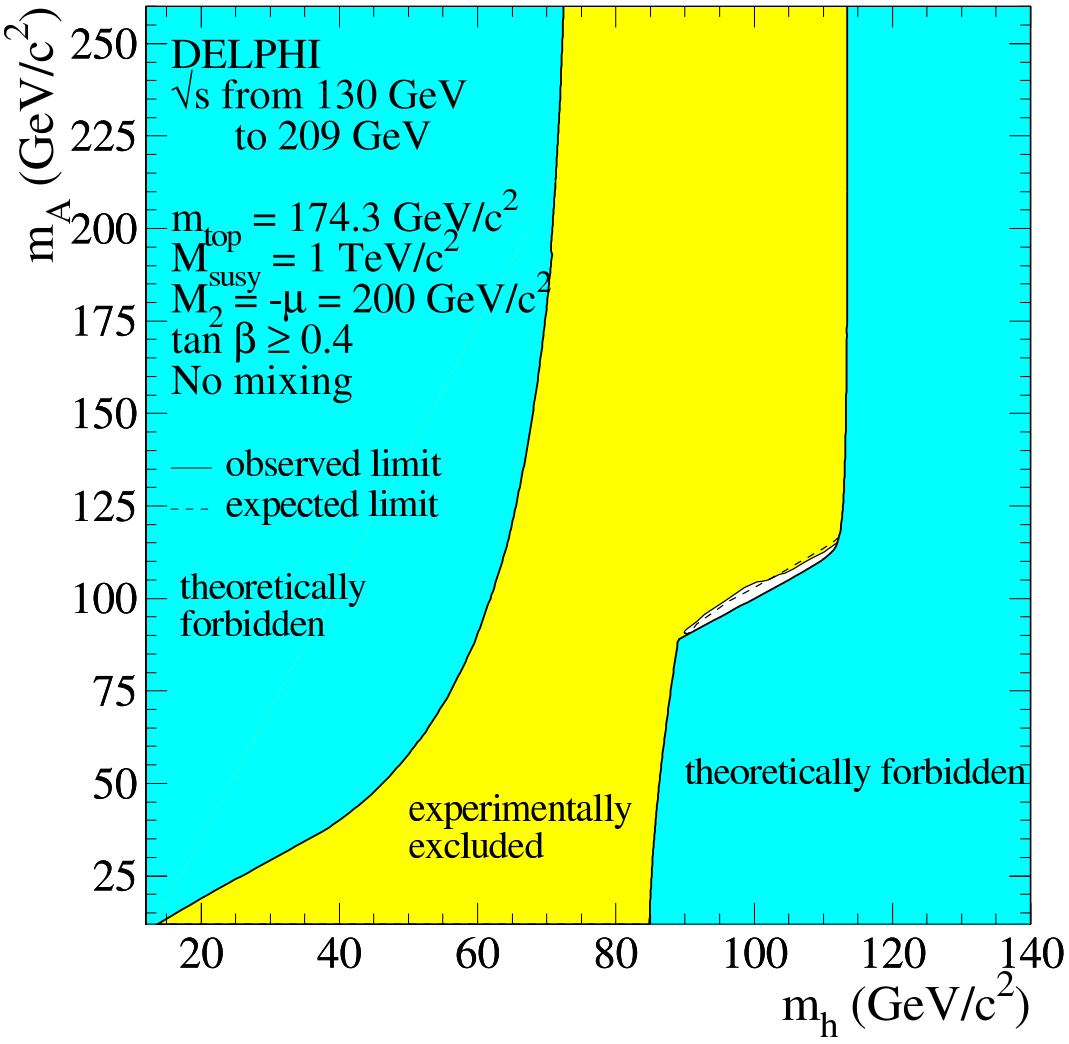
No mixing in scalar top sector (smallest scalar Higgs boson mass).





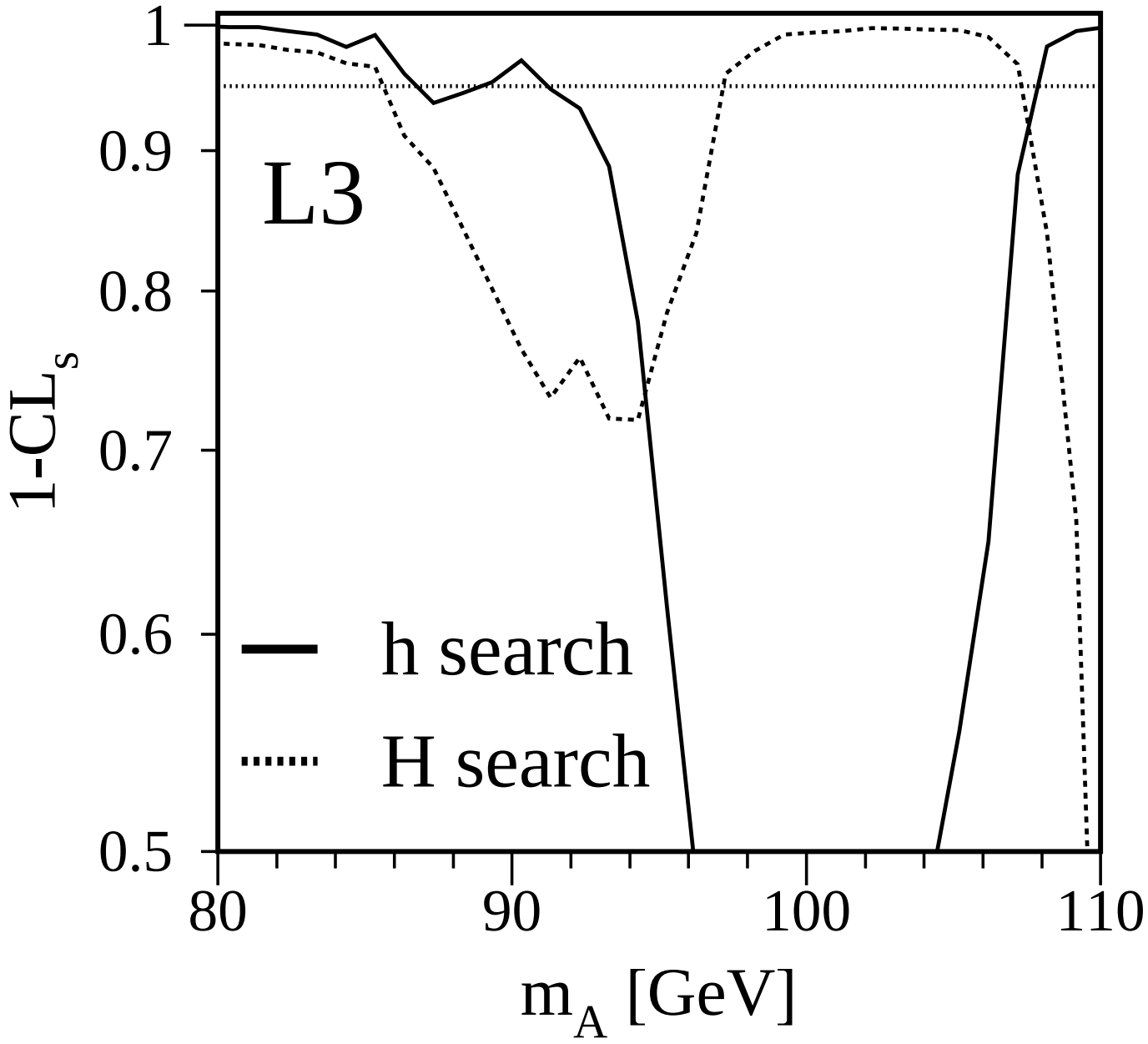
MSSM: Dedicated h → AA Searches

No mixing in scalar top sector.



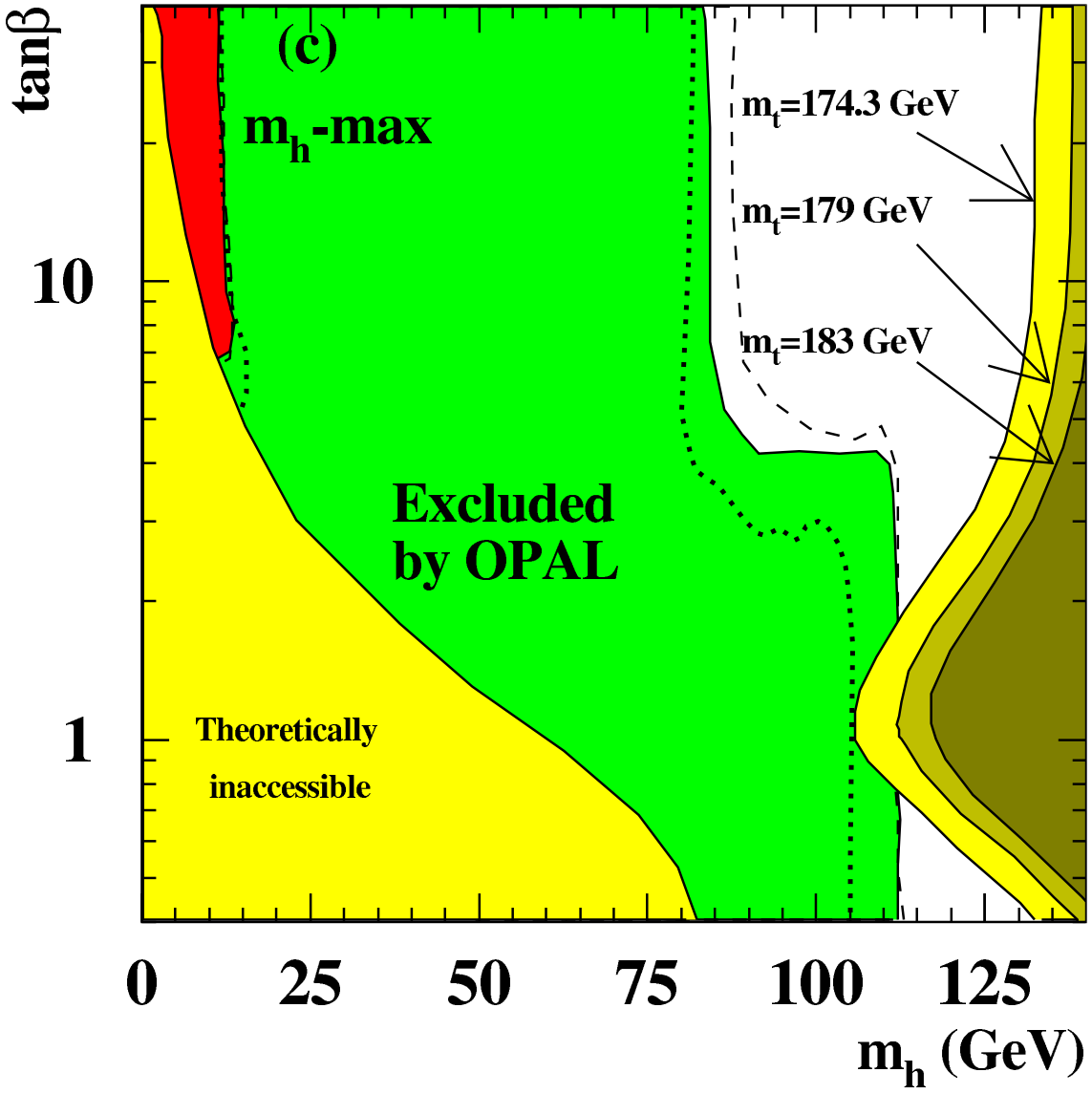
MSSM: Large $\tan\beta$ Scenario

hA is inaccessible and hZ is suppressed by $\sin(\beta-\alpha)\approx 0$, thus HZ production.



MSSM: Maximum m_{h} Scenario

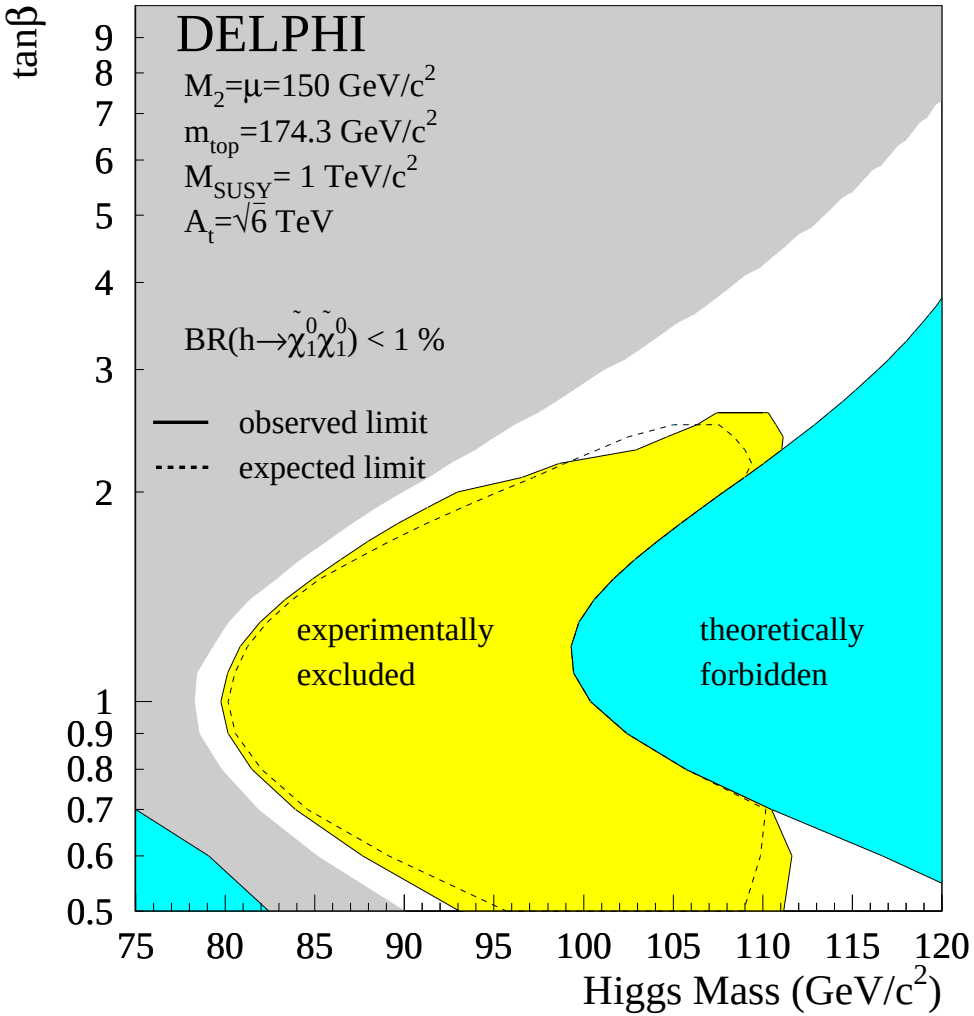
New top quark mass: 178.0 ± 4.3 GeV: $\tan\beta$ limit strongly reduced.

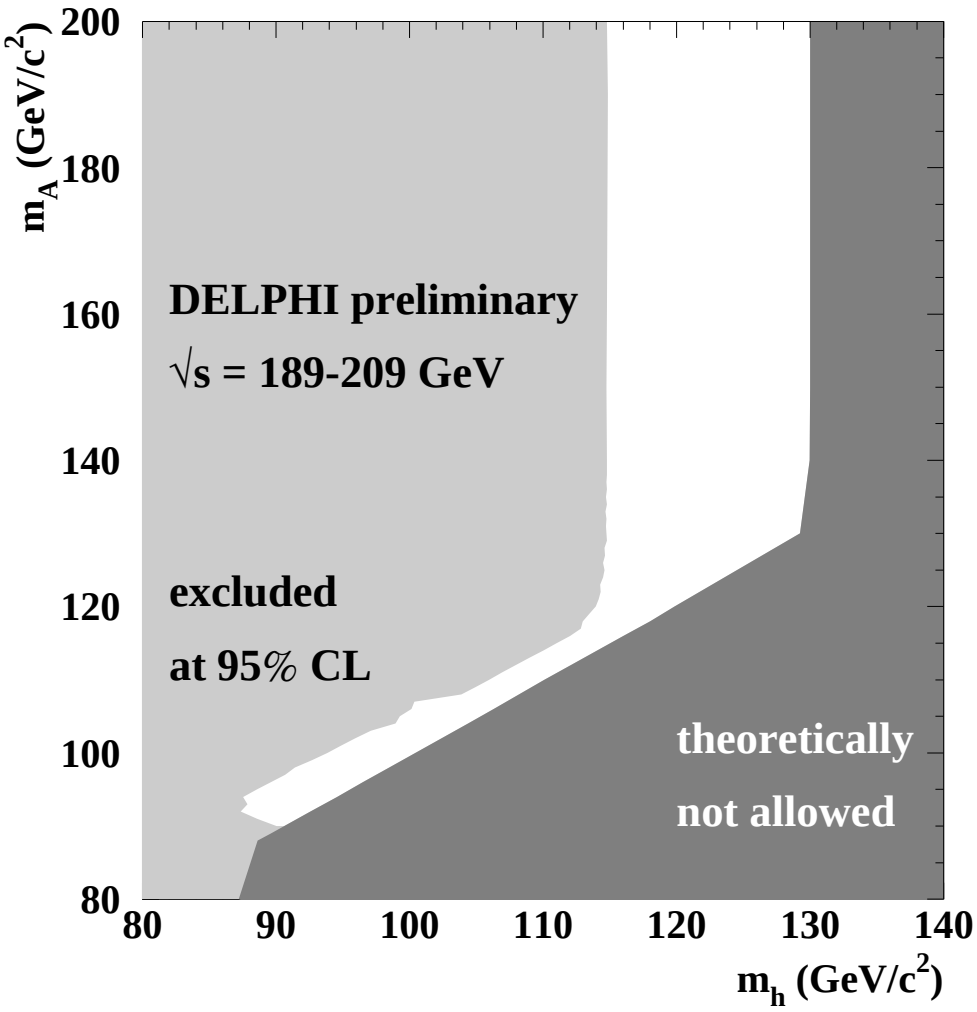


MSSM: Benchmark and Parameter Scan

Mass limits depend on invisible Higgs boson searches.

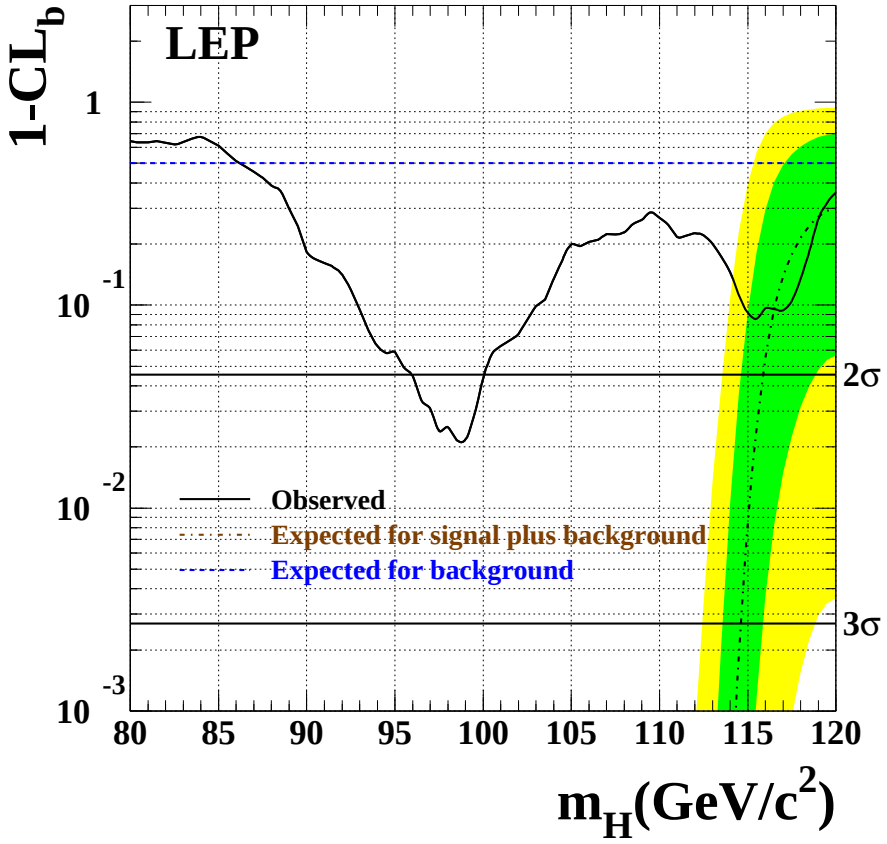
General parameter scan.

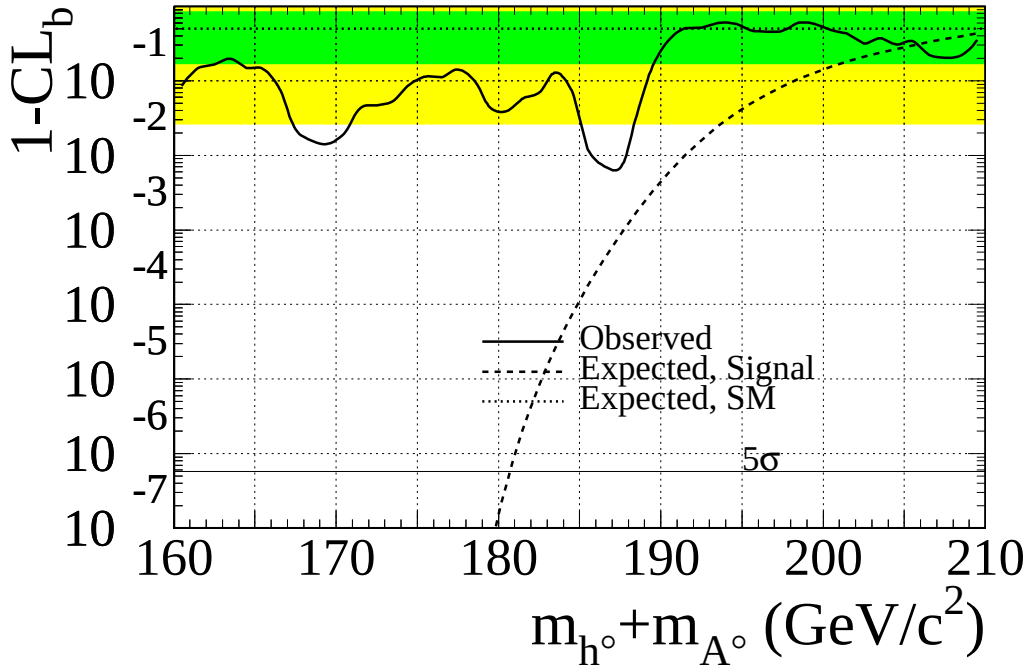




MSSM: 3 Higgs Boson Hypothesis

$m_{\mathrm{h}} \approx m_{\mathrm{A}} \approx 99$ GeV: hZ and hA production and HZ at 115 GeV.
General MSSM parameter scan gives this mass combination with reduced hZ cross section at 99 GeV compatible with data.

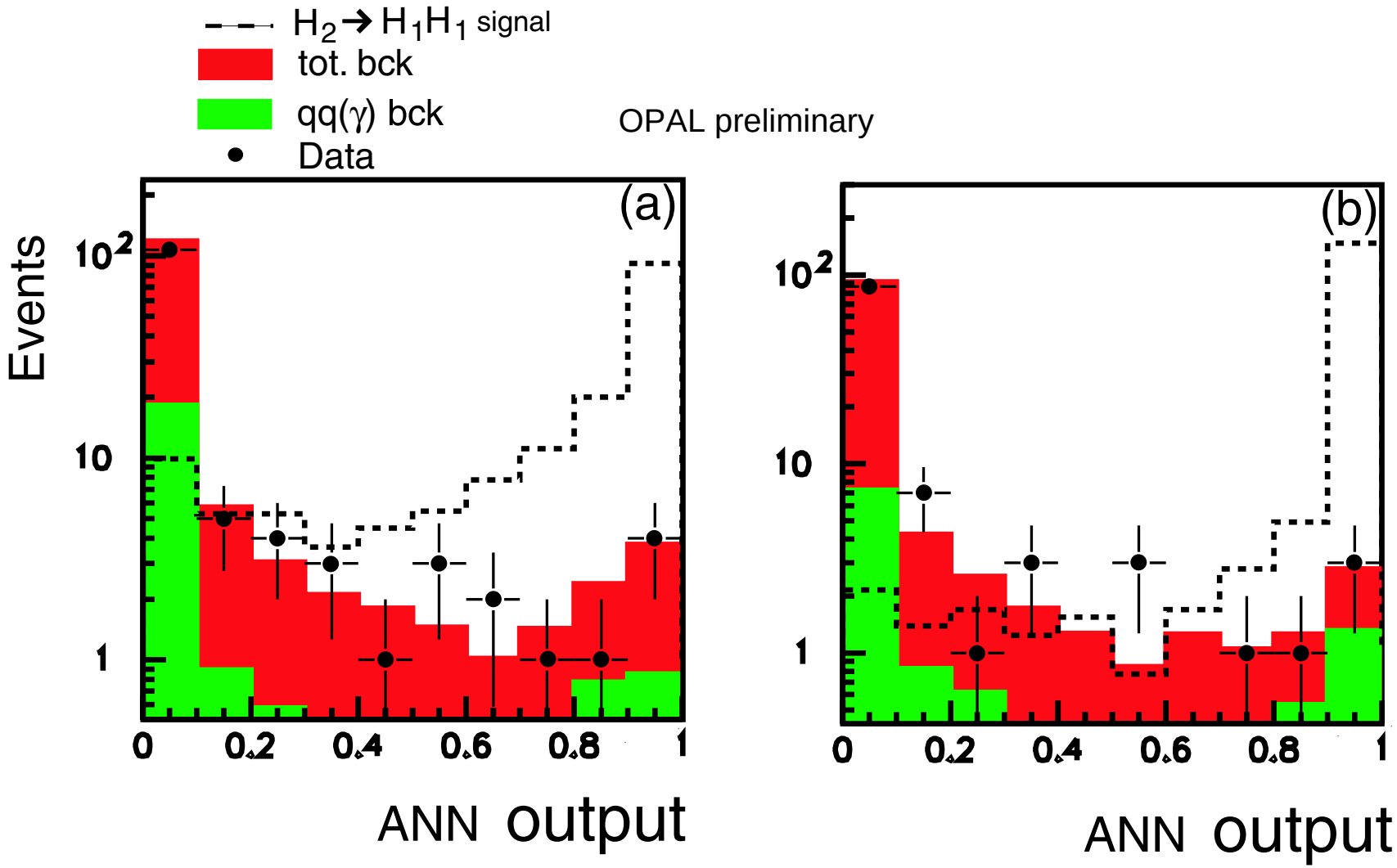




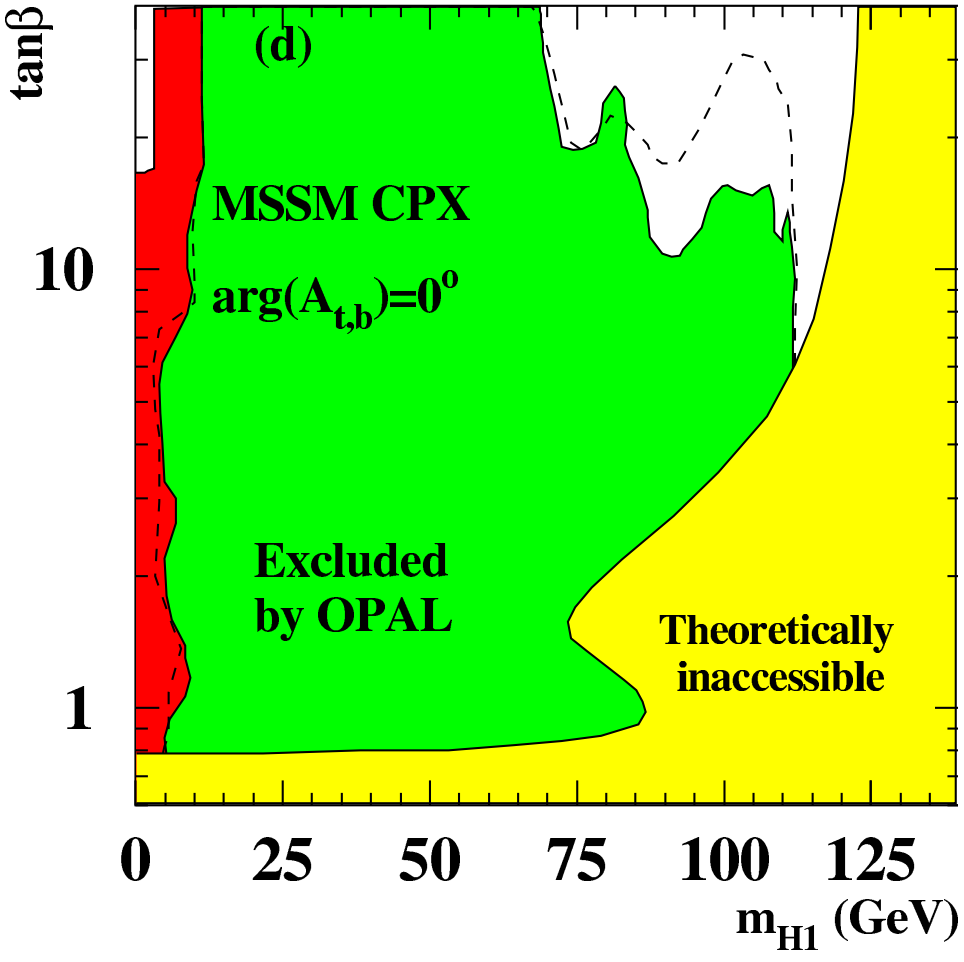
CP-Violating Models

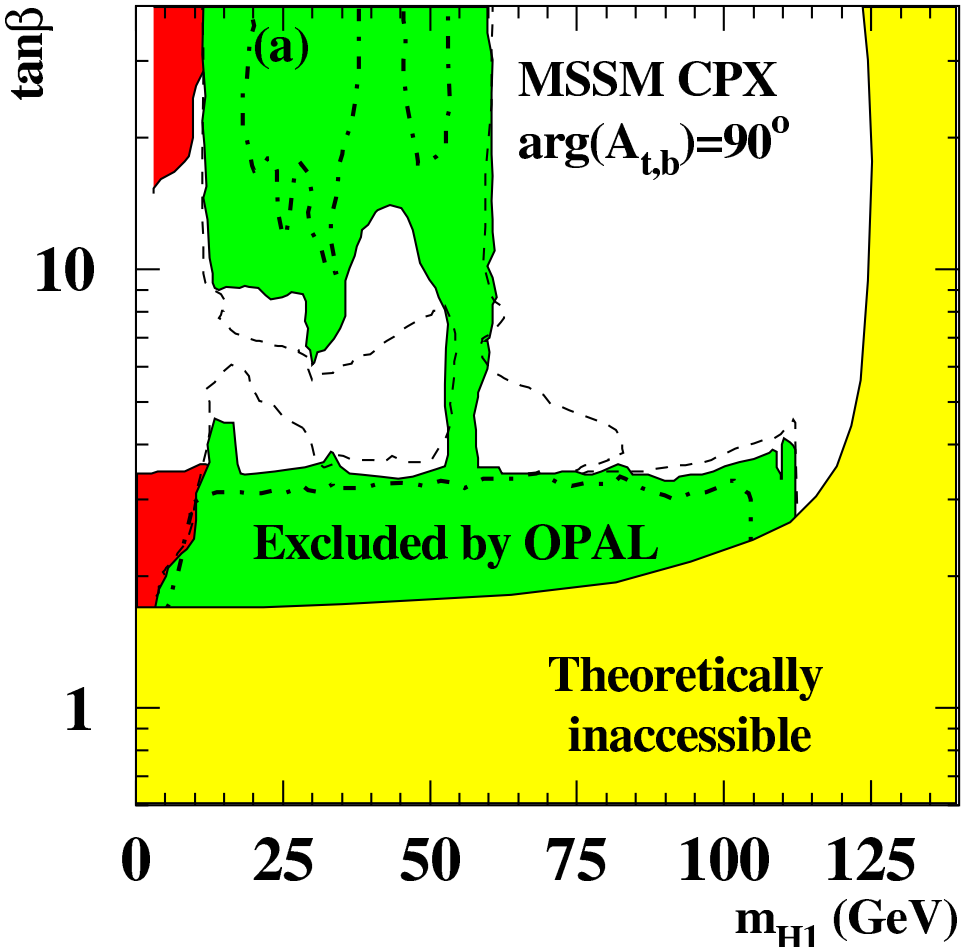
H_1, H_2, H_3 instead of h, H, A.

(a) $e^+e^- \to H_2Z \to b\bar{b}\nu\bar{\nu}$ (b) $e^+e^- \to H_2Z \to H_1H_1Z \to b\bar{b}b\bar{b}\nu\bar{\nu}$



No CP-Mixing to Full CP-Mixing: Reduced Limits





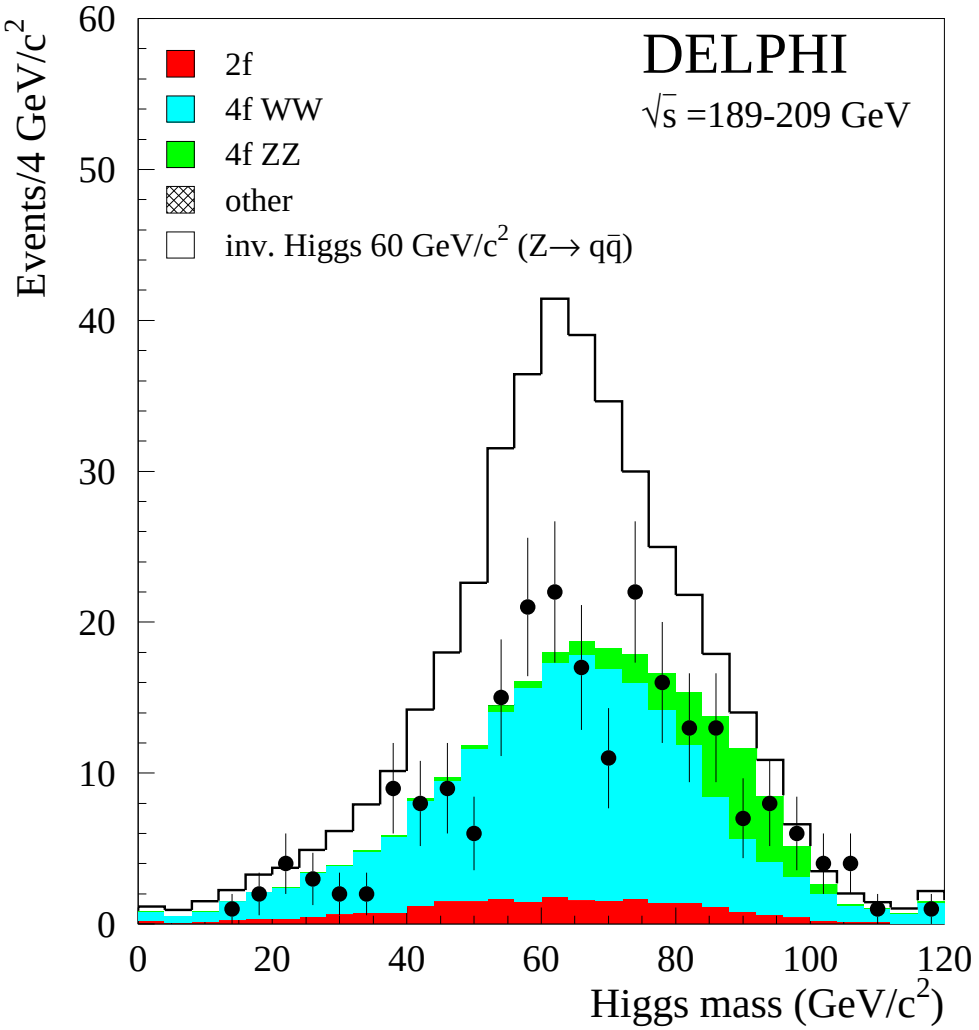
Invisible Higgs Boson Decays

$e^+e^- \rightarrow ZH$

$Z \rightarrow q\bar{q}, \mu^+\mu^-, e^+e^-$

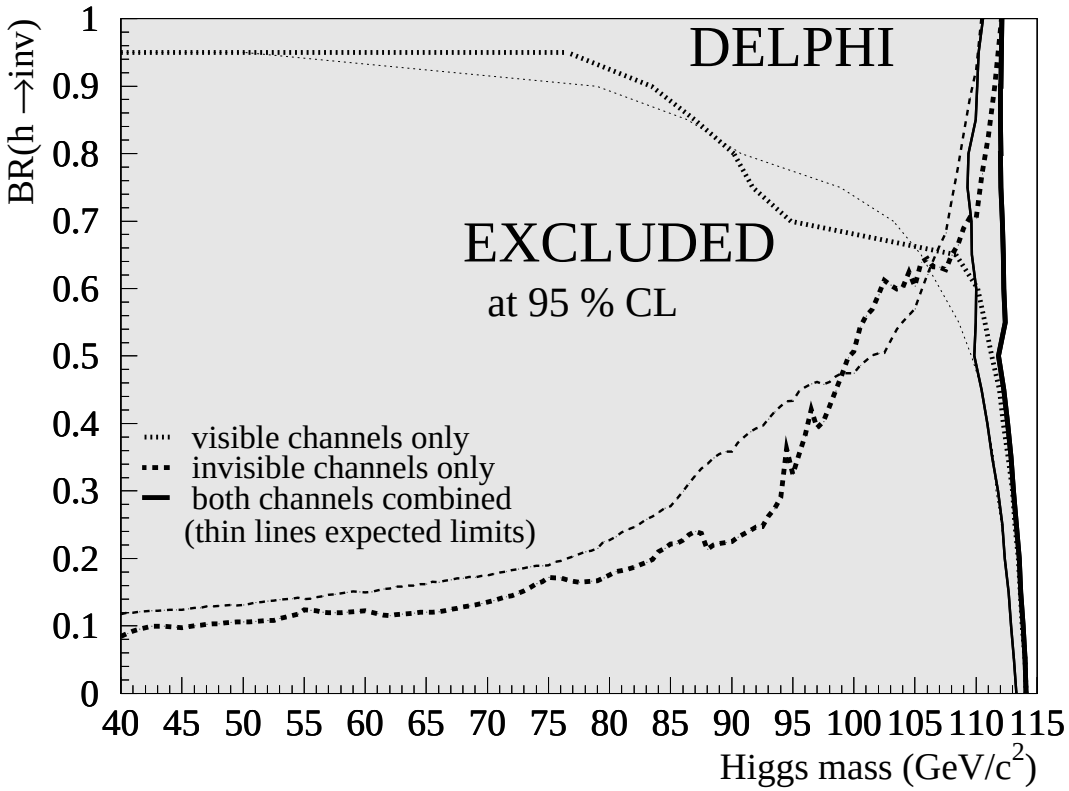
MSSM: $H \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$

Extra complex singlet: $H \rightarrow JJ$

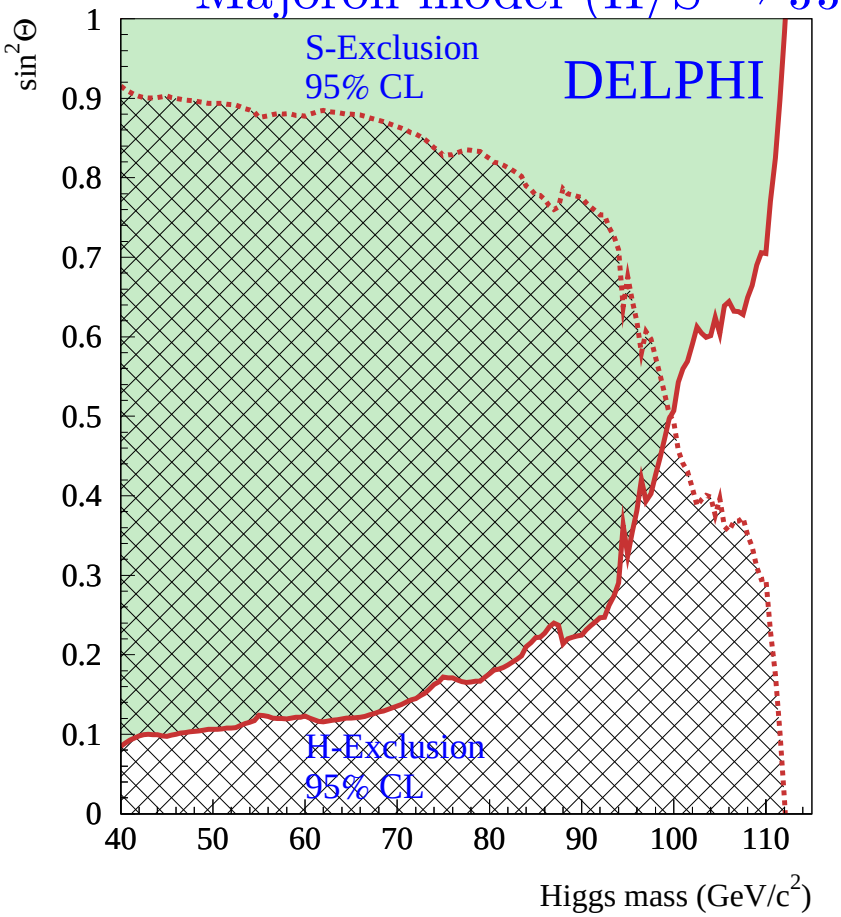


Invisible Higgs Boson Limits

SM and invisible searches combined.

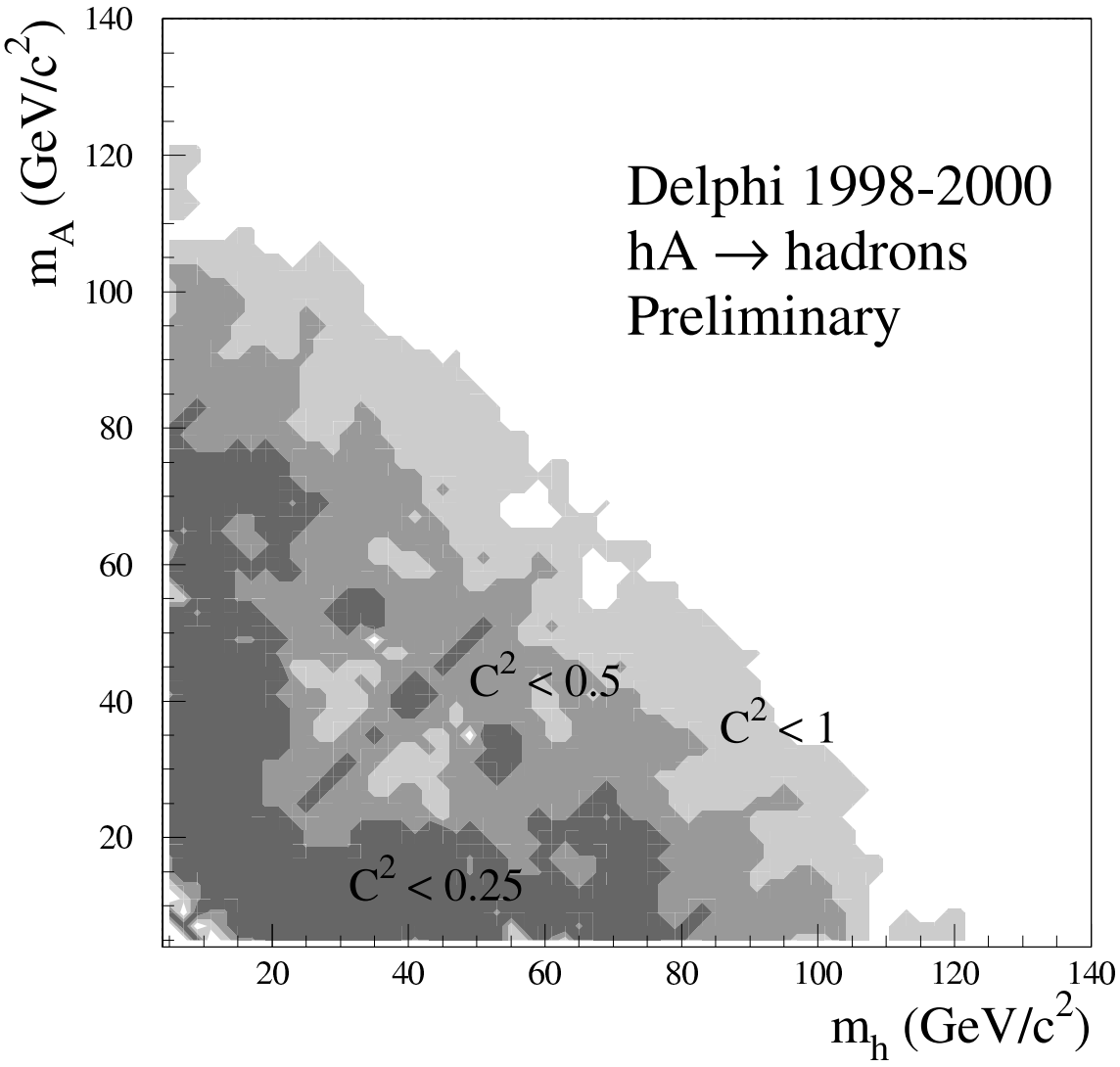


Majoron model (H/S → JJ)

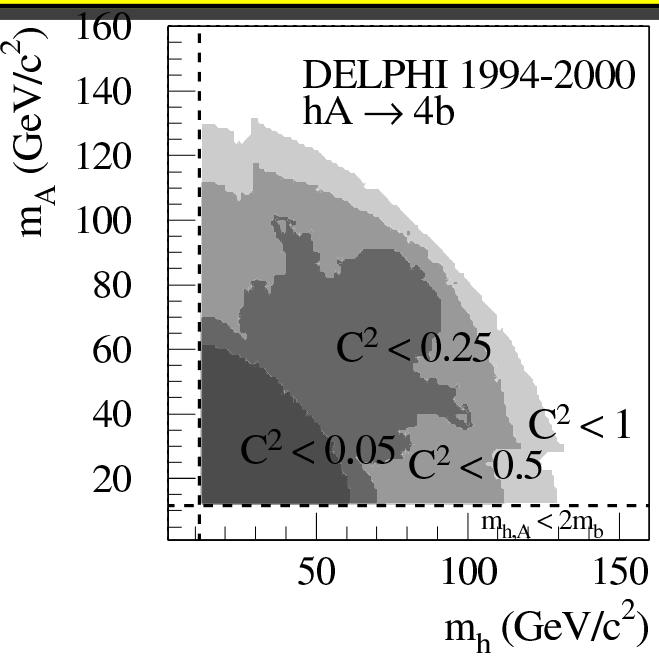


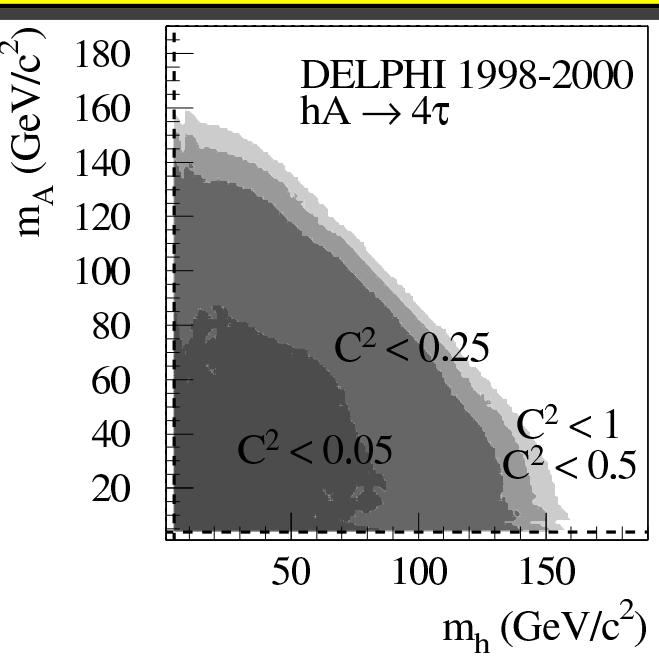
Flavor-Independent Hadronic hA Limits

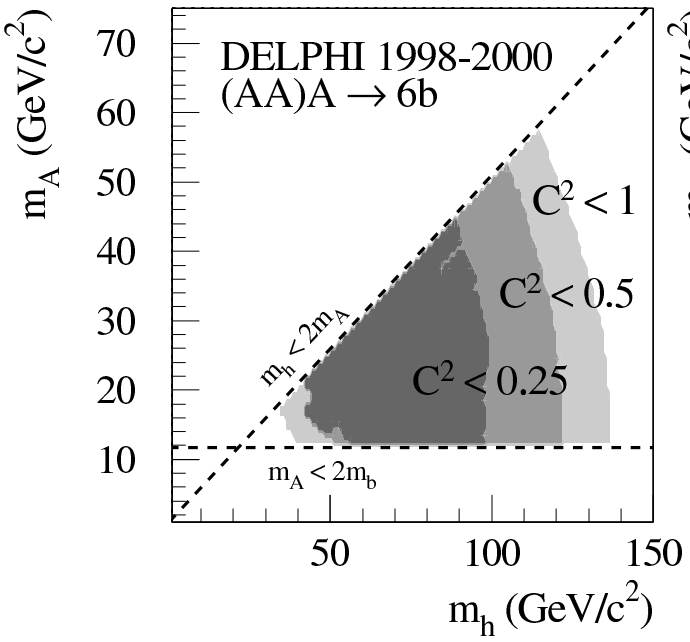
No b-tagging requirement.

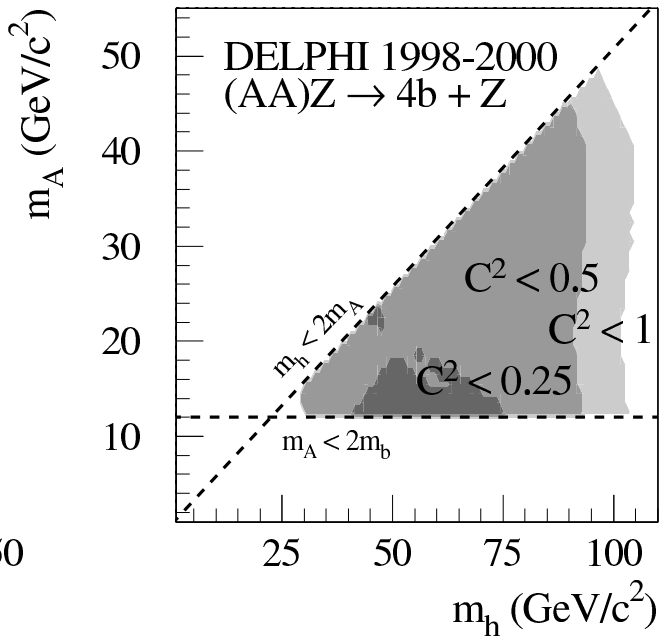


General 2-Higgs Doublet Model: hA Limits



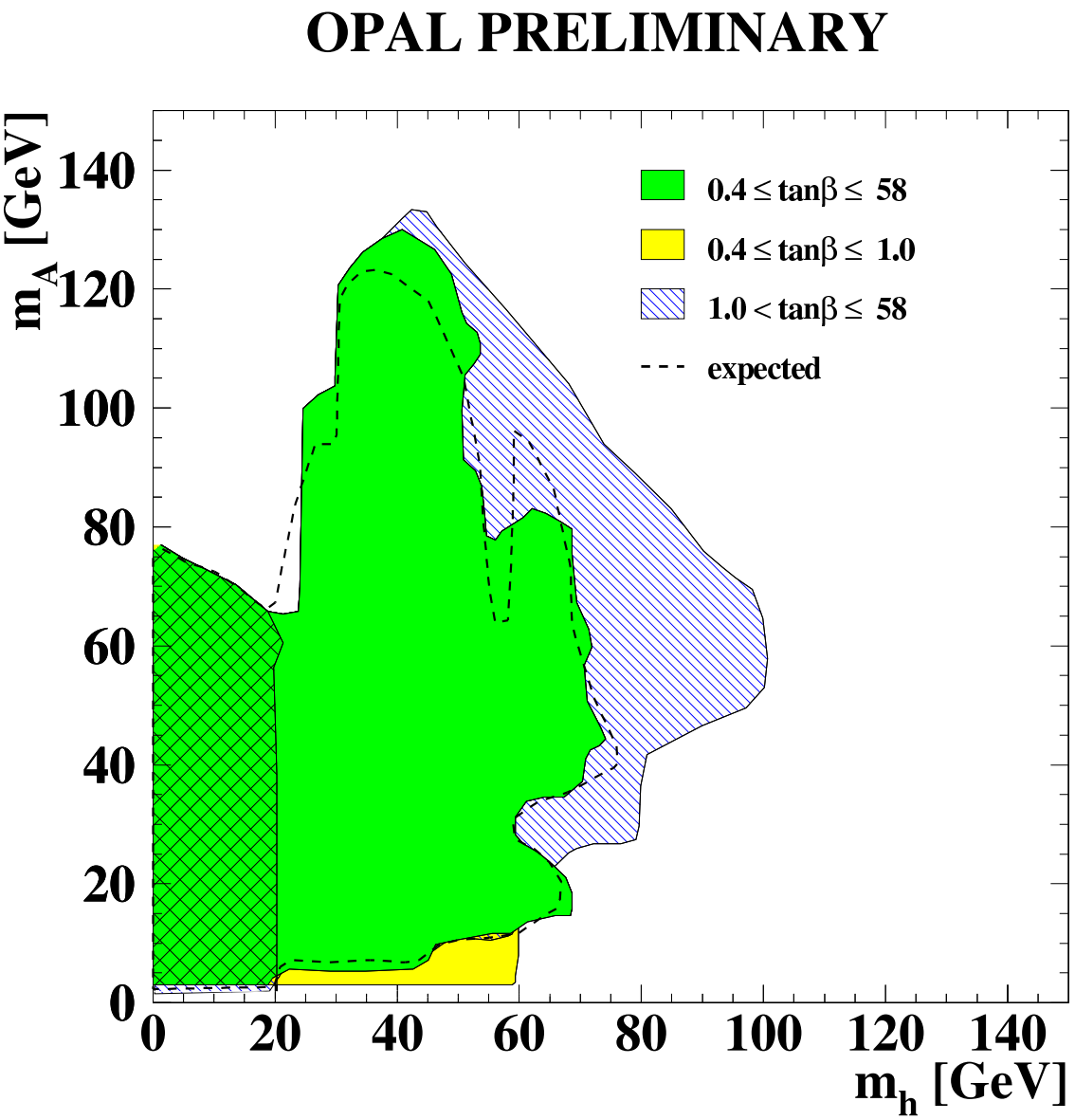






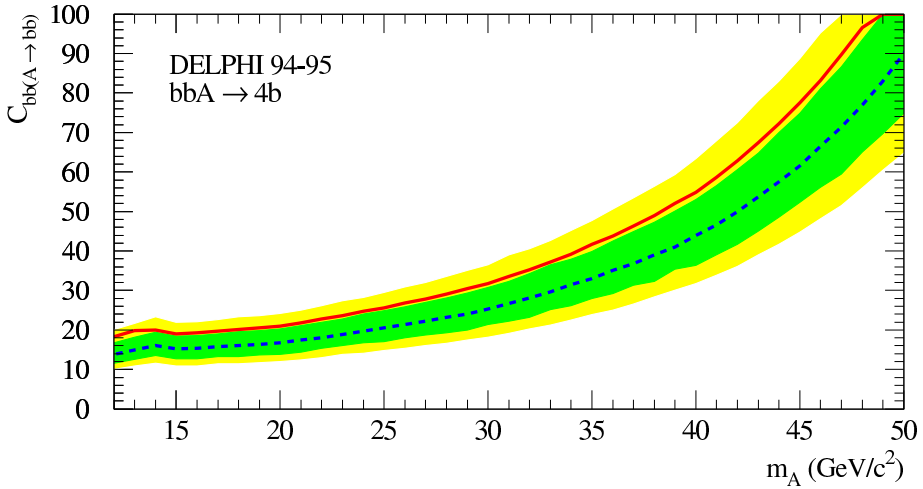
General 2-Higgs Doublet Model: Parameter Scan

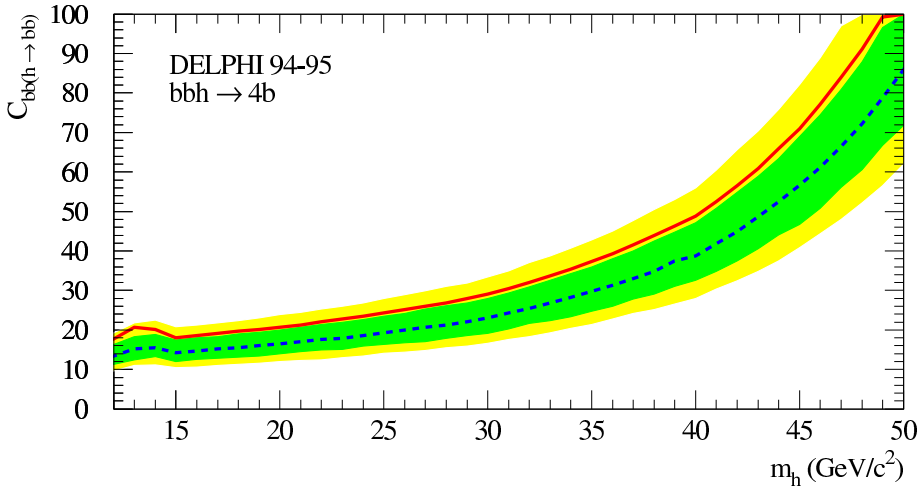
Combination of b-tagging and flavor-independent searches.

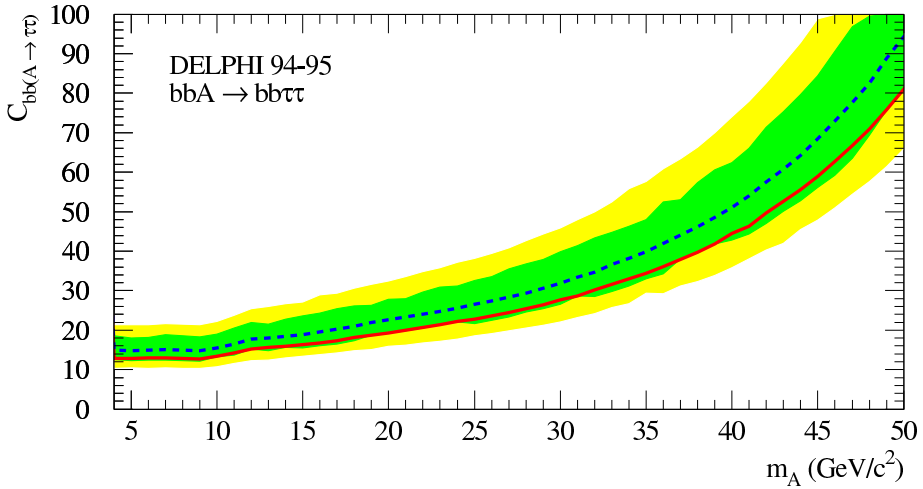


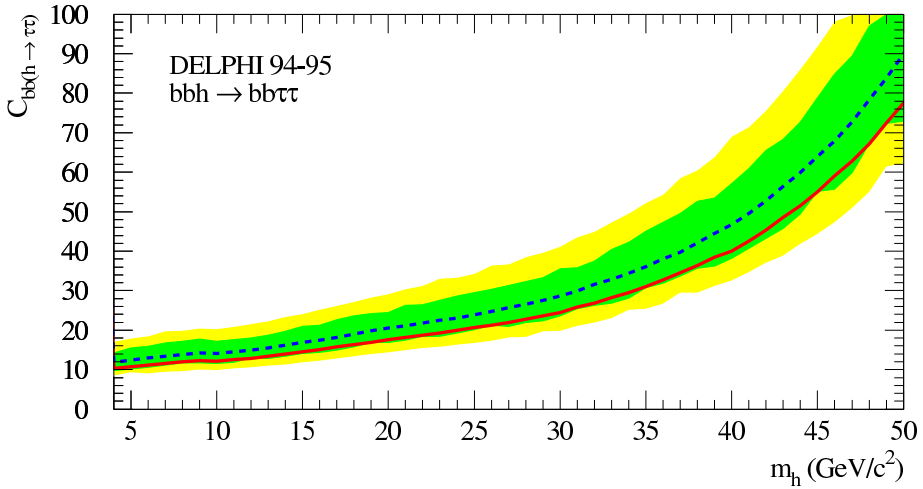
General 2-Higgs Doublet Model: Yukawa $b\bar{b}h$, $b\bar{b}A$

Enhancement (C): $\tan\beta$ for bbA, $\sin\alpha/\cos\beta$ for bbh.



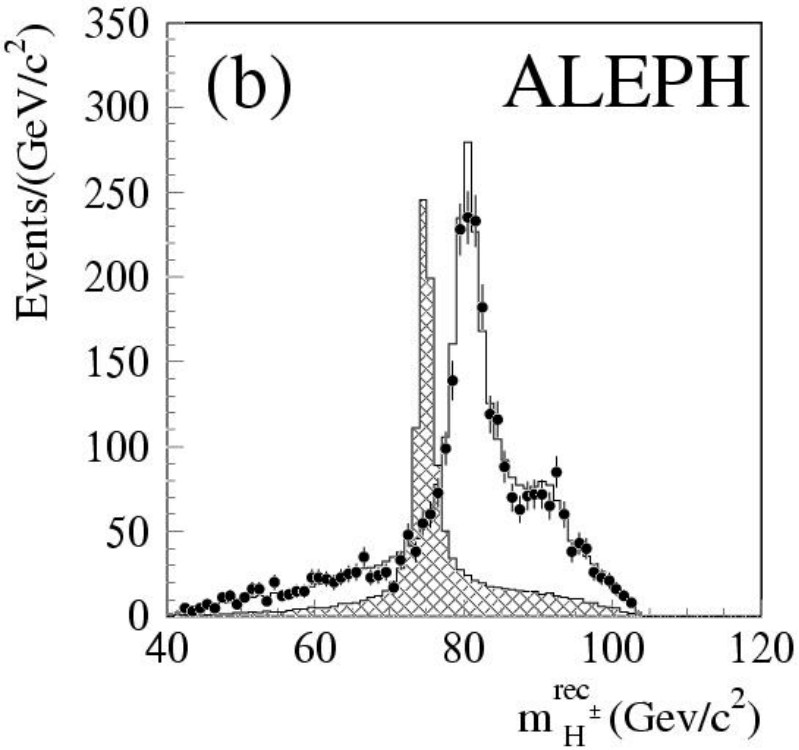


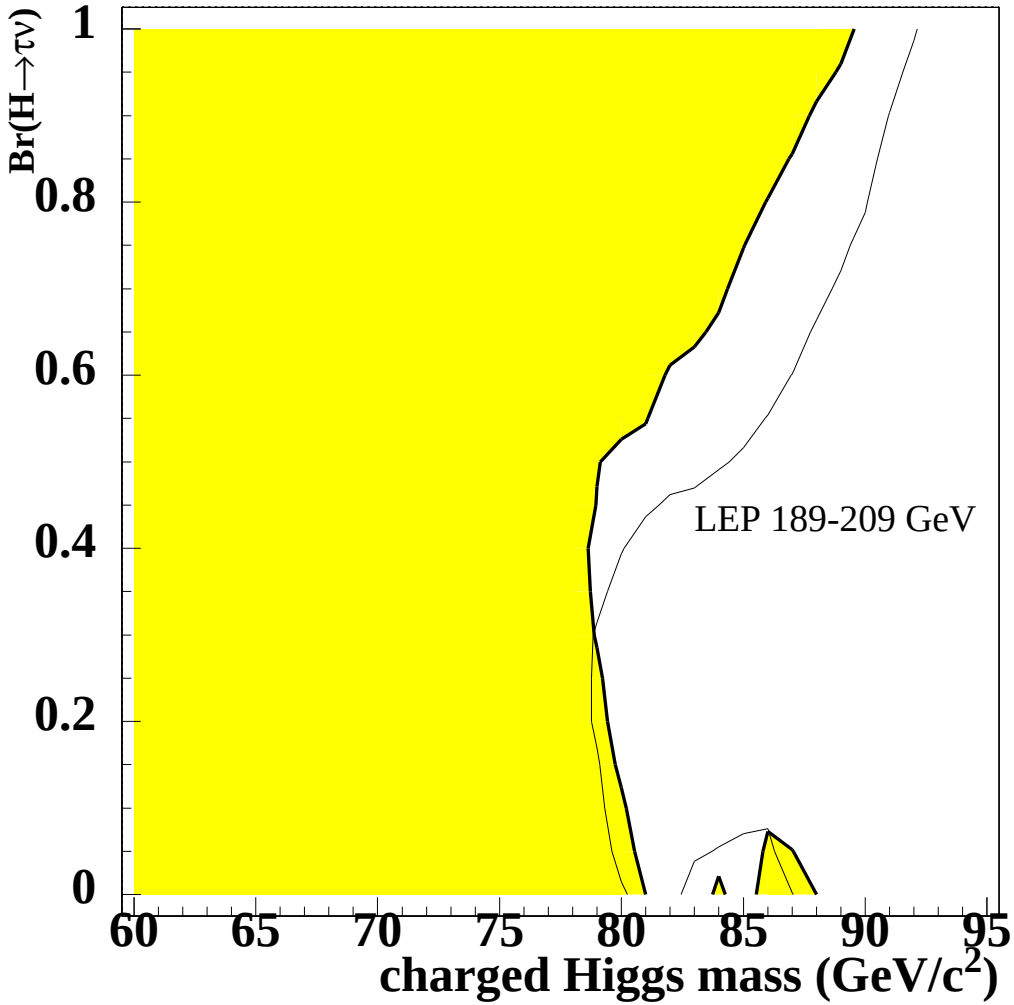




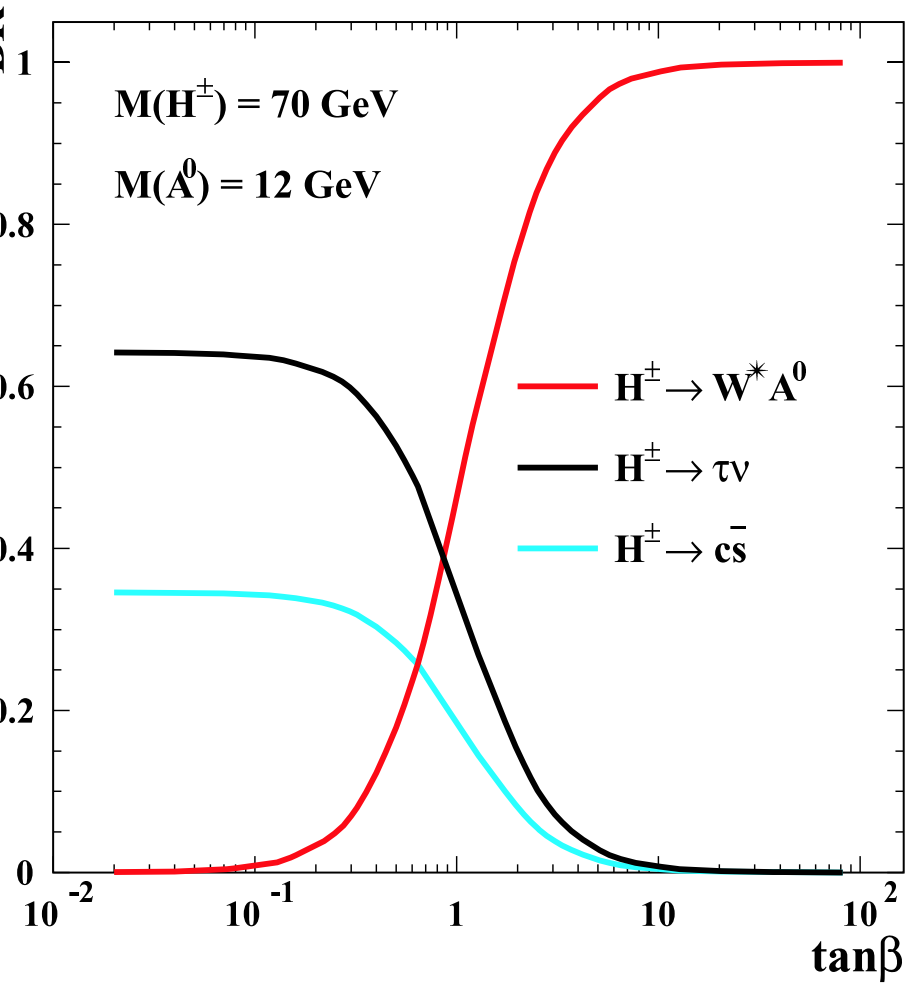
General 2-Higgs Doublet Model: $H^{\pm}$

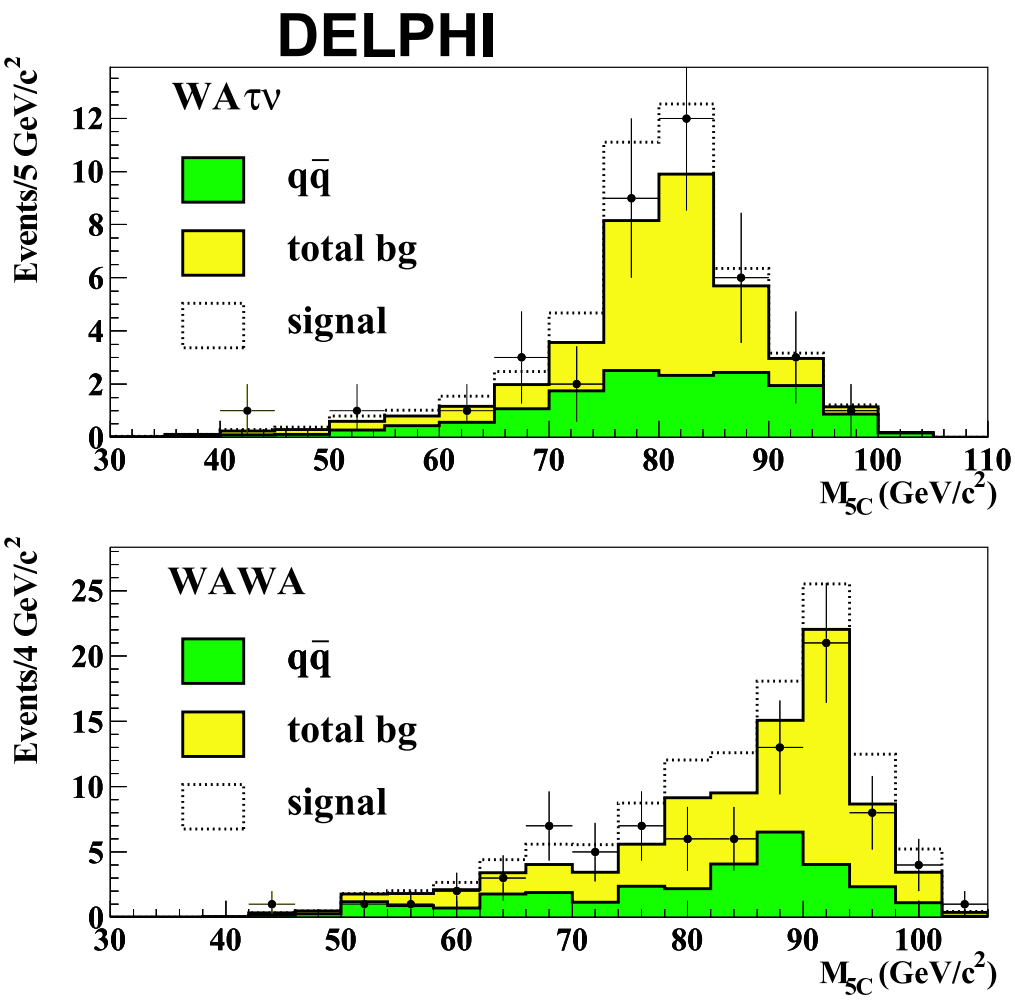
$e^+e^- \to H^+H^- \to c\bar{s}\bar{c}s,\ cs\tau\nu,\ \tau^+\nu\tau^-\bar{\nu}$



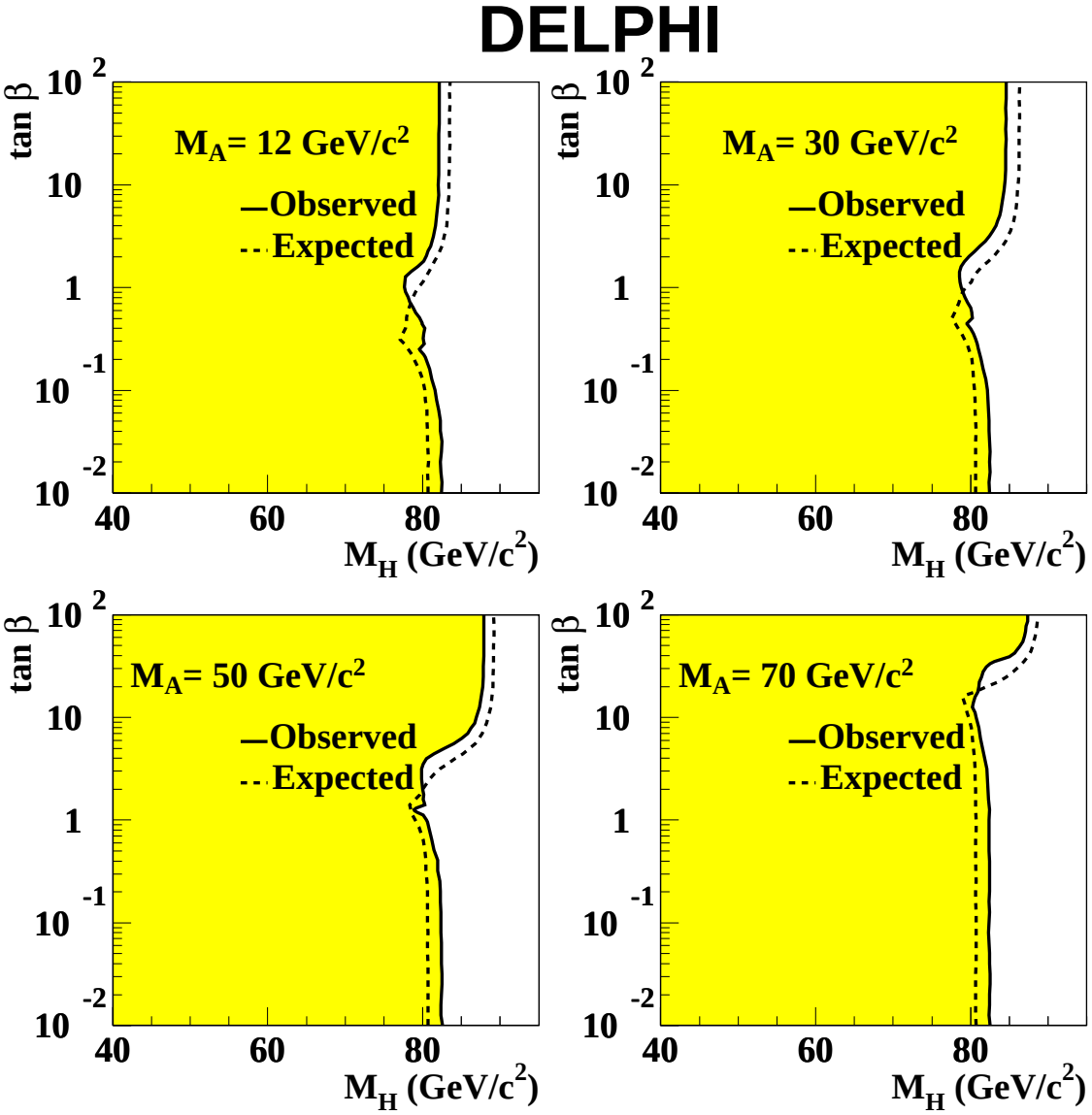


General 2-Higgs Doublet Model: $H^{\pm} \rightarrow W^{\pm}A$





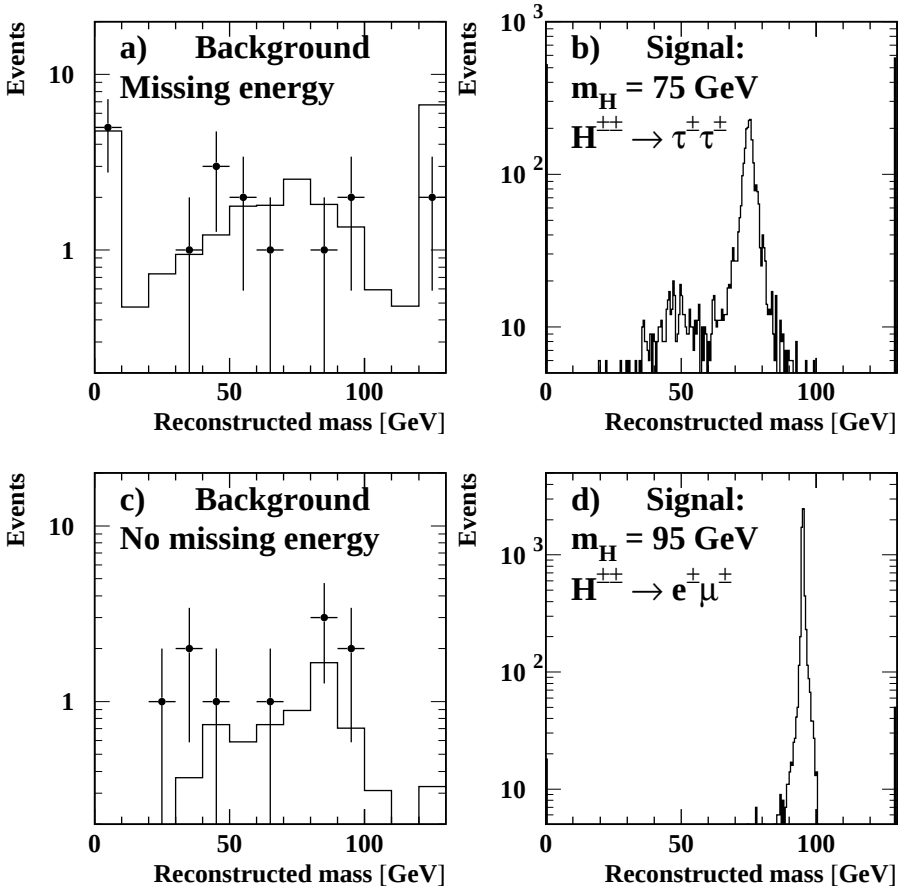
General 2-Higgs Doublet Model: $H^{\pm} \rightarrow W^{\pm}A$ Limits



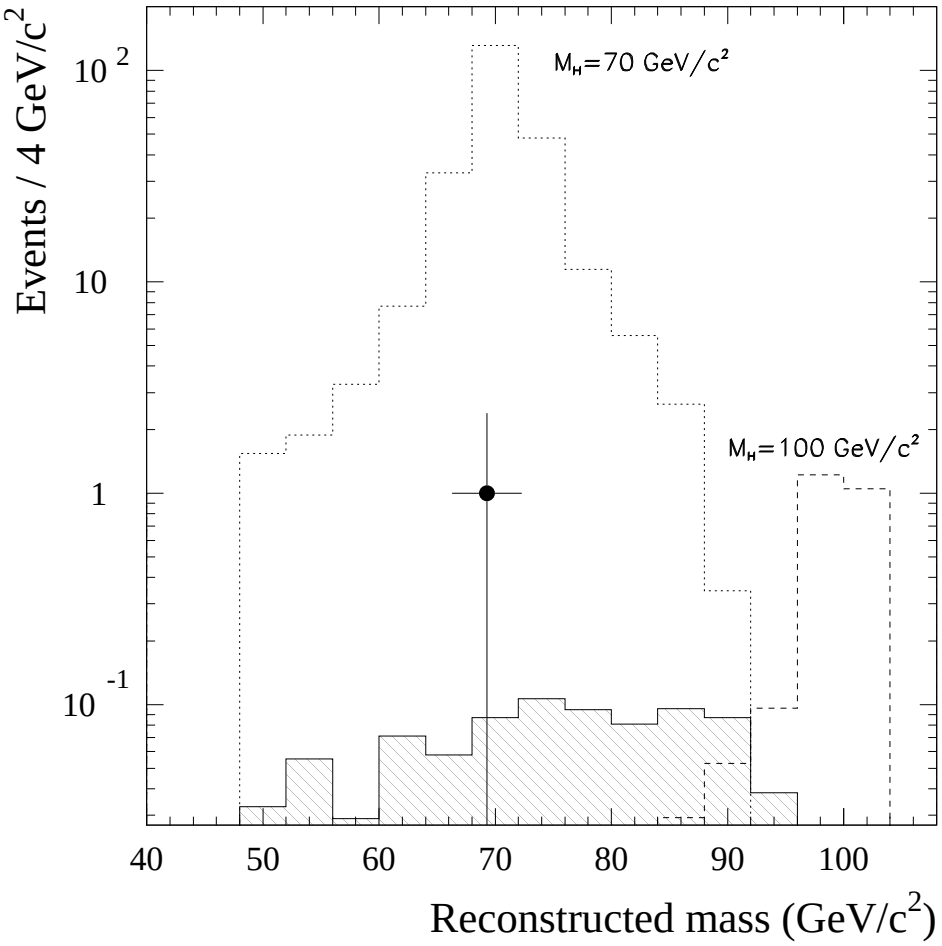
Doubly Charged Higgs Bosons: H^{++}

$e^+e^- \to H^{++}H^{--} \to \tau^+\tau^+\tau^-\tau^-$: Decay at interaction point ($h_{\tau\tau} \geq 10^{-7}$), secondary vertex signature, or stable massive particle.

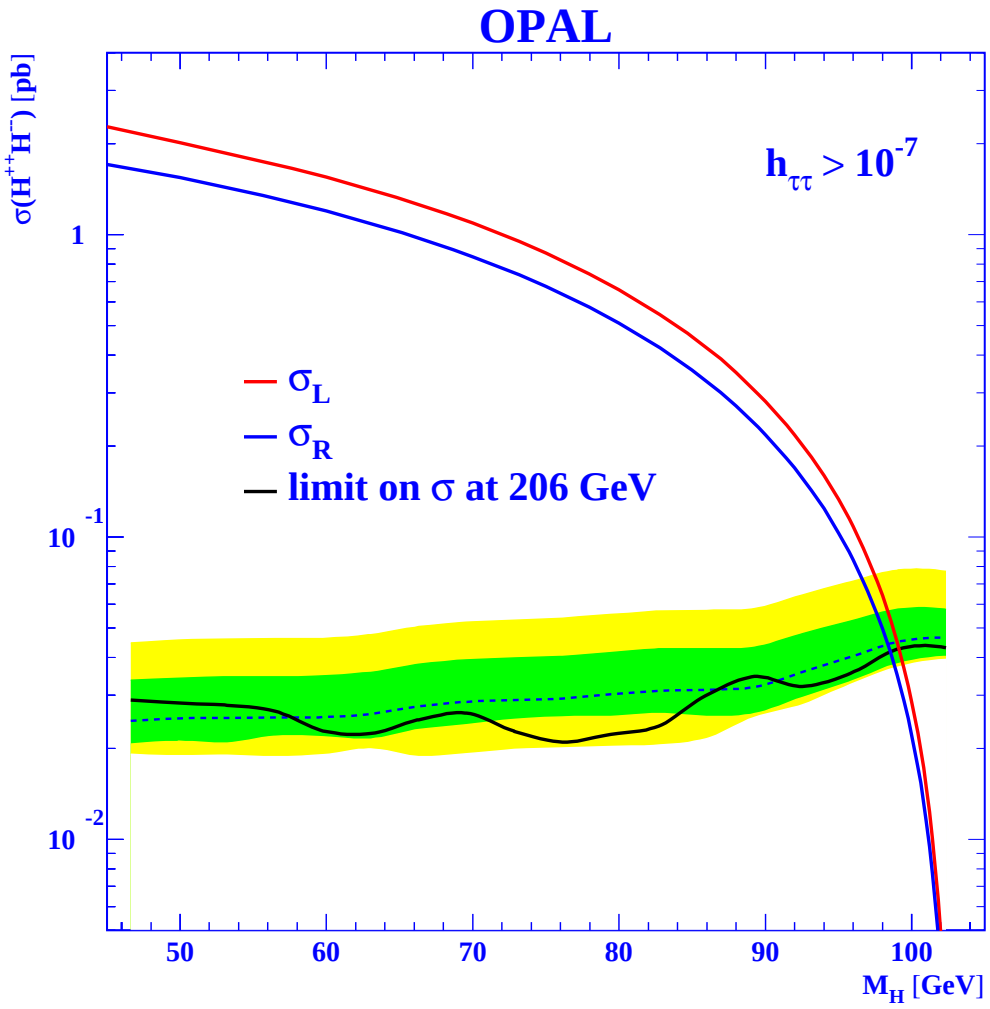
OPAL

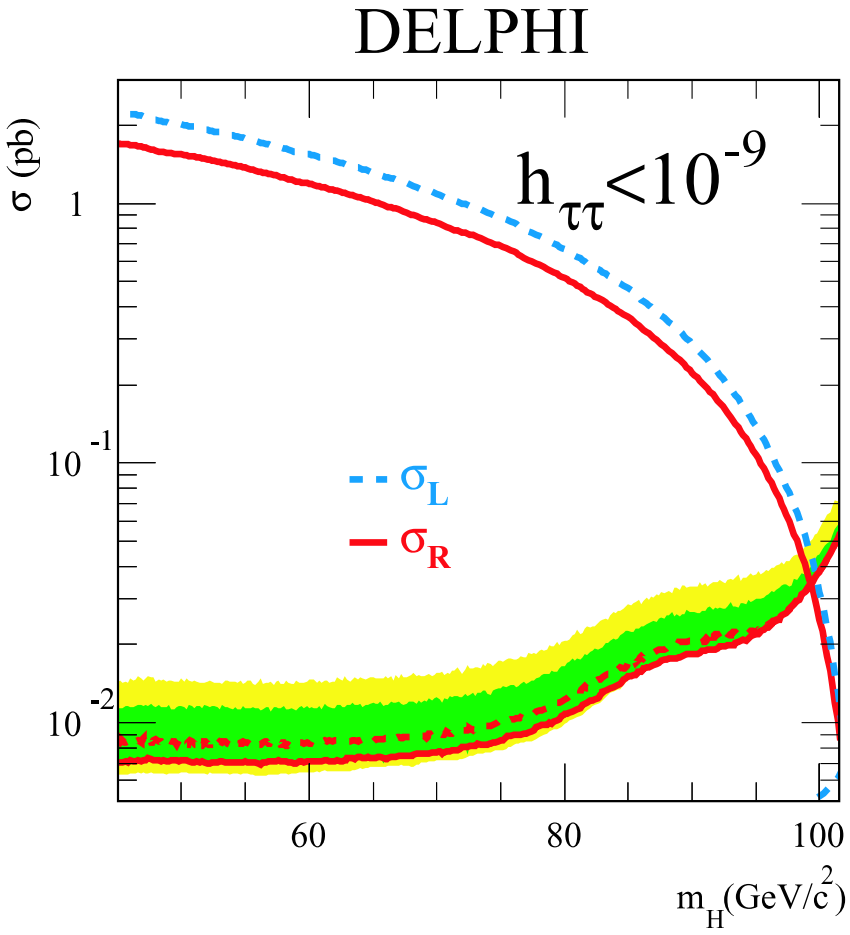


DELPHI



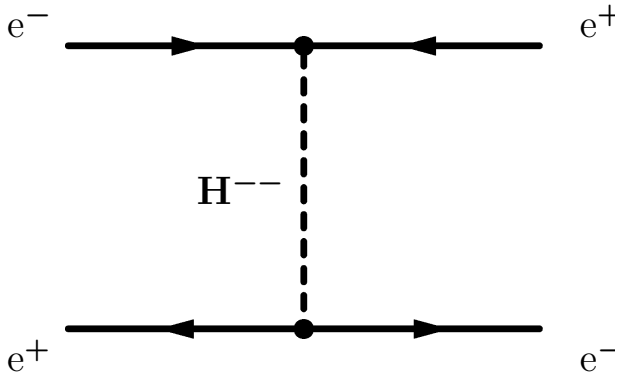
Doubly Charged Higgs Bosons: Mass Limits

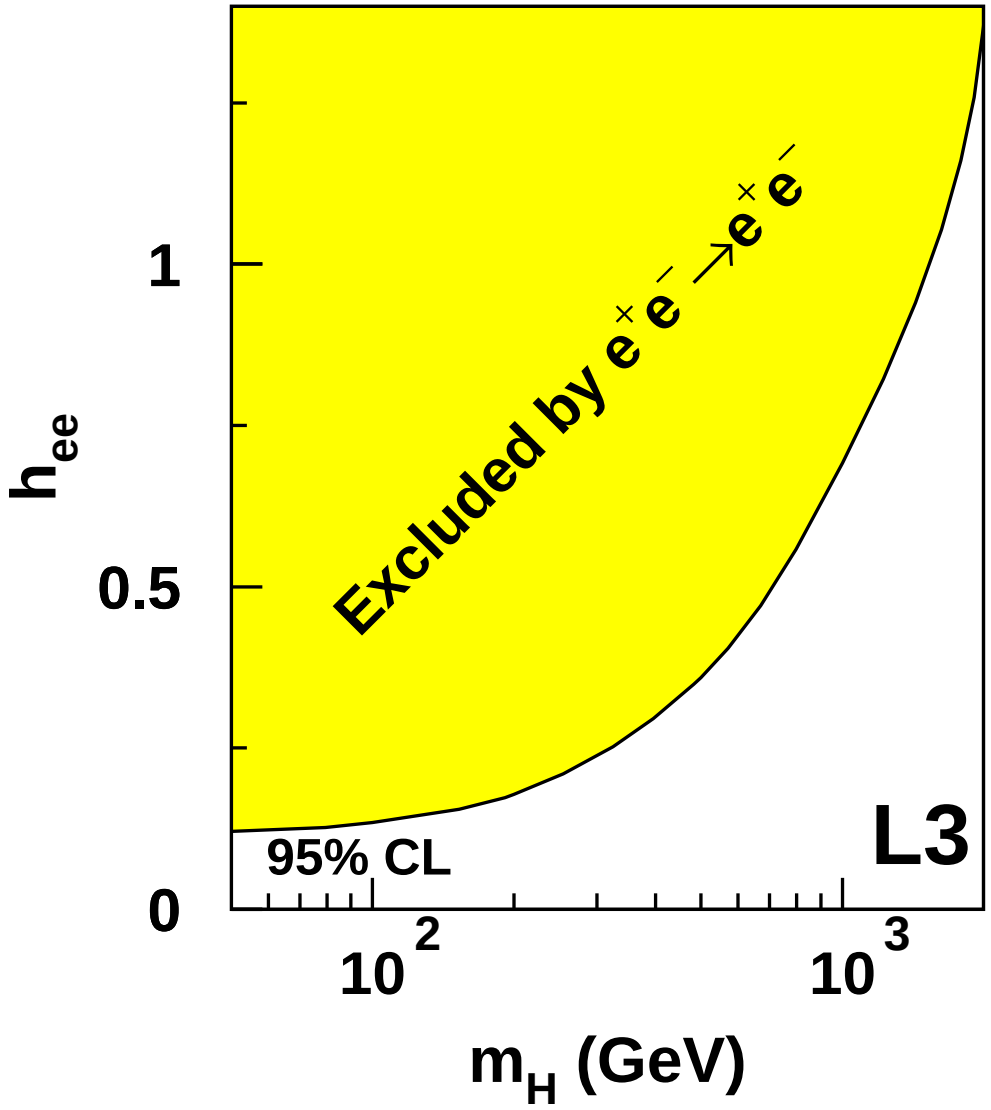




Doubly Charged Higgs Bosons: Mass Limits

Cross section and forward-backward asymmetry of $e^+e^- \to e^+e^-$ limit H^{++}.





Conclusions-I

- LEP: Immense progress over 14 years.
- Small data excess at 99 and 116 GeV. Various stringent limits.
- Excellent collaboration: theory and LEP experimental groups.
- Much knowledge gained in preparation for new searches.

Search	Experiment	Limit (95% CL)
HZZ Coupling	LEP	$\xi^2 = 1 : m_{\rm H}^{\rm SM} > 114.4$ GeV
Reduced rate and SM decay		$\xi^2 > 0.05 : m_{\rm H} > 85$ GeV
Reduced rate and $\rm b\bar{b}$ decay		$\xi^2 > 0.04 : m_{\rm H} > 80$ GeV
Reduced rate and $\tau^+\tau^-$ decay		$\xi^2 > 0.2 : m_{\rm H} > 113$ GeV
Reduced rate and hadronic decay		$\xi^2 = 1 : m_{\rm H} > 112.9$ GeV
		$\xi^2 > 0.3 : m_{\rm H} > 97$ GeV
Anomalous couplings	L3	$d,\ d_B,\ \Delta g_1^{\rm Z},\ \Delta\kappa_\gamma$ exclusions
MSSM (no scalar top mixing)	LEP	almost entirely excluded
New top mass result		strongly reduced $\tan\beta$ limits
HZ production for large $\tan\beta$	L3	$97 < m_{\rm A} < 108$ GeV excluded

Conclusions-II

General MSSM scan	DELPHI	$m_{\mathrm{h}} > 87$ GeV, $m_{\mathrm{A}} > 90$ GeV
CP-violating	OPAL	strongly reduced limits
Visible/invisible decays	DELPHI	$m_{\mathrm{H}} > 111.8$ GeV
Majoron model		max. mix.: $m_{\mathrm{H,S}} > 112.1$ GeV
Fl.-ind. had. decay(σ_{max})	DELPHI	$\mathrm{hA} \to \mathrm{q\bar{q}q\bar{q}} : m_{\mathrm{h}} + m_{\mathrm{A}} > 110$ GeV
2DHM	DELPHI	$\mathrm{b\bar{b}b\bar{b}} : m_{\mathrm{h}} + m_{\mathrm{A}} > 150$ GeV
(for σ_{max})		$\tau^+\tau^-\tau^+\tau^- : m_{\mathrm{h}} + m_{\mathrm{A}} > 160$ GeV
		$(\mathrm{AA})\mathrm{A} \to 6\mathrm{b} : m_{\mathrm{h}} + m_{\mathrm{A}} > 150$ GeV
		$(\mathrm{AA})\mathrm{Z} \to 4\mathrm{b\ Z} : m_{\mathrm{h}} > 90$ GeV
General 2DHM scan	OPAL	$\tan\beta > 1 : m_{\mathrm{h}} \approx m_{\mathrm{A}} > 85$ GeV
Yukawa process	DELPHI	$C > 40 : m_{\mathrm{h,A}} > 40$ GeV
Singly-charged Higgs	LEP	$m_{\mathrm{H}^\pm} > 78.6$ GeV
$\mathrm{W}^\pm\mathrm{A}$ decay mode	DELPHI	$m_{\mathrm{H}^\pm} > 76.7$ GeV
Doubly-charged Higgs	DELPHI/OPAL	$h_{\tau\tau} : m_{\mathrm{H}^{++}} > 99$ GeV
$\mathrm{e^+e^-} \to \mathrm{e^+e^-}$	L3	$h_{\mathrm{ee}} > 0.5 : m_{\mathrm{H}^{++}} > 700$ GeV