Searches for Higgs Bosons BSM at LEP, Part B,
(Fermiophobia, Anomalous couplings, Invisible, Charged Higgs

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CIEMAT
L3 COLLABORATION

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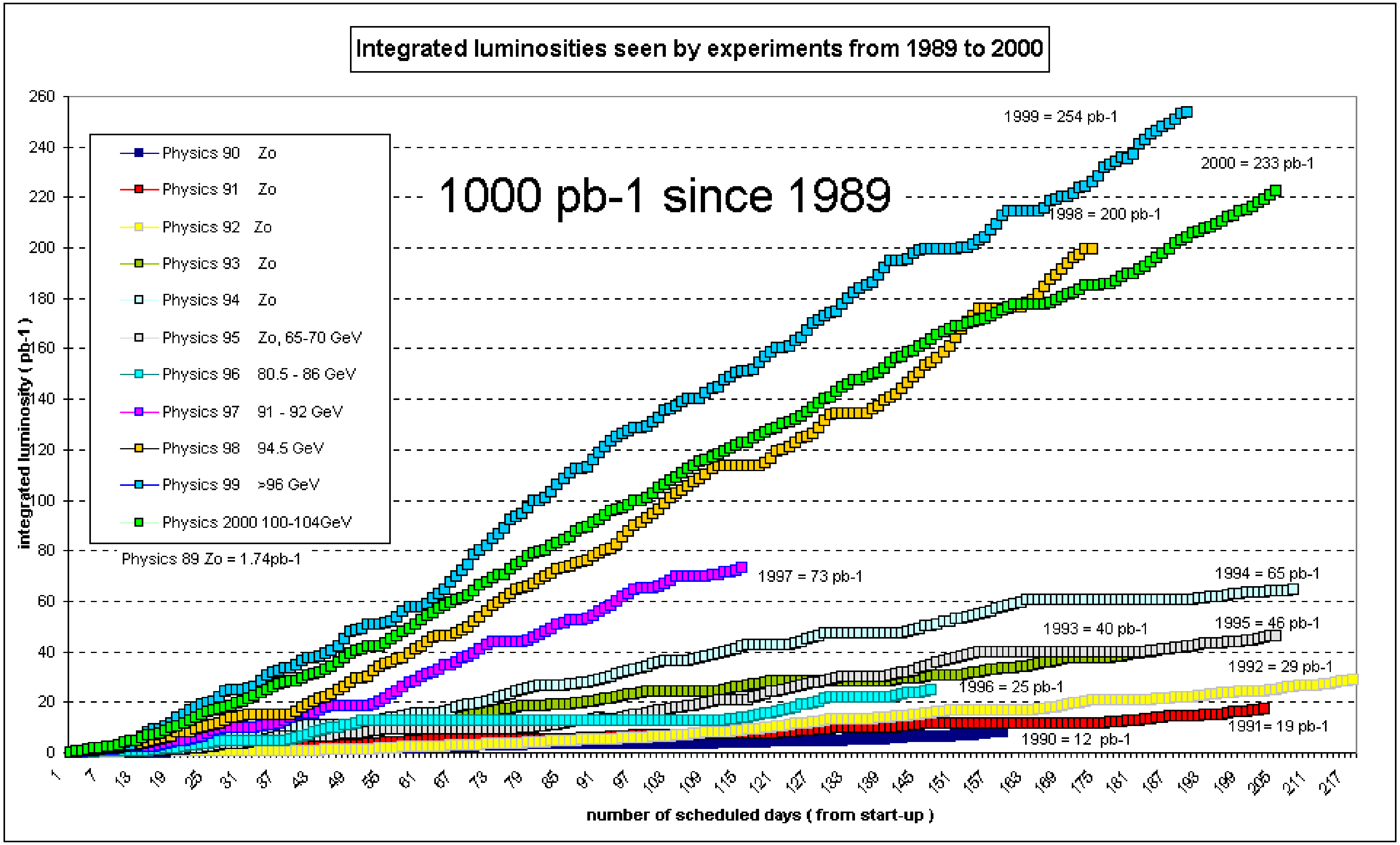
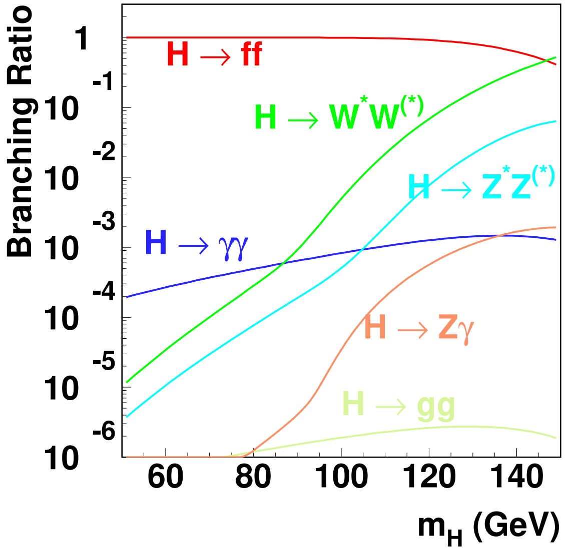
OUTLINE

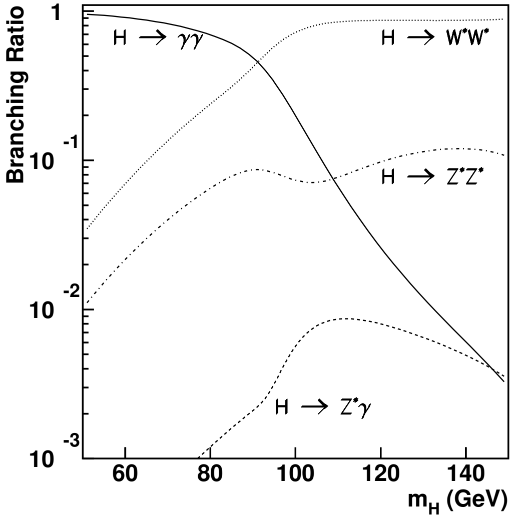
- Fermiophobic Higgs
  - Limits on $\mathrm{Br}(\mathrm{H} \to \gamma\gamma)$
  - Anomalous couplings
- Invisible Higgs
- Charged Higgs
  - Charged Higgs in THDM(II)
  - Charged Higgs in THDM(I)
- Conclusions

LEP Luminosity at High Energy

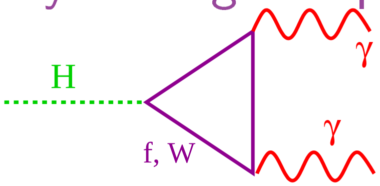


Fermiophobic Higgs





In the SM $\mathrm{H} \to \gamma\gamma$
only through loops

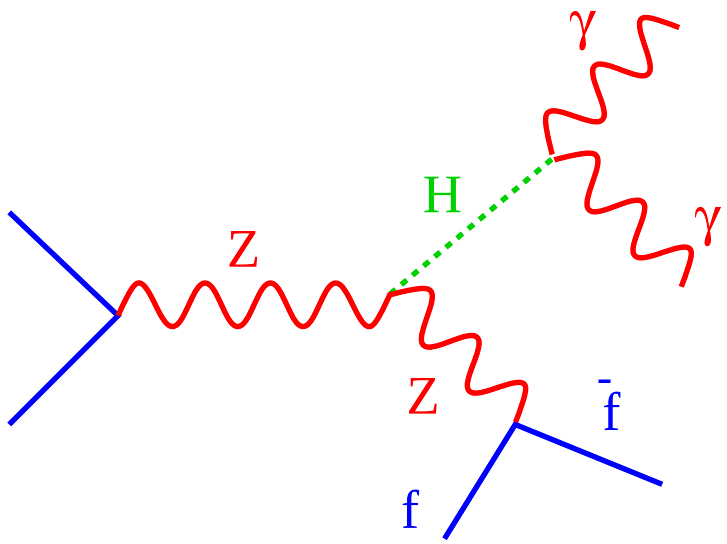


Effective Lagrangians that
include anomalous HVV couplings
Two Higgs doublet models (THDM)
Higgs Multiplet models (HMM)

$\mathrm{H} \to \gamma\gamma$ decay mode dominant for $m_{\mathrm{H}} < m_{\mathrm{Z}}$

$\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ decay mode dominant for $m_{\mathrm{H}} > m_{\mathrm{Z}}$

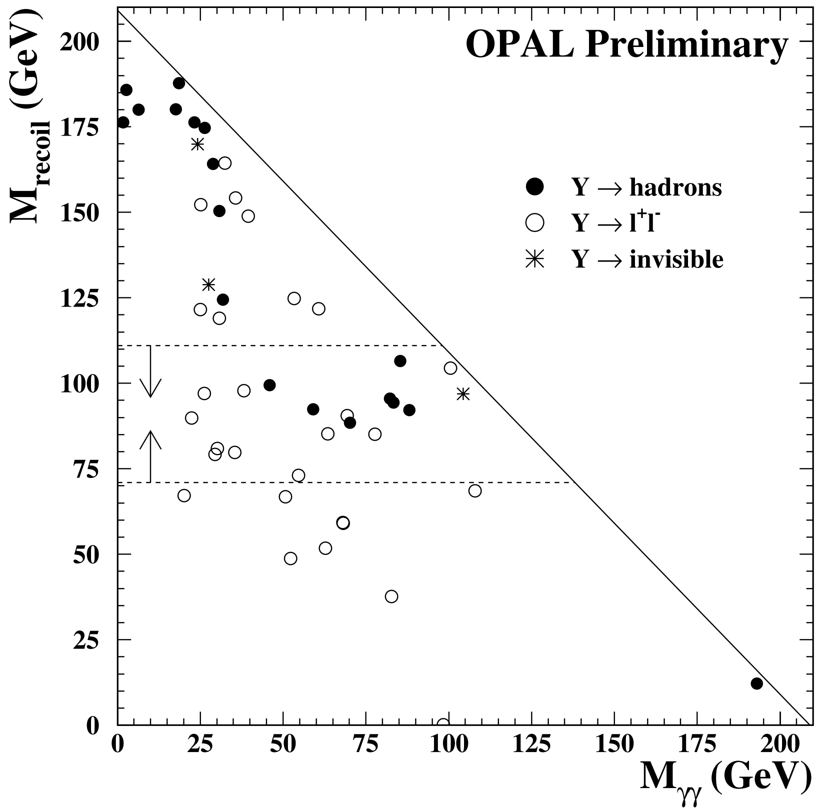
Benchmark fermiophobic Higgs



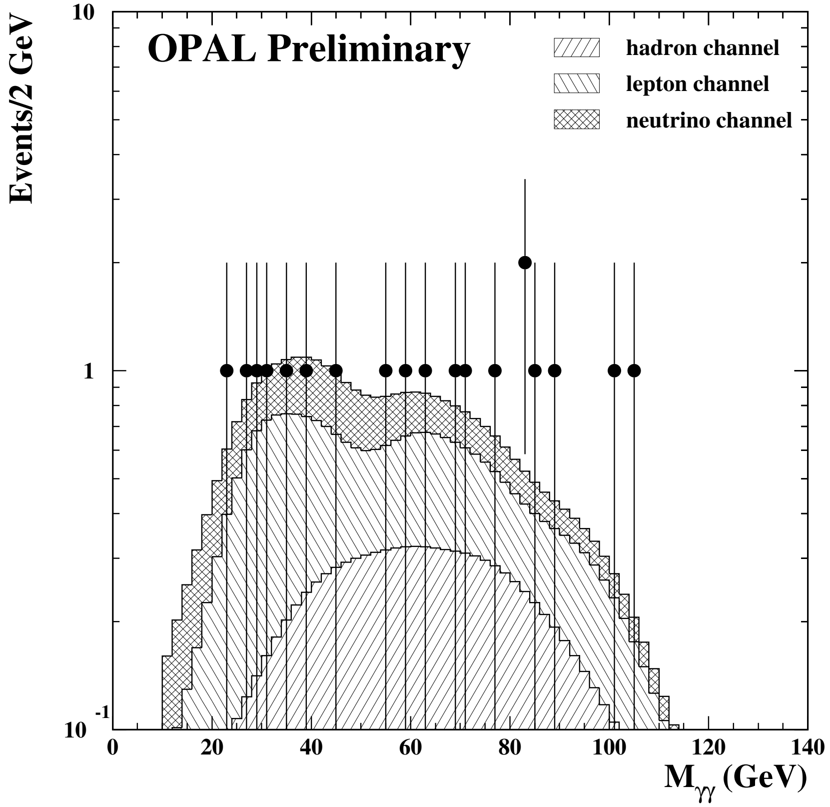
- In the assumption of SM production
- Final states:
  - $q\bar{q}\gamma\gamma$
  - $\ell\ell\gamma\gamma$
  - $\nu\bar{\nu}\gamma\gamma$
- Experimental signature:
  - Pair of isolated photons
  - Kinematical fit to improve resolution
  - Selection is done in terms of $\gamma\gamma$ invariant mass

Fermiophobic Higgs - OPAL

Recoil mass – $\gamma\gamma$ inv. mass



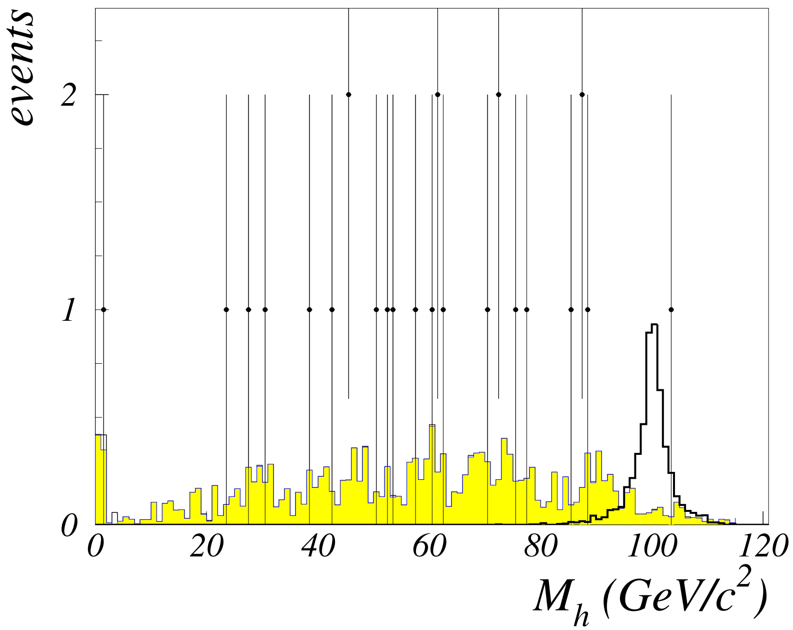
$\gamma\gamma$ inv. mass



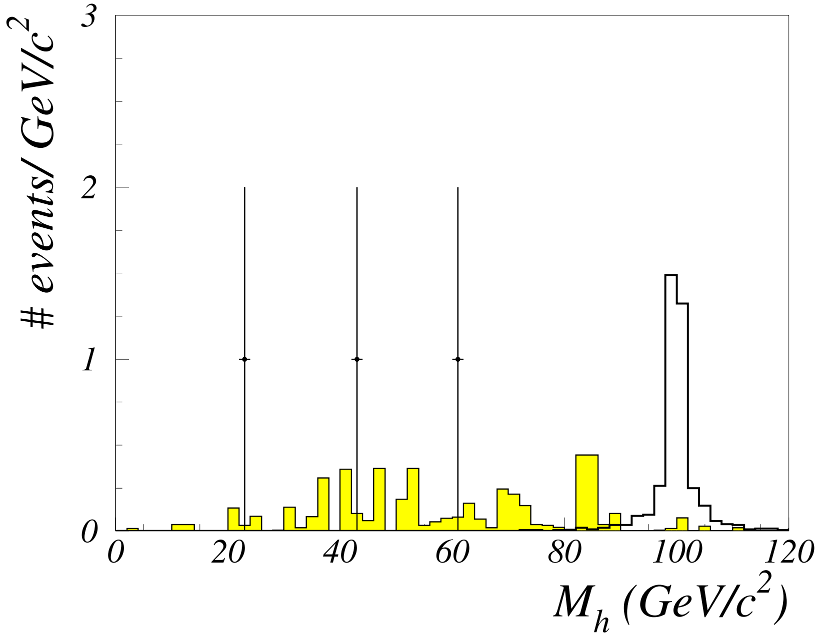
Fermiophobic Higgs - DELPHI

$\gamma\gamma$ invariant mass distribution

$e^+e^- \to Z^0H \to q\bar{q}\gamma\gamma$



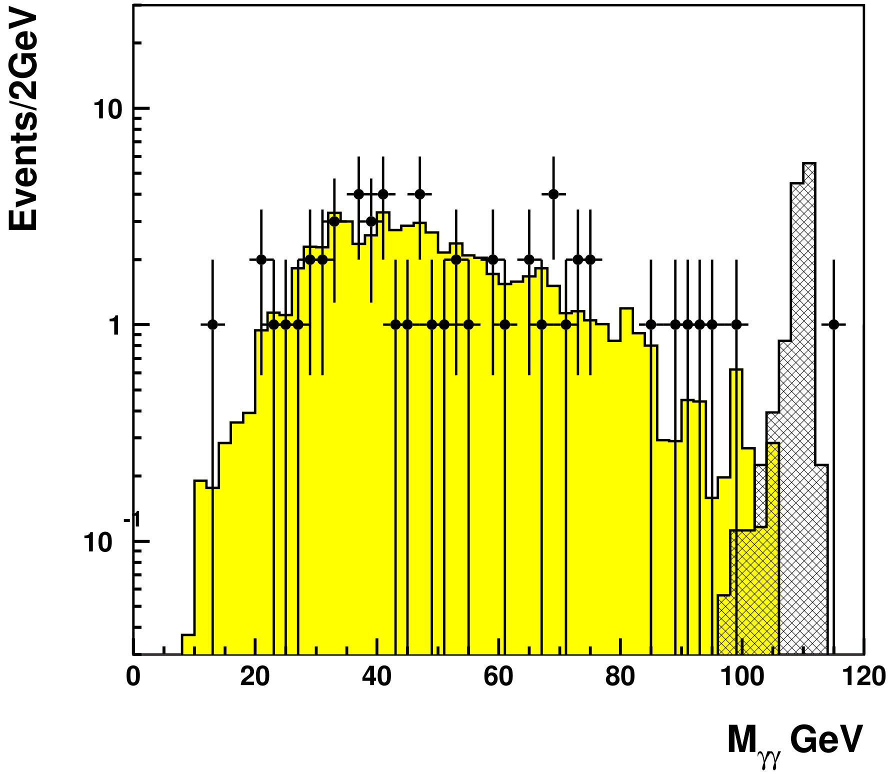
$e^+e^- \to Z^0H \to \ell\ell\gamma\gamma$



Signal prediction for $m_{\mathrm{H}} = 100$ GeV

Fermiophobic Higgs - L3

$\mathrm{H} \to \gamma\gamma$ channel



Signal prediction for $m_{\mathrm{H}} = 110$ GeV

$\mathrm{H} \to \mathrm{WW}^*$ channel included

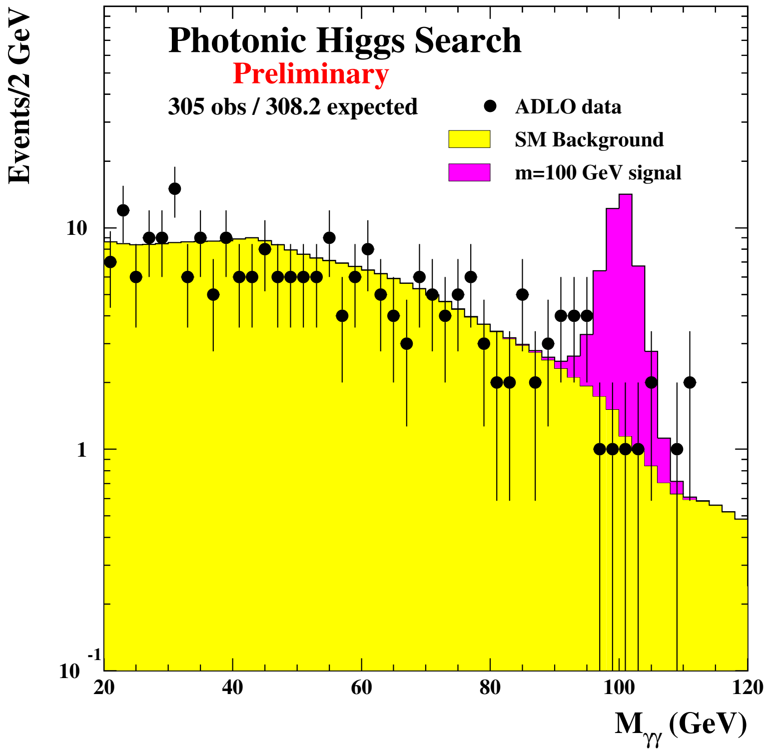
$$\mathrm{e^+e^-} \to \mathrm{HZ^0} \to \mathrm{WW^*f\bar{f}}$$

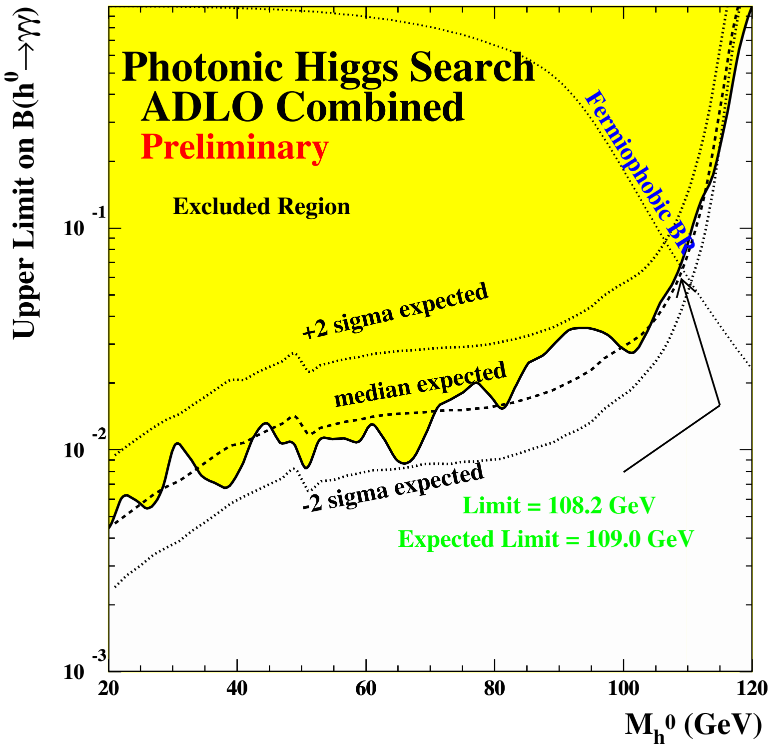
Final states:

$\mathrm{q\bar{q}q'\bar{q}'(q\bar{q})}$ (30%)
$\mathrm{q\bar{q}q'\bar{q}'}(\nu\bar{\nu})$ (10%)
$\mathrm{q\bar{q}}\ell\nu(\mathrm{q\bar{q}})$ (30%)
$\mathrm{q\bar{q}}\ell\nu(\nu\bar{\nu})$ (10%)

Limit on $\mathrm{Br}(\mathrm{H} \to \gamma\gamma)$

$\mathrm{H} \to \gamma\gamma$ (LEP Combined)





Signal prediction for $m_{\mathrm{H}} = 100$ GeV

$m_{\mathrm{H}} > 108.2$ GeV

Fermiophobic Higgs Mass limit

$H \rightarrow \gamma\gamma$

	Mass limits at 95%CL (GeV)			
Experiment	ALEPH	DELPHI	L3	OPAL
$\sqrt{s}$ (GeV)	192.– 208.	189. – 208.	189. – 209.	88. – 209.
Observed limit Expected limit	104.4 104.6	103.6 105.1	104.1 104.9	104.8 105.2

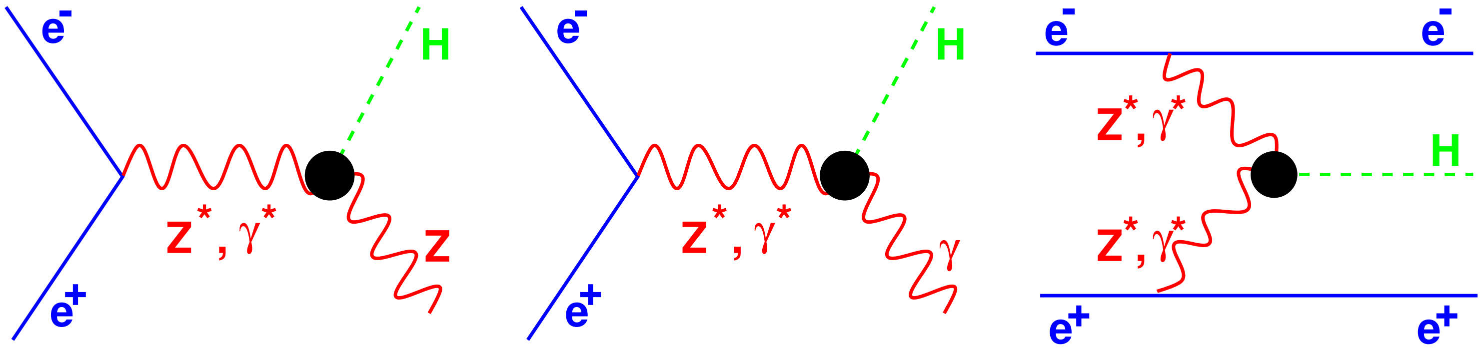
LEP Combined Observed mass limit (at 95%CL): 108.2 GeV

LEP Combined Expected mass limit (at 95%CL): 109.0 GeV

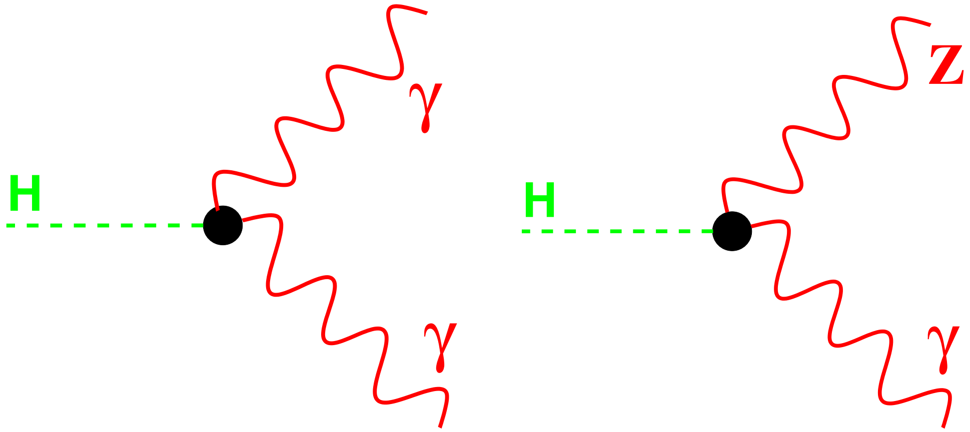
Higgs Anomalous Couplings

New couplings that modify the properties of the Higgs particle.

Production



Decay



- In addition to previous final states:
  - $e^+e^- \to H\gamma;\ \ H \to \gamma\gamma;\ e^+e^- \to e^+e^-H;\ \ H \to \gamma\gamma$

Higgs Anomalous Couplings

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

$$g^{(1)}_{\mathrm{HZ^0}\gamma} = \frac{g}{m_{\mathrm{W}}} \left(\Delta g_1^{\mathrm{Z^0}} \sin 2\theta_{\mathrm{W}} - \Delta\kappa_\gamma \tan\theta_{\mathrm{W}}\right)$$

$$g^{(2)}_{\mathrm{HZ^0}\gamma} = \frac{g}{2m_{\mathrm{W}}} \sin 2\theta_{\mathrm{W}} \; (d - d_B)$$

$$g^{(1)}_{\mathrm{HZ^0Z^0}} = \frac{g}{m_{\mathrm{W}}} \left(\Delta g_1^{\mathrm{Z^0}} \cos 2\theta_{\mathrm{W}} + \Delta\kappa_\gamma \tan^2\theta_{\mathrm{W}}\right)$$

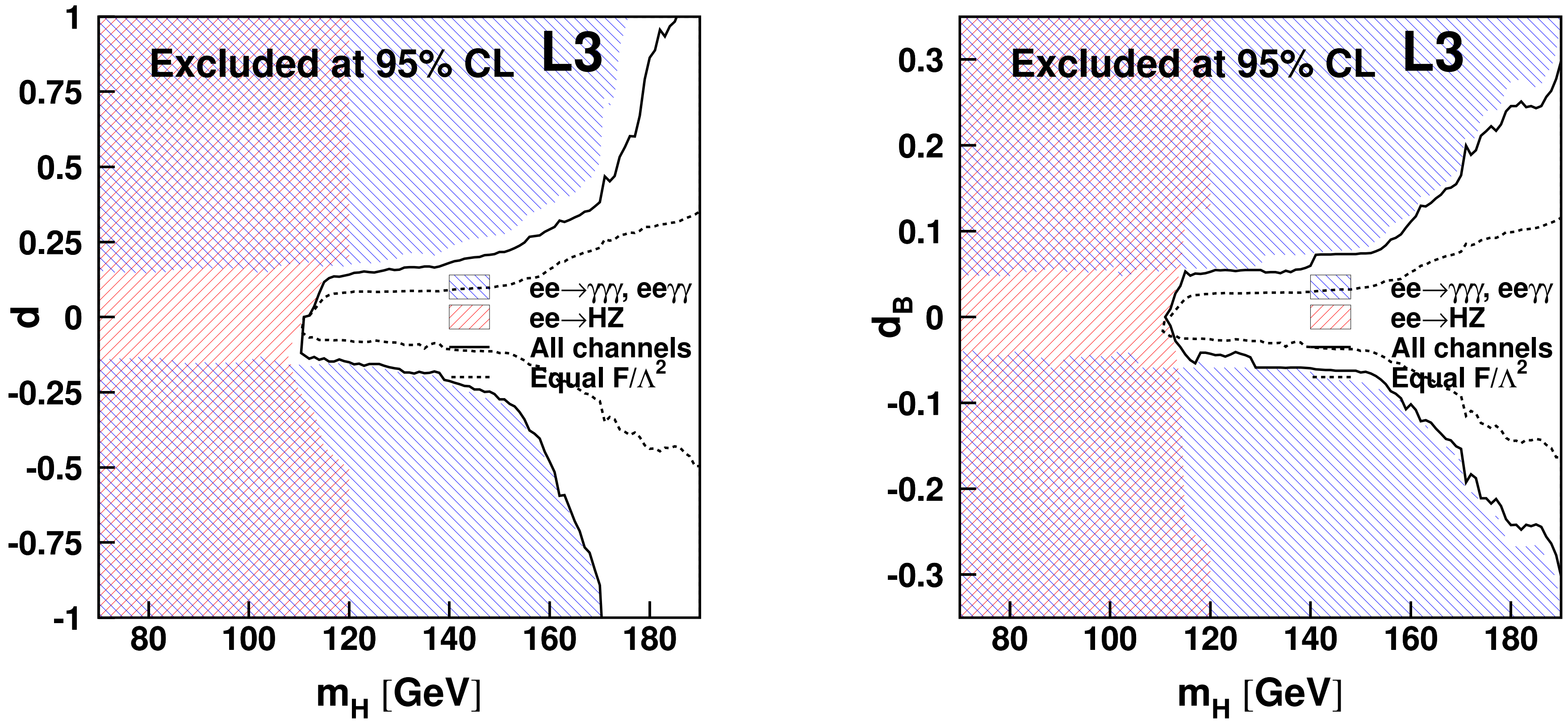
$$g^{(2)}_{\mathrm{HZ^0Z^0}} = \frac{g}{2m_{\mathrm{W}}} \left(d \cos^2\theta_{\mathrm{W}} + d_B \sin^2\theta_{\mathrm{W}}\right)$$

$$g^{(1)}_{\mathrm{HWW}} = \frac{g}{m_{\mathrm{W}}} \Delta g_1^{\mathrm{Z^0}} \cos 2\theta_{\mathrm{W}}$$

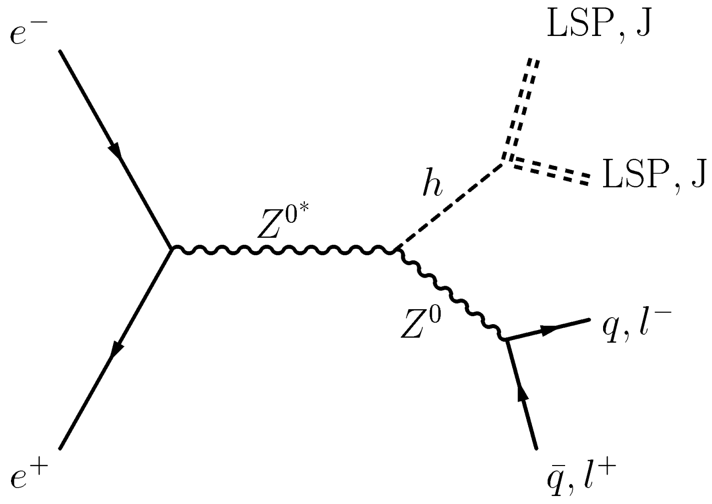
$$g^{(2)}_{\mathrm{HWW}} = \frac{g}{m_{\mathrm{W}}} d$$

Anomalous couplings limits in L3

$e^+e^- \to H\gamma;\ H \to \gamma\gamma$ and $e^+e^- \to e^+e^-H;\ H \to \gamma\gamma$



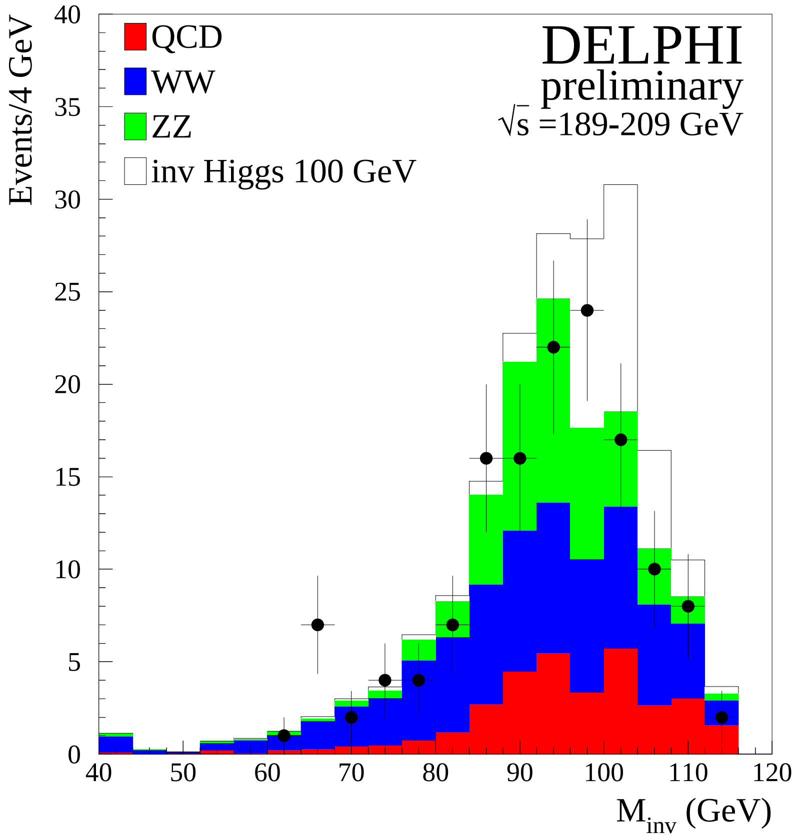
Invisible Higgs



- Several scenarios with invisible Higgs decays
  - Scalar S with $m_\mathrm{S} < \frac{1}{2} m_\mathrm{H}$: $\mathrm{h}^0 \to \mathrm{SS}$
  - MSSM when the LSP is light enough: $\mathrm{h}^0 \to \chi\chi$
  - Models with majorons (J): $\mathrm{h}^0 \to \mathrm{JJ}$
- Experimental Search
  - Higgs-strahlung process: $\mathrm{e}^+\mathrm{e}^- \to \mathrm{h}^0\mathrm{Z}^0$, $\mathrm{Z}^0 \to \mathrm{q\bar{q}}$
  - Similar to the SM $\mathrm{e}^+\mathrm{e}^- \to \mathrm{b\bar{b}}\nu\bar{\nu}$ search (but no b-tag)
  - Event mass should be consistent with m_Z
  - Backgrounds: $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q\bar{q}}\gamma$, $\mathrm{W}^+\mathrm{W}^- \to \mathrm{q\bar{q}}\ell\nu$, $\mathrm{Z}^0\mathrm{Z}^0 \to \mathrm{q\bar{q}}\nu\bar{\nu}$

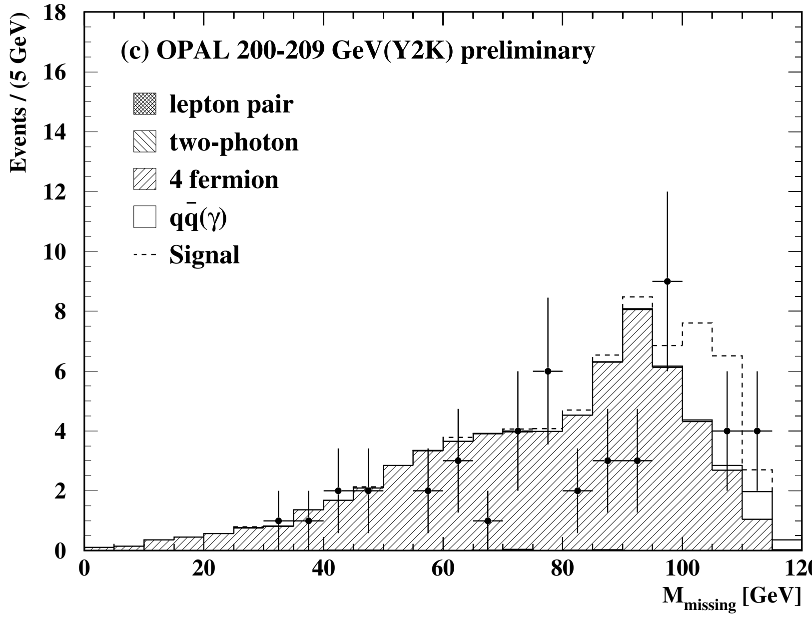
Invisible Higgs

DELPHI



Signal prediction for $m_{\mathrm{h}} = 100$ GeV

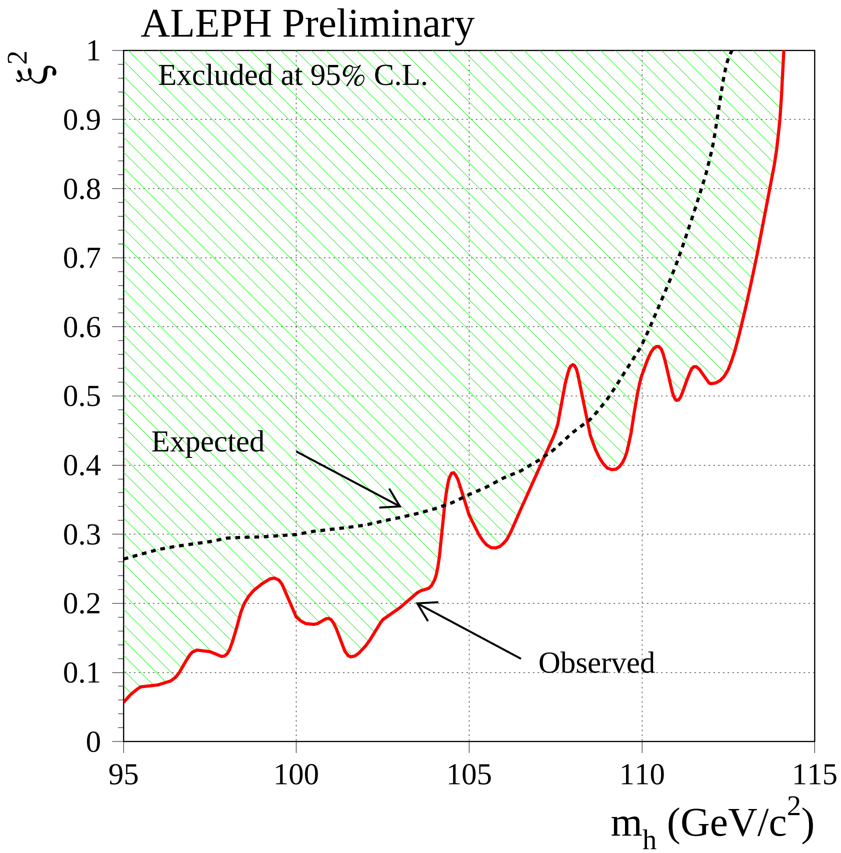
OPAL



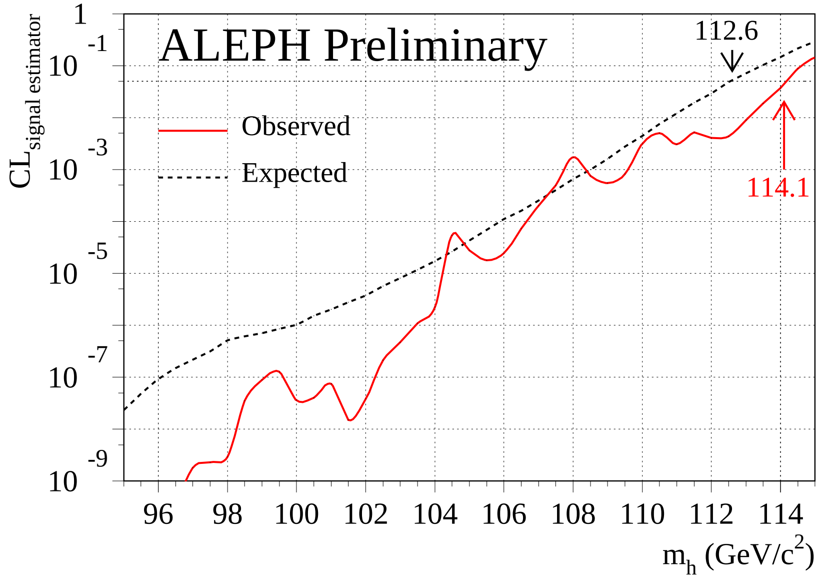
Signal prediction for $m_{\mathrm{h}} = 105$ GeV

Invisible Higgs (ALEPH)

Limit on
$\sigma(e^+e^- \to h^0Z^0)/\sigma_{SM}(e^+e^- \to h^0Z^0)$



Assuming a SM h^0Z^0 production cross-section



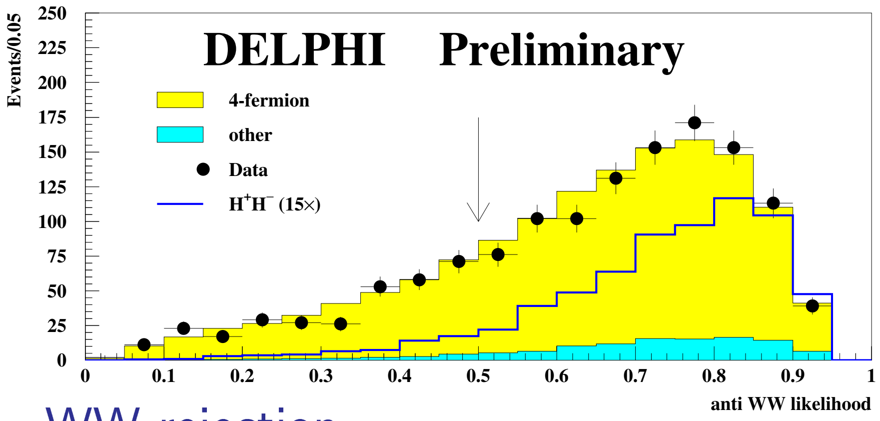
LEP combined mass limit (95% CL): 114.4 GeV

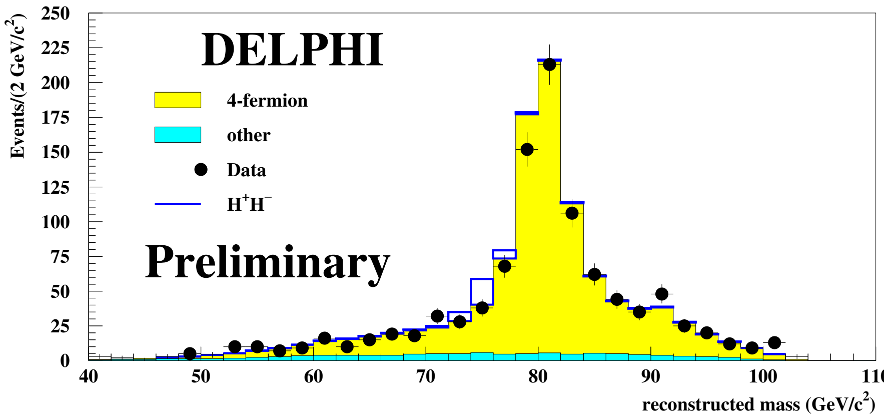
Charged Higgs (2HDM - Type II)

- Experimental assumptions:
  - Produced in pairs: $e^+e^- \to H^+H^-$
  - Decays to heaviest fermions:
    $H^+H^- \to q\bar{q}q\bar{q}$
    $H^+H^- \to q\bar{q}\tau\nu$
    $H^+H^- \to \tau\nu\tau\nu$
  - $\mathrm{Br}(H^\pm \to \tau\nu) + \mathrm{Br}(H^\pm \to c\bar{s}) = 1.$
  - $\mathrm{Br}(H^\pm \to \tau\nu)$ left as free parameter
- Background: W^+W^-production
  - Polar angle of the boson
  - W polarisation

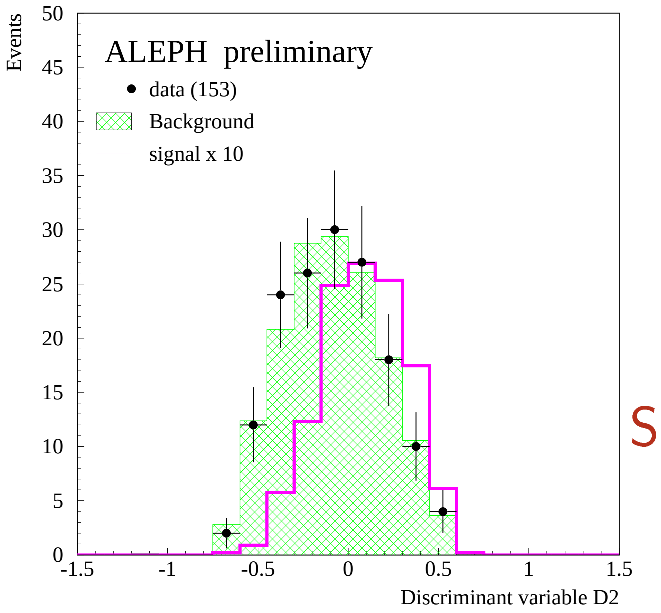
Charged Higgs

Hadronic channel



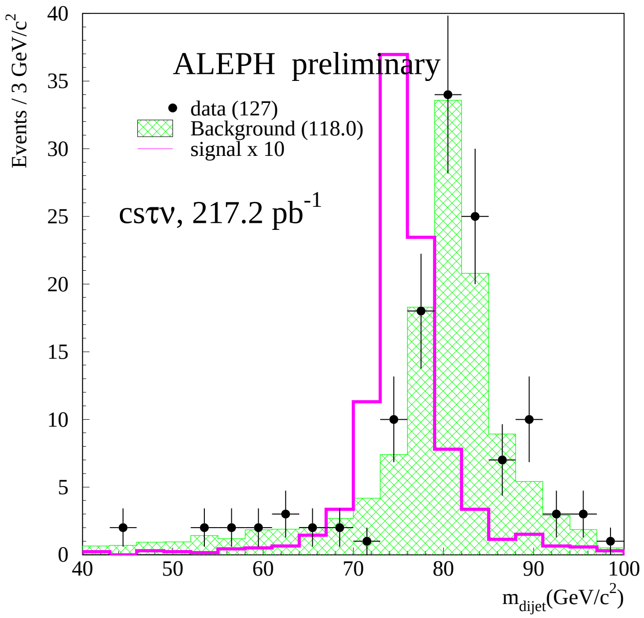


WW rejection



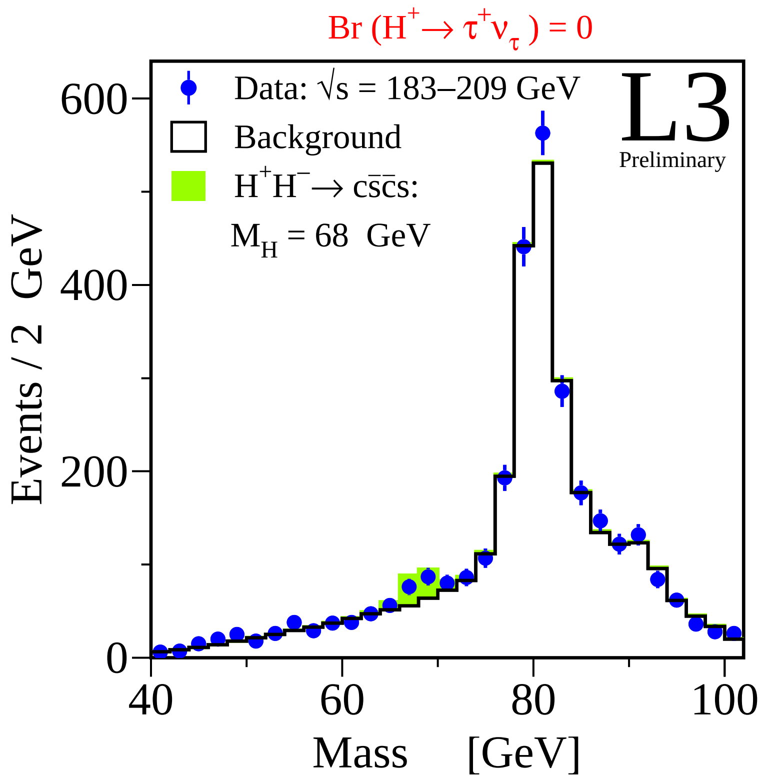
Signal prediction for $m_{H^\pm}$ = 75 GeV

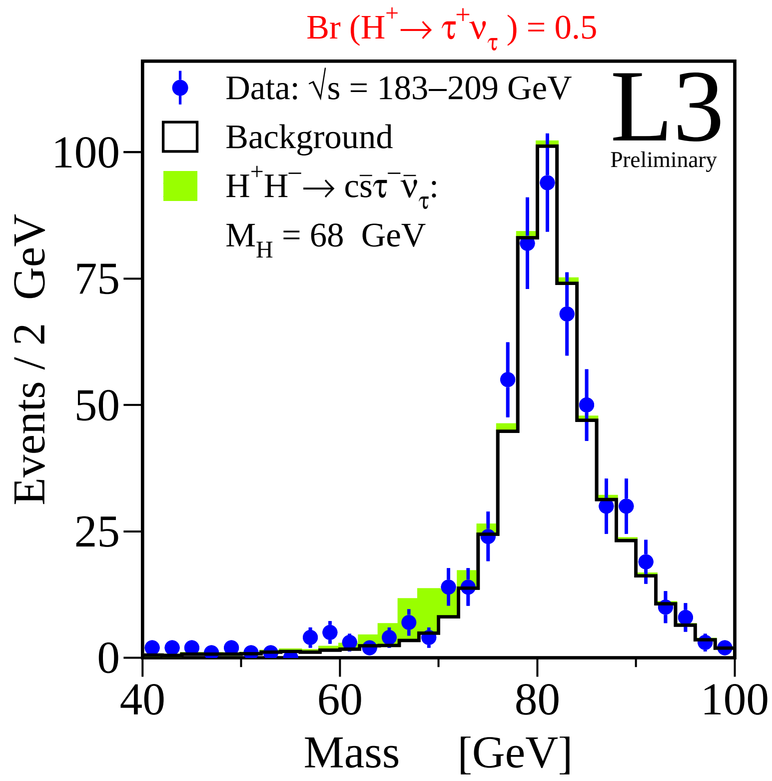
Semileptonic channel



Charged Higgs (L3)

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

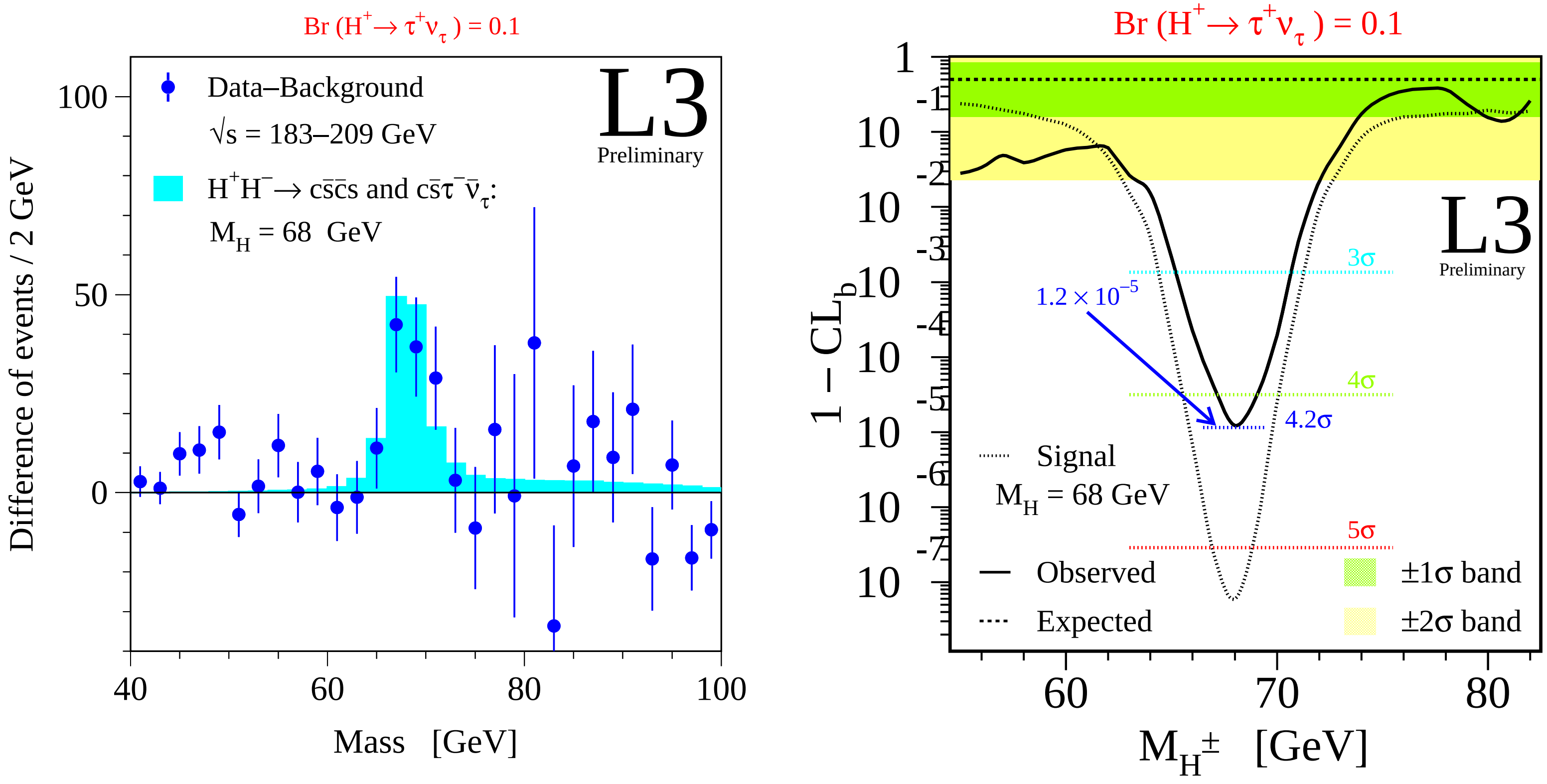




Excess of events at 68 GeV

Charged Higgs (L3)

$$\mathrm{Br}(\mathrm{H}^{\pm} \to \tau\nu) = 0.1$$

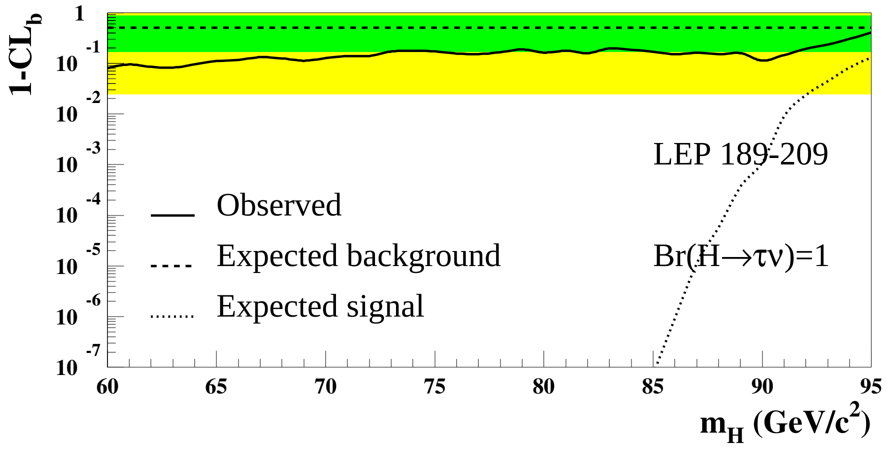


Excess not confirmed by the other LEP experiments

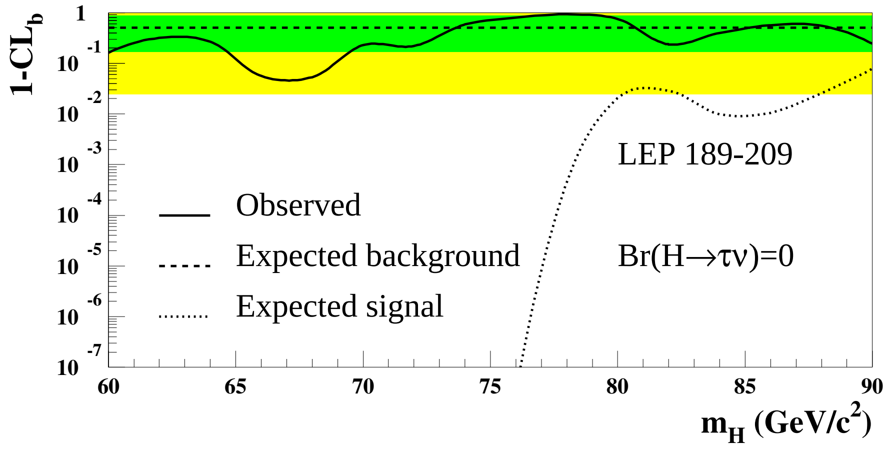
LEP combined – Confidence level

1-CLb (LEP Combined – ADLO)

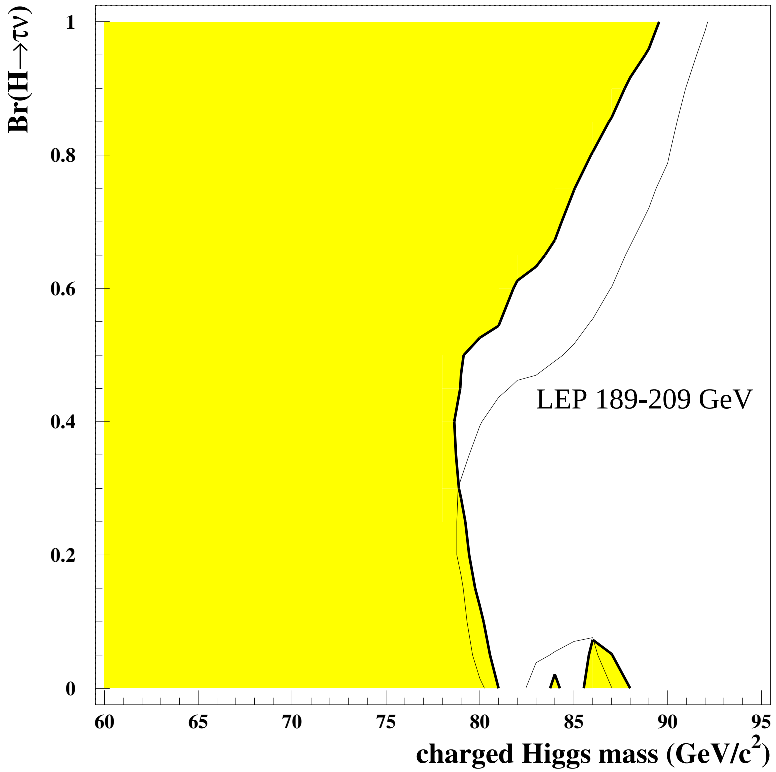
$\mathrm{Br}(\mathrm{H}^{\pm} \to \tau\nu) = 1.$



$\mathrm{Br}(\mathrm{H}^{\pm} \to \tau\nu) = 0.$

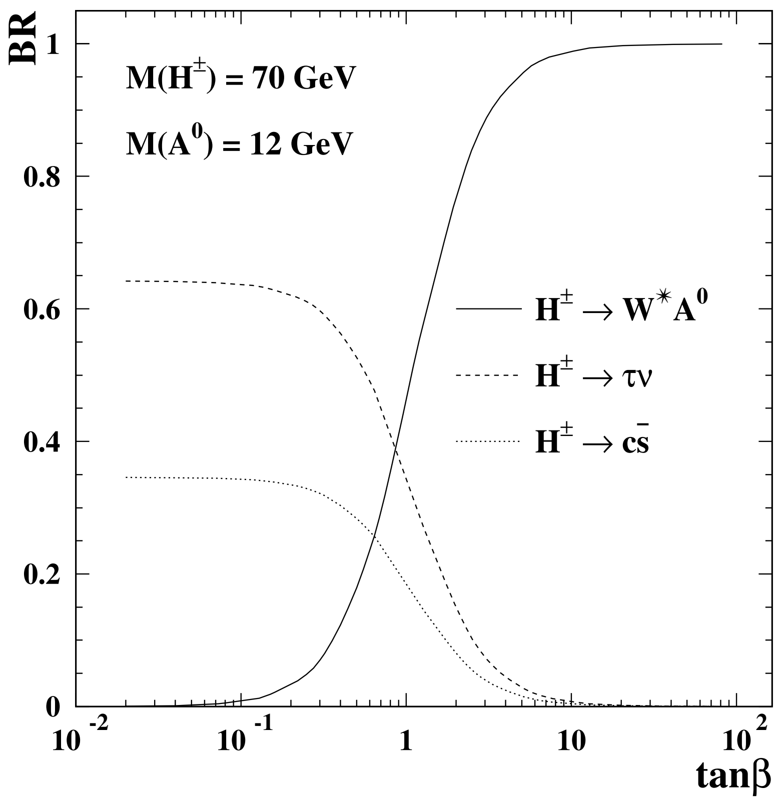


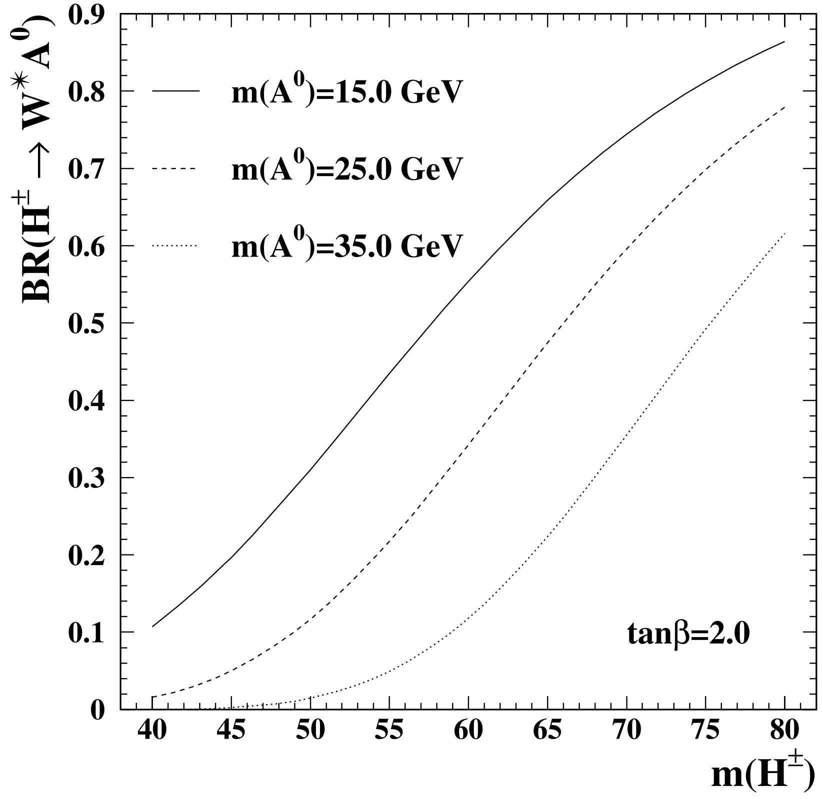
Charged Higgs, LEP combined



	Mass limit at 95% CL (GeV)
$\mathrm{Br}(\mathrm{H}^\pm \to \tau\nu) = 0.$	
Observed limit	81.2
Expected limit	80.2
$\mathrm{Br}(\mathrm{H}^\pm \to \tau\nu) = 1.$	
Observed limit	89.6
Expected limit	92.1
Any $\mathrm{Br}(\mathrm{H}^\pm \to \tau\nu)$	
Observed limit	78.6
Expected limit	78.8

Charged Higgs (2HDM - Type I)



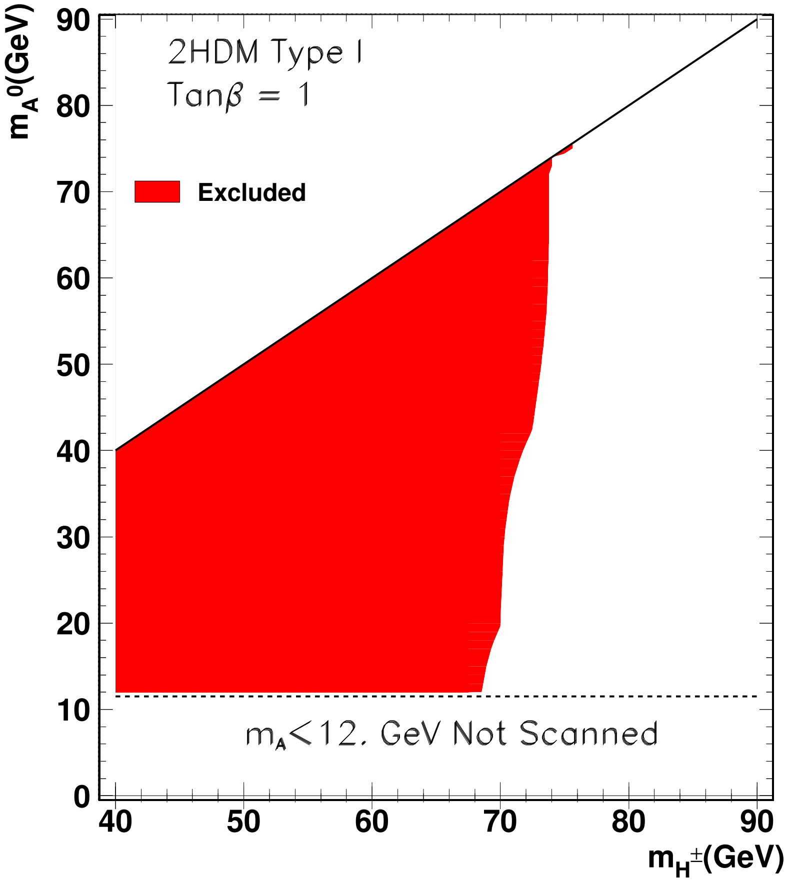


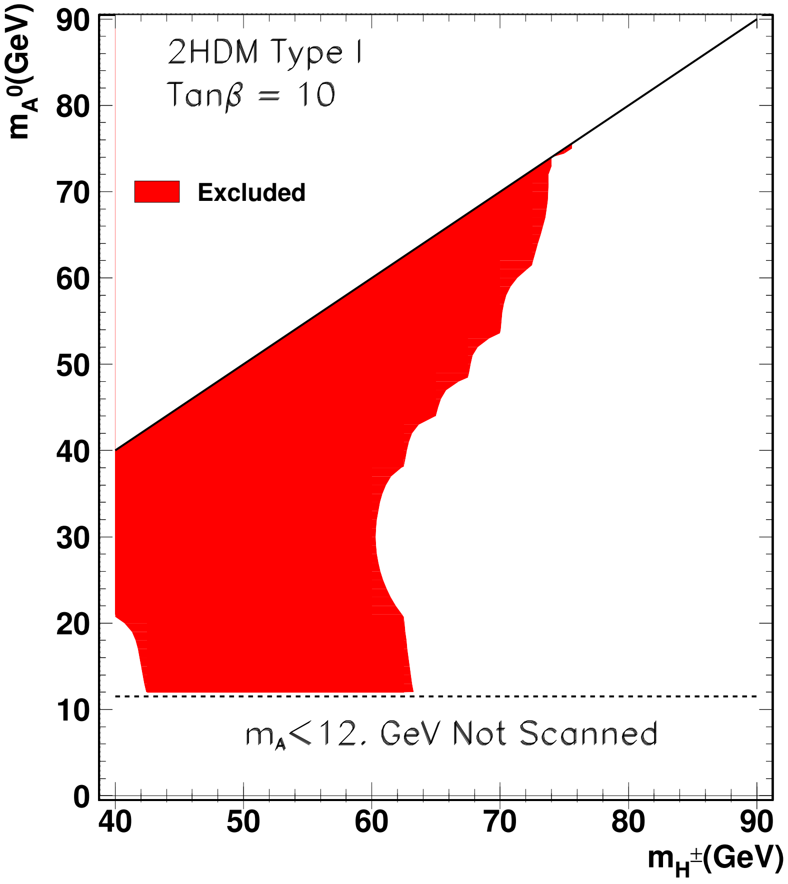
$H^{\pm} \to W^{*}A^{0}$ dominant at high $\tan\beta$

BR depends on relative values of $m_{H^{\pm}}$ and m_{A}

$H^{\pm} \to q\bar{q}$, $H^{\pm} \to \tau\nu$, $H^{\pm} \to q\bar{q}A^{0}$, $H^{\pm} \to \ell\nu A^{0}$; $A^{0} \to b\bar{b}$

Charged Higgs (2HDM - Type I) in OPAL





Conclusions

- LEP experiments have extended their search of the Higgs boson much beyond the Standard Model.

NO HIGGS FOUND

- A mass limit on Fermiophobic Higgs is set to 108.2 GeV at 95 % CL.
- Limits on Higgs anomalous couplings set.
- A mass limit on Invisible Higgs is set to 114.4 GeV at 95 % CL.
- A mass limit on Charged Higgs is set to 78.6 GeV at 95 % CL independent on $\mathrm{Br}(\mathrm{H}^{\pm} \to \tau\nu)$.
  L3 observes an excess of 4.2 σ.
- Search of $\mathrm{H}^{\pm} \to \mathrm{W}^{*}\mathrm{A}^{0}$ set limits on 2HDM parameter space.

Contributions to EPS HEP2001

- ALEPH
  - "Search for gamma-gamma decays of a Higgs boson produced in association with a fermion pair in $\mathrm{e^+e^-}$ at $\sqrt{s}$ up to 209 GeV", ALEPH/2001-015, CONF/2001-012.
  - "Search for an invisibly decaying Higgs boson at LEP at $\sqrt{s}$ =209 GeV", ALEPH/2001-008, CONF/2001-005.
  - "Search for charged Higgs bosons in $\mathrm{e^+e^-}$ collision at energies up to $\sqrt{s} =$ 209 GeV", ALEPH/2001-016, CONF/2001-013.
- DELPHI
  - "Search for a Fermiophobic Higgs at LEP2", DELPHI NOTE/2001-073, CONF 501.
  - "Searches for invisibly decaying Higgs bosons", DELPHI NOTE/2001-079, CONF 507.
  - "Search for Charged Higgs Bosons in $\mathrm{e^+e^-}$ Collisions at LEP", DELPHI NOTE/2001-071, CONF 499.

- L3
  - "Search for a fermiophobic Higgs boson at L3", L3 NOTE 2673, L3 NOTE 2685.
  - "Search for anomalous couplings in the Higgs sector at LEP", L3 NOTE 2698.
  - "Search for invisible Higgs boson decays in e^+e^- collisions at center-of-mass energies up to 209 GeV at LEP", L3 NOTE 2690.
  - "Search for Charged Higgs Bosons in e^+e^- Collisions at Centre-of-Mass Energies up to 209 GeV", L3 NOTE 2686.
- OPAL
  - "Searches for Higgs Bosons in Extensions to the Standard Model in e^+e^- Collisions at the Highest LEP Energies", OPAL PN472.
- LEP Higgs Working Group
  - "Search for Higgs Bosons Decaying into Photonic Final States: Preliminary Combined Results Using LEP Data Collected at Energies up to 209 GeV."
  - "Search for Higgs Bosons Decaying into Invisible Particles:

Preliminary Combined Results Using LEP Data Collected at Energies up to 209 GeV."

– "Search for Charged Higgs Bosons: Preliminary Combined Results Using LEP Data Collected at Energies up to 209 GeV."