Higgs Searches at LEP

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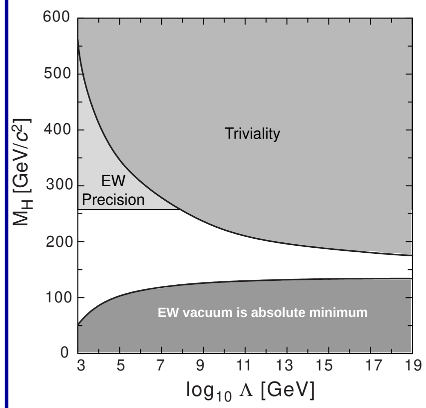
IFT Seminar, UAM

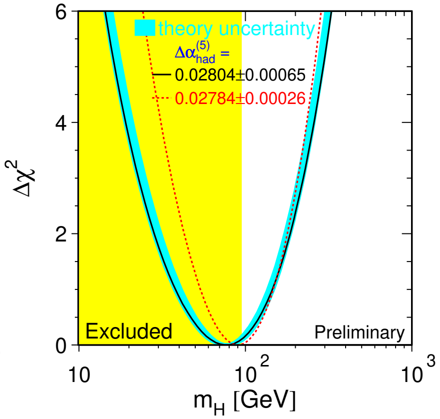
- Introduction
- Search for the Higgs boson at LEP
  - Standard Model Higgs
  - MSSM Higgses
  - Other possibilities: invisibility, fermiophobia
- Plans for next year

The relevance of the Higgs Particle

- The Standard Model (SM) has been successfully tested at collider experiments (LEP, ...) at the 1% level or better.
- One of the fundamental problems in Particle Physics at present: understanding the electroweak symmetry breaking mechanism and the origin of particle masses.
- SM, MSSM, ... models require the presence of a fundamental scalar at the electroweak scale: the Higgs particle.
- The search for the Higgs and the study of its properties constitutes the major ingredient of current (LEP, CDF) and future (LHC, LC, μ-colliders) experimental programmes.

The SM Higgs Particle



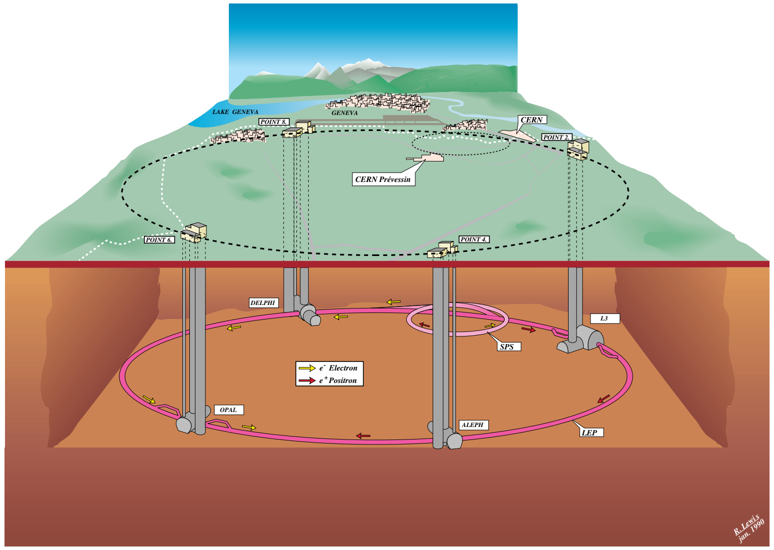


Only a narrow band is allowed if there is no new physics up to 10^{19} GeV

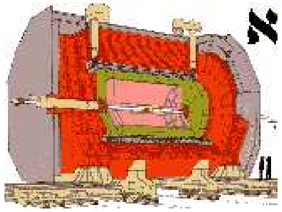
$m_H \in [38, 146]$ GeV at 68% CL

$m_H < 215$ GeV at 95% CL

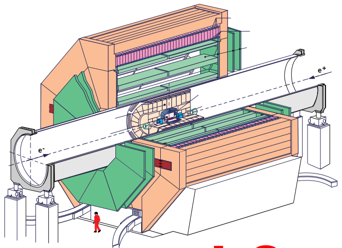
LEP



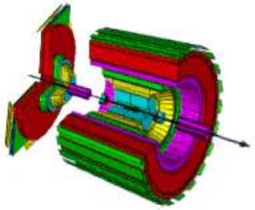
LEP detectors



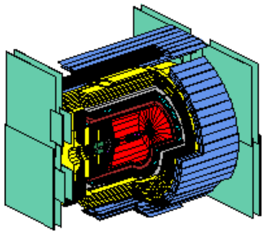
ALEPH



L3



DELPHI



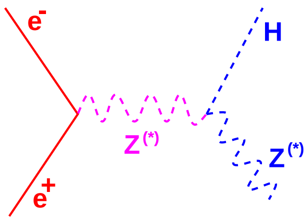
OPAL

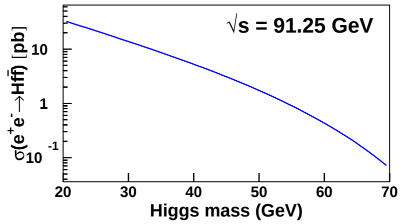
LEP

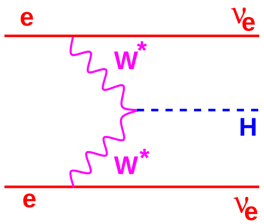
LEP PROGRAM: e^+e^- collisions at the highest energy

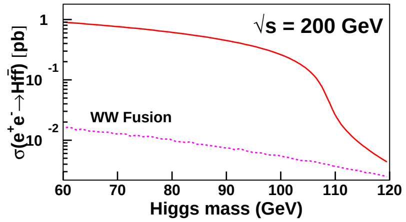
Period	$\sqrt{s}$ [GeV]	Luminosity [pb^{-1}/experiment]
1989 — 1995	88 — 94	150
1995	130 — 140	5
1996	161 170 — 172	10 10
1997	183	55
1998	189	175
1999	192 196 200 202 204	30 80 80 40 0.01
2000	???	???

The SM Higgs Particle at LEP





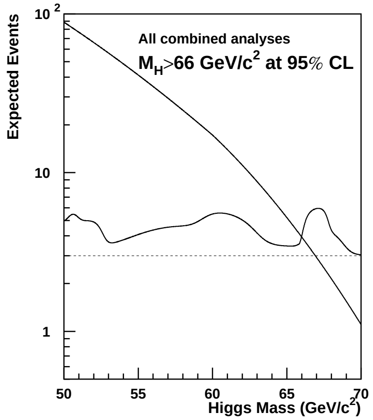




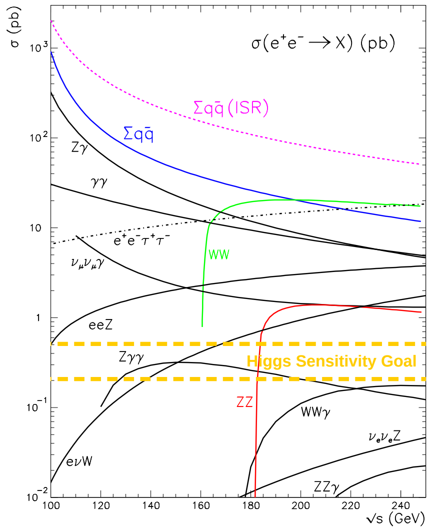
- Higgs-strahlung process is dominant at all LEP energies
- LEP2 "kinematical" limit: $m_H + m_Z \lesssim \sqrt{s}$
- LEP2 has the "potential" to observe a $m_H \lesssim 110$ GeV Higgs !!

The SM Higgs: LEP1 and LEP2

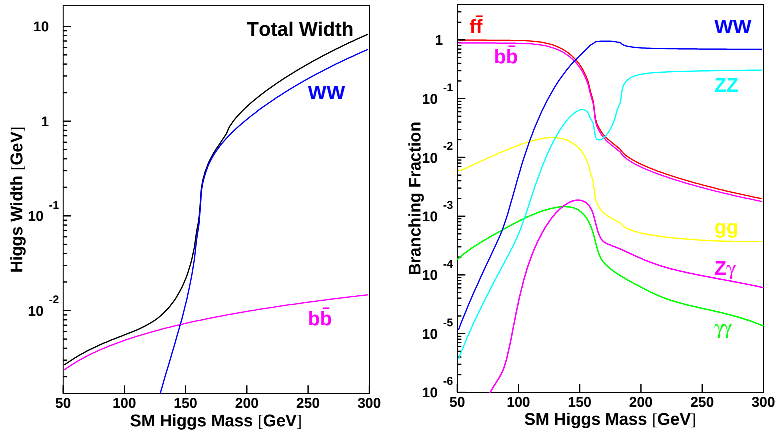
Final LEP1 combined limit (ICHEP96 Warsaw)



LEP2 experimental scenario



The SM Higgs Particle at LEP



At LEP:

"Almost stable" Higgs (but visible for $m_{\mathrm{H}} \gg 0$)

Relevant decay channel: $\mathrm{H} \to \mathrm{b\bar{b}}$

The SM Higgs: b-tagging at LEP2

Differences between b jets and light-quark jets

- b-hadrons have a: larger mass and a harder fragmentation
- harder leptonic weak-decay spectrum
- larger decay multiplicity
- larger lifetime: $\tau_{\mathrm{b}} \simeq 1.55$ ps
- large boost: $\gamma \equiv E_{\mathrm{b}}/m_{\mathrm{b}} \approx 6$

Differences at the detector level

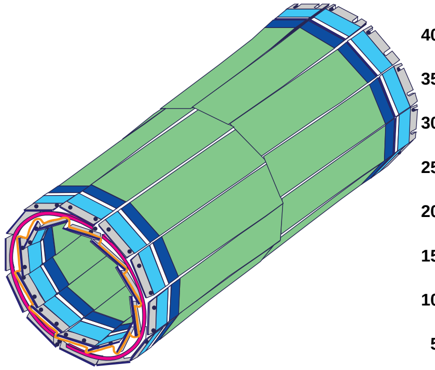
- Significant weak-decay length in average: $L \approx 3$ mm
- Large p, p_t of leptons in b-decays with respect to the jet direction
- More particles at the secondary vertices
- Large invariant mass at secondary vertices
- Large rapidities with respect to the jet direction, broad jets

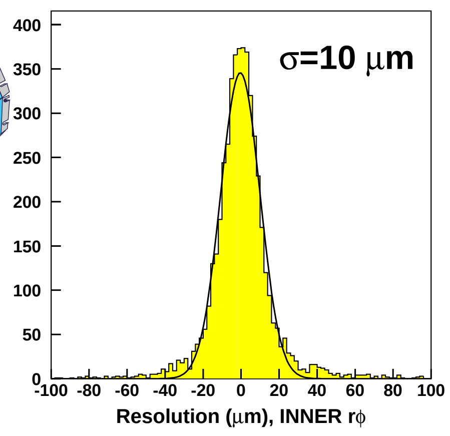
The SM Higgs: b-tagging at LEP2

L3 Silicon Microvertex Detector

$\Delta\text{vertex} \simeq 30\ \mu\text{m}$

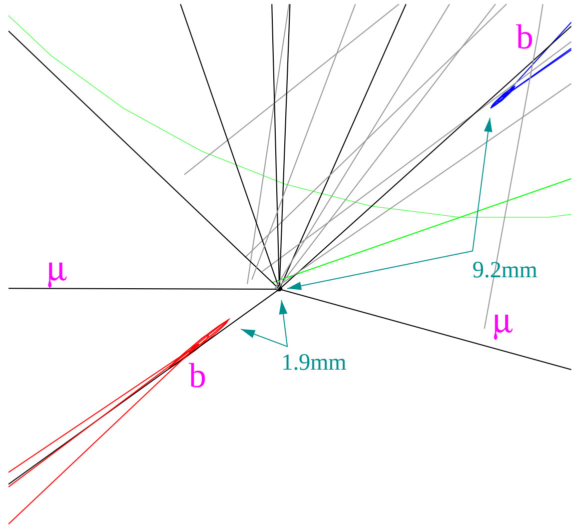
$\Delta L \lesssim 400\ \mu\text{m}$





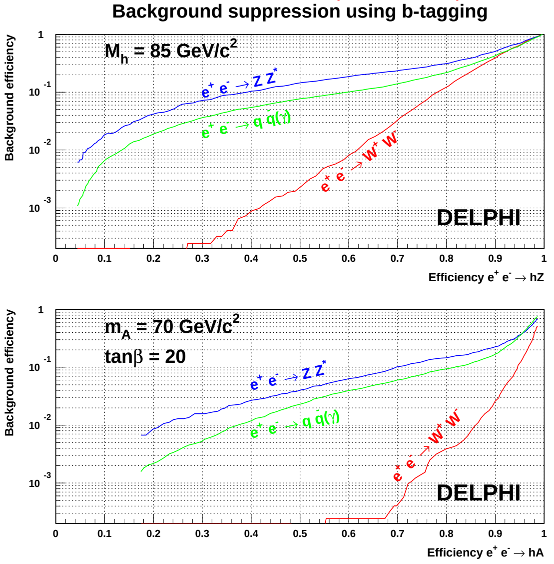
The SM Higgs: b-tagging at LEP2

At the interaction point ($\mathrm{b\bar{b}}\mu^+\mu^-$ candidate)

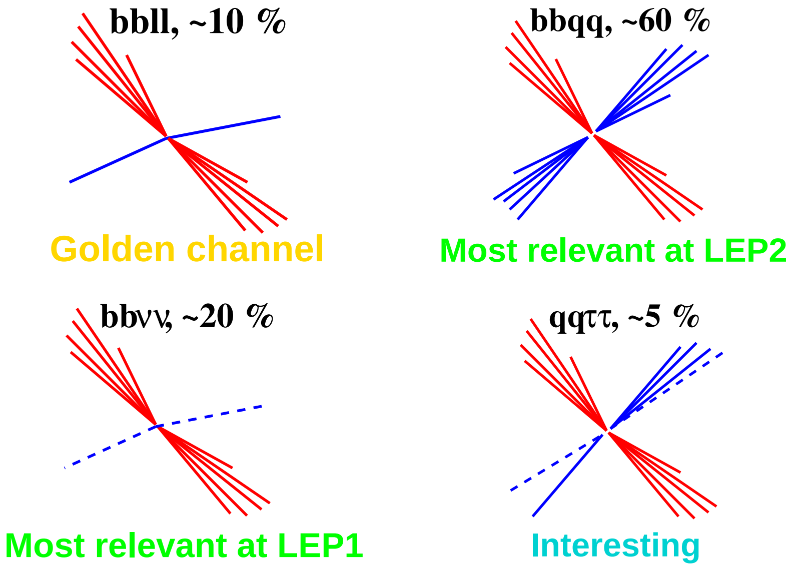


The SM Higgs: b-tagging at LEP2

Best performance (DELPHI)

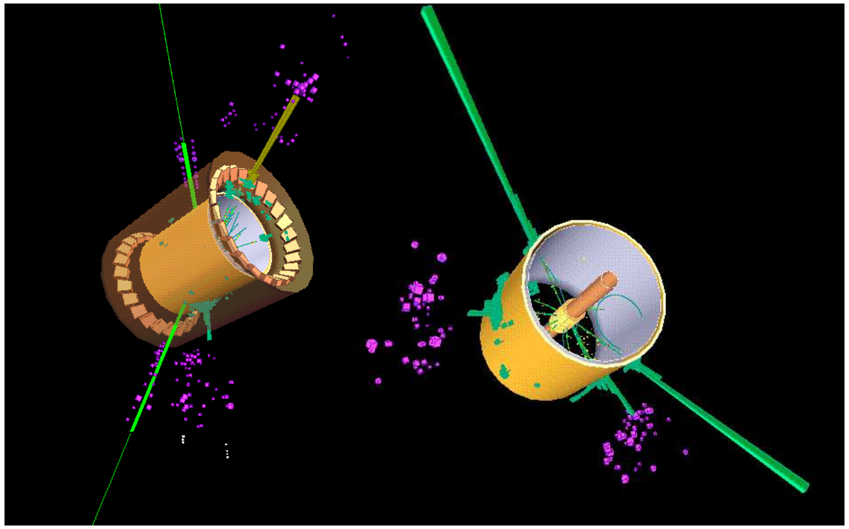


The SM Higgs: Experimental Signatures



The SM Higgs at LEP2: $HZ \to b\bar{b}e^+e^-$ and $HZ \to b\bar{b}\mu^+\mu^-$

Typical $b\bar{b}\mu^+\mu^-$ candidate   Typical $b\bar{b}e^+e^-$ candidate



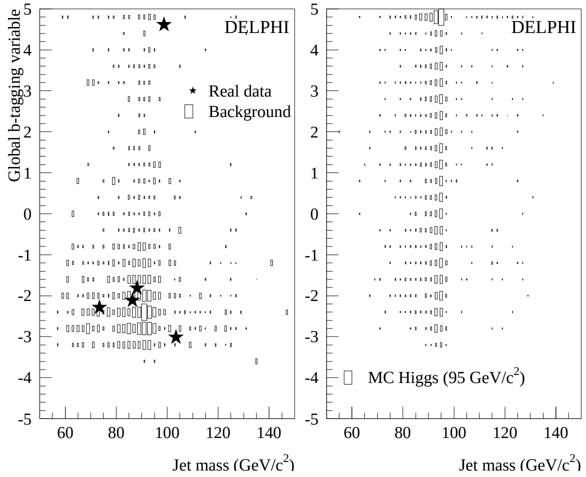
The SM Higgs at LEP2: $HZ \to b\bar{b}e^+e^-$ and $HZ \to b\bar{b}\mu^+\mu^-$

Signal

- 2 hadronic jets (b-tag helpful)
- 2 high momentum leptons
- Kinematic fit: invariant masses consistent with m_Z and m_H
- BR $\sim 5\%$

Main Backgrounds

- $ZZ \to q\bar{q}\ell^+\ell^-$



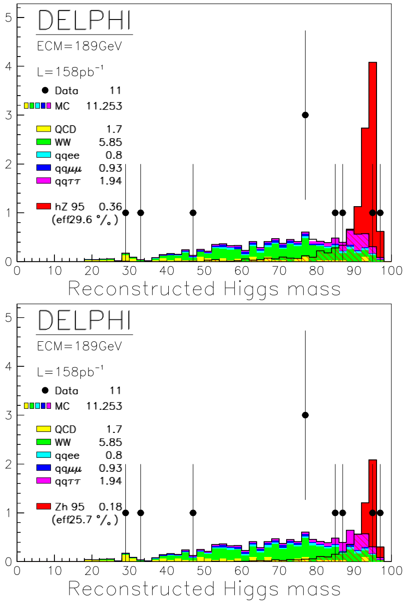
The SM Higgs at LEP2: $HZ \to b\bar{b}\tau^+\tau^-$ and $HZ \to \tau^+\tau^- q\bar{q}$

Signal

- 2 jets
- 2 isolated taus: low multiplicity jets or leptons
- For $HZ \to b\bar{b}\tau^+\tau^-$:
  - b-tag; $m_{\tau^+\tau^-} \simeq m_Z$
  - BR $\sim 3\%$
- For $HZ \to \tau^+\tau^- q\bar{q}$:
  - No b-tag; $m_{q\bar{q}} \simeq m_Z$
  - BR $\sim 5\%$

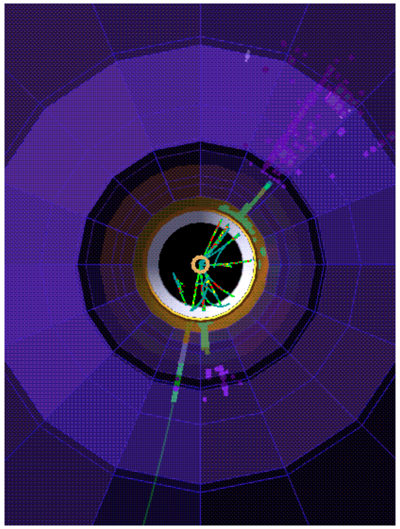
Main Backgrounds

- $WW \to q\bar{q}\ell\nu$
- $ZZ \to q\bar{q}\ell\ell$

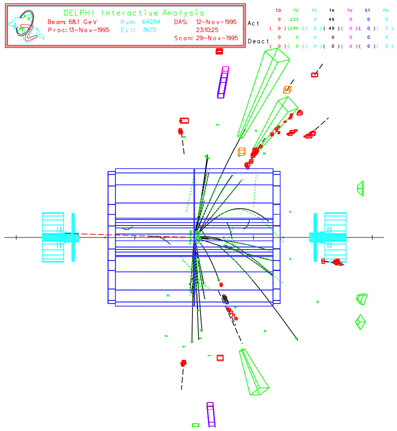


The SM Higgs at LEP2: $HZ \to b\bar{b}\nu\bar{\nu}$

$b\bar{b}\nu\bar{\nu}$ candidate



Typical background



Recoil to the Z

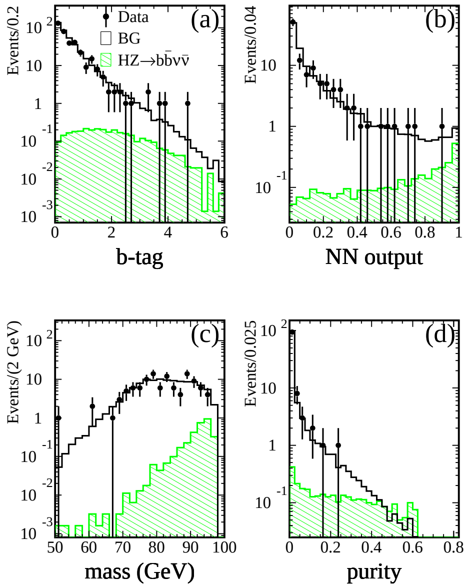
The SM Higgs at LEP2: $HZ \to b\bar{b}\nu\bar{\nu}$

Signal

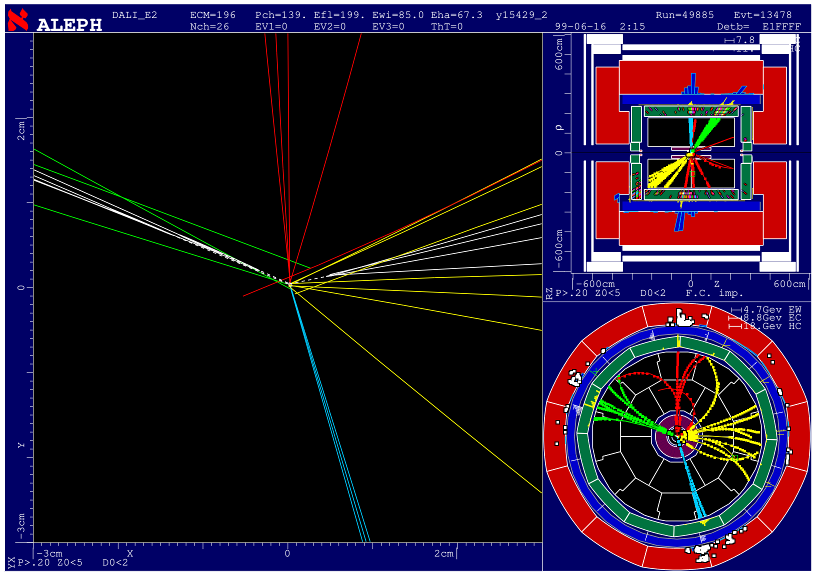
- 2 acoplanar hadronic jets
- Large missing energy
- b-tag
- Missing mass consistent with m_Z
- BR $\sim 20\%$

Main Backgrounds

- $q\bar{q} + \gamma$
- $WW \to q\bar{q}\tau\nu$
- $ZZ \to q\bar{q}\nu\bar{\nu}$



The SM Higgs at LEP2: $HZ \to b\bar{b}q\bar{q}$



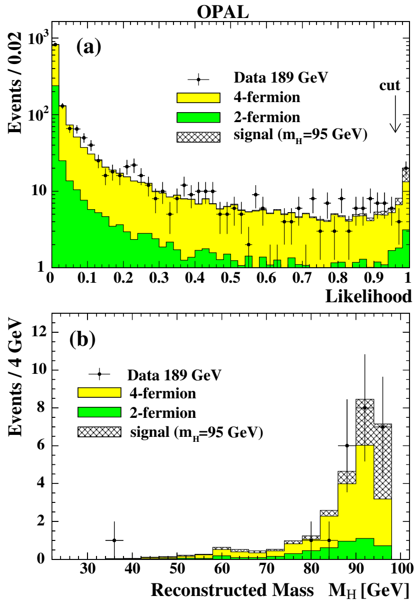
The SM Higgs at LEP2: $HZ \to b\bar{b}q\bar{q}$

Signal

- 4 hadronic jets
- No missing energy, balanced momentum
- b-tag
- Kinematic fit: invariant masses consistent with m_Z and m_H
- BR $\sim 60\%$

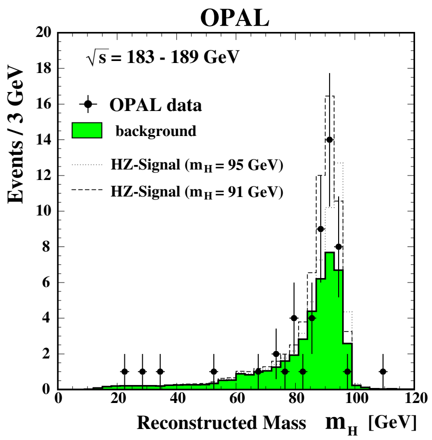
Main Backgrounds

- $q\bar{q}+$ hard gluons, $4q$
- WW $\to$ hadrons
- ZZ $\to$ hadrons

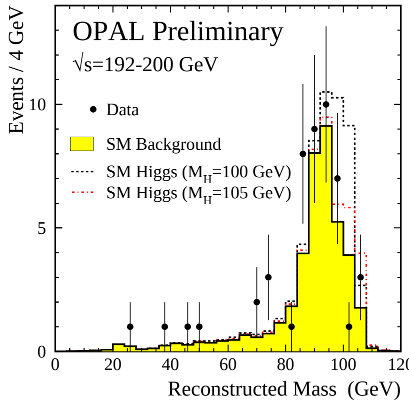


The SM Higgs: Final Mass distributions from OPAL

LAST YEAR



THIS YEAR



The SM Higgs: Limits and LEP Higgs Working Group Conventions

Let us consider an oversimplified scenario (N observed events, B expected background events, $S \equiv S(m_H)$ expected signal for m_H):

$$CL_{S+B} = \sum_{i=0}^{N} \frac{(S+B)^i}{i!} e^{-(S+B)}$$

is the classical probability of finding N or less events under the assumption of a signal S for m_H

$$CL_B = \sum_{i=0}^{N} \frac{B^i}{i!} e^{-B}$$

is the classical probability of finding N or less events under the assumption of no Higgs signal at all

$$CL_S \equiv \frac{CL_{S+B}}{CL_B}$$

is the Bayesian (prior flat distribution) probability of having a Higgs signal at m_H if we observe N or less events

The SM Higgs: Limits and LEP Higgs Working Group Conventions

Aim of the LEP Higgs Working Group: combine all LEP Higgs search results

Definition of exclusion region at the 95% CL

$$CL_S(m_H) < 5\%$$

Set of all m_H points such that if there is a real Higgs signal there, we would miss it in less than 5% of the cases ($\simeq 2$ standard deviations)

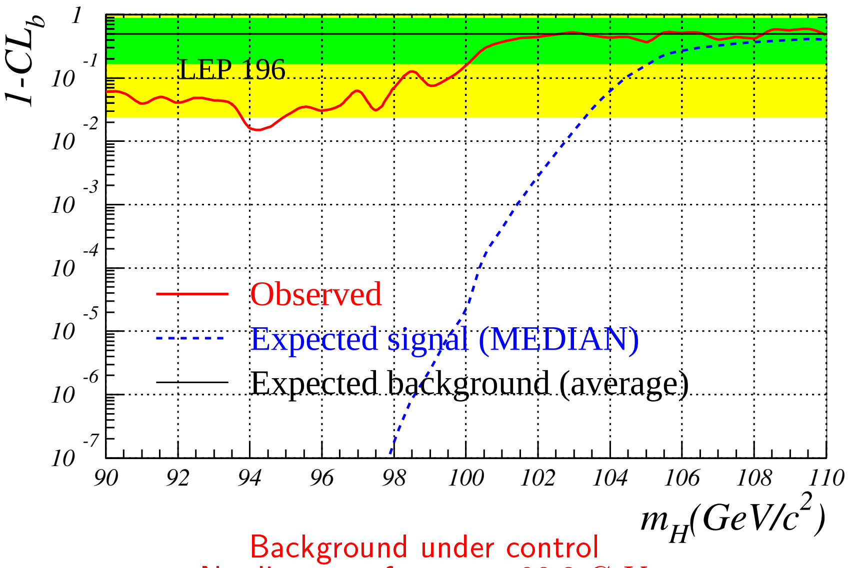
Definition of discovery for m_H

$$1 - CL_B(m_H) < 5.7\ 10^{-7}$$

The observation of N events or more is inconsistent with the background expectations at more than 5 standard deviations

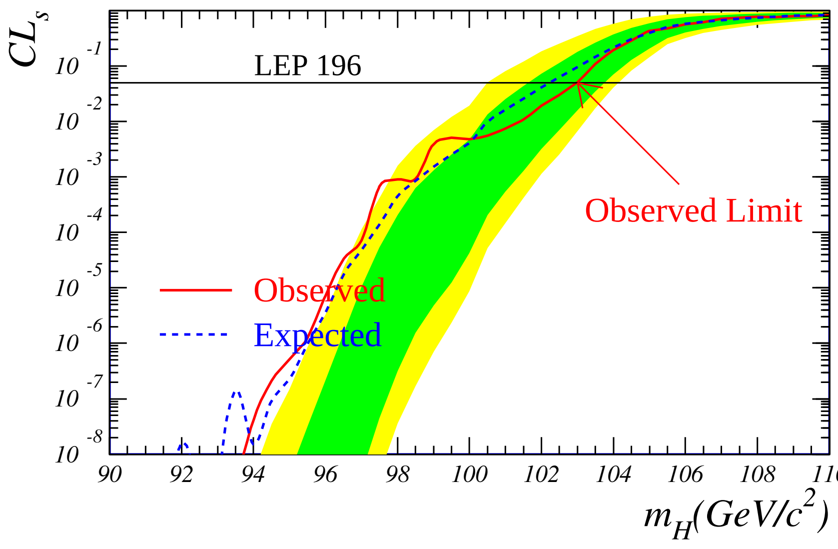
Note: Discovery Limit < Exclusion Limit

Use of CL_B



Background under control
No discovery for $m_{\mathrm{H}} < 98.3$ GeV

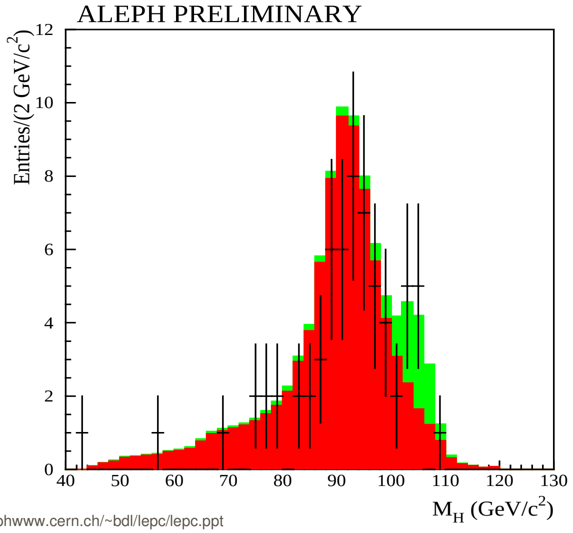
Use of CL_S



$m_{\mathrm{H}} > 102.6$ GeV at 95% CL

The SM Higgs: Latest news at $\sqrt{s} \geq 200$ GeV

What would be the shape of a 105 GeV signal?



http://alephwww.cern.ch/~bdl/lepc/lepc.ppt

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The SM Higgs: Latest news at $\sqrt{s} \geq 200$ GeV

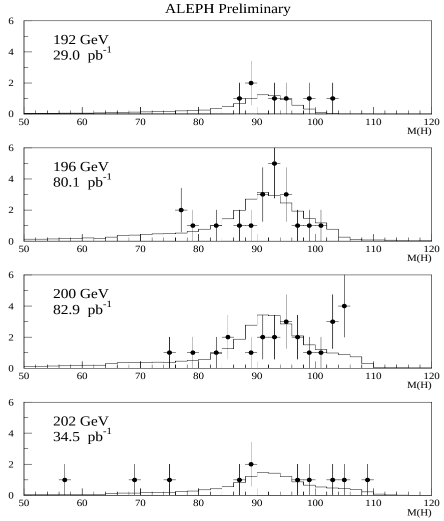
SM Higgs 1999: mass plots per energy

191.6 GeV

195.5 GeV

199.5 GeV

201.6 GeV



http://alephwww.cern.ch/~bdl/lepc/lepc.ppt

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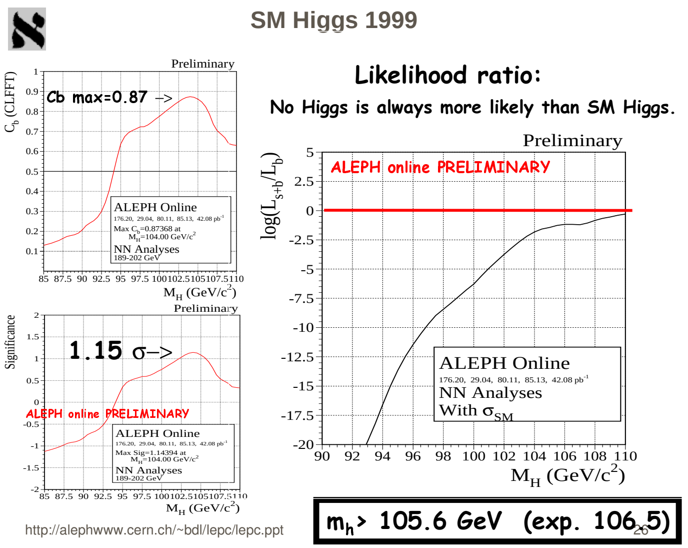
The SM Higgs: Latest news at $\sqrt{s} \geq 200$ GeV



Two Higgs Doublet Models

Many extensions of the SM predict the existence of two Higgs doublets, Φ_1 and Φ_2. After symmetry breaking only five physical states remain:

- Two neutral scalars h, H
- One neutral pseudoscalar A
- Two charged scalars $\mathrm{H}^{\pm}$

Important quantities:

- Ratio of vacuum expectation values: $\tan\beta = \frac{v_2}{v_1}$
- Mixing angle for $(\Phi_1, \Phi_2) \to (\mathrm{H}, \mathrm{h})$: α

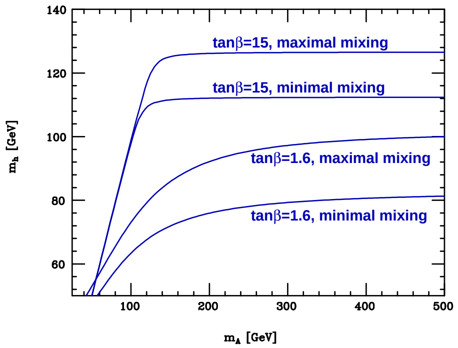
Higgs couplings:

- $g_{\mathrm{hVV}} = \sin(\beta - \alpha)\ g^{SM}_{\mathrm{HVV}}$
- $g_{\mathrm{HVV}} = \cos(\beta - \alpha)\ g^{SM}_{\mathrm{HVV}}$
- g_{ZhA}, g_{ZHA}, $g_{\mathrm{ZH^+H^-}}$ couplings exist
- Couplings to fermions of Type I: $\cos(\alpha) = 0 \Rightarrow$ fermiophobia
- Couplings to fermions of Type II (MSSM): $(\Phi_1 \to \mathrm{u},\ \Phi_2 \to \mathrm{d}, \ell)$

MSSM

Two Higgs doublet models of type II: MSSM

- Higgs sector completely determined by two parameters: $\tan\beta$ and m_{A}:
  - Standard Model recovered for $m_{\mathrm{A}} \to \infty$, $\tan\beta \to 1$
  - Theoretically motivated ranges: $1 \lesssim \tan\beta \lesssim 3$, large $\tan\beta$.
- $m_{\mathrm{h}} \leq m_{\mathrm{Z}} |\cos 2\beta|$ at tree-level
- Predictions largely affected by mixing in the $(\tilde{\mathrm{t}}, \tilde{\mathrm{b}})$ sector
- $m^2_{\mathrm{H}^\pm} = m^2_{\mathrm{A}} + m^2_{\mathrm{W}}$ at tree-level



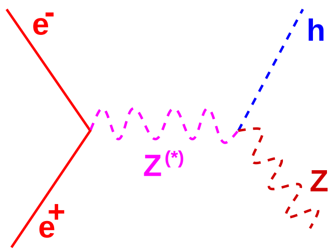
$m_{\mathrm{h}} \lesssim 130$ GeV
Interesting for LEP !!

MSSM: Target processes at LEP

MSSM h, A decay branching ratios

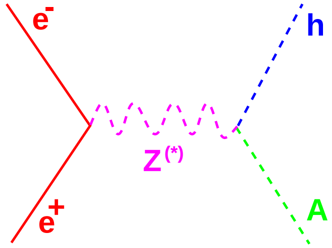
- Typical values: $\sim 90\%$ to $\mathrm{b\bar{b}}$ and $\sim 8\%$ to $\tau^+\tau^-$
- Possibility of dominant invisible decays to $\chi^0_1\chi^0_1$

$$\mathrm{e^+e^- \to hZ}$$



- $\sigma_{MSSM} = \sin^2(\beta - \alpha)\ \sigma_{SM}$
- Experimental Search $\approx$ SM search

$$\mathrm{e^+e^- \to hA}$$

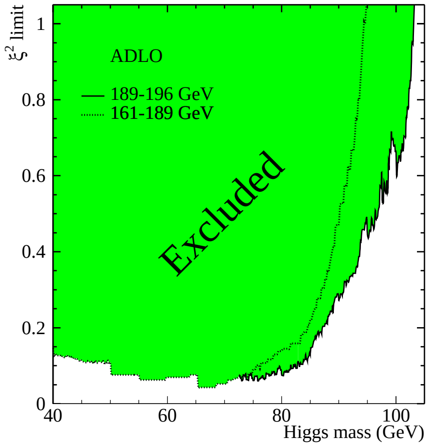


- $\sigma_{MSSM} = \lambda \cos^2(\beta - \alpha)\ \sigma_{SM}$
- Experimental signatures: $\mathrm{b\bar{b}b\bar{b}}$, $\mathrm{b\bar{b}}\tau\tau$

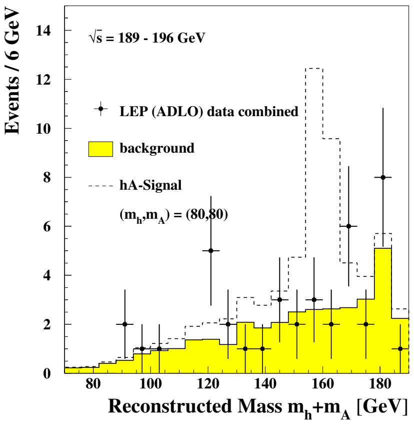
MSSM Higgses: Combined LEP limits

Limit on:

$$\xi^2 = \frac{\sigma(e^+e^- \to HZ)}{\sigma_{SM}}$$



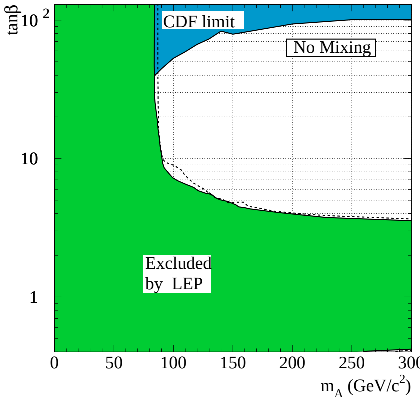
Combined Mass Plot for:
$e^+e^- \to HA$



MSSM: m_H and m_A

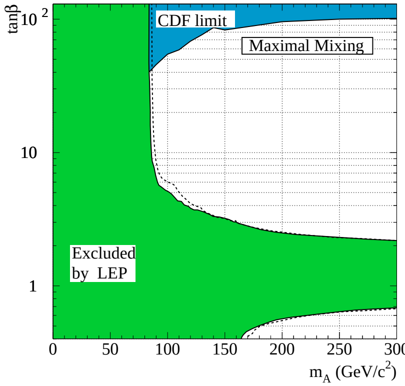
Minimal Mixing

$m_A > 84.7$ GeV at 95% CL



Maximal Mixing

$m_A > 84.5$ GeV at 95% CL

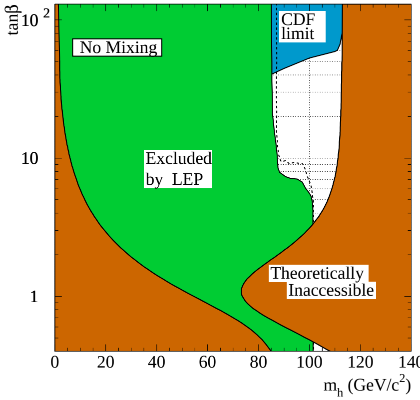


MSSM: m_H and m_A

Minimal Mixing

$m_h > 84.5$ GeV at 95% CL

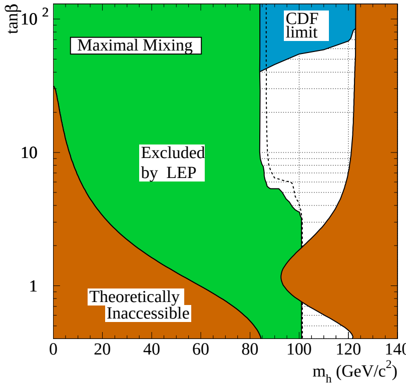
$0.5 < \tan\beta < 3.2$ excluded



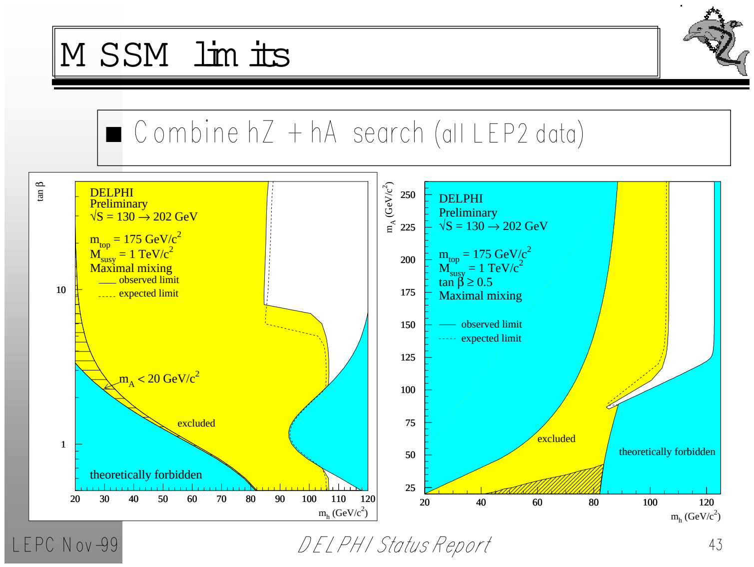
Maximal Mixing

$m_h > 84.3$ GeV at 95% CL

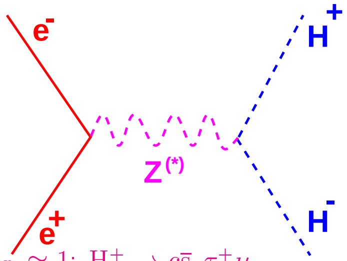
$0.8 < \tan\beta < 1.9$ excluded



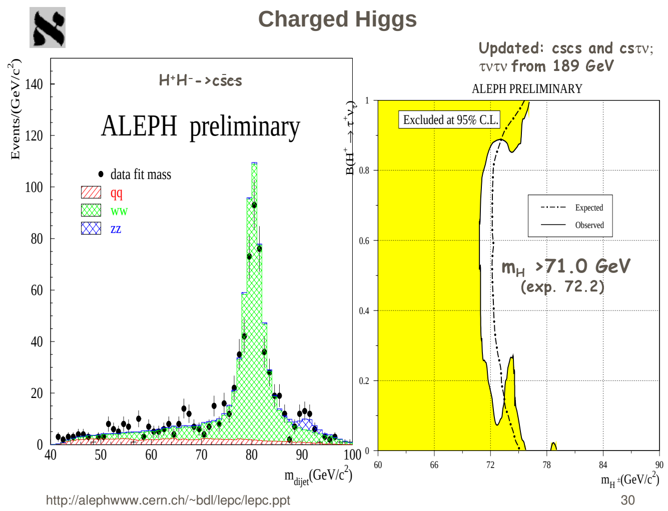
MSSM Higgs: Latest news at $\sqrt{s} > 189$ GeV



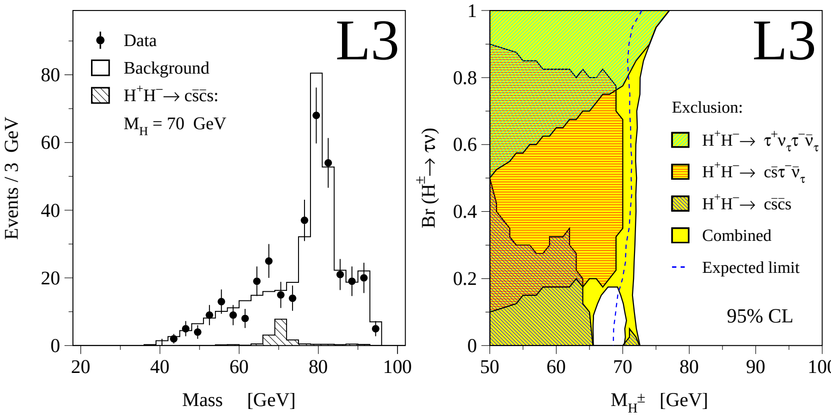
$m_{H^\pm} < m_W$ is possible in extensions of the MSSM (NMSSM)



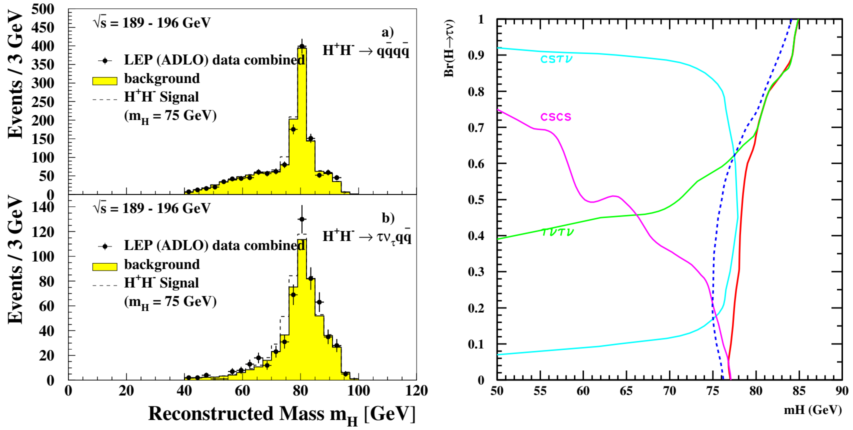
- Experimental assumptions:
  - Produced by pairs in $e^+e^- \to H^+H^-$
  - Decays into the heaviest $f\bar{f}'$ pair with $V_{ff'} \approx 1$: $H^+ \to c\bar{s}, \tau^+\nu_\tau$
  - $BR(H^+ \to \tau^+\nu_\tau)$ is left as a free parameter
- Analysis methods borrowed from WW analysis
  - $e^+e^- \to c\bar{s}\bar{c}s$: $\sum E_i = \sqrt{s}$, $\vec{p} = 0$ and $m_{H+} = m_{H-}$ $\Rightarrow$ 5 constraints
  - $e^+e^- \to cs\tau\nu_\tau$: ν missing, E_τ unavailable $\Rightarrow$ 1 constraint
  - $e^+e^- \to \tau^+\nu_\tau\tau^-\bar{\nu}_\tau$: no constraints are possible
  - Main background: $e^+e^- \to WW$



L3 at $\sqrt{s} = 189$ GeV ; published

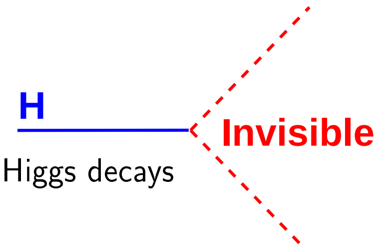


$\sqrt{s} = 189 - 196$ GeV, all LEP combined



$m_{H^\pm} > 77$ GeV, 95% CL

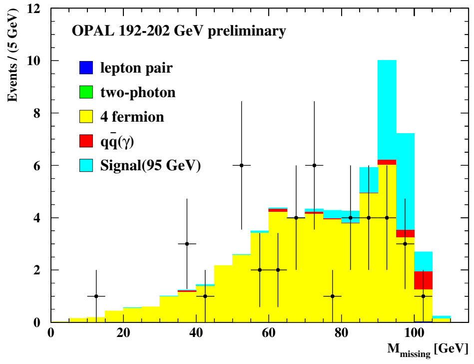
Invisible Higgs Decays

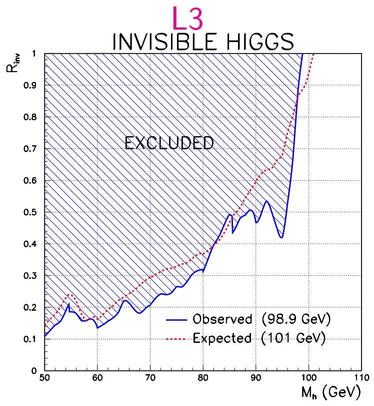


- Several scenarios with invisible Higgs decays
  - Scalar singlet S with $m_S < \frac{1}{2} m_h$: $h \to SS$
  - MSSM when the LSP is light enough: $h \to \chi\chi$
  - Models with majorons (J): $h \to JJ$
- Experimental Search
  - Higgs-strahlung process: $e^+e^- \to HZ$, $Z \to q\bar{q}$
  - Similar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

Invisible Higgs Decays

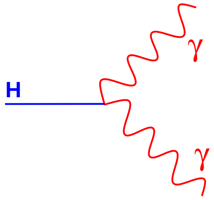
No invisible Higgs decays observed



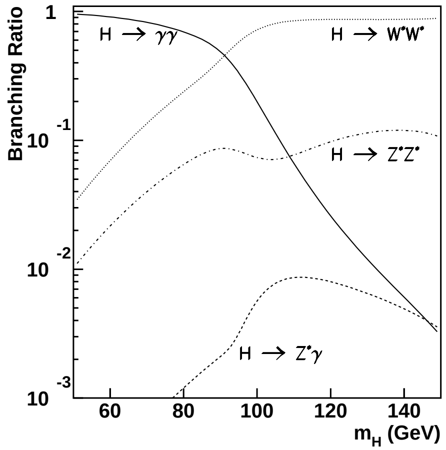


Present 95% CL Limit > 100 GeV

A fermiophobic Higgs?



- Some scenarios with fermiophobic Higgses:
  - Two Higgs Doublet Models of type I with $\alpha = \frac{\pi}{2}$
  - Some models with Higgs triplets
  - Anomalous couplings modifying HVV couplings

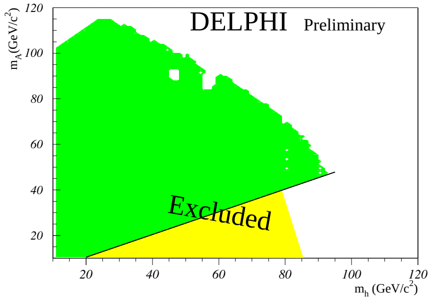


"Standard" fermiophobic model

$H \to \gamma\gamma$ dominant for $m_H < m_Z$

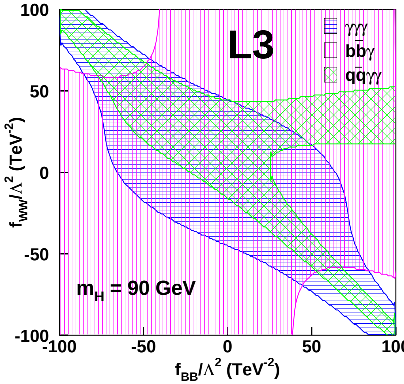
Fermiophobic Higgses

Two Higgs doublet Model



Exclusion in the m_A vs m_H plane

Anomalous Couplings



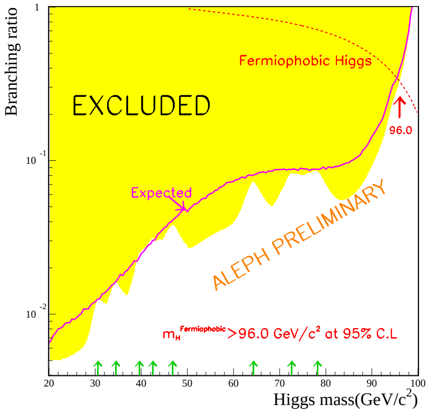
Search for the $e^+e^- \to H\gamma$ process

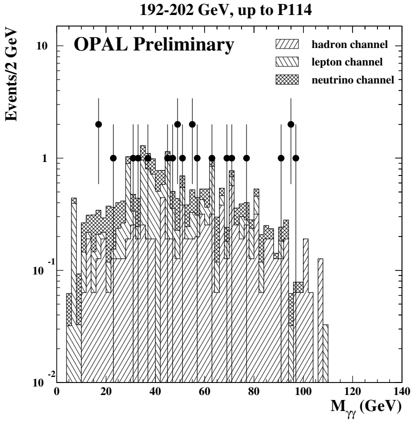
Sensitivity similar to WWV studies

Fermiophobic Higgses

"Standard" Fermiophobia

News at $\sqrt{s} \gtrsim 200$ GeV





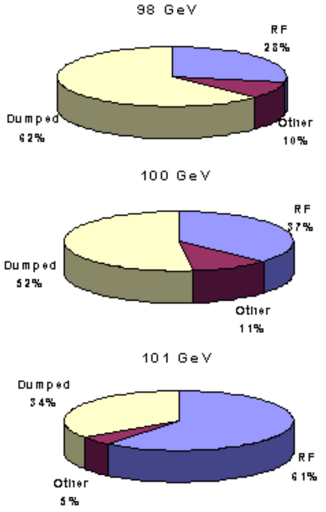
Search for $e^+e^- \to ZH \to Z\gamma\gamma$
$m_H < 96$ GeV, 95% CL

Small excess at $m_{\gamma\gamma} \simeq 100$ GeV

Next Year Plans

Coast length vs. energy

- **98 GeV**
  - Mean coast length **2h 41min**
- **100 GeV**
  - Mean coast length **2h 05min**
- **101 GeV**
  - Mean coast length **1h 38min**



LEPC November99

Next Year Plans

... and in 2000 ?

- **56 copper cavities**
  - **re-install 8 copper cavities** (adds 15-20 MV)
  - **reasonable level** **130 MV**
- **4 Solid Niobium**
  - **reasonable level** **110 MV**

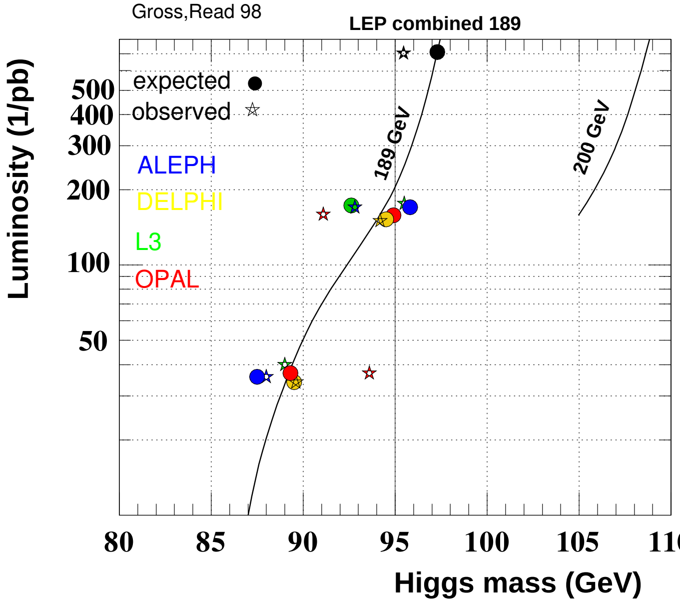
- **Total voltage (MV) needed for 1 hour quantum lifetime**
  - i_b 0.7mA, 102/90, J_x=1 (no frequency offset)
  - (Figures in parentheses are Nb film gradient in MV/m, assuming the above values for Cu and Solid Nb cavities)

	No reserve	1 klystron	2 klystrons
100 GeV	3180 (6.4)	3275 (6.6)	3370 (6.8)
101 GeV	3300 (6.6)	3395 (6.8)	3490 (7.0)
102 GeV	3430 (6.9)	3525 (7.1)	3620 (7.3)
103 GeV	3570 (7.2)	3660 (7.4)	3755 (7.6)

Have had this for extended periods
Maximum in 1999 operation
Maximum obtained in tests
Unknown territory

LEPC November99

Next Year Plans



Official Plan

Energy and luminosities:

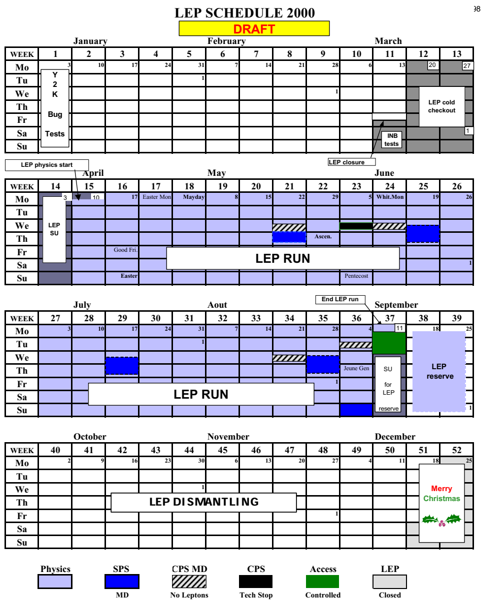
- 200 pb^{-1} at $\sqrt{s} = 202$ GeV
- At least 40 pb^{-1} at the highest energy (hope for $\sqrt{s} = 206$ GeV)

Preliminary combination of results by July 2000:

- Decision about a possible extension of LEP

If nothing happens:

- End of September: End of LEP



Conclusions

Current LEP situation

- $m_H \gtrsim \mathbf{106\ GeV}$ in the SM
- $m_h, m_A \gtrsim \mathbf{88\ GeV}$ in the MSSM
- $1 \lesssim \tan\beta \lesssim 2.2$ in the MSSM
- $m_{H^\pm} > \mathbf{77\ GeV}$
- $m_H \gtrsim \mathbf{100\ GeV}$, if invisible
- $m_H \gtrsim \mathbf{96\ GeV}$, if fermiophobic

Sensitivity by the end of LEP

- $m_H \lesssim \mathbf{113\ GeV}$ in the SM
- $m_h, m_A \lesssim m_Z$ in the MSSM
- $1 \lesssim \tan\beta \lesssim 3$ in the MSSM
- $m_{H^\pm} < m_W$
- $m_H \lesssim \mathbf{110\ GeV}$, if invisible
- $m_H \lesssim \mathbf{110\ GeV}$, if fermiophobic

More than 10 years of successful LEP running merit more than just "appreciated" precision physics:

A Higgs Discovery in 2000 !!