# Higgs Searches at LEP

André Holzner, ETH Zürich / L3 collaboration

Seminar, University of Victoria

Februrary 28 2000
Victoria, Canada

All results are still preliminary !

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André Holzner, ETH Zürich / L3 collaboration

Seminar, Lawrence Livermore National Laboratory

March 3rd 2000
Livermore, USA

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André Holzner, ETH Zürich / L3 collaboration

SLAC Seminar

March 2nd 2000
Stanford, USA

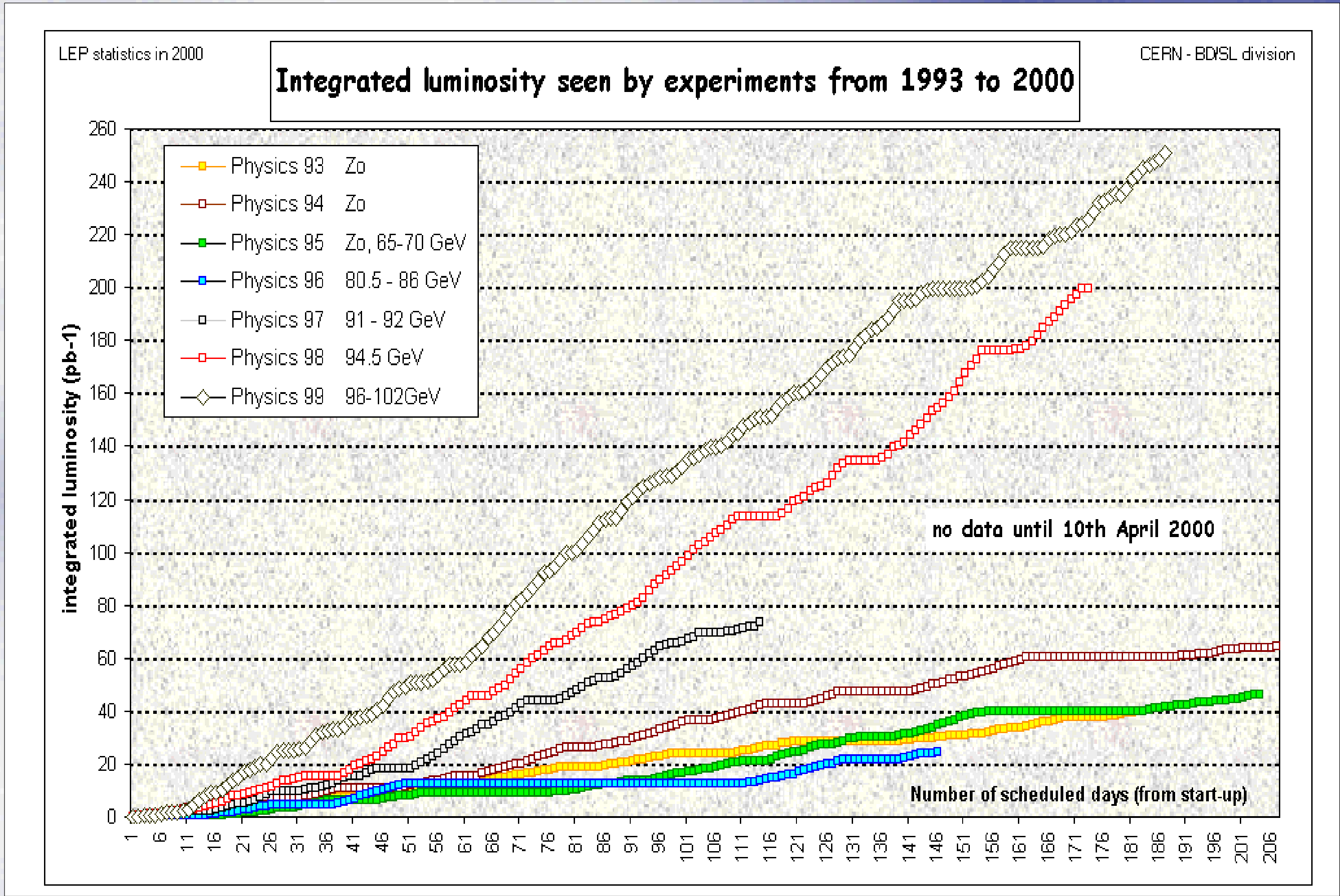
All results are still preliminary !

# Higgs Searches at LEP

Overview:

- LEP II data taking
- Motivation of Higgs Searches
- Background cross sections
- Production mechanisms at LEP, decay modes
- SM Higgs Signatures
- Results from the experiments
- MSSM Higgs production at LEP
- MSSM experimental signatures
- MSSM results
- Searches for Charged Higgs Bosons
- Invisible Higgs decays
- Fermiophobic Higgs scenario
- Conclusions and Outlook

# Lep II data taking



# Lep II data taking

| Year | CM energy | Avg. Lumi deli–vered per exp. |
|---|---|---|
| 1997 | 183 GeV | 55/pb |
| 1998 | 189 GeV | 170/pb |
| 1999 | 192 GeV | 30/pb |
| | 196 GeV | 90/pb |
| | 200 GeV | 90/pb |
| | 202 GeV | 40/pb |

Lep is performing better than ever !

# Why do we search for Higgs Bosons ?

- Standard Model of Electroweak interactions agrees extremely well with the experiments e.g.
  - anomalous magnetic moment of electrons,
  - LEP/SLC/Tevatron precision measurements of Elektroweak parameters
- Contains massive Gauge Bosons (W, Z)

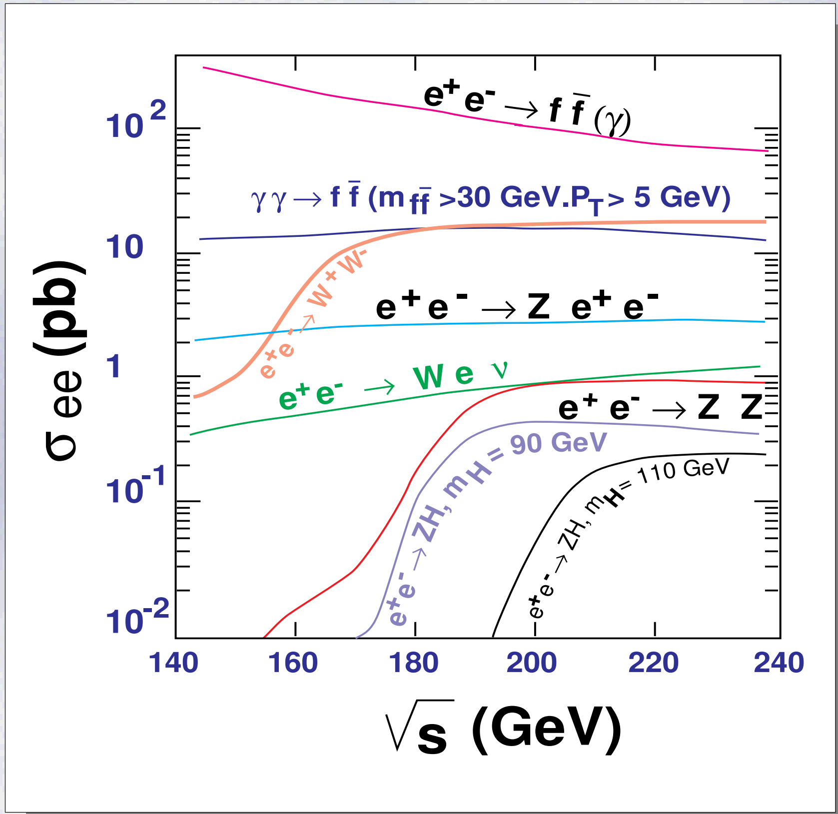
# Why do we search for Higgs Bosons ?

- $\rightarrow$ A mechanism giving masses to the Gauge Bosons and Fermions while keeping the Theory Gauge invariant is needed
- Most widely accepted Mechanism:

**The Higgs Mechanism**

- a new fundamental scalar Particle, the Higgs, of unknown mass (<1 TeV) is predicted

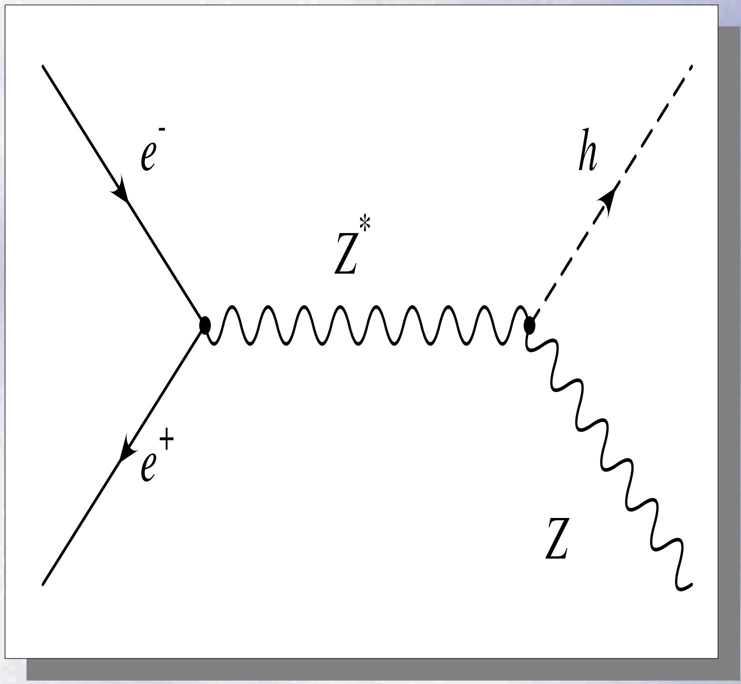
# Signal and Background cross sections



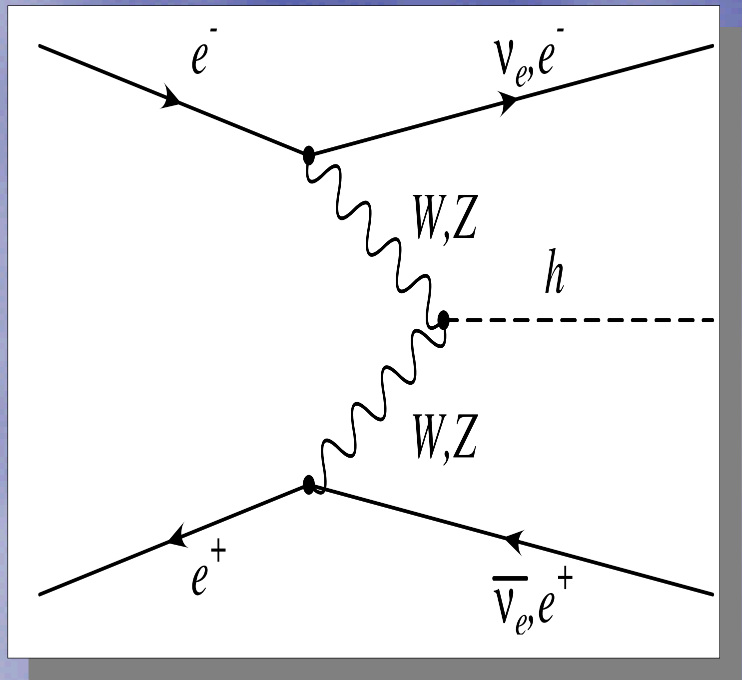

- We are looking for a small signal
- Background cross sections are up to 150 times higher

# SM Higgs Production at LEP

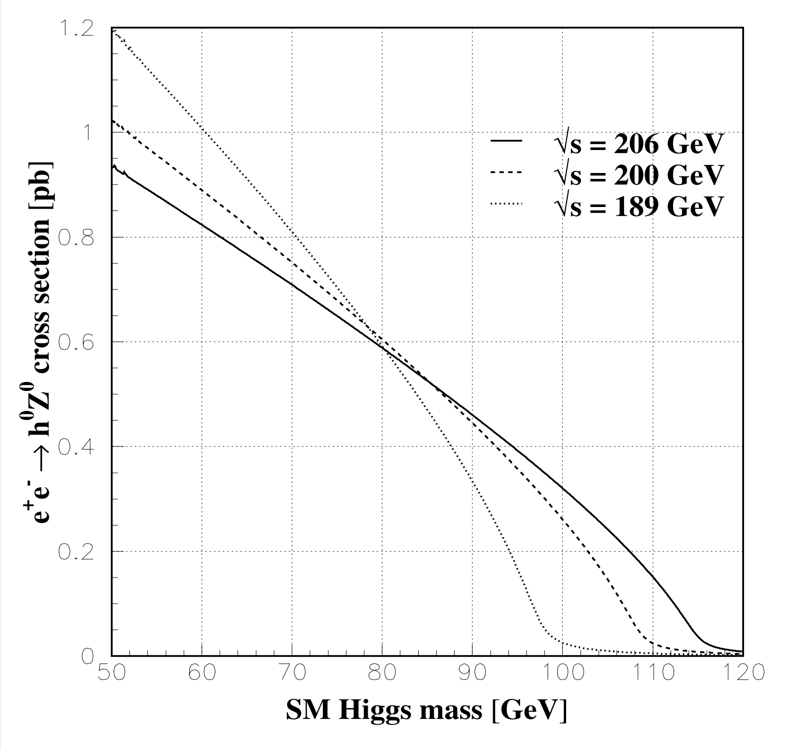
Via Higgs Strahlung:



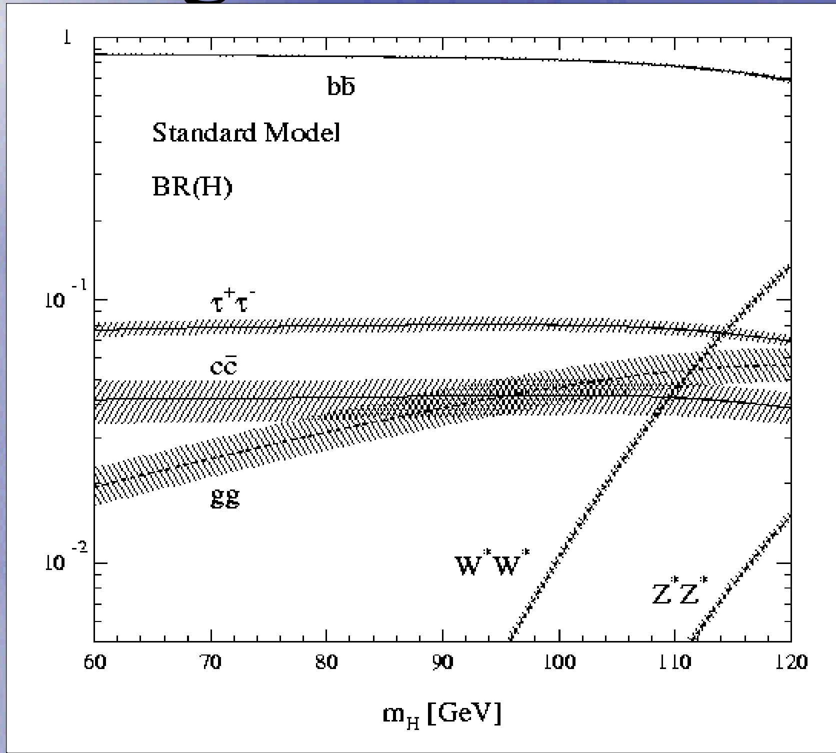

Via W/Z fusion



# $e^+e^- \to hZ$ Production cross sections and H branching ratios




Production cross sections as function of $m_h$ for different CM energies

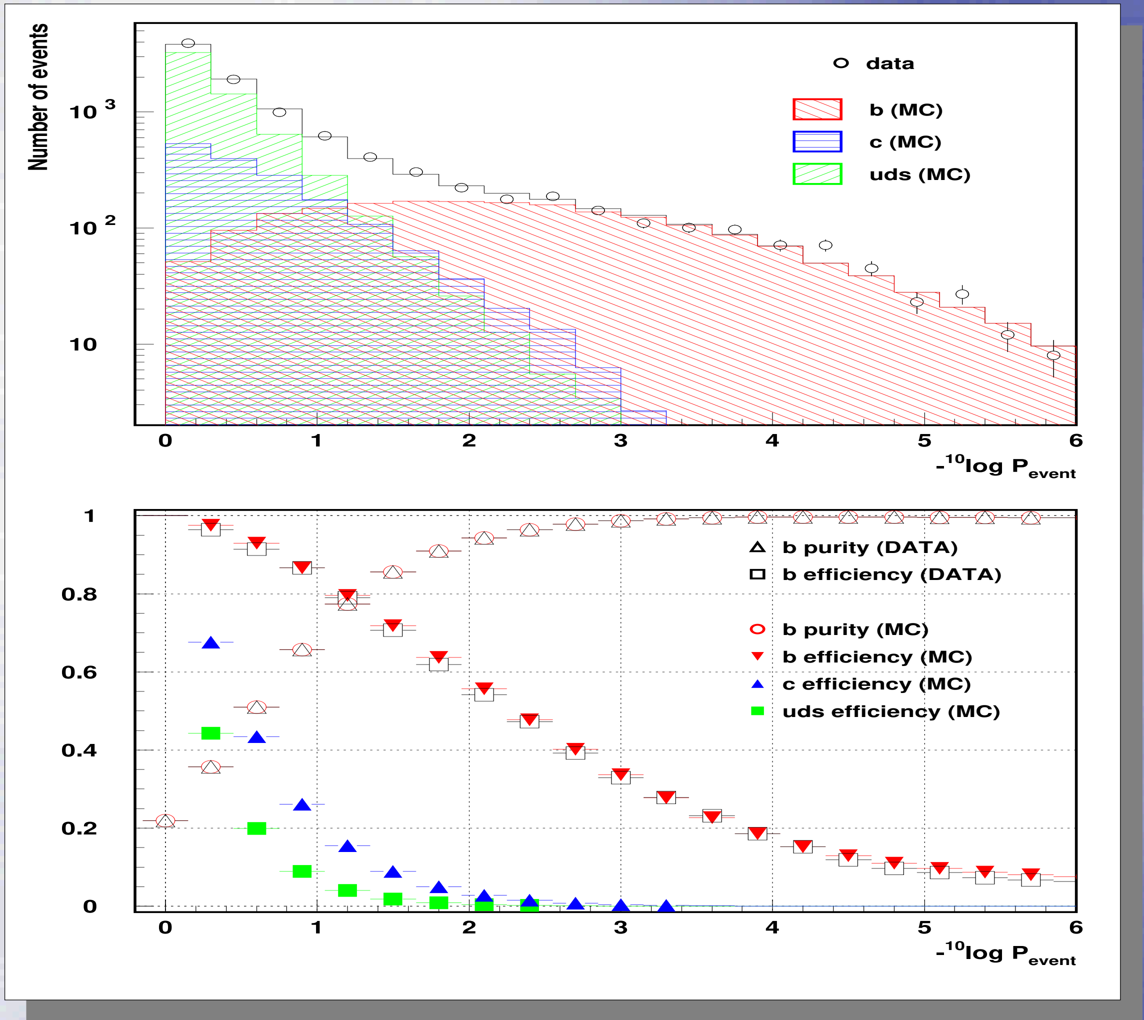



Higgs branching ratios as function of thie Higgs mass

# B Tagging

- Mostly H $\rightarrow$ bb in our accessible mass range $\rightarrow$ good B tagging is important
- Exploit features of B mesons:
  - relatively long lived $\rightarrow$ secondary decay vertices
  - Semileptonic decays $\rightarrow$ Leptons in jets
  - hard fragmentation –> fraction of high momentum tracks is higher than for ucsd quarks.
- This information is combined into a Jet tag using an Artificial Neural Network
- Jet tags are then combined into an event tag

# L3 B Tag performance



# SM Higgs signatures

$HZ \to bbqq$

Highest relative rate ($BR(Z \to qq) = 70\%$)
but also highest background:
$WW \to qqqq$, $ZZ \to qqqq$, $e^+e^- \to qq(gg)$

$HZ \to bb\nu\nu$

Second highest statistics channel
($BR(Z \to \nu\nu) = 20\%$)
most important backgrounds:
$ZZ \to qq\nu\nu$, $e^+e^- \to qqe\nu$

$HZ \to bbll$

Small statistics channel ($BR(Z \to l\,l) = 10\%$)
most important backgrounds:
$ZZ \to l\,l\,qq$, very clean ! Higgs Mass
reconstruction possible from leptons

# SM Higgs signatures

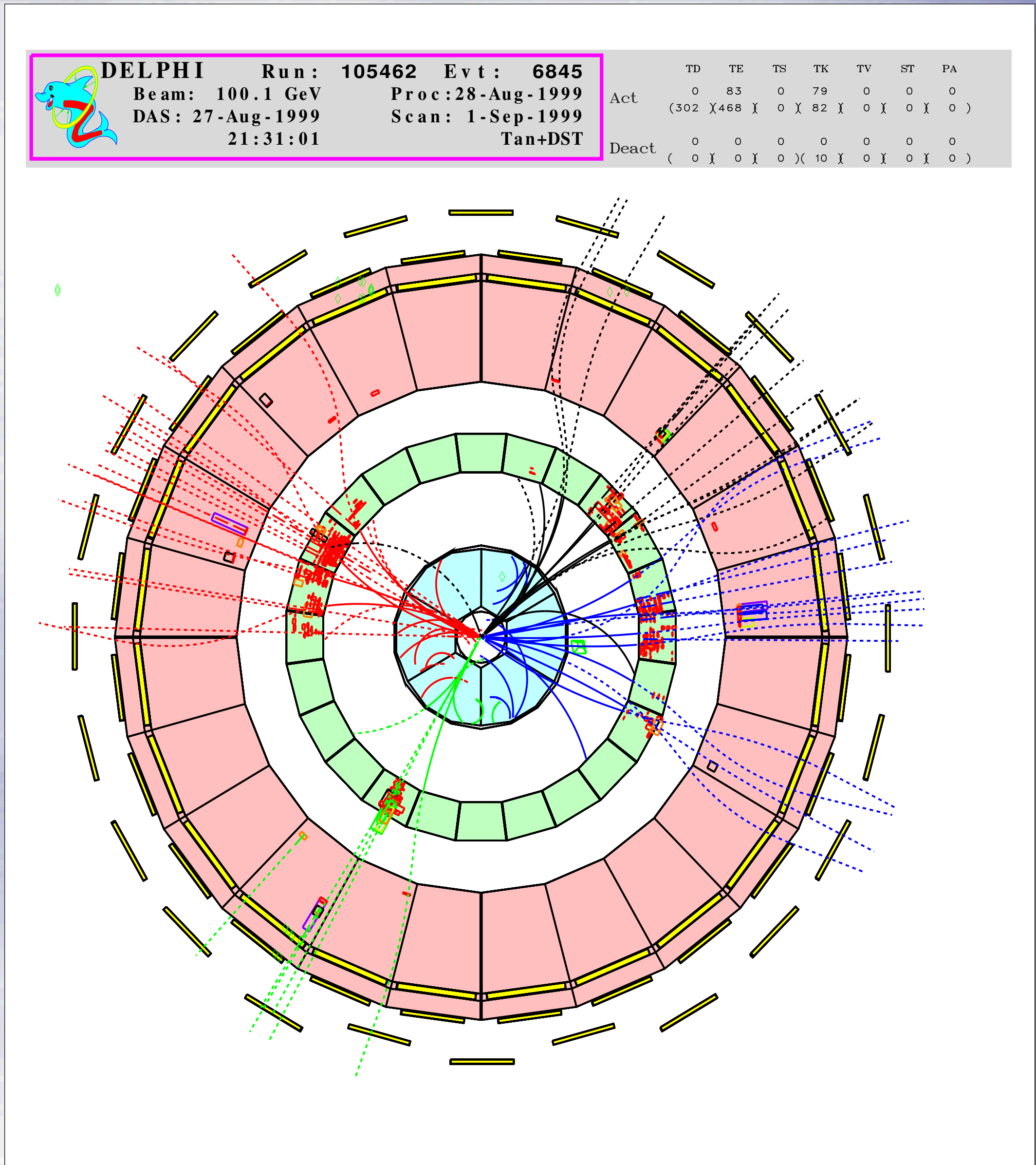
$HZ \to \tau\tau qq$

Small statistics channel ( ~6% of hZ decays)
overlap with $bb\tau\tau$ channel, lower B tag

Total coverage: 98% of hZ decays

# Analysis procedure

- The Analyses are split into
  - a Preselection, to check the quality of the data
  - a construction of a final variable
- Examples of final variables:
  - Mass distribution
  - Combination of probability of observing a higher B tag value and probability of observing a worse mass matching (for the current mass hypothesis)
  - Neural Network Output, based on event shape, multiplicity and B tag variables; combined with mass information



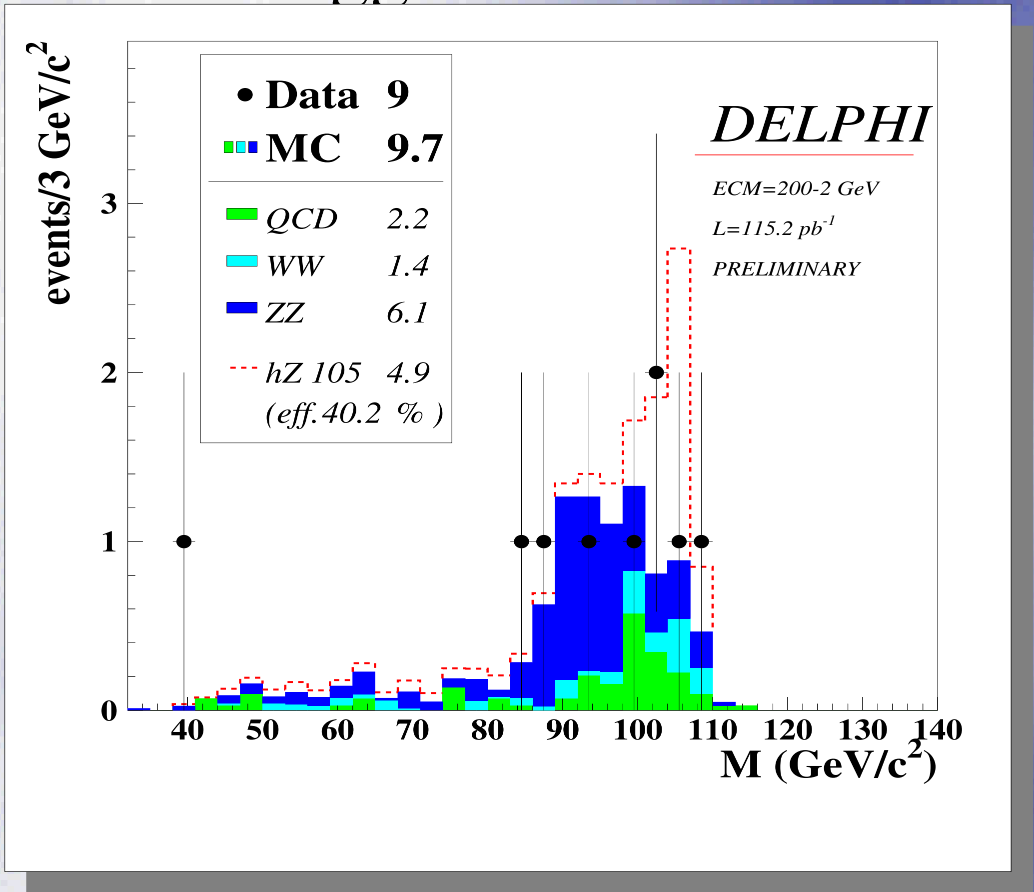

# Delphi HZ → Four jets candidate

Reconstructed Higgs mass:

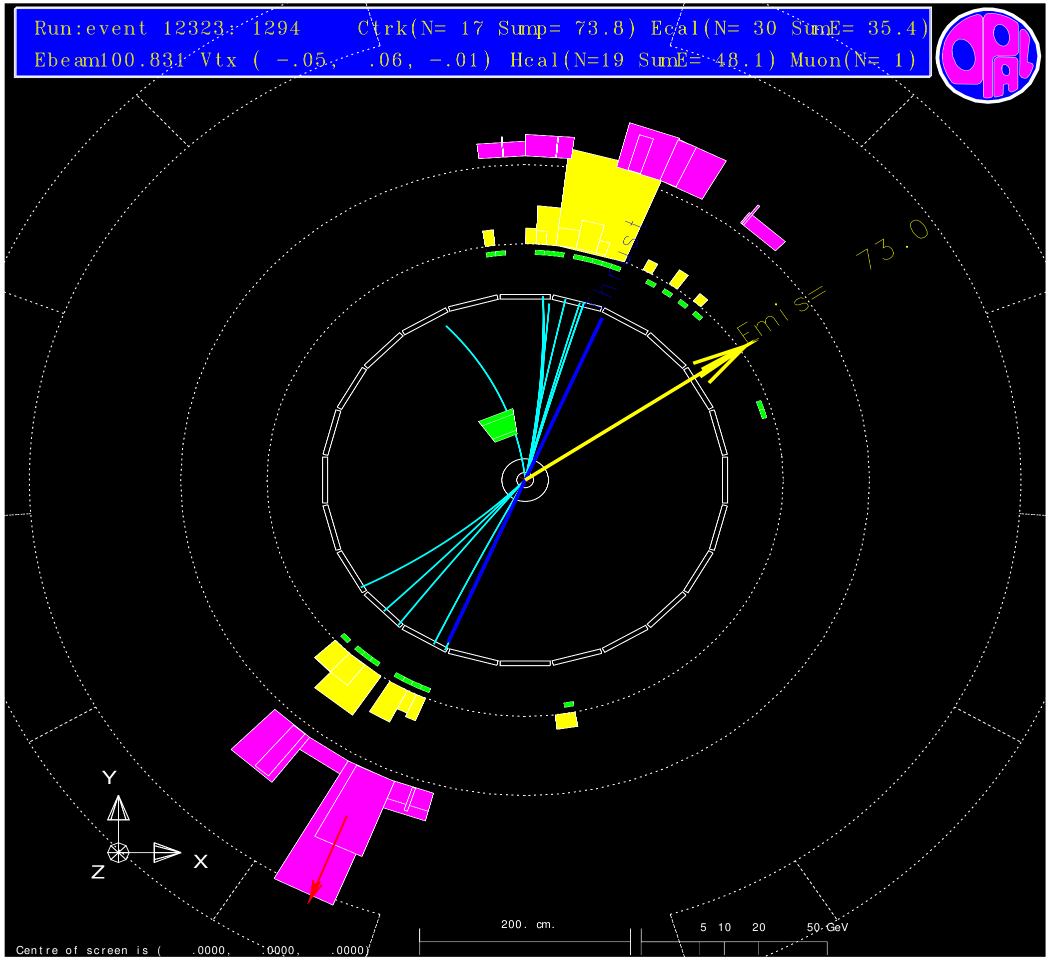
97.5 GeV

# Delphi HZ → Four jets channel

- Reconstructed Higgs mass



# HZ → qqνν candidate




Reconstructed Higgs mass:

106.9 GeV

# HZ $\rightarrow$ qq$\nu\nu$ channel

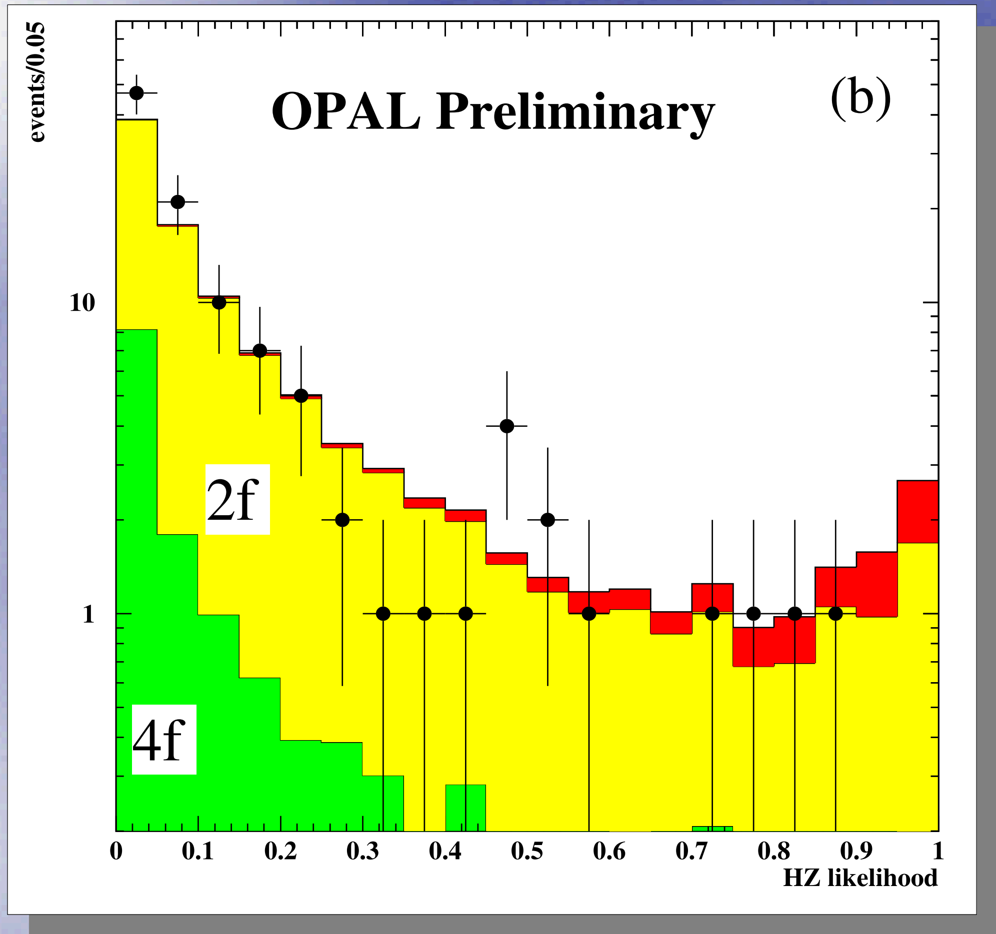
- Construction of the final variable:
  - Likelihood method, i.e. $F = P_1(x_1) \cdot P_2(x_2) \cdot \ldots \cdot P_n(x_n)$

    where $$P_i(x_i) = \frac{S_i(x_i)}{S_i(x_i) + B_i(x_i)}$$

    where $S_i(x_i), B_i(x_i)$ = prob. density functions of variable $x_i$ for signal and background
  - Neural Network output (mostly mass independent), combined with mass information

# Opal HZ → qqνν channel

- Example of a final variable distribution:



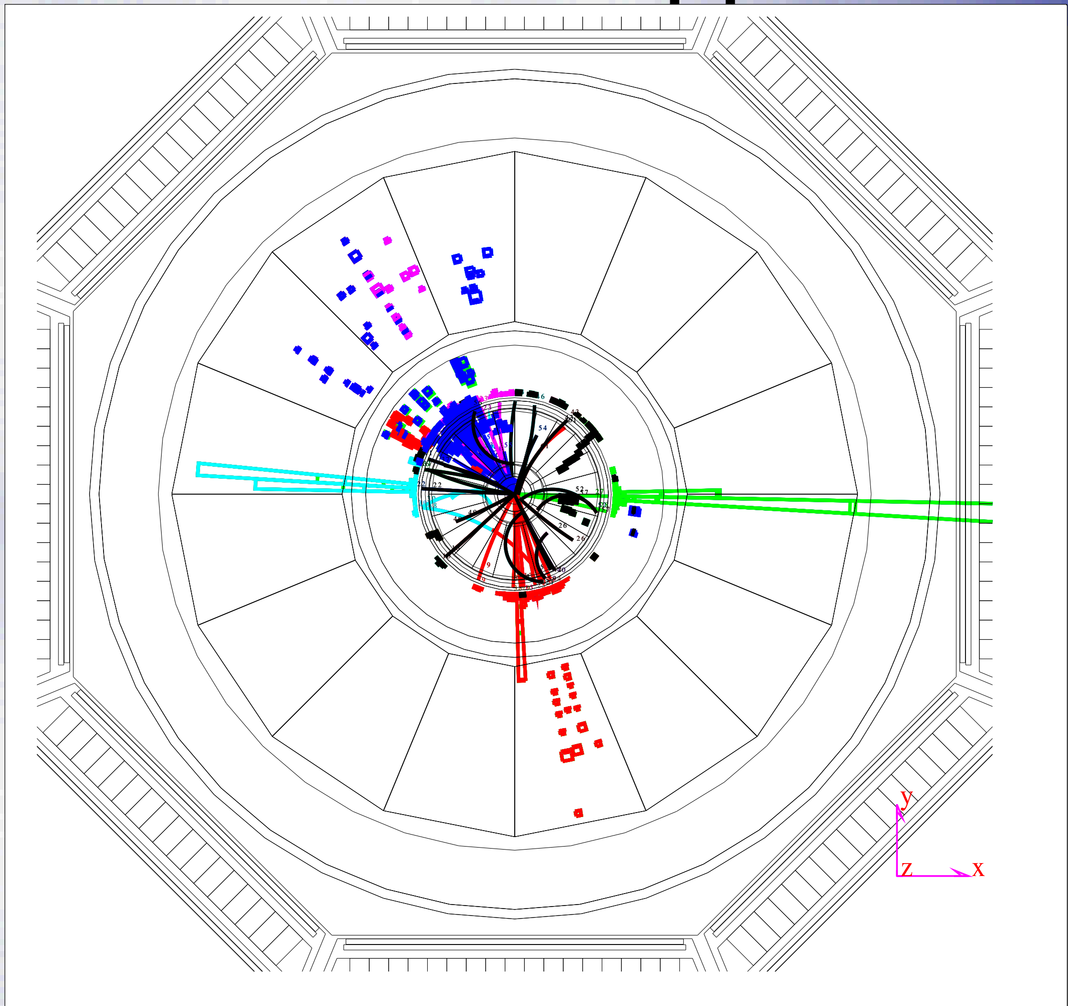

- number of events after cut:

| Signal (mh=100 GeV) | Background | Observed Data |
|---|---|---|
| 3.4 | 8.7 | 5 |

# HZ $\rightarrow$ qq l l channel

- Hadronic preselection
- Identification of two leptons
- Kinematic cuts on the dilepton system
- Final variable is a likelihood combination of the jet B tags and the reconstructed mass

# L3 HZ → qq l l candidate

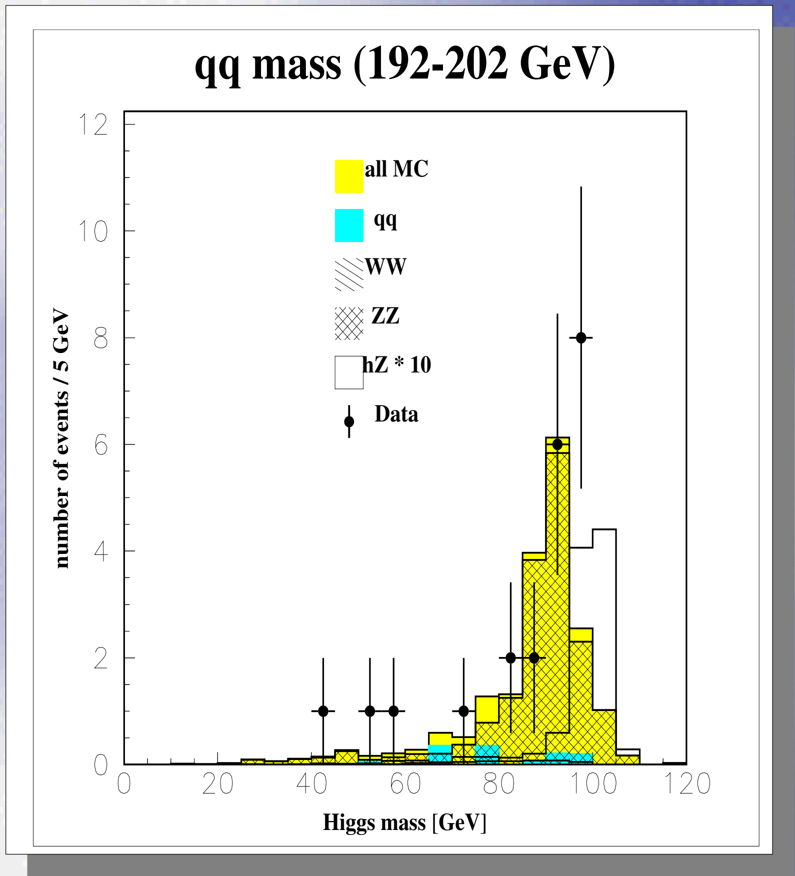



Reconstructed Higgs mass:

100.1 GeV

# L3 HZ → qq l l channel

- Reconstructed mass distribution (L3 preliminary):



# Combining the individual channels

- No indication of a signal
  $\rightarrow$ we set lower limits on the Higgs mass
  at 95% CL:

| | Aleph | Delphi | L3 | Opal |
|---|---|---|---|---|
| Expected (med.) Limit [GeV] | 106.6 | 105.9 | 105 | 102.0 |
| Observed Limit [GeV] | 105.6 | 106.2 | 103 | 102.0 |

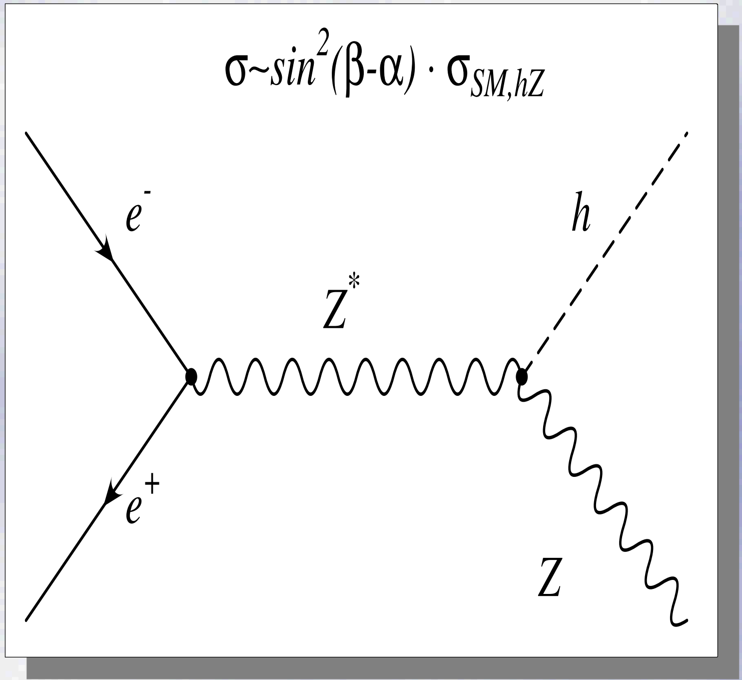
(note that different experiments analyzed different luminosities)

# Searches for MSSM Higgs Bosons

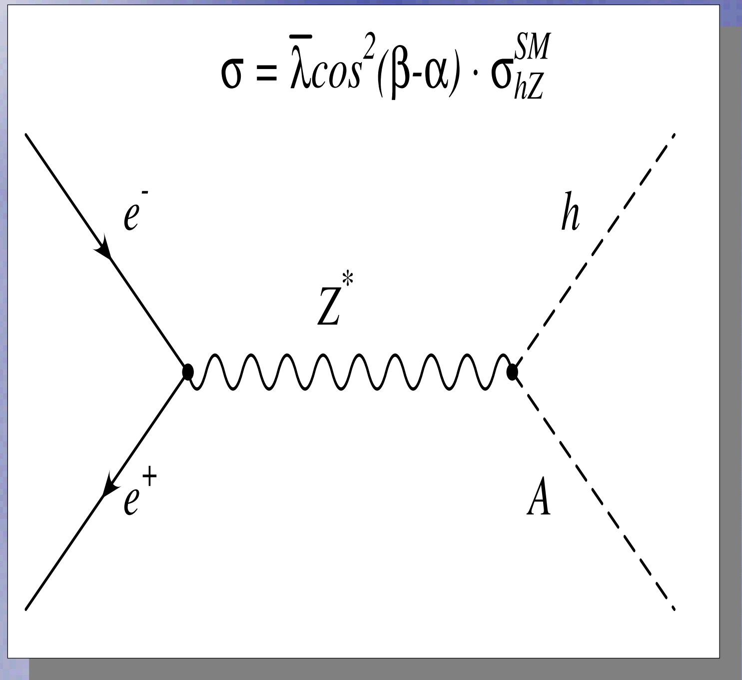
- Minimal Supersymmetric Standard Model (MSSM): Predicts five scalar Higgs Bosons:
  - two CP even Higgs Bosons h and H
  - a CP odd Higgs Boson A
  - two charged Higgs bosons $H^+, H^-$

# MSSM Higgs Production at LEP

Production of hZ




Production of hA

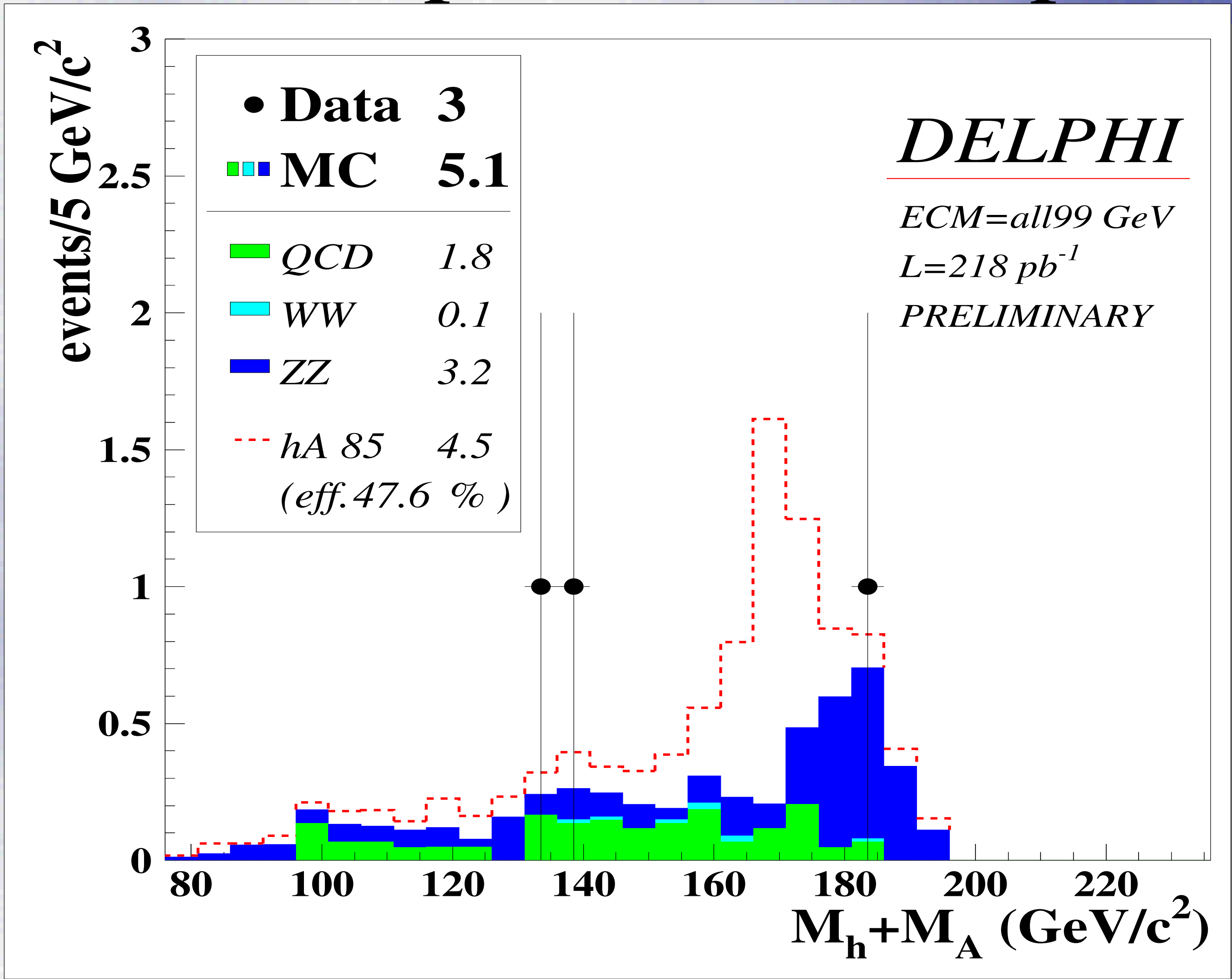



Complementary Processes !

# Experimental signatures

- Zh decays: The same as for the SM !
- For $\tan\beta \geq 1$, h and A decay mainly into b quarks and $\tau\tau \rightarrow$ the following signatures are distinguished
  - bbbb channel
  - $bb\tau\tau$ channel

# Delphi hA Mass Spectrum




No signal seen

# Constrained MSSM

- Gaugino Mass parameter $m_2$ and scalar fermion mass $m_0$ are set to 1 TeV
- Top quark mass is taken to be 175 GeV
- Two benchmark scans over tan β and $m_A$:

Minimal mixing:
 scalar quark mixing mass 0 GeV
 Higgs mass parameter –0.1 TeV

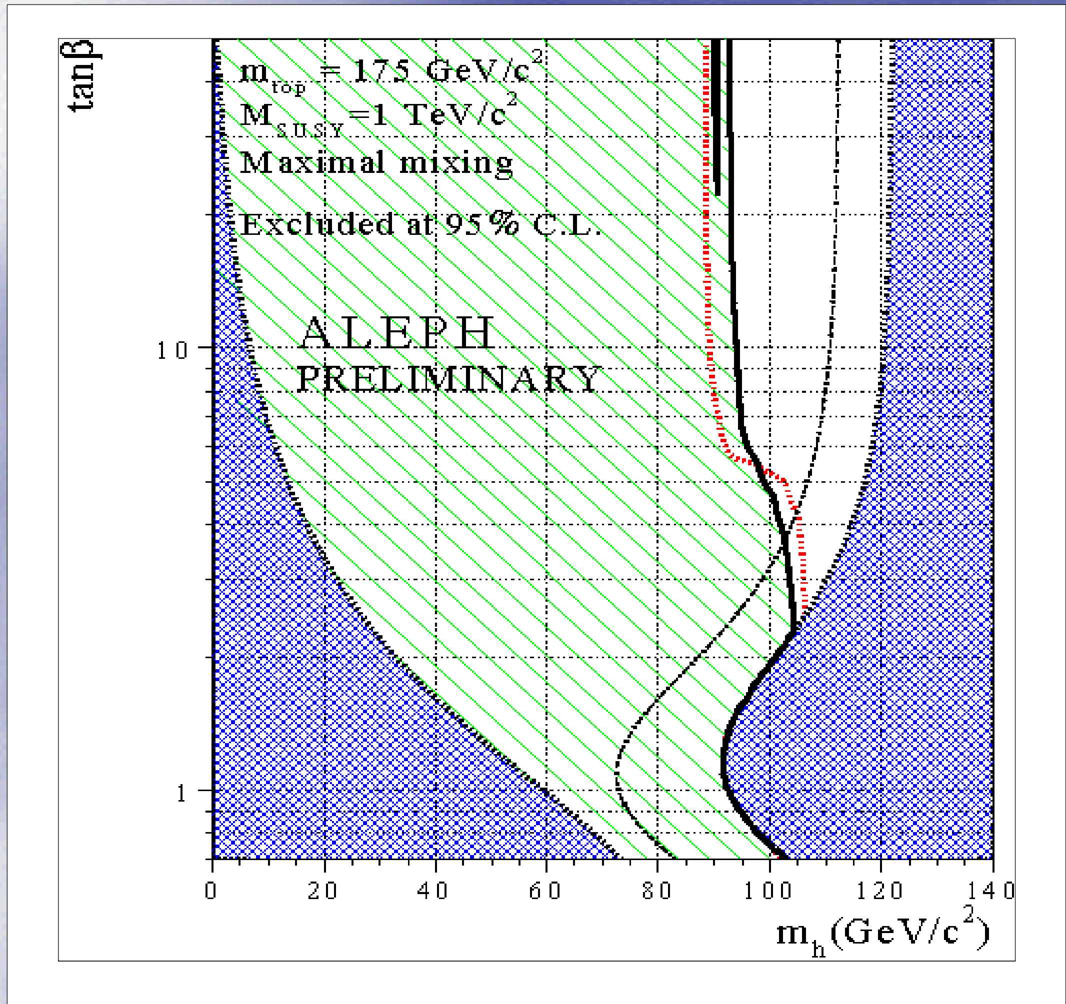
Maximal mixing:
 scalar quark mixing mass √6 TeV
 Higgs mass parameter –0.1 TeV

# MSSM parameter scan results

Maximal mixing:
(most conservative
scan)

**$m_h$ > 89.9 GeV**

**(exp: 88.3)**



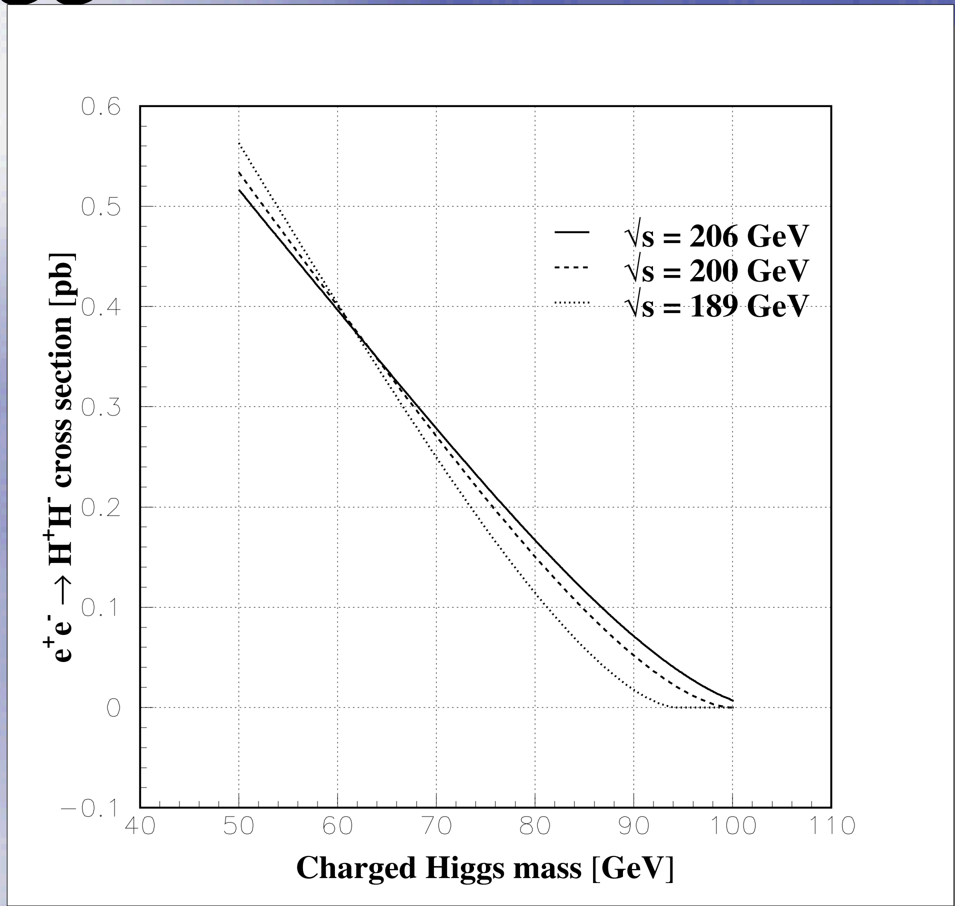
# Searches for charged Higgs Bosons

- MSSM: Charged Higgs Bosons are heavier than the W
- In General Two Doublet Models (G2DM), the Charged Higgs Bosons can also be lighter than the W
- Charged Higgs decays mainly into heaviest possible quark or lepton pair, i.e.
  - $H^+ \to c\bar{s}$
  - $H^+ \to \tau\nu$

$\to$Three different channels:
cscs, cs$\tau\nu$ and $\tau\nu\tau\nu$

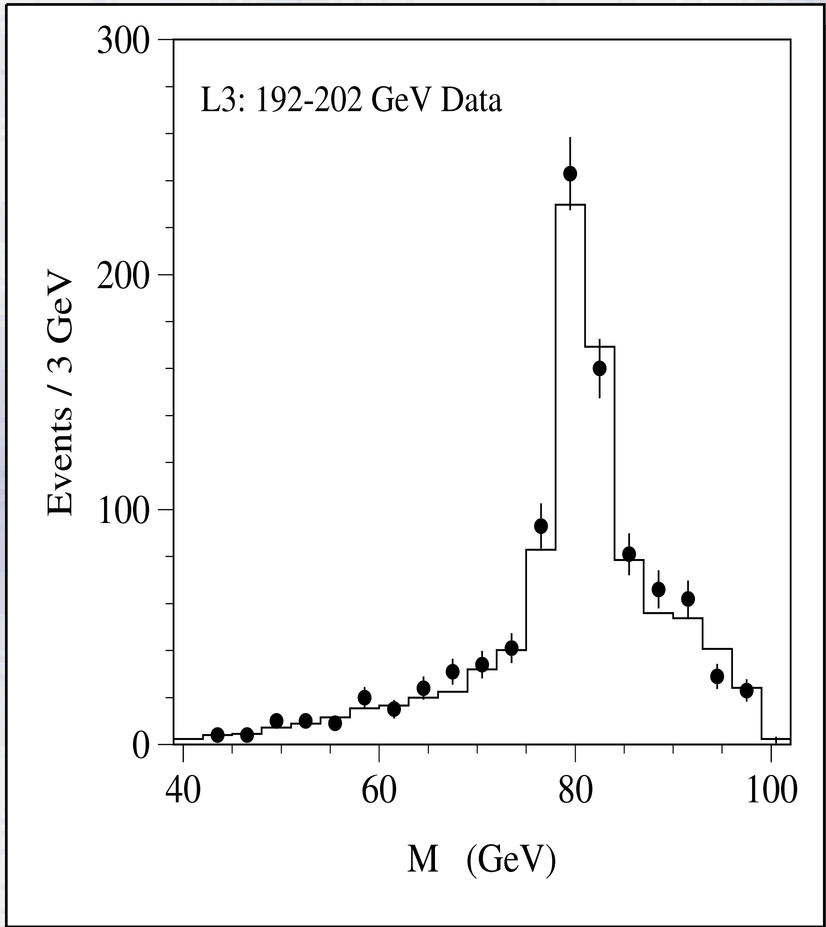
# Charged Higgs cross section

- Cross section for $H^+H^-$ pair production
- Large background from WW production !
- Charged Higgs is very similar to a W Boson

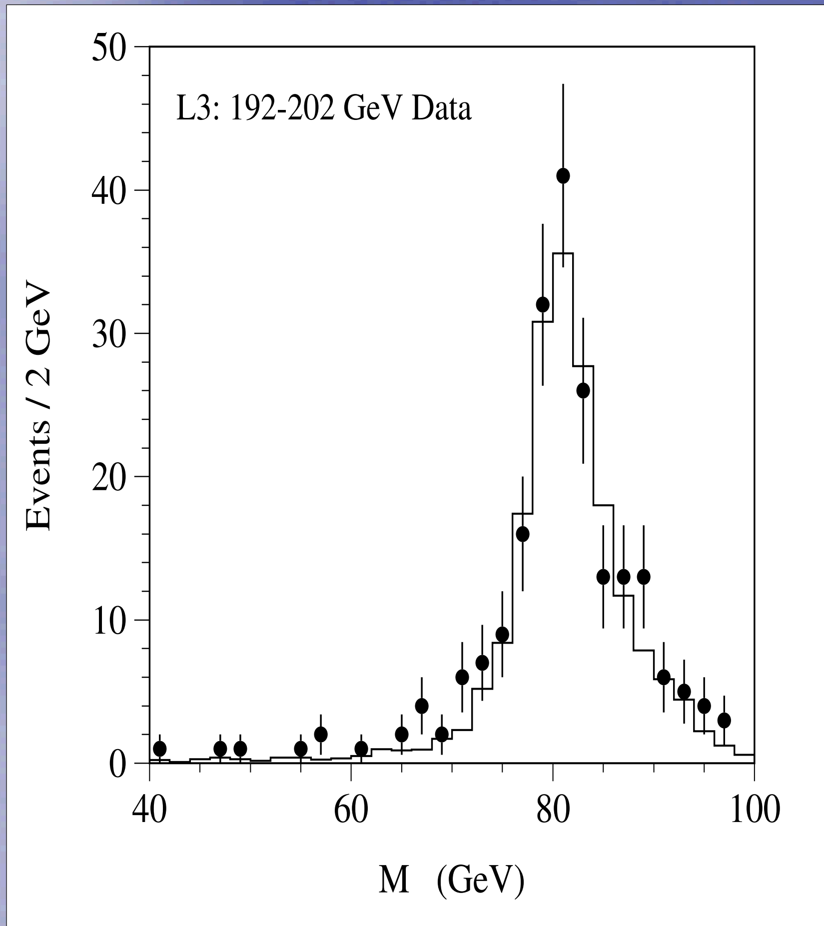


# Invariant mass spectra

cscs

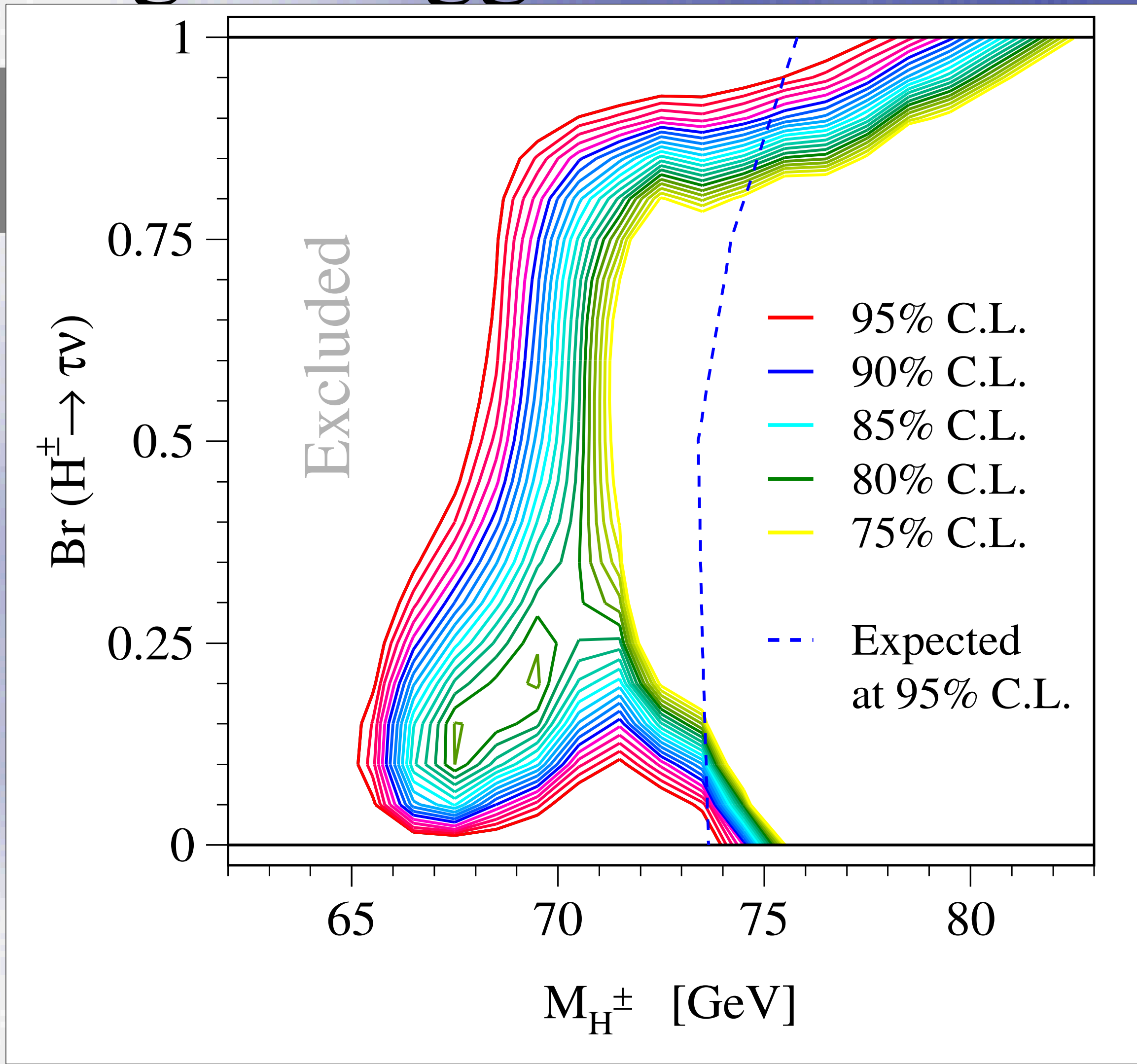



csτν



# L3 Charged Higgs limits

Data: 1172 events
BG:   1091 events

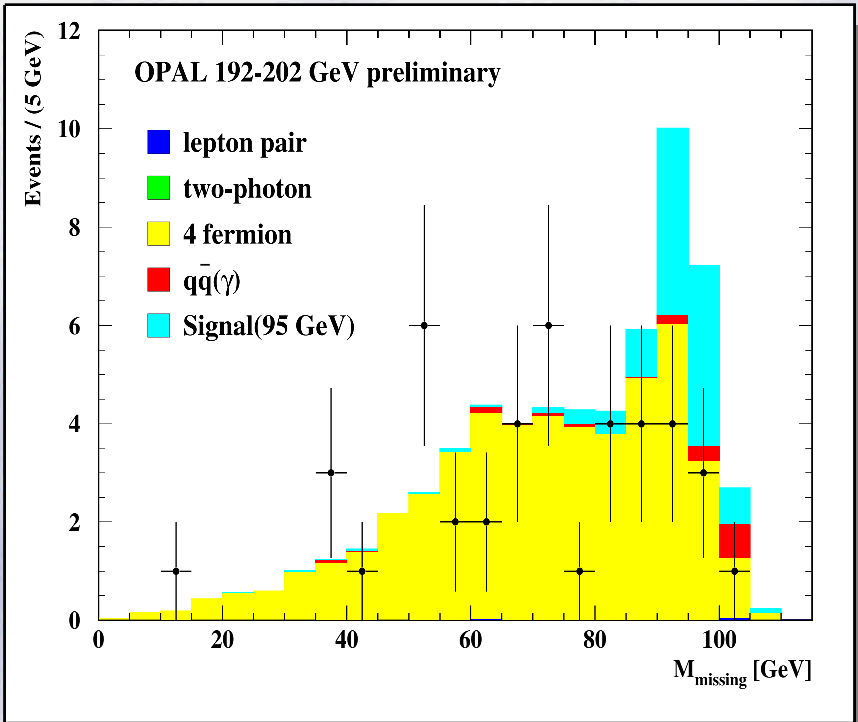


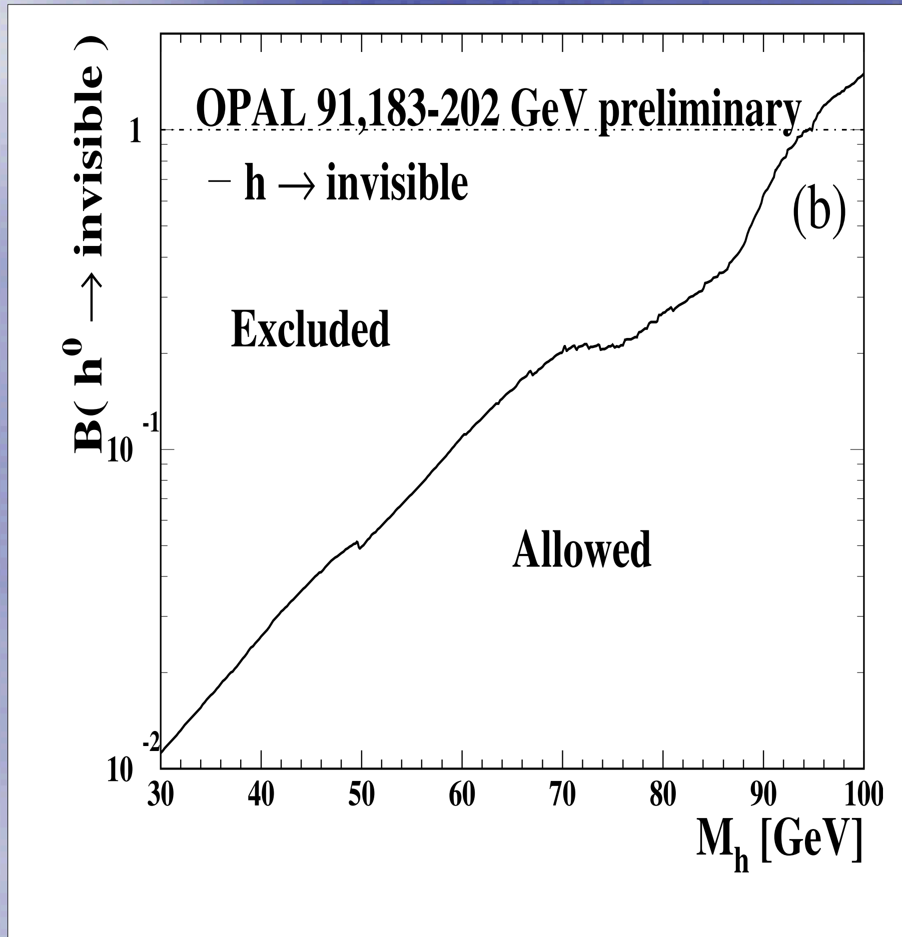
# Searches for invisible Higgs Decays

- Higgs Boson might also decay into invisible particles, like Neutralinos
- Search is performed assuming Higgs Strahlung processes
- Experimental signature:
  - Two jets or two leptons compatible with a Z decay
  - Missing Energy and Momentum
- Similar to the SM HZ $\rightarrow$ $qq\nu\nu$ search, no B tagging

# Searches for invisible Higgs Decays

- Opal analysis:




Data: 42
Background: 52.7
Signal: 10.0

# Searches for fermiophobic Higgs Bosons

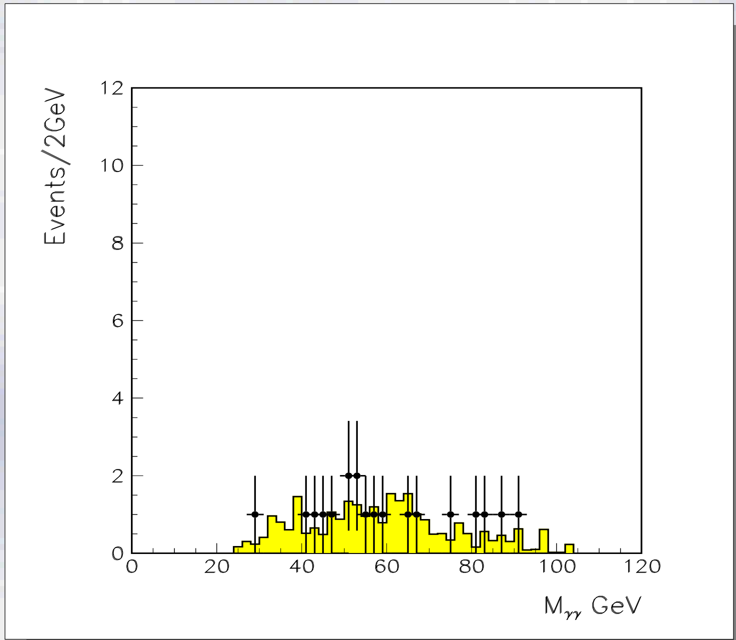
- The Higgs Boson does not have tree level couplings to fermions in this model
- Preferably decays into photons in the mass range accessible at LEP

# Searches for fermiophobic Higgs Bosons

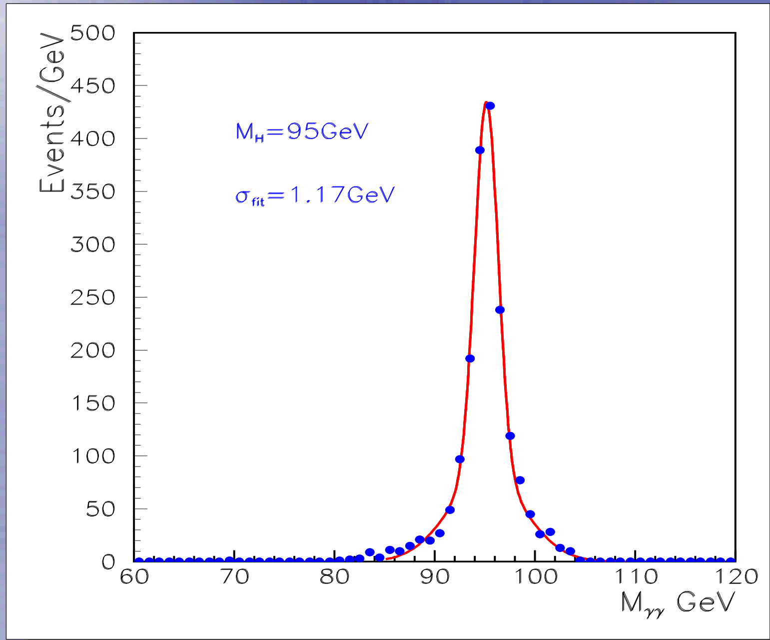
- Experimental Signature:
  - Jet or lepton pair or missing Energy compatible with a Z decay (i.e $qq\gamma\gamma$, $ll\gamma\gamma$, $\nu\nu\gamma\gamma$)
  - Two isolated, high energy photons
- The L3 detector is very well suited for this type of search due to its high performance electromagnetic calorimeter

# Searches for fermiophobic Higgs Bosons: L3 Zh $\rightarrow qq\gamma\gamma$

$\gamma\gamma$ invariant mass




$\gamma\gamma$ mass resolution




No evidence for a signal

Background: 26.6
Data: 19

# Summary

- No (clear) evidences for Higgs Signals !
- Lower limits on the Higgs masses at 95% CL :

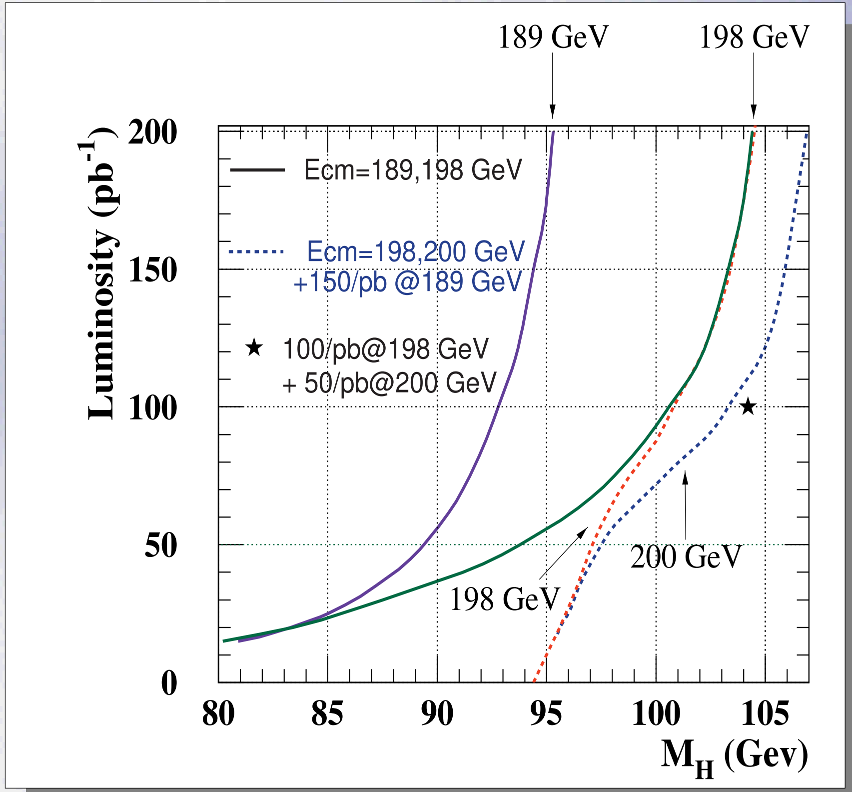
| | Aleph | Delphi | L3 | Opal |
|---|---|---|---|---|
| SM m(h) | 105.6 | 106.2 | 103 | 102.0 |
| MSSM M(h) | 89.9 | 84 | 81 | 77.1 |
| MSSM M(A) | | | 82 | 78.2 |
| m(H+/–) | 71.0 | 74 | 65.5 | 70.5 |
| m(H,inv) | | | 100 | 94.4 |
| m(h) fermiophobic | | | 94.8 | 97.8 |

All results/numbers are still preliminary !

# Outlook

- LEP operation in 2000: increase in CM energy to 206 GeV or higher planned, luminosity > 200/pb

SM potential




MSSM potential