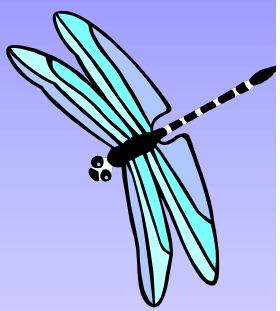
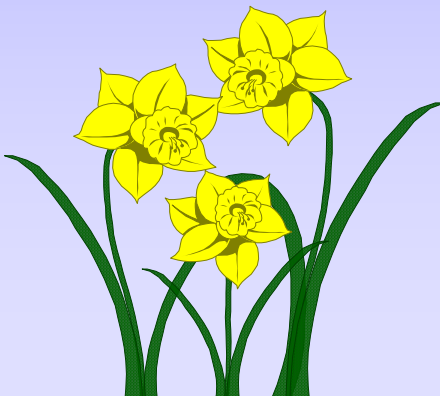
SM and Susy Higgs searches at LEP

Magali GRUWÉ

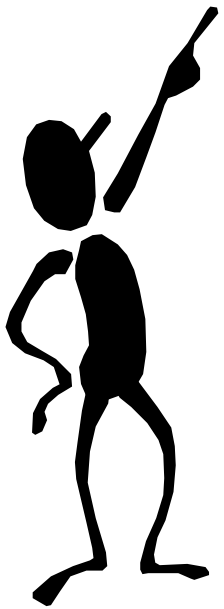
CERN



QFTHEP Workshop, September 2001



Layout



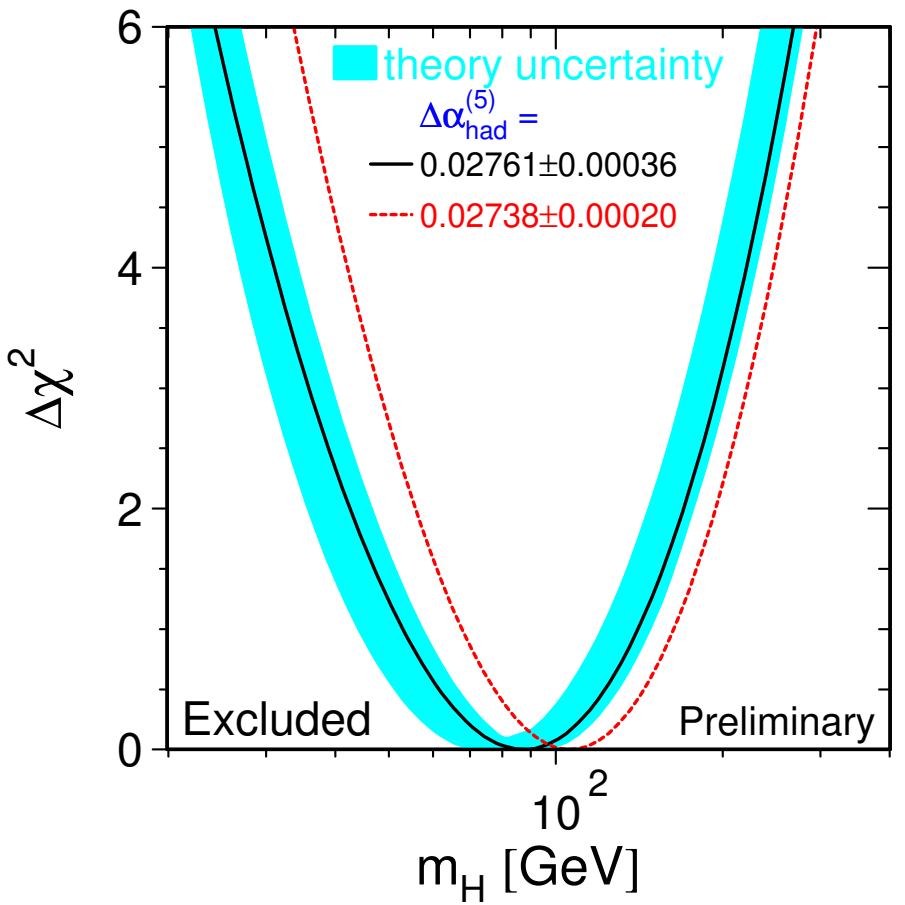
- **SM Higgs**
  - Introduction
  - Search at LEP
  - Statistics
  - Results
- **Susy Higgs bosons**
  - Introduction
  - Neutral Higgs bosons (MSSM)
  - Flavour independent search
  - Charged Higgs bosons
  - “Invisible” Higgs bosons
  - Photonic Higgs bosons
- **Conclusion**

SM Higgs

- **Indirect experimental constraints derived from precision measurements of electroweak parameters**

➡ **Preferred value:**

$$m_H = 88^{+53}_{-33} \text{ GeV}$$



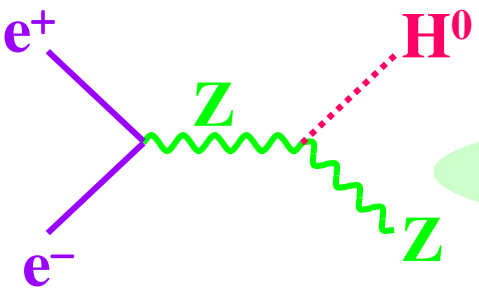
SM Higgs Production

Main production processes

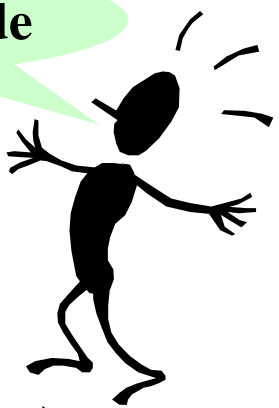
(at energies within LEP reach)

– **Higgs Strahlung**

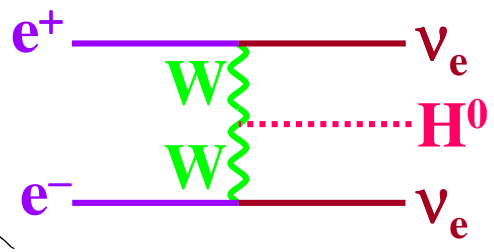
$m_H \sim (\sqrt{s} - m_Z)$



Dominant mode

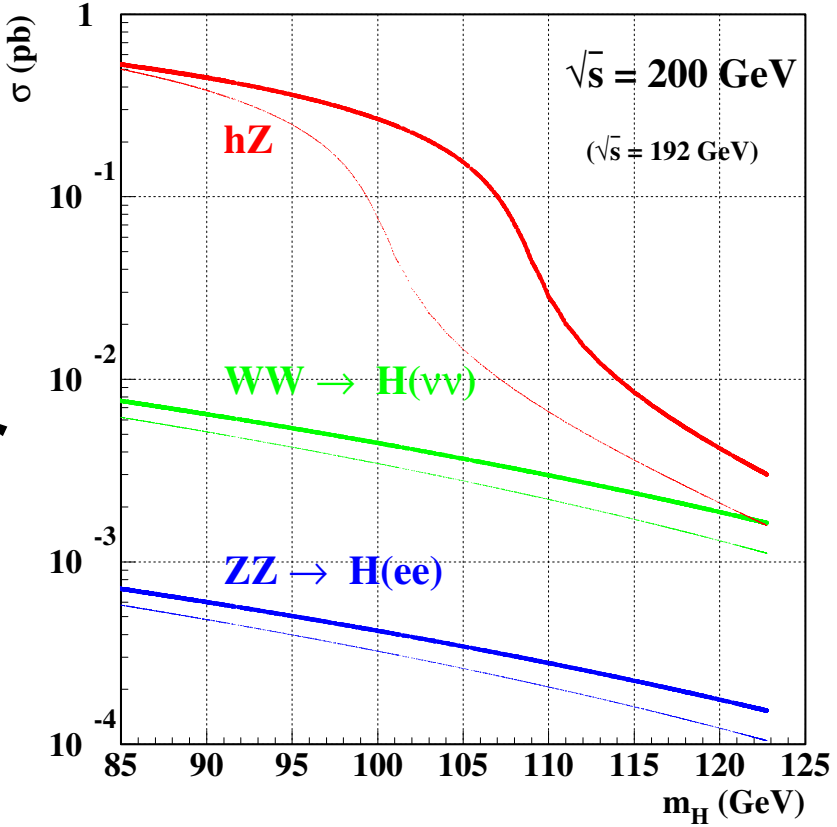


– **Fusion Processes**

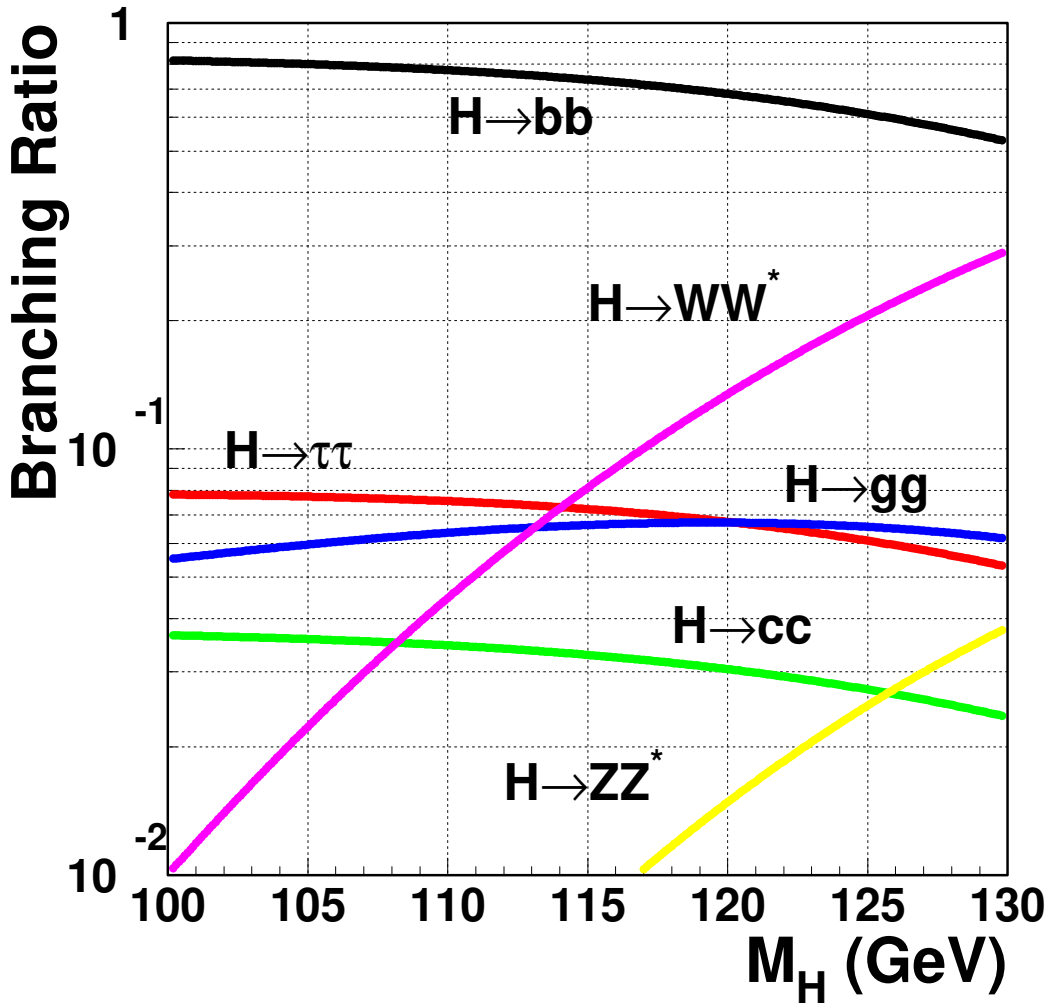


$m_H > (\sqrt{s} - m_Z)$

Small contribution



Decays of the Higgs Boson

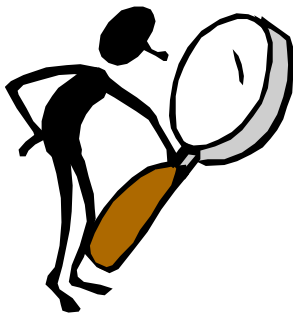


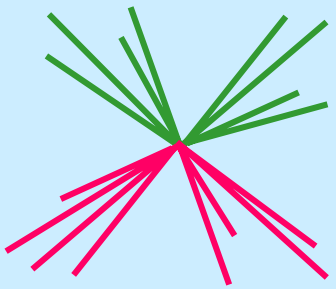
- Suppressed coupling to light fermions
- Dominant decay to bb:

  BR = 75 to 85%

➡ b tagging is essential

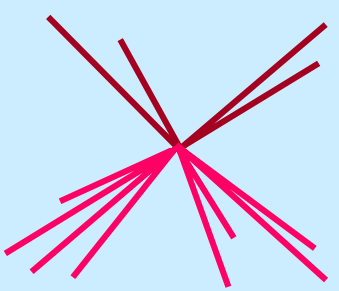
Search Topologies

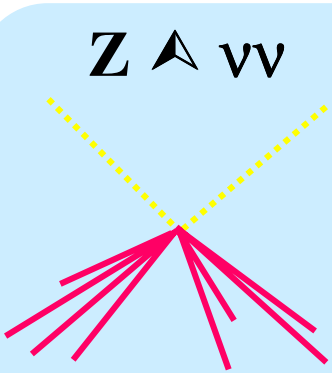




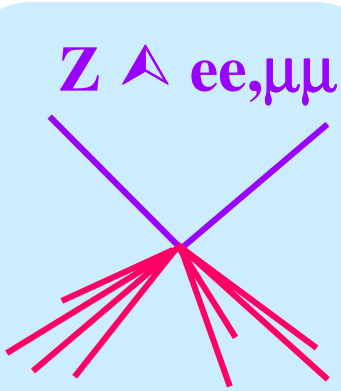
Four Jet Channel
50 - 60 %

Tau Channel
10 %



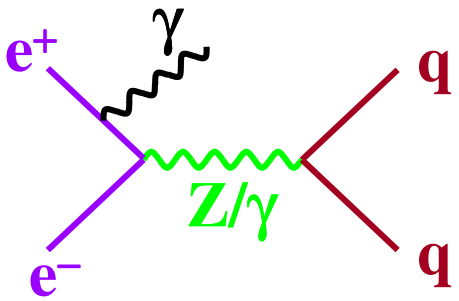


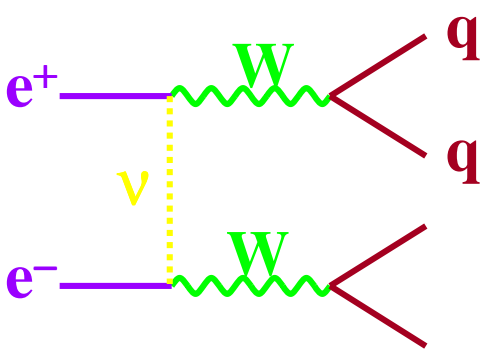
Missing Energy Channel
17 %

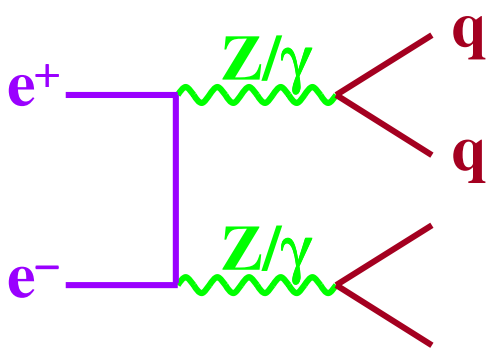


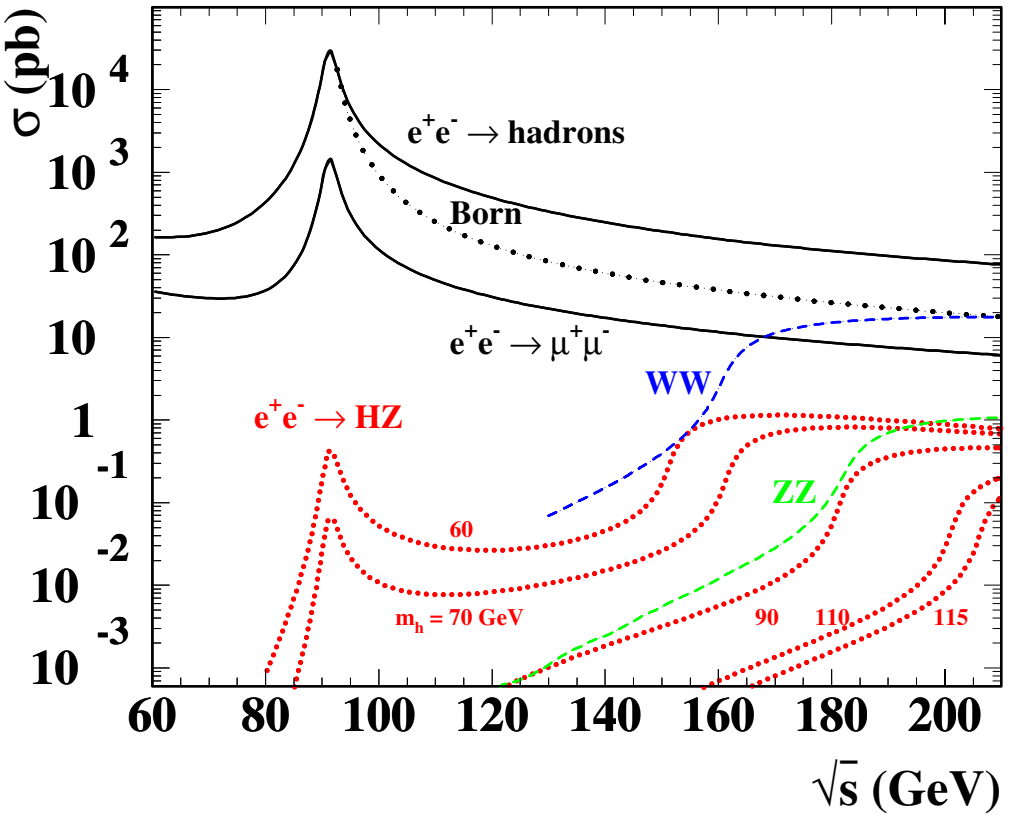
Lepton Channel
6 %

Background Processes









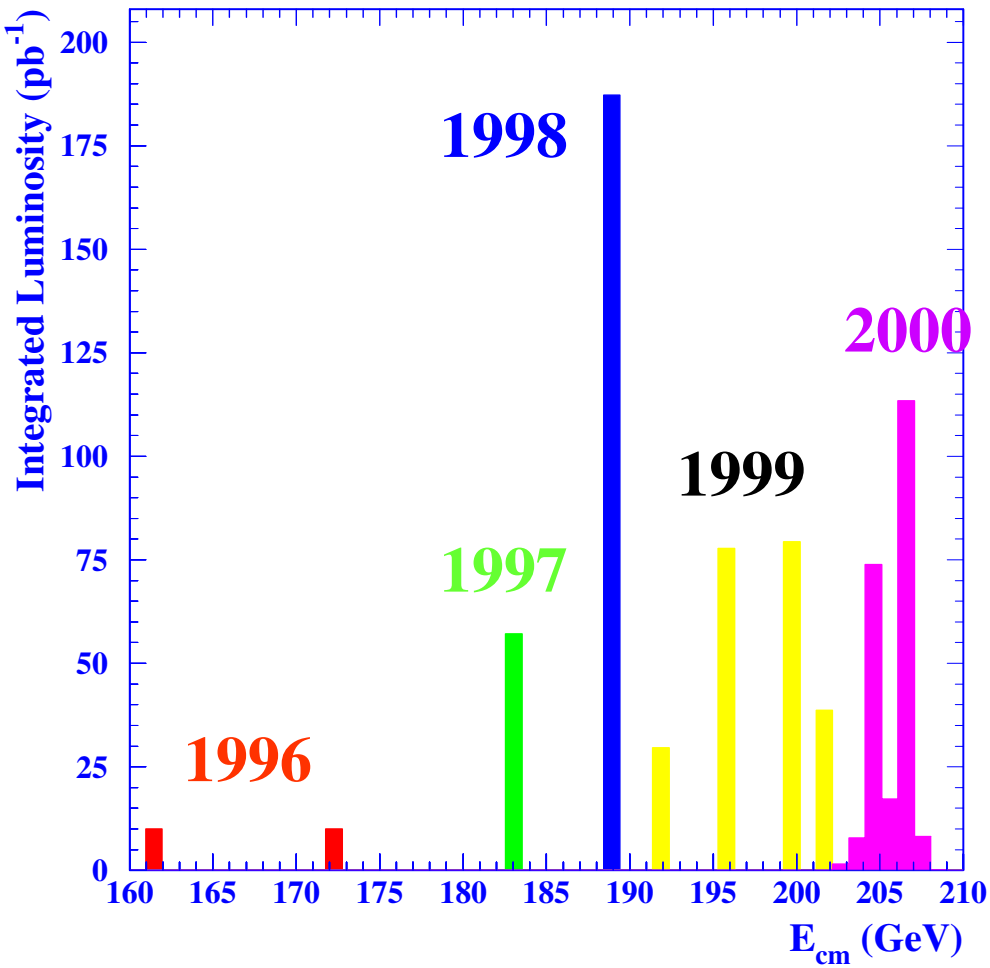
Most severe background

Data Set

Luminosities at LEP2:

- Total: ~ 700 pb^{-1}
- In 2000: ~ 210 pb^{-1}

per experiment



Analysis Strategy

Soft Preselection

- visible energy
- number of charged tracks

➡ **Reduce main background**

- two photon processes
- radiative returns to the Z boson

Likelihood-Selection

- kinematic differences between signal and background processes
- b-tagging

➡ **Reduce background from**

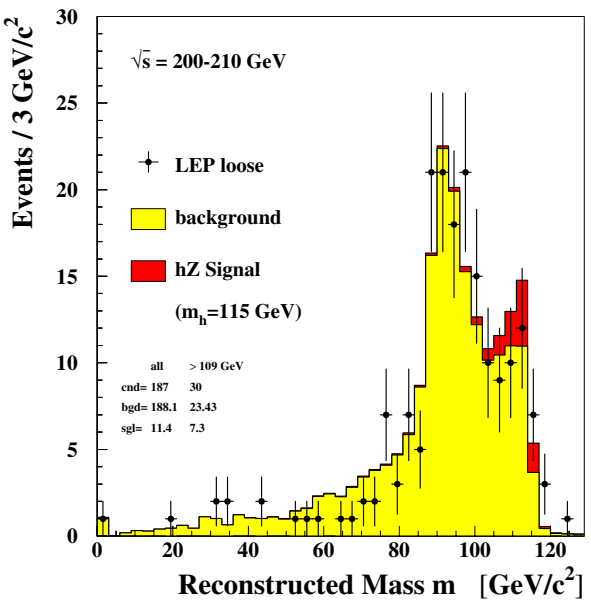
- fermion pairs
- WW
- ZZ

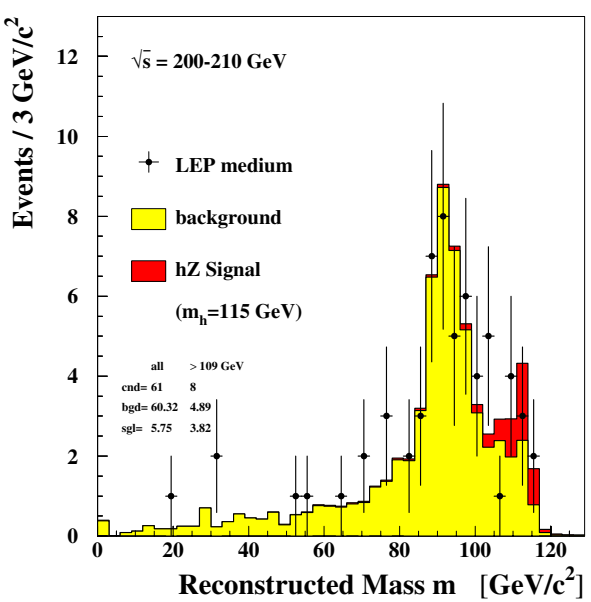
Discriminating Variable

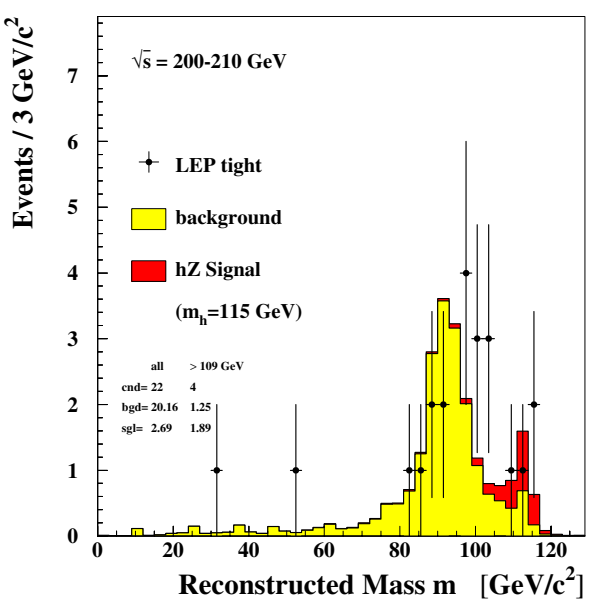
- reconstructed mass (m_H)
- likelihood value

➡ **Additional separating power**

Reconstructed Mass Distributions







Mass spectra do NOT show all the information

Statistical Estimator (I)

- **Inputs:**
  - **Binning into two discriminating variables:**
    - **reconstructed Higgs mass**
    - **global variable containing information about kinematics, b-tagging, etc…**
  - **Per bin:**
    - **Background (from MC):** b_i
    - **Signal (from MC):** $s_i(m_H)$
    - **Number of candidates (data):** N_i

Statistical Estimator (II)

- **Likelihood Ratio for test mass m_H: $Q(m_H)$**

  Statistical estimator to compare all relevant features of selected candidates with:

  - **background only hypothesis: b**
  - **signal + background hypothesis: s+b**

$$Q(m_H) = \frac{L(s+b)}{L(b)} \approx \frac{e^{-(s+b)}}{e^{-b}} \prod_{i=1}^{N_{cand}} \frac{s_i+b_i}{b_i}$$

L(s+b): Poisson distribution based on number of observed events and their features.

$$\Rightarrow \quad -2 \ln Q(m_H) = 2s - 2 \sum_{i=1}^{N_{cand}} N_i \ln \left(1 + \frac{s_i(m_H)}{b_i(m_H)} \right)$$

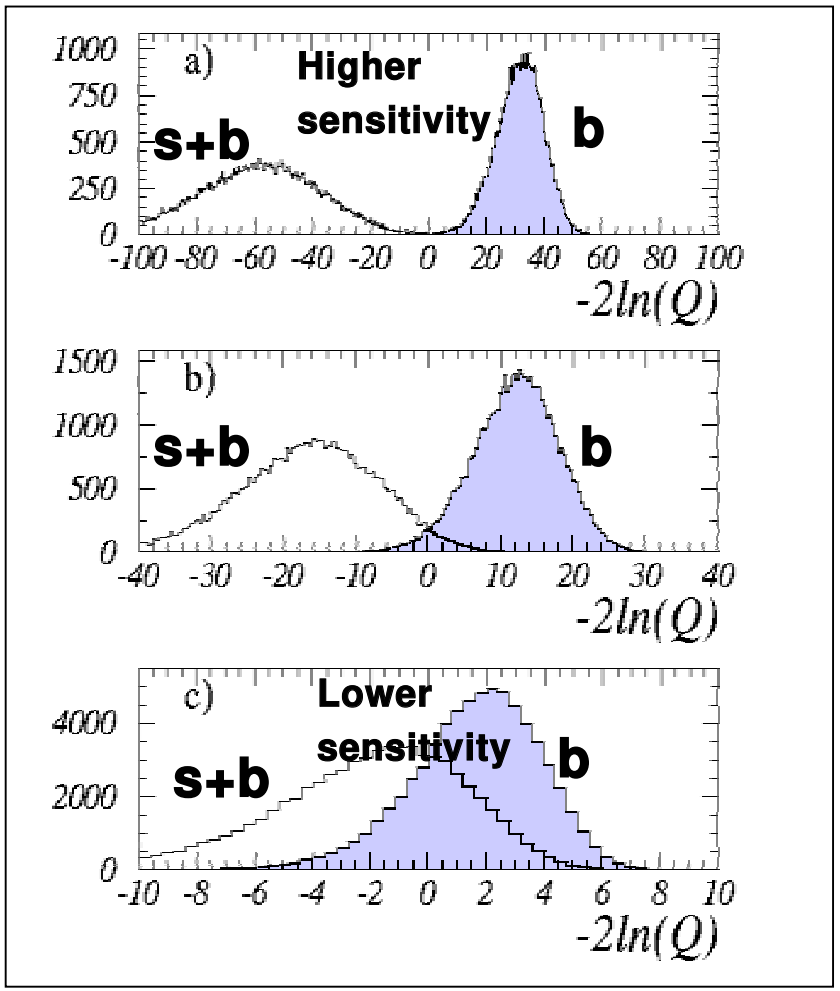
Statistical Estimator (III)

For arbitrary test mass m_H, replace data by MC sets of (s+b) and (b)

➡ **Distributions of -2lnQ for (s+b) and for (b)**

➡ **Expected curves**

Separation of curves gives sensitivity of search to signal with mass m_H



Statistical Estimator (IV)

- **Confidence levels**

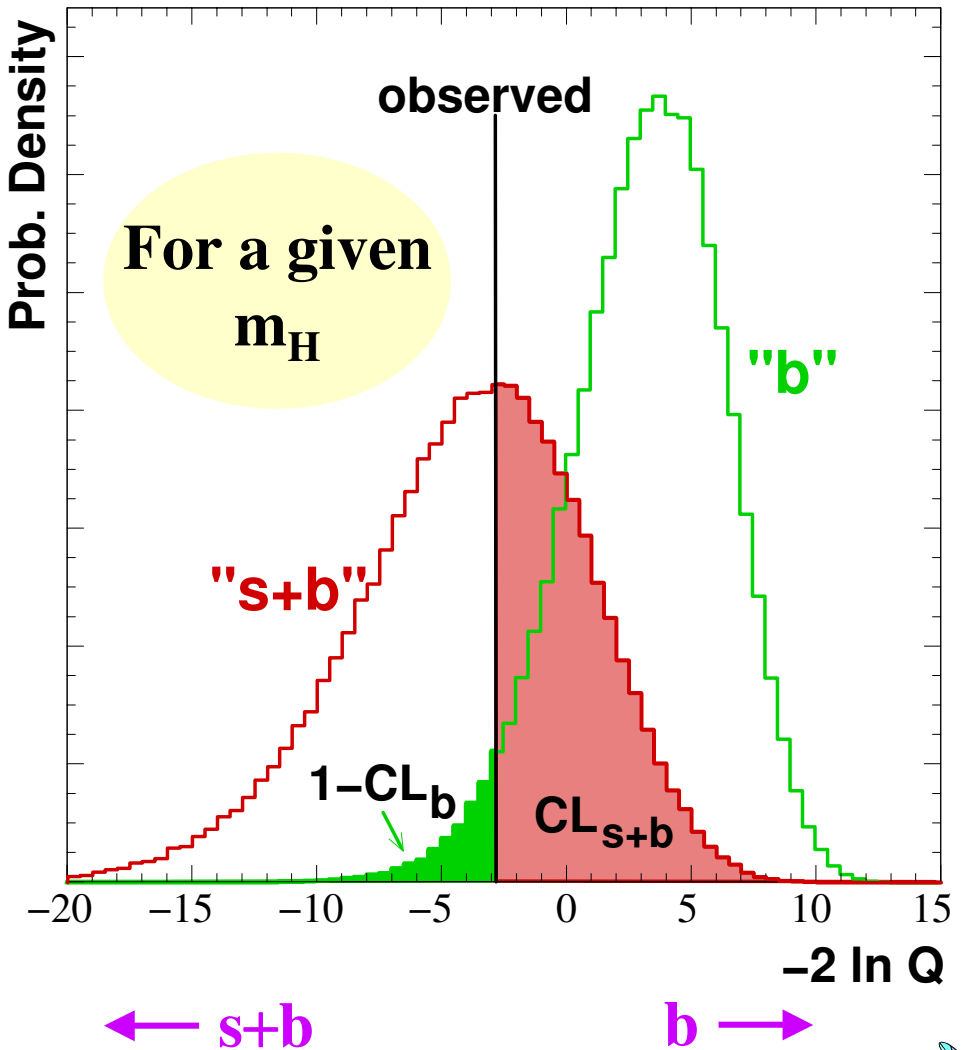
  For arbitrary test mass m_H, observed value of -2lnQ gives:

  – **$1\text{-}CL_b$ = measure of incompatibility with (b)**

  Given an ensemble of (b) experiments: probability to obtain and event configuration less background-like than the observed event configuration

  – **CL_{s+b} = measure of compatibility with (s+b)**

  Given an ensemble of (s+b) experiments: probability to obtain an event configuration more background-like than the observed event configuration

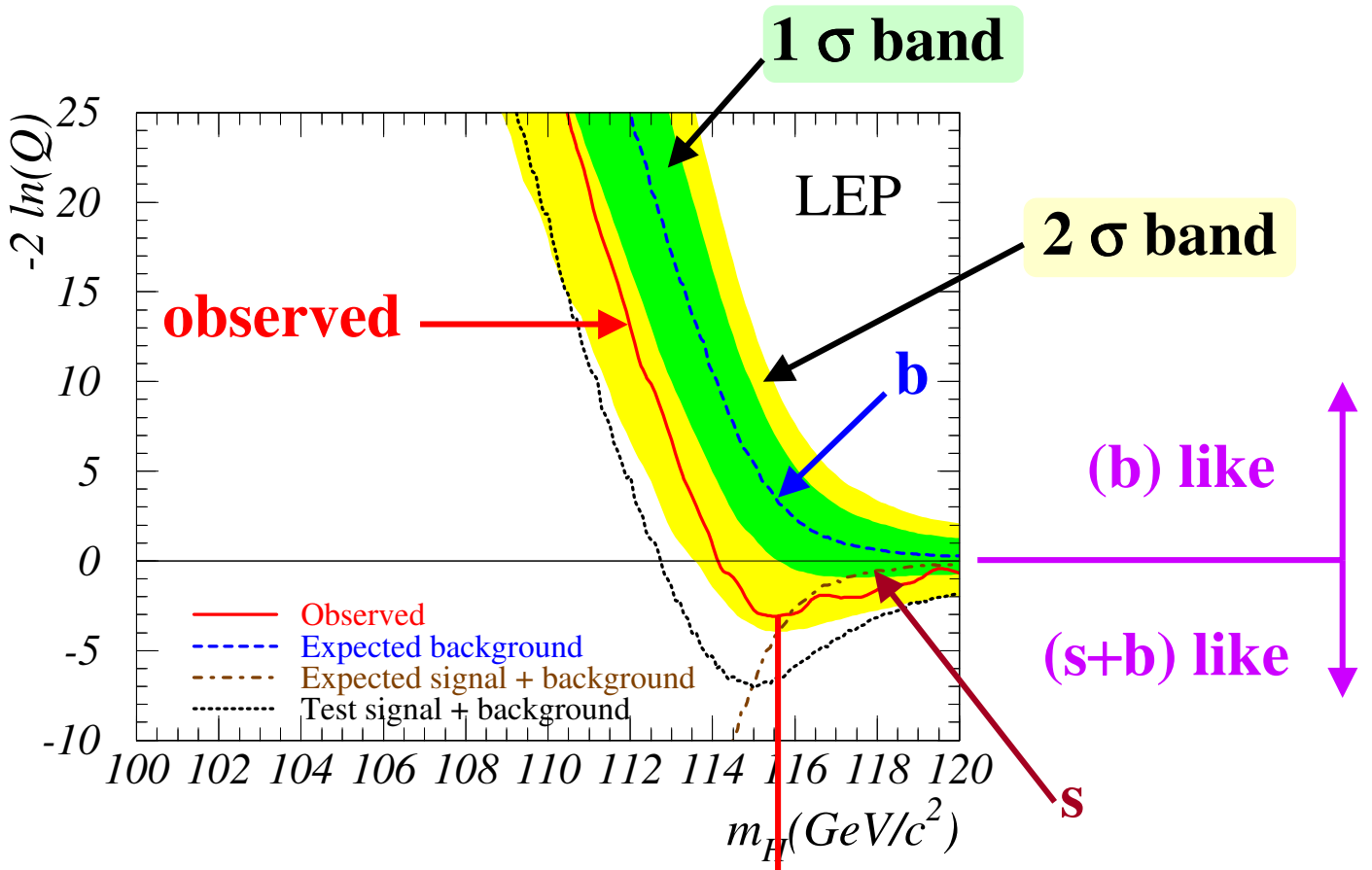


Results (I)

- **Caution:**
  - **Results from a combination of all 4 LEP experiments**
  - **Only L3 has published final numbers**
  - **Results from ALEPH, OPAL, DELPHI are still preliminary**
  - **Final combined results to be expected in a few months.**

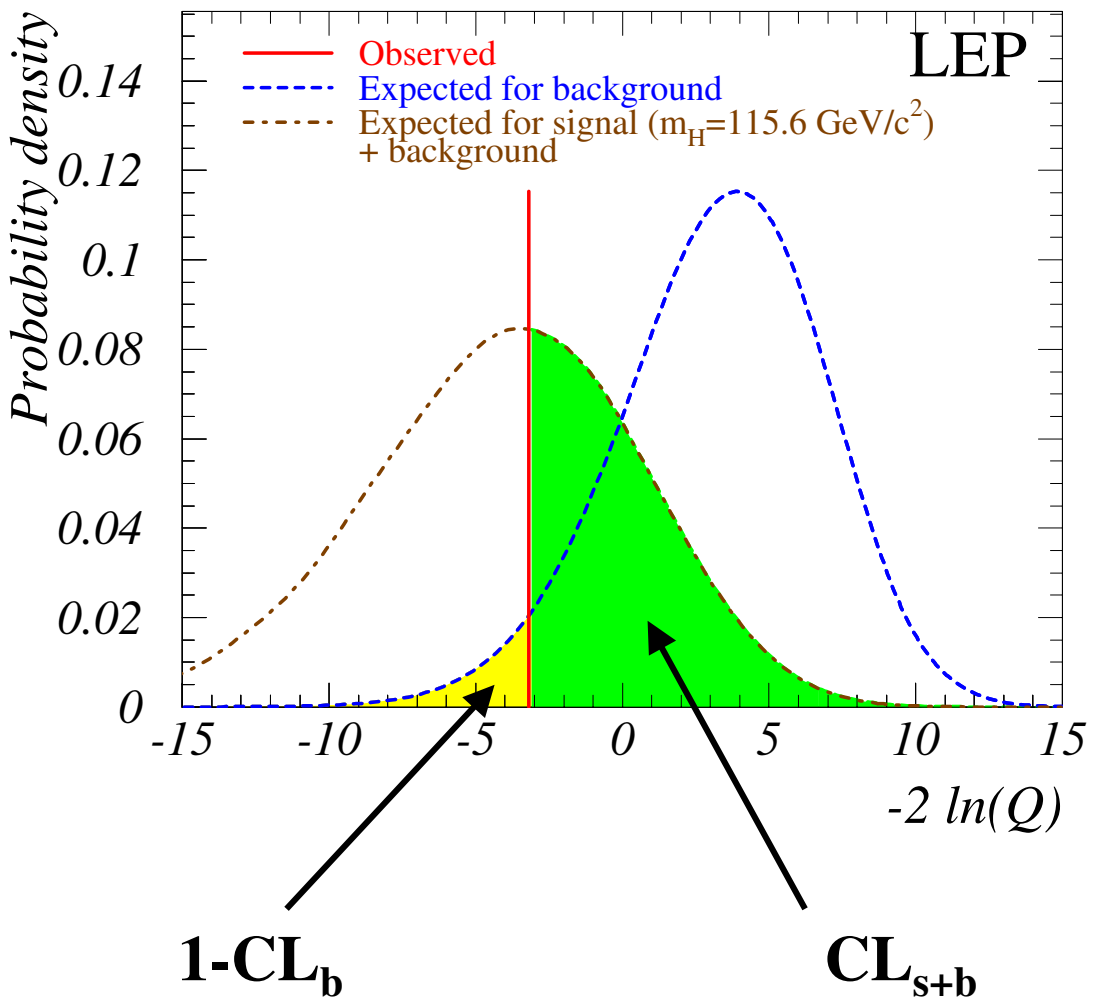
Results (II)

- ln Q versus test mass m_H



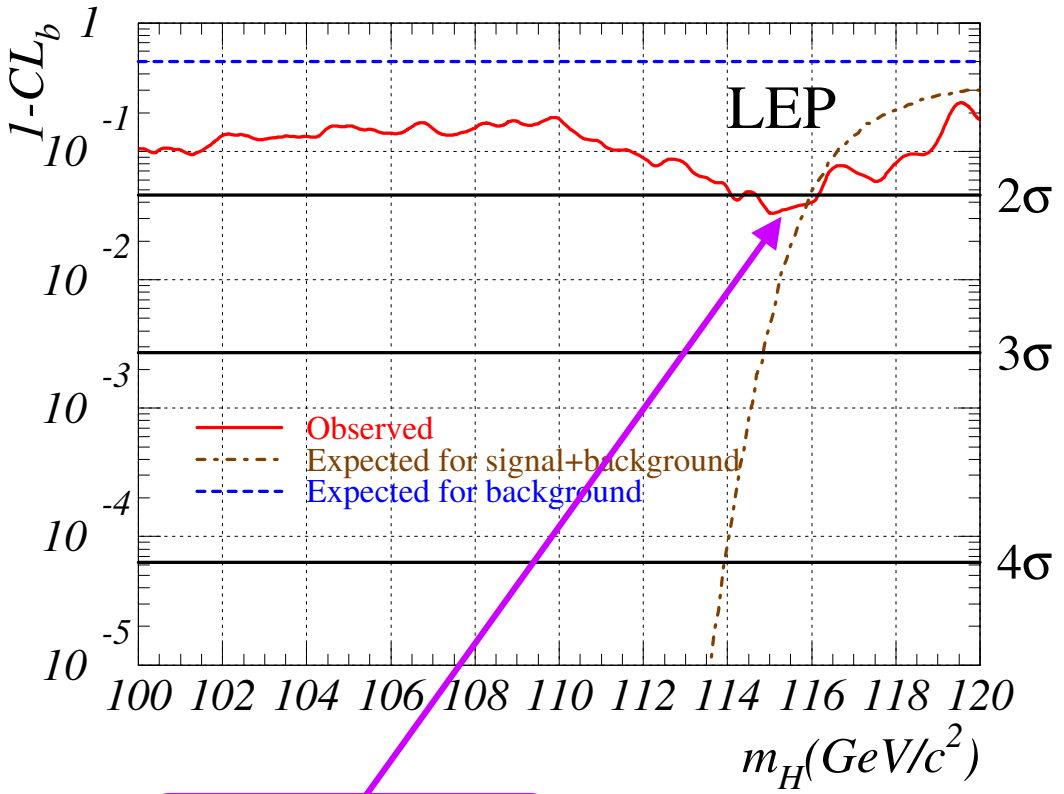
Results (III)

- **Probability densities**



Results (IV)

- **$1\text{-}CL_b$**



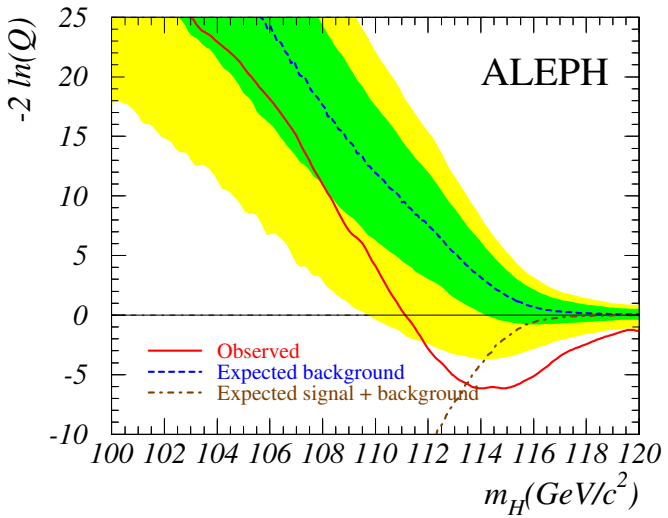
$1\text{-}CL_b$ = 0.035
↙2σ

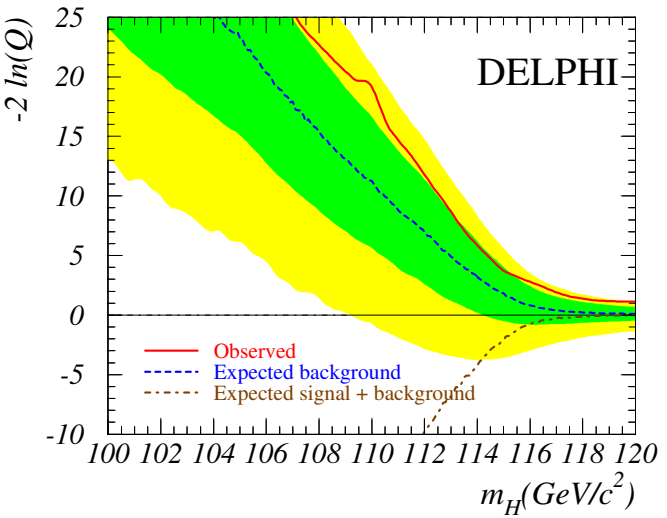
Consistent with SM Higgs signal with preferred m_H value: 115.6 GeV

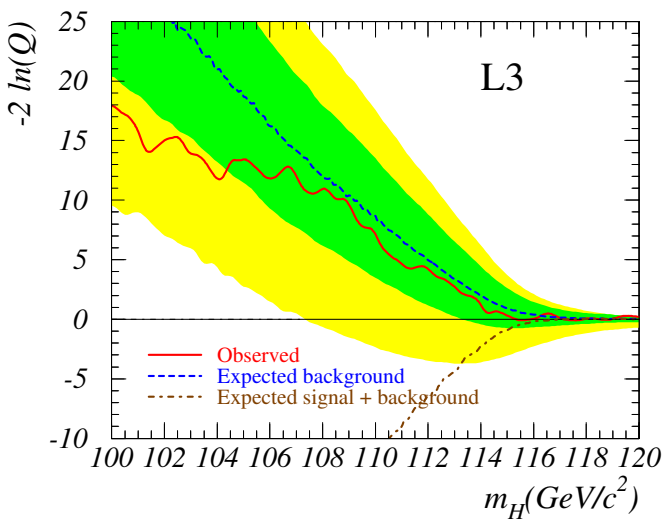
Probability of background fluctuation:

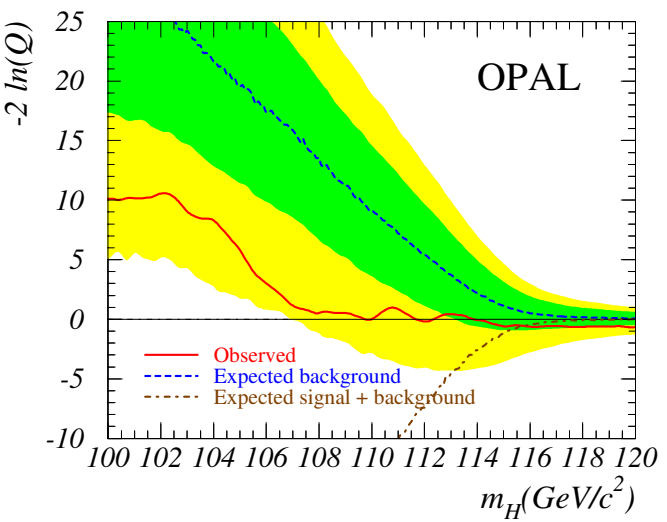
$1\text{-}CL_b$= 0.0023 (ALEPH)
0.88 (DELPHI)
0.25 (L3)
0.22 (OPAL)
0.035 (LEP)

Results from each Experiment

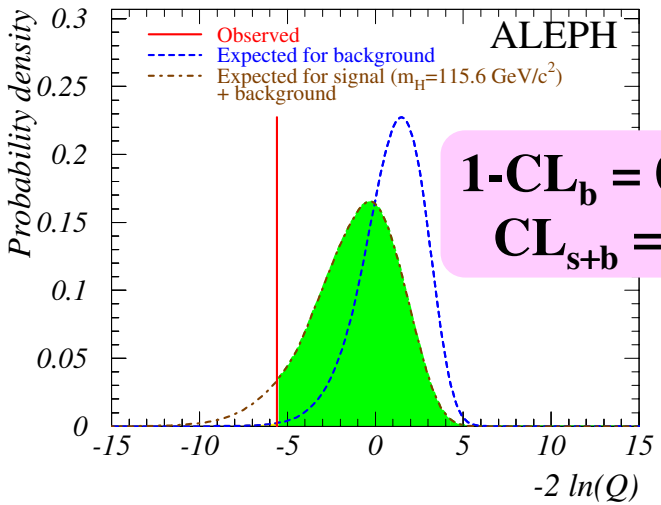




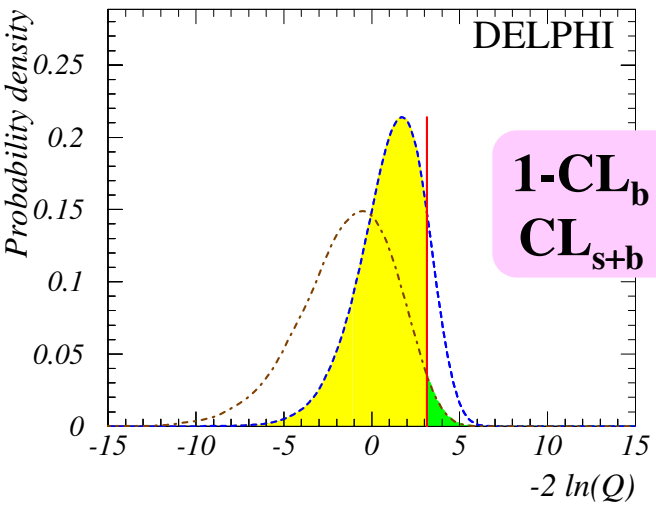




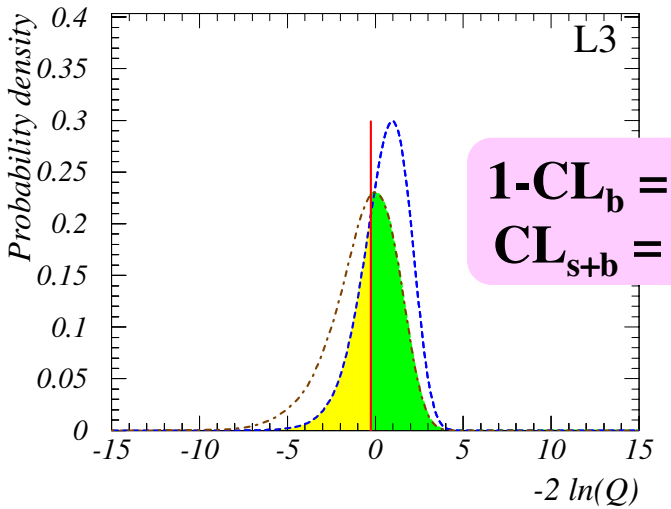
Results from each Experiment



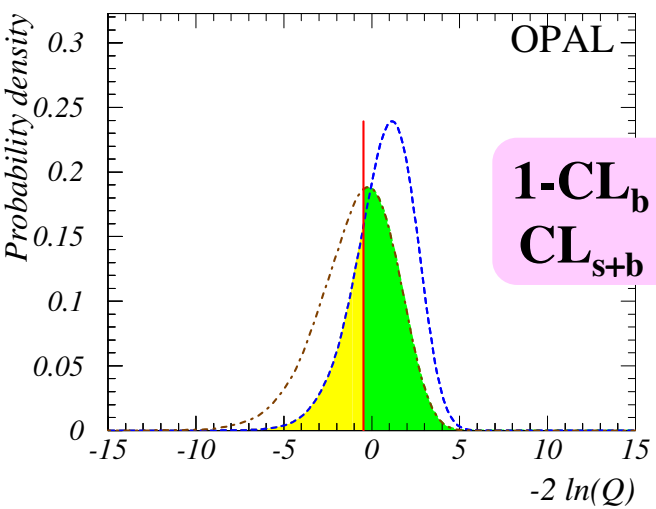
1-CL$_b$ = 0.0023
CL$_{s+b}$ = 0.94



1-CL$_b$ = 0.88
CL$_{s+b}$ = 0.02

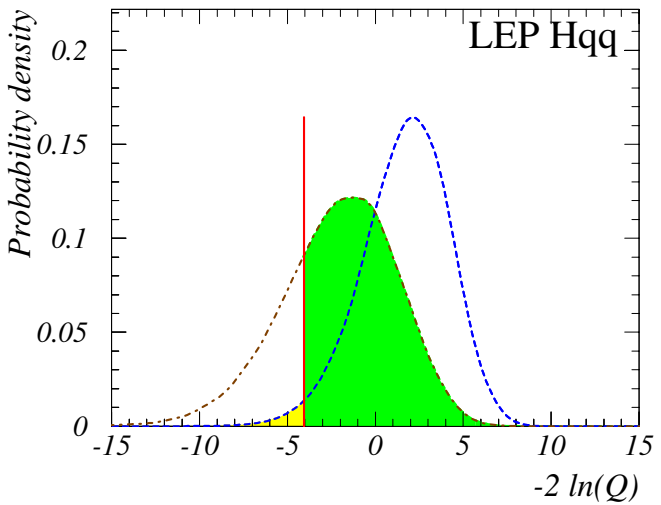


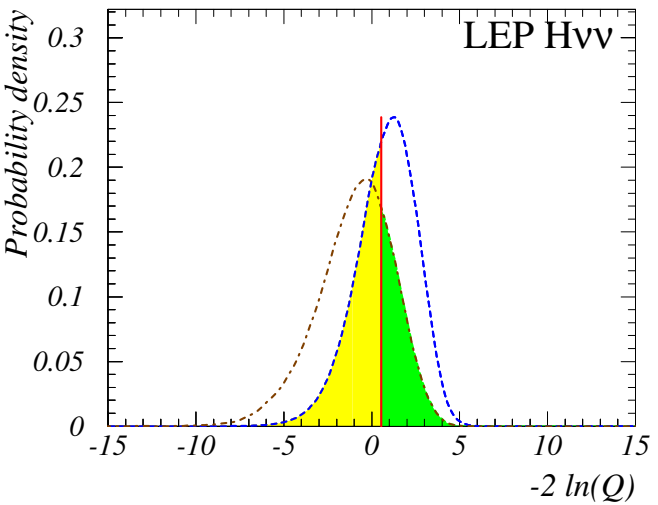
1-CL$_b$ = 0.25
CL$_{s+b}$ = 0.46

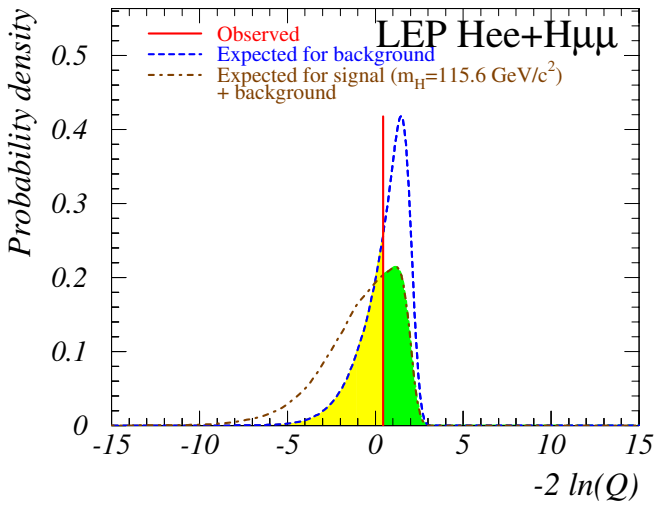


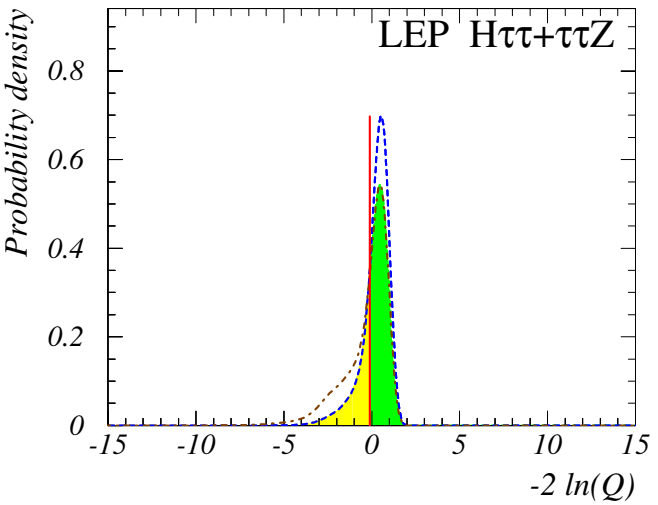
1-CL$_b$ = 0.22
CL$_{s+b}$ = 0.48

Results from each Channel









Conclusion on SM Higgs

- With data taken in 2000 ($\sqrt{s} \geq 205$ GeV): 2σ excess observed
- mainly driven by ALEPH 4-jet events
- Preferred SM Higgs mass: 115.6 GeV
- ALEPH: signal-like

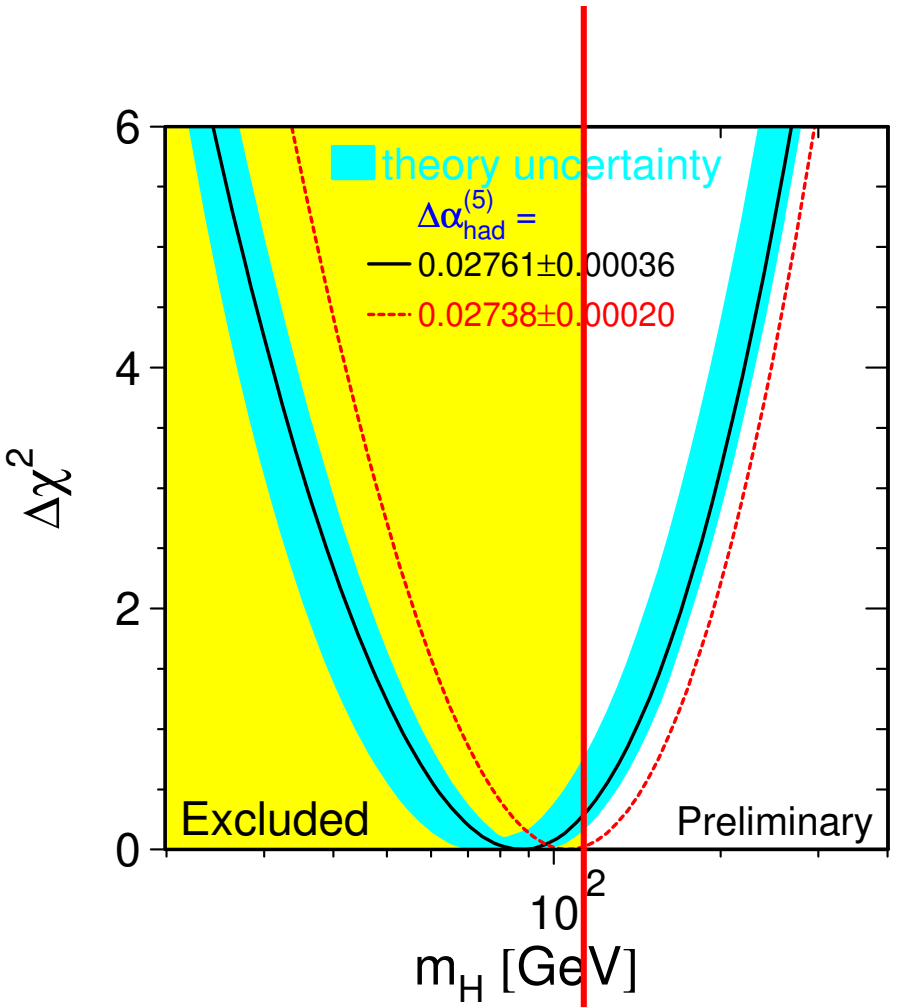
  DELPHI: background-like

  OPAL: slight excess

  L3: slight excess

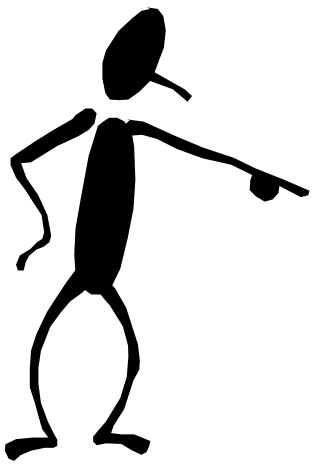
  DLO limit: 114.8GeV at 95%CL does not exclude ALEPH excess

- Probability of background fluctuation: 3.5%



- Mass limit: 114.1 GeV

Layout



- SM Higgs
  - Introduction
  - Search at LEP
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  - Results
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- Conclusion

Two Higgs Doublet Models

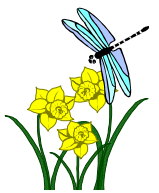
- **In SM:**
  - only one complex Higgs doublet ⇒ only one physical neutral Higgs scalar, whose mass is a free parameter

⇒ **Interesting to consider more complicated models**

- **2 Higgs Doublet Models (2HDM) attractive:**
  - adds new phenomena
  - adds the fewest new arbitrary parameters
  - such a Higgs structure is required in low-energy Susy models
- **Higgs bosons in 2HDM:**
  - 2 neutral CP-even scalars: h^0 and H^0
  - 1 CP-odd scalar: A^0
  - 2 charged scalars: $H^{\pm}$

2HDM Parameters

- **Six free parameters (if no CP-violation):**
  - **Four masses:**
    - m_h: Mass of the lightest CP-even Higgs boson
    - m_H: Mass of the heaviest CP-even Higgs boson
    - m_A: Mass of the CP-odd Higgs boson
    - $m_{H^\pm}$: Mass of the charged Higgs bosons
  - **Two angles:**
    - α: Mixing angle between h^0 and H^0: $-\pi/2 \leq \alpha \leq \pi/2$
    - $\tan\beta$: Ratio of vacuum expectation values: $0 \leq \beta \leq \pi/2$

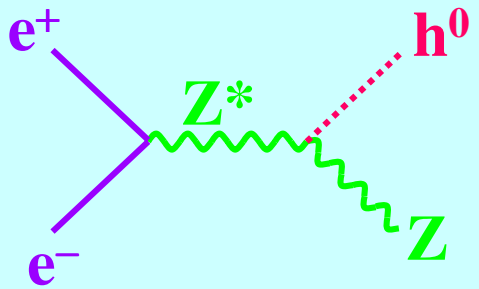


SUSY Higgs Bosons Search

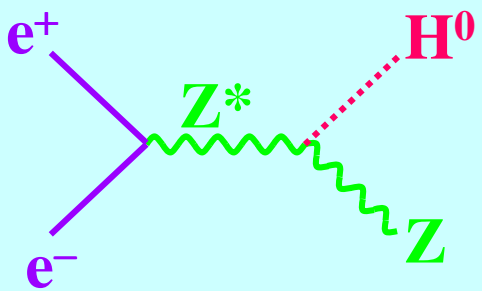
- **Neutral Higgs Bosons: h^0, H^0, A^0**
  - **Cross-sections, couplings, decays**
  - **Parameter scans**
    - **No mixing**
    - **Large mixing**
    - **Large μ ⇗ flavour independent search**
- **Charged Higgs Bosons: H^+, H^-**
- **Others**

Cross-sections

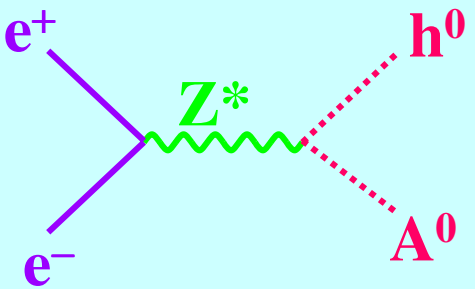
$$\sigma_{hZ} = \sin^2(\beta-\alpha)\,\sigma_{HZ}^{SM}$$



$$\sigma_{HZ} = \cos^2(\beta-\alpha)\,\sigma_{HZ}^{SM}$$



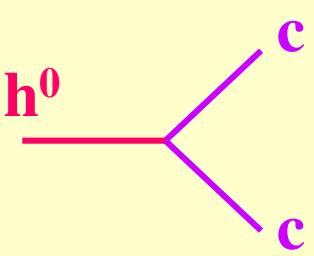
$$\sigma_{hA} = \cos^2(\beta-\alpha)\,\lambda\,\sigma_{HZ}^{SM}$$



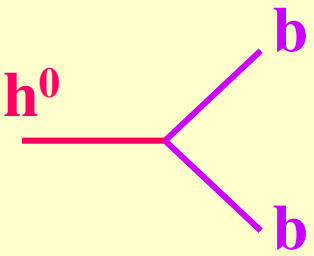
Couplings

- **Decay branching ratios of Higgs bosons to fermions depend on the masses, but also on α and β**

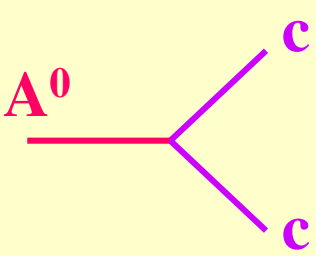
$\cos\alpha / \sin\beta$



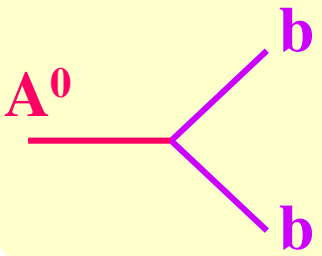
$-\sin\alpha / \cos\beta$



$\cot\beta$



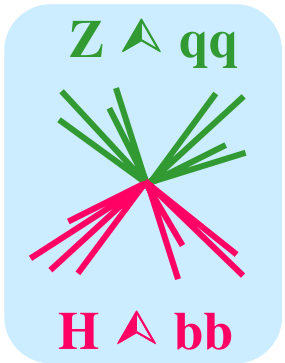
$\tan\beta$

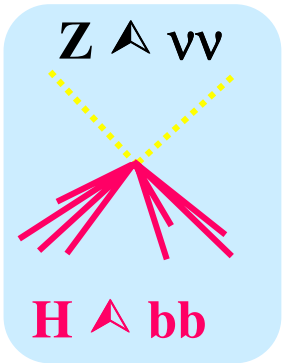


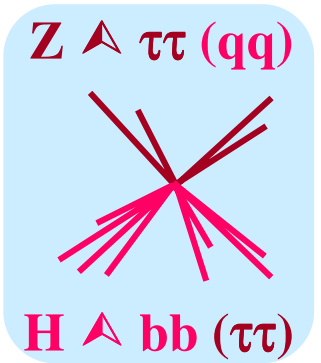
- **Over much of the parameter space considered: h^0 and A^0 decay predominantly into bb or $\tau\tau$**

Topologies

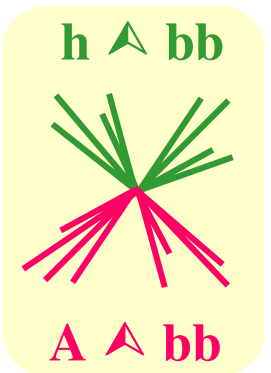
- Z^0h^0 analysis:
  - SM channels (replacing H^{SM} by h^0)
  - For low α and β: $h^0 \to bb$: flavour independent analyses

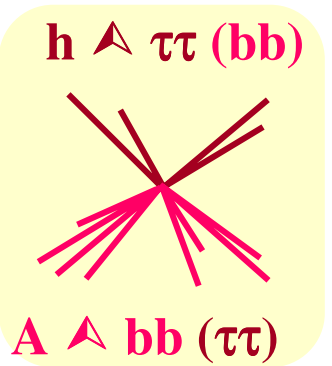






- h^0A^0 analysis:
  - 4-jet channel with no m_Z constraint
  - ττ channel with no m_Z constraint





MSSM Parameters

- **Constrained model with 7 parameters:**

$\tan\beta$	Ratio of the vev's of the two Higgs doublets
M_{SUSY}	SUSY breaking sfermion masses
M_2	SUSY breaking gaugino masses
μ	SUSY Higgs boson mass parameter
A_0	Common trilinear Higgs squark coupling
m_g	Gluino mass (affects loop corrections from sbottoms and stops)
M_A	Mass of CP-odd Higgs boson

MSSM Parameter Scans

- **Three benchmark scenarios:**
  - ☆ **No mixing in stop sector**
    - reduced parameter space

$M_{SUSY} = 1$ TeV/c^2
$M_2 = 200$ GeV/c^2
$\mu = -200$ GeV/c^2
$X_t \equiv A - \mu \cot\beta = 0$
$0.4 < \tan\beta < 30$
$m_g = 800$ GeV/ c^2
4 GeV/c^2 < m_{A^0} < 1 TeV/c^2

  - 🕐 **Max m_h: large mixing in stop sector**
    - extended parameter space
    - such that the maximum possible Higgs boson mass as a function of tanβ is obtained
      - ⮝ conservative limits

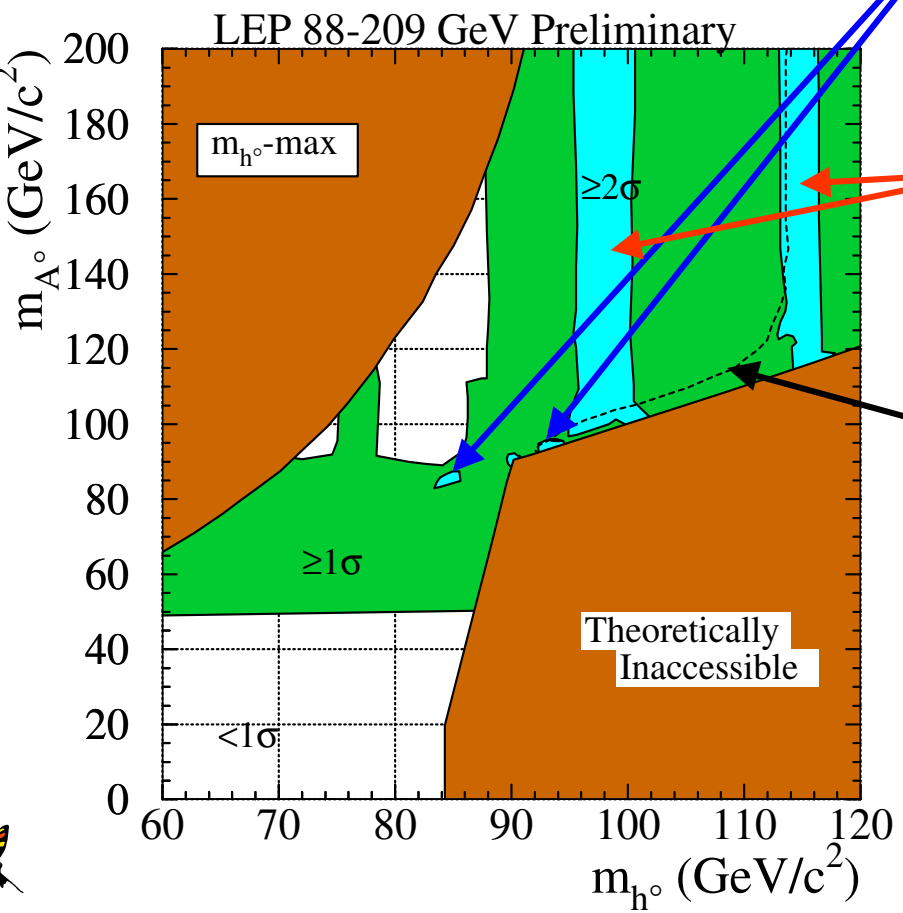
Same as above, but:
$X_t \equiv A - \mu \cot\beta = 2\, M_{SUSY}$

  - 🕐 **Large μ**
    - pathological points with BR(H⮝bb) << 1
      - ⮝ need flavour independent analysis

$M_{SUSY} = 1400$ GeV/c^2
$M_2 = 400$ GeV/c^2
$\mu = 1$ TeV/c^2
$X_t \equiv A - \mu \cot\beta = -300$ GeV/c^2
$m_g = 200$ GeV/ c^2
4 GeV/c^2 < m_{A^0} < 400 GeV/c^2

MSSM Parameter scan: Max m_h

$1 - CL_b$ in (m_h, m_A):



$e^+e^- \to hA$ searches

~ 2σ excess

$e^+e^- \to hZ$ searches

≥ 2σ excess

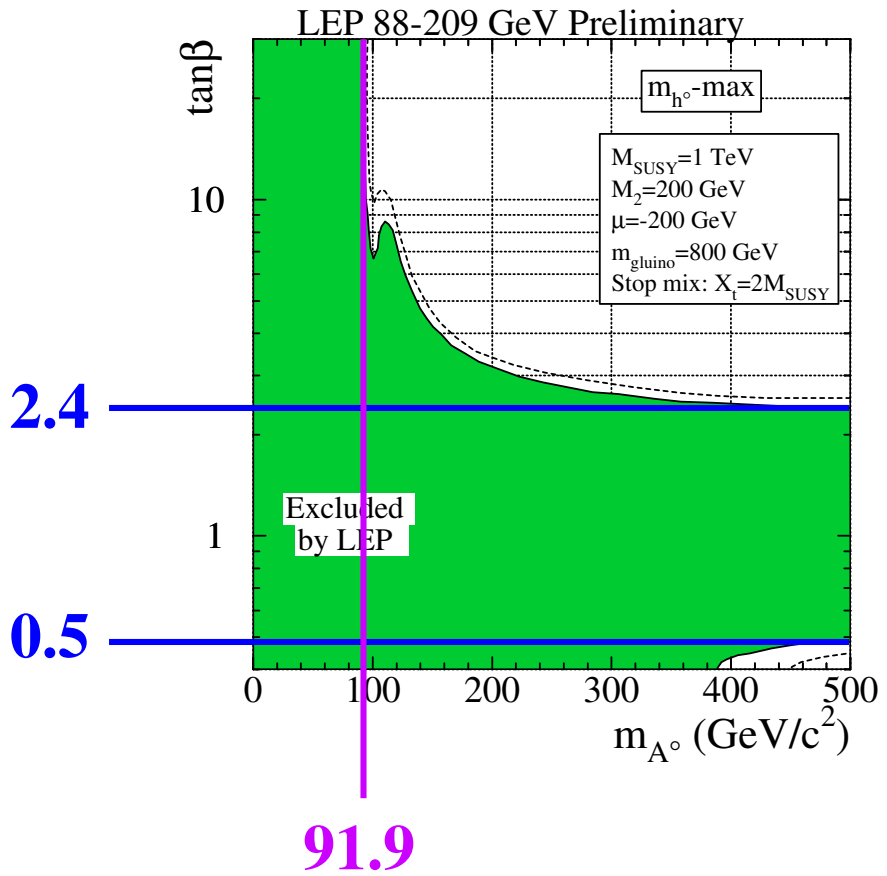
Excluded at 95% CL:

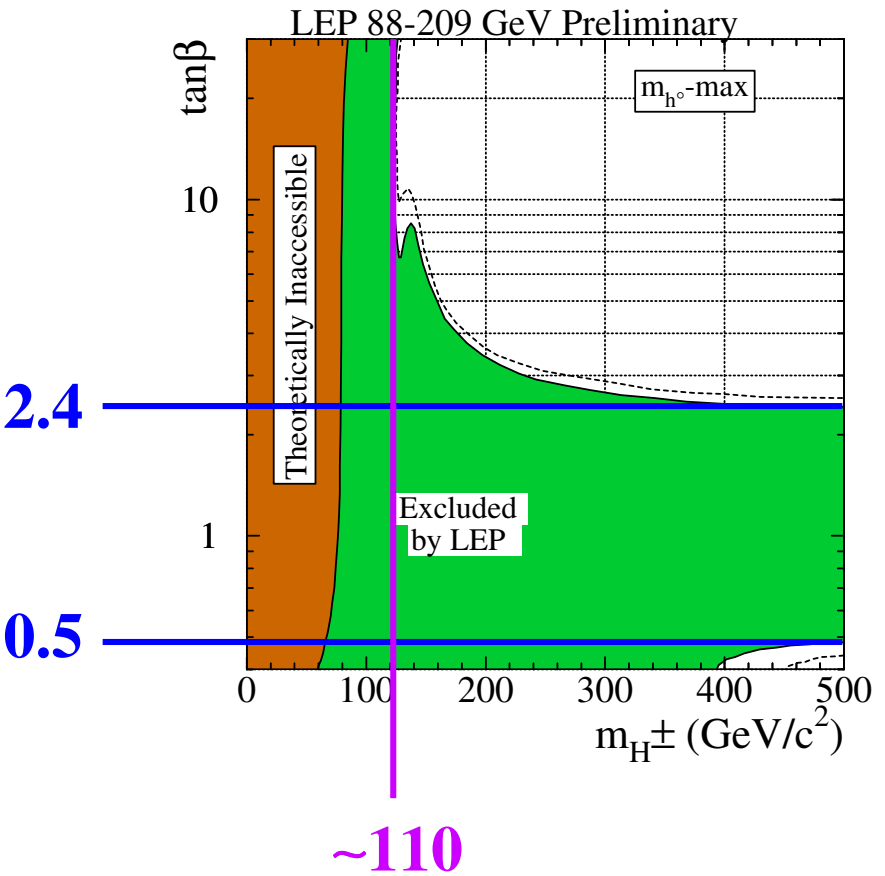
$m_h < 91.0$ GeV/c^2 (95.0 expected)

$m_A < 91.9$ GeV/c^2 (94.6 expected)

$0.5 < \tan\beta < 2.4$

MSSM Parameter scan: Max m_h

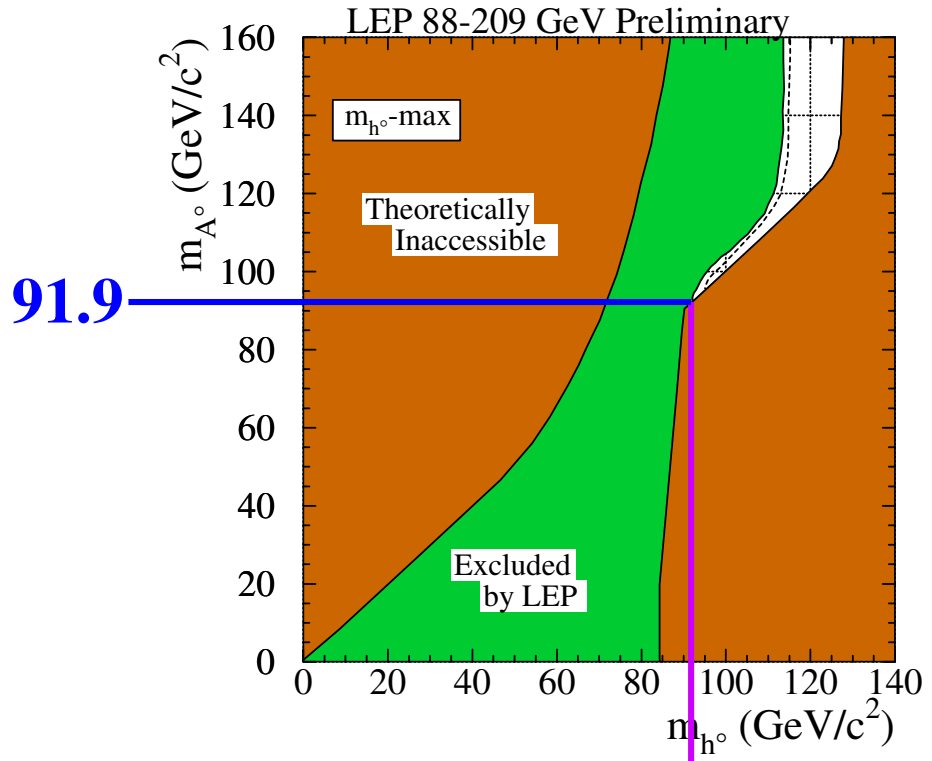


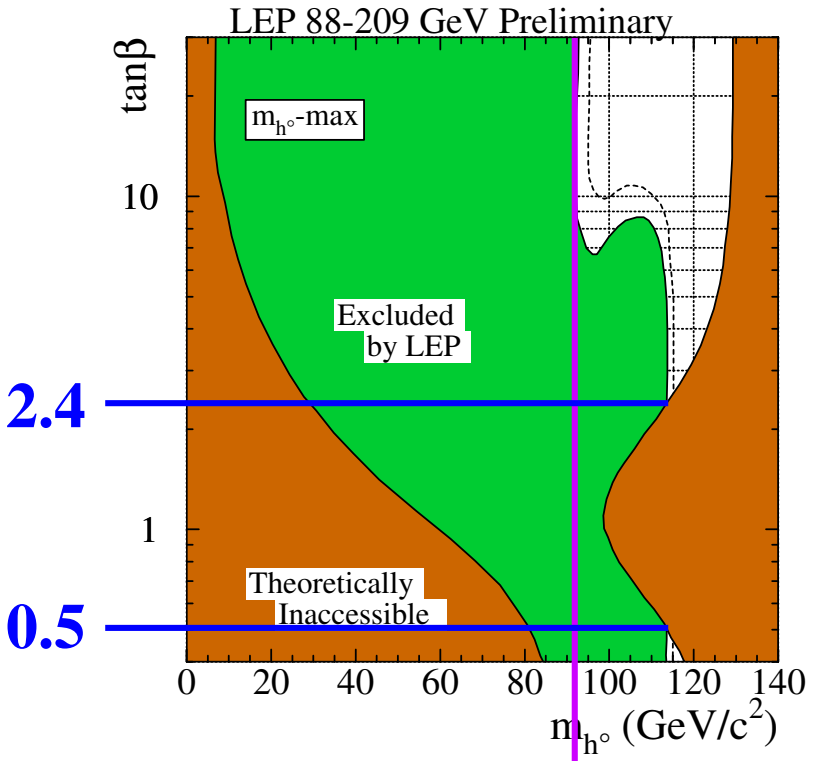


Excluded tanβ: 0.5 < tanβ < 2.4

m_A limit: 91.9 GeV/c^2

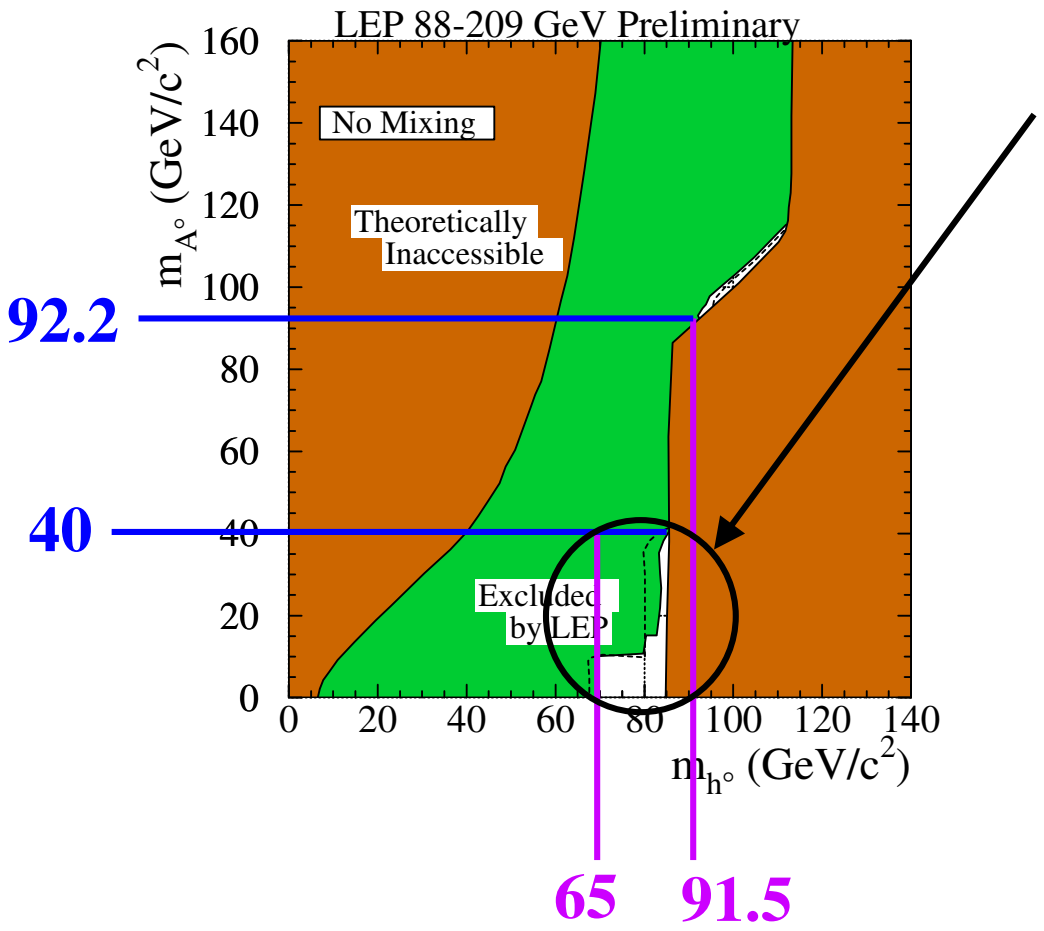
MSSM Parameter scan: Max m_h





m_h limit: 91.0 GeV/c^2

MSSM Parameter scan: No mixing



$e^+e^- \rightarrow hZ \rightarrow AAZ$

but no $A \rightarrow bb$

occurs for:

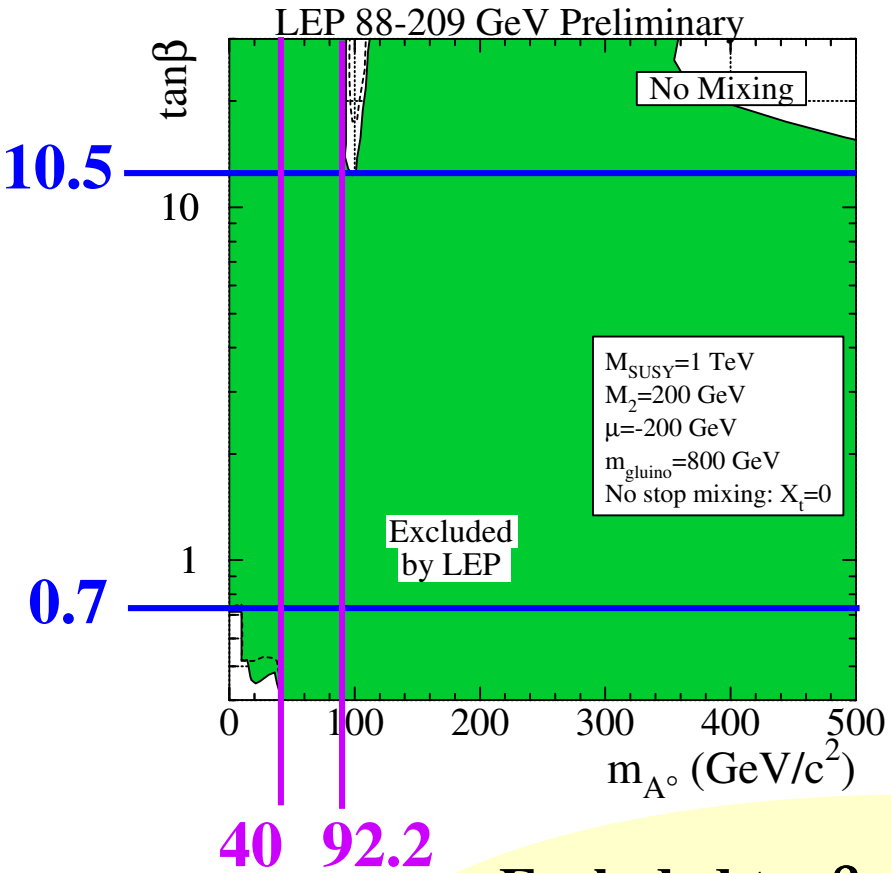
$\tan\beta < 0.7$

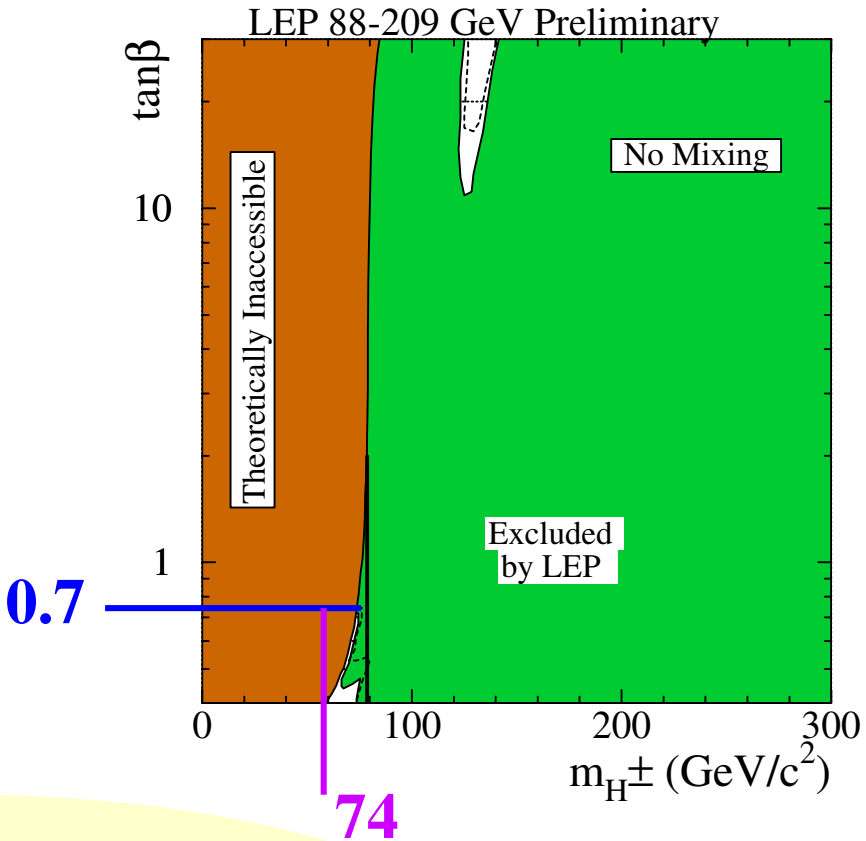
$m_{H^\pm} < 74$ GeV/c^2

Use $H^\pm$ direct searches to exclude this?

→ under investigation

MSSM Parameter scan: No mixing





Excluded tanβ: 0.7 < tanβ < 10.5

m_A limit: 92.2 GeV/c^2 for tanβ > 0.7

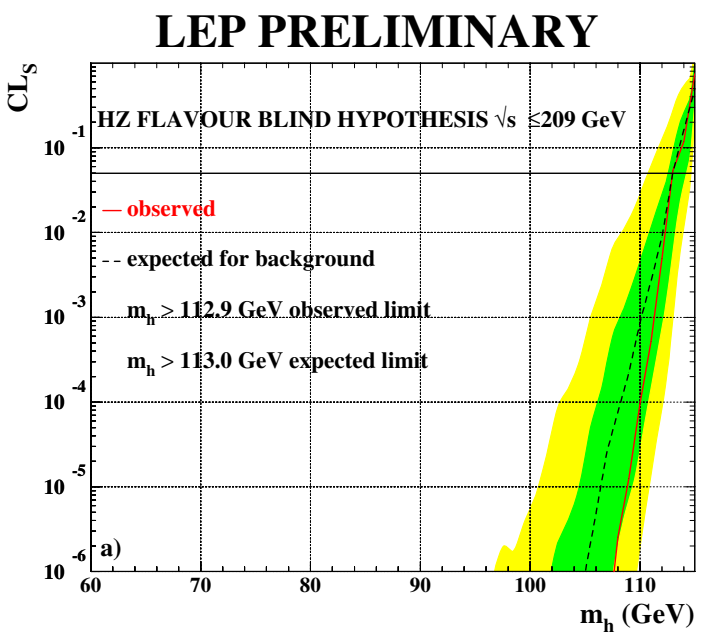
m_h limit: 91.5 GeV/c^2 for tanβ > 0.7

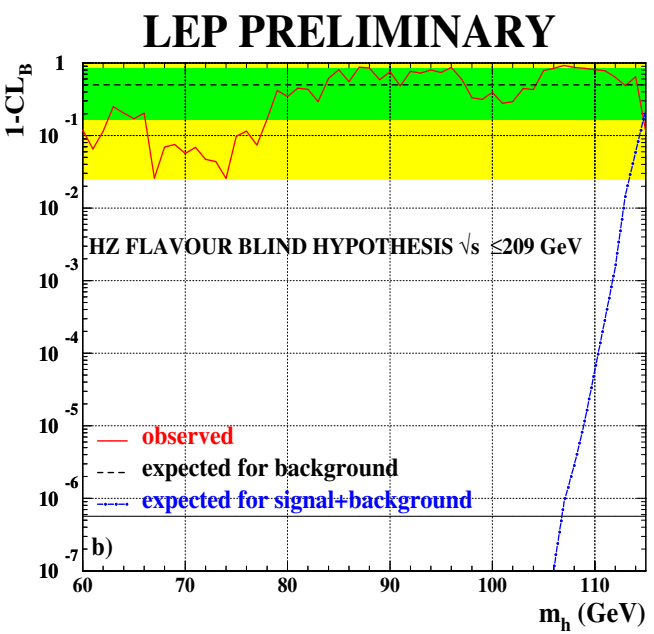
Flavour independent search

- **Extensions of the SM in which Higgs bosons have suppressed couplings into b-quarks**

  ➡ **Flavour-independent search (no b-tag)**

Observed and expected confidence levels for signal and for background-only hypotheses: very consistent





Observed limit:
$M_h < 112.9$ GeV/c^2

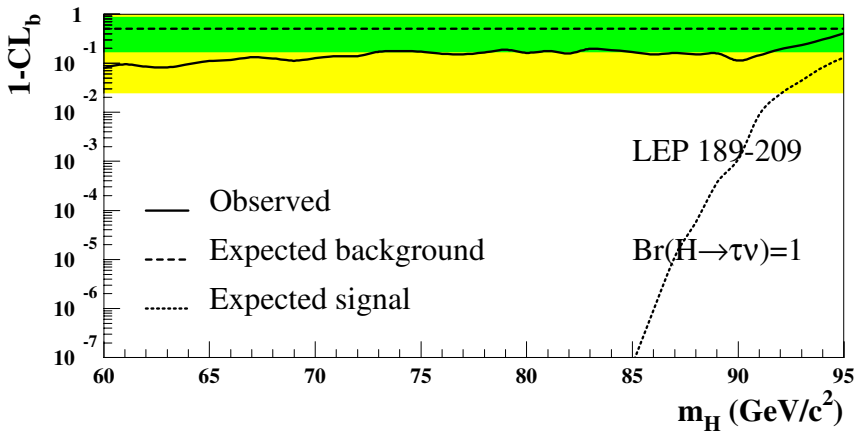
Expected:
$M_h < 113.0$ GeV/c^2

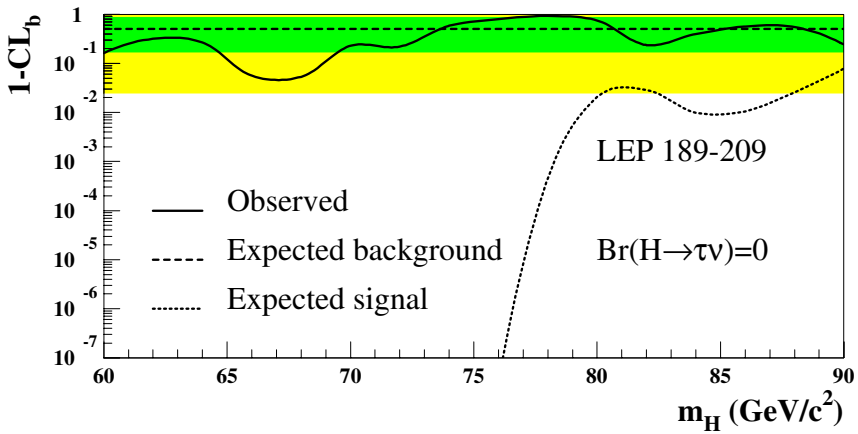
Large μ scan:
entirely excluded

Charged Higgs Bosons (I)

- **Assumption:**
  - **BR($H^+ \to cs$) + BR($H^+ \to \tau\nu$) = 1**
- **Topologies:**
  - **qqqq: 4 jets**
  - **ττττ: leptonic channel**
  - **qqττ: semileptonic channel**

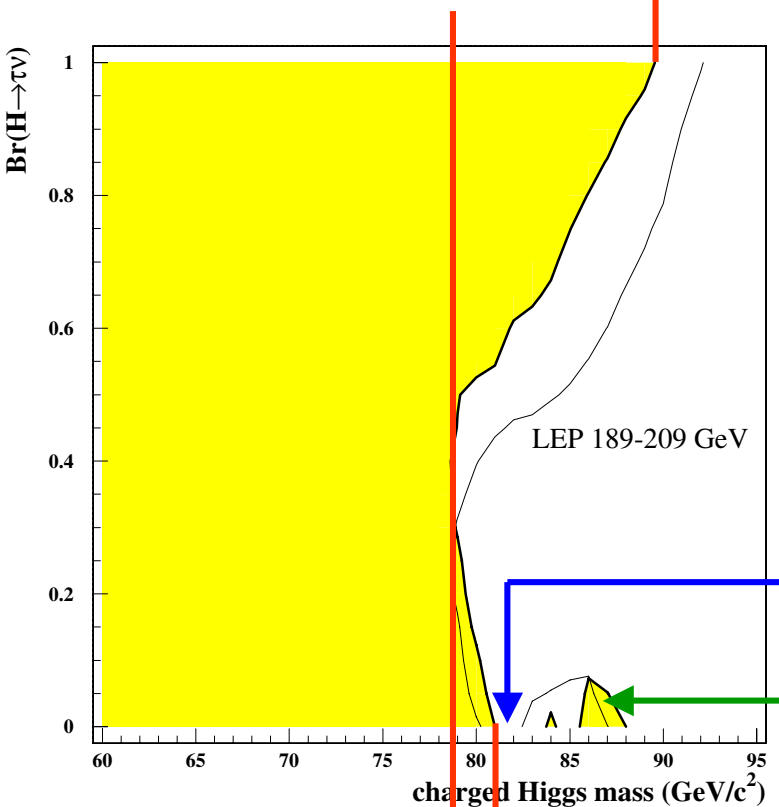
Very difficult to overcome the WW background





Charged Higgs Bosons (II)

89.6 GeV/c^2 for BR($H^+ \to \tau\nu$) = 1



Loose sensitivity due to WW background

Regain sensitivity above 82 GeV/c^2

81.0 GeV/c^2 for BR($H^+ \to \tau\nu$) = 0

78.6 GeV/c^2 for any value of BR($H^+ \to \tau\nu$)

Invisible Higgs Bosons

For example:

$h \to \chi\chi$ (χ = LSP)

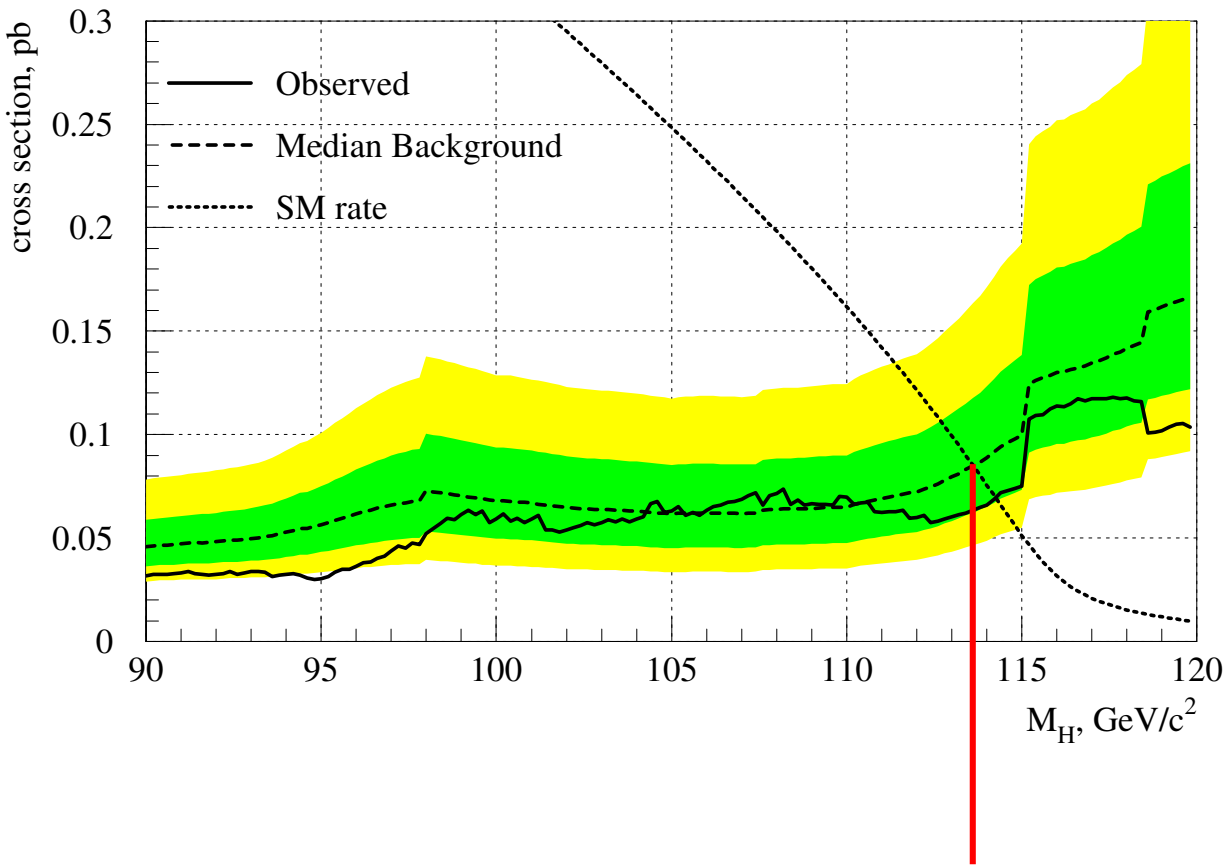
Search for

- $h \to$ invisible
- $Z \to$ qq, ll

Acoplanar jets or leptons

$m_h > 114.4$ GeV/c^2

For SM Higgs σ and B(h → invisible) = 100%



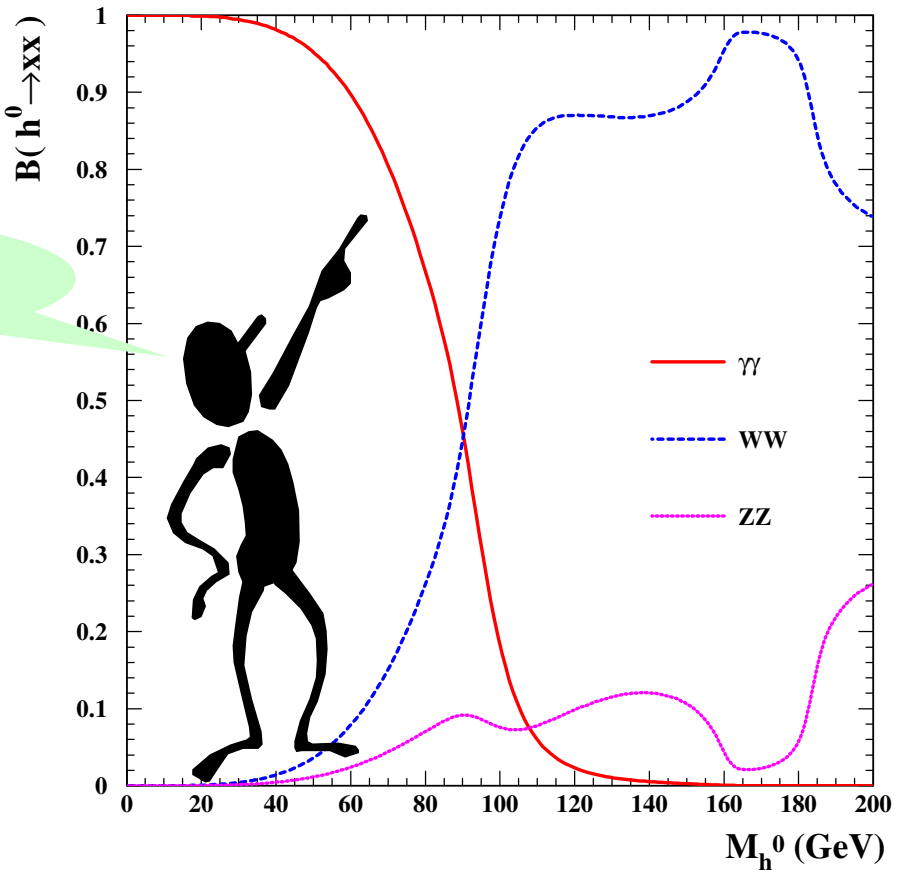
Photonic Higgs Bosons (I)

Fermiophobic Higgs bosons:

$h^0 \not\to ff$

$h^0 \not\to \gamma\gamma$
$h^0 \not\to W^+W^-$
$h^0 \not\to ZZ$

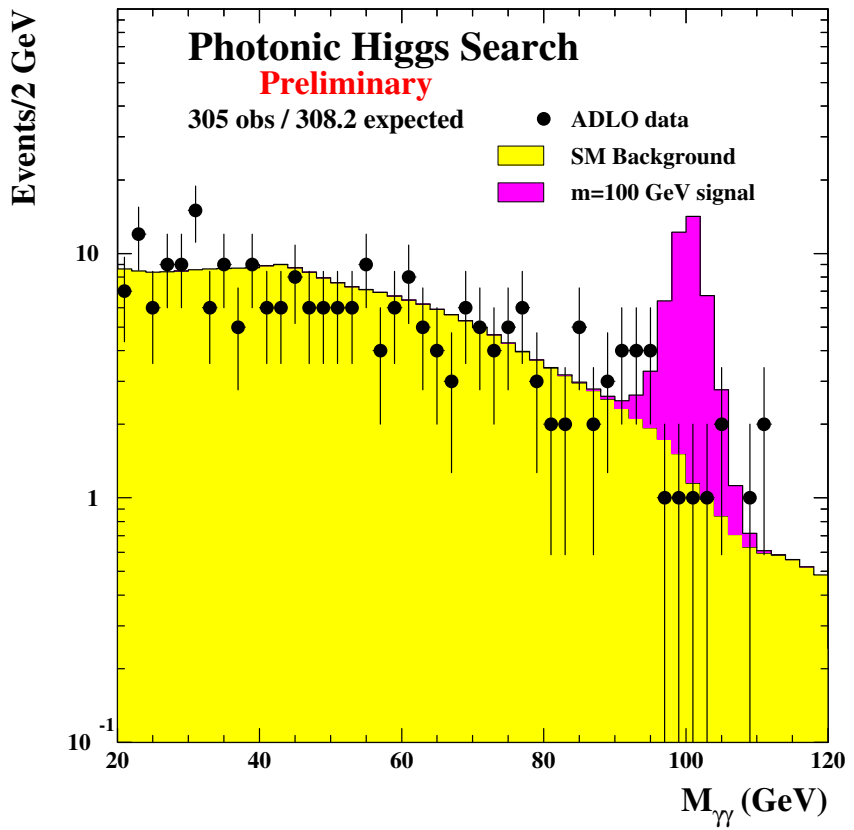
Only $h^0 \not\to \gamma\gamma$

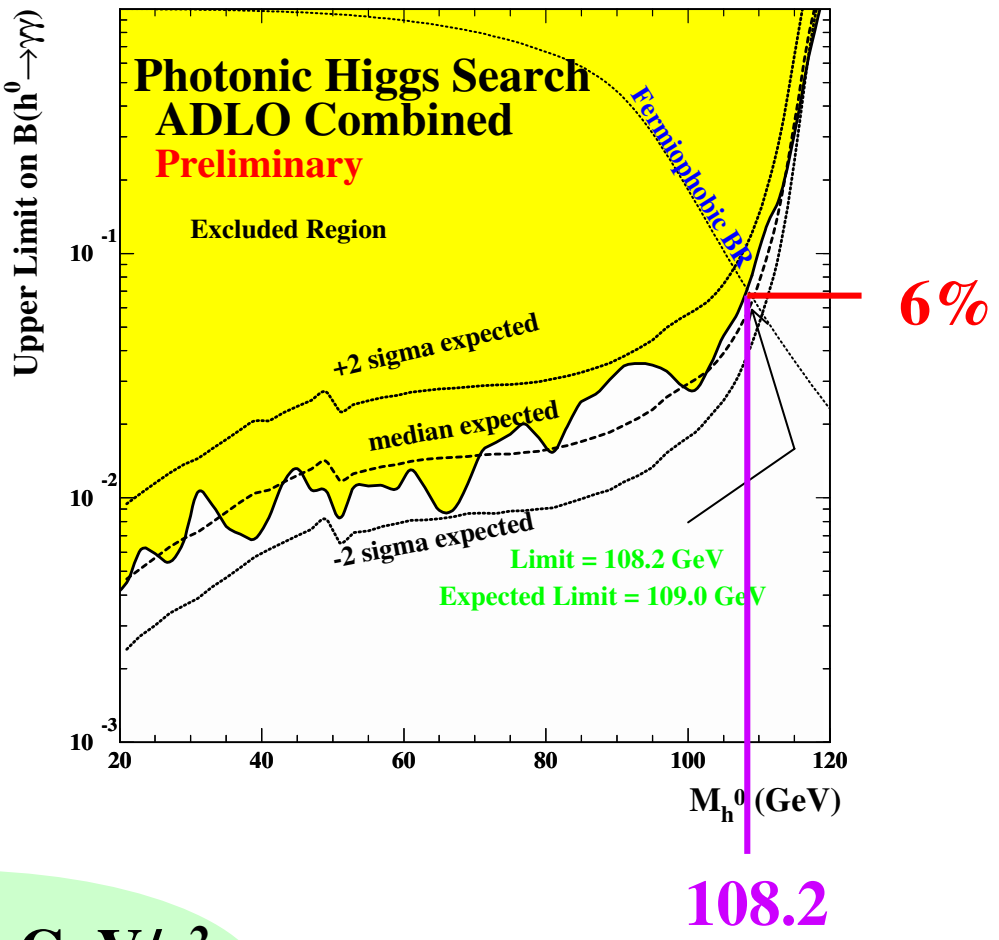


Benchmark:

SM Higgs boson production rate

Photonic Higgs Bosons (II)





$M_h > 108.2$ GeV/c^2

$B(h \to \gamma\gamma) < 6\%$

Conclusions

- **Standard Model Higgs boson**
  - **H^0 mass limit: 114.1 GeV/c^2**

- **SUSY Higgs boson**
  - **MSSM neutral h0, A^0 mass limits: ~ 91 GeV/c^2**
  - **Charged $H^{\pm}$ mass limit: 78.6 GeV/c^2**
  - **Flavour independent search: 112.9 GeV/c^2**
  - **"Invisible" Higgs mass limit: 114.4 GeV/c^2**
  - **Photonic Higgs mass limit: 108.2 GeV/c^2**