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LEP Results on Non-Standard Higgs bosons

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CPNSH, Dec 2004, CERN

M.Boonekamp, CEA-Saclay

- Overview of results
  - … on topological cross-sections
  - … in explicit models
- Holes in the LEP search
- « Persistification »
- Perspectives

…reminder…

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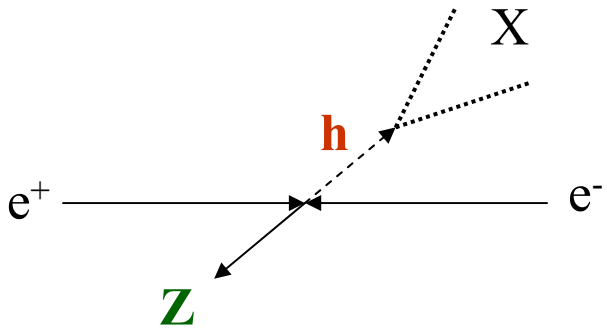

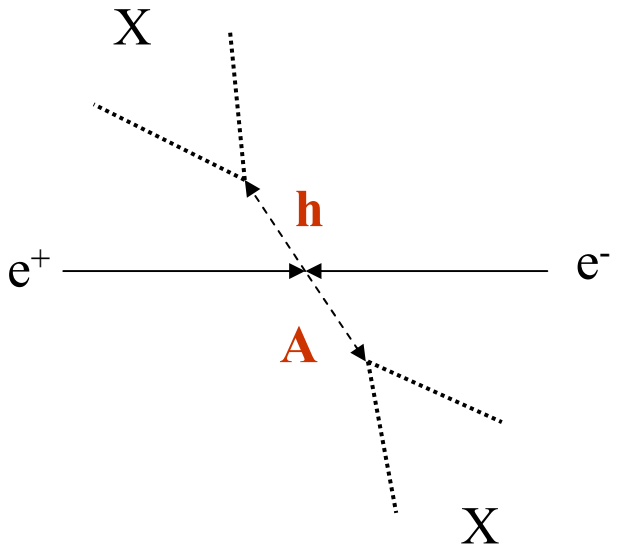

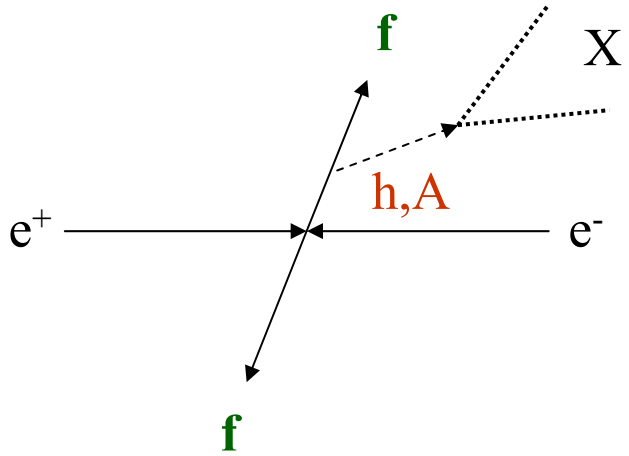

CP-conserving notation,
extends to CPV
modulo h→ h1, A → h2

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…reminder…

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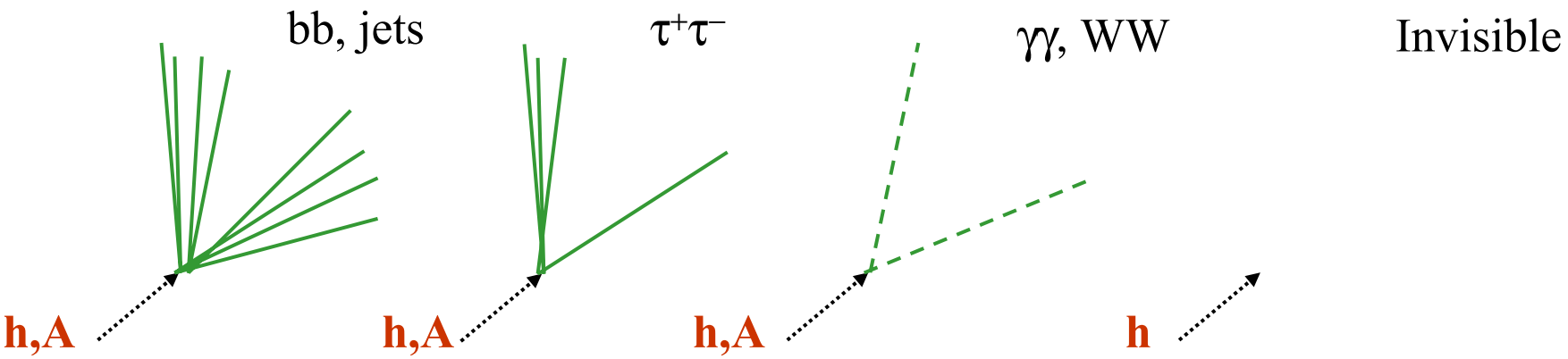
- Considered decay modes



+ intermediate decays h → AA, h → AZ,…

- From there :
  - Let theory guide your searches
  - Exhaust all possibilities (well…)

"C²" exclusions

(not new, but getting standard)

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- Can be defined for all final states : a few examples

$$\sigma_{hA\to 4f} = \sigma^{ref}_{hA} \times R_{hA} \times BR(h \to f\bar{f}) \times BR(A \to f\bar{f})$$
$$\equiv \sigma^{ref}_{hA} \times C^2_{hA\to 4f};$$

$$\sigma_{hZ\to b\bar{b}Z} = \sigma^{SM}_{hZ} \times R_{hZ} \times BR(h \to b\bar{b})$$
$$\equiv \sigma^{SM}_{hZ} \times C^2_{Z(h\to bb)};$$

$$\sigma_{(AA)A\to 6b} = \sigma^{ref}_{hA} \times R_{hA} \times BR(h \to AA) \times BR^3(A \to b\bar{b})$$
$$\equiv \sigma^{ref}_{hA} \times C^2_{hA\to 6b};$$

$$\sigma_{b\bar{b}h\to b\bar{b}\tau^+\tau^-} = \sigma^{SM}_{b\bar{b}h} \times R_{b\bar{b}h} \times BR(h \to \tau^+\tau^-)$$
$$\equiv \sigma^{SM}_{b\bar{b}h} \times C^2_{bb(h\to\tau\tau)};$$

- Easy re-use :
  - Write your model; compute Higgs couplings; multiply, divide, add…
  - Compare with excluded values
  - Simpler than cross-sections (no need for a generator interface, ISR, etc)

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Implications, caveats

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- Using C^2, the exploitation of data is not optimal
  - Cannot combine signals statistically → loss in sensitivity (moderate)
- How to combine several channels?
  - Naïvely : look at all channels; compare C^2_{mod} with C^2_{exc} ; if at least one is excluded, your scenario is excluded
  - But C^2_{exc} are 95% CL : combining them using "OR" decreases confidence
  - In practice, this is only a problem if you have many channels and predictions close to the excluded values (but keep in mind!)

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Overview of existing results - 1

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- On topological cross-sections
  - Heavy fermions : b-quarks, τ-leptons
    - LHWG-Note 2004-01
    - DELPHI, Eur.Phys.J.C38:1-28,2004
  - Hadronic modes («flavour-blind»)
    - LHWG-Note 2001-07
    - DELPHI, 2004-034
    - L3, CERN-EP/2003-069
    - OPAL, CERN-PH-EP/2004-039
  - Bosonic decay modes
    - LHWG-Note 2002-02
    - DELPHI, Eur.Phys.J.C35:313-324,2004
    - L3, Physics Letters B 589 (2004) 89-102
  - Decay-mode independent search
    - OPAL, PN495 (contributed to ’02 conferences)

Heavy fermion final states : hZ

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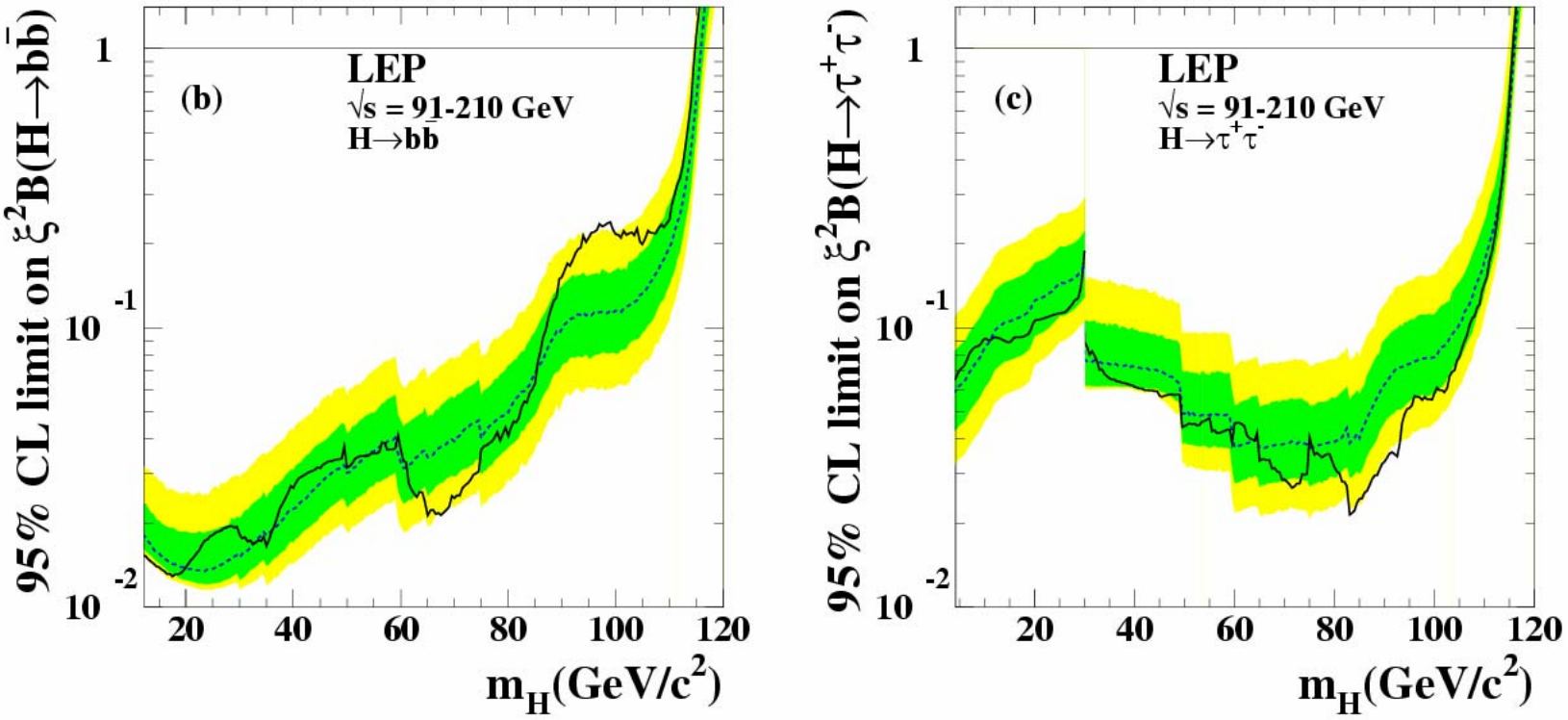

- Directly obtained from SM Higgs boson searches

Heavy fermion final states : hA

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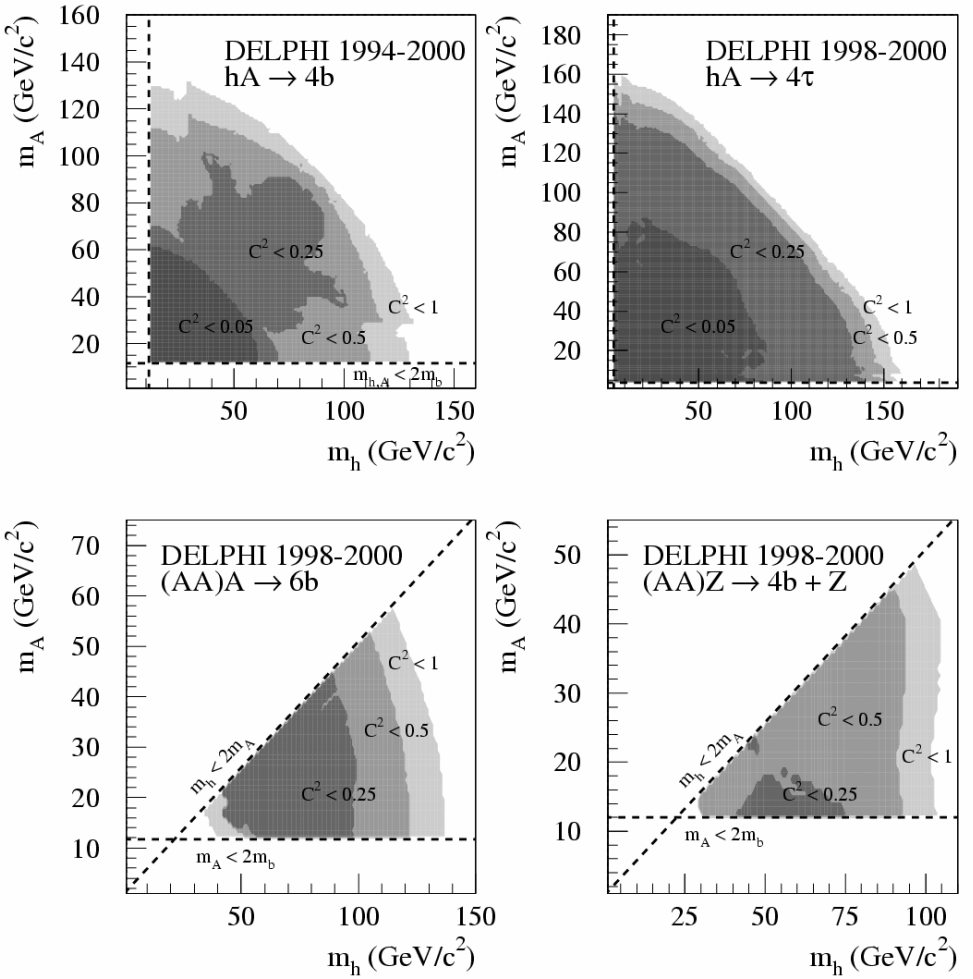
- Delphi 2004
- All final states with b's down to threshold
  - 4b, 6b, 4b+Z final states
- First 4τ search
- Lacking : bbττ (but there are data from other expts)



Flavour-blind : hZ

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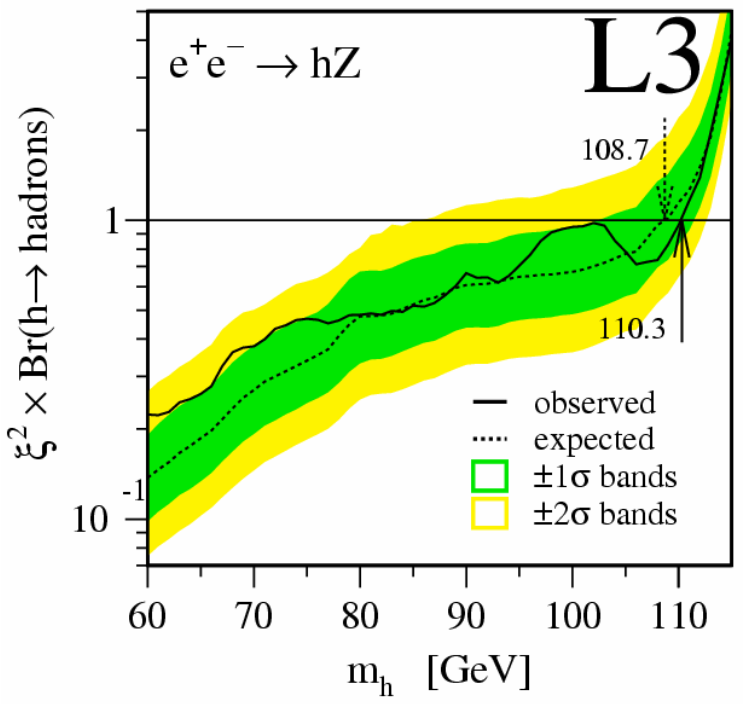

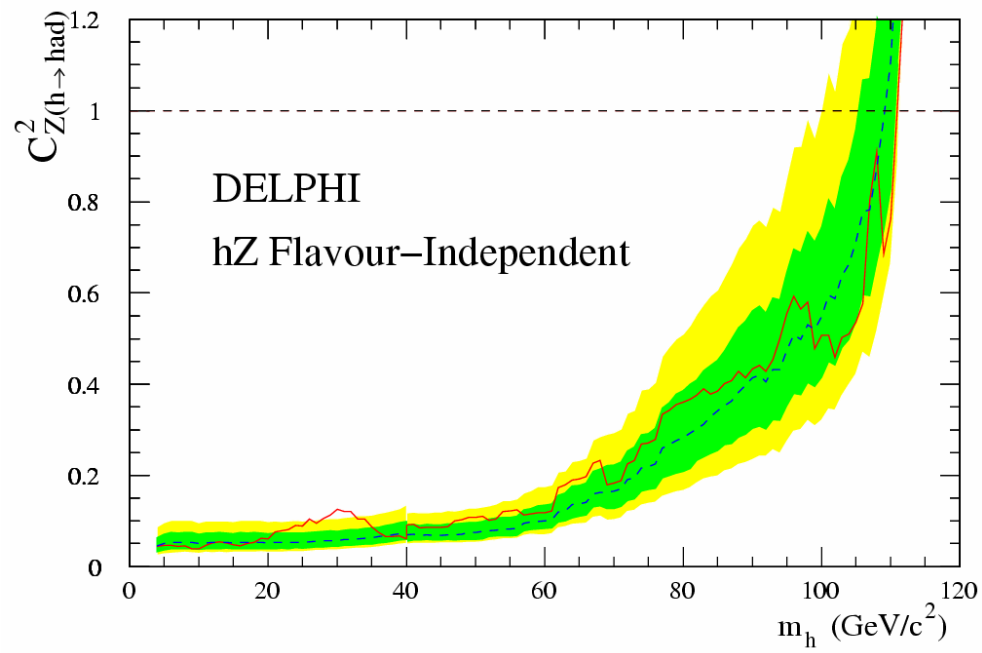

- LEP 2 results using 4-jet searches (ADLO); DELPHI extends to lower masses (m_h>4 GeV) using 3-jet and νν-jet searches

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Flavour-blind : hZ

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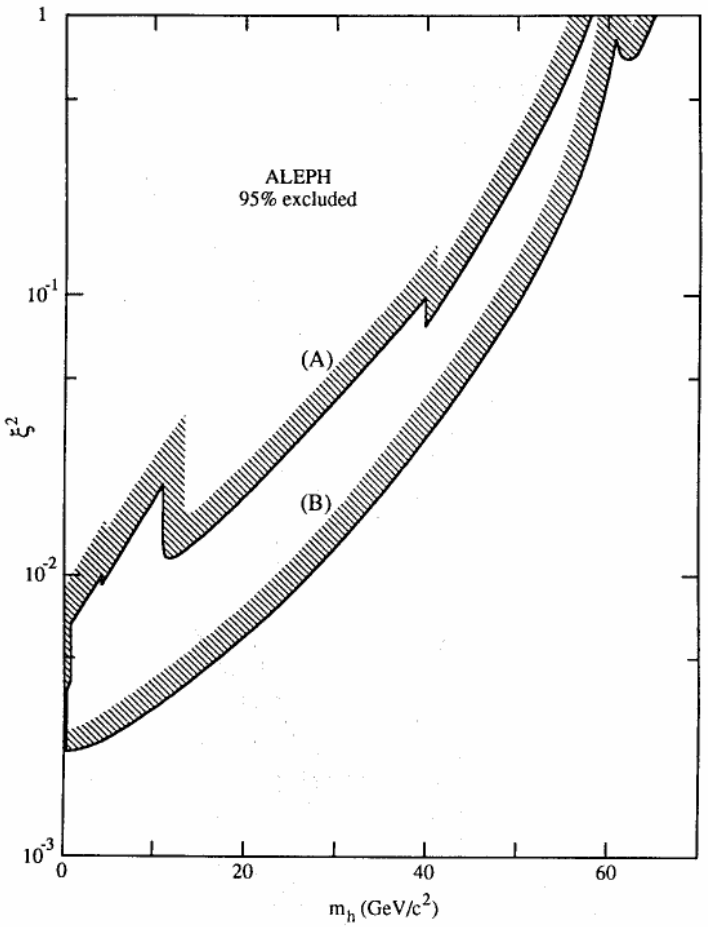
- An old (but strong) ALEPH result
  - Curve (A) from h → hadrons
  - Curve (B) from invisible Higgs decays
  - Down to m_h=0
- ALEPH, PLB 1993



Flavour blind : hA

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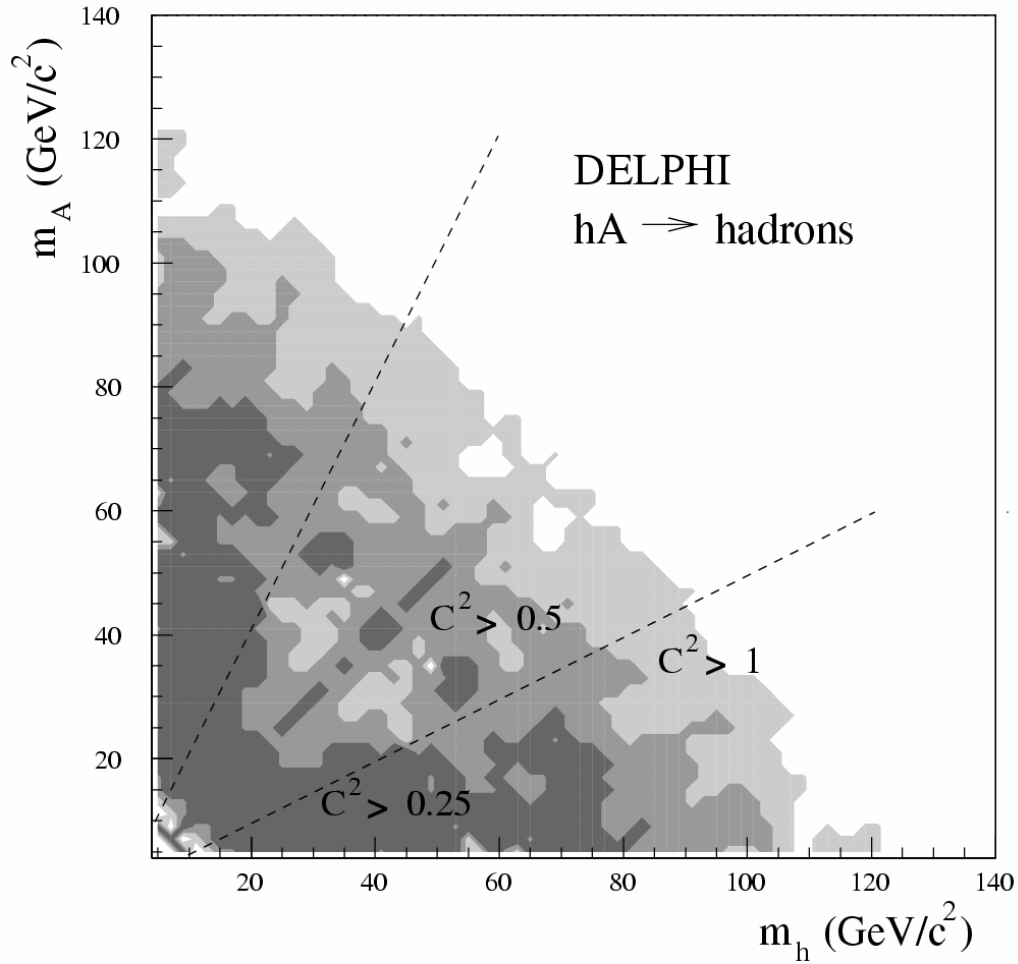
- 2-, 3-, and 4-jet searches to cover most of the mass domain
- Also data from L3, OPAL (with higher thresholds)



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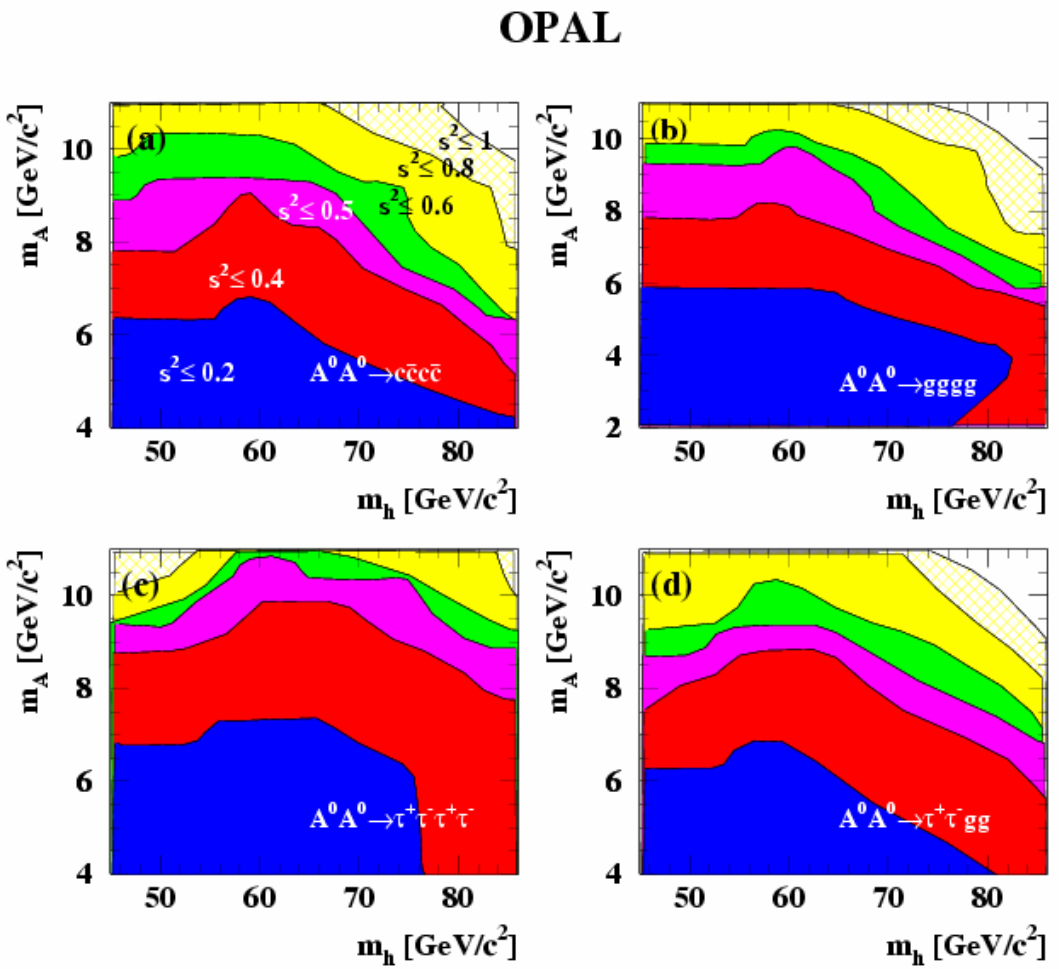
- Special search, aimed at excluding a particular MSSM param. Space region
- hZ → (AA)Z;
  A → hadrons, τ's
- $40 < m_h < 90$ GeV
  $2 < m_A < 12$ GeV



Bosonic final states : hZ

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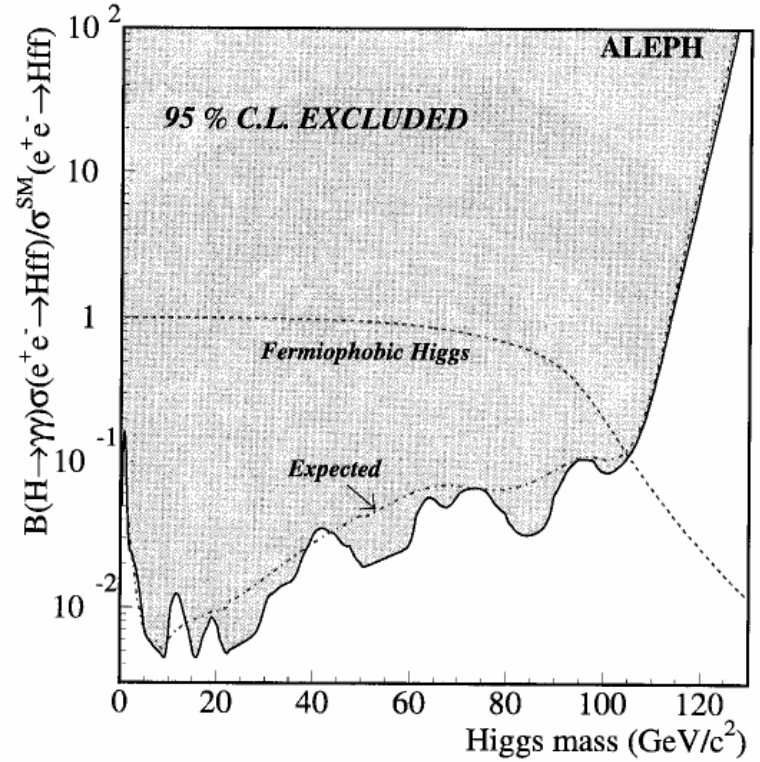

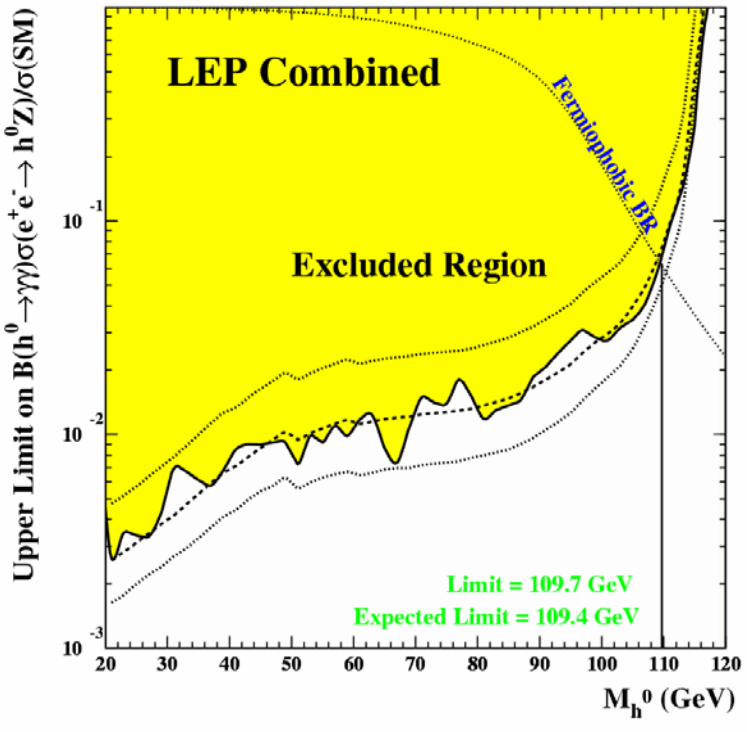

- ADLO, H → γγ (ALEPH goes to m_H~0)

Bosonic final states

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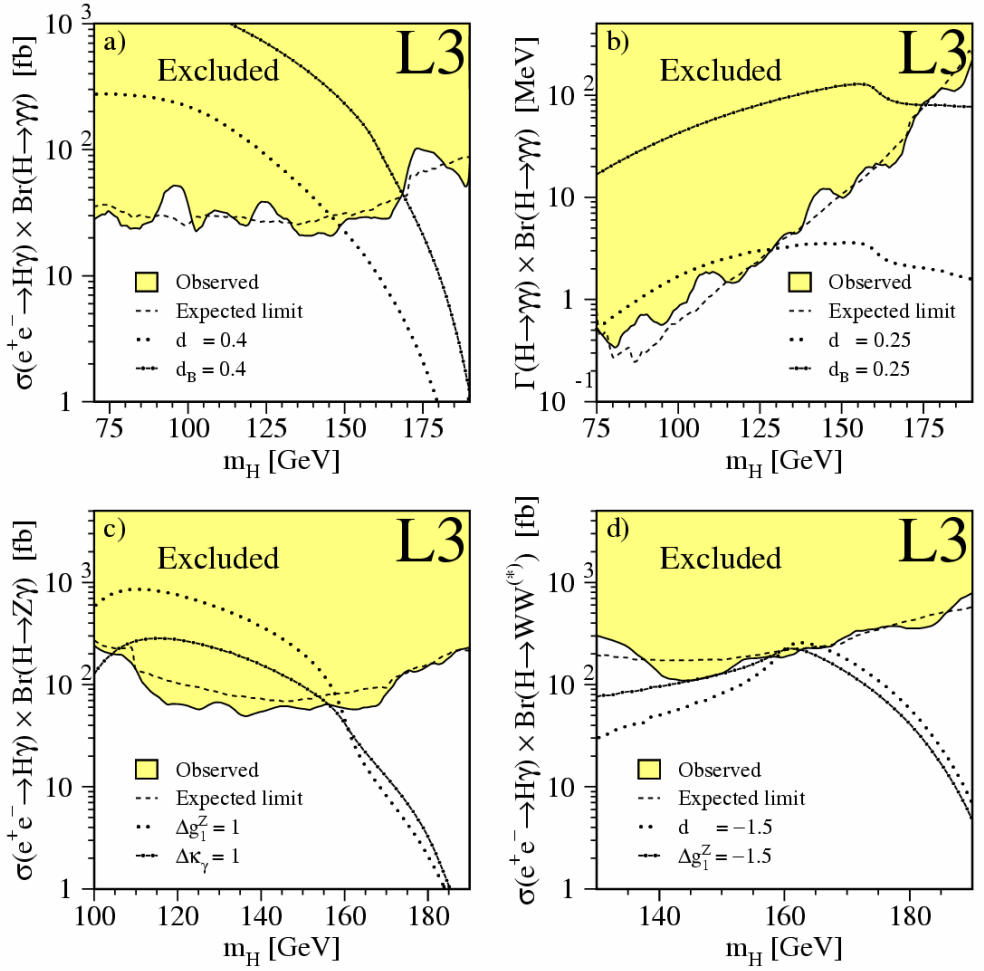
- General approach by L3 : anomalous Higgs couplings to γγ, WW, ZZ
- Production & decay modes :
  - $e^+e^- \rightarrow H\gamma$
  - $e^+e^- \rightarrow e^+e^-H$
  - $e^+e^- \rightarrow HZ$
  - Decays to γγ, WW, ZZ
- Here excluded cross-sections from $e^+e^- \rightarrow H\gamma$



OPAL decay mode indep. search

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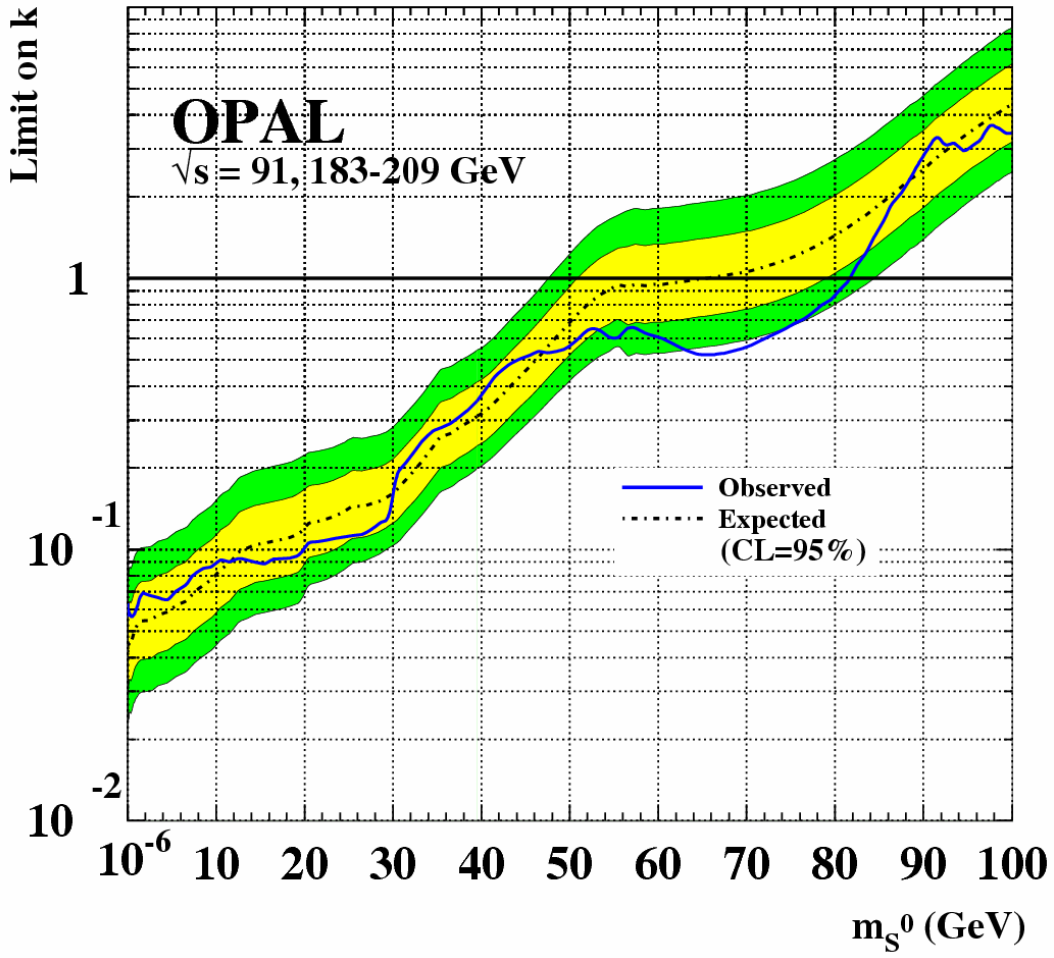
- OPAL $e^+e^- \rightarrow hZ$
  - $Z \rightarrow ee, \mu\mu$
  - $h \rightarrow X$
- Essentially an analysis of the mass recoiling against the Z



Overview of existing results - 2

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- In explicit models :
  - 2HDM
    - Neutral Higgs bosons
      - OPAL, CERN-PH-EP/2004-039
    - Charged Higgs bosons
      - LHWG-Note 2001-05
      - ADLO papers & conference notes quoted above
  - MSSM with CP violation
      - LHWG-Note 2004-01
      - ADLO conference notes quoted above

- These searches use all final states described earlier and combine them statistically, according to their relative cross-sections in each specific model (using the modified frequentist LR)

MSSM with CP violation

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- As usual :

$$\sigma_{\mathrm{H}_i\mathrm{Z}} = g^2_{\mathrm{H}_i\mathrm{ZZ}}\ \sigma^{SM}_{\mathrm{HZ}}$$

$$\sigma_{\mathrm{H}_i\mathrm{H}_j} = g^2_{\mathrm{H}_i\mathrm{H}_j\mathrm{Z}}\ \bar{\lambda}\ \sigma^{SM}_{\mathrm{HZ}}$$

- But now

$$g_{\mathrm{H}_i\mathrm{ZZ}} = \cos\beta\mathcal{O}_{1i} + \sin\beta\mathcal{O}_{2i}$$

$$g_{\mathrm{H}_i\mathrm{H}_j\mathrm{Z}} = \mathcal{O}_{3i}(\cos\beta\mathcal{O}_{2j} - \sin\beta\mathcal{O}_{1j}) - \mathcal{O}_{3j}(\cos\beta\mathcal{O}_{2i} - \sin\beta\mathcal{O}_{1i})$$

- Usual sum rules still apply. The O_{ij} are a measure of CPV effects, and are proportional to

$$\mathcal{O}^2_{ij} \propto \frac{m_t^4}{v^2}\frac{\mathrm{Im}(\mu A)}{32\pi^2 M^2_{\mathrm{SUSY}}},$$

- Hence the CPX benchmark, maximizing the CPV impact : small M_{susy}, large μA ; also arg(A) = 90°…

MSSM with CP violation

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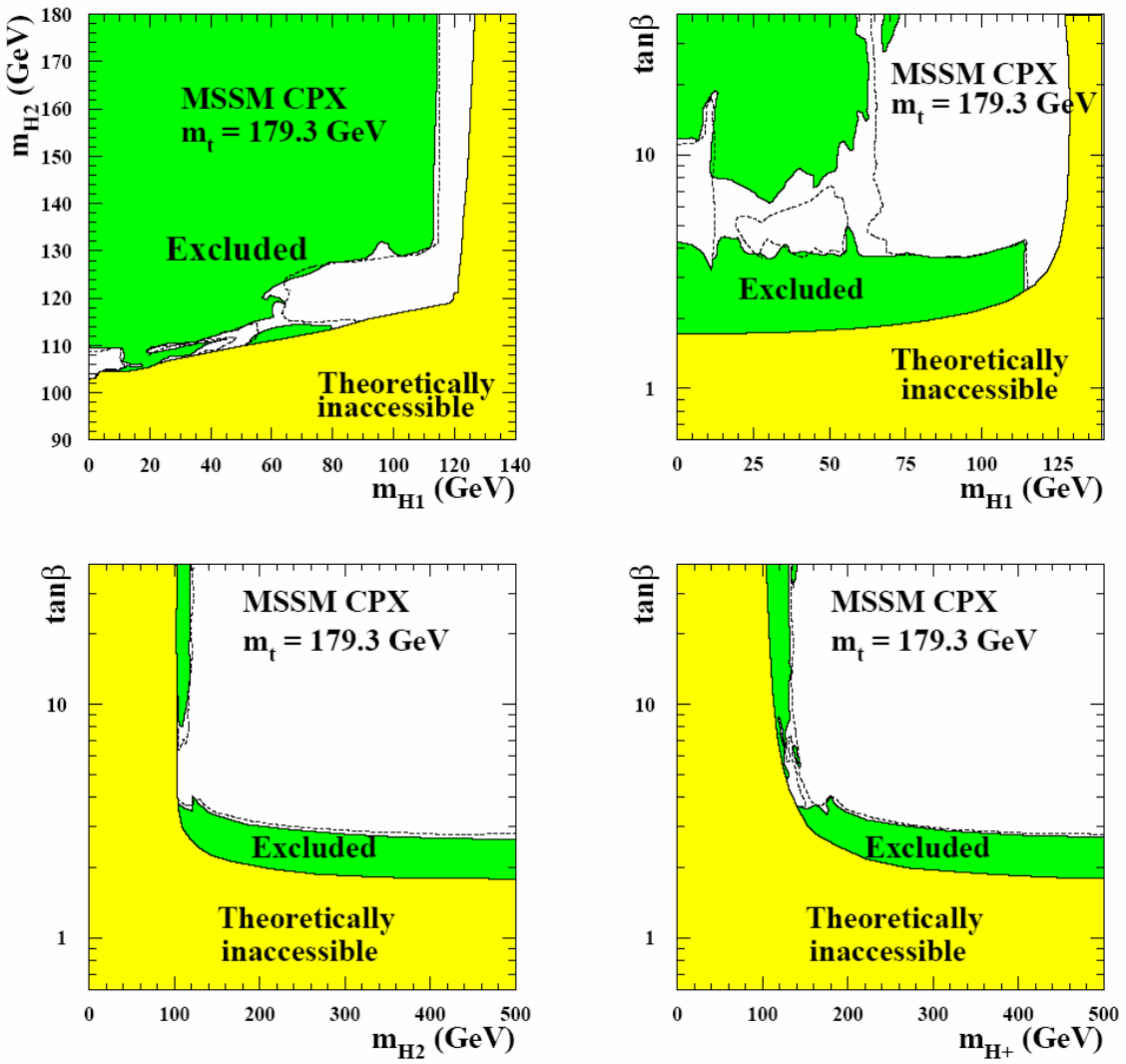

MSSM with CP violation

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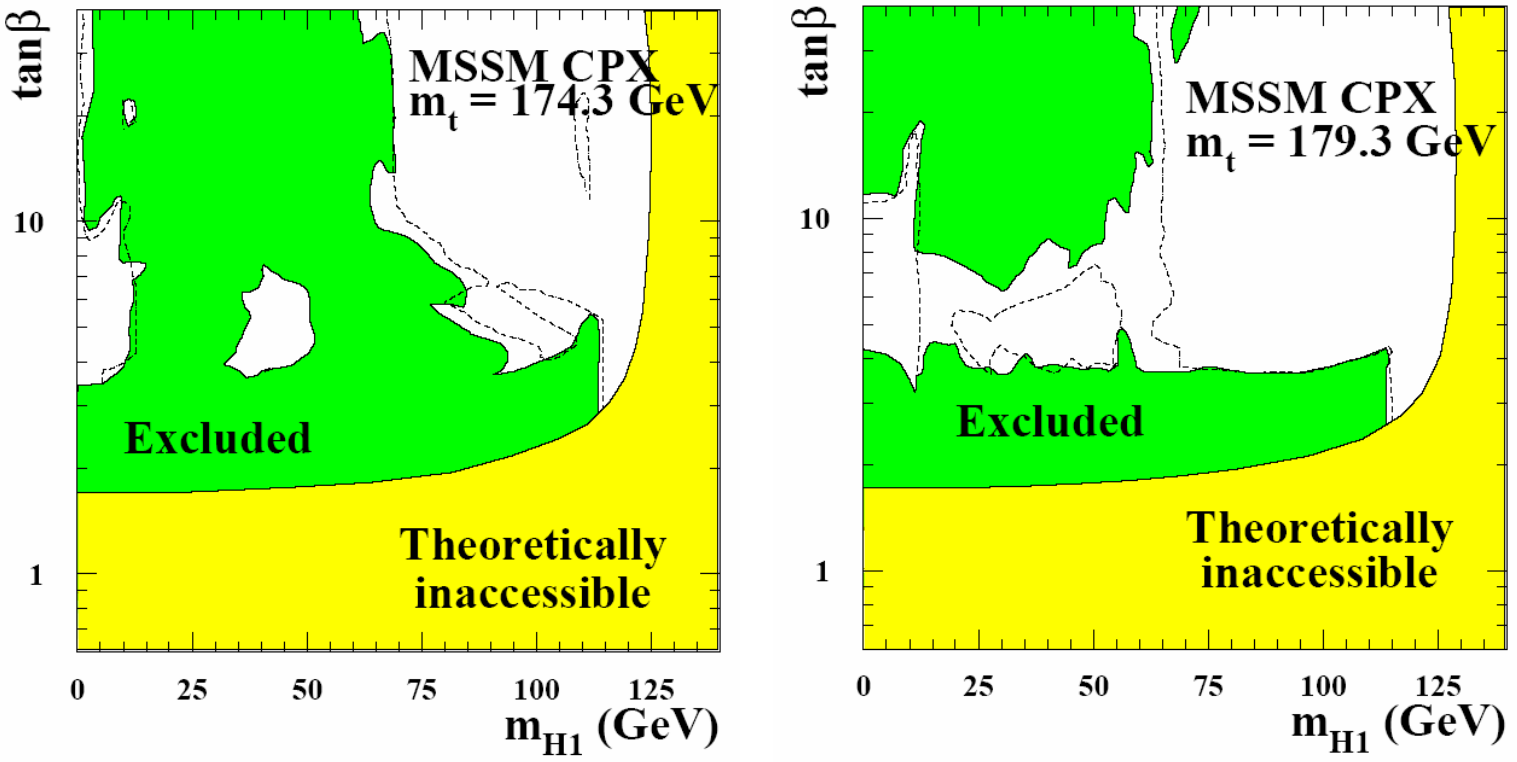

- Large impact of the new Tevatron top mass

2HDM : neutral Higgs bosons

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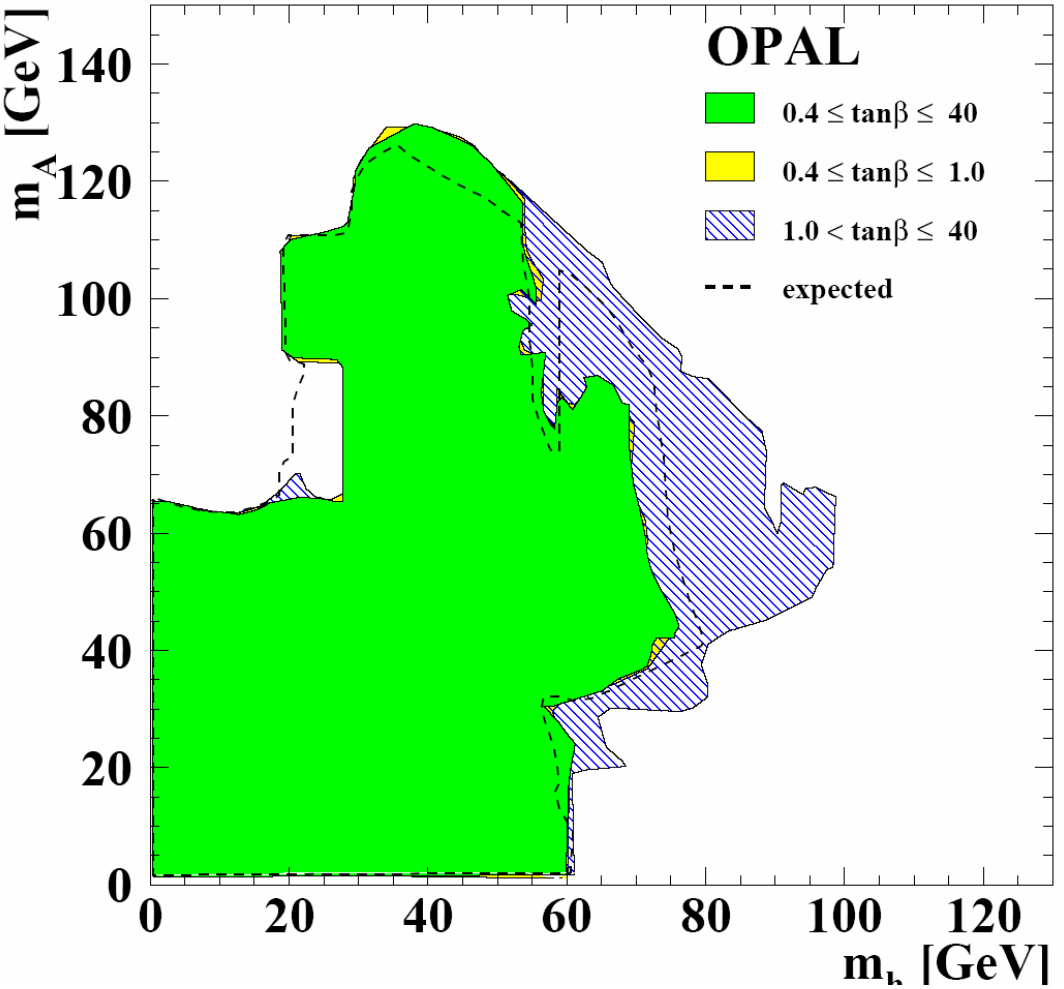
- Explicit 2HDM scan by OPAL
- Scan over m_h, m_A, α, β m_H, $m_{H^\pm}$ far away
- Only standard decay modes assumed



2HDM : Charged Higgs bosons

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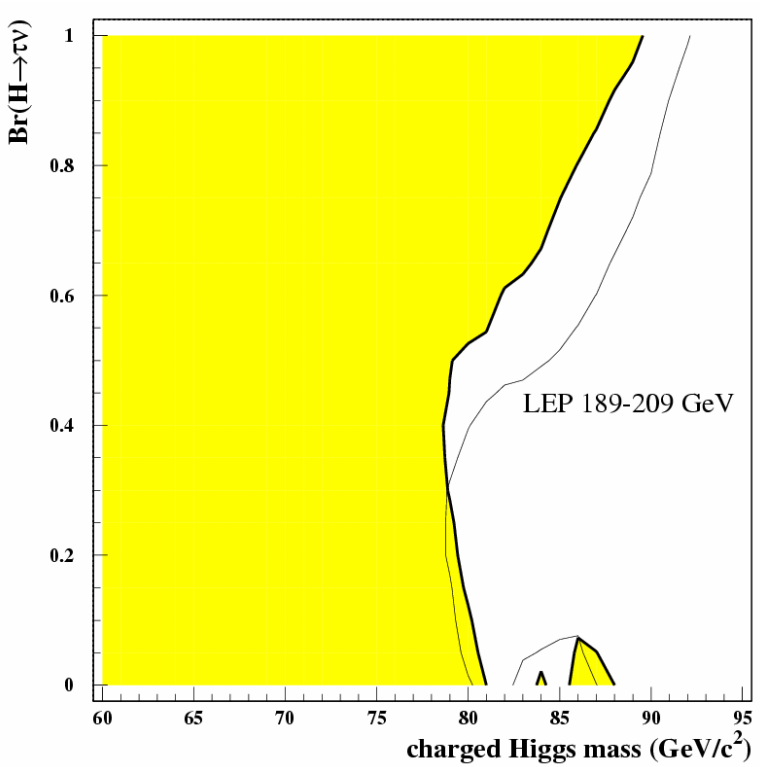

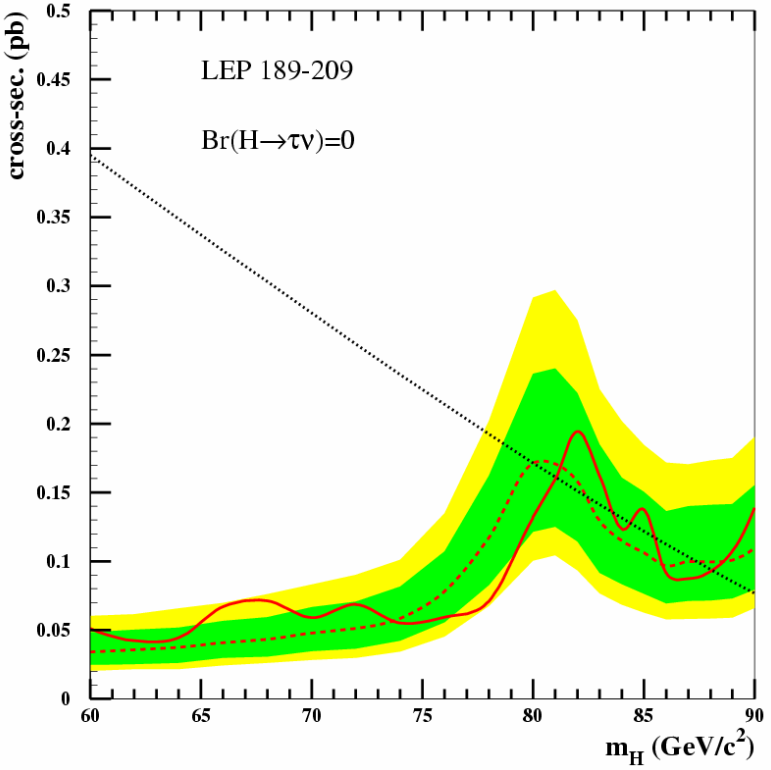

- $e^+e^- \rightarrow H^+H^-$; $H^\pm \rightarrow cs$ or $\tau\nu$

Can a Higgs boson still hide in the LEP data?

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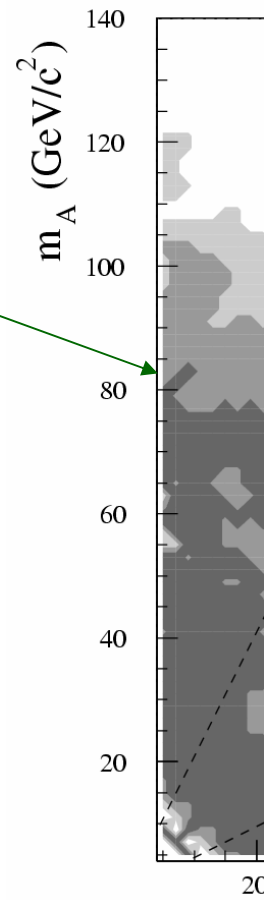
- Direct decays
  - Heavy flavours (b,τ) : down to threshold, can't do better
  - Flavour-blind : hZ down to threshold, hA down to 4 GeV
  - Photons : ADLO combination down to 20 GeV, ALEPH down to ~0 (limited sensitivity)
- Cascade decays (intermediate h→AA):
  - Complete in heavy quarks, some results in τ-decays
  - OPAL Flavour-blind results in specific mass range : $40 < m_H < 90$, $2 < m_A < 12$ GeV
- For some of these, combinations still on the way



Aim at producing results in this form:

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```
C
C The following numbers correspond to excluded coupling factors
C (i.e. the C^2 factors which, when multiplied by the full strength
C ee -> hA cross-section, are excluded at 95%CL).
C
C Channel : hA -> 4b
C Format : m1 m2 C^2    (m1<m2)
C Grid : 1 GeV x 1 GeV
C
C Ref: DELPHI-2003-037-CONF-657, CERN-EP 2003-061
C      Submitted to EPJ
C
C Problems : Maarten.Boonekamp@cern.ch
C

  12.   12.   0.0219999999
  12.   13.   0.0181000009
  12.   14.   0.0142000001
  12.   15.   0.0111999996
  12.   16.   0.00930000003
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  12.   37.   0.00829999987
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.....

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  12.   51.   0.0161000006
  12.   52.   0.0181000009
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  12.   54.   0.0219999999
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What I couldn't cover…

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- Doubly charged Higgs bosons
  - Pair-production studied by DELPHI, L3, OPAL
  - Single production studied by OPAL
- The Yukawa process : bbH, ττH, and H → bb, ττ
  - Most recent papers by DELPHI, OPAL
- Radions (not Higgs, but still 0++)
  - OPAL exploitation of theirexcluded topological cross-sections
    -- a C^2 use case

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Conclusions & Perspectives

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- The LEP results presentation tends to change
  - In data-taking : Th/Exp dialog – detailed benchmark scans by the expts
  - Beyond : legacy papers – model-independent presentation, suitable for tomorrow's benchmarks

- Still more results to come:
  - Per experiment:
    - ALEPH and OPAL on Bosonic decay modes (incl. h→WW)
    - OPAL on Charged Higgs bosons
    - OPAL on Invisible Higgs bosons
  - Results will be combined as soon as published

- Will try to make C^2 tables a standard. Priorities?

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Back-up

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Benchmark parameters				
	(1) *no-mixing*	(2) m_{h}-*max*	(3) large-μ	(4) *CPX*
Parameters varied in the scan				
$\tan\beta$	0.4–40	0.4–40	1–50	0.6–40
m_{A} (GeV)	4–1000	4–1000	4–400	–
$m_{\mathrm{H}^\pm}$ (GeV)	–	–	–	4–1000
Fixed parameters				
M_{SUSY} (GeV)	1000	1000	400	500
M_2 (GeV)	200	200	400	200
μ (GeV)	-200	-200	1000	2000
$m_{\tilde{\mathrm{g}}}$ (GeV)	800	800	200	1000
X_t (GeV),	0	$\sqrt{6}\,M_{\mathrm{SUSY}}$	-300	$A - \mu\cot\beta$
A (GeV)	$X_t + \mu\cot\beta$	$X_t + \mu\cot\beta$	$X_t + \mu\cot\beta$	1000
$\arg A$, $\arg m_{\tilde{\mathrm{g}}}$	-	-	-	90°