

# Neutral MSSM Higgs searches – the legacy of LEP



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On behalf of the LEP Higgs WG

1. MSSM Higgs Searches at LEP and Model Independent Exclusions
2. The MSSM Interpretation of the LEP Higgs Searches
3. Some prospects

# The MSSM Higgs Phenomenology

- Two Higgs doublets  $\Rightarrow$  5 physical Higgs bosons:

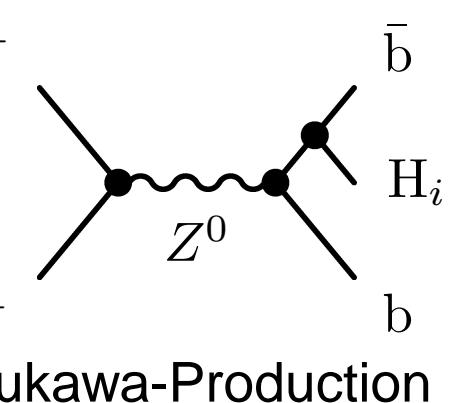
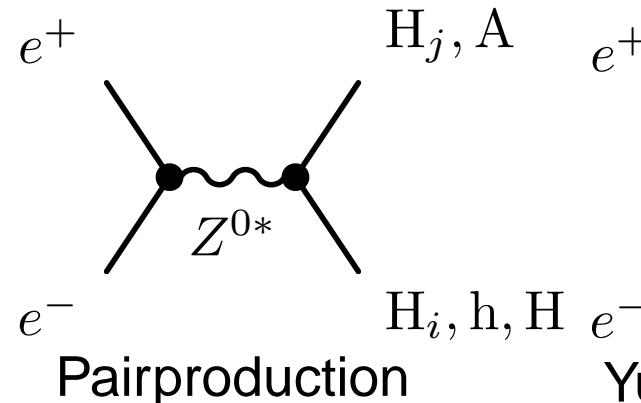
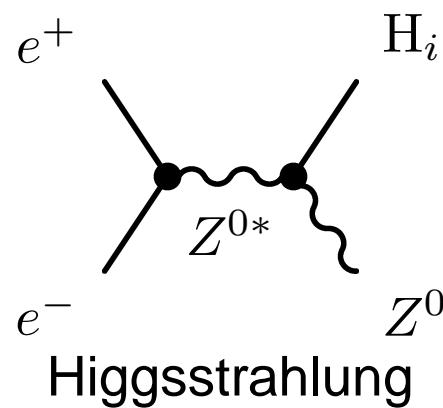
- CP-conserving models:

$$h, H \quad (\text{CP} - \text{even}) \quad A \quad (\text{CP} - \text{odd}) \quad H^\pm$$

- CP-violating models: mass eigenstates no longer CP eigenstates

$$H_1, H_2, H_3, \quad H^\pm$$

- Two main production mechanisms for neutral Higgses + Yukawa:



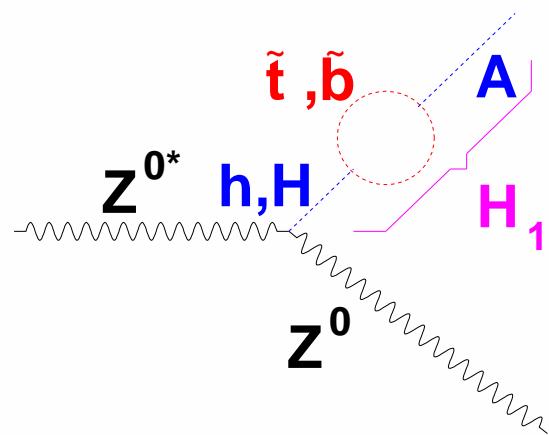
- Tree level:  $m_{H_1, \text{tree}} \leq m_Z$  but large rad. corrections  $t, \tilde{t}$

$m_{H_1, \text{loop}} \approx 1.5m_{H_1, \text{tree}}$  **Concentrate on neutral Higgses**

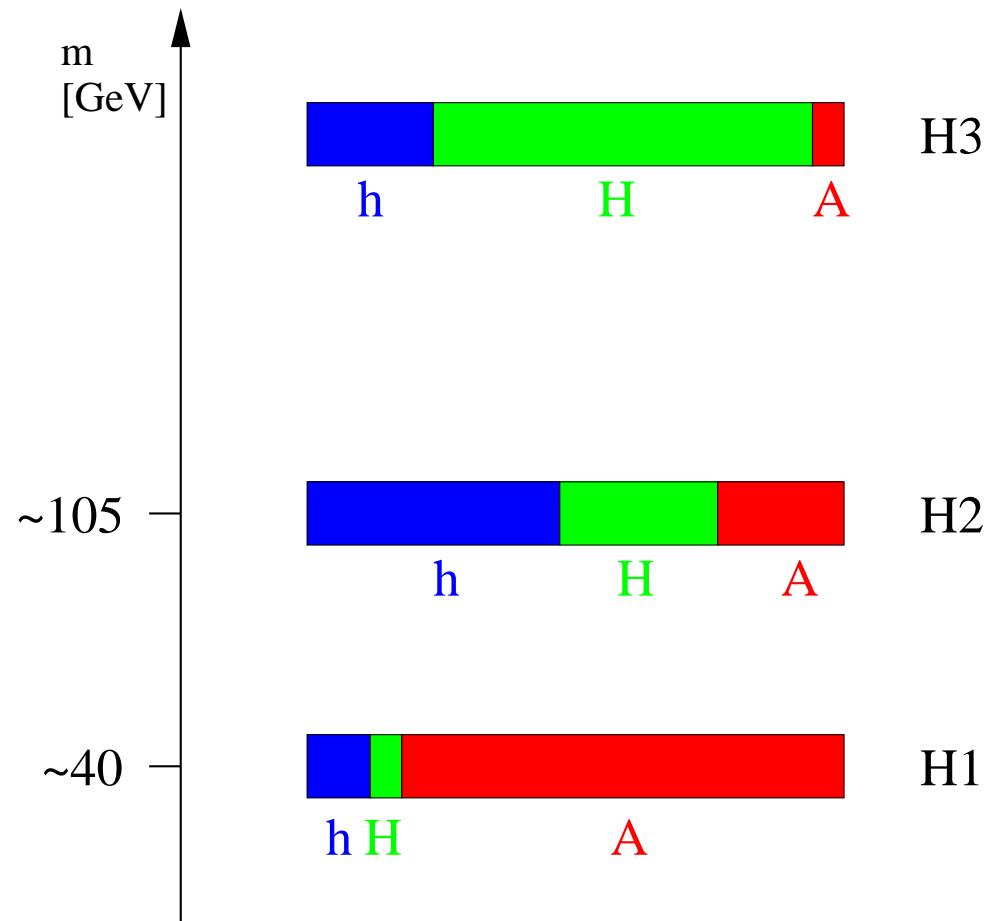
# CP-Violating MSSM Higgs Sector

- CP-conserving model: mostly just 1 Higgs  $h$  in Higgsstrahlung

Complex phases of  $A_{t,b}$  in  $A\tilde{t}\tilde{t}H$   
coupling

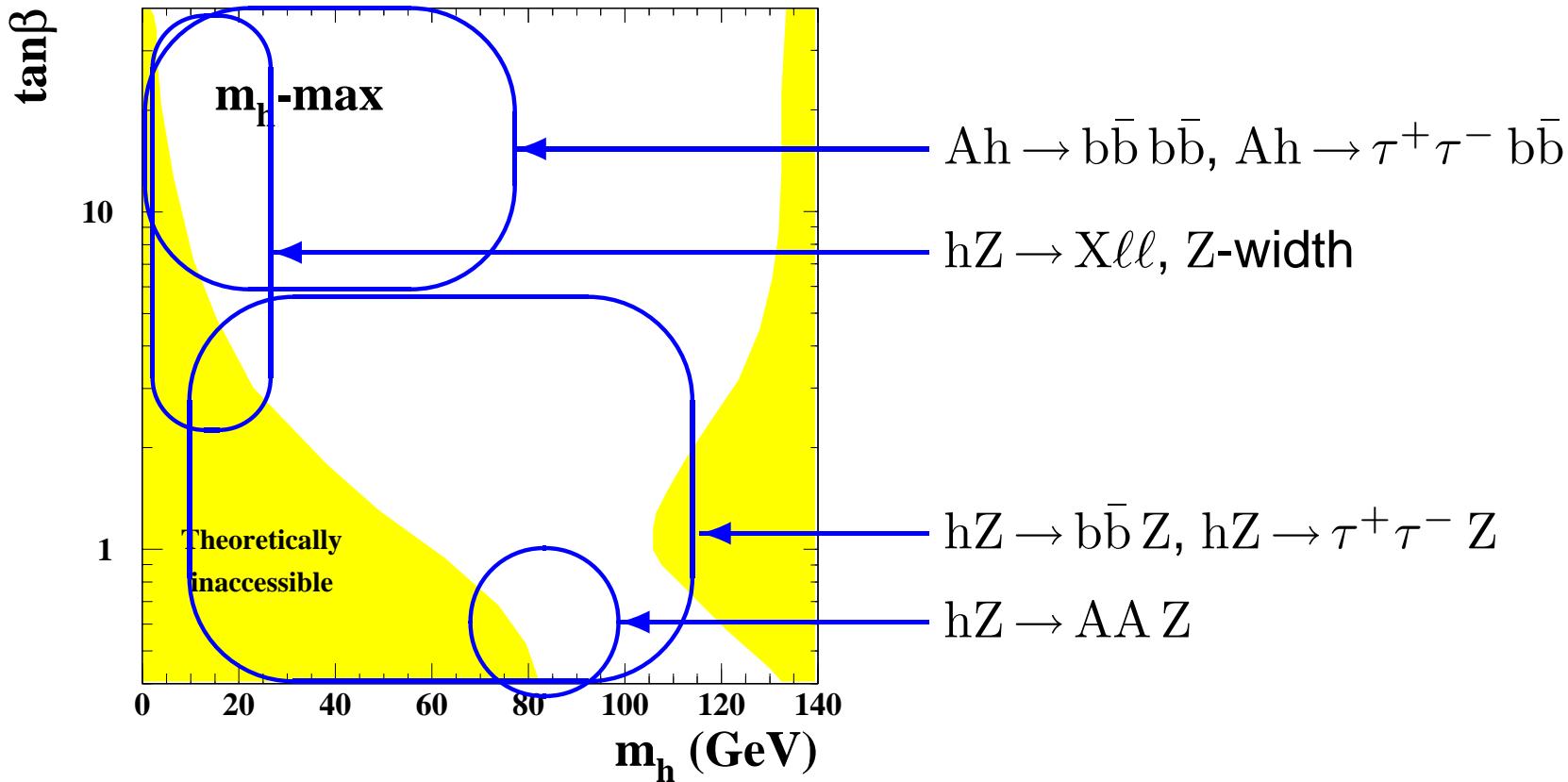


propagating particle is  $H_1$ , mixture of  
CP eigenstates  $h$ ,  $H$  and  $A$



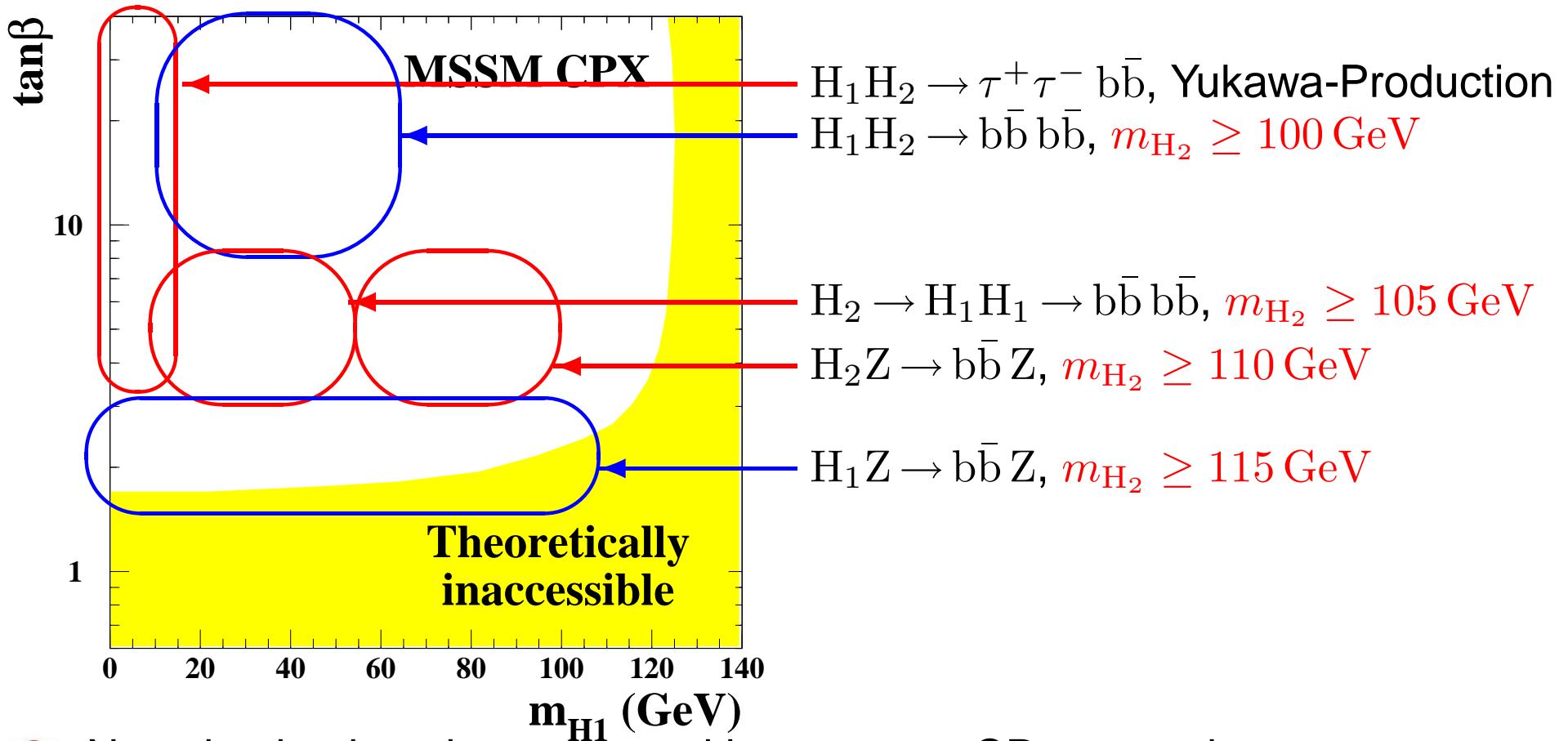
- CP-violating model: both  $H_1$  and  $H_2$  in Higgsstrahlung

# CPC scenarios: Searches



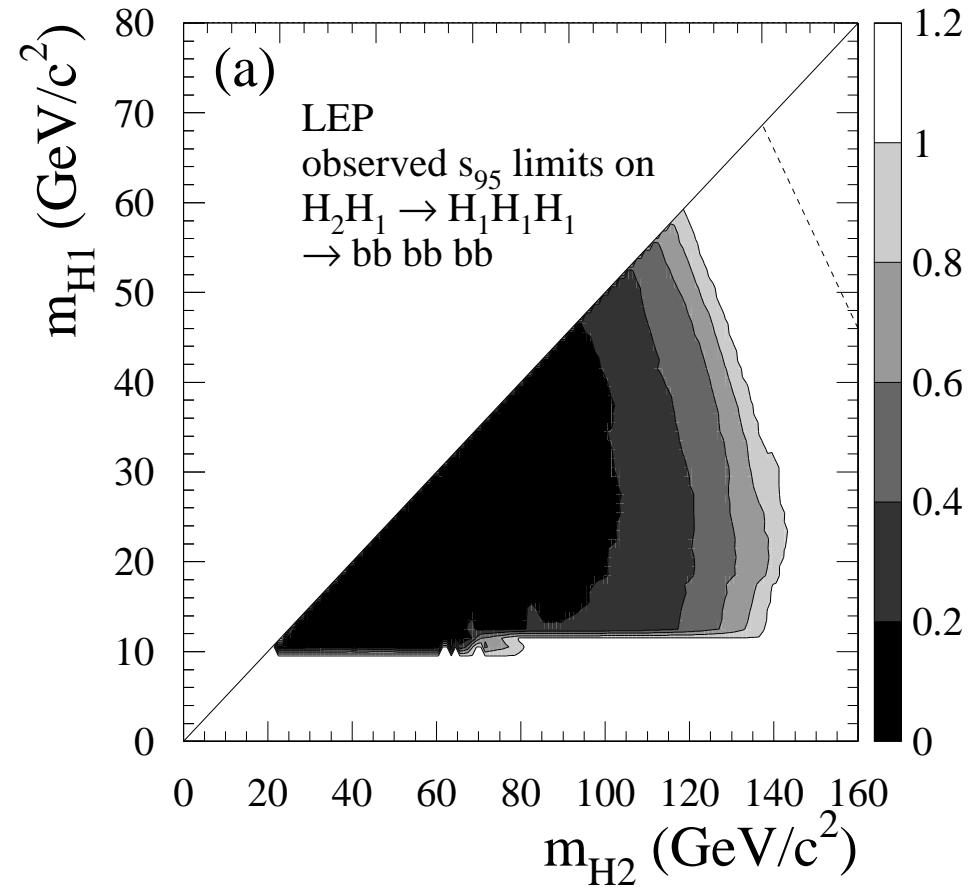
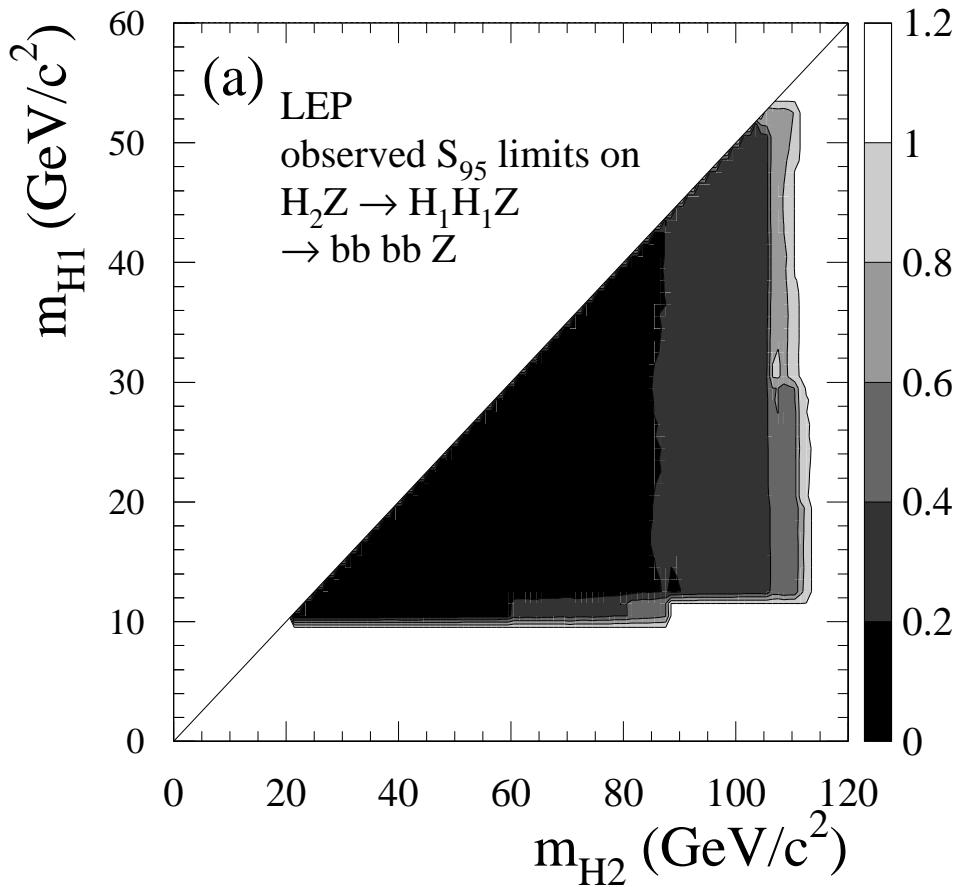
- Only areas with  $\cos^2(\beta - \alpha) \approx 1$  and  $e^+e^- \rightarrow Ah$  kinematically inaccessible are open

# • Different searches in the CPV case



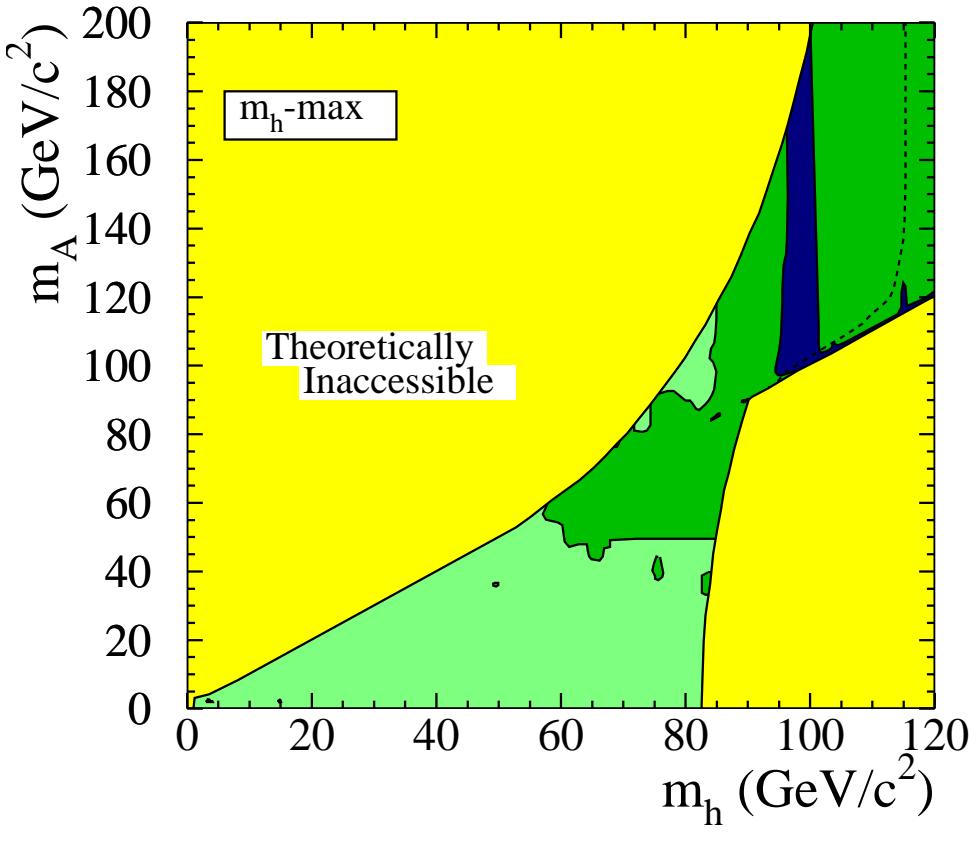
- New dominating phenomena with respect to CP conserving scans:  
 $H_2 Z \rightarrow H_1 H_1 Z \rightarrow b\bar{b} b\bar{b} Z$  decays with  $m_{H_2} \approx 100 - 110$  GeV.

# Model-Independent Coverage

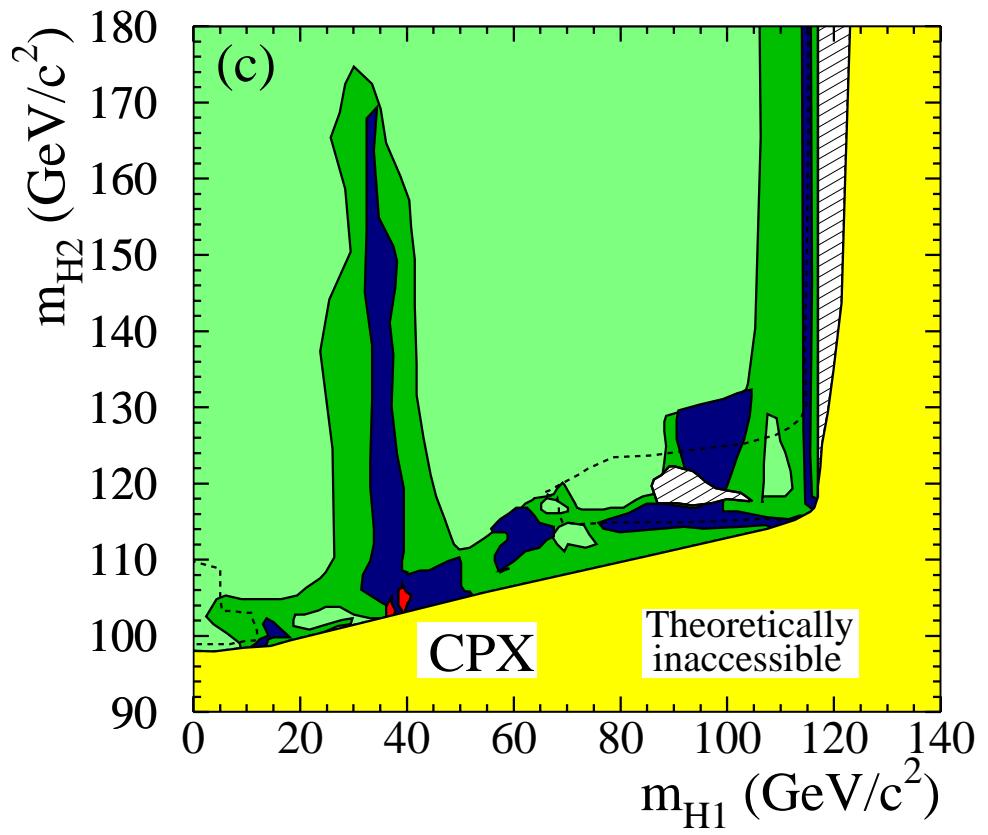


- Experimentally, LEP has good and uniform coverage of the important final states

# No significant excesses



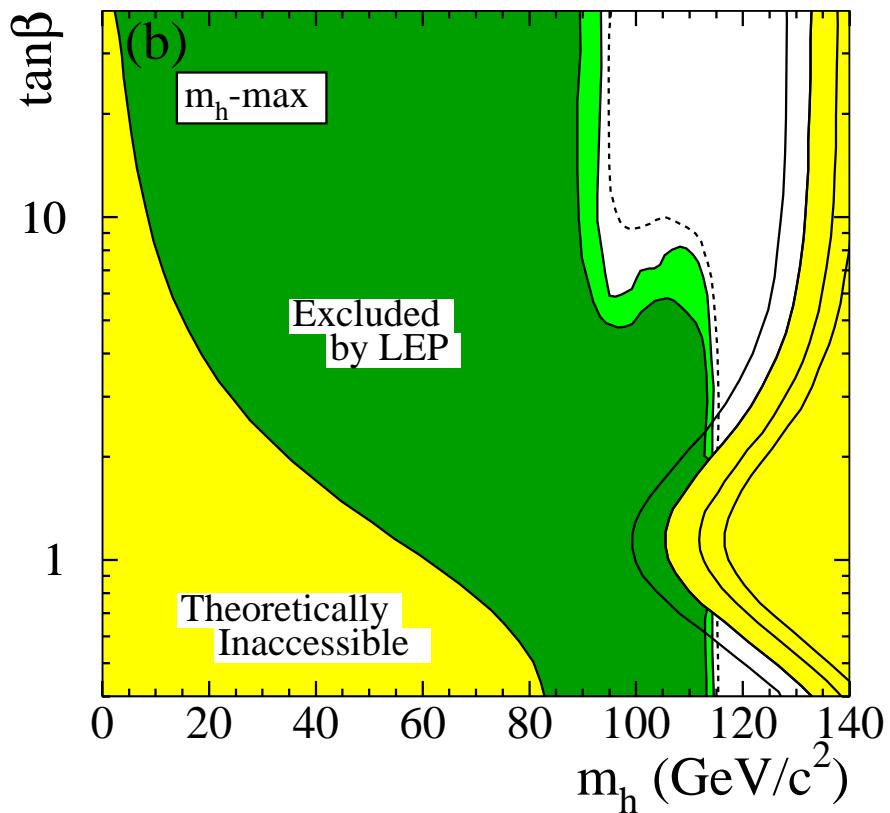
$m_h$ -max



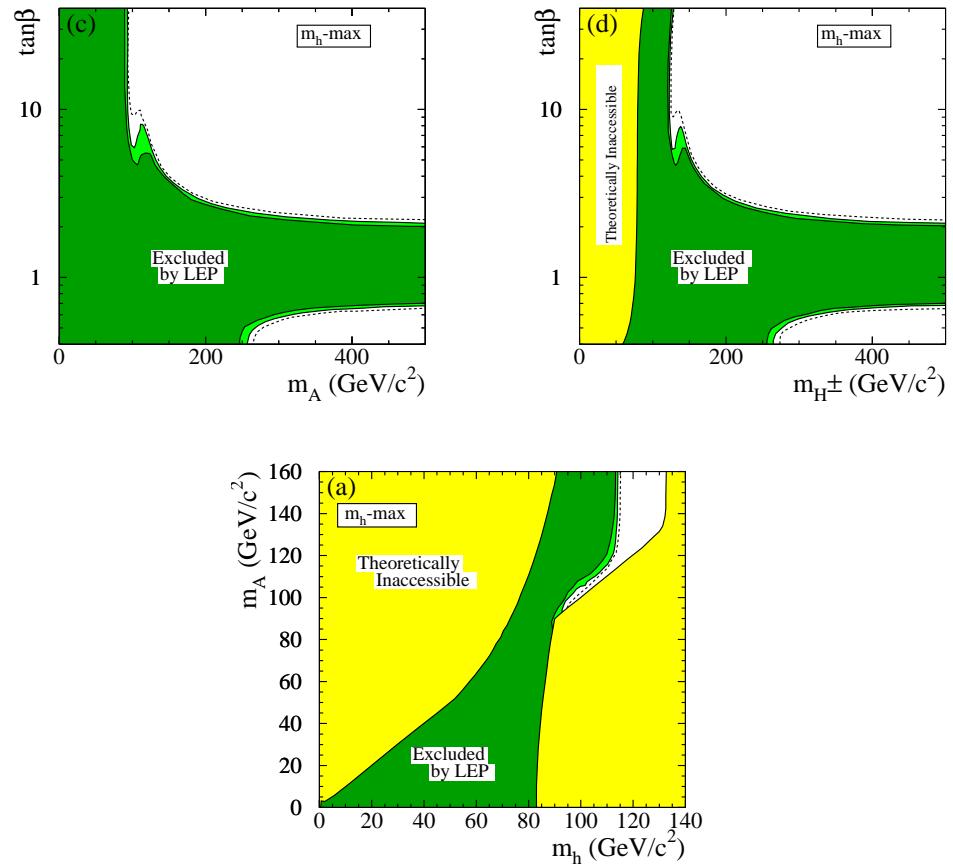
CPX

- No significant excesses. Largest excess in the CPV case at  $m_{H_1} = 40$ ,  $m_{H_2} = 105$  GeV has a probability of > 3.6 %

# Exclusion areas: typical CPC scenario



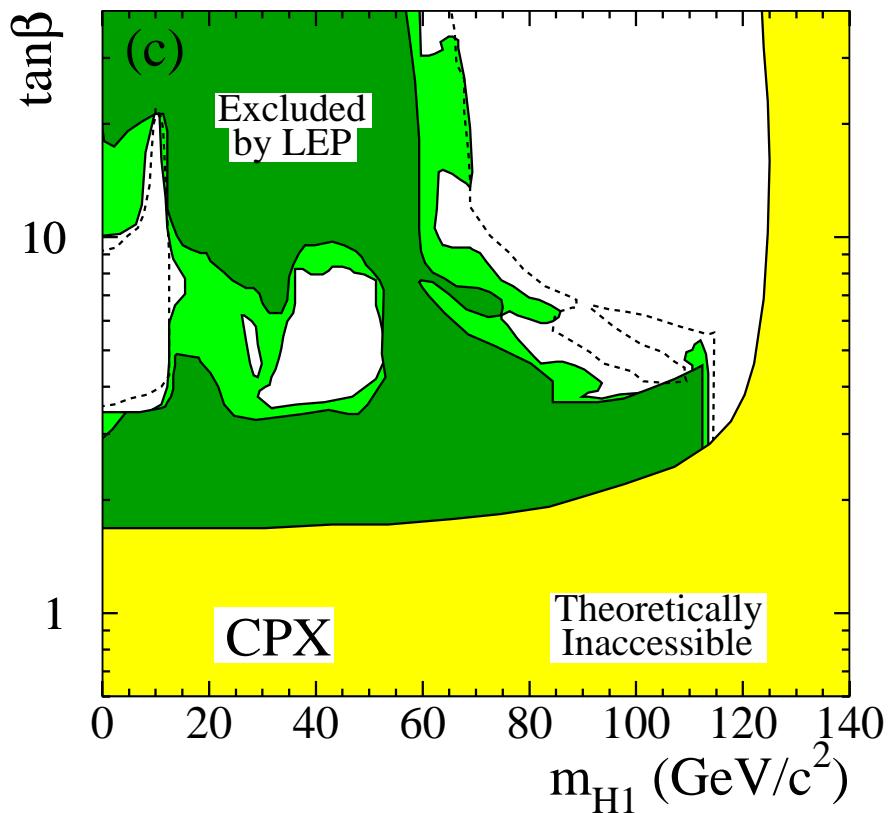
$$m_{\text{top}} = 174.3 \text{ GeV}$$



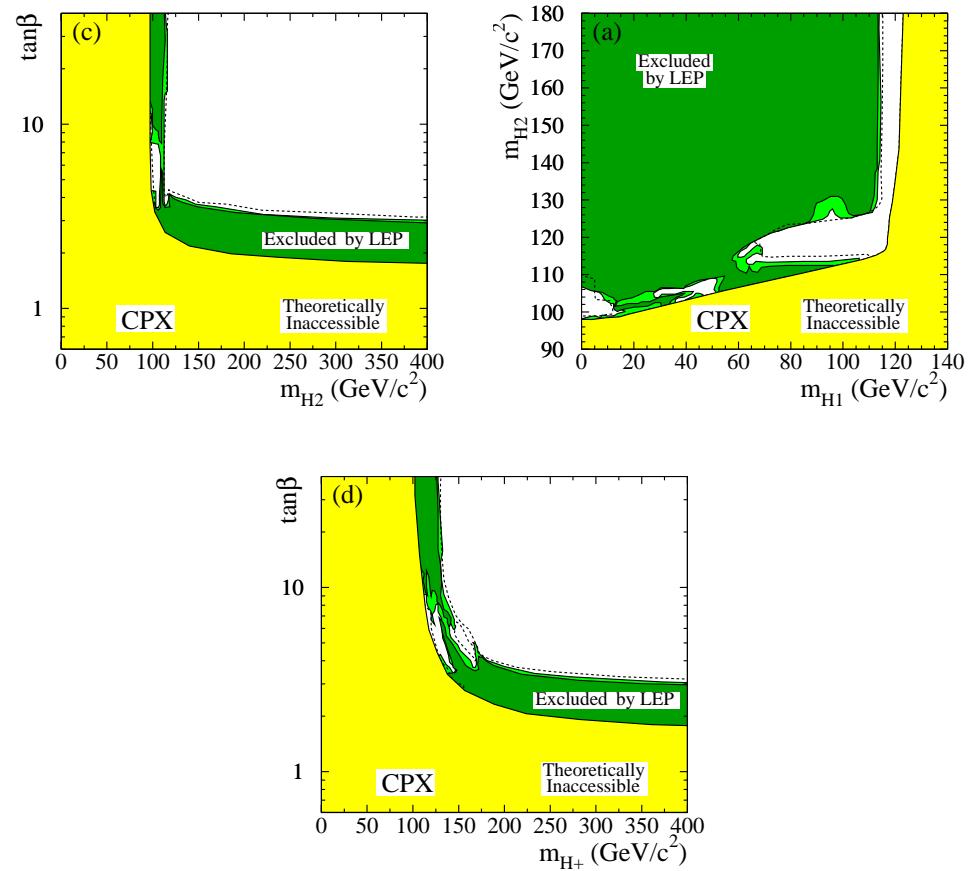
Different projections

- For all scenarios under study:  $m_h, m_A > 90 \text{ GeV}$

# Exclusion areas: The CPX scenario



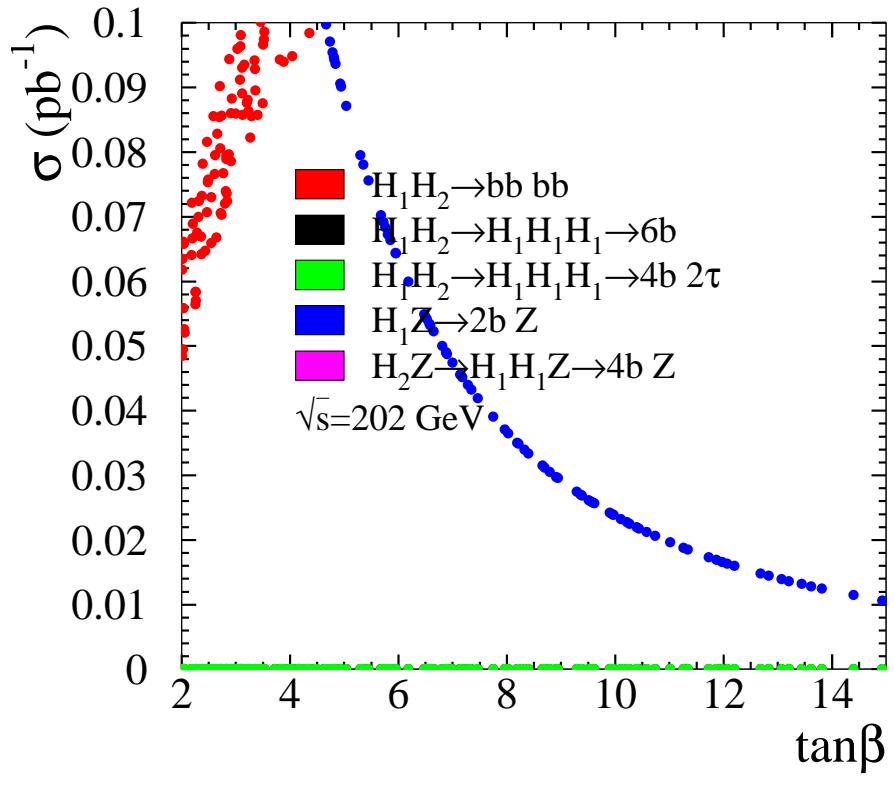
$$m_{\text{top}} = 174.3 \text{ GeV}$$



Different projections

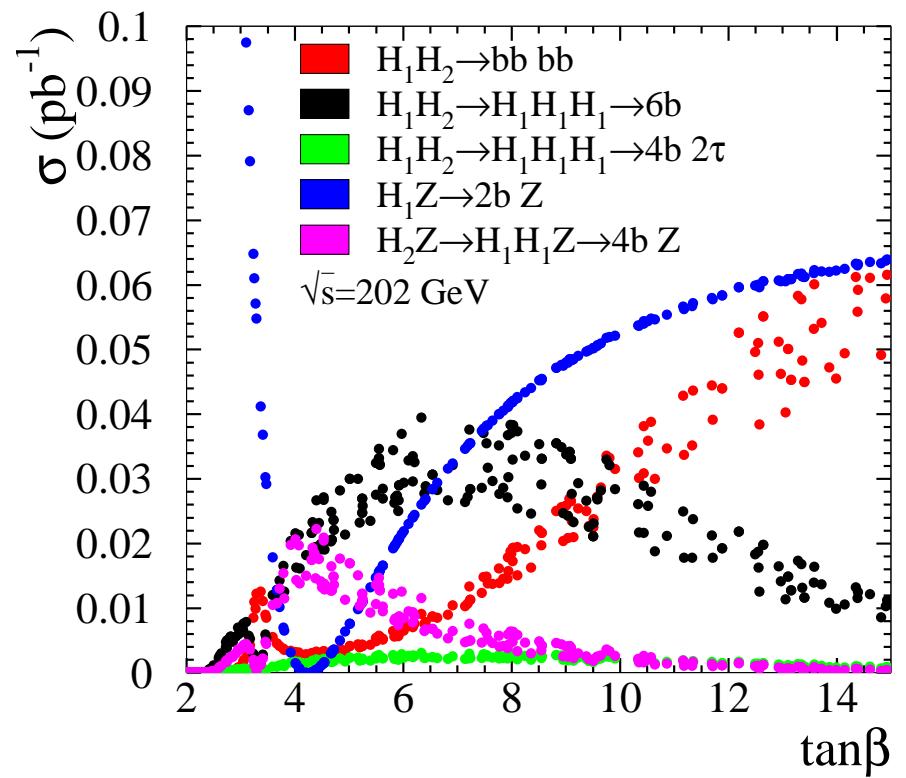
- In contrast to CP conserving scans: unexcluded regions for all  $m_{H_1}$ !

# Unexcluded regions for light $H_1$



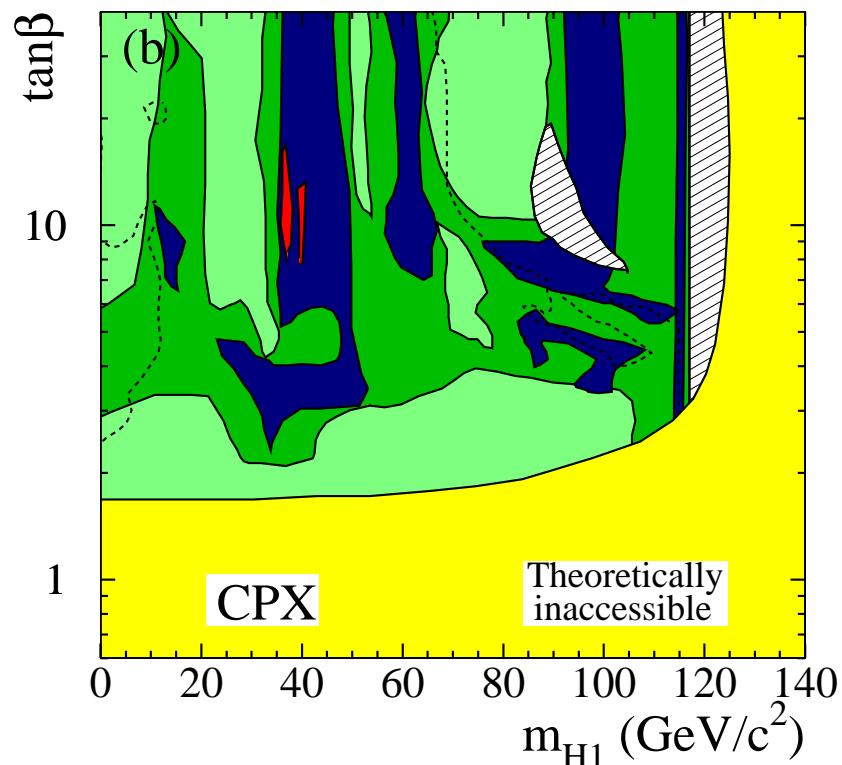
$m_h$ -max

- Comparison of the production processes and decays in the unexcluded region

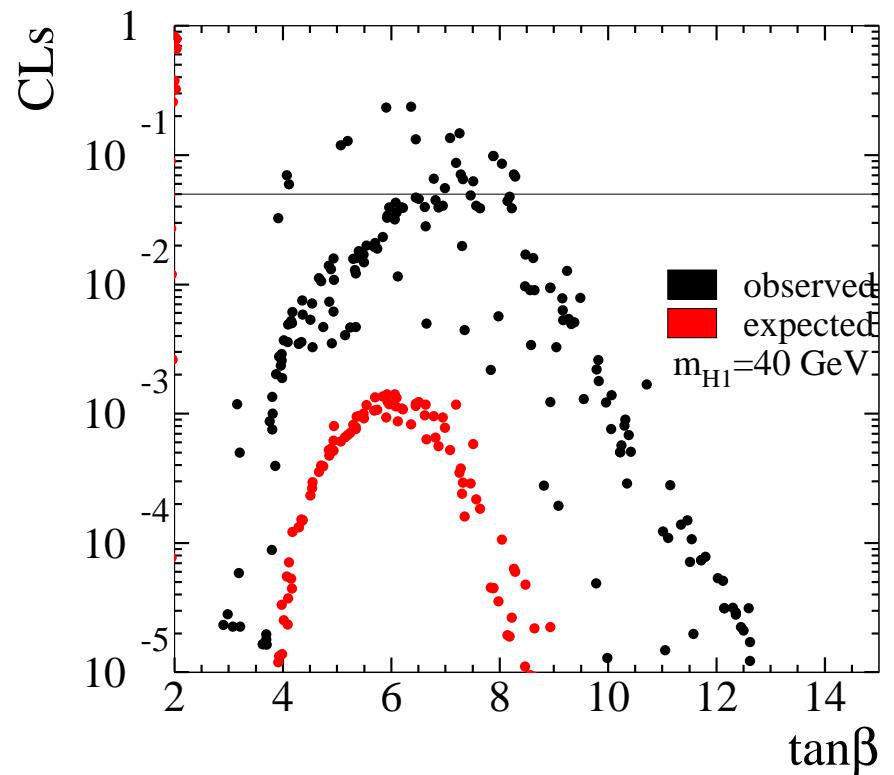


CPX

# • How deep is the unexcluded region?



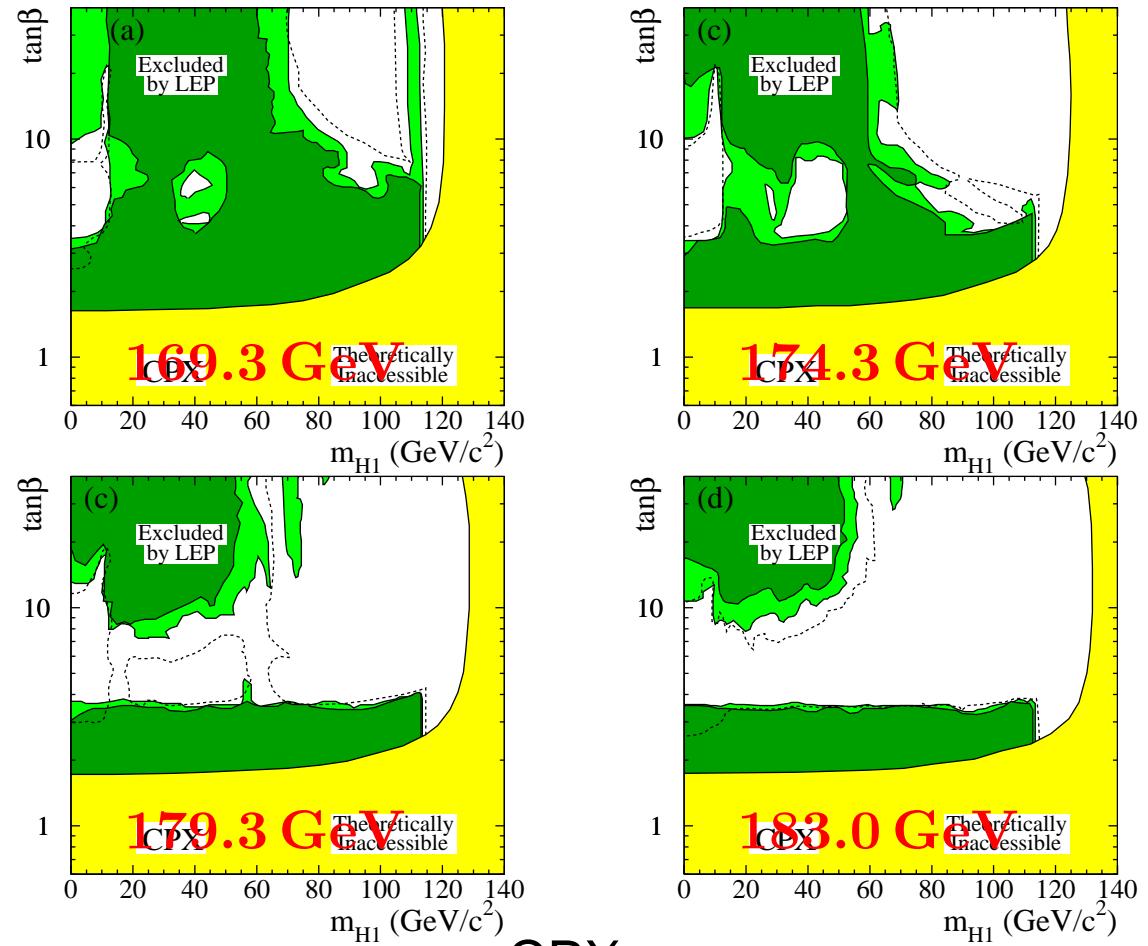
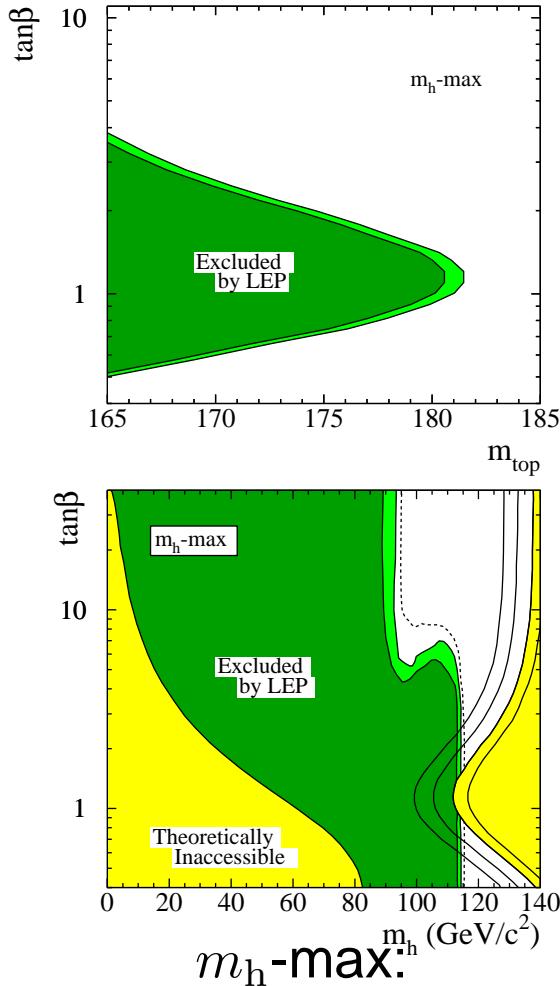
No significant excess



shallow non-excluded region

- Reasonable agreement between background and data, factor 2 more statistics would have closed the unexcluded region

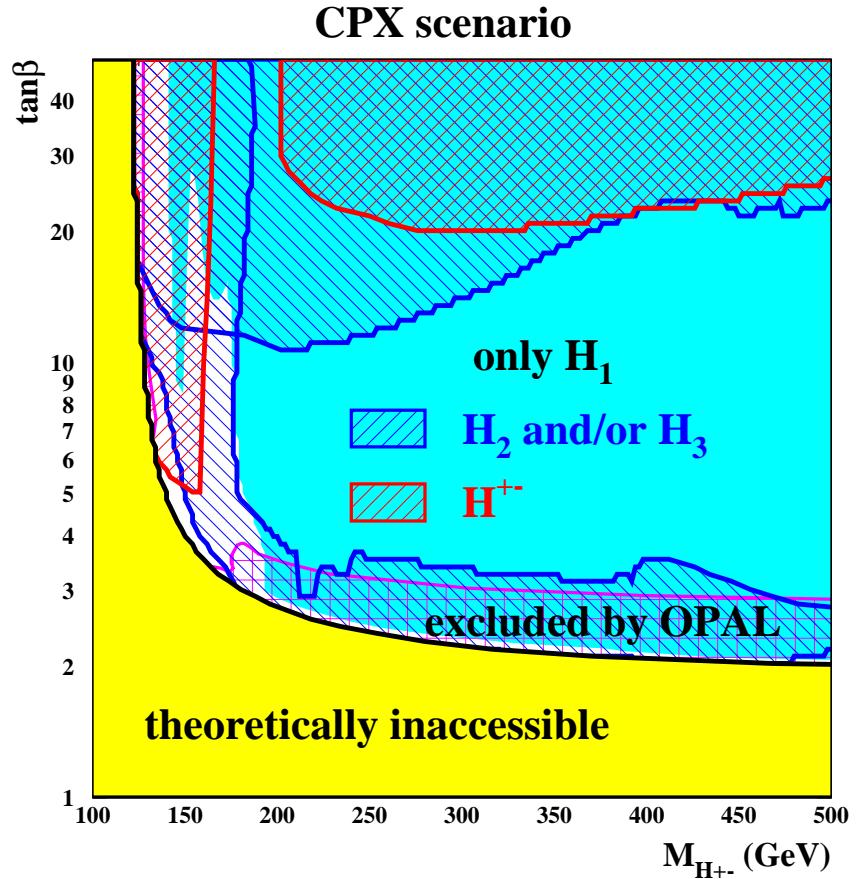
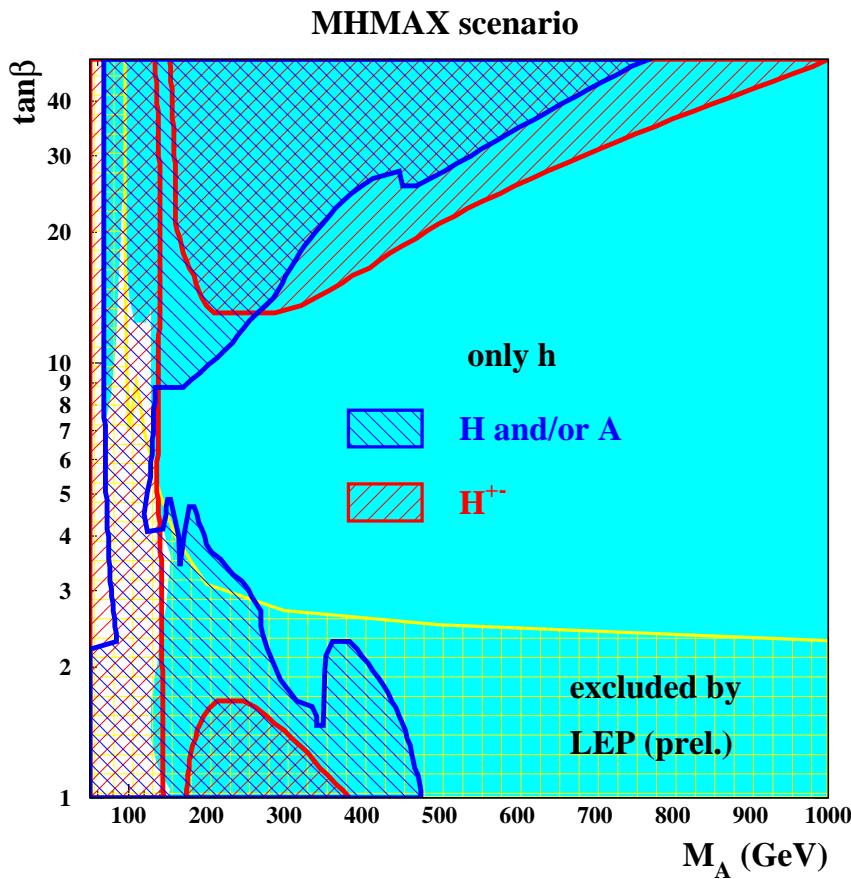
# The effect of $m_{\text{top}}$



CPX:

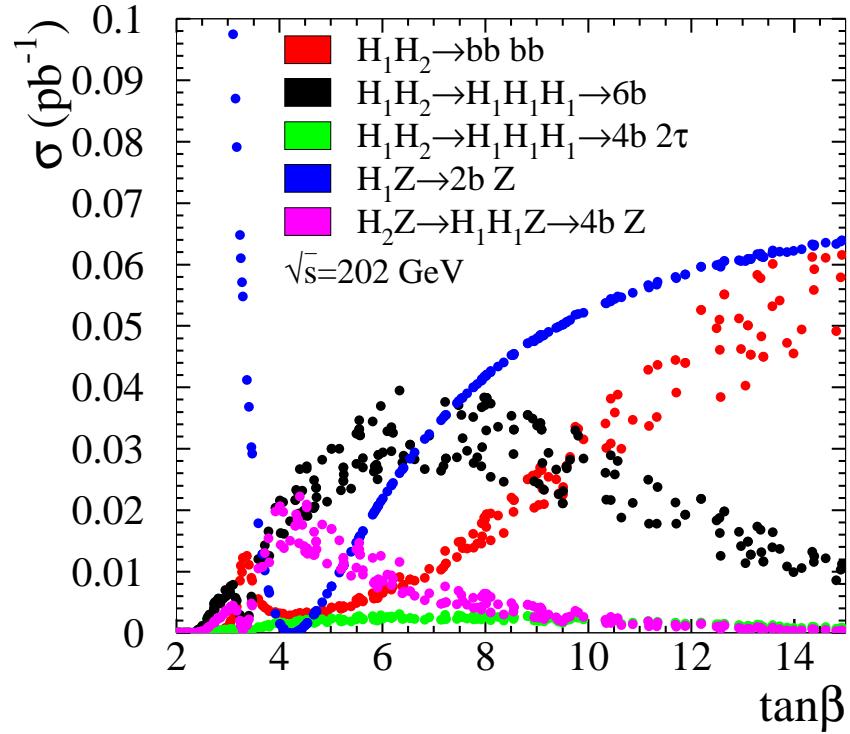
Small change in maximal  $m_{\text{H}_1}$ , large change in prediction ( $\sigma$ ,  $m_{\text{H}_1}/m_{\text{H}_2}$ ) for given  $m_{\text{H}_1}$ ,  $\tan\beta$

# • Prospects at LHC

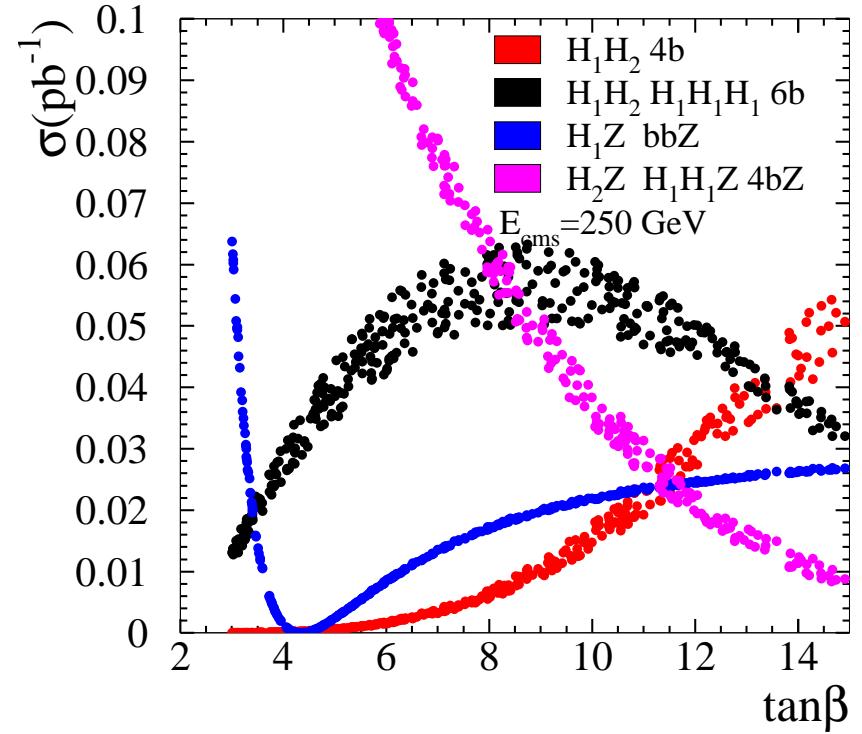


- Unexcluded region in ATLAS studies for  $300 \text{ fb}^{-1}$ , due to unstudied Higgs mass range for light  $m_{H_1} < 70 \text{ GeV}$
- With many thanks to **Markus Schumacher** ([hep-ph/0410112](#))

# • Prospects at ILC: CP-Violating Scenario



mean  $\sqrt{s}$  LEP 99/2000



$\sqrt{s} = 250 \text{ GeV}$

- Given  $\sqrt{s}$  is sufficient (which at ILC it is), discovery is ensured by

$$\sum_{i=1}^3 g_{H_i ZZ}^2 = 1,$$

$$g_{H_k ZZ} = \frac{1}{2} \sum_{i,j=1}^3 \epsilon_{ijk} g_{H_i H_j Z}$$

# Conclusion

- LEP combination of neutral CPV+CPC MSSM Higgs searches now available: [CERN-PH-EP/2006-001](#), [hep-ex/0602042](#)
- Many model independent limits on SM and MSSM-like production and decay channels available
- Many additional searches to close unconventional channels have been added
- CPV in the MSSM adds challenging signatures, low production cross-sections
- $m_{\text{top}}$  has large impact on MSSM exclusion area
- **Light Higgs bosons not excluded by LEP**
- Light unexcluded Higgs bosons not so easy for LHC either
- No indication for possible loopholes in the MSSM for the ILC: Discovery and precise measurement should be guaranteed if MSSM is realized

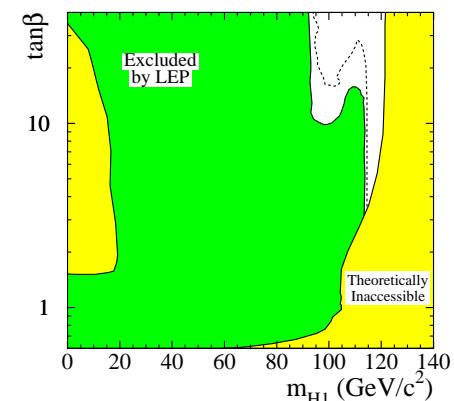
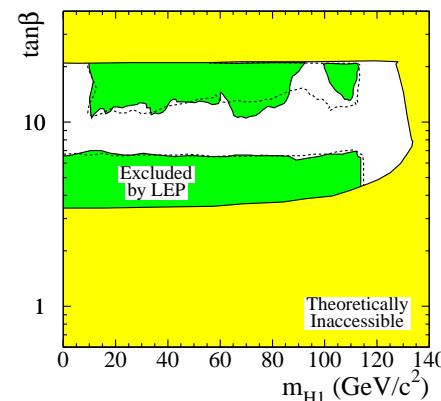
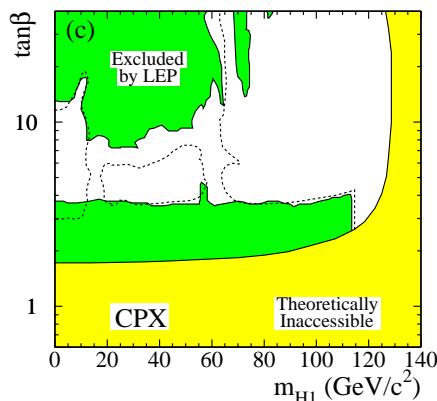
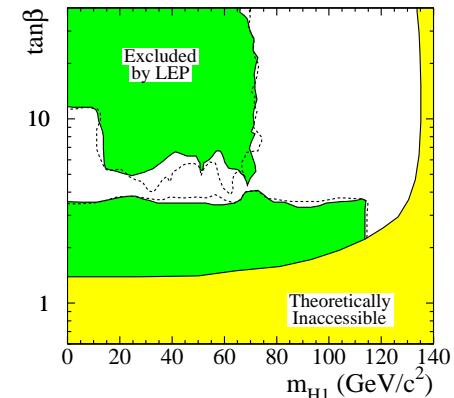
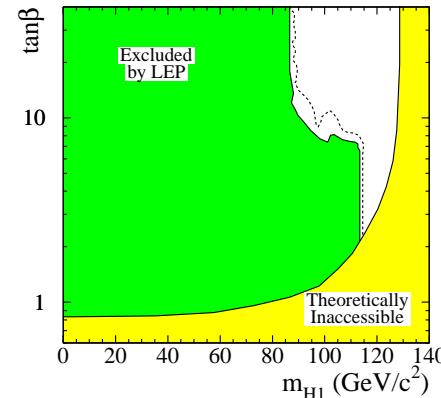
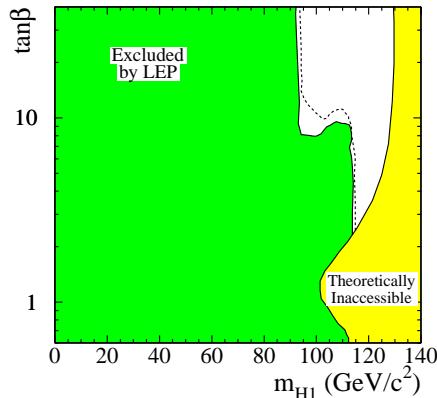
# The CPX Parameters

tree-level parameters (GeV)			
$\tan \beta$	=	0.6 – 40	ratio of Higgs v.e.v.
$m_A$ or $m_{H^+}$	=	0 – 1000	CP odd Higgs mass or charged Higgs mass
loop-level parameters (GeV)			
$ A_q $	=	1000	strength of trilinear coupling
$\arg(A_q)$	=	90°	⇒ CP-violation
$ m_{\tilde{g}} $	=	1000	gluino mass parameter
$\arg(m_{\tilde{g}})$	=	90°	⇒ CP-violation
$\mu$	=	2000	Higgs doublet mixing
$m_{\text{SUSY}}$	=	500	SUSY breaking scale = $m_{\tilde{q}}$
$m_2$	=	200	SU(2) gaugino mass matrix parameter

# The Searches

- Higgsstrahlung and boson fusion (SM like)
  - $e^+e^- \rightarrow Zh; h \rightarrow b\bar{b}, \tau^+\tau^-, Z \rightarrow X$
- Higgsstrahlung (SUSY)
  - $e^+e^- \rightarrow Zh; h \rightarrow \text{Invisible}, Z \rightarrow q\bar{q}, \ell\ell$  (**DELPHI**)
  - $e^+e^- \rightarrow H_2Z; H_2 \rightarrow H_1H_1, H_1 \rightarrow b\bar{b}, Z \rightarrow q\bar{q}, \nu\bar{\nu}$  (**OPAL**)
  - $e^+e^- \rightarrow H_2Z; H_2 \rightarrow H_1H_1, H_1 \rightarrow gg, c\bar{c}, \tau^+\tau^-, Z \rightarrow \ell\ell, \nu\bar{\nu}$  (**OPAL**)
  - $e^+e^- \rightarrow Zh; h \rightarrow \text{Anything}, Z \rightarrow \ell\ell$
  - $e^+e^- \rightarrow Zh; h \rightarrow q\bar{q}, Z \rightarrow q\bar{q}$
- Pair Production
  - $e^+e^- \rightarrow Ah; Ah \rightarrow b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-$
  - $e^+e^- \rightarrow H_1H_2; H_2 \rightarrow H_1H_1, H_1 \rightarrow b\bar{b}$  (just like  $Ah \rightarrow AAA \rightarrow 6b$ )
- Yukawa search
  - $e^+e^- \rightarrow b\bar{b}h, b\bar{b}A; h, A \rightarrow \tau^+\tau^-$

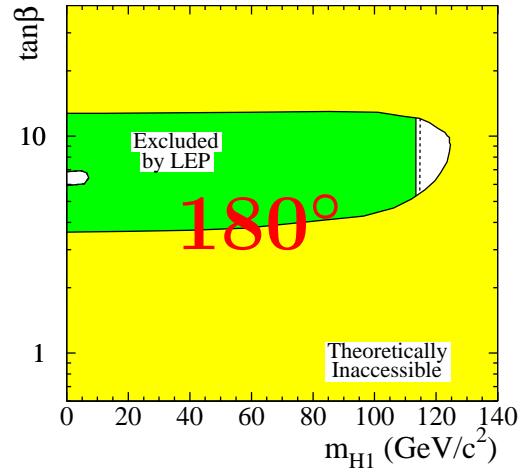
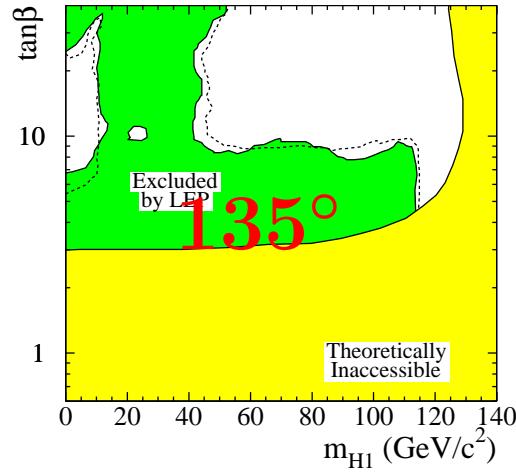
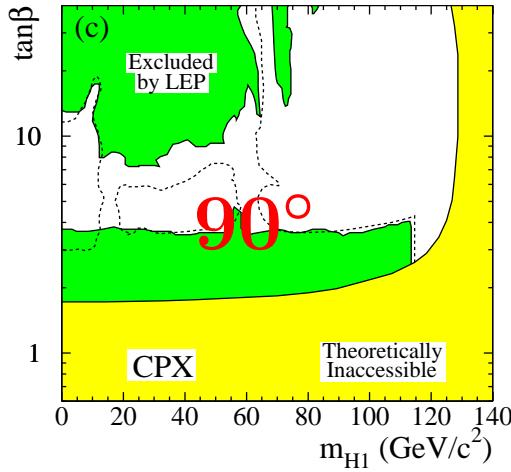
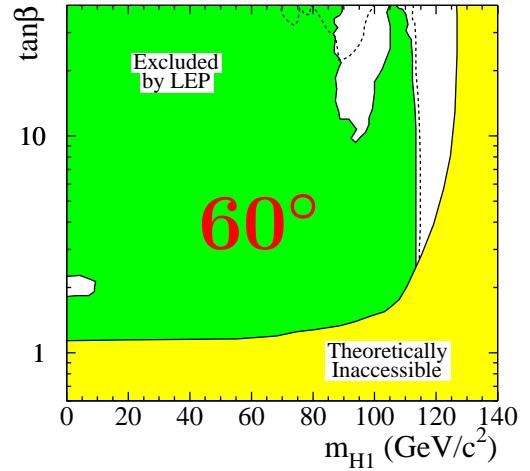
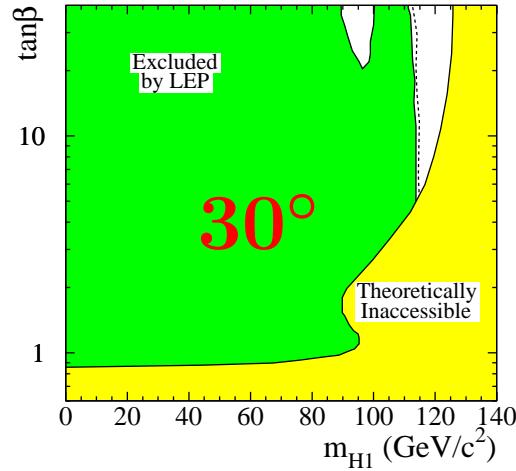
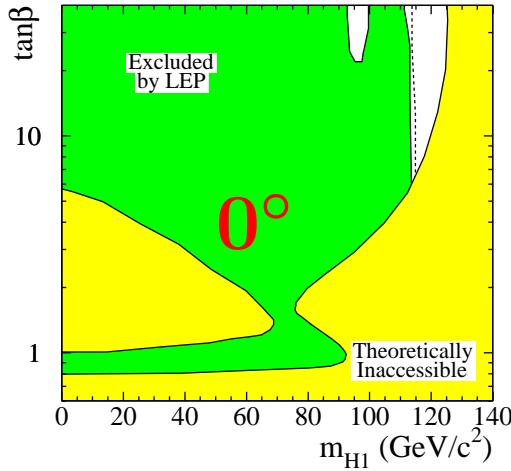
# Other Parameter Variations



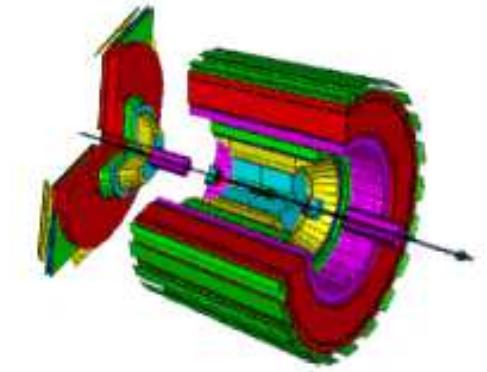
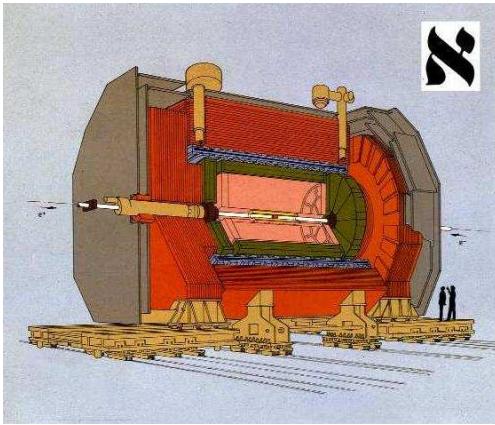
$\mu = 500, 1000, 2000, 4000 \text{ GeV}$

Variation of  $M_{\text{SUSY}}$

# The effect of $\arg(A_{t,b})$



# The LEP Experiments



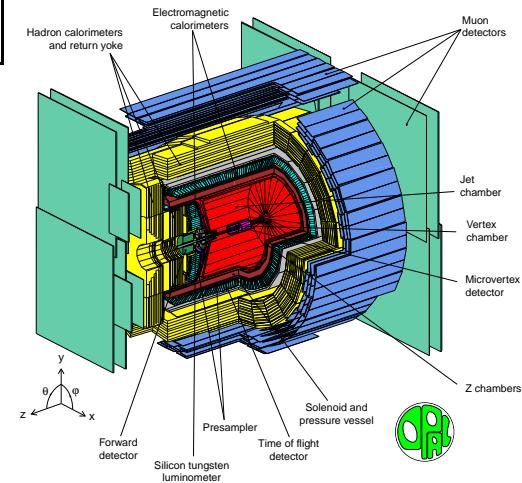
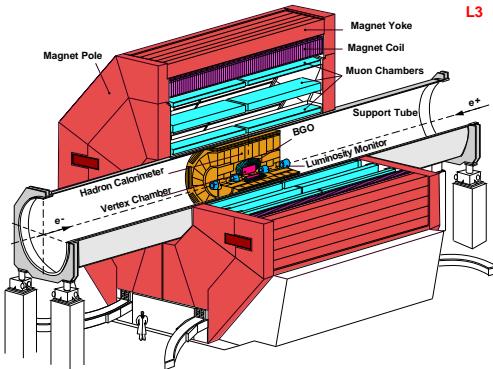
LEP data taking from 1989 to 2000

$$\sqrt{s} = 91 - 209 \text{ GeV}$$

Overall  $\mathcal{L} \approx 2600 \text{ pb}^{-1}$

$> 20 \times 10^6 Z$  on peak,

40000  $W^\pm$  pairs, 1200  $Z$  pairs



# • CP-Violating MSSM Benchmarks

- Too many free parameters to scan them all
- Construct **benchmark scenarios**, maximising certain effects:
- **CPX**: Mixing of CP- and mass-eigensates
  - Introduce mixing: complex phases of trilinear couplings  $A_{t,b}$  and  $m_{\tilde{g}}$
  - Mixing matrix 
$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \begin{pmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22} & V_{23} \\ V_{31} & V_{32} & V_{33} \end{pmatrix} \begin{pmatrix} h \\ H \\ A \end{pmatrix}$$
  - Mixing through  $V_{x3} \sim \frac{m_{\text{top}}^4}{v^2} \frac{\text{Im}(\mu A_{t,b})}{M_{\text{SUSY}}^2}$
  - constrained also by  $e^-$  and  $n$  EDM
- From **Carena et al.** hep-ph/0202167 and hep-ph/0009212
- Theoretical predictions from  
**CPH** (Carena, Pilaftsis, Wagner), **FeynHiggs 2.0** (Heinemeyer, Weiglein)