Searches for Neutral Higgs Bosons in the MSSM and Interpretations at LEP

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DESY

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On behalf of the LEP Collaborations

1. (New) SUSY Scenarios
2. New and Updated Searches
3. The Interpretations and their Results

Abstracts 158, 209, 210, 248, 320, 742, 746

The MSSM Higgs Phenomenology

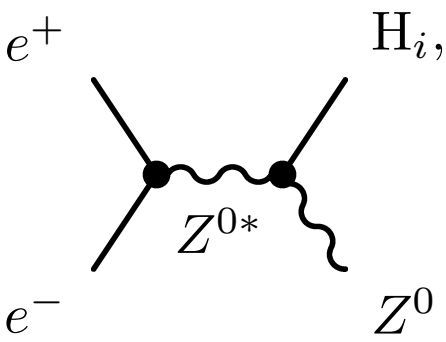
- Two Higgs doublets $\Rightarrow$ 5 physical Higgs bosons:
  - CP-conserving models:

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

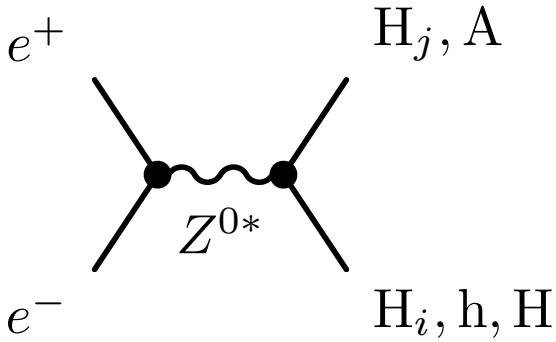
  - CP-violating models: mass eigenstates no longer CP eigenstates

$$\mathrm{H}_1, \mathrm{H}_2, \mathrm{H}_3, \qquad \mathrm{H}^{\pm}$$

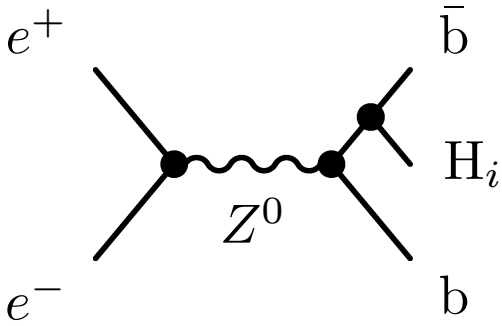
- Two main production mechanisms for neutral Higgses + Yukawa:



Higgsstrahlung



Pairproduction



Yukawa-Production

- Different channels are principally complementary

$$\sigma_{\mathrm{Zh}} = \sigma_{\mathrm{Zh}}^{\mathrm{SM}} \sin^2(\beta-\alpha) \qquad \sigma_{\mathrm{Ah}} = \sigma_{\mathrm{Zh}}^{\mathrm{SM}} \lambda \cos^2(\beta-\alpha)$$

- Tree level: $m_{\mathrm{h,tree}} \leq m_{\mathrm{Z}}$ but large rad. corrections $\mathrm{t}, \tilde{\mathrm{t}}$ $m_{\mathrm{h,loop}} \approx 1.5 m_{\mathrm{h,tree}}$

The MSSM Higgs Sector Parameters

	tree-level parameters
$\tan\beta$	ratio of Higgs v.e.v.
$m_{\rm A}$ or m_{H^+}	CP odd Higgs mass or charged Higgs mass
	loop-level parameters
$\lvert A_q\rvert$	strength of trilinear coupling
$\arg(A_q)$	$\Rightarrow$ CP-violation
$\lvert m_{\tilde{\rm g}}\rvert$	gluino mass parameter
$\arg(m_{\tilde{\rm g}})$	$\Rightarrow$ CP-violation
μ	Higgs doublet mixing
$m_{\rm SUSY}$	SUSY breaking scale $= m_{\tilde{q}}$
m_2	SU(2) gaugino mass matrix parameter

The MSSM Benchmarks

- Too many free parameters to scan them all
- Construct benchmark scenarios, maximising certain effects:
- CP conserving
  - No Mixing: No mixing in the stop-sbottom sector
  - m_h max: Maximum m_{h} for given $\tan\beta, m_{\mathrm{A}}$
  - Large μ: Always kinematically accessible, but $\mathrm{h} \to \mathrm{b}\bar{\mathrm{b}}$ suppressed
  - New gluophobic: hgg coupling suppressed, bad for LHC...
  - New small α_{eff}: $\mathrm{h} \to \mathrm{b}\bar{\mathrm{b}}$ suppressed by cancellation of $\tilde{\mathrm{b}} - \tilde{\mathrm{g}}$ loops
  - 2 more new scans, m_h max derivates
- CP violating
  - Partly new CPX: Mixing of CP- and mass-eigensates
- From Carena *et al.* hep-ph/0202167 and hep-ph/0009212

The Searches

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

The Invisible Higgs Search

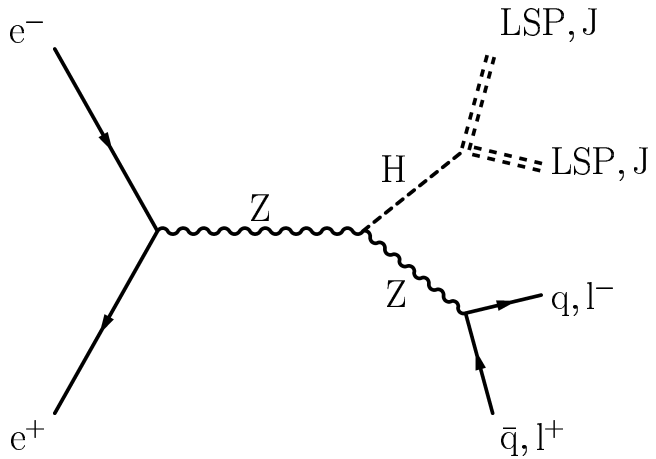
The Search for the Invisible Higgs

- Motivation:

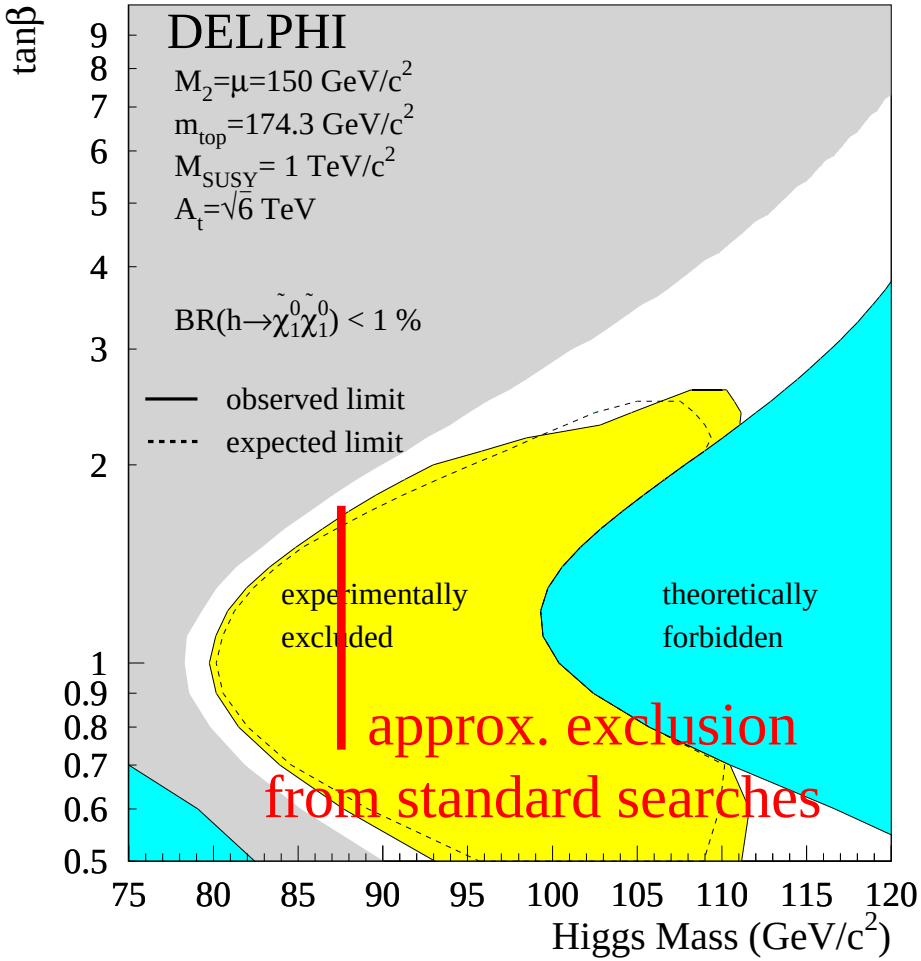
  mSUGRA: $\chi_1^0 > 51$ GeV,

  cMSSM: $\chi_1^0 > 45$ GeV

  Higgs might decay invisibly



- Search for
  - acoplanar and acolinear leptons with central p_{mis} and m_{Z}
  - acoplanar jets with E_T



Modified m_{h}-max with low $M_2 = \mu = 150$ GeV

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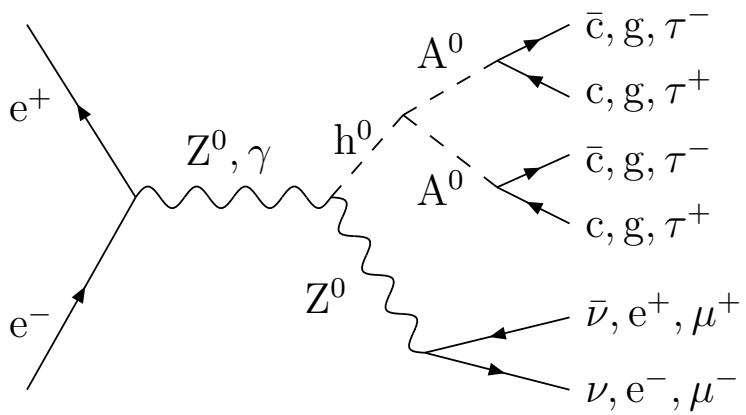
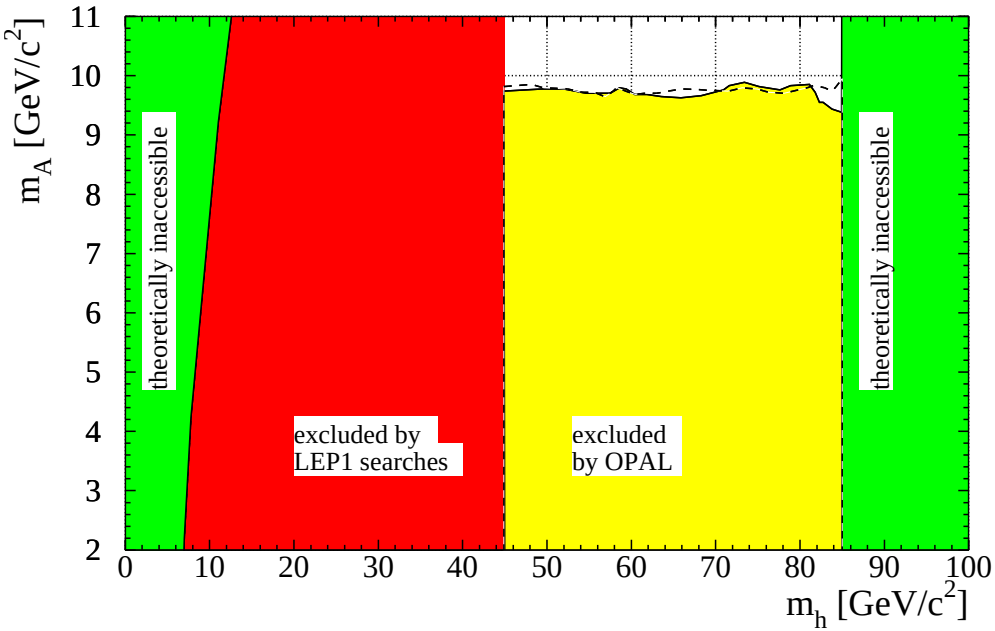
The Search for $h \longrightarrow AA$ with low m_A

- In MSSM models, e.g. No Mixing, for small m_A:

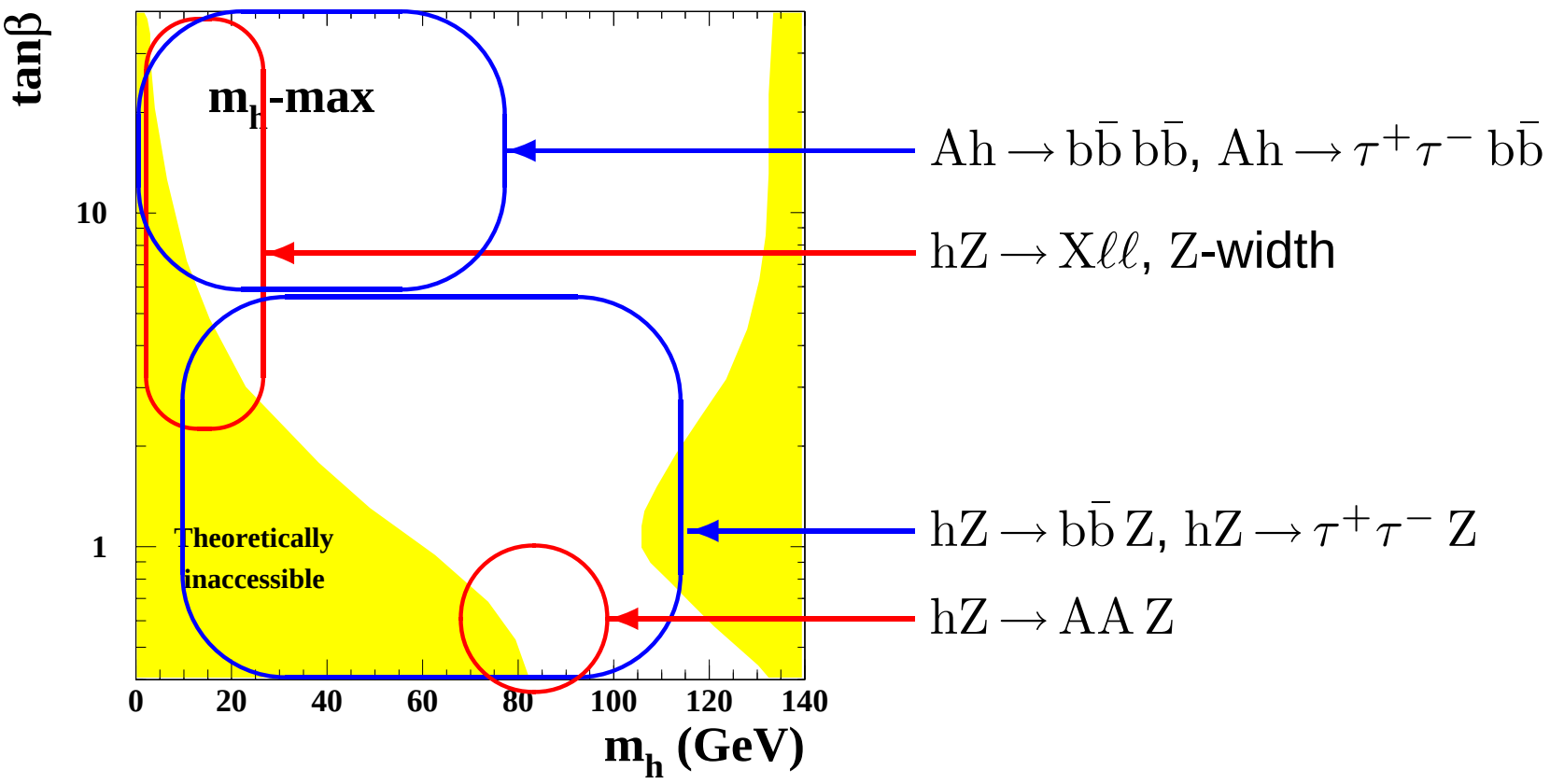




- Cover area of $m_A < 2\,m_b$ GeV
- Search for
  - A to one jet
  - two A recoiling against a Z

For $2 < m_A < 10$ GeV:
A excluded up to upper m_h limit of the old FeynHiggs version

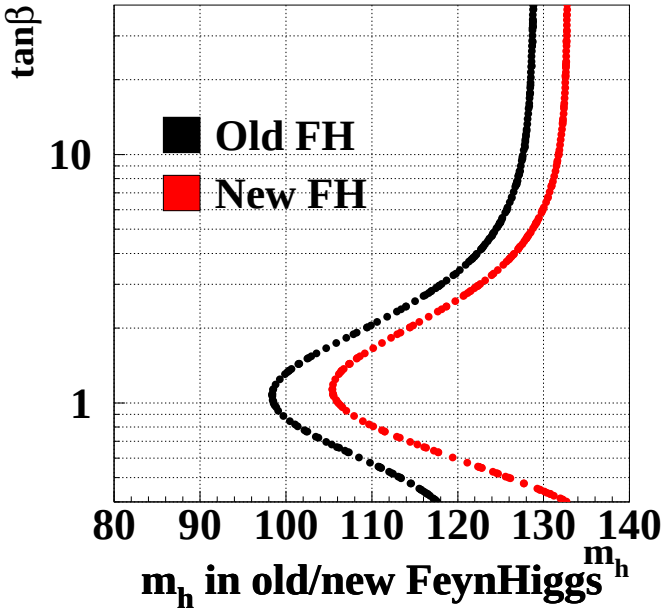
The use of the different searches

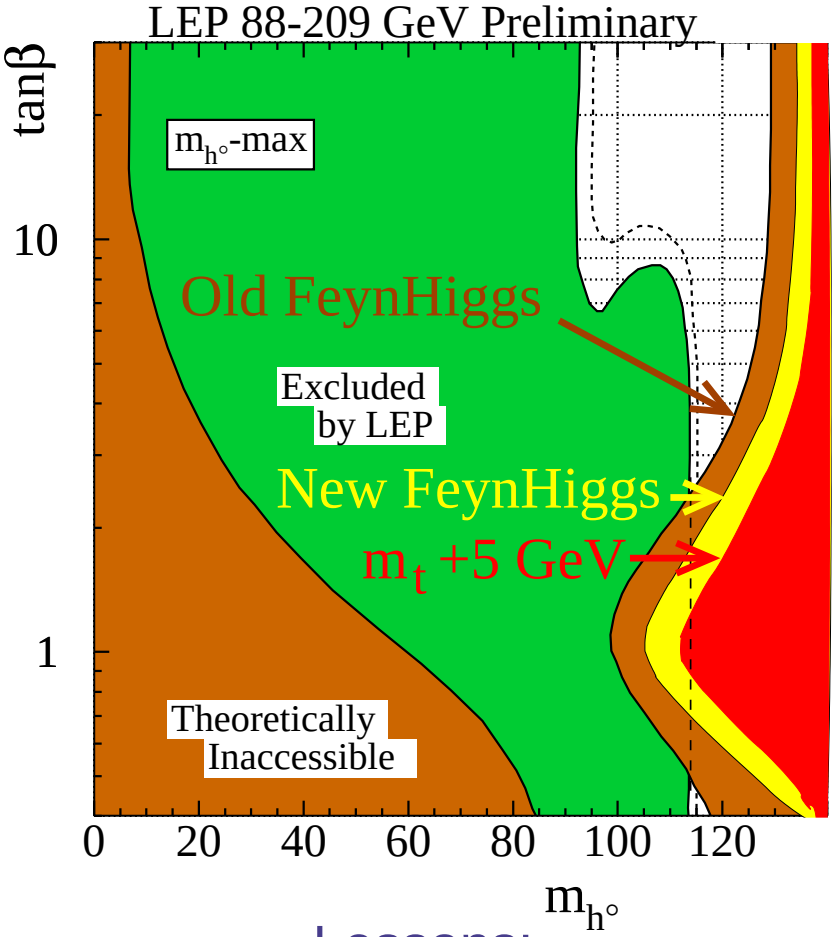


- Only areas with $\cos^2(\beta-\alpha) \approx 1$ and $\mathrm{e^+e^-} \to \mathrm{Ah}$ kinematically inaccessible are open

Exclusion areas: m_{h}-max

- Use of new FeynHiggs theory prediction:
  - new subleading non-log $\mathcal{O}(\alpha^2)$ loops in the top sector increase upper mass bound by ≈ 4 GeV
- Will be used in LEP combination





Lessons:

- Better precision of m_{t} needed
- Large m_{t} might spoil $\tan\beta$ exclusion

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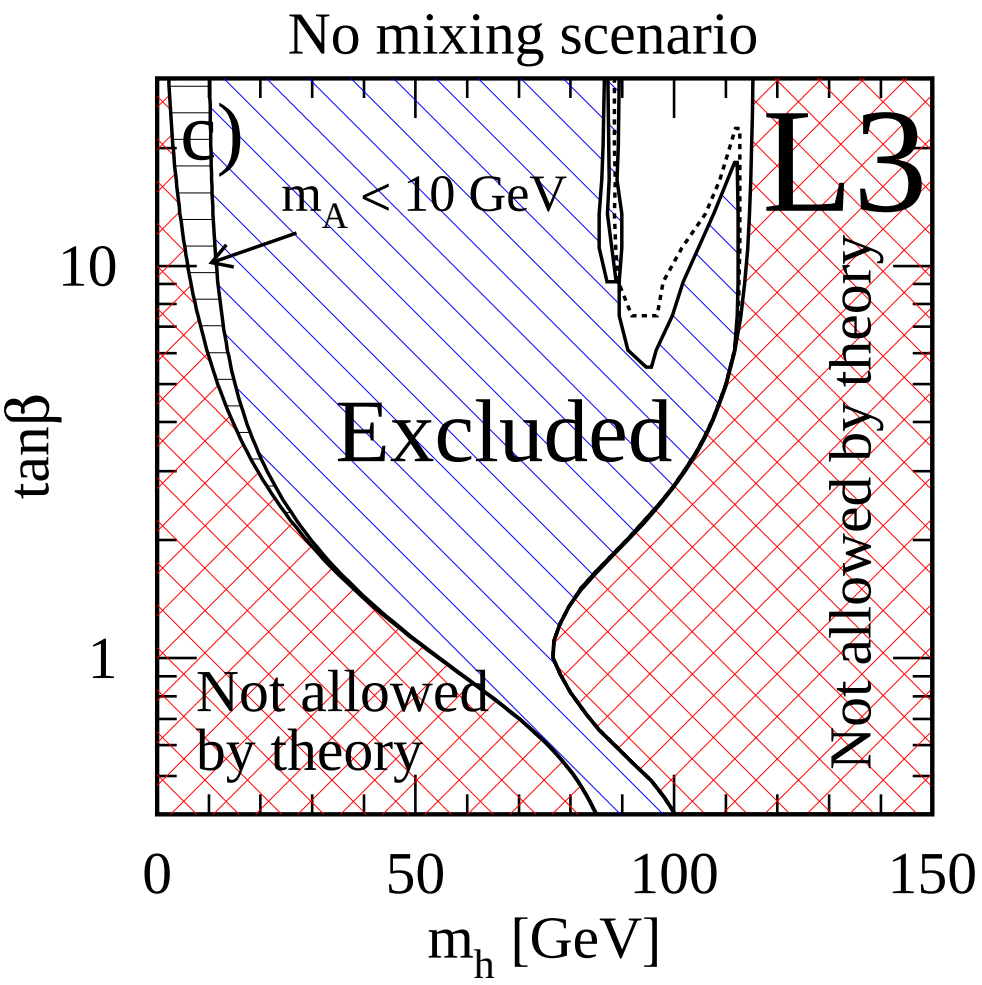
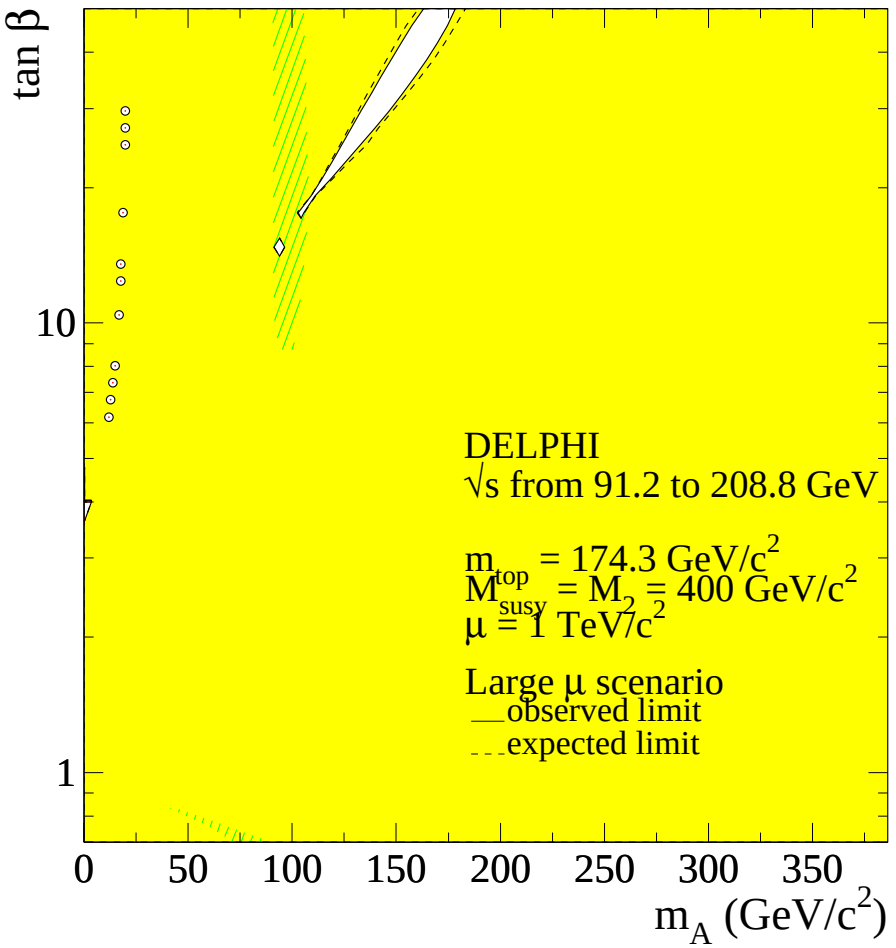
Exclusion areas: No-mixing and large μ

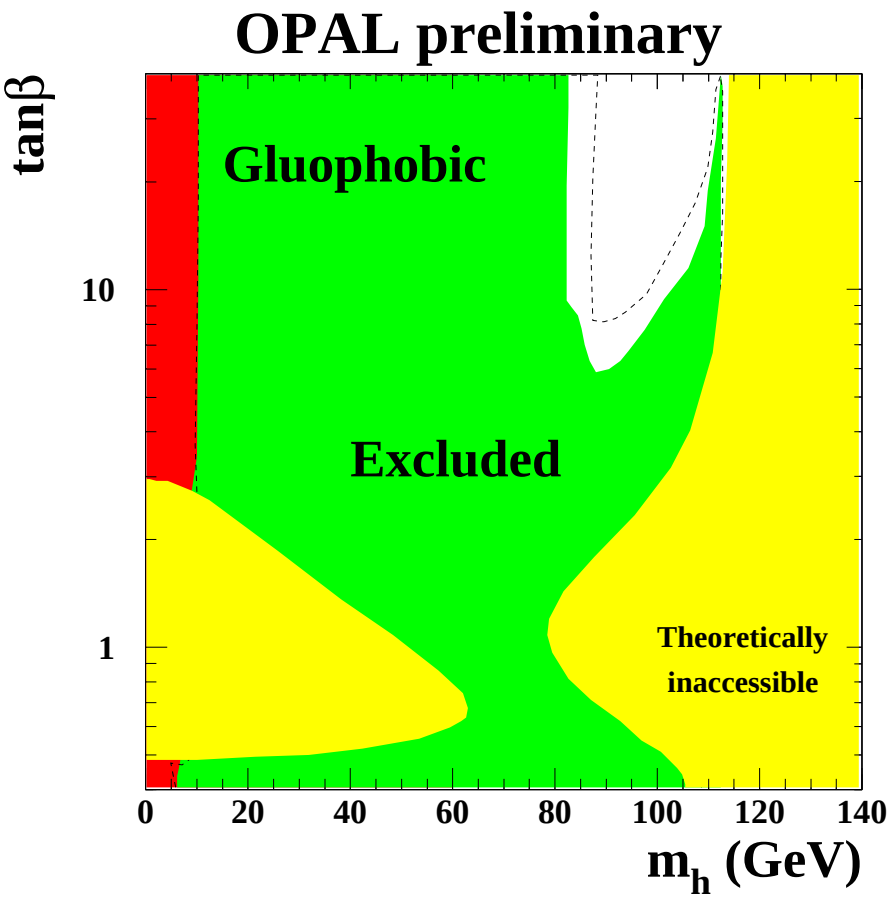


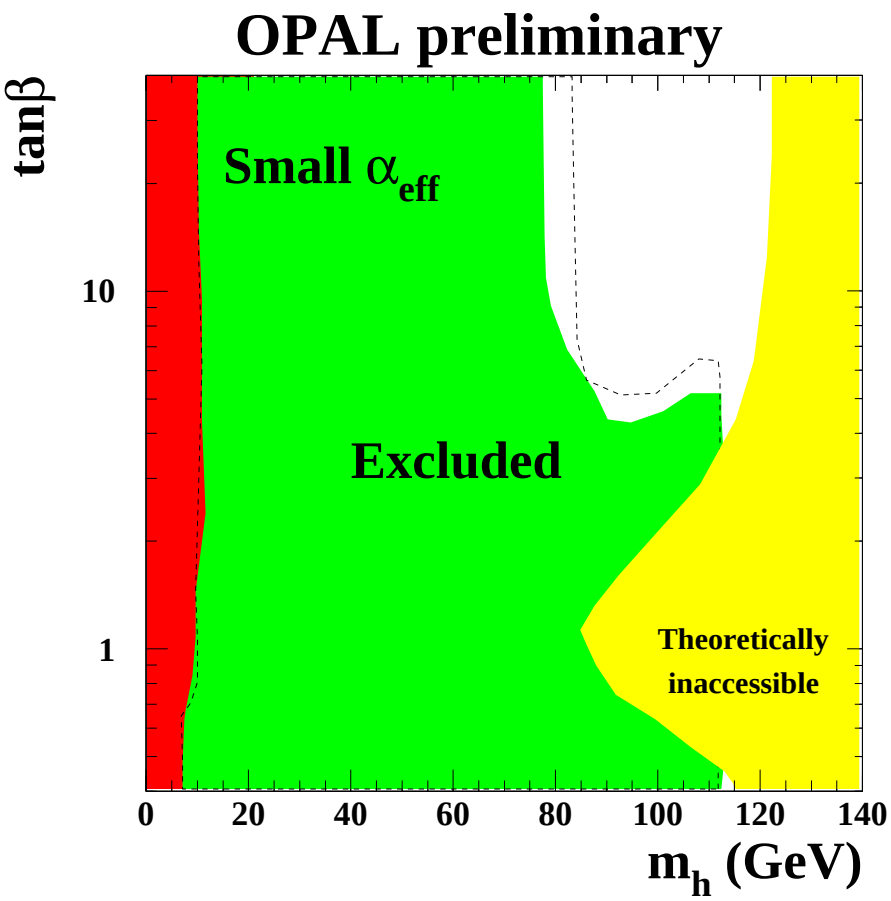
Unexcluded regions out of kinematical reach of Ah searches



Unexcluded regions at $m_{\mathrm{h}} \approx 107$ GeV, $\mathrm{BR}(\mathrm{h} \to \mathrm{b\bar{b}}) \to 0$

Exclusion areas: New Scans





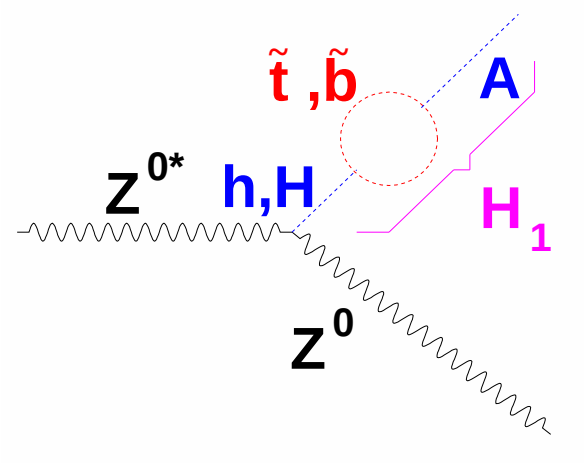
Gluophobic

Small $\alpha_{\rm eff}$

- No big surprises for LEP, $\mathrm{h} \to \mathrm{b\bar{b}}$ suppression is out of kin. reach

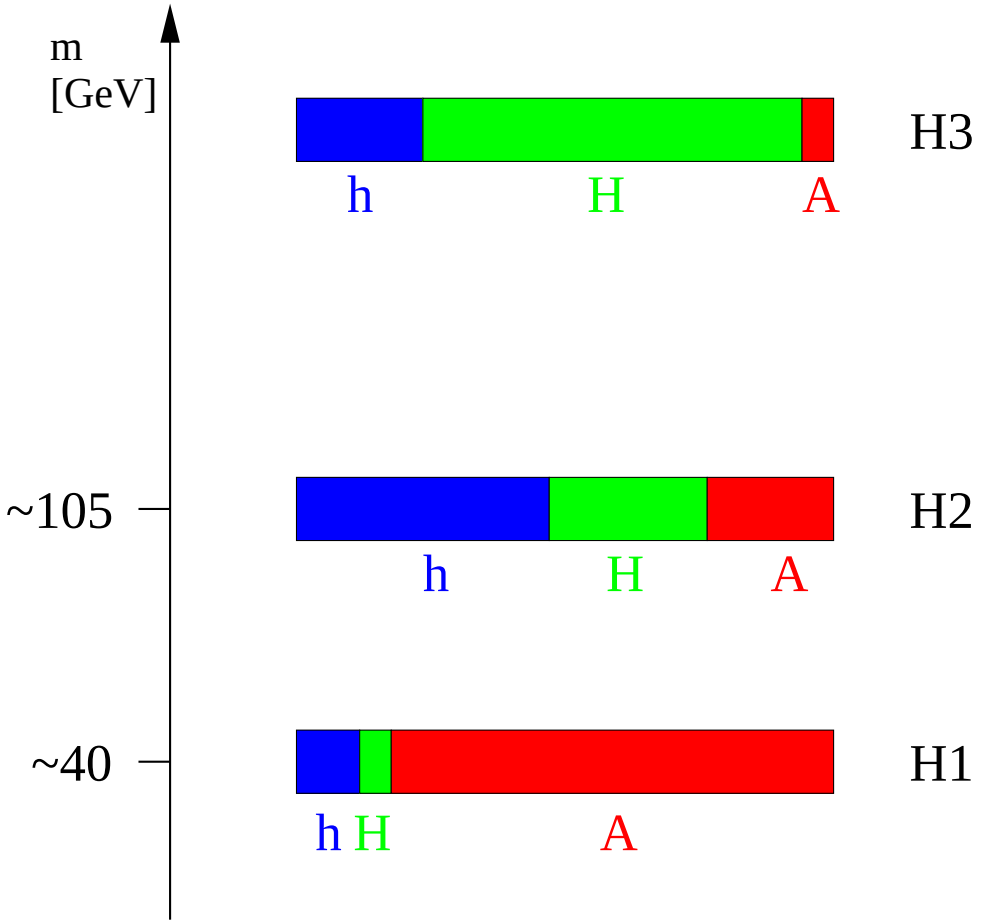
Mass eigenstates and CP-eigenstates

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



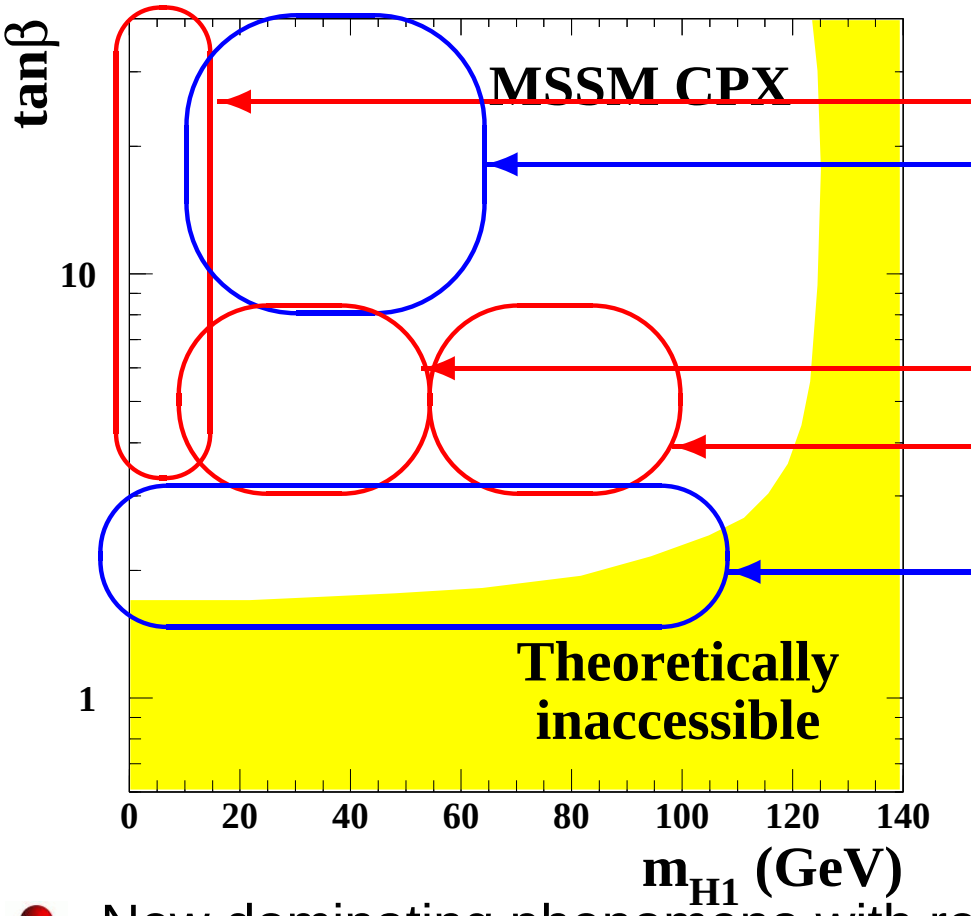
Only CP eigenstates h and H can couple to the Z, but the propagating particle is H_1

Lightest Higgs boson might have escaped detection at LEP2



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

The use of the different searches



$H_1H_2 \to \tau^+\tau^- b\bar{b}$, Yukawa-Production

$H_1H_2 \to b\bar{b}\,b\bar{b}$

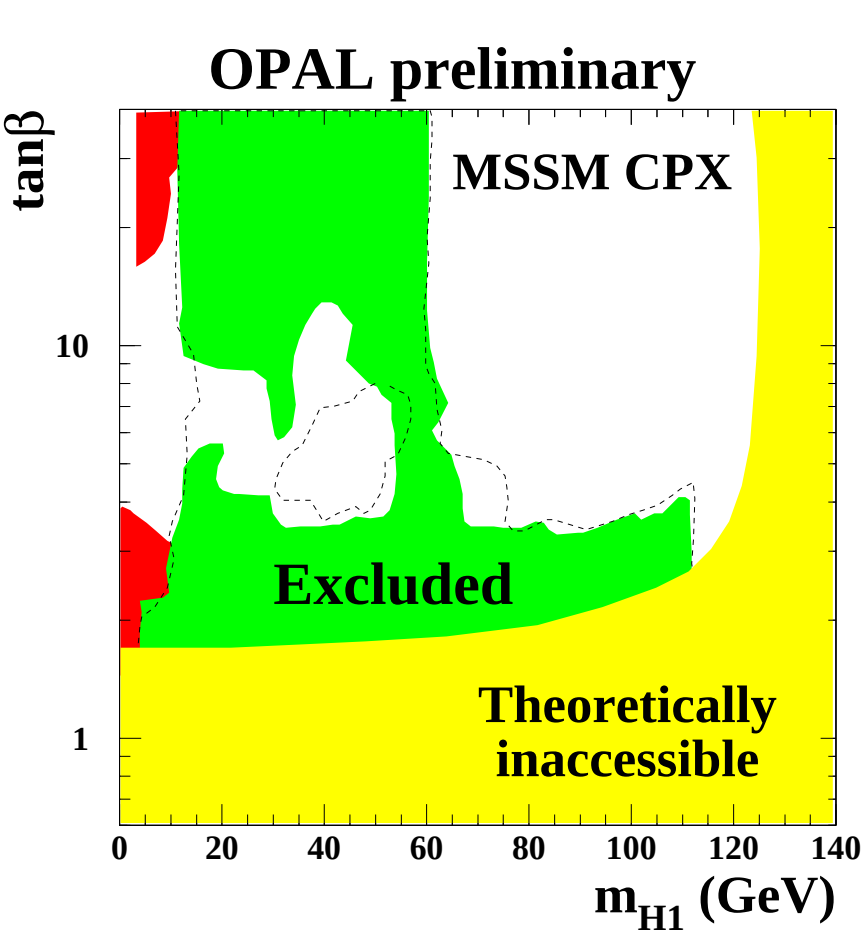
$H_2 \to H_1H_1 \to b\bar{b}\,b\bar{b}$

$H_2Z \to b\bar{b}\,Z$

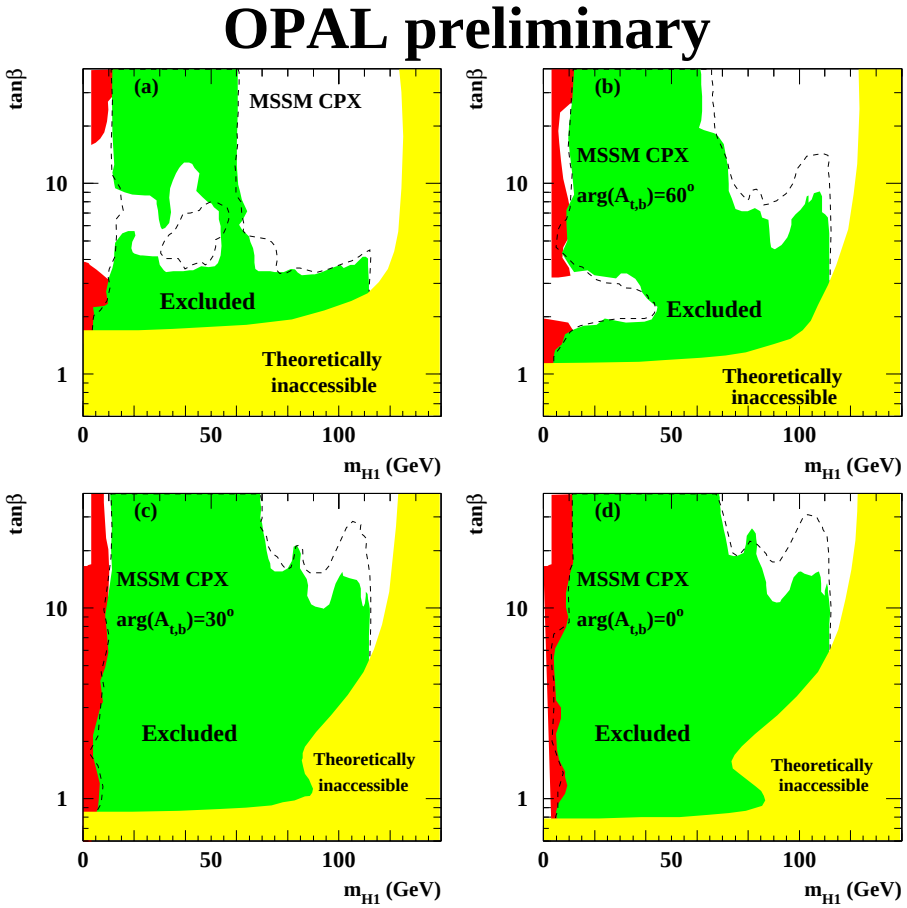
$H_1Z \to b\bar{b}\,Z$

- New dominating phenomena with respect to CP consering scans:
  $H_2Z \to H_1H_1Z \to b\bar{b}\,b\bar{b}\,Z$ decays with $m_{H_2} \approx 100 - 110$ GeV.

Exclusion areas: Example CP-violating



CPX



Different complex phases

$90° - 60° - 30° - 0°$

- In contrast to CP conserving scans: unexcluded regions at very low m_{H_1}!

The Results

- Be aware: Results are based on different scan databases $\rightarrow$ different $m_{\mathrm{h\,max}}$
- No final LEP combination yet, therefore best limits only:

Limits on the MSSM scenarios				
Scenario	lower limit on m_{h} (GeV)	lower limit on m_{A} (GeV)	Excluded $\tan\beta$	Exp.
no mixing	89.8	90.1	$0.5 < \tan\beta < 9.36$	ADLO
$m_{\mathrm{h}}-\mathrm{max}$	92.0	93.0	$0.7 < \tan\beta < 2.2$	ADLO
gluophobic	82.0	87.5	$\tan\beta < 6.0$	O
small α_{eff}	79.0	90.0	$0.44 < \tan\beta < 3.6$	O
$m_{\mathrm{h}}-\mathrm{max}^{+}$	84.5	84.0	$0.7 < \tan\beta < 1.95$	O
constr. $m_{\mathrm{h}}-\mathrm{max}$	84.0	85.0	$0.6 < \tan\beta < 2.2$	O
CPX	–	–	$\tan\beta < 2.8$	O
Allowed regions in the "large μ" scenario				
large μ	$90.0 < m_{\mathrm{h}} < 107.0$	$87.0 < m_{\mathrm{A}} < 200.0$	$\tan\beta > 15$	ADLO

ADLO

Conclusion

- The MSSM Higgs search at LEP is still very active
- New Theory:
  - 4 new LHC-motivated scans available
  - New variations of the CPX scenario exist: varying μ, m_{SUSY}
  - New Generation of Benchmark Scan Databases exists with both CPH (subhpole) and FeynHiggs2.0: $\tan\beta$ exclusion shrinks
- New Searches available
- Larger m_{t} could further reduce $\tan\beta$ exclusion
- Message from LEP to LHC: Don't forget low $\tan\beta$
- Question to LEP: Did we really exclude a low mass Higgs ($m_{\mathrm{h}} < 2m_{\mathrm{b}}$) which is not produced in Higgsstrahlung?
- LEP combination to follow asap.