QCD and Hadronic interactions

Recontres de Moriond-La Thuille 12-19 March 2005

Searches for Higgs in the MSSM
CP-conserving and CP-violating scenarios at LEP

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on behalf of the LEP experiments

- -model introduction
- -the CP-conserving MSSM
- -the CP-violating MSSM
- -2HDM

2 Higgs Doublet Models

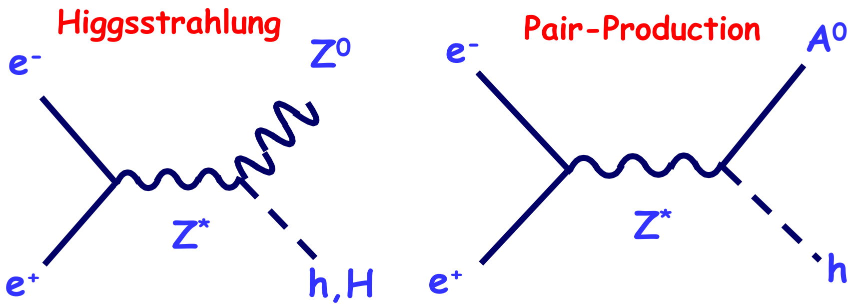
- Simplest extension of SM are 2HDMs

  $\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_w} \sim 1$ and no FCNC

- Two complex scalar field doublets Φ_1 and Φ_2, 5 scalar Higgses:
  - Real parts mix with α-> CP even scalars h^0, H^0
  - Imaginary part -> CP odd scalar A^0
  - Two charged scalars H^{+-}

- Two production processes :
  - $\sigma_{hZ} = \sin^2(\beta-\alpha)\sigma^{SM}_{HZ}$
  - $\sigma_{HZ} = \cos^2(\beta-\alpha)\sigma^{SM}_{HZ}$
  - $\sigma_{HA} = \cos^2(\beta-\alpha)\lambda\sigma^{SM}_{HZ}$

  β =ratio of VEV of scalar fields



- The type of 2HDM determined by the couplings of Φ_1 , Φ_2 to fermions:
  - Only Φ_1 couples to fermions 2HDM (I)
  - Φ_1 (Φ_2) couples to down (up) type fermions 2HDM(II)

The MSSM

- 2HDM(II) are interesting since by adding supesymmetry

⇓

CP-conserving MSSM

- CP-conserving MSSM is interesting since it provides framework for unification of Gauge interactions and stability of universe at EW scale

m_h < 140 GeV after radiative corrections

- to explain matter-antimatter asymmetry in universe we need

⇓

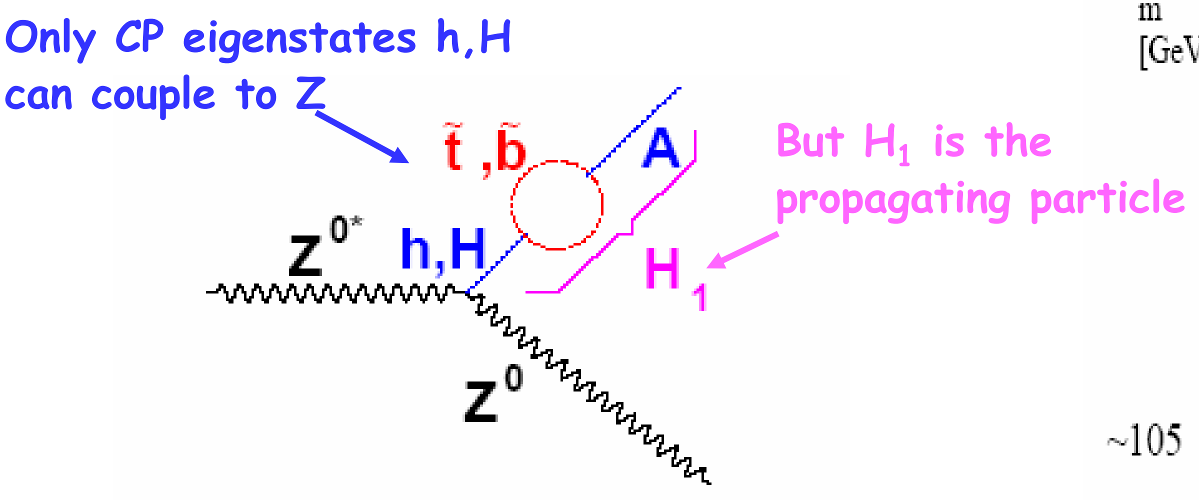
CP-violation >> than in SM

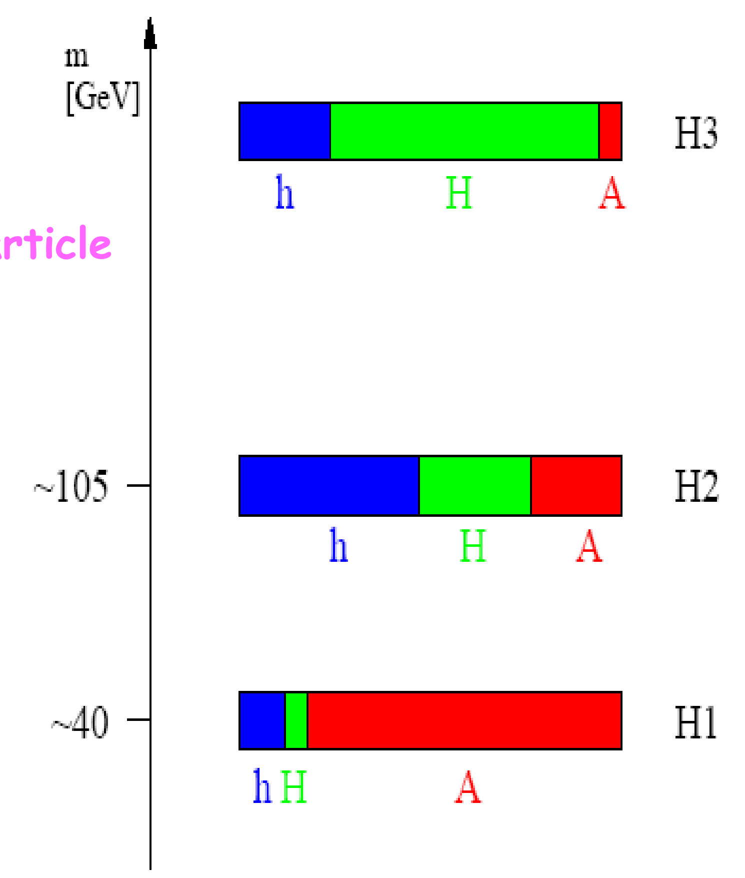
Justifies introduction of CP-violation in MSSM: can be done via radiative corrections (in particular from 3rd generation s-quarks)

CP-violation in MSSM

Mass eigenstates and CP-eigenstates do not coincide:

H_1, H_2, H_3 are mixtures of CP-even and CP-odd Higgs fields





- Lightest Higgs boson might have escaped detection at LEP2: H_1 might decouple almost completely from the Z
- Search for both H_1Z and H_2Z production

Experimental searches

ALEPH, DELPHI, OPAL & L3
data @ 91 GeV< $\sqrt{s}$ < 209 GeV
Interpreted in MSSM
CPC and CPV and 2HDM(II)

b-tagging HZ

- ($H \to bb$) ($Z \to qq$)
- ($H \to bb, \tau\tau$) ($Z \to \nu\nu$)
- ($H \to bb, qq$) ($Z \to ee, \mu\mu$)
- ($H \to \tau\tau$) ($Z \to qq$), ($H \to bb, \tau\tau$) ($Z \to \tau\tau$)

Flavour independent HZ

- ($H \to qq$) Z
- ($H_2 \to H_1 H_1$) Z dominant when kinematically allowed

b-tagging pair production H_2H_1

- ($H_2 \to bb$) ($H_1 \to bb$)
- ($H_2 \to \tau\tau$) ($H_1 \to bb$)
- ($H_2 \to H_1 H_1 \to bbbb$)(($H_1 \to bb$)

Flavour independent H_2H_1 used only for 2HDM(II) scan

- ($H_2 \to qq$) ($H_1 \to qq$)

Additional constraints

- Z width, decay mode independent search for HZ, light Higgs from Yukawa production

MSSM CPC benchmarks

7 parameters: (Carena et al. hep-ph/9912223)
m_{top}= 179.3 GeV (178.0±4.3 GeV CDF & D0)
M_{SUSY} sfermion mass at EW scale
μ Higgs mixing parameter
M_2 gaugino mass at EW scale
m_g gluino mass
X_t= Stop mixing parameter
A_b=A_t= Xt +$\mu\cot\beta$ =trilinear Higgs-squark coupling

Traditional scans:

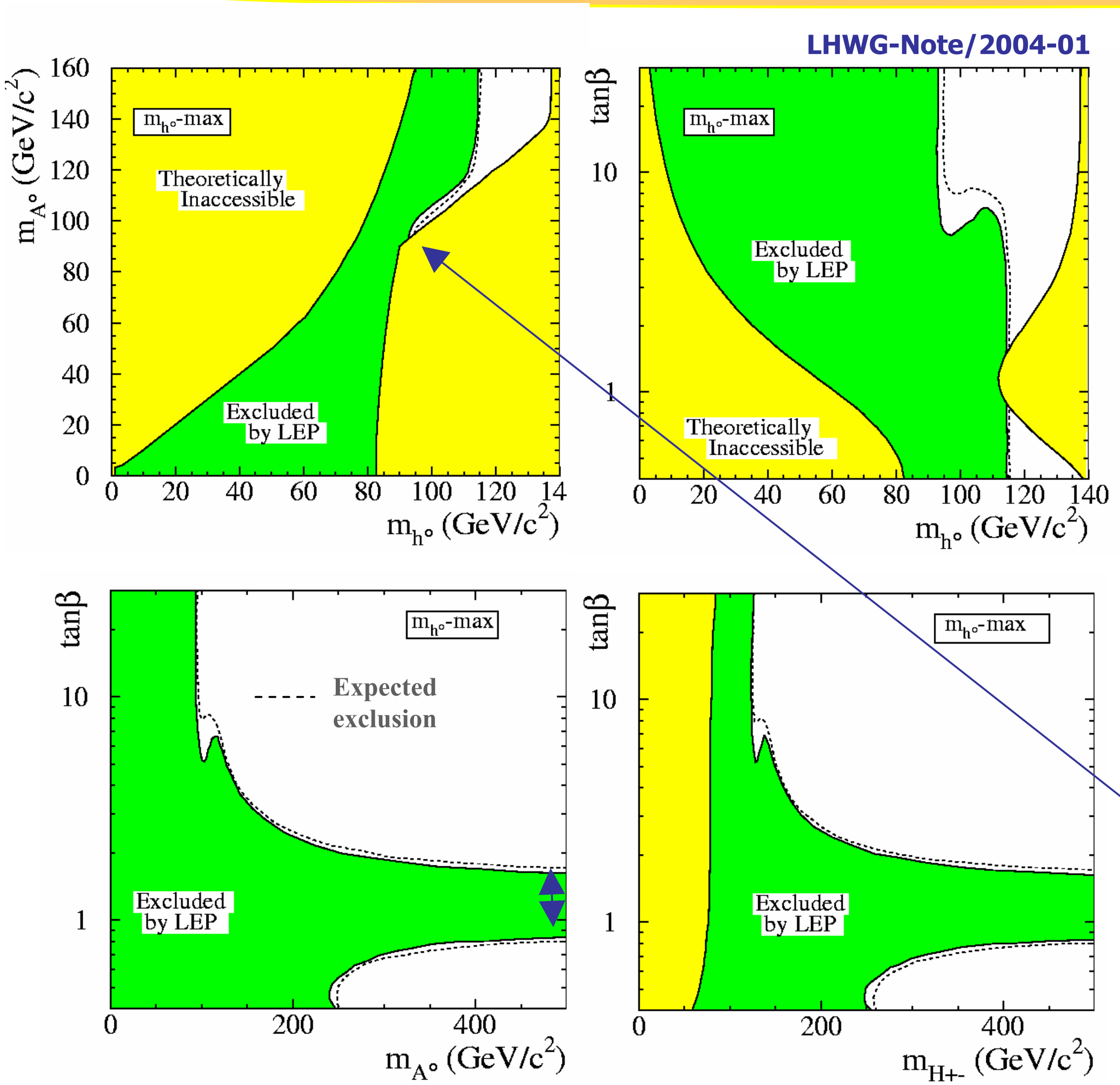
- No mixing: in stop sector
- m_h max: yields maximal bound on m_h^{TH}
- Large μ: suppressed h-> bb

New scans: envisaged for final LEP combination but not yet done

- Favoured by $(g-2)_\mu$ and Br(b->sγ)
  - No mixing (2TeV) reversed μ sign motivated by $(g-2)_\mu$
  - m_h-max+ with reversed μ sign motivated by $(g-2)_\mu$
  - constrained m_h-max reversed sign for A_t and X_t motivated by Br(b->sγ)

- Regions where Hadron colliders might have problems in detecting the Higgs
  - gluophobic gg->h suppressed
  - small α_{eff} h->bb,$\tau\tau$ suppressed

CPC m_h-max scan



2 calculations used:

- FeynHiggs 2.0: 2-loop diagrammatic approach & OS scheme
  S.Heinemeyer et al. hep-ph/0212037
- SUBHPOLE: 1-loop renormalization group, $\overline{MS}$ scheme
  M.Carena et al hep-ph/9912223

FeynHiggs is chosen:

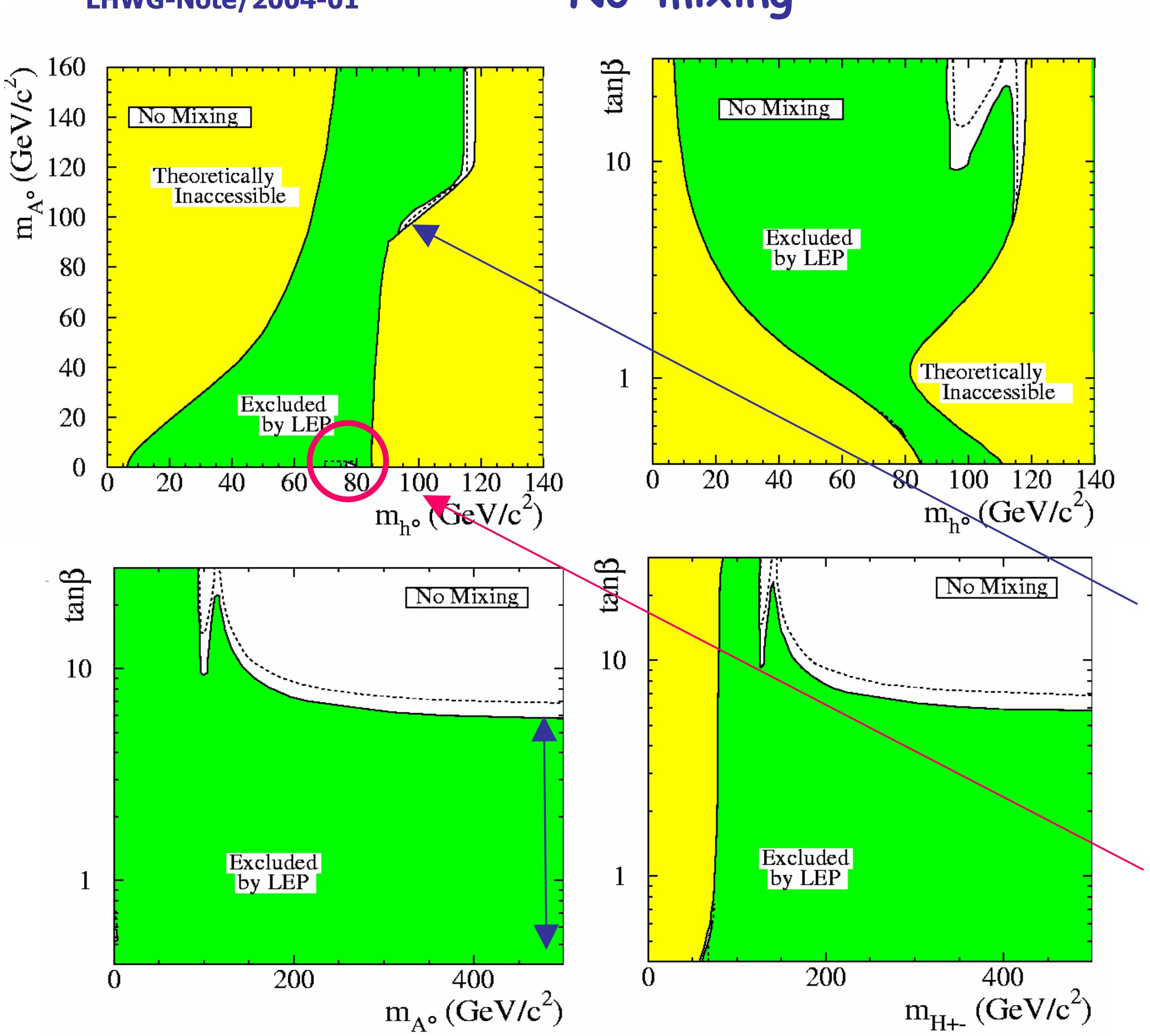
more accurate, conservative results

	m_h (GeV/c^2)	m_A (GeV/c^2)	tanβ
Obs	92.9	94.8	0.9-1.5
Exp	94.8	95.1	0.8-1.6

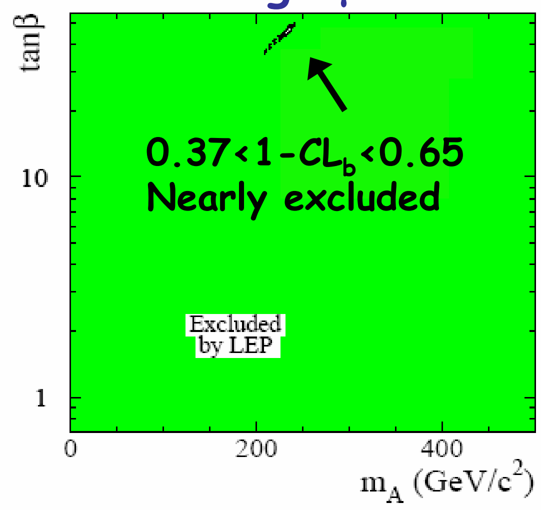
No-mixing & large μ scans

LHWG-Note/2004-01

No-mixing



Large μ

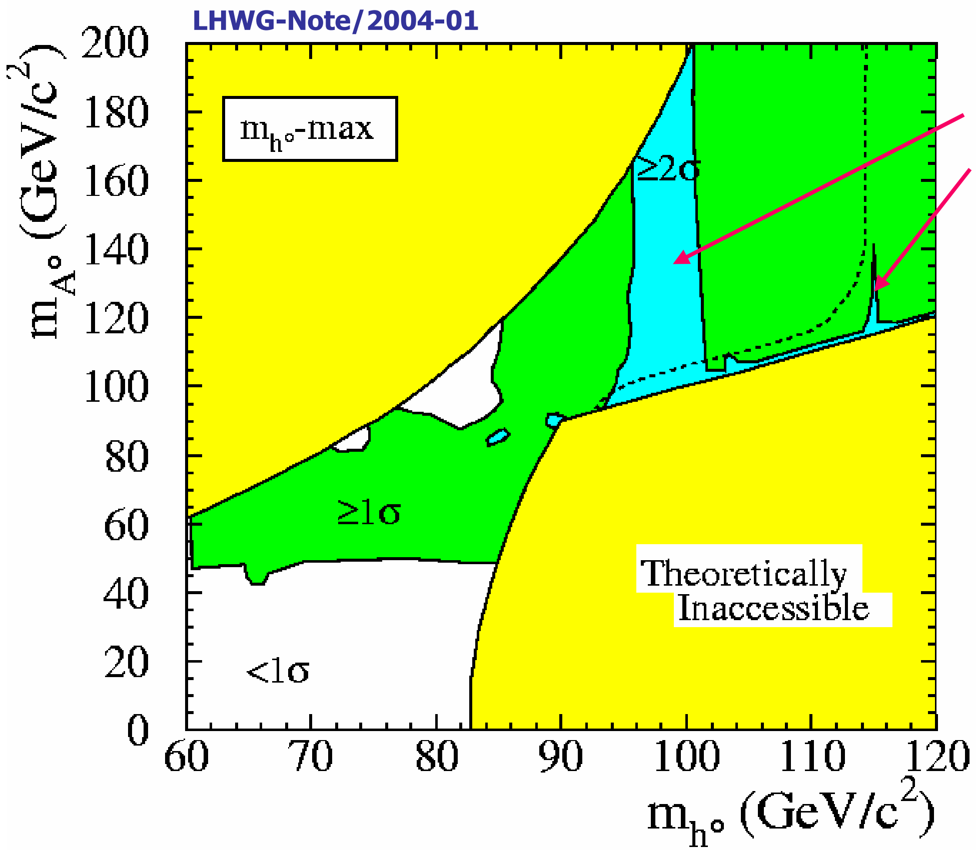


No-mixing

	m_h (GeV/c^2)	m_A (GeV/c^2)	tanβ
Obs	93.3	93.3	0.4-5.6
Exp	95.0	95.0	0.4-6.5

For m_h~80 GeV and tanβ<0.7, m_A<ττ threshold:
A decays uncertain
h→bb small

Did we miss the Higgs?



No excess larger than 3 σ:

- ≥ 2 σ @ m_h~98 GeV
- ≥ 2 σ @ m_h~115 GeV.

Recent interpretations:

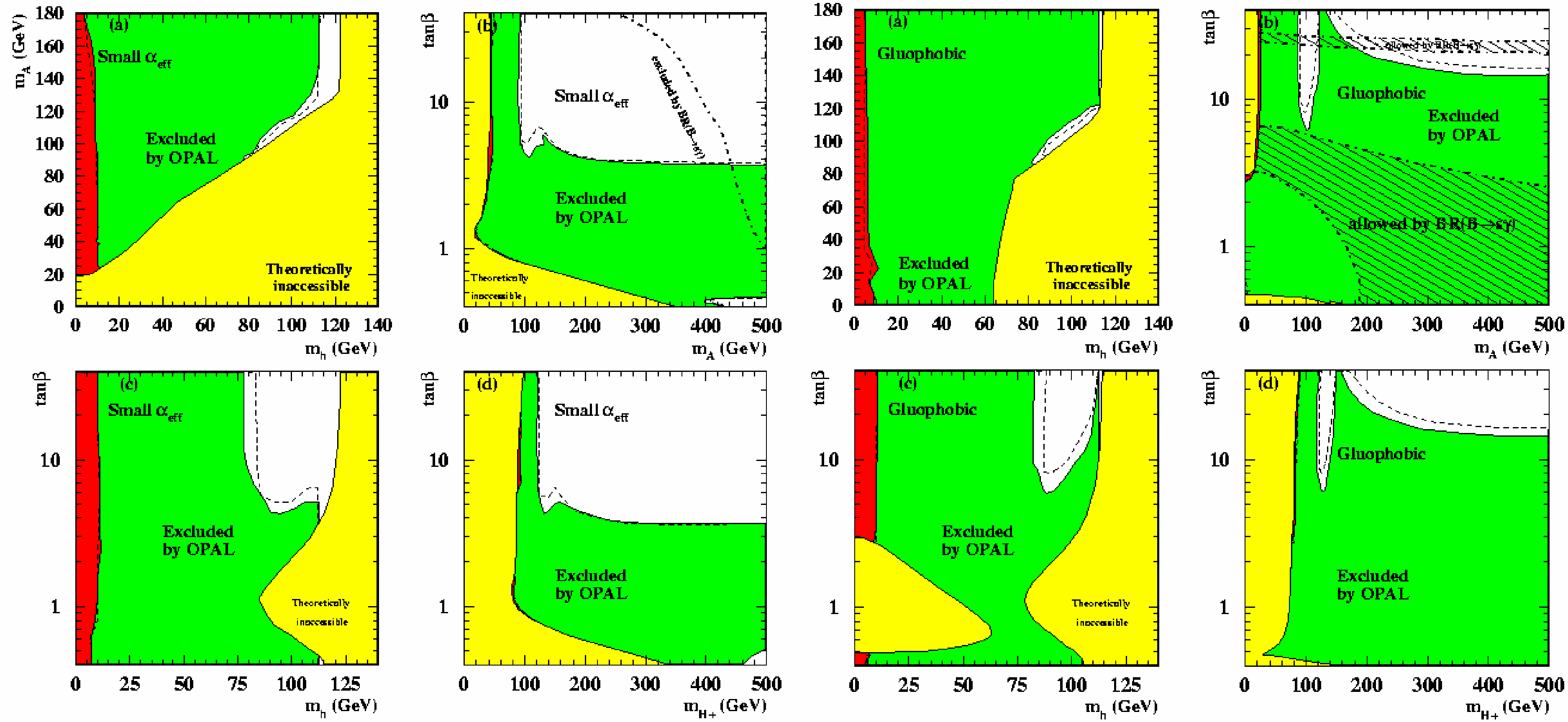
M.Drees hep-ph/0502075
G.L. Kane et al. hep-ph/0407001

Explain this kind of "excess" within

- *CP-conserving MSSM*
- *CP-violating MSSM*
- 2HDM

Example of new scans

OPAL Eur.Phys.J.C37:49-78,2004

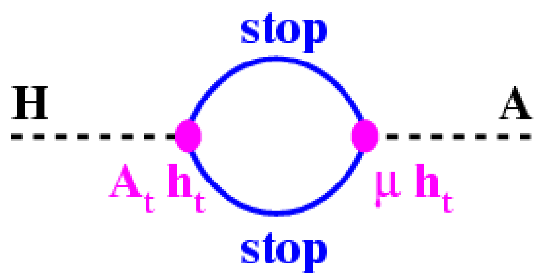


Only OPAL data: exclusion will be larger for LEP combination

Large regions of the parameters space are excluded

CP-violating MSSM

Phases of A_t ,A_b and $m_{\tilde{g}}$ introduce CP violation in the Higgs potential via loop effects leading off-diagonal contributions to higgs mass matrix



Theoretically: argA_u ≠0 most general case, can be motivated by Baryogenesis.

Size of CP violating effects proportional to:

$$M_{SP}^2 \propto \frac{m_t^4}{v^2}\frac{\mathrm{Im}(\mu A_t)}{32\pi^2 m_{SUSY}^2}$$

- benchmark: large argA_u ≠0, large μ, relatively small m_{SUSY}
- the CP violation increases with m_t

CPX benchmark

Carena et al., Phys.Lett B495 155(2000)

$\tan\beta$	m_{H^+}(GeV)	μ (GeV)	m_{SUSY} (GeV)	M_2 (GeV)	$\|A_q\|$ (TeV)	arg(A_q)	$m_{\tilde{g}}$ (TeV)	arg($m_{\tilde{g}}$)
0.6-40	4-1000	2000	500	200	1	90°	1	90°

EDM measurements of n and e fullfilled

Maximal CP violation

<u>Feynhiggs and CPH are a priori equivalent:</u>

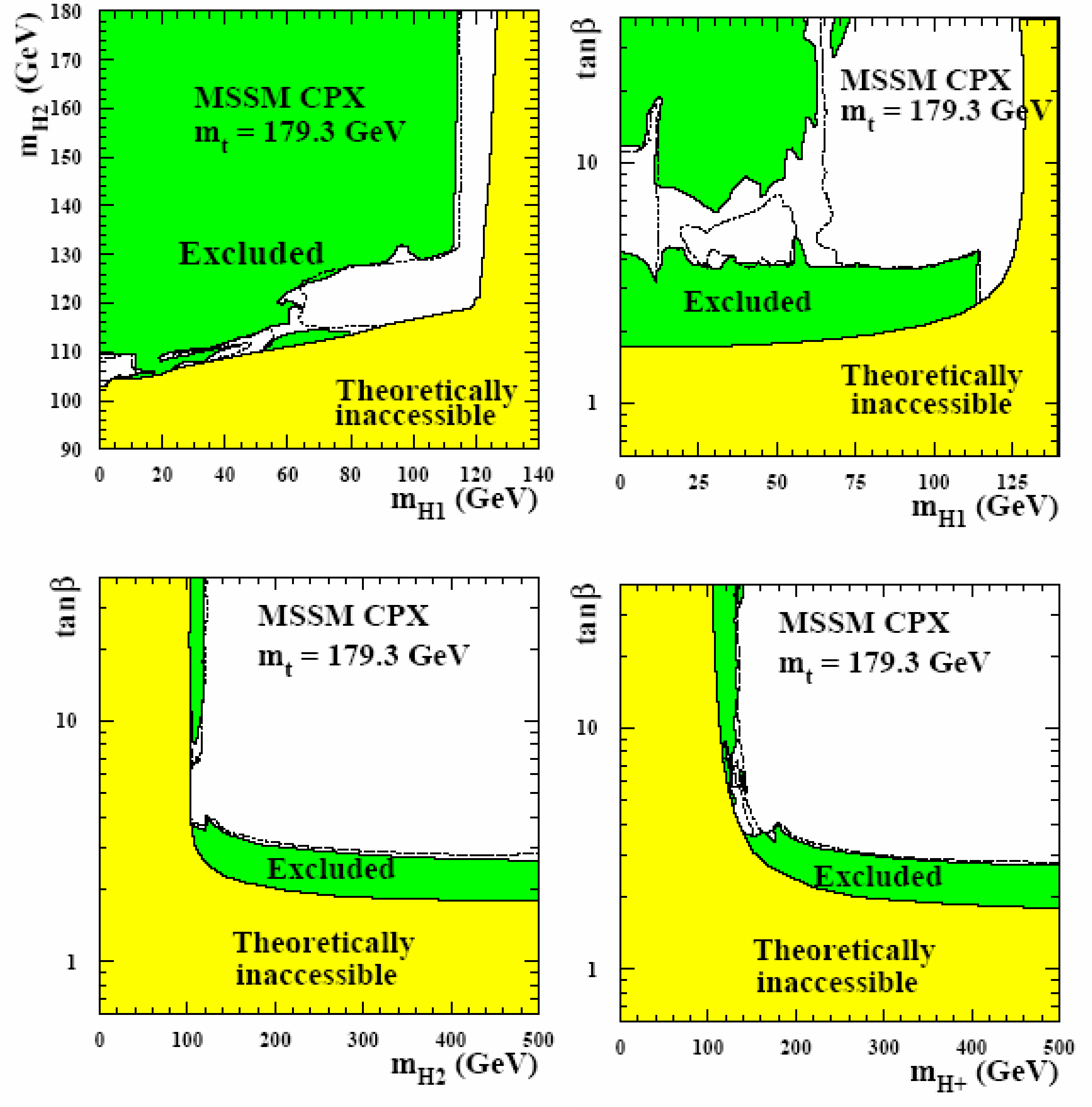
- Feynhiggs has more advanced one-loop corrections
- CPH (CPV version of SUBHPOLE) is more precise at the two-loop level

In each parameter space point the most conservative result is used

All implemented in HZHA with ISR and interference between identical final states from Higgstrahlung and boson fusion process

CPX scan

LHWG-Note/2004-01



- No lower $m_{H_{1,2}}$ limit

m_t dependent 95%CL on tanβ:

m_t(GeV/c^2)	Expected tanβ	Observed tanβ
174.3	>2.9	>3.0
179.3	>2.6	>2.7
183.0	>2.5	>2.5

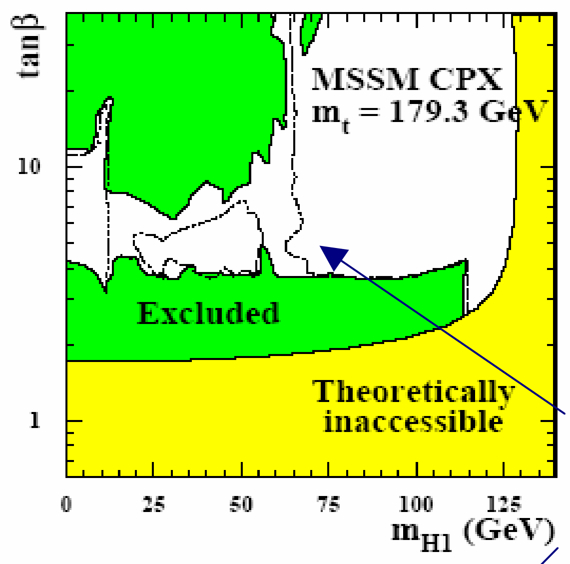
m_t=178.0±4.3 GeV CDF & D0

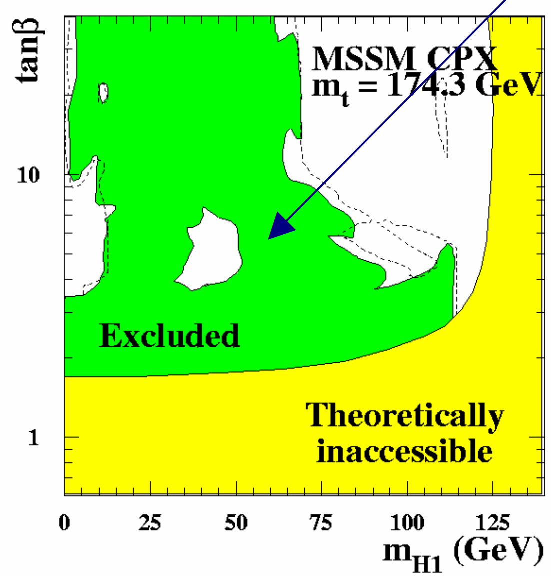
For heavy H_2:

- $H_1 \approx H_{SM}$
- $m_{H_1} \gtrsim$ 115 GeV

CPX scan

LHWG-Note/2004-01

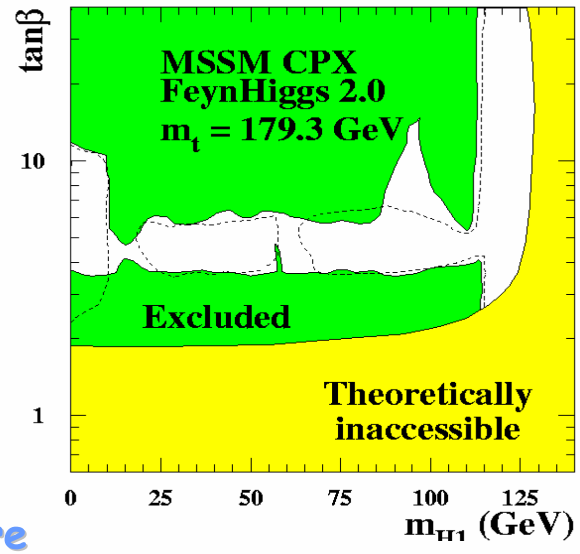


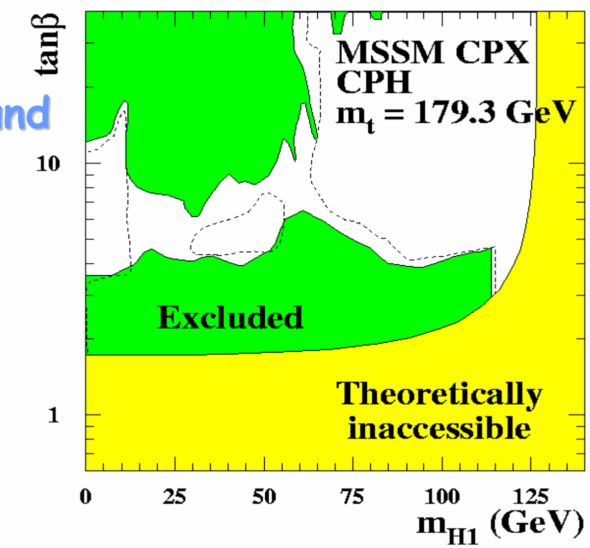


Strong reduction of exclusion increasing $m_t \Rightarrow$ CP-violation:

for example 4<tanβ<10, where both H_1Z & H_2Z are open

No excess larger than 3σ found



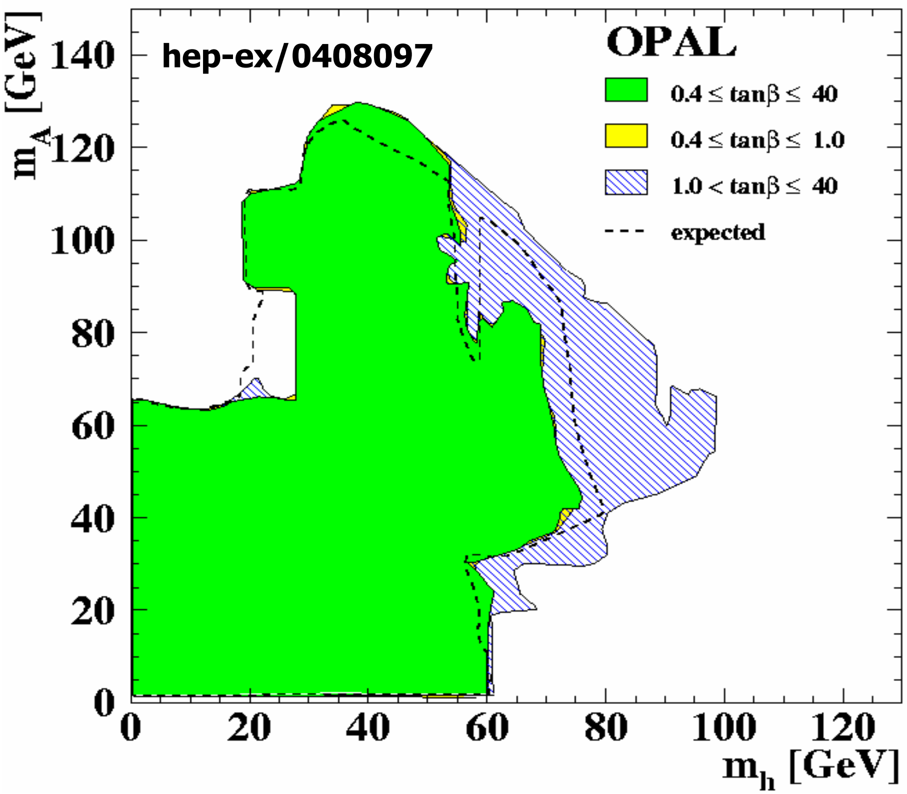


OPAL general 2HDM(II) scan

2HDM(II) have no constraint derived from SUSY:

- $h \rightarrow bb$ is not dominant decay, e.g for $\alpha=0$ BR($h \rightarrow bb/\tau\tau$)=0 ⇨ flavour-indep. searches
- large regions of the parameter space cannot be exlcuded by LEP

light Higgs not ruled out



Signal generated with HZHA

Free parameters:

- $1 < m_h < 130$ GeV
- 3 GeV $< m_A <$ 2 TeV
- $\alpha = \pm\pi/2, \pm\pi/4, 0$
- $0.4 < \tan\beta < 40$

m_H and $m_{H^\pm}$ kinematically unaccessible

Excluded rectangular region for $1 < m_h < 55$ GeV when $3 < m_A < 63$ GeV
But for $m_A > 63$ values of m_h down to 0 are still allowed !

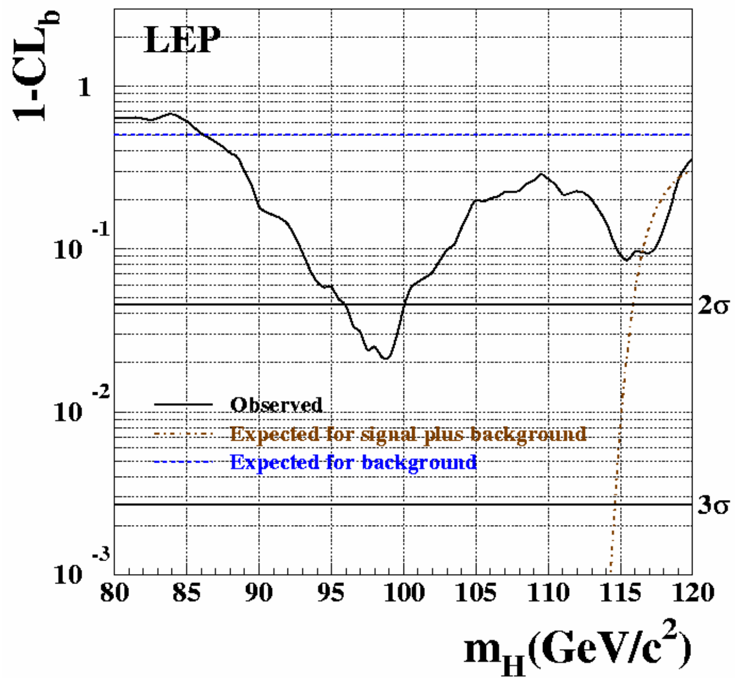
No $\tan\beta$ exclusion independent of m_h/m_A

Conclusions

- At LEP we have searched for Higgses in several extensions of SM:
  CP-conserving MSSM
  CP-violating MSSM
  2HDM
- No evidence of the presence of a signal has been found
- Still there is room for the presence of a light Higgs:
  In CP-violating MSSM
  In 2HDMs
- Some theoretical papers interpreting small data-background discrepancy (about 2 σ) in the context of specific CPC MSSM scenarios (require quite some tuning) as well as CPV MSSM and 2HMD.

Back-up

SM vs MSSM excess



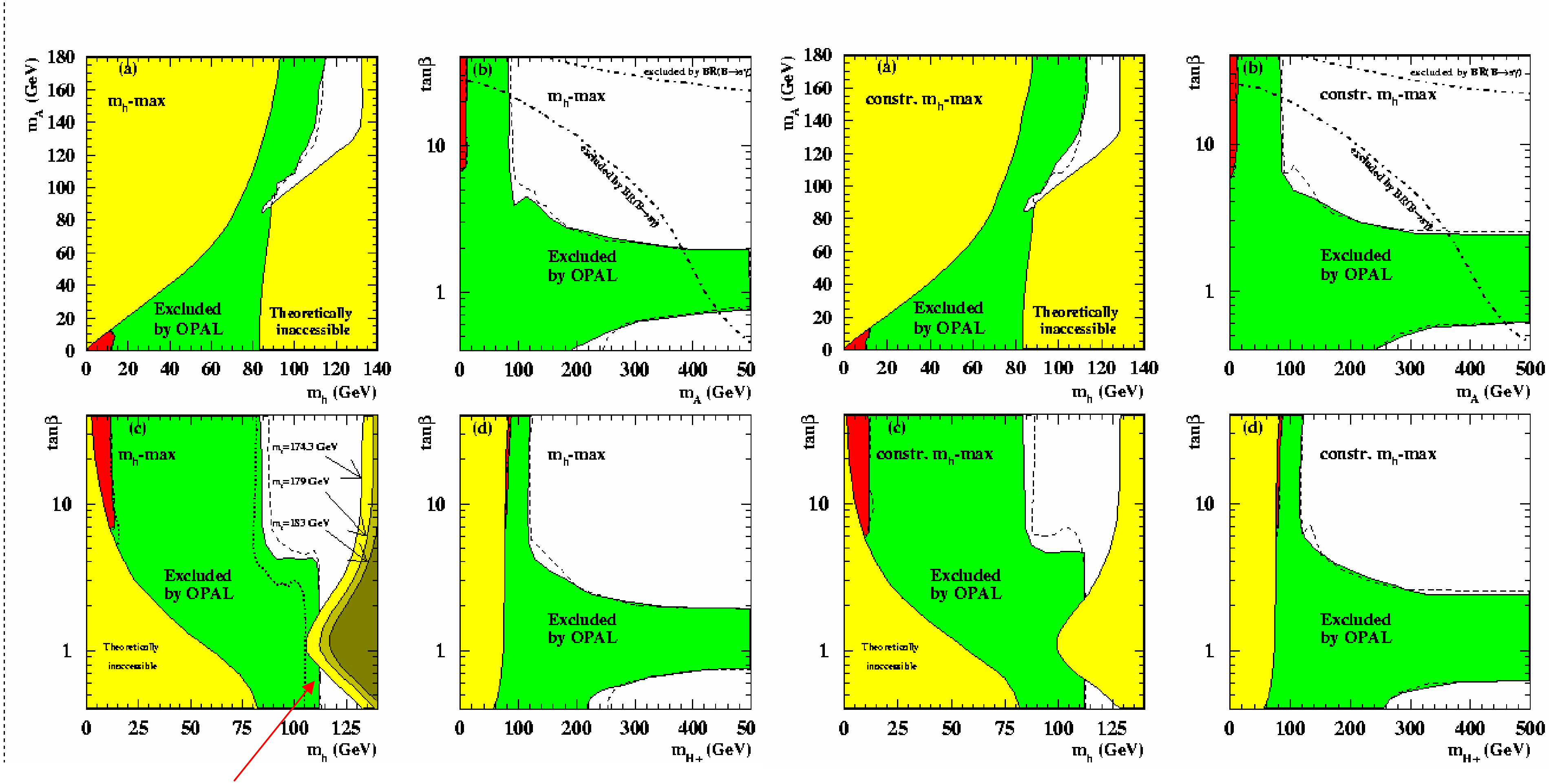
The excesses at m_h=98 & 115 GeV Observed in MSSM are the same that where observed in the SM searches:

- m_h~98 GeV 2.3 σ excess 1-CL_b= 2% from all hZ channels Not Compatible with a SM signal.
- m_h~115 GeV 1.7 σ excess 1-CL_b= 9% from ALEPH hZ 4-jet channel Compatible with a SM signal.

1-CL_b gioves the Probability of a local fluctuation of background. Probability that a fluctuation appears anywhere within a certain mass range is given by:

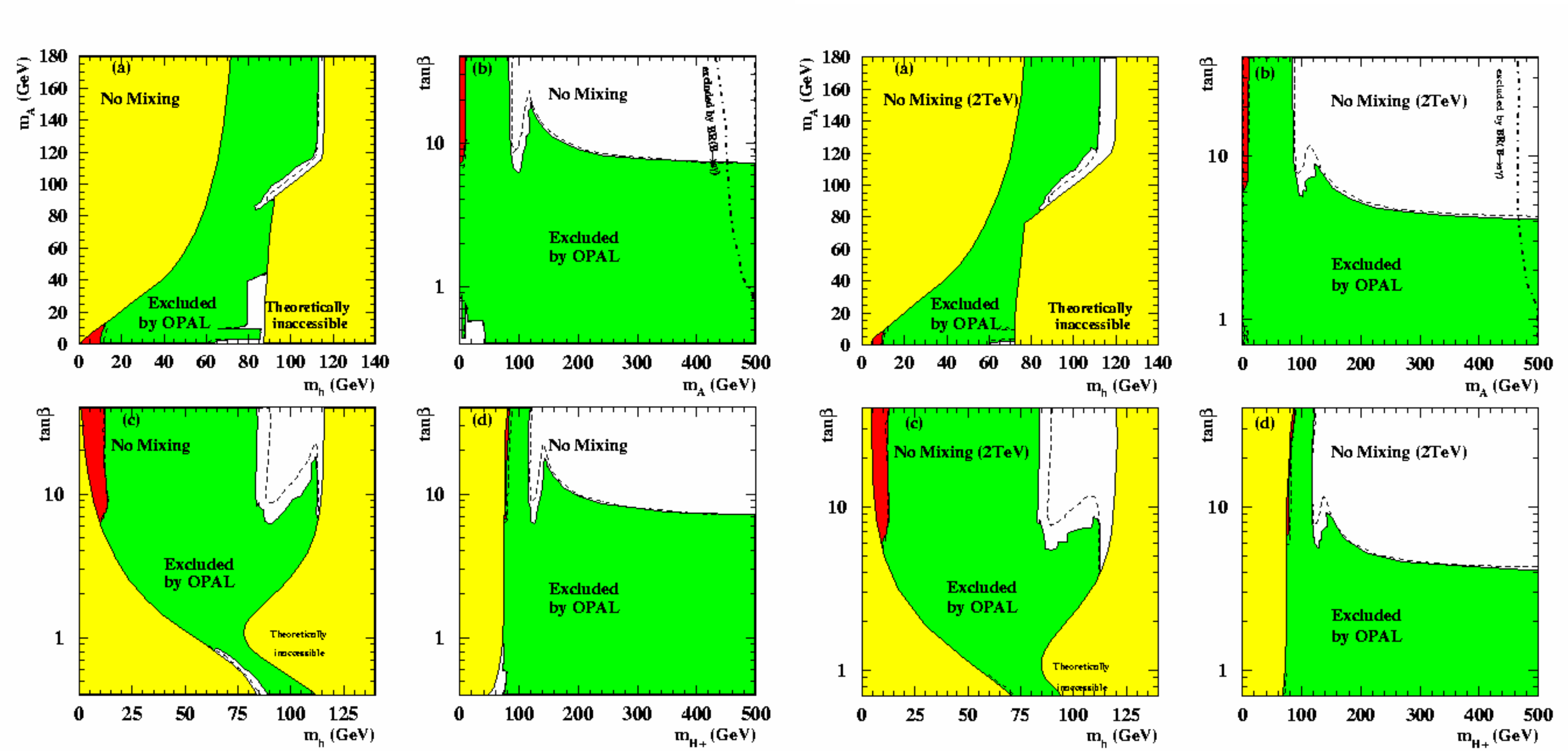
$$(1-CL_b)\times\frac{\Delta\ (\text{mass range})}{\text{mass resolution}}$$

m_h max scans



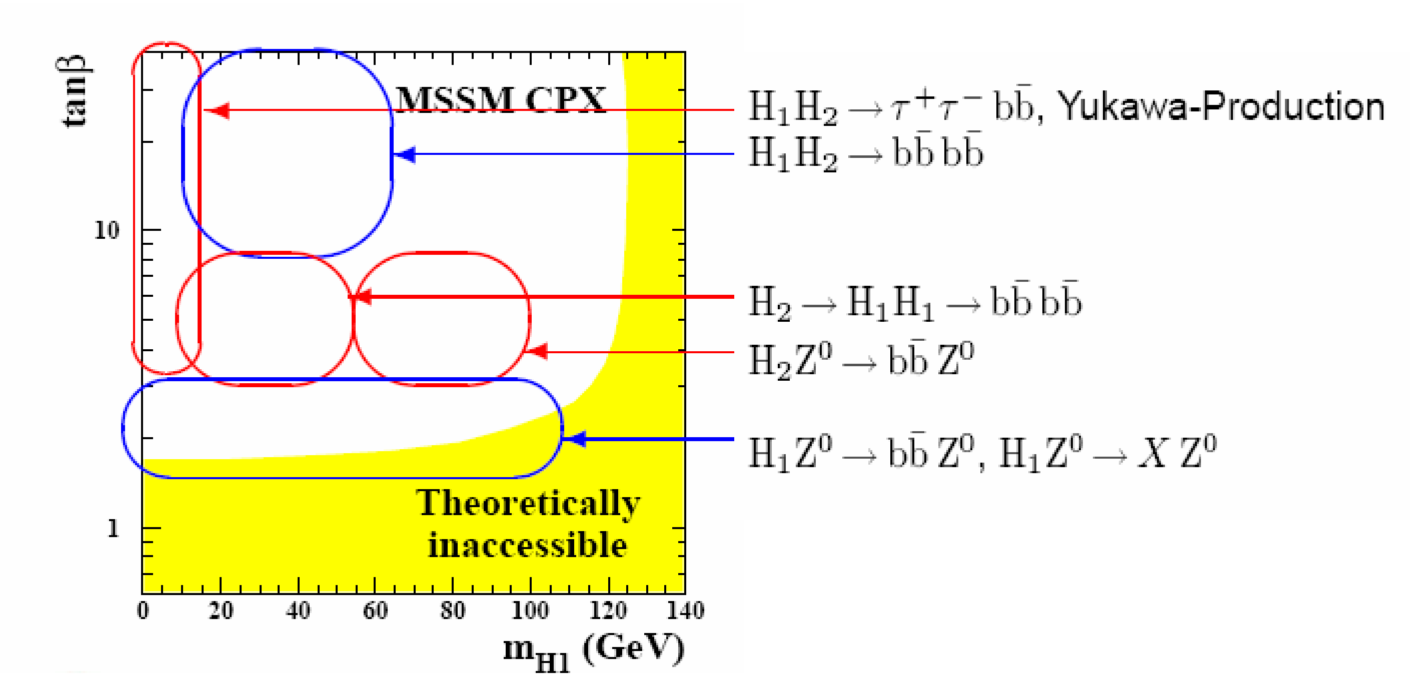
m_t=174.3,179,183 GeV

No-mixing



No Mixing
Excluded by OPAL
Theoretically inaccessible
No Mixing (2TeV)

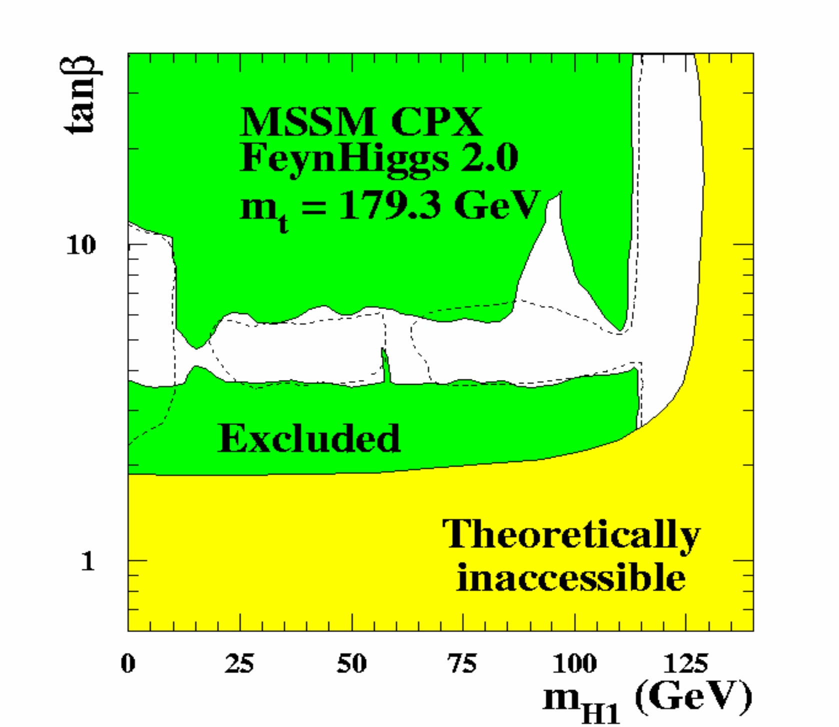
Useful searches for CPV MSSM

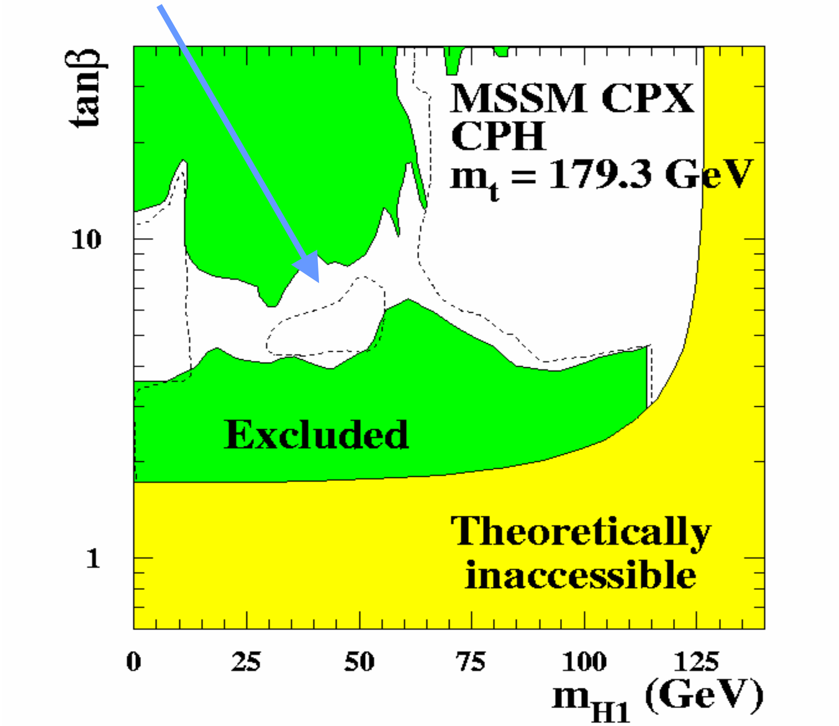


CPH vs FEYNHIGGS

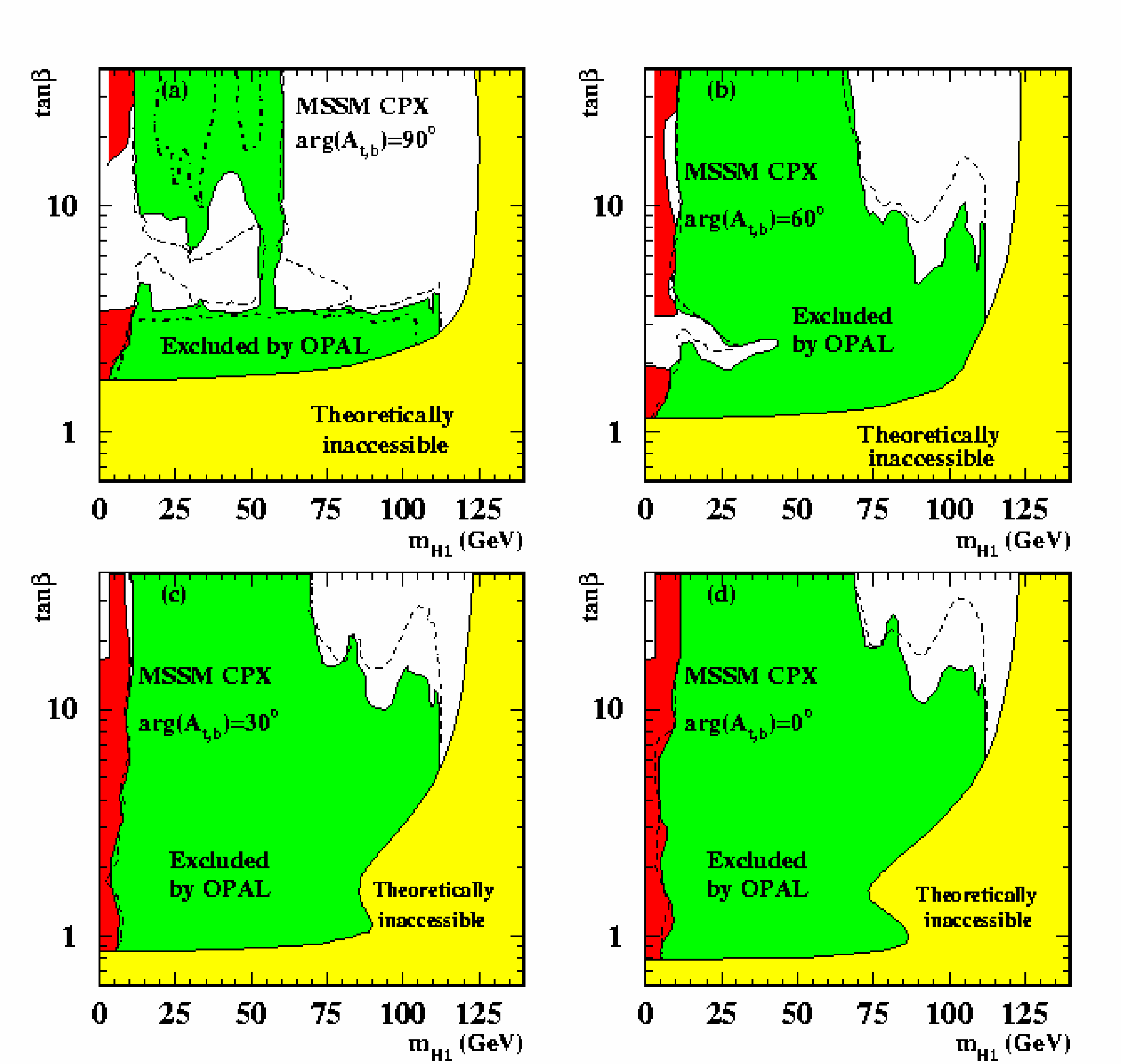
- The largest discrepancy occurs for large tanβ where Feynhiggs predicts a higher x-section for Higgstrahlung
- Data/background discrepancy in intemediate tanβ region:

due to excess at m_h~98 GeV which is the m_{H_2} mass in this region



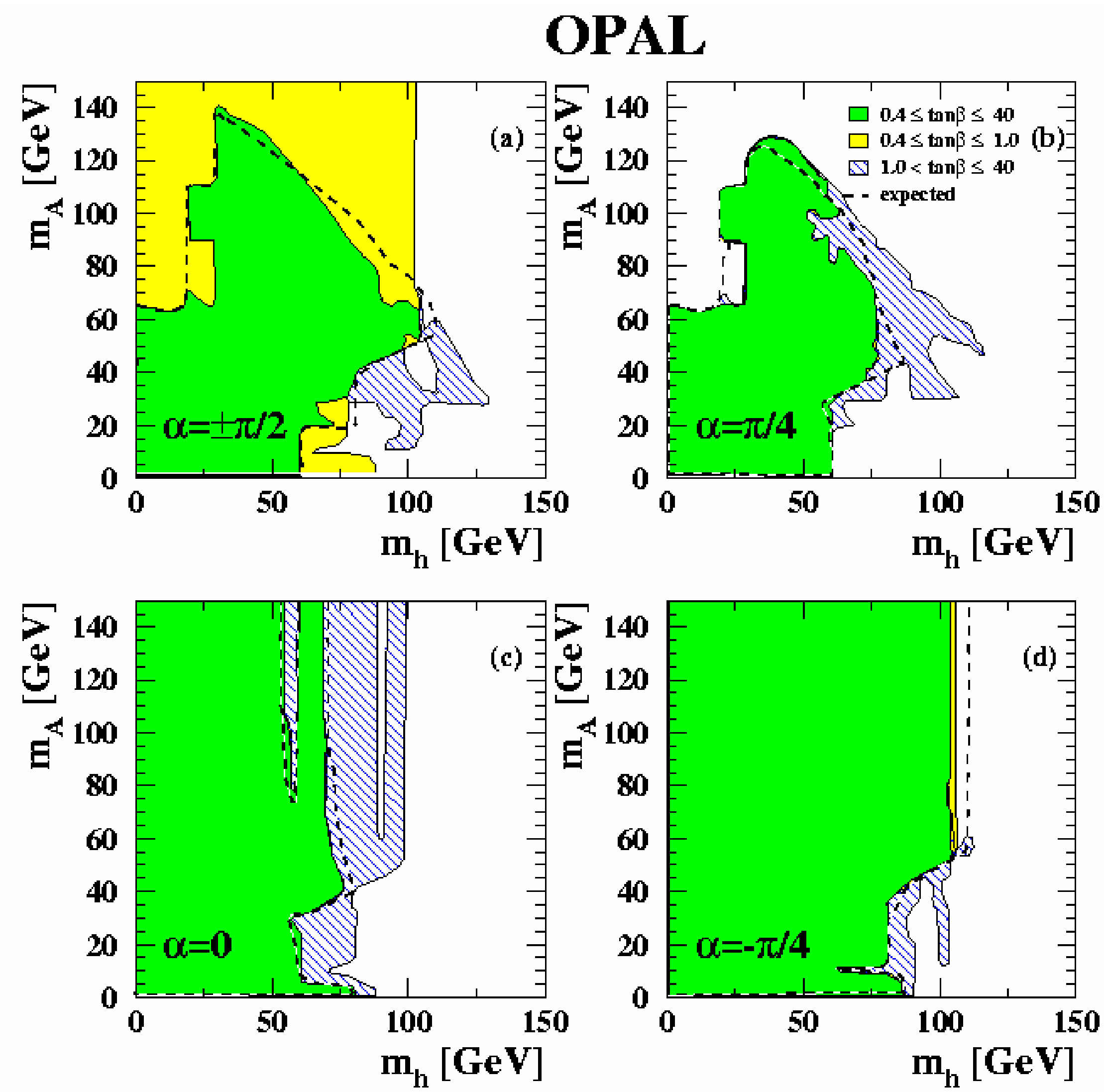


CPX-phases

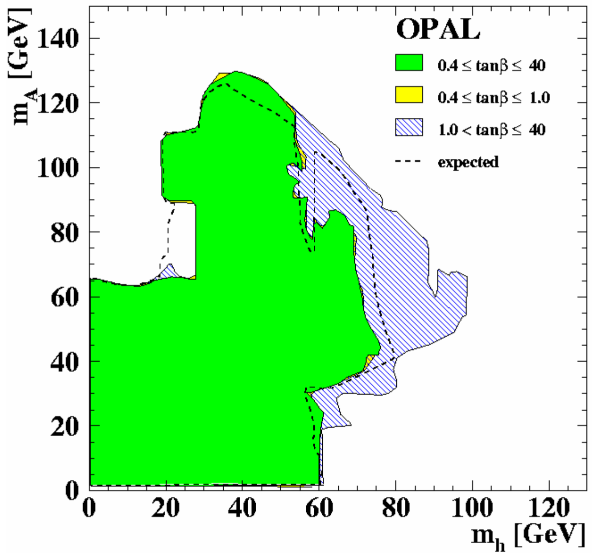


Exclusion decreases With increasing $argA_{t,b}$ (CP-Violation)

2HDM scan

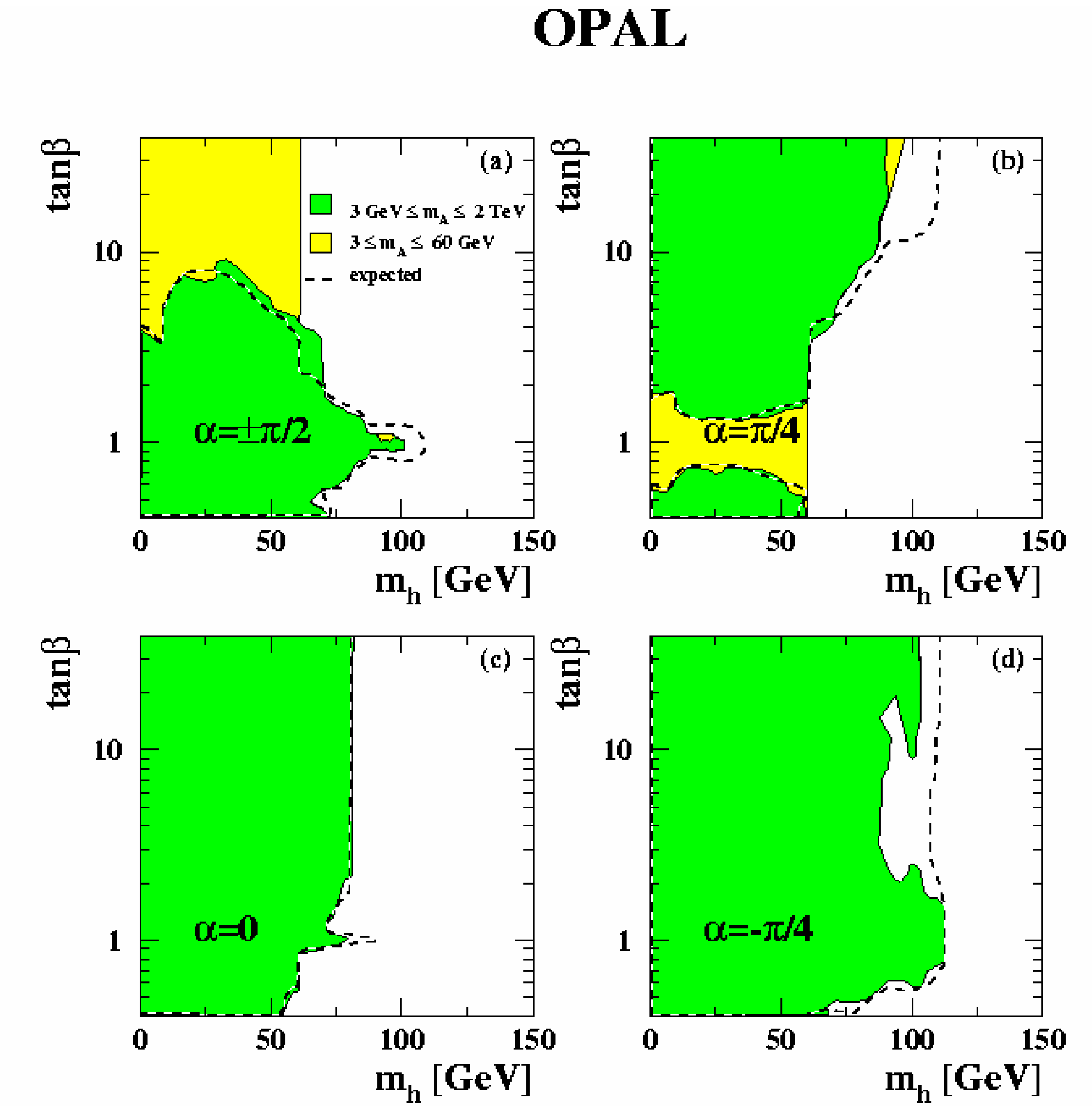


OPAL
(a)
(b)
(c)
(d)
α=±π/2
α=π/4
α=0
α=-π/4
0.4 ≤ tanβ ≤ 40
0.4 ≤ tanβ ≤ 1.0
1.0 < tanβ ≤ 40
expected
m_A [GeV]
m_h [GeV]



OPAL
0.4 ≤ tanβ ≤ 40
0.4 ≤ tanβ ≤ 1.0
1.0 < tanβ ≤ 40
expected
m_A [GeV]
m_h [GeV]

2HDM scan tanβ exclusion



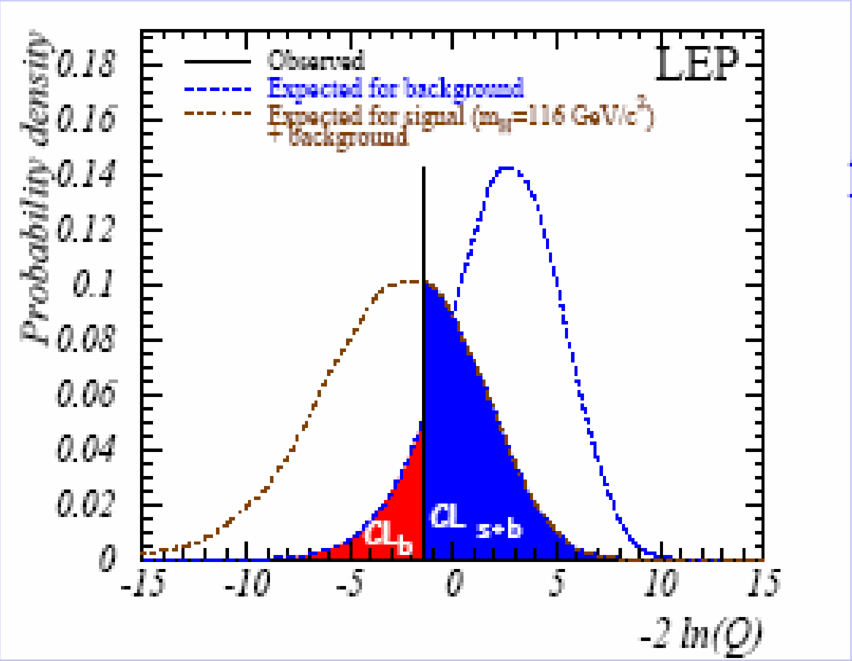
No tanβ exclusion independent from m_h and m_A

The statistical method:"likelihood ratio"

- Data are subject to likelihood test ratio of 2 hypothesis
  - Data receive contributions from background processes only
  - Data receive contribution from background+SM Higgs boson signal of test mass m_H
- *Channels are binned in 2-dimensional space* $(m_H^{rec}, \mathcal{G})$

$$Q = \mathcal{L}_{s+b}/\mathcal{L}_b \quad \text{or} \quad -2\ln Q = 2s_{tot} - 2\sum_i n_i \ln(1+s_i/b_i)$$

signal (→ s_i), candidates (→ n_i), background (→ b_i)



1-CL_{s+b}=measure of compatibility with s+b

1-CL_b=measure of incompatibility with b

1-CL_b	0.32	0.064	2.7×10^{-3}	6.3×10^{-5}	5.7×10^{-7}
	1σ	2σ	3σ	4σ	5σ

$CL_s = CL_{s+b}/CL_b$