Search for Higgs bosons at LEP:
SM, MSSM, 2HDM
and model independent results

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Outline & introduction

- *Combined results from the LEP Higgs WG*
  - *SM (2003 April)*
  - *Flavour independent hZ (since 2001 LEP combination, new results from A,D, O)*
  - *MSSM (since 2001 LEP combination, new results from A,D, L)*
- *Specific analyses, interpretations*
  - *Flavour independent hA (DELPHI, 2003 March)*
  - *Decay-mode independent search (OPAL, 2002 April)*
  - *Low-mass A in hZ hAA (OPAL, 2002 July)*
  - *CP-violating MSSM (OPAL, 2003 March)*
  - *2HDM (OPAL)*
  - *Yukawa production (DELPHI 2002 July; OPAL)*
  - *"Model-independent" (DELPHI, 2002 July)*
- *LEP data sample (ADLO total)*
  - *2461 pb^{-1} for $\sqrt{s} \geq 189$ GeV of which 536 pb^{-1} for $\sqrt{s} \geq 206$ GeV*
  - *32.5 pb^{-1} for $\sqrt{s} \geq 208$ GeV*

See next talk for invisible, fermiophobic, charged, doubly charged Higgs and Higgs anomalous coupling searches

Standard Model

- *Neutral scalar : H*

  m_H free parameter ⇒ phenomenology fully determined

- *Theoretical bound on m_H from self-consistency arguments*

  if SM valid up to Λ_{Planck}:

  130 GeV ≤ m_H ≤ 200 GeV

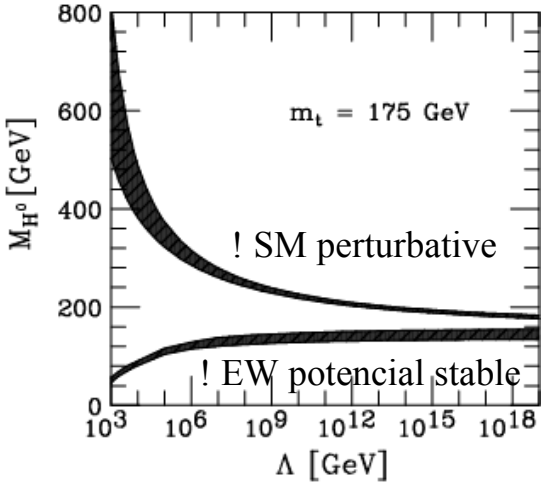
- *Indirect bounds from EW precision data*

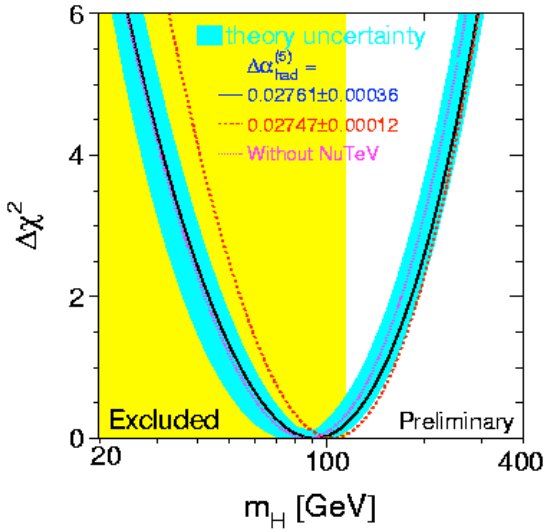
  radiative corrections depend on m_{top}^2 and log(m_H)

  $m_H = 91^{+58}_{-37}$ GeV @ 68% CL

  m_H < 211 GeV @ 95% CL

  (incl. theory uncertainty)





SM Higgs search

- *Higgs-strahlung: $e^+e^- \to HZ$*

  m_H=115 GeV @ $\sqrt{s}$=206 GeV: $\sigma \sim 8$ fb

- *Vector-boson fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$*

  Negligible except close to the kinematic limit

  m_H=115 GeV @ $\sqrt{s}$=206 GeV: $\sigma \sim 5.5$ fb incl. interference

- *H decay*

  m_H=115 GeV: 77% bb, 7% $\tau\tau$, 7% gg, 5% W^*W^*, 4% cc, <1% Z^*Z^*

- *Search channels*

Four-jet:	*$HZ \to$ bb qq*
Missing energy:	*$HZ \to$ bb $\nu\bar{\nu}$*
Leptonic (electron/muon):	*$HZ \to$ bb ee, bb $\mu\mu$*
Tau:	*$HZ \to$ bb $\tau\tau$, $\tau\tau$qq*

- *Backgrounds*

  ZZ (irreducible for $m_H \sim m_Z$ and $Z \to$ bb), WW and qq(γ)

  $\Rightarrow$ b-tagging crucial, multi-variant selections to improve sensitivity

Statistical method

- *Likelihood ratio:*

  $Q(m_H) = L_{s+b}(m_H)/L_b(m_H) = L(m_H;1)/L(m_H;0)$

- *Binned likelihood function*

$$L(m_H;\mu) = \prod_{k=1}^{N} \frac{e^{-(\mu s_k(m_H)+b_k(m_H))}(\mu s_k(m_H)+b_k(m_H))^{n_k}}{n_k!} \prod_{j=1}^{n_k} \frac{\mu s_k(m_H) S_k(\vec{x}_{jk}, m_H) + b_k(m_H) B_k(\vec{x}_{jk}, m_H)}{\mu s_k(m_H) + b_k(m_H)}$$

k=1…N channels

j=1…n_k observed candidates

s_k,b_k: signal and background rates

S_k, B_k:p.d.f. of discriminating variables for signal and background

X_{jk}: discriminating variables, typically (m_H^{rec}, A)

Statistical method (cont.)

- Test statistics:

$$X = -2\ln Q(m_H) = 2\sum_{k=1}^{N} s_k(m_H) - \sum_{j=1}^{n_k} \ln\left(1 + \frac{s_k(m_H)S_k(\vec{x}_{jk};m_H)}{b_k(m_H)B_k(\vec{x}_{jk};m_H)}\right)$$

$$= 2\sum_{k=1}^{N} s_k(m_H) - \sum_{j=1}^{n_k} w_{jk}(\vec{x}_{jk};m_H)$$

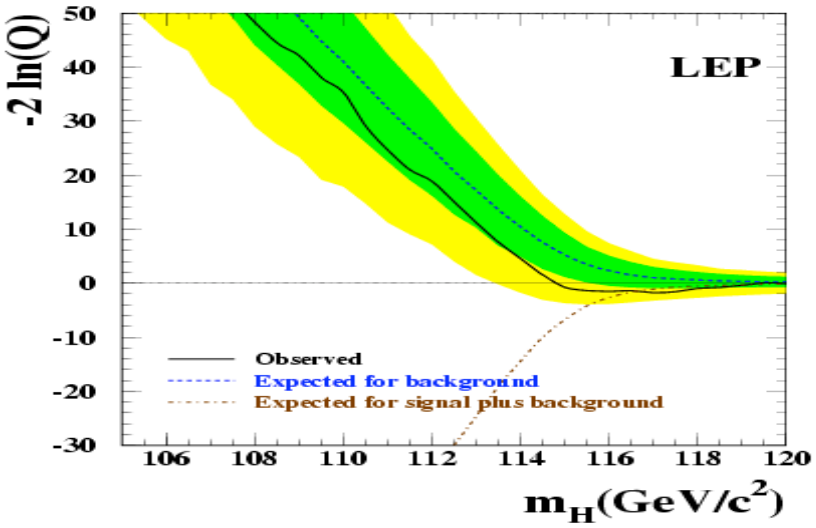
- Confidence levels:

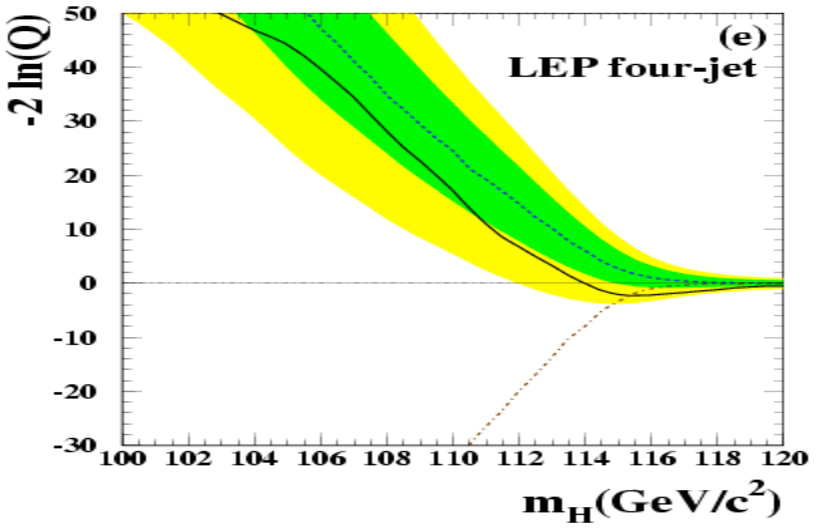
$$1-CL_b = \int_{-\infty}^{X_{obs}} P_b(X) \qquad CL_{s+b} = \int_{X_{obs}}^{\infty} P_{s+b}(X)$$

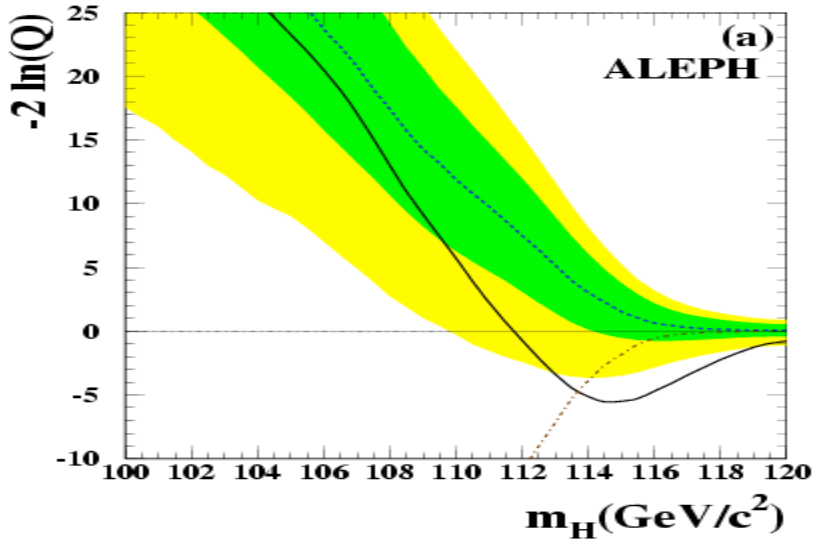
Observation with 3(5)s: $1\text{-}CL_b = 2.7\times10^{-3}$ (5.7×10^{-5})

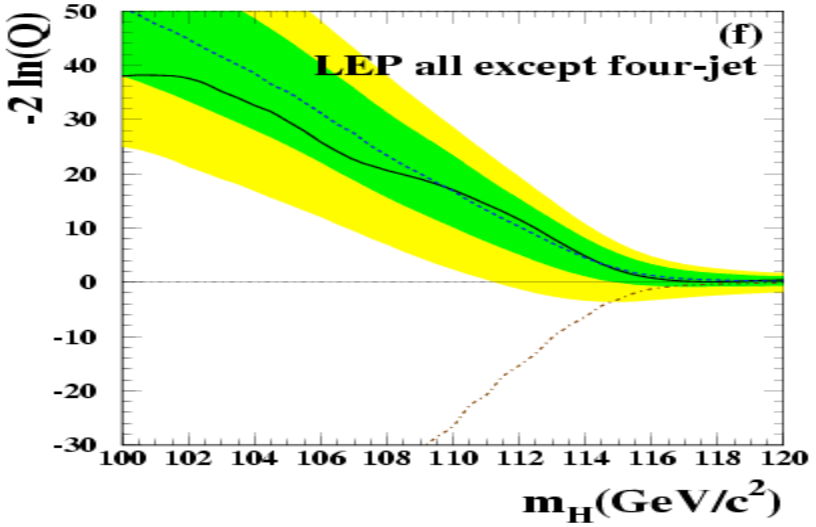
Exclusion @ 95% CL: $CL_s = CL_{s+b}/CL_b < 0.05$

Test statistic

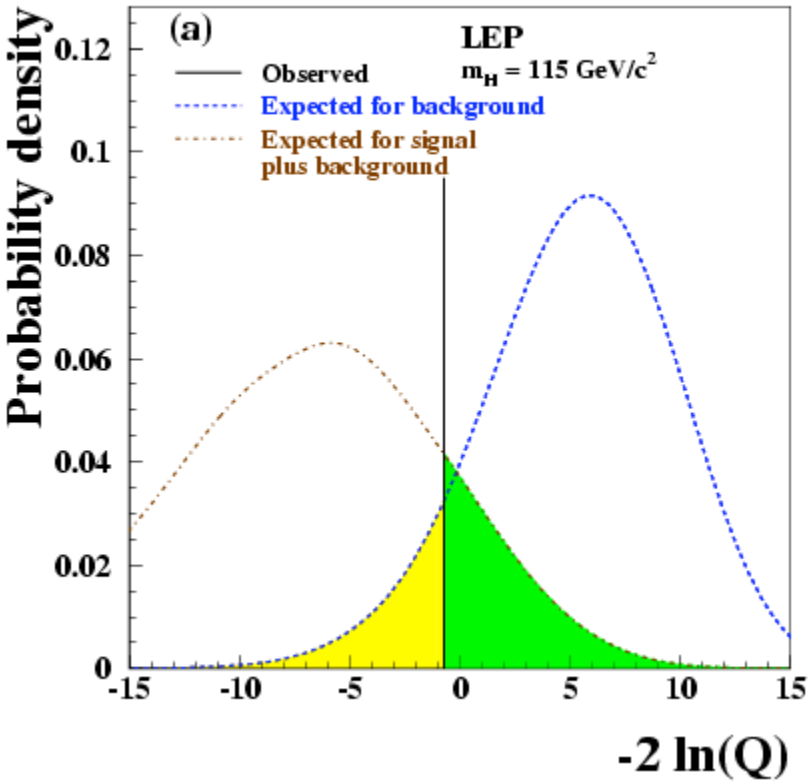


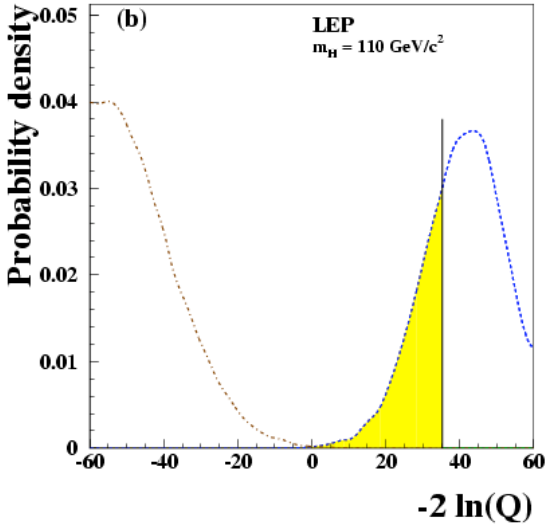


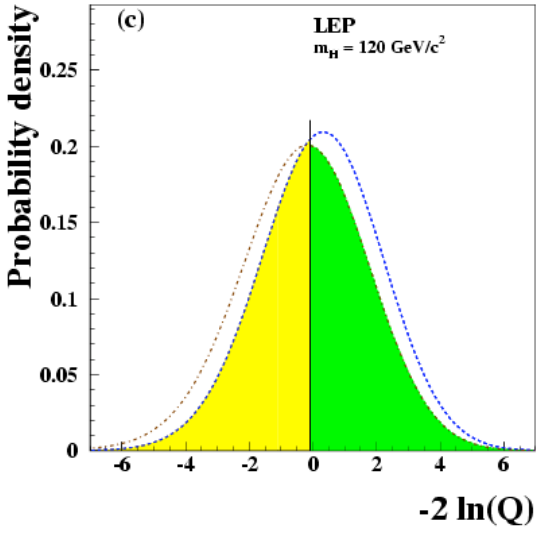




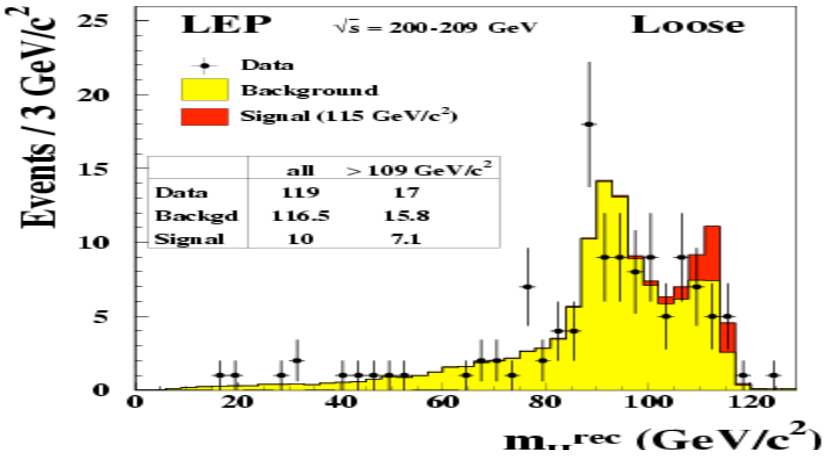
Probability density

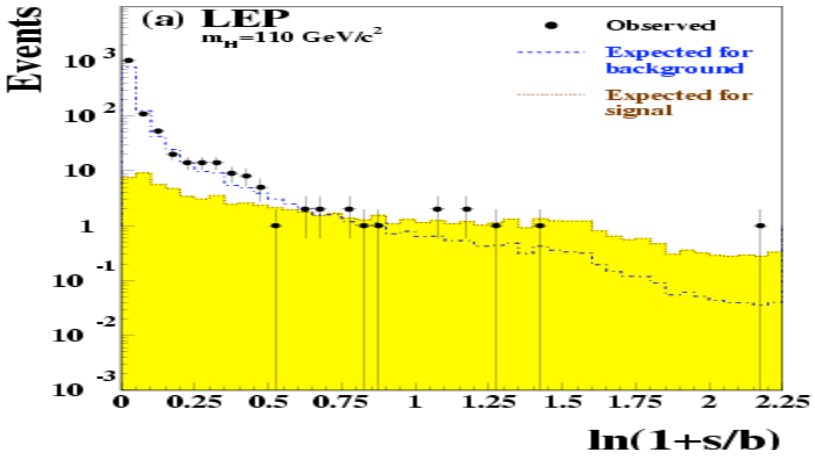


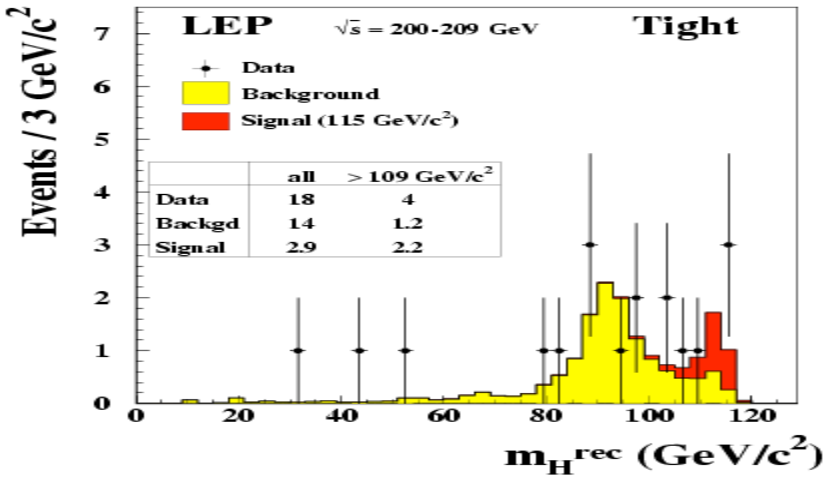


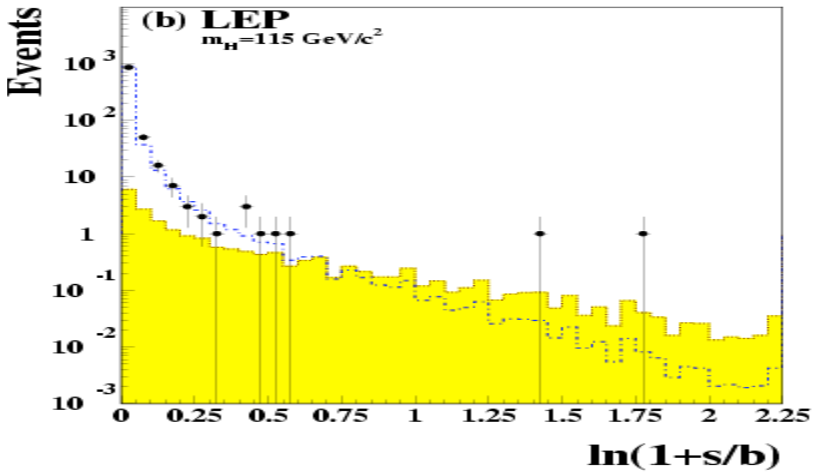


Reconstructed mass and event weights

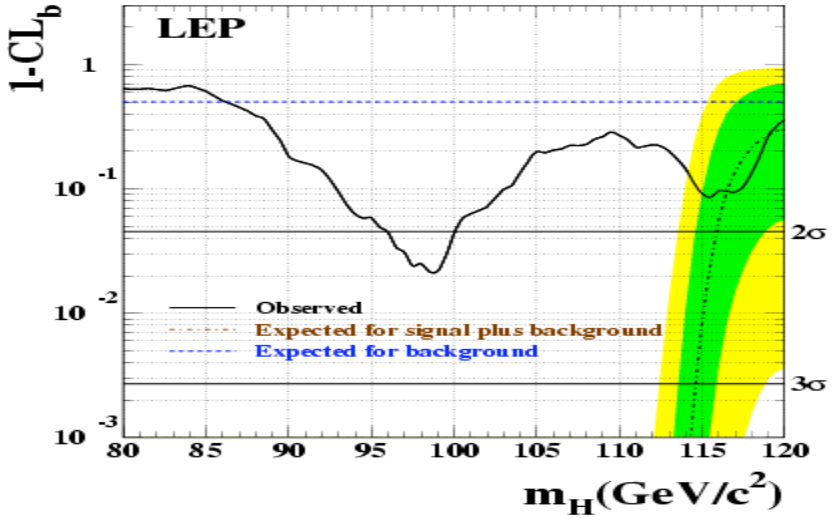


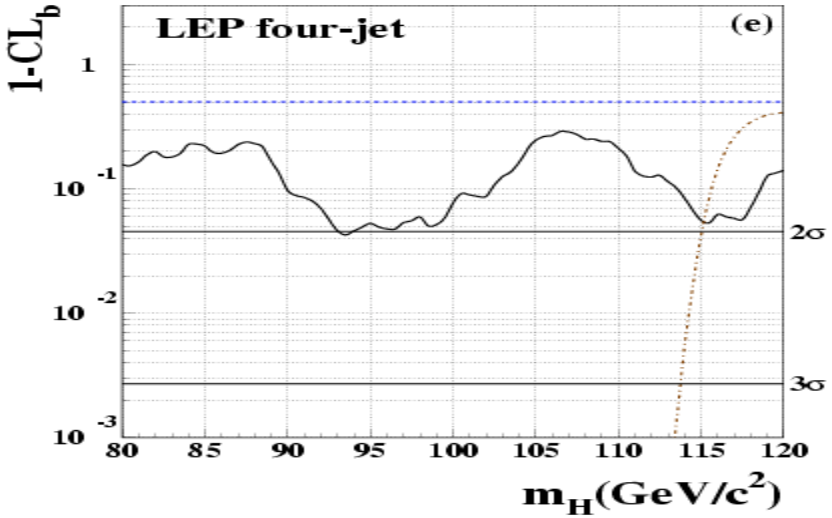


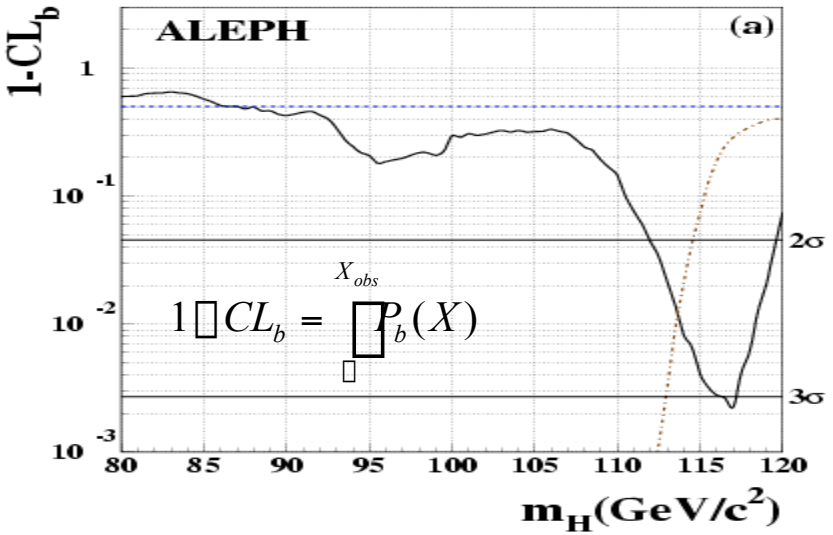


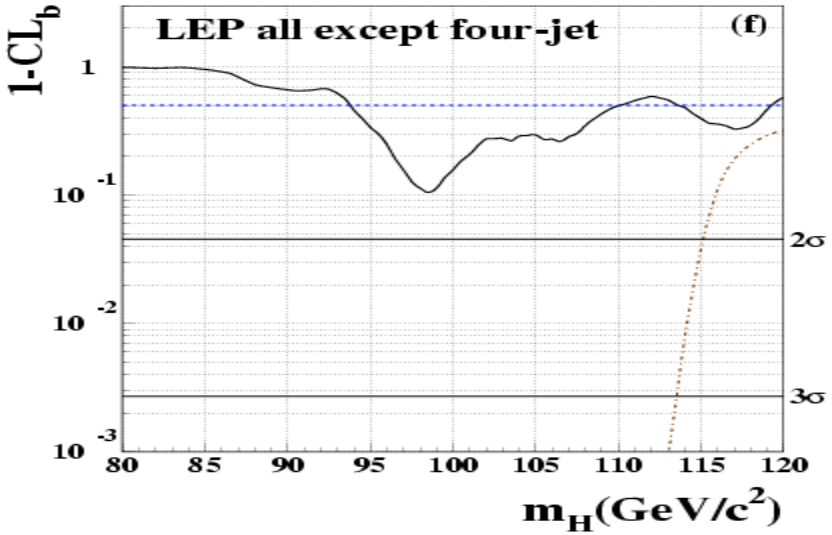


Compatibility with background hypothesis: $1-CL_b$



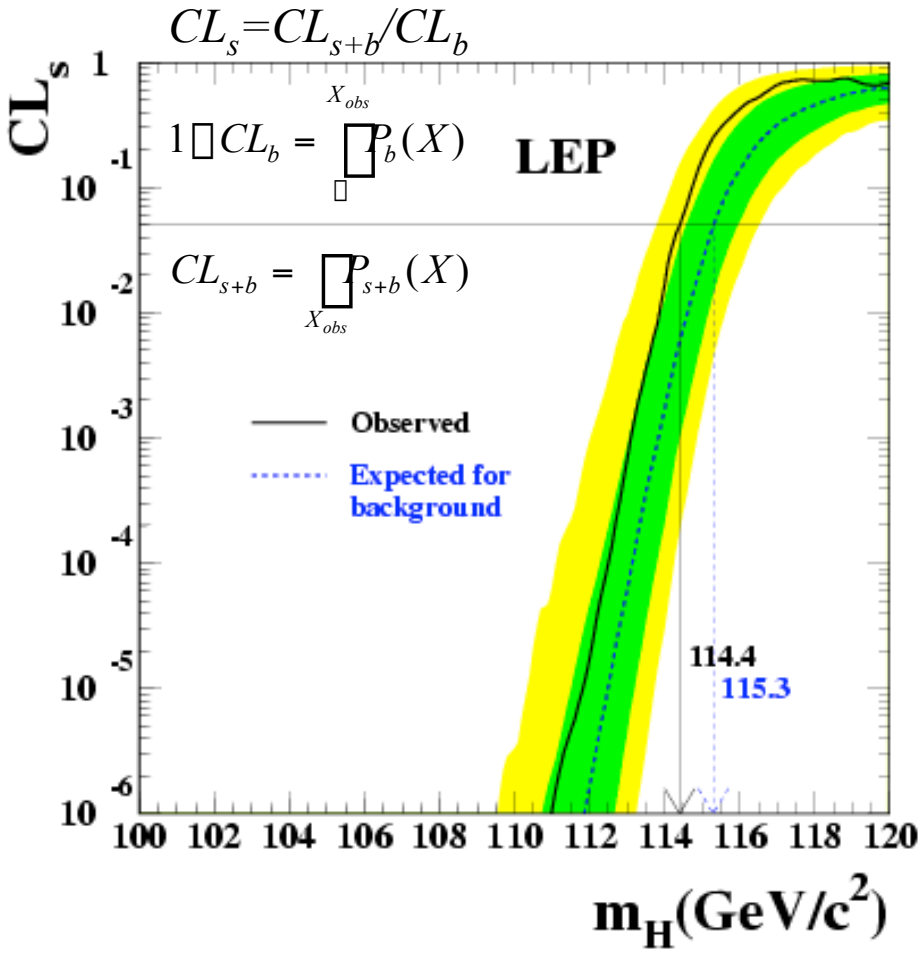






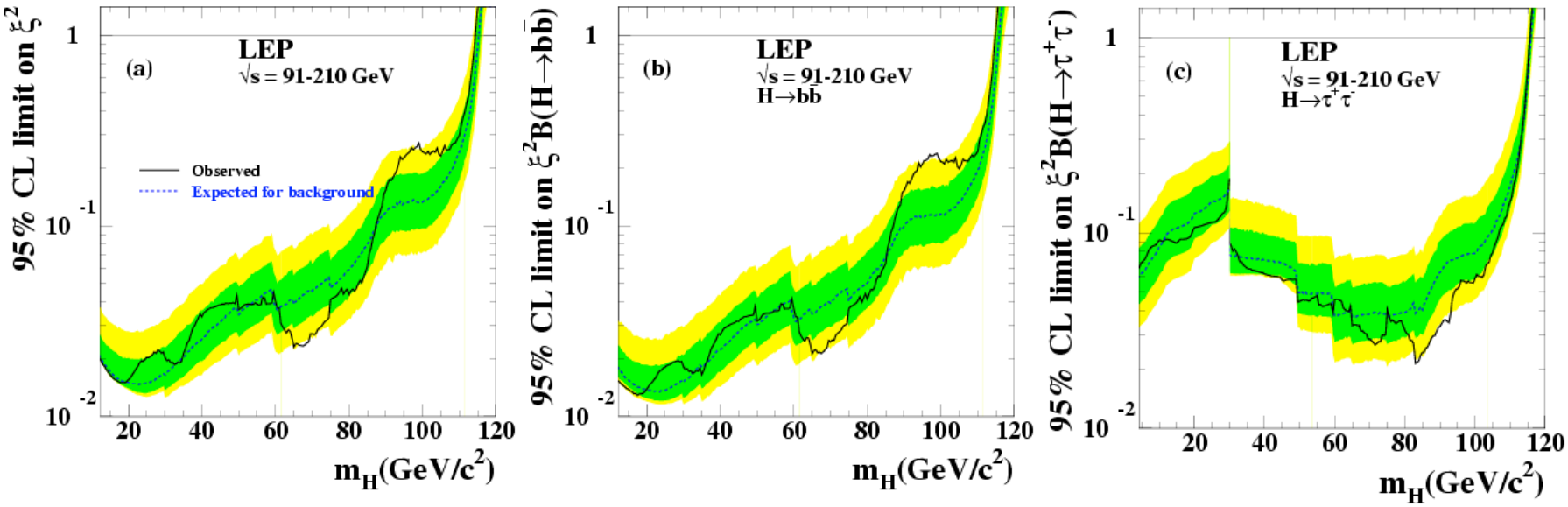
SM Higgs: Mass limit

	Expected (GeV)	Observed (GeV)
A	113.5	111.5
D	113.3	114.3
L	112.4	112.0
O	112.7	112.8
LEP	115.3	114.4
4-jet	114.5	113.3
other	114.2	114.2



Coupling limits

SM branchina ratios H bb decay H decay



$$\xi^2 = (g_{HZZ} / g^{SM}_{HZZ})^2$$

LEP1+LEP2

Models with two Higgs Doublets

- **Higgs sector**

  h, H (CP-even) , A (CP-odd),

  H^+, H^- (charged)

- **Cross-sections**

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

  $\sigma_{hA} = C_{phase} \cdot \cos^2(\beta-\alpha)\ \sigma_{SM}$

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

  $\sigma_{HA} = C_{phase} \cdot \sin^2(\beta-\alpha)\ \sigma_{SM}$

- **Couplings in type II**

  ($l_d, q_d \to \Phi_1$, $q_u \to \Phi_2$)

  hcc μ $\cos\alpha / \sin\beta$

  hbb μ $-\sin\alpha / \cos\beta$

  Hcc μ $\sin\alpha / \sin\beta$

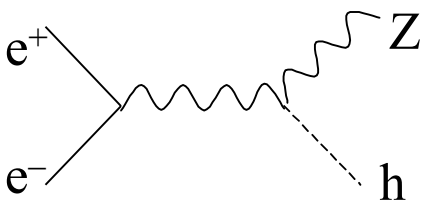
  Hbb μ $\cos\alpha / \cos\beta$

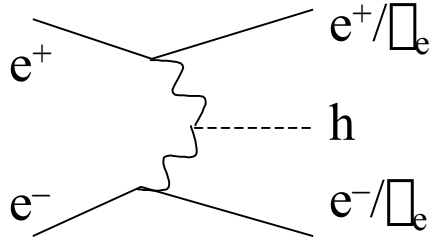
  Acc μ $\cot\beta$

  Abb μ $\tan\beta$

  hAA ~ $\cos(2\alpha)\sin(\beta+\alpha)$

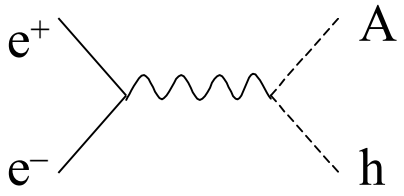
Higgs-strahlung

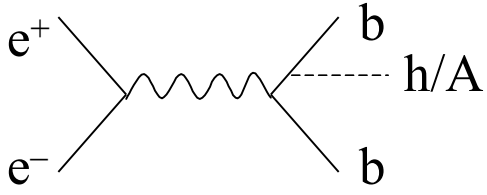




WW-, ZZ-fusion

Pair-production





Yukawa production

SM-like

$v^2 = v_1^2 + v_2^2 = 4m_W^2/g^2$, $\tan\beta = v_2/v_1$ $(0 < \beta < \pi/2)$

α: Higgs mixing angle

Search topologies

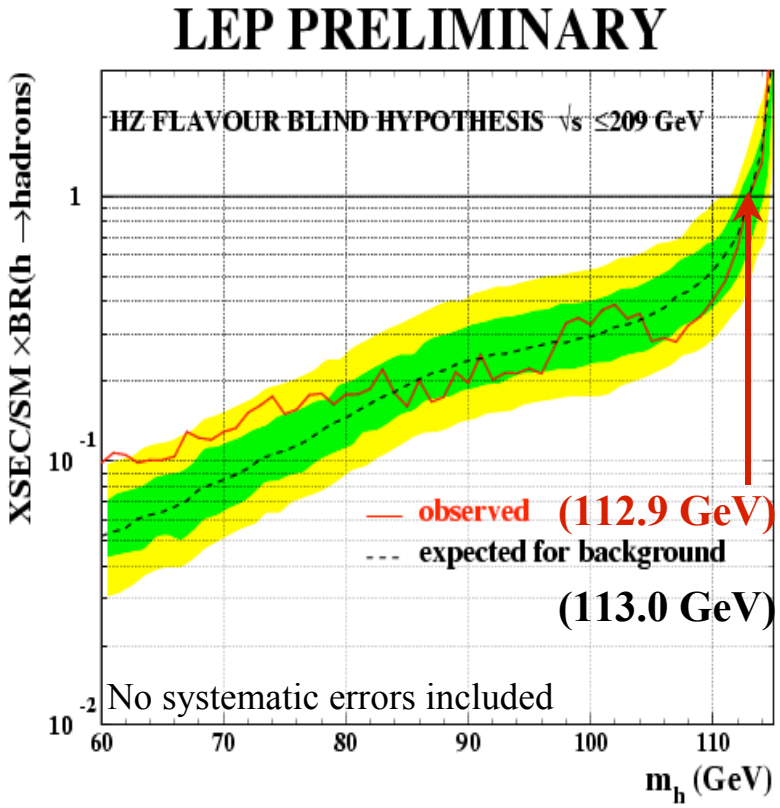
- $e^+e^- \to hZ \to bbff, \tau\tau ff, qq\tau\tau$ (SM like)
  $qqff, ggff$ (flavour independent)
- $e^+e^- \to hZ \to AAZ \to bbbbff$
  $fff'f'll$ (low mass, f=c,)
- $e^+e^- \to hZ$ (decay mode independent)

- $e^+e^- \to hA \to bbbb, bb\tau\tau, \tau\tau\tau\tau$
  $qqqq, ggqq, gggg$ (flavour independent)
- $e^+e^- \to hA \to AAA \to bbbbbb$
- $e^+e^- \to hA \to hhZ \to bbbbqq$

- $e^+e^- \to bbh \to bbbb, bb\tau\tau$ (Yukawa)
- $e^+e^- \to bbA \to bbbb, bb\tau\tau$ (Yukawa)

Flavour independent neutral Higgs boson search

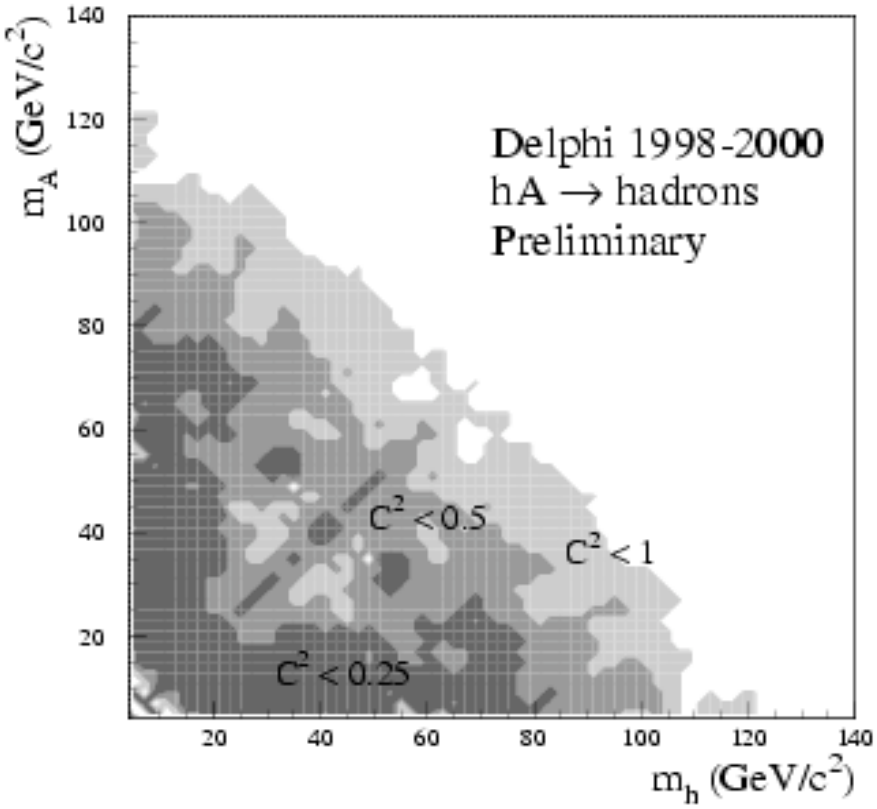
- Motivated by models with suppressed couplings to b-quarks (e.g. 2HDM)
- hZ followed by h → qq, gg and Z → νν, ll, qq
- SM-like searches without b-tagging
- Test-mass dependent selections for 4-jet channel to fight huge background



Flavour independent neutral Higgs boson search (cont.)

- *hA → hadrons*
- *gluon jets:*
  - *higher multiplicity: higher efficiency*
  - *broader jets: worse mass resolution*
- *3 topologies:*
  - *4-jet (close to kinematic limit, $m_h \approx m_A$)*
  - *3-jet (larger Δm, decay products of lighter Higgs not resolved)*
  - *3-jet with high thrust (both Higgs bosons with small mass)*

C^2=1 for maximal cross-section allowed by EWSB and for Br(hadrons)=1



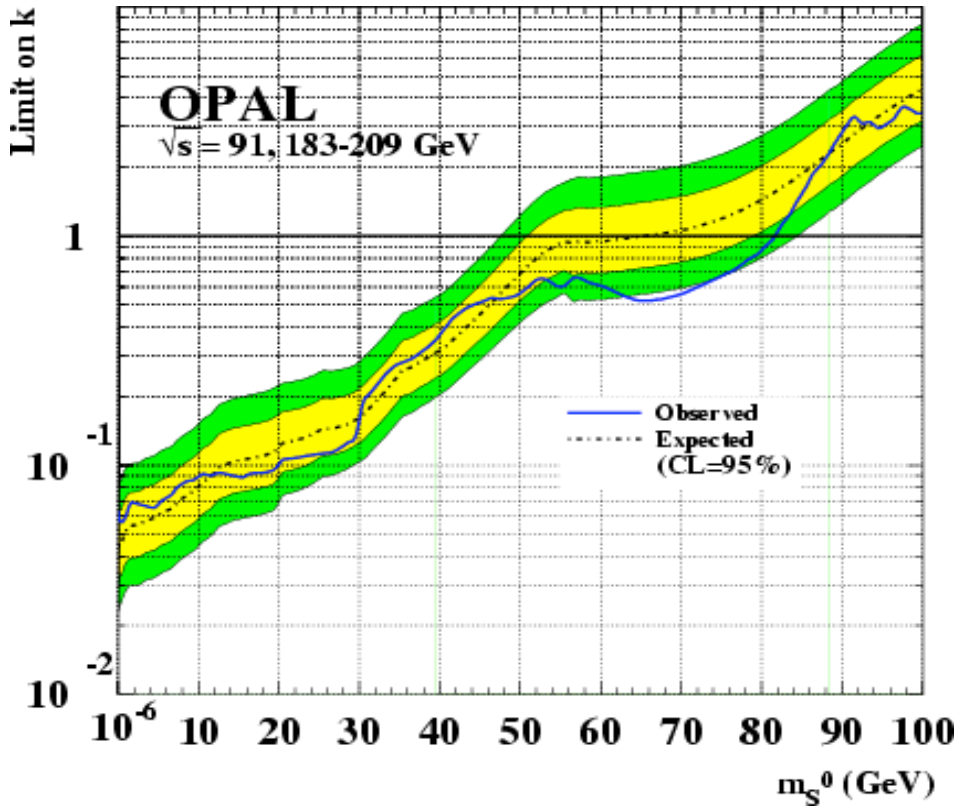
Decay-mode independent neutral scalar boson search

- Topological search for $e^+e^- \to SZ$ with $Z \to ee, \mu\mu$
- Signal: acoplanar, high momentum lepton pair
- LEP2:
  - invariant mass of lepton pair constrained to m_Z
  - photon veto against radiative processes
- LEP1:
  - stronger cuts to suppress background result in insensitivity to $S \to \tau\tau$ and for low masses (below 500 MeV) also to $S \to ee$
  - Dedicated analyses for $e^+e^- \to SZ$ with $Z \to \tau\tau$ to recover the lost sensitivity

Decay-mode independent neutral scalar boson search (cont.)

Constrain specific parameter regions in MSSM, 2HDM, or exotic models (e.g. Uniform and Stealthy Higgs scenarios)

$$k = \square_{SZ} / \square_{HZ}^{SM} (m_H = m_S)$$



Parameters of Constrained MSSM

CP-conservation assumed

M_{SUSY}: sfermion sector soft SUSY breaking params at EW scale

M_2: SU(2) gaugino mass at EW scale

from GUT relation: $M_1 = 5/3 \sin^2\theta_W/\cos^2\theta_W \, M_2$

A: common trilinear Higgs-squark coupling parameter

largest contribution to m_H from stop, smaller from sbottom loops

m_{gluino}: gluino mass

affects loop corrections from stop, sbottom (relevance of M_3)

μ: SUSY Higgs boson mass parameter

$\tan\beta$: ratio of the v.e.v.'s of the two Higgs doublets

m_A: CP-odd neutral Higgs boson mass

CP-conserving MSSM benchmark scenarios

- *No-mixing between left- and right-handed stop fields*
  M_{SUSY}=1 TeV, M_2=200 GeV, μ=-200 GeV, $X_t=A_t-\cot\beta=0$
  m_{gluino}=800 GeV *(small effect on phenomenology in this scenario)*
  4 GeV < m_A < 1 TeV, 0.4< tanβ < 50 *(small h and A width assumed: tanβ<30)*
- m_h*-max designed to yield maximal value for* m_h
  gives most conservative excluded tanβ *range for fixed* m_{top} *and* M_{SUSY}
  parameters fixed as for no-mixing except $X_t=2M_{SUSY}$
- *Large-*μ *designed to suppress h*$\rightarrow$ *bb decay due to large corrections from SUSY loop processes*
  1-loop RG improved calculations are used for scan
  M_{SUSY}=400 GeV, M_2=400 GeV, μ=1 TeV, X_t=-300 GeV
  m_{gluino}=200 GeV, 4 GeV < m_A < 400 GeV, 0.4 < tanβ < 50
- *Results in new LHC motivated scenarios to be presented in final publication…*

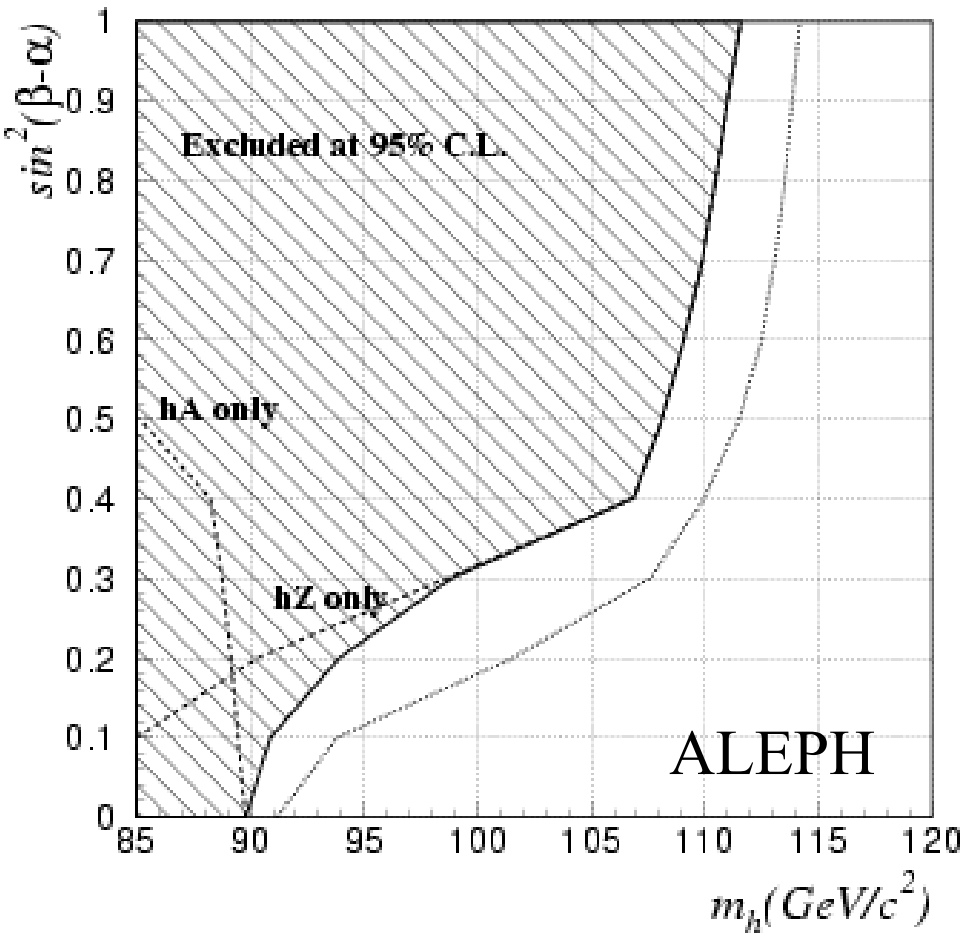
2-loop diagrammatic calculations implemented in FeynHiggs

New benchmark scenarios

- m_h-maxμ^+: m_h-max with +ve μ
  preferred by $b \to s\gamma$ and (g-2)$_\mu$
  gives maximum m_h as a function of tanβ
- No mixing(2 TeV): no mixing with M_{SUSY}=2 TeV and μ=200 GeV
  preferred by (g-2)$_\mu$
  large M_{SUSY} to avoid LEP Higgs exclusion
- Constrained m_h-max: m_h-maxμ^+ with flipped sign of X_t
  preferred by $b \to s\gamma$
  less conservative tanb exclusion since m_h lowered by ~5 GeV
- Gluophobic: M_{SUSY}=350 GeV, M_2=300 GeV, μ=300 GeV, X_t=-750 GeV, m_{gluino}=500 GeV, 4 GeV < m_A < 1 TeV, 0.4 < tanβ < 50
  Hgg coupling suppressed due to cancellation between top and stop loops at the production vertex, large impact on Higgs production at LHC
- Small α_{eff}: M_{SUSY}=800 GeV, M_2=500 GeV, μ=2 TeV, X_t=-1.1 TeV, m_{gluino}=500 GeV, 4 GeV < m_A < 1 TeV, 0.4 < tanβ < 50
  bb and $\tau\tau$ decay suppressed by a factor of $-\sin\alpha_{eff}/\cos\alpha$ and bb also due to corrections from sbottom-gluino loops (similarly to the large-μ scenario the suppression occurs for large tanβ and not too large m_A)

MSSM Higgs search

- hZ and hA b-tag searches
- Excluded regions in $[m_h - \sin^2(\square\square\square)]$ assuming SM BRs for h
- $m_h > 89.8$ GeV



m_h-max scenario

Designed to yield maximal value for m_h

Gives most conservative excluded tanβ range for fixed m_{top} and M_{SUSY}

parameters fixed as for no-mixing except X_t:

M_{SUSY} = 1 TeV

M_2 = 200 GeV

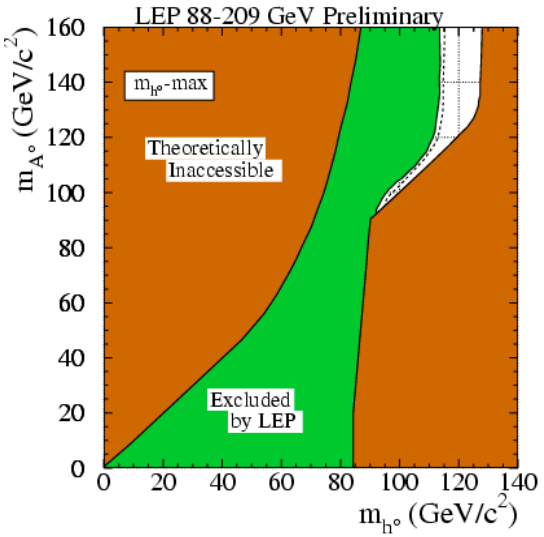
μ = -200 GeV

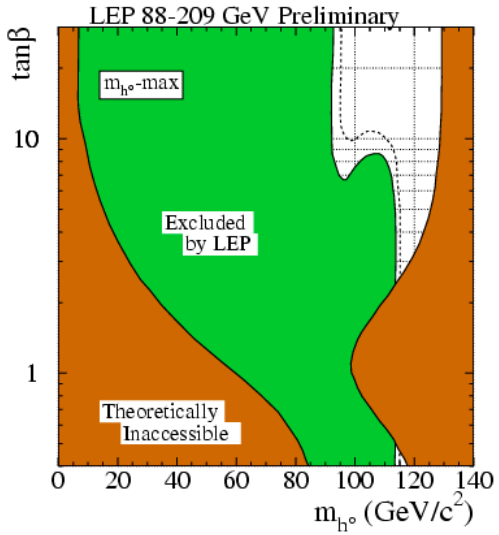
$X_t = A_t - \cot\beta = 0$

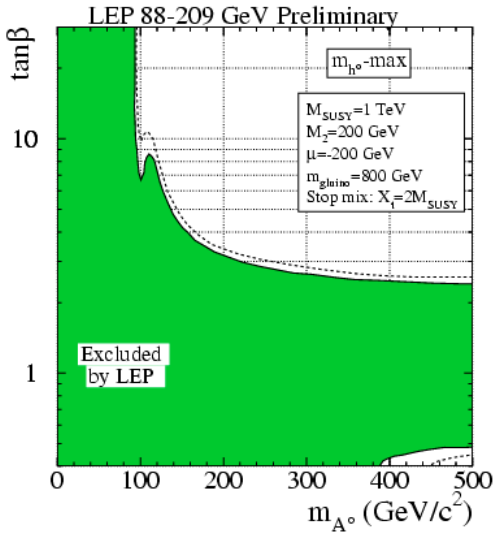
m_{gluino}=800 GeV

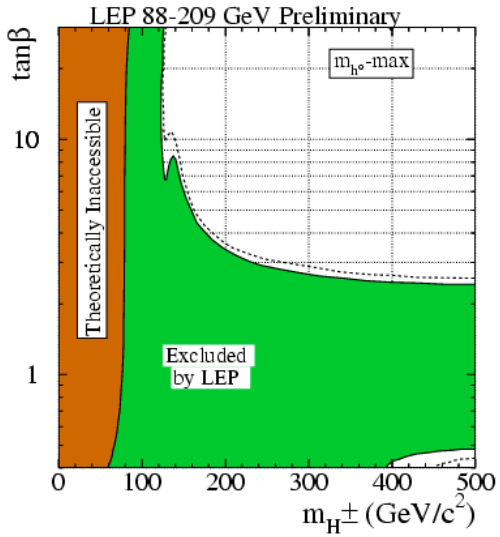
4 GeV < m_A < 1 TeV

0.4< tanβ < 30

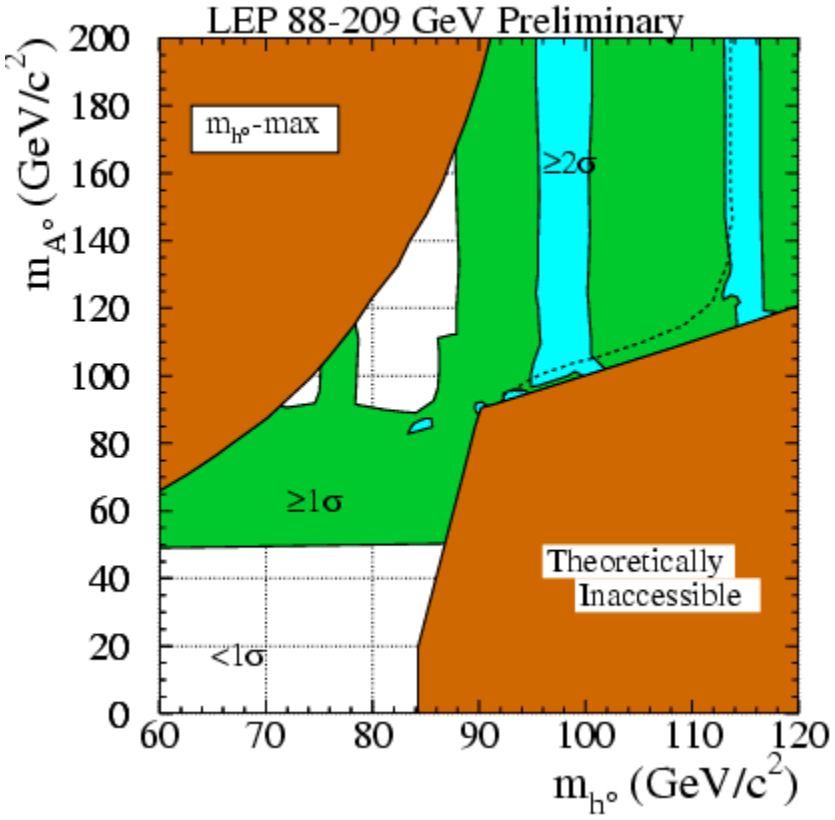


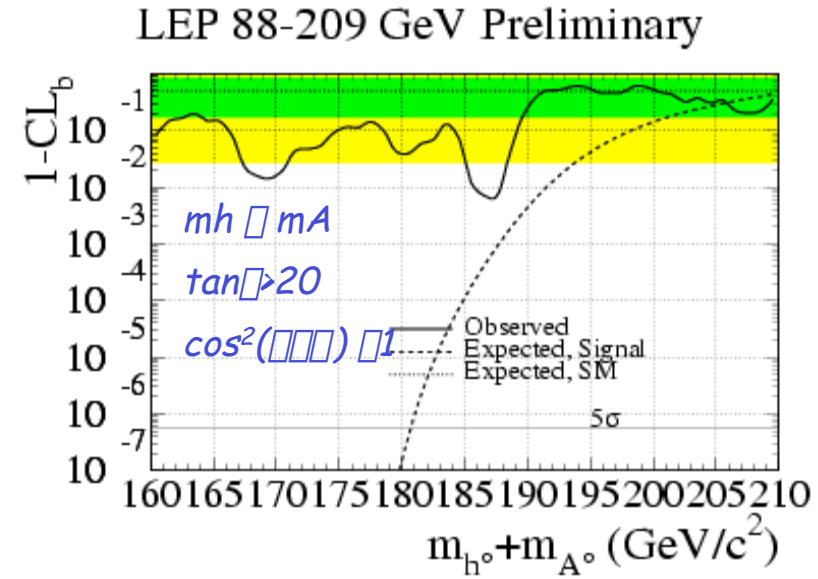


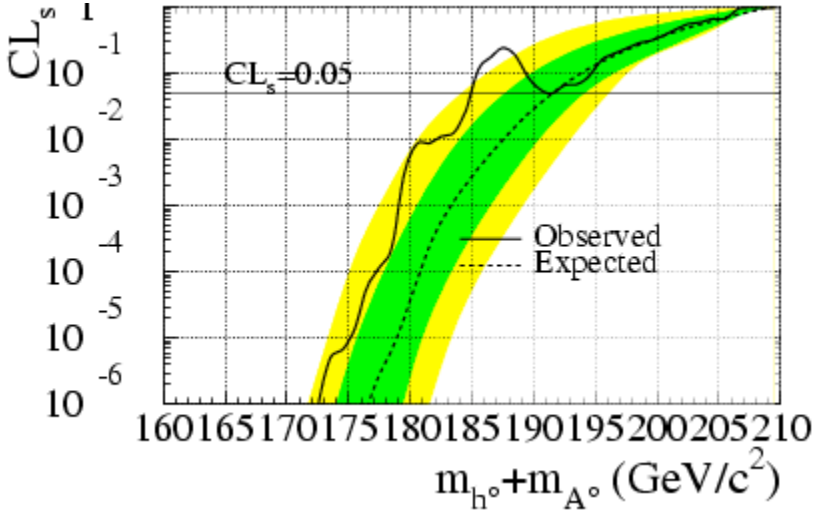




m_h-max scenario



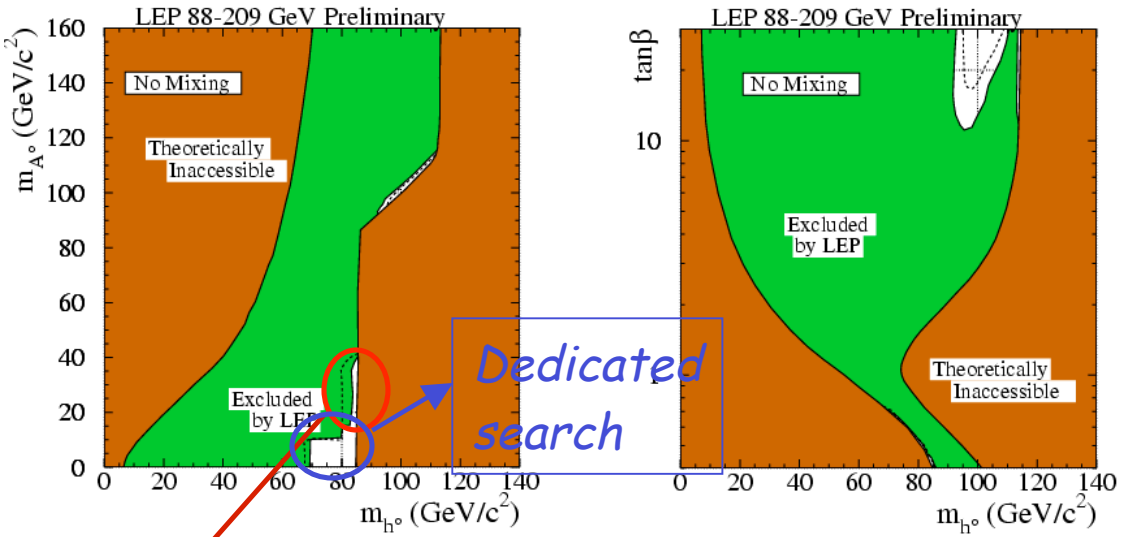




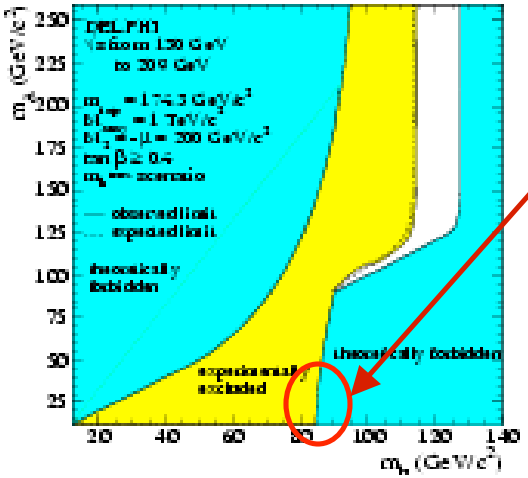
No-mixing scenario

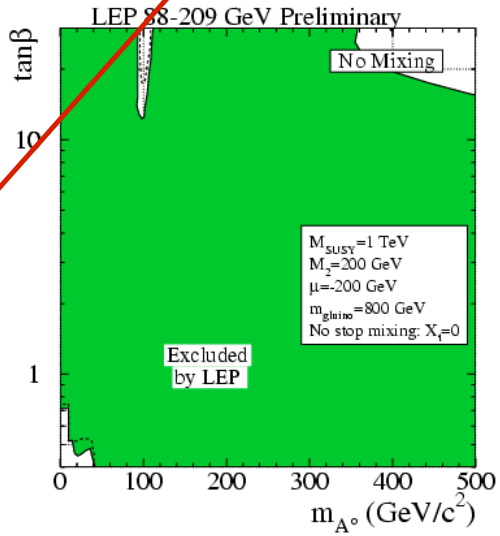
No-mixing between left- and right-handed stop fields

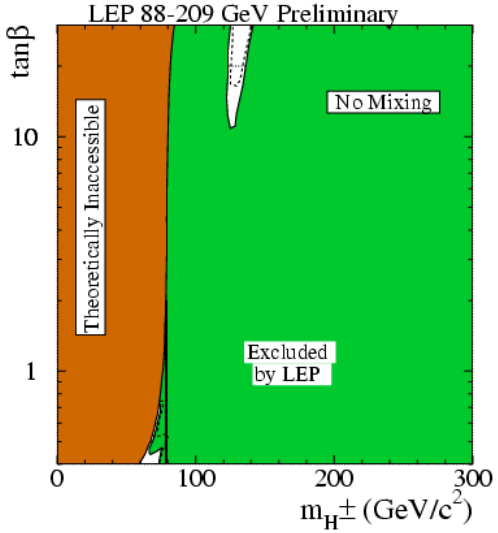
- M_{SUSY} = 1 TeV
- M_2 = 200 GeV
- μ = -200 GeV
- $X_t = A_t - \cot\beta = 0$
- m_{gluino}=800 GeV
- 4 GeV < m_A < 1 TeV
- 0.4< tanβ < 30



Dedicated search







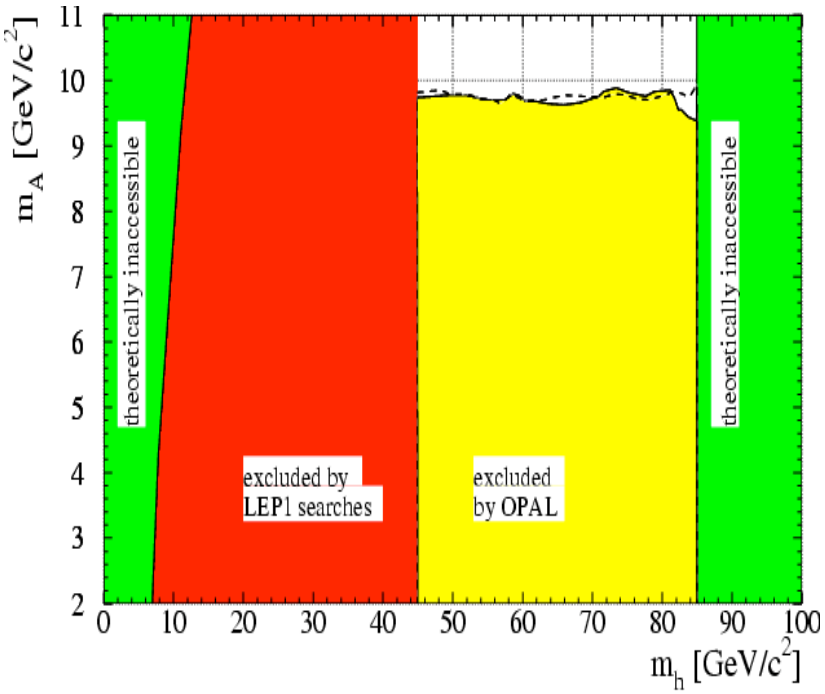
Low mass CP-odd Higgs boson search

- $hZ \to AAZ$ followed by $A \to c\bar{c}, \tau\tau, gg$, $Z \to \tau\tau, ee, \mu\mu$

  $2\ \mathrm{GeV} \le m_A \le 11\ \mathrm{GeV}$ and $45\ \mathrm{GeV} \le m_h \le 86\ \mathrm{GeV}$

  Resonances are not included in the simulation of A decay

- Model independent limits for each final state on $s^2 = \xi / \xi_{hZ,SM}$
- Excluded areas in MSSM no-mixing scenario:



Large-μ scenario

- Designed to suppress $h \to bb$ decay due to large corrections from SUSY loop processes

  M_{SUSY}=400 GeV, M_2=400 GeV, μ=1 TeV, X_t=-300 GeV
  m_{gluino}=200 GeV, 4 GeV < m_A < 400 GeV, 0.4< tanβ < 50

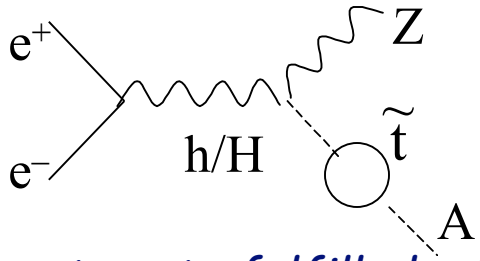
- m_h<108 GeV for any (m_A, tanβ)
- HZ is accessible when $\sin^2(\beta-\alpha)$ small (hZ suppressed) and $m_h+m_A > \sqrt{s}$
- Requires flavour independent searches
- $\Rightarrow$ Entirely excluded by LEP

CP-violating MSSM

- Higgs potential is CP invariant but it is possible to break CP via radiative corrections
- The phases of A_x and m_{gluino} introduce CP violation and lead to sizable off diagonal contribution to the mass matrix
- The off diagonal contribution scales as

$$M_{ij}^2 \mu \frac{m_t^4}{v^2} \frac{\mathrm{Im}(\Box A_t)}{32\Box^2 M_{SUSY}^2}$$

- H_1, H_2, H_3 mass-eigenstates do not correspond to h, H, A CP-eigenstates
- All H_i can couple to Z in Higgs-strahlung (depending on the parameters)

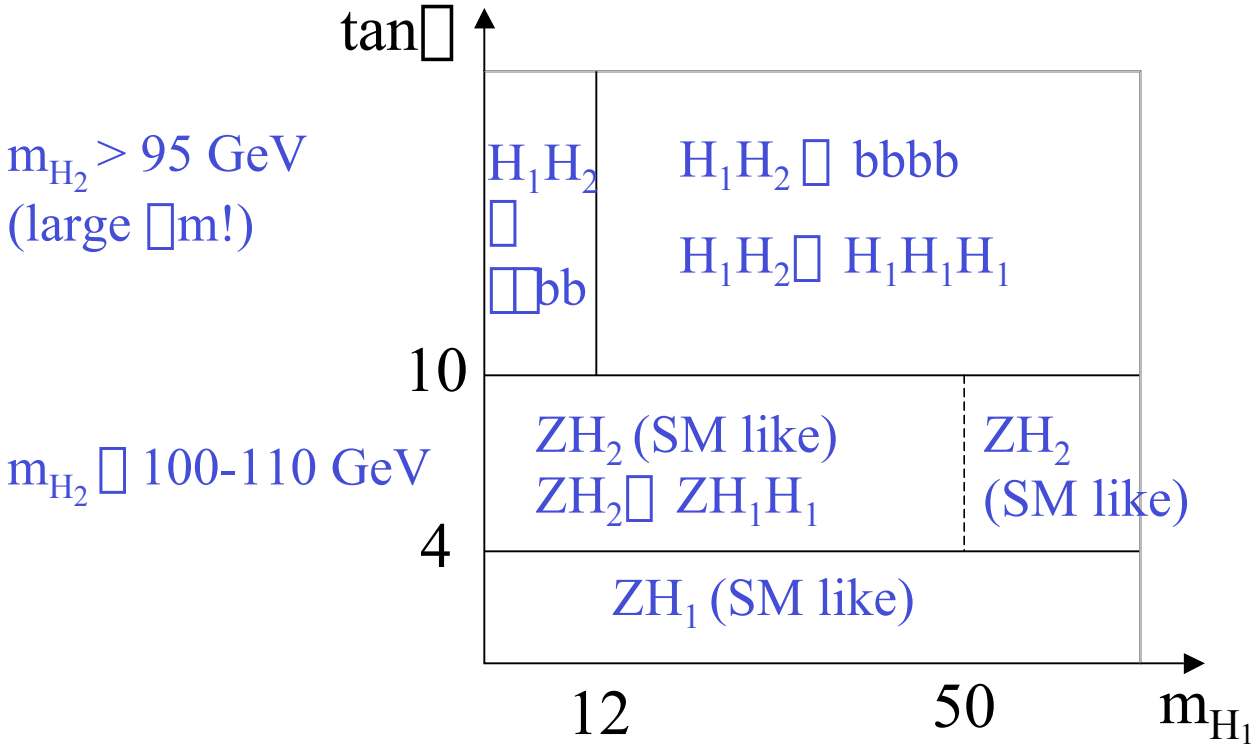


- Choose parameters to fulfill electron and neutron EDM constraints and maximize CPV effects: CPX scenario

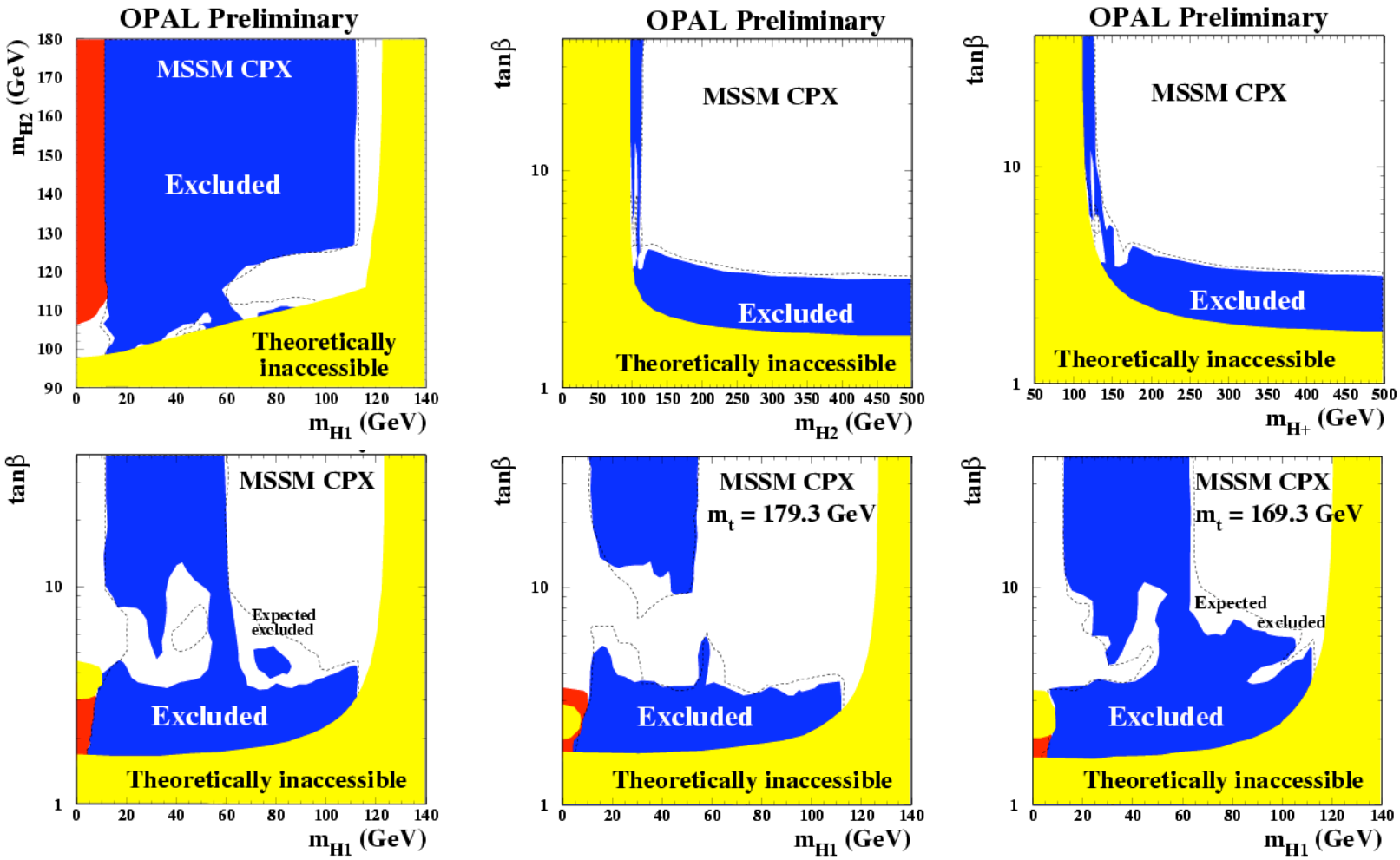
  M_{SUSY} = 500 GeV, M_2 = 200 GeV, □ = 2 TeV, A_q = 1 TeV, m_{gluino}=1 TeV,
  0 TeV < m_{H^+} < 1 TeV, 0.4< tan□ < 40, $arg(A_q)$ = 90°, $arg(m_{gluino})$=90°

Search for CP-violating MSSM

- Reinterpret CP-conserving MSSM searches
- New or reoptimized searches for large mass differences



CPX scenario



Large dependence on top mass

CP-violating MSSM scan

Large dependence on phases

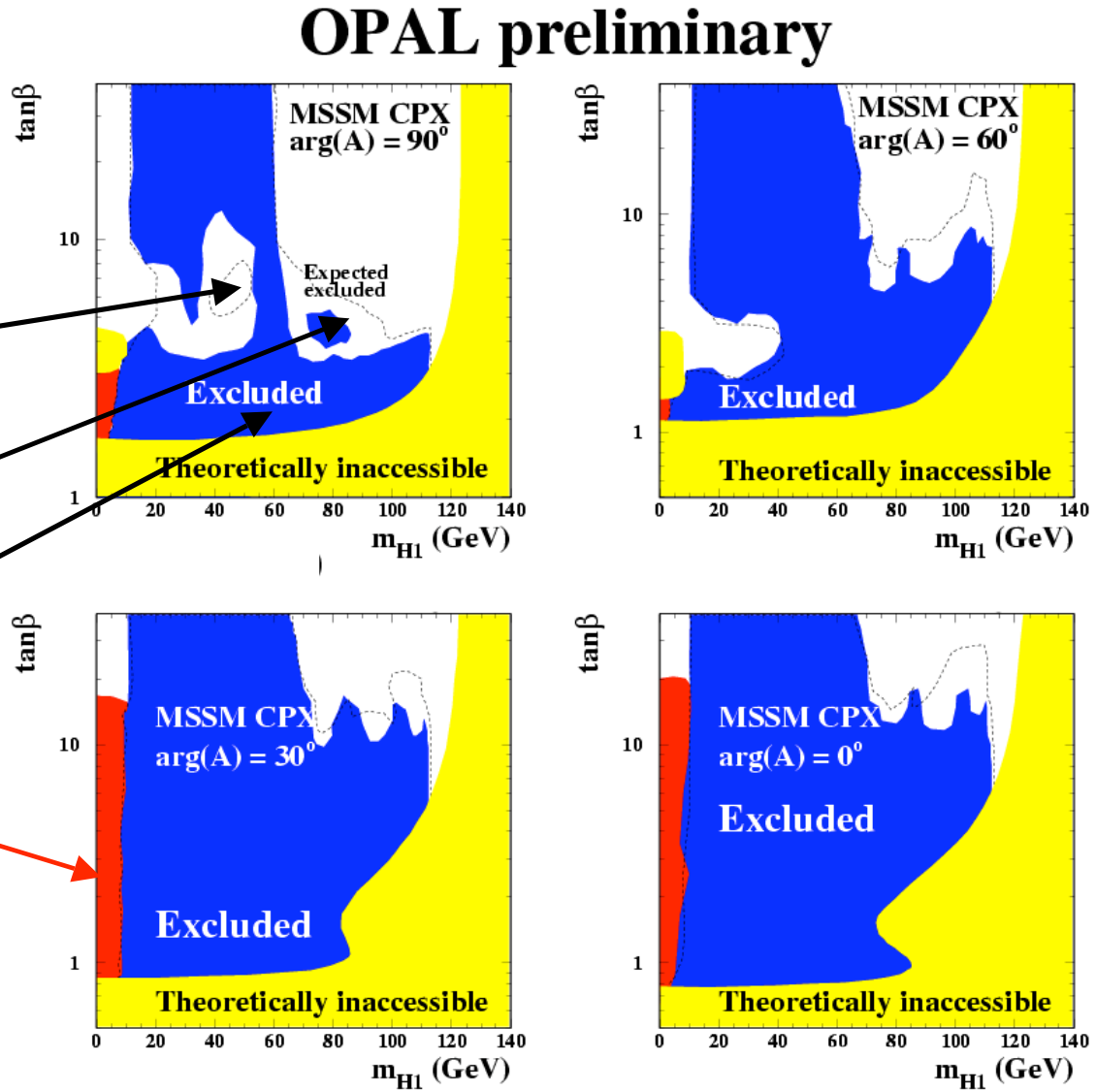
$arg(A_q)=arg(m_{gluino})$

ZH_1H_1 with large Δm broadened signal distribution

SM-like ZH_2 (2σ excess)

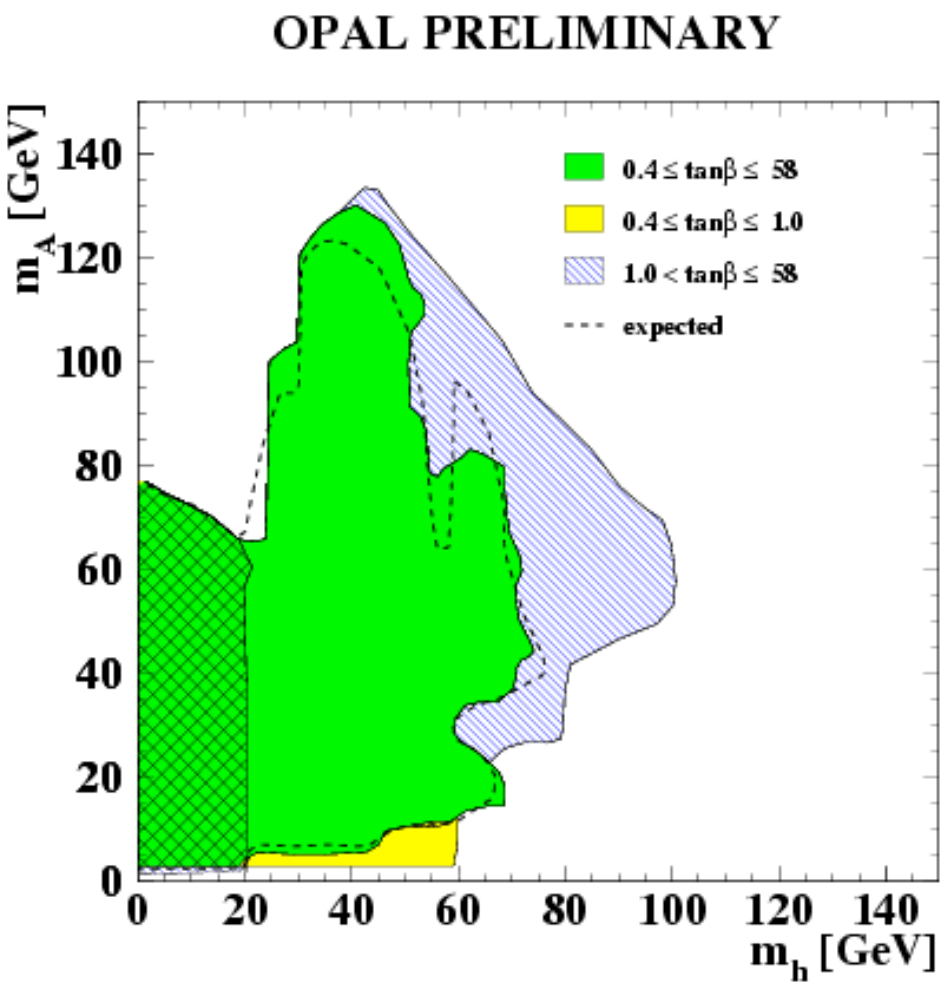
SM-like ZH_1

Excluded by Z width constraint or decay-mode independent Higgs searches

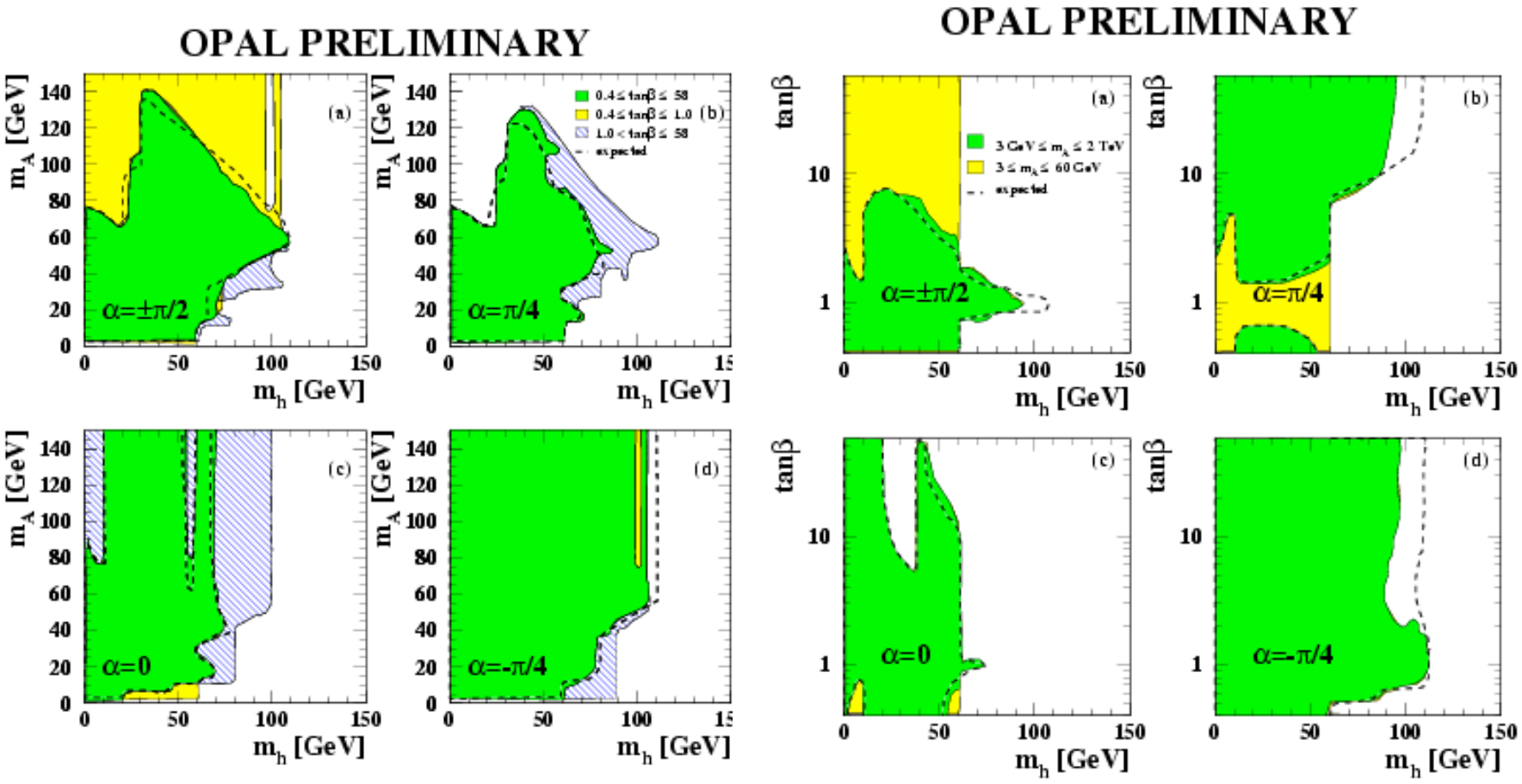


2HDM type II

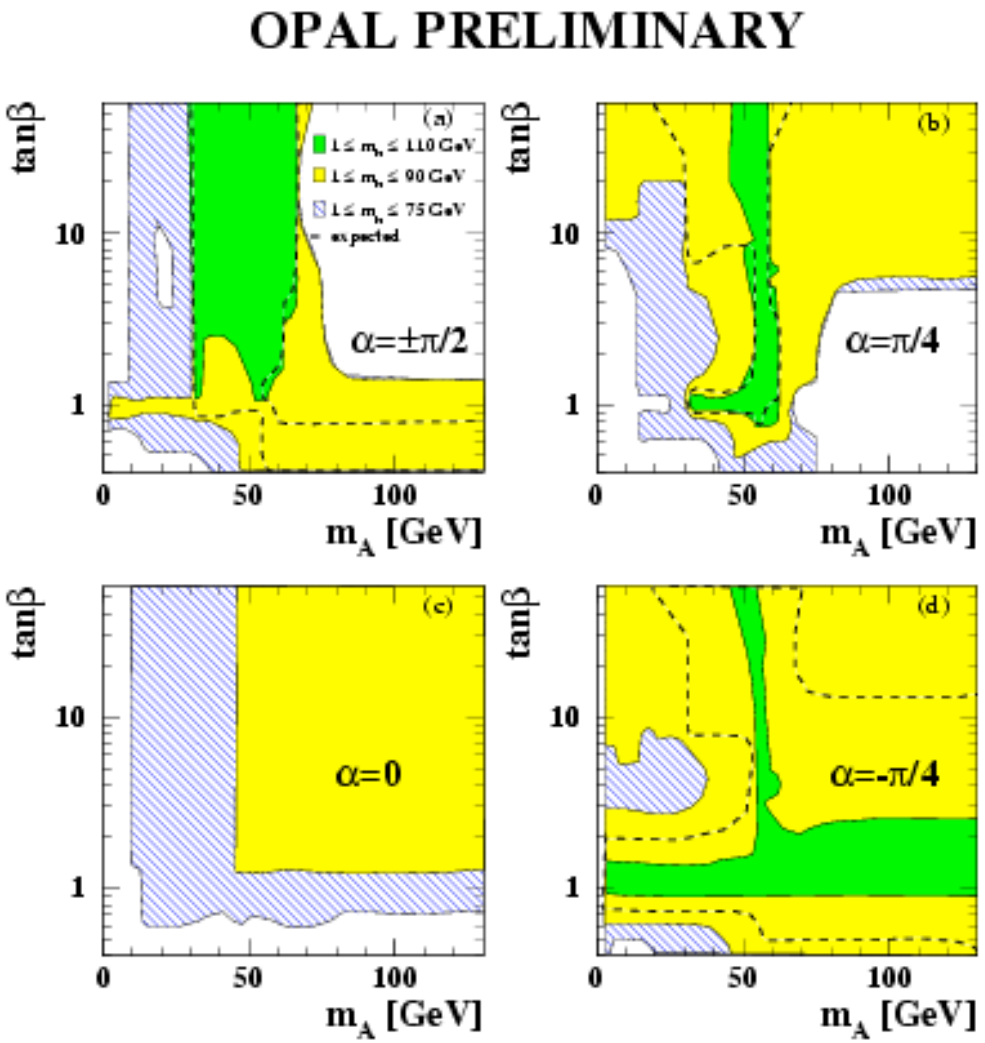
- *CP-conservation assumed*
- *Parameter scan:*
  1 □ m_h □120 GeV
  3 □ m_A □2000 GeV
  0.4 □tan□ □58
  □ = 0 (Br(h□ bb)=0)
  ±□/4 (max mixing)
  ± □/2 (min mixing)
- *Improvements expected after inclusion of new results and LEP combination*



2HDM type II (cont.)



2HDM type II (cont.)



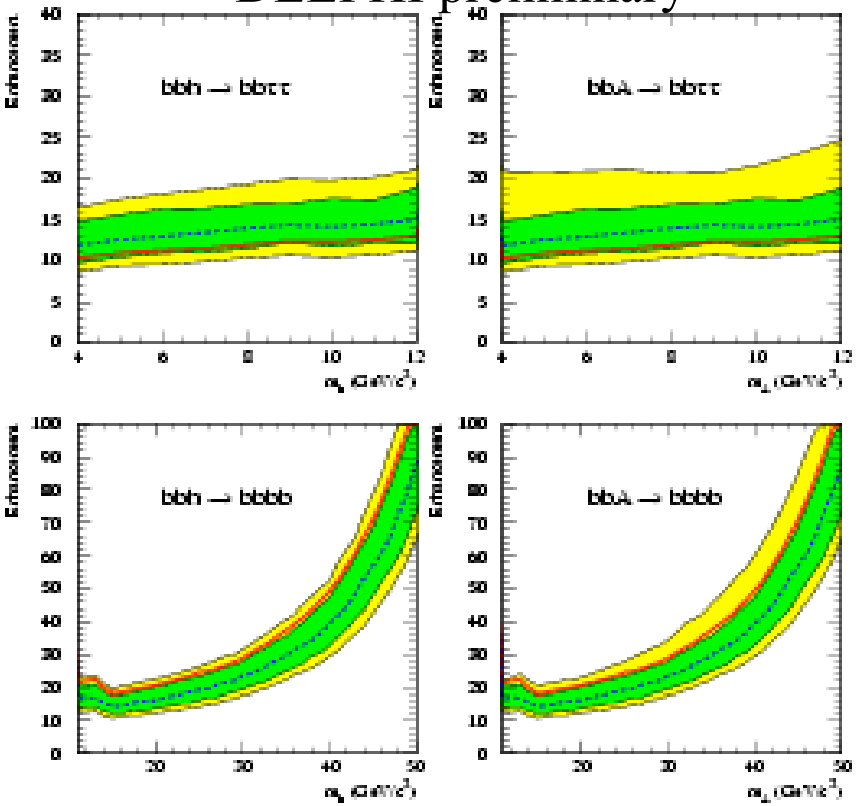
Yukawa production

Cross section: □ ~ $m_f^2 N_c$ □$_f^2$

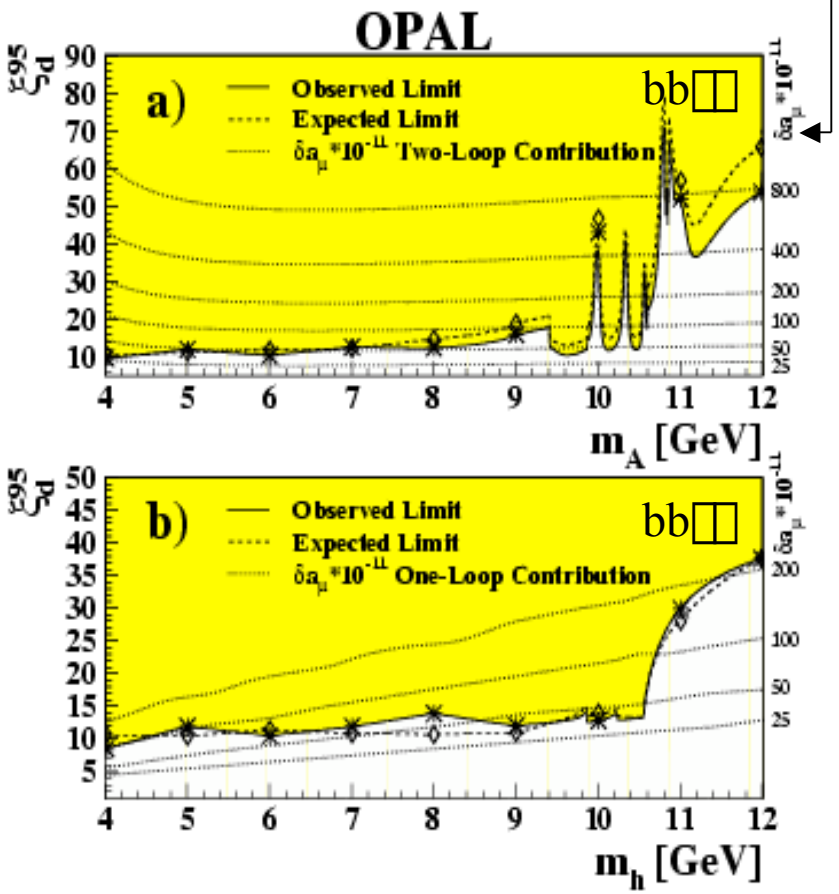
Enhancement=□$_d$=tan□ (for Abb)

=-sin□/cos□ (for hbb)

DELPHI preliminary



Contribution to □ anom. magn. moment



A/h mixes with bb bound states □/□$_0$

□□branching ratios calculated according to Drees, Hikasa, PR D41 (1990) 1547

Summary

- Final LEP result on SM Higgs: $m_h > 114.4$ GeV
  $1\text{-}CL_b = 0.09$, $CL_{s+b} = 0.15$ at $m_h = 115$ GeV
- Severe constraints on MSSM benchmarks within LEP kinematic range
  m_h-max scenario: $m_h > 91.0$ GeV, $m_A > 91.9$ GeV,
  $0.5 < \tan\beta < 2.4$ excluded
  large-μ scenario: excluded
- Searches for BSM (BMSSM) Higgs sector
  2HDM (II): $(1 < m_h < 58$ GeV, $10 < m_A < 65$ GeV) excluded
- Final LEP papers on CP-conserving and -violating MSSM , 2HDM and model independent bounds by end of 2003
- Results in new, hadron collider motivated MSSM benchmark scenarios to appear in final publication to prepare for the searches at Tevatron & LHC