Search for Higgs in the two Doublet Models

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representing the LEP collaborations

- **Description of the Model**
- **The Neutral sector**
  - **2HDM general scan**
  - **Yukawa production mechanism**
- **The Charged sector**
- **Conclusions**

Two Higgs Doublet Models

- 2HDMs are interesting since they add new phoenomena wrt to the SM with the fewest parameters:

SM		2HDM
1Higgs doublet	$\Rightarrow$	2 Higgs doublets
1 physical Higgs		5 physical Higgs bosons

✓ Five physical Higgs bosons:

- two neutral CP even scalars, h^o and H^o ($m_h < m_H$)
- one CP odd scalar, A^o
- two charged scalars, $H^{\pm}$

✓ $\rho = \dfrac{m_w^2}{m_Z^2 \cos^2 \vartheta_w} \sim 1$

✓ no FCNC

✓ in the absence of SUSY no extra particles besides those of the SM are required

The Type of 2HDM determined by the couplings of the Higgs doublets to the fermions:

Type I: is the case in which quarks and leptons do not couple to the first Higgs doublet, but couple to the second Higgs doublet in a manner analogous to the minimal Higgs model: 2HDM(I)

Type II: is the case in which the first Higgs doublet couples only to down-type quarks and leptons and the second doublet couples only to up-type quarks and neutrinos: 2HDM(II)

The Higgs sector of the MSSM is a 2HDM Type II in which the introduction of supersymmetry adds new particles and constrains the parameter space of the model.

⇩

study of 2HDM (II) more "general"

2HDM(II) Parameters

6 free parameters, assuming no CP violation :

4 masses:

- m_h, m_H, m_A, $m_{H^\pm}$

2 angles:

- α mixing angle that relates physical mass eigenstates with the field doublets

$$h^0 = \sqrt{2}[(Re(\varphi_2) - \upsilon_2)\cos\alpha - (Re(\varphi_1) - \upsilon_1)\sin\alpha]$$

$$-\pi/2 \leq \alpha \leq \pi/2$$

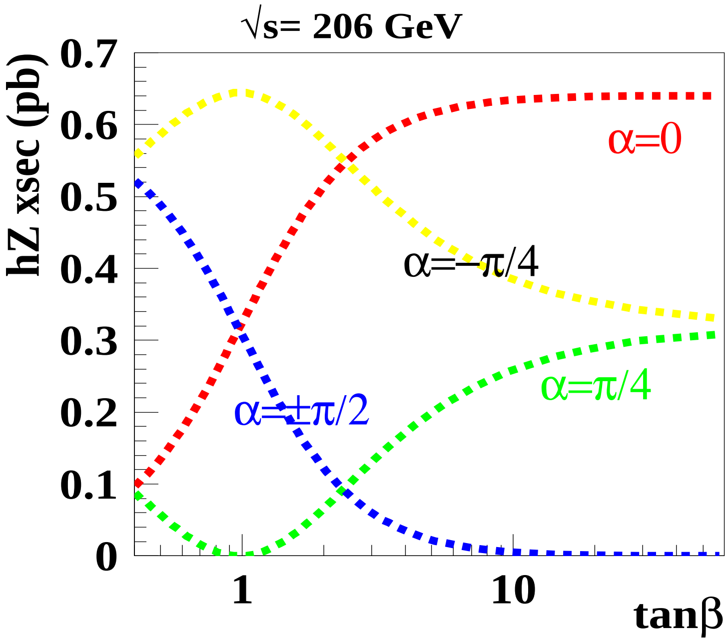
- β, where $\tan\beta = v_2/v_1$ ratio of the vacuum expectation values of the scalar fields

$$0 \leq \beta \leq \pi/2$$

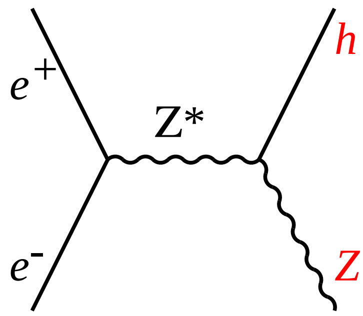
Neutral Sector

- tree level production cross-sections

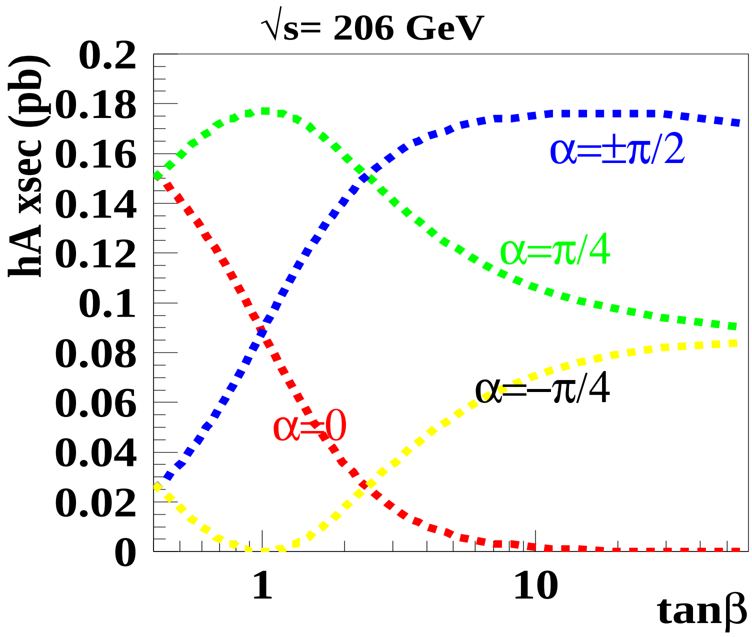
$$\sigma_{hZ} = \sin^2(\beta-\alpha)\,\sigma_{HZ}^{SM}$$



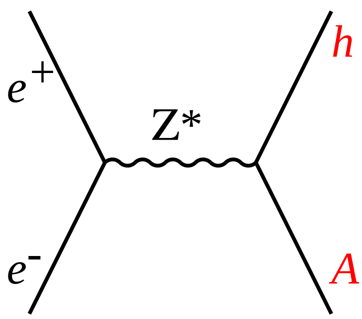
Higgs-Strahlung



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



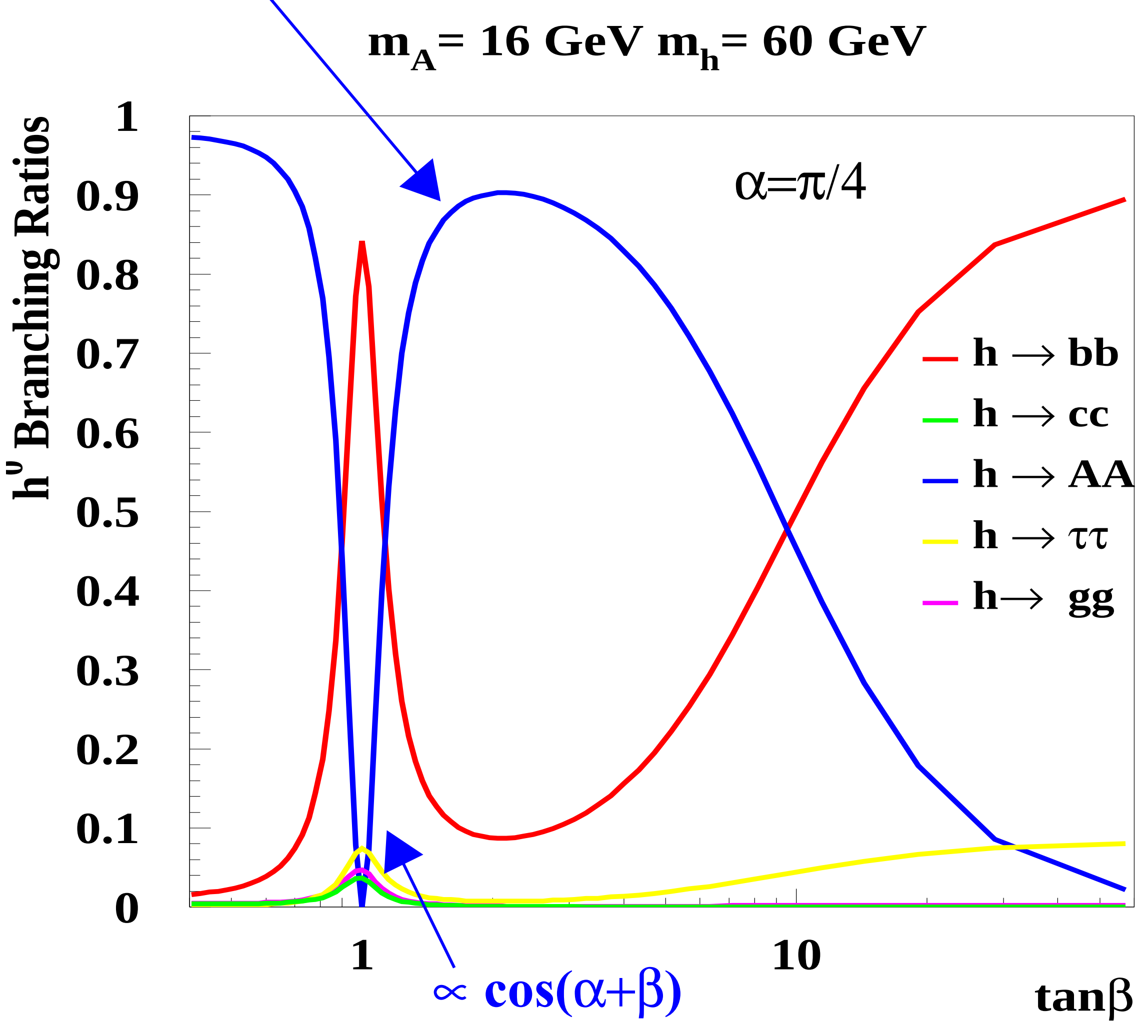
Pair-Production



- tree level couplings relative to SM values

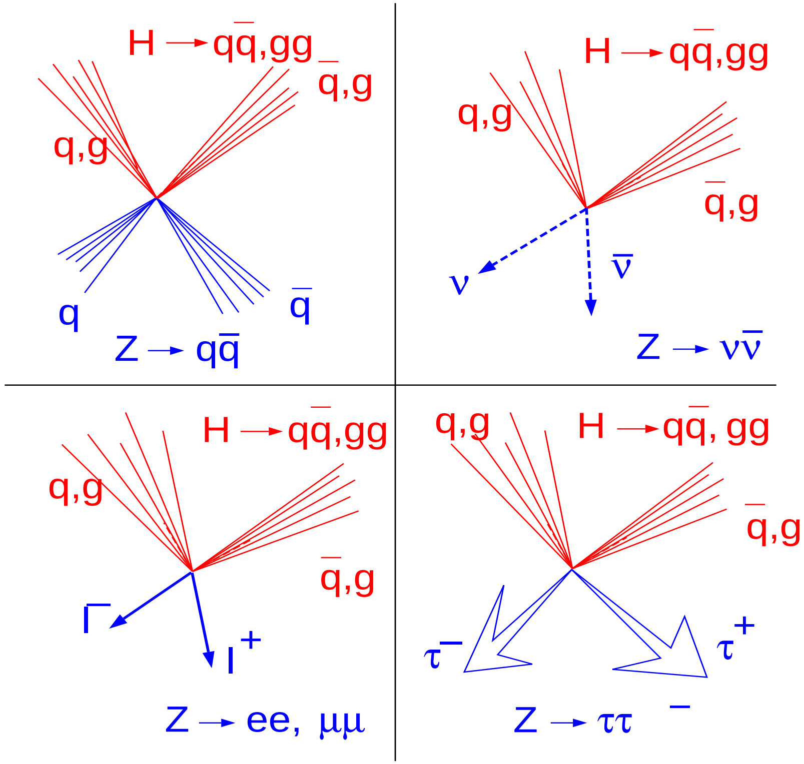
$h^0 c\bar{c} = \dfrac{\cos\alpha}{\sin\beta}$	$h^0 b\bar{b} = -\dfrac{\sin\alpha}{\cos\beta}$
$A^0 c\bar{c} = \cot\beta$	$A^0 b\bar{b} = \tan\beta$

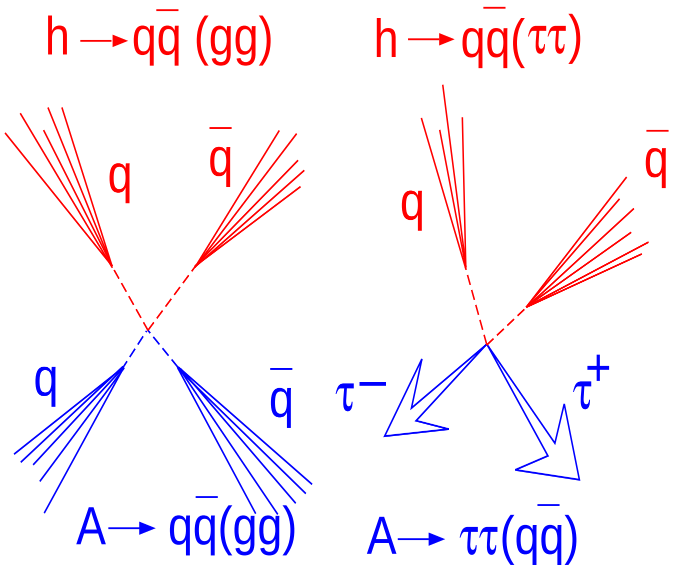
where allowed the $h^0 \to A^0 A^0$ decay can be the dominant one



2HDM final state topologies

hZ analysis	hA analysis





- SM hZ channels with $H^0_{SM}=h^0$ with h^0 decaying into $b\bar{b}$ can be reinterpreted in 2HDM
- the decay $h^0 \to A^0A^0$ is relevant where $m_h > 2m_A$: $Z^0A^0A^0$ / $A^0A^0A^0$ channels with $A^0 \to b\bar{b}$
- for low $|\alpha|$ and β BR($h^0/A^0 \to b\bar{b}$) ~ 0 both b-tag and flavour independent searches are needed

2HDM(II) general scan by OPAL

- Eur. Phys. J. C18(2001)425
- PN475, submitted to EPS01

HZHA generator (P. Janot CERN 96-01) to extract σ_{hZ}, σ_{hA}, BR's

Covered parameter space :

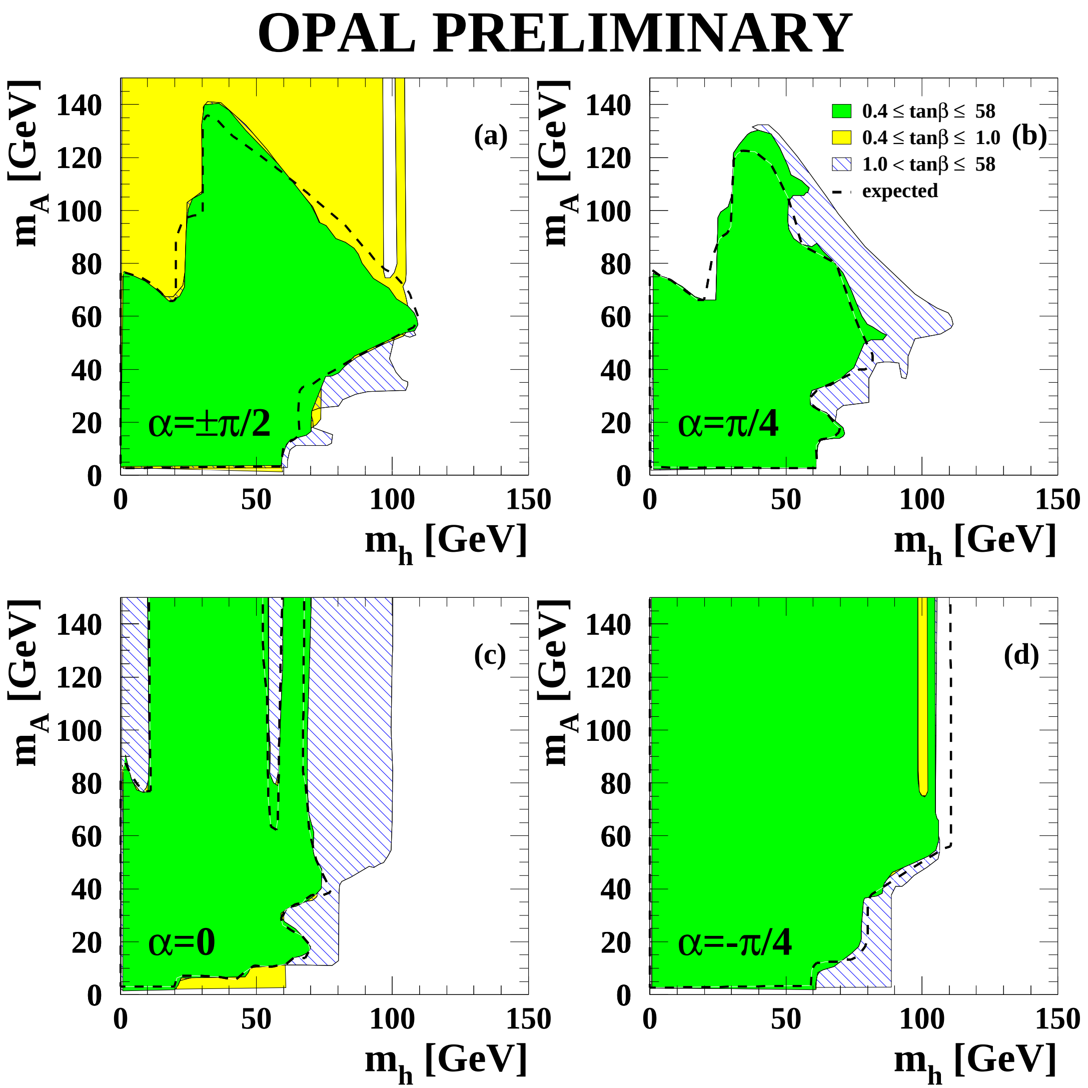
- $1 \leq m_h \leq 120$ GeV
- $3\,\mathrm{GeV} \leq m_A \leq 2$ TeV
- $0.4 \leq \tan\beta \leq 58.0$
- $\alpha = +\pi/2, +\pi/4, 0, -\pi/4$ and $-\pi/2$
- m_{H^+} and m_H above the kinematically accessible region

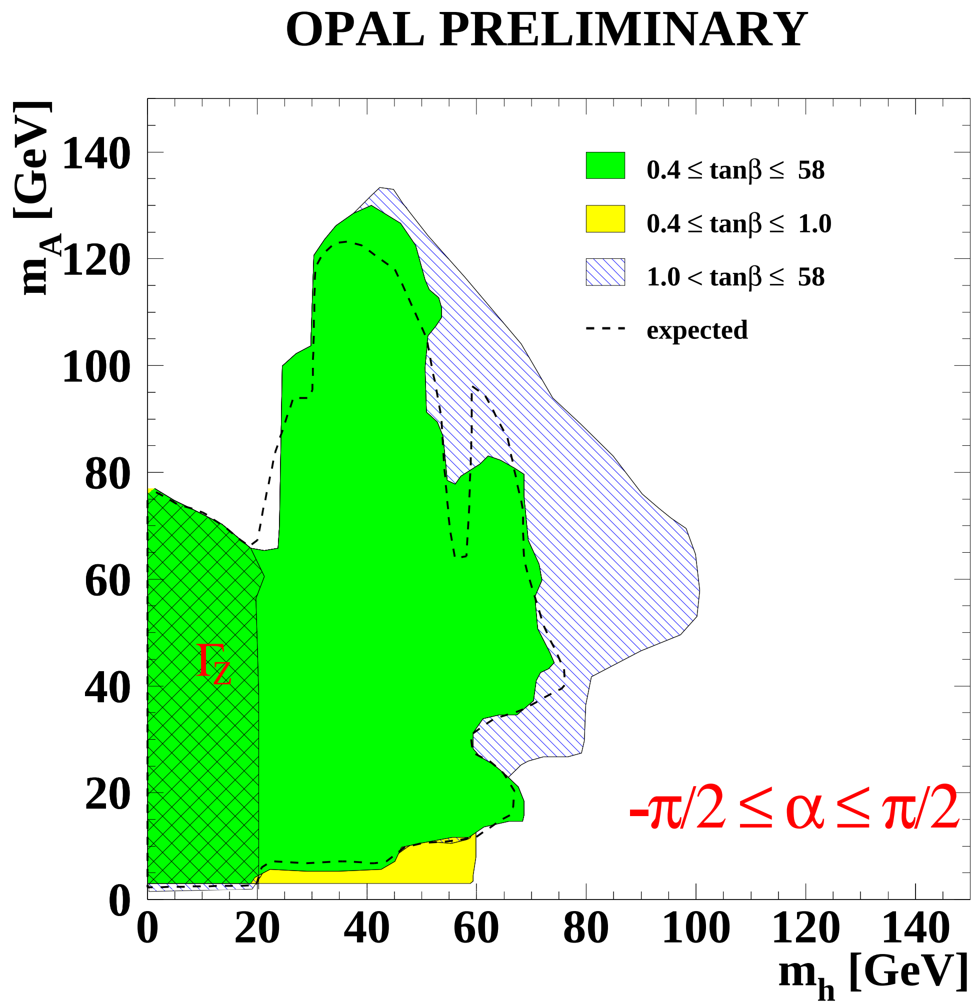
LEP1+ LEP2 Data

Year	$\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]
<1999	m_Z, 183,189	115, 55, 171
1999	202,192,196, 200	215
2000	200- 209	208

- h^0Z^0 and h^0A^0 channels with and without b-tagging
- Constraint extracted by the limit on non standard contributions to the Z^0 width:
  $\Delta\Gamma_{inv} < 2.0$ MeV @95%CL (CERN-EP 2000-153)

m_A vs m_h projection: a particular (m_h, m_A, α) point is excluded at 95%CL if it is excluded for all scanned values of $\tan\beta$ - $0.4 < \tan\beta < 58$

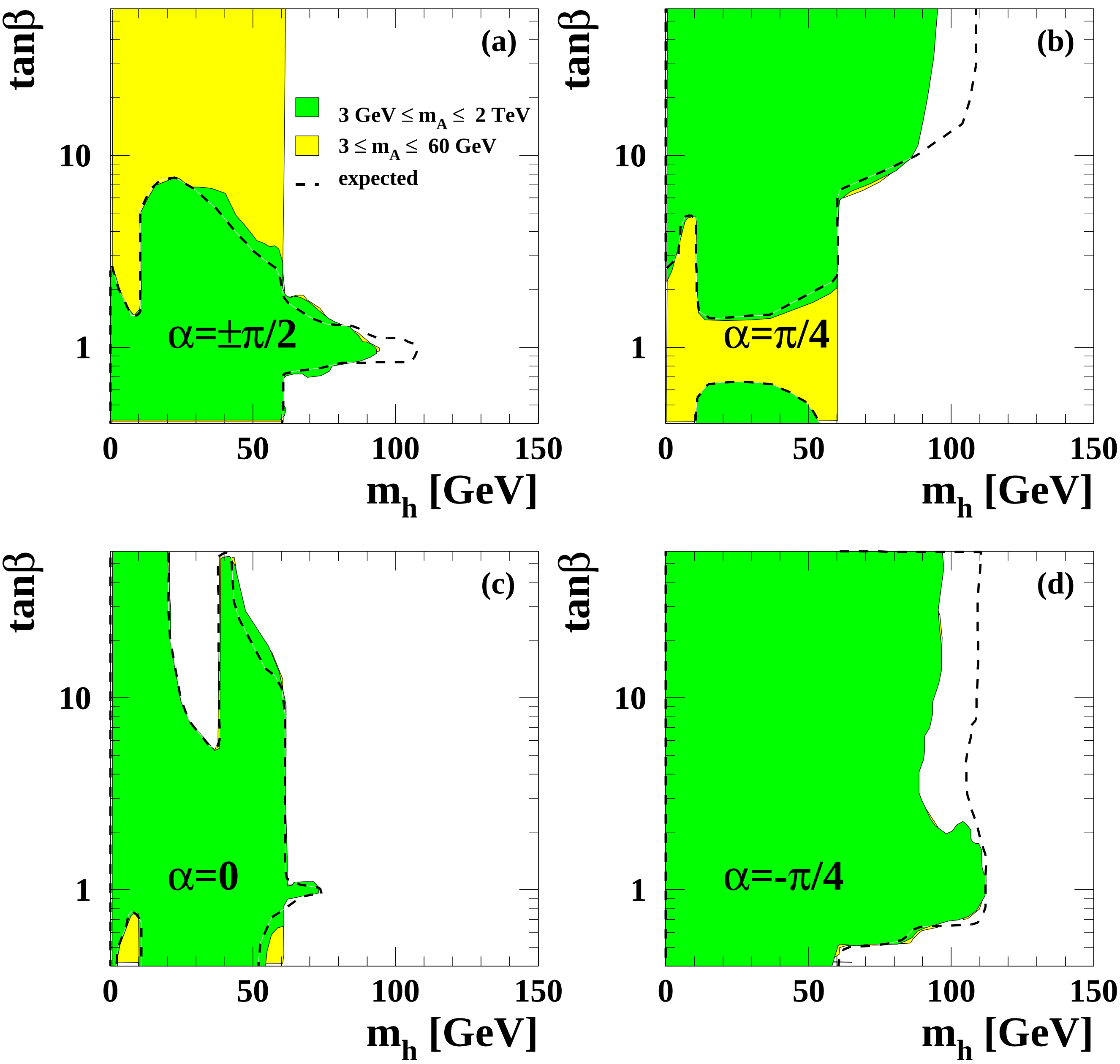




$\tan\beta$ vs m_h projection

a particular (m_h, $\tan\beta$, α) point is excluded at 95%CL
if it is excluded for all scanned values of m_A

OPAL PRELIMINARY



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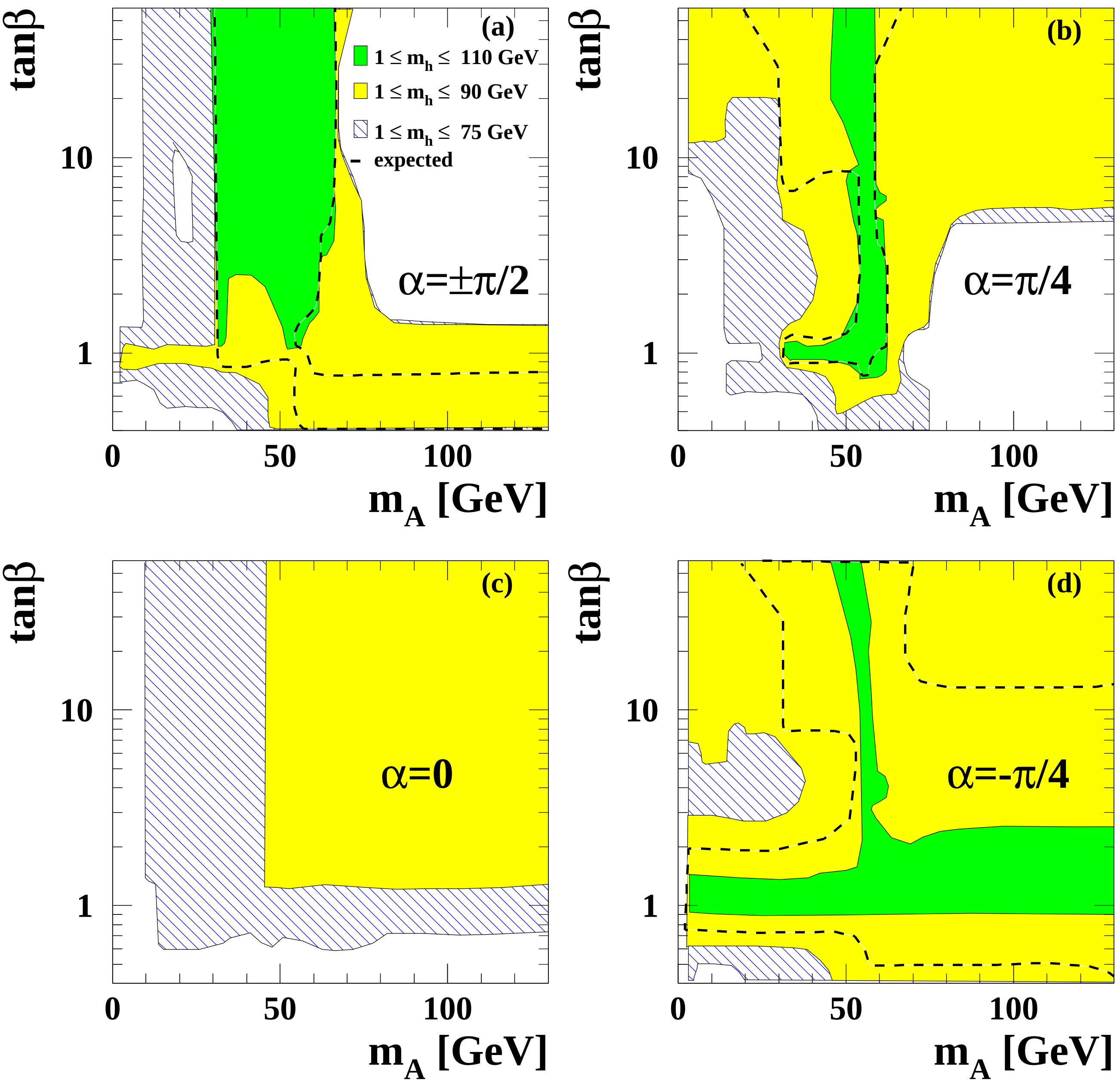
OPAL PRELIMINARY



DELPHI study (DELPHI 2001-068 CONF 496)

This study is dedicated to specific final states
all Higgs decays are into b final states :

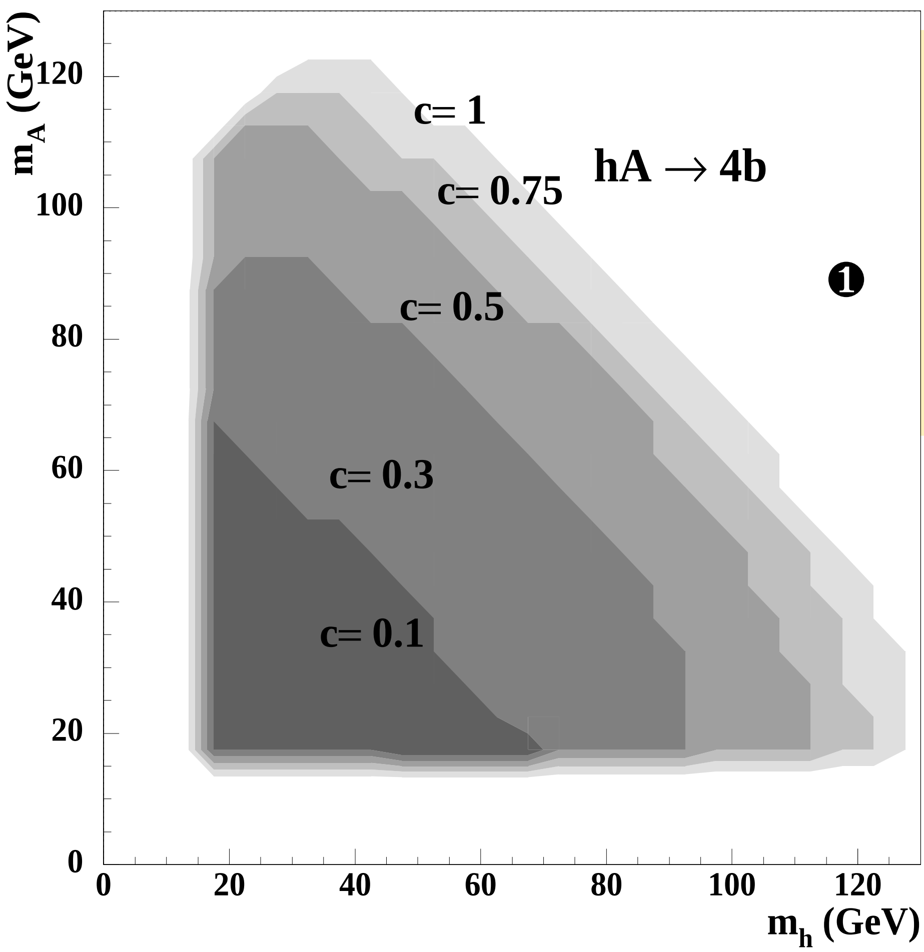
❶ $e^+e^- \to Z^0 \to A^0h^0 \to 4b$

❷ $e^+e^- \to Z^0 \to A^0h^0 \to A^0A^0A^0 \to 6b$
❸ $e^+e^- \to Z^0 \to Z^0h^0 \to Z^0A^0A^0 \to 4b2q$
} dominant if $m_h > 2m_A$

$e^+e^- \to Z^0 \to A^0h^0 \to A^0Z^0A^0$
$e^+e^- \to Z^0 \to Z^0h^0 \to Z^0Z^0A^0$
} dominant if $m_h > m_Z + m_A$
not present in HZHA

❹ $e^+e^- \to Z^0 \to A^0h^0 \to h^0Z^0h^0 \to 4b2q$ dominant if $m_A > m_h + m_Z$

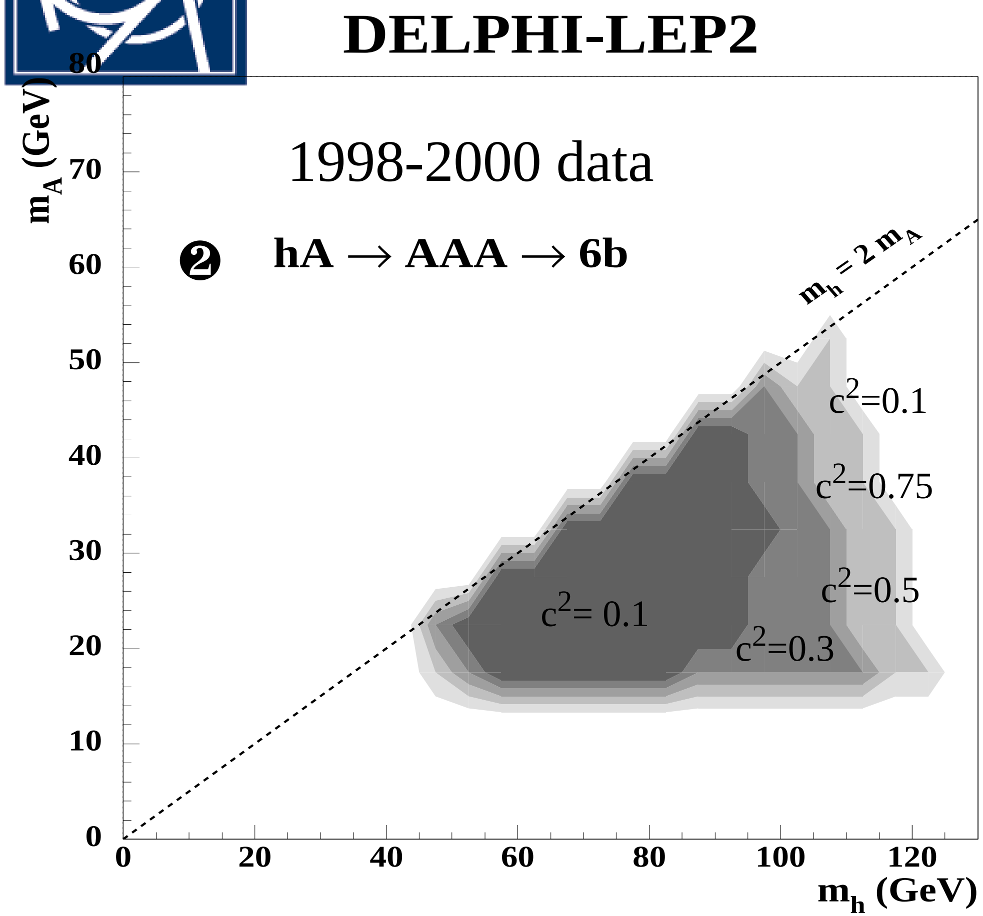
DELPHI-LEP2

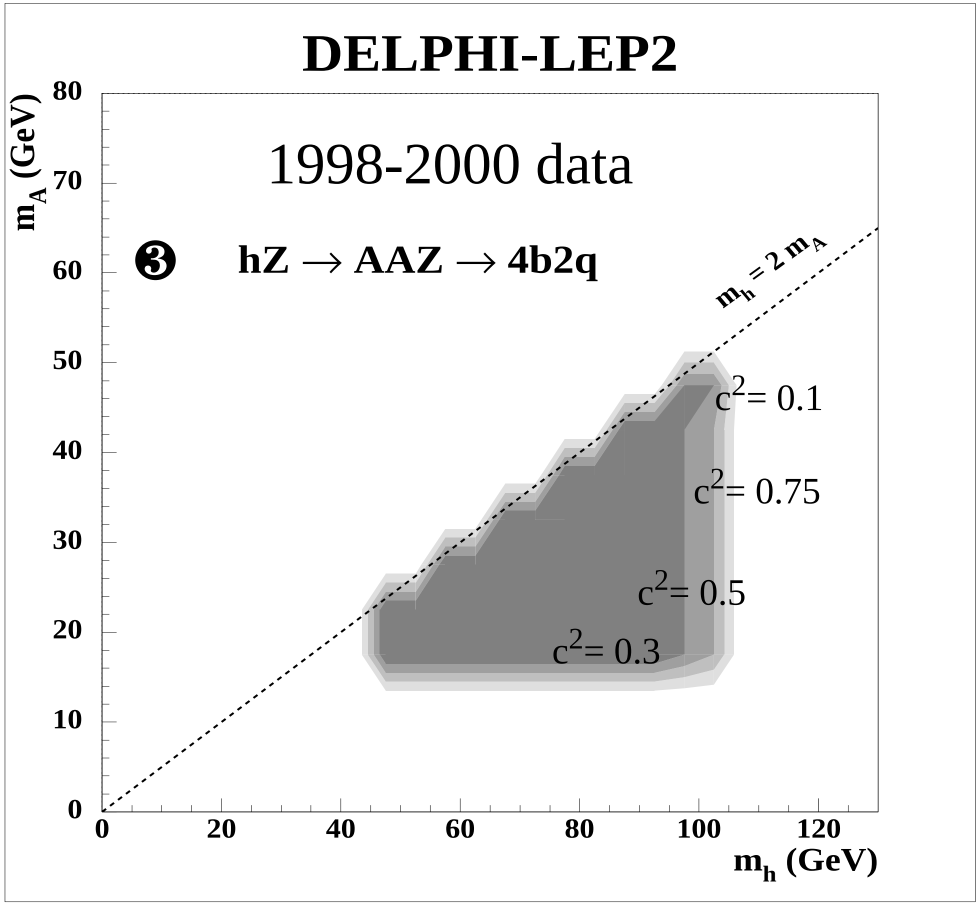


Year	Lumi(pb^{-1})	$\sqrt{s}$(GeV)
1998	158.0	189
1999	228.0	192-202
2000	225.1	205-208

$c = \cos^2(\beta-\alpha) * \sin\alpha / \cos\beta * \tan\beta$

suppression factor for x-sec and BR

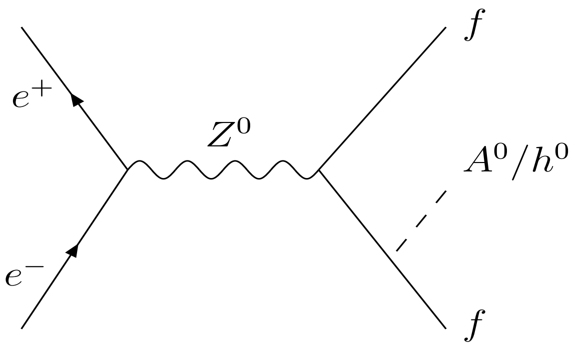




❹ No exclusion for process $e^+e^- \rightarrow Z^0 \rightarrow A^0h^0 \rightarrow h^0Z^0h^0 \rightarrow 4b2q$

Yukawa Production in 2HDM

$$\boxed{\sigma_{\mathbf{Yukawa}} \propto m_f^2 N_c \phi^2_{\;h/A}}$$



m_f = fermion mass

N_c = colour factor of emitting fermion

$\phi^2_{\;h/A}$ = enchancement factor , describes the coupling of h/A to the emitting fermion

SM Yukawa production suppressed by m_f^2/m_h^2

✓ dominant process for Higgs production if

$\sin^2(\beta-\alpha) \sim 0$	⇨	Higgs-Strahlung process suppressed
$m_A+m_h > \sqrt{s}$	⇨	Pair-Prodution kinematically forbidden

✓ Yukawa enhancement factor to down-quarks(leptons)

$hb\bar{b}$ $(h\tau^-\tau^+) \propto$ $-\sin\alpha/\cos\beta \sim \tan\beta$ if $\sin(\beta-\alpha) \sim 0$

$Ab\bar{b}$ $(h\tau^-\tau^+) \propto$ $\tan\beta$

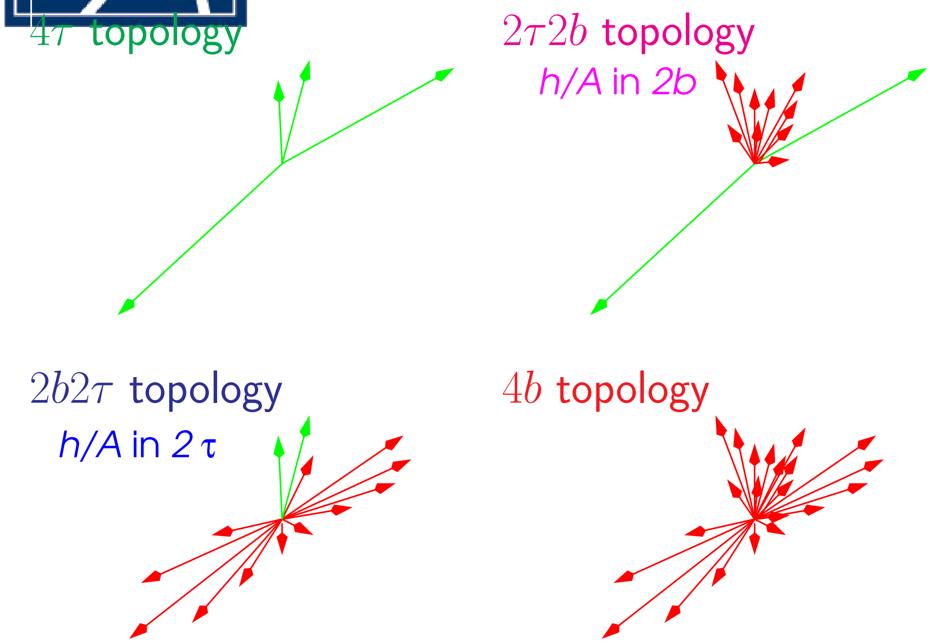
$\tan\beta >> 1$

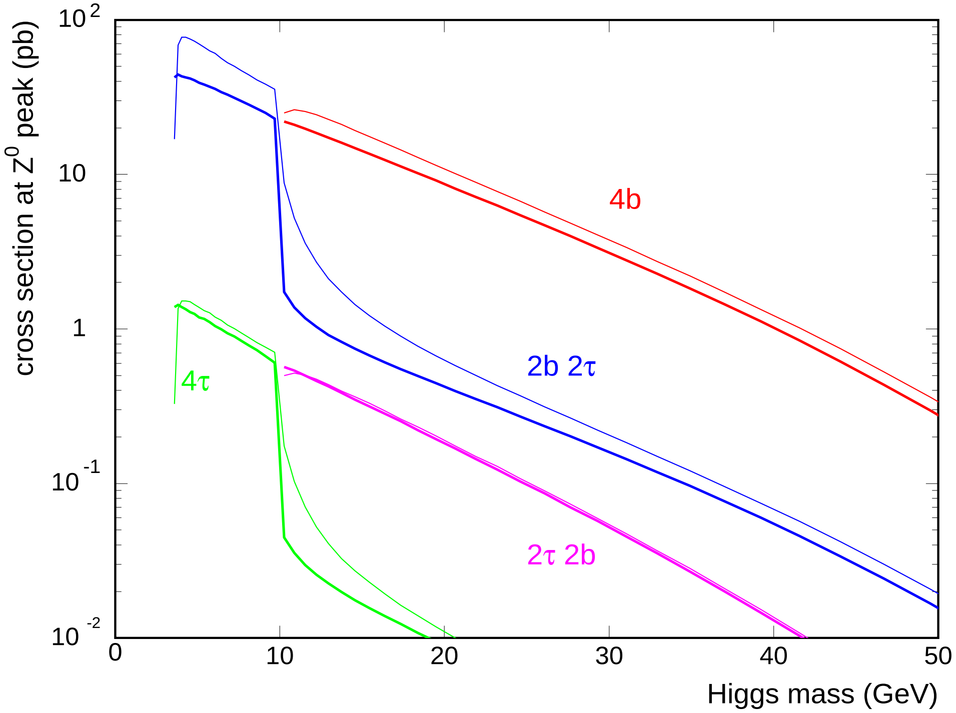
✗ enhancement of coupling to up-quarks(leptons) for $\tan\beta << 1$

Not sufficient for the production and detection - is already excluded by search for $Z \rightarrow h^o(A^o)\,\gamma$

(M.Krawczyk et al. hep-ph/9811256)

Yukawa final topologies at LEP1





LEP2 number of produced b quarks 100 times smaller than LEP1 $\Rightarrow$ LEP1 data analysed

Contributions from:

- ALEPH PA13-027 (ICHEP'96),DELPHI 99-76 CONF 263 (EPS'99), L3 submitted to EPS'95
- DELPHI 01-68 CONF-496, submitted to EPS'01, Budapest
- OPAL PN483, submitted to EPS'01, Budapest

DELPHI study

(DELPHI 2001-068 CONF 496)

New study: $e^+e^- \to b\bar{b}A^0/h^0 \to b\bar{b}b\bar{b}$

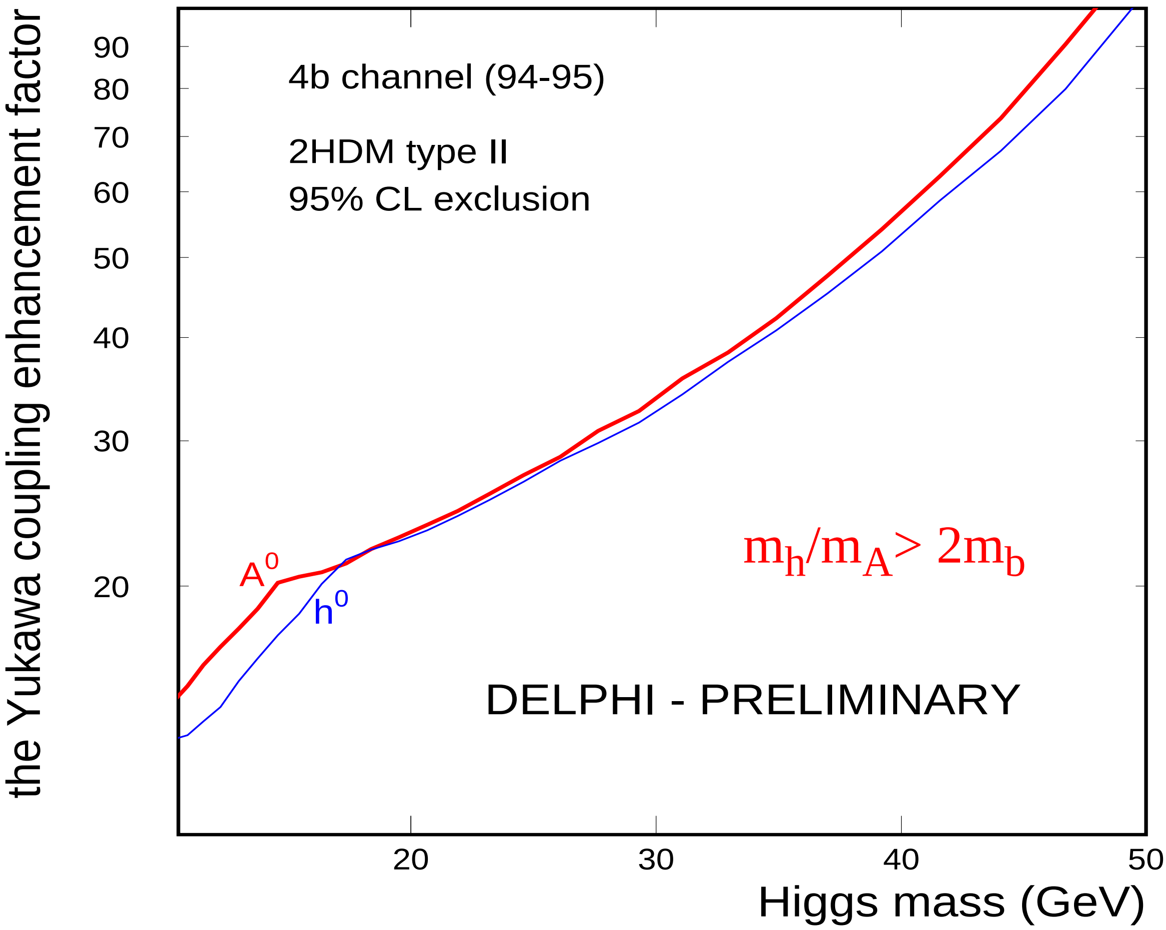
- 3-jet topology (one of bb pair ~m_b)
- 4-jet topology ($m_{h/A}$~$m_Z/2$)

b-tagging

study performed on 1994-1995 LEP1 data

Previous study :

- measurement of gluon splitting into $b\bar{b}$ in the process $Z^0 \to b\bar{b}g \Rightarrow$ ***Not optimal*** (DELPHI 99-76 CONF 263)
- 4τ final state (DELPHI 99-76 CONF 263)

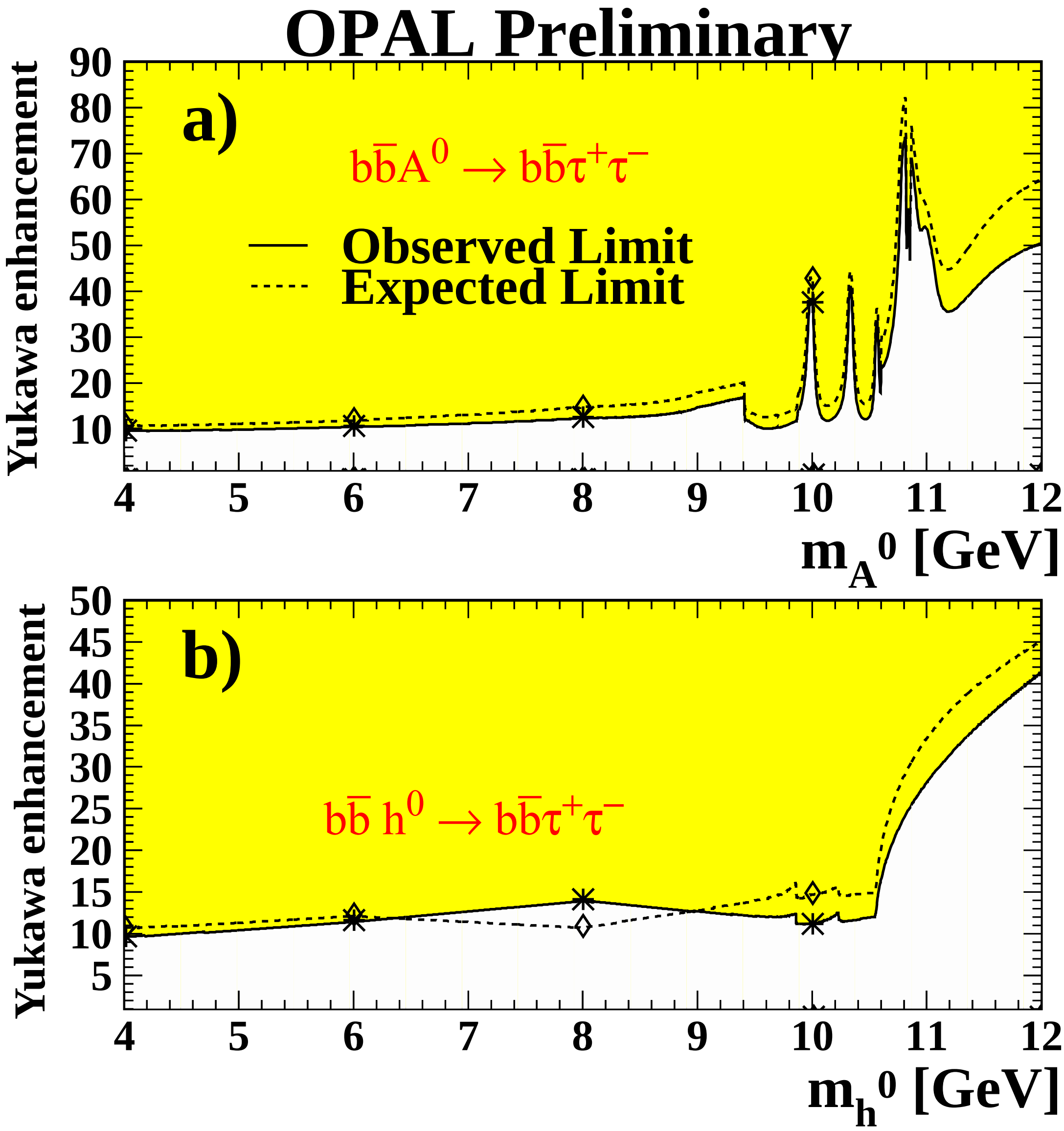


OPAL study (OPAL PN 483)

$e^+e^- \rightarrow b\bar{b}A^0/h^0 \rightarrow b\bar{b}\tau^+\tau^-$

- 2HDM(II) BRs ($A^0/h^0 \rightarrow \tau^+\tau^-$)
- mixing of $b\bar{b}$ bound states and h/A inlcuded

Luminosity =113.1 pb^{-1} 1992-1995 data (5% off peak)



Anomalous Muon Magnetic Moment Implications

Precise Measurement of a_μ, Muon(g-2) Collaboration:

(PRL 86 (2001) 2227)

$$a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (43 \pm 16) \times 10^{-10}$$

2.6 σ deviation

The contribution of the Higgs sector of the SM is suppressed by a factor m_μ^2/m_h^2, but 2HDM(II) can explain a_μ

1-loop 2HDM contribution

positive contribution from light h^0 enhanced wrt SM:

- enhanced $h\mu\mu$ coupling $\propto \tan\beta$ $\Rightarrow$ $\tan\beta >> 1$
- suppressed hZZ coupling $\propto \sin(\beta-\alpha)$ $\Rightarrow$ $\sin(\beta-\alpha) \sim 0$
  (to have m_h below LEP SM limit)

M.Krawczyk and J. Zochowshi, **PRD 55 (1997) 6968,**
M.Krawczyk , May 2001, **hep-ph/0103223,**
A.Dedes and H.Haber, **hep-ph/0102297**

2-loop 2HDM contribution

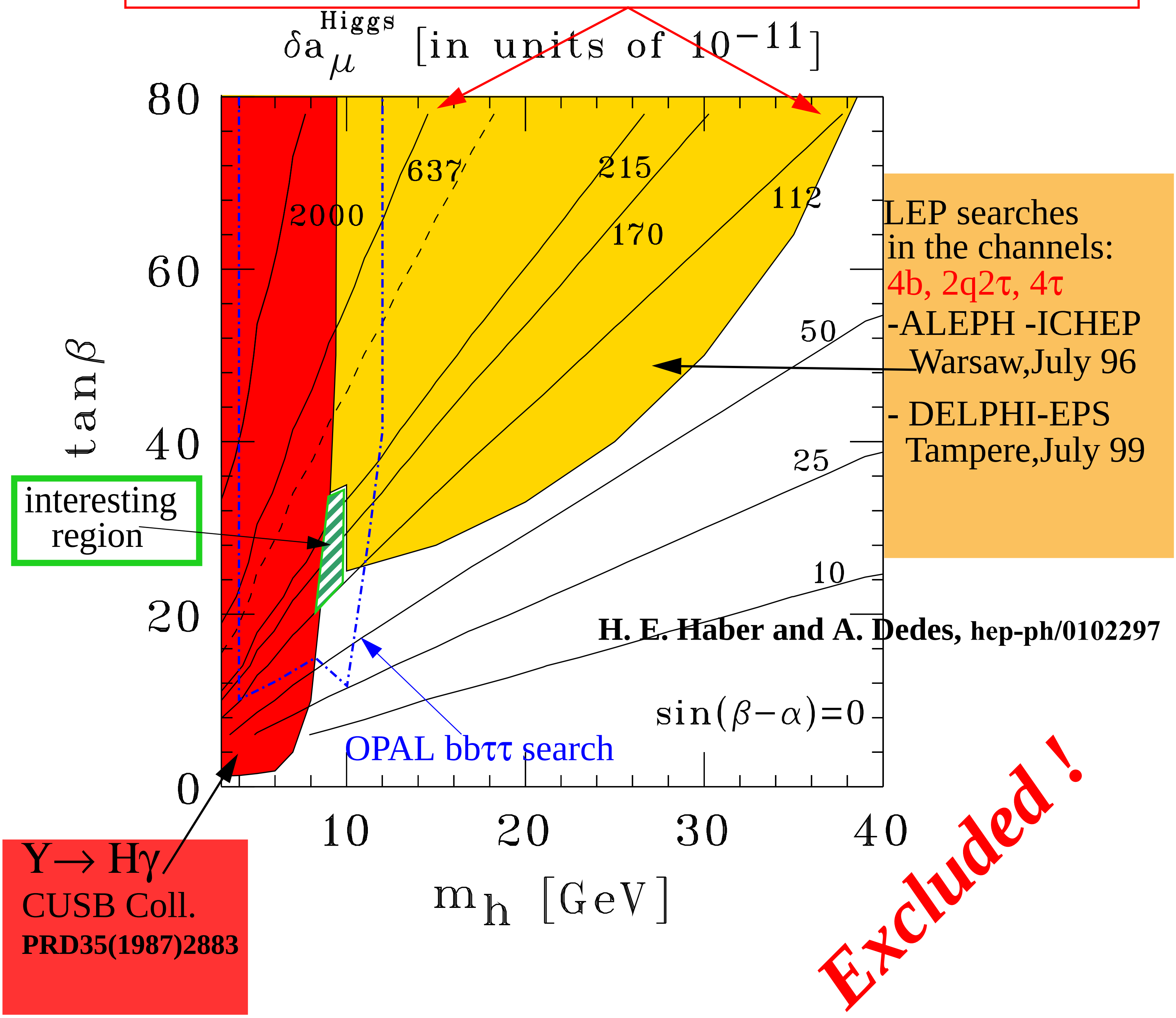
positive contribution from light A^0 $\propto \tan\beta \Rightarrow$ $\tan\beta >> 1$

K.Cheung et al.,**hep-ph/0103183**

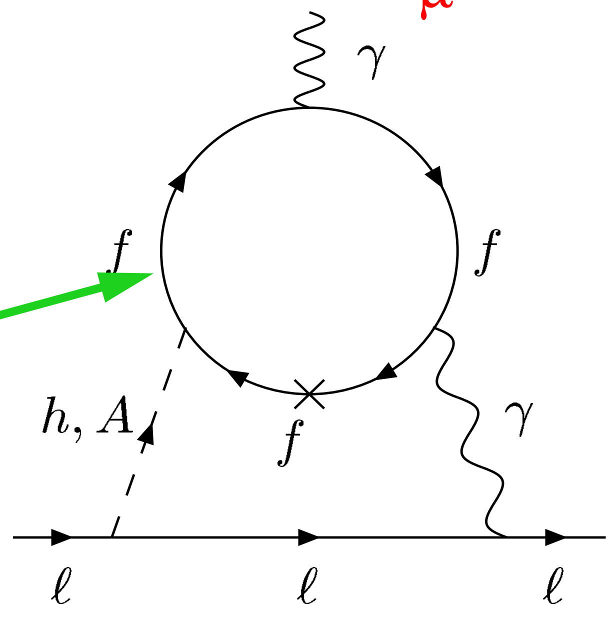
1-loop contribution to a_μ

if 2HDM(II) is contributing to a_μ, then with $\sin^2(\beta-\alpha)=0$ at 90%CL at 1-loop order:

- $215\times10^{-11} \leq \delta a_\mu \leq 637\times10^{-11}$ (A.Czarnecki and W.J. Marciano, PRD64(2001)013014)
- $170\times10^{-11} \leq \delta a_\mu \leq 690\times10^{-11}$ (M.Davier and A.Hoker, PLB435(1998)427)
- $112\times10^{-11} \leq \delta a_\mu \leq 537\times10^{-11}$ (S.Narison, hep-ph/013199(2001))



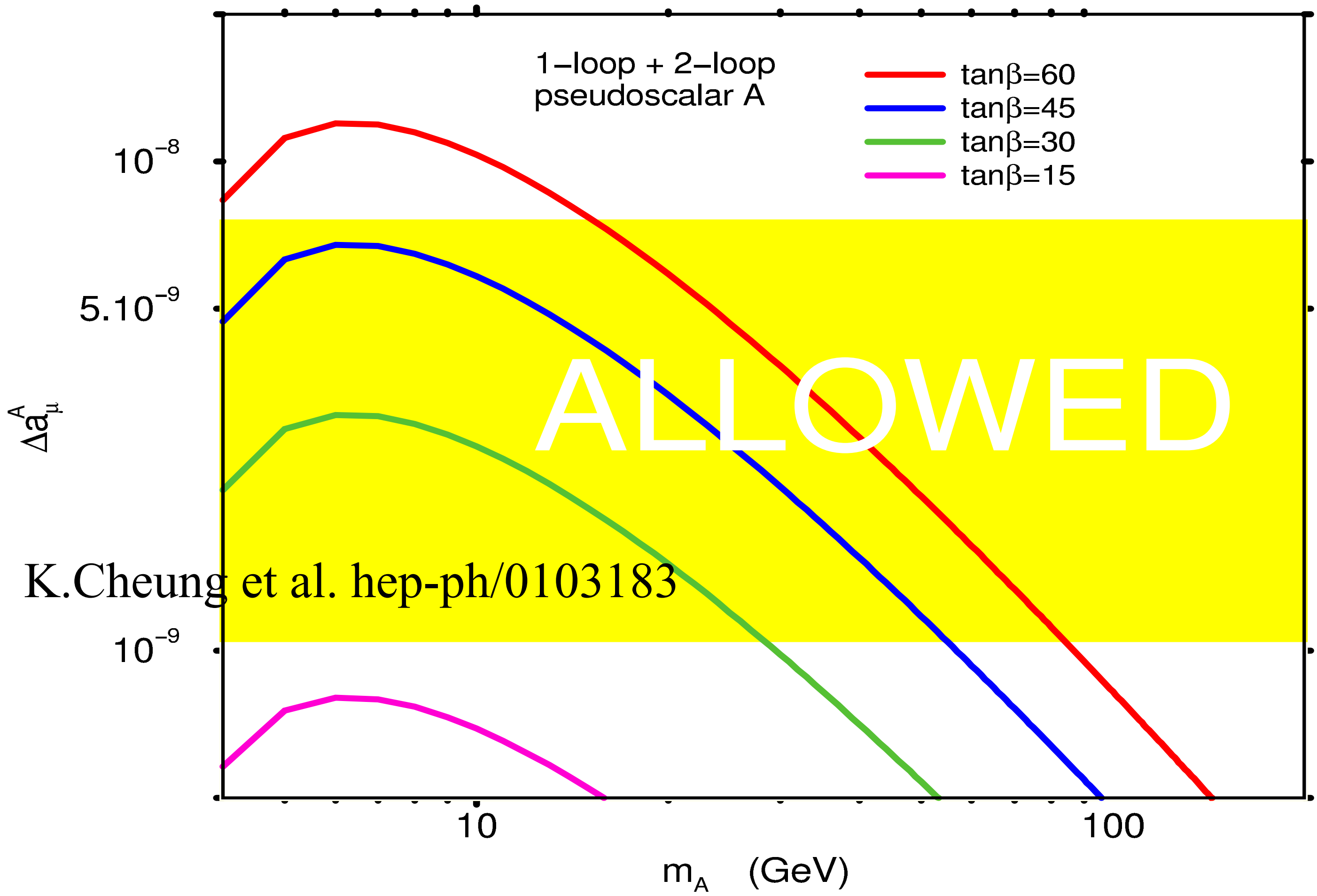
Two-Loop Contributions to a_μ



become larger than one-loop contributions for $m_{h/A}$ larger than few GeV.

Largest contribution from

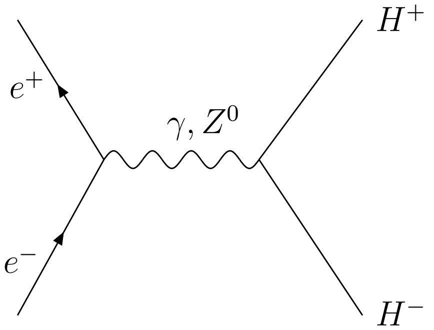
$\Delta\alpha_\mu$ is preferred to come from the pseudoscalar A^0: the 2-loop contribution of the h^0 is negative, while the data require a positive contribution to $\Delta\alpha_\mu$



K.Cheung et al. hep-ph/0103183

Large portion of the admissible solution is excluded by DELPHI Yukawa study and OPAL 2HDM(II) general scan.

Charged Higgs $H^{\pm}$

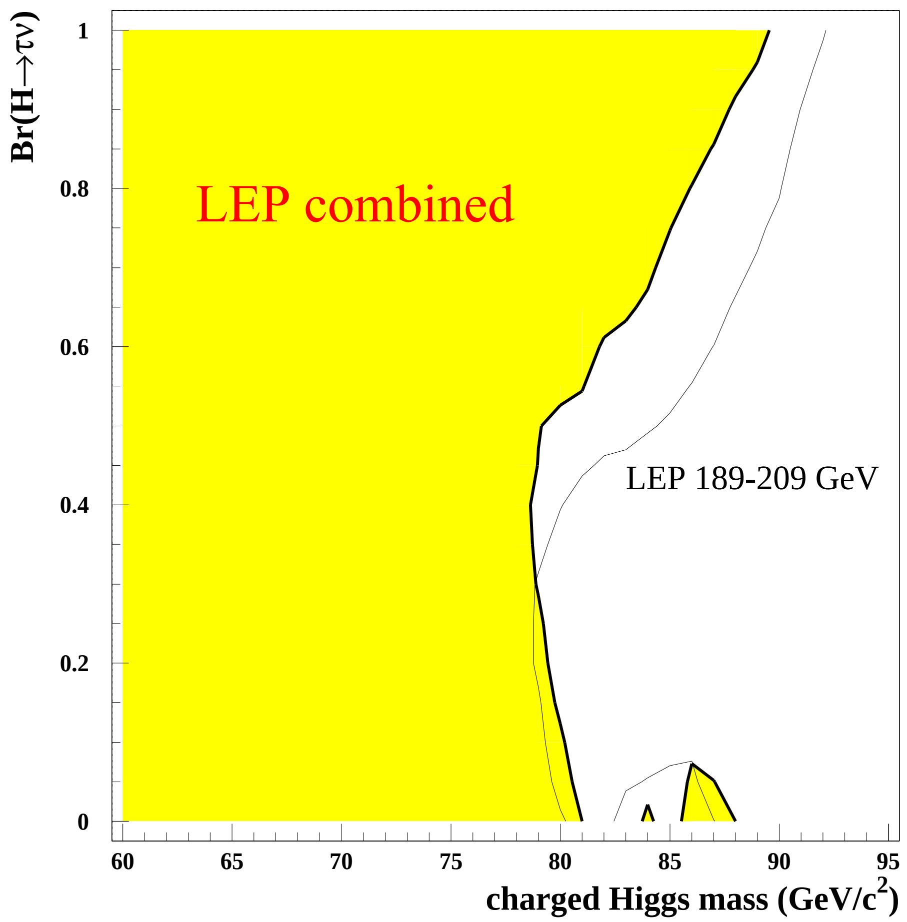


searched in 2HDM since

in the MSSM $m_{H^{\pm}} > m_W \Rightarrow$ no sensitivity because of WW backg.

$B(H^+ \to c\bar{s}) + B(H^+ \to \tau^+\nu) = 1$

$e^+e^- \to H^+H^- \to c\bar{s}\,s\bar{c}$
$e^+e^- \to H^+H^- \to c\bar{s}\,\tau^+\bar{\nu} + s\bar{c}\,\tau^-\nu$
$e^+e^- \to H^+H^- \to \tau^+\nu\tau^-\bar{\nu}$



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$m_{H^{\pm}} > 78.6$ (78.8 exp.) GeV 95%CL for any $B(H^+ \to \tau^+\nu)$

Conclusions

- The study of 2HDM is appealing and interesting

- 2HDM study has stimulated the developement of several new analyses:

  - flavour independent channels
  - $h^0 \rightarrow A^0A^0$ channels
  - $A^0 \rightarrow h^0Z^0$
  -Yukawa process

- still new results have to be expected from all the collaborations together with the ADLO combined general scan of the 2HDM parameter space