Upper limit on the mass of charged Higgs boson from the leptonic τ decays

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in collaboration with David Temes – hep-ph/0410248

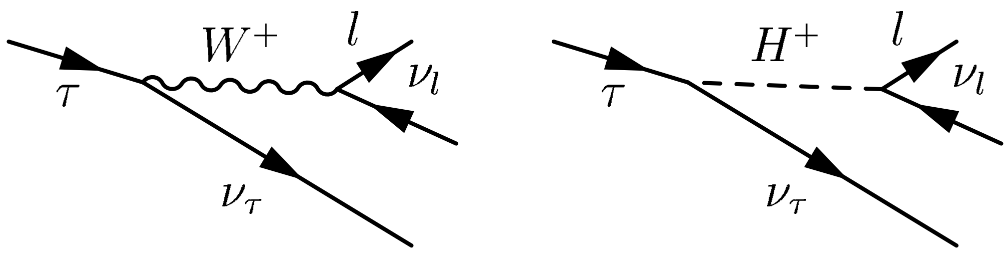
- The tau lepton
- Two Higgs Doublet Model (CP conservation)
- Loop radiative corrections for leptonic tau decays
- Constraints on mass and couplings for neutral and charged Higgs bosons

The τ lepton

Discovery 1975 - M. Perl (Nobel '95)

A unique laboratory to test the Standard Model

large mass $\sim$ 2 GeV allows for decays into lighter leptons AND hadrons



The coupling of the τ lepton to the W: g_τ = coupling $(\tau\nu_\tau W)$

In Standard Model $\rightarrow$ lepton universality: $g_e = g_\mu = g_\tau$

Tests of a universality of the couplings

The leptonic tau decay

$$\Gamma^l|_{SM} = \frac{g_\tau^2 g_l^2 m_\tau^5}{192 \cdot 32\pi^3 M_W^4} f(\frac{m_l^2}{m_\tau^2})$$

•From τ lifetime (τ_τ) and leptonic branching fractions ($Br = \Gamma\tau$):

$$\tau_\tau = \tau_\mu \left(\frac{g_\mu}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 B(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$$

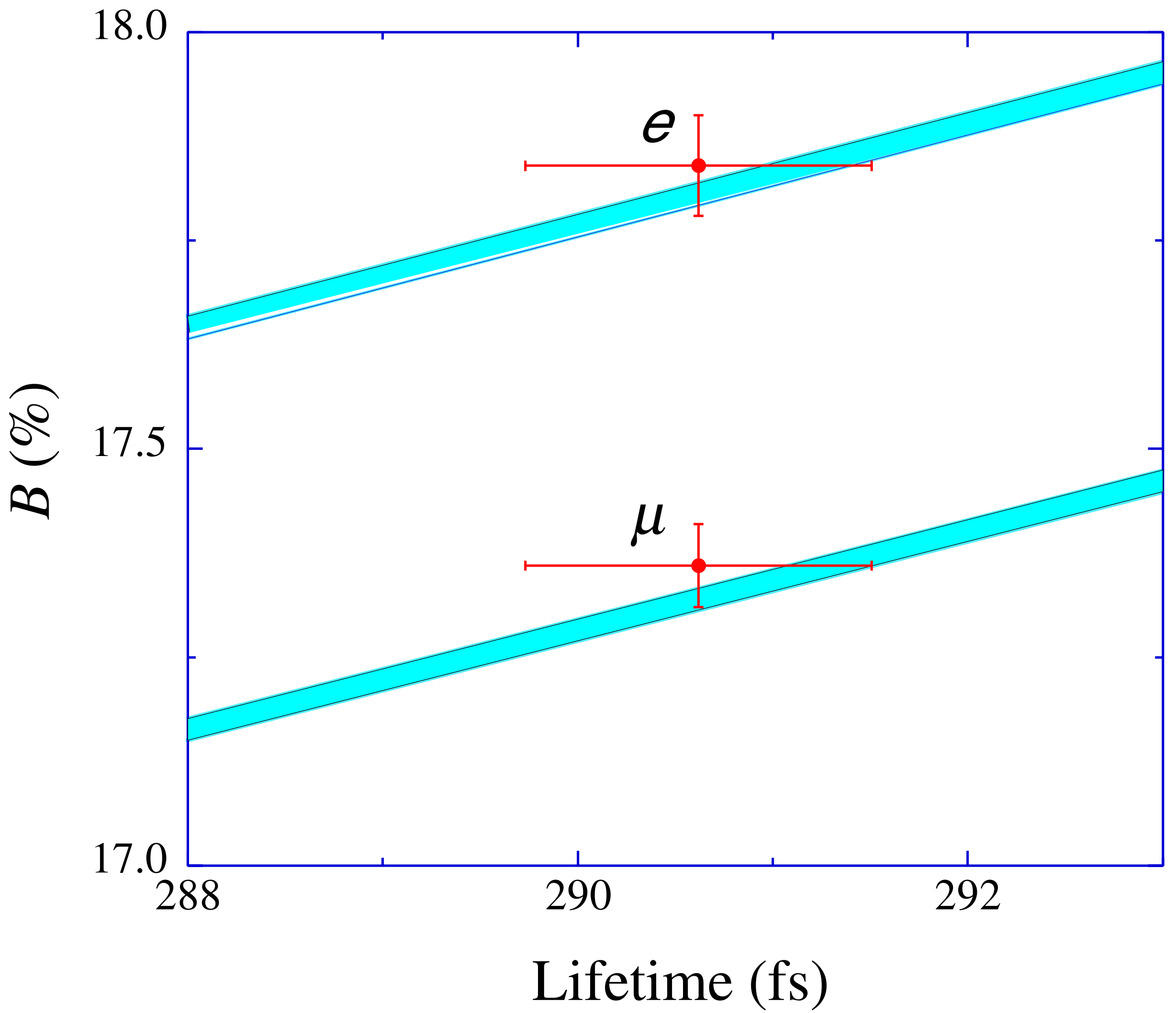
$$\tau_\tau = \tau_\mu \left(\frac{g_e}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) f\left(\frac{m_\mu^2}{m_\tau^2}\right)$$

the phase space factor $f(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x$ (for muon = 0.9726)

•From data for lifetime and Br's one can extract:

$$\frac{g_\mu}{g_\tau} = 0.9990 \pm 0.0023 \quad \frac{g_e}{g_\tau} = 0.9988 \pm 0.0021$$

Or assuming lepton universality $g_e = g_\mu = g_\tau$



Consistent with the Standard Model

K. Gan: hep-ex/0311047

Early papers and motivation

- Radiative coorections in 2HDM –Rosiek '90
- <u>A τ puzzle:</u>

Data on leptonic branching ratio (from LEP combined with ARGUS and CLEO' 92) too low by 2.5σ than expected in SM
→ "Tau decay in the two Higgs doublet model"
Guth, Hoang, Kuhn '92

→ "Can a second Higgs doublet diminish the leptonic tau decay width?"
Hollik, Sack '92,

- New - Morse '2004 considered hadronic contribution to g-2,

"Is the Difference Between the Pion Form Factor Measured in e^+e^- Annihilations and τ - Decays Due to an H^+ Propagator?"

- Our motivation - precise data can constrain parameters of 2HDM

Standard Model

SM Higgs Potential:

$$V = \frac{1}{2}\lambda(\phi^\dagger\phi)^2 - \frac{1}{2}m^2(\phi^\dagger\phi)$$

One scalar (spin zero) doublet ϕ • basic parameter v - vacuum expecation value of scalar field one Higgs boson • one unknown parameter describing whole sector: mass or selfcoupling • interaction with gauge bosons: $M_V \sim gv$ ($v \sim$ 246 GeV), Higgs coupling to $V \sim M_V$ • Yukawa interaction with fermions: $g_f \sim m_f$ •

Direct LEP searches: $M_{H_{SM}}$ larger than 114.4 GeV

2HDM models without and with CP violation

2HDM Potential: quartic and quadratic terms separated:

$$V = \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)$$
$$+ \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] + \left\{\left[\lambda_6(\phi_1^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2)\right](\phi_1^\dagger\phi_2) + \text{h.c.}\right\}$$
$$- \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}$$

14 parameters, with complex $\lambda_5, \lambda_6, \lambda_7$, $\text{Re}\, m_{12}^2$,$\text{Im}\, m_{12}^2$

No (ϕ_1, ϕ_2) mixing if Z_2 symmetry satisfied (NO FCNC & NO CPV):
$\phi_1 \to -\phi_1$, $\phi_2 \to \phi_2$ (or vice versa) $\Rightarrow \lambda_6 = \lambda_7 = m_{12}^2 = 0$

- Hard violation of Z_2 symmetry: quartic terms with λ_6, λ_7
- Soft violation of Z_2 symmetry ($\lambda_6, \lambda_7 = 0$): governed by $\mu^2 \propto \text{Re}\, m_{12}^2$

Lee, Diaz-Cruz, Mendez, Haber, Pomarol, Barroso, Santos, Hollik, Djouadi, Illana, Branco,Gunion, Grzadkowski, Akeroyd, Arhrib, Kalinowski, Zerwas, Choi, Kanemura, Okada, GKO

SSB and physical Higgs bosons

Two scalar (spin zero) doublets ϕ_1 and ϕ_2 with vev v_1 and v_2

(with $v^2 = v_1^2 + v_2^2$, with $\tan\beta = v_2/v_1$)

• CP conservation: Higgs sector: h,H,A, $H^\pm$; $\tan\beta, \alpha$ (h,H), μ^2
h,H - CP-even, A - CP-odd

• CP violation: mixing between h_1, h_2, h_3, more mixing angles
and CP parity of Higgs bosons - not defined

Interaction with gauge bosons

$$(g_W^h)^2 + (g_W^H)^2 + (g_W^A)^2 = (g_W^{H_{SM}})^2$$

Various models of Yukawa interaction with fermions:

Model II: where one scalar doublet couples to up-type quarks, other to down-type quarks and charged leptons

CP conservation: Higgs masses and couplings

Physical content of the Higgs potential:

- Higgs masses -
  mass of H^+, A can be large due large μ^2 or large $\lambda's$ (nondecoupling)
- Higgs trilinear couplings
- Higgs quartic couplings

Independent of the form of Higgs potential are:

- couplings to gauge bosons: hWW, HWW, while $AWW = AZZ = 0$
- couplings to fermions (Yukawa) e.g. Model **II**:

$\phi_1 \to u$-type fermions $\phi_2 \to d$-type fermions

The relative "basic couplings":

$$\boxed{\chi_j^i = \frac{g_j^i}{g_j^{\mathrm{SM}}}} \quad i = h, H, A;\ j = V, u, d$$

Relations between relative couplings: eg. $\Sigma_i (\chi_j^i)^2 = 1$, for $j = V, u, d$

Existing constraints for 2HDM (II)

CP conserv. 2HDM(II) with soft violation of Z_2 symmetry (μ^2 term):

$\Rightarrow$ five Higgs bosons: h,H,A,$H^{\pm}$

$\Rightarrow$ 7 parameters: $M_h, M_H, M_A, M_{H^\pm}$, α, β, and μ^2

MODEL II (as in MSSM)

Couplings (relative to SM):	$\boxed{h}$	$\boxed{A}$
to W/Z:	$\chi_V = \sin(\beta-\alpha)$	0
to down quarks/leptons:	$\chi_d = \chi_V - \sqrt{1-\chi_V^2}\tan\beta$	$-i\gamma_5 \tan\beta$
to up quarks:	$\chi_u = \chi_V + \sqrt{1-\chi_V^2}/\tan\beta$	$-i\gamma_5/\tan\beta$

For H couplings like for h with:

$\sin(\beta-\alpha) \leftrightarrow \cos(\beta-\alpha)$ and $\tan\beta \rightarrow -\tan\beta$.

For large $\tan\beta$ $\rightarrow$ enhanced couplings to $d-$type fermions (and τ, μ, e)!

For $\chi_V^h = \sin(\beta-\alpha) = 0 \rightarrow \chi_d^{h,A} \sim \tan\beta$

DATA

LEP • **direct:(h) Bjorken process** $Z \to Zh$, $\to \sin(\beta - \alpha)$

(hA) pair prod. $e^+e^- \to hA$, $\to \cos(\beta - \alpha)$

(h/A) Yukawa process $e^+e^- \to bbh/A$, $\tau\tau h/A$, $\to \tan\beta$

($H^\pm$) $e^+e^- \to H^+H^-$

via loop:(h/A, and $H^\pm$) $Z \to h/A\gamma$

Others exp. • **via loop:(h/A) Wilczek process** $\Upsilon \to h/A\gamma$

loop: ($H^\pm$) $b \to s\gamma$, $\to$ **lower limit for** $M_{H^\pm}$

leptonic tau decay $\to$

g-2 data , $\to$ **upper limit for** χ_d

Global fit • **(all Higgses)**

Chankowski at al.,'99 (EPJC 11,661;PL B496,195)

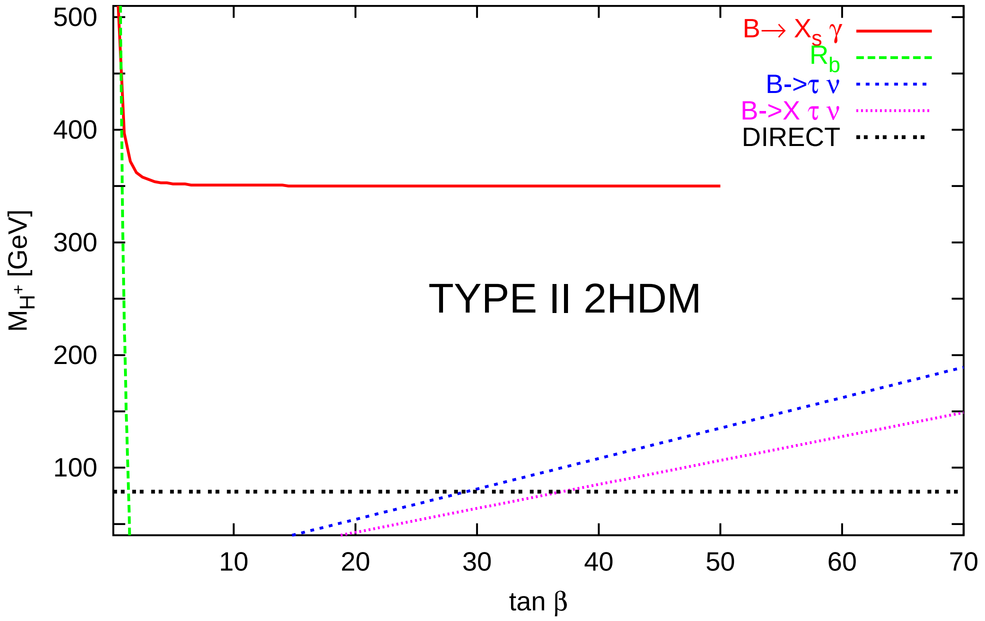
Cheung and Kong '03

Constraints from $b \to s\gamma$ - Gambino, Misiak'01

Strong constraints on new physics from $\bar{B} \to X_s\gamma$
The weighted average for BR$_\gamma$ $\equiv$BR$[\bar{B} \to X_s\gamma]$

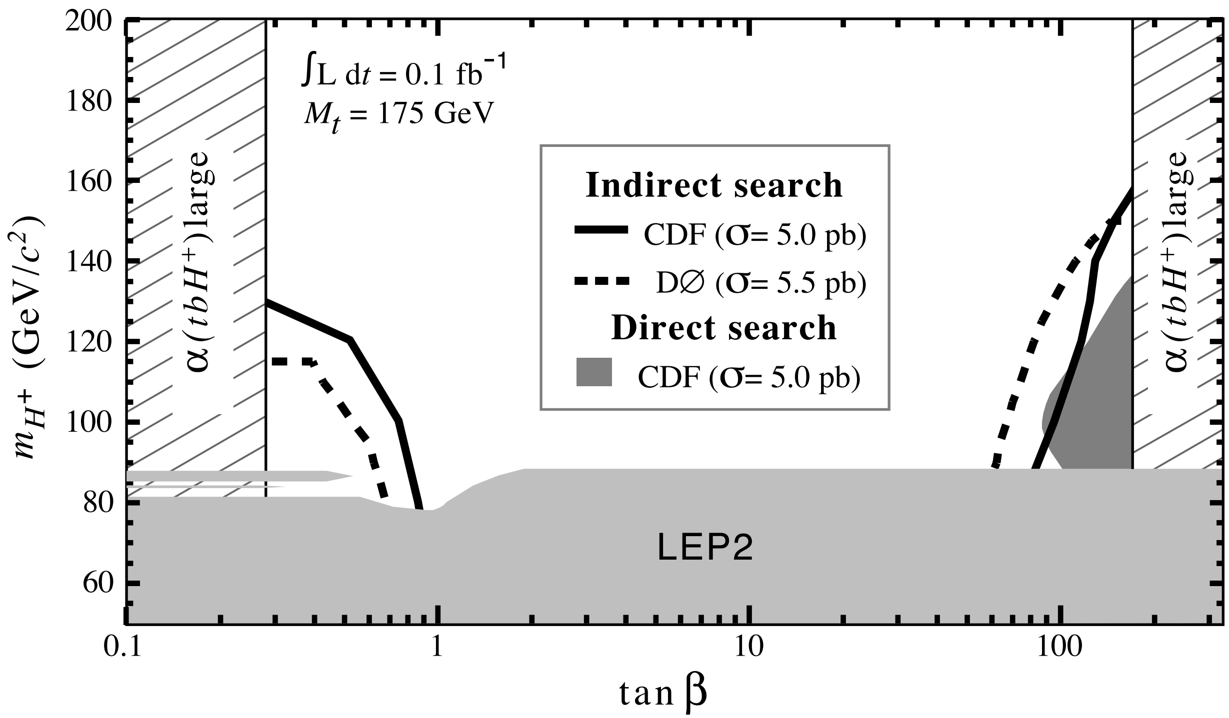
$$\mathrm{BR}_\gamma^{\mathrm{exp}} = (3.23 \pm 0.42) \times 10^{-4}$$

NLO prediction (Misiak, Gambino'01): M_{H+} above 490 GeV (95%)



Here mass limit 350 GeV corresponds to 99 % CL !

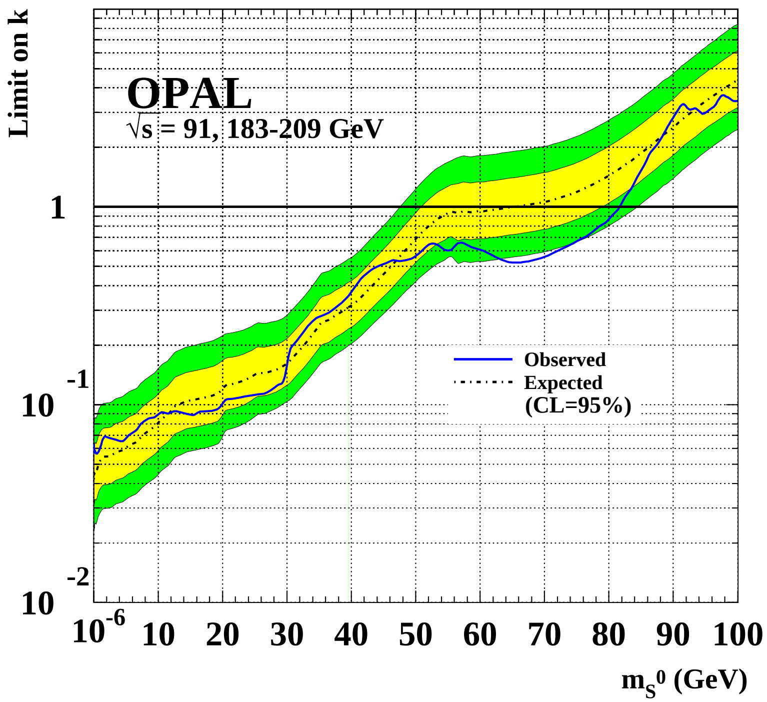
Direct and undirect limits for charged Higgs boson - PDG2004

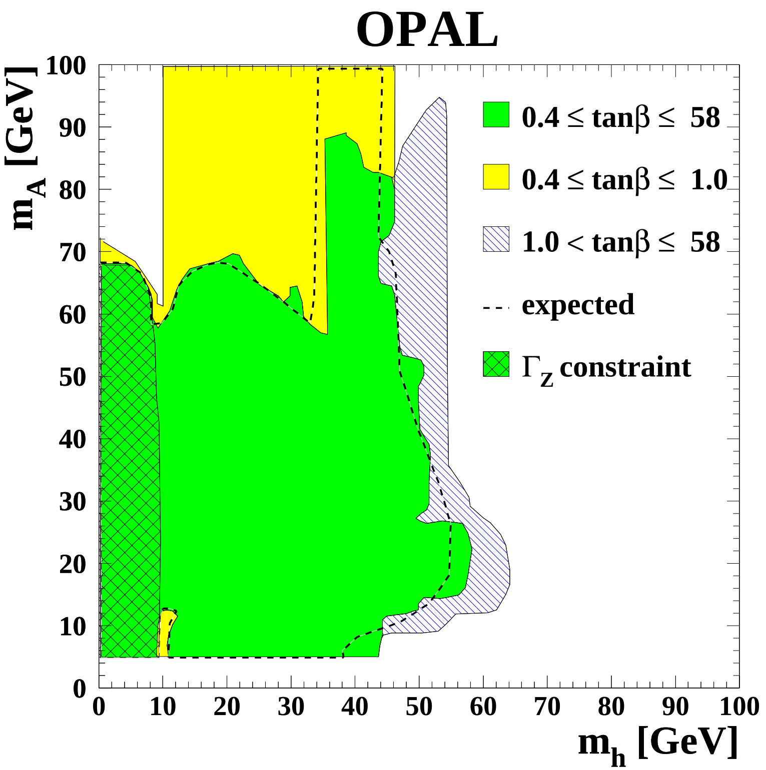


Tevatron and LEP limits (90 GeV)

Light h OR light A in agreement with current data

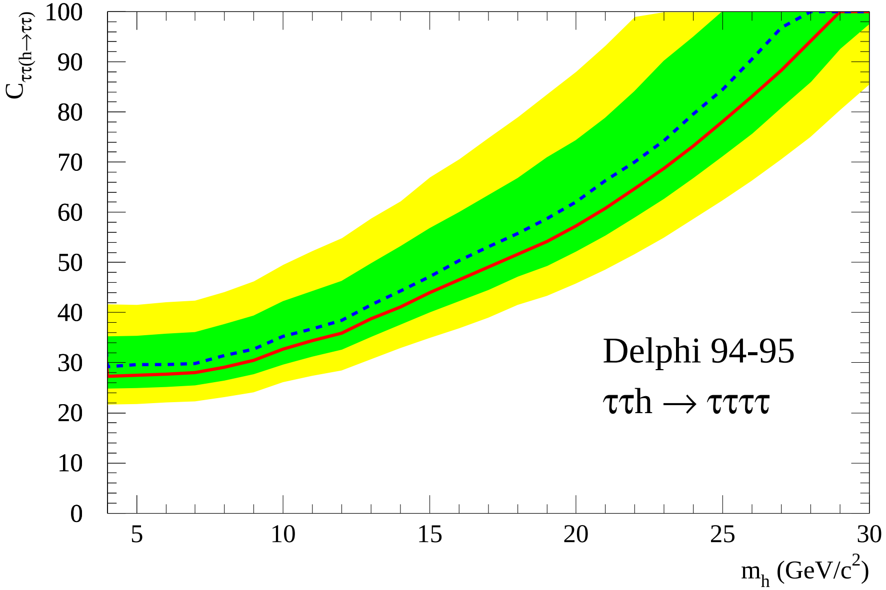
hZZ: $sin(\beta - \alpha)$ and hAZ: $cos(\beta - \alpha)$

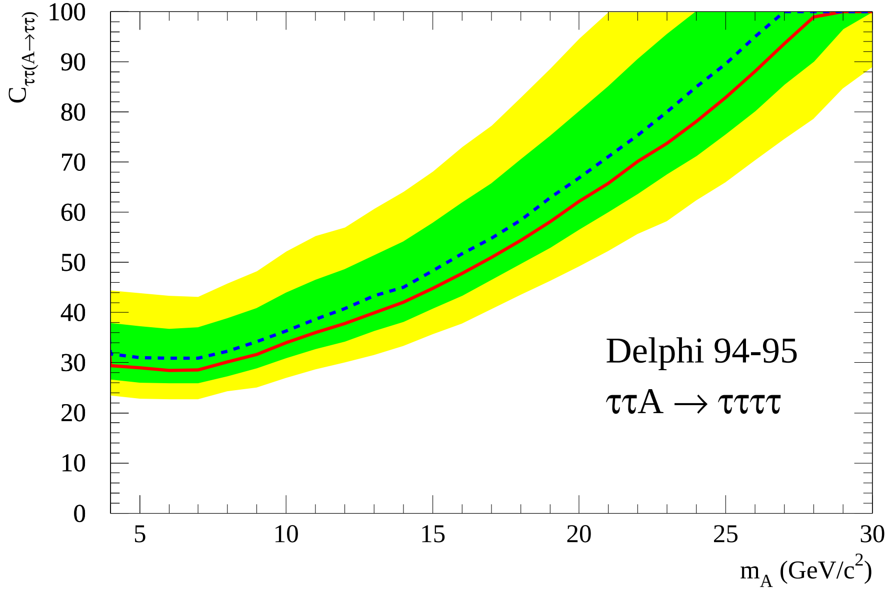




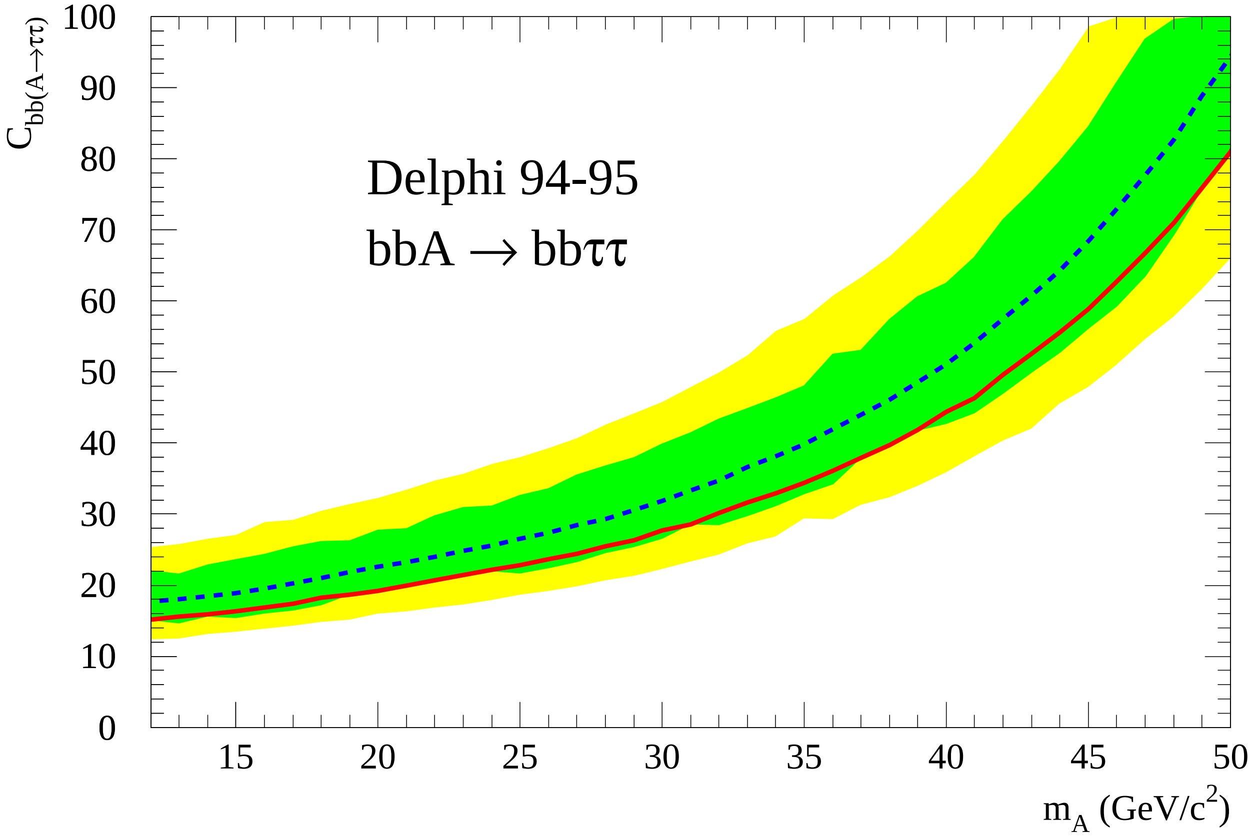
Light scalar $h \rightarrow$ small $k = sin^2(\beta - \alpha)$!

Yukawa couplings 2HDM (II) with CP conservation





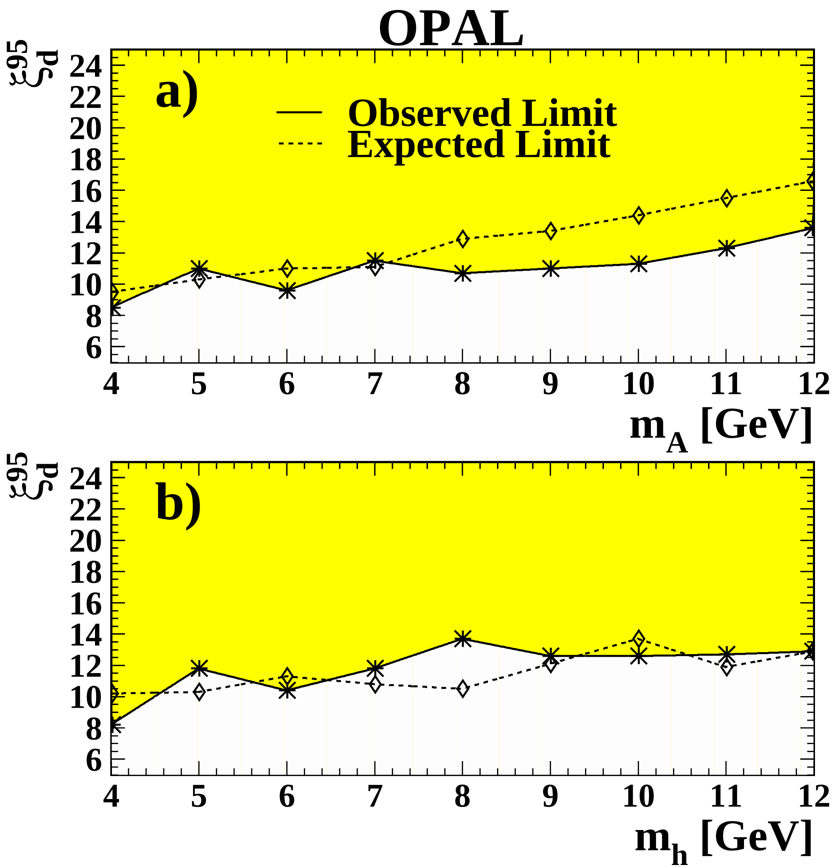
Upper (95%) limits for Yukawa couplings χ_d $(\tan\beta)$



Yukawa coupling ($\tan\beta$) up to 20 allowed (95%) for eg. M_A larger than 35 GeV!

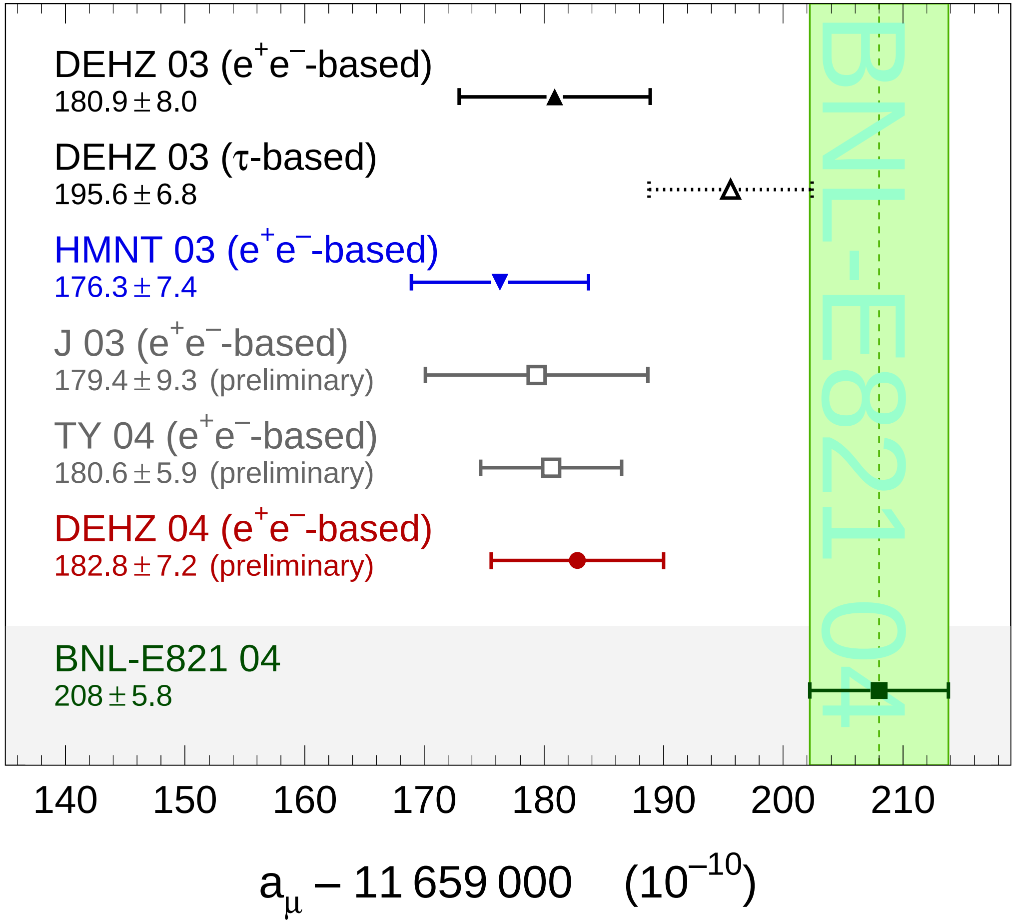
Yukawa coupling for very light h or A

Maximal allowed at 95% CL coupling to down-type quarks/leptons for very light h and A



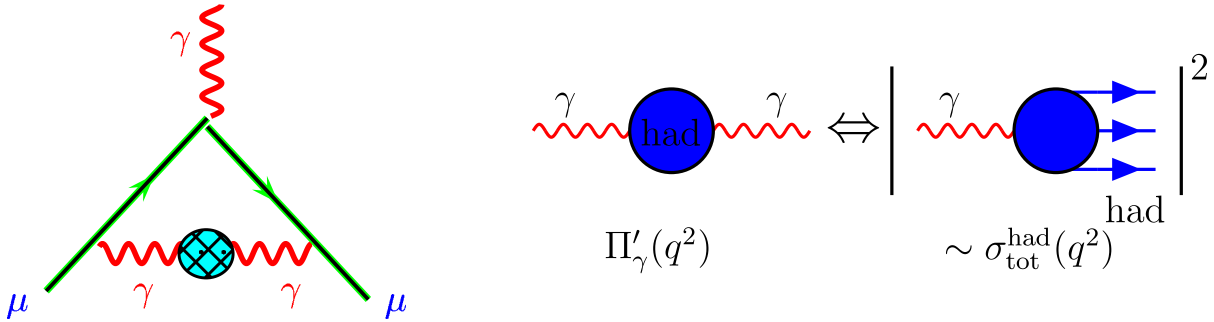
DATA and SM prediction for $g-2$ for muon $a_\mu \equiv \frac{(g-2)_\mu}{2}$

Summer 2004 Summary

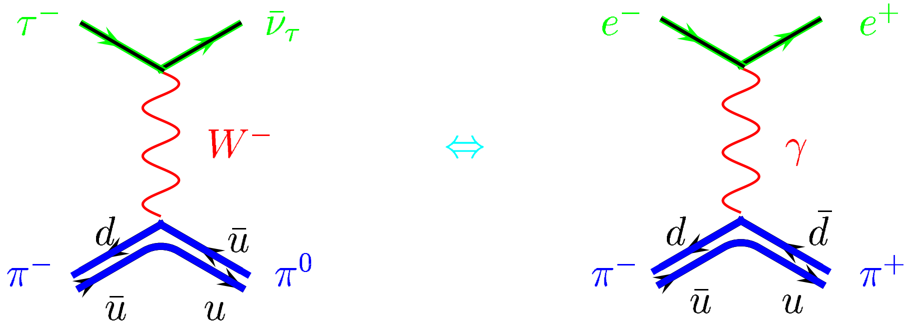


Average: $a_\mu(\text{exp}) = 11\,659\,208(6) \times 10^{-10}(0.5\,ppm)$

Hadronic contribution



Assuming isospin symmetry $\rightarrow$ using tau decay data



It does not work!

Fred Jegerlehner was right! Using e^+e^- is safer.

figs from F. Jegerlehner

SM and data

SM contribution		[in 10^{-11}]
QED	116 584 705.7	(2.9)
had[FJ02]	6 869.0	(70.7)
EW	152.0	(4.0)
tot	116 591 726.7	(70.9)
$\Delta a_\mu(\sigma)$		303.3 (106.9)
lim(95%)		$93.8 \leq \delta a_\mu \leq 512.8$

In hadronic part data for e^+e^- are used
- using hadronic tau decay problematic...

Jegerlehner, Talk at Marseille, March 2002
Hagiwara et al (hep-ph/0209187v2)
Davier et al (hep-ph/0208177)
Hocker (e^+e^- Oct. 2004) $\boxed{\Delta a_\mu(\sigma) = 252(92) \rightarrow 96.96 \leq \delta a_\mu \leq 505}$

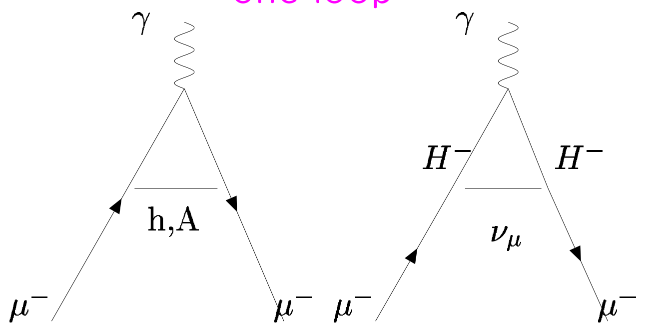
δa_μ (positive only) can be used to constrain parameters of models at 95% CL

2HDM contribution to a_μ: $a_\mu^{\text{2HDM}} = a_\mu^h + a_\mu^A + a_\mu^H + a_\mu^{H^\pm}$

•light h scenario : $a_\mu^{\text{2HDM}} \approx a_\mu^h$

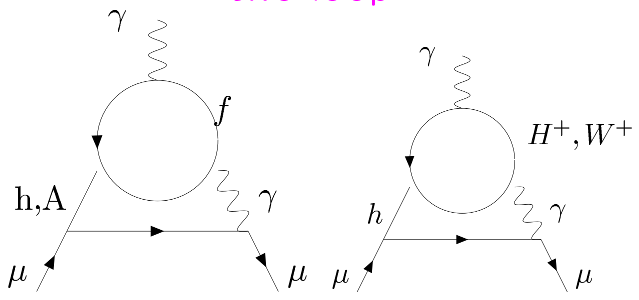
•light A scenario : $a_\mu^{\text{2HDM}} \approx a_\mu^A$

one loop



Zochowski,MK'96,MK'01;Dedes,Haber'01

two loop

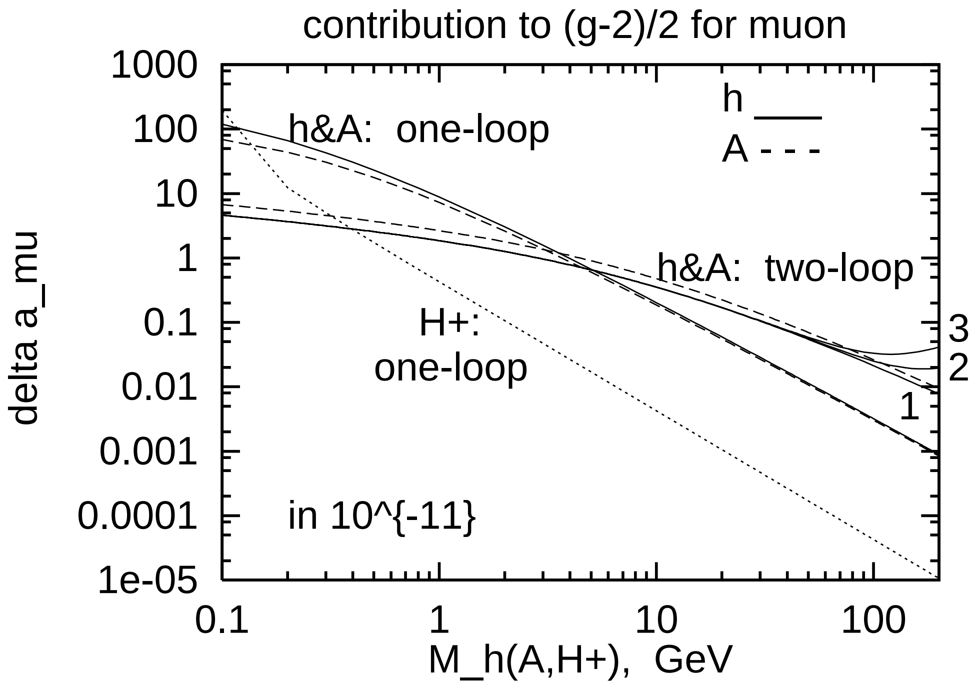


Chang at al.,Cheung at al, Wu,Zhou, MK'01,'02..

Two loop contributions larger than one-loop for mass ∼ few GeV!

MK, hep-ph/0103223v3
MK, hep-ph/0112112 Snowmass proc
MK, Acta Phys. Pol. B 33 (2002) 2621
(hep-ph/020807)

Various 2HDM(II) contributions for couplings = 1



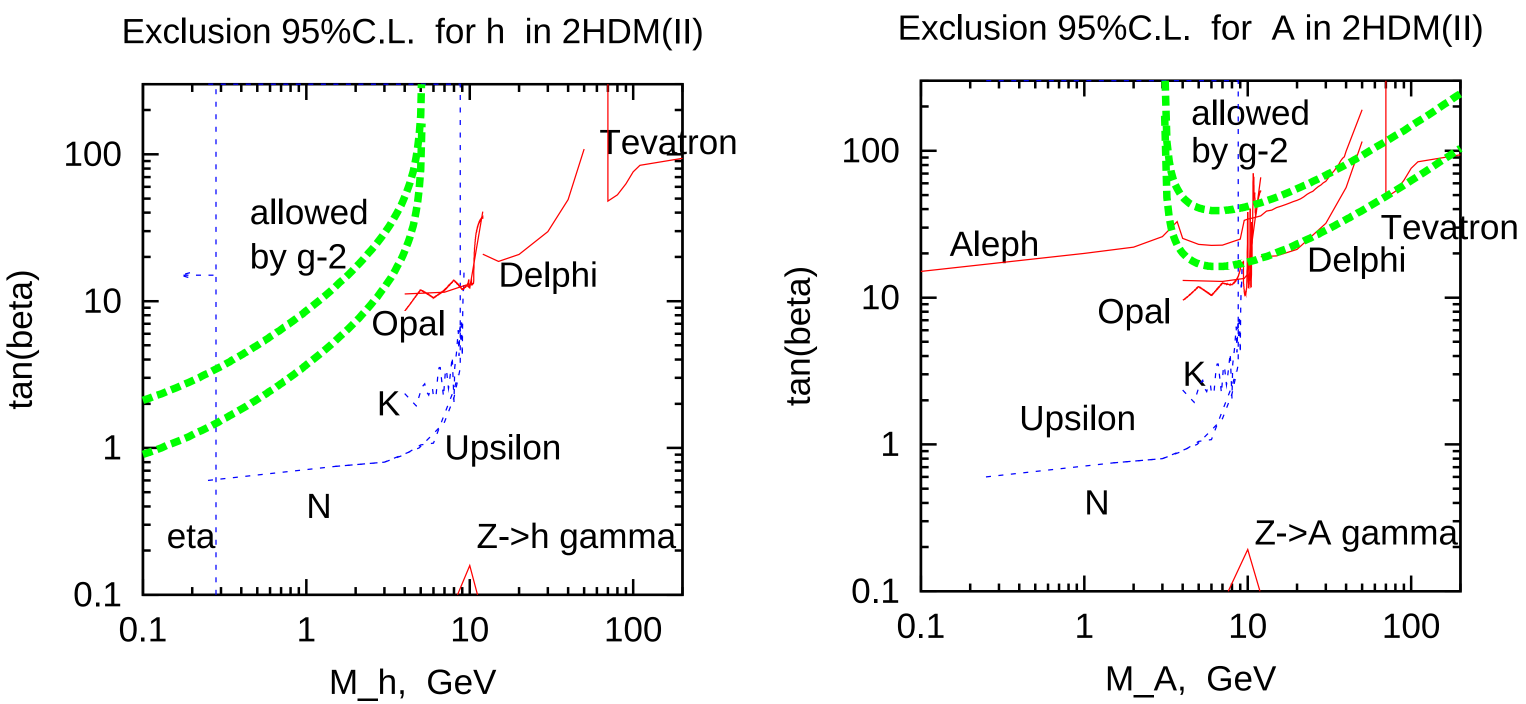
1–
no H^+
2–
$M_{H^\pm}$=800GeV
3–
$M_{H^\pm}$=400GeV

light A
contr. positive
for mass above 5 GeV

light h
contr. positive
for mass below 3 GeV
$\beta - \alpha = 0$, $\mu^2 = 0$

Combined 95% CL constraints for h and A in 2HDM(II) '2004

scalar h for $\beta - \alpha = 0$, $\mu^2 = 0$ — pseudoscalar A



thick lines : upper & lower limits from g-2

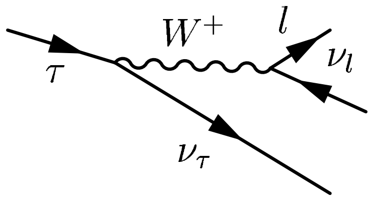
plus LEP data, etc

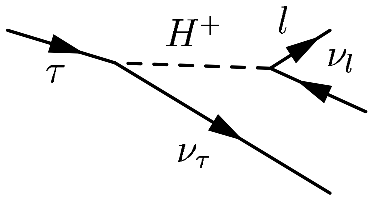
If all existing data are taken into account $\rightarrow$ allowed regions for A only

A with mass 25-70 GeV and $25 < \tan\beta < 115$ in agreement with data

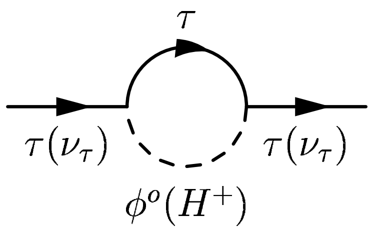
Leptonic tau decays

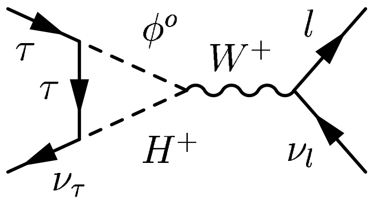
In SM - tree-level W exchange, in 2HDM: tree-level charged Higgs





In 2HDM loop corrections involve also neutral Higgs bosons $\rightarrow$ dominant contributions at large $\tan\beta$





The branching ratios for leptonic decays

- We consider

$$\tau \to e\bar{\nu}_e\nu_\tau \text{ and } \tau \to \mu\bar{\nu}_\mu\nu_\tau.$$

- The '04 world av. data for the leptonic τ decays and τ lifetime:

$$Br^e|_{exp} = (17.84 \pm 0.06)\%, \quad Br^\mu|_{exp} = (17.37 \pm 0.06)\%$$

$$\tau_\tau = (290.6 \pm 1.1) \times 10^{-15} s.$$

- The SM prediction defined as

$$Br^l|_{SM} = \frac{\Gamma^l|_{SM}}{\Gamma^{tot}_{exp}} = \Gamma^l|_{SM}\tau_\tau$$

- A possible beyond the SM contribution $\to \Delta^l$

$$Br^l = Br^l|_{SM}(1 + \Delta^l)$$

95% CL extra contributions

The lowest order of SM

$$Br^e|_{SM} = (17.80 \pm 0.07)\%, \;\; Br^\mu|_{SM} = (17.32 \pm 0.07)\%.$$

Together with the experimental data we get

$$\Delta^e = (0.20 \pm 0.51)\%, \quad \Delta^\mu = (0.26 \pm 0.52)\%.$$

95% C.L. bounds on Δ^l, for the electron and muon decay mode:

$$(-0.80 \leq \Delta^e \leq 1.21)\%, \quad (-0.76 \leq \Delta^\mu \leq 1.27)\%.$$

The negative contributions are constrained more strongly..

Partial widths or leptonic τ decays: SM vs 2HDM

SM at tree-level = the $W^{\pm}$ exchange (with leading order corrections to the W propagator, and dominant QED one-loop contributions)

2HDM extra tree contribution due to the exchange of H^{+}

$$\Gamma^{H^{\pm}}_{tree} = \Gamma_0 \left[\frac{m_\tau^2 m_l^2 \tan^4\beta}{4M^4_{H^\pm}} - 2\frac{m_l m_\tau \tan^2\beta}{M^2_{H^\pm}} \frac{m_l}{m_\tau} \kappa\left(\frac{m_l^2}{m_\tau^2}\right)\right],$$

where $\kappa(x) = \frac{g(x)}{f(x)}$, $g(x) = 1 + 9x - 9x^2 - x^3 + 6x(1+x)\ln(x)$.

The second term coming from the interference with the SM amplitude much more important

It gives negative contribution. $-m_l^2/M^2_{H^\pm}\tan\beta^2$

One loop contribution for large $\tan\beta$

$$\Delta_{oneloop} \approx \frac{G_F m_\tau^2}{8\sqrt{2}\pi^2} \tan^2\beta\, \tilde{\Delta}$$

$$\begin{aligned}\tilde{\Delta} = \quad & \left[- \left(\ln\left(\frac{M_{H+}^2}{m_\tau^2}\right) + F(R_{H^\pm}) \right) \right. \\ & + \frac{1}{2} \left(\ln\left(\frac{M_A^2}{m_\tau^2}\right) + F(R_A) \right) \\ & + \frac{1}{2} \cos^2(\beta - \alpha) \left(\ln\left(\frac{M_h^2}{m_\tau^2}\right) + F(R_h) \right) \\ & \left. + \frac{1}{2} \sin^2(\beta - \alpha) \left(\ln\left(\frac{M_H^2}{m_\tau^2}\right) + F(R_H) \right) \right], \qquad (1)\end{aligned}$$

where $R_\phi \equiv M_\phi / M_{H^\pm}$ and $F(R) = -1 + 2\, R^2 \ln R^2/(1 - R^2)$

NOTE, $\tilde{\Delta}$ does not depend on m_τ!

Loop corrections the same for e and μ channels

The exact and approximated expressions can not be distinguished

Loop corrections for some scenarios

Interesting scenarios:

• light h and $\sin^2(\beta-\alpha)=0$, $\rightarrow \tilde{\Delta}$ does not depend on M_H:

$$M_A = M_{H^\pm} \rightarrow \tilde{\Delta} = \ln\frac{M_h}{M_{H^\pm}} + 1 \text{ or } M_A \ll M_{H^\pm} \rightarrow \tilde{\Delta} = \ln\frac{M_h}{M_{H^\pm}} + \ln\frac{M_A}{M_{H^\pm}} + 2.$$

h does not couple to gauge bosons and the Higgsstrahlung process at LEP is not sensitive to such Higgs boson, while the leptonic tau decays have maximal sensitivity to h!

• For arbitrary $\sin(\beta-\alpha)$ and degenerate $H, A, H^\pm$ (with mass M):

$$\tilde{\Delta} = \cos^2(\beta-\alpha)\ [\ln\frac{M_h}{M} + 1].$$

Large effects for large mass splitting - watch data for ρ !

• SM-like scenario, with light h, $\sin^2(\beta-\alpha)=1$ and very heavy degenerate additional Higgs bosons, $\tilde{\Delta} \rightarrow 0$.

Mass charged Higgs boson

If the tree level H^+ exchange only (as in PDG04, Dova98, Stahl'97..): we obtain the 95% CL deviation from the SM prediction

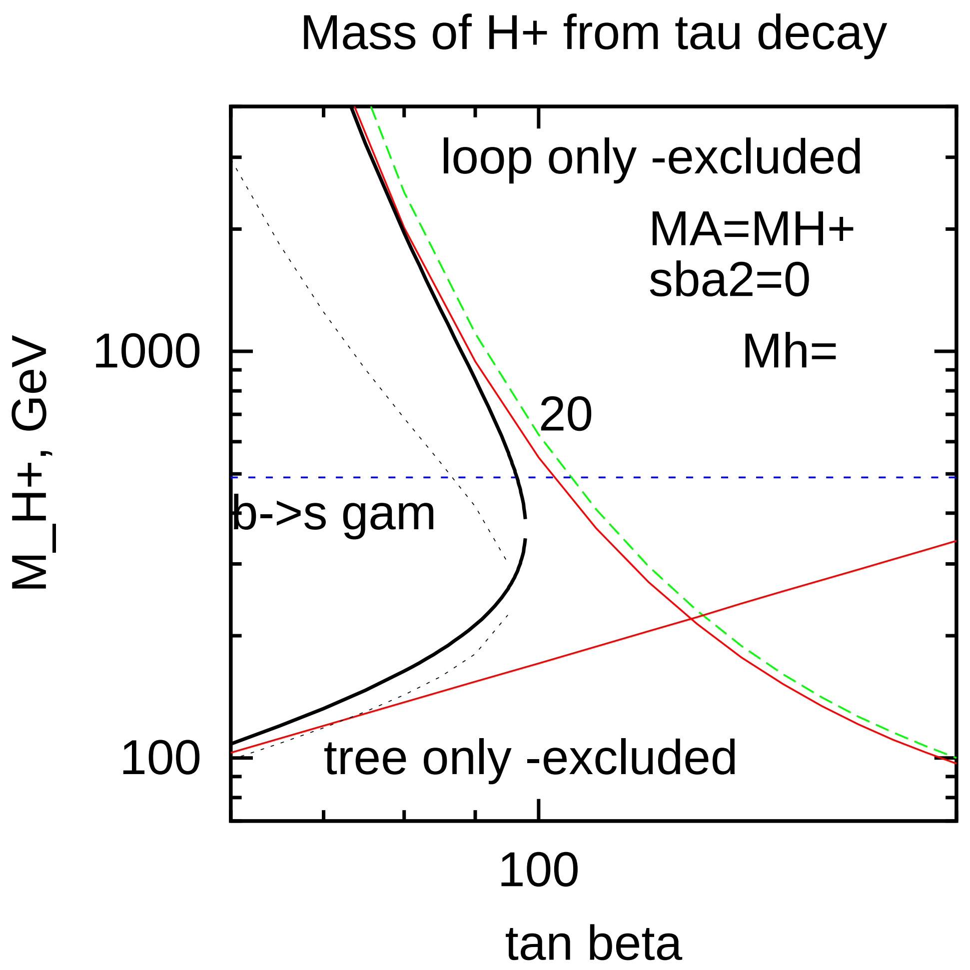
$$M_{H^\pm} \gtrsim 1.71 \tan\beta \;\; \text{GeV}$$

coefficient to be compared to 1.86 (1.4) from Dova at al (Stahl)

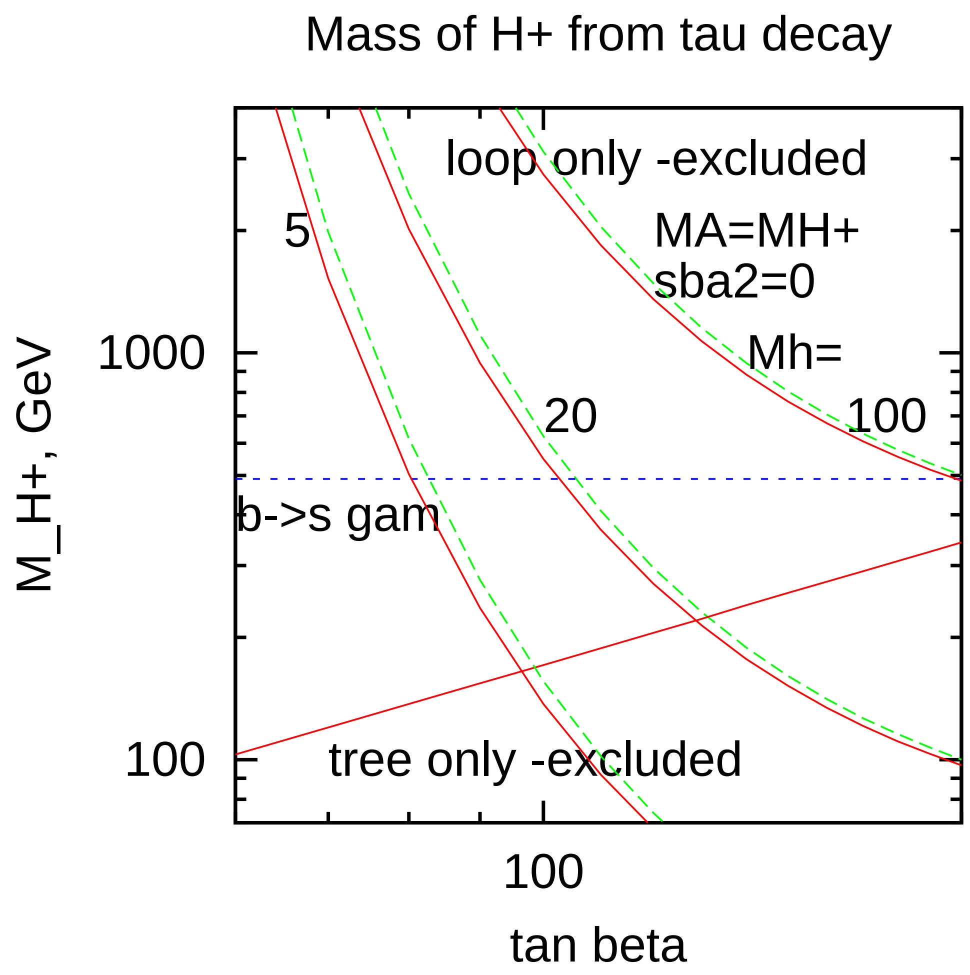
(the Michel parameter η in the 2HDM (II))

However loop effects large...

Limits for mass of H^+: One-loop and tree contr.



dotted: $M_A = 100$ GeV; μ (red), e (green)

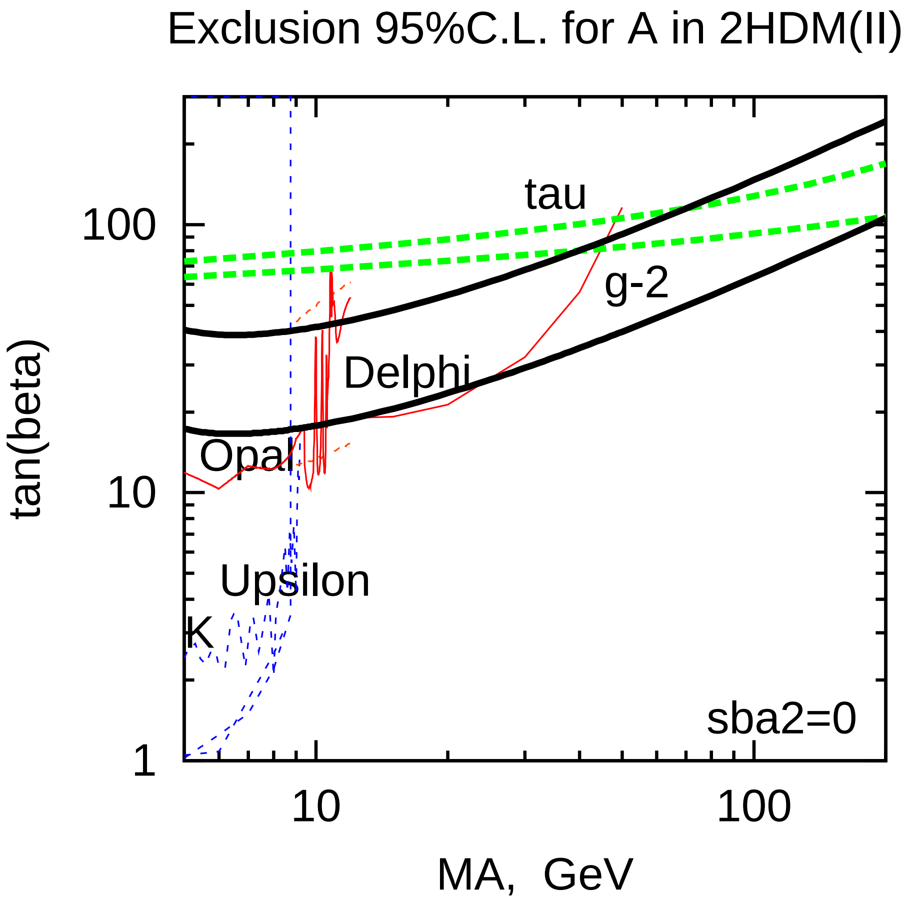


The upper limits:

for $M_h = 5, 20, 100$ GeV and $\sin^2(\beta - \alpha) = 0$, assuming $M_A = M_H^+$

Combining limits for A

Upper limits for $\tan\beta$ from the leptonic τ decay (degenerate masses of h, H, H^+) and the allowed region from the newest $g-2$ for muon data



1/4 TeV (upper/lower green line)

Conclusion

•The one-loop contributions to the branching ratios for leptonic τ decays are calculated in the CP conserving 2HDM(II) at large $\tan\beta$ - agreement with previous results by Guth & Kuhn, Rosiek, Chankowski et al, extension of Hollik & Sack.

•One-loop contributions, involving both neutral and charged Higgs bosons, dominate over the tree-level $H^{\pm}$ exchange
(the latter one being totally negligible for e).

•We show that the leptonic branching ratios of τ are complementary to the Higgsstrahlung processes for $h(H)$

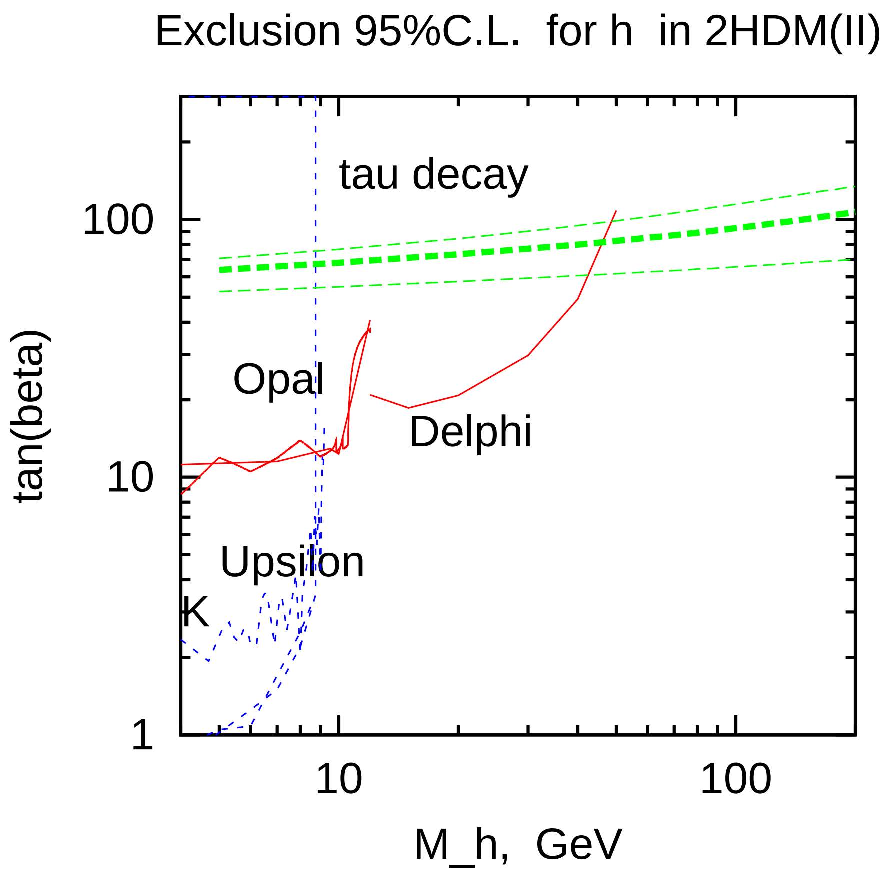
•We got upper limits on Yukawa couplings for both light h and light A scenarios

•New lower limit on mass of $M_{H^{\pm}}$ as a function of $\tan\beta$, which differs significantly from what was considered as standard constraint (based on the tree-level $H^{\pm}$ exchange only)

•We obtain also a upper limit on $M_{H^{\pm}}$!

Constraints for h and A

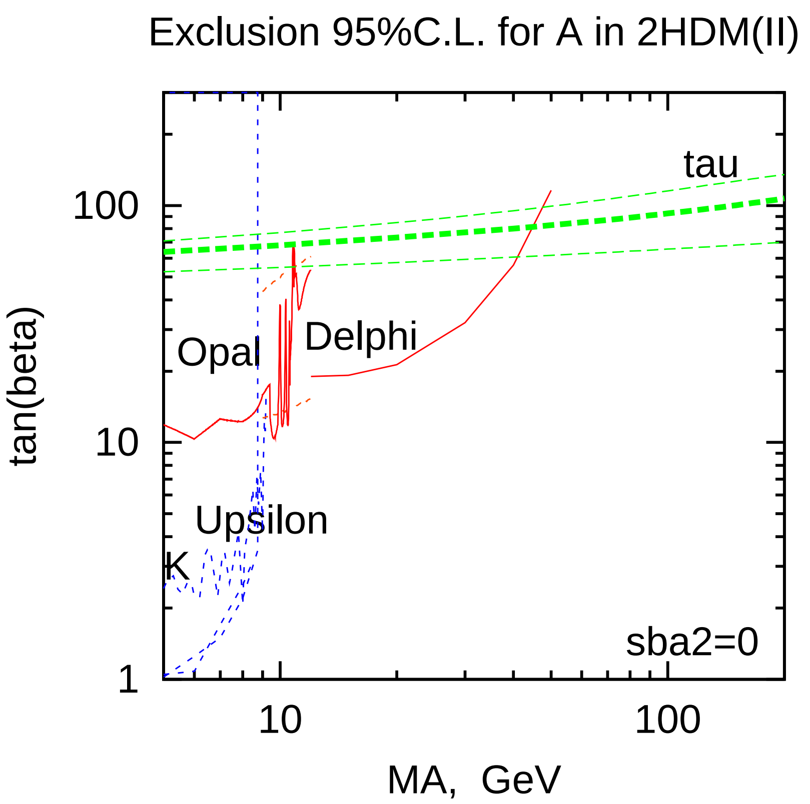
We also derive constraits for neutral Higgs bosons. For light h:



$\sin(\beta - \alpha) = 0$, $M_A = 100$ GeV, $M_{H^\pm} = 500$ GeV and 4 TeV, upper and lower green lines; degenerate A and H^+ (mass 4 TeV) -thick green line

Constraints for pseudoscalar A

Upper limits for Yukawa coupling ($\tan\beta$) for light A



Limits from tau decay:
$M_h = 100$ GeV, $M_{H^\pm} = 500$ GeV and 4 TeV, upper and lower green line
The degenerate h and $H^\pm$ with mass 4 TeV - thick green line