Tauola meeting 2012
Kraków, 15.05. 2012

Leptonic tau decay in 2HDM (II)

- 2HDMs
- Non-decoupling
- ggh and gam gam h
- Constraints on H+

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Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

SU(2) x U(1) → ?

Two Higgs Doublet Models

Two doublets of SU(2) (Y=1, ρ =1) - Φ_1 , Φ_2

Masses for $W^{+/-}$, Z (ρ =1), no mass for photon?

Fermion masses via Yukawa interaction –

various models – Model I, II, III, IV...

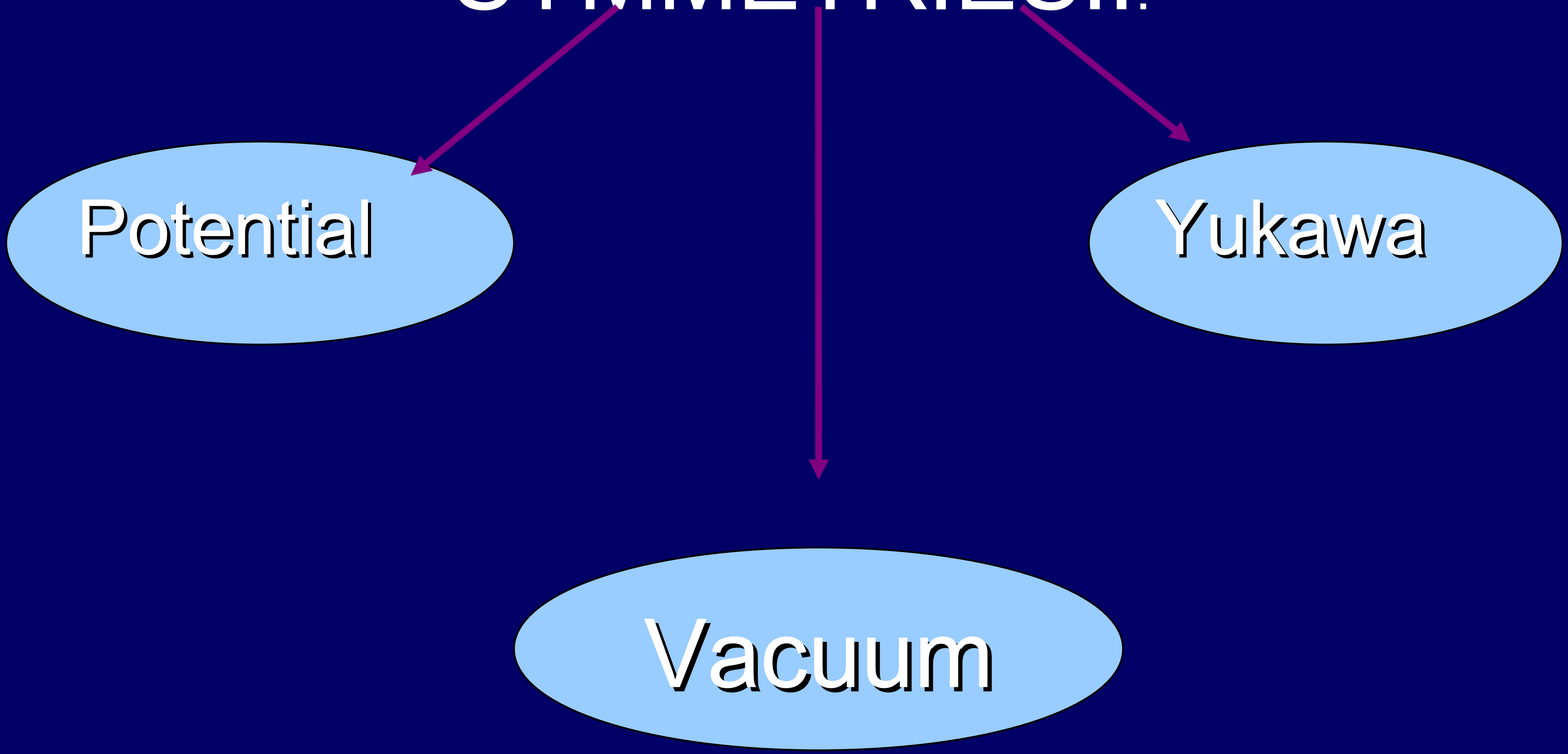
5 scalars: H+ and H- and neutrals:

- CP conservation: CP-even h, H & CP-odd A
- CP violation: h_1,h_2,h_3 with undefinite CP parity*

Sum rules (relative couplings to SM χ)

2HDMs

SYMMETRIES!!!



2HDM Potential (Lee'73)

$$V = \lambda_1(\Phi_1^\dagger\Phi_1)^2+\lambda_2(\Phi_2^\dagger\Phi_2)^2+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)+ [\lambda_5(\Phi_1^\dagger\Phi_2)^2+h.c]$$

$$+ [(\lambda_6(\Phi_1^\dagger\Phi_1)+\lambda_7(\Phi_2^\dagger\Phi_2))(\Phi_1^\dagger\Phi_2)+h.c]$$

$$-m^2_{11}(\Phi_1^\dagger\Phi_1)-m^2_{22}(\Phi_2^\dagger\Phi_2)-[m^2_{12}(\Phi_1^\dagger\Phi_2)+h.c.]$$

Z_2 symmetry transformation: $\Phi_1\rightarrow\Phi_1$ $\Phi_2\rightarrow -\Phi_2$

Hard Z_2 symmetry violation: λ_6, λ_7 terms

Soft Z_2 symmetry violation: m^2_{12} term (Re $m^2_{12}=\mu^2$)

Explicit Z_2 symmetry in V: $\lambda_6, \lambda_7, m^2_{12}=0$

Z_2 symmetry: $\Phi_1 \to \Phi_1 \quad \Phi_2 \to -\Phi_2$

- Explicit Z_2 symmetry <u>in the Lagrangian L</u> $\to$
  no CP violation in the scalar sector *Branco, Rebelo*
- Softly broken $Z_2 \to$ *Weinberg,Paschos*
  CP violation possible, tree-level FCNC absent,decoupling
- Hard breaking $Z_2 \to$
  CP violation possible, even without CP mixing (*)
  tree-level FCNC danger

Ma'78

Today ?

Z_2 symmetry both <u>in L and in vacuum</u> – Inert Model

$\to$ Φ_1 as in SM, with Higgs boson h SM-like

$\to$ Φ_2 - <u>no vev</u>, with 4 scalars (no Higgs bosons!) no interaction with fermions (inert doublet)

$\to$ The lightest scalar -candidate for a dark matter.

Conserved Z_2- parity, only Φ_2 has Z_2-odd parity.

Possible vacuum states
(real parameters in V)

The most general vacuum state

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}v_1 \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} u \\ \frac{1}{\sqrt{2}}v_2 e^{i\xi} \end{pmatrix}$$

with v_1, v_2, u , ξ - real, positive

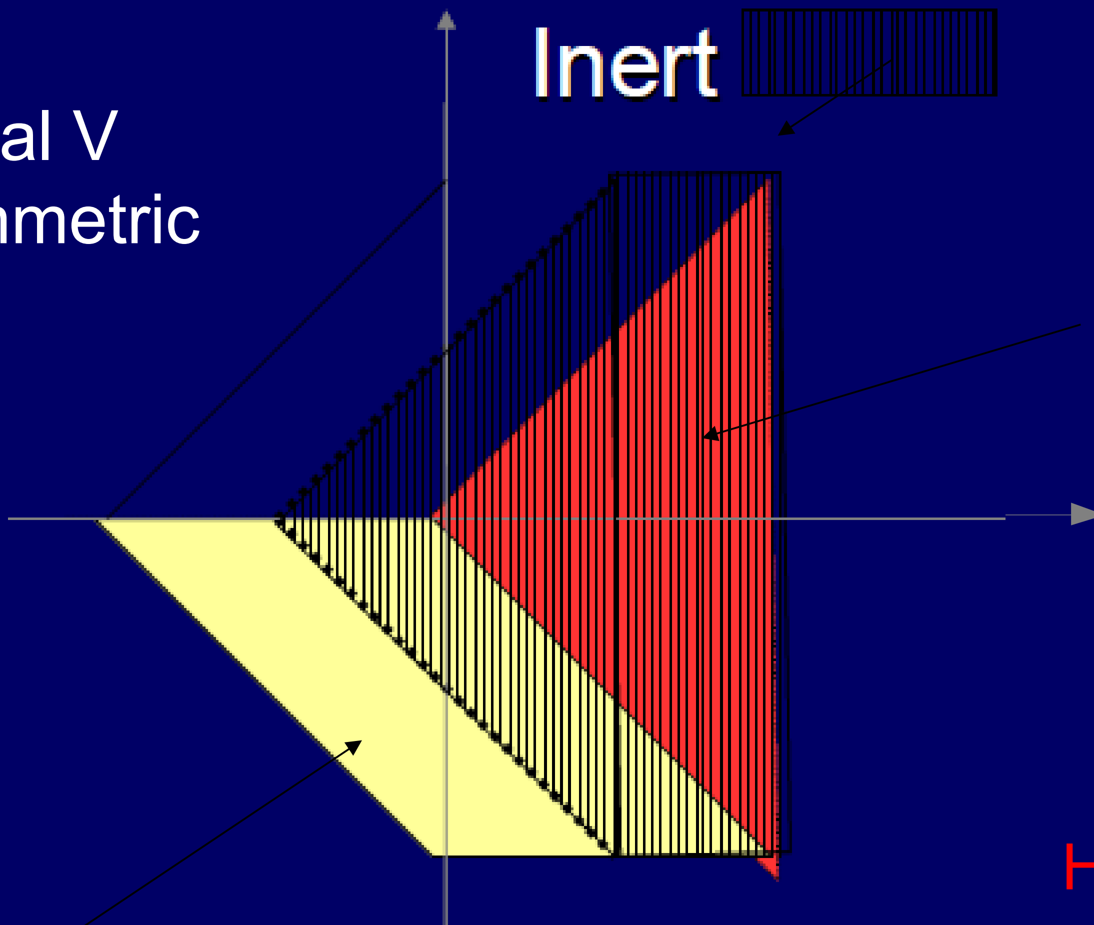
the Inert vacuum $u = v_2 = 0, v = v_1$

the CP conserving CPc $u = \xi = 0$

the Charge Breaking ChB $v_2 = \xi = 0$

Various vacua on $\lambda_5 \times \lambda_4$ plane

Potential V
Z2 symmetric



Charge
Breaking
ChB

Here $\sqrt{\lambda_1 \lambda_2} - \lambda_3 > 0$

CP conserving – CPc

Yukawa interactions
(with or without Z_2 symmetry)

Model I - only Φ_1 interacts with fermions

Model II - Φ_1 with down-type fermions d

Φ_2 with up-type fermions u

Model III - both doublets interact with fermions

Model IV - leptons interacts with one doublet, quarks with other

Top 2HDM – top with one doublet

+ Extra dim 2HDM models

Relative couplings (respect SM)

For neutral Higgs particles h_i , i = 1,2,3

$$\chi_j^{(i)} = \frac{g_j^{(i)}}{g_j^{SM}} \quad j = V, u, d$$

there are relations among couplings, eg.

$$\Sigma_i (\chi_j^{(i)})^2 = 1, \text{ for } j = V, u, d$$

So, if one neutral Higgs boson has SM-like coupling χ=1 - others have vanishing couplings

Existing constraints for 2HDM (II) with CP conservation

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: $M_h, M_H, M_A, M_{H^\pm}$, $\alpha, \tan\beta$, and μ^2

MODEL II (as in MSSM)

Couplings (relative to SM):	h	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 $\tan\beta \to -\tan\beta$.

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

•$\chi^h_{VH+} = \cos(\beta-\alpha)$ - complementarity to hVV!

Decoupling and non-decoupling (or SM-like h)

Decoupling property and masses of heavy Higgs bosons depend on μ^2 ($\nu = \text{Re}\, m_{12}^2/2v_1v_2$), since

- $M_{H^\pm}^2 = v^2[\nu - \frac{1}{2}\text{Re}(\lambda_4 + \lambda_5 + \lambda_{67})]$, $M_A^2 = v^2[\nu - \text{Re}\,\lambda_5]$

- small $\nu \to$ non-decoupling observed

eg. h SM-like (tree) with deviation from SM for loop couplings due to heavy Higgs particles; unitarity constraints (for λ_i) crucial if heavy Higgs bosons exist and ν is small

- large $\nu \to$ decoupling, h SM-like (tree and loop couplings)

Can be tested eg. in hH^+H^- coupling

Also in corrections to hhh - Kanemura...

Signal of a SM-like h (LHC)

- Scalar h – mass region as allowed for H_{SM}

– direct couplings as for H_{SM}

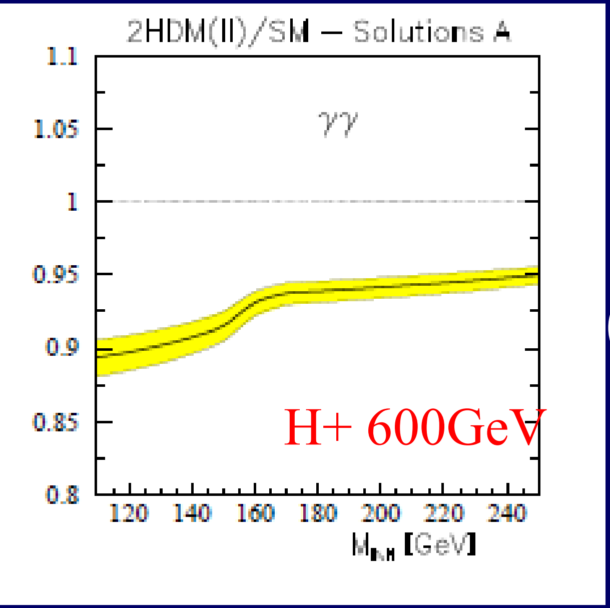
(within exp. accuracy) $\chi = 1$;

in practice $|\chi| = 1$, sign may differ.

So, loop coupling ggh and $\gamma\gamma$ h

may differ from the SM prediction

(also other contributions possible)



Note: both h and H can be SM-like !

– no other Higgs particle seen

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) $\Upsilon \to h/A\gamma$ $\to$ upper limits for χ_d

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

leptonic tau decay $\to$ $\to$ lower & upper limit for $M_{H^\pm}$

g-2 data , $\to$ allowed bound for χ_d

B $\to$ tau nu, D $\to$ tau nu $\to$ lower limit on mass H+

Global fit (2HDM) • (all Higgses)

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

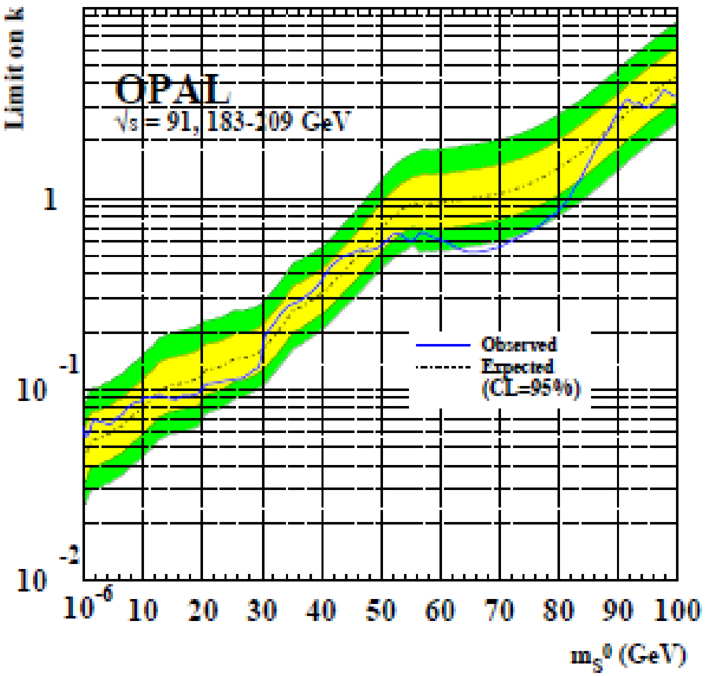
Cheung and Kong '03 Akesson et al...

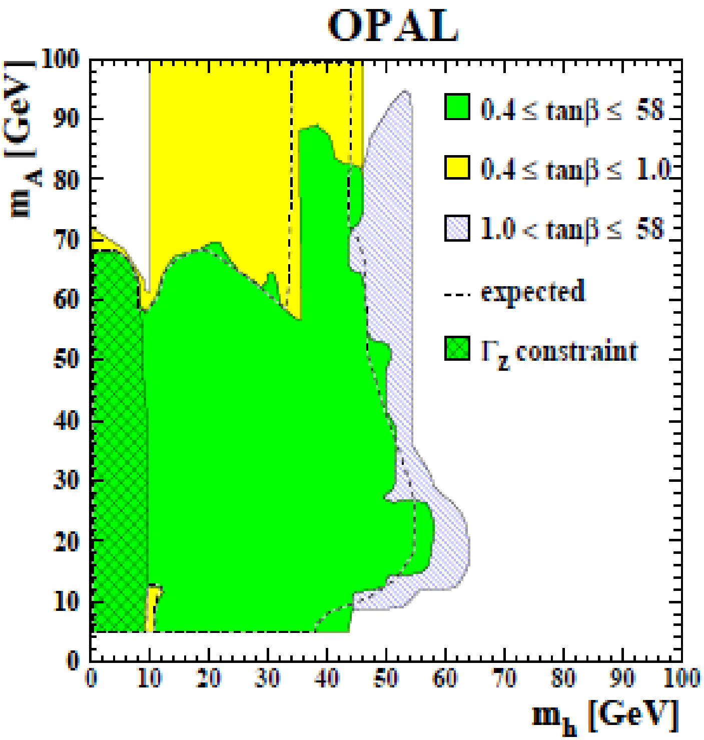
Neutral Higgs bosons - couplings to gauge boson, and mass exclusion

LEP: 2HDM with Z2 symmetry

Light h OR light A in agreement with current data

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

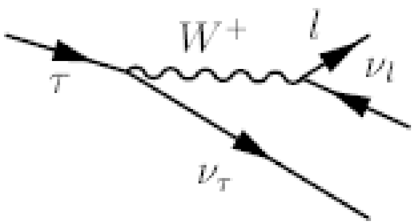




Light scalar $h \rightarrow$ small $k = sin^2(\beta-\alpha)$!

The τ lepton

A unique laboratory to test the Standard Model and beyond



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

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

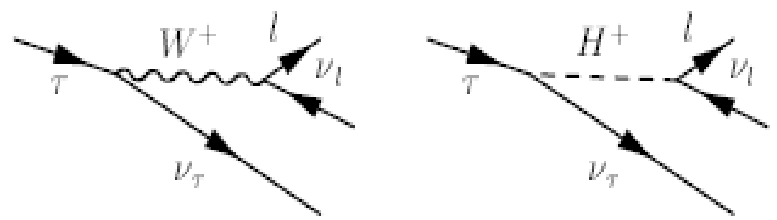
- Radiative corrections in 2HDM –Rosiek '90
- A τ puzzle '92: Data on leptonic branching ratio too low by 2.5σ than expected in SM

$\rightarrow$ "Tau decay in the two Higgs doublet model": Guth, Hoang, Kuhn '92
$\rightarrow$ "Can a second Higgs doublet diminish the leptonic tau decay width?" Hollik, Sack '92,

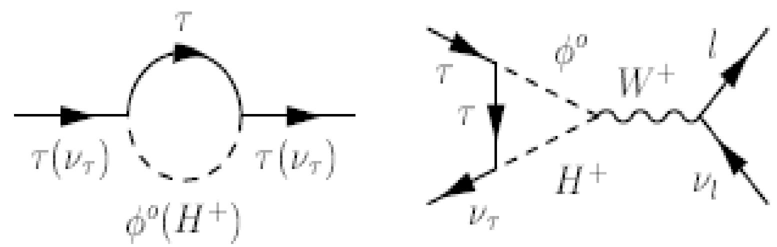
- Precise data in agreement with SM - can be used to constrain 2HDM

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 $\tan\beta$ ($\phi^0 = h, H, A$) - with D. Temes EPJC 2005



The branching ratios for leptonic decays

D. Temes, MK 2005

Eur.Phys.J. C44 (2005) 435

- 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:

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

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

Babar2010

$$(17.46 \pm 0.03 \pm 0.08)\%$$
$$(17.82 \pm 0.05)\%$$

- 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 tau 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 - from the interference with the SM - much more important. It gives negative contribution to Br:

$$-m_l^2/M^2_{H^\pm} \tan\beta^2$$

One loop contribution for large $\tan\beta$

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

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

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 are the same for e and μ channels

The exact and approximated expressions can not be distinguished

Loop corrections for some scenarios

Interesting scenarios: $\sin^2(\beta-\alpha)$=0,any,1

- 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. The leptonic tau decays have maximal sensitivity to h!

- For arbitrary $\sin^2(\beta-\alpha)$ and degenerate $H, A, H^\pm$ (with mass M):

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

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

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))

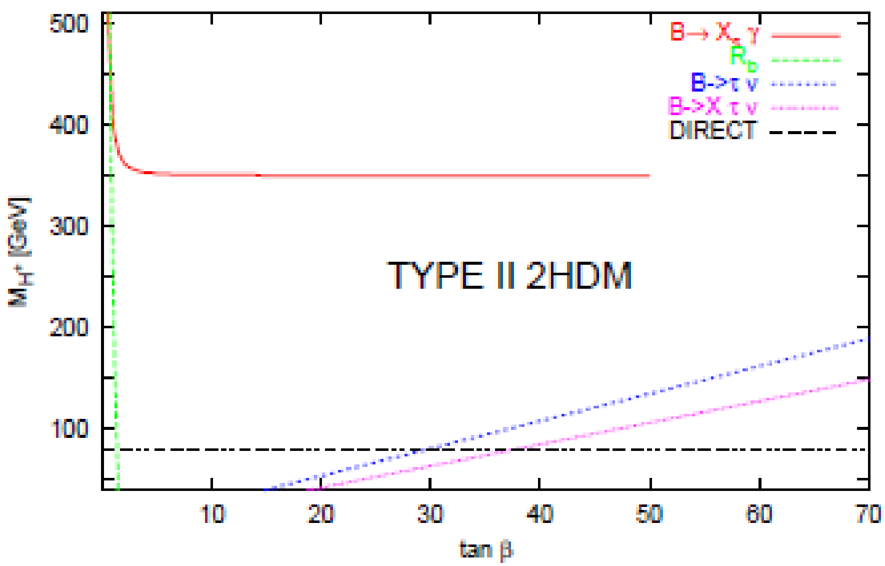
However loop effects large...

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 $\mathrm{BR}_\gamma \equiv \mathrm{BR}[\bar{B} \to X_s\gamma]$

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

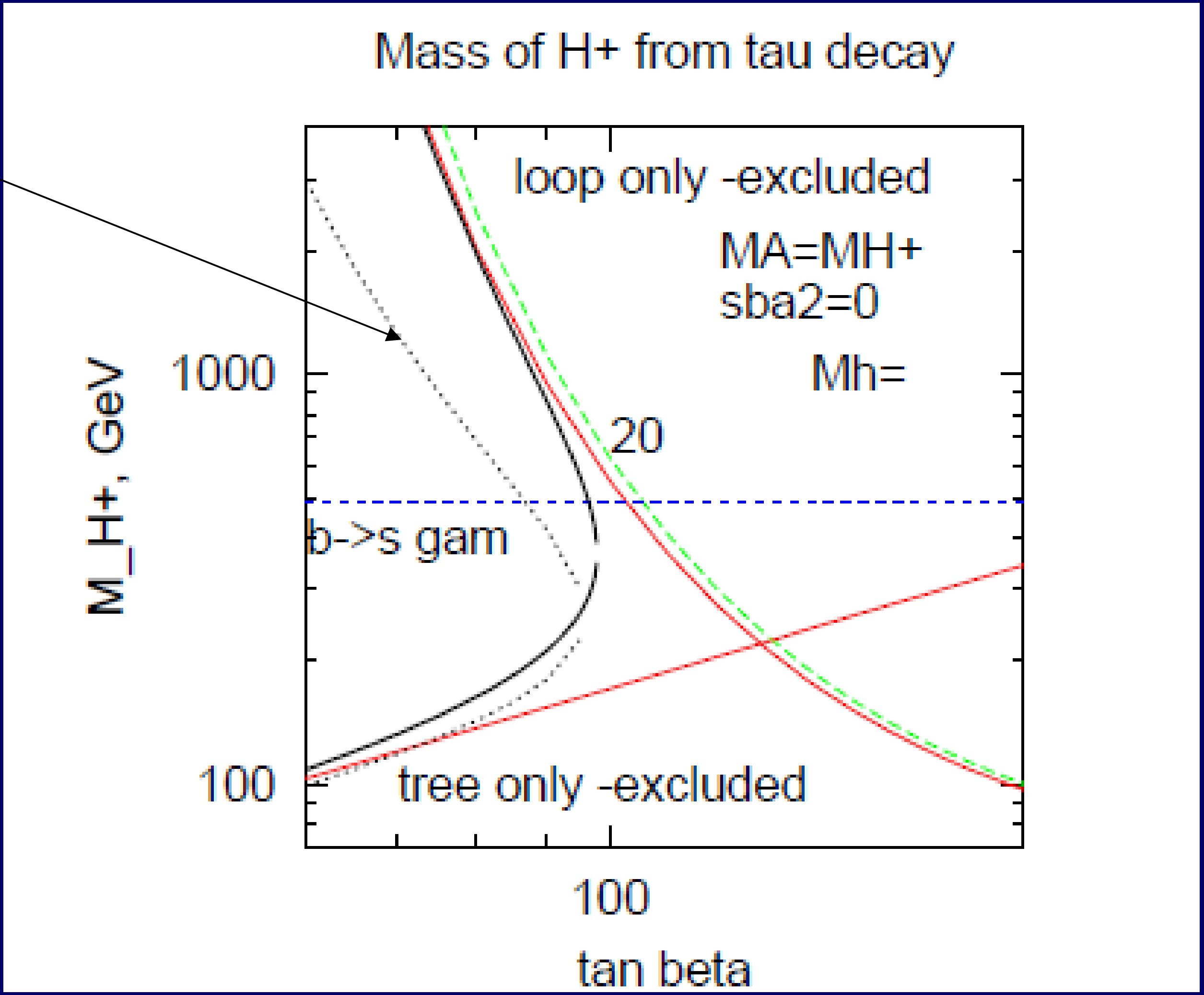
NLO prediction (Misiak, Gambino'01): M_{H+} above 490 GeV (95%)



Here mass limit 350 GeV corresponds to 99 % CL !

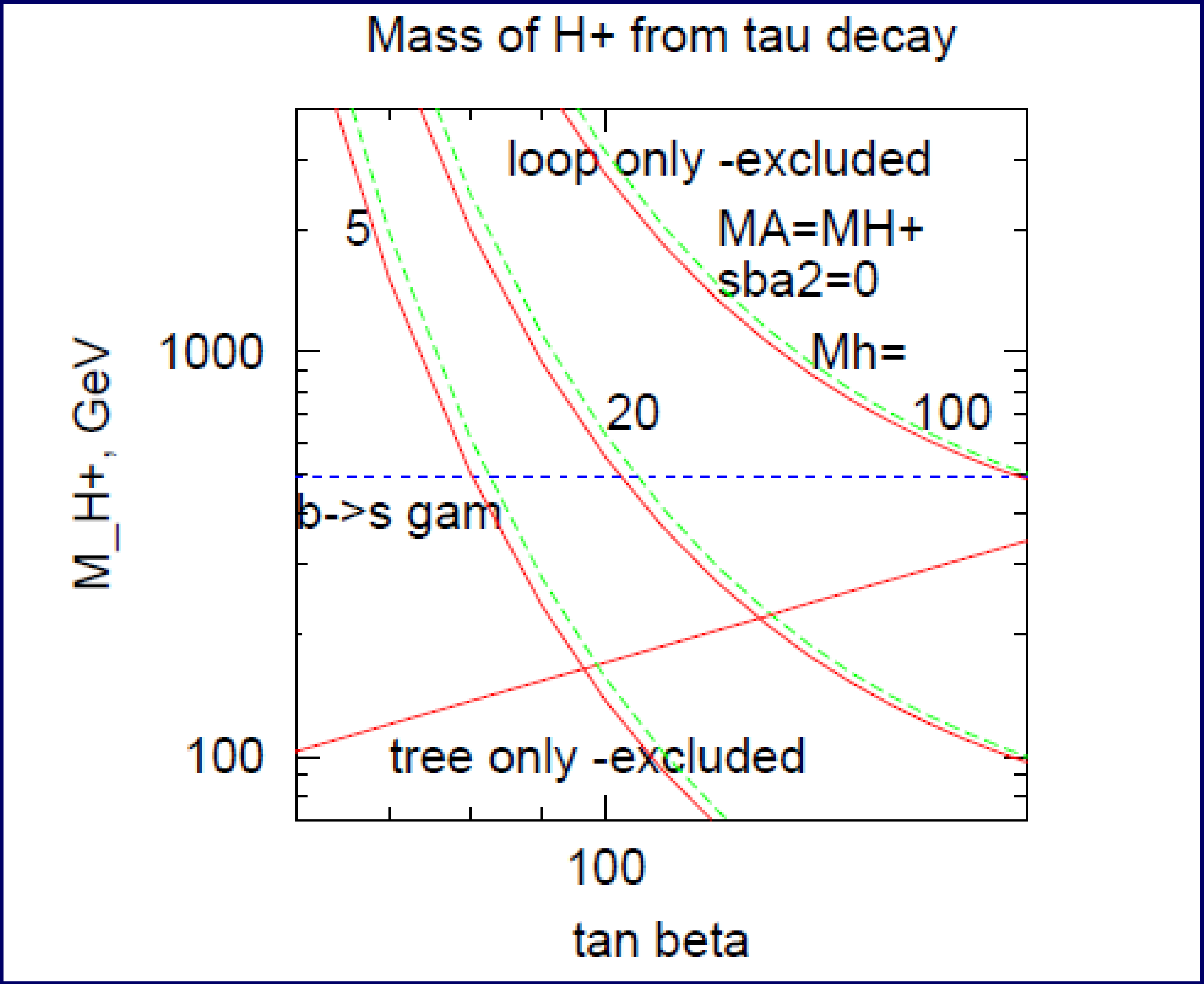
Constraints

MA = 100 GeV



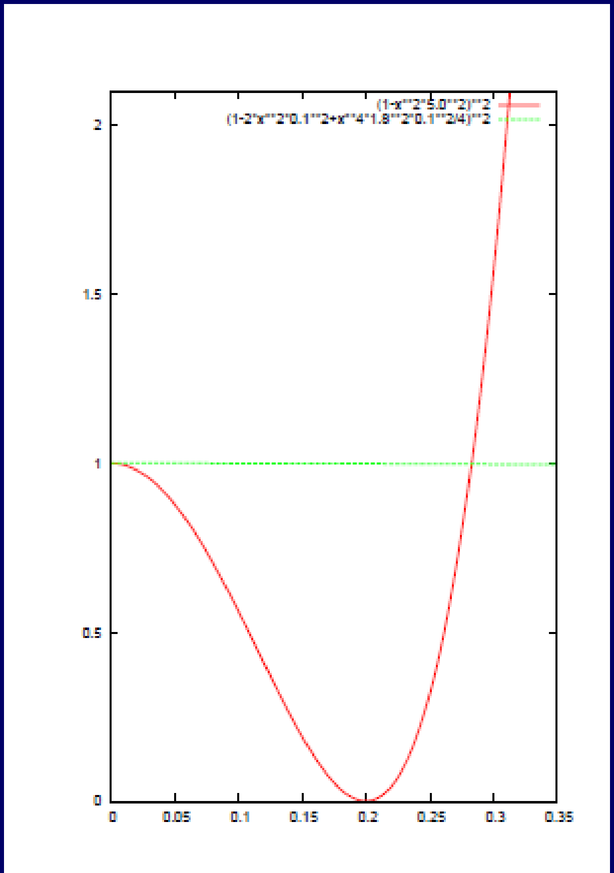
μ (red), e (green)

sin(beta-alpha)=0

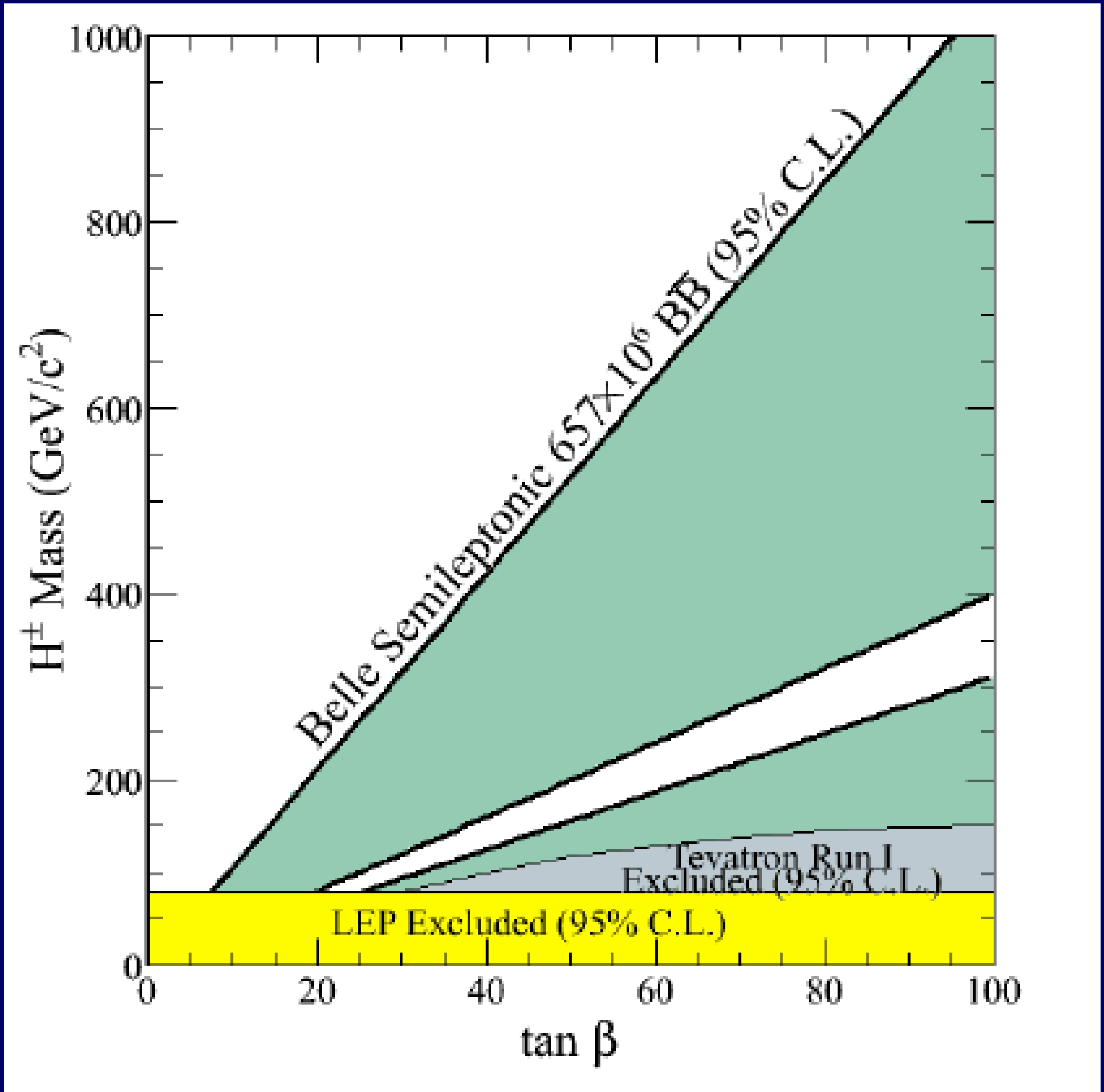


The upper limits:
for $M_h = 5, 20, 100$ GeV and $\sin^2(\beta - \alpha) = 0$, assuming $M_A = M_H^+$

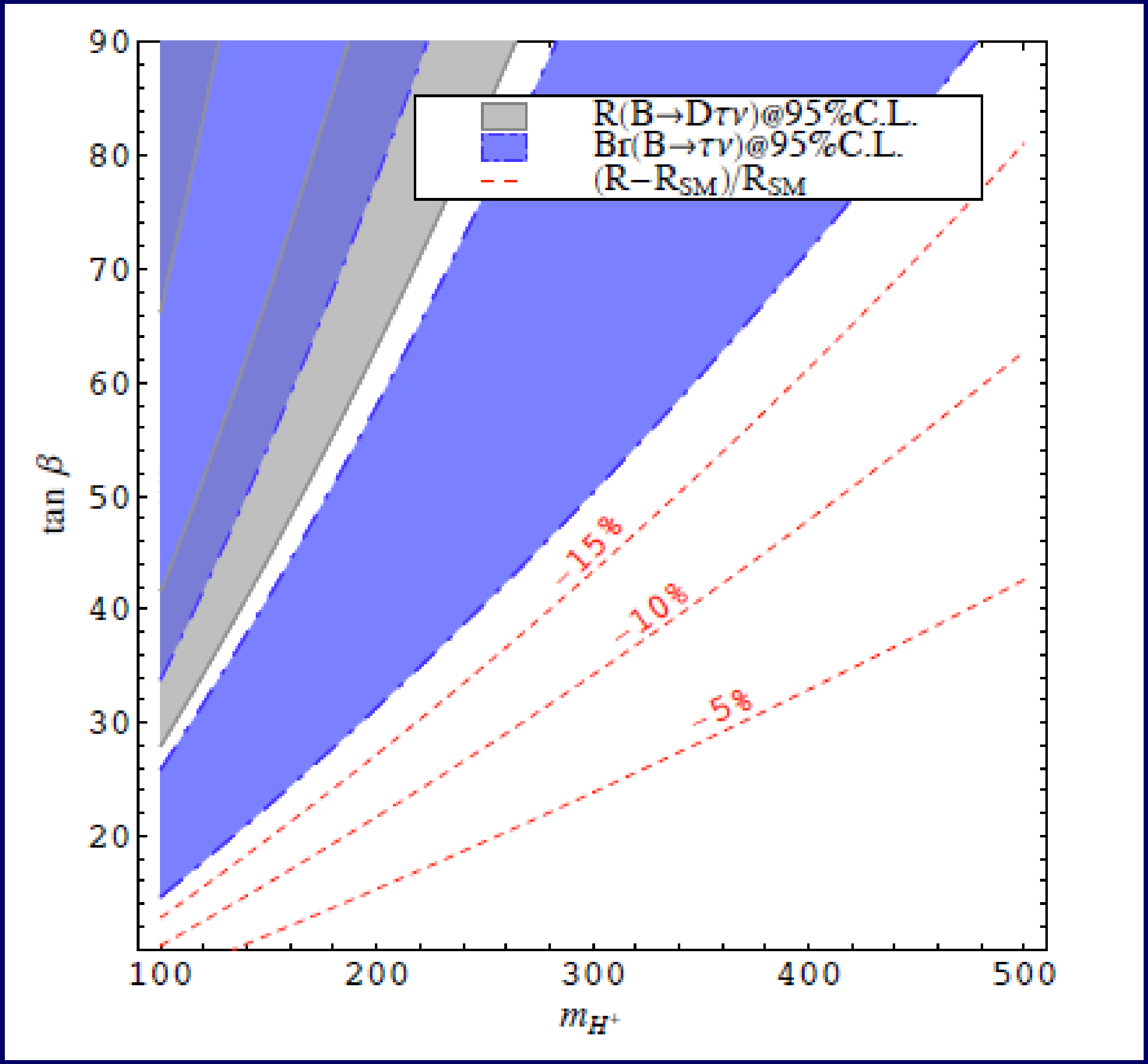
B to tau nu



(1-x**2*5.0**2)**2
(1-2*x**2*0.1**2+x**4*1.8**2*0.1**2/4)**2
0
0.5
1
1.5
2
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35



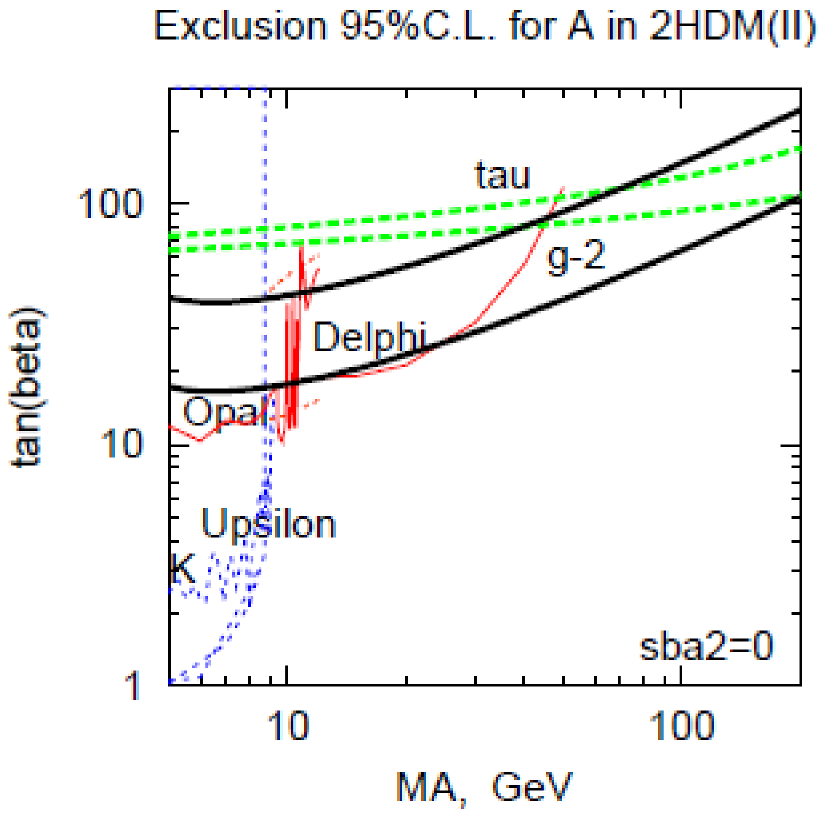
Belle Semileptonic 657×10^6 BB̄ (95% C.L.)
Tevatron Run I
Excluded (95% C.L.)
LEP Excluded (95% C.L.)
H± Mass (GeV/c²)
tan β
0
200
400
600
800
1000
0
20
40
60
80
100



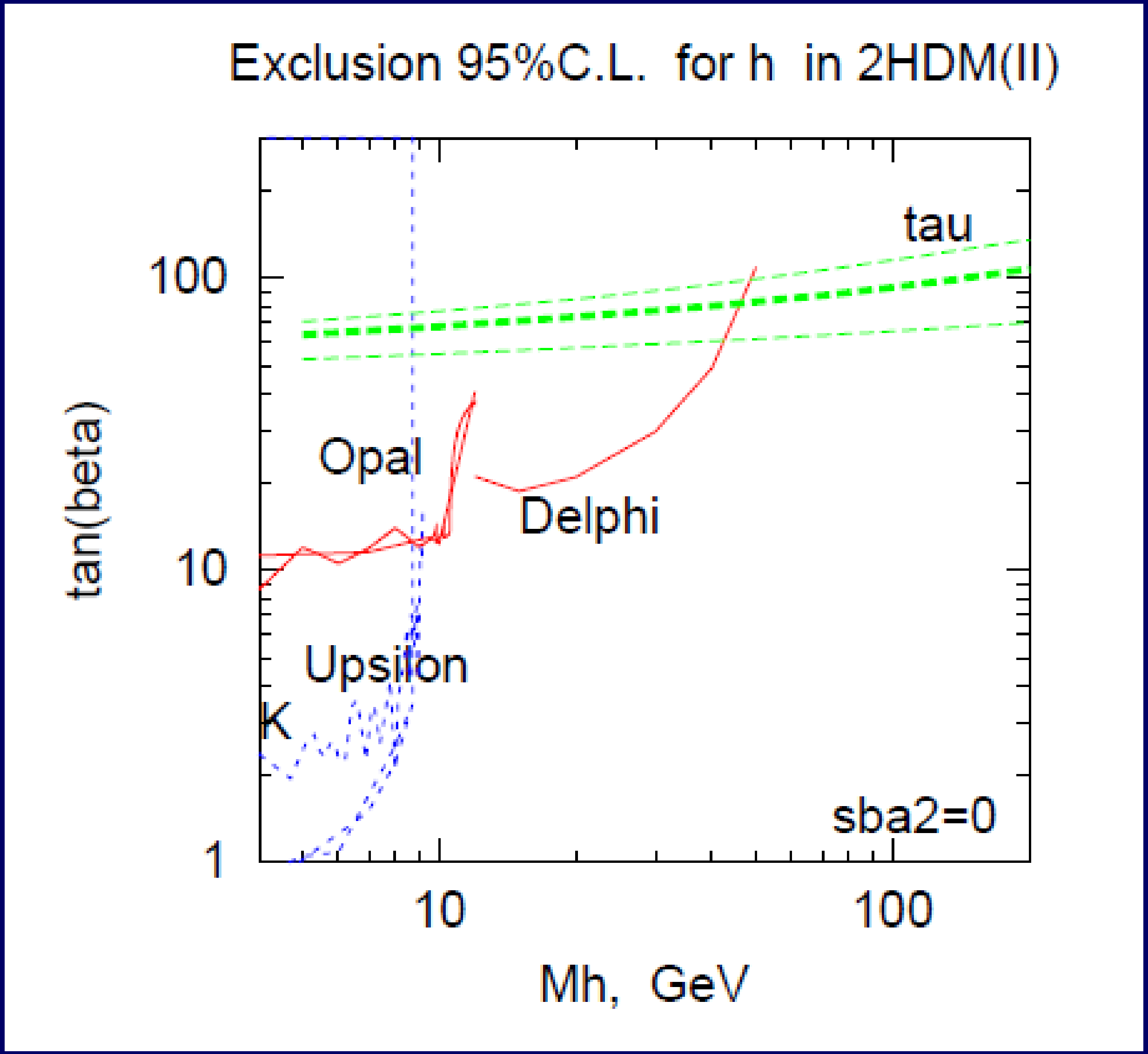
R(B→Dτν)@95%C.L.
Br(B→τν)@95%C.L.
(R−R_SM)/R_SM
−15%
−10%
−5%
tan β
m_H+

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)



horizontal lines (in green) corresponds to $M_A = 100$ GeV, for $M_{H^\pm} = 500$ GeV and 4 TeV, upper and lower lines, respectively. The results for the degenerate A and H^+ with mass 4 TeV are plotted by using thicker 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 $h(H)$

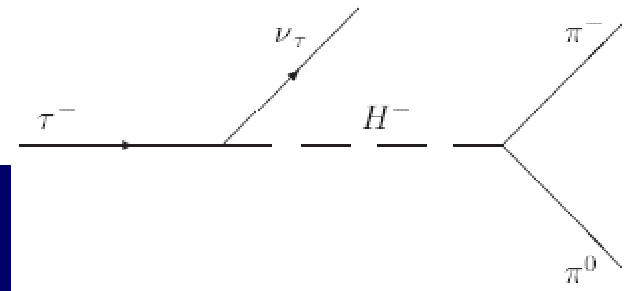
- We got upper limits on Yukawa couplings for both light h and light A scenarios

- 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 $M_{H^{\pm}}$!

Angular distribution asymmetry in $\tau^- \to \pi^-\pi^0\nu_\tau$ decay in the two-Higgs-doublet model with large $\tan\beta$

Dao-Neng Gao[†]



the large $\tan\beta$ limit (so we can neglect the term proportional to m_u), one has

$$F_S = \frac{m_d \tan^2\beta}{m_{H^\pm}^2} \frac{m_\pi^2}{m_u + m_d}.$$

$$m_{H^\pm} > 1.28 \ \tan\beta \ \text{GeV} \quad (95\%\text{CL}), \ [16]$$
$$\tan\beta/m_{H^\pm} < 0.53 \ \text{GeV}^{-1} \quad (95\%\text{CL}), \ [17]$$
$$\tan\beta/m_{H^\pm} < 0.40 \ \text{GeV}^{-1} \quad (90\%\text{CL}). \ [18]$$

$$s = (p_{\pi^-} + p_{\pi^0})^2$$

Using the above bounds and from eq. (13), we find that F_S could be up to 10^{-3} in the 2HDM of type II with large $\tan\beta$. Of course, this small value of F_S could only give the negligible contribution to $d\Gamma/ds$ defined in eq. (8) or (5), however, it may lead to an interesting angular distribution asymmetry $\mathcal{A}(s)$ in $\tau^- \to \pi^-\pi^0\nu_\tau$ decay defined in eq. (7). To illustrate

The general invariant amplitude for $\tau^- \to \pi^-\pi^0\nu_\tau$, by assuming only left-handed neutrinos, can be parameterized as

$$\mathcal{M} = G_F \cos\theta_C \; [F_V (p_{\pi^-} - p_{\pi^0})_\mu \bar{u}(p_{\nu_\tau})\gamma^\mu(1-\gamma_5)u(p_\tau) \\ + F_S m_\tau \bar{u}(p_{\nu_\tau})(1+\gamma_5)u(p_\tau)] \,, \tag{2}$$

where F_V is the vector form factor, and F_S the scalar one. It is straightforward to get the differential decay rate

$$\frac{d\Gamma(\tau^- \to \pi^-\pi^0\nu_\tau)}{ds} = \frac{\cos^2\theta_C \Gamma_e^{(0)}}{2m_\tau^2}\lambda^{1/2}(1, m_{\pi^0}^2/s, m_{\pi^-}^2/s)\left(1 - \frac{s}{m_\tau^2}\right)$$

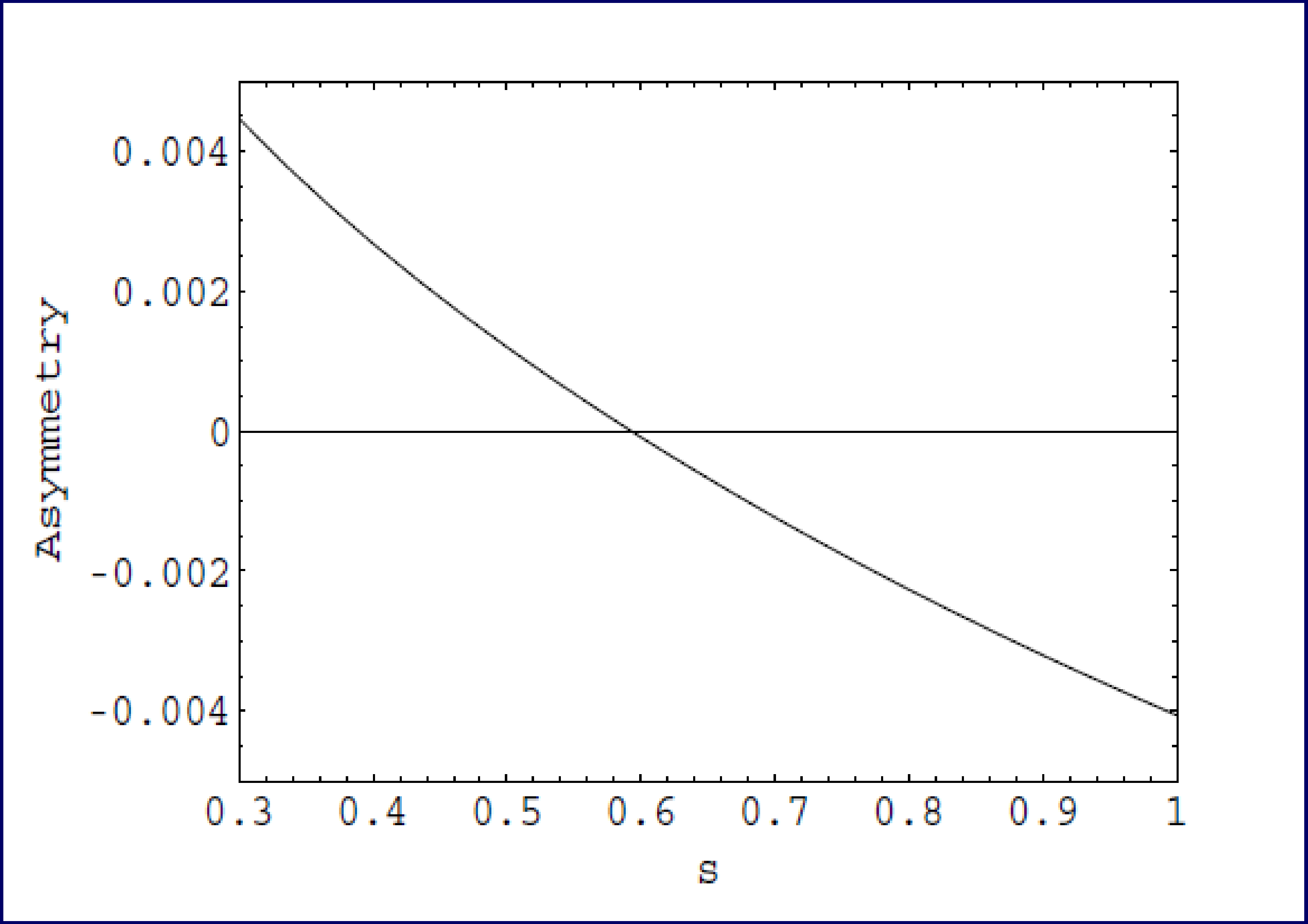
$$\times \left\{ |F_V|^2 \left[\lambda(1, m_{\pi^0}^2/s, m_{\pi^-}^2/s)\left(1 + \frac{2s}{m_\tau^2}\right) + \frac{3(m_{\pi^-}^2 - m_{\pi^0}^2)^2}{s^2}\right] \right. \\ \left. + 3|F_S|^2 - 6\mathrm{Re}(F_V F_S^*)\frac{m_{\pi^-}^2 - m_{\pi^0}^2}{s} \right\},$$

θ, the angle between the three-momentum of π^- and the three-momentum of τ^- in $\pi^-\pi^0$ rest frame

$$\frac{d^2\Gamma}{ds\, d\cos\theta}$$

angular distribution asymmetry, $\mathcal{A}(s)$

Large contribution to F_S due to H+ for large tan beta

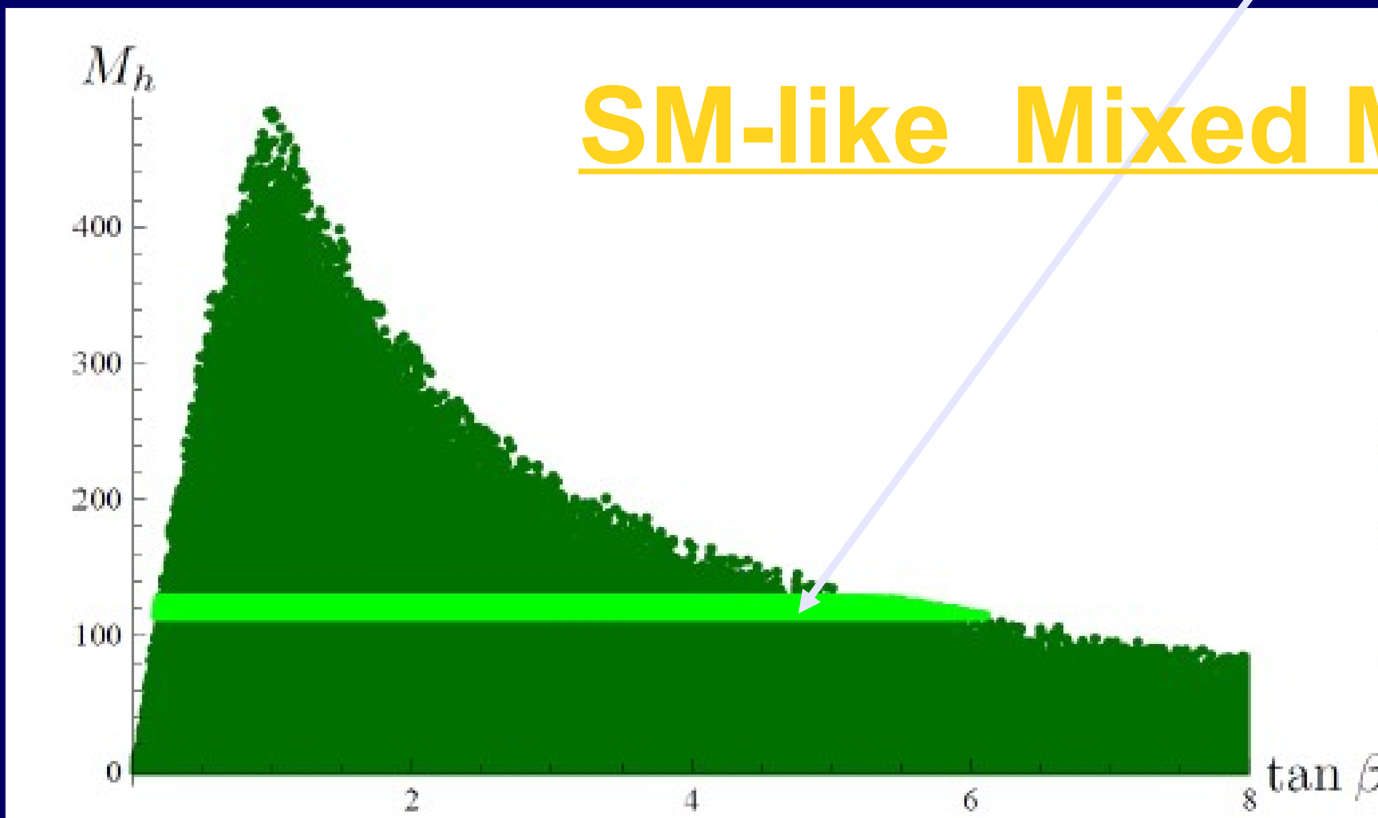


$\tan\beta/m_{H^\pm} = 0.4\ \mathrm{GeV}^{-1}$

M_h vs tan β

For h mass 115 -127 GeV

SM-like Mixed Model



B.Gorczyca, MK

1112.5086v2 [hep-ph]

tan β

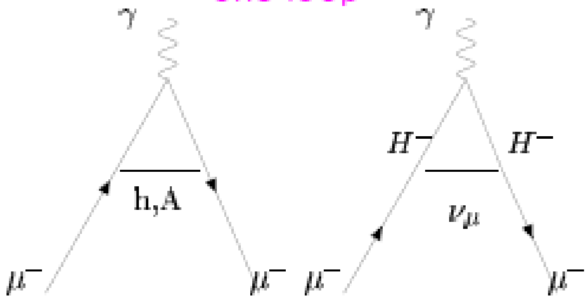
constrained by mass not Yukawa!

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

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

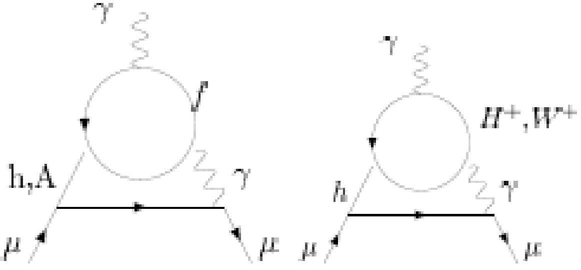
g-2 for muon

one loop



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

two loop



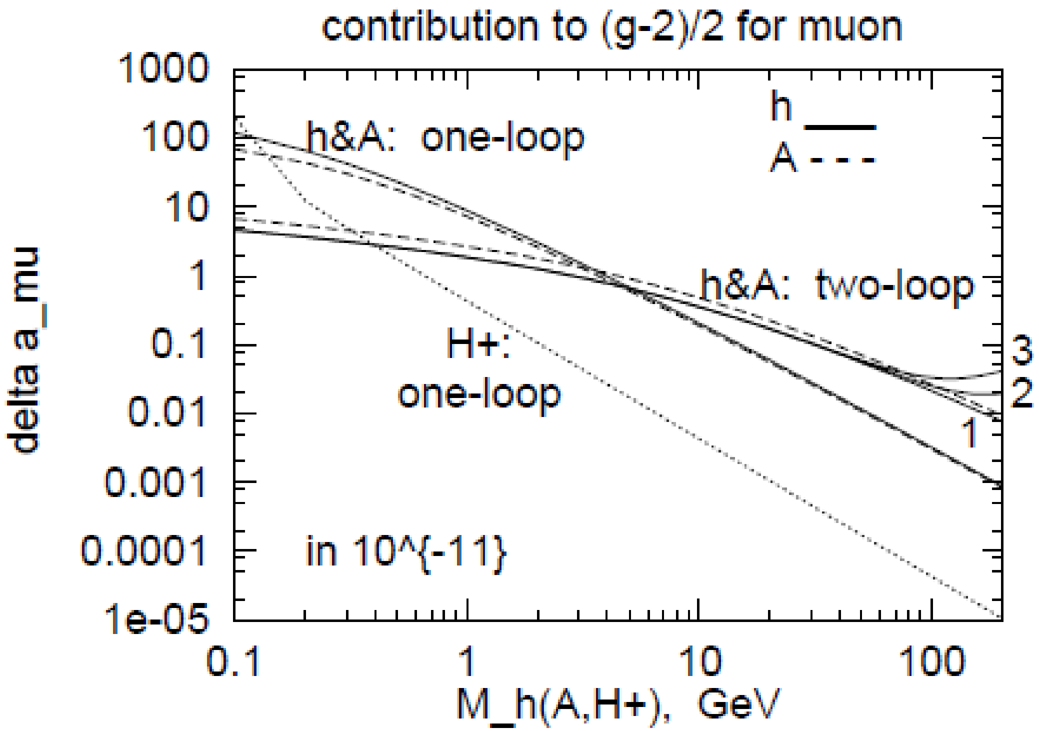
Chang at al.,Cheung at al, Wu,Zhou, MK'01,'02..

Two loop contributions larger than one-loop for mass $\sim$ few GeV!

Note, that $\gamma\gamma h$ and $\gamma\gamma A$ effective couplings enter !
So, hH^+H^- coupling relevant...

MK, hep-ph/0103223v3, 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 h

contr. positive

for mass below 3 GeV

$\beta - \alpha = 0,\ \mu^2 = 0$

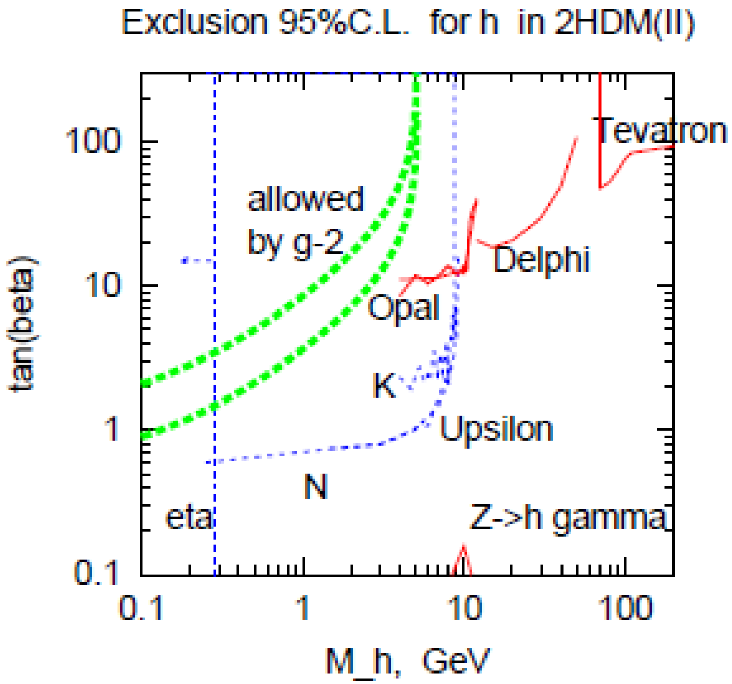
light A

contr. positive

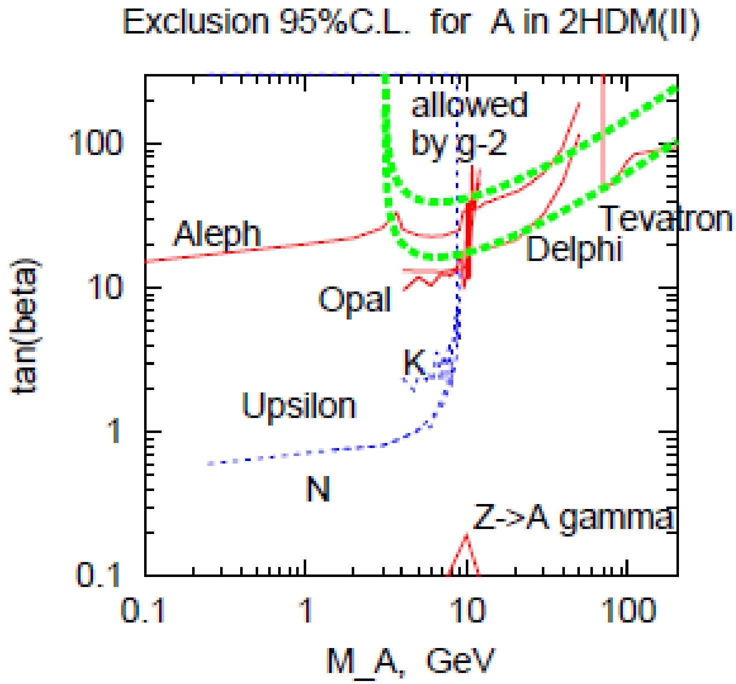
for mass above 5 GeV

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 → allowed regions for A only

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

Conclusions

- 2HDM – a great laboratory for physics BSM
- In many Standard Models SM-like scenarios

can be realized:

[Higgs mass >114 GeV, SM tree-level couplings]

- In models with two doublets:

- MSSM with decoupling of heavy Higgses

$\rightarrow$ *LHC-wedge*

- 2HDM with and without CP violation

both h or H can be SM-like

- Dark 2HDM (Intert Model)

Loop effects = a window to heavy sector