Multi-Higgs Models
Lisbon, 18.09.2009

Constraining the 2HDMs

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THE THEORY OF MATTER and STANDARD MODEL(S)

F. Wilczek, LEPFest, Nov.2000 (hep-ph/0101187)

Theory of Matter = $SU(2)_{I\ weak} \times U(1)_{Y\ weak} \times SU(3)_{color}$

Theory of Matter refers to the core concepts:
- quantum field theory
- gauge symmetry
- spontaneous symmetry breaking
- asymptotic freedom
- the assignments of the lightest quarks and leptons

Standard Models: Choose the number of Higgs (scalar) doublets
SM=1HDM, 2HDM (MSSM), 3HDM ...
Note, that the lightest scalar is often SM-like

NonStandard Models are based on more radical assumptions.
See eg. CP Study and the Nonstandard Higgs Workshop 2002-2006 (CERN Report hep-ph/0608079)

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

$SU(2) \times U(1) \rightarrow U(1)_{QED}$

Standard Model

Doublet of SU(2): $\Phi = (\varphi^{+}, v+H+i\zeta)^{T}$

Masses for $W^{+/-}$, Z (tree $\rho = 1$) , no mass for the photon

Fermion masses via Yukawa interaction

Higgs particle H_{SM} - spin 0, neutral, CP even

couplings to WW/ZZ, Yukawa couplings to fermions

mass $\leftrightarrow$ selfinteraction unknown

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 , no mass for photon?

Fermion masses via Yukawa interaction –

various models: Model I, II, III, IV,X,Y,...

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)

2HDM Potential

Lee'73, Haber, Gunion, Glashow, Weinberg, Paschos, Despande, Ma, Wudka, Branco, Rebelo, Lavoura, Ferreira, Barroso, Santos, Bottela, Silva, Diaz-Cruz, Grimus, Ecker, Ivanov, Ginzburg, Krawczyk, Osland, Nishi, Nachtmann, Akeroyd, Kanemura, Kalinowski, Grządkowski ,Hollik, Rosiek..

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

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

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

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

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

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

- If Z_2 symmetry holds <u>in the Lagrangian L</u>

  no CP violation in the scalar sector

Lee' 73

Glashow, Weinberg'77, Paschos '77

Despande, Ma' 78

- Softly broken $Z_2 \to$ *Branco, Rebelo '85*

  CP violation possible, tree-level FCNC absent,

  Decoupling and non-decoupling possible *Haber'95*

- Hard breaking $Z_2 \to$

  CP violation possible [* even without CP mixing]

Lavoura, Silva' 94 ; Kanishev, MK, Sokołowska' 2008

  tree-level FCNC

Possible vacuum states (for real V)

A. Barroso, P.M. Ferreira, R. Santos, J.P. Silva, hep-ph/0507329,

The most general vacuum state

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

v_1, v_2, u , ξ - real, ≥ 0

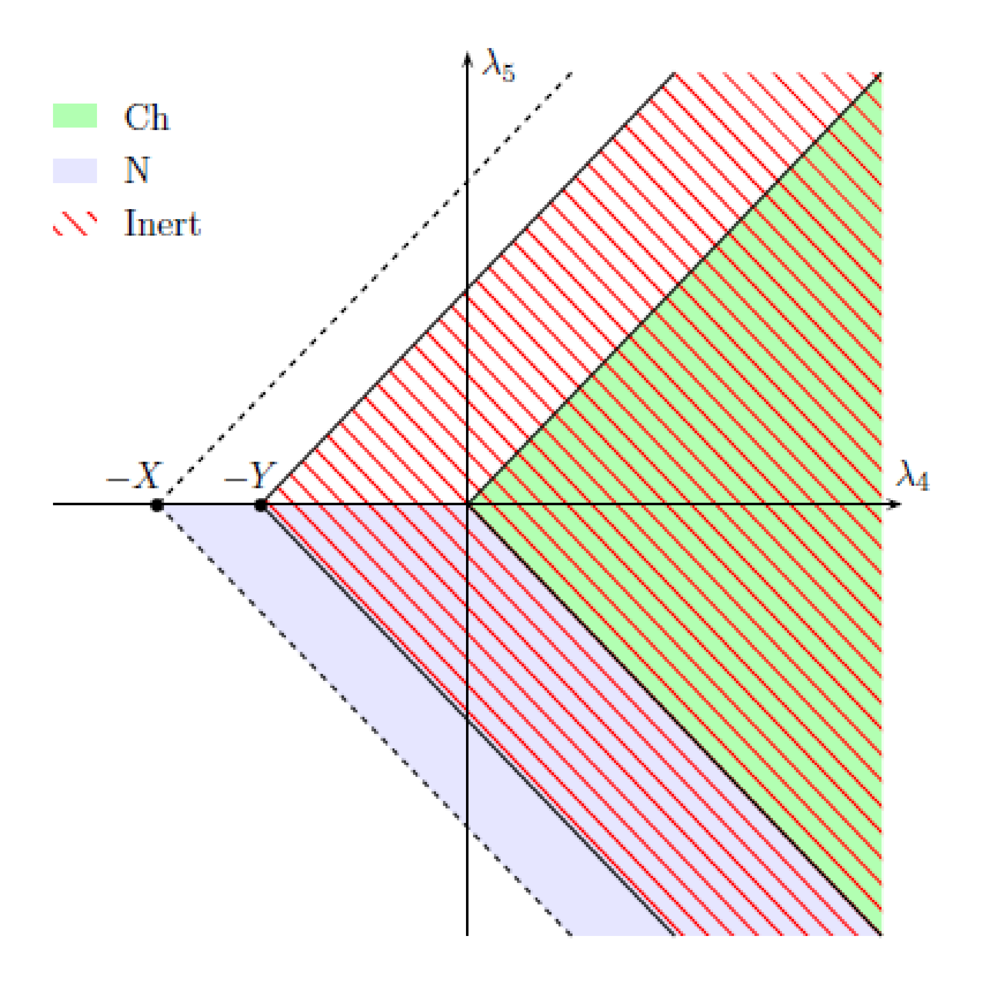
$v^2 = v_1^2 + v_2^2 + u^2 = (246\ \text{GeV})^2$

Inert	I	$u = v_2 = 0$
Normal (CP conserving)	N	$u = \xi = 0$
Charge Breaking	Ch	$u \neq 0 \quad v_2 = 0$
[Vacuum	B	$u = v_1 = 0$]
CP violating	CP	$u = 0 \ \xi \neq 0$

Various vacua on (λ_4 , λ_5) plane (Z_2 sym)

Positivity constrains on V: $X=\sqrt{\lambda_1\lambda_2}+\lambda_3>0$

$\lambda_4 \pm \lambda_5 > -X$



Inert (or B)

$Y = M_{H+}^2 \, 2/v^2$

Charge Breaking Ch

Normal

Note the overlap of the Inert with N and Ch !

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 , l

Φ_2 with up-type fermions u

Model III - both doublets interact with fermions

Model IV (X) - leptons interacts with one doublet, quarks with other

Model Y - Φ_1 with down-type quarks d

Φ_2 with up-type quarks u and leptons

Top 2HDM – top with one doublet

Fermiophobic 2HDM – no coupling to the lightest Higgs

\+ Extra dim 2HDM models

Inert or Dark 2HDM

Ma'78
Barbieri'06

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

both in L and in vacuum → Inert Model

Today

$<\Phi_1^T> = (0,v) \qquad <\Phi_2^T> = (0,0)$

→ Φ_1 as in SM, with Higgs boson h (SM-like)

→ Φ_2 - no vev, with 4 scalars (no Higgs bosons!) no interaction with fermions (inert doublet)

Conservation of the Z_2 symmetry; only Φ_2 has odd Z_2-parity

→ The lightest scalar – a candidate for dark matter (Φ_2 dark doublet with dark scalars) .

2HDMs

- 2HDM potential, its symmetry before & after EWSB
  theoretical constraints: positivity, unitarity
  vacua and physical masses
  gauge interaction, selfinteraction
- Models of the Yukawa interaction
  symmetry, perturbativity
- Sum rules and pattern relation
- SM-like scenarios (decoupling and nondecoupling), very light neutral scalar scenarios
- Constraints on Model I, II..., Inert Model
- Future measurements LHC, ILC/CLIC, PLC

2HDM: old idea and recent progress

- T.D. Lee 1973 – mainly for spontaneous CP violation
- Rich phenomenology ....
- 2004-2009: deeper understanding of V using symmetry (reparametrization freedom or is tan β a physical parameter?, condition for CP conservation, vacuum states)- *Haber, Gunion; Ginzburg, MK; Nishi, Nachtmann, Maniatis, Manteiffel, Ivanov, Kanishev, Sokołowska, Barroso, Santos, Ferreira, Silva, Botella, Lavoura, Branco, Rebelo, Grimus, Osland, Vives...*
- *2006-9* Dark matter: *Ma, Barbieri;*
  Evolution of the Universe: *Ginzburg, Ivanov, Kanishev, MK, Sokołowska*

New analyses for LHC, ILC, PLC
Constraints from Flavour data
Generators for 2HDM

The explicit and spontaneous CP violation

Sokołowska, Kanishev, MK' 08

Distinguishing the explicit and spontaneous CP violation using the I- and J -invariants

(CP-odd weak-basis invariants)

Special case: CP violation without CP mixing,

i.e. CP violation in V only in selfinteraction

- a hard CP violation due to the hard Z_2 violating terms

Distinguishing direct vs spontaneous CP violation

Sokołowska, Kanishev, MK' 08

- We must identify CP-invariant part in order to determine CP transformation

Branco, Rebelo, Grimus,

Nachtmann, Nishi, Haber,...

- The simplest CP transformation:

$$\Phi(x,t) \rightarrow \Phi^\dagger(-x,t)$$

- Then

  CP-even η_1, η_2

  CP-odd A

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{v+\eta_1+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{\eta_2+iA}{\sqrt{2}} \end{pmatrix}$$

Higgs basis

J-invariants

Mass matrix: $J_1 \sim \mathrm{Im}\,(\Lambda_5{}^*\Lambda_6{}^2)$

Interactions: $J_2 \sim \mathrm{Im}\,(\Lambda_5{}^*\Lambda_7{}^2)$, $J_3 \sim \mathrm{Im}\,(\Lambda_7{}^*\Lambda_6)$

- CP conservation: all J =0

- If J_1 not zero → CP mixing in states, no definite CP-parity for h1,h2,h3

- If J_1=0 and $J_{2,3}$ not zero → no CP mixing

CP violation in the interaction at the tree level

Lavoura, Silva, Botella' 94

I-invariants

- Other invariants formed from the parameters of the potential:

$$V = Y_{a\bar{b}}\Phi^\dagger_{\bar{a}}\Phi_b + \frac{1}{2}Z_{a\bar{b}c\bar{d}}(\Phi^\dagger_{\bar{a}}\Phi_b)(\Phi^\dagger_{\bar{c}}\Phi_d)$$

$$I_1 = \mathrm{Im}(Z^{(1)}_{a\bar{c}}Z_{e\bar{b}}Z_{b\bar{e}c\bar{d}}Y_{d\bar{a}}) \qquad I_2 = \mathrm{Im}(Y_{a\bar{b}}Y_{c\bar{d}}Z_{b\bar{a}d\bar{f}}Z^{(1)}_{f\bar{c}})$$

$$I_3 = \mathrm{Im}(Z_{a\bar{c}b\bar{d}}Z^{(1)}_{b\bar{f}}Z^{(1)}_{d\bar{h}}Z_{f\bar{a}j\bar{k}}Z_{k\bar{j}m\bar{n}}Z_{n\bar{m}h\bar{c}}), \quad I_4 = \mathrm{Im}(Z_{a\bar{c}b\bar{d}}Z_{c\bar{e}d\bar{g}}Z_{e\bar{h}f\bar{q}}Y_{g\bar{a}}Y_{h\bar{b}}Y_{q\bar{f}})$$

- 4 invariants formed from quartic and quadratic parameters of V
- The **potential** is explicitly CP conserving $\Leftrightarrow$ all I_i are 0
$\Leftrightarrow$ there exists „real basis" of fields Φ_1, Φ_2 in which all λ_i, m^2_{ij} are real
$\Rightarrow$ CP symmetry can be conserved **or** violated spontaneously
- If $\exists I_i \neq 0$ then CP is explicitly violated.

[Haber, Gunion '05]

Branco et al.

J- and I-invariants: a comparison

Model properties	J-invariants	I-invariants
CP explicitly violated	$\exists J_i \neq 0$	$\exists I_i \neq 0$
CP spontaneously violated	$\exists J_i \neq 0$	$\forall I_i = 0$
CP conserved	$\forall J_i = 0$	$\forall I_i = 0$

- if $\forall J_i = 0$ then we have CP conserving case
- if $\exists J_i \neq 0$ then we have CP violation
  - if $\forall I_i = 0$ then we have spontaneous CP violation
  - if $\exists I_i \neq 0$ then we have explicit CP violation

2HDM – what do we know?

Most results for the Normal (CPconserving) case

- Direct measurements
- Undirect measureament

Sum rules useful !

Relative couplings (respect to SM)

Haber, Wudka';
Kalinowski, Grządkowski, Gunion

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

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

there are relations among couplings, eg.

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

Pattern relation- for each h_i (or h,H,A)

$$(\chi_u^{(i)} + \chi_d^{(i)})\chi_V^{(i)} = 1 + \chi_u^{(i)}\chi_d^{(i)} \, ,$$

$$(\chi_u^{(i)} - \chi_V^{(i)})(\chi_V^{(i)} - \chi_d^{(i)}) = 1 - (\chi_V^{(i)})^2 \, .$$

Ginzburg, MK, Osland

In Model II: one can determine tan β $=v_2/v_1=$tan β_{II} via :

$$\tan^2\beta_{II} = \frac{(\chi_V^{(i)} - \chi_d^{(i)})^*}{\chi_u^{(i)} - \chi_V^{(i)}} = \frac{1 - |\chi_d^{(i)}|^2}{|\chi_u^{(i)}|^2 - 1} = \frac{\mathrm{Im}\,\chi_d^{(i)}}{\mathrm{Im}\,\chi_u^{(i)}} \, .$$

for h_i (h,H)

Haber, Gunion
Ginzburg, MK

Higgs search at colliders

→

The Standard Model and Beyond Standard Model:
2HDM/MSSM

Colliders: LEP, Tevatron and LHC

Low energy measurements:

B-decays constraining Higgs sector,

g-2 for muon – new physics?

Future colliders ILC and PLC

Cosmic connection

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

Re m^2_{12}

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!

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)

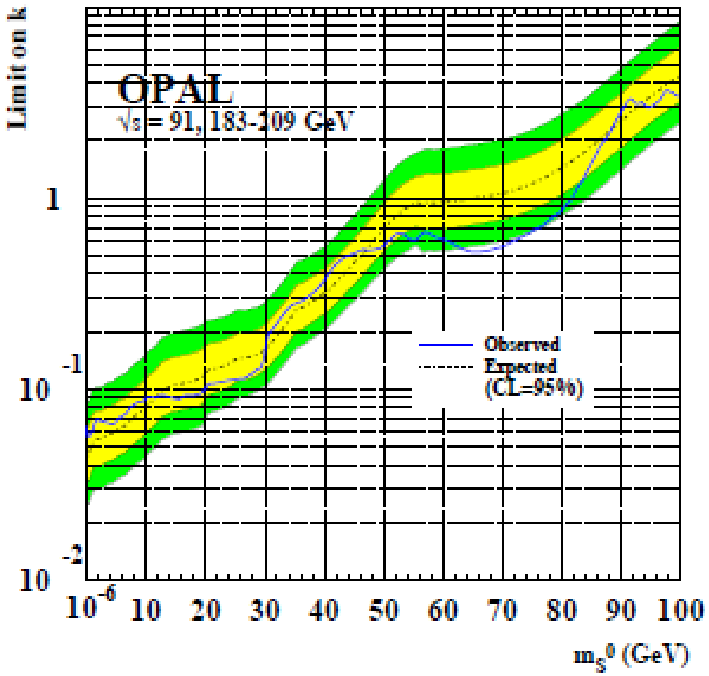
Cheung and Kong '03 Akesson et al...

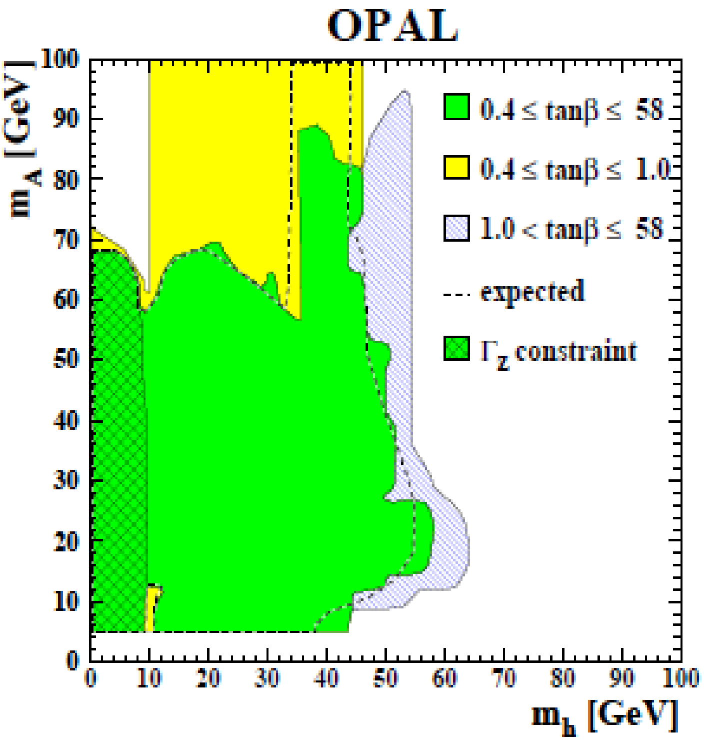
Neutral Higgs bosons - couplings to gauge boson, and mass exclusion

LEP: 2HDM with Z2 symmetry

Light h OR light A in agreement with current data

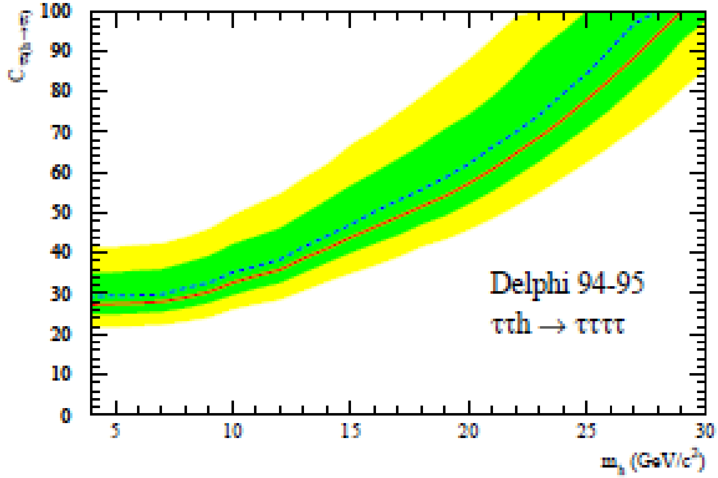
hZZ: $sin(\beta - \alpha)$ and hAZ: $cos(\beta - \alpha)$

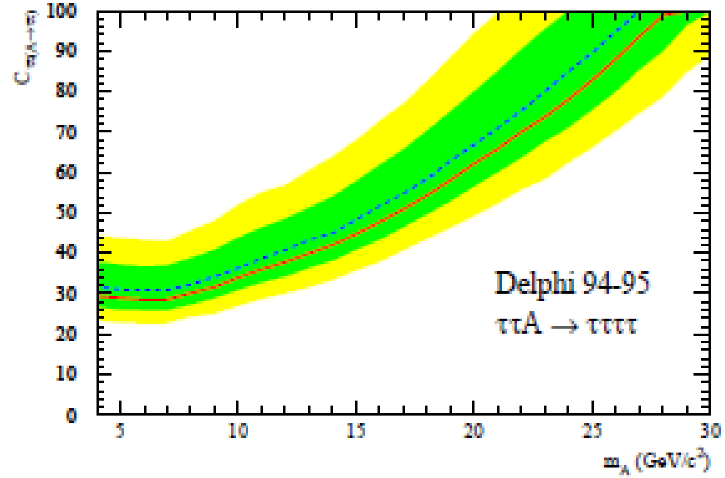




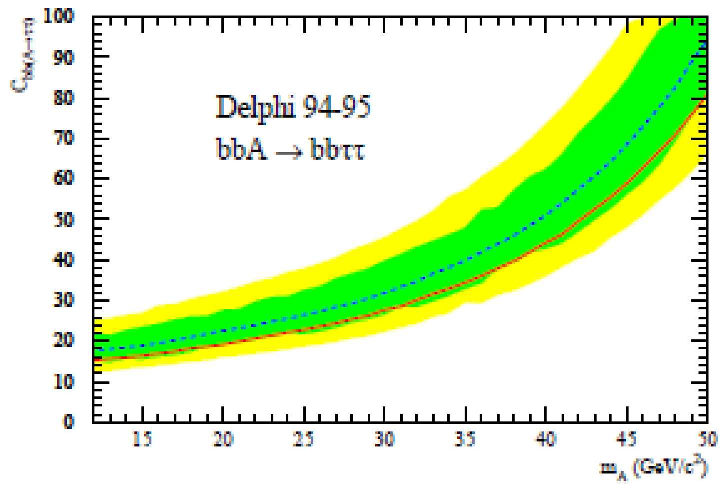
Light scalar $h \rightarrow$ small $k = sin^2(\beta - \alpha)$!

Upper (95%) limits for Yukawa couplings χ_d ($\tan\beta$) in 2HDM (II)





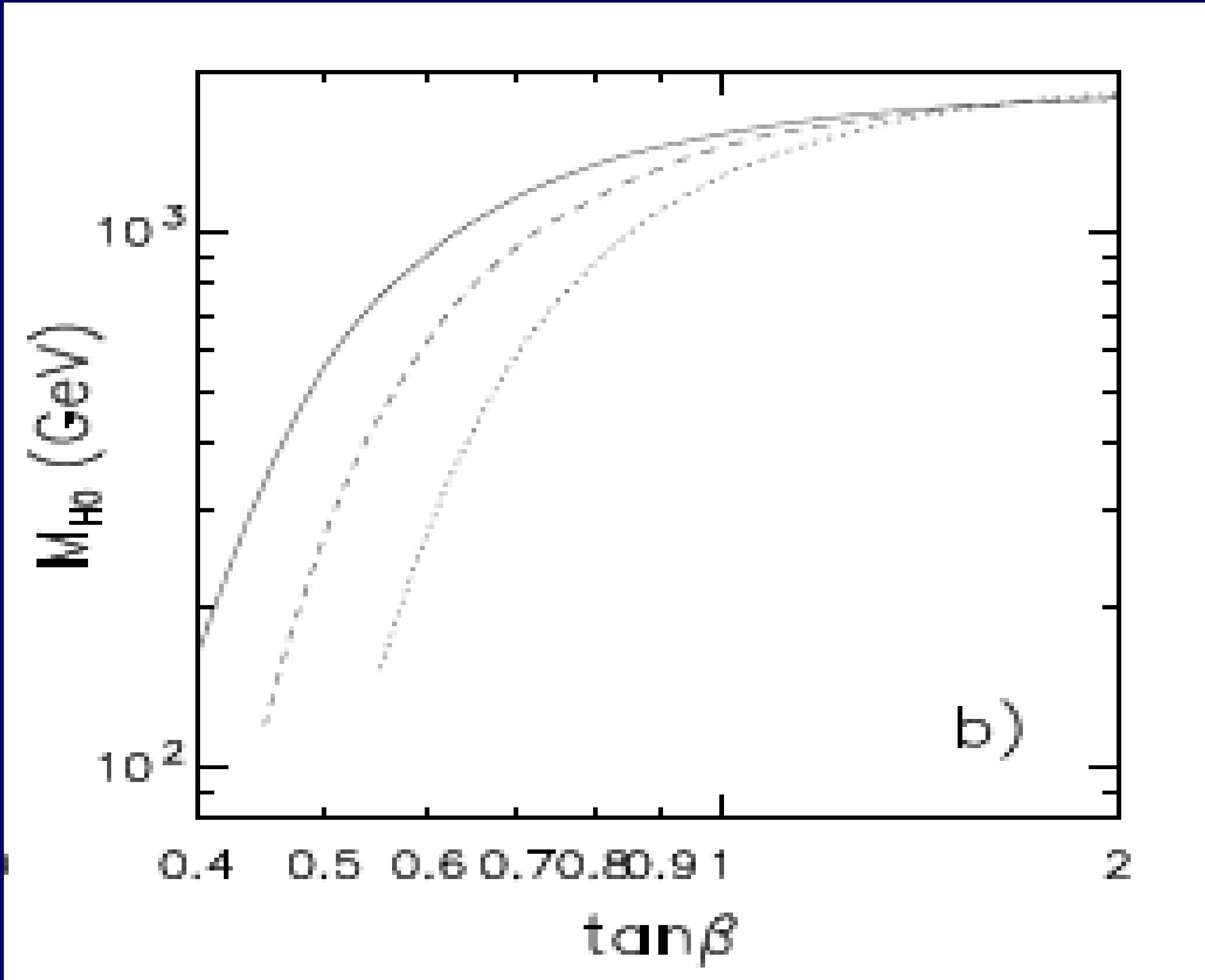
Yukawa coupling ($\tan\beta$) up to 20 allowed mass larger than 35 GeV!



Global fit to EW precision data

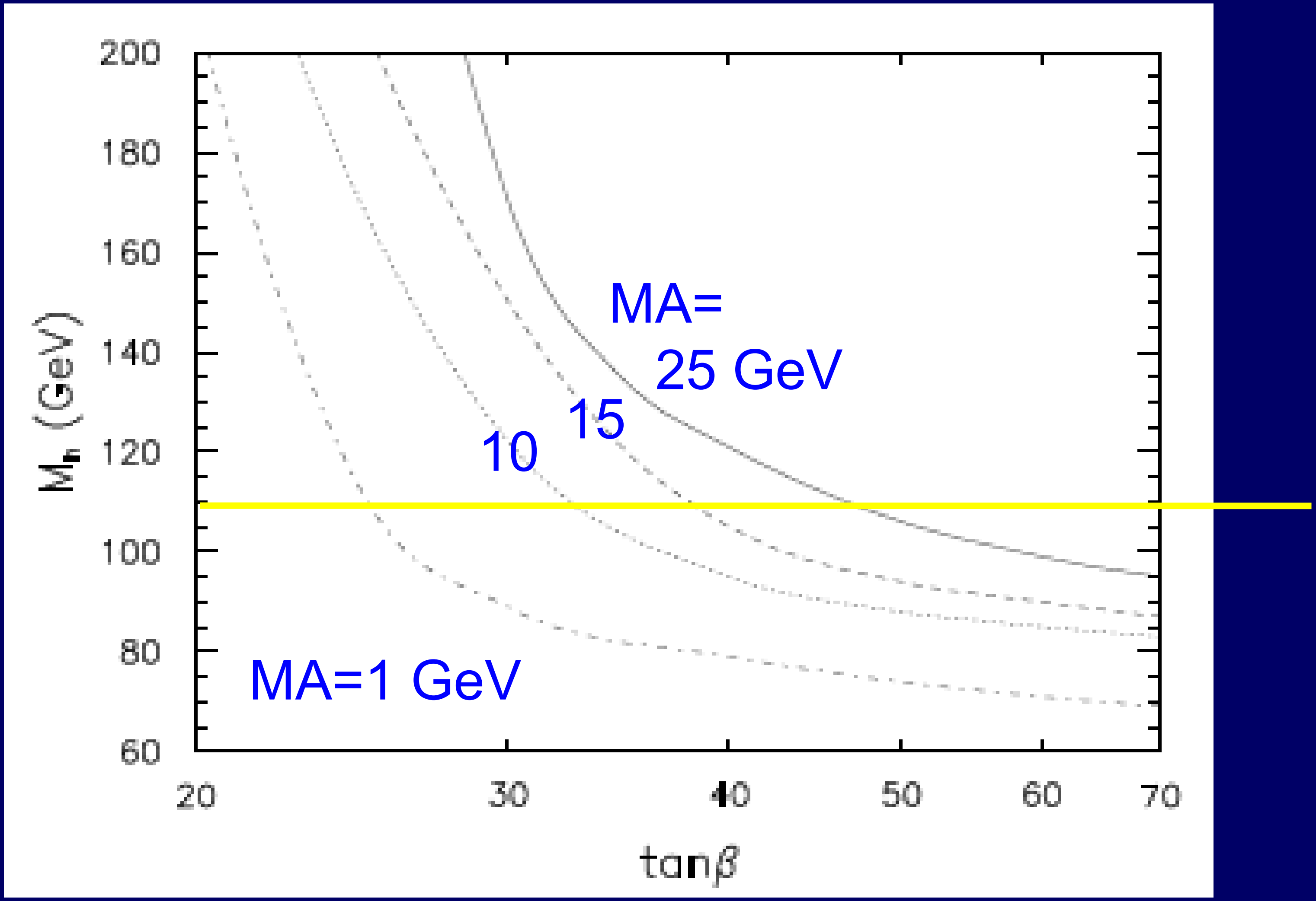
Upper limit for MH for light h (20 GeV) sin(β-α) =0 for H+ =1000-800-600 GeV

Chankowski, MK, Żochowski' 99

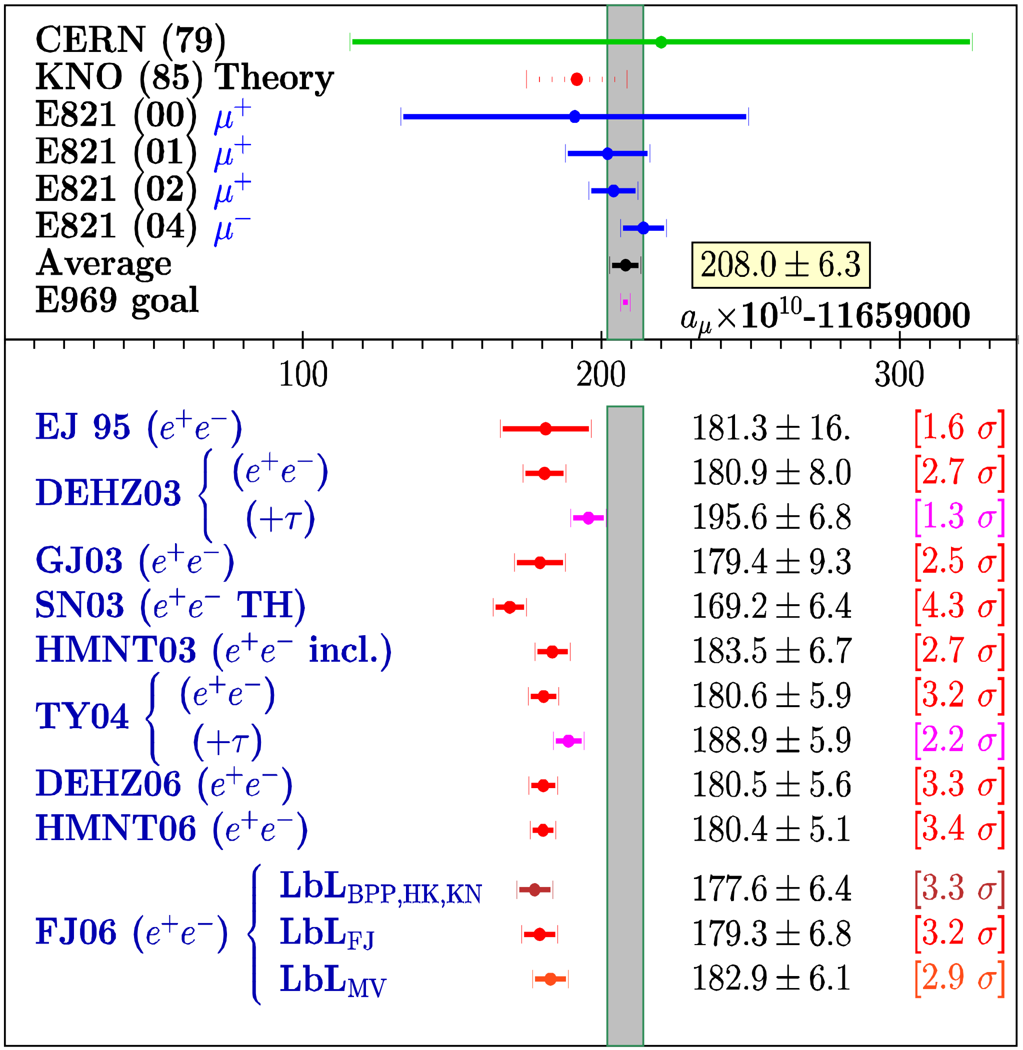


A very light Higgs boson scenarios (h or A)

upper limits for mass of h



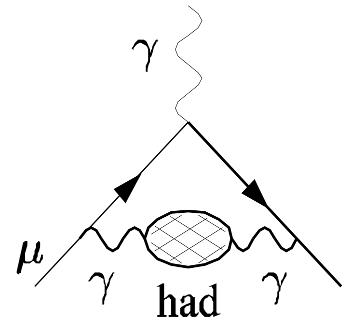
g-2 for muon (Jegerlehner'07)

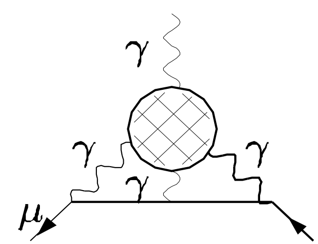


New Physics?

$$\delta a_\mu = (287 \; +/- \; 91) \; 10^{-11}$$

3.2 σ



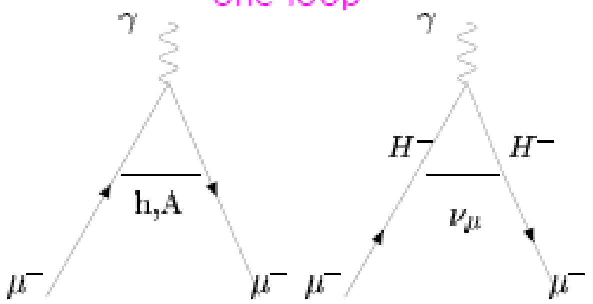


2HDM contribution to a_μ: $a_\mu^{\text{2HDM}} = a_\mu^h + a_\mu^A + a_\mu^H + a_\mu^{H^\pm}$

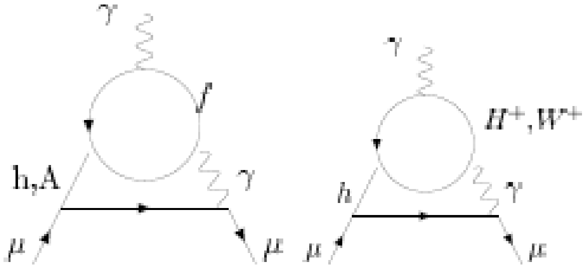
- light h scenario : $a_\mu^{\text{2HDM}} \approx a_\mu^h$
- light A scenario : $a_\mu^{\text{2HDM}} \approx a_\mu^A$

g-2 for muon

one loop



two loop



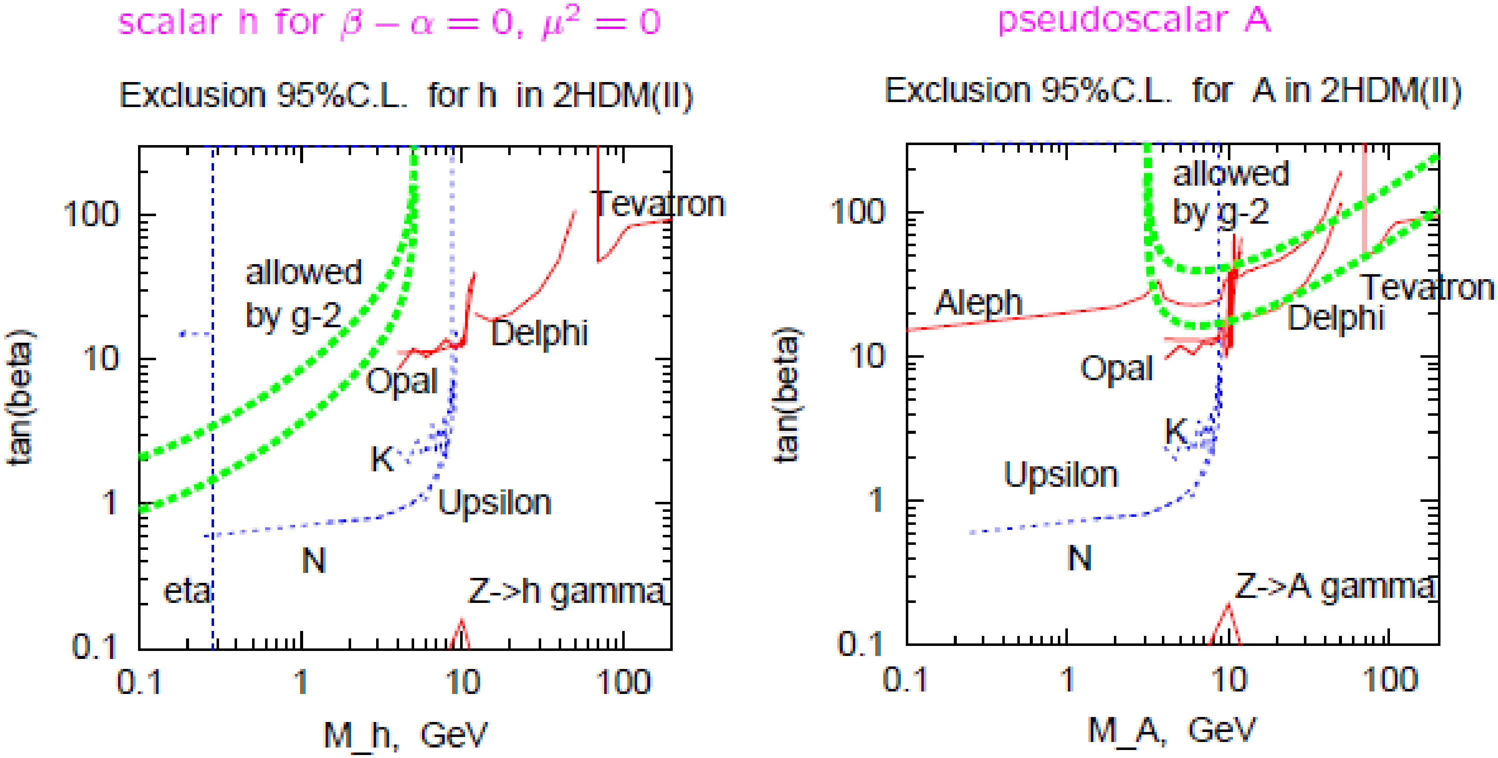
Zochowski,MK'96,MK'01;Dedes,Haber'01 Chang at al.,Cheung at al, Wu,Zhou, MK'01,'02..

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)

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



thick lines : upper & lower limits from g-2

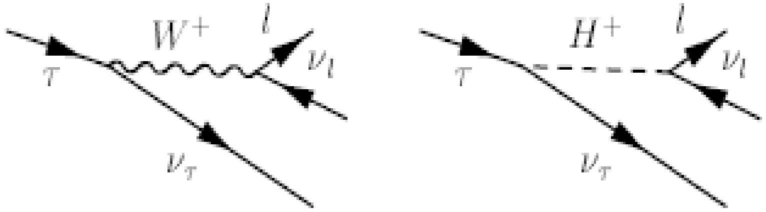
plus LEP data, etc

If all existing data are taken into account → allowed regions for A only

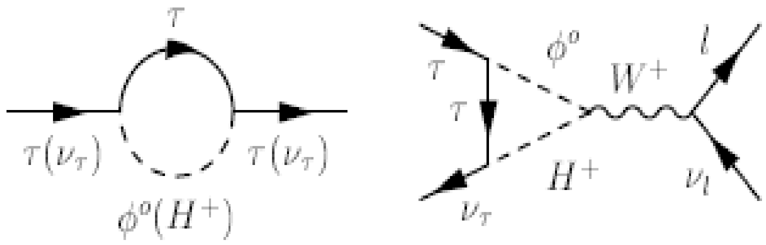
A with mass 25-70 GeV and $25 < \tan\beta < 115$ in agreement with data

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



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 $\tan\beta$

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

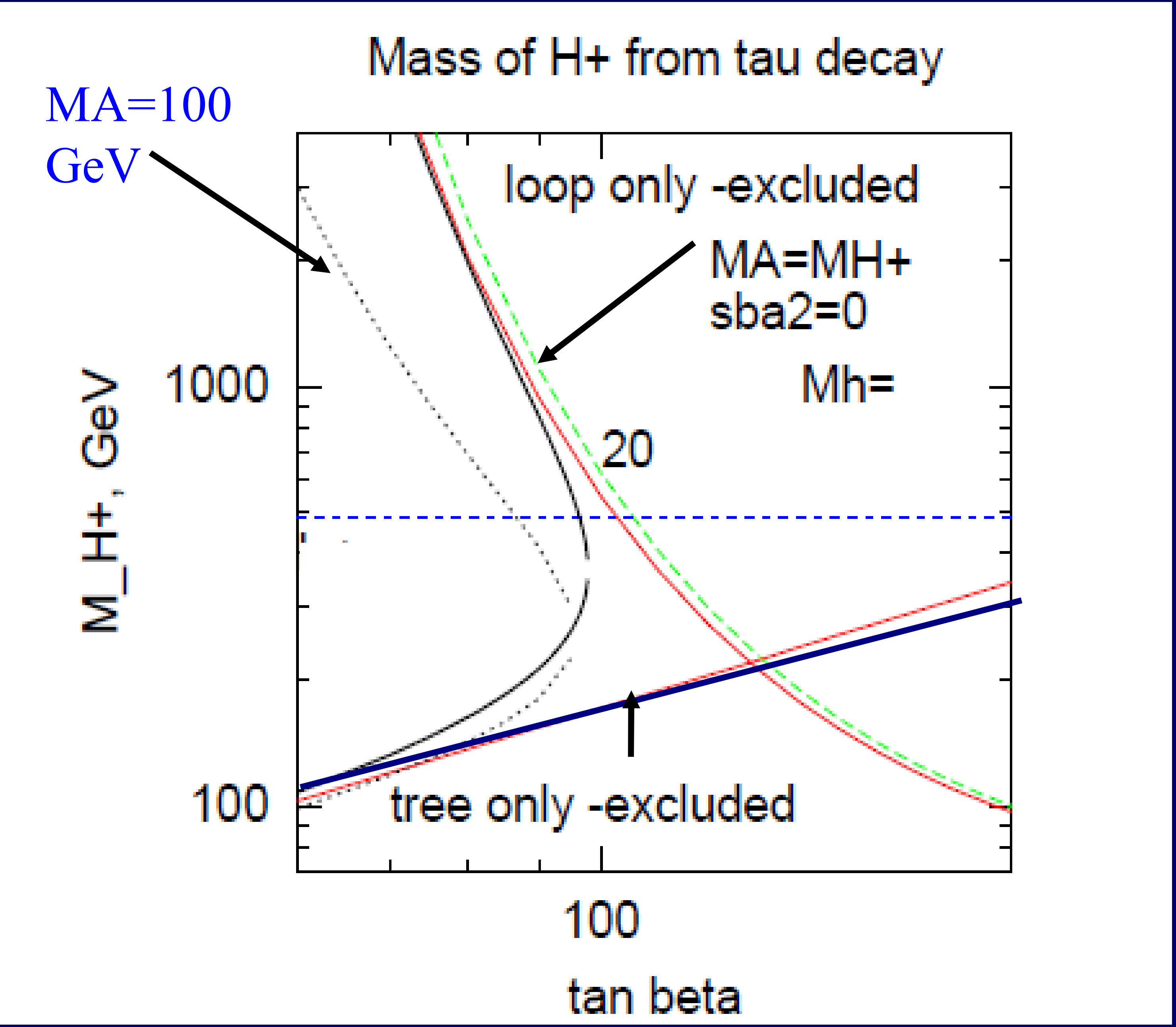
$$\begin{aligned}\tilde{\Delta} = \quad & \Bigg[-\left(\ln\left(\frac{M_{H^+}^2}{m_\tau^2}\right) + F(R_{H^\pm}) \right) \\ & + \frac{1}{2}\left(\ln\left(\frac{M_A^2}{m_\tau^2}\right) + F(R_A) \right) \\ & + \frac{1}{2}\cos^2(\beta-\alpha)\left(\ln\left(\frac{M_h^2}{m_\tau^2}\right) + F(R_h) \right)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

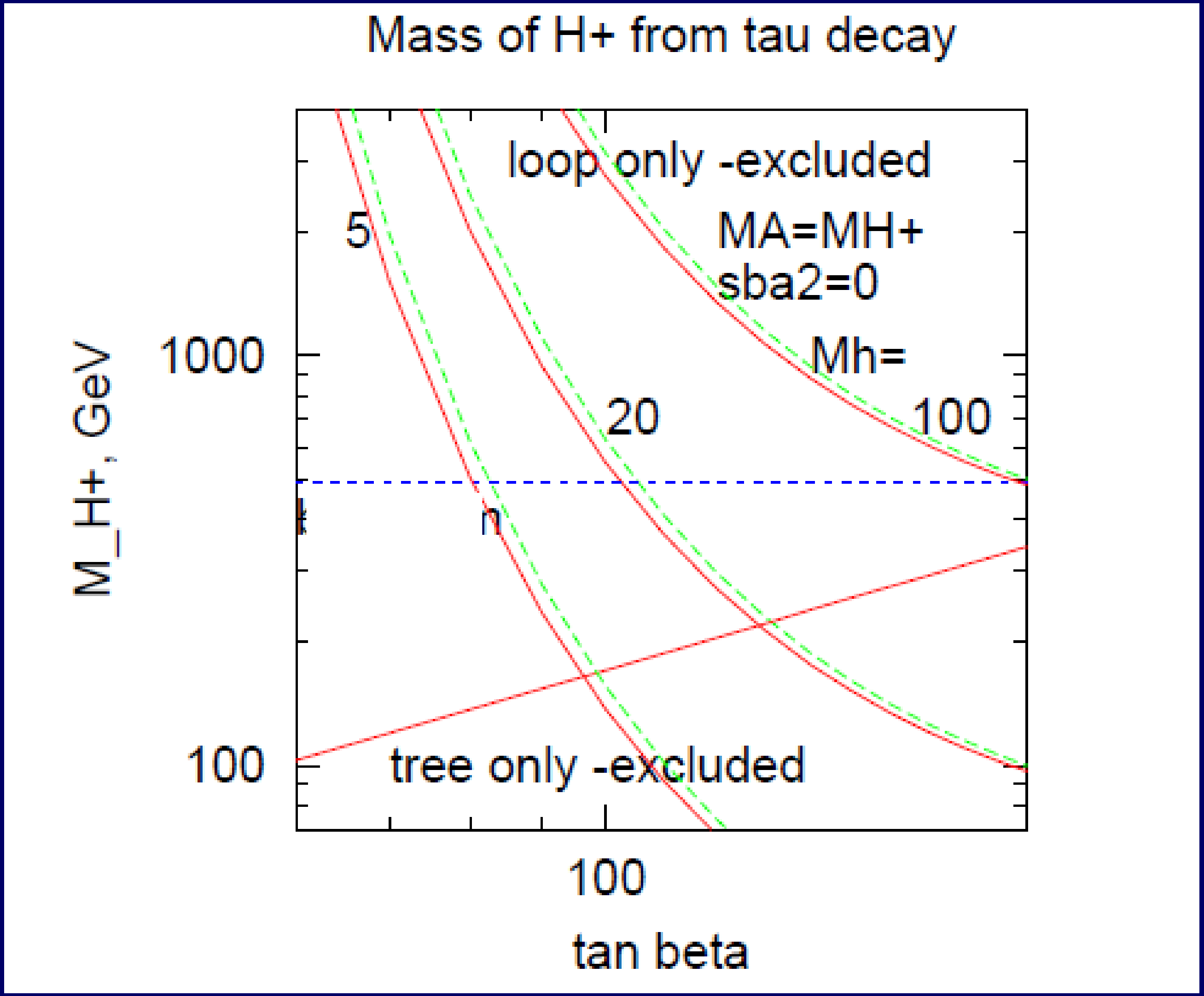
where $R_\phi \equiv M_\phi / M_{H^\pm}$ and $F(R) = -1 + 2\,R^2 \ln R^2/(1-R^2)$

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


Mass of H+ from tau decay
MA=100
GeV
loop only -excluded
MA=MH+
sba2=0
Mh=
20
1000
100
M_H+, GeV
tree only -excluded
100
tan beta


Mass of H+ from tau decay
loop only -excluded
5
MA=MH+
sba2=0
Mh=
20
100
1000
100
tree only -excluded
M_H+, GeV
100
tan beta

Inclusive b →s γ

Experiment – NNLO Theory = +1.2σ

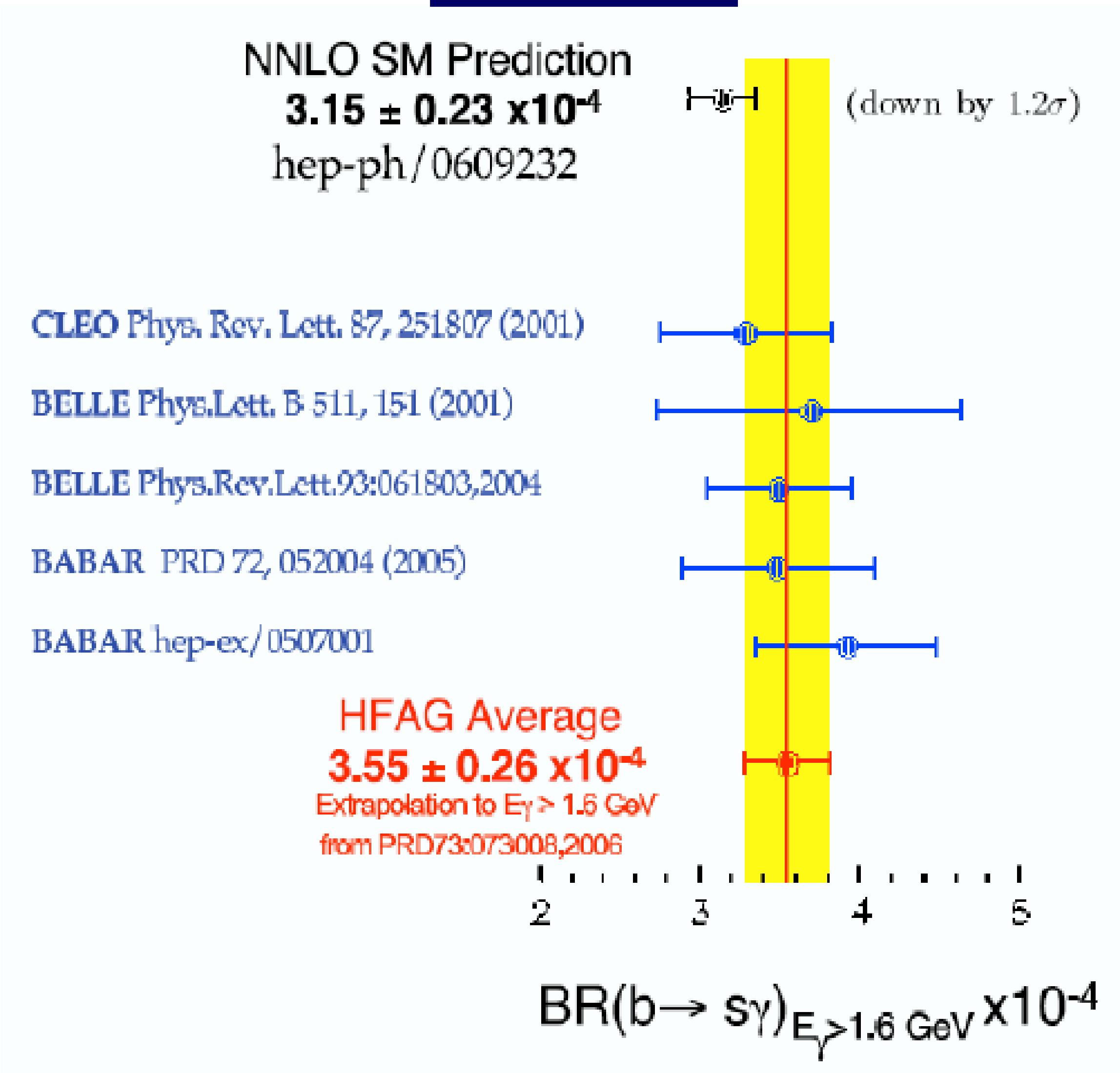
B factories
are likely to improve
precision to 5%

Super B could push
down Eγ cutoff from current
1.8 GeV to 1.5 GeV

Super B incl. ACP precision:
0.9 % @ 5 ab^{-1}
0.3% @ 50ab^{-1}

Super B can measure incl.
b →dγ rate to
25% with 5 ab^{-1}

Misiak PRL98



The weak radiative $\bar{B}$-meson decay branching ratio:

$$\mathcal{B}(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6\ \mathrm{GeV}} = \mathcal{B}(\bar{B} \to X_c e\bar{\nu})_{\mathrm{exp}} \left[\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\bar{\nu})}\right]_{\mathrm{LO\ EW}} f\left(\frac{\alpha_s(M_W)}{\alpha_s(m_b)}\right)\times$$

$$\times \left\{1 + \underset{\text{NLO}}{\mathcal{O}(\alpha_s)} + \underset{\text{NNLO}}{\mathcal{O}(\alpha_s^2)} + \mathcal{O}(\alpha_{\mathrm{em}}) + \mathcal{O}\left(\frac{\Lambda^2}{m_b^2}\right) + \mathcal{O}\left(\frac{\Lambda^2}{m_c^2}\right) + \mathcal{O}\left(\frac{\Lambda}{m_b}\alpha_s\right)\right\}$$

$\sim 30\%$ $\quad \sim 10\%$ $\quad \sim 4\%$ $\quad \sim 1\%$ $\quad \sim 3\%$ $\quad <\sim 5\%$

perturbative corrections

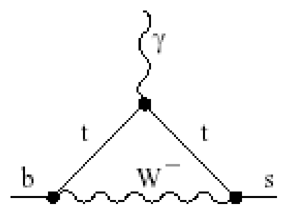
non-perturbative corrections
(methods: Optical Theorem,
Operator Product Expansion,
Heavy Quark Effective Theory)

The latest HFAG average: $(3.55 \pm 0.24\ {}^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$

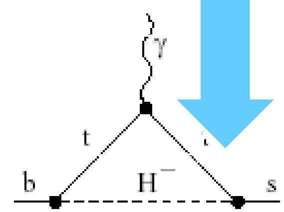
(hep-ex/0603003, does not yet include the new BaBar result from hep-ex/0607071)

Combined error of the HFAG average $\sim 7.4\%$
$\Rightarrow$ need for the NNLO.

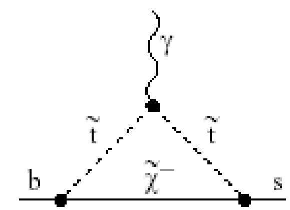
Sample LO EW diagrams:



SM



2HDM

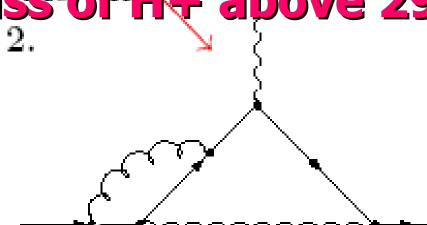


MSSM

Mass of H+ above 295 GeV at 95 % CL

LO QCD effects that originate from two-loop diagrams like this
enhance the $\bar{B} \to X_s\gamma$ rate by more than a factor of 2.

The function $f\left(\alpha_s(M_W)/\alpha_s(m_b)\right)$ arises from
resummation of $\left(\alpha_s \ln M_W^2/m_b^2\right)^n$ using
the renormalization group techniques.



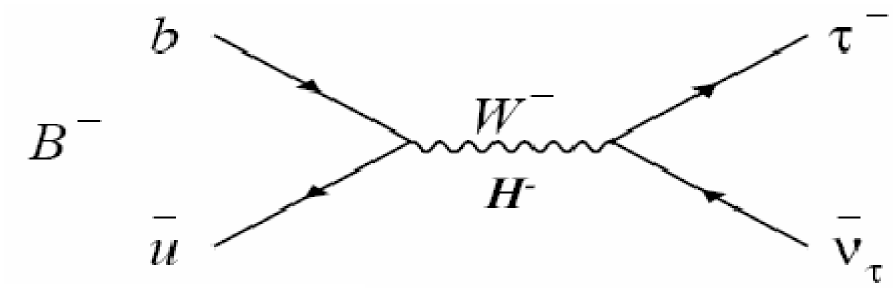
Two loops at the LO
$\Rightarrow$ Four loops at the NNLO

B to tau nu' 2006-7

B+ → $\tau^+\nu$

Simple decay through weak annihilation

Sensitive to B decay constant f_B or to charged Higgs boson



$$\mathcal{B}(B_u \to \tau\nu)^{\rm SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B = (1.59 \pm 0.40) \times 10^{-4}$$

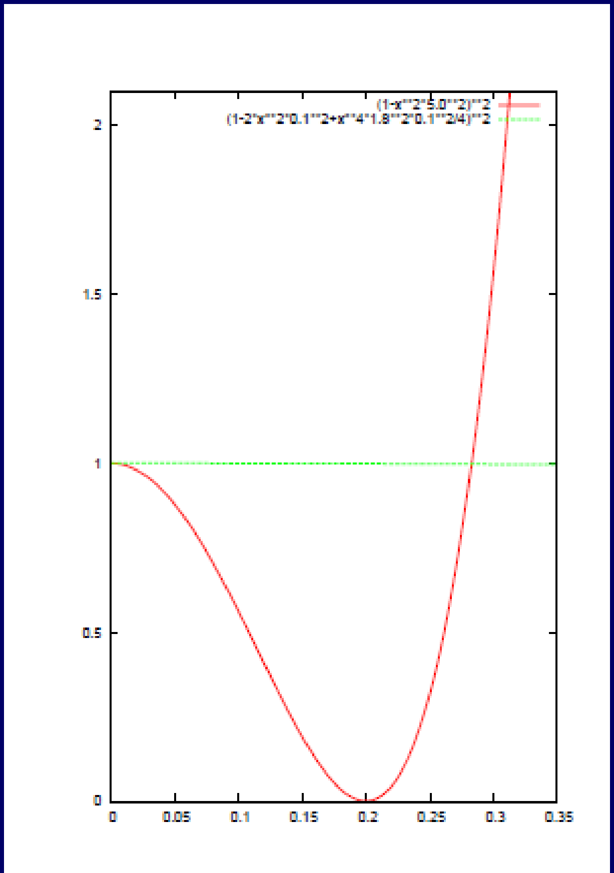
$\tan^4\beta$ modifications in 2HDM II model:

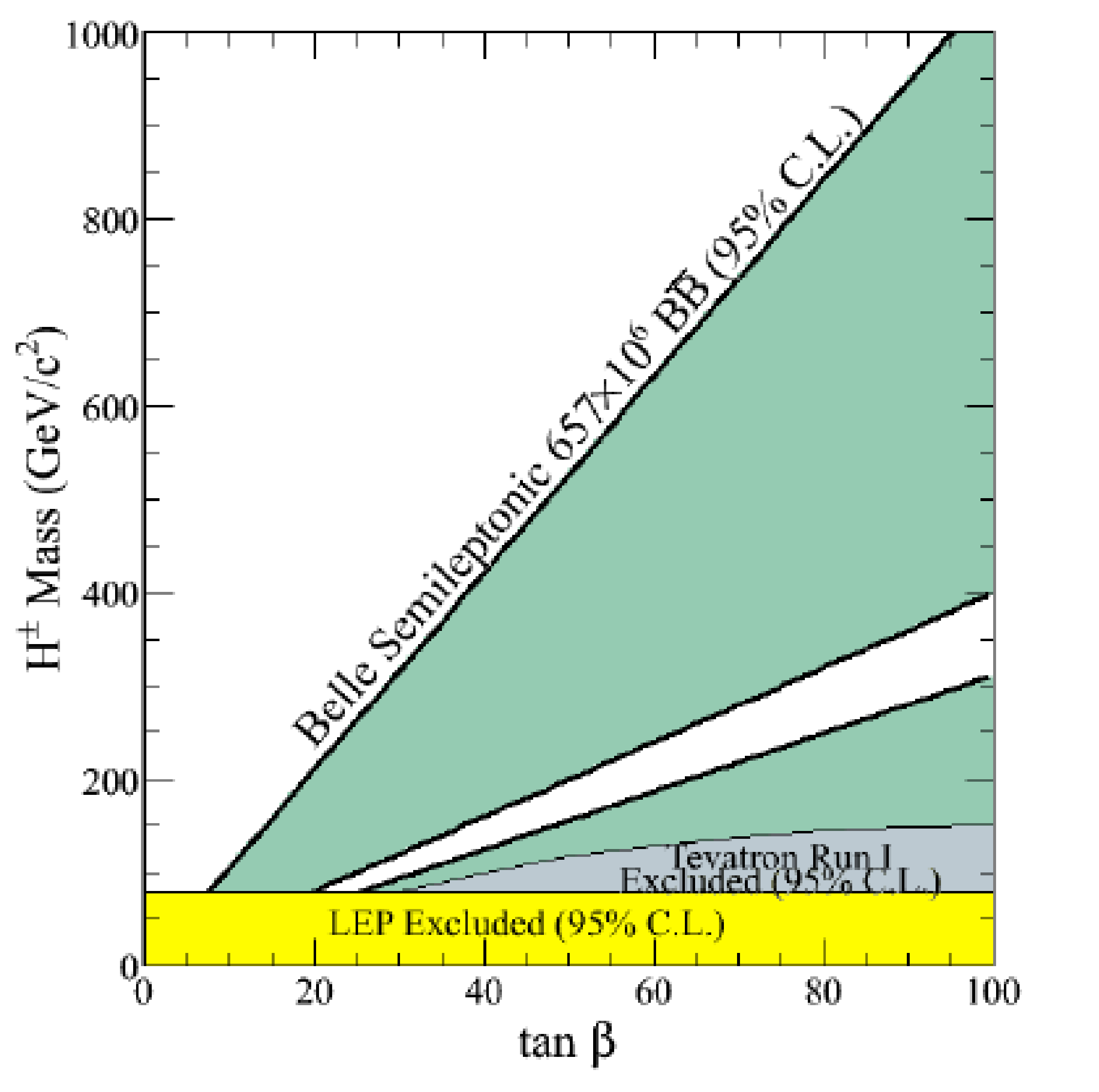
$$R_{B\tau\nu} = \frac{\mathcal{B}(B_u \to \tau\nu)}{\mathcal{B}(B_u \to \tau\nu)^{\rm SM}} = r_H = \left[1 - \tan^2\beta \, \frac{m_B^2}{m_{H^\pm}^2}\right]^2$$

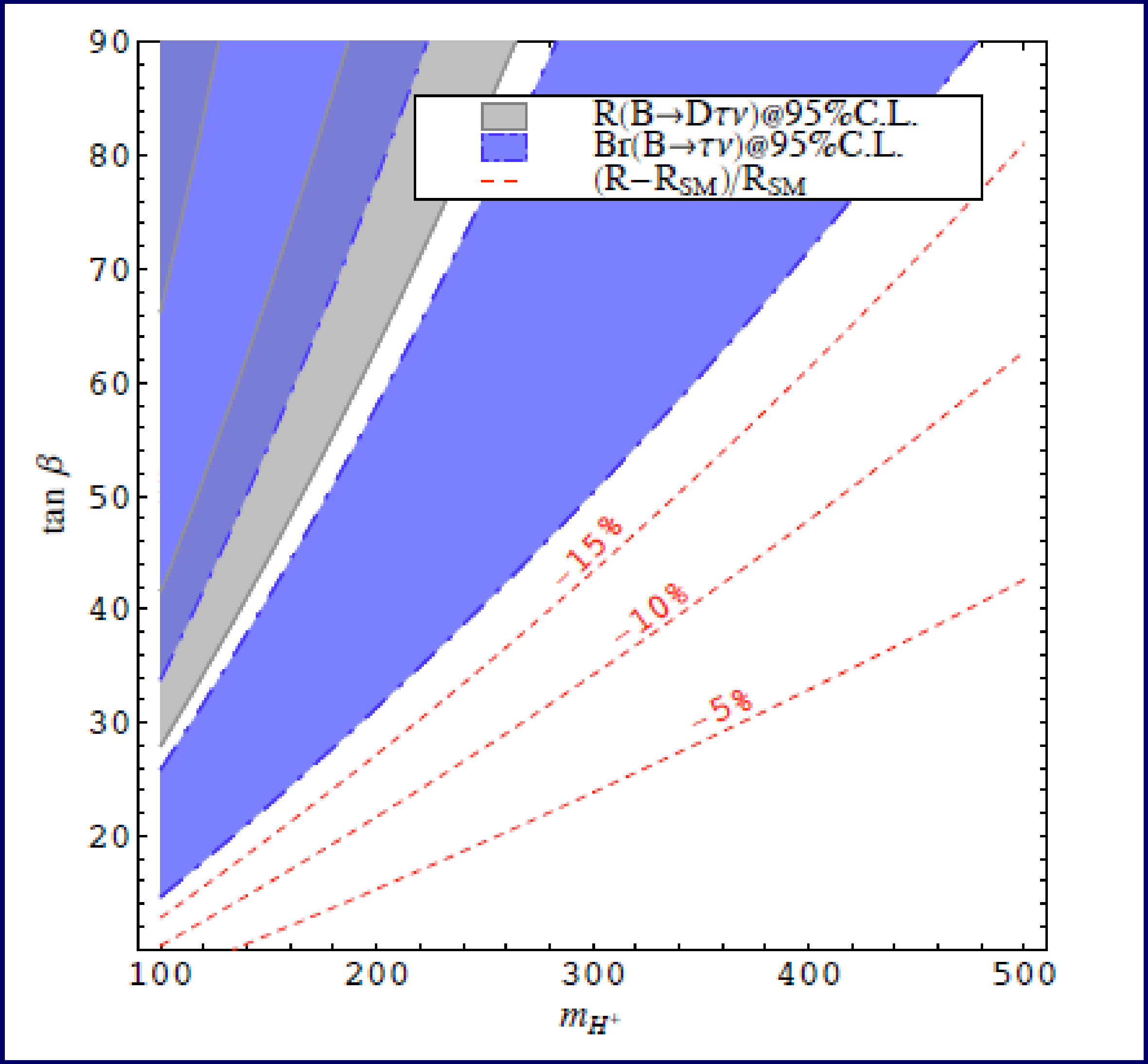
f_B dependence can be removed via ratio with Δm_d, error shrinks 25% → <13% (Isidori & Paradisi)

$$\left.\frac{\mathcal{B}(B_u \to \tau\nu)}{\tau_B \Delta M_{B_d}}\right|^{\rm SM} = 1.77 \times 10^{-4} \left(\frac{|V_{ub}/V_{td}|}{0.464}\right)^2 \left(\frac{0.836}{\hat{B}_{B_d}}\right)$$

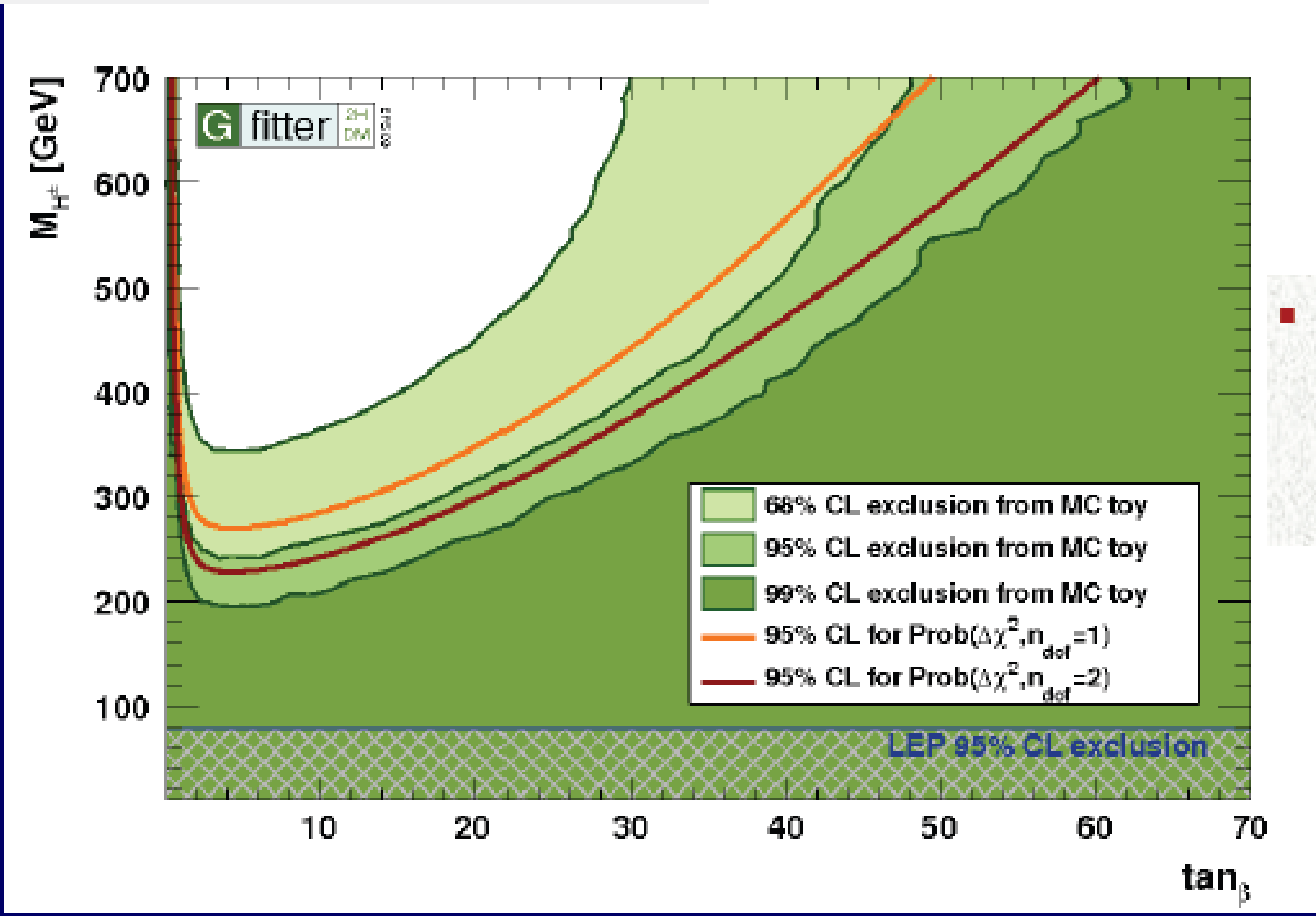
B to tau nu


(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
0.05
0.1
0.15
0.2
0.25
0.3
0.35


Belle Semileptonic 657×10⁶ 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
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+
90
80
70
60
50
40
30
20
100
200
300
400
500

2HDM: Combined Fit



Baak, EPS2009: Gfitter

Flavour constraints in 2HDM *F. Mahmoudi, O.Stahl*

Model I, II
Model III → Y
Model IV → X

CP conserving, soft Z2 + Z2

arXiv:0907.1791v1 [hep-ph] 10 Jul 2009

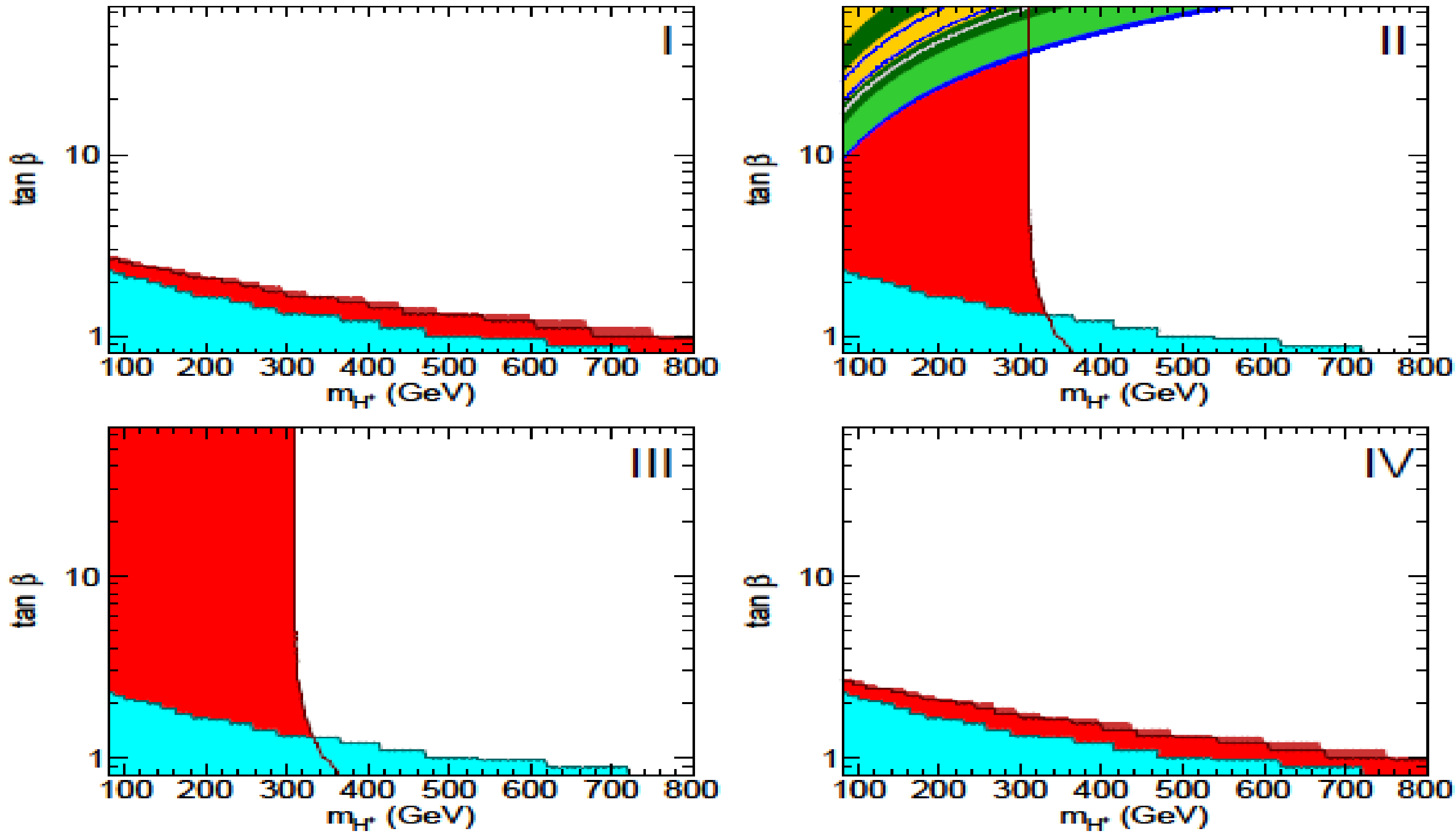
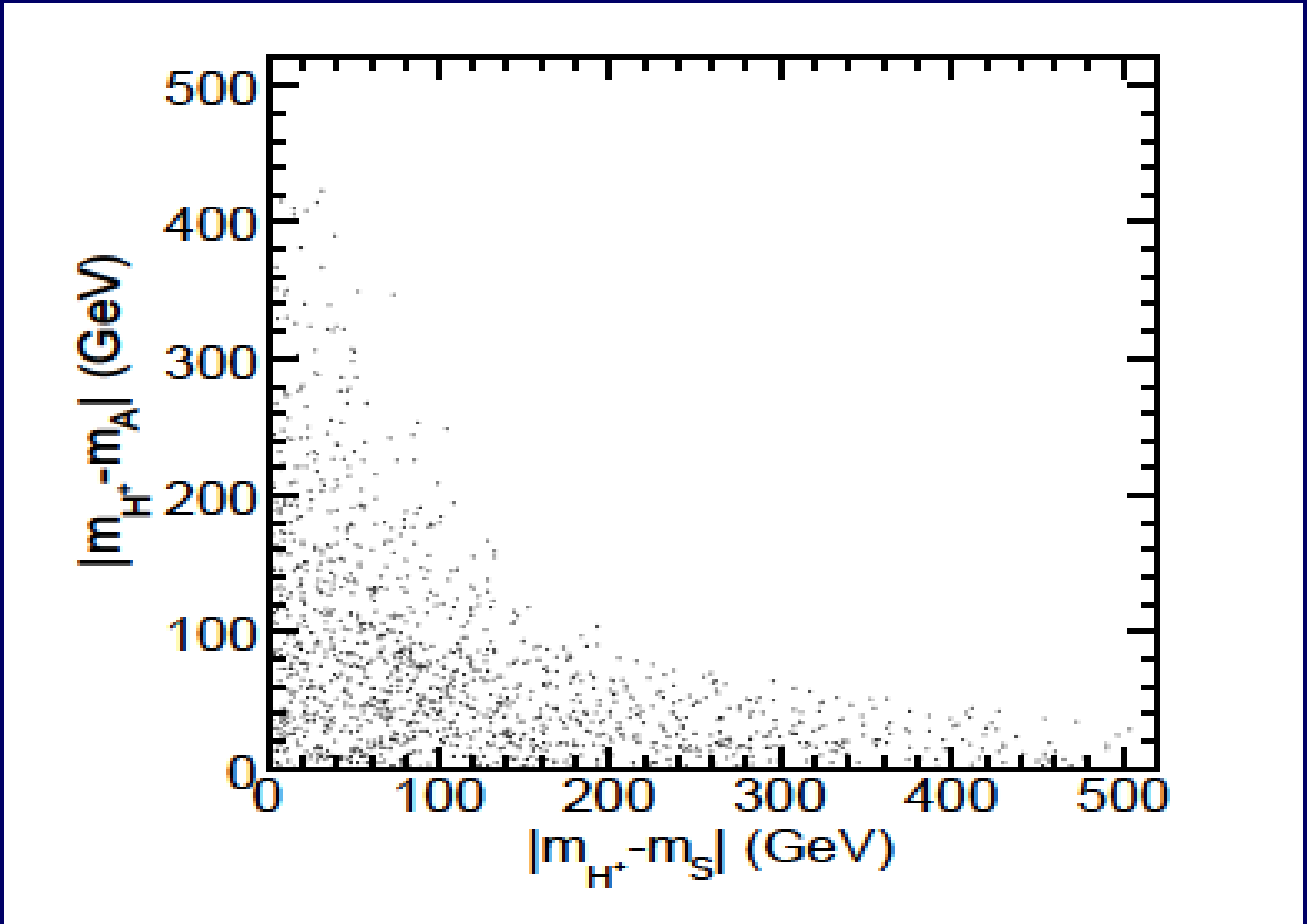


Figure 10: Excluded regions of the $(m_{H^+}, \tan\beta)$ parameter space for Z_2-symmetric 2HDM types. The color coding is as follows: BR($B \to X_s\gamma$) (light red), Δ_{0-} (dark red), ΔM_{B_d} (cyan), $B_u \to \tau\nu_\tau$ (blue), $B \to D\tau\nu_\tau$ (yellow), $K \to \mu\nu_\mu$ (gray contour), $D_s \to \tau\nu_\tau$ (light green), and $D_s \to \mu\nu_\mu$ (dark green).



S, T, U - from Grimus..08

Mh=114 GeV; others Higgses heavier

PDG limits [19] at the 2σ level are illustrated in Fig. 1. The figure shows the mass splittings $|m_{H^+} - m_A|$ and $|m_{H^+} - m_S|$, where $m_S^2 = m_H^2 \sin^2(\beta - \alpha) + m_h^2 \cos^2(\beta - \alpha)$ is a combined scalar mass. We see that the custodial symmetry, which ensures $T = 0$, is restored in either of the two cases: i) $m_{H^+} \simeq m_A$, or ii) $m_{H^+} \simeq m_S$ [8, 20].

Observable	Couplings	Experimental value	SM prediction
$\mathrm{BR}(\mathrm{B} \to \mathrm{X_s}\gamma)$	λ_{tt}^2, $\lambda_{tt}\lambda_{bb}$	$(3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$ [26]	$(3.11 \pm 0.22) \times 10^{-4}$
$\Delta_0(B \to K^*\gamma)$	λ_{tt}^2, $\lambda_{tt}\lambda_{bb}$	$(3.1 \pm 2.3) \times 10^{-2}$ [24]	$(8.2 \pm 2.0) \times 10^{-2}$
ΔM_{B_d}	λ_{tt}^2	(0.507 ± 0.004) ps^{-1} [26]	(0.67 ± 0.15) ps^{-1}
$\mathrm{BR}(\mathrm{B_u} \to \tau\nu_\tau)$	$\lambda_{bb}\lambda_{\tau\tau}$	$(1.73 \pm 0.35) \times 10^{-4}$ [27]	$(1.06 \pm 0.33) \times 10^{-4}$
$\xi_{D\ell\nu}$	$\lambda_{bb}\lambda_{\tau\tau}$, $\lambda_{cc}\lambda_{\tau\tau}$	$0.416 \pm 0.117 \pm 0.052$ [28]	0.29 ± 0.02
$R_{\ell 23}(K \to \mu\nu_\mu)$	$\lambda_{ss}\lambda_{\mu\mu}$	1.004 ± 0.007 [29]	1
$\mathrm{BR}(\mathrm{D_s} \to \mu\nu_\mu)$	$\lambda_{ss}\lambda_{\mu\mu}$, $\lambda_{cc}\lambda_{\mu\mu}$	$(5.8 \pm 0.4) \times 10^{-3}$ [30]	$(4.98 \pm 0.15) \times 10^{-3}$
$\mathrm{BR}(\mathrm{D_s} \to \tau\nu_\tau)$	$\lambda_{ss}\lambda_{\tau\tau}$, $\lambda_{cc}\lambda_{\tau\tau}$	$(5.7 \pm 0.4) \times 10^{-2}$ [30]	$(4.82 \pm 0.14) \times 10^{-2}$

An alternative to imposing a discrete symmetry is to make the dangerous off-diagonal elements sufficiently small to avoid experimental bounds from FCNC, but still allow for non-zero values. The trick is to achieve this without introducing too much fine-tuning. A step towards this end is taken by introducing a Cheng-Sher ansatz [22]

$$[\rho^F]_{ij} = [\lambda^F]_{ij}\frac{\sqrt{2m_i m_j}}{v} \qquad \text{(no sum)}, \tag{14}$$

which leads to a natural suppression of the off-diagonal elements for $\lambda \sim \mathcal{O}(1)$. This is true in particular for the lighter generations, where the experimental constraints are most restrictive.

Fit for Model II

best fit for mass H+ 608 GeV
and tan beta = 6.4 !

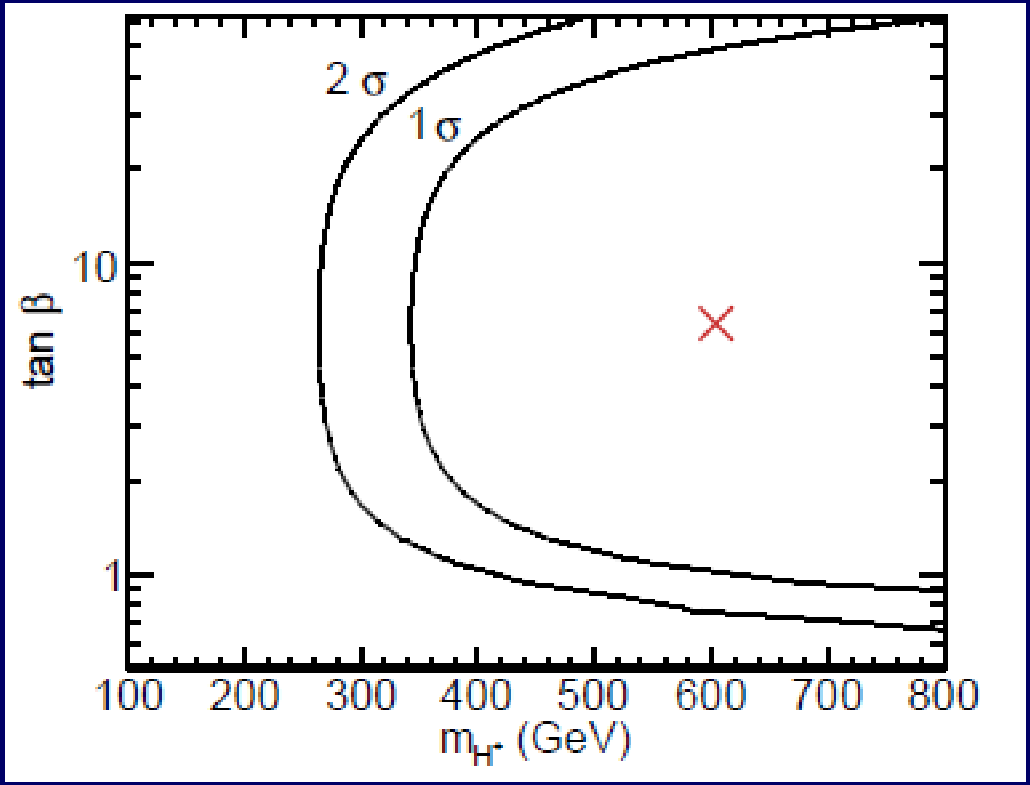


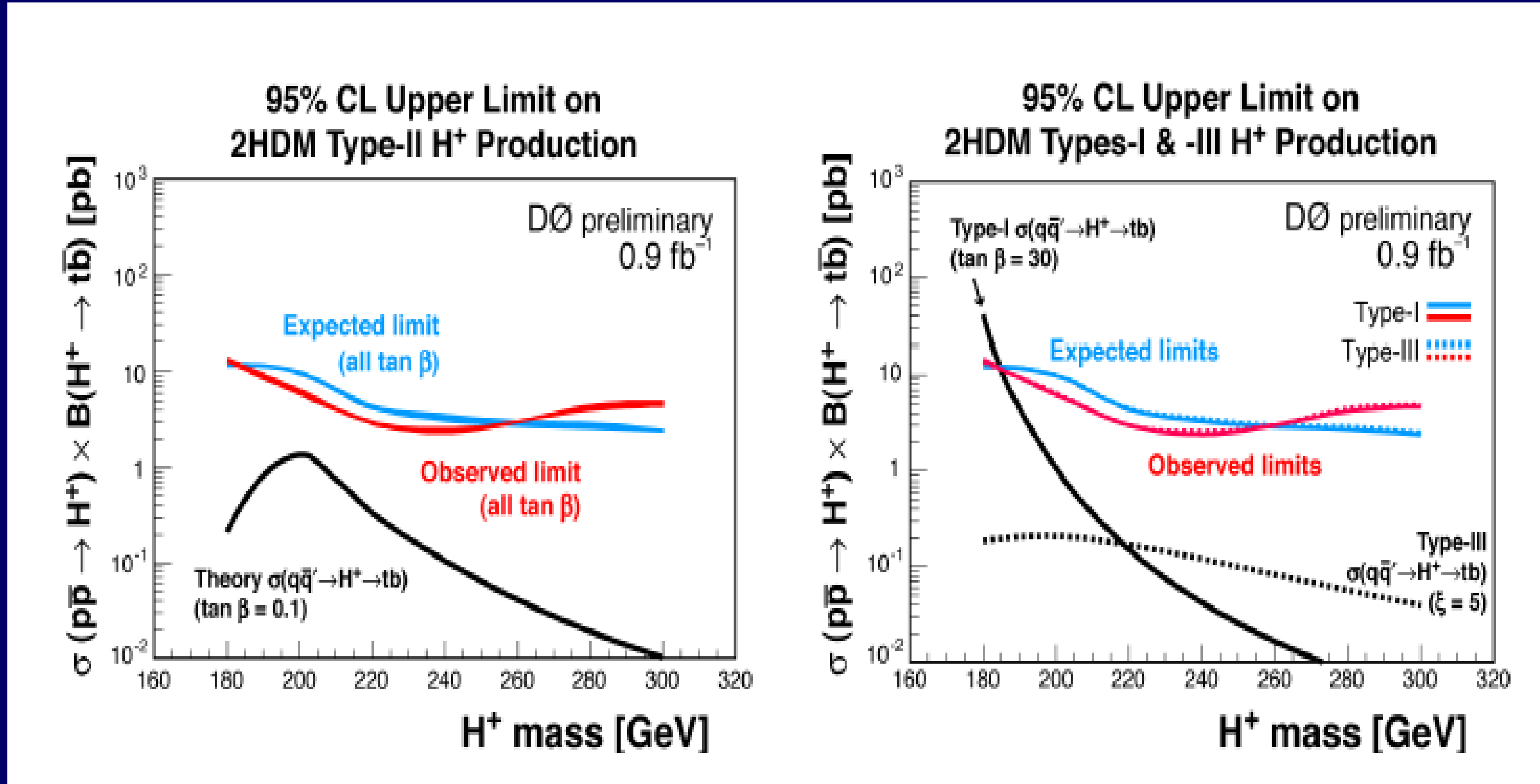
Figure 11: Combined parameter estimation in $(m_{H+}, \tan\beta)$ for the 2HDM II. The red cross indicates the best fit point $m_{H+} = 608$ GeV, $\tan\beta = 6.4$. The contours show levels of $\Delta\chi^2 = 2.30$ (6.18), corresponding to probabilities for $1\,\sigma$ $(2\,\sigma)$ Gaussian confidence intervals with two degrees of freedom.

Observable	Experimental	SM prediction	$\Delta\chi^2_{\rm SM}$	2HDM fit	$\Delta\chi^2_{\rm 2HDM}$	Pull
$\mathrm{BR}(\mathrm{B} \to \mathrm{X_s}\gamma)$	3.52×10^{-4}	3.11×10^{-4}	1.37	3.59×10^{-4}	0.04	0.20
$\Delta_0(B \to K^*\gamma)$	3.1×10^{-2}	8.2×10^{-2}	2.80	7.3×10^{-2}	1.90	1.38
ΔM_{B_d} (ps^{-1})	5.07×10^{-1}	6.72×10^{-1}	1.18	6.75×10^{-1}	1.22	1.10
$\mathrm{BR}(\mathrm{B_u} \to \tau\nu_\tau)$	1.73×10^{-4}	1.06×10^{-4}	1.07	1.05×10^{-4}	1.09	−1.04
$\xi_{D\ell\nu}$	0.416	0.29	0.84	0.297	0.84	−0.91
$R_{\ell 23}(K \to \mu\nu_\mu)$	1.004	1.000	0.33	1.000	0.33	−0.58
$\mathrm{BR}(\mathrm{D_s} \to \mu\nu_\mu)$	5.8×10^{-3}	4.98×10^{-3}	3.32	4.98×10^{-3}	3.36	−1.83
$\mathrm{BR}(\mathrm{D_s} \to \tau\nu_\tau)$	5.7×10^{-2}	4.82×10^{-2}	3.82	4.82×10^{-2}	3.82	−1.95
		Total $\chi^2(\nu)$:	14.7 (8)		12.6 (6)	

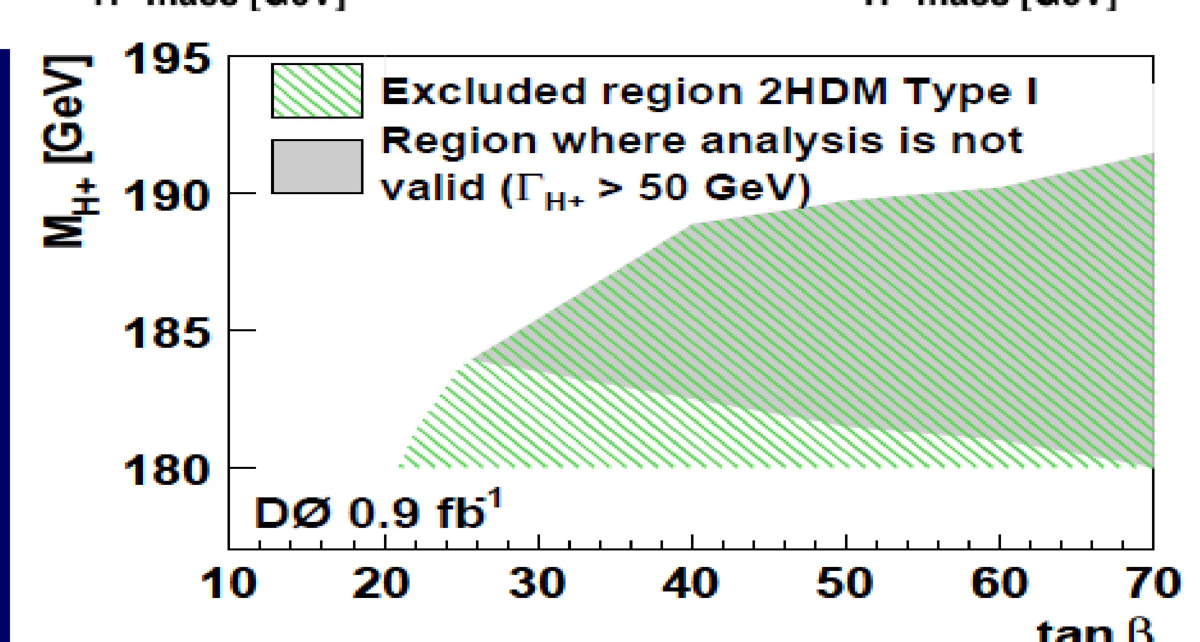
[23] D. Eriksson, J. Rathsman, and O. Stål arXiv:0902.0851. Code website: http://www.isv.uu.se/thep/MC/2HDMC.

[24] F. Mahmoudi *Comput. Phys. Commun.* **178** (2008) 745–754, [arXiv:0710.2067]; F. Mahmoudi arXiv:0808.3144. Code website: http://superiso.in2p3.fr.

D0



95% CL Upper Limit on
2HDM Type-II H+ Production
DØ preliminary
0.9 fb-1
Expected limit
(all tan β)
Observed limit
(all tan β)
Theory σ(qq̄′→H+→tb)
(tan β = 0.1)
σ (pp̄ → H+) × B(H+ → tb̄) [pb]
H+ mass [GeV]
95% CL Upper Limit on
2HDM Types-I & -III H+ Production
DØ preliminary
0.9 fb-1
Type-I σ(qq̄′→H+→tb)
(tan β = 30)
Type-I
Type-III
Expected limits
Observed limits
Type-III
σ(qq̄′→H+→tb)
(ξ = 5)
σ (pp̄ → H+) × B(H+ → tb̄) [pb]
H+ mass [GeV]



Excluded region 2HDM Type I
Region where analysis is not
valid (ΓH+ > 50 GeV)
DØ 0.9 fb-1
MH+ [GeV]
tan β

SM-like scenarios

- In many Standard Models
  SM-like scenarios are realized
  (Higgs mass >114 GeV, SM tree-level couplings
  or SM tree-level decay width)
- 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)

Signal of SM-like 2HDM

- 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)

  – no other Higgs particle seen

  typical decoupling (in 2HDM, MSSM)

Loop couplings ggh, γγh in 2HDM

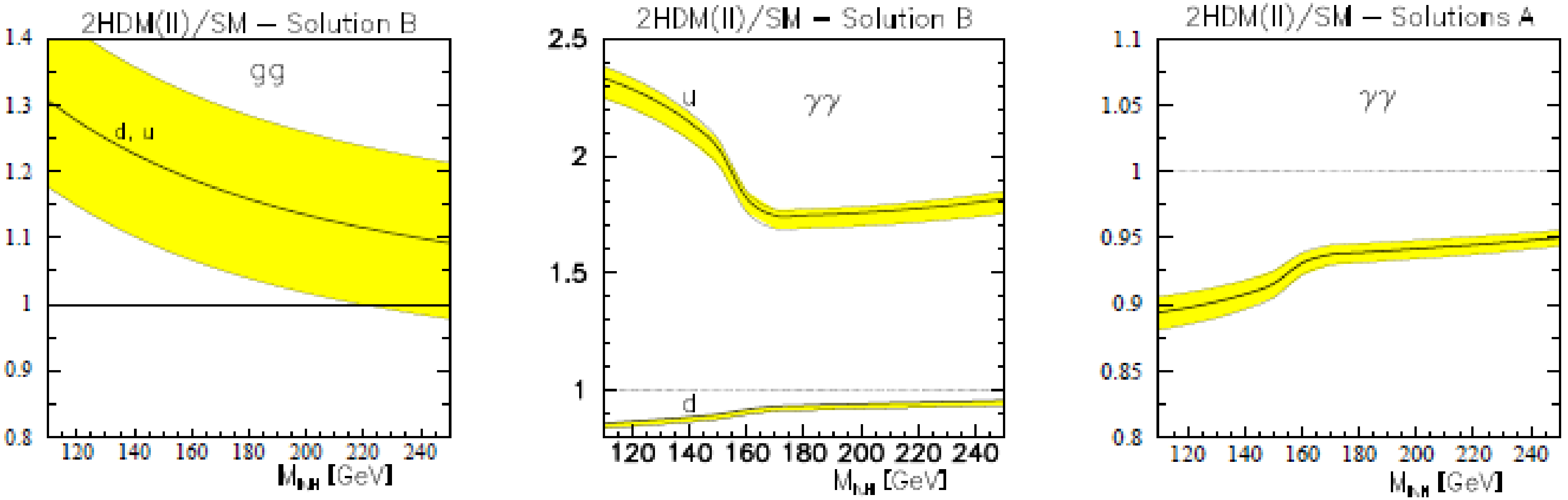
The coupling between neutral and charged Higgs bosons: $h_i H^+ H^-$

γγh

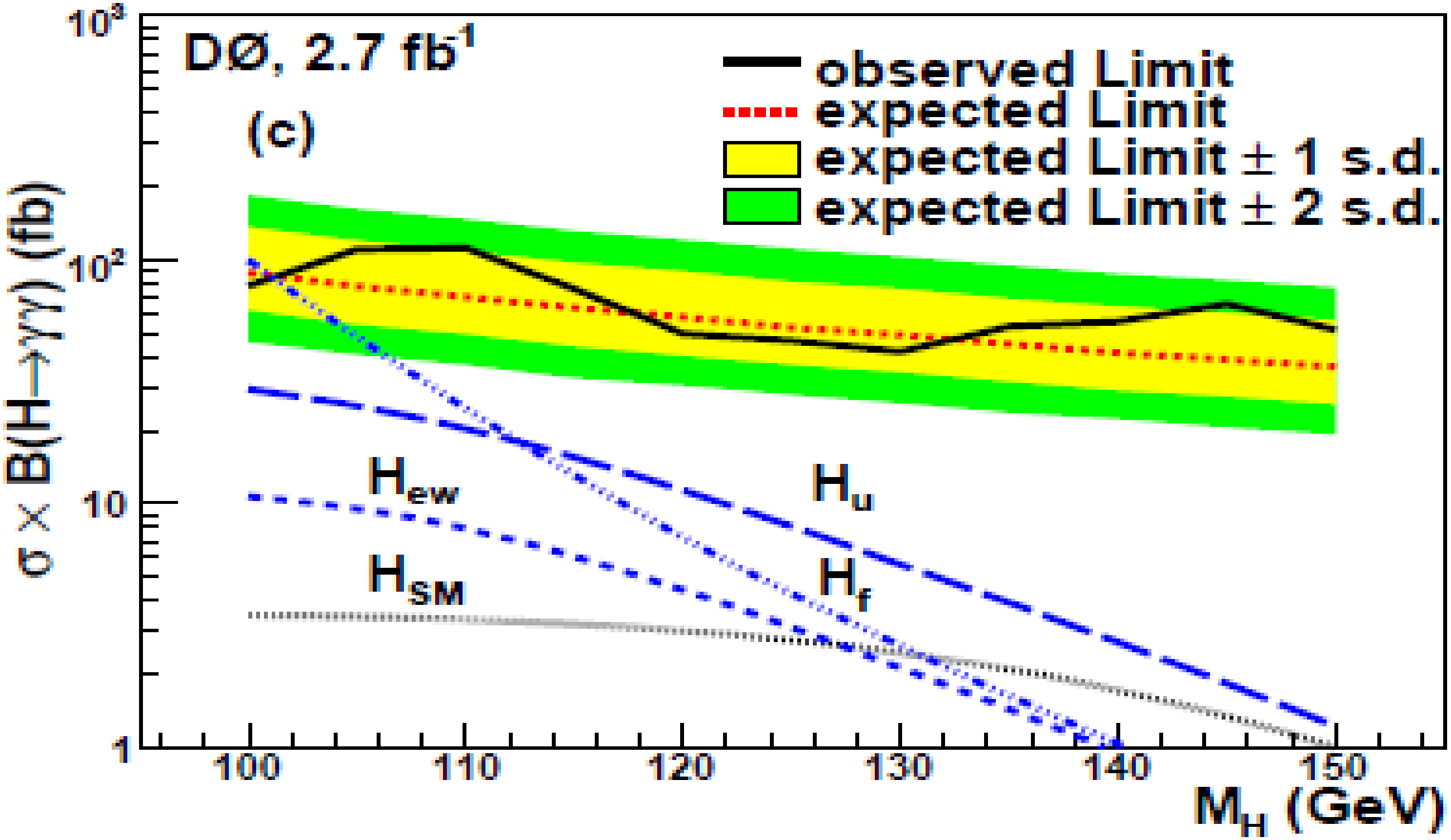
$$\chi_{H^\pm}^{(i)} = \left(1 - \frac{M_i^2}{2M_{H^\pm}^2}\right)\chi_V^{(i)} + \frac{M_i^2 - \nu v^2}{2M_{H^\pm}^2}\,\mathrm{Re}(\chi_u^{(i)} + \chi_d^{(i)}).$$

Ginzburg, Osland, MK

For small ν^2 m^2_{12} ...even for χ_V, χ_u, χ_d equal 1, (SM-like scenario A) → large non-decoupling effects due to heavy $H^\pm$. 600 GeV



ggh - solution B „wrong" signs of fermion couplings



the SM Higgs production rate at the Tevatron is not sufficient to observe it in the $\gamma\gamma$ mode, the Hgg and $H\gamma\gamma$ couplings, being loop-mediated, are particularly sensitive to new physics effects. Furthermore, in some models beyond the SM [2], $B(H \to \gamma\gamma)$ can be enhanced significantly relative to the SM prediction.

Often just opposite

Inert Model or Dark 2HDM

Ma..' 78, Barbieri.. ' 2006

- exact Z_2 in L <u>and</u> in vacuum →
  Z_2 parity – odd are only dark scalars

- nonzero vev only doublet Φ_1 → only it couples to fermions (Model I) → Higgs boson h SM-like

$$M^2_h = m_{11}^2 = \lambda_1 v^2$$

- four scalars from Φ_2 with Z_2-odd parity (dark scalars D) (no Yukawa interaction (so „inert"))

- the lightest dark scalar candidate for a dark matter
  here we consider H

Testing Inert Model

- To consider

  properties of SM-like h (light and heavy)

  properties of dark scalars

  (produced only in pairs!)

  DM candidate

- Colliders signal/constraints

  Barbieri et al '2006 for heavy h

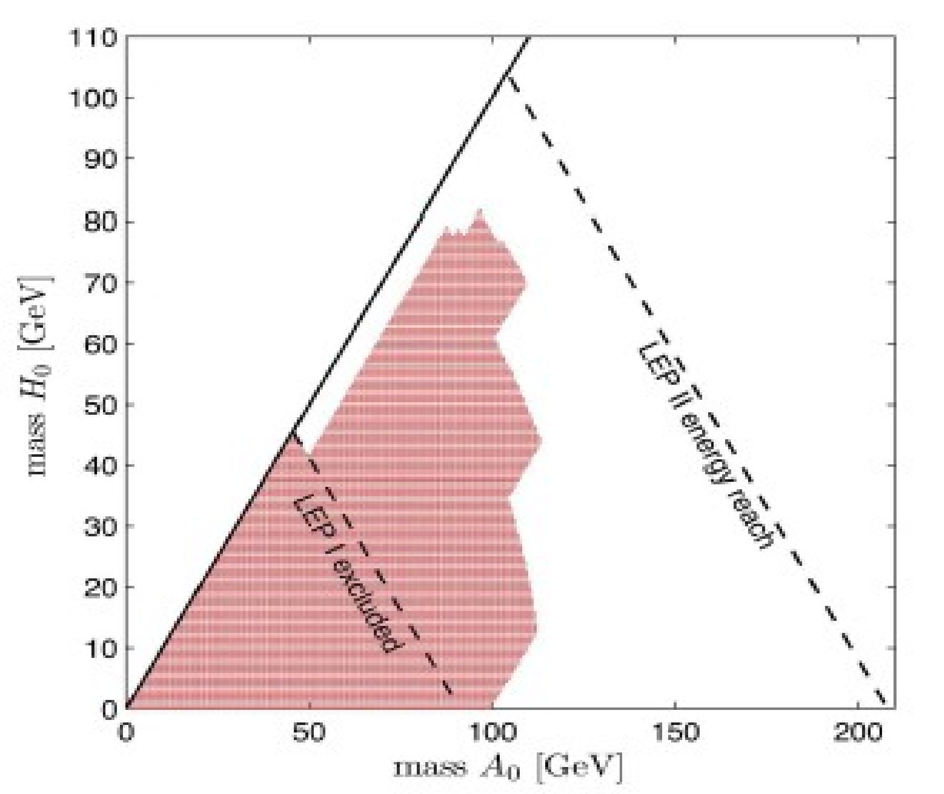
  Cao, Ma, Rajasekaren' 2007 for a light h

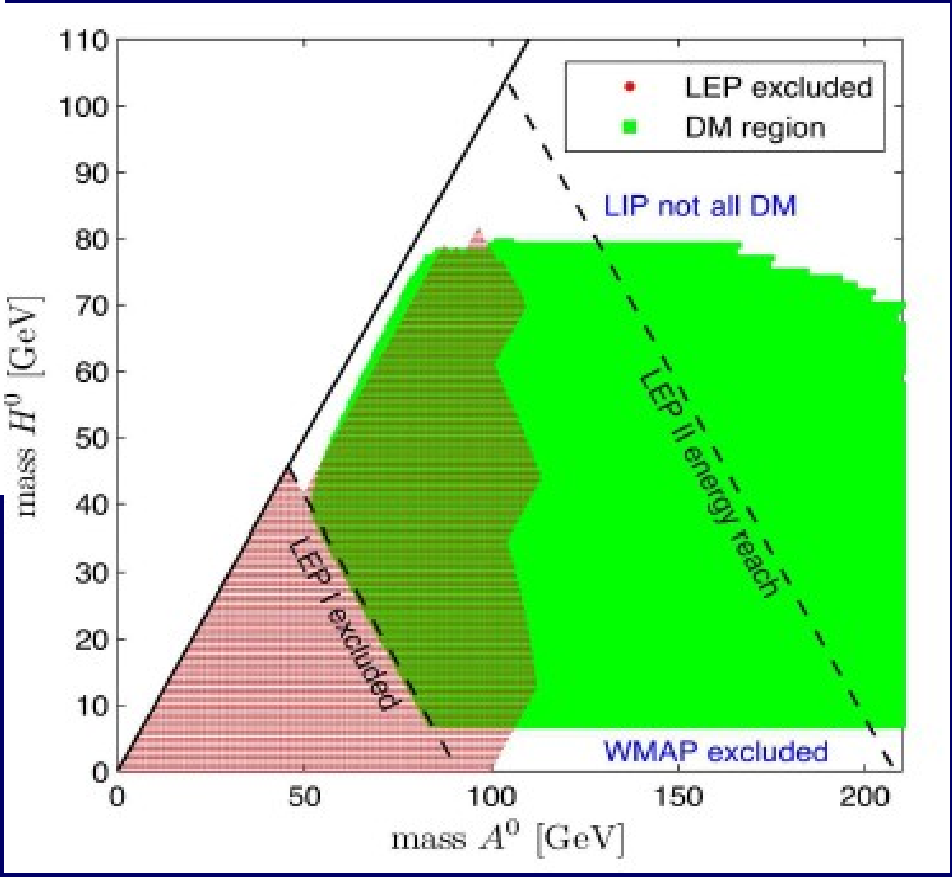
LEP II: $M_H + M_A > M_Z$, $\Delta(A, H) = 5 - 30$ GeV for $M_h = 105 - 110$ GeV

EW precision data: $(M_{H+} - M_A)(M_{H+} - M_H) = M^2, M = 120^{+20}_{-30}$ GeV

Dark 2HDM: LEP II exclusion

Lundstrom et al 0810.3924





LEP II + WIMP

M_h = 200 GeV

$M_A - M_H > 8$ GeV

Inert Model: constraints LEP+DM → LHC

E. Dolle, S. Su, 0906.1609 [hep-ph]

LEP (exclusion and EW precision data)

+ relic density using MicroOMEGA/CalCHEP

$\delta_1 = m_{H\pm} - m_S$ $\delta_2 = m_A - m_S$

Viable region for relic density

S=H

	DM	SM h	m_S	δ_1, δ_2	λ_L
(I)	low m_S	low m_h	30 – 60 GeV	50 - 90 GeV	-0.2 to 0
(II)			60 – 80 GeV	at least one is large	-0.2 to 0.2
(III)		high m_h	50 – 75 GeV	large δ_1, $\delta_2 < 8$ GeV	-1 to 3
(IV)			~ 75 GeV	large δ_1, δ_2	-1 to 3
(V)	high m_S	low m_h	500 – 1000 GeV	small δ_1, δ_2	-0.2 to 0.3

Collider reach @ LHC

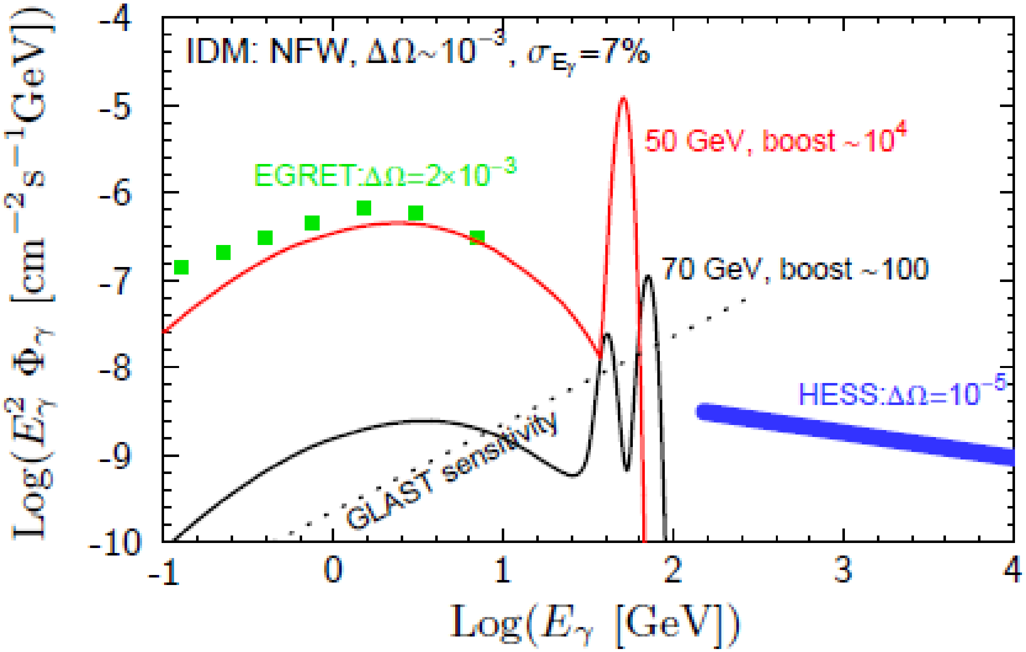
S = H (DM)

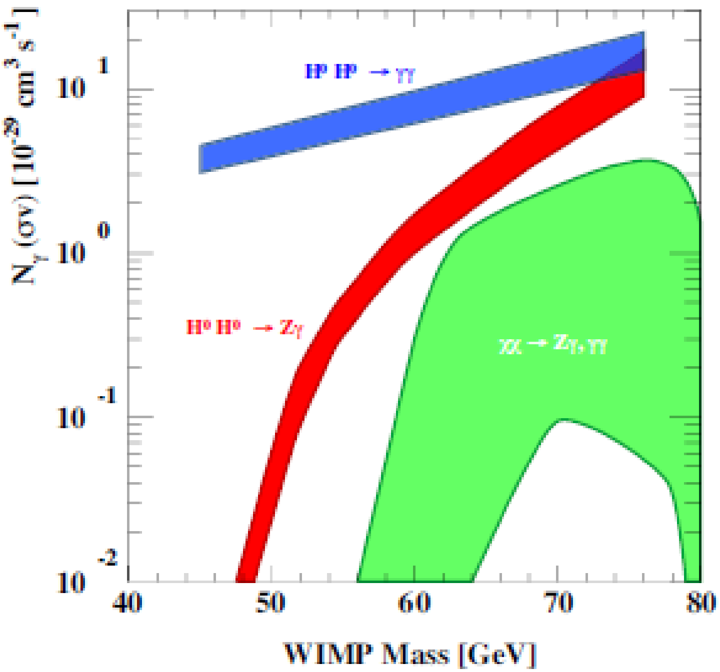
$pp \to SA \to SSZ^{(*)} \to SSl^+l^-$

	m_S	(δ_1, δ_2)	S	B	S/B	$S/\sqrt{(B)}$
	GeV	GeV	fb	fb	L=100 fb^{-1}	
LH1	40	(100,100)	3.68	102.18	0.04	3.64
LH2	40	(70,70)	0.97	0.88	1.11	10.37
LH3	82	(50,50)	0.19	0.47	0.40	2.75
LH4	73	(10,50)	0.22	0.47	0.47	3.23
LH5	79	(50,10)	0.33	0.30	0.09	0.52
HH1	76	(250,100)	0.69	27.17	0.03	1.33
HH2	76	(200,30)	1.22	27.65	0.04	2.32

Significant Gamma Lines from Inert Doublet Model

Gustafsson, Lundstrom, Bergstrom, Edsjo' 2007 studied direct annihilation of HH into $\gamma\gamma$ and $Z\gamma$ for M_H between 40-80 GeV (loop process, energy below WW threshold).





Conclusion on gamma lines

- Gustafsson et al.2007: *striking DM line signals -promising features to search with GLAST*

Mass of: H = 40-80 GeV, H+ = 170 GeV,

A = 50-70 GeV, h = 500 and 120 GeV

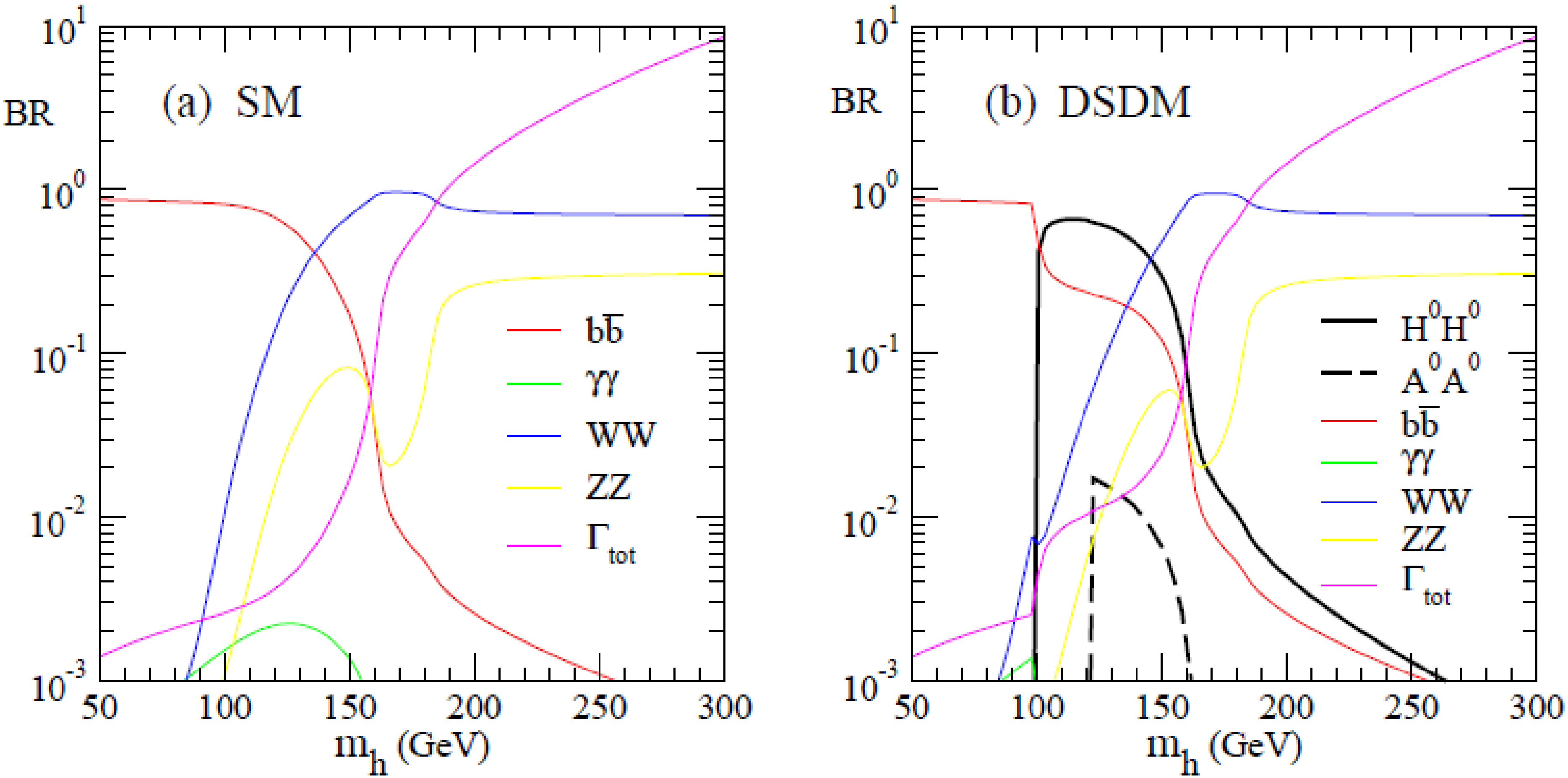
- Honorez, Nezri, Oliver, Tytgat 2006-7

H as a perfect example or arcgetype of WIMP – within reach of GLAST (FERMI)

Here mass of h = 120 GeV, large mass H+ close to A = 400-550 GeV

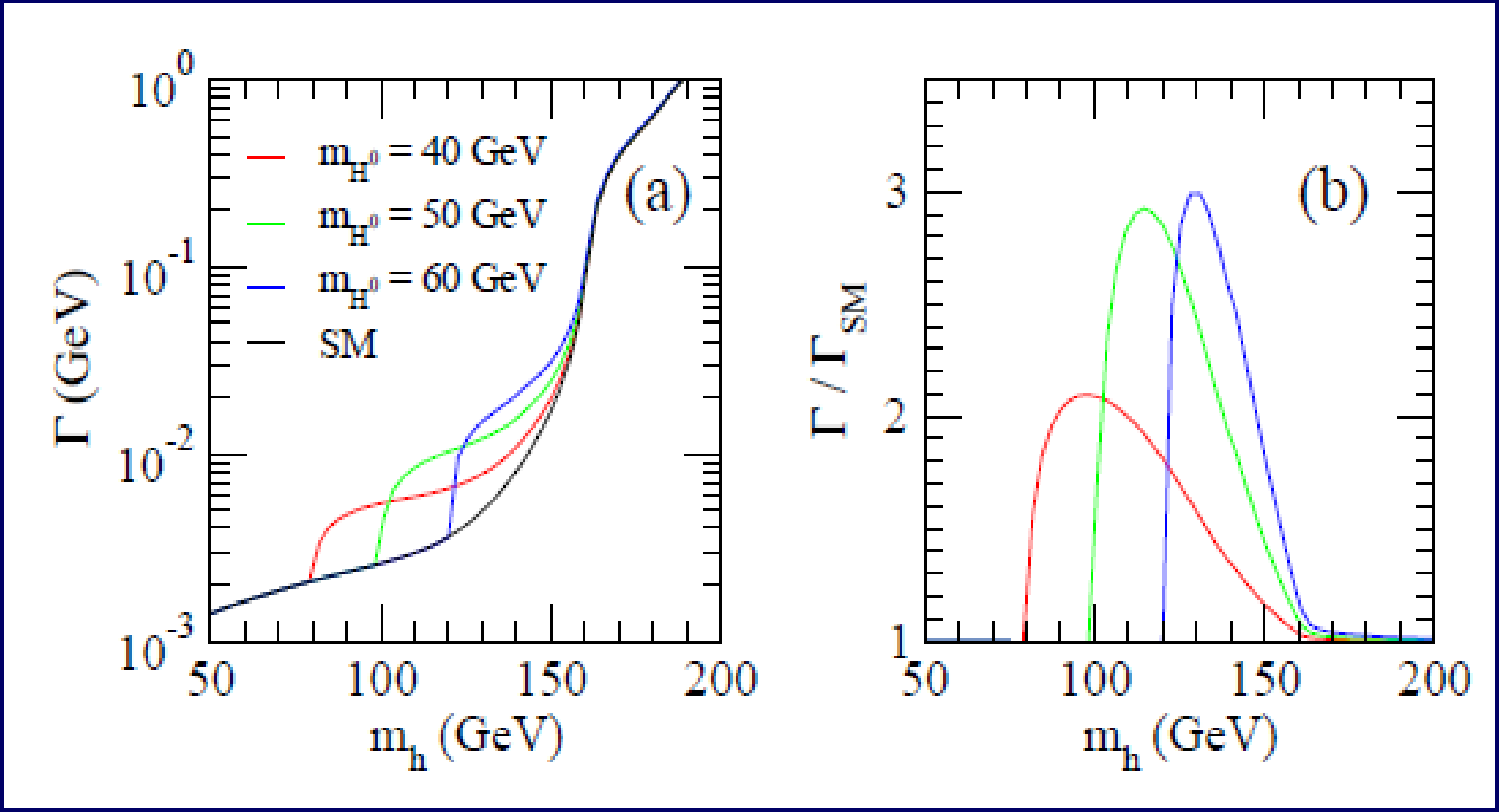
Dark 2HDM – additional decays for h

Ma' 2007

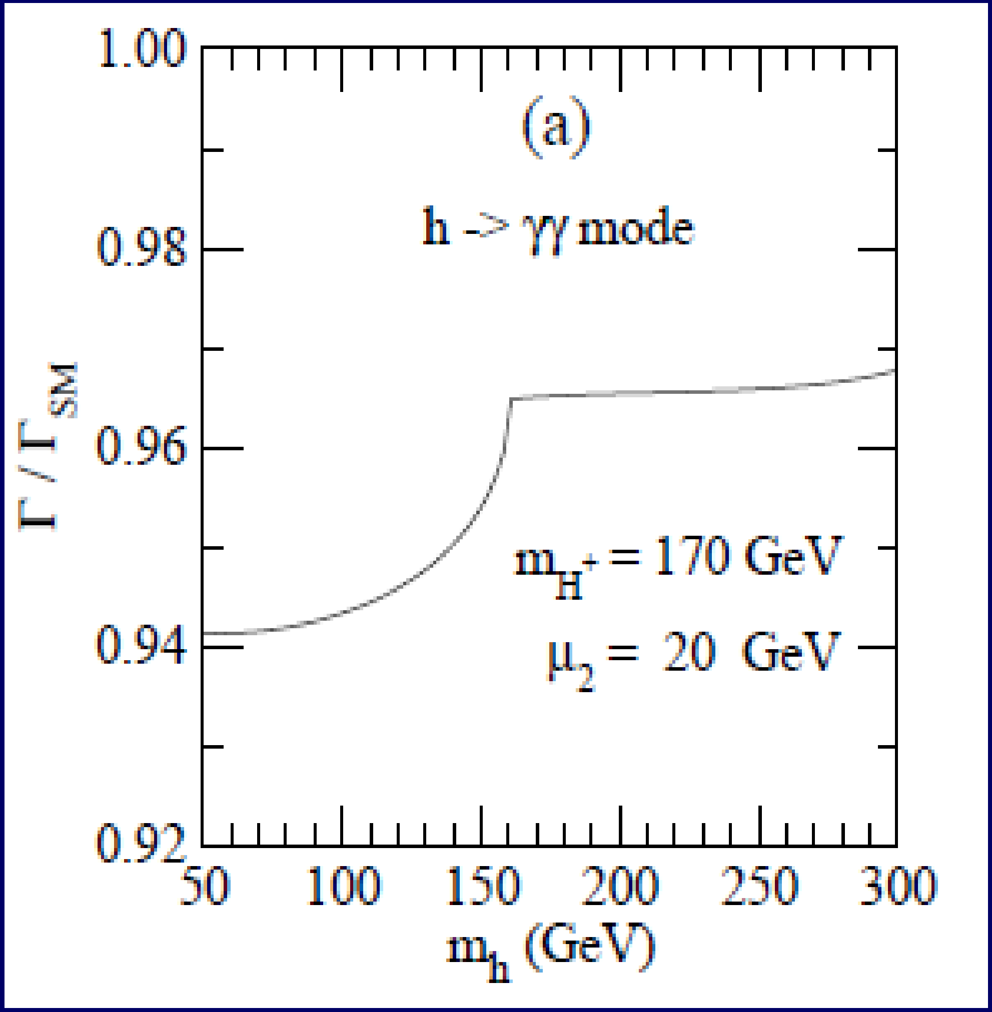


For $M_H = 50$ GeV, $\Delta(A,H)$=10 GeV, M_{H+}=170 GeV, m_{22}=20 GeV

Dark 2HDM – total width of h



Dark 2HDM: $\gamma\gamma$h



ILC experiments

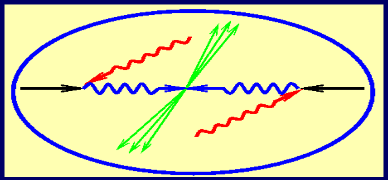
- Highest e^+e^- energy and variable energy: 200-500 GeV
- High luminosity: 500-1000/fb
- >80% e^- polarization (mandatory)

  >50% e^+ polarization
- Upgrade to ~1 TeV in the second stage.
- Possible Options: GigaZ, e^-e^-, $\gamma\gamma$, $e\gamma$ (PLC)
- Excellent detector performance: tracking, vertexing, jet energy resolution.

Energy scan, polarization, detector performance are all essential for physics studies at ILC.

Some of options may become very important from the results from LHC and early stage of ILC.

PLC: Photon Linear Collider
$\gamma\gamma$ and e γ



- Resonance production of C=+ states (eg. Higgs) Ginzburg et al
- Higher mass reach
- Polarised beams – CP filter Gunion, Grzadkowski, Godbole,Zarnecki
- H $\gamma\gamma$ coupling – sensitive to charged particles in theory (nondecoupling) Ginzburg et al.., Gunion..

- Direct production of charged scalars, fermions and vectors – higher cross section Monig,
- Pair production of neutral particles (eg. light-on-light) via loops Jikia, Gounaris…
- Study of hadronic interaction of the photon Godbole,Pancheri; MK Brodsky, deRoeck,Zerwas

Higgs coupling to $\gamma\gamma$: Br ~2%

$$\gamma\gamma \to h \to b\bar{b}$$

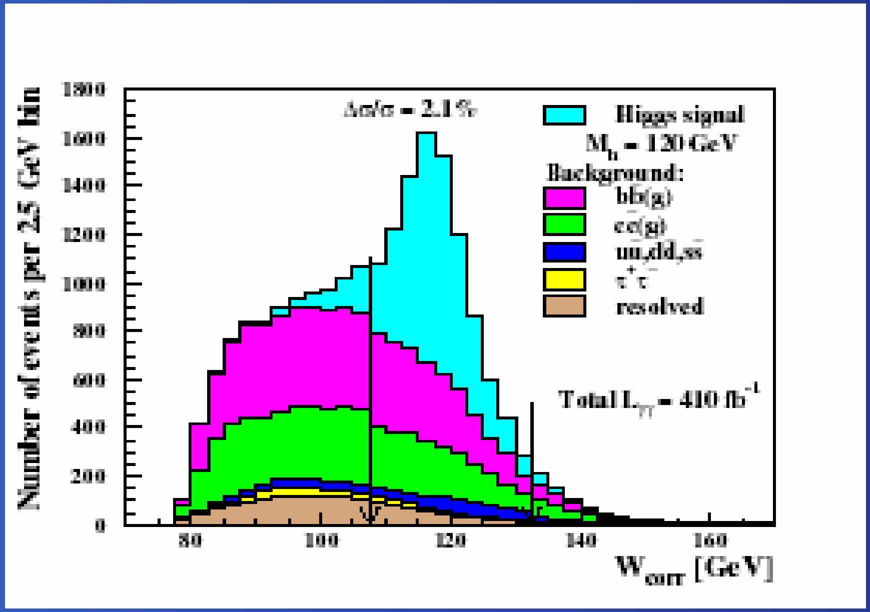
NŻK

SM summary

Niezurawski et al.,

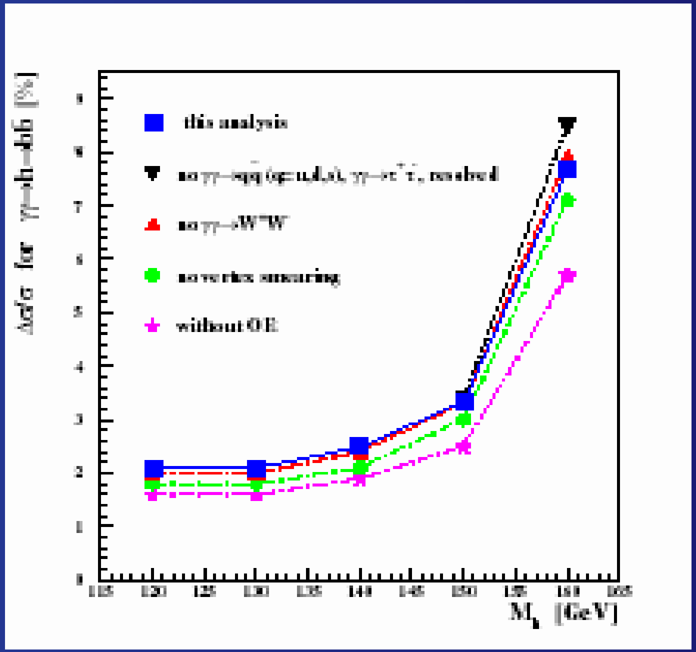
Monig, Rosca

→ Results for $M_h = 120$ GeV



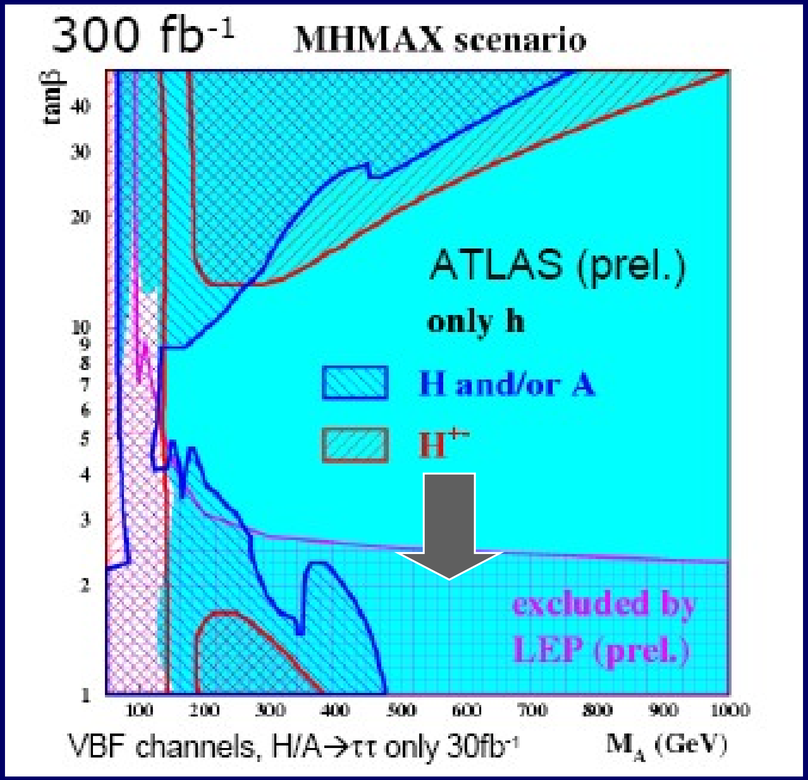
Corrected invariant mass distributions for signal and background events

Results for $M_h = 120$-160 GeV



For $M_h = 150, 160$ GeV additional cuts to reduce $\gamma\gamma \to W^+W^-$

MSSM Higgs searches/overall discovery potential (300 fb^{-1})



Result assuming no H→SUSY

at least 1 Higgs boson is observable

- in some parts >1 Higgs bosons observable in the whole parameter space

- But large area in which only one Higgs boson observable

LHC wedge!!!

Jack Gunion

Basic question: Could we distinguish between SM and MSSM Higgs sector
- e.g via rate measurements?

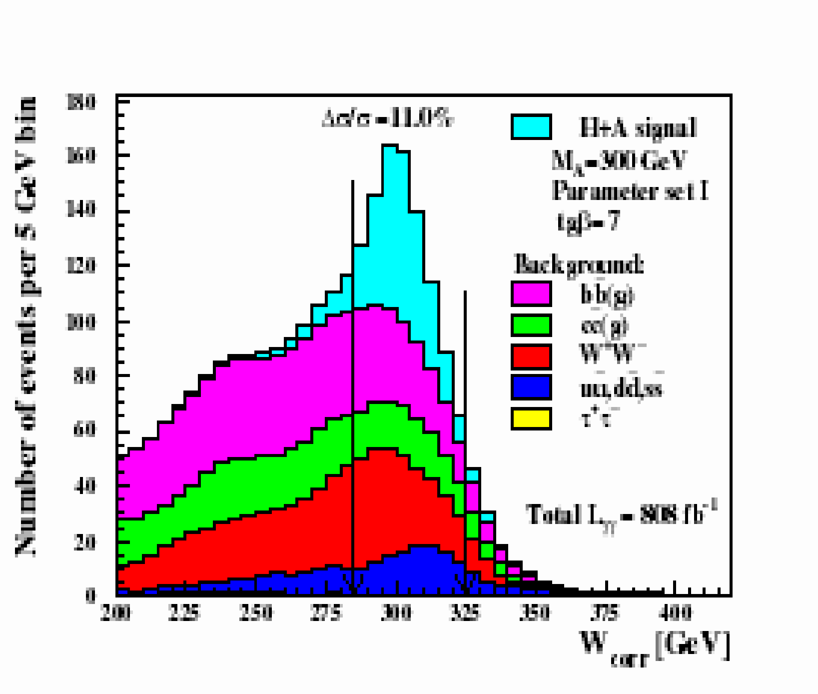
MSSM: Precision at PLC

Niezurawski et al., Spira et al

Covering the LHC wedge

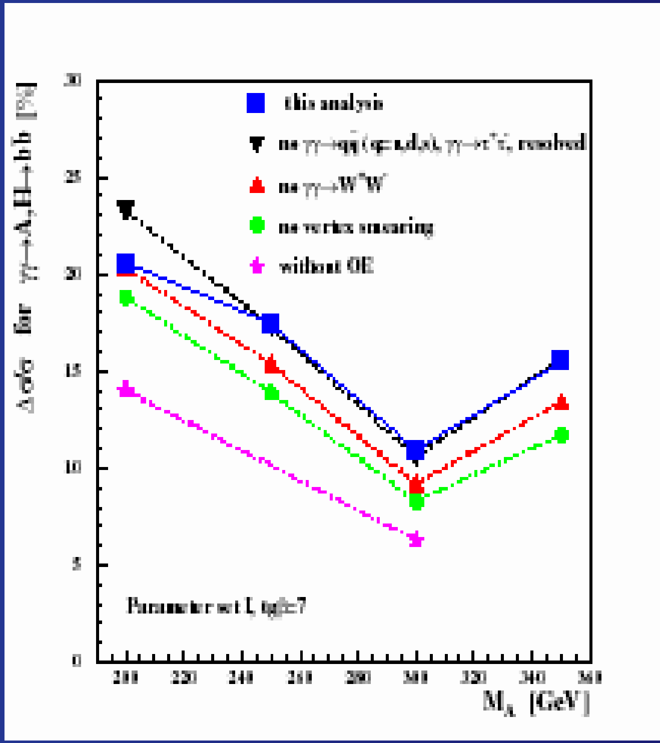
Precision of $\sigma(\gamma\gamma \to A, H \to b\bar{b})$ mesurement

Results for $M_A = 300$ GeV



Corrected invariant mass distributions

Results for $M_A = 200$-350 GeV



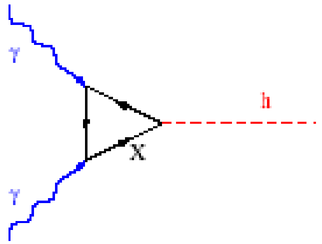
our previous results compared

Neutral Higgs bosons decaying into WW/ZZ pairs with mass above 200 GeV at PLC
Simulations for CP conserving and violating 2HDM

PLC

Żarnecki et al.

Cross section for the Higgs boson production at the Photon Collider is proportional to the two-photon width



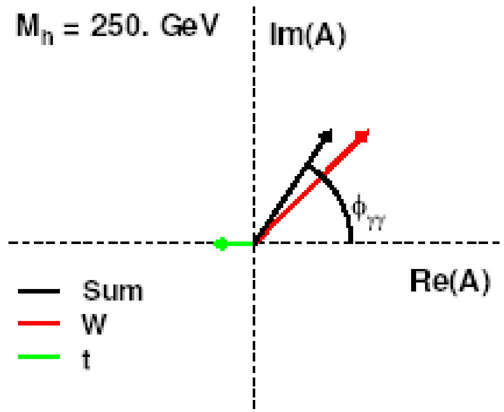
$$\Gamma(h \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\,\pi^3} \cdot |\mathcal{A}|^2$$

where:

$$\mathcal{A} = A_W(M_W) + \sum_f N_c Q_f^2 A_f(M_f) + \ldots$$

two-photon amplitude

In SM, dominant contributions to two-photon amplitude $\mathcal{A}$ are due to $W^{\pm}$ and top loops.



Phases of $W^{\pm}$ and top contributions differ

Phase of top distribution changes with Φ_{HA} !

$\Rightarrow$ Both $\Gamma_{\gamma\gamma}$ and the phase of the amplitude $\phi_{\gamma\gamma}$ depend on χ_V and χ_t

Interference with SM - both partial width and phase for h γ γ vertex can be tested.

Similar effect in the tt final state - Asakawa et al

2HDM (II) with CP violation

$H - A$ mixing

Mass eigenstates of the neutral Higgs-bosons h_1, h_2 and h_3
do not need to match CP eigenstates h, H and A.

We consider weak CP violation through a small mixing between H and A states:

$$\chi_X^{h_1} \approx \chi_X^{h}$$
$$\chi_X^{h_2} \approx \chi_X^{H} \cdot \cos\Phi_{HA} + \chi_X^{A} \cdot \sin\Phi_{HA}$$
$$\chi_X^{h_3} \approx \chi_X^{A} \cdot \cos\Phi_{HA} - \chi_X^{H} \cdot \sin\Phi_{HA}$$

$\Rightarrow$ additional model parameter: **CP-violating mixing phase Φ_{HA}**

$\Rightarrow$ see our paper JHEP 0502:041,2005 [hep-ph/0403138]

In general case

combined analysis of LHC, Linear Collider and Photon Collider data is needed

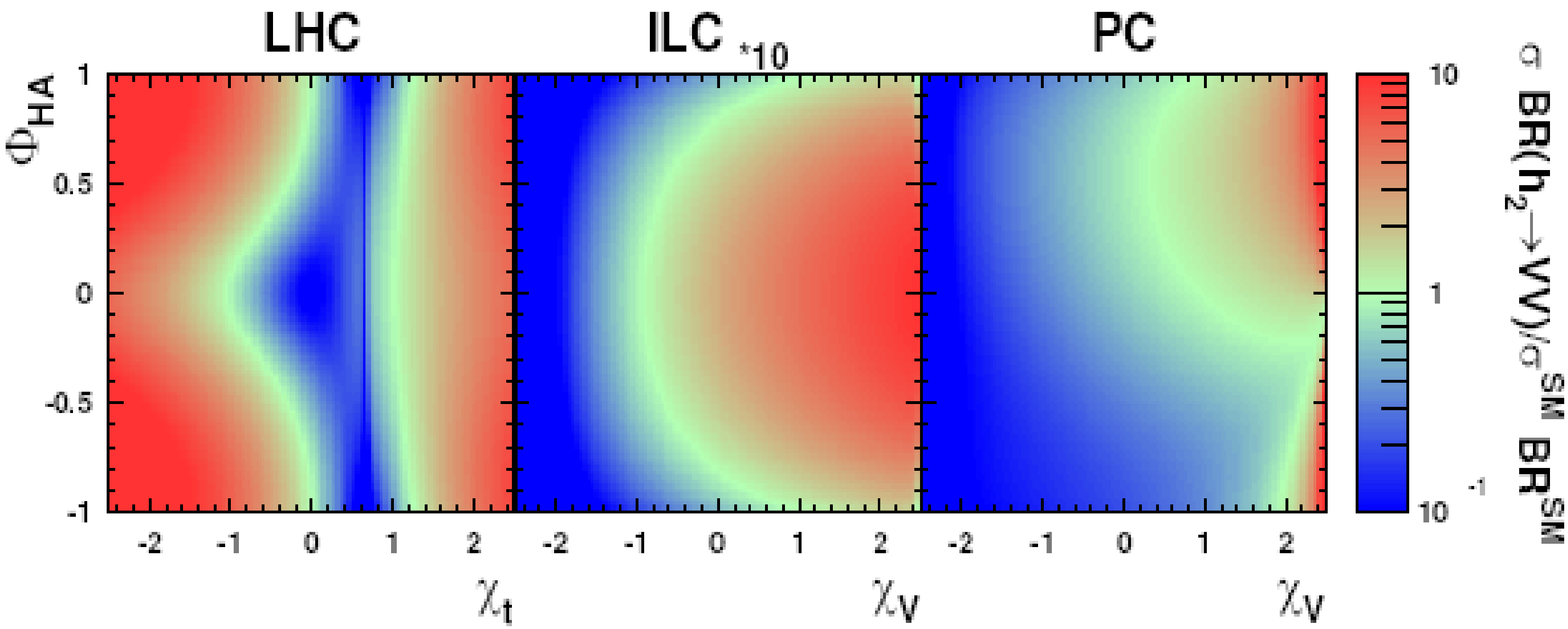
We consider h_2 production and decays, for $|\Phi_{HA}| \ll 1$ (weak CP violaion)

Zarnecki, Niezurawski, MK

LHC $\oplus$ ILC $\oplus$ PC

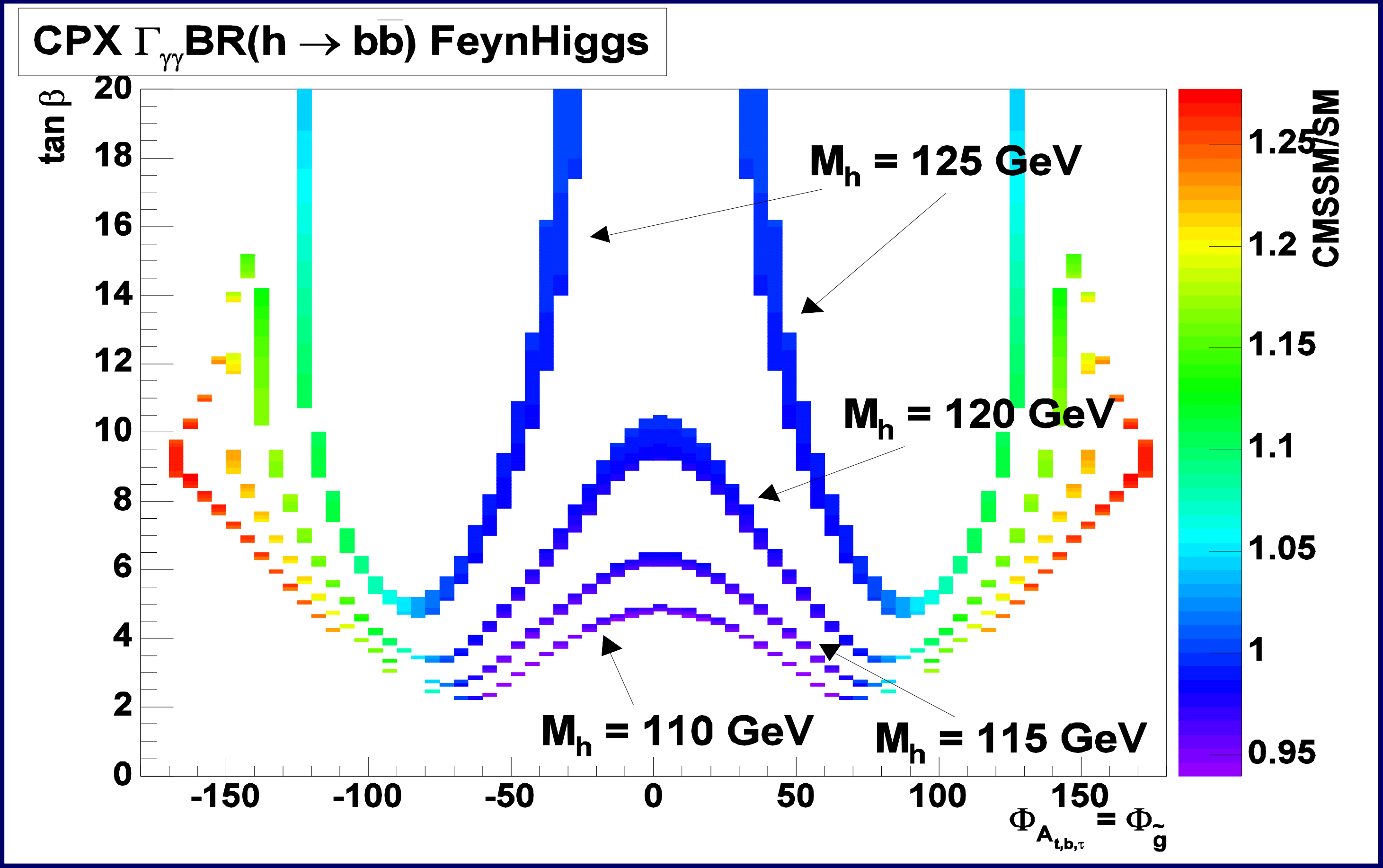
Sensitivity of LHC, ILC and Photon Collider measurements to CP-violating mixing phase Φ_{HA}

Cross sections $\times$ BR relative to SM $\qquad M_H = 250 GeV$



CPX scenario (max CP violation in CMSSM) studied for LHC, ILC, PLC (CLIC ?)

by Heinemeyer, Velasco 2004



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:

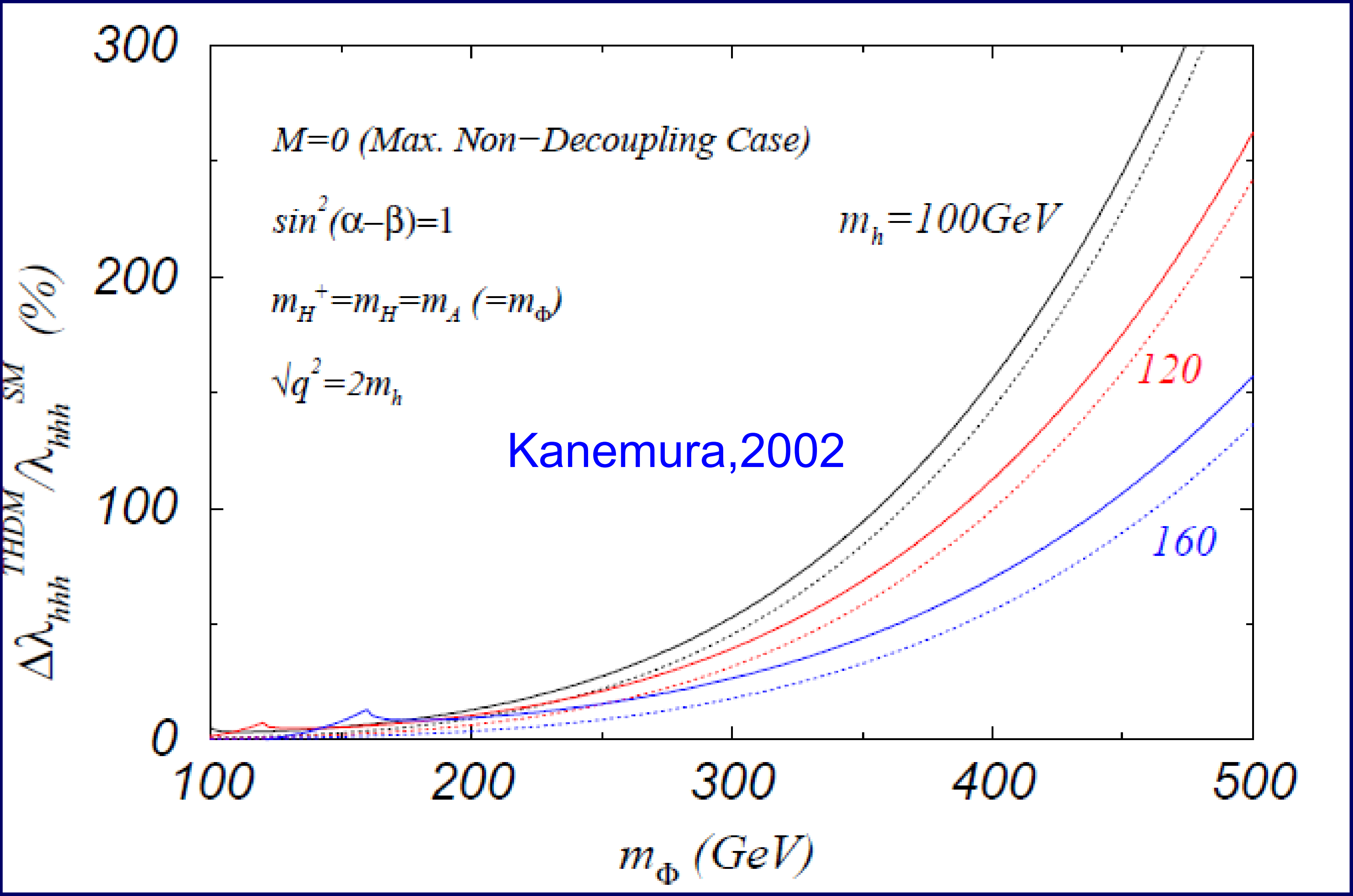
- MSSM with decoupling of heavy Higgses

  → *LHC-wedge*

- 2HDM with and without CP violation

  both h or H can be SM-like

- Dark 2HDM (Intert Model)



M=0 (Max. Non−Decoupling Case)
sin²(α−β)=1
m_H+=m_H=m_A (=m_Φ)
√q²=2m_h
m_h=100GeV
120
160
Kanemura,2002
Δλ_hhh^THDM/λ_hhh^SM (%)
m_Φ (GeV)
0
100
200
300
400
500

Search for Higgs bosons predicted in two-Higgs-doublet models via decays to tau lepton pairs in 1.96 TeV $p\bar{p}$ collisions

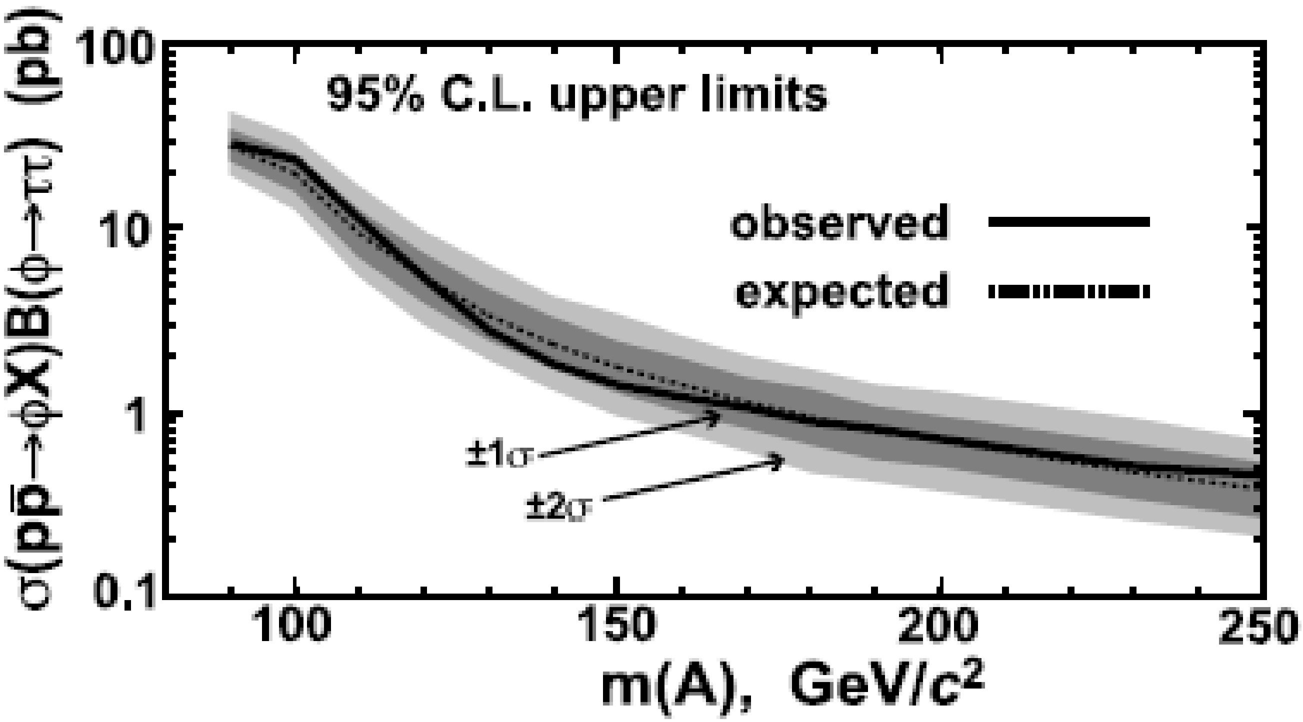


FIG. 2: Observed 95% C.L. upper limits on the cross section for $\phi = h/A/H$ production as a function of m_A. The grey bands show the median expected limit under the null hypothesis, and indicate the ±1- and ±2-standard-deviation ranges.