

# H<sup>+</sup> Workshop 2012

## Uppsala 10.10.2012

# H<sup>+</sup> Benchmarks for 2HDM

**Maria Krawczyk  
(University of Warsaw)**

in collaboration with P. Osland and R. Santos, S. Moretti, M. Pruna, M. Raidal, T. Hurth, A. Akceroyd, I. Ginzburg, B. Świeżewska and many others

# Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

$$SU(2) \times U(1) \rightarrow ?$$

T.D. Lee 1973

## Two Higgs Doublet Models

Two doublets of  $SU(2)$  ( $Y=1, \rho=1$ ) -  $\Phi_1, \Phi_2$

Masses for  $W^{+-}, Z$ , no mass for photon?

Fermion masses via Yukawa interaction –

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

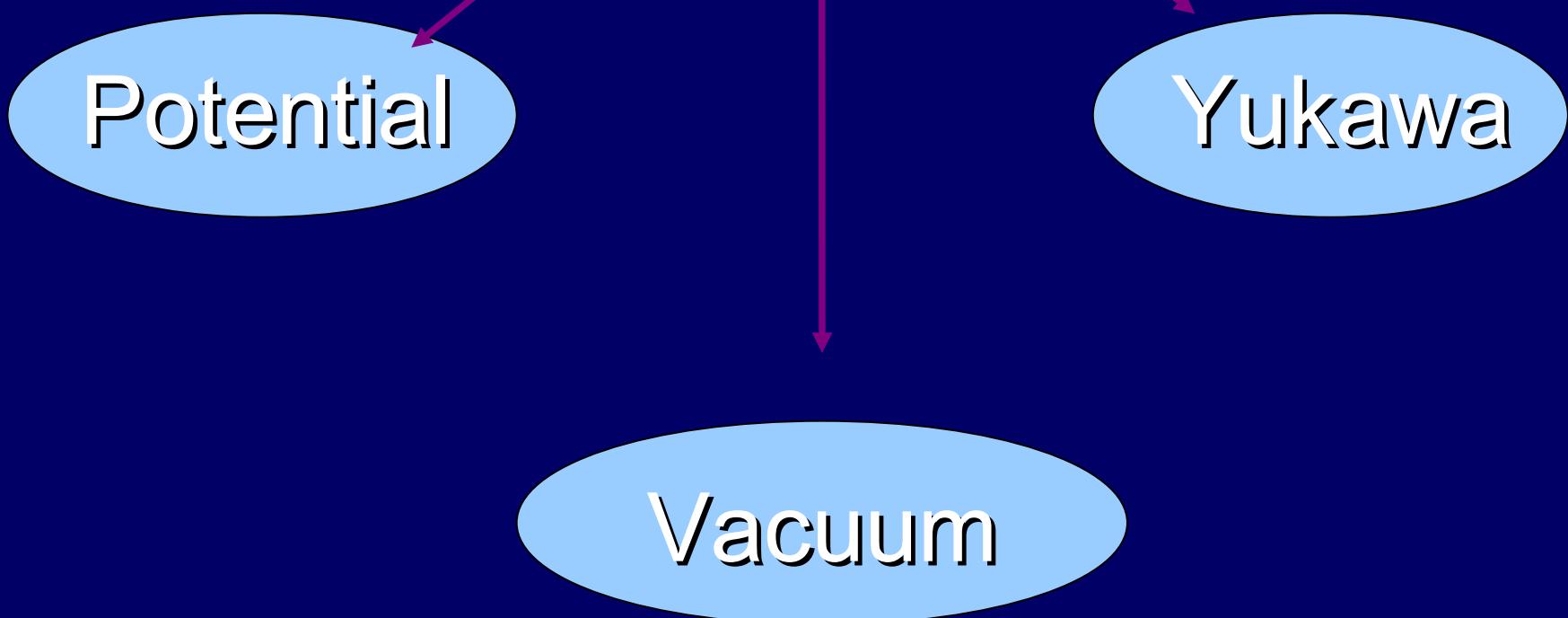
5 scalars:  $H^+$  and  $H^-$  and neutrals:

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

Sum rules (relative couplings to SM  $\chi$ )

# 2HDM's

SYMMETRIES!!



# 2HDM Potential (Lee'73)

$$\begin{aligned} V = & \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ & + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2} [\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}] \\ & + [(\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2))(\Phi_1^\dagger\Phi_2) + \text{h.c.}] \\ & - \frac{1}{2}m_{11}^2(\Phi_1^\dagger\Phi_1) - \frac{1}{2}m_{22}^2(\Phi_2^\dagger\Phi_2) - \frac{1}{2}[m_{12}^2(\Phi_1^\dagger\Phi_2) + \text{h.c.}] \end{aligned}$$

$Z_2$  symmetry transformation:  $\Phi_1 \rightarrow \Phi_1$   $\Phi_2 \rightarrow -\Phi_2$   
(or vice versa)

Hard  $Z_2$  symmetry violation:  $\lambda_6, \lambda_7$  terms

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

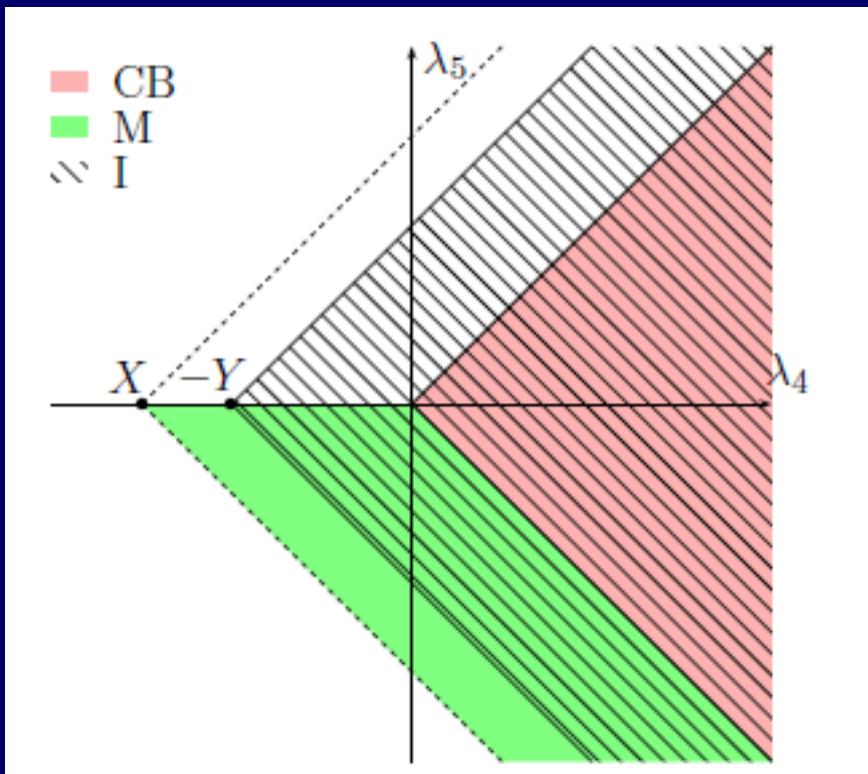
Explicit  $Z_2$  symmetry in  $V$ :  $\lambda_6, \lambda_7, m_{12}^2 = 0$

# Z2 symmetric potential

## Stable vacuum (positivity)

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad R + 1 > 0, \quad R_3 + 1 > 0$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad R = \lambda_{345}/\sqrt{\lambda_1\lambda_2}, \quad R_3 = \lambda_3/\sqrt{\lambda_1\lambda_2}.$$



$$Y = M_{H^+}^{-2} 2/v^2|_{\text{Inert}}$$

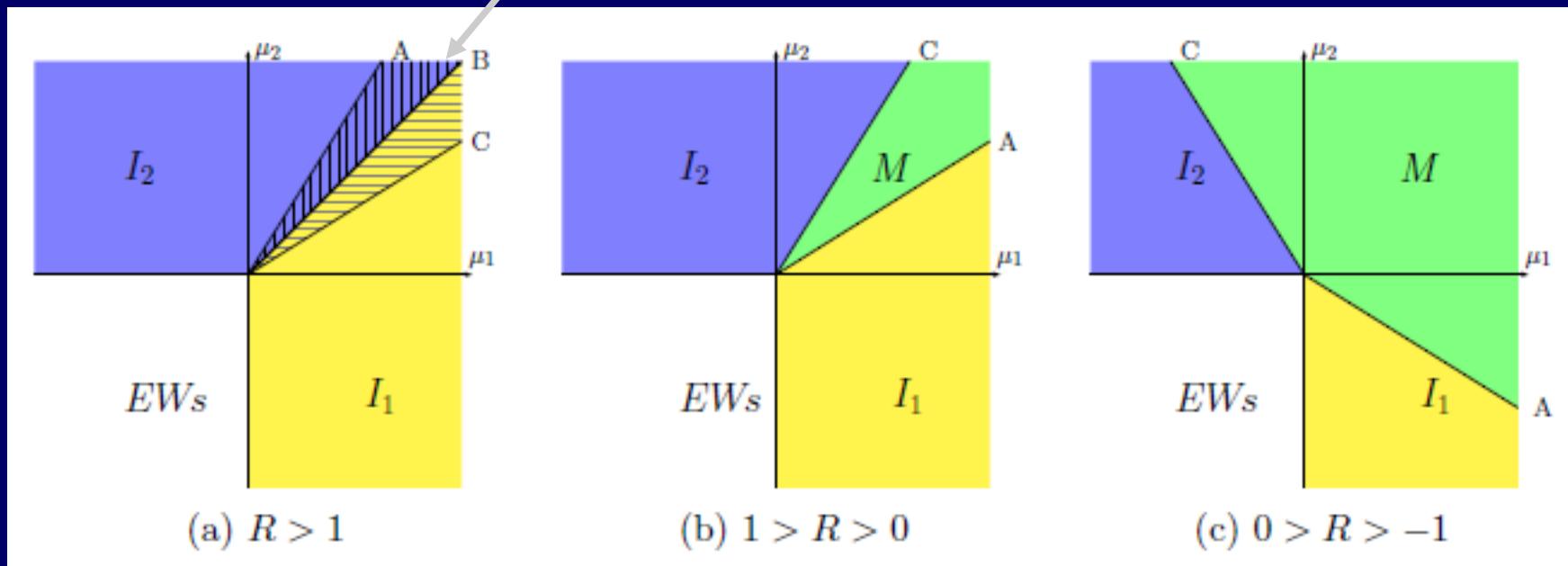
Neutral vacua  
Mixed ( $v_1$  and  $v_2 \neq 0$ )  
Inert ( $v_1$  or  $v_2 \neq 0$ )  
[Z2 exact, D parity (R-type)  $\rightarrow$  dark matter]

Charged breaking  
vacuum CB

# Phase diagrams Z2 sym. V

coexistence  
of minima

$$\mu_1 = \frac{m_{11}^2}{\sqrt{\lambda_1}}, \quad \mu_2 = \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$



Inert I1 vacuum  
for  $M_h=125$  GeV

$$m_{22}^2 \lesssim 89 \cdot 10^3 \text{ GeV}^2.$$

# Charged Higgs boson benchmarks in nonsupersymmetric 2HDM –status report

(mainly CP conserving)

- Potential and states ( $\lambda_{1-5}$ , if  $m_{12}^2 \neq 0$  CPV possible)

Various extrema (minima) possible

Mixed ( $v_1 \text{ and } v_2 \neq 0$ )  $\tan\beta = v_2/v_1$

Inert ( $v_1 \text{ or } v_2 = 0$ )

SM-like  $h$  with mass 125 GeV

$H^\pm$  masses in Mixed vacuum

(Z2 exact  $m_{12}^2=0$ )

$$M_{H^\pm}^2 = \mu^2 - \frac{v^2}{2}(\lambda_4 + \operatorname{Re} \lambda_5),$$

$$u^2 \equiv (v^2/2v_1v_2)\operatorname{Re} m_{12}^2.$$

Inert

$$M_{H^+}^2 = -\frac{m_{22}^2}{2} + \frac{\lambda_3}{2}v^2$$

Decoupling for large mass parameter – very large  $M_{H^+}$  without conflict with pert. unitarity

# Unitarity constraints on parameters of V ( $Z_2$ symmetry)

analysis by B. Gorczyca, MSc Thesis, July 2011

Full scattering matrix macierz 25x25 for scalars (including Goldstone's)

$$M = \begin{pmatrix} M_1 & & & & & \\ & M_2 & & & & \\ & & M_3 & & & \\ & & & M_4 & & \\ & & & & M_5 & \\ & & & & & M_6 \end{pmatrix}.$$

in high energy limit

Block-diagonal  
form due electric  
charge and CP  
conservation

M1: G+H-, G-H+, hA, GA, GH, hH

M2: G+G-, H+H-, GG, HH, AA, hh

M3: Gh, AH

M4: G+G, G+H, G+A, G+h, GH+, HH+, AH+, hH+

M5: G+G+, H+H+

M6: G+H+

Unitarity constraints  
 $\rightarrow |\text{eigenvalues}| < 8\pi$

# Unitarity constraints for lambdas

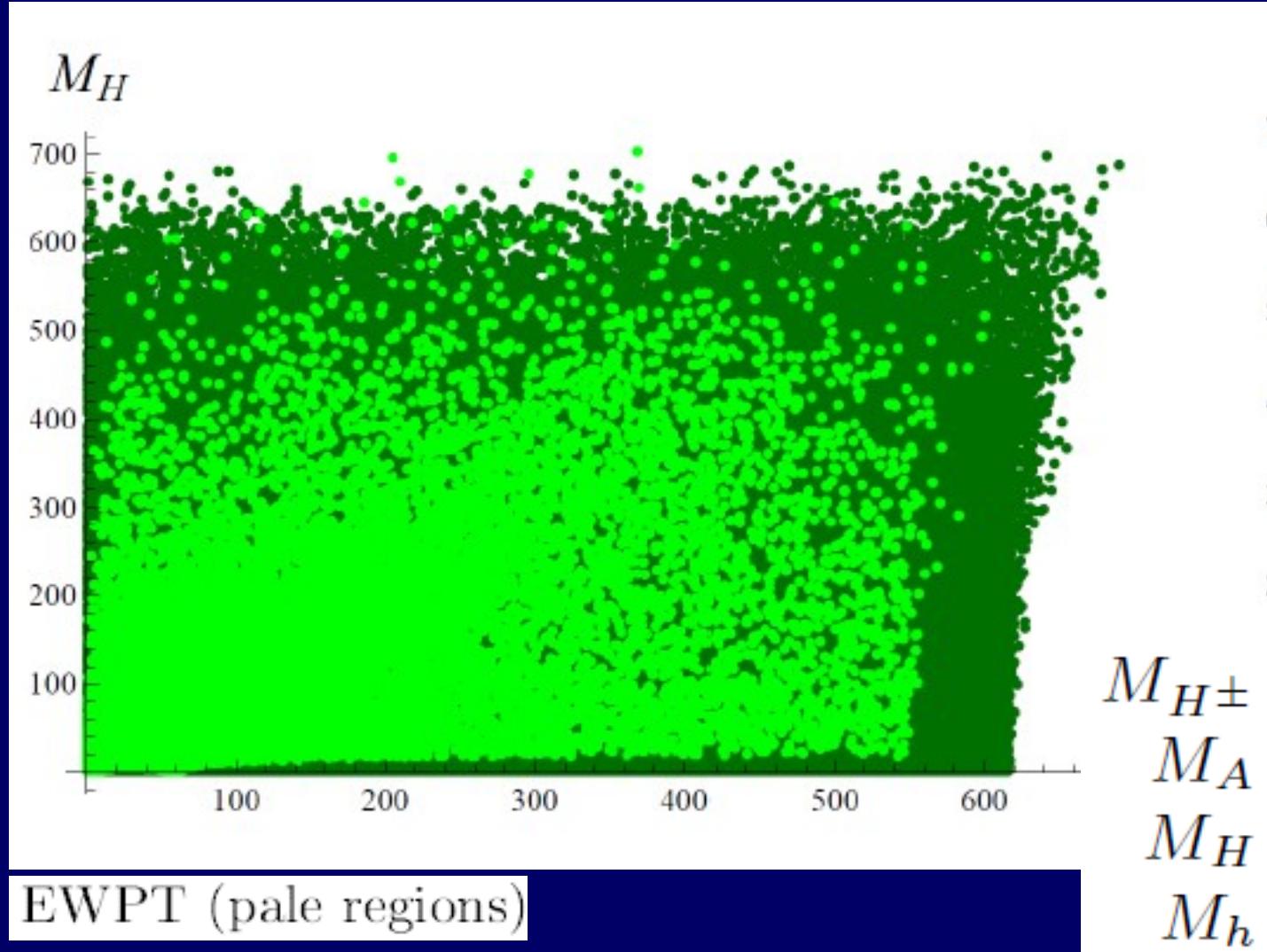
$$\begin{aligned}0 &\leq \lambda_1 \leq 8.38, \\0 &\leq \lambda_2 \leq 8.38, \\-6.05 &\leq \lambda_3 \leq 16.44, \\-15.98 &\leq \lambda_4 \leq 5.93, \\-8.34 &\leq \lambda_5 \leq 0.\end{aligned}$$

Couplings for dark particles in IDM  $\longrightarrow$

$$\begin{aligned}\lambda_{345} &= \lambda_3 + \lambda_4 + \lambda_5 \\ \lambda_{45} &= \lambda_4 + \lambda_5\end{aligned}$$

$$\begin{aligned}-8.10 &\leq \lambda_{345} \leq 12.38, \\-7.76 &\leq \lambda_{345}^- \leq 16.45, \\-8.28 &\leq \frac{1}{2}\lambda_{45} \leq 0, \\-7.97 &\leq \frac{1}{2}\lambda_{45}^- \leq 6.08,\end{aligned}$$

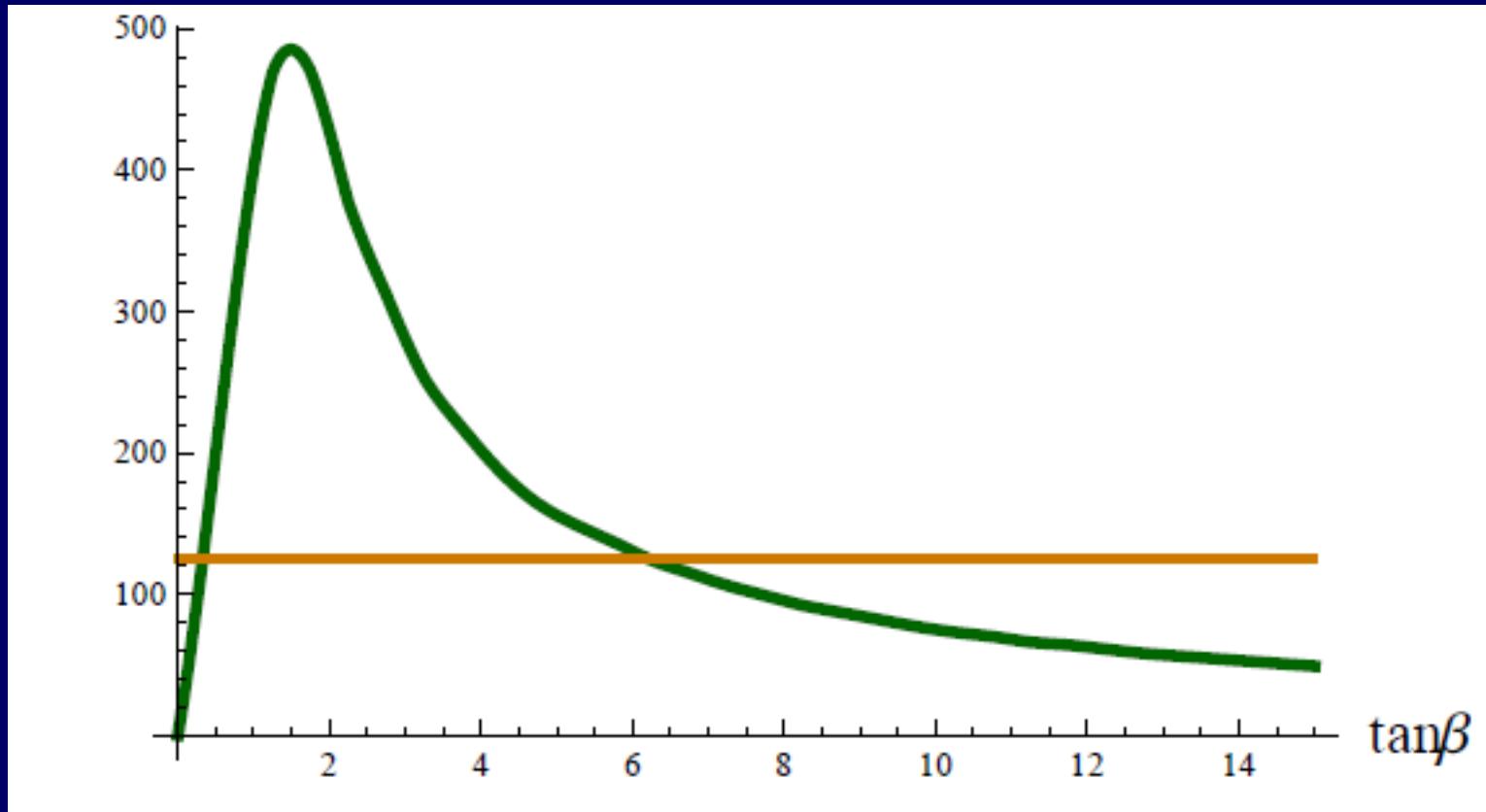
# Mixed vacuum allowed region MH vs MH+



# Max M<sub>h</sub> vs tan beta

Mixed vacuum

Limit on tan  $\beta$  !



For  $M_h = 125$  GeV

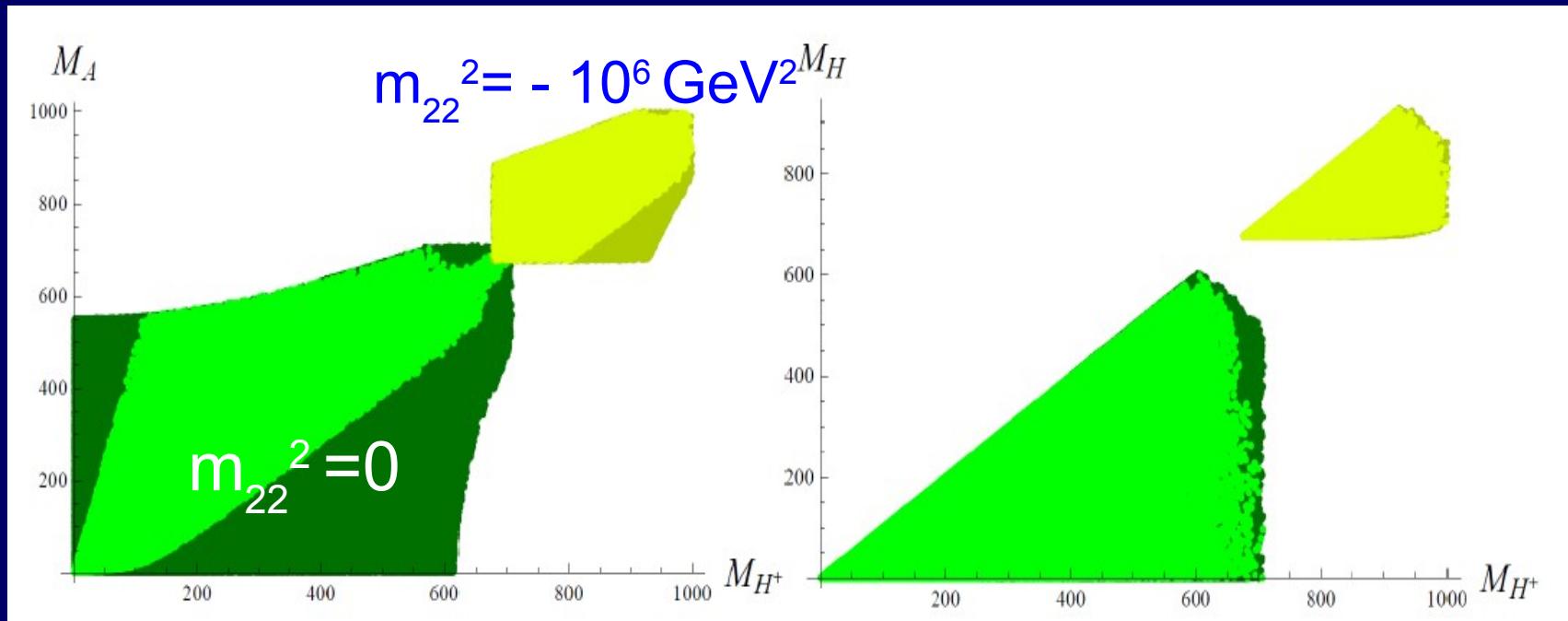
$$0.2 \lesssim \tan \beta \lesssim 6.2.$$

# Inert vacuum with $M_h=125$ GeV

Analysis based on unitarity,  
positivity, EWPT constraints

arXiv:1209.5725

$$\begin{aligned} M_H &\leq 602 \text{ GeV}, \\ M_{H^\pm} &\leq 708 \text{ GeV}, \\ M_A &\leq 708 \text{ GeV}. \end{aligned}$$



valid up to  $|m_{22}^2| = 10^4 \text{ GeV}^2$

EWPT (pale regions)

# Couplings of Higgs bosons to gauge bosons

Mixed

$\frac{\cos(\beta - \alpha)}{HW^+W^-}$	$\frac{\sin(\beta - \alpha)}{hW^+W^-}$
$HZZ$	$hZZ$

relative to SM

Inert

$$hWW/ZZ = 1$$

0  
 $\sin(\beta-\alpha) \rightarrow 1$   
the same

$$\begin{aligned} H^\mp W^\pm h : & \quad \frac{\mp ig}{2} \cos(\beta - \alpha) (p_\mu - p_\mu^\mp), \\ H^\mp W^\pm H : & \quad \frac{\pm ig}{2} \sin(\beta - \alpha) (p_\mu - p_\mu^\mp), \\ H^\mp W^\pm A : & \quad \frac{g}{2} (p_\mu - p_\mu^\mp). \end{aligned}$$

# Various models of Yukawa inter.

typically with some Z2 type symmetry to avoid FCNC

Model I - only one doublet interacts with fermions

Model II – one doublet with down-type fermions d , l  
other with up-type fermions u

Model III - both doublets interact with fermions

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

Model Y - one doublet with down-type quarks d  
other with up-type quarks u and leptons

Top 2HDM – top only with one doublet

Fermiophobic 2HDM – no coupling to the lightest Higgs  
+ Extra dim 2HDM models

# Yukawa interactions

Model	$d$	$u$	$\ell$
I	$\Phi_2$	$\Phi_2$	$\Phi_2$
II	$\Phi_1$	$\Phi_2$	$\Phi_1$
III	$\Phi_1 \& \Phi_2$	$\Phi_1 \& \Phi_2$	$\Phi_1 \& \Phi_2$
X	$\Phi_2$	$\Phi_2$	$\Phi_1$
Y	$\Phi_1$	$\Phi_2$	$\Phi_2$

$\Phi_1$	$\Phi_2$	This work	HHG	BHP	G, AS	ARS	AKTY	BFLRSS
$u, d, \ell$	$u, d, \ell$	I	I	I	I (*)	—	I	I
$d, \ell$	$u$	II	II	II	II	—	II	II
$u, d, \ell$	$u, d, \ell$	III	—	—	—	III	—	III
$\ell$	$u, d$	X	—	IV	I' (*)	—	X	lepton specific
$d$	$u, \ell$	Y	—	III	II'	—	Y	flipped

Table 8: Dictionary of notations. “HHG”: Higgs Hunter’s Guide [1]. “BHP”: Barger, Hewett, Phillips [142]. “G”: Grossman [130], “AS”: Akeroyd, Stirling [5]. The (\*) denotes interchange  $\Phi_1 \leftrightarrow \Phi_2$ . “ARS”: Atwood, Reina, Soni [181]. “AKTY”: Aoki, Kanemura, Tsumura, Yagyu [180]. “BFLRSS”: Branco, Ferreira, Lavoura, Rebelo, Sher, Silva [182].

# Yukawa couplings

## Mixed (Model II)

$$H^+ b \bar{t} : \quad \frac{ig}{2\sqrt{2}m_W} V_{tb} [m_b(1 + \gamma_5) \tan \beta + m_t(1 - \gamma_5) \cot \beta],$$
$$H^- t \bar{b} : \quad \frac{ig}{2\sqrt{2}m_W} V_{tb}^* [m_b(1 - \gamma_5) \tan \beta + m_t(1 + \gamma_5) \cot \beta].$$

## Inert (Model I)

First (Higgs) doublet like in SM  $\Phi_1 \rightarrow \Phi_S$

Second (Dark) doublet has no vev  
(no couplings to fermions)  $\Phi_2 \rightarrow \Phi_D$

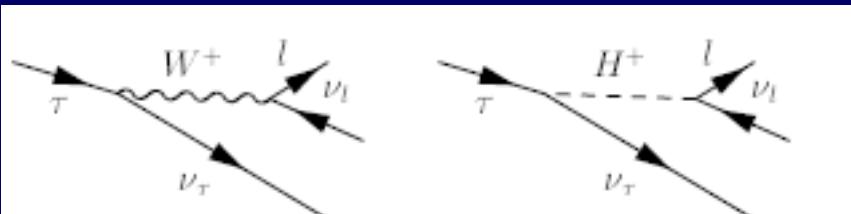
# Minimal Flavour Violation - 2HDM

Z<sub>2</sub> symmetry in Yukawa int.- how stable under radiative corrections ?  
(T. Hurth at al)

The minimal flavour violation (MFV) hypothesis is a formal solution to the NP flavour problem. It assumes that the flavour and the CP symmetry are broken as in the SM. Thus, it requires that all flavour- and CP-violating interactions be linked to the known structure of Yukawa couplings (called  $Y_U$  and  $Y_D$  in the following). A renormalization-group-invariant definition of MFV based on a symmetry principle is given in [12, 13, 14]; this is mandatory for a consistent effective field theoretical analysis of NP effects.

- Mixed Model (a'la MSSM) - Z<sub>2</sub> sym. V and Yukawa int., but Z<sub>2</sub> is violated spontaneously by vacuum
- Inert Doublet Model= Z<sub>2</sub> exact  
(potential, Yukawa int. Model I and vacuum)

# Large 2HDM(II) one-loop corrections in leptonic tau decays

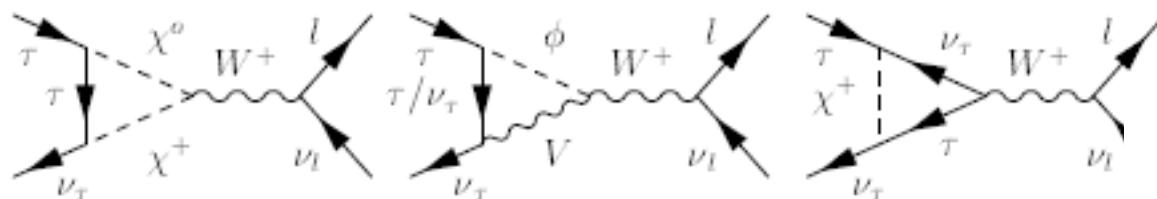


Model Mixed (II)

D. Temes, MK

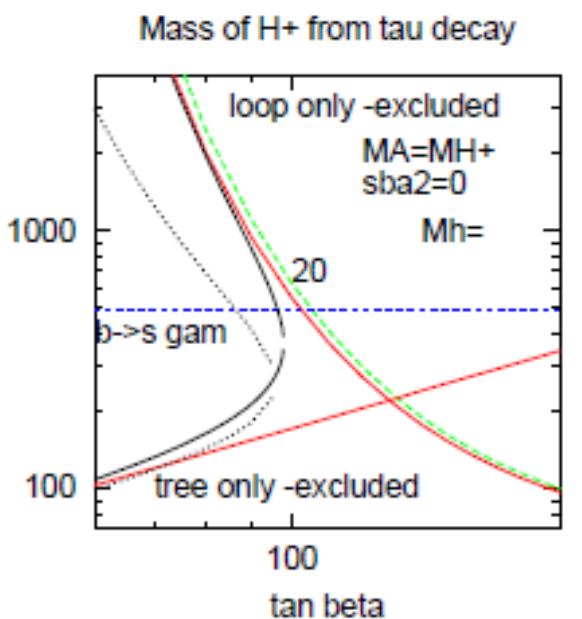
Eur.Phys.J.C44(2005)435

Comment to B decay  
- exclusion based only  
on tree diagram...

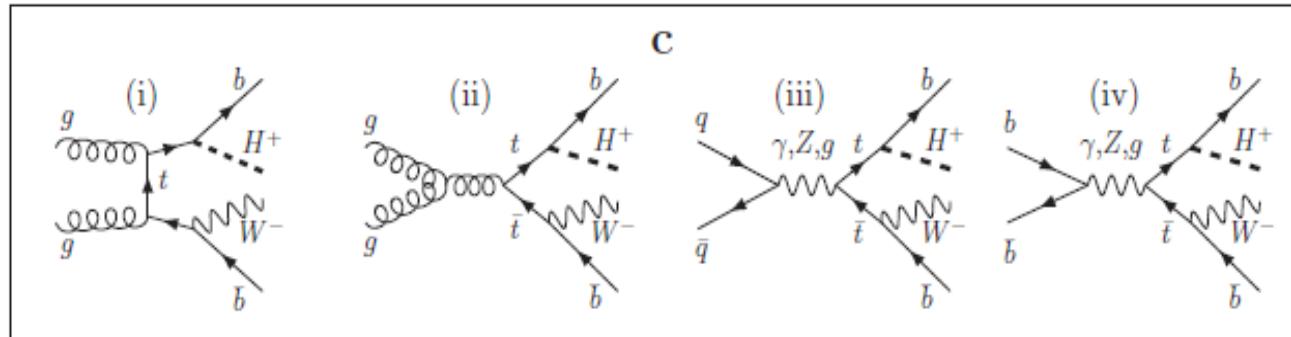
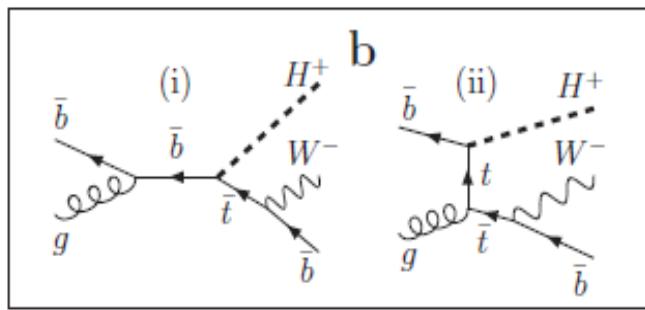
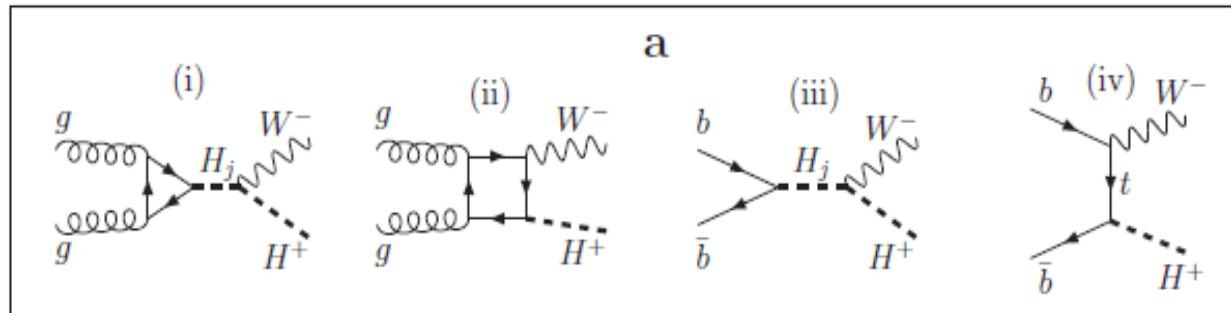
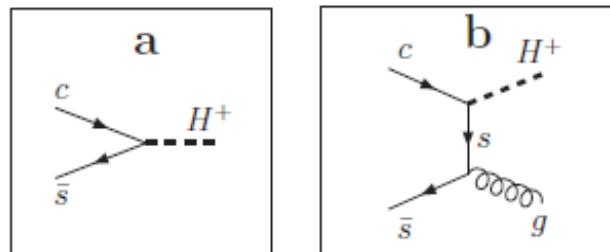


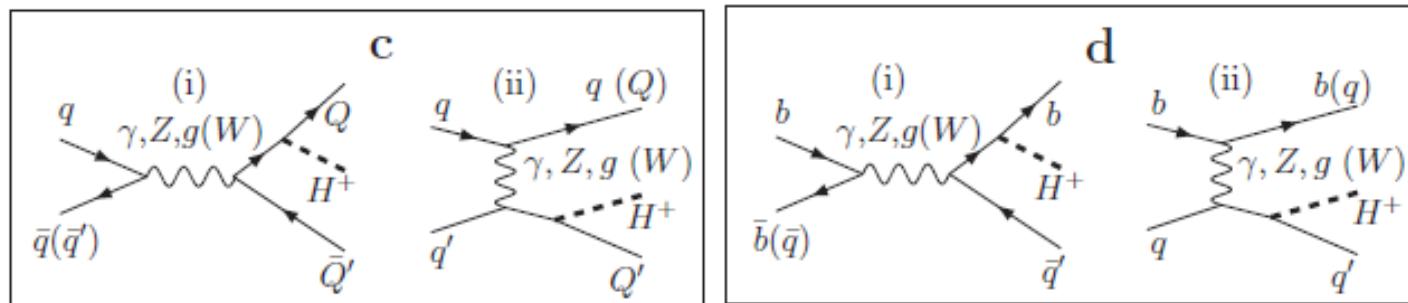
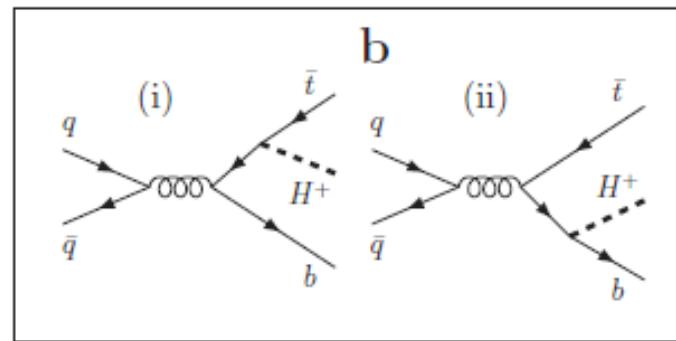
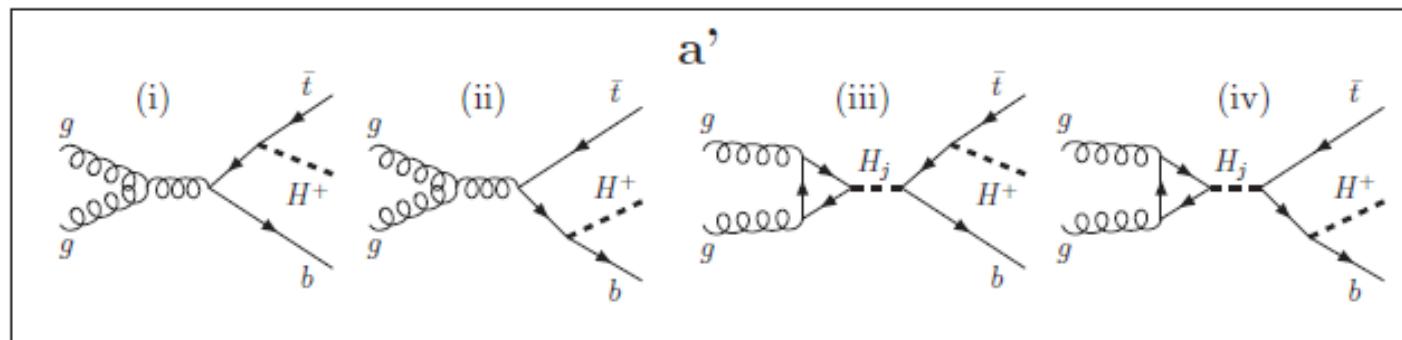
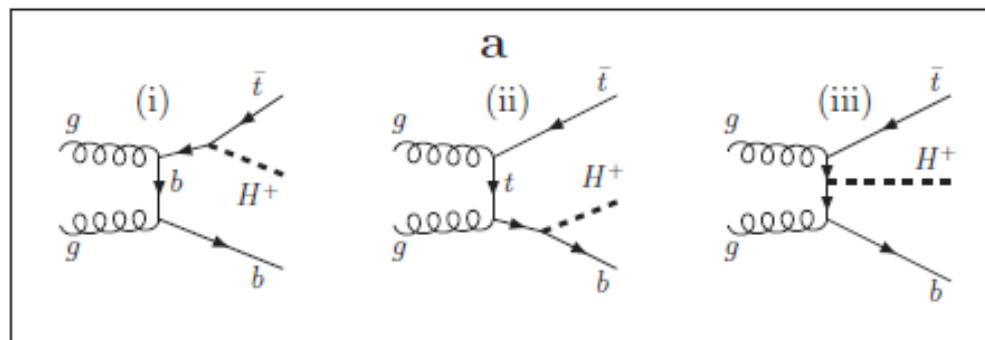
$$\Delta_{\text{oneloop}} \approx \frac{G_F m_\tau^2}{8\sqrt{2}\pi^2} \tan^2 \beta \bar{\Delta}$$

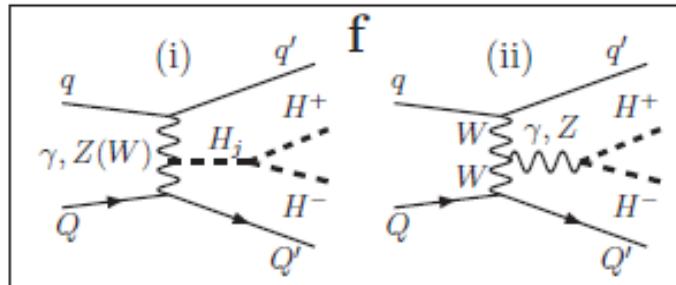
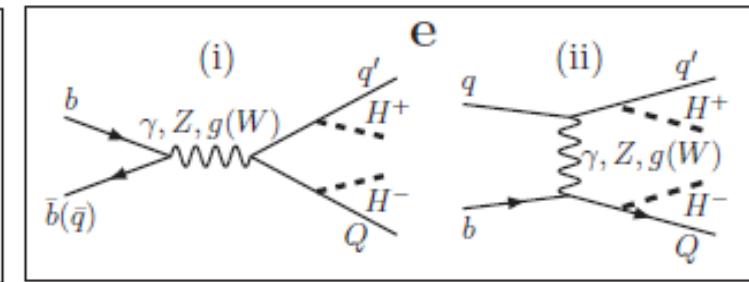
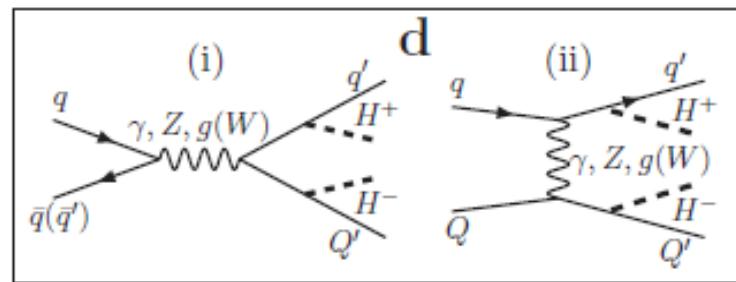
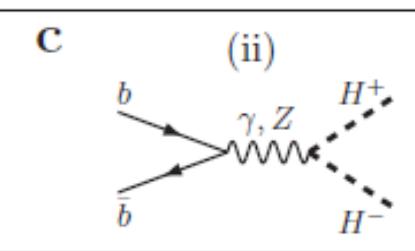
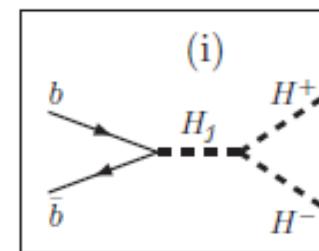
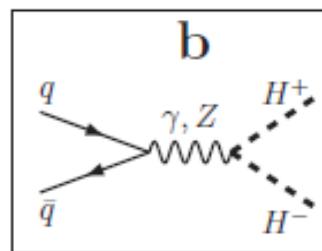
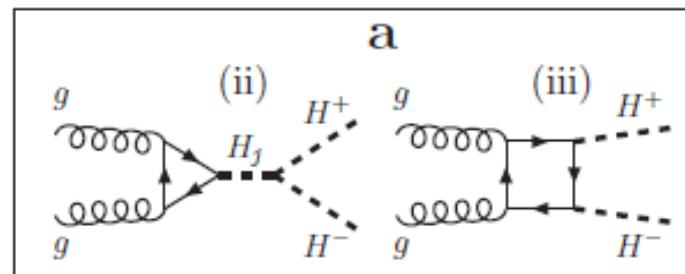
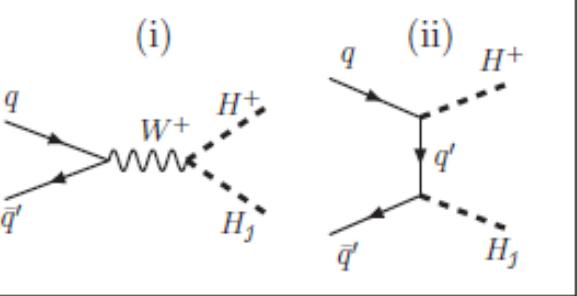
$$\bar{\Delta} = \left[ - \left( \ln \left( \frac{M_{H^\pm}^2}{m_\tau^2} \right) + F(R_{H^\pm}) \right) \right. \\ \left. + \frac{1}{2} \left( \ln \left( \frac{M_A^2}{m_\tau^2} \right) + F(R_A) \right) \right. \\ \left. + \frac{1}{2} \cos^2(\beta - \alpha) \left( \ln \left( \frac{M_h^2}{m_\tau^2} \right)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



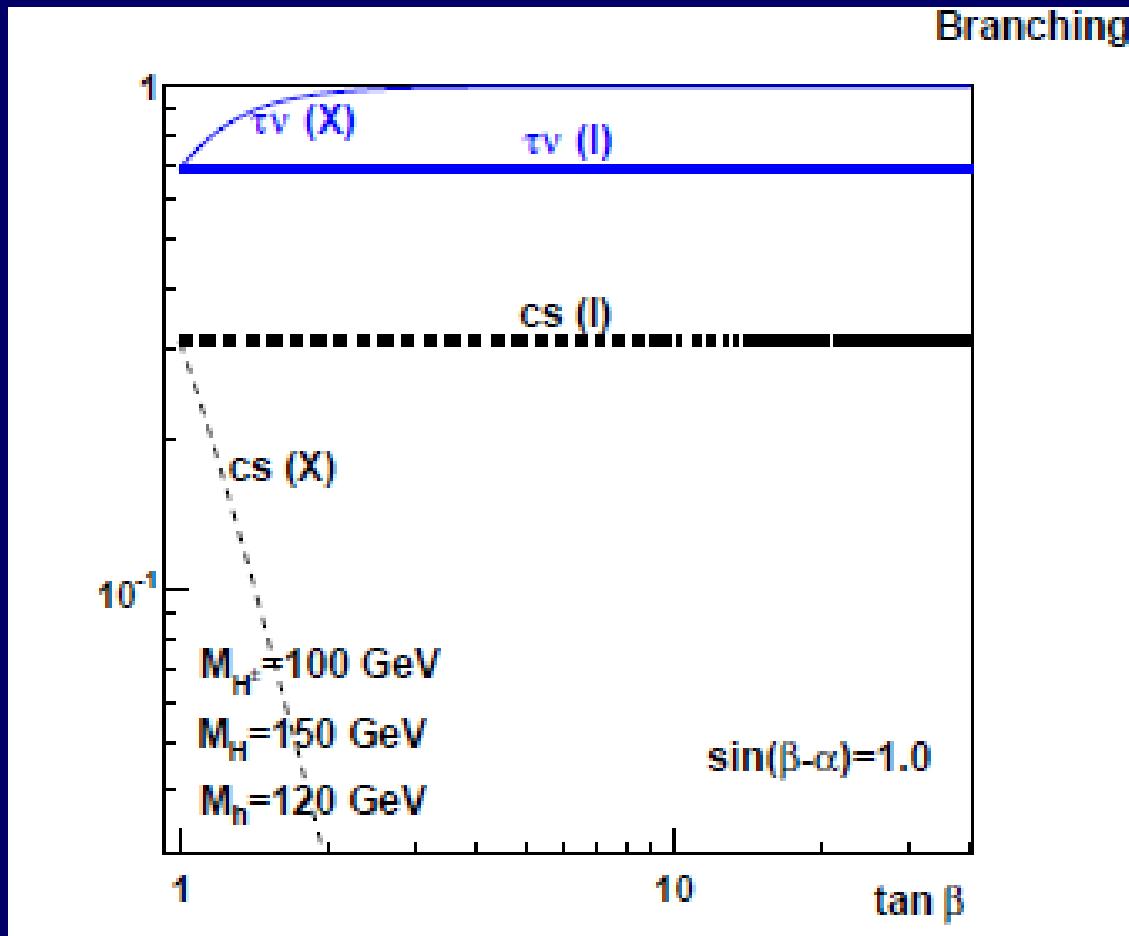
# LHC (Mixed)





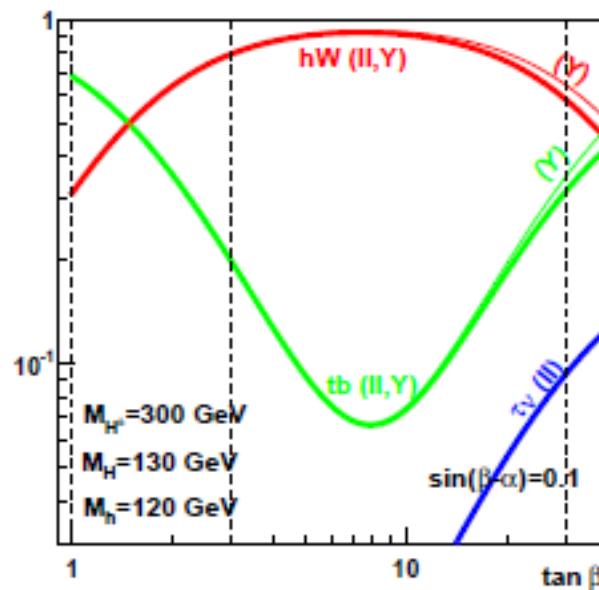
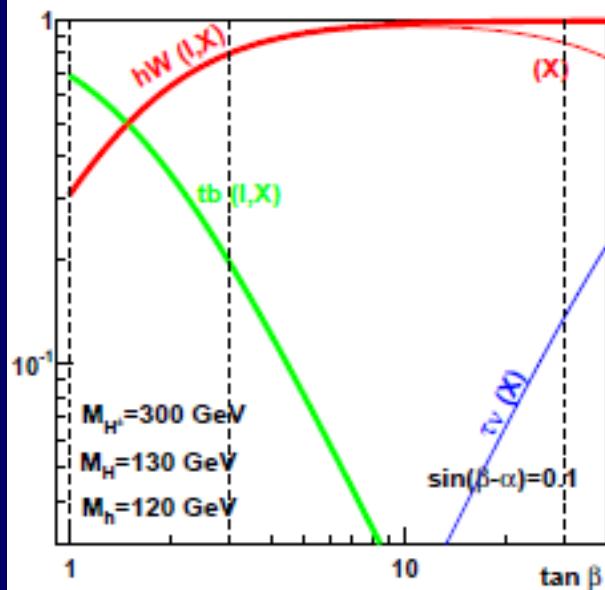
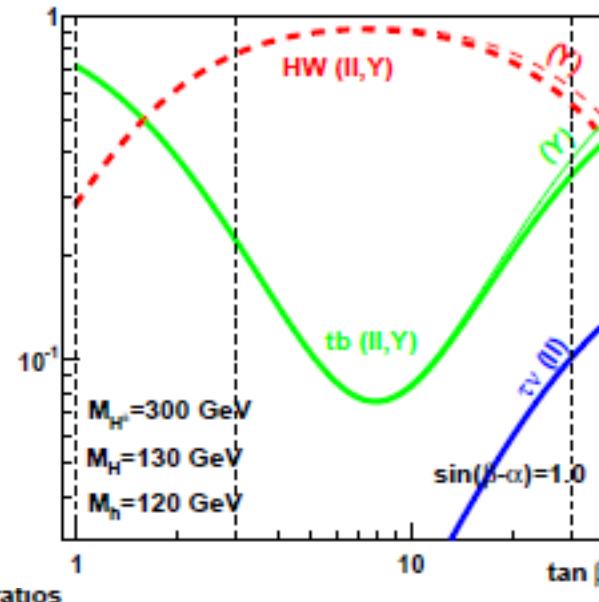
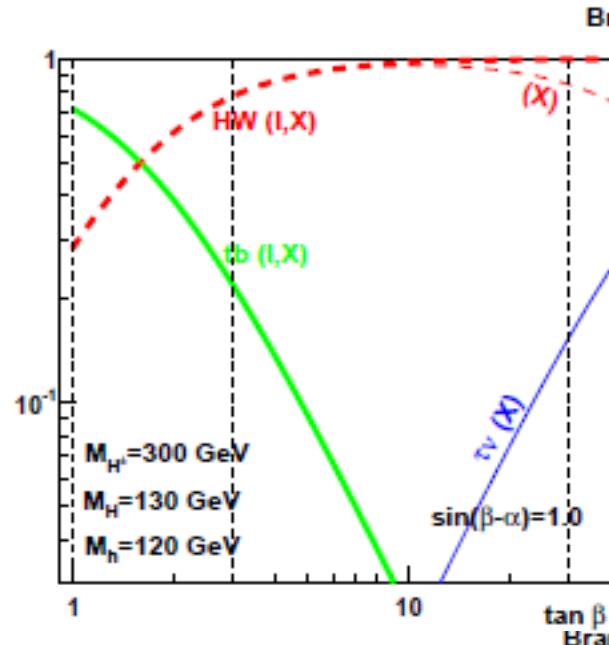


# Br – light H+



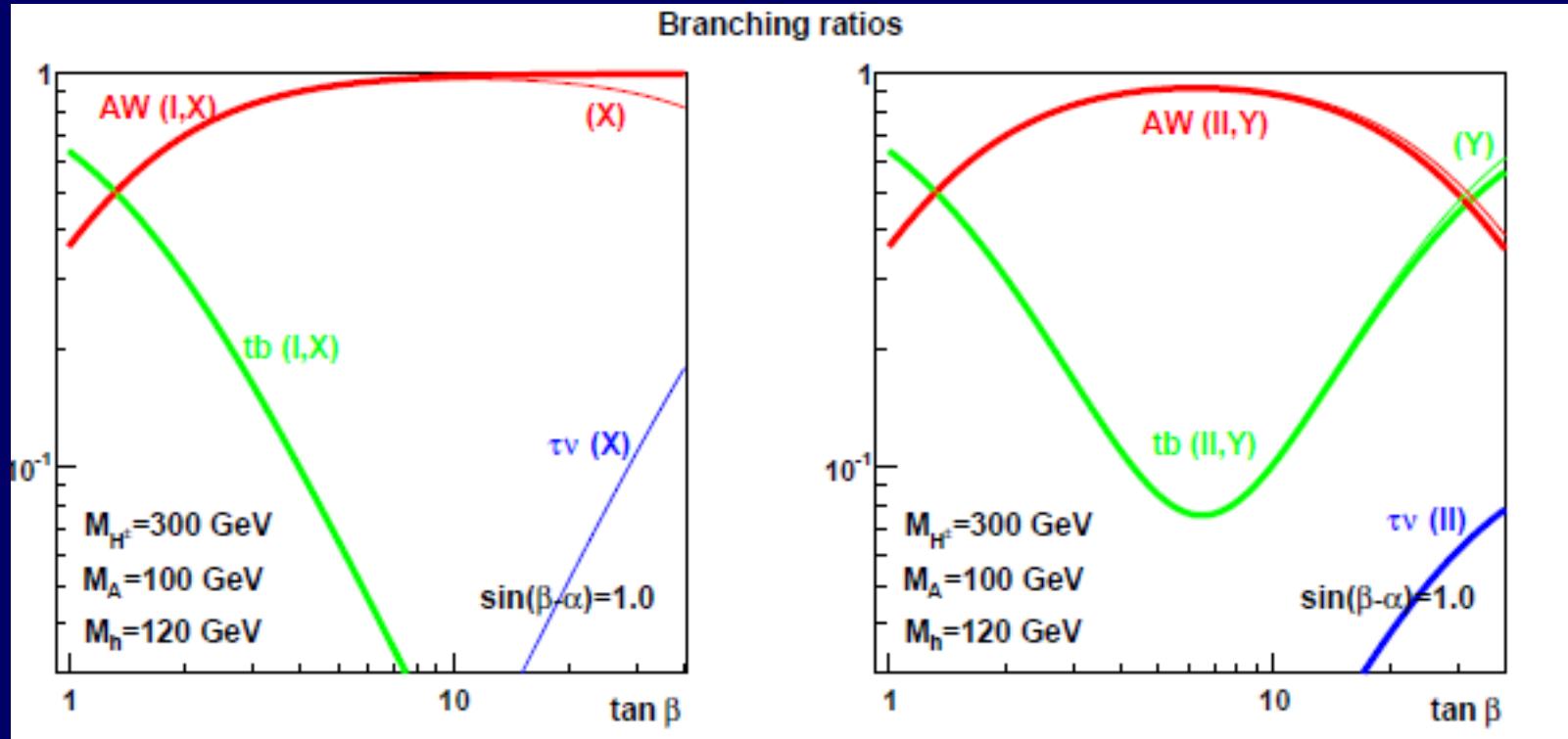
# BR

$$M_{H^\pm} = 300 \text{ GeV}, \quad (M_h, M_H, M_A) = (120, 130, 300) \text{ GeV},$$



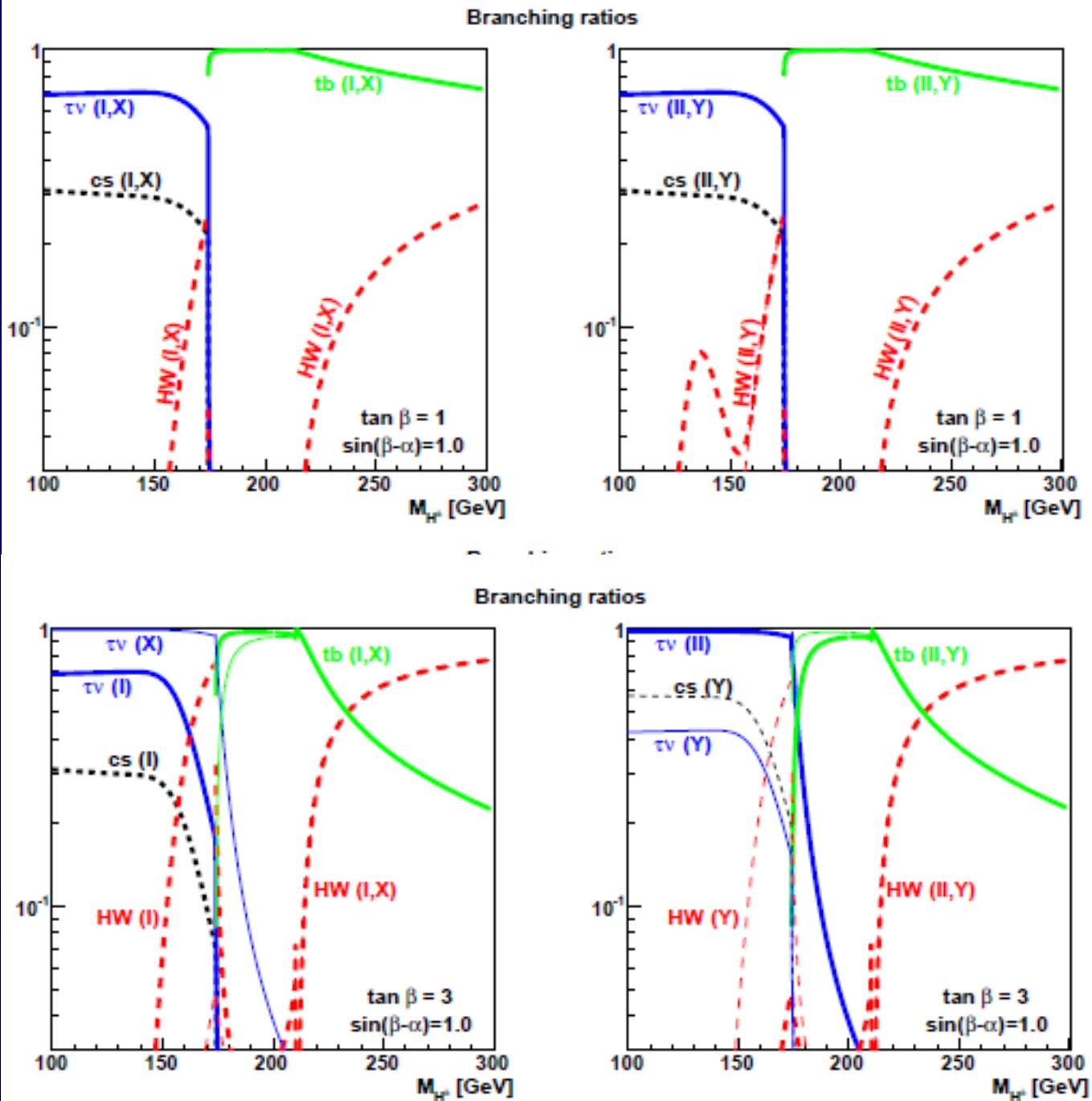
$H^+ \rightarrow Wh$ ,  
WH open,  
WA not

$$M_{H^\pm} = 300 \text{ GeV}, \quad (M_h, M_H, M_A) = (120, 300, 100) \text{ GeV}.$$



$H^+ \rightarrow W^+ A$  and  $H^+ \rightarrow W^+ h$  are both open, whereas  $H^+ \rightarrow W^+ H$  is not.

# BR



# Exp. constraints (mainly Model II)

- Some observables depends solely on H+  
(indep. on CPV) others also on neutral scalars
- 1/ tree-level H+ (eg. $B \rightarrow \tau\nu$  )
  - 2/ loop H+ (eg. $B \rightarrow X_s \gamma$ , mass  $H+ > 380$  GeV)
  - 3/ LEP (mass H+ above 75 GeV)
  - 4/ LHC – SM h search
  - 5/ TeVatron  $t \rightarrow H+ b$
  - 6/ LHC
  - 7/ Other precise data: EWPT, g-2 for muon,  
electron el. dipole moment (CPV)

# Cross sections at LHC

$m_{H^\pm}$	100 GeV			150 GeV		
$\tan \beta$	3	10	30	3	10	30
$H^\pm(g)$ (6.1)	✗	✗	✗	✗	✗	✗
$b\bar{b}W^\pm H^\mp$ (6.2c)	✓	✓	✗	✓	✗	✗
$H^\pm b\bar{q}$ (6.3d)	✓	(✓)	✗	✓	✗	✗

Table 2: Low-mass benchmarks for Models I and X at  $30 \text{ fb}^{-1}$ . The case denoted by (✓) requires higher luminosity.

$$\begin{aligned} pp \rightarrow H^\pm W^\mp X &\rightarrow W^+ W^- H_1 X \\ &\rightarrow \ell \nu j j b\bar{b} X \end{aligned}$$

	$\alpha_1/\pi$	$\alpha_2/\pi$	$\alpha_3/\pi$	$\tan \beta$	$M_2$	$M_{H^\pm}^{\min}, M_{H^\pm}^{\max}$
$P_2$	0.35	-0.014	0.48	1	300	380,415
$P_3$	0.35	-0.015	0.496	1	350	380,450
$P_4$	0.35	-0.056	0.43	1	400	380,455
$P_5$	0.33	-0.21	0.23	1	450	380,470
$P_7$	0.39	-0.07	0.33	2	300	380,405

Other talks..

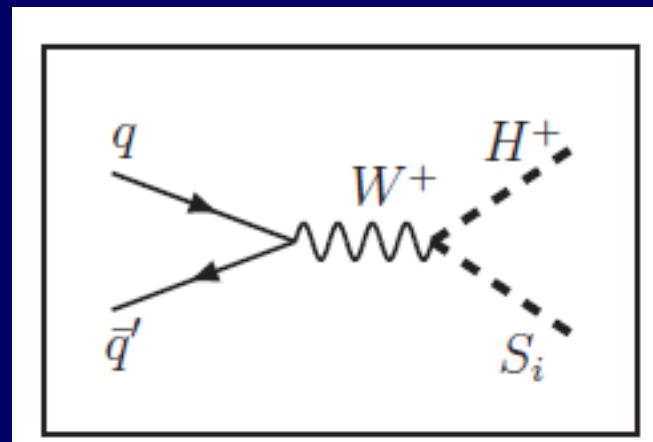
# Models with several H+

## Models with DM candidates

IDM

SO(10) and GUT-induced scalar DM scenario

LHC:  
production  
 $H^+H^-$  or  
+ S singlet



$$H^\pm \rightarrow S_i f \bar{f}',$$

- via real or virtual W
- el. neutral Dark scalar

In the considered models  $H^\pm$  and  $S_{\text{DM}}$  may be close in mass. The  $H^\pm$  will then be long-lived, travel a macroscopic distance inside the tracker of an LHC experiment, and decay far from the interaction point, leading to a charged lepton and missing  $E_T$ . The displaced vertices of  $H^\pm$  decays are theoretically free from SM background and enable discovery of the  $H^\pm$  at the LHC for the constrained scenario [162].

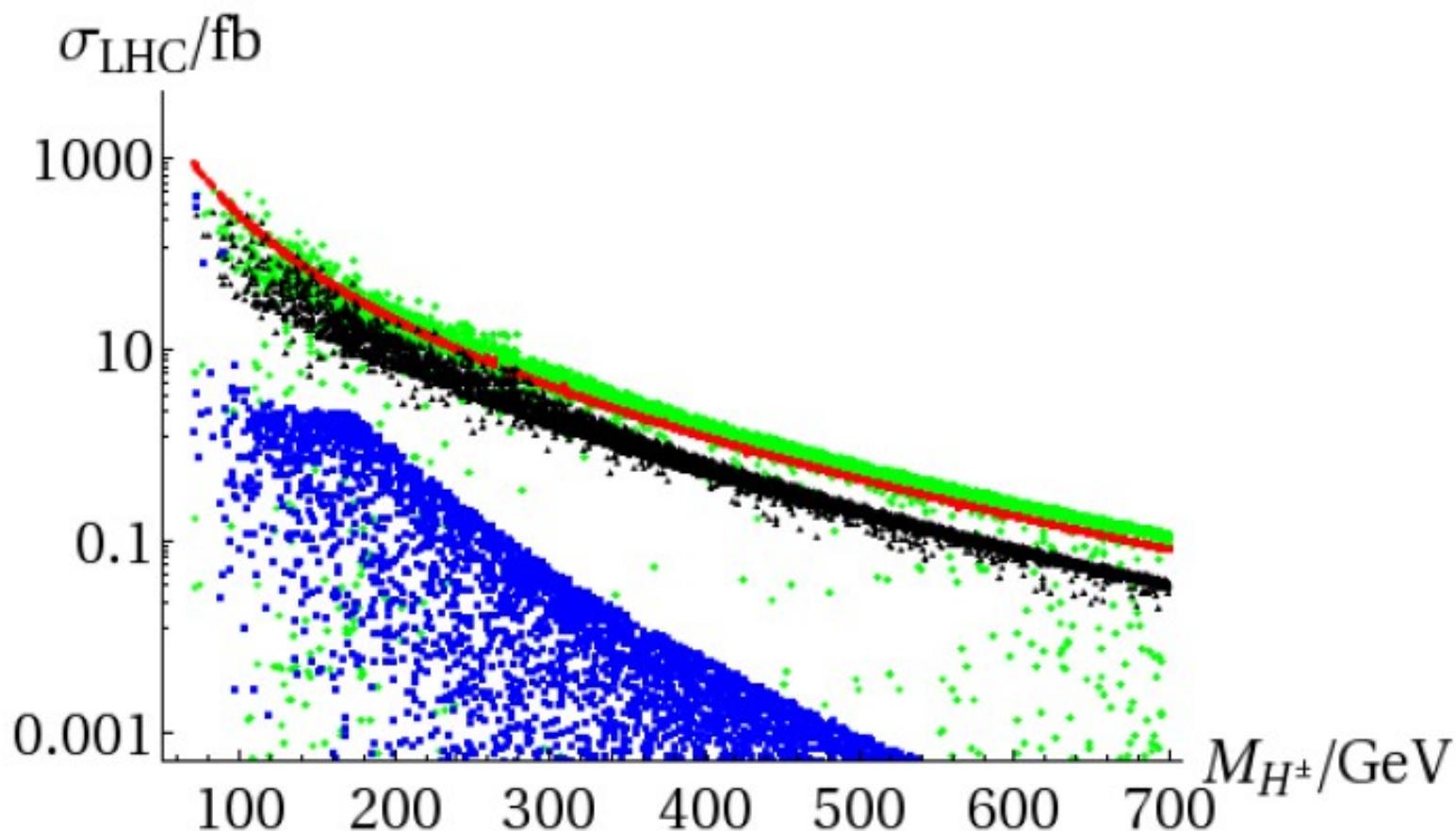
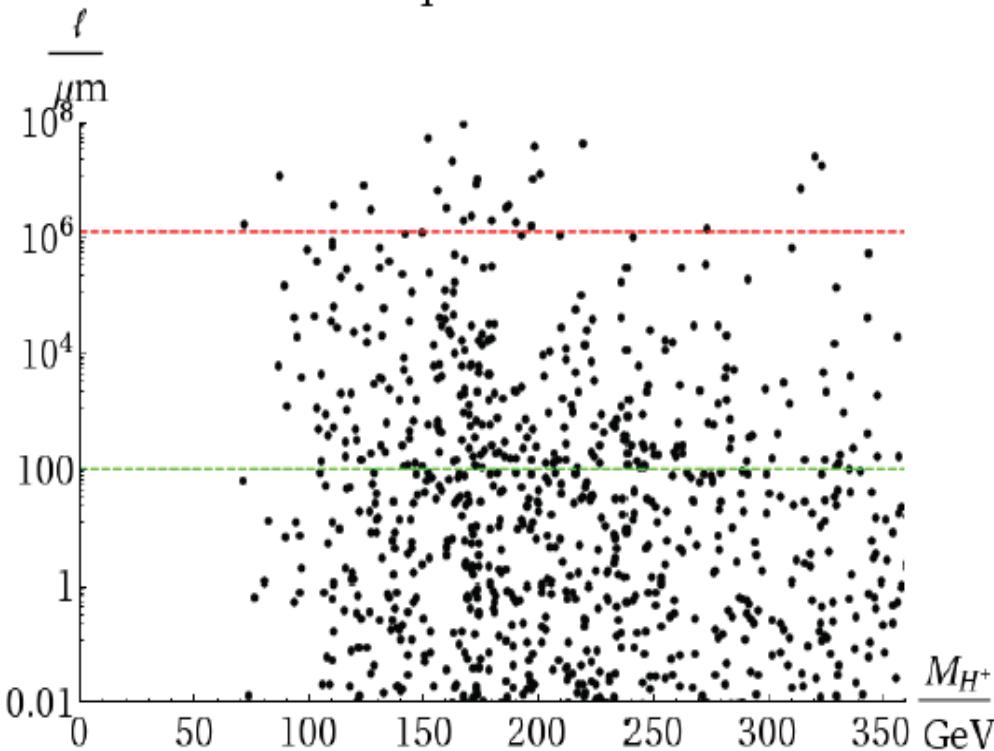


Figure 17: Cross-sections for  $pp \rightarrow H^+H^-$  via  $q\bar{q}$  (red),  $pp \rightarrow H^+H^-$  via  $gg$  (blue),  $pp \rightarrow S_i H^+$  (green) and  $pp \rightarrow S_i H^-$  (black) at the LHC for  $\sqrt{s} = 14$  TeV. The labels  $i = 3, 4$  refer to the two heavier neutral scalars

# Benchmarks for LHC (14 TeV)

$H^+$  displaced vertex



	$M_{H^\pm}$	$M_{S_{\text{DM}}}$	$M_h$	$\eta$	$\ell$
P1	224.9	210.7	124.9	$4.49 \times 10^{-4}$	$3.4 \times 10^{-4}$
P2	164.3	163.6	126.0	0.17	$16.4 \times 10^{-2}$
P3	173.8	168.183	125.7	$9.9 \times 10^{-5}$	10.2

# Summary

Non supersymmetric 2HDM –  
a great laboratory  
It offers Higgs boson and DM

Various SM-like scenarios possible  
 $H^+$  (Higgs or just scalar)  
Work in progress on report

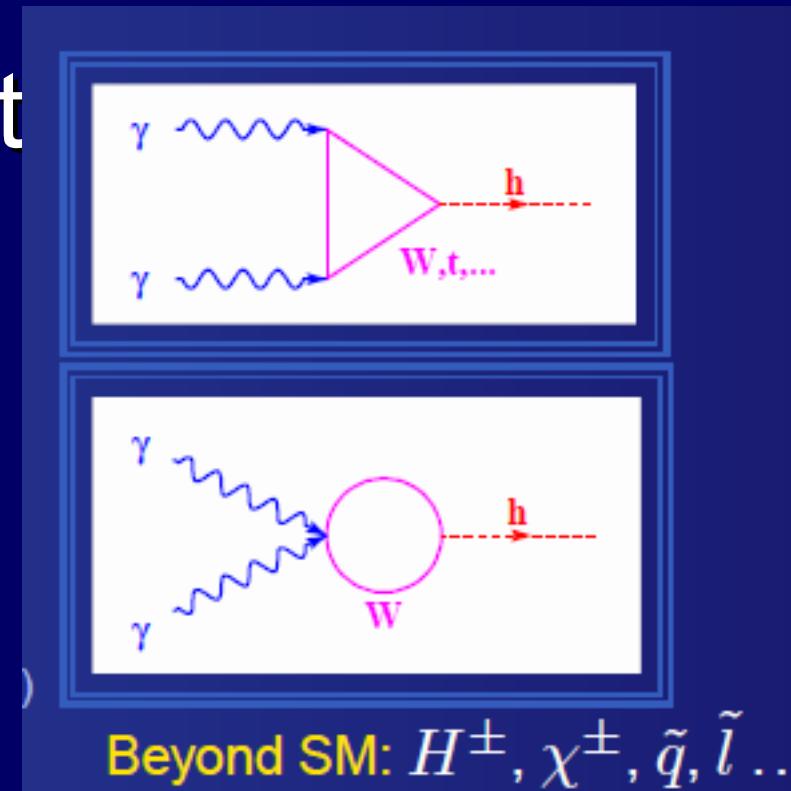
# Loop couplings $hgg$ and $h\gamma\gamma$

For  $hgg$

- b and t important

For  $h\gamma\gamma$

- t (b), W, H+  
(in 2HDMs)



W and t destructive interference in SM, so...

# Identifying an SM-like Higgs particle at future colliders

LC-TH-2003-089

I. F. GINZBURG<sup>1</sup>, M. KRAWCZYK<sup>2</sup> AND P. OSLAND<sup>3</sup>

**SM-like scenario.** One of the great challenges at future colliders will be the SM-like scenario that no new particle will be discovered at the Tevatron, the LHC and electron-positron Linear Collider (LC) except the Higgs boson with partial decay widths, for the basic channels to fundamental fermions (up- and down-type) and vector bosons  $W/Z$ , as in the SM:

$$\left| \frac{\Gamma_i^{\text{exp}}}{\Gamma_i^{\text{SM}}} - 1 \right| \lesssim \delta_i \ll 1, \quad \text{where } i = u, d, V. \quad (1)$$

Then for the relative couplings (vs SM)

for  $i = u, d, V$ .

$$\chi_i^{\text{obs}} = \pm(1 - \epsilon_i), \quad \text{with } |\epsilon_i| \ll 1. \quad |\epsilon_i| \leq \delta_i.$$

Using pattern relation for 2HDM (II)  $(\chi_u + \chi_d)\chi_V = 1 + \chi_u\chi_d$ .

# Loop couplings ggh/H, $\gamma\gamma h/H$

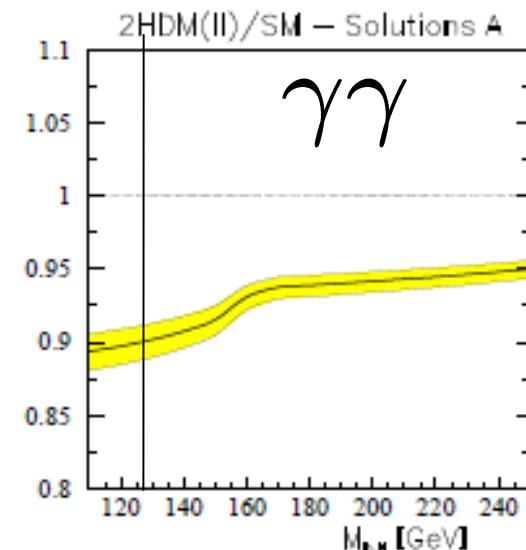
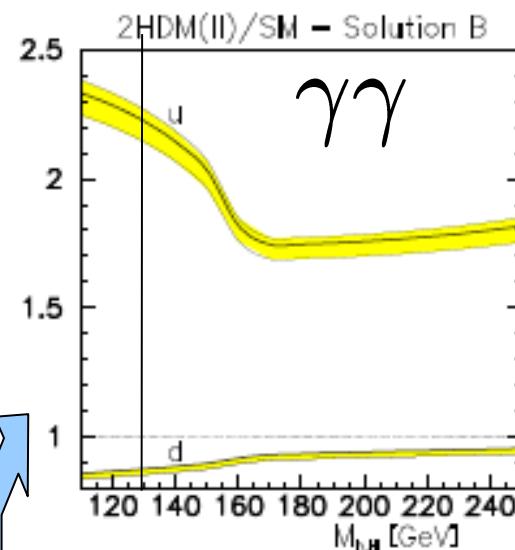
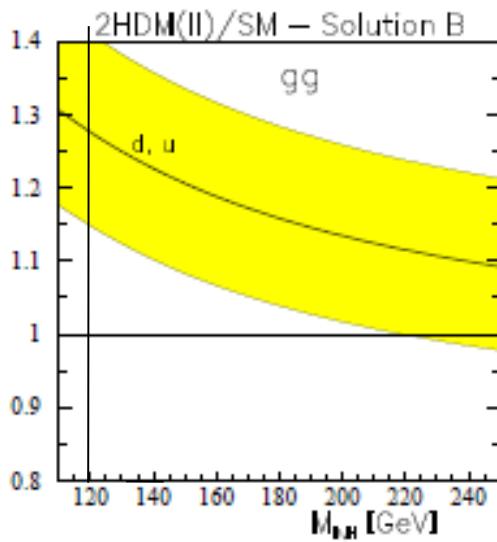
2HDM( $Z_2$ ) = Mixed

$\Gamma(h/H \rightarrow gg, \gamma\gamma)$   
including exp. uncertainties

Ginzburg, Osland, MK '2001

Tree couplings as in SM - close to 1 (solution A)

suppression due to  $H^+$  (600GeV)



solution B  $\rightarrow$  „wrong” signs of fermion couplings

# Both h and H maybe SM-like

Two solutions:

A – all couplings close to 1

B – one Yukawa coupling close to -1

Loop induced couplings  $gg$ ,  $\gamma\gamma$ ,  $Z\gamma$   
different for A and B

$M_{H^\pm}=600$  GeV

For h or H  
with mass  
120 GeV

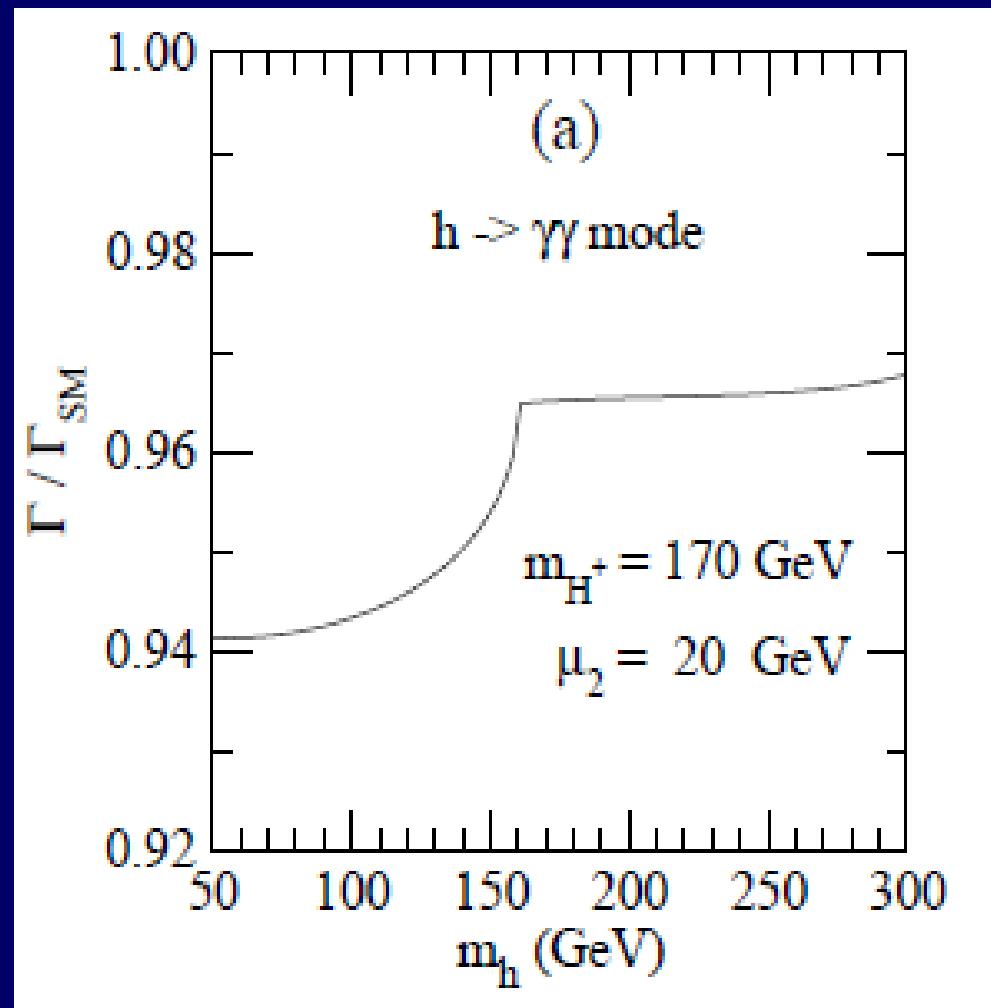
solution	basic couplings	$ \chi_{gg} ^2$	$ \chi_{\gamma\gamma} ^2$	$ \chi_{Z\gamma} ^2$
$A_{h^\pm}/A_{H_-}$	$\chi_V \approx \chi_d \approx \chi_u \approx -1$	1.00	0.90	0.96
$B_{h^\pm d}/B_{H_- d}$	$\chi_V \approx -\chi_d \approx \chi_u \approx +1$	1.28	0.87	0.96
$B_{h^\pm u}$	$\chi_V \approx \chi_d \approx -\chi_u \approx -1$	1.28	2.28	1.21

Collider. The observation of loop-induced couplings can distinguish models in the frame of the “current SM-like scenario” determined via currently measured coupling constants. Even at the Tevatron the solution  $B_{h^\pm u}$  can easily be distinguished via a study of the process  $gg \rightarrow \phi \rightarrow \gamma\gamma$  with rate about three times higher than that in the SM (the product

# IDM: decay width $\gamma\gamma h$

For negative  $\lambda_3$   
It maybe larger  
than in SM

Ma'2007

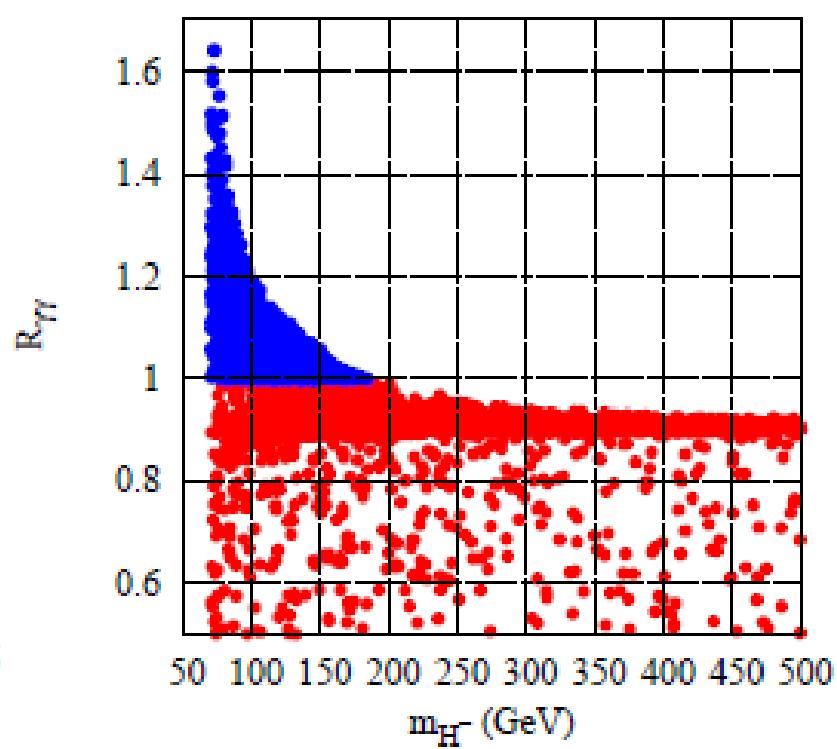
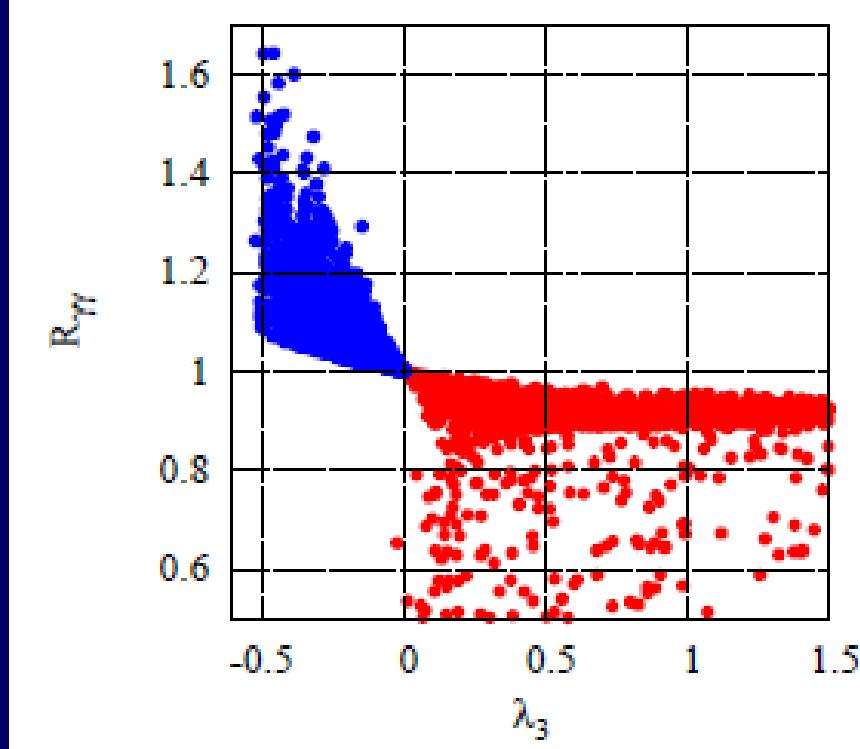


$$= \frac{G_\mu \alpha^2 m_h^3}{128 \sqrt{2} \pi^3} \left| \sum_f N_C Q_f^2 g_{hff} \mathcal{A}_{1/2}(\tau_f) + g_{hWW} \mathcal{A}_1(\tau_W) + \frac{m_{H^\pm}^2 - \mu_2^2}{\sqrt{2} m_{H^\pm}^2} \mathcal{A}_0(\tau_{H^\pm}) \right|^2,$$

# gg $\rightarrow$ h $\rightarrow$ $\gamma\gamma$ in IDM

arXiv:1201.2644v2 [hep-ph]

$$R_{\gamma\gamma} = \frac{\sigma_h^{\gamma\gamma}}{\sigma_{h_{SM}}^{\gamma\gamma}} = \frac{\sigma(gg \rightarrow h) \times Br(h \rightarrow \gamma\gamma)}{\sigma(gg \rightarrow h)^{SM} \times Br(h \rightarrow \gamma\gamma)^{SM}} = \frac{Br(h \rightarrow \gamma\gamma)}{Br(h \rightarrow \gamma\gamma)^{SM}}$$



Arhrib at al

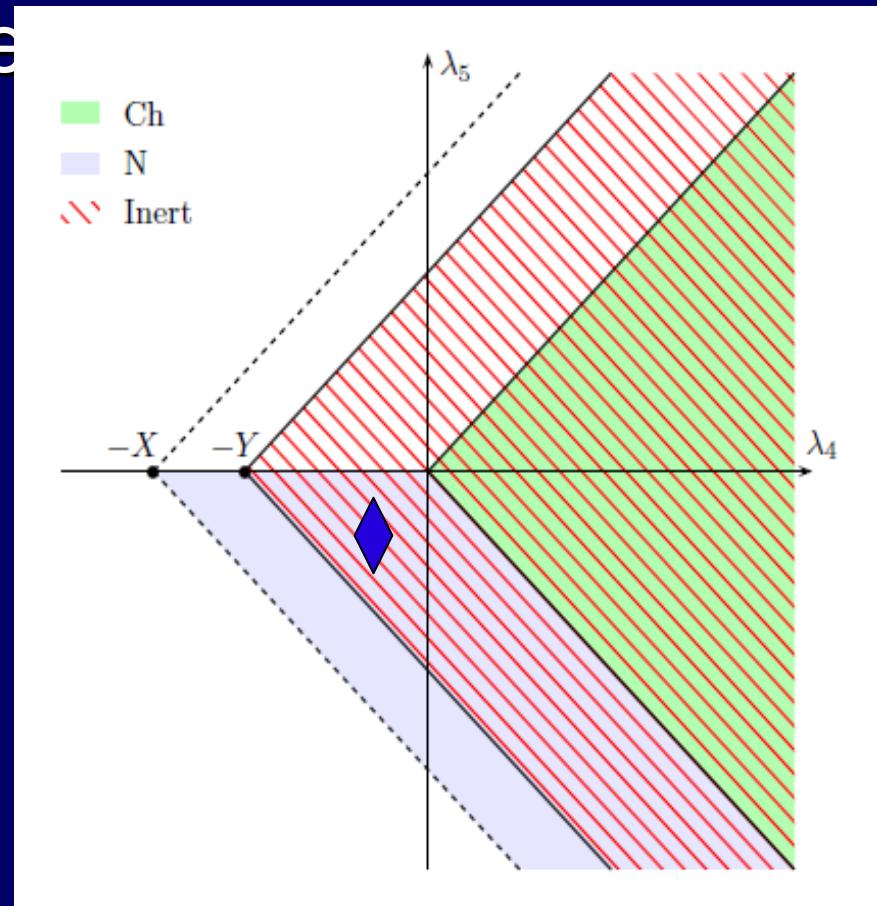
Blue :  $R > 1$   
When  $\lambda_3 < 0$  (and  $\lambda_{345} < 0$ )

# From the EW symmetric phase to the INERT phase in T2 approximation

In the simplest T2 approximation only *mass terms* in  $V$  vary with temperature like  $T^2$ , while  $\lambda'$  are fixed

Various scenarios possible in one, two or three steps, with 1<sup>st</sup> or 2<sup>nd</sup> type phase transitions → *Sokołowska talk*

Ginzburg, Kanishev, MK,  
Sokołowska Phys. Rev D 2010



# Phases at T=0 (beyond T2)

