Unusual decay and production modes of charged Higgs bosons

Glenn Wouda
Uppsala University, Sweden

Scalars 2013, 12-16 September
Warsaw, Poland

In collaboration with
Rikard Enberg (Uppsala) and **Johan Rathsman** (Lund)

References: *JHEP 1308 (2013) 79, arXiv:1304.1714, arXiv:1306.6855*
+ new paper to be submitted very soon!
Stay tuned!

The **new found boson** seems to be **very SM-like!**

Ongoing search for a **Charged boson** → “*Smoking gun*” for new BSM physics!

By “unusual” I will refer to production and decay modes of the charged boson which are **not:**

pp → tt and t decay into bH^+
pp → tbH^+

H^+ → tb, cs, τν

Which are the **dominating modes in MSSM, THDM type-I and II** *(neglecting hW at the moment, see the talk by M. Sher)*

The Stealth Doublet Model

(earlier called “the Lopsided Doublet Model”)

Start with the **THDM scalar potential**:

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

The Z_2 symmetry $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$

is **broken** by some terms in the potential hard and soft.

Global U(2) symmetry, basis redefinition, is broken by postulating a specific **Yukawa coupling structure** (type-I, type-II etc.)

The Stealth Doublet Model (cont.)

Let only **one doublet couple to fermions** (Φ_1)

Let only **one double get VEV** (Φ_1) (*Higgs Basis* physically realized)

→ Just as in the Inert Doublet Model

Let the **Z_2 symmetry be broken softly**

→ FCNC are naturally small, the Z_2 symmetry are restored at very high energies (*c.f.* Soft SUSY breaking)

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*If the **Z_2 symmetry is exact**, one has the **Inert Doublet Model,** see talk by B. Swiezewska*

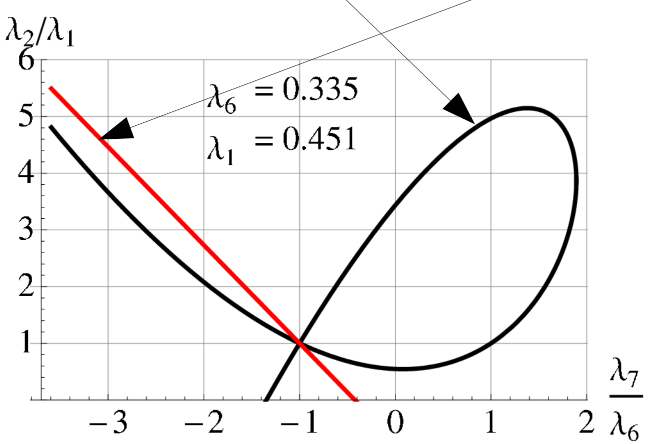
Soft Z_2 breaking in the Higgs basis, **one loses manifest soft breaking** due to one of the **minimization conditions**

$$m_{12}^2 = \frac{1}{2} v^2 \lambda_6$$

However, the Z_2 symmetry is broken softly if these **conditions are fulfilled**:

$$(\lambda_1 - \lambda_2)\left[\lambda_{345}(\lambda_6 + \lambda_7) - \lambda_2\lambda_6 - \lambda_1\lambda_7\right] - 2(\lambda_6 - \lambda_7)(\lambda_6 + \lambda_7)^2 = 0,$$

$$(\lambda_1 - \lambda_2)m_{12}^2 + (\lambda_6 + \lambda_7)(m_{11}^2 - m_{22}^2) \neq 0.$$



Free parameters of the model are:

m_h , m_H , m_A , $m_{H\pm}$, $\sin\alpha$, λ_3 , λ_7

($\sin\alpha$ sets the amount of Z_2 breaking)

Reference: S. Davidson, H. E. Haber, Phys.Rev. D72 (2005) 035004

Scalars and couplings of the Stealth Doublet Model

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ v + \phi_1 + \mathrm{i} G^0 \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} H^+ \\ \phi_2 + \mathrm{i} A \end{pmatrix}$$

The states in Φ_2 are **fermiophobic** at tree-level.

Soft Z_2 breaking → **mixing** between Φ_1 and Φ_2
via the CP-even mass-eigenstates h and H:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \quad 0 \leq \alpha \leq \tfrac{\pi}{2}$$

$m_h < m_H$

H and h have interactions with 2 fermions, and with 2 gauge bosons (due to Φ_1 component)

$$-\mathcal{L}_{\text{Yukawa}} = \frac{m_f}{v} \bar{\Psi}_f \Psi_f \left(H \cos\alpha - h \sin\alpha \right)$$

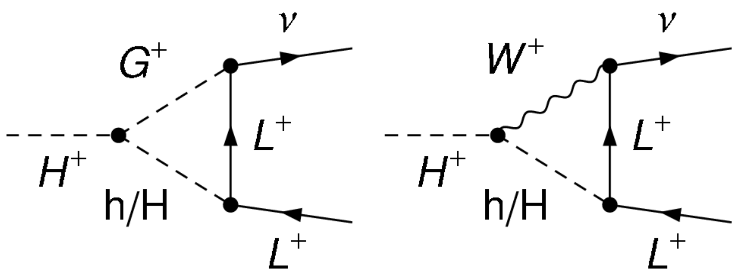
H^+ and A have the following interactions with gauge bosons:

H^+Wh	~sin α
H^+WH	~cos α
H^+WA	independent of sin α

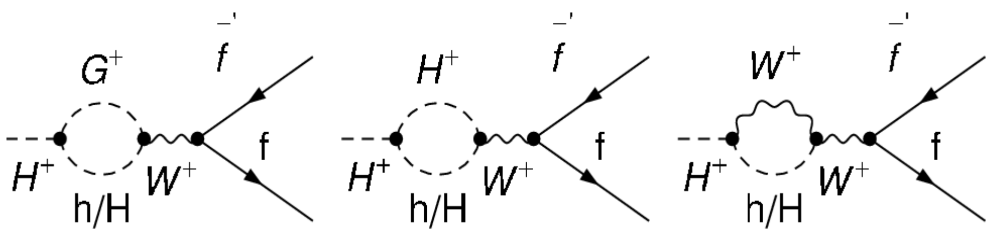
AZh	~sin α
AZH	~cos α

There are of course many more,
e.g. 3scalars, 4scalars, 2scalar-2gauge bosons
"THDM with tan β = 0"

Due to the **mixing** (sin α) H^+ and A can have **loop-genereted couplings to 2 fermions**!



Loop-generated coupling



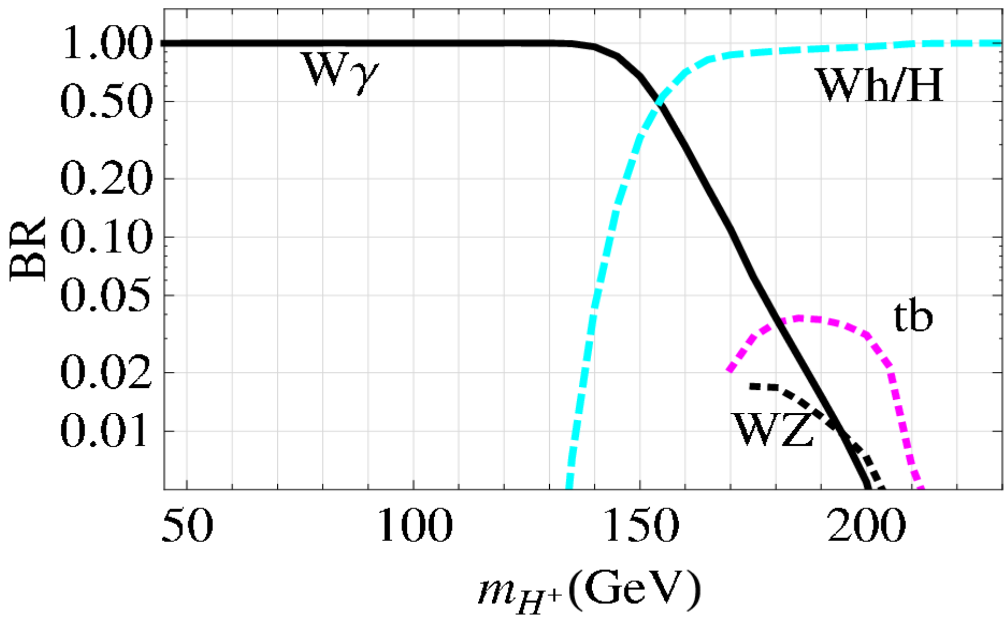
H^+W mixing, requires renormalization

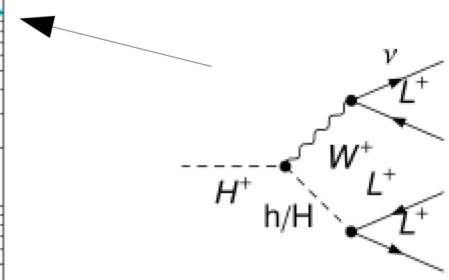
Every diagram is proportional to sin α cos α

For vast majority of the (allowed) parameter space ...

(after taken theoretical constraints such as stable potential, perturbative scalar interactions, unitarity, EWPT and collider searches, see references and backup slides)

...The Branching Ratios of the charged scalar looks like:





\+ more

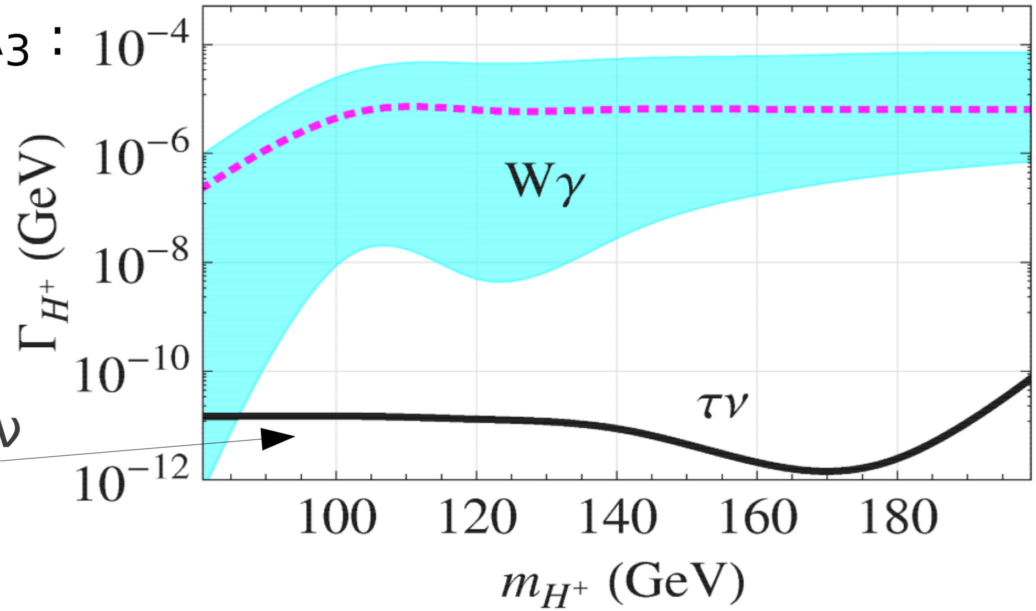
Off-shell W are treated with the “smeared mass unstable particle model”
Reference: V.I.Kuksa, Phys.Atom.Nucl.72:1063-1073,2009 & arXiv:0910.4644

This is because **Wγ and cs, τν proceeds at lowest order via one-loop**

(i.e same order!)

Furthermore, cs and τν modes are suppressed by small Yukawa couplings (m$_c$/v etc.)

By scanning over allowed λ_3 :



cs has similar magnitude as τν

(the purple line is same parameter used in the plot on the previous slide)

Since **the H^+tb coupling vanishes at tree-level**,

H^+ production in top-quark decays and in association with top → **suppressed**!

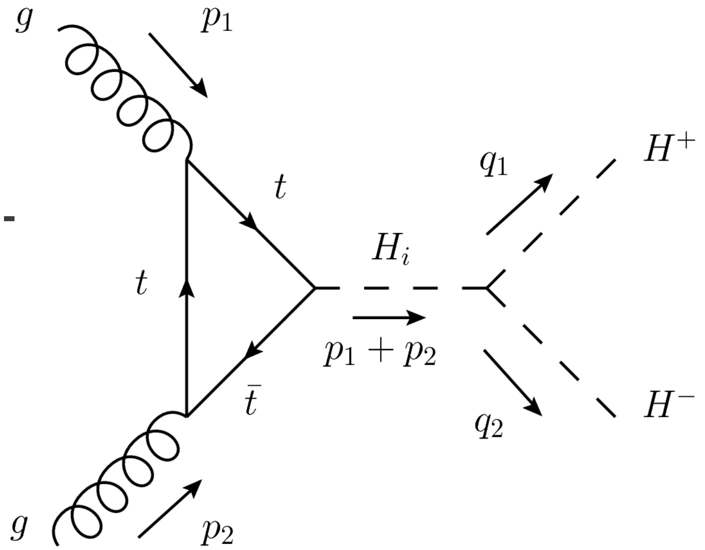
$$BR(t \to H^+ b) < 10^{-6}$$

Consider Drell-Yan **pair production**

(model independent),

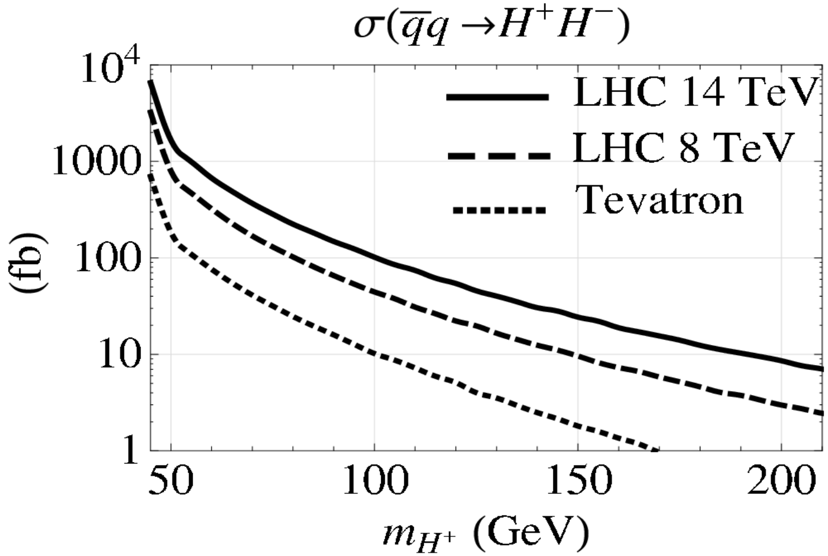
Or in **H decays**,

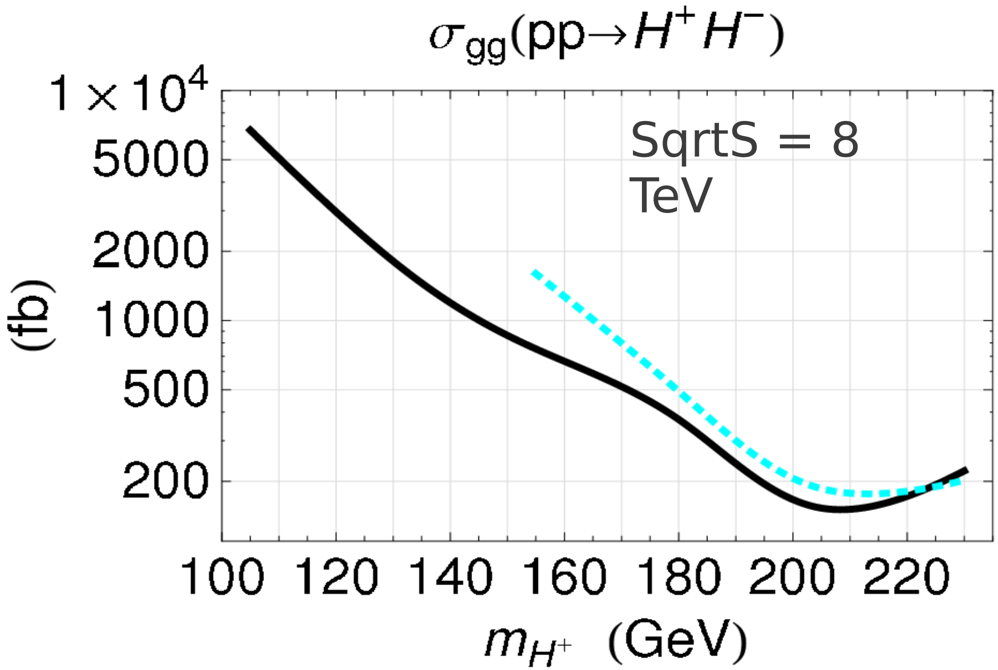
Or **via off-shell h and H to H^+H^-**



Leading order hadronic cross sections for H^+H^-

Drell-Yan, small
but model independent





Via off-shell h and H

Shown is max cross section by scanning over allowed λ_3

Black line: mH = 200 GeV

Cyan line: mH = 300 GeV

Model dependent though!

The $H^+ \to W\gamma$ signal at colliders

$H^+ \to W\gamma$ dominates if H^+ is the lighest scalar (for most parameter space)

Pair production of $H^+ \to$ **signal will be $W^+W^-\gamma\gamma$**

Either let one W decay leptonically and the other one hadronically

Observable will be a **cluster transverse mass**

Or let both W decay leptonically

Observable will be some sort of **MT2 variable**

Signal photons have relatively low pT ... many challenging backgrounds

(such as fake photons and photons from pion decays... can probably not be well simulated)

Summary & outlook

the **Stealth Doublet Model**:

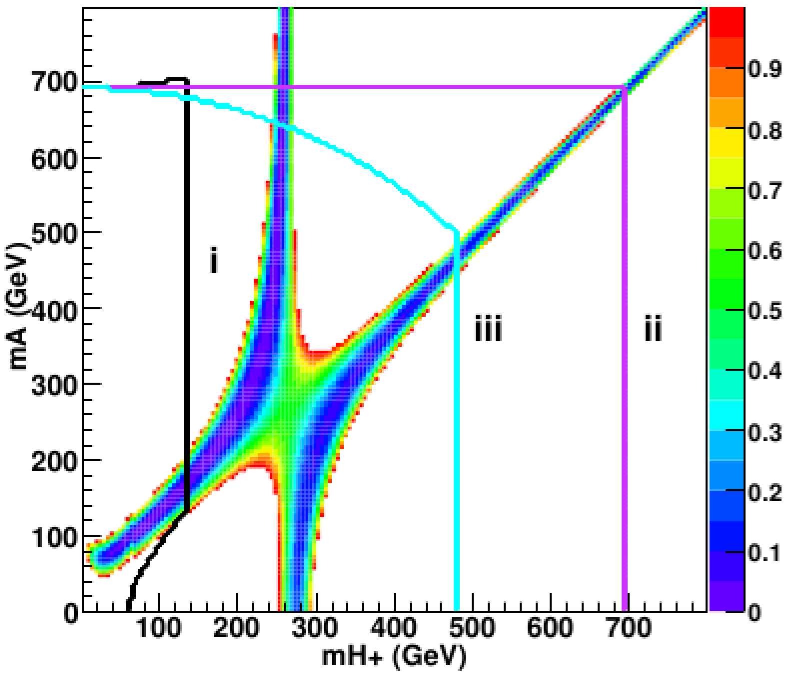
- a new version of THDM

"Generalization of the IDM"

Mixing between the doublets, generates loop couplings to fermions for the charged scalar →

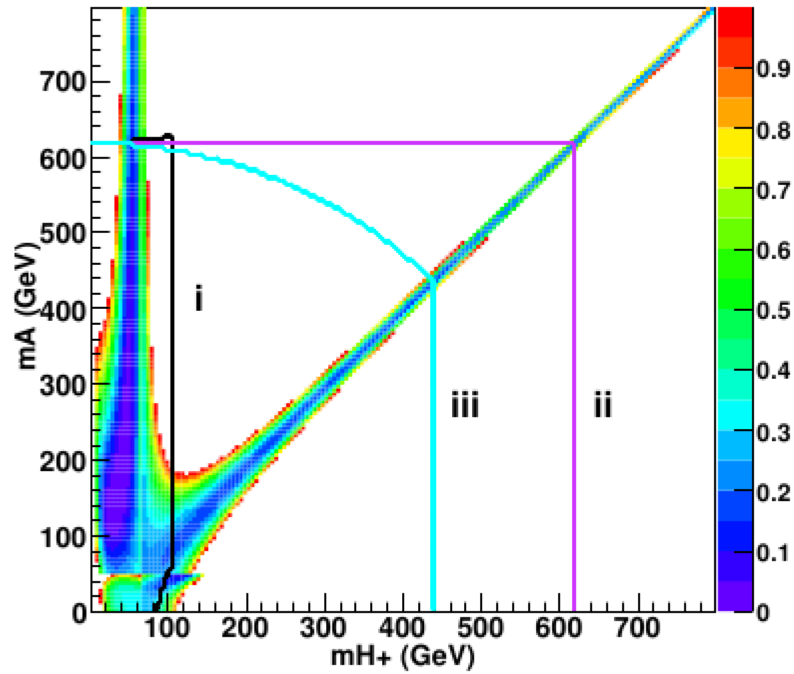
Unusual decay and production modes of the charged scalar

$H^+ \rightarrow W\gamma$ is an interesting but probably a difficult signal!



(a)

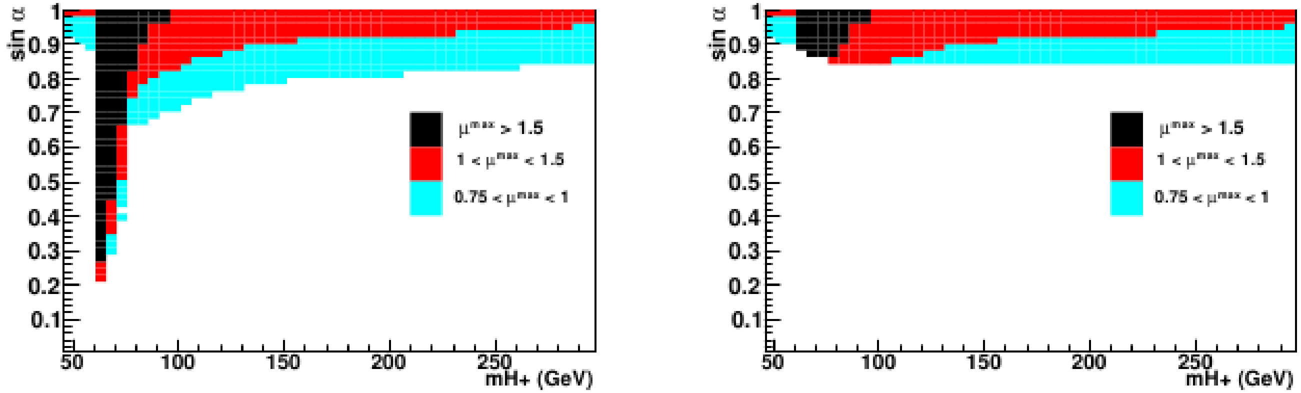
$m_h = 125$ GeV, $m_H = 300$ GeV, $s_\alpha = 0.9$.



(b)

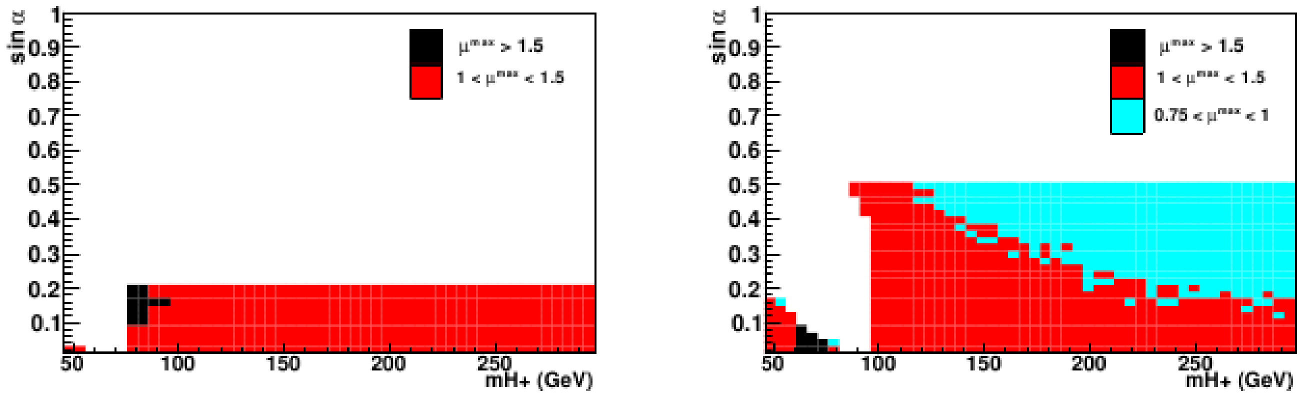
$m_h = 75$ GeV, $m_H = 125$ GeV, $s_\alpha = 0.1$.

To the left of the bands in the figure are the allowed regions by theoretical constraints for different values of λ_3 displayed: black (i) $\lambda_3 = 0$, magenta (ii) $\lambda_3 = 2m_{H^\pm}^2/v^2$ and cyan (iii) $\lambda_3 = 4m_{H^\pm}^2/v^2$. Here, we have also used $\lambda_2 = \lambda_1$ and $\lambda_7 = \lambda_6$.



(a) (b)

Figure 5. The maximally obtained $\mu_{h\gamma\gamma} \equiv \mu^{\max}_{h\gamma\gamma}$, with $m_h = 125$ GeV and $m_H = 300$ GeV, for parameters that satisfy all constraints from theory, collider searches with the use of HiggsBounds version 3.8. In (b) the requirement $\mu_{hZZ} > 0.7$ is added. λ_7 and λ_3 are scanned over according to eq. (4.4).



(a) $m_h = 75$ GeV and $m_H = 125$ GeV.

(b) $m_h = 95$ GeV and $m_H = 125$ GeV.

Figure 6. The maximally obtained $\mu_{H\gamma\gamma} \equiv \mu^{\max}_{H\gamma\gamma}$ for parameters that satisfy all constraints from theory, collider searches with the use of HiggsBounds version 3.8, and $\mu_{HZZ} > 0.7$. λ_7 and λ_3 are scanned over according to eq. (4.4).