W+4gamma signature from light charged Higgs boson at the LHC Run-II

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Cadi Ayyad University
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Outline

HEP Activities in Safi

1. Introduction
2. Two Higgs doublet model: potential and Yukawa couplings
3. Charged Higgs boson decays
4. $H^{\pm}$ production mechanisms at the LHC
5. W+4γ signatures from light $H^{\pm}$
6. Conclusions

HEP Activities: Safi team

- Rachid Benbrik
- Abdessamad Rouchad
- Souad Semlali
- Hicham Harouiz
- Yahya Mekaoui
- Abdeljalil Habjia
- Abdekarim Mahfoud
- Khadija El Menaour

Expertise

- Extended Higgs scalars
- Bluiding Models
- Higgs Phenomelongies
- B-Physics
- High order corrections

HEP Activities: Collaborations and projects

Local groups:

- Tanger
- Marrakech
- Agadir
- Beni-Mellal

International groups:

- Europe: Spain, Portugal, France, UK, Sweden
- Aisa: China, Taiwan, India

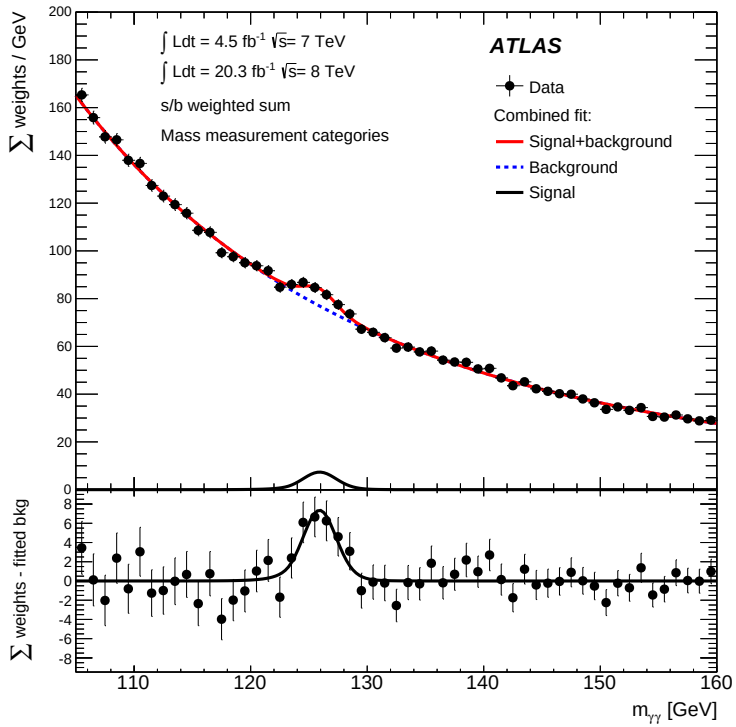
Projects:

- H2020
- Moroccan ministry of higher Education and scientific research
- Fellowship PIFI program

Evidence for a Standard Model like Higgs boson

- In the summer of 2012 an SM-like particle (h) was found at the LHC.
- So far its properties agree with SM predictions at tthe 20% level.
- Its mass derived from the $\gamma\gamma$ and ZZ channels is

$$m_h = 125.09 \pm 0.24 \ \ \mathrm{GeV}$$



Beyond the SM

- The SM-like limit exists in various models with extra neutral Higgs.
- Any extended Higgs sector a Charged Higgs would be a signal.
- Such scalars appear in multi-Higgs doublet (MHDM).
- From EWO are in agreement with SM with $\rho = 1$.
- in this talk I will focus on a very popular model such as 2HDM .

Potential with sotf Z_2-violating

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

Apart from the term m_{12}^2, this potential exhibits a Z_2 symmetry,

$$(\Phi_1,\Phi_2) \leftrightarrow (\Phi_1,-\Phi_2) \quad \text{or} \quad (\Phi_1,\Phi_2) \leftrightarrow (-\Phi_1,\Phi_2). \quad (2)$$

The most general potential contains in addition two more quartic terms, with coefficients λ_6 and λ_7, and violates Z_2 symmetry in a hard way T.D.Lee PRD8,1226'73," JF.Gunion *et al.*The HHG" .

- The parameters λ_1–λ_4, m_{11}^2 and m_{22}^2 are real.
- The potential (1) can lead to CP violation when λ_5 and m_{12}^2 are complex.

Mass eigenstates

We use the following decomposition of the doublets:

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ (v_1 + \eta_1 + i\chi_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ (v_2 + \eta_2 + i\chi_2)/\sqrt{2} \end{pmatrix}, \tag{3}$$

Here $v_1 = \cos\beta\, v$, $v_2 = \sin\beta\, v$, $v = 2\, m_W/g$, with $\tan\beta = v_2/v_1$. The charged Higgs bosons are the combination orthogonal to the charged Nambu–Goldstone bosons:

$$H^\pm = -\sin\beta\varphi_1^\pm + \cos\beta\varphi_2^\pm \tag{4}$$

and their mass is given by

$$M_{H^\pm}^2 = \mu^2 - \frac{v^2}{2}(\lambda_4 + \Re\lambda_5), \tag{5}$$

where we define a mass parameter μ by

$$\mu^2 \equiv (v^2/2v_1v_2)\Re m_{12}^2. \tag{6}$$

Mass eigenstates and gauge couplings

With all momenta incoming, we have the $H^{\mp}W^{\pm}\phi$ gauge couplings:

$$\begin{aligned} H^{\mp}W^{\pm}h: &\quad \frac{\mp ig}{2}\cos(\beta-\alpha)(p_\mu - p_\mu^{\mp}), \\ H^{\mp}W^{\pm}H: &\quad \frac{\pm ig}{2}\sin(\beta-\alpha)(p_\mu - p_\mu^{\mp}), \\ H^{\mp}W^{\pm}A: &\quad \frac{g}{2}(p_\mu - p_\mu^{\mp}). \end{aligned} \tag{7}$$

The strict SM-like limit corresponds to $\sin(\beta-\alpha)=1$.

$$\begin{aligned} VVh: &\quad \sin(\beta-\alpha), \\ VVH: &\quad \cos(\beta-\alpha), \\ VVA: &\quad 0. \end{aligned} \tag{8}$$

$V = W^{\pm}, Z$

Theoretical constraints

The 2HDM is subject to various theoretical constraints.

- Stability or positivity of the potential:

$$V(\Phi_1, \Phi_2) > 0 \qquad \text{as} \qquad |\Phi_1|, |\Phi_2| \to \infty. \tag{9}$$

This requirement gives the following conditions on λ's
PM. Ferreira *et al* ,PLB,2005

$$\lambda_1 > 0\,,\ \lambda_2 > 0\,,\ \lambda_3 + 2\sqrt{\lambda_1 \lambda_2} > 0\ ,\ \lambda_3 + \lambda_4 - |\lambda_5| > 2\sqrt{\lambda_1 \lambda_2}. \tag{10}$$

- Perturbativity: satisfy $|\lambda_i| \leq 8\pi$ $(i = 1, ..., 5)$. has significant effect on $(\tan\beta, M_{H^\pm})$ plane.
- Unitarity: all $2 \to 2$ processes scattering are under control.

$$\mathrm{Max}(\mathrm{Eigenvalues}(\mathrm{M})) < 0.5 \tag{11}$$

Yukawa Interaction for the 2HDM T.D.Lee PRD8,1226'73

$$-\mathcal{L}_{\rm Yukawa} = \overline{Q}_L \Phi_a F_a^D D_R + \overline{Q}_L \widetilde{\Phi}_a F_a^U U_R + \overline{L}_L \Phi_a F_a^L L_R + {\rm h.c.}, \quad (12)$$

Model	d	u	ℓ
I	Φ_2	Φ_2	Φ_2
II	Φ_1	Φ_2	Φ_1
III	$\Phi_1 \& \Phi_2$	$\Phi_1 \& \Phi_2$	$\Phi_1 \& \Phi_2$
X	Φ_2	Φ_2	Φ_1
Y	Φ_1	Φ_2	Φ_2

Table 1: The most popular models of the Yukawa interactions in the 2HDM.

in Type II (MSSM)

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

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

Charged Higgs boson decays

a charged Higgs boson can decay to a fermion-antifermion pair

$$H^+ \to c\bar{s}, \tag{14a}$$
$$H^+ \to c\bar{b}, \tag{14b}$$
$$H^+ \to \tau^+ \nu_\tau, \tag{14c}$$
$$H^+ \to t\bar{b}, \tag{14d}$$

to gauge bosons,

$$H^+ \to W^+ \gamma, \tag{15a}$$
$$H^+ \to W^+ Z, \tag{15b}$$

or to a neutral Higgs boson and a gauge boson:

$$H^+ \to hW^+, \quad AW^+ \tag{16}$$

and their charge conjugates.

Light H^+ ($M_{H^\pm} < m_t$)

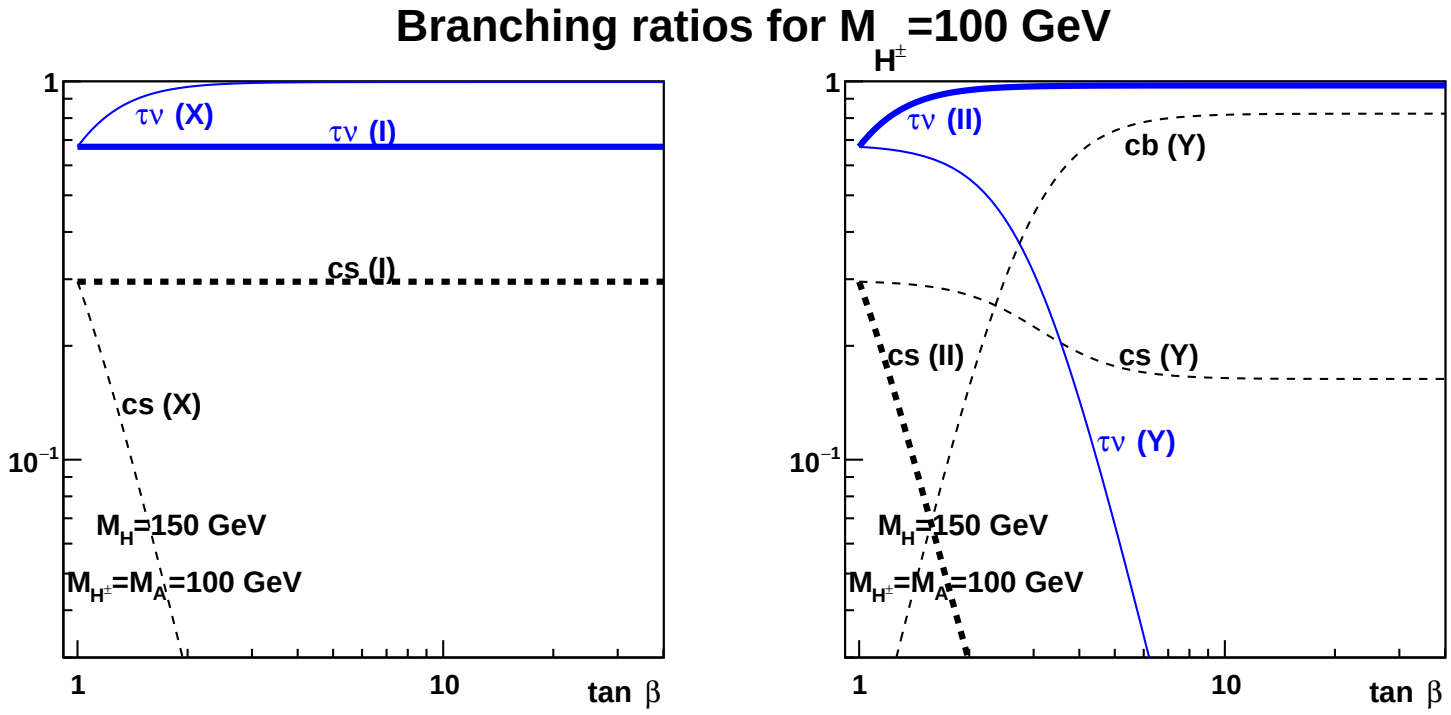


Figure 1: Light charged-Higgs branching ratios vs tan β.

- We focus on CPC case and set $M_h = 125$ GeV.

Heavy H^+ ($M_{H^\pm} > m_t$)

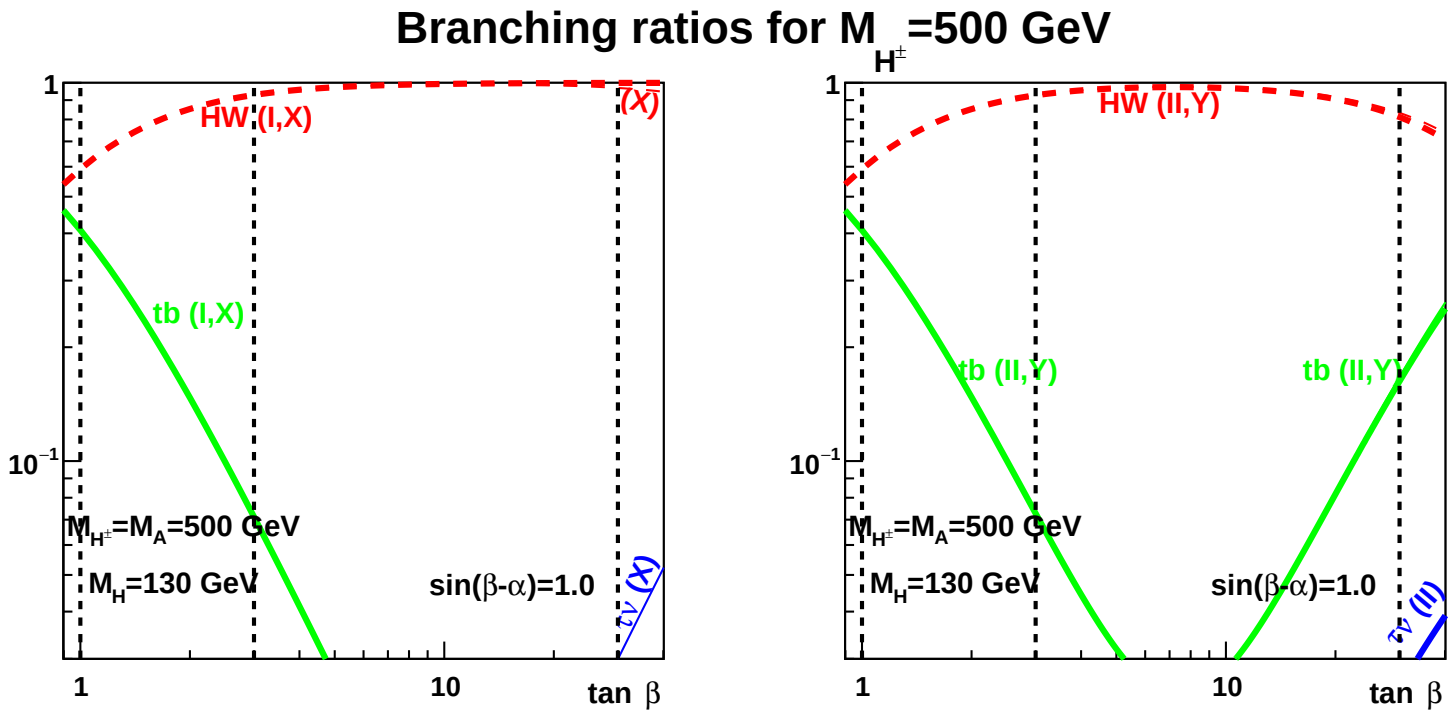


Figure 2: Heavy charged-Higgs branching ratios vs tan β.

- $\sin(\beta - \alpha) = 1$.

Heavy H^+ ($M_{H^\pm} > m_t$)

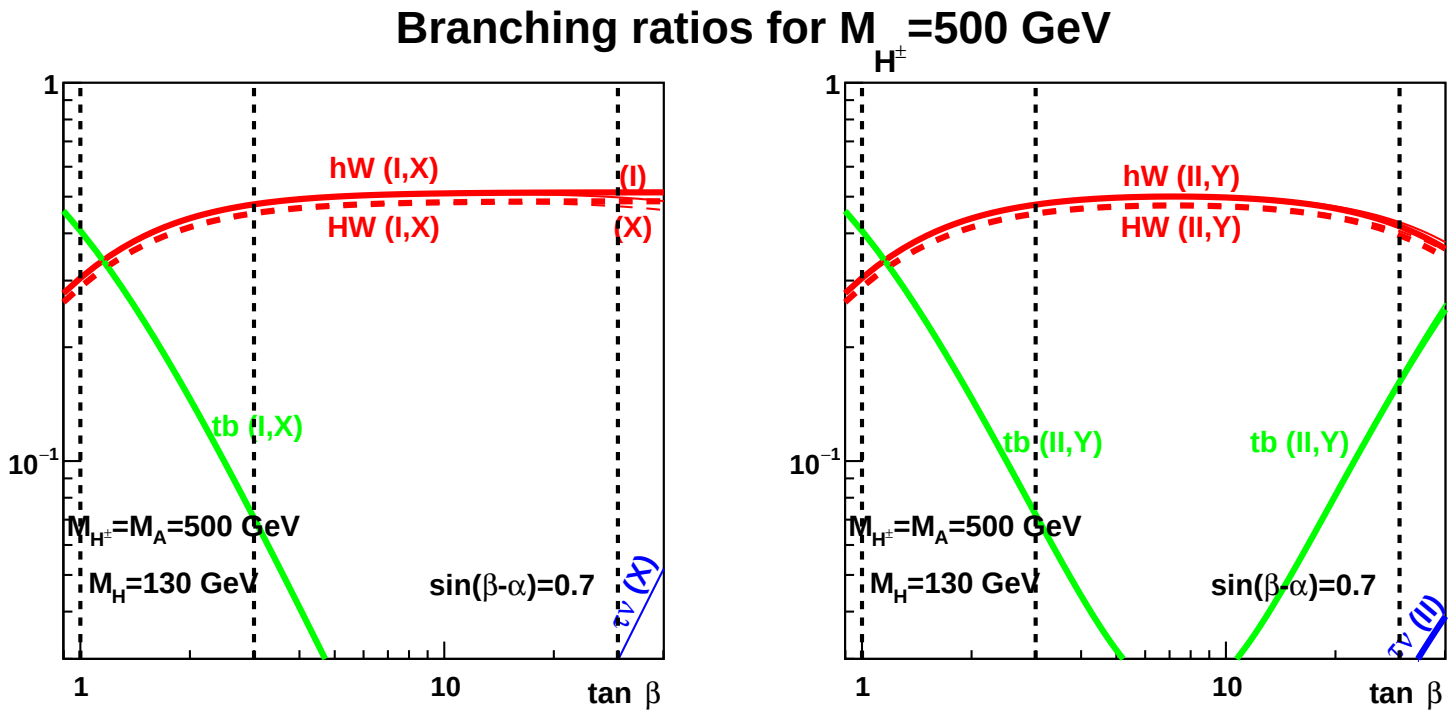


Figure 3: Heavy charged-Higgs branching ratios vs tan β.

- $\sin(\beta - \alpha) = 0.7$

Branching ratios vs $M_{H^\pm}$ in Type I

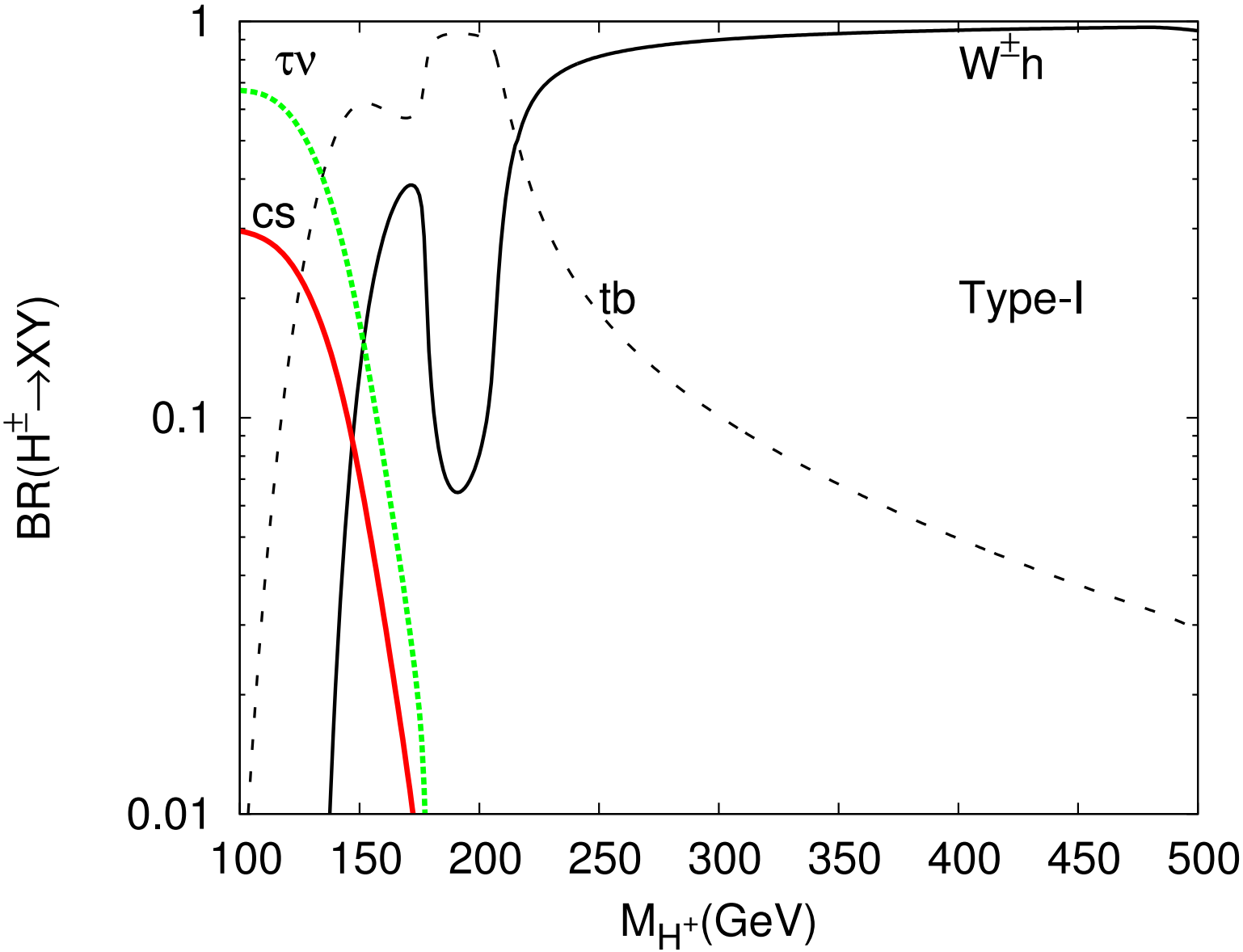


Figure 4: Branching ratios of charged-Higgs as a function of $M_{H^\pm}$ in Type I with $\sin(\beta-\alpha)=0.81$ and $\tan\beta=8$.

Branching ratios vs $M_{H^\pm}$ in Type X

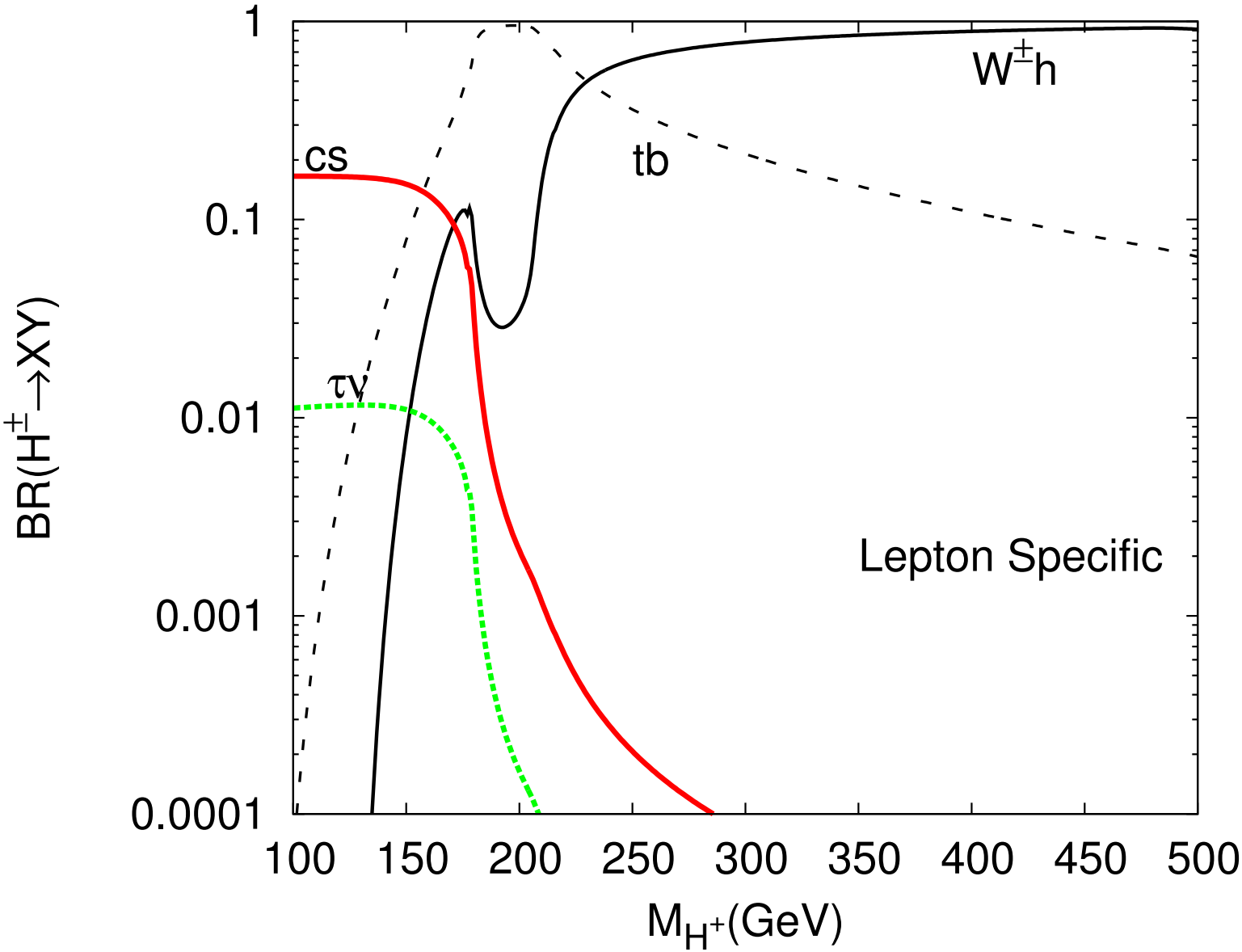


Figure 5: Branching ratios of charged-Higgs as a function of $M_{H^\pm}$ in Type I with $\sin(\beta-\alpha)=0.81$ and $\tan\beta=8$.

Production processes: Single production at the LHC

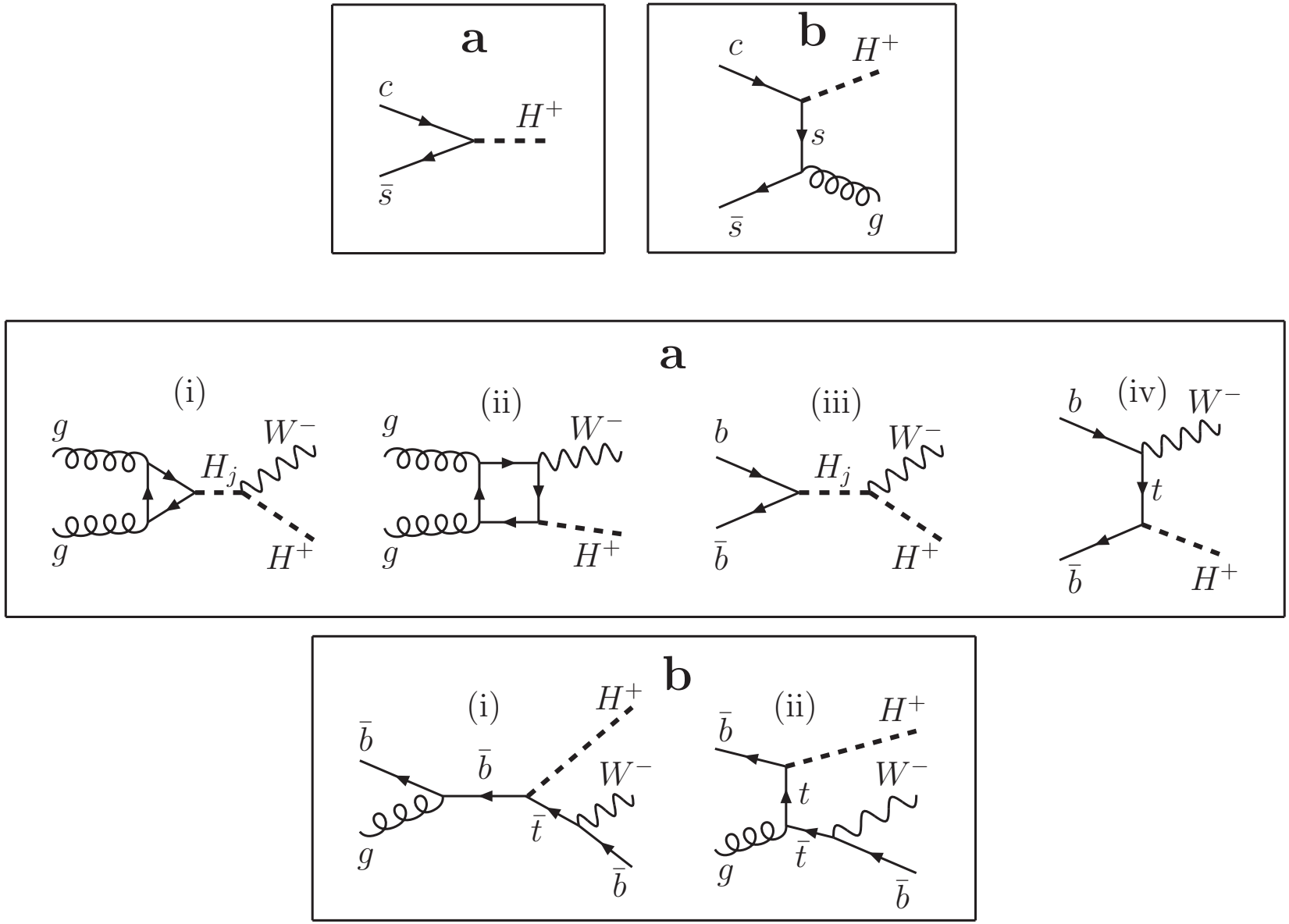
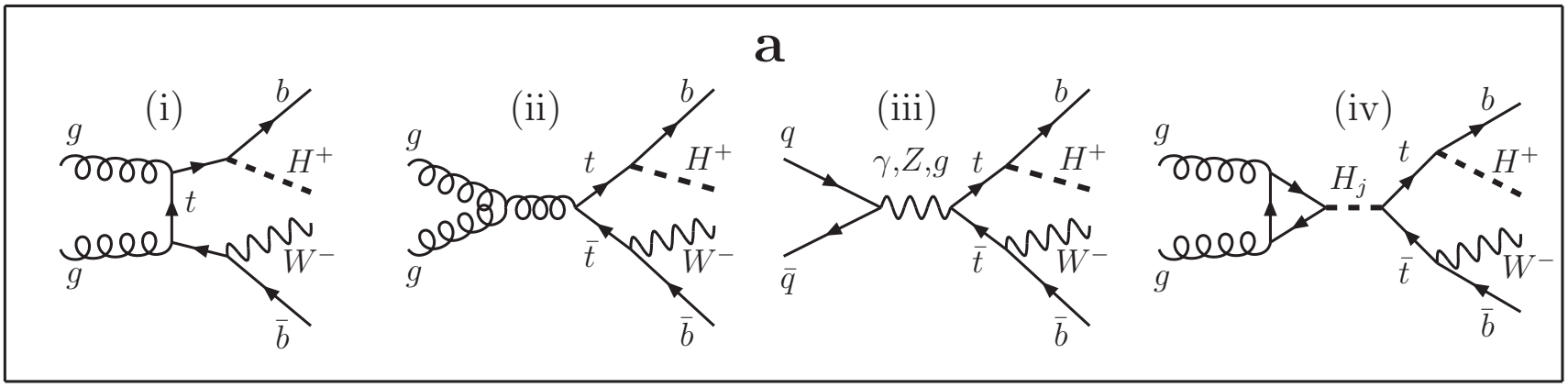
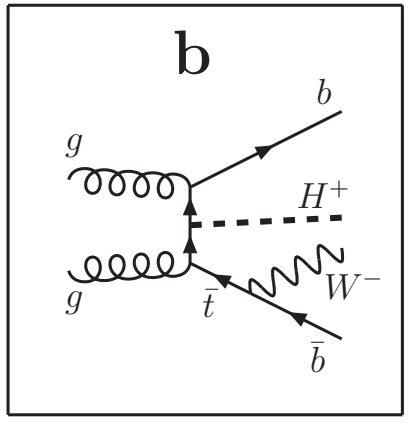
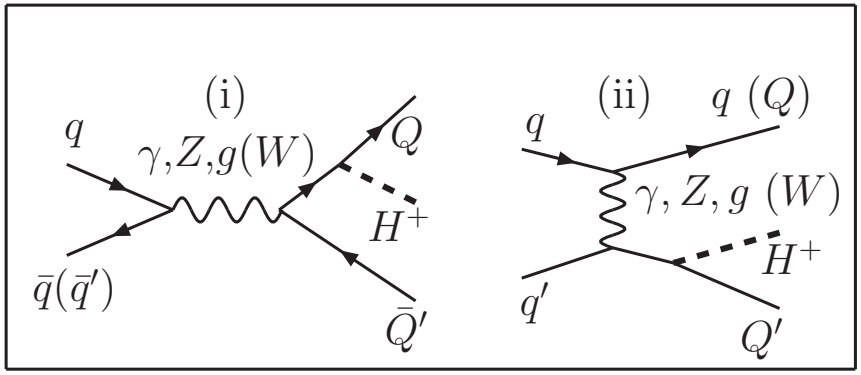


Figure 6: Feynman diagrams contributing in Single production at the LHC production processes.

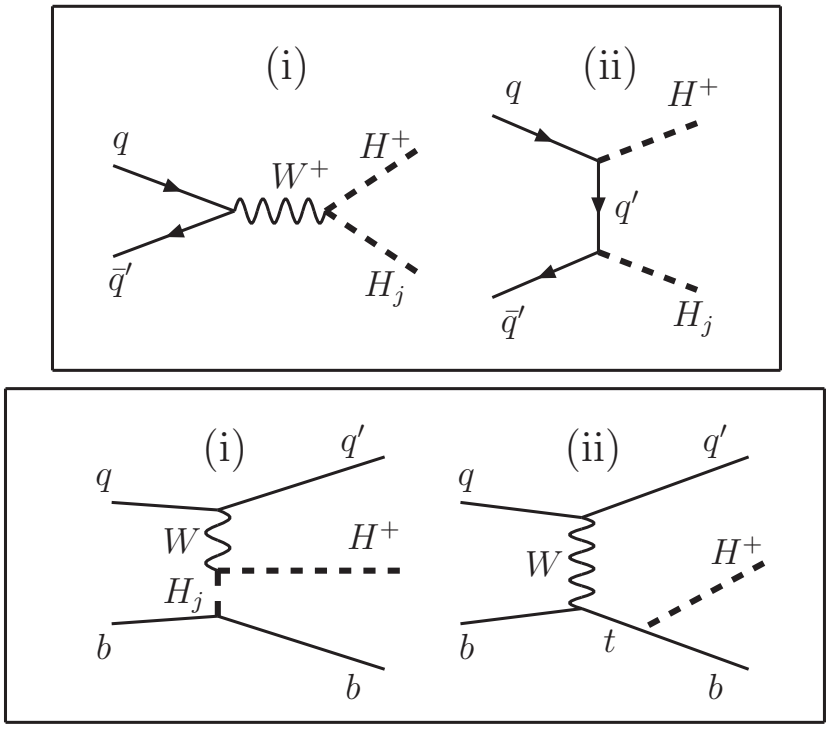
Production processes: Single production at the LHC



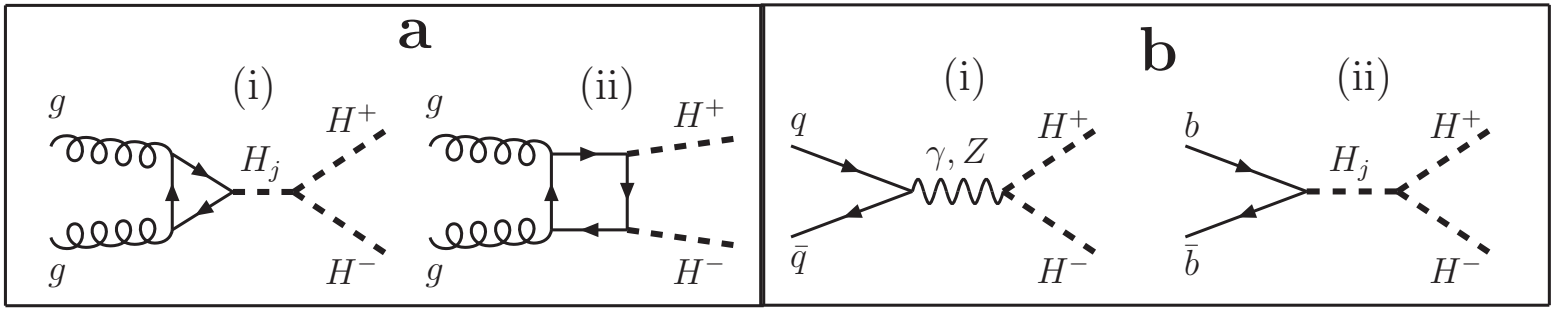


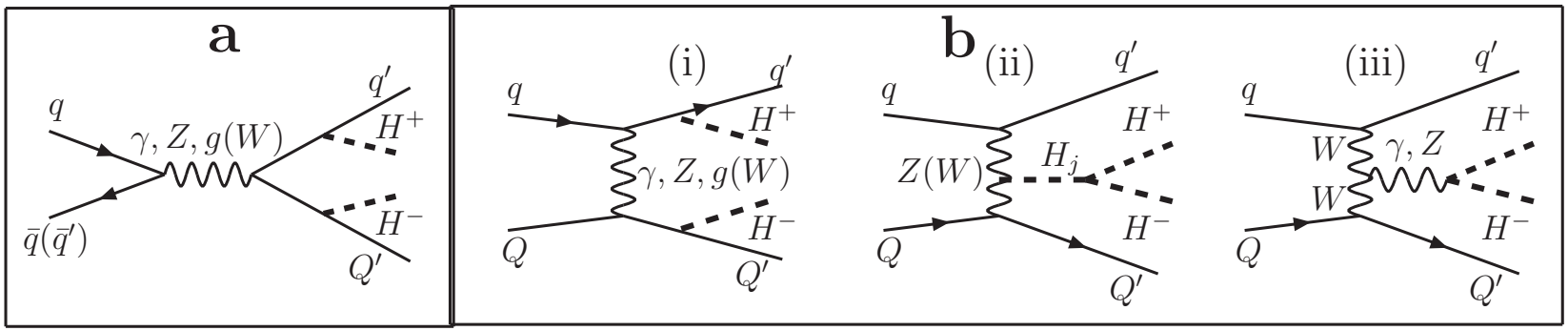


Production processes: Single production at the LHC



Production processes: Pair production at the LHC





Production cross sections $pp \to H^{\pm}X$

We use CTEQ6L, $\sqrt{s} = 14$ TeV and $\sin(\beta - \alpha) = 1$ in Types I and II.

- $g\bar{b} \to H^{+}\bar{t}$, (solid),
- $gg \to H^{+}b\bar{t}$, (dotted),
- $gg \to H_j \to H^{+}W^{-}$, (dash-dotted).

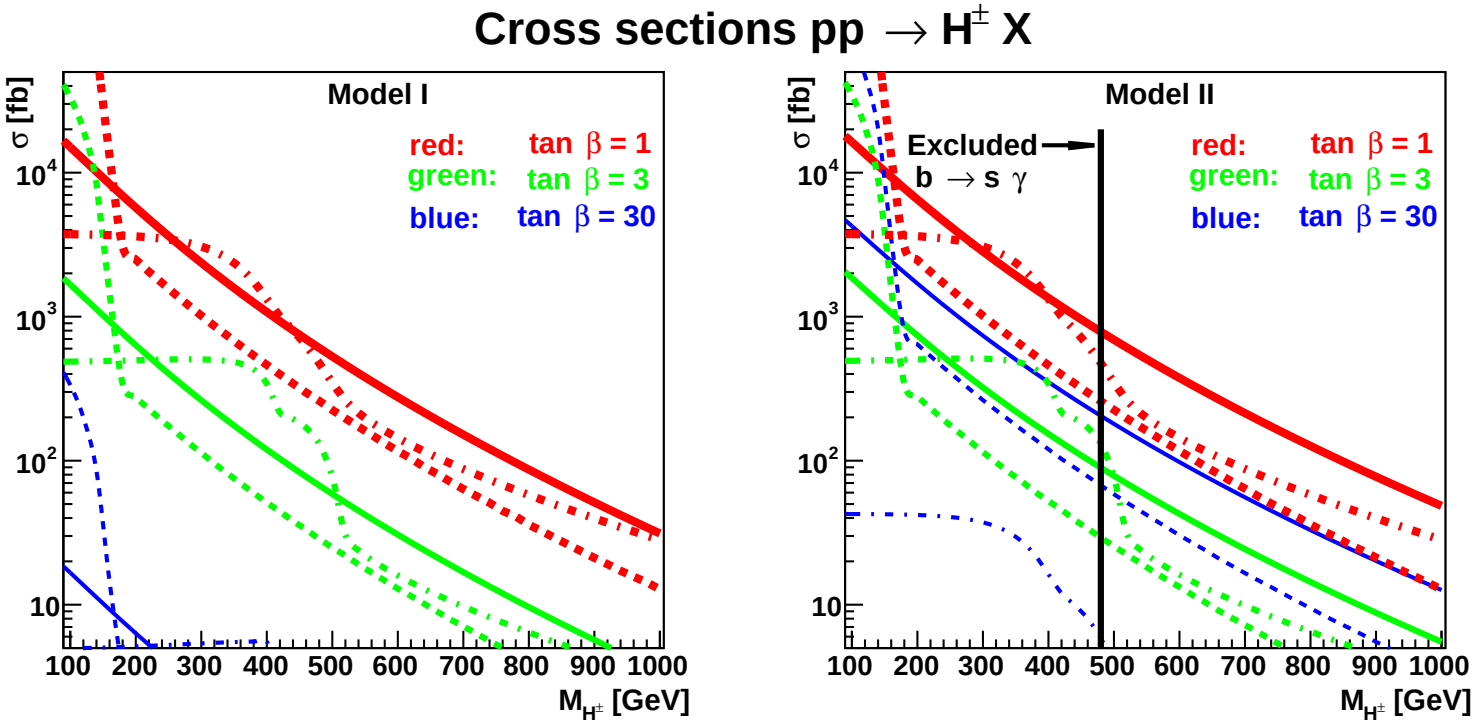
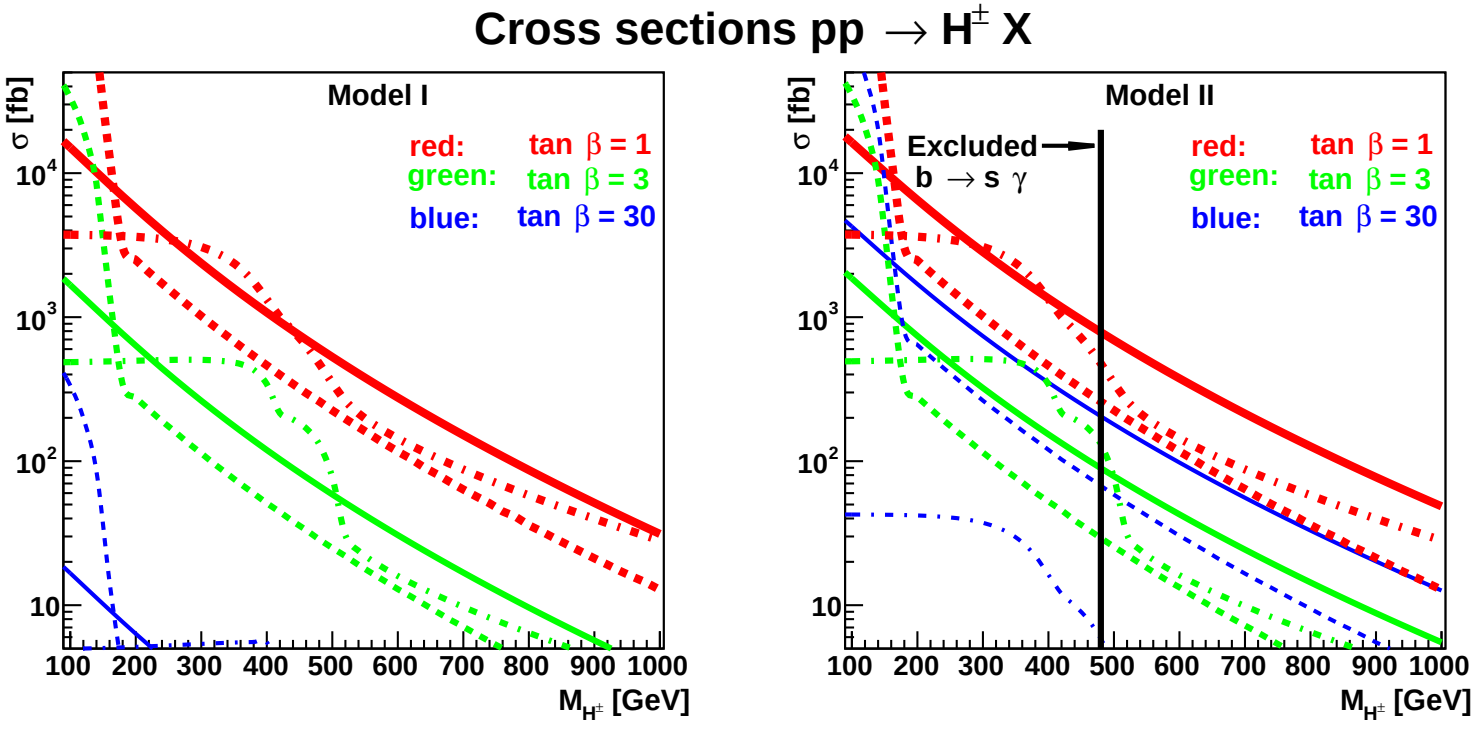


Figure 7: Charged Higgs production cross sections in the 2HDM, at 14 TeV

Production cross sections $pp \to H^{\pm}X$

We use CTEQ6L, $\sqrt{s} = 14$ TeV and $\sin(\beta - \alpha) = 1$ in Types I and II.

- For $\tan\beta = 1$, type-I and type-II are diffrent due to sign Yukawa.
- Models X and Y will have the same predictions except for $(\tau\nu)$.
- The bumpy structure is due to resonnance of neural Higgs.



Allowed regions in type-1

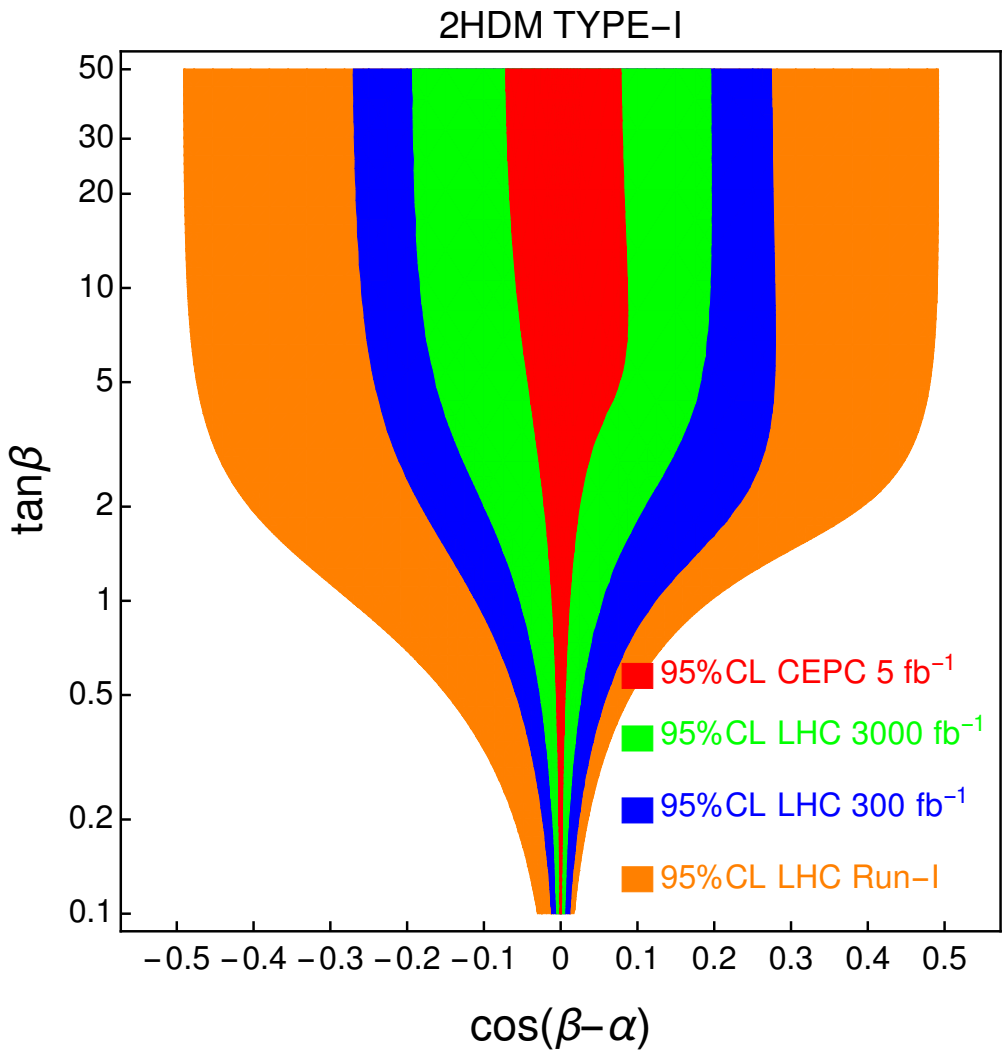


Figure 8: Allowed regions of the $[\cos(\beta - \alpha), \tan\beta]$ plane for the 2HDM Model I.

W+4γ signatures from light $H^{\pm}$ at Run-II

Here we focus on on the following scenario:

- H is the SM-like
- h is fermiophibic state
- $pp \to H^{\pm}h$ follwoed by $H^{\pm} \to W^{\pm}h$

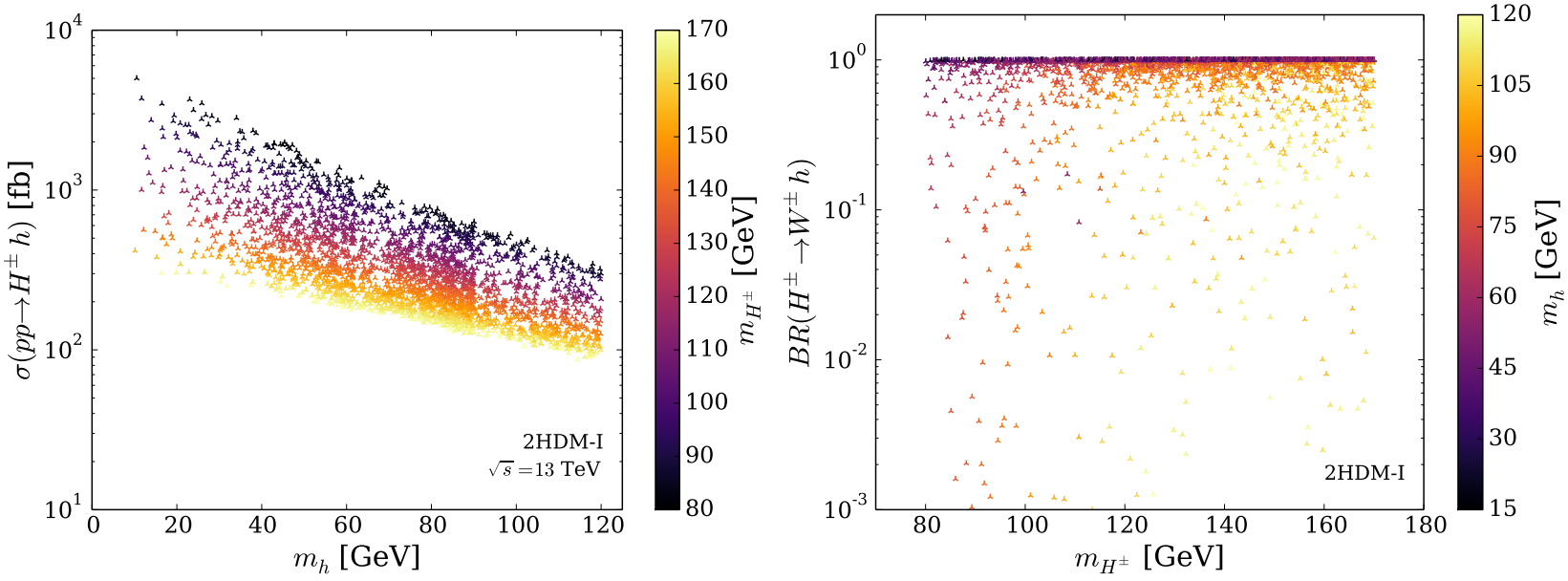


Figure 9: The maximun of cross-sections $pp \to H^{\pm}h$ and $H^{\pm} \to W^{\pm}h$

W+4γ signatures from light $H^{\pm}$ at Run-II

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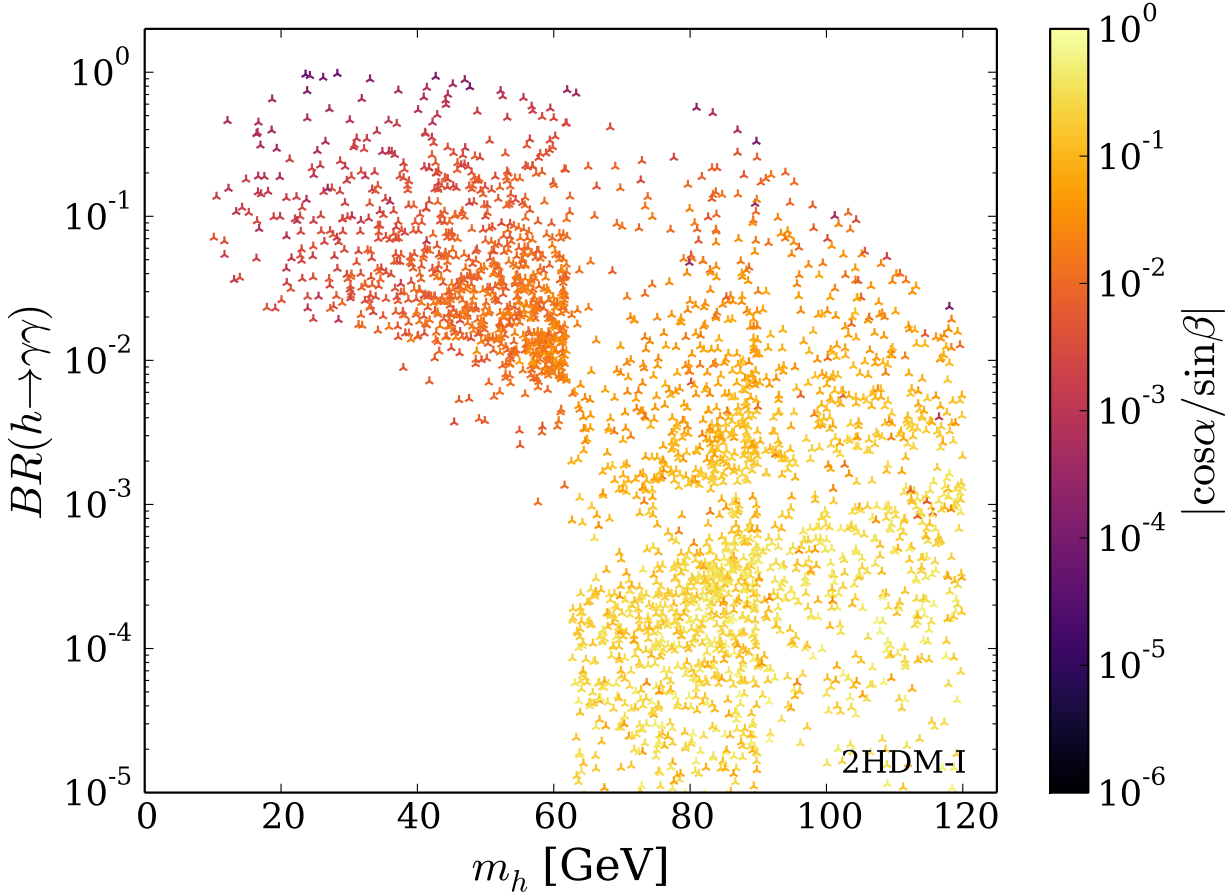

Figure 10: The maximun of Branching ratio of $h \to \gamma\gamma$

W+4γ signatures from light $H^{\pm}$ at Run-II

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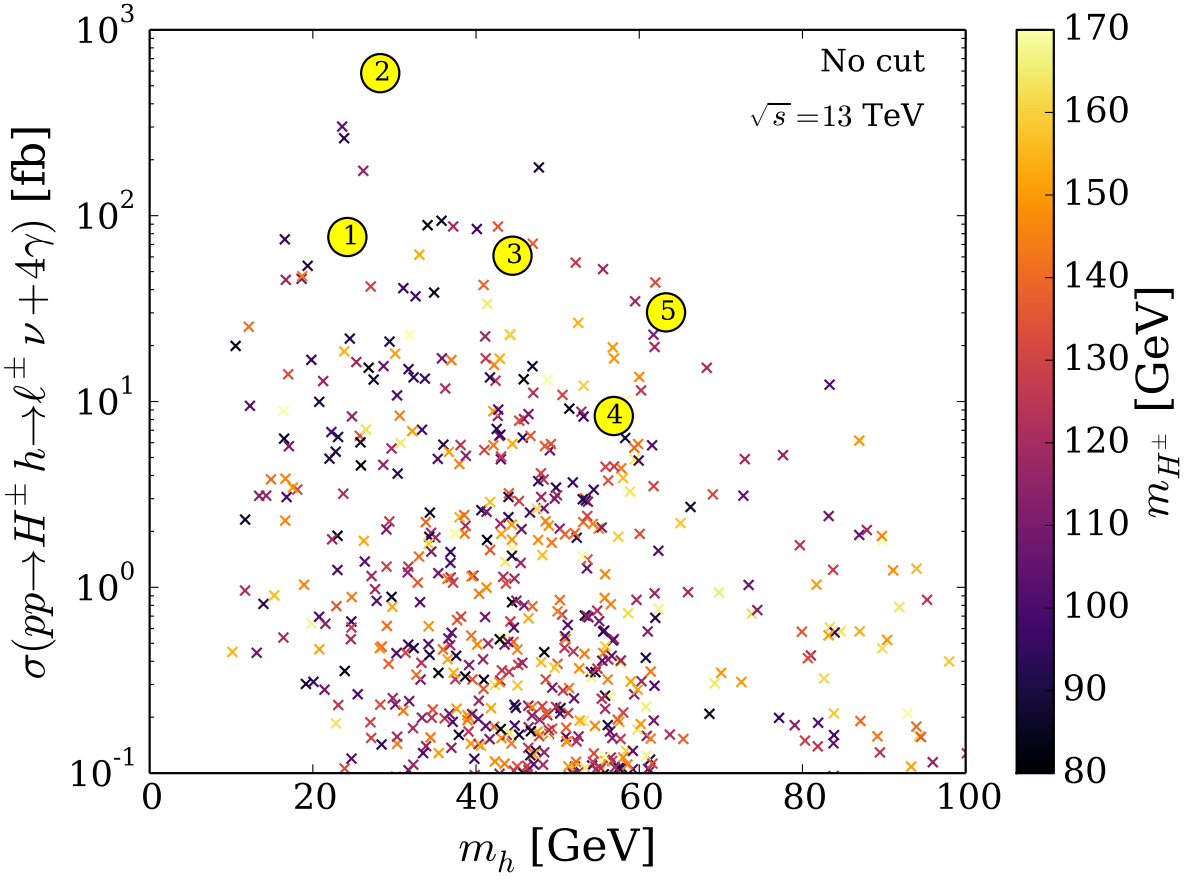

Figure 11: The maximun of XS in fb.

W+4γ signatures from light $H^{\pm}$ at Run-II

Here we focus on on the following scenario:

- H is the SM-like
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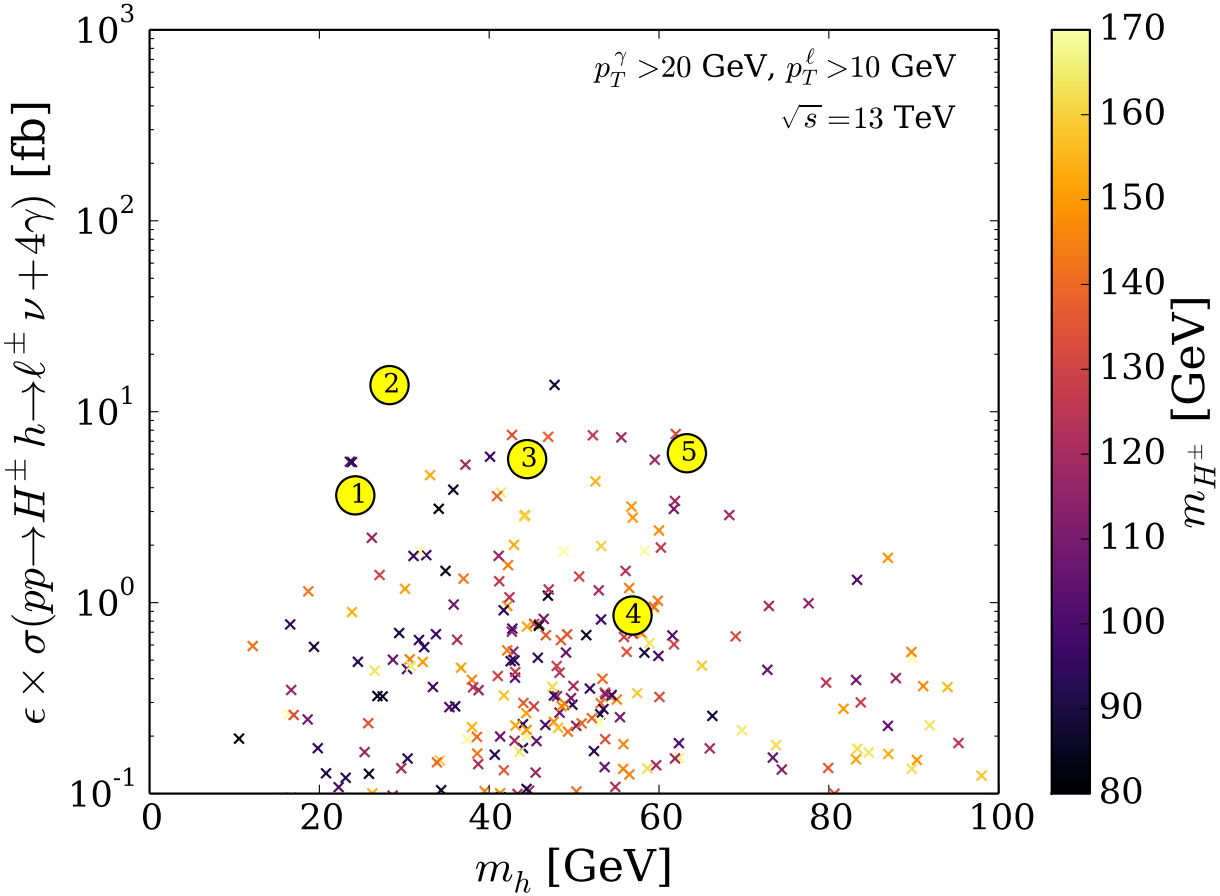

Figure 12: The maximun of XS in fb.

W+4γ signatures from light $H^{\pm}$ at Run-II

Here we focus on on the following scenario:

- H is the SM-like
- h is fermiophibic state
- $pp \to H^{\pm} h$ follwoed by $H^{\pm} \to W^{\pm} h$

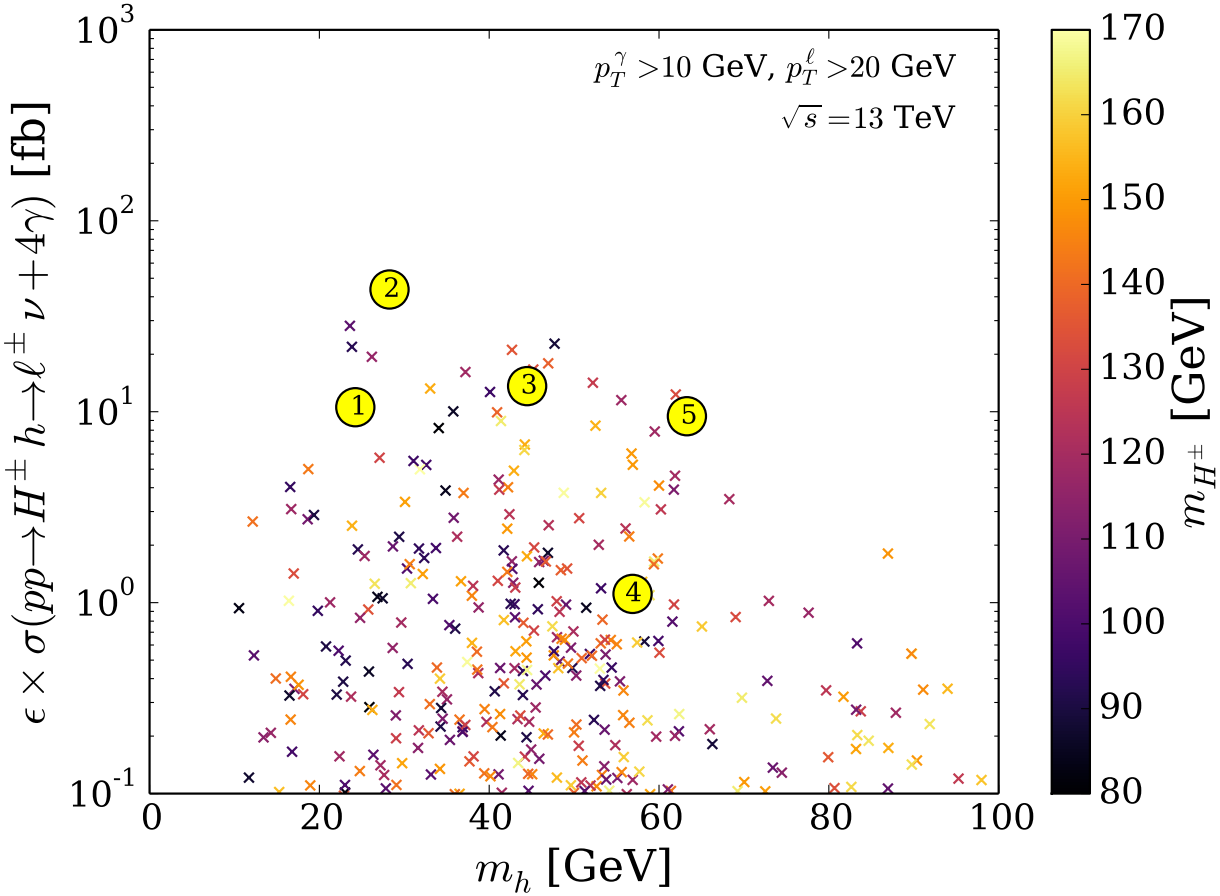

Figure 13: The maximun of XS in fb.

Conclusions

- Various SM like models exsist with extra Higgs scalars.
- A charged Higgs would be the most striking signal of a Higgs with extra doublets.
- In this talk we have analyzed type 1 2HDM by focusing on the most "natural" decay modes are :$\tau\nu$ or $W\phi$ with any neutral Higgs.
- With a reasonable cuts on the p_T^{ℓ} and p_T^{γ}, $\sigma(W + 4\gamma)$ still large.
- We therefore look forward to the ATLAS and CMS experiments testing this scenario.

Thank you!