Bounds on Neutral and Charged Higgs from the LHC

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Two-Higgs doublet models

- The Higgs basis:

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1 + iG^0\right) \end{bmatrix} \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(S_2 + iS_3\right) \end{bmatrix}$$

- If $\varphi_i^0(x) = \{h(x), H(x), A(x)\} \;\Rightarrow\; \varphi_i^0(x) = \mathcal{R}_{ij} S_j(x)$

- When the potential is CP-conserving:

$$\begin{pmatrix} h \\ H \\ A \end{pmatrix} = \begin{pmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} & 0 \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

- $\tilde{\alpha} \equiv \alpha - \beta\ ,\ \ v = \sqrt{v_1^2 + v_2^2} \approx 246\ \text{GeV},\ \ \tan\beta \equiv v_2/v_1 .$

Yukawa Lagrangian

- The general Yukawa Lagrangian in the Higgs basis:

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\left\{ \bar{Q}'_L\,(M'_d\Phi_1 + Y'_d\Phi_2)\,d'_R + \bar{Q}'_L\,(M'_u\Phi_1 + Y'_u\Phi_2)u'_R + \bar{L}'_L\,(M'_l\Phi_1 + Y'_l\Phi_2)\,l'_R \right\}$$

- with M'_f and Y'_f complex independent matrices (non simultaneously diagonalizable) $\Rightarrow$ tree level FCNCs.

- One usually imposes a discrete $\mathcal{Z}_2$ symmetry on the Higgs doublets: $\phi_1 \to \phi_1\,,\ \phi_2 \to -\phi_2$ (in a generic basis), etc.

- However, a more general approach is to impose alignment in the flavour space: $Y'_f \sim M'_f$.

Yukawa Lagrangian

- Now we can simultaneously diagonalize both matrices and:

$$Y_{d,l} = \varsigma_{d,l}\, M_{d,l} \qquad\qquad Y_u = \varsigma_u^*\, M_u$$

- The Yukawa Lagrangian now reads:

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\, H^+ \left\{ \bar{u} \left[\varsigma_d\, V M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V \mathcal{P}_L \right] d \,+\, \varsigma_l\, \bar{\nu} M_l \mathcal{P}_R l \right\} - \frac{1}{v} \sum_{\varphi_i^0, f} y_f^{\varphi_i^0}\, \varphi_i^0 \,\left[\bar{f}\, M_f \mathcal{P}_R f \right] \,+\, \mathrm{h.c.}$$

[A.Pich, P.Tuzon '09]

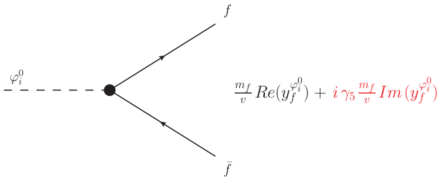
- If the Higgs potential is CP-conserving then the neutral Yukawas read:

$$y_{d,l}^h = \cos\tilde{\alpha} + \varsigma_{d,l}\, \sin\tilde{\alpha} \qquad y_{d,l}^H = -\sin\tilde{\alpha} + \varsigma_{d,l}\, \cos\tilde{\alpha} \qquad y_{d,l}^A = i\, \varsigma_{d,l}$$

$$y_u^h = \cos\tilde{\alpha} + \varsigma_u^*\, \sin\tilde{\alpha} \qquad y_u^H = -\sin\tilde{\alpha} + \varsigma_u^*\, \cos\tilde{\alpha} \qquad y_u^A = -i\, \varsigma_u^*$$

Yukawa Lagrangian

- The complex parameters still allow for new sources of CP-violation in the neutral Yukawa sector:



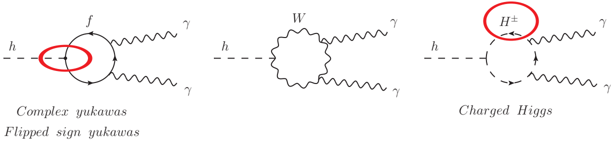
- SM: $Re(y_f^{\varphi_i^0}) = 1$ and $Im(y_f^{\varphi_i^0}) = 0$.
- For real ς_f we can recover the usual $\mathcal{Z}_2$ models:

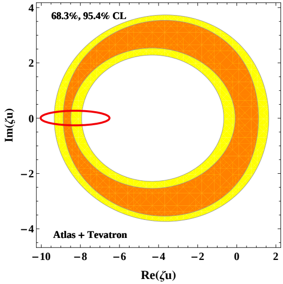
Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

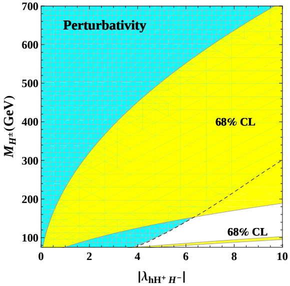
NEUTRAL SECTOR

χ^2 fit, CP-conserving potential & yukawas

- If $h \to \gamma\gamma$ excess is "real"





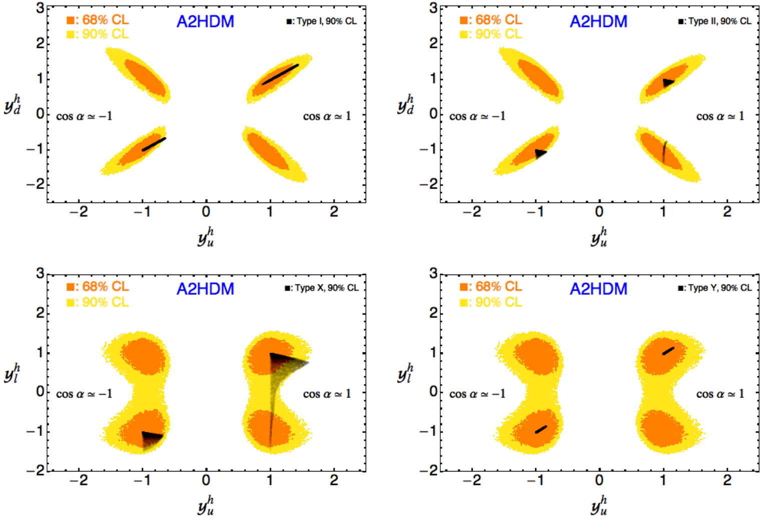


$$y_u^h = \cos\tilde{\alpha} + \varsigma_u^* \sin\tilde{\alpha} \qquad \mathcal{L}_{hH^+H^-} = -v\,\lambda_{hH^+H^-}\, hH^+H^-$$

[A.Pich, A.Celis, V.I. '13]

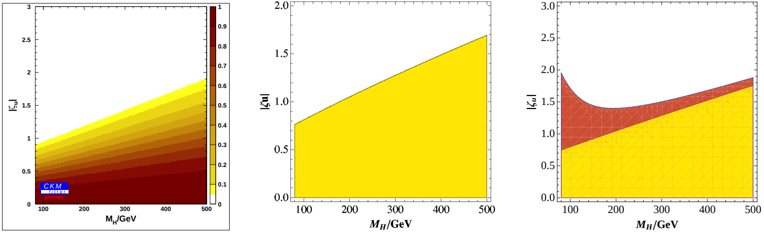
χ^2 fit, CP-conserving potential & yukawas

- ATHDM and $\mathcal{Z}_2$ types with Atlas + Tevatron + CMS: [A.Pich, A.Celis V.I. '13]

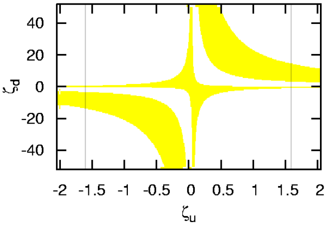


Flavour sector

- Flavour constraints on ς_u: R_b, ϵ_K, $\bar{B} - B$ mixing [A.Pich, M.Jung, P.Tuzon '10]

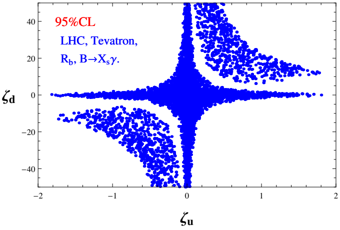


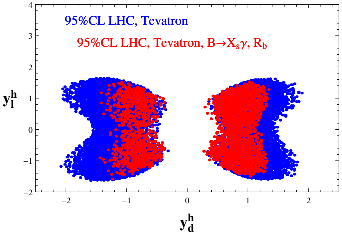
- Flavour constraints on $(\varsigma_u, \varsigma_d)$: $B \to X_s \gamma$



Combined constraints

- Joining all the relevant constraints LHC + Tevatron + R_b + $B \to X_s \gamma$ we obtain at 95 % CL:



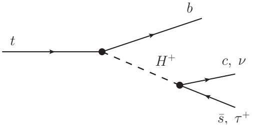


[A.Pich, A.Celis, V.I. '13]

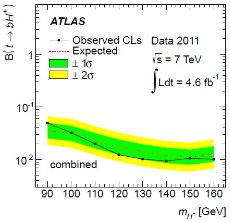
CHARGED SECTOR

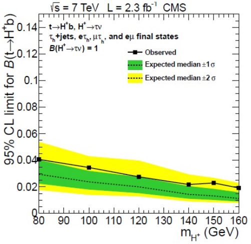
Direct $H^{\pm}$ searches

- Atlas and CMS direct $H^{\pm}$ searches:



- Limits on: $BR(t \to H^{+}b) \times BR(H^{+} \to c\bar{s},\ \tau^{+}\nu)$





Direct $H^{\pm}$ searches

- For the di-quark final state searches, $H^+ \to c\bar{s}$ is assumed to be the dominant decay rate ($|V_{cb}| << |V_{cs}|$), however in the ATHDM:

$$\frac{\Gamma(H^+ \to c\bar{b})}{\Gamma(H^+ \to c\bar{s})} \approx \frac{|V_{cb}|^2 \left(|\varsigma_d|^2 \; m_b^2 + |\varsigma_u|^2 \; m_c^2\right)}{|V_{cs}|^2 \left(|\varsigma_d|^2 \; m_s^2 + |\varsigma_u|^2 \; m_c^2\right)}$$

for $|\varsigma_d| >> |\varsigma_u|$ the $H^+ \to c\bar{b}$ can also contribute.

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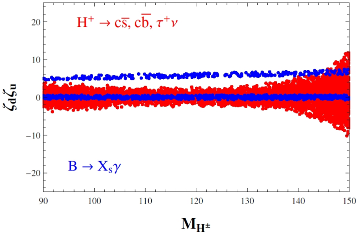
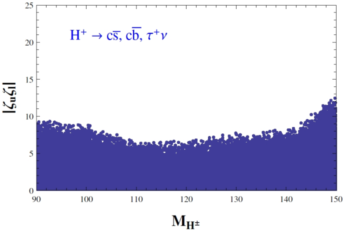
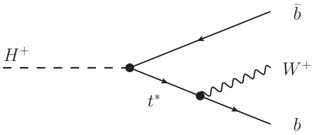




[A.Pich, A.Celis, V.I. '13]

$H^{\pm} \to t^{*} b\bar{b} \to W^{+} b\bar{b}$ decay

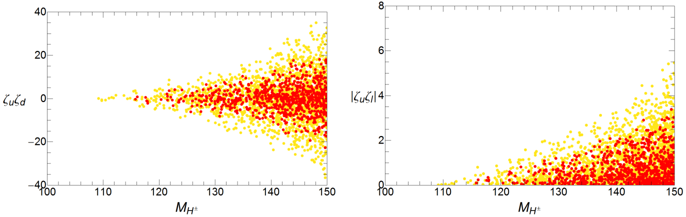
- When $M_{H^{\pm}} > M_W + 2m_b$ there is a extra decay mode that can play a important role:



- It has been previously analysed in MSSM and $\mathcal{Z}_2$ models $\rightarrow$ important contributions when $M_{H^{\pm}} \gtrsim 135 - 145$ GeV, depending on the model and on $\tan\beta$.
- In the ATHDM it can bring sizeable contributions $BR \sim 10 - 20\%$ already when $M_{H^{\pm}} \gtrsim 110$ GeV.

$H^{\pm} \to t^{*} b\bar{b} \to W^{+} b\bar{b}$ decay

- Red: $BR(H^{+} \to W^{+} b\bar{b}) > 20\%$, Yellow: $BR(H^{+} \to W^{+} b\bar{b}) > 10\%$

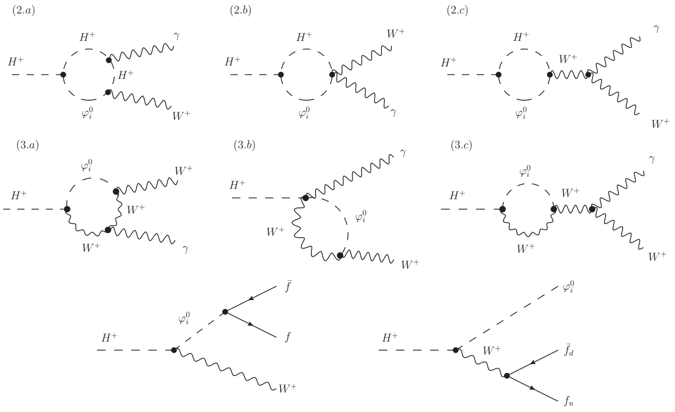


- Wide regions - partially overlap with the allowed parameter space region from direct searches. Therefore this decay mode should be included for a correct analysis and
- The experimental searches should be enlarged by also including this channel!

[A.Pich, A.Celis, V.I. '13]

Fermiophobic $H^{\pm}$

- For a fermiophobic charged Higgs ($\varsigma_f = 0$) therefore H^+ does not couple to fermions at tree level.
- All experimental bounds are trivially satisfied; other production channels and decay rates would be needed to prove such a scenario.



[A.Pich, V.I. '14]

$H^+ \to W^+\gamma$

$$\mathcal{M} \;=\; \Gamma^{\mu\nu}\,\varepsilon^*_\mu(q)\,\varepsilon^*_\nu(k)\,, \qquad \Gamma^{\mu\nu} \;=\; (g^{\mu\nu}\,k\cdot q - k^\mu q^\nu)\;S \;+\; i\,\epsilon^{\mu\nu\alpha\beta}\,k_\alpha\,q_\beta\;\tilde{S}$$

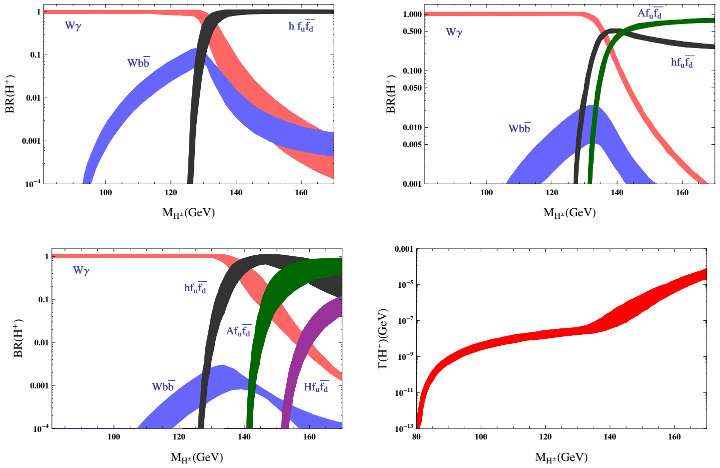
$$S_{(2)} \;=\; \frac{\alpha\, v}{2\pi\, s_W}\,\sum_i \lambda_{\varphi_i^0 H^+ H^-}\,(\mathcal{R}_{i2} - i\mathcal{R}_{i3})\,\int_0^1 dx \int_0^1 dy$$
$$\times\;\frac{x^2 y\,(1-x)}{M_W^2\,x\,(x-1) + M^2_{\varphi_i^0}\,(1-x) + M^2_{H^\pm}\,x + (M_W^2 - M^2_{H^\pm})\,xy\,(1-x)}\,,$$

$$S_{(3)} \;=\; \frac{\alpha}{2\pi\, v\, s_W}\,\sum_i \mathcal{R}_{i1}\,(\mathcal{R}_{i2} - i\mathcal{R}_{i3})\,\int_0^1 dx \int_0^1 dy\;\; x^2$$
$$\times\;\frac{2M_W^2 \;+\; (M^2_{H^\pm} + M_W^2 - M^2_{\varphi_i^0})\,y\,(x-1)}{M_W^2\,x^2 + M^2_{\varphi_i^0}\,(1-x) + (M_W^2 - M^2_{H^\pm})\,xy\,(1-x)}$$

$$\Gamma(H^+ \to W^+\gamma) \;=\; \frac{M^3_{H^\pm}}{32\pi}\,\left(1 - \frac{M_W^2}{M^2_{H^\pm}}\right)^3\,\left(|S|^2 + |\tilde{S}|^2\right)\,.$$

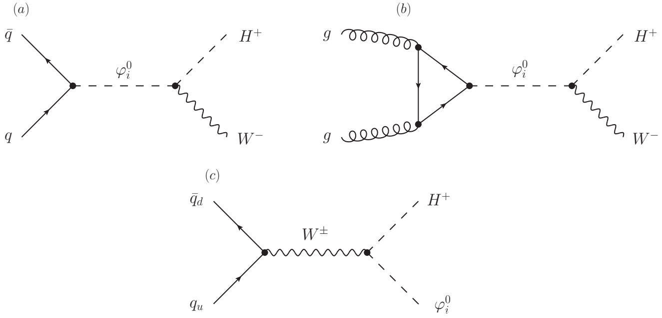
BRs and total decay width

- Different mass configurations and couplings



Fermiophobic $H^{\pm}$

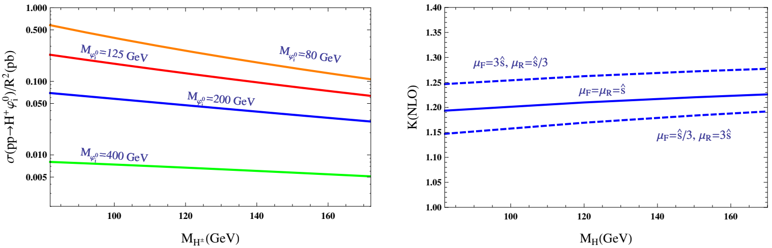
- Dominating production modes.



$+$ QCD corrections

$H^+\varphi_i^0$ associated production

$$\hat{\sigma}(q_u\bar{q}_d \to H^+\varphi_i^0) = \frac{g^4\ |V_{ud}|^2}{768\ \pi\ N_c\ \hat{s}^2}\ \frac{(\mathcal{R}_{i2}^2+\mathcal{R}_{i3}^2)}{(\hat{s}-M_W^2)^2}\ \lambda^{3/2}(\hat{s}, M_{H\pm}^2, M_{\varphi_i^0}^2)$$

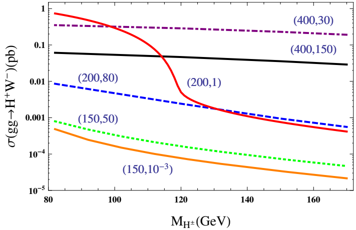


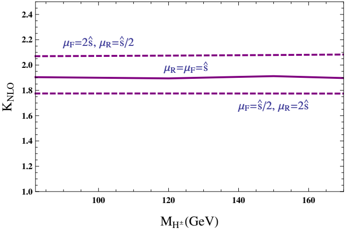
LO production cross section $\sigma(pp \to H^+\varphi_i^0)/R^2$ at $\sqrt{s} = 14$ TeV (left), as function of $M_{H\pm}$, for different values of $M_{\varphi_i^0}$. The QCD K factor is shown (right) for $M_{\varphi_i^0} = 125$ GeV and different choices of μ_R and μ_F

- $K_{NLO} \equiv \sigma_{NLO}/\sigma_{LO}$

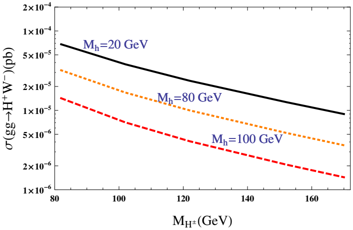
H^+W^- associated production

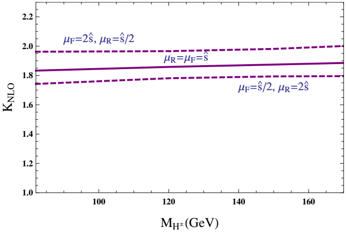
- If $M_h = 125$ GeV H can reach on-shell region $\rightarrow$ estimate Γ_H





- If $M_H = 125$ GeV both h and H are always off-shell.





Conclusions

- The $BR(H^{\pm})$ depend sensitively on the chosen parameters.
- There are only a few decay channels to be analysed.
- The largest decay widths are the tree-level ones, (on-shell production of scalar bosons).
- Thus, the number of decay channels decreases as the number of neutral scalar bosons that are heavier than the charged Higgs (i.e., $M_{\varphi_i^0} > M_{H^\pm}$) increases.
- The $W\gamma$ decay mode can bring sizeable contributions below and close to the the on-shell production threshold of a scalar boson φ_i^0.
- $\tau_{H^\pm}$ is short, ranging from 10^{-11} to 10^{-23} s $\rightarrow$ its direct detection very compelling at the LHC.
- If a fermiophobic $H^{\pm}$ is discovered the precise value of its mass would provide priceless information about all other parameters.
- The masses of the remaining scalars would also be highly constrained by the electroweak oblique parameters.

Backup slides

- The one loop corrections introduce some misalignment. Using the renormalization-group equations one finds FCNCs structures:

$$\mathcal{L}_{FCNC} = \frac{C(\mu)}{4\pi^2 v^3}(1 + \varsigma_u^* \varsigma_d) \sum_i \varphi_i^0 \times \\ \times \Big\{ (\mathcal{R}_{i2} + i\mathcal{R}_{i3})(\varsigma_d - \varsigma_u) \Big[\bar{d}_L V^\dagger M_u M_u^\dagger V M_d d_R \Big] \\ - (\mathcal{R}_{i2} - i\mathcal{R}_{i3})(\varsigma_d^* - \varsigma_u^*) \Big[\bar{u}_L V M_d M_d^\dagger V^\dagger M_u u_R \Big] \Big\} + h.c.$$

- The leptonic coupling ς_l does not introduce any FCNC interaction.
- Assuming the alignment to be exact at some scale μ_0 ($C(\mu_0) = 0$), a non-zero value is generated when running to another scale:

$$C(\mu) = -\log(\mu/\mu_0)$$

- These effects are very suppressed by $m_q m_q' / v^3$ and by the quark mixing factors, avoiding the stringent experimental constraints.

Backup slides

- The χ^2 used for the fit is defined as:

$$\chi^2 = \sum_{a \neq b} \left(\frac{(\mu_a - \hat{\mu}_a)^2}{\sigma_a^2} + \frac{(\mu_b - \hat{\mu}_b)^2}{\sigma_b^2} - 2\rho_{ab} \frac{(\mu_a - \hat{\mu}_a)(\mu_b - \hat{\mu}_b)}{\sigma_a \sigma_b} \right)$$

- $\hat{\mu}_a$ and σ_a are the experimental signal strength and error; ρ_{ab} is the correlation coefficient and:

$$\mu_a^{\varphi_i^0} = \frac{\sigma(pp \to \varphi_i^0)}{\sigma(pp \to h)_{SM}} \frac{\mathrm{Br}(\varphi_i^0 \to a)}{\mathrm{Br}(h \to a)_{SM}}$$

$$\frac{\mathrm{Br}(\varphi_i^0 \to a)}{\mathrm{Br}(h \to a)_{SM}} = \frac{1}{\rho(\varphi_i^0)} \frac{\Gamma(\varphi_i^0 \to a)}{\Gamma(h \to a)_{SM}}$$

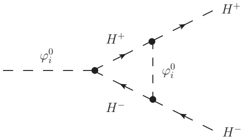
$$\Gamma(\varphi_i^0) = \rho(\varphi_i^0)\Gamma_{SM}(h) \qquad (1)$$

Backup slides

- For THDMs with a general potential $\lambda_{\varphi_i^0 H^+ H^-}$ is a free parameter. When the potential is CP-conserving ($\lambda_i \in \mathbb{R}$):

$$\lambda_{hH^+H^-} = \lambda_3 \cos\tilde{\alpha} + \lambda_7 \sin\tilde{\alpha}$$
$$\lambda_{HH^+H^-} = -\lambda_3 \sin\tilde{\alpha} + \lambda_7 \cos\tilde{\alpha}$$

- As it depends on yet unknown parameters we can calculate the one-loop correction:



$$(\lambda_{\varphi_i^0 H^+ H^-})_{\text{eff}} = \lambda_{\varphi_i^0 H^+ H^-}\,(1+\Delta)$$

- and impose $\Delta \leqslant 50\%$.

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