Flavour Physics meets Heavy Higgs Searches

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this is how it all began…

not just a fairytale

- ✓ The flavour paradigm of models with an extra Higgs doublet is often limited to escape flavour bounds. But there there are the recent results for $h \longrightarrow \tau\mu$ and $t \rightarrow ch$.

- ✓ Stringent bounds on the masses of the expanded Higgs sector can be avoided by proposing certain flavour textures for the Yukawa interactions.

- ✓ We show that we can go beyond the flavour diagonal regime for the couplings of the SM fermions to the neutral Higgs states, yet respect bounds from flavour phsyics.

- ✓ Once we allow for one or more of the expanded Higgs family to have lower masses, interesting and yet unexplored collider signatures can arise.

- ✓ We show this with a axion variant model with the right handed top quark charged -1, two Higgs doublets charged 0 and -1 under a Peccei-Quinn symmetry.

- ✓ We also introduce a top-charm mixing between right handed up-quark sector. We implement a similar structure in the lepton sector too.

$$U_R \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\frac{\rho_u}{2} & \sin\frac{\rho_u}{2} \\ 0 & -\sin\frac{\rho_u}{2} & \cos\frac{\rho_u}{2} \end{pmatrix}, \quad L_R \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\frac{\rho_\ell}{2} & \sin\frac{\rho_\ell}{2} \\ 0 & -\sin\frac{\rho_\ell}{2} & \cos\frac{\rho_\ell}{2} \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_Y^u &= -\Phi_1 \overline{u}_{Ra}[Y_{u1}]_{ai} Q_i - \Phi_2 \overline{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.} \\ &= -\Phi^{\text{SM}} \overline{u}_{Ri}[Y_u^{SM}]_{ij} Q_j - \Phi' \overline{u}_{Ri}[Y_u']_{ij} Q_j + \text{h.c.} \end{aligned}$$

Some details

$$Y_{u1} = \begin{pmatrix} * & * & * \\ * & * & * \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_{u2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ * & * & * \end{pmatrix}$$

$$\epsilon^d = 0_{3\times 3}$$ ← THDM type II structure

$$\epsilon^u = \begin{pmatrix} \frac{m_u}{v\cos\beta} & 0 & 0 \\ 0 & \frac{m_c}{v\cos\beta}\frac{1+\cos\rho_u}{2} & -\frac{m_c\sin\rho_u}{2v\cos\beta} \\ 0 & -\frac{m_t\sin\rho_u}{2v\cos\beta} & \frac{m_t}{v\cos\beta}\frac{1-\cos\rho_u}{2} \end{pmatrix}$$

$$\epsilon^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{m_\mu}{v\sin\beta}\frac{1-\cos\rho_\ell}{2} & \frac{m_\mu\sin\rho_\ell}{2v\sin\beta} \\ 0 & \frac{m_\tau\sin\rho_\ell}{2v\sin\beta} & \frac{m_\tau}{v\sin\beta}\frac{1+\cos\rho_\ell}{2} \end{pmatrix}$$

Goes beyond the THDM type II structure

$$\boxed{\rho_u = \rho_\ell \equiv \rho}$$ ← model parameter

neutral Higgs couplings $(H_k^0 = H, h, A)$

$$\Gamma^{H_k^0}_{u_L^f u_R^i} = x_u^k \left(\frac{m_{u_i}}{v_u}\delta_{fi} - \epsilon^u_{fi}\cot\beta\right) + x_d^{k\star}\epsilon^u_{fi}$$

$$\Gamma^{H_k^0}_{d_L^f d_R^i} = x_d^k \left(\frac{m_{d_i}}{v_d}\delta_{fi} - \epsilon^d_{fi}\tan\beta\right) + x_u^{k\star}\epsilon^d_{fi}$$

$$x_u^k = \left(-\frac{1}{\sqrt{2}}\sin\alpha,\, -\frac{1}{\sqrt{2}}\cos\alpha,\, \frac{i}{\sqrt{2}}\cos\beta\right)$$

$$x_d^k = \left(-\frac{1}{\sqrt{2}}\cos\alpha,\, \frac{1}{\sqrt{2}}\sin\alpha,\, \frac{i}{\sqrt{2}}\sin\beta\right)$$

charged Higgs couplings

$$\Gamma^{H^\pm}_{u_L^f d_R^i} = \sin\beta \sum_{j=1}^{3} V_{fj}\left(\frac{m_{d_i}}{v_d}\delta_{ji} - \epsilon^d_{ji}(\tan\beta + \cot\beta)\right)$$

$$\Gamma^{H^\pm}_{d_L^f u_R^i} = \cos\beta \sum_{j=1}^{3} V^\star_{jf}\left(\frac{m_{u_i}}{v_u}\delta_{ji} - \epsilon^u_{ji}(\tan\beta + \cot\beta)\right)$$

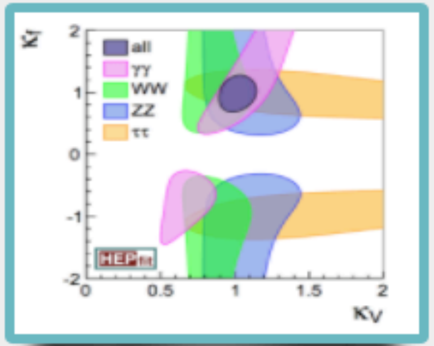
lepton - Higgs couplings (charged and neutral)

$$\Gamma^{H_k^0}_{\ell_L^f \ell_R^i} = x_d^k \left(\frac{m_{\ell_i}}{v_d}\delta_{fi} - \epsilon^\ell_{fi}\tan\beta\right) + x_u^{k\star}\epsilon^\ell_{fi}\,,$$

$$\Gamma^{H^\pm}_{\nu_L \ell_R^i} = \sin\beta \sum_{j=1}^{3}\left(\frac{m_{\ell_i}}{v_d}\delta_{ji} - \epsilon^\ell_{ji}(\tan\beta + \cot\beta)\right)$$

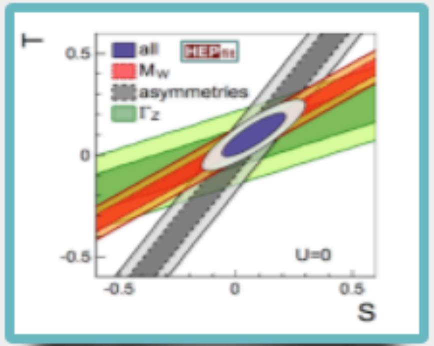
home developers samples documentation

HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.



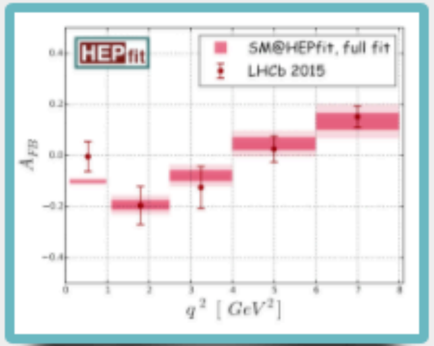
Higgs Physics

HEPfit can be used to study Higgs couplings and analyze data on signal strengths.



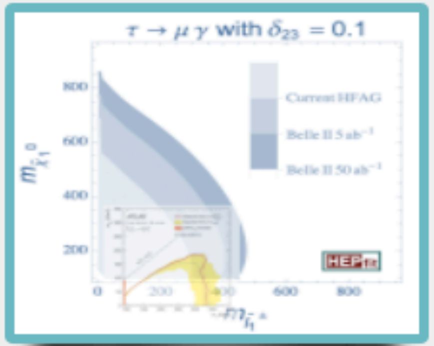
Precision Electroweak

Electroweak precision observables are included in HEPfit



Flavour Physics

The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.



BSM Physics

Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

fits to the Higgs couplings

$$\kappa_{gZ} = \frac{\kappa_g \kappa_Z}{\kappa_h} \quad \text{and} \quad \lambda_{ij} = \frac{\kappa_i}{\kappa_j}, \quad (i,j) = (Z,g),(t,g),(W,Z),(\gamma,Z),(\tau,Z),(b,Z)$$

Higgs width modifier:

$$\kappa_h^2 \simeq 0.57\kappa_b^2 + 0.22\kappa_W^2 + 0.09\kappa_g^2 + 0.06\kappa_t^2 + 0.03\kappa_Z^2 + 0.03\kappa_c^2$$
$$+ 2.3\times10^{-3}\kappa_\gamma^2 + 1.6\times10^{-3}\kappa_{Z\gamma}^2 + 10^{-4}\kappa_s^2 + 2.2\times10^{-4}\kappa_\mu^2$$

Higgs-gauge field coupling modifier:

$$\kappa_W = \kappa_Z = \sin(\beta-\alpha),$$
$$\kappa_{Z\gamma}^2 = 0.00348\kappa_t^2 + 1.121\kappa_W^2 - 0.1249\,\kappa_t\kappa_W,$$
$$\kappa_g^2 = 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\,\kappa_b\kappa_t,$$
$$\kappa_\gamma^2 = 1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.66\,\kappa_W\kappa_t,$$

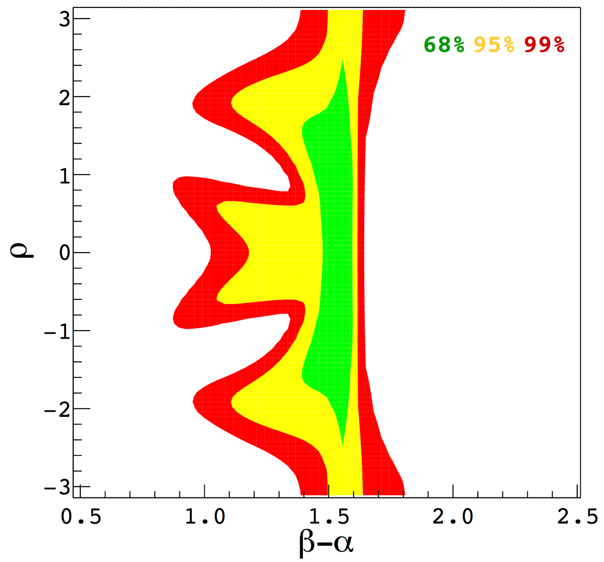
Higgs-fermion coupling modifier:

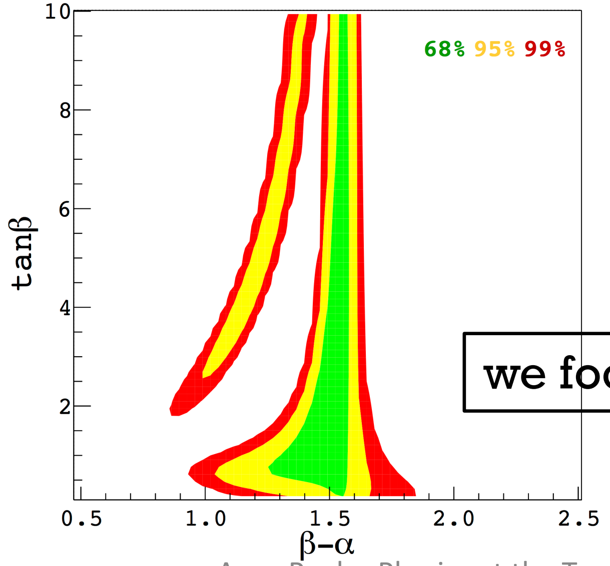
$$\kappa_f = \frac{\sqrt{2}v}{m_f} c_f^h$$

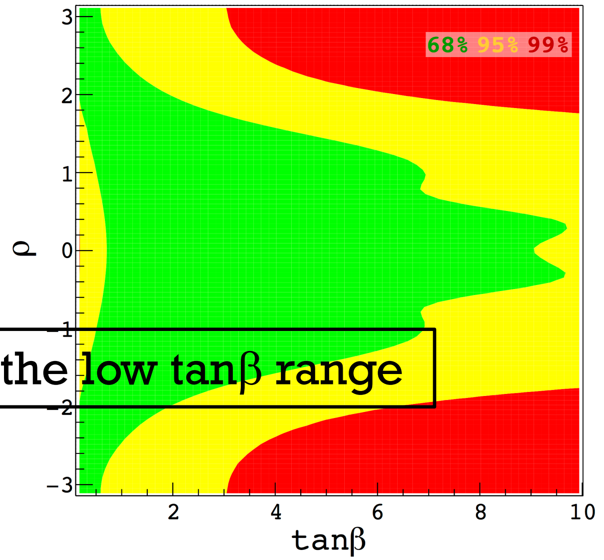
	Mean	RMS
κ_{gZ}	1.090	0.110
λ_{Zg}	1.285	0.215
λ_{tg}	1.795	0.285
λ_{WZ}	0.885	0.095
$\|\lambda_{\gamma Z}\|$	0.895	0.105
$\|\lambda_{\tau Z}\|$	0.855	0.125
$\|\lambda_{bZ}\|$	0.565	0.175

	κ_{gZ}	λ_{Zg}	λ_{tg}	λ_{WZ}	$\|\lambda_{\gamma Z}\|$	$\|\lambda_{\tau Z}\|$	$\|\lambda_{bZ}\|$
κ_{gZ}	1.00	-0.03	-0.24	-0.62	-0.57	-0.38	-0.34
λ_{Zg}	-0.03	1.00	0.51	-0.59	-0.51	-0.62	-0.54
λ_{tg}	-0.24	0.51	1.00	-0.21	-0.23	-0.28	-0.35
λ_{WZ}	-0.62	-0.59	-0.21	1.00	0.66	0.55	0.55
$\|\lambda_{\gamma Z}\|$	-0.57	-0.51	-0.23	0.66	1.00	0.58	0.51
$\|\lambda_{\tau Z}\|$	-0.38	-0.62	-0.28	0.55	0.58	1.00	0.49
$\|\lambda_{bZ}\|$	-0.34	-0.54	-0.35	0.55	0.51	0.49	1.00

Run 1 ATLAS-CMS combination
arXiV:1606.02266





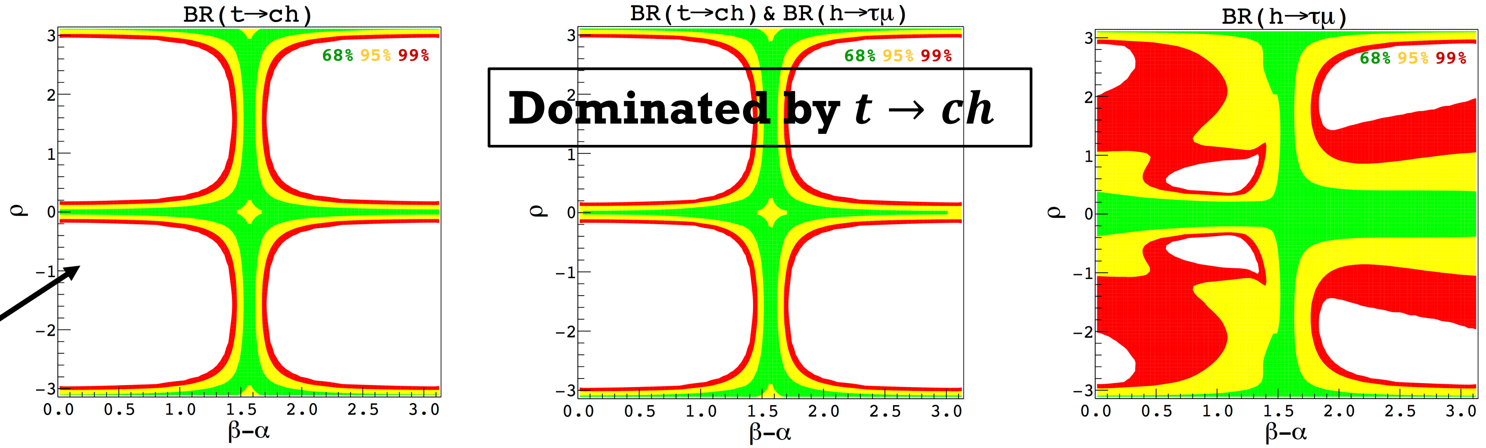


we focus on the low tanβ range

68.2 %
95.4 %
99.7 %

fits to flavour violating Higgs and top decays

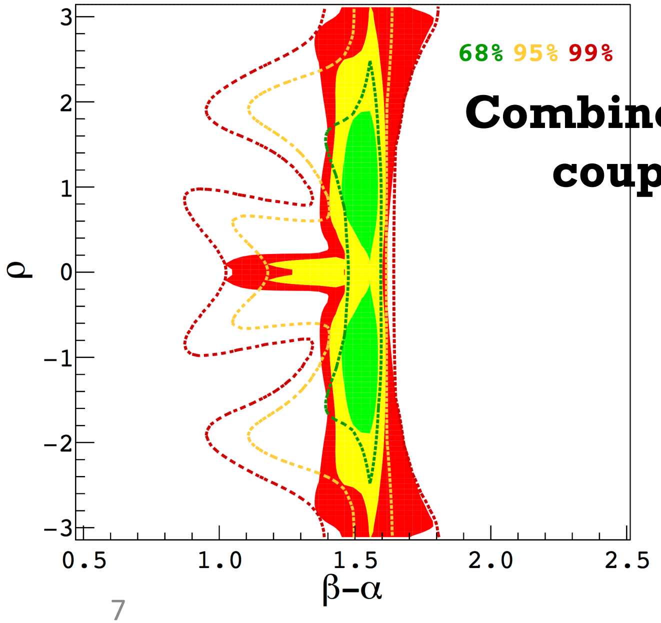
Experiment	$\mathrm{BR}(h \to \tau\mu)$	$\mathrm{BR}(t \to ch)$
ATLAS 8 TeV 20.3 fb^{-1}	$(0.53 \pm 0.51)\%$	$(0.22 \pm 0.14)\%$
CMS 8 TeV 19.7 fb^{-1}	$(0.84^{+0.39}_{-0.37})\%$	$< 0.40\%$ @ 95% CL†
ATLAS 13 TeV 36.1 fb^{-1}	–	$(0.069^{+0.075}_{-0.054})\%$
CMS 13 TeV 35.9 fb^{-1}	$(0.00 \pm 0.12)\%$	–
Average	$(0.10 \pm 0.11)\%$	$(0.109 \pm 0.061)\%$



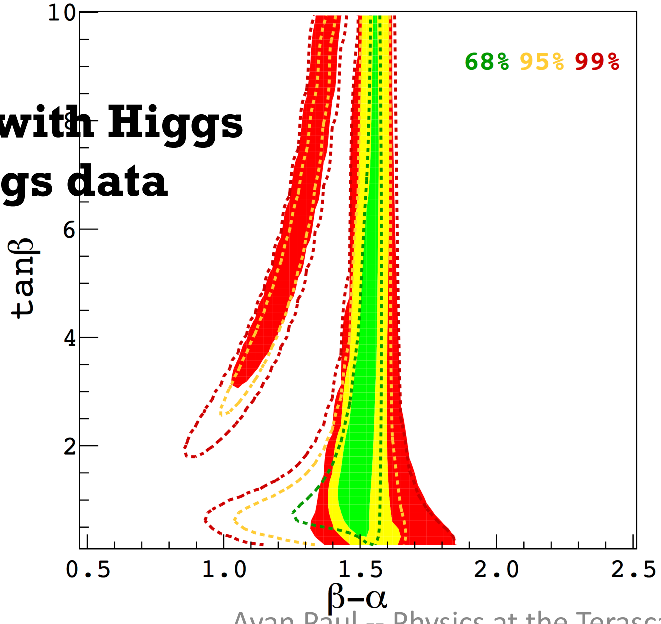
$$\mathrm{BR}(t \to ch) \simeq 3.24 \times 10^{-2} a^2 \sin^2 \rho$$

$$\mathrm{BR}_{\mathrm{exp}}(h \to \tau\mu) = \frac{\sigma^{pp\to h}}{\sigma^{pp\to h}_{\mathrm{SM}}} \mathrm{BR}_{\mathrm{th}}(h \to \tau\mu) \simeq \frac{(\kappa_g)^2 a^2 \sin^2 \rho}{36.5(\kappa_b)^2 + 14.64 \sin^2(\beta - \alpha) + 5.44(\kappa_g)^2 + 4(\kappa_\tau)^2}$$

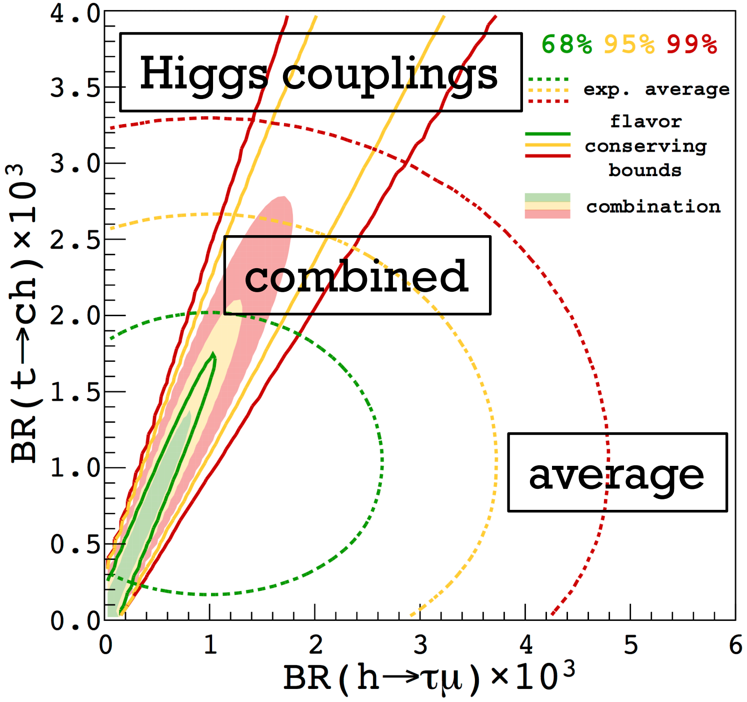
$$a = (\tan\beta + \cot\beta)\cos(\beta - \alpha)$$



Combined with Higgs couplings data



68.2 %
95.4 %
99.7 %



fits to low energy FCNC and charged current decays

Process	Measurement	SM Prediction
$\mathrm{BR}(b \to s\gamma)$	$(3.32 \pm 0.15) \times 10^{-4}$	$(3.36 \pm 0.23) \times 10^{-4}$
$\mathrm{BR}(B \to \tau\nu)$	$(1.06 \pm 0.19) \times 10^{-4}$	$(0.807 \pm 0.061) \times 10^{-4}$
R_D	0.403 ± 0.47	0.299 ± 0.003
R_{D*}	0.310 ± 0.17	0.257 ± 0.003

$$\mathrm{BR}(B \to \tau\nu) = \frac{G_F^2 |V_{ub}|^2}{8\pi} m_\tau^2 f_B^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_B \left|1 + \frac{m_B^2}{m_b m_\tau} \frac{C_R^{ub} - C_L^{ub}}{C_{\mathrm{SM}}^{ub}}\right|^2$$

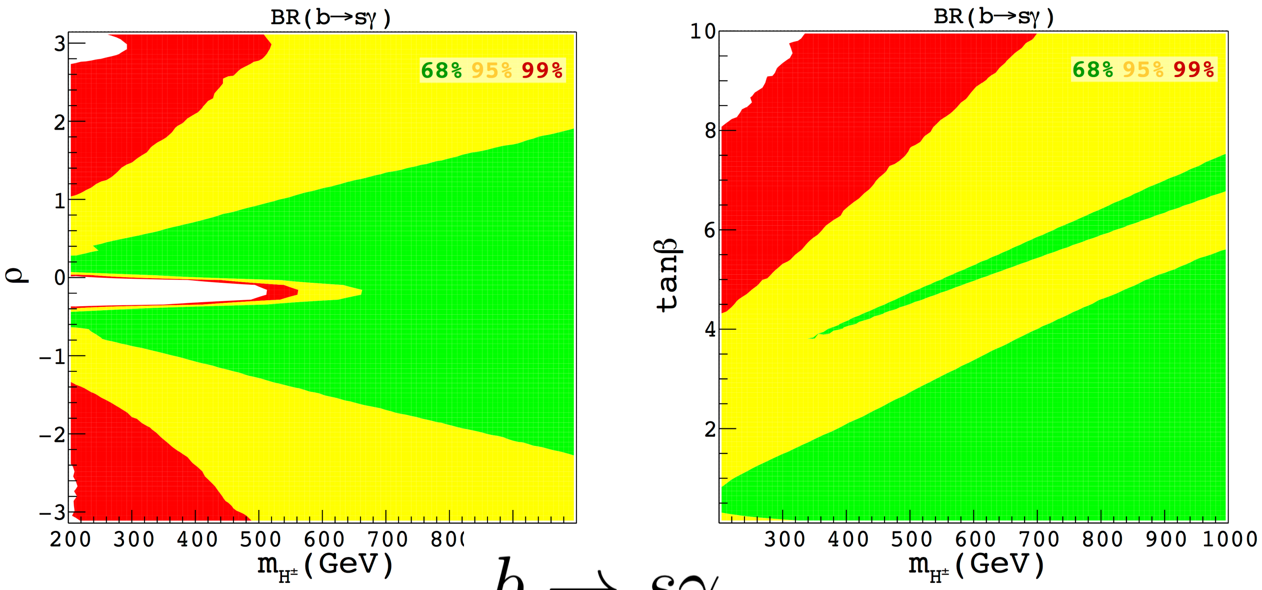
$$C_R^{ub} = -\frac{1}{m_{H^\pm}^2} \Gamma^{H^\pm}_{b_R u_L} \Gamma^{H^\pm}_{\nu_L \tau_R} \text{ and } C_L^{ub} = -\frac{1}{m_{H^\pm}^2} \Gamma^{H^\pm}_{b_L u_R} \Gamma^{H^\pm}_{\nu_L \tau_R}$$

Large contributions to $B \to \tau\nu$ are not generated by this model

$$R_D = R_D^{\mathrm{SM}} \left(1 + 1.5\Re\left(\frac{C_R^{cb} + C_L^{cb}}{C_{\mathrm{SM}}^{cb}}\right) + 1.0 \left|\frac{C_R^{cb} + C_L^{cb}}{C_{\mathrm{SM}}^{cb}}\right|^2\right),$$

$$R_{D^*} = R_{D^*}^{\mathrm{SM}} \left(1 + 0.12\Re\left(\frac{C_R^{cb} - C_L^{cb}}{C_{\mathrm{SM}}^{cb}}\right) + 0.05 \left|\frac{C_R^{cb} - C_L^{cb}}{C_{\mathrm{SM}}^{cb}}\right|^2\right),$$

R_D and R_{D^*} are not explained by this model but the fit to the parameter space is affected by these measurements



$b \to s\gamma$

$$\delta C_7^0 = \frac{v^2}{\lambda_t} \frac{1}{m_b} \sum_{j=1}^{3} \Gamma^{H^\pm *}_{u_R^j s_L} \Gamma^{H^\pm}_{u_L^j b_R} \frac{C^0_{7,XY}(y_j)}{m_{u^j}} + \frac{v^2}{\lambda_t} \sum_{j=1}^{3} \Gamma^{H^\pm *}_{u_R^j s_L} \Gamma^{H^\pm}_{u_R^j b_L} \frac{C^0_{7,YY}(y_j)}{m_{u^j}^2},$$

$$\delta C_8^0 = \frac{v^2}{\lambda_t} \frac{1}{m_b} \sum_{j=1}^{3} \Gamma^{H^\pm *}_{u_R^j s_L} \Gamma^{H^\pm}_{u_L^j b_R} \frac{C^0_{8,XY}(y_j)}{m_{u^j}} + \frac{v^2}{\lambda_t} \sum_{j=1}^{3} \Gamma^{H^\pm *}_{u_R^j s_L} \Gamma^{H^\pm}_{u_R^j b_L} \frac{C^0_{8,YY}(y_j)}{m_{u^j}^2}$$

strong bound on charged Higgs mass (typical of THDM type II) is alleviated because of cancellations with the SM contributions at low $\tan\beta$

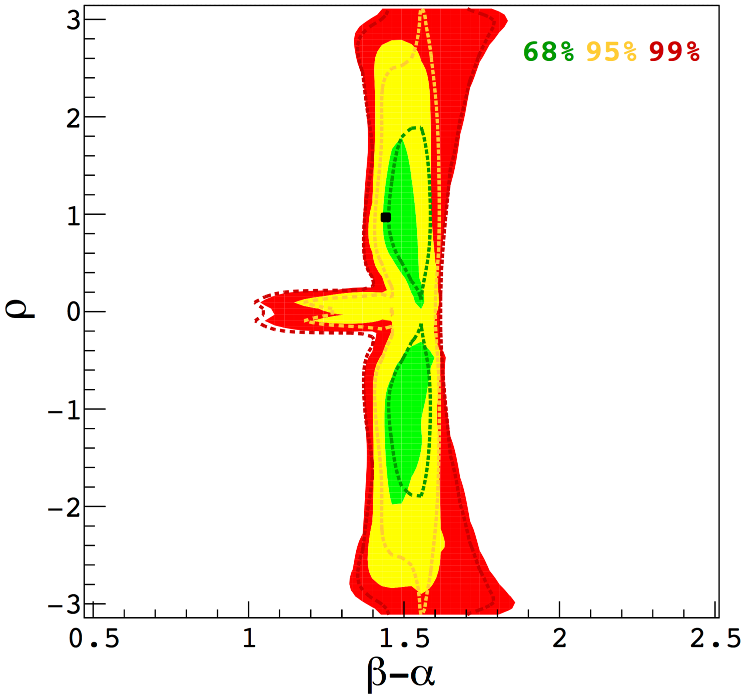
$m_{H^\pm} \gtrsim$ 580 GeV @ 95% CL in THDM type II

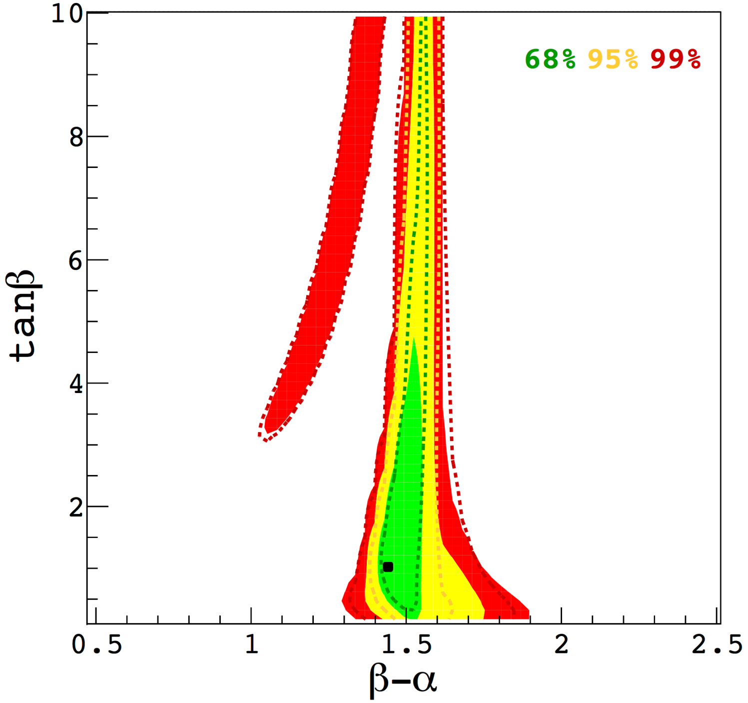
combining all constraints

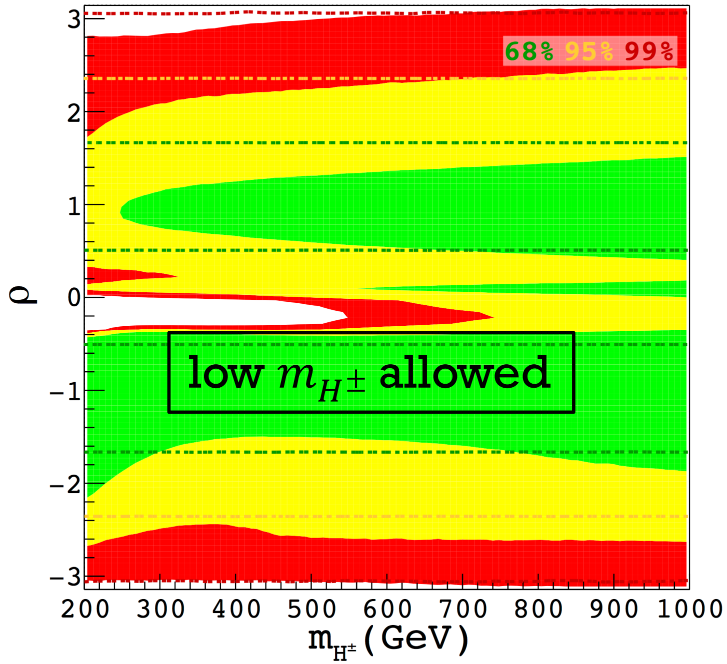
The picture is not only hopeful but quite promising!!

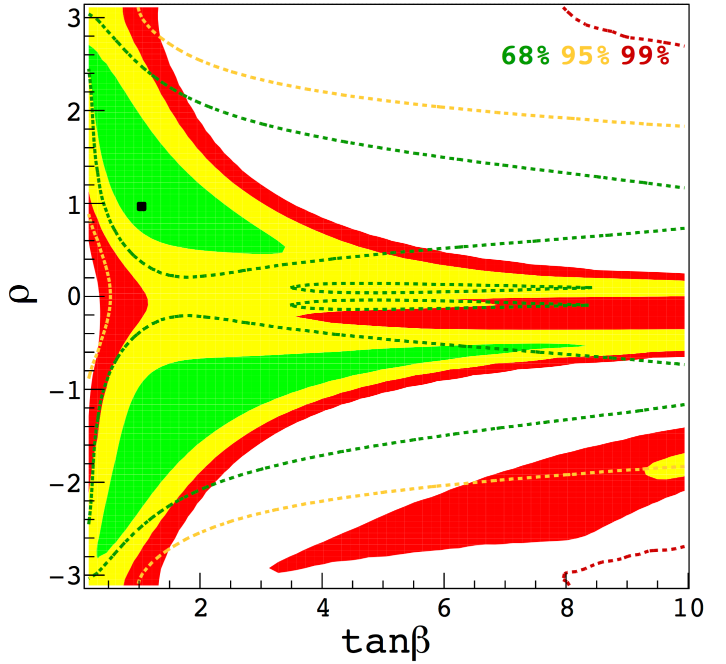
a preference for $\rho \neq 0$

a preference for low $\tan\beta$



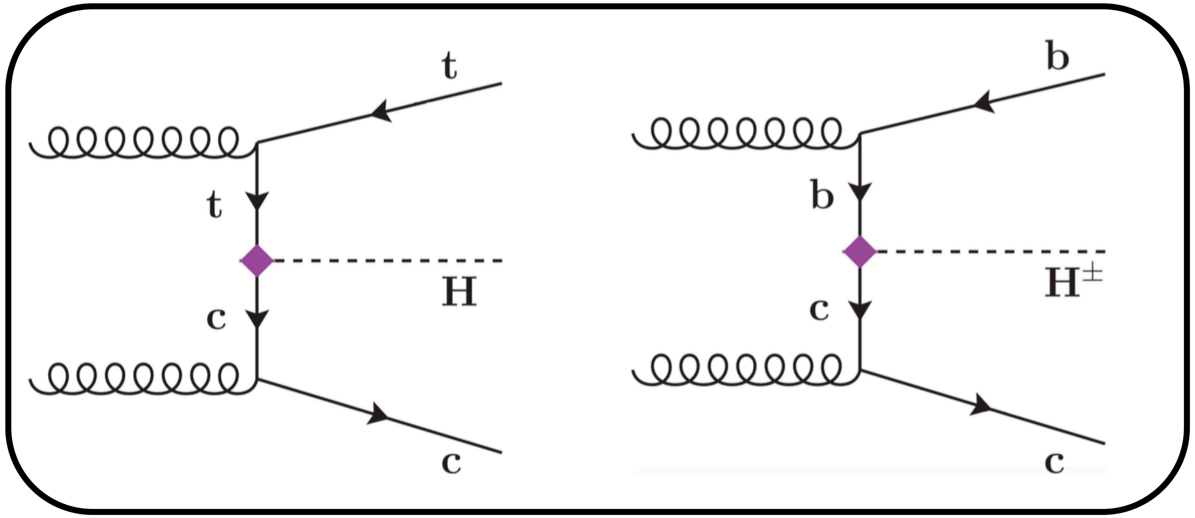


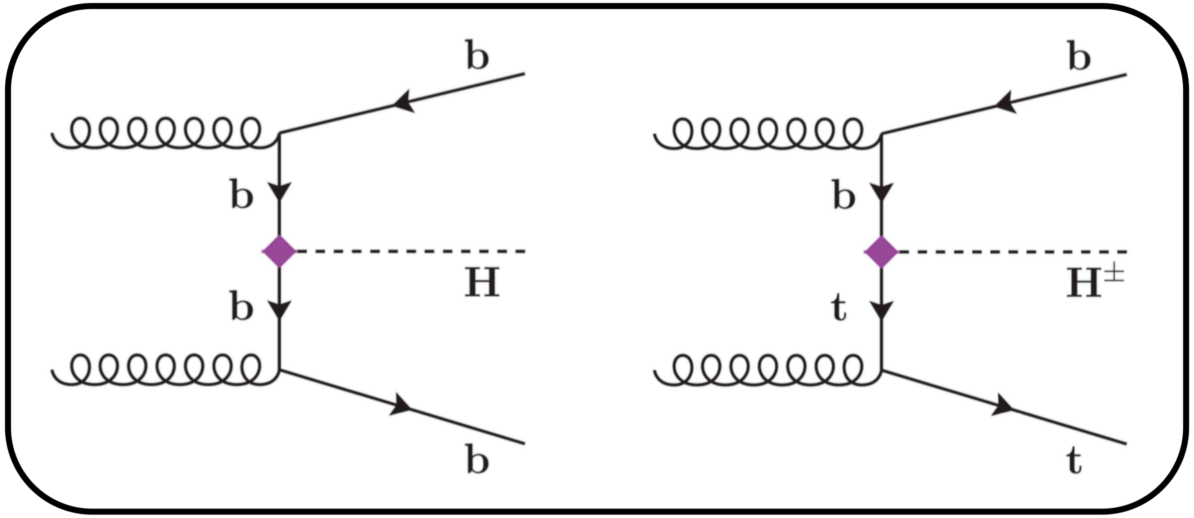




The black dots mark the benchmark point with discuss in our study of collider phenomenology

collider phenomenology of the heavy Higgs





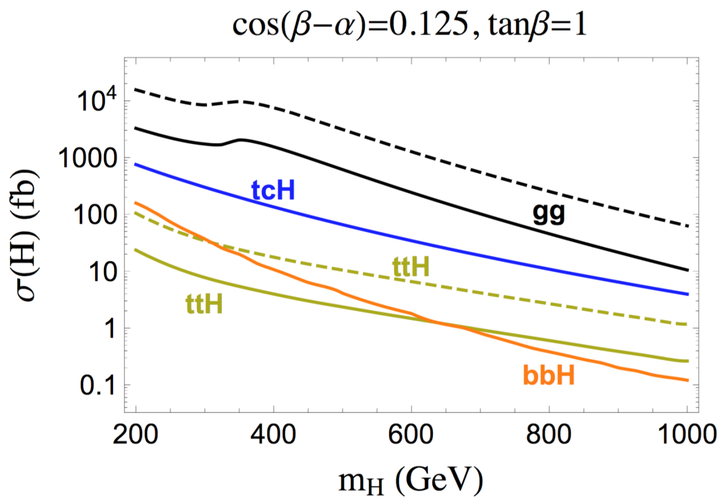
THDM type III
that we use

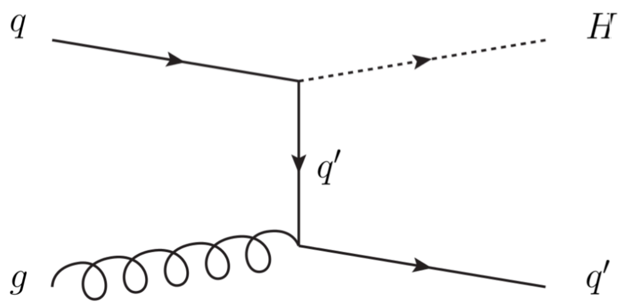
THDM type II

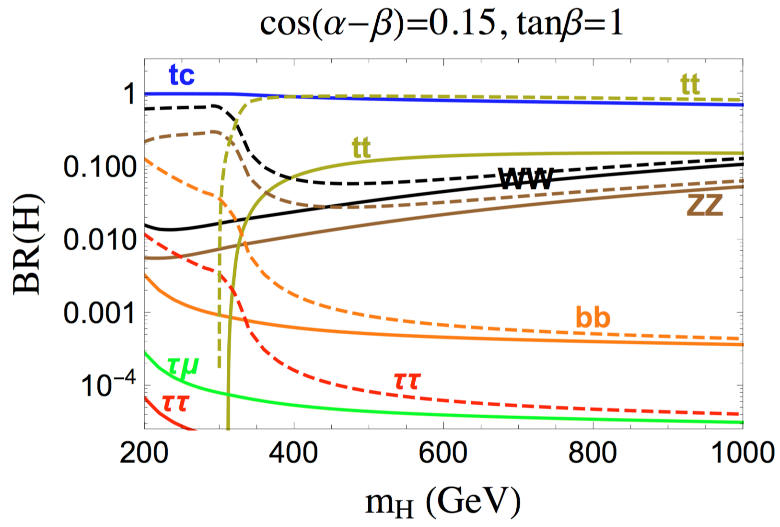
$pp \to H \to tc$	$pp \to tcH(\to tc)$	$pp \to bcH^{\pm}(\to bc)$	$pp \to bcH^{\pm}(\to Wh)$
1 charged lepton E_T^{miss} 1 b-jet 1 c-jet	2 same-sign leptons 2 b-jets $\geq$1 c-jet	dijet resonance $\geq$1 b-jet $\geq$1 c-jet	Wh resonance $\geq$1 b/c-jet

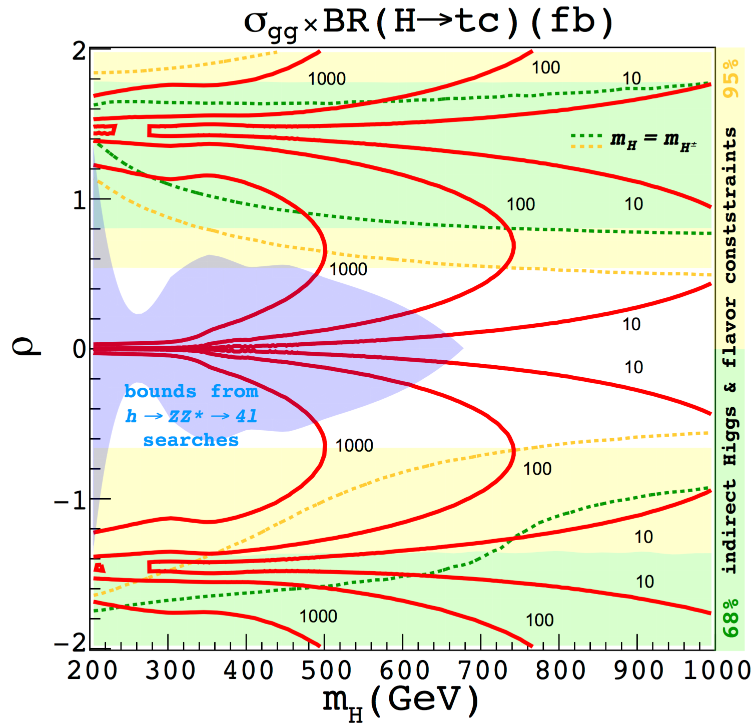
a list of interesting signatures

collider phenomenology of the heavy neutral Higgs









excluded by 13 TeV

$gg \longrightarrow H \longrightarrow ZZ^* \longrightarrow 4l$

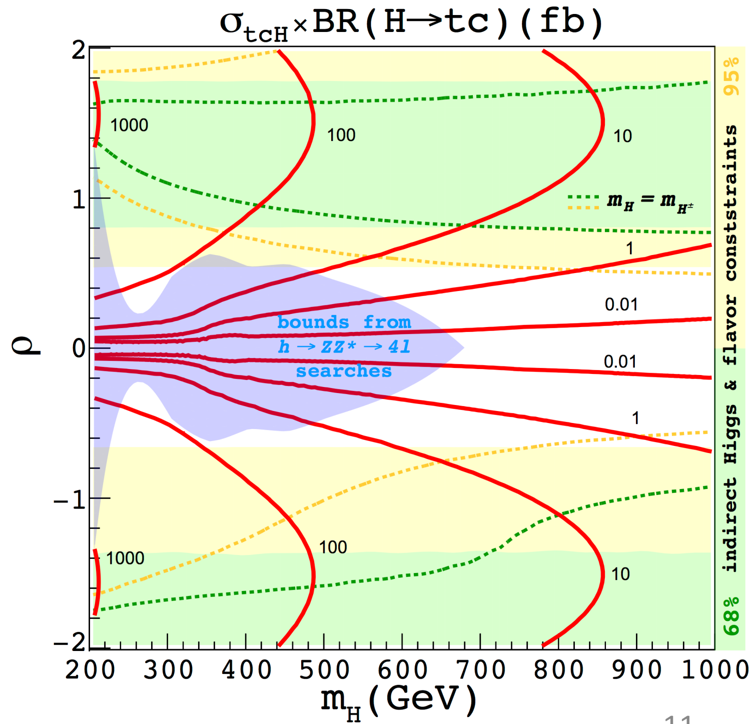
$\cos(\beta - \alpha) = 0.125$ and $\tan\beta = 1$

68.2 %

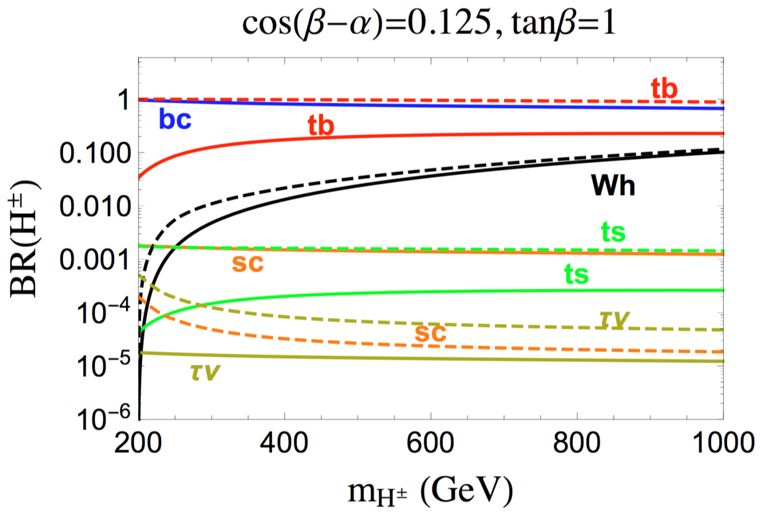
95.4 %

$m_{H^\pm} = m_{H^0}$

marginalized over $m_{H^\pm}$

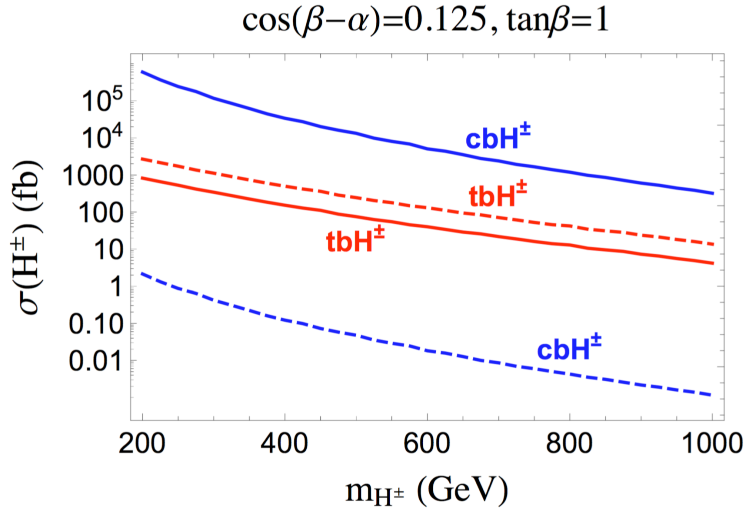


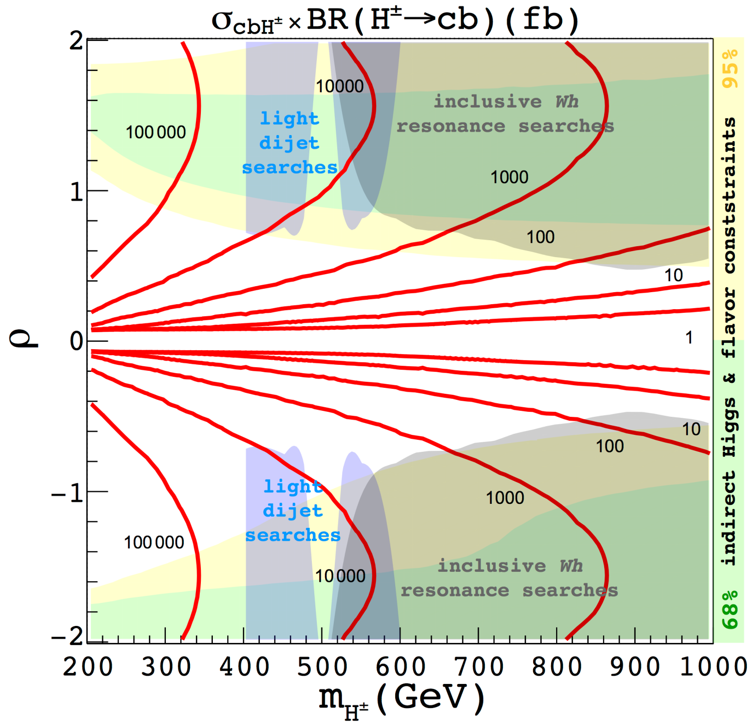
collider phenomenology of the charged Higgs

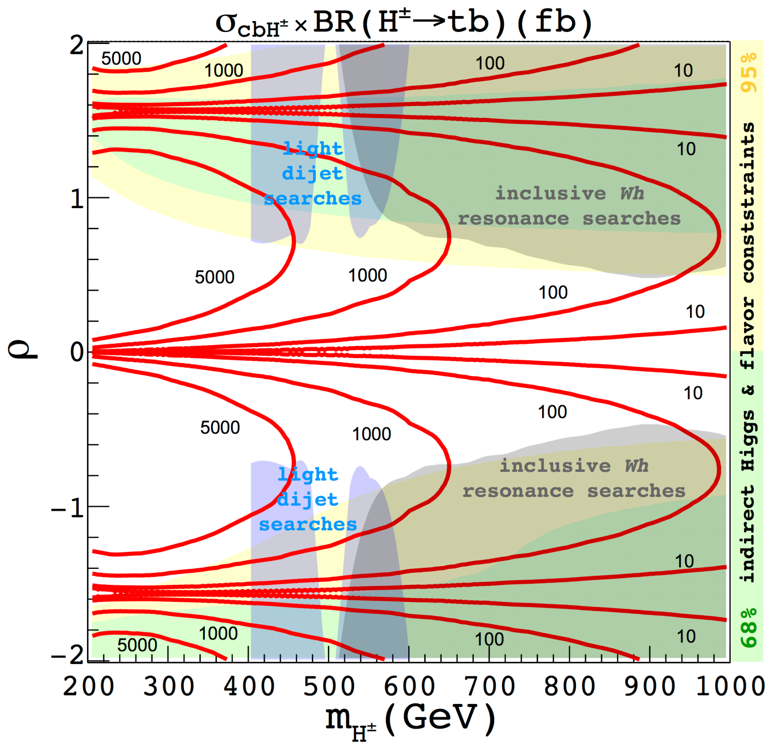


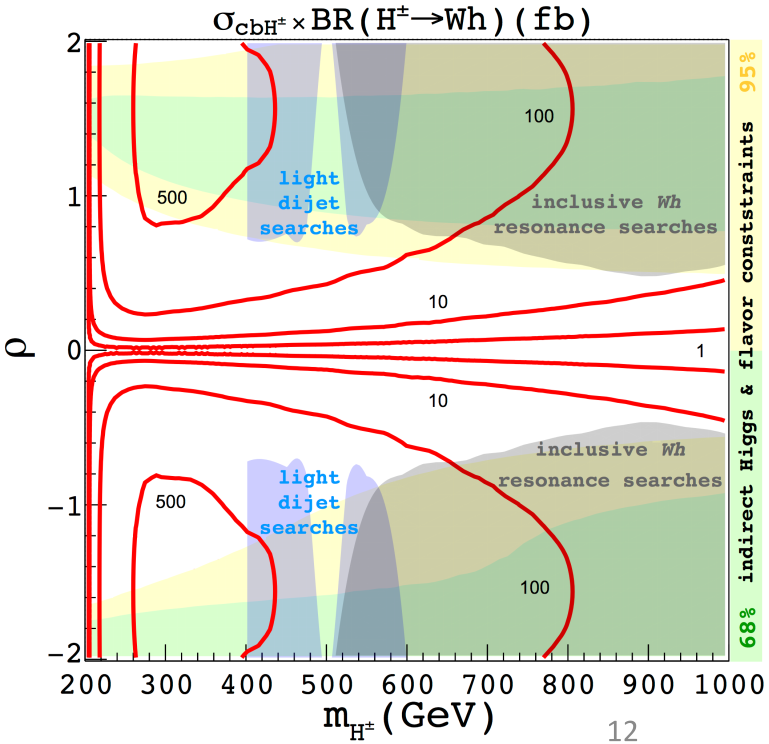
$\cos(\beta-\alpha) = 0.125$ and $\tan\beta = 1$

Already probed by light dijet searches









summary

- ✓ The intricate alleys of a general THDM are not often navigated leaving interesting phenomenology untouched.
- ✓ The (pseudo)scalar family is awaiting the arrival of other members for which we must search in the right place.
- ✓ We also show that these degrees of freedom leave collider signatures that remain unsearched for.
- ✓ At times, these collider signatures can be quite bold and easily searched for.
- ✓ Stringent lower bounds on the mass of the charged Higgs can be alleviated by a more intricate flavour structure of the Yukawa interactions.

The lower bounds on new (pseudo)scaler states, both neutral and charged, should be reconsidered and collider searches should be open to the possibility of production and decays of these states.

Out beyond the ideas of right and wrong there is a field. I will meet you there. - Rumi

Thank you…!!

the model

$$\epsilon^d = 0_{3\times 3}$$

$$U_R \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\frac{\rho_u}{2} & \sin\frac{\rho_u}{2} \\ 0 & -\sin\frac{\rho_u}{2} & \cos\frac{\rho_u}{2} \end{pmatrix}, \quad L_R \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\frac{\rho_\ell}{2} & \sin\frac{\rho_\ell}{2} \\ 0 & -\sin\frac{\rho_\ell}{2} & \cos\frac{\rho_\ell}{2} \end{pmatrix}$$

$$\epsilon^\ell = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{m_\mu}{v\sin\beta}\frac{1-\cos\rho_\ell}{2} & \frac{m_\mu \sin\rho_\ell}{2v\sin\beta} \\ 0 & \frac{m_\tau \sin\rho_\ell}{2v\sin\beta} & \frac{m_\tau}{v\sin\beta}\frac{1+\cos\rho_\ell}{2} \end{pmatrix}$$

$$c_f^h = \frac{m_f}{\sqrt{2}v}\begin{cases} \sin(\beta-\alpha) + \left(\cot\beta - \frac{1-\cos\rho_u}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=t)\,, \\ \sin(\beta-\alpha) - \left(\tan\beta - \frac{1-\cos\rho_u}{2}(\tan\beta+\cot\beta)\right)\cos(\beta-\alpha) & (\text{for } f=c)\,, \\ \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) & (\text{for the others}) \end{cases}$$

$$\epsilon^u = \begin{pmatrix} \frac{m_u}{v\cos\beta} & 0 & 0 \\ 0 & \frac{m_c}{v\cos\beta}\frac{1+\cos\rho_u}{2} & -\frac{m_c\sin\rho_u}{2v\cos\beta} \\ 0 & -\frac{m_t\sin\rho_u}{2v\cos\beta} & \frac{m_t}{v\cos\beta}\frac{1-\cos\rho_u}{2} \end{pmatrix}$$

$$c_f^H = \frac{m_f}{\sqrt{2}v}\begin{cases} \cos(\beta-\alpha) - \left(\cot\beta - \frac{1-\cos\rho_u}{2}(\tan\beta+\cot\beta)\right)\sin(\beta-\alpha) & (\text{for } f=t)\,, \\ \cos(\beta-\alpha) + \left(\tan\beta - \frac{1-\cos\rho_u}{2}(\tan\beta+\cot\beta)\right)\sin(\beta-\alpha) & (\text{for } f=c)\,, \\ \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha) & (\text{for the others}) \end{cases}$$

$$c_f^A = \frac{m_f}{\sqrt{2}v}\begin{cases} -\cot\beta + \frac{1-\cos\rho_u}{2}(\tan\beta+\cot\beta) & (\text{for } f=t)\,, \\ \tan\beta - \frac{1-\cos\rho_u}{2}(\tan\beta+\cot\beta) & (\text{for } f=c)\,, \\ \tan\beta & (\text{for the others}) \end{cases}$$

$$\begin{aligned} c_{23}^h &= \frac{m_t}{2\sqrt{2}v}(\cot\beta+\tan\beta)\cos(\beta-\alpha)\sin\rho_u\,, \\ c_{32}^h &= \frac{m_c}{2\sqrt{2}v}(\cot\beta+\tan\beta)\cos(\beta-\alpha)\sin\rho_u\,, \\ c_{23}^H &= -\frac{m_t}{2\sqrt{2}v}(\cot\beta+\tan\beta)\sin(\beta-\alpha)\sin\rho_u\,, \\ c_{32}^H &= -\frac{m_c}{2\sqrt{2}v}(\cot\beta+\tan\beta)\sin(\beta-\alpha)\sin\rho_u\,, \\ c_{23}^A &= \frac{m_t}{2\sqrt{2}v}(\cot\beta+\tan\beta)\sin\rho_u\,, \\ c_{32}^A &= \frac{m_c}{2\sqrt{2}v}(\cot\beta+\tan\beta)\sin\rho_u\,. \end{aligned}$$

To my Mother and Father, who showed me what I could do,

and to Ikaros, who showed me what I could not.

"To know what no one else does, what a pleasure it can be!"

– adopted from the words of

Eugene Wigner.