Charged Higgs & flavor

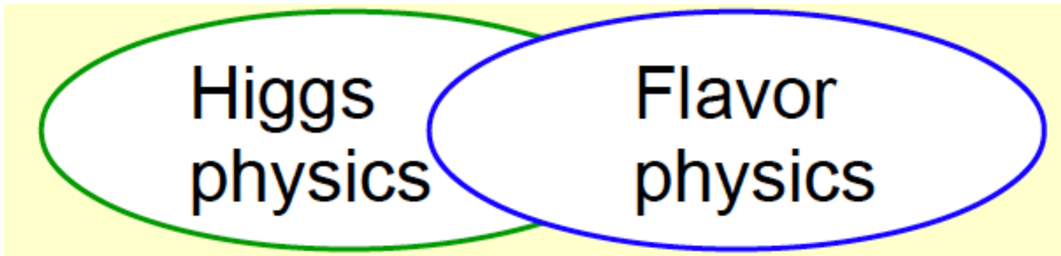
Stefania Gori
UC Santa Cruz

Charged Higgs online workshop

August 31, 2021

Outline

Topic: testing the flavor structure of Nature through the Higgs



LHC,
future colliders

Babar, Belle(II),
LHCb, ...

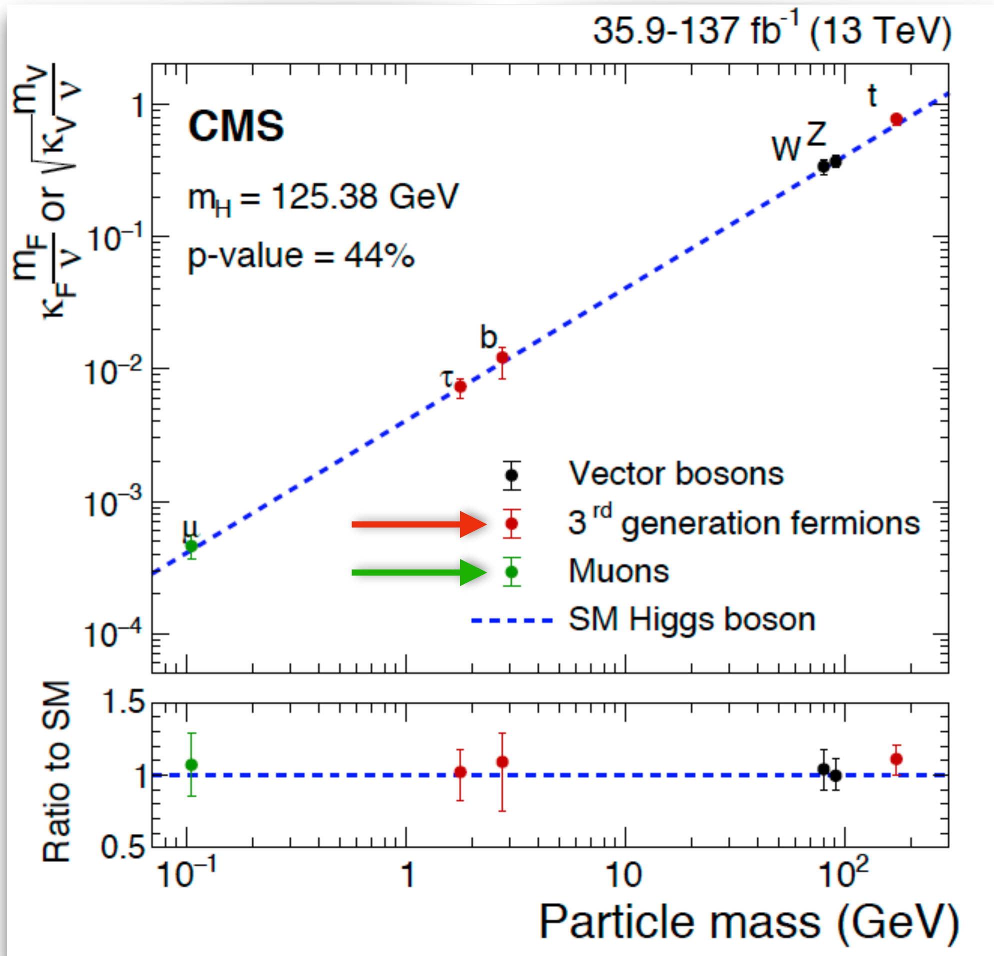
Lessons and guidelines for charged Higgs searches

Any holes in our searches coming from the assumption of Natural Flavor Conservation?

Some references

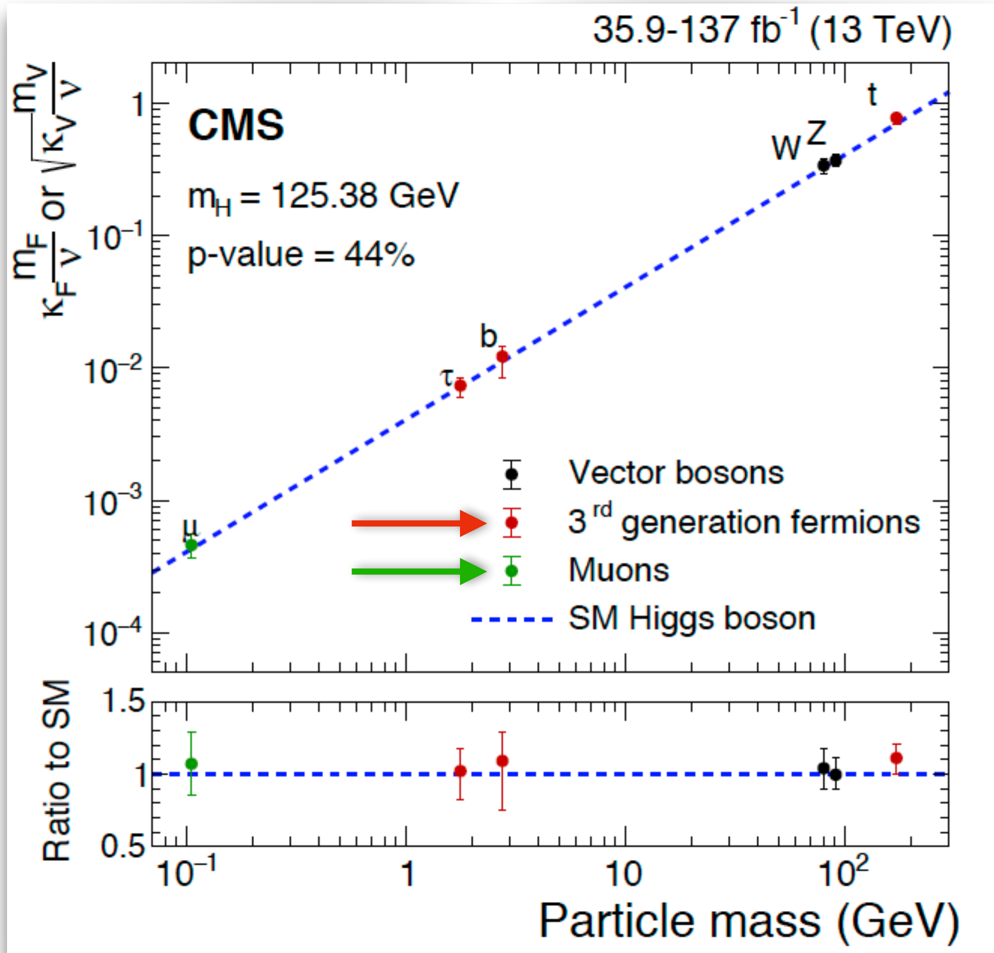
W. Altmannshofer, S. Gori, A. Kagan, L. Silvestrini, J. Zupan, 1507.07927
W. Altmannshofer, J. Eby, S. Gori, M. Lotito, M. Martone, D. Tuckler, 1610.02398
W. Altmannshofer, S. Gori, D. Robinson, D. Tuckler, 1712.01847
S. Gori, H. Haber, E. Santos, 1703.05873
W. Altmannshofer, S. Gori, G. Kribs, 1210.2465

Higgs couplings proportional to the mass!



CMS, 2009.04363

Higgs couplings proportional to the mass!



CMS, 2009.04363

In the SM the Higgs couplings to

* fermions are proportional to the fermion mass
* gauge bosons are proportional to the gauge boson mass square

This plot confirms the expectation!

Manifestation of the SM flavor puzzle

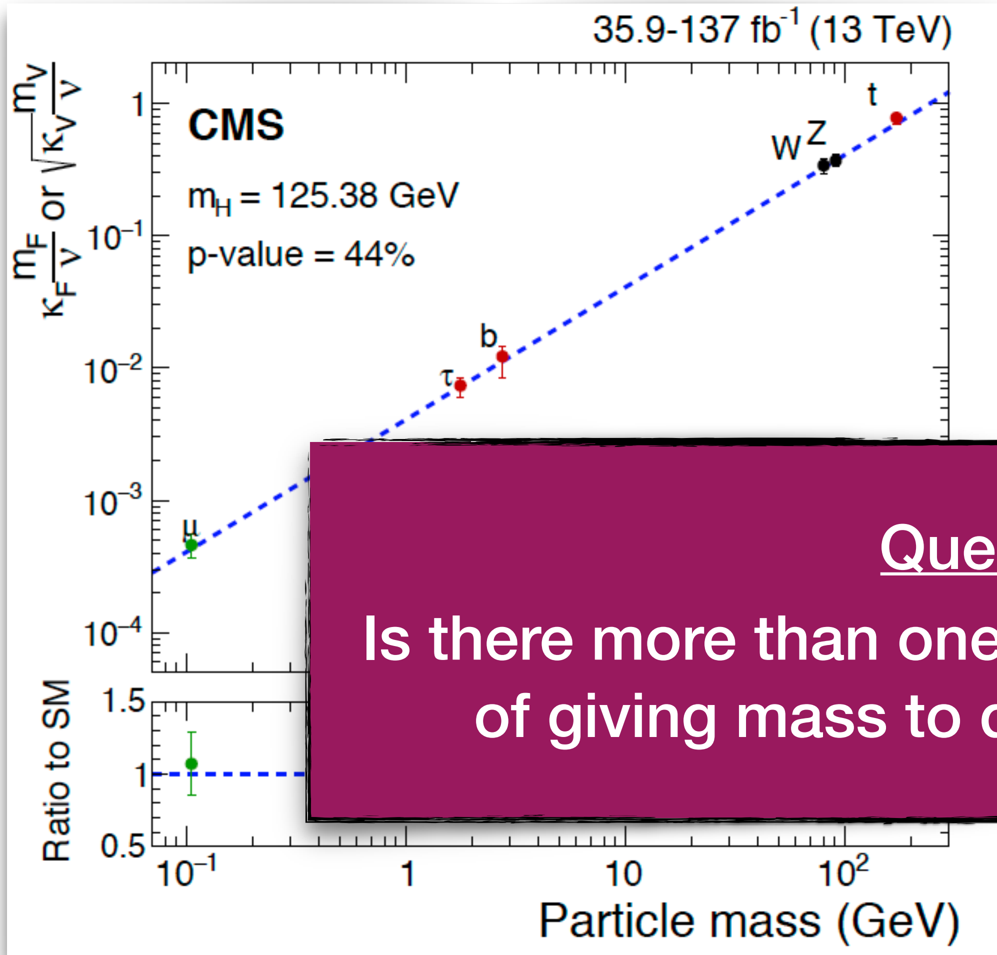
Relatively recent evidence for the Higgs decay into muons:

$$\mu = 1.2 \pm 0.6$$ (ATLAS, 2007.07830)

$$\mu = 1.19^{+0.40}_{-0.39}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$$ (CMS, 2009.04363)

We (almost) do not know anything about the couplings to light quarks and electrons

Higgs couplings proportional to the mass!



CMS, 2009.04363

In the SM the Higgs couplings to
- fermions are proportional to the fermion mass
- gauge bosons are proportional to the gauge boson mass square

This plot confirms the expectation!

vor puzzle

or the Higgs

Question:

Is there more than one Higgs field responsible of giving mass to quarks and leptons?

$$\mu \;=\; 1.2 \pm 0.6$$ (ATLAS, 2007.07830)

$$\mu \;=\; 1.19^{+0.40}_{-0.39}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$$ (CMS, 2009.04363)

We (almost) do not know anything about the couplings to light quarks and electrons

Natural flavor conservation & beyond

Natural conservation laws for neutral currents*

Sheldon L. Glashow and Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 20 August 1976)

Up quarks, down quarks, and leptons are only coupled to one Higgs doublet

Type I-IV Two-Higgs-Doublet-Models (2HDMs)

Natural flavor conservation & beyond

Natural conservation laws for neutral currents*

Sheldon L. Glashow and Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 20 August 1976)

Up quarks, down quarks, and leptons are only coupled to one Higgs doublet

➡ Type I-IV Two-Higgs-Doublet-Models (2HDMs)

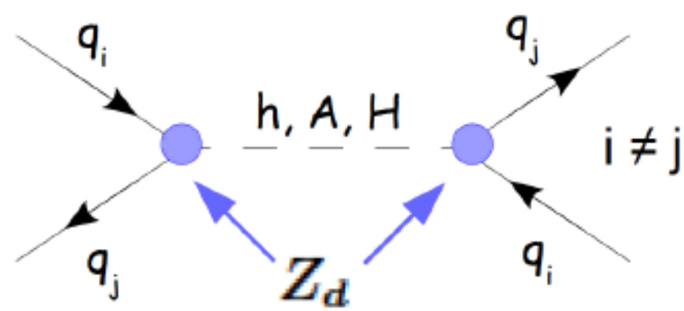
Indeed, generic 2HDMs are "dangerous" for flavor changing neutral currents:

$$\mathcal{H}_Y \supset \bar{Q}_L Y D_R H + \bar{Q}_L Y' D_R H'$$

$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H' \\ H \end{pmatrix} \qquad \langle \Phi_v^\dagger \Phi_v \rangle = v^2/2, \quad \langle \Phi_H^\dagger \Phi_H \rangle = 0$$

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L \left[\frac{\sqrt{2}}{v} M_d \Phi_v + Z_d \Phi_H \right] D_R -$$

$$\begin{cases} Z_d = c_\beta Y - s_\beta Y' \\ M_d = \frac{v}{\sqrt{2}} (c_\beta Y' + s_\beta Y) \end{cases}$$



For $Z_d = O(1)$
Kaon mixing ➡ $m_H \geq \mathcal{O}(10^5\ \mathrm{TeV})$

Natural flavor conservation & beyond

Natural conservation laws for neutral currents*

Sheldon L. Glashow and Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 20 August 1976)

Up quarks, down quarks, and leptons are only coupled to one Higgs doublet

→ Type I-IV Two-Higgs-Doublet-Models (2HDMs)

Indeed, generic 2HDMs are "dangerous" for flavor changing neutral currents:

$$\mathcal{H}_Y \supset \bar{Q}_L Y D_R H + \bar{Q}_L Y' D_R H'$$

$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H' \\ H \end{pmatrix} \qquad \langle \Phi_v^\dagger \Phi_v \rangle = v^2/2,$$

$$\mathcal{H}_Y^{\rm gen} =$$

Conclusion:

We need a "clever" flavor structure

$$\begin{cases} Z_d = c_\beta Y - s_\beta Y' \\ M_d = \frac{v}{\sqrt{2}}(c_\beta Y' + s_\beta Y) \end{cases}$$

For $Z_d = O(1)$

Kaon mixing → $m_H \geq \mathcal{O}(10^5 \text{ TeV})$

Chapter I

Charged Higgs

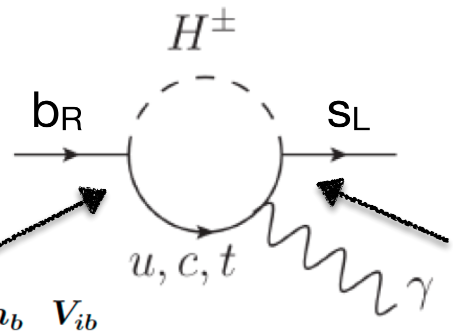
&

Natural flavor conservation.

Type I-II models

H± effects on flavor transitions, Type I-II

b → sγ



Type I, II : $\sim \frac{m_i}{v} \frac{V_{ib}^*}{\tan\beta}$

Type I : $\sim \frac{m_b}{v} \frac{V_{ib}}{\tan\beta}$

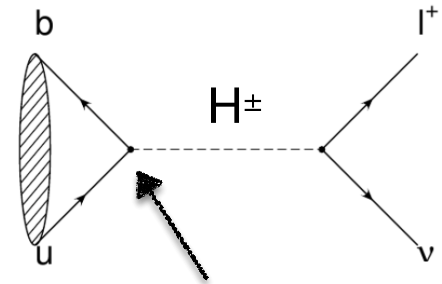
Type II : $\sim \frac{m_b}{v} V_{ib} \tan\beta$

Misiak et al., 2002.01548

$$\mathrm{BR}(B \to X_s\gamma)_{\mathrm{SM}} = (3.40 \pm 0.17) \times 10^{-4}$$
$$\mathrm{BR}(B \to X_s\gamma)_{\mathrm{exp}} = (3.32 \pm 0.15) \times 10^{-4}$$

B → $X_s\gamma$ rate with a fixed cut at $E_\gamma > 1.6$ GeV

B → τν



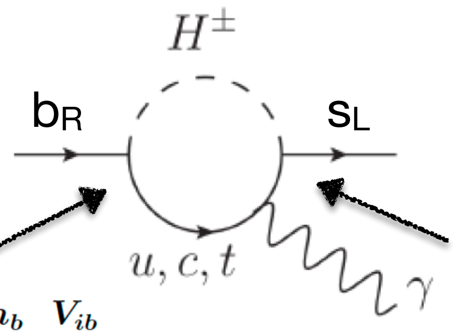
Type I : $\sim \frac{m_b}{v} \frac{V_{ub}}{\tan\beta}$

Type II : $\sim \frac{m_b}{v} V_{ub} \tan\beta$

$$\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}} = (0.812 \pm 0.054) \times 10^{-4}$$
$$\mathrm{BR}(B \to \tau\nu)_{\mathrm{exp}} = (1.09 \pm 0.24) \times 10^{-4}$$

$H^{\pm}$ effects on flavor transitions, Type I-II

b → sγ



Type I, II : $\sim \frac{m_i}{v} \frac{V_{ib}^*}{\tan\beta}$

Type I : $\sim \frac{m_b}{v} \frac{V_{ib}}{\tan\beta}$

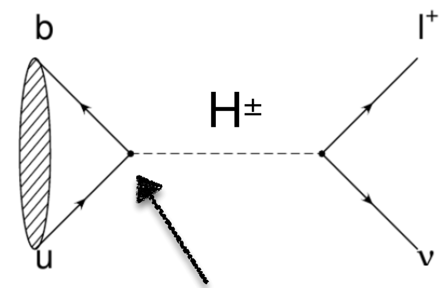
Type II : $\sim \frac{m_b}{v} V_{ib} \tan\beta$

Misiak et al., 2002.01548

$$\mathrm{BR}(B \to X_s \gamma)_{\mathrm{SM}} = (3.40 \pm 0.17) \times 10^{-4}$$
$$\mathrm{BR}(B \to X_s \gamma)_{\mathrm{exp}} = (3.32 \pm 0.15) \times 10^{-4}$$

B → $X_s\gamma$ rate with a fixed cut at $E_\gamma > 1.6$ GeV

B → τν



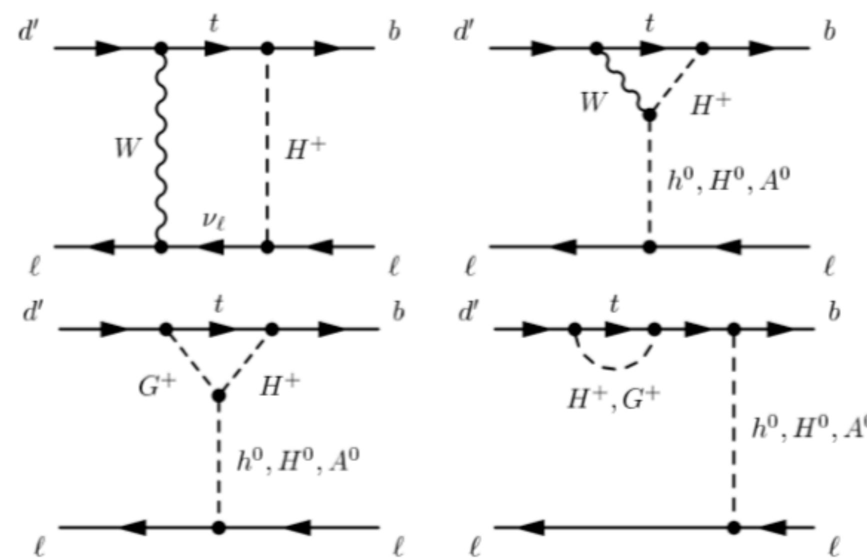
Type I : $\sim \frac{m_b}{v} \frac{V_{ub}}{\tan\beta}$

Type II : $\sim \frac{m_b}{v} V_{ub} \tan\beta$

$$\mathrm{BR}(B \to \tau\nu)_{\mathrm{SM}} = (0.812 \pm 0.054) \times 10^{-4}$$
$$\mathrm{BR}(B \to \tau\nu)_{\mathrm{exp}} = (1.09 \pm 0.24) \times 10^{-4}$$

$B_{s,d} \to \mu\mu$

$$\mathrm{BR}(B_s \to \mu\mu)_{\mathrm{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathrm{BR}(B_s \to \mu\mu)_{\mathrm{exp}} \underset{(*)}{=} (2.93 \pm 0.35) \times 10^{-9}$$
$$\mathrm{BR}(B_d \to \mu\mu)_{\mathrm{SM}} = (1.03 \pm 0.05) \times 10^{-10}$$
$$\mathrm{BR}(B_d \to \mu\mu)_{\mathrm{exp}} \underset{(*)}{=} (0.56 \pm 0.70) \times 10^{-10}$$

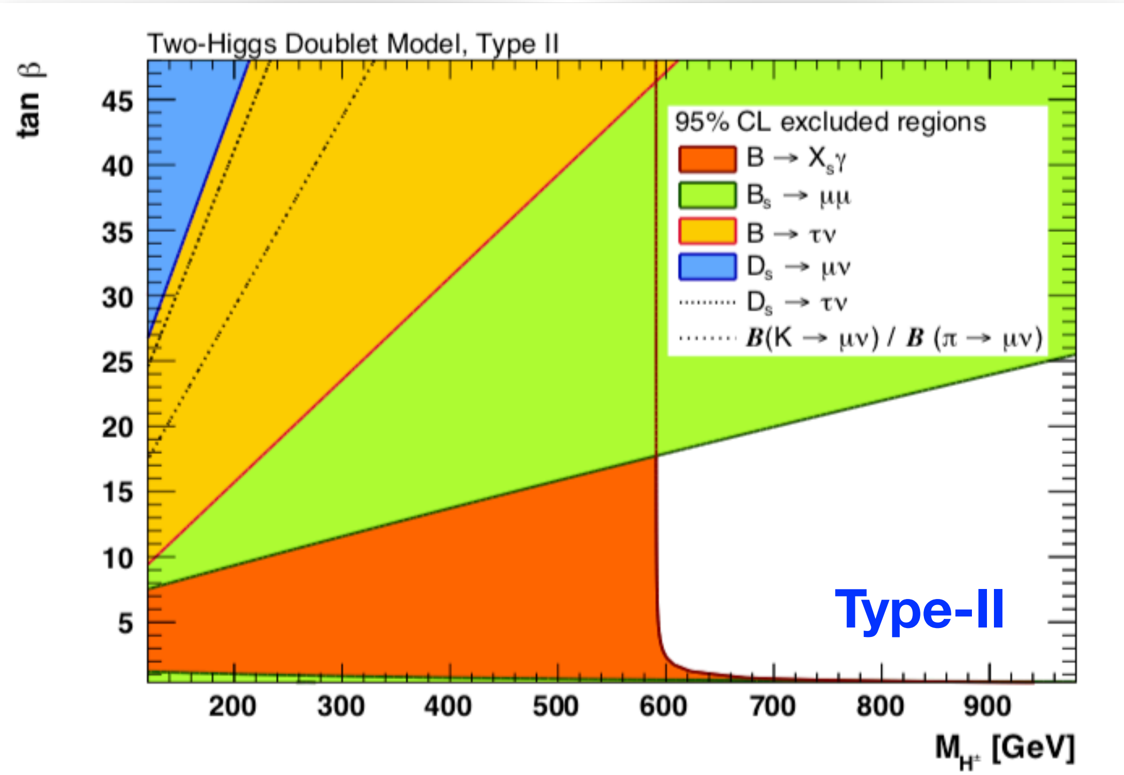


S.Gori (*) new Moriond results. Altmannshofer et al., 2103.13370

Logan, Nierste, 0004139

Flavor bounds on the H± in type I-II

adapted from GFitter group, 1803.01853



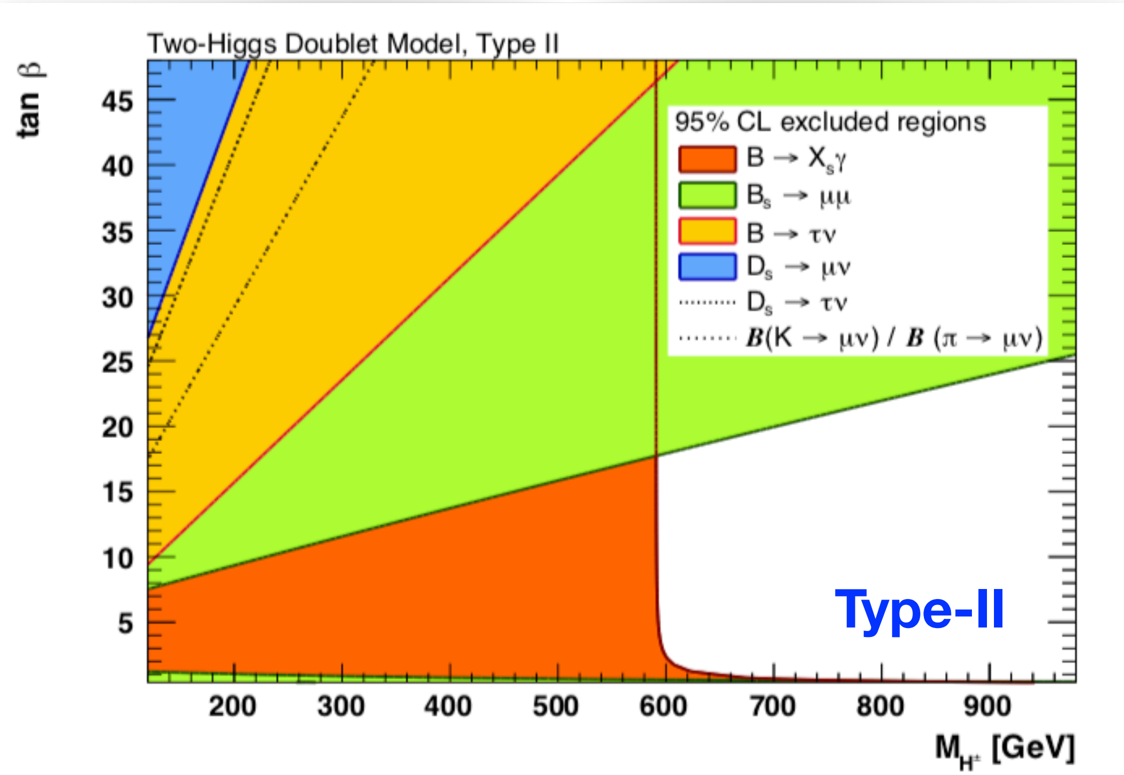
New result
by Misiak et al., 2002.01548

$$m_{H^\pm} \gtrsim 800 \text{ GeV}$$

"Our results suggest that the uncertainties in the extracted $B \to X_s\gamma$ rate have been underestimated by up to a factor of two, leaving more room for beyond-SM contributions." Bernlochner et al, 2007.04320.

Flavor bounds on the H± in type I-II

adapted from GFitter group, 1803.01853



Only very low values of tanβ are excluded in **Type-I** (tanβ < 2)

New result
by Misiak et al., 2002.01548

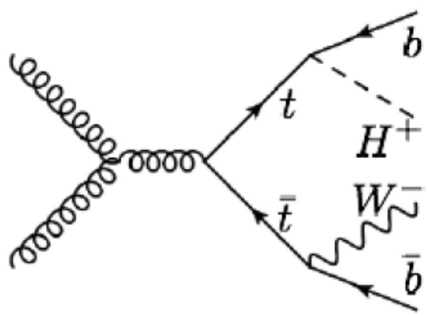
$$m_{H^\pm} \gtrsim 800 \text{ GeV}$$

"Our results suggest that the uncertainties in the extracted B → X$_s$γ rate have been underestimated by up to a factor of two, leaving more room for beyond-SM contributions." Bernlochner et al, 2007.04320.

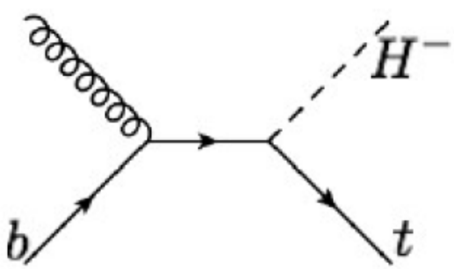
Type I-II charged Higgs at the LHC

Production

Below
the top threshold:



Above
the top threshold:



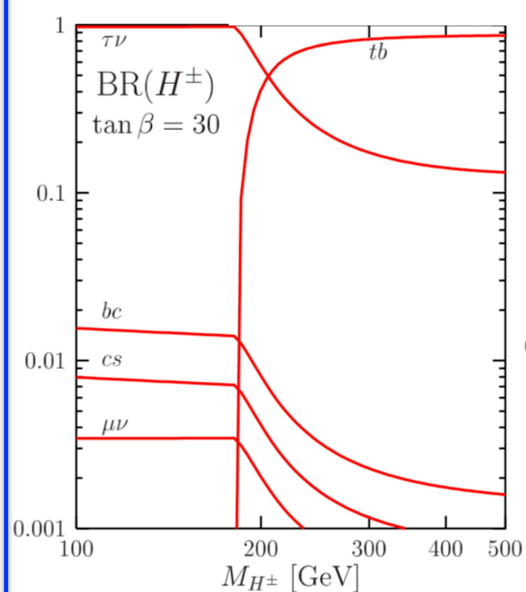
Additional production mechanisms
if away from the alignment limit.

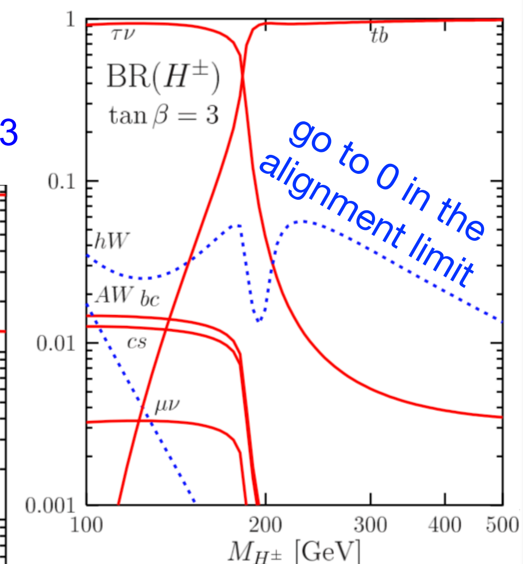
Eg. VBF production,
production with a massive gauge boson, …

Decay

Type-II 2HDM

Djouadi, 0503173

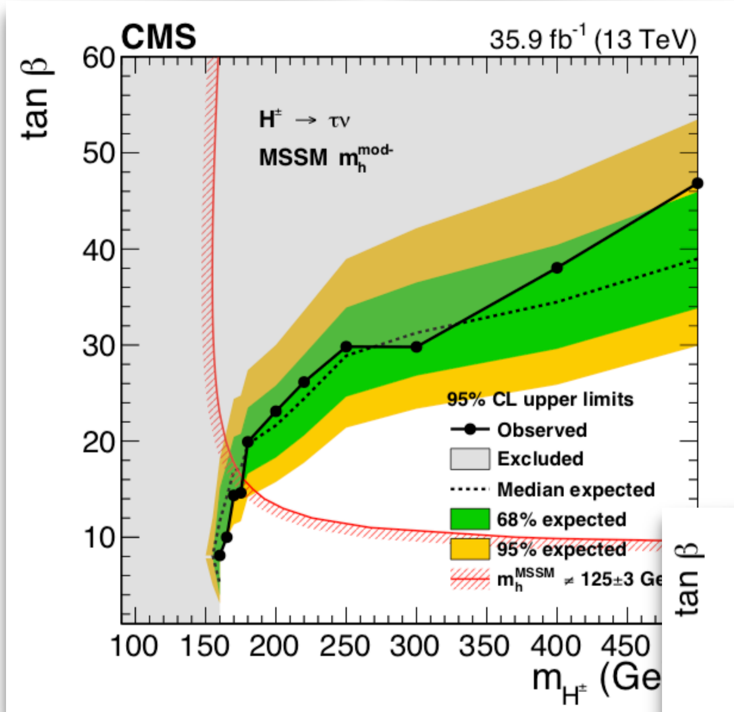




At very low values of tanβ (~1), cs is comparable to τν.

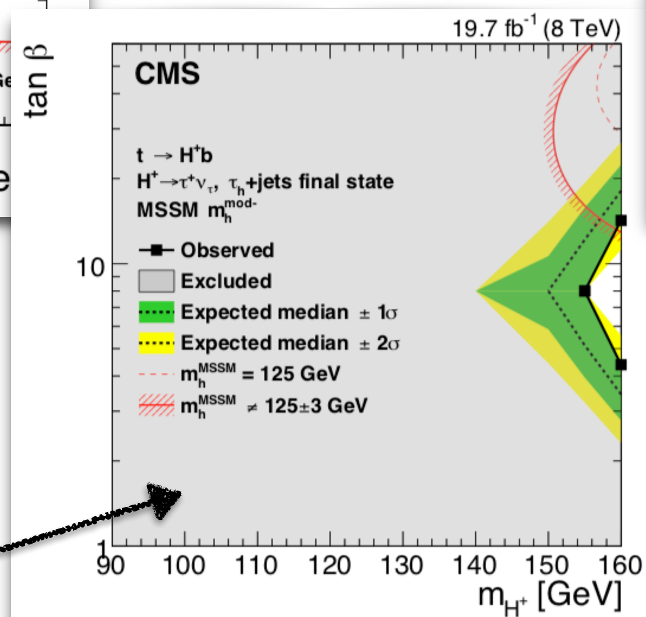
Type-I 2HDM:
all fermionic widths suppressed by $(\tan\beta)^2$

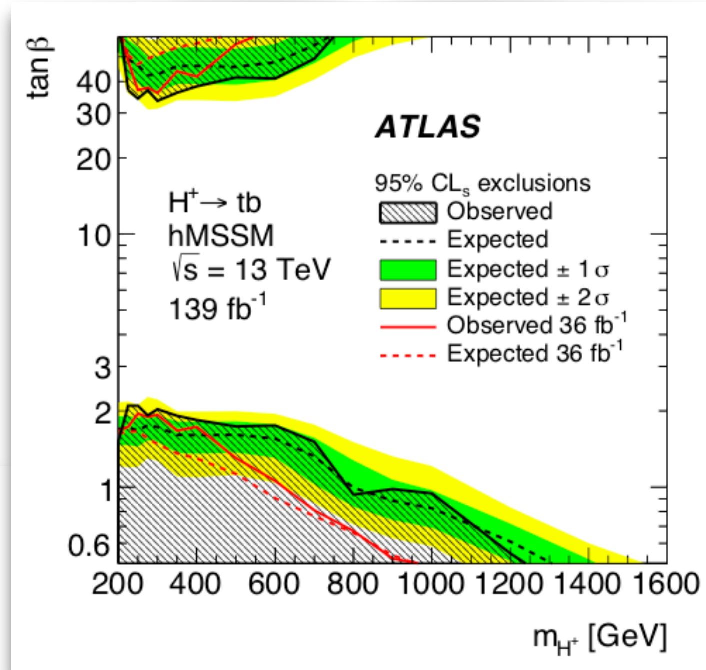
Charged Higgs LHC bounds



1903.04560

1508.07774





2102.10076

In a Type II 2HDM the region below the top mass is fully explored! 1903.04560

Warning: this is very model dependent.

Chapter II

Charged Higgs
&
Breaking of natural flavor conservation

1. Aligned 2HDM

2. Flavorful 2HDM

1.

The aligned 2HDM

- Going back to our generic Yukawa Lagrangian:

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

- An alternative way to protect the model from large FCNCs (without natural flavor conservation): Alignment

$$X_{d2} = \epsilon_d \cdot X_{d1}, \; X_{u1} = \epsilon_t \cdot X_{u2}, \; X_{\ell 2} = \epsilon_\ell \cdot X_{\ell 1}$$

Pich, Tuzon, 0908.1554

(it can be rotated away)

No tree level FCNCs!

1.

The aligned 2HDM

- Going back to our generic Yukawa Lagrangian:

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

- An alternative way to protect the model from large FCNCs (without natural flavor conservation): Alignment

$$X_{d2} = \epsilon_d \cdot X_{d1}, \;\; X_{u1} = \epsilon_t \cdot X_{u2}, \;\; X_{\ell 2} = \epsilon_\ell \cdot X_{\ell 1}$$

Pich, Tuzon, 0908.1554

(it can be rotated away)

No tree level FCNCs!

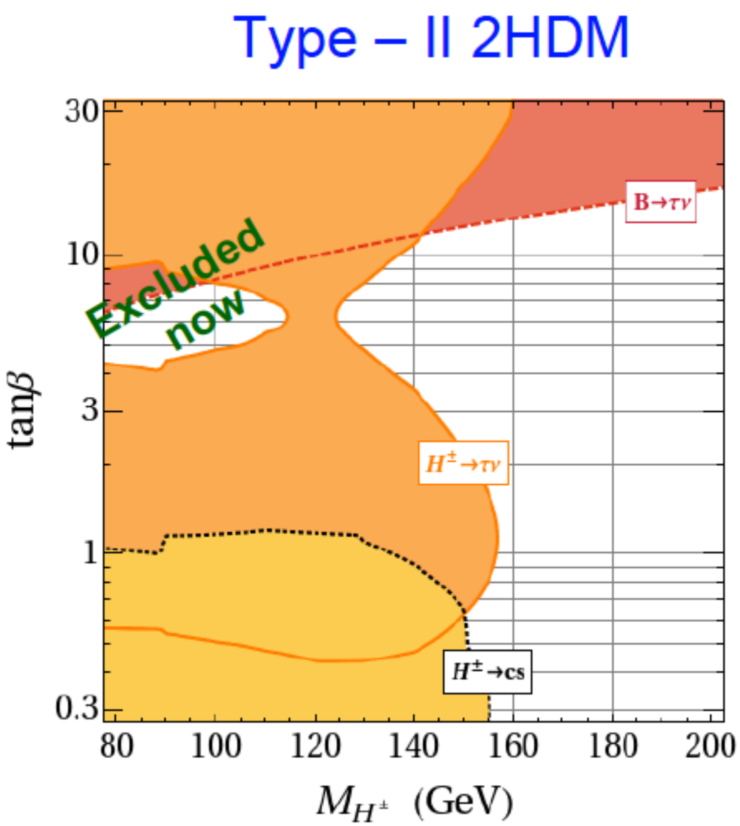
- The couplings of the several Higgs bosons are different with respect to Type I-IV

$$\begin{cases} \xi_u^h = \dfrac{c_\alpha}{s_\beta} \\ \xi_d^h = \dfrac{-s_\alpha + \epsilon_d c_\alpha}{c_\beta + \epsilon_d s_\beta} \\ \xi_\ell^h = \dfrac{-s_\alpha + \epsilon_\ell c_\alpha}{c_\beta + \epsilon_\ell s_\beta} \end{cases} \qquad \begin{cases} \xi_u^- = \dfrac{1}{t_\beta} \\ \xi_d^- = \dfrac{t_\beta - \epsilon_d}{1 + \epsilon_d t_\beta} \\ \xi_\ell^- = \dfrac{t_\beta - \epsilon_\ell}{1 + \epsilon_\ell t_\beta} \end{cases}$$

$\epsilon_d \to \infty, \; \epsilon_l \to \infty$	(Type I)
$\epsilon_d \to 0, \; \epsilon_l \to 0$	(Type II)
$\epsilon_d \to \infty, \; \epsilon_l \to 0$	(Type III)
$\epsilon_d \to 0, \; \epsilon_l \to \infty$	(Type IV)

1. Very different bounds on the A2HDM

Altmannshofer, SG, Kribs, 1210.2465

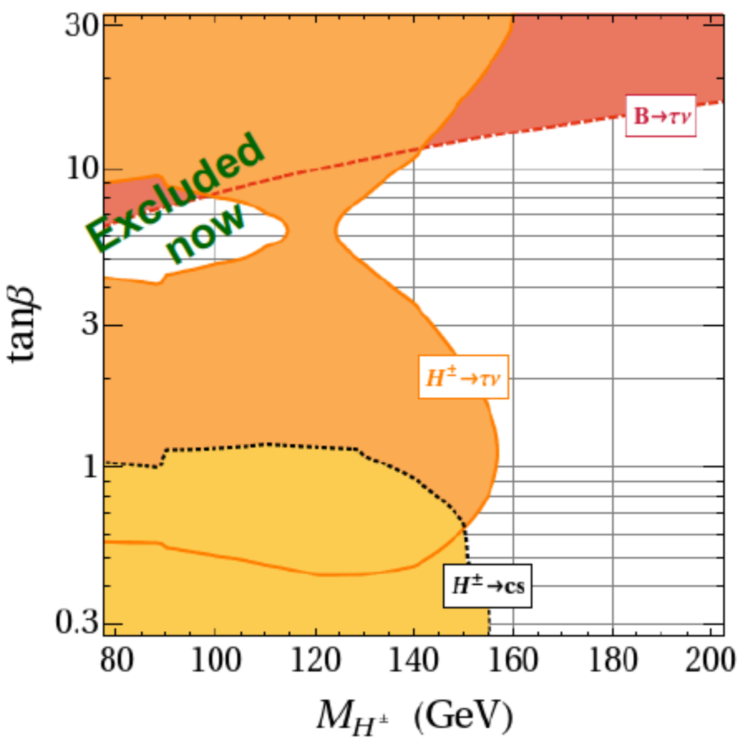


$$\frac{\mathrm{BR}(B\to\tau\nu)}{\mathrm{BR}(B\to\tau\nu)^{\mathrm{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} t_\beta^2\right)^2$$

1. Very different bounds on the A2HDM

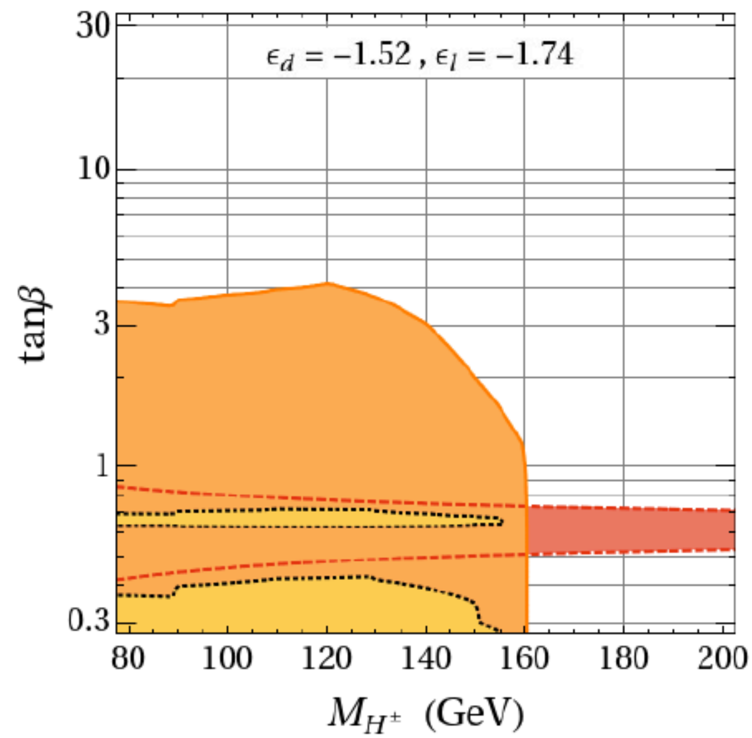
Altmannshofer, SG, Kribs, 1210.2465

Type – II 2HDM



$$\frac{\mathrm{BR}(B\to\tau\nu)}{\mathrm{BR}(B\to\tau\nu)^{\mathrm{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} t_\beta^2\right)^2$$

Aligned 2HDM



$$\frac{\mathrm{BR}(B\to\tau\nu)}{\mathrm{BR}(B\to\tau\nu)^{\mathrm{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} \frac{t_\beta^2}{1+\epsilon_b t_\beta(1+\epsilon_\tau t_\beta)}\right)^2$$

At low values of tanβ LHC constraints are un-avoidable since $\xi_u^+ = 1/t_\beta$

2.

A flavorful 2HDM

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

2 Higgs doublets H and H′ with vevs v and v′ and Yukawas Y and Y′

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H'$$

125 Higgs (h) | Additional Higgses (H, A, H±)

Fermions receive mass from both Higgs bosons

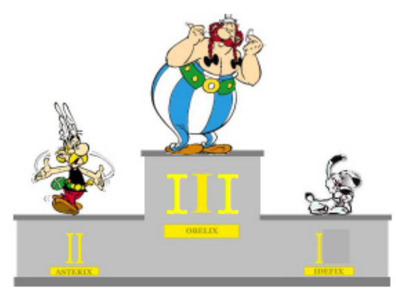
$$\mathcal{M} = vY + v'Y'$$

we have one parameter, $\tan\beta = v/v'$, that can explain the hierarchy between 3rd and 2nd generation

Invoke some mechanism such that the Yukawa Y is rank 1, while the Yukawa Y' is generic (apart from 1st/2nd generation hierarchy)

Flavor-locking mechanism

(Altmannshofer, SG, Robinson, Tuckler, 1712.01847)



Something else | Higgs | Something else

2.

A flavorful 2HDM

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

2 Higgs doublets H and H′ with vevs v and v′ and Yukawas Y and Y′

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H'$$

125 Higgs (h)   Additional Higgses (H, A, $H^\pm$)

Fermions receive mass from both Higgs bosons

$$\mathcal{M} = vY + v'Y'$$

we have one parameter, $\tan\beta = v/v'$, that can explain the hierarchy between 3rd and 2nd generation

Invoke some mechanism such that the Yukawa Y is rank 1, while the Yukawa Y' is generic (apart from 1st/2nd generation hierarchy)

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

Similar structure for the up quark sector. For the down sector:

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_d & \mathcal{O}(\lambda m_s) & \mathcal{O}(\lambda^3 m_b) \\ \mathcal{O}(m_d) & m_s & \mathcal{O}(\lambda^2 m_b) \\ \mathcal{O}(m_d) & \mathcal{O}(m_s) & \mathcal{O}(m_s) \end{pmatrix}$$

It also generates the correct CKM matrix

2.

A flavorful 2HDM

Altmannshofer, SG, Kagan, Silvestrini, Zupan, 1507.07927

2 Higgs doublets H and H′ with vevs v and v′ and Yukawas Y and Y′

$$\mathcal{L} = \bar{f} Y f H + \bar{f} Y' f H'$$

125 Higgs (h) Additional Higgses (H, A, $H^\pm$)

Fermions receive mass from both Higgs bosons

$$\mathcal{M} = vY + v'Y'$$

we have one parameter, $\tan\beta = v/v'$, that can explain the hierarchy between 3rd and 2nd generation

Invoke some mechanism such that the Yukawa Y is rank 1, while the Yukawa Y' is generic (apart from 1st/2nd generation hierarchy)

$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_e & \mathcal{O}(m_e) & \mathcal{O}(m_e) \\ \mathcal{O}(m_e) & m_\mu & \mathcal{O}(m_\mu) \\ \mathcal{O}(m_e) & \mathcal{O}(m_\mu) & \mathcal{O}(m_\mu) \end{pmatrix}$$

Approximate U(2) symmetry

Similar structure for the up quark sector. For the down sector:

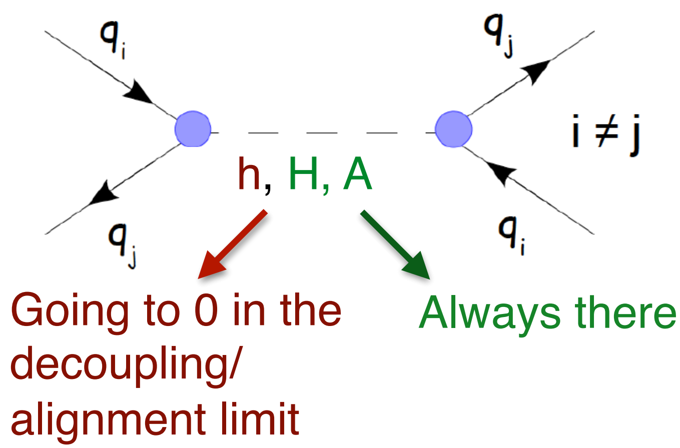
$$\mathcal{M}_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix}, \quad \Delta\mathcal{M} = \begin{pmatrix} m_d & \mathcal{O}(\lambda m_s) & \mathcal{O}(\lambda^3 m_b) \\ \mathcal{O}(m_d) & m_s & \mathcal{O}(\lambda^2 m_b) \\ \mathcal{O}(m_d) & \mathcal{O}(m_s) & \mathcal{O}(m_s) \end{pmatrix}$$

It also generates the correct CKM matrix

2. Low-energy flavor constraints

Altmannshofer, SG, Robinson, Tuckler, 1712.01847

Natural Flavor conservation is broken → Tree-level flavor changing Higgs couplings



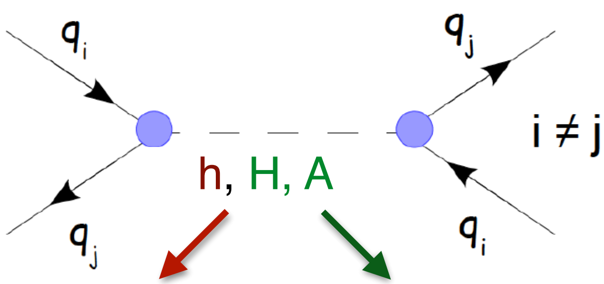
→ New Physics (NP) effects in meson mixing

2.

Low-energy flavor constraints

Altmannshofer, SG, Robinson, Tuckler, 1712.01847

Natural Flavor conservation is broken → Tree-level flavor changing Higgs couplings



→ New Physics (NP) effects in meson mixing

Going to 0 in the decoupling/ alignment limit

Always there

For Kaon mixing: $\mathcal{H}_{\rm eff} = C_2(\bar d_R s_L)^2 + \tilde C_2(\bar d_L s_R)^2 + C_4(\bar d_R s_L)(\bar d_L s_R)$

$$C_2, \tilde C_2, C_4 \propto \left(\frac{m_d m_s}{m_b}\right)^2 \frac{1}{m_H^2 v^2}$$

Approximate U(2) symmetry helps reducing the NP effects

Numerical example:
Tanβ=30, cos(α-β)=0
→ $m_H(\sim m_A) \gtrsim 200$ GeV

Large regions of parameter space are open even for light new Higgs bosons

Similarly, constraints on the charged Higgs are very weak

Heavy Higgs couplings & non-universality

Comparing to the other flavor structures…

Neutral Heavy Higgs

	W,Z κ_V^H	up quarks $\kappa_t^H, \kappa_c^H, \kappa_u^H$	down quarks $\kappa_b^H, \kappa_s^H, \kappa_d^H$	leptons $\kappa_\tau^H, \kappa_\mu^H, \kappa_e^H$
2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$

Charged Higgs

	$H^\pm \bar{d}_L^i u_R^j$	$H^\pm \bar{u}_L^i d_R^j$	$H^\pm \bar{\nu}_L^i \ell_R^j$
Type 1	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
Type 2	$\frac{1}{t_\beta}$	t_β	t_β

Heavy Higgs couplings & non-universality

Comparing to the other flavor structures…

Neutral Heavy Higgs

	W,Z κ_V^H	up quarks $\kappa_t^H,\ \kappa_c^H,\ \kappa_u^H$	down quarks $\kappa_b^H,\ \kappa_s^H,\ \kappa_d^H$	leptons $\kappa_\tau^H,\ \kappa_\mu^H,\ \kappa_e^H$
2HDM type 1	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$
2HDM type 2	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$	$t_\beta\frac{c_\alpha}{s_\beta}$
Flavorful 2HDM	$c_{\beta-\alpha}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$	$\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta},\ t_\beta\frac{c_\alpha}{s_\beta},\ t_\beta\frac{c_\alpha}{s_\beta}$

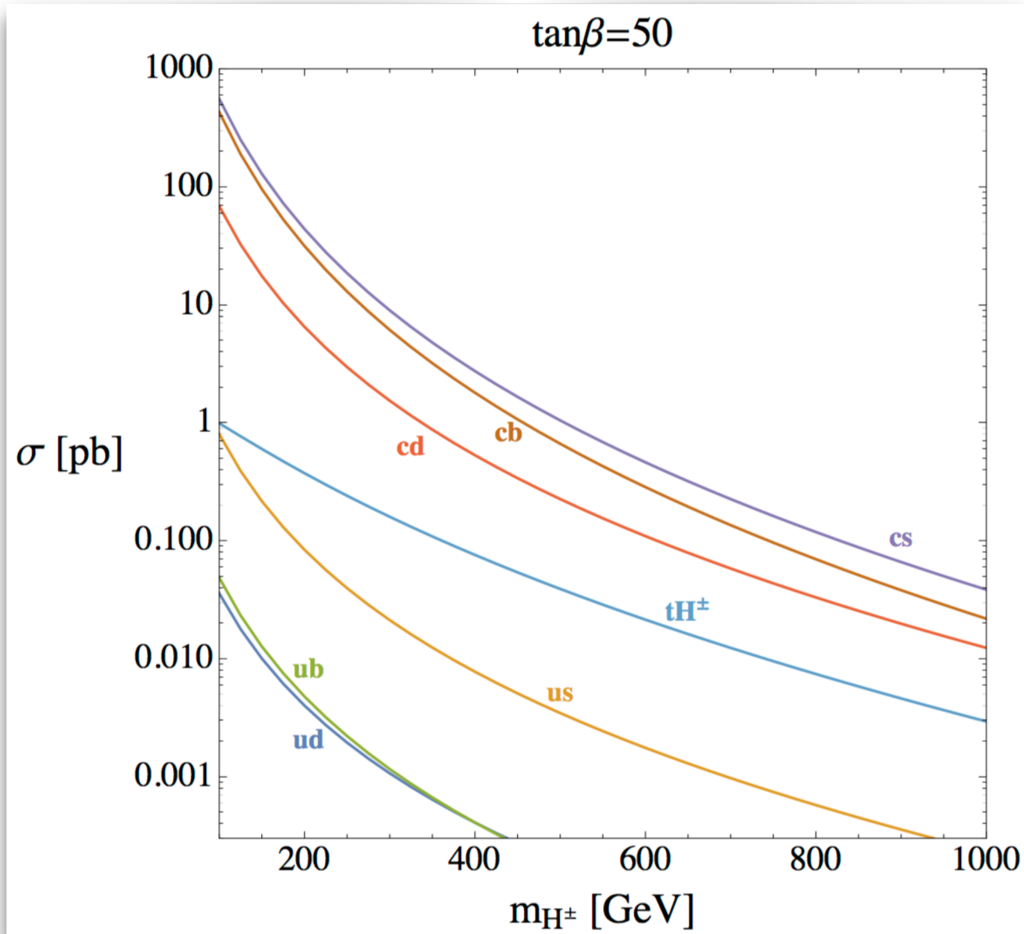
Charged Higgs

	$H^\pm \bar{d}_L^i u_R^j$	$H^\pm \bar{u}_L^i d_R^j$	$H^\pm \bar{\nu}_L^i \ell_R^j$
Type 1	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$	$\frac{1}{t_\beta}$
Type 2	$\frac{1}{t_\beta}$	t_β	t_β
Flavorful	$\frac{1}{t_\beta},\ t_\beta,\ t_\beta$	$\frac{1}{t_\beta},\ t_\beta,\ t_\beta$	$\frac{1}{t_\beta},\ t_\beta,\ t_\beta$
	j=3,2,1	j=3,2,1	j=3,2,1

In the flavorful 2HDM there are additional corrections to the κ's of the order of $O(m_c/m_t)$, $O(m_s/m_b)$, $O(m_\mu/m_\tau)$

Production and decays of $H^{\pm}$

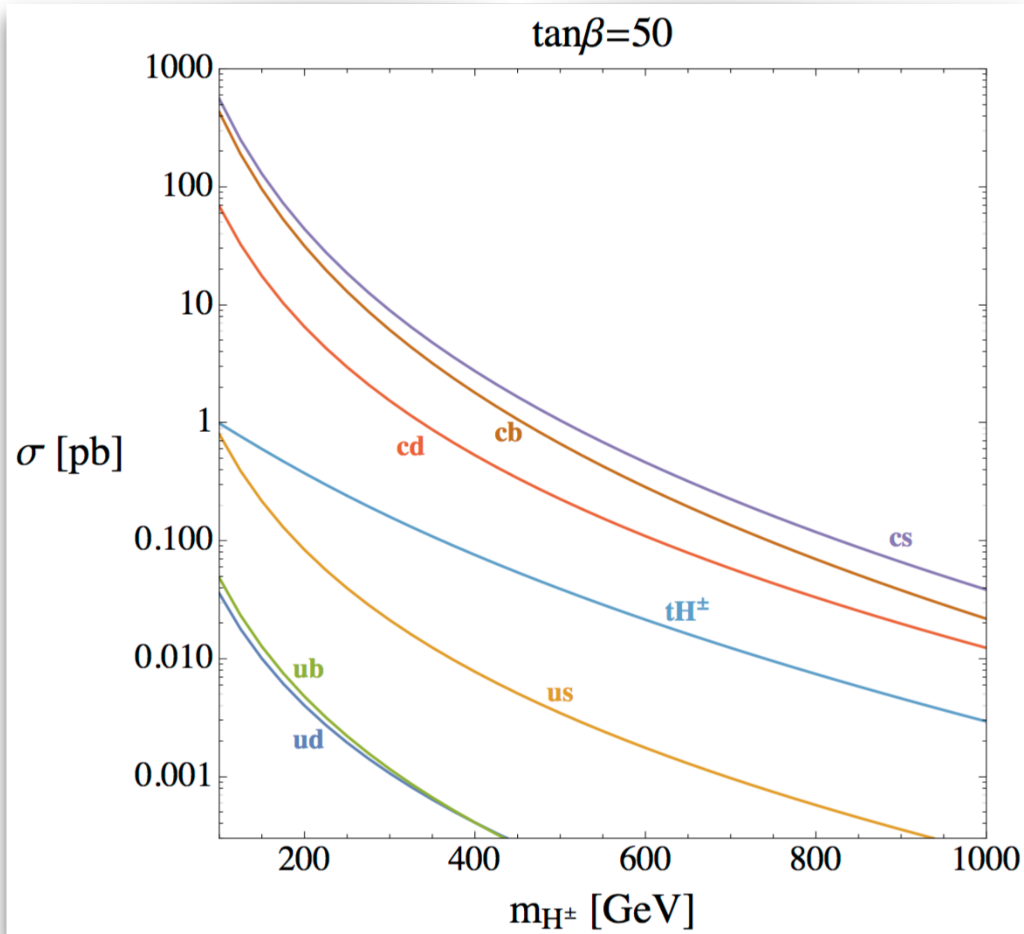
Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

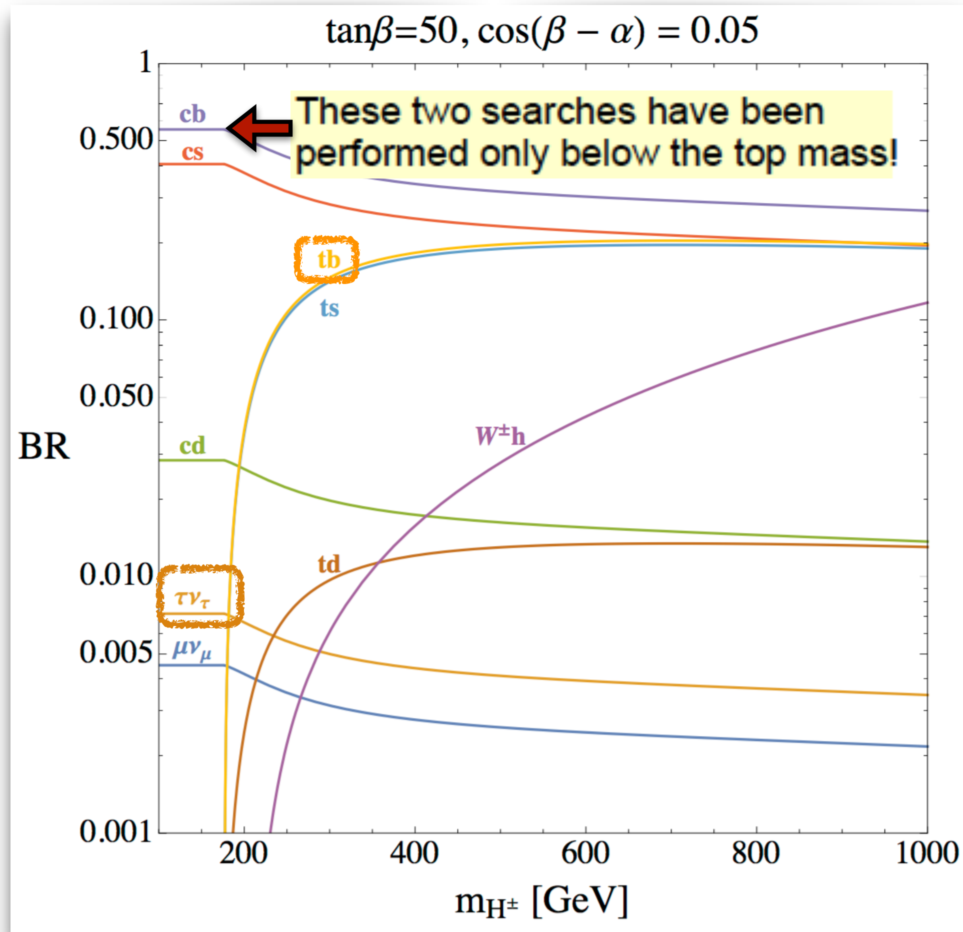


s-channel production (quark-quark fusion) is the dominant one

Production and decays of H±

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398





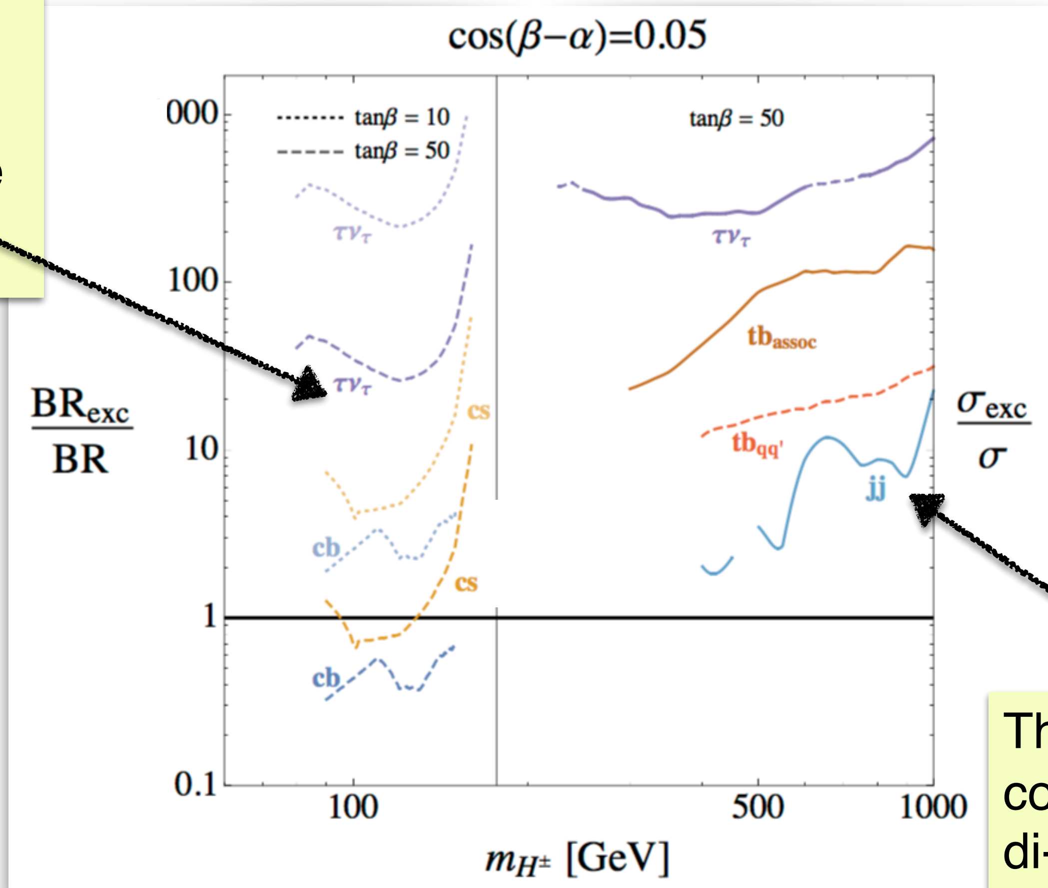
s-channel production (quark-quark fusion) is the dominant one

The branching ratio to the "golden" channels, tb, τν, are suppressed

Weak LHC constraints

Warning: the numbers are not updated (sorry!)

For tanβ=10, even below the top mass, the parameter space is completely open



The most interesting constraints come from di-jet and top-bottom resonance searches

No bound above the top threshold even at very high values of tanβ.

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

What to look for at the LHC? (H±)

Targeting quark-quark fusion production

charm-bottom resonances (also above the top threshold).
Data scouting with bottom (charm)-tagging?

$$\boxed{pp \to H^\pm \to cs,\ cb}$$

charm-strange resonances (also above the top threshold).
Present searches focus on

$$pp \to t\bar{t} \to (Wb)(H^\pm b),\ H^\pm \to cs$$

used for triggering
(mono-lepton trigger)

$$\boxed{pp \to H^\pm \to Wh}$$

Wh resonances (not necessarily in the boosted regime!)

What to look for at the LHC? ($H^{\pm}$)

Targeting quark-quark fusion production

charm-bottom resonances (also above the top threshold).
Data scouting with bottom (charm)-tagging?

$$\boxed{pp \to H^{\pm} \to cs,\ cb}$$

charm-strange resonances (also above the top threshold).
Present searches focus on

$$pp \to t\bar{t} \to (Wb)(H^{\pm}b),\ H^{\pm} \to cs$$

used for triggering
(mono-lepton trigger)

$$\boxed{pp \to H^{\pm} \to Wh}$$

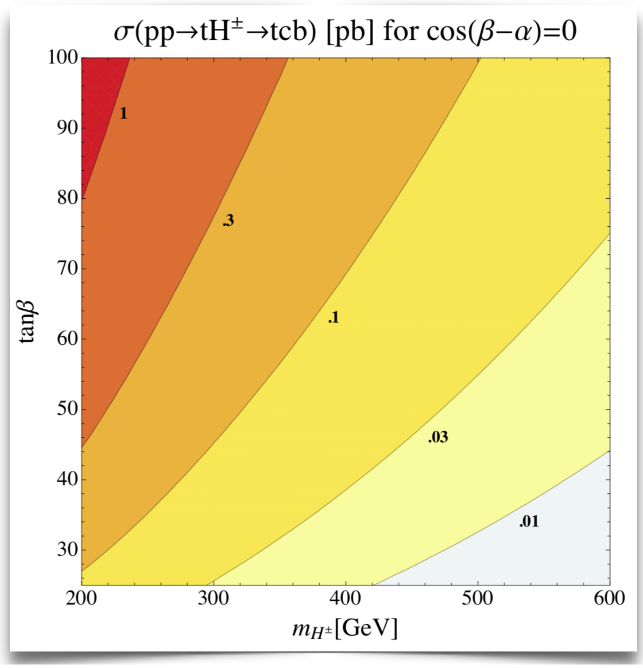
Wh resonances (not necessarily in the boosted regime!)

Charged Higgs-top associated production

charm-bottom and charm-strange resonances

$$pp \to tH^{\pm},\ H^{\pm} \to cs,\ cb$$

Less challenging thanks to the additional top
(that can be used for triggering)



Summary & outlook

Flavor is still an unresolved problem in particle physics.

We currently don't know if the Higgs gives mass to the light flavor quarks and leptons.

What if there are additional sources of EWSB that do not obey to the Natural Flavor conservation ansatz?

There is room!

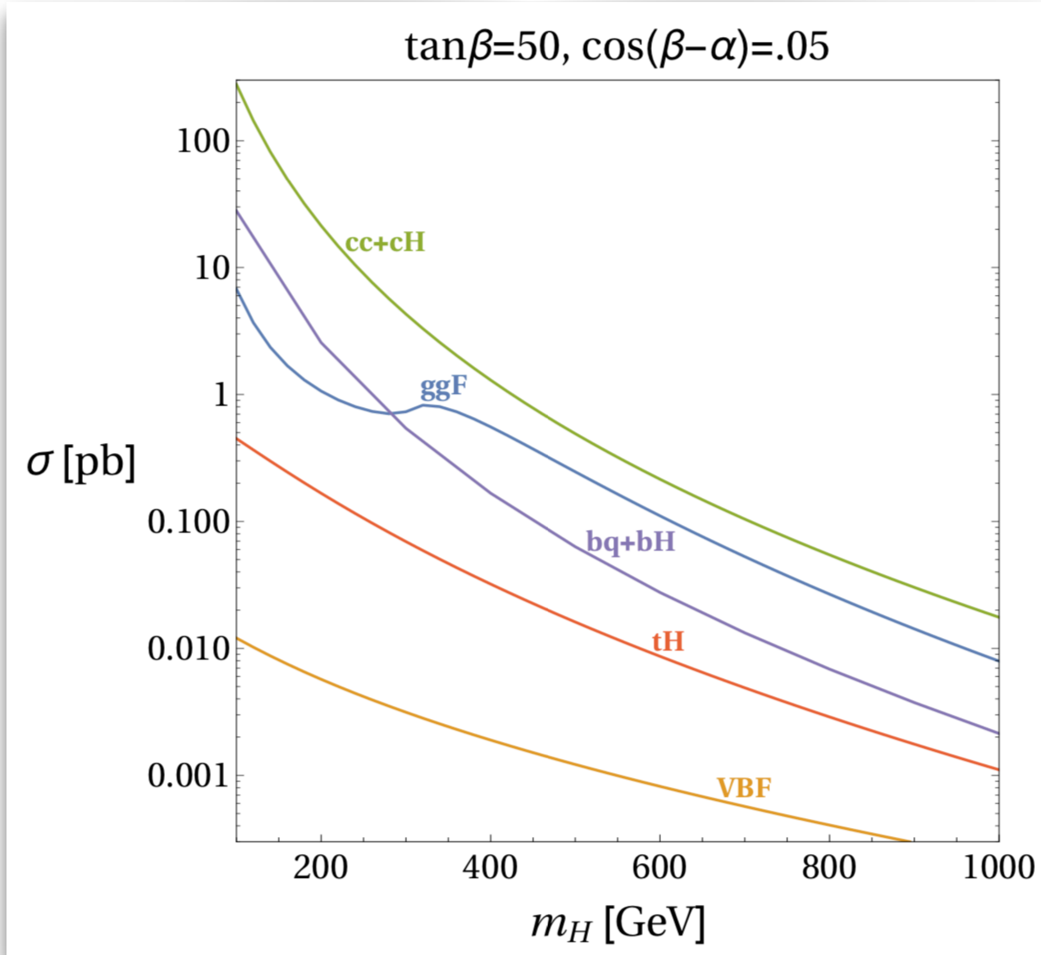
For this talk:
* Aligned 2HDM
* Flavorful 2HDM

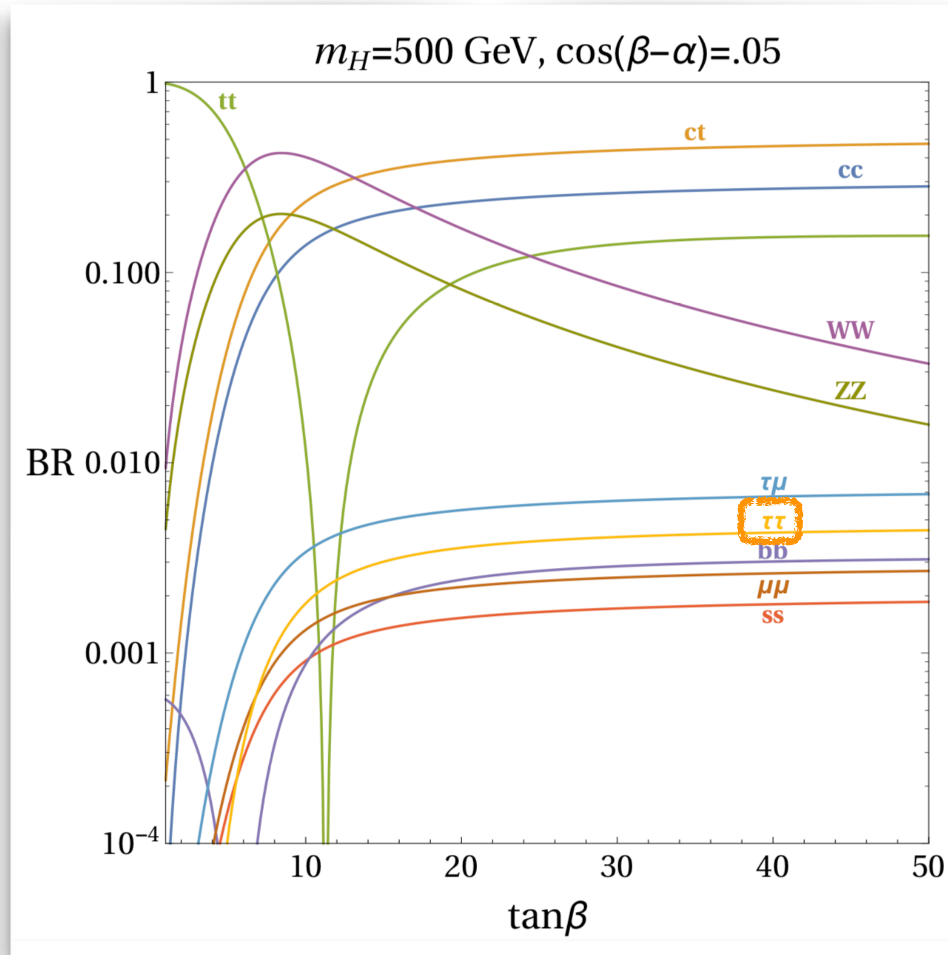
Several more in the literature

Low energy flavor bounds ($b \to s\gamma$, $B \to \tau\nu$, ...) on the charged Higgs can dramatically change.

The LHC charged Higgs phenomenology can also change.
New possible signatures to look for at the LHC!

Production and decays of the scalars H/A





Charm quark fusion + charm associated production are the dominant modes.

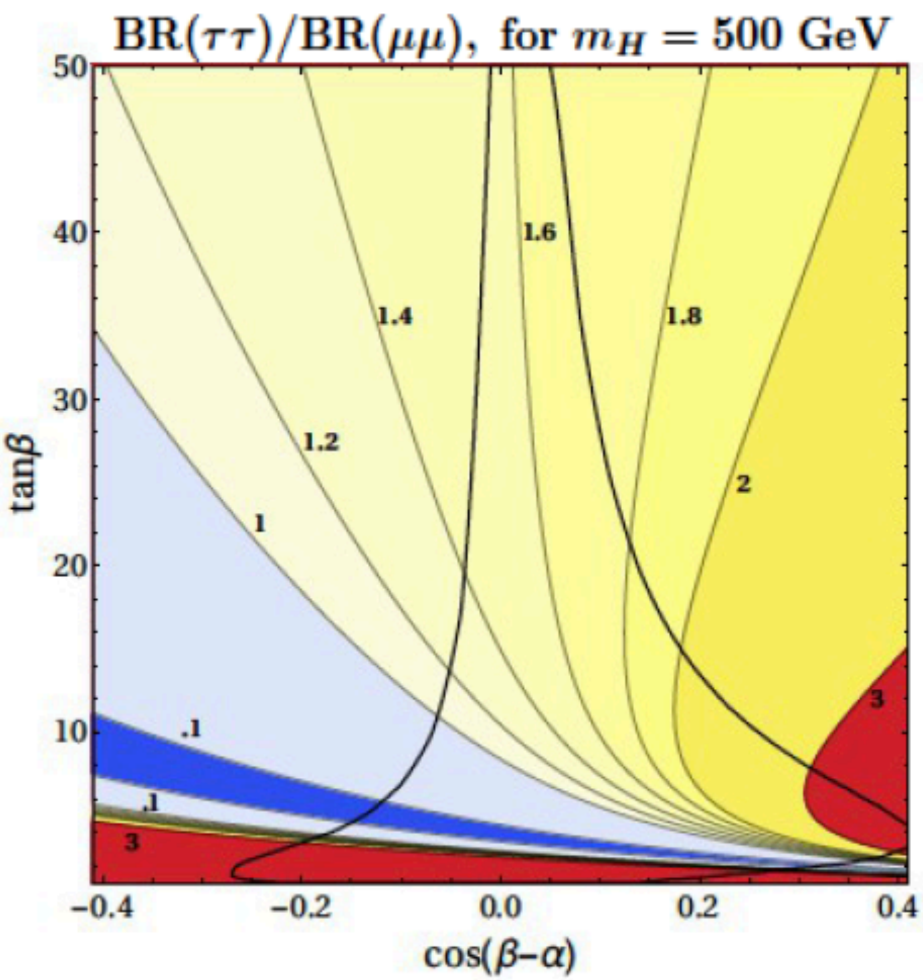
Di-jet and top-charm are the dominant decay modes

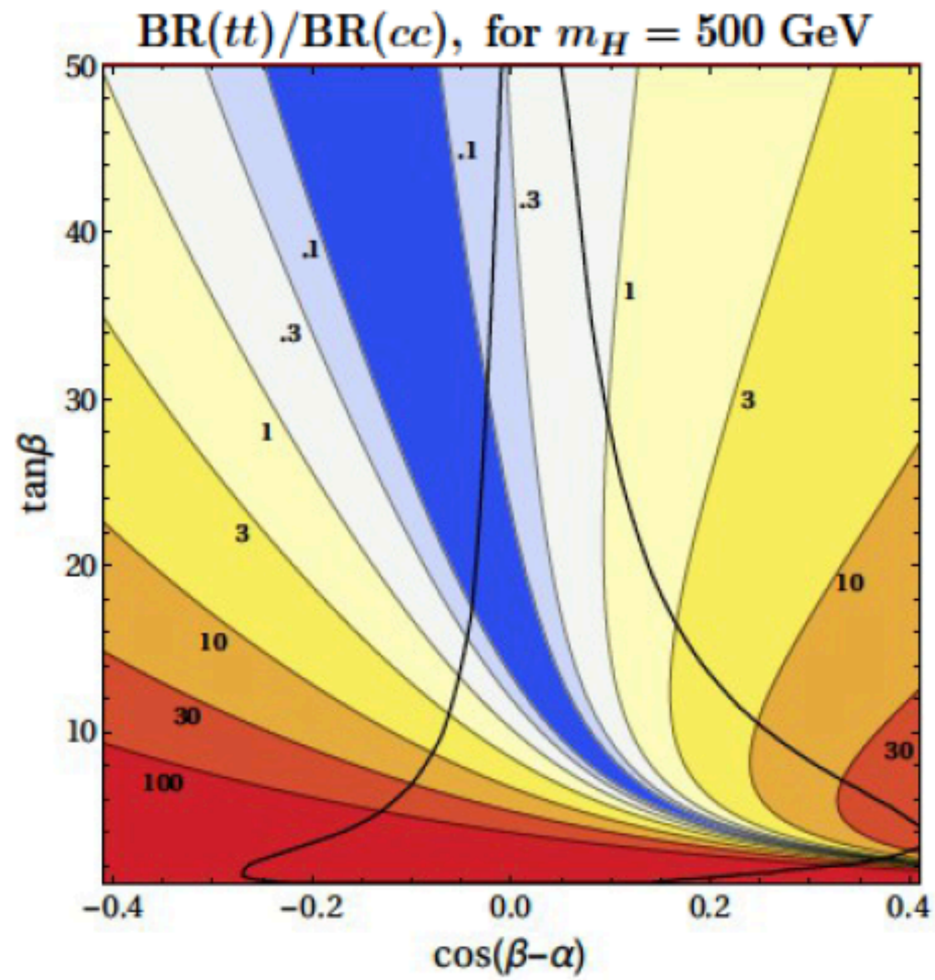
bH production is typically suppressed, if compared to a Type-II 2HDM

The branching ratio to the "golden" channel, τ τ, is suppressed

Novel hierarchies in the branching ratios

Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398





as opposed to **~300** in models with natural flavor conservation

as opposed to **~6*10⁴** in models with natural flavor conservation

What to look for at the LHC? (H)

Higgs quark-quark fusion production:

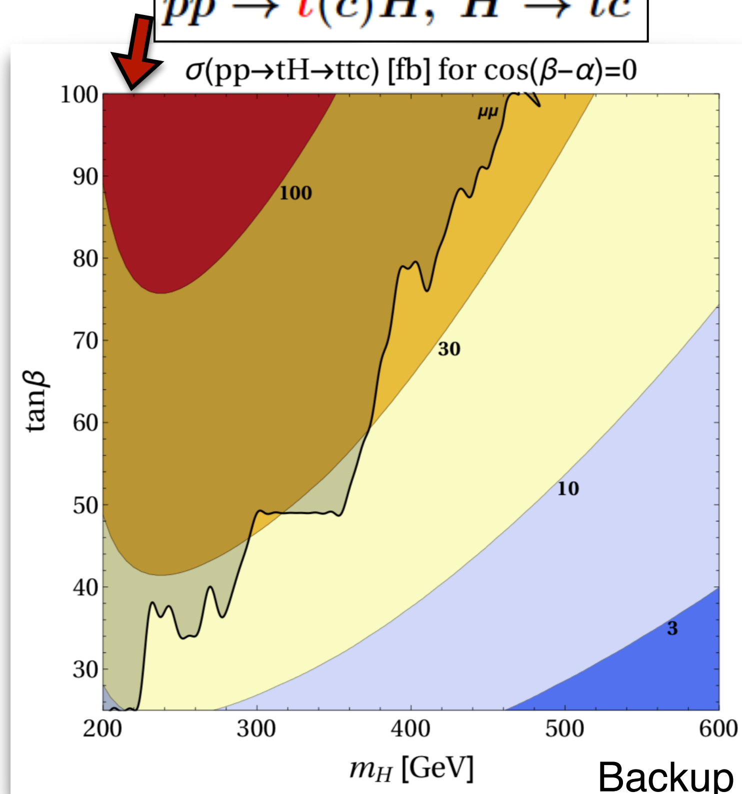
Light di-jet resonances! Eventually adding charm tagging
Data scouting, trigger level analysis

$$\boxed{pp \to H(c), H \to cc}$$

Top-charm resonances
boosted regime or leptonic top to trigger on the events.

$$\boxed{pp \to H(c), H \to tc}$$

$$\boxed{pp \to t(c)H,\ H \to tc}$$



Higgs-top (charm) associated production:

Top-charm or top-top resonances

<u>hadronic:</u>

tt + (heavy) jet backgrounds with large theory uncertainties.
Kinematic reconstruction of the heavy Higgs boson mass?

<u>fully leptonic:</u>

same-charge dilepton plus bottom and charm jets

Tau-mu resonances

$$\boxed{pp \to t(c)H,\ H \to \tau\mu}$$

Light di-jet resonances

$$\boxed{pp \to t(c)H,\ H \to cc}$$

S.Gori

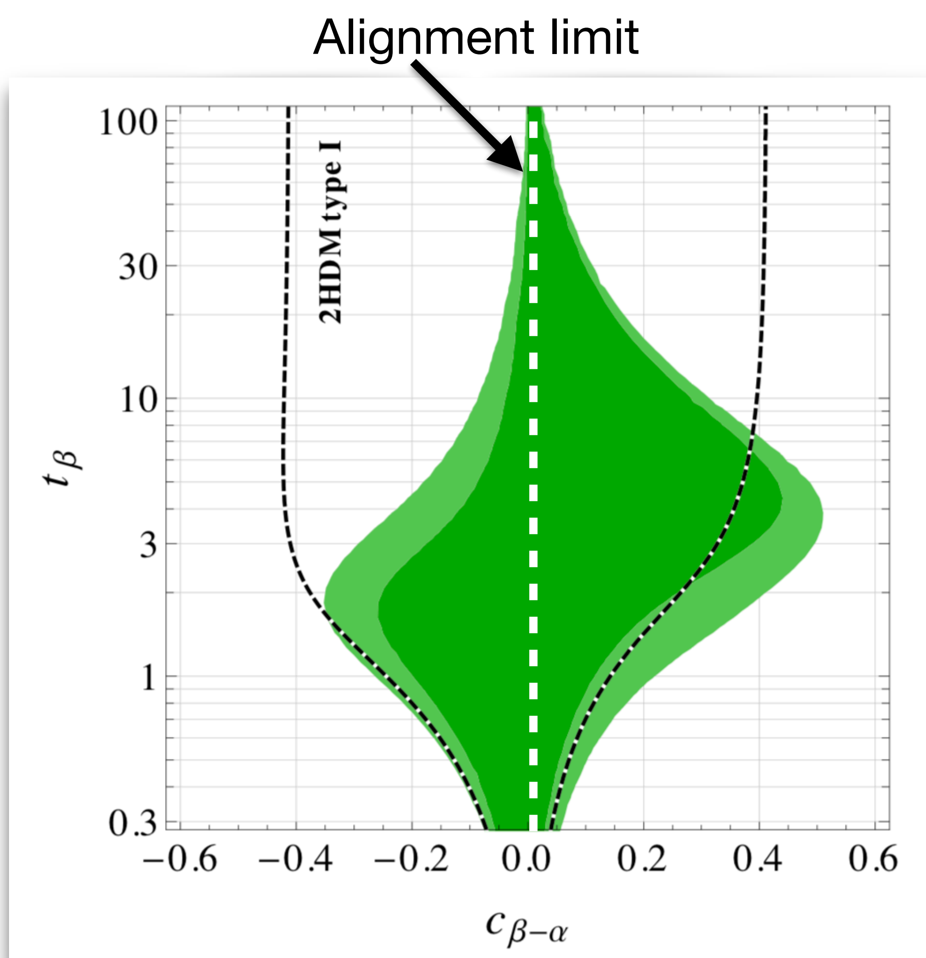
Backup

Modification of the Higgs couplings

1. Large enhancement of the charm Yukawa that suppresses all the other rates.

Also the muon Yukawa is large.

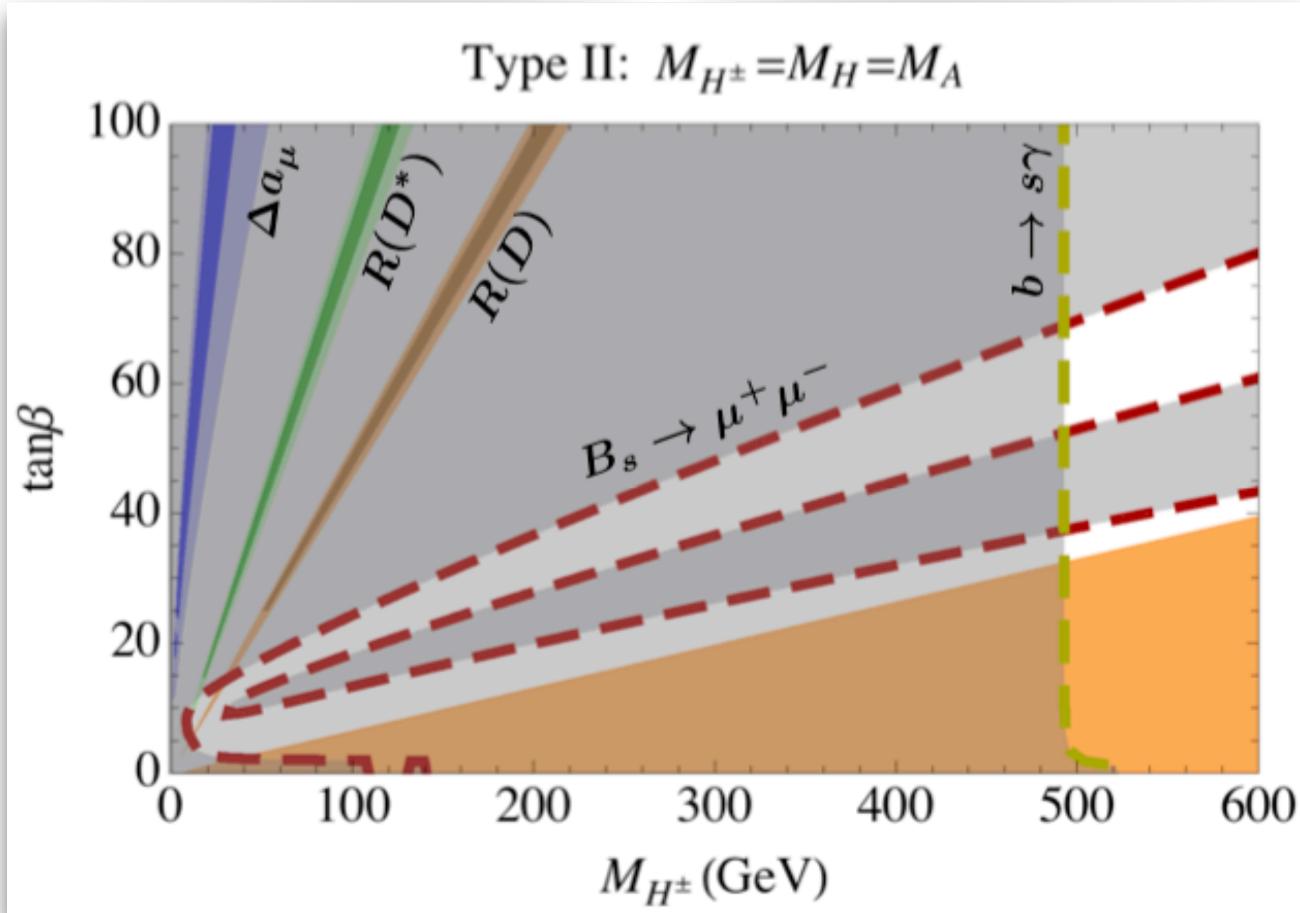
2. Here the constraints are similar to a type I 2HDM.
The couplings to 3[rd] generation fermions & gauge bosons drive the fit.



Altmannshofer, Eby, SG, Lotito, Martone, Tuckler, 1610.02398

Couplings to the 3rd, 2nd, and 1st generations: $\frac{c_\alpha}{s_\beta}$, $\frac{-s_\alpha}{c_\beta}$, $\frac{-s_\alpha}{c_\beta}$ **Breaking of flavor universality!**

R(D$^{(*)}$) and the charged Higgs



Enomoto, Watanabe, 1511.05066