# Flavor perspective on heavy Higgs searches


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New Physics interpretations at the LHC 2

Argonne National Laboratory,
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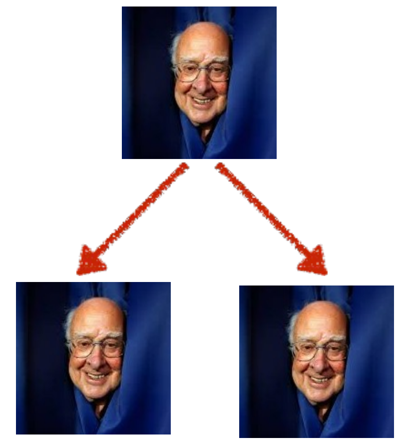
# The second Higgs boson

## Additional Higgs scalars often arise in natural theories of EWSB:

- Higgs sector of the MSSM/NMSSM
- Little Higgs, Composite Higgs
- Twin Higgs, Neutral Naturalness ...



## More broadly:

The spin-1/2 and spin-1 sectors of our universe are rich in multiplicity.

Why not also the spin-0 sector?

## From the naturalness perspective

The existence of a new Higgs would imply parametrically worse fine-tuning with no compelling connection to anthropic reasoning.

(see Draper, Haber, Ruderman, 1605.03237 for exceptions)

**paradigm shift**

# Organization principles

How to organize our searches in such a way to cover all our theories?

From the bottom up:

- Not too far away from the alignment limit

  (and therefore not too large couplings to massive gauge bosons)

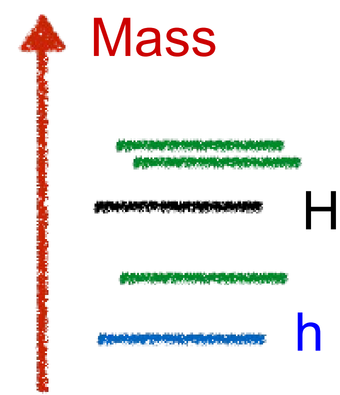
$$|\cos(\alpha-\beta)| \lesssim \text{few}\cdot\mathcal{O}(0.1)$$

- Additional EW scale particles in the spectrum

  that talk to the heavy Higgs?

Examples:

$$\begin{aligned} gg &\to H \to W H^{\pm} \\ T &\to Ht \end{aligned}$$



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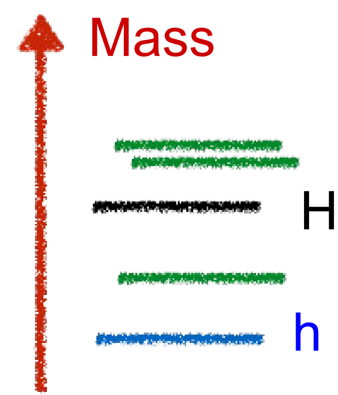


- Flavor structure:

The topic of this talk

(searches almost exclusively assume Natural Flavor Conservation... so far)

# Current heavy Higgs searches

**H**

| bb | ττ | μμ | γγ | hh | WW | ZZ | tt |
|---|---|---|---|---|---|---|---|
| bH | gg,bH | gg,bH | | gg | all | all | gg (tt) |

**A**

| bb | ττ | μμ | γγ | Zh | tt |
|---|---|---|---|---|---|
| bH | gg,bA | gg,bA | | gg,bA | gg (tt) |

**$H^{\pm}$**

| τν | tb | Wh | cs | μν | cb |
|---|---|---|---|---|---|
| (t)$H^{\pm}$ t dec | (t)$H^{\pm}$ t dec | qq fus | t decay | qq fus | t decay |

New since ICHEP 2016

Not targeted at a new Higgs

What about different flavor combinations?

# New flavor structure beyond NFC?

What about scenarios that break the Natural Flavor Conservation ansatz?

(up, down quarks and leptons couple
to both doublets)

**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)

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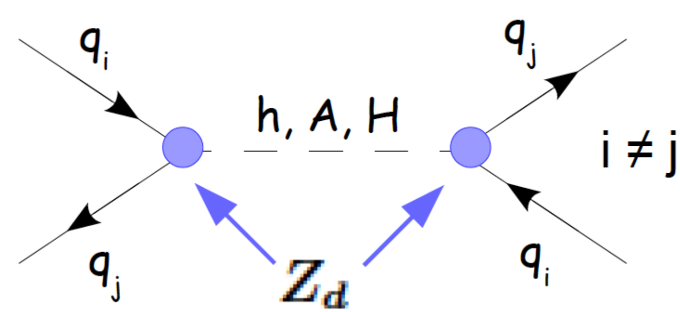
$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H' \\ H \end{pmatrix} \qquad \langle \Phi_v^\dagger \Phi_v \rangle = v^2/2, \quad \langle \Phi_H^\dagger \Phi_H \rangle = 0$$

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

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

Tree level flavor changing neutral currents




We need a "clever" flavor structure

1. Flavor-alignment
2. Flavorful U(2) ...

see also Bauer, Carena Gemmler, '15

# 1. Flavor-aligned 2HDMs

$$-\mathcal{L}_Y = \bar{Q}_L \left[\kappa^U(\mathrm{EW})H_1 + \rho^U(\mathrm{EW})H_2\right] U_R + \bar{Q}_L \left[\kappa^{D\dagger}(\mathrm{EW})H_1 + \rho^{D\dagger}(\mathrm{EW})H_2\right] D_R + \bar{L}_L \left[\kappa^{L\dagger}(\mathrm{EW})H_1 + \rho^{L\dagger}(\mathrm{EW})H_2\right] L_R + \mathrm{h.c.}$$

$$\begin{cases} \rho^D(\mathrm{EW}) = a^D \kappa^D(\mathrm{EW}), \\ \rho^U(\mathrm{EW}) = a^U \kappa^U(\mathrm{EW}), \\ \rho^L(\mathrm{EW}) = a^\ell \kappa^L(\mathrm{EW}) \end{cases}$$

Flavor-alignment
at the EW scale

Pich, Tuzon, 0908.1554

→ No FCNCs

From the theory point of view,
It is hard to enforce flavor-alignment at the EW scale

What if some new dynamics enforces flavor-alignment at some very high energy scale $\Lambda$?

$$\rho^D(\Lambda) = a^D \kappa^D(\Lambda)$$

SG, Haber, Santos, 1703.05873

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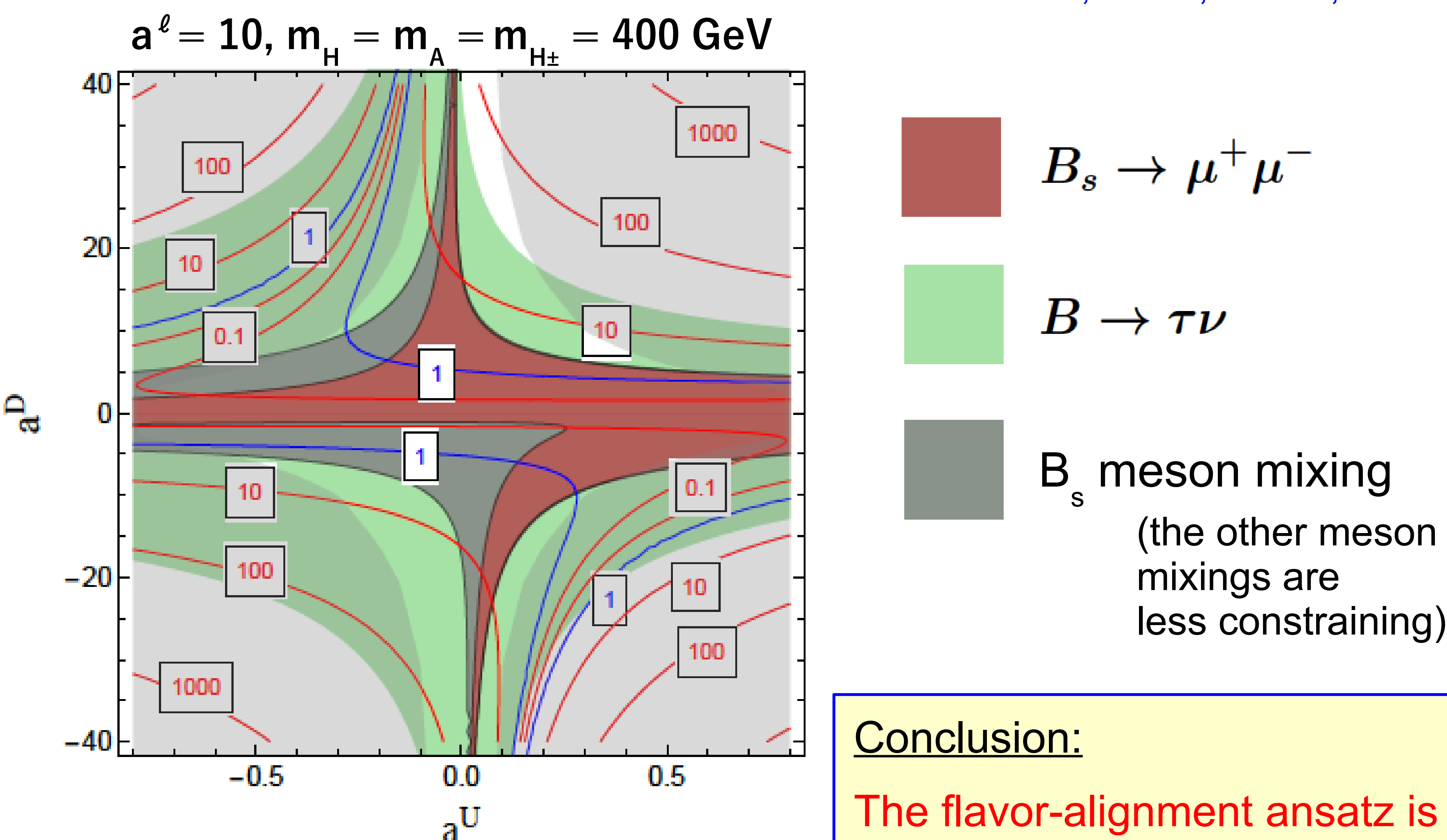
Renormalization group running generates non-aligned terms

$$\rho^D(\mathrm{EW}) = \left[a^D + \frac{F_1(a^U, a^D, M_i)}{4\pi^2}\log\left(\frac{\mathrm{EW}}{\Lambda}\right)\right]\kappa^D(\mathrm{EW}) + \kappa^D(\mathrm{EW})(a^U - a^D)\frac{F_2(a^U, a^D, M_i)}{4\pi^2}\log\left(\frac{\mathrm{EW}}{\Lambda}\right)\underbrace{V^\dagger_{\mathrm{CKM}}\kappa^U(\mathrm{EW})V_{\mathrm{CKM}}}_{\text{FCNCs}}$$

A particular type of Minimal Flavor Violation

# Flavor physics effects

SG, Haber, Santos, 1703.05873



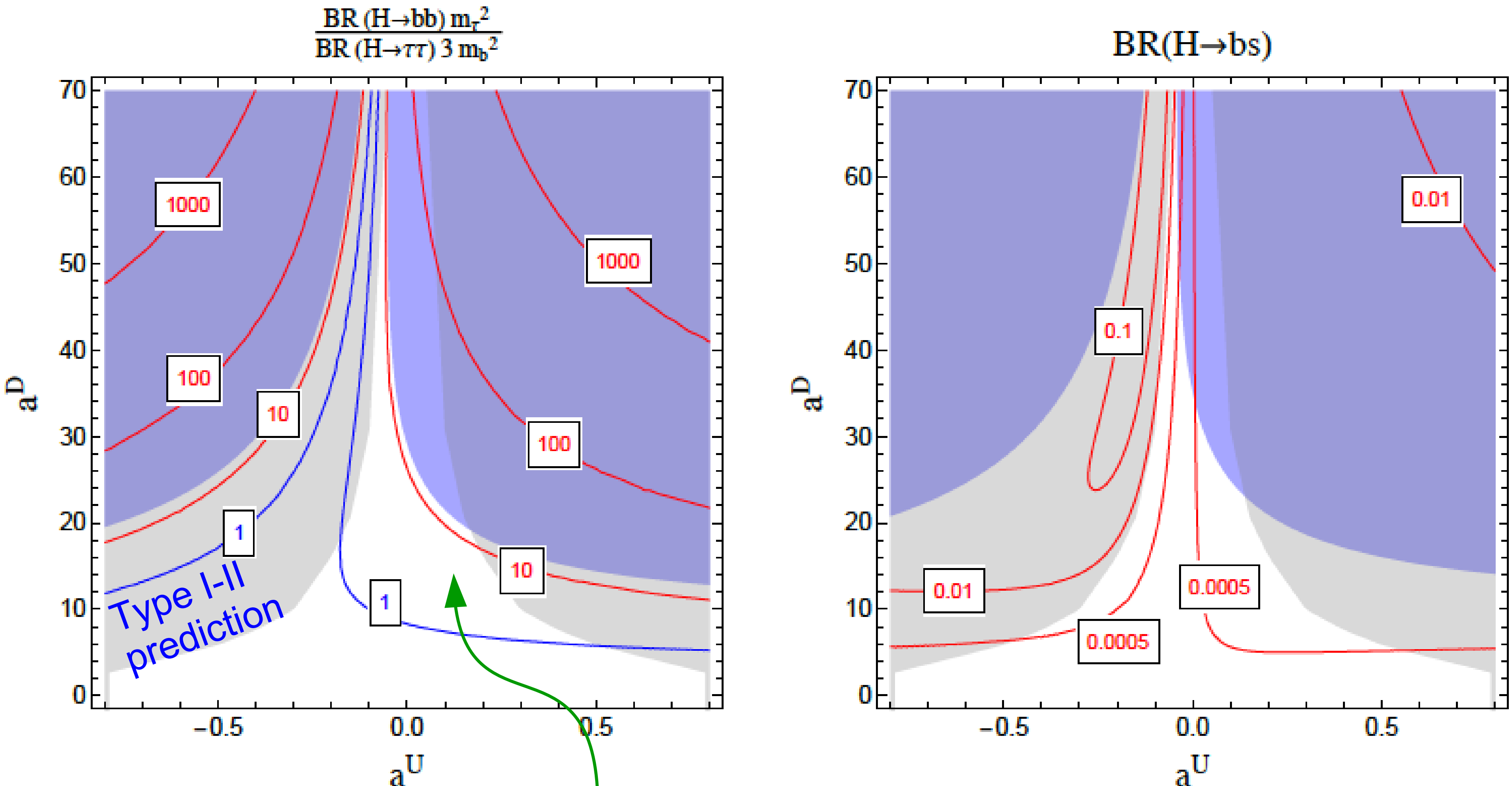

<u>Conclusion:</u>

The flavor-alignment ansatz is not perturbatively stable but the FCNC effects are under control

# Pheno of the heavy Higgs boson

**$a^\ell = 10$, $m_H = 400$ GeV**

SG, Haber, Santos, 1703.05873




In this region, the H → bb searches
Have a better sensitivity than
in a Type I-II 2HDM

Exclusion from b(b)H, H → bb

 S.Gori

# 2. Going beyond MFV: flavorful U(2)

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, tanβ = 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

Indeed, we do not know if the 125 GeV Higgs couples to first and second generations or not!

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$$(\mathcal{M}_0 + \Delta\mathcal{M})$$

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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

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Approximated U(2) symmetry protecting from too large FCNCs

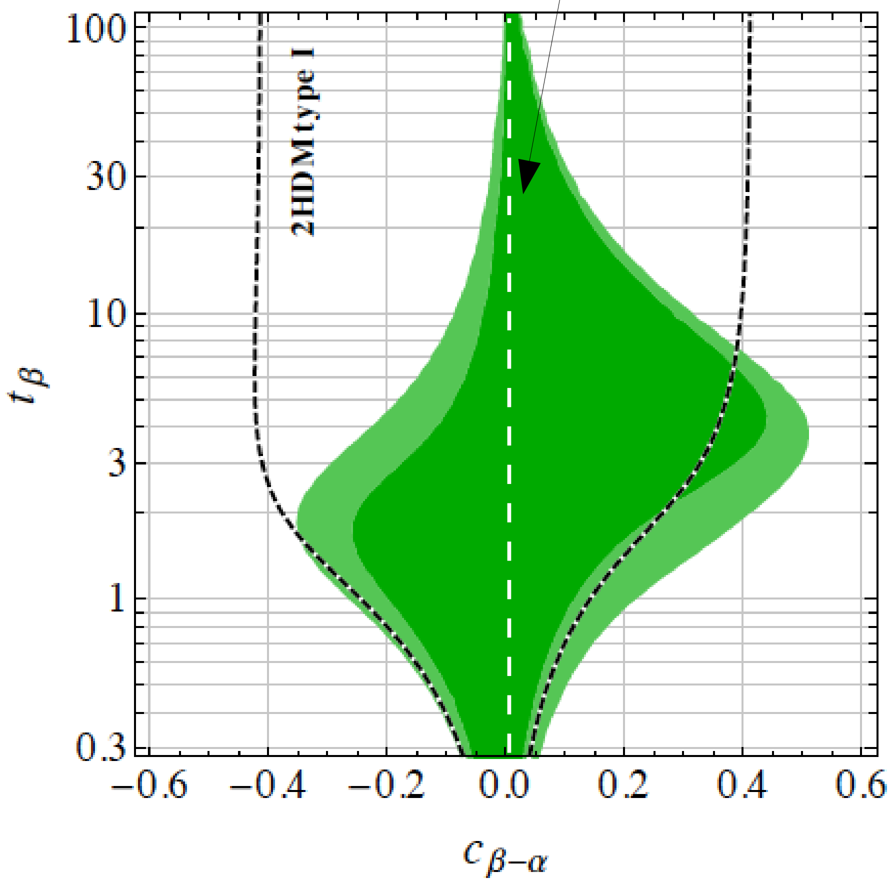
In progress with Altmannshofer, Tuckler

# Constraints from the 125 GeV Higgs rates

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

Constraint in the tβ, cos(β-α) plane from the 125 GeV Higgs coupl. measurements

Decoupling/alignment limit



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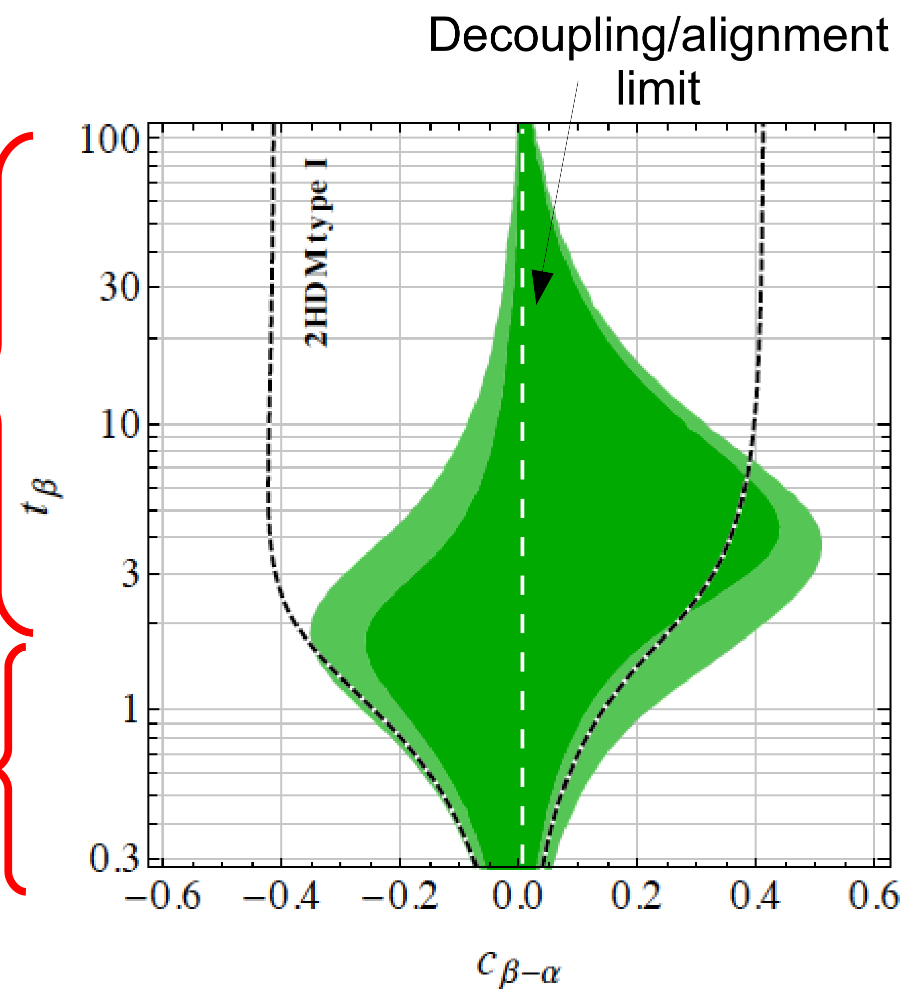
Constraint in the tβ, cos(β-α) plane from the 125 GeV Higgs coupl. measurements

**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 3rd generation fermions & gauge bosons drive the fit.

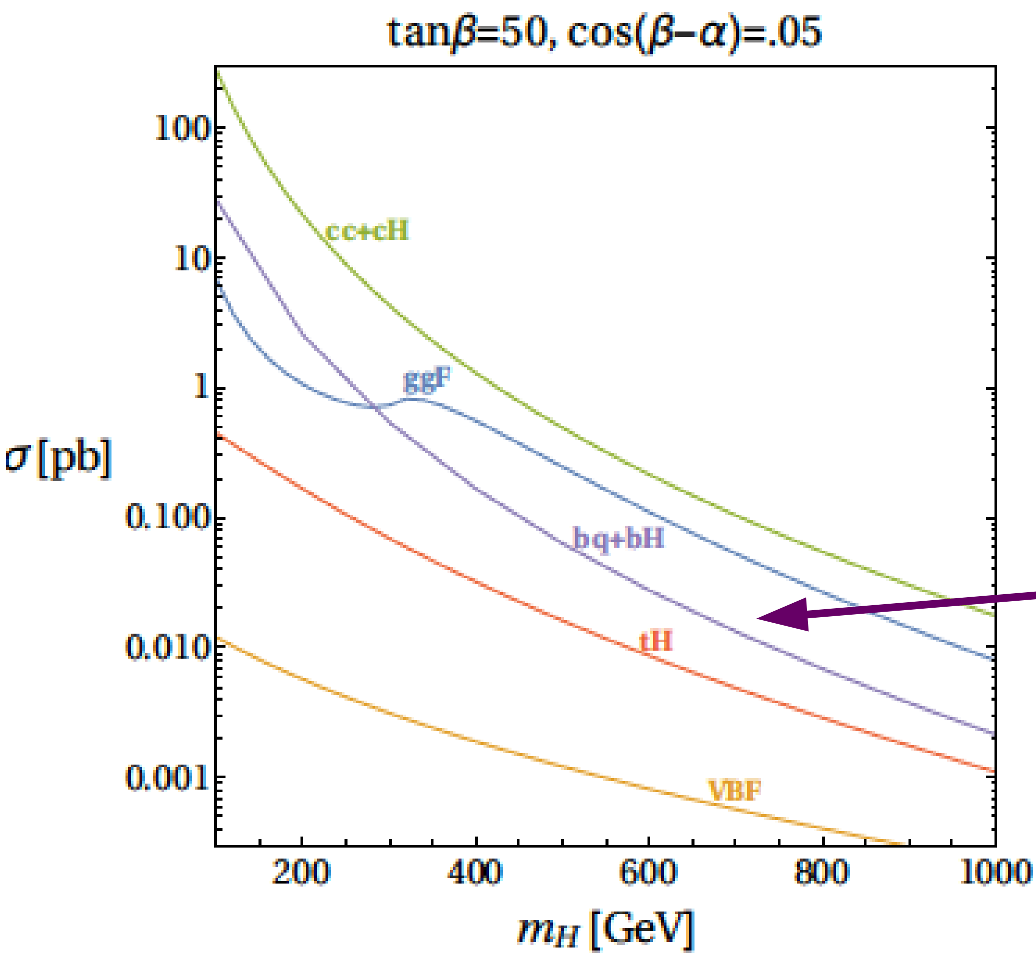


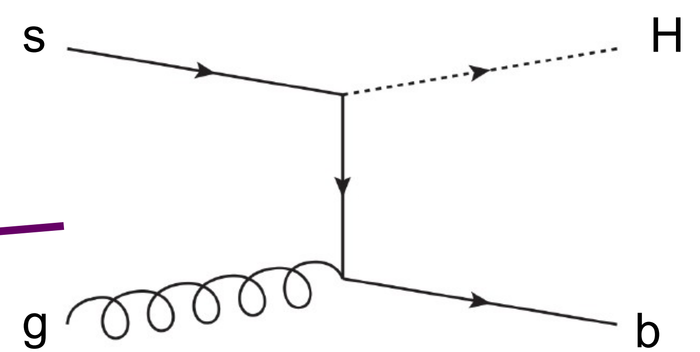

Couplings to the 3rd, 2nd, and 1st generations: $\frac{c_\alpha}{s_\beta}$, $\frac{-s_\alpha}{c_\beta}$, $\frac{-s_\alpha}{c_\beta}$

+ 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 the scalars H/A

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




Production from charm-quark
fusion is the dominant production mode

bH production is typically suppressed
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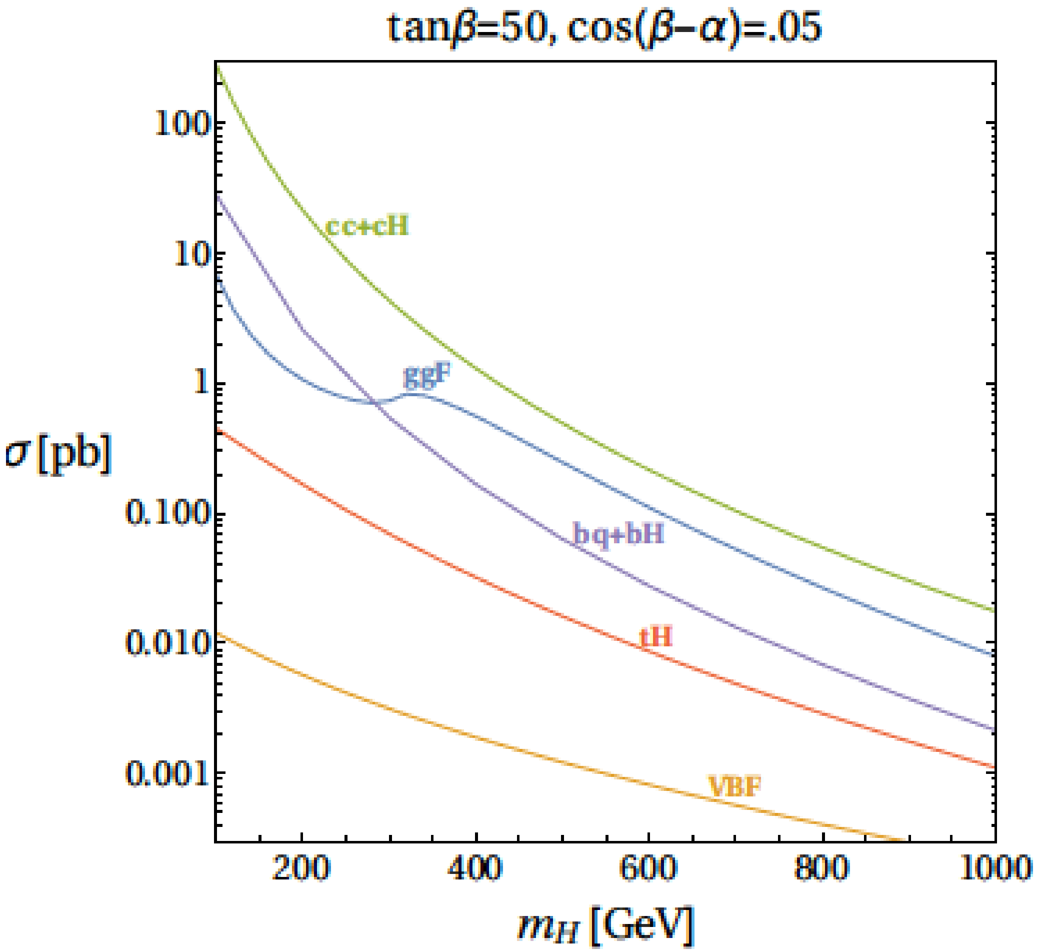
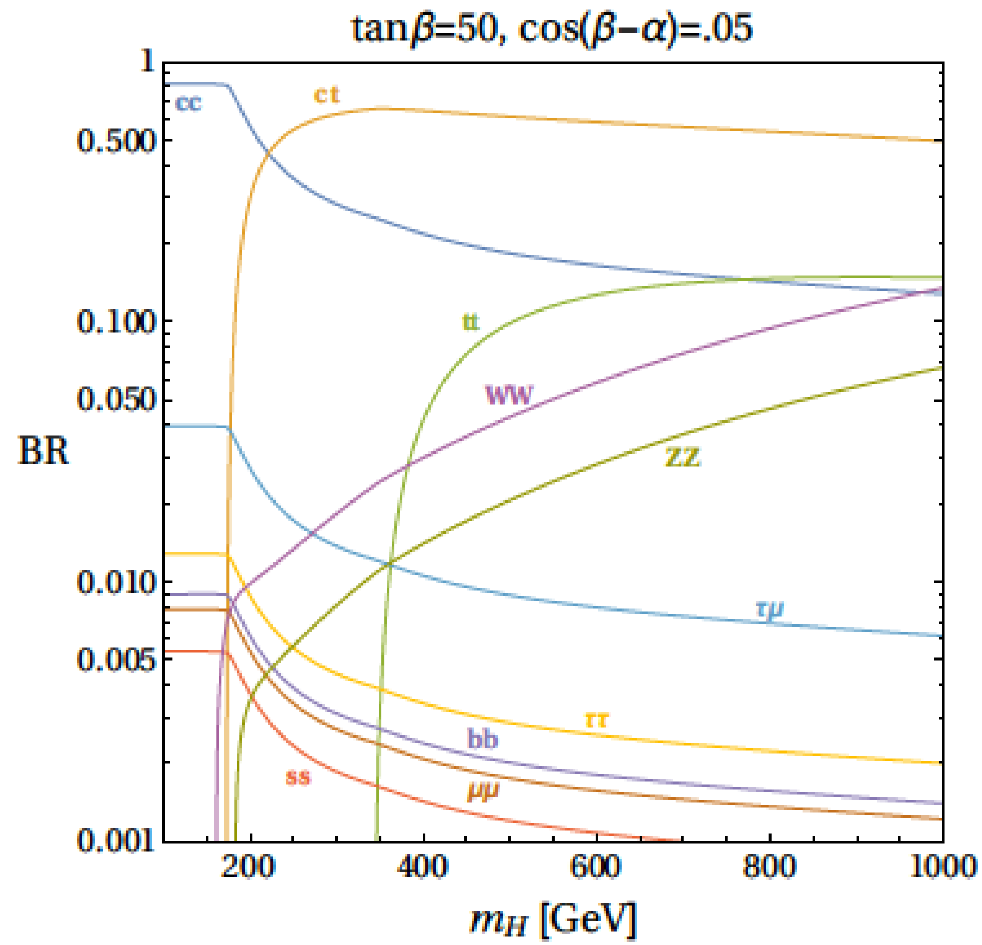



Production from charm-quark fusion is the dominant production mode

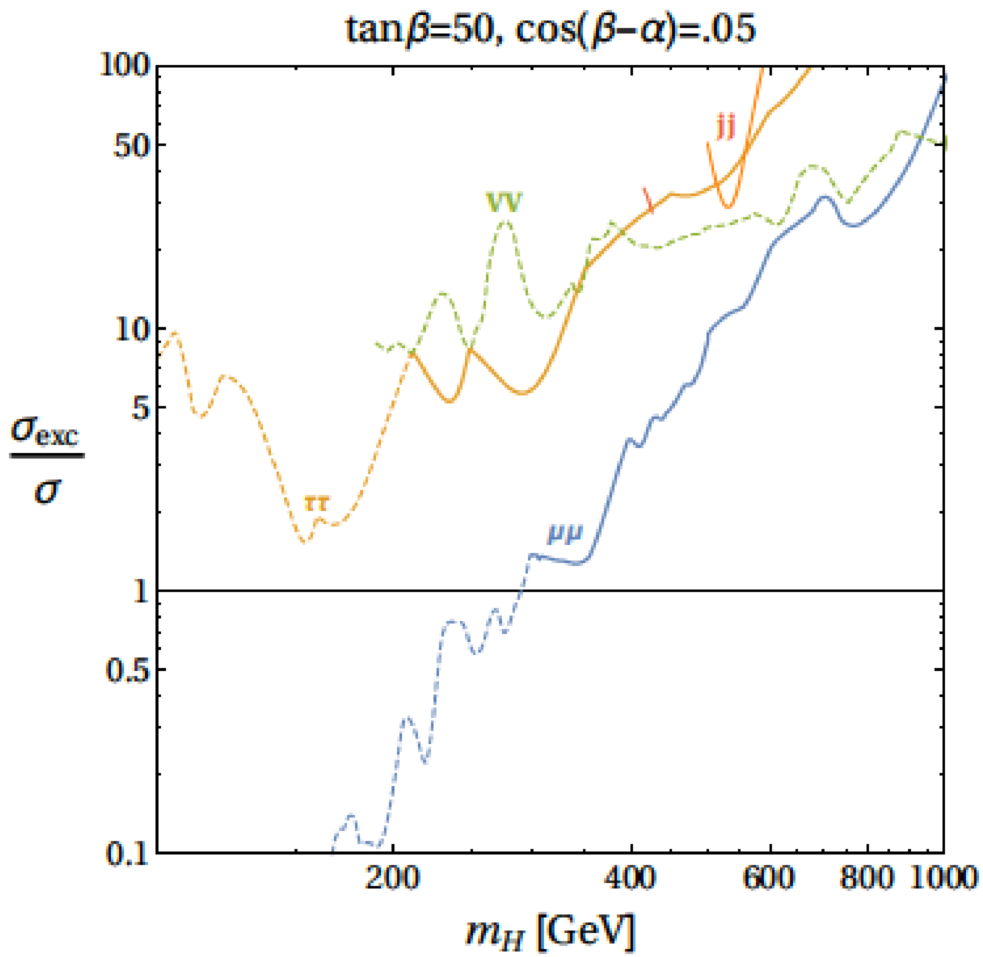
Di-jet and top-charm decay modes are the dominant ones

bH production is typically suppressed compared to type II 2HDMs

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

# Current and future searches (H/A)

The present constraints are weak.
Even at very large values of tanβ:




No bound beyond LEP for tanβ ≤ 12!

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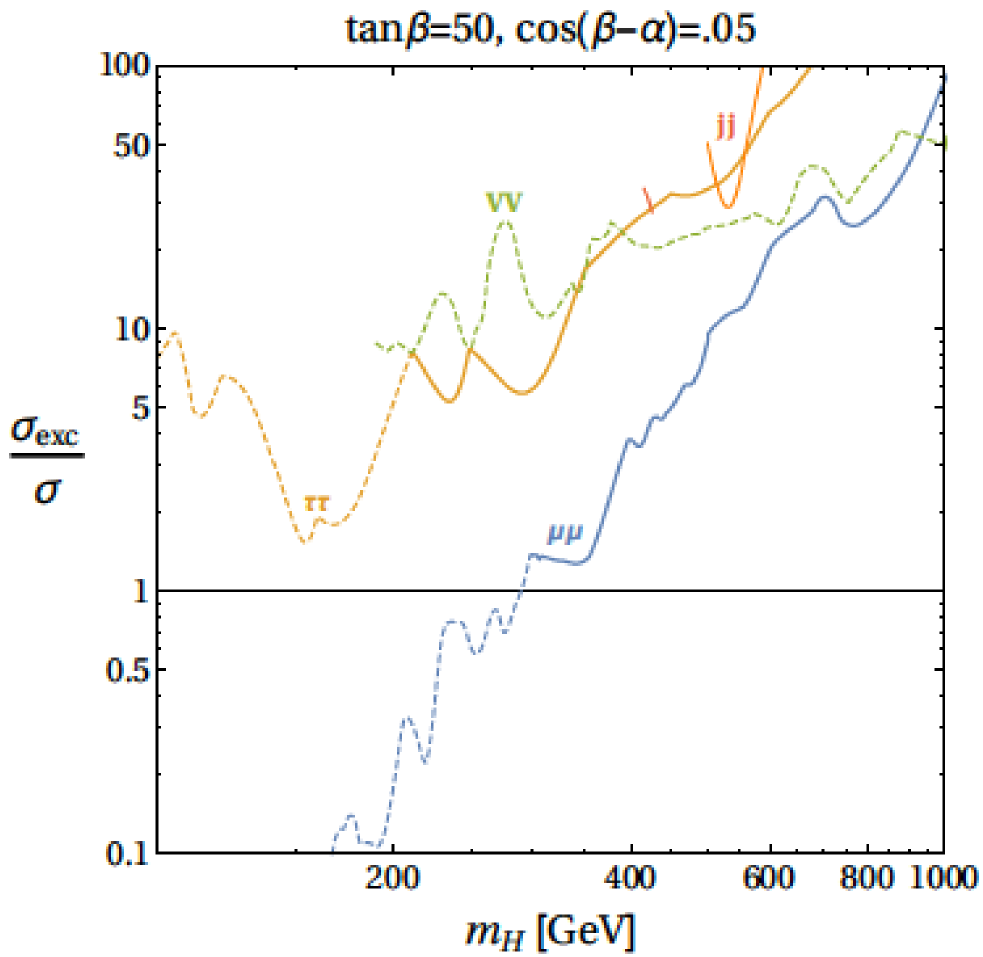
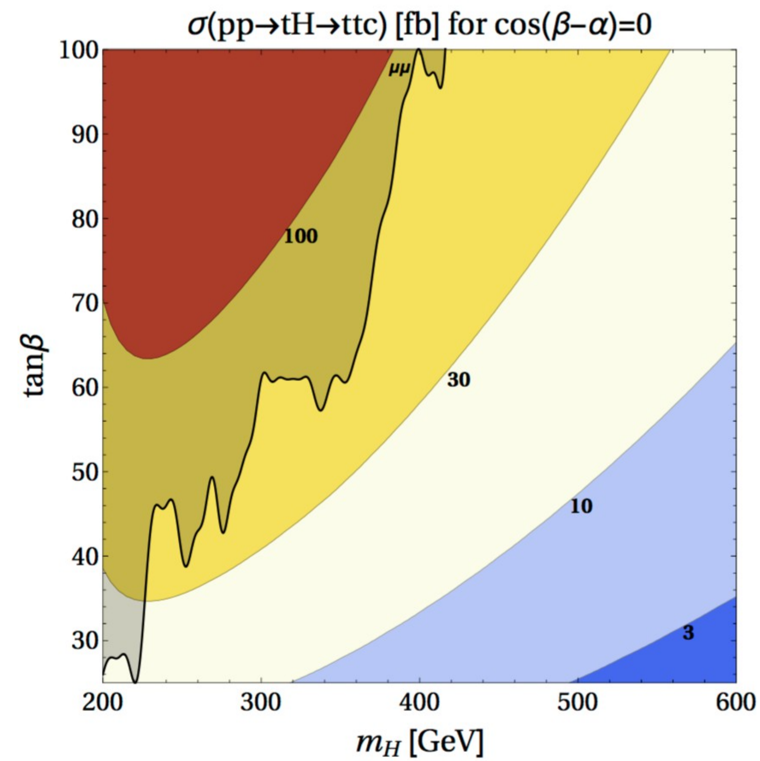



No bound beyond LEP for tanβ ≤ 12!

Future possible searches

$$pp \to H/A \to tc,\ \ pp \to t(c)H/A, H/A \to tc,$$
$$pp \to t(c)H/A, H/A \to tt$$
$$pp \to H/A \to \tau\mu\ \ pp \to t(c)H/A, H/A \to \tau\mu$$
$$pp \to c(c)H/A \to \mu\mu, \cdots$$

s-channel productions too!

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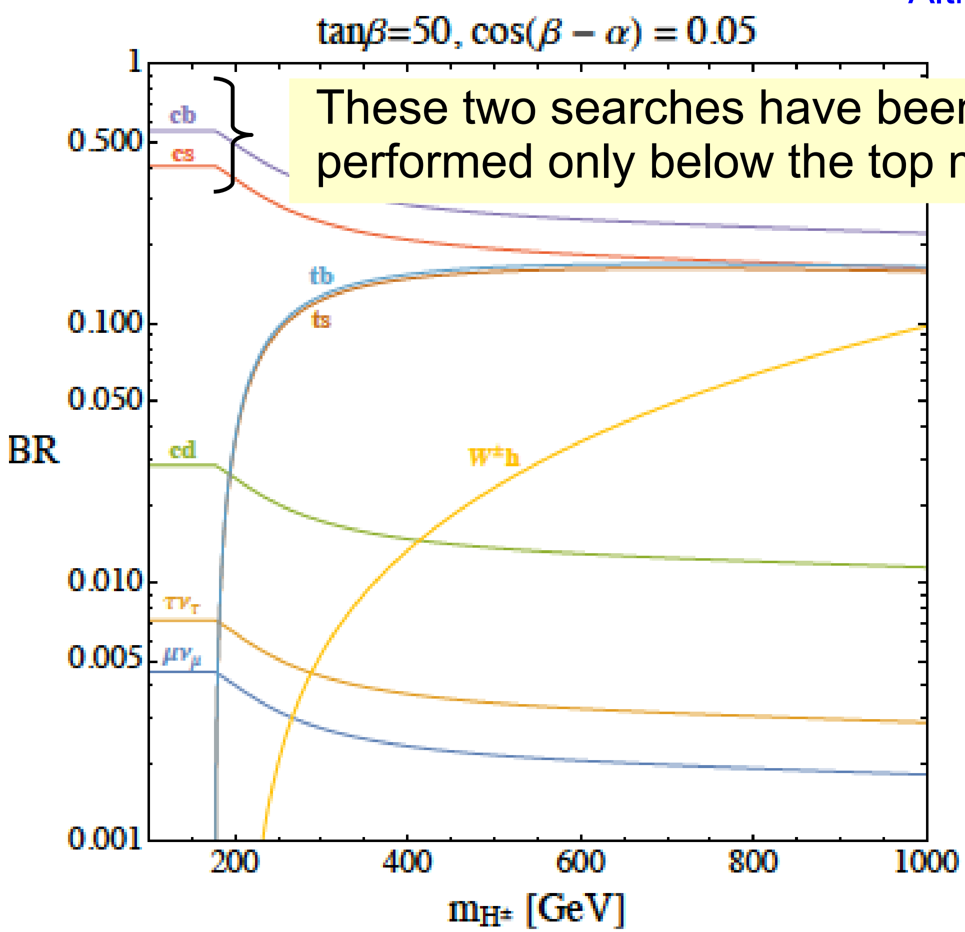
# Exotic charged Higgs signals

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




These two searches have been performed only below the top mass!

Di-jet and bottom-charm decay modes are the dominant ones

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

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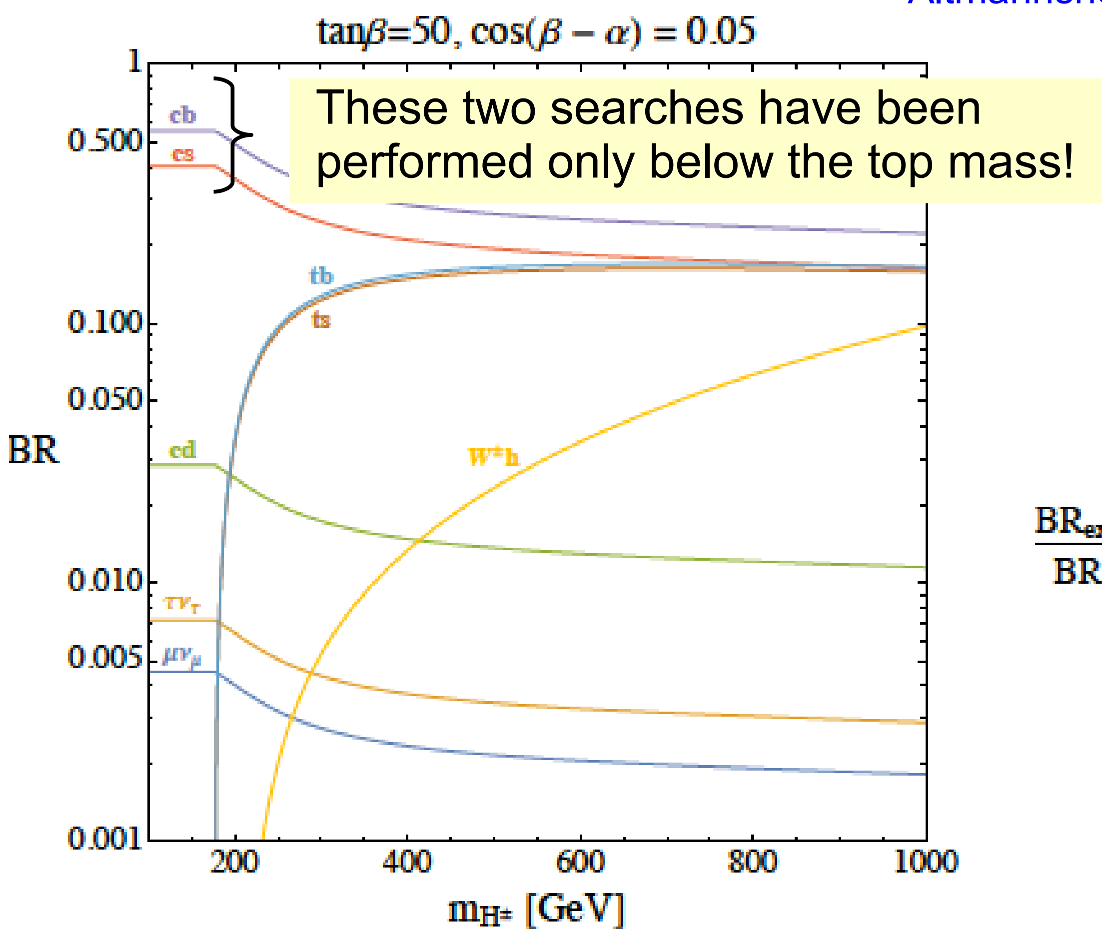
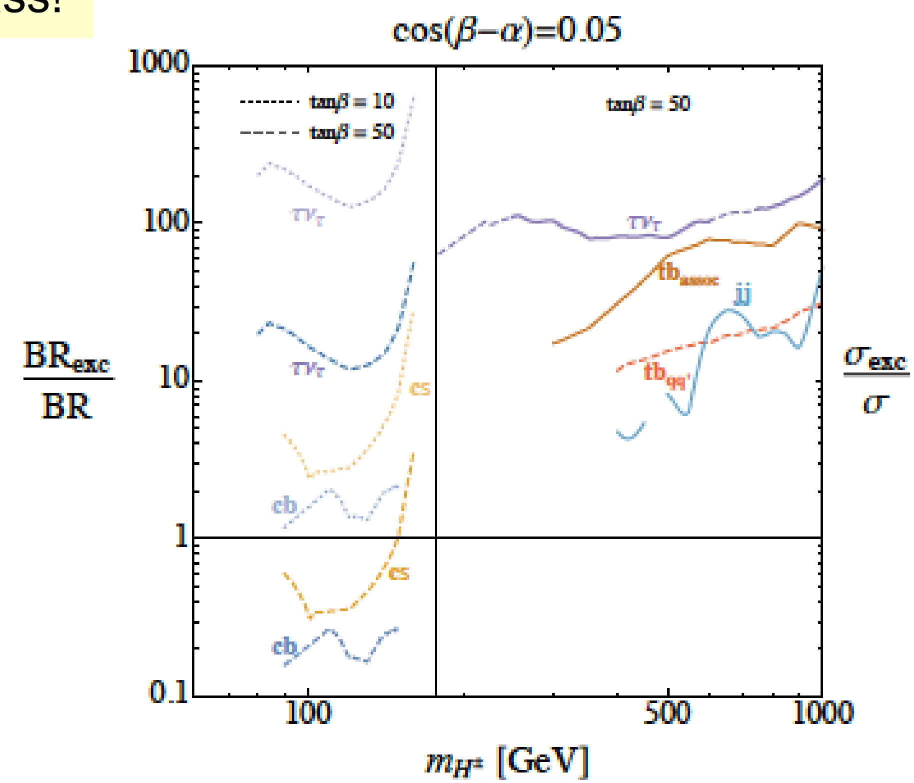



The present constraints are super-weak

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Future possible searches

$$pp \to tH^\pm, H^\pm \to cb$$
$$pp \to tH^\pm, H^\pm \to cs$$
$$pp \to tH^\pm, H^\pm \to \mu\nu$$

# Conclusions

Flavor physics offers a new perspective on searches for additional Higgs bosons

- Low energy flavor constraints leave room for structures beyond natural flavor conservation. Two examples:

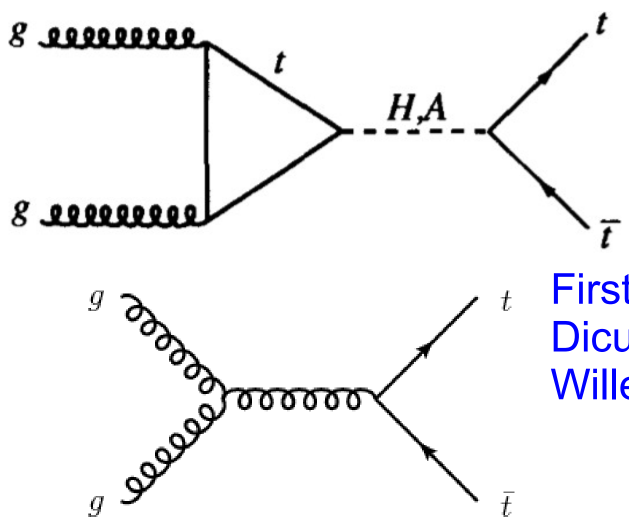
- Flavor-aligned 2HDMs
- Flavorful U(2) 2HDMs

- The additional Higgs phenomenology can drastically change

- Flavor conserving BRs with a novel hierarchy (even BR(ττ) ~ BR(μμ))
- New production modes. Interesting s-channel productions
- Smoking gun: heavy Higgs flavor violating decays

# Di-top resonances (1)

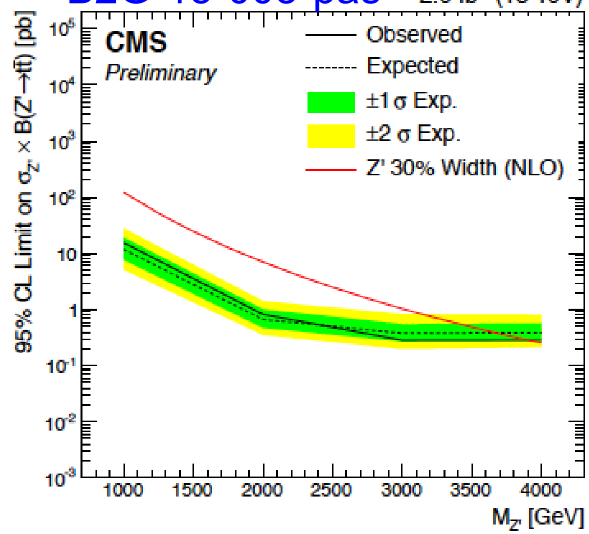
Large interference between



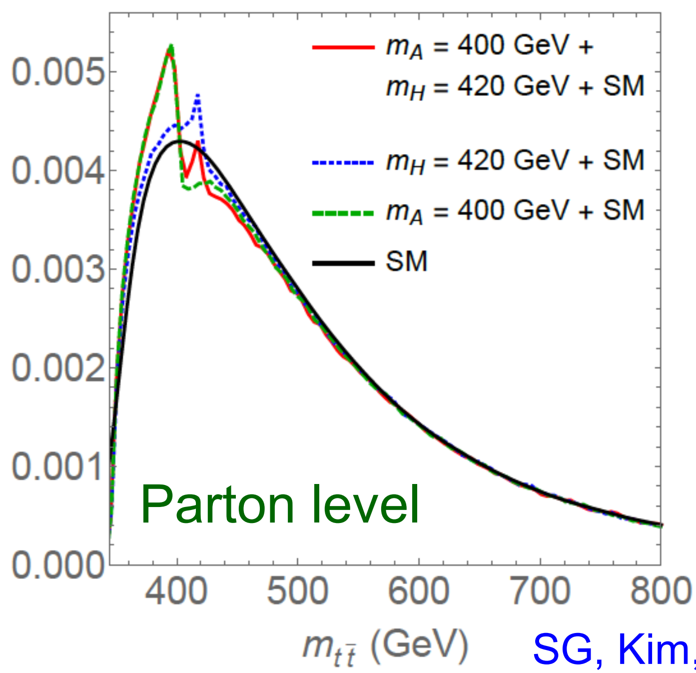

First computed by Dicus, Stange, Willenbrock '94

Not a simple rescaling of Z' di-top searches!

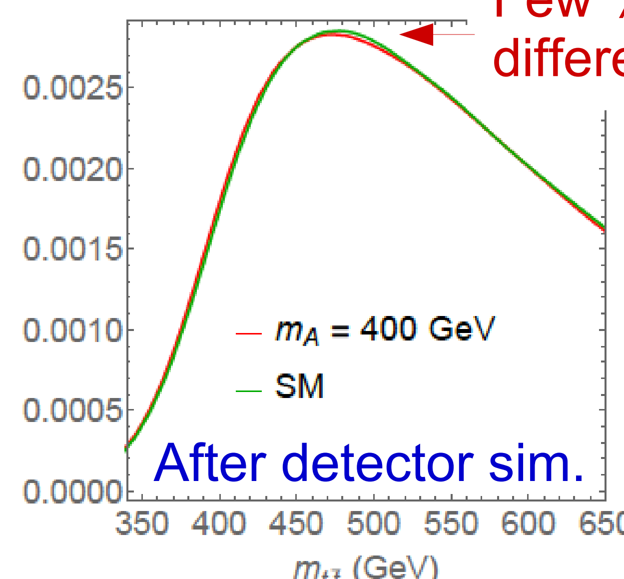
B2G-15-003-pas




Very nice:




But



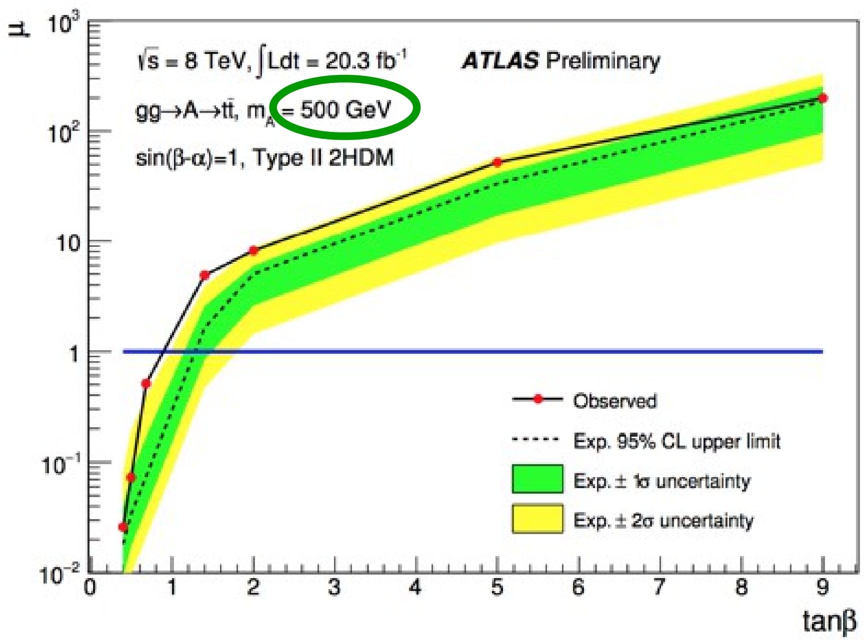

SG, Kim, Shah, Zurek, 1602.02782

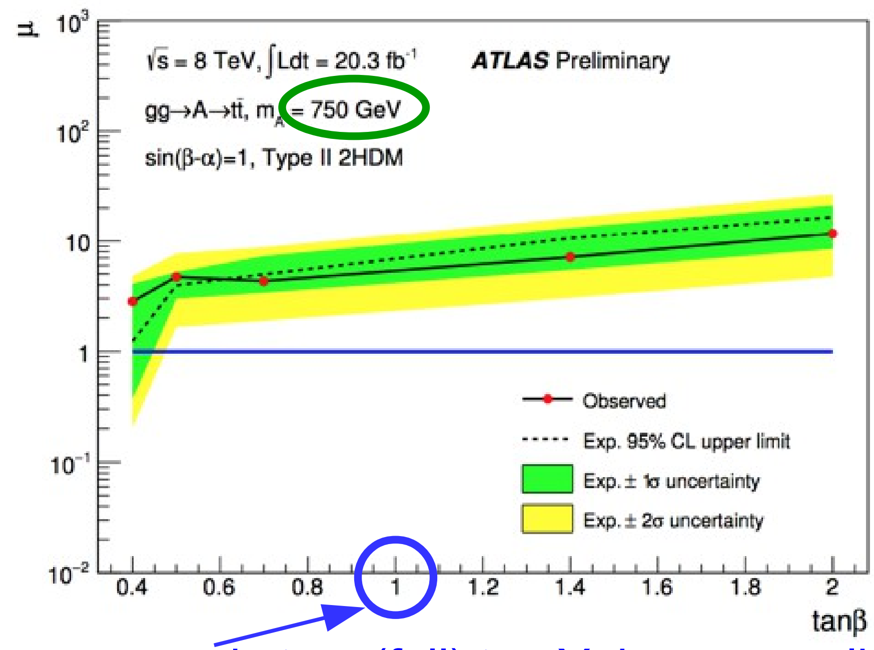
# Di-top resonances (2)

## ICHEP 2016: A first look by ATLAS

ATLAS-CONF-2016-073, 8 TeV data

Search performed for two mass points: 500 GeV and 750 GeV



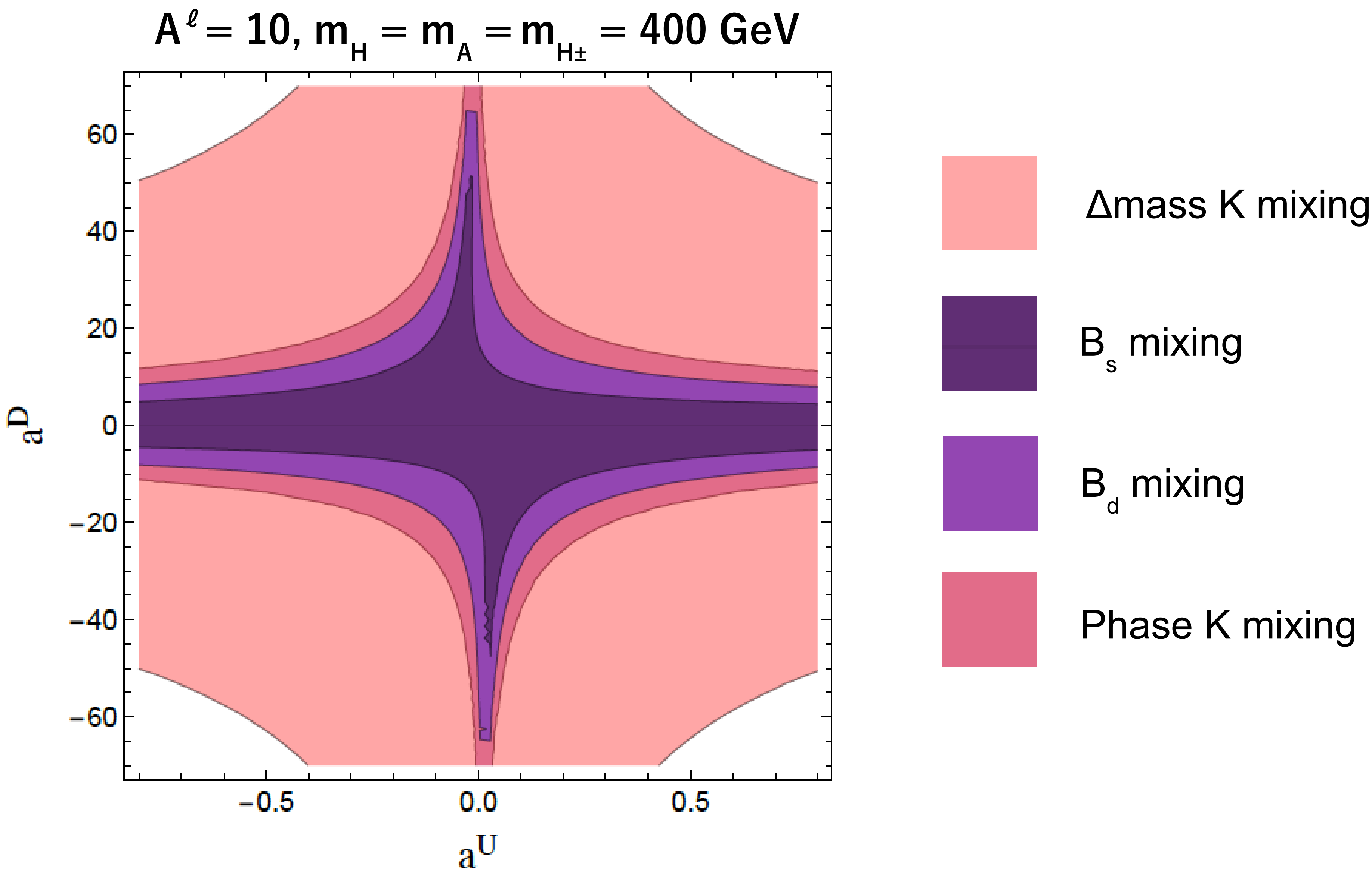

It corresponds to a (full) top Yukawa coupling of the heavy Higgs with tops

Great control of systematics thanks to data driven $t\bar{t}$ measurement of sidebands

Still far from probing our scenario (factor of ~500 too small)

# Meson mixing bounds on flavor-alignment

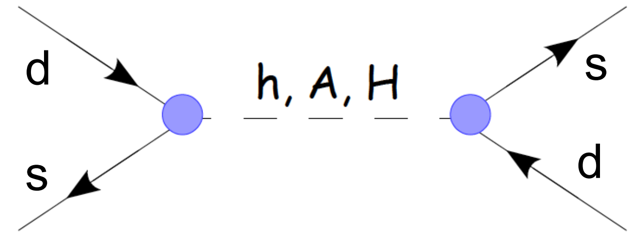
SG, Haber, Santos, 1703.05873



# Flavor constraints, flavorful U(2)

Flavor observables as meson mixings will set some (relatively weak) constraints

Example: K meson mixing




$$\mathcal{H}_{\rm eff} = C_2(\bar{d}_R s_L)^2 + \tilde{C}_2(\bar{d}_L s_R)^2 + C_4(\bar{d}_R s_L)(\bar{d}_L s_R)$$

$$C_2 = \frac{(m'_{sd})^2}{2v^2}\frac{1}{s_\beta^2 c_\beta^2}\left(\frac{c^2_{\beta-\alpha}}{m_h^2} + \frac{s^2_{\beta-\alpha}}{m_H^2} - \frac{1}{m_A^2}\right),$$

$$\tilde{C}_2 = \frac{(m'^*_{ds})^2}{2v^2}\frac{1}{s_\beta^2 c_\beta^2}\left(\frac{c^2_{\beta-\alpha}}{m_h^2} + \frac{s^2_{\beta-\alpha}}{m_H^2} - \frac{1}{m_A^2}\right),$$

$$C_4 = \frac{m'_{sd} m'^*_{ds}}{v^2}\frac{1}{s_\beta^2 c_\beta^2}\left(\frac{c^2_{\beta-\alpha}}{m_h^2} + \frac{s^2_{\beta-\alpha}}{m_H^2} + \frac{1}{m_A^2}\right).$$

$$m_{sd} \sim m_{ds} \sim \frac{m_d m_s}{m_b}$$

Numerical example:

Tanβ=30, cos(α-β)=0

$\Rightarrow$ $m_H(\sim m_A) \gtrsim 200$ GeV

(in presence of additional maximal phases constraints will be somewhat stronger)

Work in progress with W.Altmannshofer, D.Tuckler

# Flavor violating signatures, flavorful U(2)

**High energy**

Flavor violating rare top decays with branching ratios as large as

$$\mathrm{BR}(t \to ch) \sim |V_{cb}|^2 \sim 10^{-3}$$

$$\mathrm{BR}(t \to uh) \sim |V_{ub}|^2 \sim 10^{-5}$$

Target for the future of the LHC

Present bounds:

ATLAS 8 TeV (1509.06047)
BR(t → ch) < 0.46% (0.25%)
BR(t → uh) < 0.45% (0.29%)

CMS 8 TeV (CMS-PAS-TOP-14-020)
BR(t → ch) < 1.16% (0.89%)
BR(t → uh) < 1.92% (0.85%)

Paper in preparation...

**Low energy**

Lepton flavor violating rare B meson decays with sizable branching ratios

$$\mathrm{BR}(B_s \to \tau\mu) \sim \text{few} \times 10^{-7}$$

$$\mathrm{BR}(B \to K\tau\mu) \sim \text{few} \times 10^{-7}$$

$$\mathrm{BR}(B \to K^*\tau\mu) \sim \text{few} \times 10^{-7}$$

No searches yet.

LHCb and Belle II might be sensitive to the K and K* rates

$$\frac{\mathrm{BR}(\mathrm{B_s} \to \tau\mu)}{\mathrm{BR}(\mathrm{B_s} \to \mu\mu)_{\mathrm{SM}}} \propto \left(\frac{4\pi^2}{e^2}\right)^2 t_\beta^4 \frac{m_{B_s}^4}{m_A^4}$$

vs.

$$\frac{\mathrm{BR}(\mathrm{B_s} \to \mu\mu)}{\mathrm{BR}(\mathrm{B_s} \to \mu\mu)_{\mathrm{SM}}} \propto \left[1 + \frac{1}{C_{10}^{\mathrm{SM}}}\left(\frac{4\pi^2}{e^2}\right)\frac{m_{B_s}^2}{m_A^2}\left(t_\beta - \frac{m_\mu}{m_\tau}\frac{t_\beta^2+1}{t_\beta}\right)^2\right]^2$$

# Flavor diagonal couplings of the 125 GeV h

Comparing to other extended Higgs sectors...

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

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

# Flavor violating couplings of the Higgs boson

Fermion masses and the h couplings
cannot be diagonalized simultaneously

Example: $$\frac{y_{\mu\tau}}{y_\mu^{SM}} = -\frac{\Delta\mathcal{M}_{\mu\tau}}{m_\mu}\frac{\cos(\beta-\alpha)}{\sin\beta\cos\beta}$$ → It becomes larger at larger values of tanβ

Generic expectations for lepton flavor violating Higgs decays

$$BR(h\to\tau\mu) \sim \frac{m_\mu^2}{3m_b^2} \sim 10^{-3}$$

$$BR(h\to\tau e) \sim \frac{m_e^2}{3m_b^2} \sim 10^{-7}$$

$$BR(h\to\mu e) \sim \frac{m_e^2 m_\mu^2}{3m_\tau^2 m_b^2} \sim 10^{-10}$$

→ Reasonable target for the LHC.

Racall the present bounds:

| Process | CMS | ATLAS |
|---|---|---|
| H→τμ | BR<1.20% | BR<1.40% |
| H→τe | BR<0.69% | BR<1.04% |
| H→eμ | BR<0.048% | - |

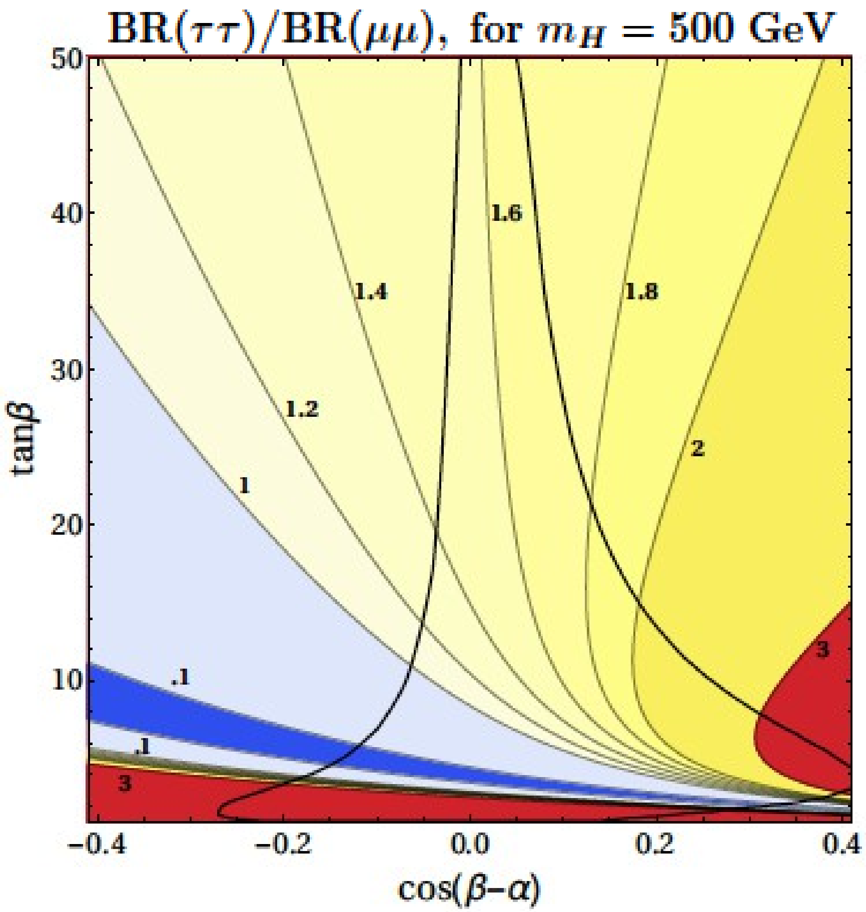
# Flavor diagonal couplings of the additional H

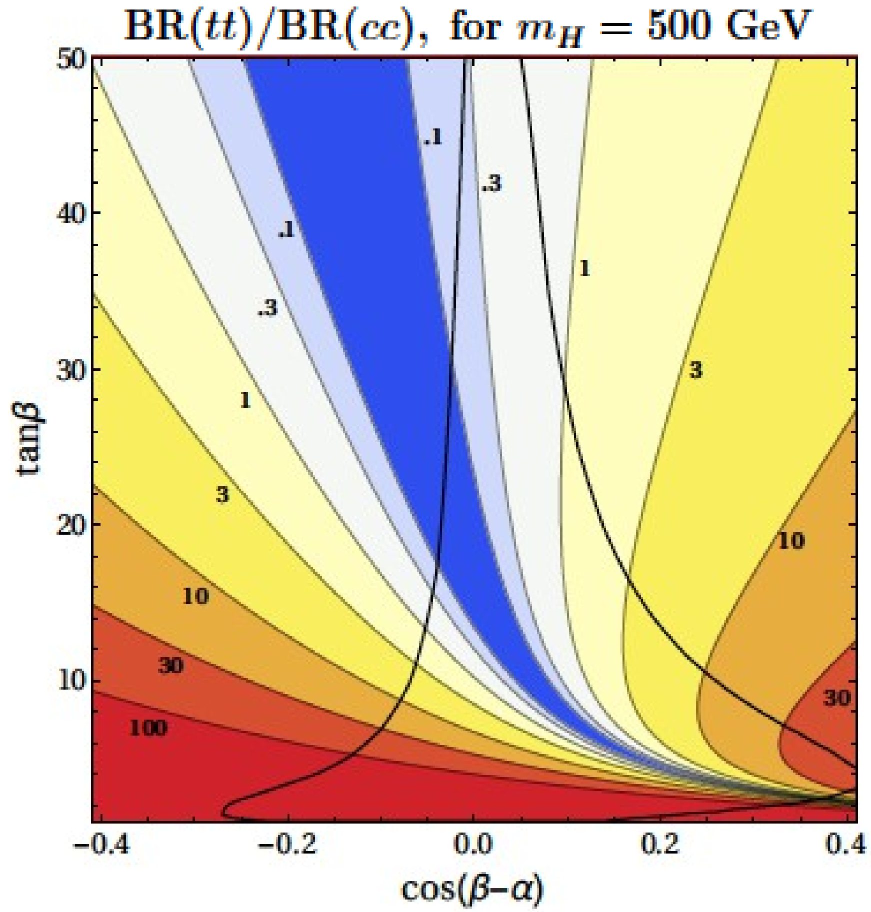
Comparing to other extended Higgs sectors...

| | W,Z $\kappa_V^H$ | 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 | $c_{\beta-\alpha}$ | $\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}, t_\beta\frac{c_\alpha}{s_\beta}, t_\beta\frac{c_\alpha}{s_\beta}$ | $\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}, t_\beta\frac{c_\alpha}{s_\beta}, t_\beta\frac{c_\alpha}{s_\beta}$ | $\frac{1}{t_\beta}\frac{s_\alpha}{c_\beta}, t_\beta\frac{c_\alpha}{s_\beta}, t_\beta\frac{c_\alpha}{s_\beta}$ |

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

# Different hierarchies of branching ratios




As opposed to ~ 300, in models with natural flavor conservation

As opposed to ~ $7 \times 10^4$, in models with natural flavor conservation