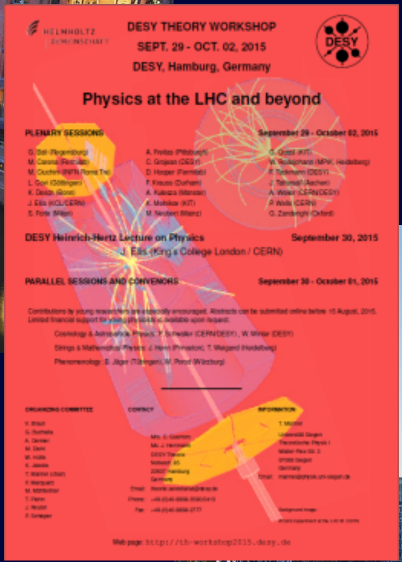
Flavour from the Electroweak Scale

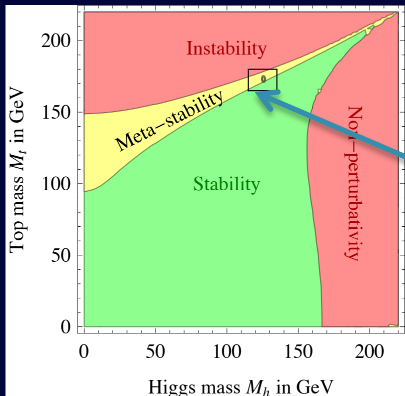


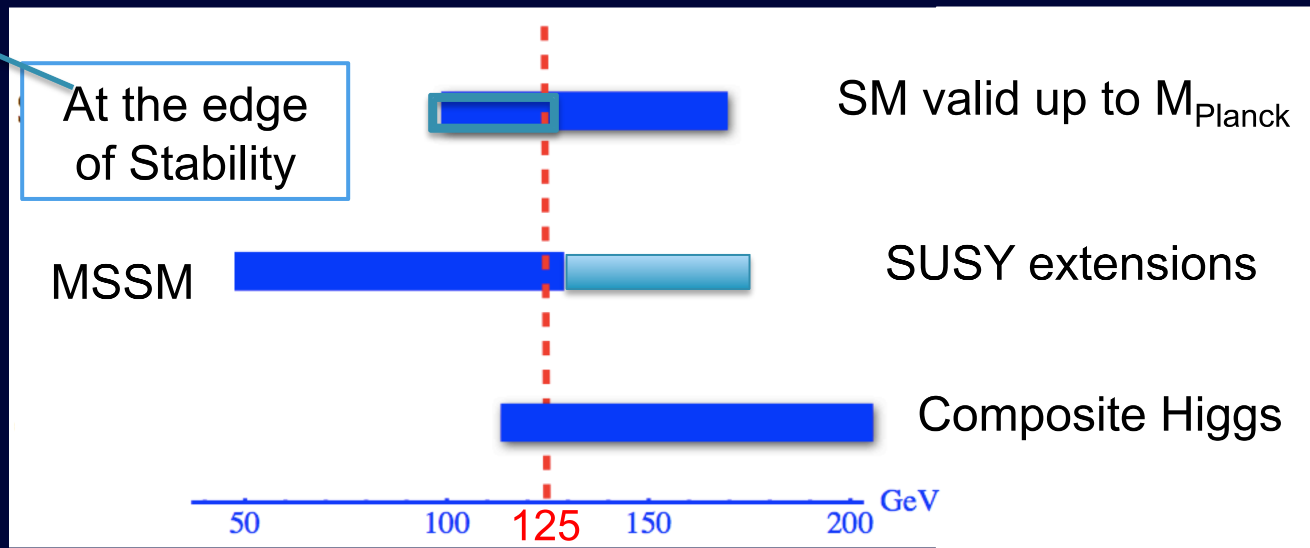
Marcela Carena
Fermilab and U. of Chicago

DESY THEORY WORKSHOP: **Physics at the LHC and beyond**
DESY, Hamburg, October 1st, 2015

Looking under the Higgs lamp-post:

What type of Higgs have we seen?





Also, back in fashion:
Twin Higgs and Mirror Worlds

This talk:

Use the Higgs to explain flavor from the electroweak scale

In collaboration with M. Bauer & K. Gemmler: arXiv:1506.01719 (JHEP) and work to appear

Theories of Flavor

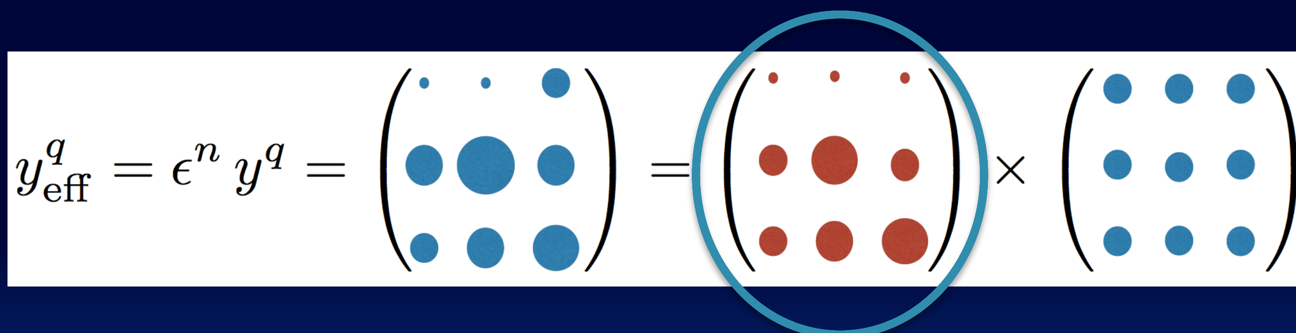
Yukawa interactions in terms of effective Yukawa couplings

$$\mathcal{L} = \mathbf{y_t \bar{Q}_L \tilde{H} t_R + y_b^{eff} \bar{Q}_L H b_R} + \ldots$$

Such that $\mathbf{m_t = y_t v/\sqrt{2}}$

$$\mathbf{m_b = y_b^{eff} v/\sqrt{2}} \longrightarrow \mathbf{y_q^{eff}} = \epsilon^{\mathbf{n}} \mathbf{y_q}$$

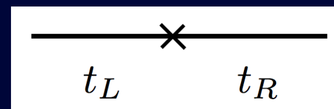
- y_t and all y_q are of order one
- Lighter quarks ➔ more powers of ε



How does this structure emerge?

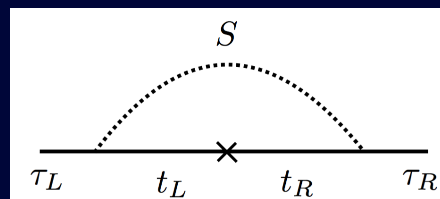
A theory of Flavor: a few basic possibilities

1) Loop Induced



$$m_t = y_t \frac{v}{\sqrt{2}}$$

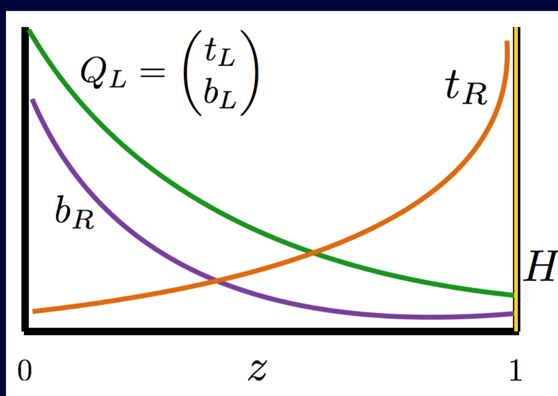
Georgi, Glashow ’72
Dobrescu, Fox ‘08



$$m_\tau \sim \frac{1}{16\pi^2} m_t \ln\left(\frac{m_s^2}{\Lambda^2}\right)$$

$$\epsilon \approx \frac{1}{16\pi^2} \ln\left(\frac{m_s^2}{\Lambda^2}\right)$$

2) Geometry Induced ➔ Warped Extra Dimension



$$H = \delta(z-1)\, \tilde{H}(x_\mu)$$

$$q = f_q(z)\, \tilde{q}(x_\mu)$$

$$f_q(1) \sim e^{c_q \ln\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)}$$

$$m_t = y_t\, f_{t_R}(1)\, f_{Q_L}(1) \frac{v}{\sqrt{2}}$$

$$m_b = y_b\, f_{b_R}(1)\, f_{Q_L}(1) \frac{v}{\sqrt{2}}$$

$$\epsilon^n \approx e^{(c_Q - c_q) \ln\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)}$$

Grossman, Neubert ‘99
Gherghetta, Pomarol ‘00

3) The Froggatt-Nielsen Mechanism

- Introduce a Flavor Symmetry   Frogatt, Nielsen '79

$$\mathcal{L}_{\mathrm{Yuk}} = y_t \bar{Q}_L \tilde{H} t_R + y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R + \cdots$$

- Quarks & scalars are charged under a global $U(1)_F$ flavor symmetry with flavor charge "a"

$$n_b a_S = a_{Q_L} - a_H - a_{b_R}$$

- New scalar singlet S obtains a vev: <S> = f
- Quarks Masses: $\mathbf{m_t = y_t \frac{v}{\sqrt{2}}}$ $\mathbf{m_b = y_b \frac{v}{\sqrt{2}} \left(\frac{f}{\Lambda}\right)^{n_b}}$
- Lighter quarks have more S insertions: $\mathbf{m_{q_i} = y_i \frac{v}{\sqrt{2}} \left(\frac{f}{\Lambda}\right)^{n_i}}$

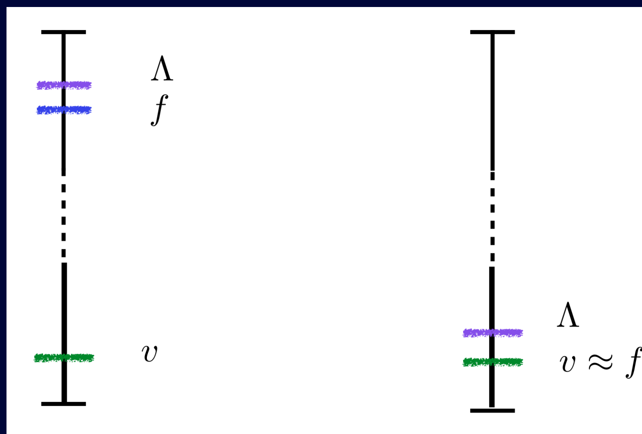
$$\mathbf{y_i^{eff}} = \epsilon^{\mathbf{n_i}} \mathbf{y_i} \quad \epsilon = f/\Lambda$$

Scales undetermined and hence can be arbitrarily high

How to define the scales? Can the Higgs play the role of the Flavon?

$$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H\, b_R \to y_b \left(\frac{H^\dagger H}{\Lambda^2}\right)^{n_b} \bar{Q}_L H\, b_R$$

Babu, Nandi ‘00, Giudice-Lebedev ‘08



Effective Yukawa coupling:

$$\mathbf{y_i^{eff}} = \left(\frac{\mathbf{v^2}}{\mathbf{2\Lambda^2}}\right)^{\mathbf{n_i}} \mathbf{y_i}$$

Suppression factor:

$$\epsilon = \mathbf{v^2/2\Lambda^2} \equiv \mathbf{m_b/m_t} \to \mathbf{\Lambda} \approx \mathbf{(5-6)v}$$

Flavour Scale is fixed by electroweak scale

Two Main Problems

- **The flavon is a flavor singlet**
- **The Higgs coupling to bottom quarks is too large**

$$\mathbf{g_{hbb}} \propto \mathbf{3\ m_b/v} \longrightarrow \frac{\mathbf{\Gamma(H \to b\bar{b})}}{\mathbf{\Gamma(H \to b\bar{b})_{SM}}} = \mathbf{9}$$

A Flavoured Higgs Sector

Bauer, MC, Gemmler '15

2HDFM with different flavor charges a_u and a_d for H_u and H_d , respectively.

Type II : $$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R \to y_b \left(\frac{H_u H_d}{\Lambda^2}\right)^{n_b} \bar{Q}_L H_d b_R$$ (Type II for $n_b \to 0$)

Type I : $$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R \to \tilde{y}_b \left(\frac{H_u^\dagger H_d^\dagger}{\Lambda^2}\right)^{n_b} \bar{Q}_L \tilde{H}_u b_R$$ (Type I for $n_b \to 0$)

We will consider the tau Yukawa operator to have the same flavor charge as the b quark

With effective Yukawa coupling: $$y_i^{\text{eff}} = \left(\frac{v_u v_d}{2\Lambda^2}\right)^{n_i} y_i$$

$$v^2 = v_u^2 + v_d^2$$

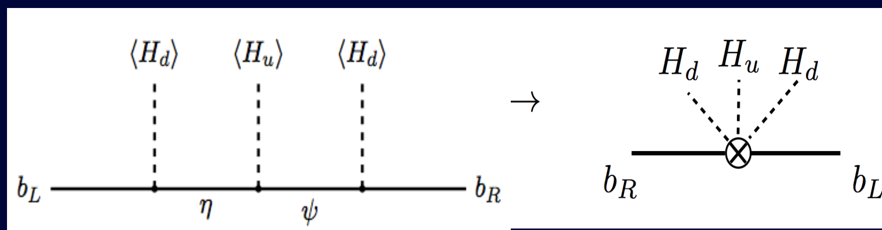
$$\tan\beta = v_u/v_d$$

And suppression factor $$\epsilon = v_u v_d/2\Lambda^2 \equiv m_b/m_t \to \Lambda \approx (5-6)v\left(\frac{\tan\beta}{1+\tan^2\beta}\right)^{1/2}$$

The value of $\Lambda \sim 4$ v $\sim$ 1TeV (maximal for tan $\beta = 1$)
and can be slightly larger depending on the specific UV completion

A Simple UV completion Sector: Vector Fermions

The value of $\Lambda \sim 4$ v $\sim$ 1TeV (maximal for tan $\beta = 1$)
and can be slightly larger depending on the specific UV completion

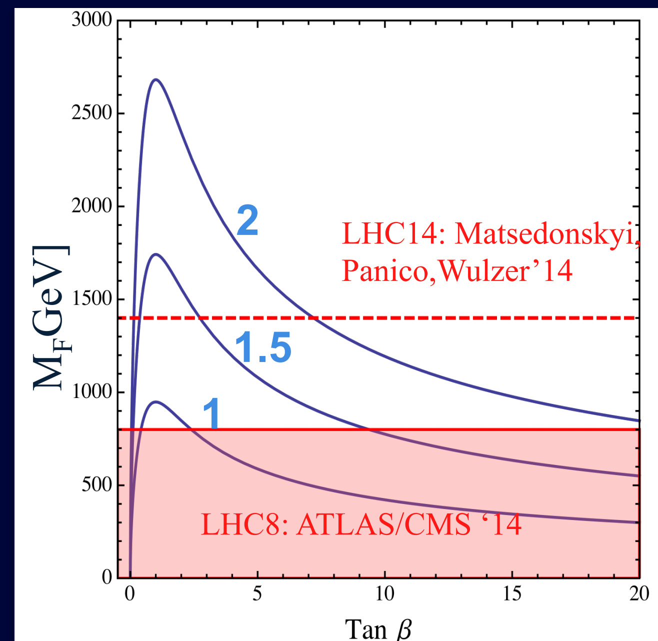


e.g.

$$\mathcal{L}_{\rm UV} = y_1\, \bar{b}_L\, H_d\, \eta_R + y_2\, \bar{\eta}_R\, H_u\, \psi_L + y_3\, \bar{\psi}_L\, H_d\, b_R \; + M_\eta \bar{\eta}_L \eta_R + M_\psi \bar{\psi}_L \psi_R$$

$$\mathcal{L}_{EFT} = Y_b^{\rm eff}\, \bar{b}_L\, H_d\, b_R$$ with $$Y_b^{\rm eff} \equiv \varepsilon\, y^d = \frac{y_1\, y_2\, y_3}{M_\eta\, M_\psi}\, \frac{v_u v_d}{2}$$

$\longrightarrow$ We define: $\boxed{\overline{M} \equiv \sqrt{M_\eta M_\psi}}$ $\boxed{\bar{y} = (y_1 y_2 y_3)^{1/3}}$



Two Higgs Doublet Flavor Model Type II

$$\mathcal{L}^{\mathrm{II}}_{\mathrm{Yuk}} = y^u_{ij}\left(\frac{H_u H_d}{\Lambda^2}\right)^{a_i - a_{u_j} - a_{H_u}} \bar{Q}_i H_u u_{Rj} + y^d_{ij}\left(\frac{H_u H_d}{\Lambda^2}\right)^{a_i - a_{d_j} - a_{H_d}} \bar{Q}_i H_d d_{Rj} + h.c.$$

After rotation to mass eigenstates, we obtain the flavor structure from fixing the flavor charges

$$\begin{aligned} a_{H_u} &= 1\,, & a_1 &= 2\,, & a_u &= -2\,, & a_d &= -1 \\ a_{H_d} &= 0\,, & a_2 &= 2\,, & a_c &= 0\,, & a_s &= 0 \\ & & a_3 &= 1\,, & a_t &= 0\,, & a_b &= 0 \end{aligned}$$

$\rightarrow$

$$m_t \approx \frac{v_u}{\sqrt{2}}\,, \quad \frac{m_b}{m_t} \approx \frac{m_c}{m_t} \approx \varepsilon^1\,, \quad \frac{m_s}{m_t} \approx \varepsilon^2\,, \quad \frac{m_d}{m_t} \approx \frac{m_u}{m_t} \approx \varepsilon^3$$

$$(V_{\mathrm{CKM}})_{12} \approx \varepsilon^0\,, \qquad (V_{\mathrm{CKM}})_{13} \approx (V_{\mathrm{CKM}})_{23} \approx \varepsilon^1$$

The Higgs-quark couplings can then be computed: e.g. for the light (SM-like) Higgs

$$g_{hu_iu_j} = \left(\frac{m_u}{v}\right)_{ij} \delta_{ij}\left[\frac{c_\alpha}{s_\beta} - a_{H_u} f(\alpha,\beta)\right] + f(\alpha,\beta)\boxed{\left[\mathcal{Q}^u_{ij}\left(\frac{m_u}{v}\right)_{jj} - \left(\frac{m_u}{v}\right)_{ii} \mathcal{U}_{ij}\right]}$$

$$g_{hd_id_j} = \left(\frac{m_d}{v}\right)_{ij} \delta_{ij}\left[-\frac{s_\alpha}{c_\beta} - a_{H_d} f(\alpha,\beta)\right] + f(\alpha,\beta\boxed{\left[\mathcal{Q}^d_{ij}\left(\frac{m_d}{v}\right)_{jj} - \left(\frac{m_d}{v}\right)_{ii} \mathcal{D}_{ij}\right]}$$

Universal function
$$f(\alpha,\beta) = \frac{c_\alpha}{s_\beta} - \frac{s_\alpha}{c_\beta} = c_{\beta-\alpha}\left(\frac{1}{t_\beta} - t_\beta\right) + 2s_{\beta-\alpha}$$

Process dependent factors

Similar functions for 1) for the Heavy CP-even Higgs replacing cα → sα & -sα → cα
2) for the CP-odd Higgs by subsequently multiplying by i and replacing cα → sβ & sα → cβ
3) Charged Higgs boson couplings are independent of flavor charges; Same as in Type II

Many interesting, measurable effects can probe this idea

Modified quark-Higgs couplings ⟷ Precision measurements/Global Higgs Fit

FCNCs at tree-level ⟷ Numerous Flavour constraints

Direct collider probes of heavy scalars ⟷ ATLAS and CMS searches

Propose Benchmark scenarios to probe the model

Lightest Higgs Boson Couplings

Couplings are re-scaled $g_{hVV} = \kappa_V \, g_{hVV}^{\rm SM} \quad g_{hff} = \kappa_f \, g_{hff}^{\rm SM}$

- Higgs couplings to W and Z → fixed by gauge symmetry $\kappa_V = \sin(\beta - \alpha)$
- Higgs coupling to the top quark $\kappa_t = \dfrac{\cos(\beta-\alpha)}{\tan\beta} + \sin(\beta-\alpha)$

Higgs Production (at leading order) equivalent to a 2HDM type II

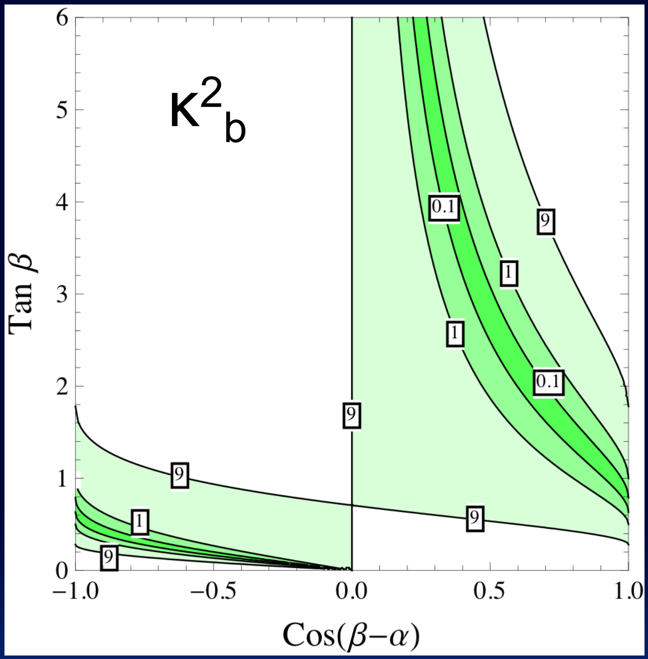
- Higgs coupling to the bottom (& charm) quarks

$$\kappa_b = 3\sin(\beta-\alpha) + \cos(\beta-\alpha)\left(\frac{1}{\tan\beta} - 2\tan\beta\right)$$

→VERY different behavior:

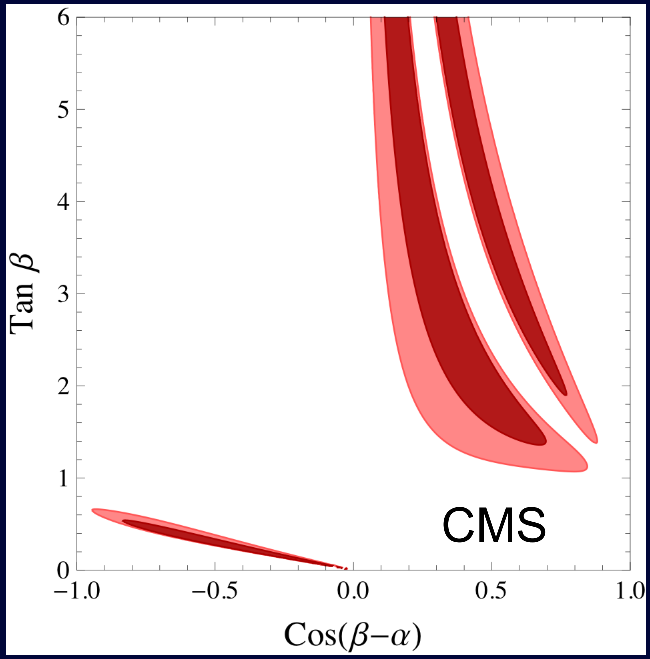
~ modified b-quark coupling strongly affects total width ~

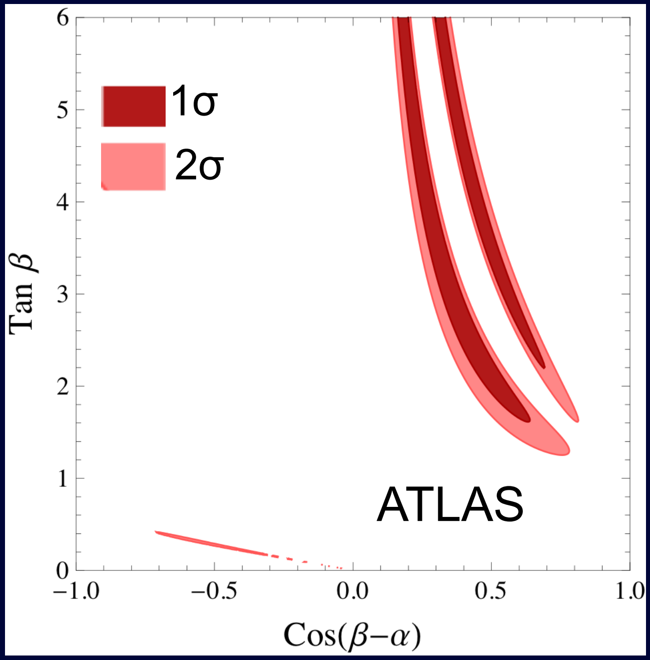
- Values of order one or below for sizeable values of $c_{\beta\text{-}\alpha}$
- Two acceptable branches with positive and negative values of the bottom Yukawa coupling



Babu/Nandi-Giudice-Lebedev limit recovered in the Decoupling/Alignment limit ($c_{\beta\text{-}\alpha}$ → 0)

Lightest Higgs Global Fit to ATLAS and CMS data





Decay Mode	Production Channels $\sigma_{gg\to h}, \sigma_{t\bar{t}\to h}$	Production Channels $\sigma_{VBF}, \sigma_{VH}$	Experiment
$h \to WW^*$	$\mu_W = 1.02^{+0.29}_{-0.26}$ [17] $\mu_W \simeq 0.75 \pm 0.35$ [18]	$\mu_W = 1.27^{+0.53}_{-0.45}$ [17] $\mu_W \simeq 0.7 \pm 0.85$ [18]	ATLAS CMS
$h \to ZZ^*$	$\mu_Z = 1.7^{+0.5}_{-0.4}$ [19] $\mu_Z = 0.8^{+0.46}_{-0.36}$ [20]	$\mu_Z = 0.3^{+1.6}_{-0.9}$ [19] $\mu_Z = 1.7^{+2.2}_{-2.1}$ [20]	ATLAS CMS
$h \to \gamma\gamma$	$\mu_\gamma = 1.32 \pm 0.38$ [21] $\mu_\gamma = 1.13^{+0.37}_{-0.31}$ [22]	$\mu_\gamma = 0.8 \pm 0.7$ [21] $\mu_\gamma = 1.16^{+0.63}_{-0.58}$ [22]	ATLAS CMS
$h \to \bar{b}b$	$\mu_b = 1.5 \pm 1.1$ [23] $\mu_b = 0.67^{+1.35}_{-1.33}$ [25]	$\mu_b = 0.52 \pm 0.32 \pm 0.24$ [24] $\mu_b = 1.0 \pm 0.5$ [26]	ATLAS CMS
$h \to \tau\tau$	$\mu_\tau = 2.0 \pm 0.8^{+1.2}_{-0.8} \pm 0.3$ [27] $\mu_\tau \simeq 0.5^{+0.8}_{-0.7}$ [28]	$\mu_\tau = 1.24^{+0.49}_{-0.45}{}^{+0.31}_{-0.29} \pm 0.08$ [27] $\mu_\tau \simeq 1.1^{+0.7}_{-0.5}$ [28]	ATLAS CMS

$$\mu_X = \frac{\sigma_{\rm prod}}{\sigma_{\rm prod}^{\rm SM}} \frac{\Gamma_{h\to X}}{\Gamma_{h\to X}^{\rm SM}} \frac{\Gamma_{h,\,\rm tot}^{\rm SM}}{\Gamma_h}.$$

The global fit accomodates tanβ of O(1)
for sizable values of cos(β-α)
away from alignment/decoupling

We assumed $\kappa_b \sim \kappa_\tau$

Flavor Changing Higgs Couplings

Down type quarks couple to the neutral Higgs bosons: Φ = h,H,A

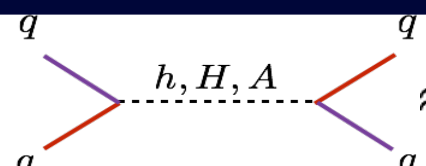
$$g_{\phi d_i d_j} = g_d^{\phi}(\alpha,\beta)\left(\frac{m_d}{v}\right)_{ij}\delta_{ij} + f^{\phi}(\alpha,\beta)\left[\mathcal{Q}^d_{ij}\left(\frac{m_d}{v}\right)_{jj} - \left(\frac{m_d}{v}\right)_{ii}\mathcal{D}_{ij}\right]$$

recall: functions $f^{\Phi}(\alpha, \beta)$ are flavor universal

$$\mathcal{Q}^d \sim \begin{pmatrix} 2 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & 2 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix} \qquad \mathcal{D} \sim \begin{pmatrix} -1 & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon^2 & \varepsilon^2 \\ \varepsilon & \varepsilon^2 & \varepsilon^2 \end{pmatrix} \longrightarrow \mathcal{M} \sim \begin{pmatrix} x & ds & db \\ sd & x & sb \\ bd & bs & x \end{pmatrix}$$

Different flavors couple with different powers of ε & quark masses to the Higgs bosons

These couplings are importantly constrained from neutral meson oscillations
➔ they appear in Higgs mediated tree-level processes



$$\approx \boxed{\varepsilon^X \frac{m_q^2}{v^2}} \left\{ \frac{f^h(\alpha,\beta)^2}{m_h^2} + \frac{F^H(\alpha,\beta)^2}{M_H^2} \pm \frac{F^A(\alpha,\beta)^2}{M_A^2} \right\}$$

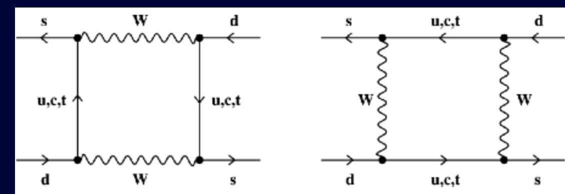
Process dependent factors c_i / v^2

Universal functions

Constraints from Meson-Antimeson Mixing

Mesons are very sensitive to New Physics since they are governed by box-diagrams in the SM

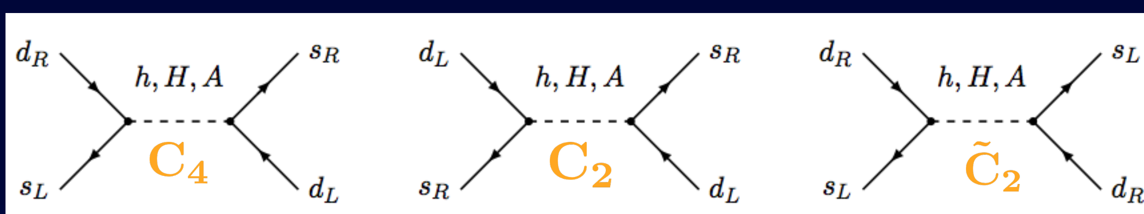
For example K-mesons $K^0 = (\bar{s}d)\,,\ \bar{K}^0 = (s\bar{d})$



Contributions from Higgs mediated FCNCs can be captured by

$$\mathcal{H}_{\rm NP}^{\Delta S=2} = C_1^{sd}\,(\bar{s}_L\,\gamma_\mu\,d_L)^2 + \tilde{C}_1^{sd}\,(\bar{s}_R\,\gamma_\mu\,d_R)^2 + C_2^{sd}\,(\bar{s}_R\,d_L)^2 + \tilde{C}_2^{sd}\,(\bar{s}_L\,d_R)^2$$
$$+\,C_4^{sd}\,(\bar{s}_R\,d_L)\,(\bar{s}_L\,d_R) + C_5^{sd}\,(\bar{s}_L\,\gamma_\mu\,d_L)\,(\bar{s}_R\,\gamma^\mu d_R) + h.c.\,.$$

With tree-level contributions to the Wilson coefficients given by



$$C_2^{sd} = -\frac{(g^*_{hds})^2}{m_h^2} - \frac{(g^*_{Hds})^2}{M_H^2} - \frac{(g^*_{Ads})^2}{M_A^2}\,,$$
$$\tilde{C}_2^{sd} = -\frac{g^2_{hsd}}{m_h^2} - \frac{g^2_{Hsd}}{M_H^2} - \frac{g^2_{Asd}}{M_A^2}\,,$$
$$C_4^{sd} = -\frac{g_{hsd}\,g^*_{hds}}{2m_h^2} - \frac{g_{Hsd}\,g^*_{Hds}}{2M_H^2} - \frac{g_{Asd}\,g^*_{Ads}}{2M_A^2}\,.$$

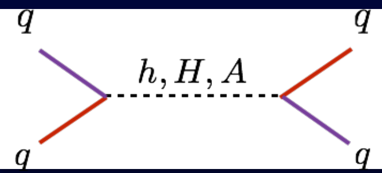
Similar contributions/expressions hold for $\mathrm{B_s} - \bar{\mathrm{B}}_\mathrm{s}$ mixing, with sd → bs, $\mathrm{B_d} - \bar{\mathrm{B}}_\mathrm{d}$ mixing, with sd → bd and $\mathrm{D} - \bar{\mathrm{D}}$ mixing with sd → uc

Constraints from Meson-Antimeson Mixing (cont'd)

The Froggatt-Nielsen mechanism induces an additional suppression mechanism of flavour off diagonal couplings prop. to fermion masses and powers of the parameter ε

➔ The relative size of Wilson coefficients depends strongly on the flavor structure

$$\mathcal{H}_{\rm NP}^{\Delta S=2} = C_1^{sd}\,(\bar s_L\,\gamma_\mu\,d_L)^2 + \tilde C_1^{sd}\,(\bar s_R\,\gamma_\mu\,d_R)^2 + C_2^{sd}\,(\bar s_R\,d_L)^2 + \tilde C_2^{sd}\,(\bar s_L\,d_R)^2 + C_4^{sd}\,(\bar s_R\,d_L)\,(\bar s_L\,d_R) + C_5^{sd}\,(\bar s_L\,\gamma_\mu\,d_L)\,(\bar s_R\,\gamma^\mu d_R) + h.c.\,.$$



$$\approx \frac{c_i}{v^2}\left\{\frac{f^h(\alpha,\beta)^2}{m_h^2} + \frac{F^H(\alpha,\beta)^2}{M_h^2} \pm \frac{F^A(\alpha,\beta)^2}{M_A^2}\right\}$$

Flavor specific part of Wilson coefficients for flavor charges tailored to explain quark mass hierarchy and CKM mixing angles

$\Delta F = 2$	c_2^{ij}	$\tilde c_2^{ij}$	c_4^{ij}
sd	$\varepsilon^4\,m_s^2$	$\varepsilon^2\,m_s^2$	$\varepsilon^3\,m_s^2$
bd	$\varepsilon^2\,m_b^2$	$\varepsilon^2\,m_b^2$	$\varepsilon^2\,m_b^2$
bs	$\varepsilon^2\,m_b^2$	$\varepsilon^4\,m_b^2$	$\varepsilon^3\,m_b^2$
uc	$\varepsilon^4\,m_c^2$	$\varepsilon^4\,m_c^2$	$\varepsilon^4\,m_c^2$

$\mathbf{K} - \bar{\mathbf{K}}$ Mixing :

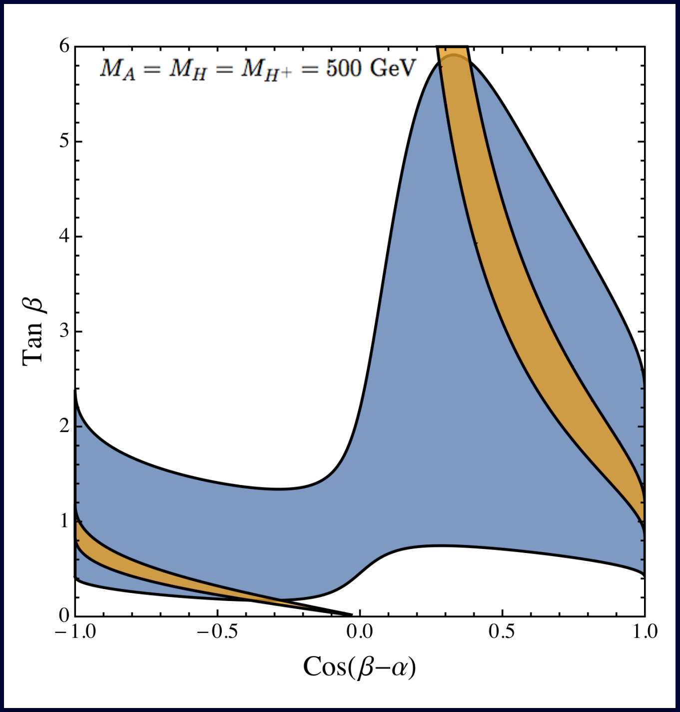
Largest coefficient is $\tilde{\mathbf{C}}_2^{\mathbf{sd}}$

$$\tilde{C}_2^{sd} = -\frac{\tilde{c}_2^{sd}}{v^2}\left\{\frac{f(\alpha,\beta)^2}{m_h^2} + \frac{F(\alpha,\beta)^2}{M_H^2} - \left(t_\beta + \frac{1}{t_\beta}\right)^2 \frac{1}{M_A^2}\right\}$$
$$\approx \frac{-10^{-15}}{\mathrm{GeV}^2}\left\{f(\alpha,\beta)^2 + F(\alpha,\beta)^2 \frac{m_h^2}{M_H^2} - \left(t_\beta + \frac{1}{t_\beta}\right)^2 \frac{m_h^2}{M_A^2}\right\}$$

Similar expression for $\mathbf{C}_2^{\mathbf{sd}}$, but with extra ε^2 suppression due to $\tilde{\mathbf{c}}_2^{\mathbf{sd}} \to \mathbf{c}_2^{\mathbf{sd}}$

$\mathbf{C}_4^{\mathbf{sd}}$ is ε suppressed with respect to $\tilde{\mathbf{C}}_2^{\mathbf{sd}}$ but has constructive interference (also RG running relevant)

$$C_4^{sd} = -\frac{c_4^{sd}}{v^2}\left\{\frac{f(\alpha,\beta)^2}{m_h^2} + \frac{F(\alpha,\beta)^2}{M_H^2} + \left(t_\beta + \frac{1}{t_\beta}\right)^2 \frac{1}{M_A^2}\right\}$$
$$\approx \frac{-1.7\times 10^{-17}}{\mathrm{GeV}^2}\left\{f(\alpha,\beta)^2 + F(\alpha,\beta)^2 \frac{m_h^2}{M_H^2} + \left(t_\beta + \frac{1}{t_\beta}\right)^2 \frac{m_h^2}{M_A^2}\right\}$$



Tree-level contributions

$|\tilde{C}_2^{sd}| \leq 10^{-16}/\mathrm{GeV}^2$ (orange)

$|C_4^{sd}| \leq 7\times 10^{-17}/\mathrm{GeV}^2$ (blue)

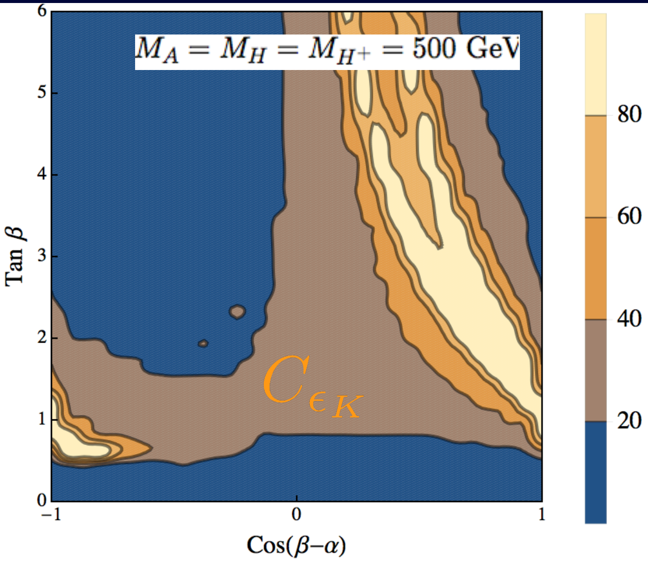
$\mathbf{K} - \bar{\mathbf{K}}$ Mixing :

Given $$C_{\epsilon_K} = \frac{\mathrm{Im}\,\langle K^0|\mathcal{H}^{\Delta S=2}_{\rm full}|\bar{K}^0\rangle}{\mathrm{Im}\,\langle K^0|\mathcal{H}^{\Delta S=2}_{\rm SM}|\bar{K}^0\rangle}$$

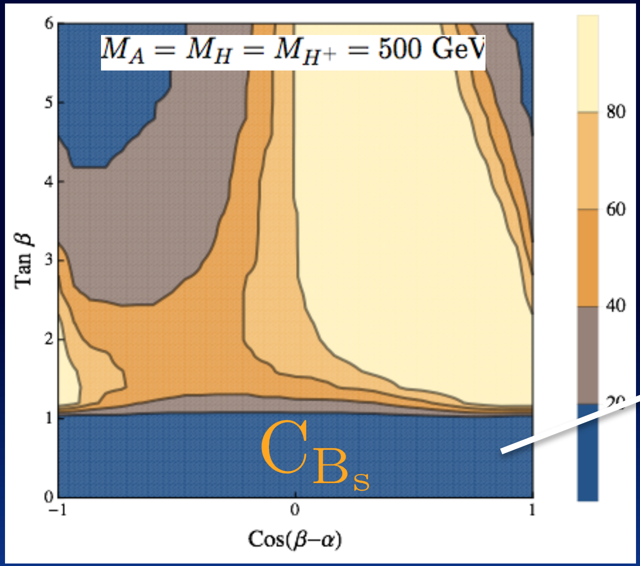
Generate randomly a sample set of points of $|y_{ij}^{u,d}| \rightarrow [0.5, 1.5]$ with arbitrary phases & require SM quark masses and CKM param. to be within 2 σ

Percentage of sample points that reproduce within 2 σ

$C^{\rm exp}_{\epsilon_K} = 1.05^{+0.36}_{-0.28}$ @ 95% CL (UTfit value) →

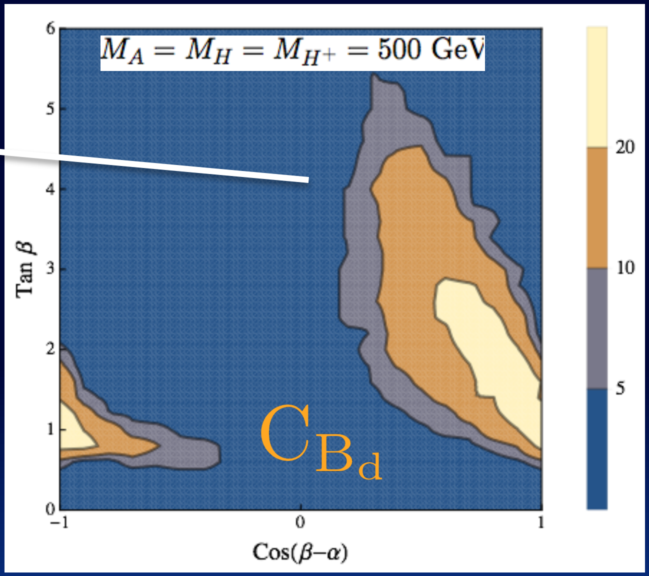


Analogously for $\mathrm{B_{d,s}} - \bar{\mathrm{B}}_{\mathrm{d,s}}$ Mixing :



Strongest upper bound on tan β

strongest lower bound on tan β



strongest bound, O(10)% fine-tuning required

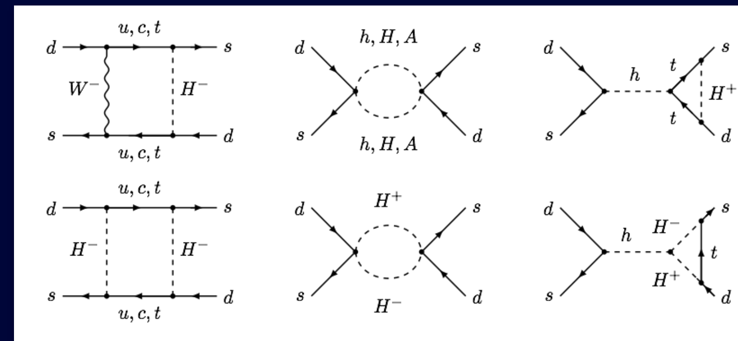
- **Loop Contributions:** most relevant are charged Higgs box diagrams for small tanβ in the Bs-system

- **Contributions to rare decays** depend on the lepton flavor sector

- **Bounds from b ➔ sγ** constrain the mass of the charged scalar

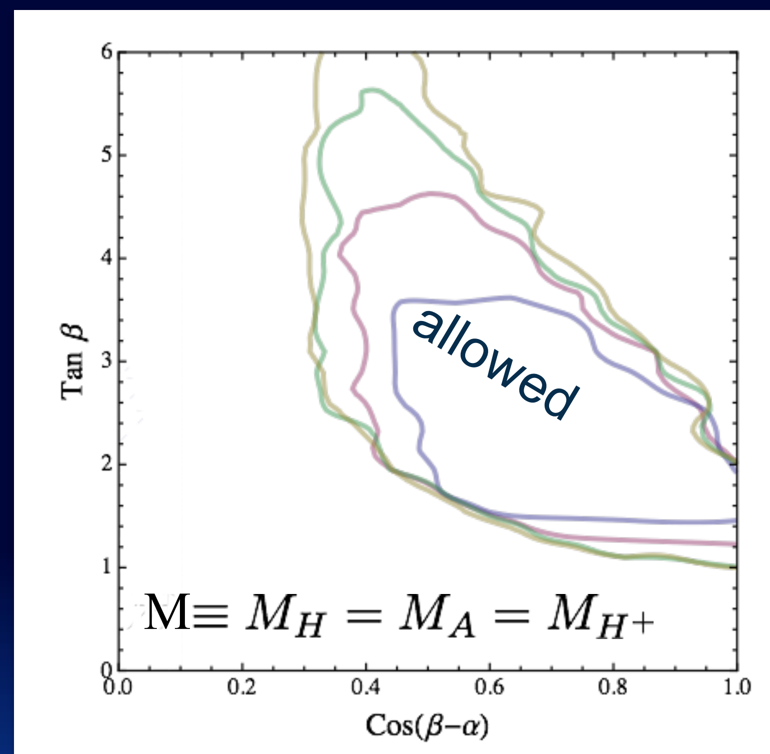
$$M_{H^\pm} \gtrsim 358\,(480)\ \mathrm{GeV} \quad @\,99\%(95\%)\ \mathrm{CL}$$

Misiak et al. '15

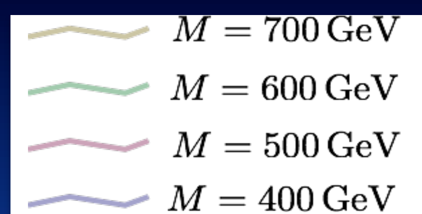


Combined Flavour Bounds ➔

Restricted Mass Range for the additional Higgs Bosons



10% Contours

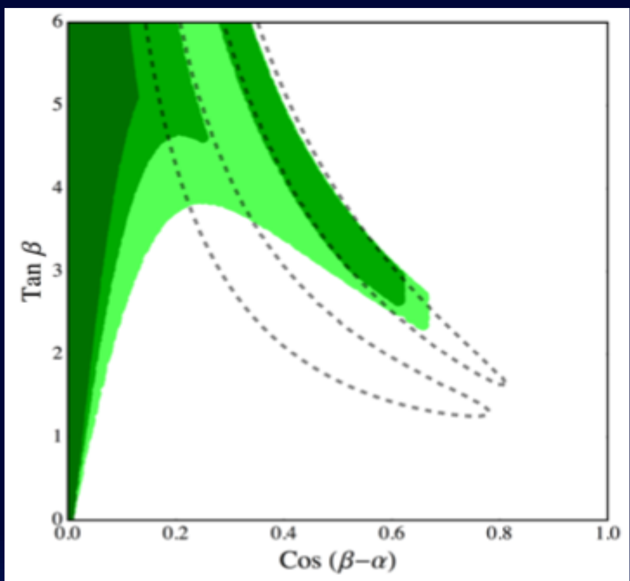


Mass Range for the Additional Higgs Bosons

- The global Higgs fit (and Flavour bounds) demand large cos(β-α)
- Flavour bounds demand heavy extra scalars

Bounds from Perturbativity, Unitarity, and Electroweak Precision Measurements

Degenerate masses $M_A \approx M_H \approx M_{H^+}$

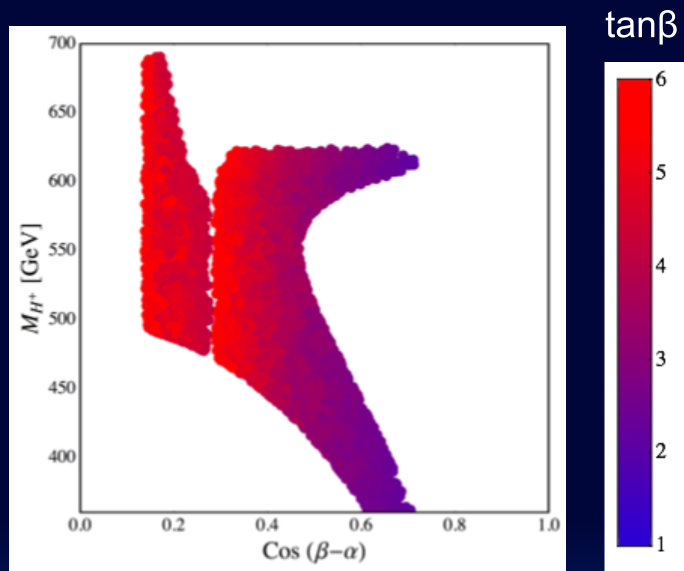


M= 700 GeV

M= 600 GeV

M= 500 GeV

2σ global fit to ATLAS data



A lighter Charged Higgs

$M_{A,H} - M_{H^+} \gtrsim 100$ GeV

Preferred by perturbativity up to a few TeV

Additional Higgs Boson Couplings and Total Width

Couplings of H and A to gauge bosons and third generation quarks normalized to the SM

$$\kappa_t^H = c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}\,, \qquad \kappa_b^H = 3c_{\beta-\alpha} + s_{\beta-\alpha}\left(2t_\beta - \frac{1}{t_\beta}\right)$$

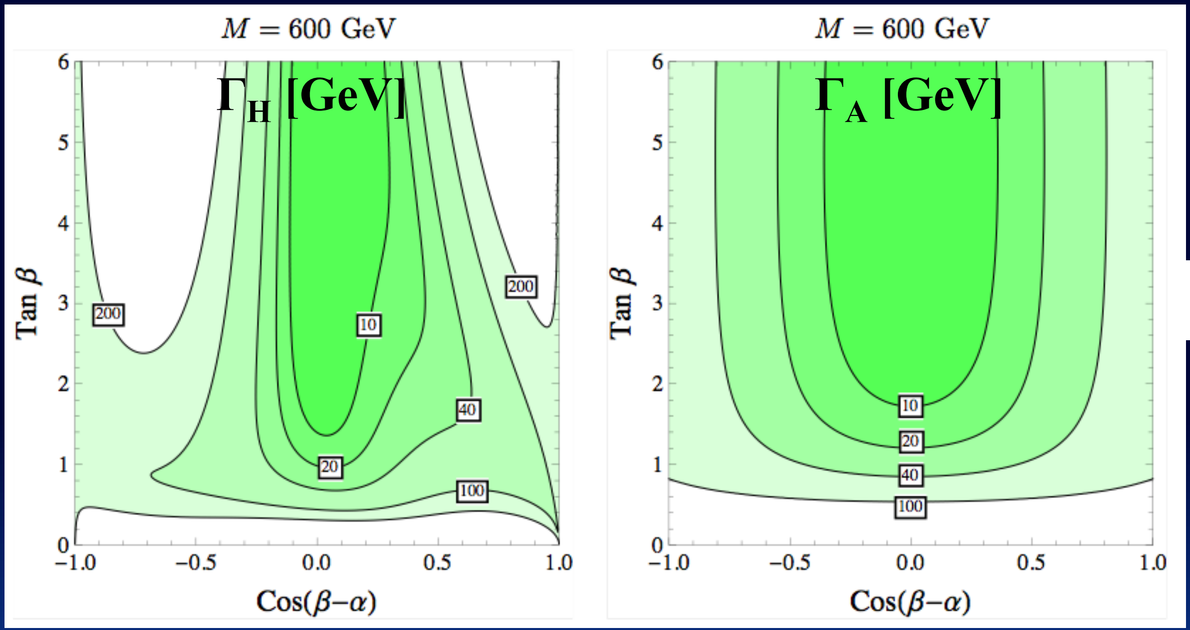
$$\kappa_t^A = \frac{1}{t_\beta}\,, \qquad \kappa_b^A = 2t_\beta + \frac{1}{t_\beta}\,,$$

$$\kappa_\tau^H = \kappa_b^H\,, \qquad \kappa_\tau^A = \kappa_b^A$$

$$\kappa_V^H = c_{\beta-\alpha}$$

κ_V^H, κ_t^A, κ_t^H , the self-couplings between the scalars and the couplings between two Higgs bosons and one gauge boson are the same as in a type II 2HDM

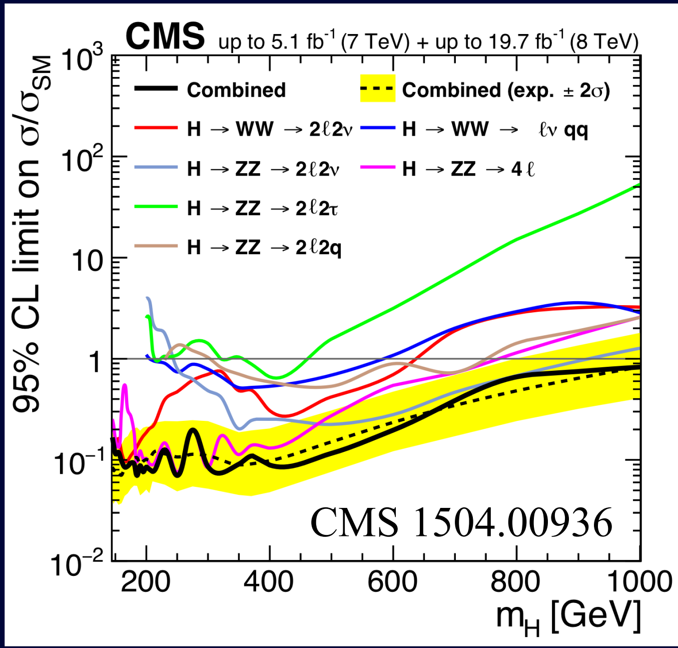
Total width for scalar and pseudoscalar becomes large in relevant regions of parameter space

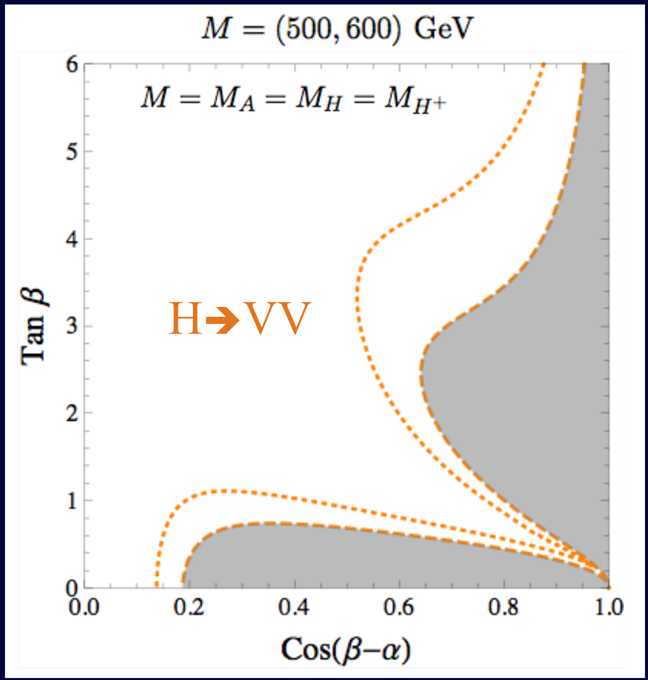


Most promising LHC Discovery channels for A and H

Inclusive H production with subsequent decay H →WW/ZZ

$$\sigma(pp \to H+X) \times \mathrm{Br}(H \to VV)/(\sigma(pp \to H+X) \times \mathrm{Br}(H \to VV))_{\mathrm{SM}}$$





$$\frac{\sigma(gg \to H) \times \mathrm{Br}(H \to VV)}{(\sigma(gg \to H) \times \mathrm{Br}(H \to VV))_{\mathrm{SM}}} = (\kappa_t^H)^2 \left(1 + \xi_b^H \frac{\kappa_b^H}{\kappa_t^H}\right)^2 (\kappa_V^H)^2 \frac{\Gamma_H^{\mathrm{SM}}}{\Gamma_H}$$

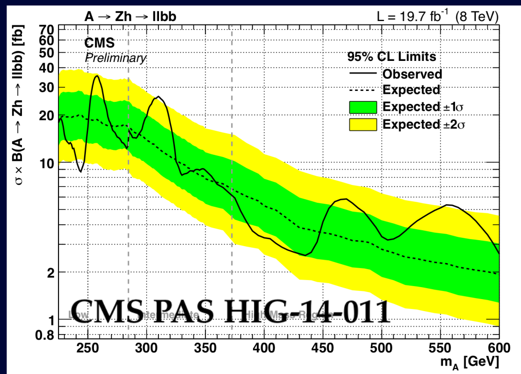
$$\frac{\sigma(pp \to qqH) \times \mathrm{Br}(H \to VV)}{(\sigma(pp \to qqH) \times \mathrm{Br}(H \to VV))_{\mathrm{SM}}} = (\kappa_V^H)^4 \frac{\Gamma_H^{\mathrm{SM}}}{\Gamma_H}$$

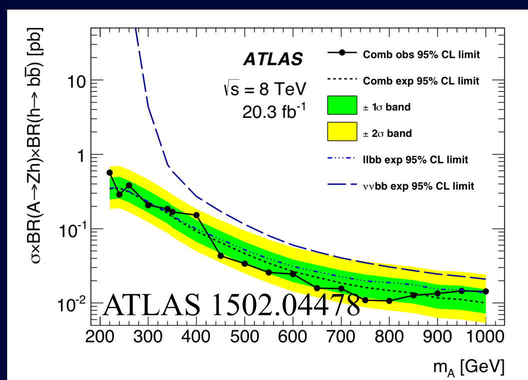
CMS-PAS-HIG-13-022 ➔ no sensitivity yet

Increasing relevance of VBF channels due to strong gluon fusion suppression in relevant regions of parameter space

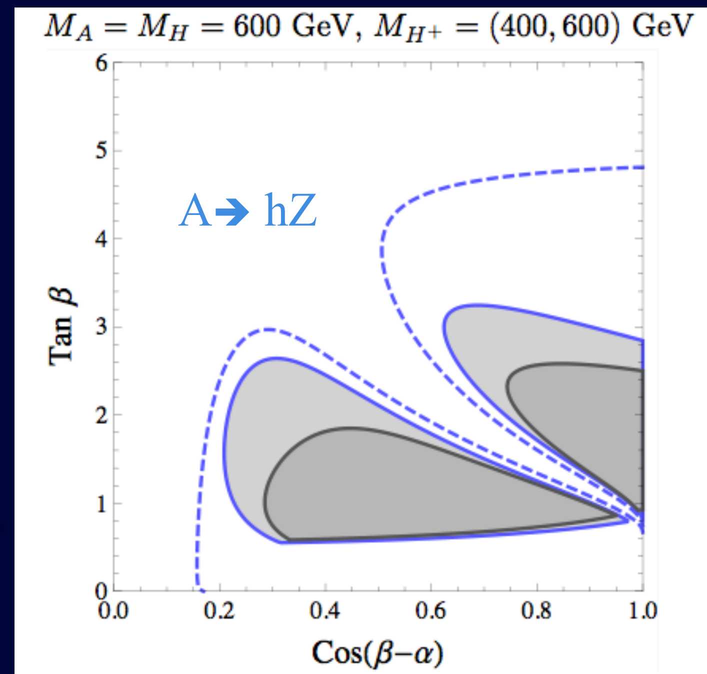
~ Very small κ_t^H ~

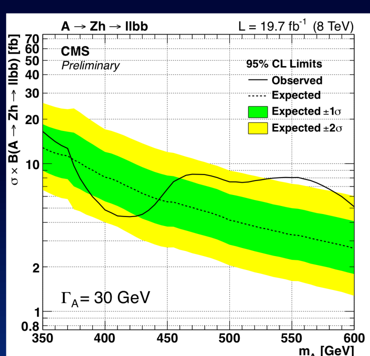
Most promising LHC Discovery channels for A and H

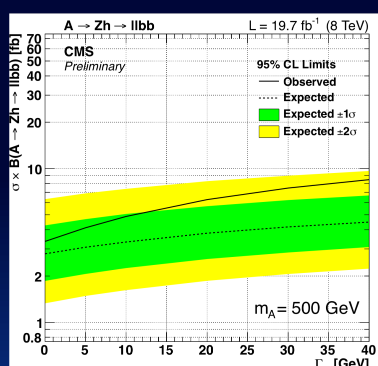




$$\sigma(gg \to A) \times \mathrm{Br}(A \to hZ) \times \mathrm{Br}(h \to b\bar{b})$$







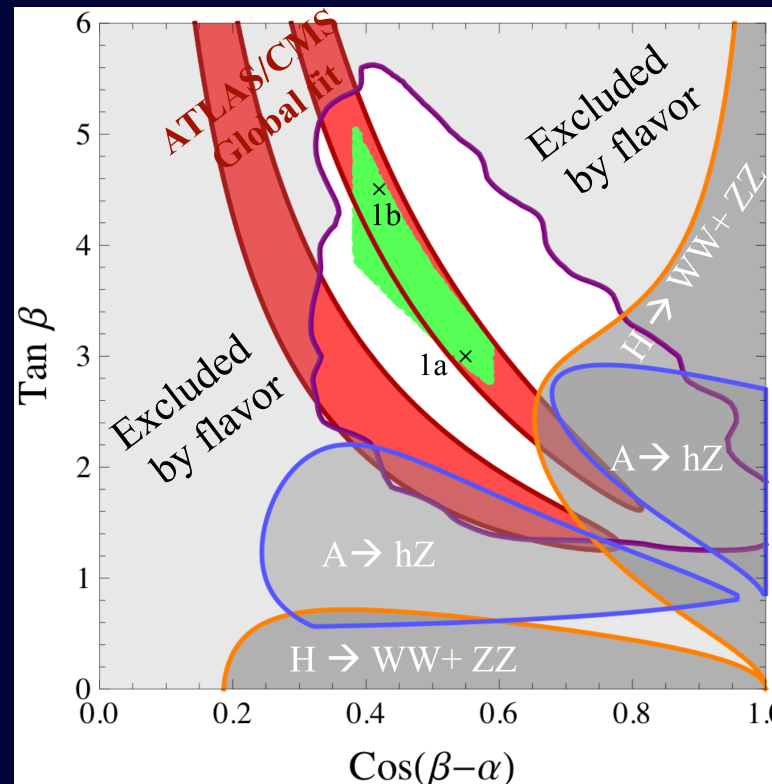
Finite Width Effects

Exclusion bound from ATLAS data for M = 600 GeV in the narrow width approximation, and after considering finite width effects (with and without splitting)

2HDFM - type II: Benchmark Scenarios

A predictive model with new Physics at LHC reach (shaded green)

- Interplay of flavor physics with precision Higgs global fit {ATLAS/CMS)
- Great possibilities for direct collider searches for additional Higgs bosons



Benchmark 1 : $M_A = M_H = 600$ GeV, $M_{H^+} = 450$ GeV

1a $\cos(\beta-\alpha) = 0.55\,, \quad \tan\beta = 3,$

1b $\cos(\beta-\alpha) = 0.42\,, \quad \tan\beta = 4.5,$

1a	$\kappa_t = 1.02\,,$	$\kappa_V = 0.84\,,$	$\kappa_b = \kappa_\tau = -0.61\,,$	$\kappa_c = 1.22$
1b	$\kappa_t = 1.00\,,$	$\kappa_V = 0.91\,,$	$\kappa_b = \kappa_\tau = -0.96\,,$	$\kappa_c = 1.02$

Higgs Signal Strength:

1a	μ_V	μ_γ	μ_b	μ_c
$\sigma_{gg\to h}$	1.38	1.21	0.74	2.95
$\sigma_{t\bar{t}\to h}$	1.33	1.17	0.71	2.84
$\sigma_{VBF}, \sigma_{VH}$	0.89	0.78	0.48	1.91

1b	μ_V	μ_γ	μ_b	μ_c
$\sigma_{gg\to h}$	0.96	0.91	1.09	1.22
$\sigma_{t\bar{t}\to h}$	0.90	0.85	1.02	1.14
$\sigma_{VBF}, \sigma_{VH}$	0.74	0.70	0.84	0.94

Heavy Scalar Decay Modes:

A	Γ_i/Γ_A	
	1a	**1b**
Zh	70.2%	62%
W^-H^+	14.4%	21.8%
$b\bar{b}$	1.6%	5.2%
$t\bar{t}$	12.9%	8.7%
$\tau^+\tau^-$	0.2%	0.7%
$t\bar{c}$	0.4%	1.1%

H	Γ_i/Γ_H	
	1a	**1b**
WW	52.9%	43%
ZZ	25.6%	20.9%
hh	9.2%	16.9%
W^-H^+	6.8%	11.2%
$t\bar{t}$	3.9%	3.5%

H^+	Γ_i/Γ_{H^+}	
	1a	**1b**
hW	78.7%	81.5%
$t\bar{b}$	21.2%	18.2%
$\tau\nu$	0.048%	0.33%

Outlook

Flavor hierarchies can arise from the electroweak scale via a Froggatt-Nielsen mechanism with two Higgs doublets jointly acting as a flavon

The Quark sector flavor structure can be reproduced in agreement with flavor observables

This 2HDFM predicts that the additional Higgs bosons should be below 700 GeV.

The scale of the UV completion is fixed at a few TeV

Other possible realizations to be explored:

- explore the lepton sector
- consider the connection with a dark sector
- extend the 2HDFM to a Type I inspired one
- consider Higgs triplets and the connection with neutrino masses