Flavor from the Electroweak Scale

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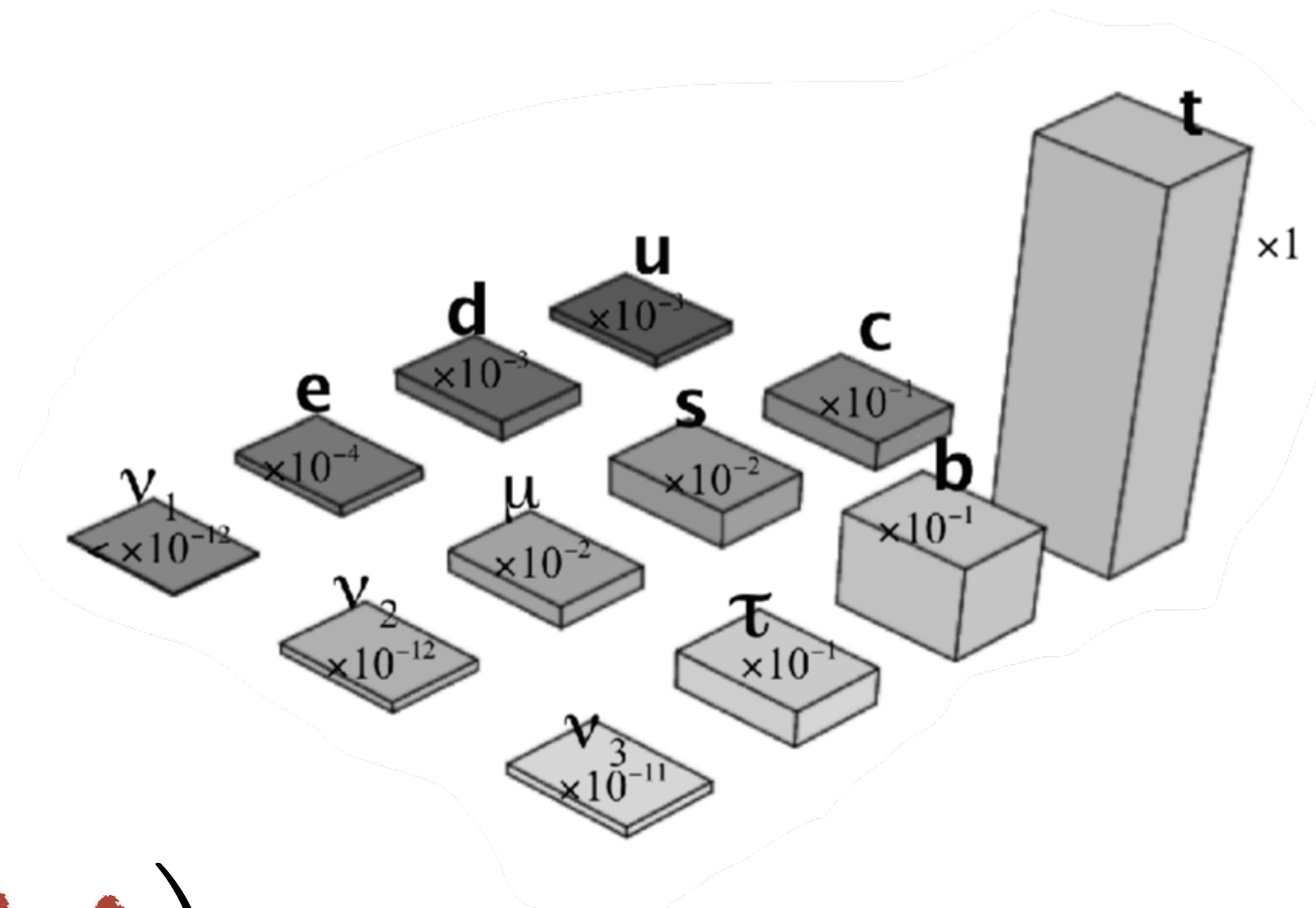
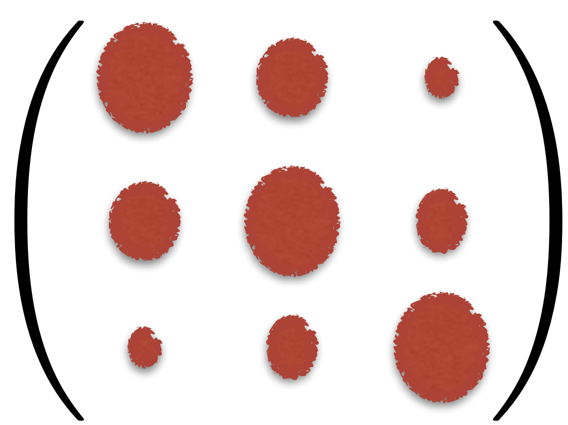
Fermilab

Johann Balmer discovered the Balmer series in 1885

$$\lambda = \frac{hm^2}{m^2 - n^2}$$

Today, the mass spectrum of the Standard Model fermions presents a similar puzzle

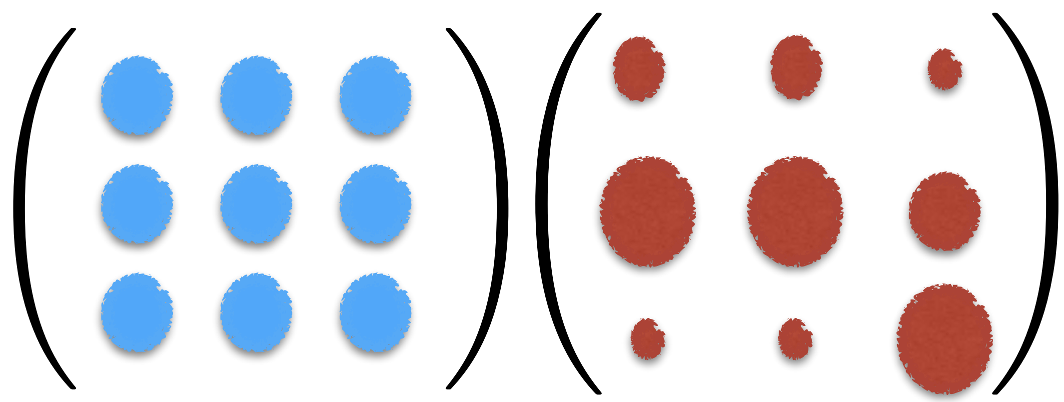


$V_{\mathrm{CKM}} =$ 

We have something like a Balmer Formula for fermion masses

$$\mathcal{L}_{\rm Yuk} = y^u_{ij}\ \overline{Q}_i\ \tilde{H} u_j + y^d_{ij}\ \overline{Q}_i\ H d_j + h.c.$$

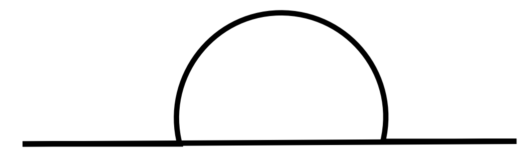
$$y^q_{ij} = \tilde{y}^q_{ij}\, \epsilon^{n_{ij}} =$$



There are many ways to generate a small number

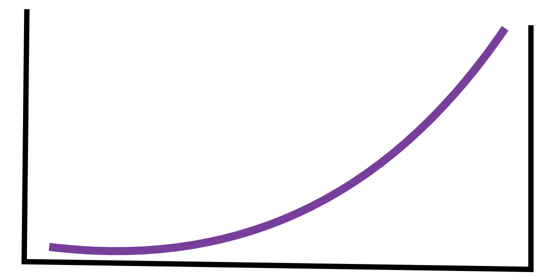
$$y_{ij}^q = \tilde{y}_{ij}^q \; \epsilon^{n_{ij}}$$

Glashow, Georgi' 72



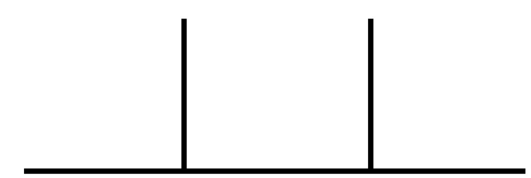
$$\sim \left(\frac{1}{16\pi^2}\right)^n$$

Gherghetta, Pomarol 0003129



$$\sim \epsilon^{c_Q - c_q}$$

Froggatt, Nielsen' 79



$$\sim \left(\frac{\langle S \rangle}{\Lambda}\right)^n$$

Nelson, Strassler 0006251

$$\epsilon \, q \, \mathcal{O}_q \qquad \sim \left(\frac{\mu}{\Lambda}\right)^\gamma$$

Froggatt, Nielsen' 79

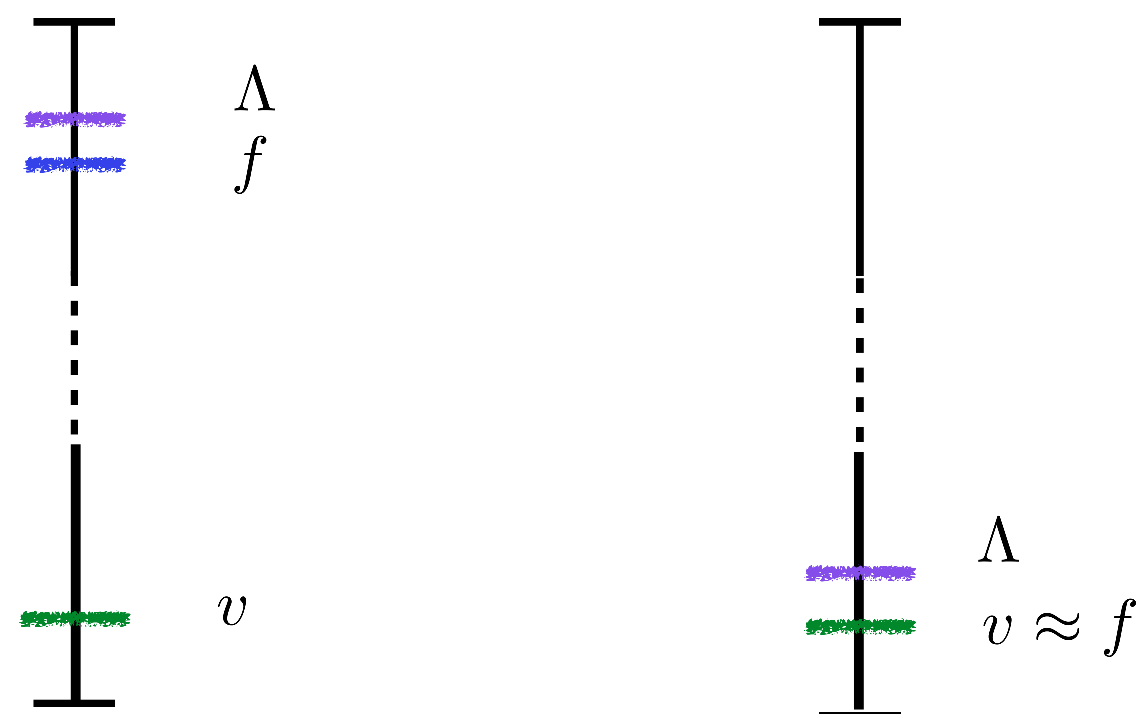
Froggatt and Nielsen proposed a flavor $U(1)$,
with Yukawa couplings

$$\mathcal{L}_{\text{Yuk}} = y^u_{ij} \left(\frac{S}{\Lambda}\right)^{a_i - a_{u_j}} \bar{Q}_i \tilde{H} u_j + y^d_{ij} \left(\frac{S}{\Lambda}\right)^{a_i - a_{d_j}} \bar{Q}_i H d_j + h.c.$$

Such that the flavor structure is generated by

$$\epsilon = \frac{\langle S \rangle}{\Lambda} = \frac{f}{\Lambda}$$

Where are these scales ?



This idea has been proposed by Babu, Nandi and Giudice, Lebedev

$$\mathcal{L}_{\rm Yuk} = y^u_{ij} \left(\frac{HH^\dagger}{\Lambda^2}\right)^{a_i - a_{u_j}} \bar{Q}_i \tilde{H} u_j + y^d_{ij} \left(\frac{HH^\dagger}{\Lambda^2}\right)^{a_i - a_{d_j}} \bar{Q}_i H d_j + h.c.$$

with $\epsilon = \dfrac{v^2}{2\Lambda^2} = \dfrac{m_b}{m_t} \quad \Rightarrow \quad \Lambda \approx (5-6)\, v$

but two problems:

- The flavor is a flavor singlet: $\quad S \to \dfrac{HH^\dagger}{\Lambda}$
- The coupling to b quarks is

$$g_{hb_L b_R} \sim 3\frac{m_b}{v} \quad \Rightarrow \quad \Gamma(h \to b\bar{b}) \sim 9 \times \Gamma_{\rm SM}(h \to b\bar{b})$$

Babu 033002 Giudice Lebedev 0804.1753

We consider a two Higgs doublet model (based on type II)

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

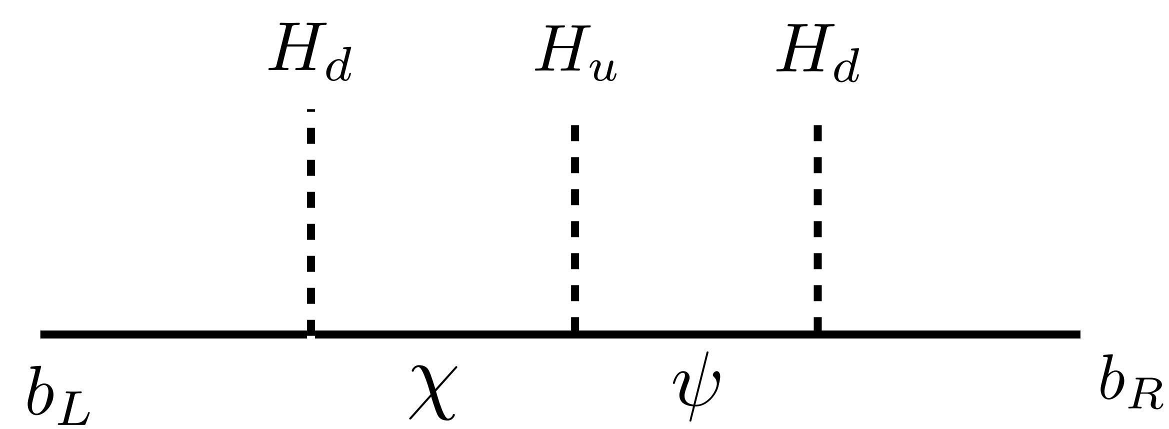
with $\quad \epsilon = \dfrac{v_u v_d}{2\Lambda^2} \quad \Rightarrow \quad \Lambda \approx (5-6)\, v \sqrt{\dfrac{\tan\beta}{1+\tan\beta^2}}$

$$\tan\beta = 1\,, \quad \Lambda \approx 1\,\mathrm{TeV}$$

$$\tan\beta = 2\,, \quad \Lambda \approx 850\,\mathrm{GeV}$$

$$\tan\beta = 3\,, \quad \Lambda \approx 750\,\mathrm{GeV}$$

$$\tan\beta = 5\,, \quad \Lambda \approx 600\,\mathrm{GeV}$$



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with $\quad \epsilon = \dfrac{v_u v_d}{2\Lambda^2} \qquad \Rightarrow \qquad \Lambda \approx (5-6)\, v \sqrt{\dfrac{\tan\beta}{1+\tan\beta^2}}$

In this model

- We have a “genuine” flavon: $\quad S \to \dfrac{H_u H_d}{\Lambda}$
- The coupling to b quarks is

$$g_{hb_L b_R} \sim \left(2\frac{\sin\alpha}{\cos\beta} - \frac{\cos\alpha}{\sin\beta}\right)\frac{m_b}{v}$$

Higgs couplings:

$$g_{hff} = \kappa_f \, g_{hff}^{\mathrm{SM}}$$

$$g_{hVV} = \kappa_V \, g_{hVV}^{\mathrm{SM}}$$

- To $W^{\pm}, Z$: fixed by gauge symmetry $\kappa_V = \sin(\beta - \alpha)$
- To the top : $\kappa_t = \dfrac{\cos\alpha}{\sin\beta}$

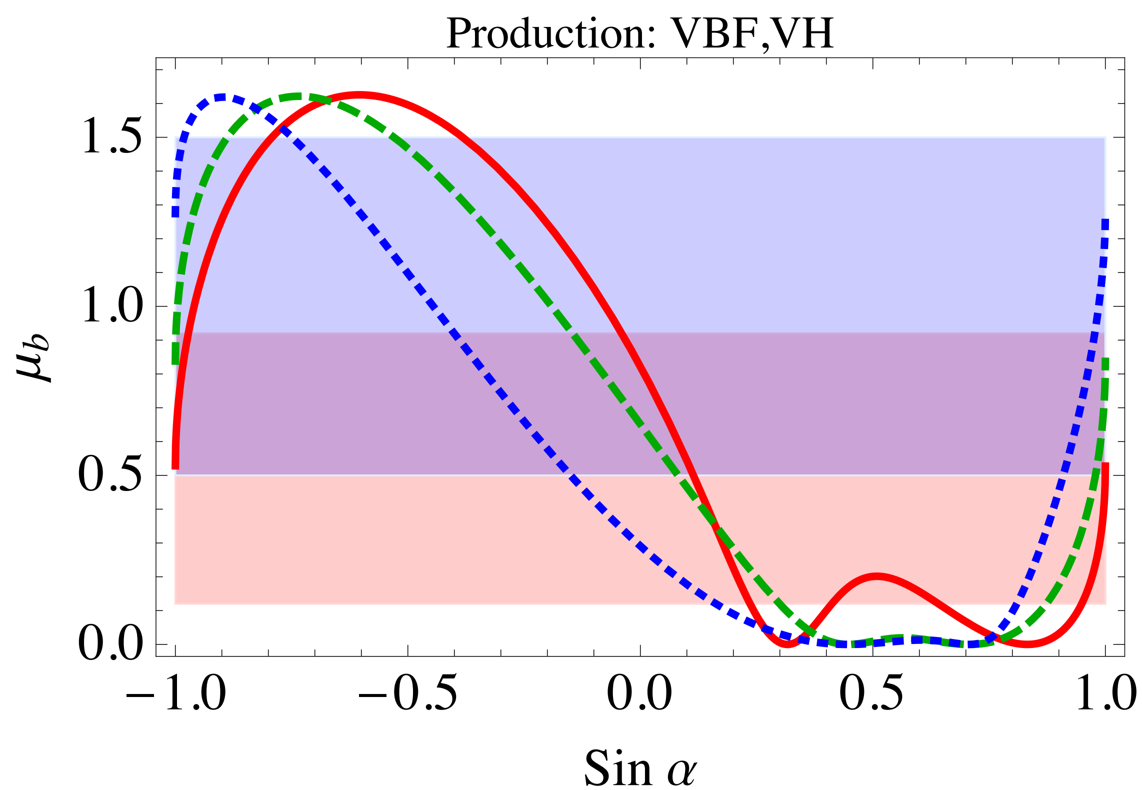
Higgs production exactly like a type II 2HDM!

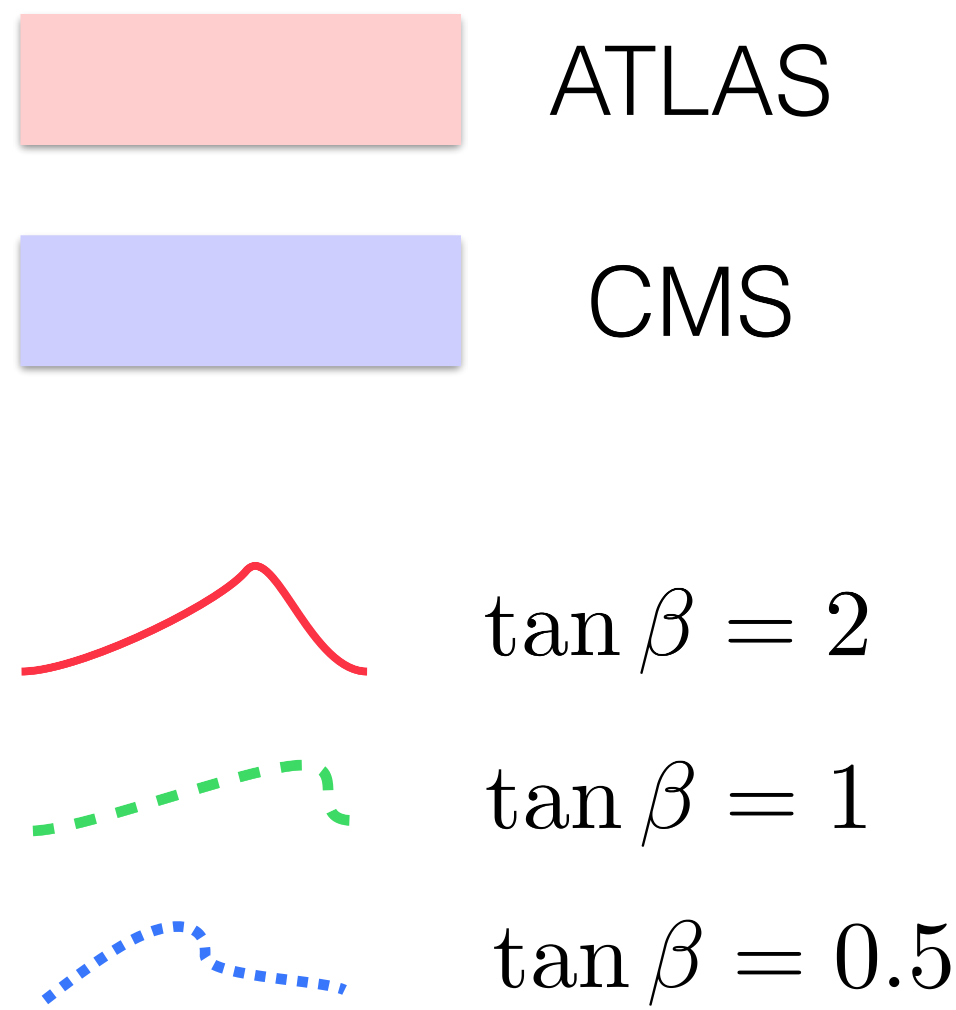
- To the bottom : $\kappa_b = -2\,\dfrac{\sin\alpha}{\cos\beta} + \dfrac{\cos\alpha}{\sin\beta}$

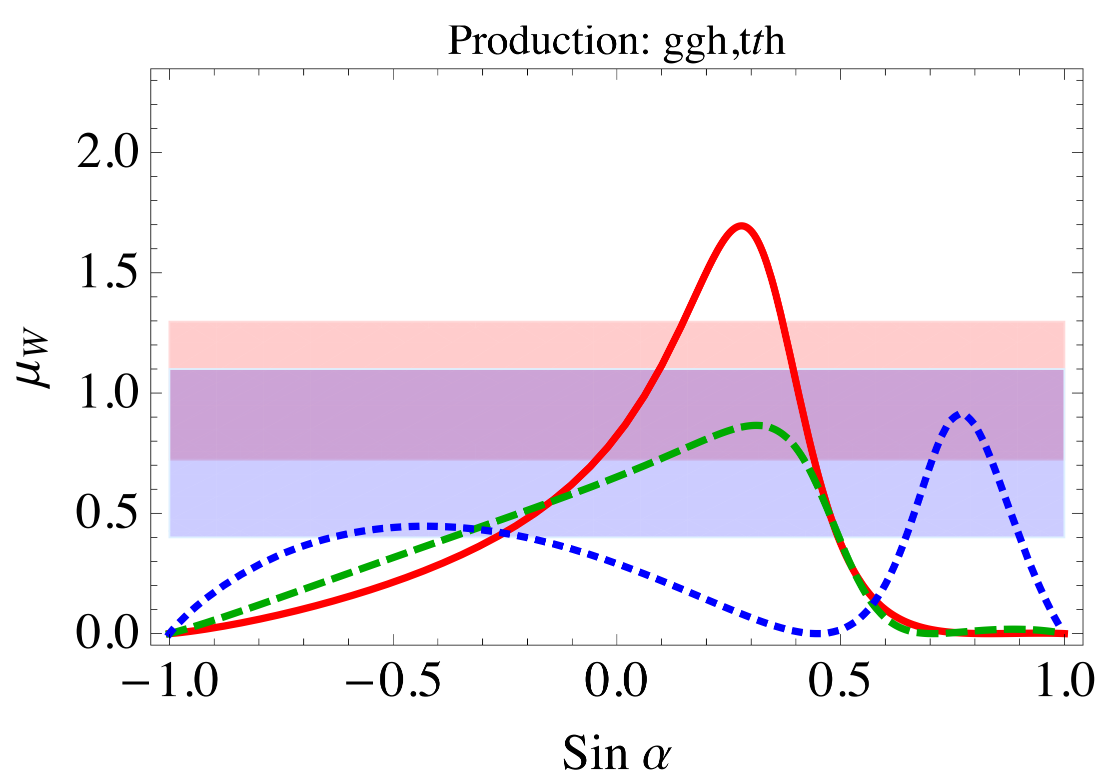
Higgs width and decays are modified
with respect to a generic 2HDM!

Higgs couplings:

$$\mu_X = \frac{\sigma_{\rm prod}}{\sigma^{\rm SM}_{\rm prod}} \frac{\Gamma_{h\to X}}{\Gamma^{\rm SM}_{h\to X}} \frac{\Gamma^{\rm SM}_{h,\,\rm tot}}{\Gamma_{h,\,\rm tot}}$$



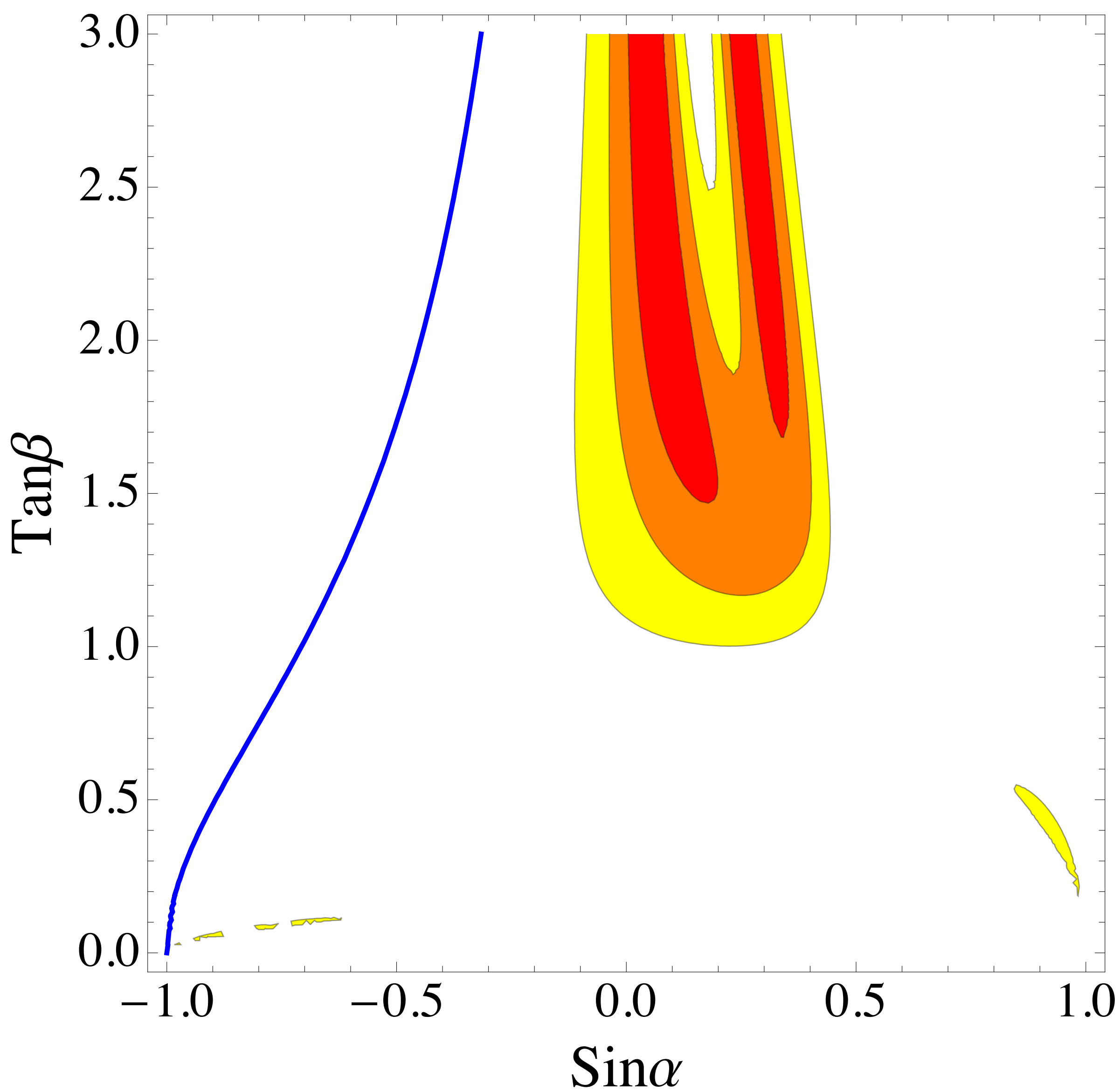




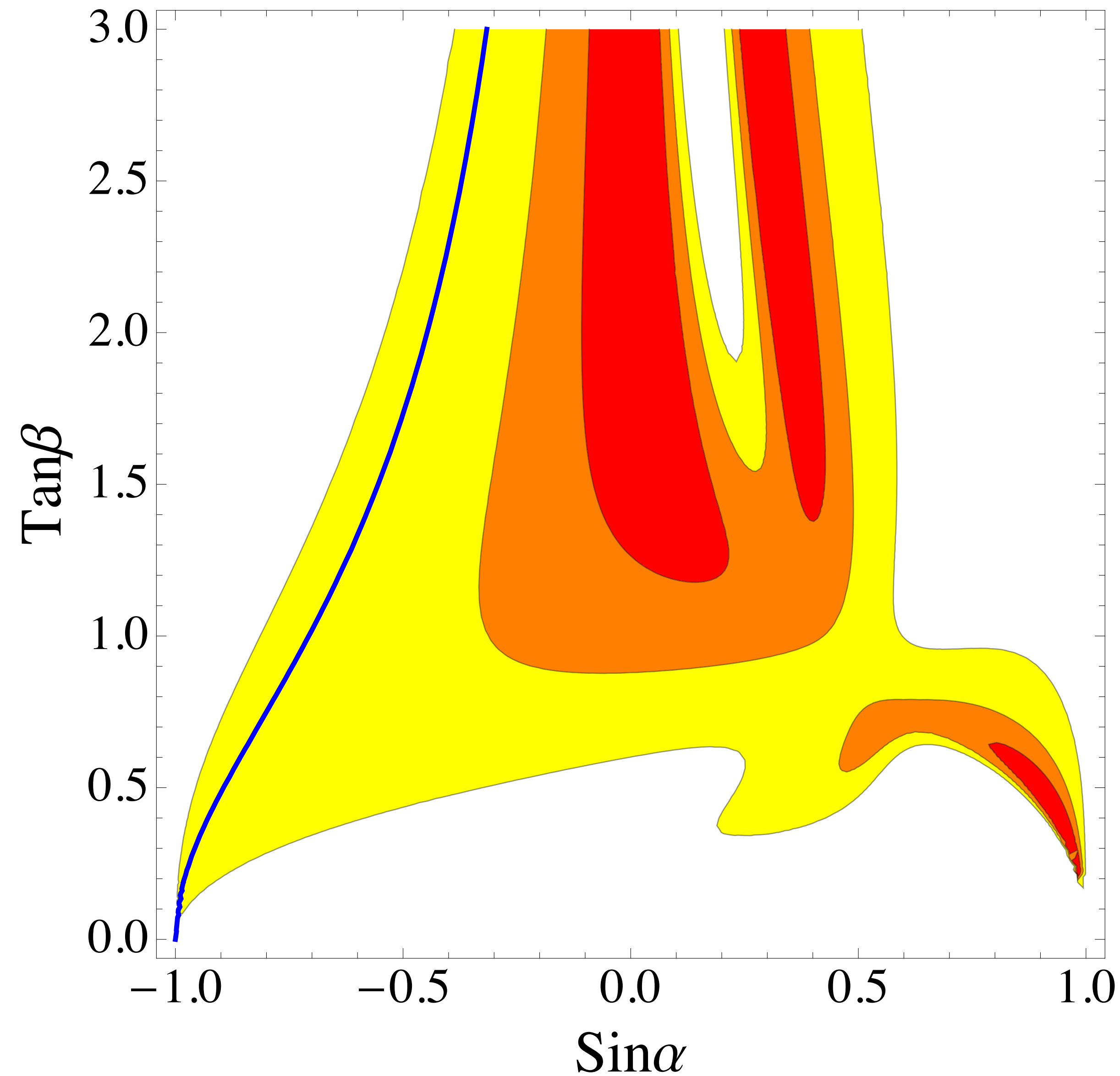
- Preliminary Plots-

Global fit to 7 (8) different channels for ATLAS (CMS)

CMS



ATLAS



- Preliminary Plots-

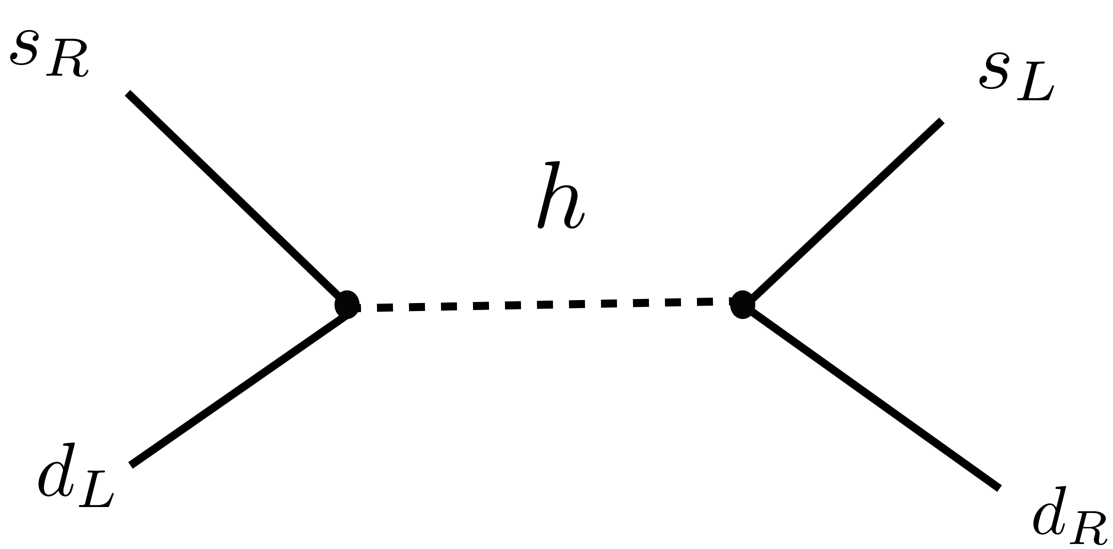
Flavor violating Higgs couplings

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

$$f(\alpha,\beta) = \sqrt{1+\tan^2\beta}\left(\frac{\cos\alpha}{\tan\beta} - \sin\alpha\right)$$

$$\mathcal{Q}, \mathcal{D} \sim \mathcal{O}(\epsilon)$$

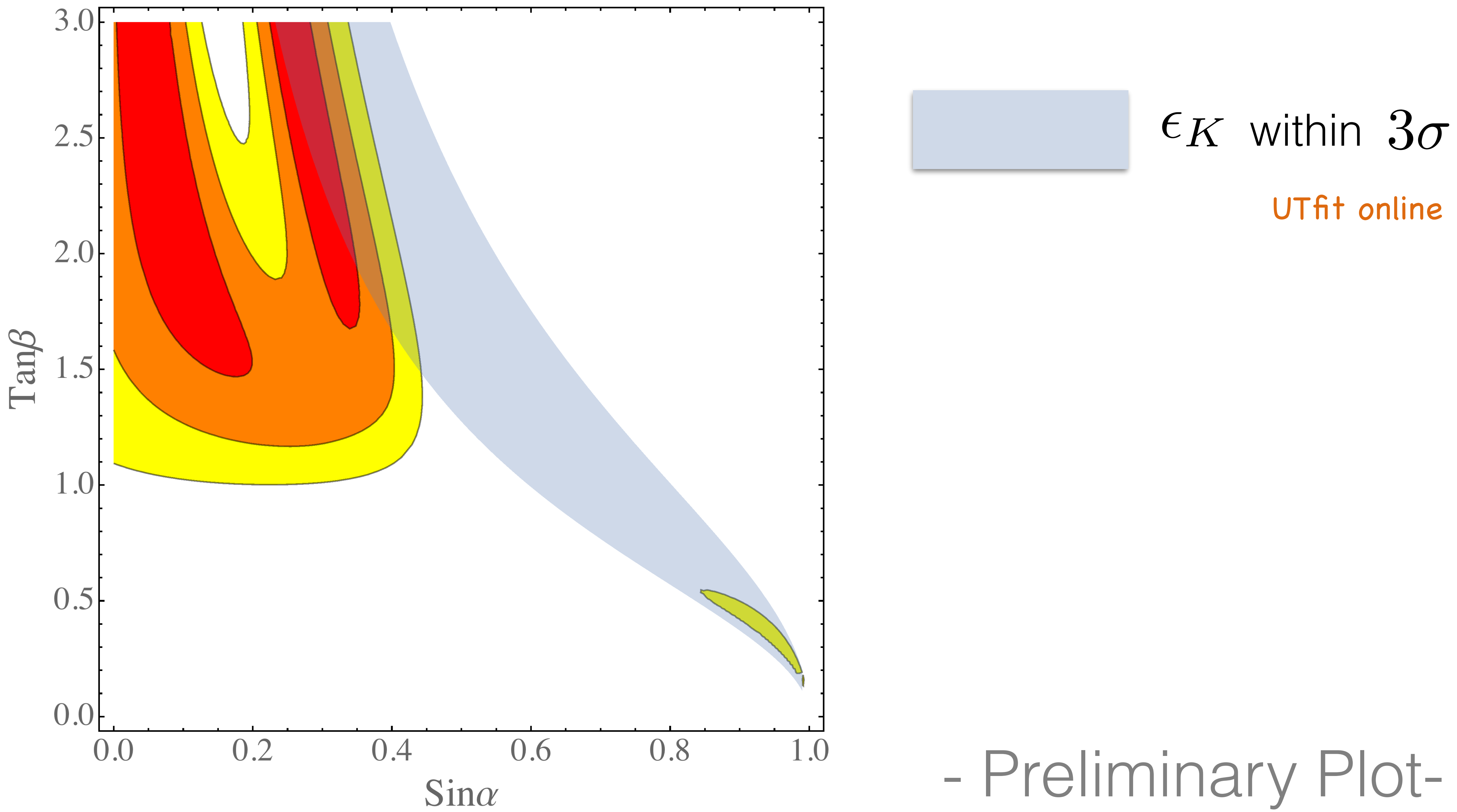
FCNCs can be suppressed



$$\propto \frac{1}{m_h^2} f^2(\alpha,\beta) g^2(y) \left[\frac{m_s}{v}\,\epsilon\right]^2 \approx \frac{10^{-15}}{\text{GeV}^2}$$

Exp Bound: $\lesssim 10^{-17}$

Let us assume all Yukawa couplings are order one and see what region in parameter space is preferred by flavor

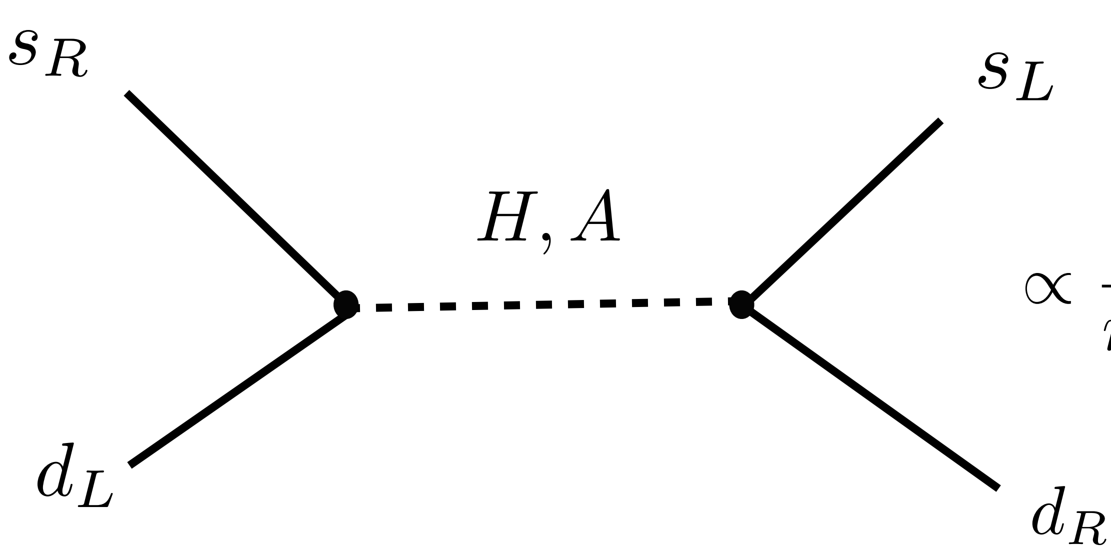


- Preliminary Plot-

Heavy Higgs couplings

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

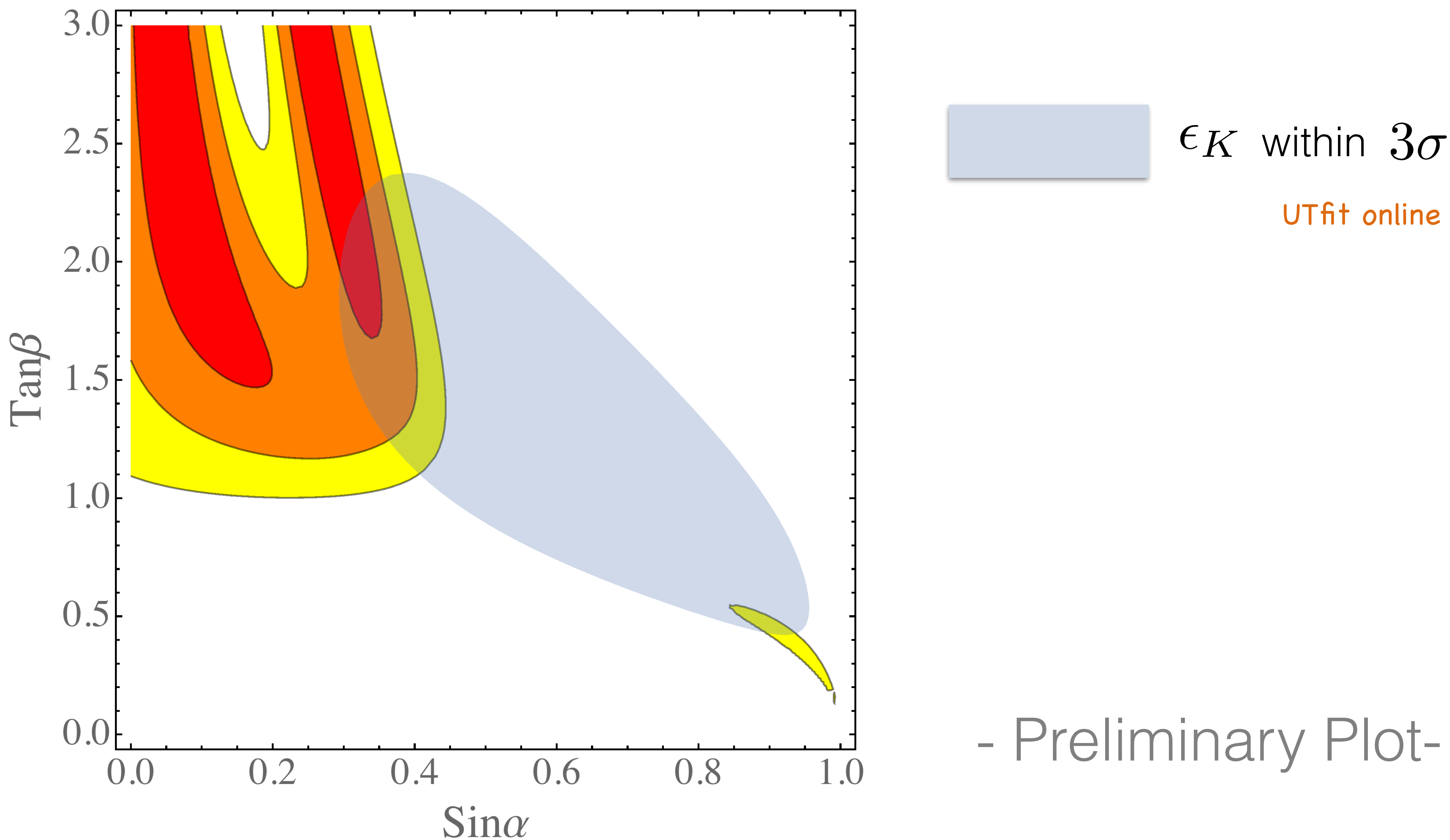
$$F(\alpha,\beta) = \sqrt{1+\tan^2\beta}\, \left(\frac{\cos\alpha}{\tan\beta} + \sin\alpha\right)$$



$$\propto \frac{1}{m_H^2} F^2(\alpha,\beta) g^2(y) \left[\frac{m_s}{v}\, \epsilon\right]^2 \approx \frac{10^{-16}}{\mathrm{GeV}^2} \left(\frac{300\,\mathrm{GeV}}{m_H}\right)^2$$

Exp Bound: $\lesssim 10^{-17}$

Slightly tuned Yukawa couplings and including heavy Higgses



- Preliminary Plot-

How to find this model?

Large deviations from the decoupling limit means relatively light extra scalars.

Existing searches are already very constraining.

New colored vector fermions have to show up around a TeV.

$\Gamma(h \to b\bar{b}) < \Gamma^{\rm SM}(h \to b\bar{b})$ preferred.

Additional sources of flavor breaking are necessary in order to avoid a QCD axion

$$
\begin{aligned}
V(H_u, H_d) = {} & \mu_u^2\, H_u\, H_u^\dagger + \mu_d^2\, H_u\, H_u^\dagger - [\underline{b\, H_u\, H_d} + h.c.] \\
& + \frac{\lambda_1}{2}\,(H_u\, H_u^\dagger)^2 + \frac{\lambda_2}{2}(H_d\, H_d^\dagger)^2 + \lambda_3\,(H_u\, H_u^\dagger)(H_d\, H_d^\dagger) + \lambda_4 (H_u\, H_d^\dagger)(H_d\, H_u^\dagger)\,.
\end{aligned}
\tag{A.1}
$$

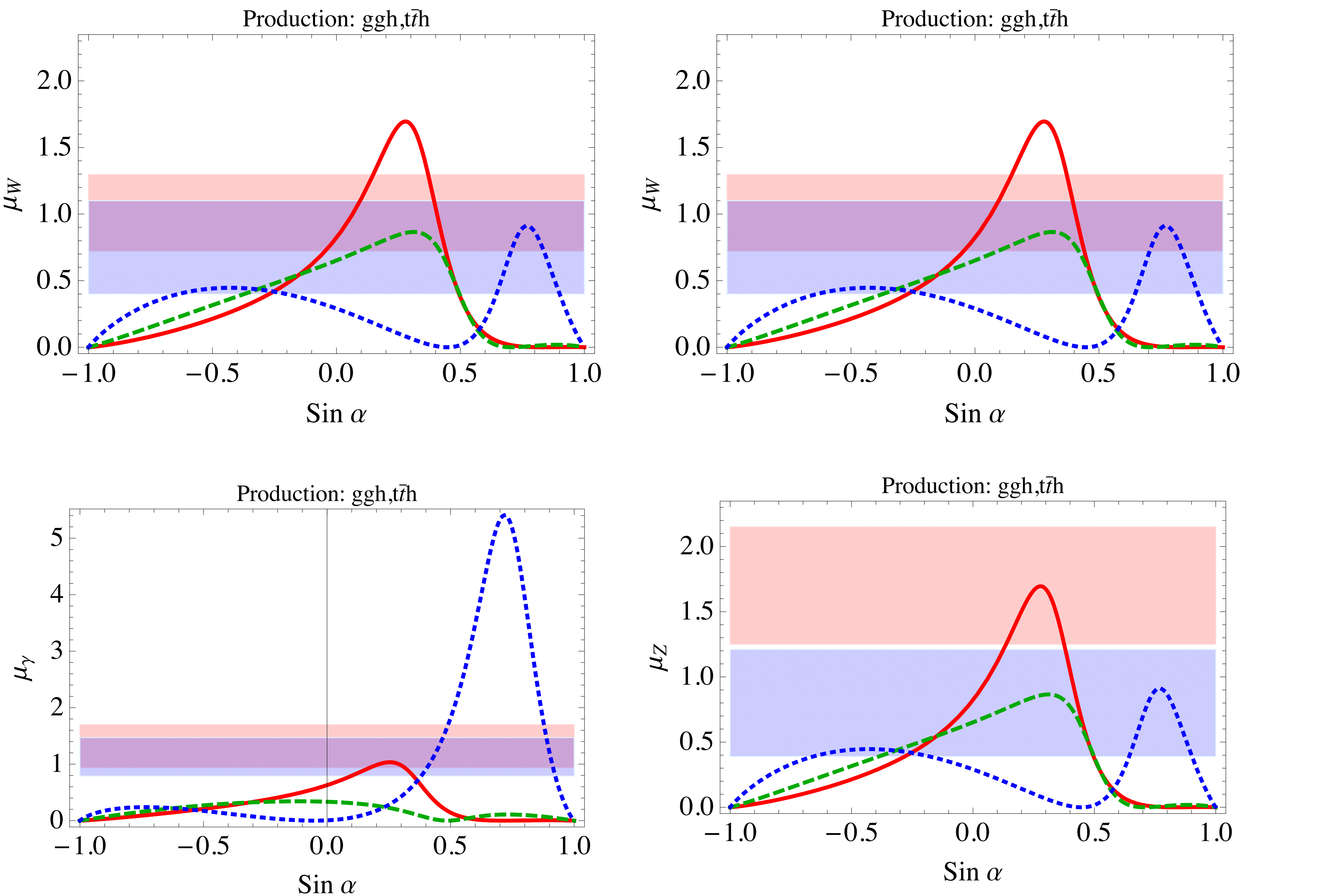
This has interesting implications for a supersymmetrized version

$$b \sim \mu^2$$

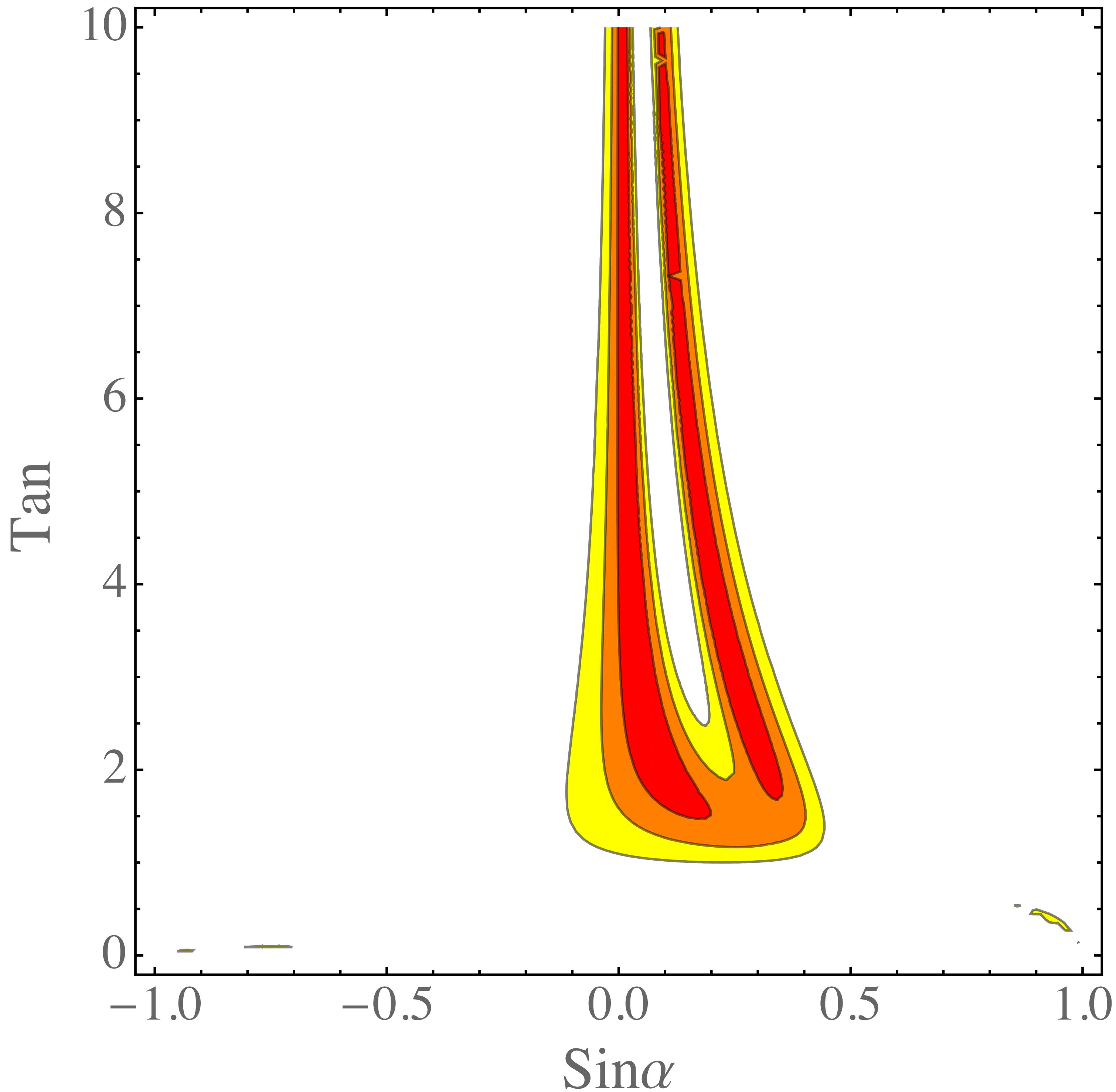
Conclusions

- Yukawa texture can be explained at the EW scale
- Parameter space preferred by Higgs physics and Flavor overlaps
- This model will be discovered/ excluded in the second run

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



- Preliminary Plots-



Global fit

Input for the global fit

Decay Mode	Production Channels $\sigma_{gg\to h}$, $\sigma_{t\bar{t}\to h}$	Production Channels σ_{VBF}, σ_{VH}	Experiment
$h \to W^+W^-$	$\mu_W = 1.01 \pm 0.19^{+0.20}_{-0.17}$ [15] $\mu_W \sim 0.75 \pm 0.35$ [16]	$\mu_W = 1.28^{+0.44}_{-0.40}{}^{+0.29}_{-0.21}$ [15] $\mu_W \sim 0.7 \pm 0.85$ [16]	ATLAS **PRELIM** CMS
$h \to ZZ$	$\mu_Z = 1.7^{+0.5}_{-0.4}$ [17] $\mu_Z = 0.8^{+0.46}_{-0.36}$ [18]	$\mu_Z = 0.3^{+1.6}_{-0.9}$ [17] $\mu_Z = 1.7^{+2.2}_{-2.1}$ [18]	ATLAS CMS
$h \to \gamma\gamma$	$\mu_\gamma = 1.32 \pm 0.38$ [19] $\mu_\gamma = 1.13^{+0.37}_{-0.31}$ [20]	$\mu_\gamma = 0.8 \pm 0.7$ [19] $\mu_\gamma = 1.16^{+0.63}_{-0.58}$ [20]	ATLAS CMS
$h \to \bar{b}b$	$-$ $\mu_b = 0.67^{1.35}_{-1.33}$ [22]	$\mu_b = 0.52 \pm 0.32 \pm 0.24$ [21] $\mu_b = 1.0 \pm 0.5$ [23]	ATLAS **PRELIM** CMS