Flavor-Changing Neutral Interactions in the Higgs Sector

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1. Standard Model and extended Higgs sectors
2. Reasons FCNC in the Higgs sector are dangerous
3. The 2HDM with FCNC
    1. The Cheng-Sher ansatz
        1. The rise
        2. The fall
    2. Minimal Flavor Violation
        1. The BGL models
        2. Flavorful models
4. Heavy Higgs Decays
5. Conclusions

The Standard Model has a single Higgs doublet, Φ, which acquires a vacuum expectation value

$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

where v ≈ 246 GeV. The most general Yukawa coupling is given by

$$\mathcal{L}_Y = y_{ij}\bar{f}_{Li}f_{Rj}\Phi + \text{h. c.}$$

When expanding about the vacuum, one gets the mass matrix:

$$M_{ij} = y_{ij}v/\sqrt{2}$$

So, when the mass matrix is diagonalized, the Yukawa coupling matrix is automatically diagonalized, so the Higgs only couples in a flavor-diagonal way. This is a good thing, because non-flavor-diagonal terms are dangerous. Consider the simplest extension, the two-Higgs doublet model.

The most general Yukawa couplings are:

$$\mathcal{L}_Y = y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\Phi_2$$

where i and j are generation indices. This gives

$$M_{ij} = y^1_{ij}\frac{v_1}{\sqrt{2}} + y^2_{ij}\frac{v_2}{\sqrt{2}}$$

Since y^1 and y^2 are, in general, not simultaneously diagonalizable, this will lead to tree level FCNC

These are very problematic-- the $\tilde{d}sH$ coupling will lead to very large K - $\tilde{K}$ mixing, unless the coupling is very small or the H is very heavy.

If the coupling is f $\bar{d}sH$, then the lower bound to the Higgs mass would be approximately 7000 f^2 TeV . So f has to be very small to be acceptable.

Other bounds come from $B-\bar{B}, B_s-\bar{B}_s, D-\bar{D}$ mixing as well as rare B decays, tau and muon decays, etc

Paschos, Phys. Rev. D15, 1966 (1977)
Glashow, Weinberg, Phys. Rev. D 15, 1958 (1977)

Only way to eliminate tree level FCNC is a discrete symmetry. Paschos-Glashow-Weinberg theorem, applied to a model with doublets and singlets, states that this can only be done if all **quarks** of a given charge couple to only one Higgs doublet.

For example:

Type I: All fermions couple to one doublet, Φ_2

Type II: The Q=2/3 quarks couple to Φ_2 , the Q=-1/3 quarks and leptons couple to Φ_1

Note – in this talk I will refer to the angle $\beta-\alpha$. This gives the angle between the Higgs basis (only one gets a vev) and the mass eigenstate basis. The coupling of the 125 GeV Higgs to vector bosons is proportional to $\sin(\beta-\alpha)$.

MODELS WITH TREE-LEVEL FCNC

One of the earliest models is the so-called type III 2HDM. In this case, it is much more convenient to rotate to a basis in which one field gets a vev and the other does not. In that case:

$$L_{\text{Yukawa}} = \eta^U_{ij}\bar{Q}_{iL}\tilde{H}_1 U_{jR} + \eta^D_{ij}\bar{Q}_{iL}H_1 D_{jR} + \eta^L_{ij}\bar{L}_{iL}H_1 E_{jR} \quad ($$

$$+ \quad \hat{\xi}^U_{ij}\bar{Q}_{iL}\tilde{H}_2 U_{jR} + \hat{\xi}^D_{ij}\bar{Q}_{iL}H_2 D_{jR} + \hat{\xi}^L_{ij}\bar{L}_{iL}H_2 E_{jR} \quad ($$

$$\langle H_1\rangle_0 = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad \langle H_2\rangle_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Diagonalizing the mass matrix does diagonalize the η_{ij} couplings, but NOT the ξ_{ij} couplings, leading to tree level FCNC

Is this a problem? It depends on the size of the couplings, of course.

Early 80s

The introduction of an ad hoc Z_2 symmetry seemed epicyclic. How necessary was it?

Experimenter in 1980 measuring $K_L \rightarrow \mu e$ looked at the bound assuming Higgs exchange and claimed "if the flavor-changing coupling is O(1), we find a lower bound on the Higgs mass of 60 TeV -- this is higher than the energy of the SSC!!" Of course, this ignored mixing, the difference between the two Higgs, etc.....

A more realistic assumption made by Shankar (1980) and by McWilliams and Li (1981). Assume that the flavor-changing coupling was the heaviest fermion of that particular charge times a mixing angle. Since the angle is unknown, assume it is O(1). That still gave a bound of a few TeV from $K_L \rightarrow \mu e$ and an even higher bound of 100 TeV from Δm_K (although there are greater uncertainties in that).

Partly for these reasons (and the rise of SUSY which gave the type II structure), FCNC at tree level was generally ignored for most of the decade.

In the early 80's, CKM matrix elements weren't well-known, and there was great interest in Fritzsch type matrices.

$$\begin{pmatrix} 0 & A \\ A & B \end{pmatrix}$$

If A << B, then the eigenvalues are A^2/B and B, so the off-diagonal term is the geometrical mean of the eigenvalues. If this is the down quark mass matrix, this leads to the numerically correct result that

$$\sin\theta_c = \sqrt{m_d/m_s}$$

Leads to the suggestion that the FCNC couplings should be the geometric mean of the individual Yukawa couplings. How general is this?

In ‘86, I moved to Washington Univ. and Ta-Pei Cheng from Missouri, St. Louis was a few miles away. Cheng and Li had just been published and I had questions about matrix elements.

We looked at 3x3 Fritzsch matrices and found precisely the same pattern – the FCNC couplings were the geometric mean of the individual couplings. Then Ta-Pei realized it was even more general – if you just require that there be no precise cancellations in getting the eigenvalues, it followed.

The ansatz was then written as

$$y_{ij} = \lambda_{ij} \frac{\sqrt{m_i m_j}}{v/\sqrt{2}}$$

where the λ_{ij} are O(1). This is order of magnitude – one expects mixing angles, etc.

At the time, the strongest bound on the λ_{ij} came from Δm_K, and gave (for $\lambda_{ij} = 1$) a lower bound on the exchanged scalar (pseudoscalar) mass of 300 GeV (1 TeV). These are now lower due to somewhat smaller current quark masses. It ignores contributions from charged Higgs, and any mixing angles.

RISE

The CS ansatz received very little attention for a few years. Then the top turned out to be heavy, and the B-factories (BELLE/BABAR) began. The ansatz gave experimenters a target (give bounds in terms of λ_{ij} instead of a generic coupling whose value was arbitrary). It also meant that B decays and mixings would have a huge increase in precision, and thus $\lambda_{ij} =1$ was in reach. It got a lot of citations. Alas, Nature is having the last word.

FALL

Over the years, bounds have become much more precise. The best and most recent analysis is Babu and Jana, arxiv: 1812.11943.

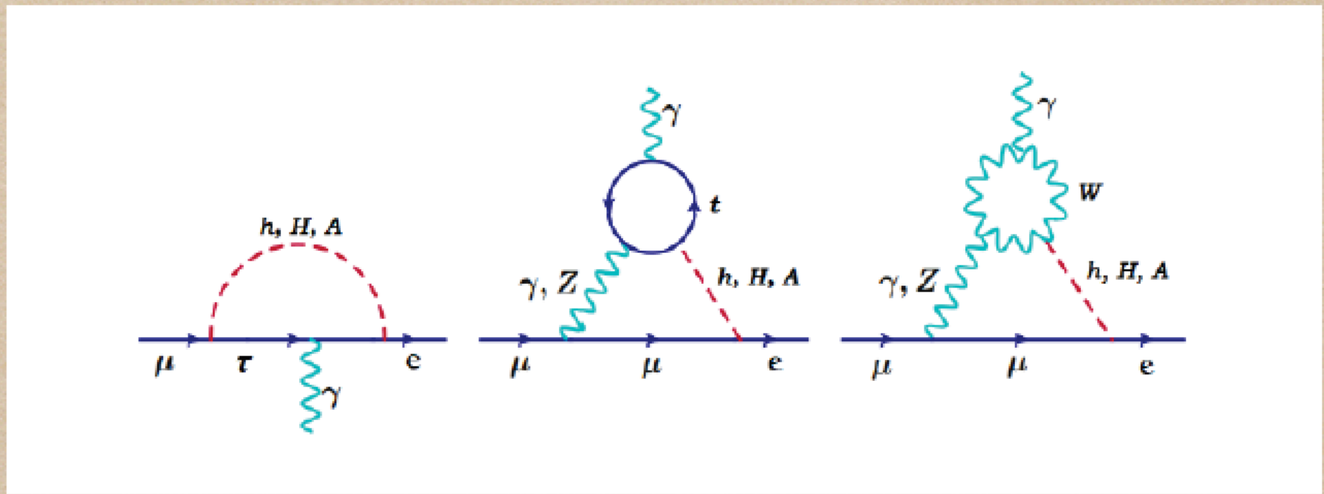
Strongest bounds are still from meson-meson mixing, but now we also have D, B and B_s mixing

Table from Babu and Jana arxiv:1812.11943.

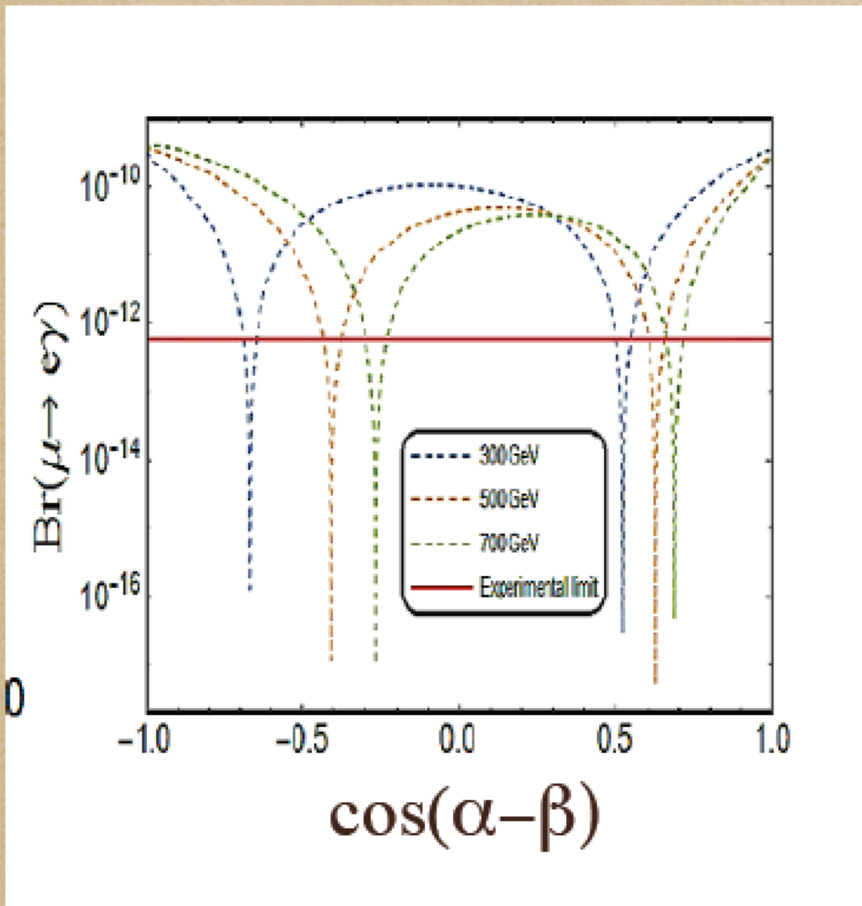
Upper bound on C_{ij}	Cheng-Sher Ansatz
$K^0 - \overline{K^0}$ mixing constraint	0.26
$B_s^0 - \overline{B_s^0}$ mixing constraint	0.436
$B_d^0 - \overline{B_d^0}$ mixing constraint	0.379
$D^0 - \overline{D^0}$ mixing constraint	0.222

Bounds on λ_{ij} obtained from meson mixing, assuming a pseudoscalar mass of 500 GeV (bound scales approximately linearly). The bound from scalar exchange is a factor of 3 or so weaker. This assumes real couplings. If there is a CP-violating phase bigger than .005, then the bounds become even worse

Radiative muon decay



The two-loop diagrams give a bigger contribution (Barr-Zee). The result does depend on the mixing angle, $\sin(\alpha-\beta)$. Assuming the λ_{ij} are all equal to one:



Taking cos(α−β) =0.4 and a mass of H to be 500 GeV, one finds $\lambda_{\mu e}$ must be less than 0.12 to satisfy current bounds.

$h \to \mu\tau$

The branching ratio is $0.0076\ \lambda_{\mu\tau}^2 \cos^2(\alpha-\beta)$. The current CMS experimental bound is 0.0025, or $\lambda_{\mu\tau} < .6/\cos(\alpha-\beta)$. This gives a weak bound, not yet lethal.

Sher, Thrasher (2016)
Hou, et al (2019)

SIDE NOTE: The branching ratio for $H \to \mu\tau$ is proportional to $\sin^2(\alpha-\beta)$, which is much larger. Same is true for other FNCN decays of H.

The Cheng-Sher ansatz parametrizes tree-level flavor-changing neutral currents in terms of coefficients that, in the absence of fine-tuning, should be O(1).

Now, 30 years later, data has challenged this ansatz. Five of the nine off-diagonal coefficients must be substantially smaller then 1. It is possible that there might be some wiggle-room, but it appears that the ansatz is no longer viable. It may still be useful in parametrizing and comparing FCNC studies.

MINIMAL FLAVOR VIOLATION

requires that all flavor (and CP) violation are linked to the known structure of Yukawa couplings.

More precisely, the Standard Model without Yukawa couplings has a $G_F = U(3)^5$ symmetry.

This symmetry is broken in the Standard Model by Yukawa couplings. One can introduce auxiliary fields Y_U, Y_D, Y_E and choose their quantum numbers to restore G_F.

For example – looking at the quark sector, there is an $SU(3)_Q \times SU(3)_U \times SU(3)_D$ symmetry without Yukawas. One can introduce auxiliary fields Y_U and Y_D which transform as (3,3,1) and (3,1,3) respectively. This will then retain the flavor symmetry.

An effective theory satisfies Minimal Flavor Violation if all higher-dimensional operators, constructed from SM and Y fields, are invariant under G_F. In other words, there is no new physics that violates G_F

Chivukula et al, PLB 188, 99 (1987); Buras et al, PLB 500, 161 (2001); D'Ambrosio et al., NPB 645, 155 (2002); Blanke, et al., JHEP 10, 003 (2006), Botella, et al., PLB 687 (194) 2010, Grzadkowski et al, , JHEP 10, 085 (2010).

First suggested by Chivukula and Georgi in the context of technicolor; Buras et al. also extended it to a 2HDM but only for particular models. The most cited work (which used a more formalized EFT description) was D'Ambrosio, Guidice, Isidori and Strumia (over 1700 cites). Grzadkowski et al used the EFT approach to categorize dim-6 operators, Blanke et al. found model-independent tests of MFV and Botella et al. generalized to multi-doublet models. A very readable review is Isidori et al (Ann. Rev. Nucl. Part. Sci. 60, 355 (2010)).

The BGL models are a nice UV completion of MFV (and were proposed in 1996, before the words "MFV" were known)

BGL Models

Branco, Grimus, Lavoura, Phys. Lett B380, 119 (1996), hep-ph/9601383

Grimus, Branco and Lavoura (BGL) constructed models in which the FCNC couplings depend on the elements of the CKM matrix. They make the FCNC couplings dependent only on the CKM elements using discrete symmetries.

They note that one can write the couplings of the Higgs to down quarks in the 2HDM as (where D is the diagonal matrix, and the U's bidiagonalize the down quark mass matrix).

$$N_d = \frac{v_2}{v_1} D_d - \frac{v_2}{\sqrt{2}} \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) U_{dL}^\dagger Y_2^d U_{dR}$$

The FCNC appear in the last term. The CKM matrix is $V = U_{uL}^\dagger U_{dL}$

So one needs to get rid of the dependence on U_{dR} and relate $U_{dL}^\dagger$ to V

BGL show that a symmetry of the form:

$$Q_{3L} \to e^{i\psi} Q_{3L}, \qquad u_{3R} \to e^{2i\psi} u_{3R}, \qquad \Phi_2 \to e^{i\psi} \Phi_2$$

which automatically give Yukawa matrix textures of the form

$$Y_1^d = \begin{pmatrix} x & x & x \\ x & x & x \\ 0 & 0 & 0 \end{pmatrix}, Y_2^d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ x & x & x \end{pmatrix},$$

$$Y_1^u = \begin{pmatrix} x & x & 0 \\ x & x & 0 \\ 0 & 0 & 0 \end{pmatrix}, Y_2^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & x \end{pmatrix}$$

Plugging these in automatically gives the relation:

$$(N_d)_{ij} = \frac{v_2}{v_1}(D_d)_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right) V_{i3}^\dagger V_{3j} (D_d)_{jj}$$

which is precisely what is needed. Note that it only depends on the ratio of vevs, and is thus very predictive.

In the quark sector, there are six BGL models (one can replace the "3" with a "2" or "1", and focus on the up sector instead of the down). There are also three models involving the lepton sector.

In these models, one can still relate the couplings to the Model III notation. For example, in the BGL model above:

$$\lambda_{bs}\frac{(2m_b m_s)^{1/2}}{v} \leftrightarrow \frac{m_b}{v}\left(\frac{v_1}{v_2}+\frac{v_2}{v_1}\right)V_{ts}^* V_{tb}\cos(\beta-\alpha)$$

which numerically gives $\lambda_{bs} = 0.14(\frac{v_1}{v_2} + \frac{v_2}{v_1})\cos(\beta-\alpha)$

This is quite reasonable and consistent with meson mixing

In the lepton sector, the BGL model correspondence to Model III is

$$\lambda_{\mu\tau}\frac{(2m_\tau m_\mu)^{1/2}}{v} \leftrightarrow \frac{m_\tau}{v}\left(\frac{v_1}{v_2}+\frac{v_2}{v_1}\right)V^*_{\nu\mu}V_{\nu\tau}\cos(\beta-\alpha)$$

which numerically gives

$$\lambda_{\mu\tau} = 1.4\left(\frac{v_1}{v_2}+\frac{v_2}{v_1}\right)\cos(\beta-\alpha)$$

Note that if one were considering the heavy neutral scalar, the cosine factor would be a sine, which is much larger, giving possibly large FCNC effects. This will be discussed shortly.

Flavorful models

Altmannshofer, et al. 1507.07927, 1712.01847, 1805.08659
Ghosh, Gupta, Perez, 1508.01501
Botella, et al., 1602.08011

These models couple the first two generations to one doublet and the third generation to another. It is assumed that one set of Yukawa couplings is rank-1, so that the G_F symmetry acting on the first two generations is preserved. This protects flavor transitions between the first two generations.

An early (2015) paper by Altmannshofer et al. proposed a 2HDM as well as a composite Higgs model which does this – the paper focused on the now vanished $h \to \mu\tau$ signal but also mentioned the quark sector. Ghosh (2015) proposed a similar model motivated by the small 1st and 2nd generation masses. Botella, Branco, Rebelo and Silva-Marcos (2016) consider the model in the quark sector, noting a relationship between the 2HDM model and a BGL model – they studied the phenomenology in detail and also considered an EFT analysis involving heavy vector-like quarks.

Altmannshofer et al (2016) performed a comprehensive analysis of the collider phenomenology of the 2HDM model, studying the dimuon decay of the Higgs, the mu-tau decay and noted that the charmed decays of a heavy Higgs could be comparable to top decays. The charged Higgs decays into third generation fields was suppressed. They also note that $B_s \rightarrow \mu\tau$ and $B \rightarrow K\,\mu\tau$ could be substantial. A method of generating the flavorful 2HDM structure naturally is by generating Yukawa coupling by the vev of a flavon potential, "locking" the flavors by horizontal symmetries (see Altmannshofer et al, 2017)

A very comprehensive review of all of the flavorful models, including other "twisted" versions, with a very extensive list of references can be found in the PhD thesis (March 2020) of Brian Maddock.

FCNC effects on heavy Higgs decays

In the limit in which the heavy scalars all decouple, $\cos(\beta - \alpha)$ vanishes, so the light Higgs has couplings identical to the SM. Thus, the flavor-changing neutral couplings of the light Higgs (which vanish in the SM limit) are proportional to $\cos(\beta - \alpha)$

But this means that the flavor-changing neutral decays of heavy Higgs scalars will be proportional to $\sin(\beta - \alpha)$ which is much bigger.
In addition, in BGL models, the couplings in the lepton sector are proportional to the PMNS elements, which are much larger than the CKM elements.

BGL Model

The flavor changing couplings of the light Higgs in the BGL model are (no sum on j)

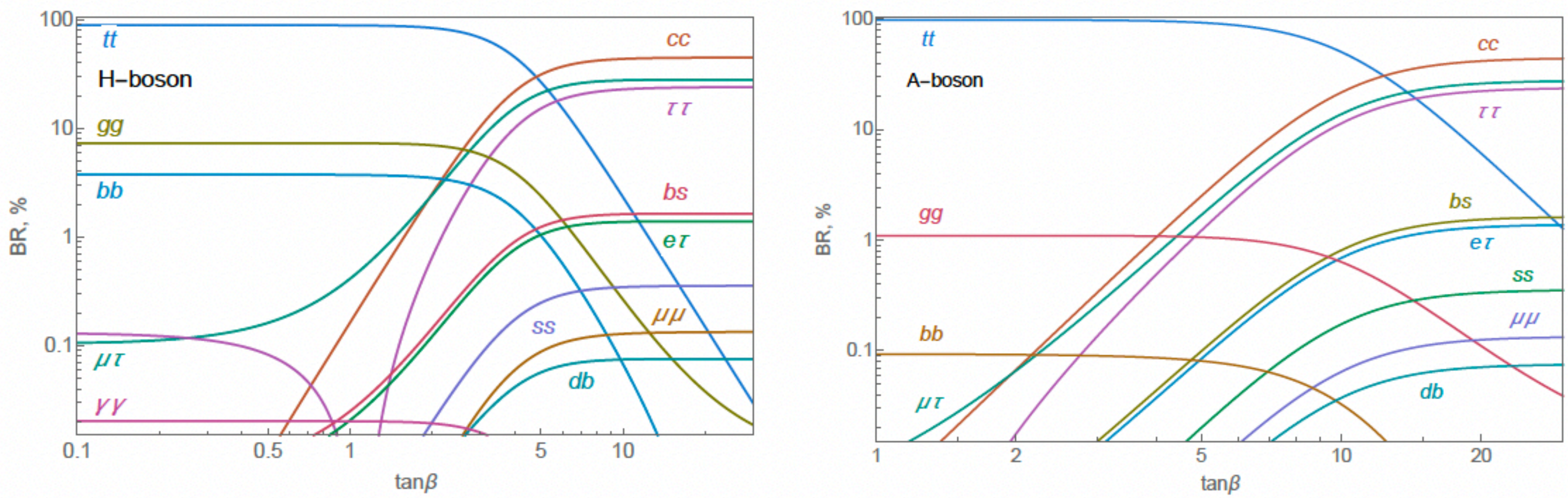
$$Y_{\mu\tau} = -U^*_{\mu j} U_{\tau j} \frac{M_\tau}{v} \cos(\beta - \alpha)\left(\frac{v_1}{v_2} + \frac{v_2}{v_1}\right)$$

This corresponds to three different models, depending on j.

For the couplings of the heavy Higgs, the cos(β−α) turns into sin (β−α), which is close to one. Thus, H → μτ can occur at a substantial rate. This is also true for pseudoscalar decay.

M. Sher and K. Thrasher, 1601.03973
A. Bednyakov and V. Rutberg, 1809.09358

MS and Thrasher studied this and argued that for a substantial part of parameter space, the branching ratios of H → μτ and A → μτ can be as high as 60%. An error was found by Bednyakov and Rutberg who showed that it was only as high as 30%



The above is for an H or A mass of 350 GeV. If it is a little lower, the top-top decay disappears.

Thus the BGL model can have a huge branching ratio of a heavy neutral scalar into a muon and a tau.

The analysis of this process at the LHC was carried out by Hou, et al (1901.10498)

Conclusions

Extensions of the Higgs sector will generally have tree-level FCNC.
A discrete symmetry can get rid of them, but there is often no other motivation for it.

A popular ansatz for the size of the FCNC couplings has been severely challenged recently and is close to/has been excluded.

An example of Minimal Flavor Violation, the BGL models, are still viable, but still require an otherwise unmotivated global symmetry.

In many of these models, the heavy Higgs bosons can have very large FCNC decays, which will affect LHC search strategies