Possible Anomalies in Higgs Decay: Charm Suppression and Flavour-Violation

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Abstract

It is suggested that the Higgs boson may have a branching ratio into the $c\bar{c}$ mode suppressed by several orders of magnitude compared with conventional predictions and in addition some small but detectable flavour-violating modes such as $b\bar{s}$ and $\tau\bar{\mu}$. The suggestion is based on a scheme proposed and tested earlier for explaining the mixing pattern and mass hierarchy of fermions in terms of a rotating mass matrix. If confirmed, the effects would cast new light on the geometric origin of fermion generations and of the Higgs field itself.
Particle physics is, and has been for some time, in the unusual position of having in the Standard Model an excellent description of experiment, with as yet no established deviation to give a hint of the origin of those very intricate but ad hoc structures built into the model. Fortunately, the situation may soon change with the commissioning of the LHC (Large Hadron Collider). One of the first discoveries by the LHC is likely to be the Higgs boson, if it exists, and a study of its properties, looking for departures from Standard Model predictions, may well provide us with the first indications for new physics lying behind and/or beyond.

It is thus with considerable interest for us to note that a scheme we have previously suggested to “explain” fermion mixing and mass hierarchy, two outstanding features built into the Standard Model, may in fact lead to deviations from the standard predictions for Higgs decay. Two in particular, namely, the suppression of the $c\bar{c}$ mode, and the occurrence of the flavour-violating modes $b\bar{s}$ and $\tau\bar{\mu}$, may be detectable soon after the Higgs boson’s discovery. To display how these conclusions result, based on a fermion mass matrix rotating with scale, we shall need first to outline briefly how this rotation scheme works.

As already noted, two outstanding features inserted as inputs to the Standard Model are the mixing patterns and hierarchical masses of quarks and leptons, which remain among the subject’s greatest mysteries, having as yet no generally accepted explanation and accounting for some two-thirds of the model’s twenty odd empirical parameters. Among those attempts on offer for explaining the origin of these features is that of ours which suggests that both these two phenomena arise from the change in orientation (rotation) with change in scale of the fermion mass matrix in generation space. Just as the strength of couplings and mass values can change with scale under renormalization, so can, no doubt, the orientation of fermion mass matrices. Indeed, even in the Standard Model as conventionally formulated, rotation of fermion mass matrices will result as a consequence of mixing from the renormalisation group equations [[1]]. But, whereas in the Standard Model it is the pre-assumed fermion mixing which is driving the rotation, the suggestion now is that it is the rotation instead which is giving rise to the mixing of fermions, and as a by-product, also the mass hierarchy.

That a rotating fermion mass matrix can give rise to both mixing and mass hierarchy is in itself a very simple idea which can easily be seen as follows. One starts with a fermion mass matrix of the usual form:

$$m_\frac{1}{2}^{(1 + \gamma_5)} + m_\frac{1}{2}^{(1 - \gamma_5)},$$

(1)
which, following Weinberg [2], one can always rewrite by a relabelling of the singlet right-handed fields, with no change in physics, in a Hermitian form independent of $\gamma_5$, a form we shall henceforth adopt. Suppose now this matrix is factorisable, meaning that it is of the form:

$$m = m_T \alpha \alpha^\dagger,$$

(2)

where $\alpha$ is a global (i.e. $x$-independent) vector in generation space. We can even suppose that $\alpha$ is universal and that only the numerical coefficient $m_T$ depends on the fermion type (species), i.e. whether up-type quarks ($T = U$), down-type quarks ($T = D$), charged leptons ($T = L$), or neutrinos ($T = N$). Obviously, such a mass matrix has only one massive state represented by the vector $\alpha$, and zero mixing, i.e. only the identity matrix as the mixing matrix. This is not unattractive as a starting point at least for quarks, as has occurred already a long time ago to many people [3], but is clearly insufficiently realistic in detail.

However, if one now says that the vector $\alpha$ rotates with changing scale $\mu$, as proposed, then the situation becomes very interesting. All quantities now depend on the scale $\mu$ and one has to specify at which scale the mass or state vector of each particle is to be measured. Suppose one follows the usual convention and define the mass of each particle as that measured at the scale equal to its mass, we find then that mixing and mass hierarchy would immediately result. This is apparent already in a situation where one takes account only of the two heaviest states in each species, e.g. $t, c$ in up-type quarks ($U$), $b, s$ in down-type quarks ($D$), which “planar approximation”, as we shall see, is already good enough for most of the considerations in this paper.

By (2) then, taking for the moment $\alpha$ to be real and $m_T$ constant for simplicity, we would have $m_t = m_U$ as the mass of $t$ and the eigenvector $\alpha(\mu = m_t)$ as its state vector $v_t$. Similarly, we have $m_b = m_D$ as the mass and $\alpha(\mu = m_b)$ as the state vector $v_b$ of $b$. Next, the state vector $v_c$ of $c$ must be orthogonal to $v_t$, $c$ being by definition an independent quantum state to $t$. Similarly, the state vector $v_s$ of $s$ is orthogonal to $v_b$. So we have the situation as illustrated in Figure 1 where the vectors $v_t$ and $v_b$ are not aligned, being the vector $\alpha(\mu)$ taken at different values of its argument $\mu$, and $\alpha$ by assumption rotates. This gives then the following CKM mixing (sub)matrix in the “planar approximation” for the two heaviest states:

$$
\begin{pmatrix}
V_{cs} & V_{cb} \\
V_{ts} & V_{tb}
\end{pmatrix} = 
\begin{pmatrix}
\langle v_c | v_s \rangle & \langle v_c | v_b \rangle \\
\langle v_t | v_s \rangle & \langle v_t | v_b \rangle
\end{pmatrix} = 
\begin{pmatrix}
\cos \theta_{tb} & \sin \theta_{tb} \\
-\sin \theta_{tb} & \cos \theta_{tb}
\end{pmatrix},
$$

(3)
which is no longer the identity; hence mixing. Clearly, the same argument can be extended to the three generation case and, just by virtue of rotation, a full, non-trivial CKM matrix would result. The same again when applied to leptons will lead to a nontrivial MNS mixing matrix and give rise to neutrino oscillations.

Next, what about hierarchical masses? From (2), it follows that $v_c$ must have zero eigenvalue at $\mu = m_t$. But this value is not to be taken as the mass of $c$ which we agreed has to be measured at $\mu = m_c$. In other words, $m_c$ is instead to be taken as the solution to the equation:

$$\mu = \langle v_c | m(\mu) | v_c \rangle = m_c |\langle v_c | \alpha(\mu) \rangle|^2.$$  \hspace{1cm} (4)

A nonzero solution exists since $\alpha$ by assumption rotates so that at $\mu \neq m_t$, it would have rotated to some direction different from $v_t$, as illustrated in Figure 2 and acquired a component, say $\sin \theta_{tc}$, in the direction of $v_c$ giving thus:

$$m_c = m_t \sin^2 \theta_{tc},$$  \hspace{1cm} (5)

which will be small if the rotation is not too fast. Clearly, similar arguments when applied to the 3 generation case would lead to a small nonzero mass for $u$. They could be repeated also for the down-type quarks and charged leptons, and with a further twist supplied by the see-saw mechanism, for neutrinos as well. Hence we have the mass hierarchy as claimed, with the two lowest generations of each type (or species) acquiring their small nonzero masses as if by “leakage” from the heaviest generation, again simply by virtue of the rotation.
Figure 2: Masses for lower generation fermions from a rotating mass matrix via the “leakage” mechanism.

The examples in the preceding paragraphs show that both mixing and mass hierarchy will naturally follow as consequences of rotation, (For a more detailed discussion, see e.g. [4]) but will the results be anything like those experimentally observed? This question was examined in an earlier paper [5] where the rotation angles needed for explaining the mixing parameters and mass ratios obtained in experiment were plotted against the scale $\mu$. If the explanation is correct, then the angles so extracted should all lie on one smooth curve. The figure so obtained in the “planar approximation” is reproduced in Figure 3 here as it will be of use to us later. One sees that the idea is well-sustained. A full analysis taking account of all three generations has also been performed which, though still entirely consistent with the rotation hypothesis, does not add too much to Figure 3 given the imprecision of neutrino data yet available [5]. We have not updated the fit in Figure 3 with more recent data since there have been only small changes for most of the quantities needed, which will not materially affect the fit and any conclusions that will be drawn from it later.

Suppose we take seriously the proposal that rotation does offer a feasible explanation for fermion mixing and hierarchy. Then one has to pose oneself the following two questions. First, can one device a physically viable and

\[ \alpha \text{ at } \mu = m_c \]

\[ t \]

\[ \theta_{tc} \]
Figure 3: The rotation angle changing with scale as extracted from data on mass ratios and mixing angles and compared with the best fit to the data (dashed curve) and the earlier calculation by DSM (full curve) [6], in the planar approximation.
theoretically consistent model in which the rotation required by experiment is reproduced? Secondly, apart from explaining existing data, are there any new predictions which can be tested by experiment? The answer to the first has been and is still being diligently pursued. So far two quite detailed models have been constructed, one phenomenological [6, 7] which fits experiment quite well but is theoretically incomplete, while the other starts from a much sounder theoretical base but has not yet been sufficiently studied to show if it yields a good fit to experiment [8]. However, the details of these models need not bother us in this paper which is devoted to the second question and, as we shall see, the predicted anomalies in Higgs decay we are discussing all depend only on the general concept of mass matrix rotation, not on any details of either of the two models proposed.

To investigate Higgs decay, we shall need its Yukawa coupling. One obvious possibility which will give the required factorisable mass matrix (2) is the following:

\[ A_{YK} = \rho_T \alpha_\alpha \bar{\psi}_L \phi \psi_R \alpha^\dagger + \text{h.c.} \]  

and indeed, this is the Yukawa coupling obtained in our theoretical model [8]. Choosing the gauge in which \( \phi \) points in the up direction and is real, then expanding the remaining real component about its minimum value \( \zeta_W, \) thus: \( \zeta_W + H \), we obtain to zeroth order the fermion mass matrix as in (2) with \( m_T = \rho_T \zeta_W \), and to first order the coupling matrix of the Higgs boson to the fermions as:

\[ Y = \rho_T \alpha \alpha^\dagger. \]

Superficially, this result looks familiar, namely that the fermion mass and Higgs coupling are proportional to each other. However, as usually meant, the proportionality is between the mass and the Higgs coupling of each of the fermions individually, namely that \( m_i = \zeta_W y_i \), with \( i \) denoting the individual fermion state, but here it is a proportionality between matrices: \( m = \zeta_W Y \). And both these matrices rotate. Having seen above that the rotation of the mass matrix \( m \) alone already leads to intriguing consequences, we shall not be surprised that here too the rotation of the Higgs coupling matrix \( Y \) will give some new and interesting results.

For the present, let us concentrate just on Higgs boson decay into fermion-antifermion pairs, where the relevant couplings are to be extracted from (7). Since (7) depends on the vector \( \alpha \) which in turn depends on the scale \( \mu \), i.e. rotates, we have first to specify at what scale to take this \( \alpha \) and what value it will then possess. For Higgs decay, the conventional wisdom is to take the scale at the Higgs mass \( M_H \), a convention we adopt. Now, \( \alpha \) rotates
with scale according, presumably, to some renormalization group equation, which is a differential equation in $\mu$ telling us how $\alpha$ varies with changes in $\mu$. Therefore, to evaluate $\alpha$ at $\mu = M_H$ as prescribed, we shall need first to calibrate $\alpha$ by an initial condition. We propose to do so as follows. At the energy scale $\mu = 2m_f$, i.e. at the threshold of production of the $f\bar{f}$-pair, we say the fermions are at rest so that the Higgs coupling there should be proportional to the fermion mass, thus:

$$\langle \nu_f | Y(\mu = 2m_f) | \nu_f \rangle = \rho_T |\langle \nu_f | \alpha(\mu = 2m_f) \rangle|^2 = m_f / \zeta_W. \quad (8)$$

Recall now that previously, when extracting the fermion masses from the rotating mass matrix, we had put:

$$m_f = \zeta_W \rho_T |\langle \nu_f | \alpha(\mu = m_f) \rangle|^2, \quad (9)$$

though without stating so explicitly. We see that we have now in (8) calibrated our $\alpha$ differently; namely we have shifted the scale by an overall factor 2 compared with (9), but otherwise there is no difference between the two calibrations. This means first that our calibration here is self-consistent, being independent of the fermion $f$ with which we choose to calibrate. Secondly, it also means that the value we seek for the factor $\alpha_H \alpha_H^\dagger$ for Higgs decay at $\mu = M_H$, which we may interpret as the “state tensor” of the Higgs state, can just be read off, for phenomenological purposes, from the trajectory for $\alpha(\mu)$ obtained in [5] by fitting fermion masses and mixing parameters, i.e. apart from a change in scale by a factor 2, or just a shift of the origin by $\ln 2$ there on the $\ln \mu$ plot. That there should be such a shift in scale between the calibrations (8) and (9) is not surprising, given that we are dealing here with two different types of processes, one type, Higgs decays, involving two fermions in the final states, and the other type, fermion propagation as concerns masses and mixing angles, involving only a single fermion. Nor is this shift, as we shall see later, of much qualitative significance.

The conclusions of the preceding paragraph then give the coupling for Higgs decaying into an $f\bar{f}$ pair as:

$$A(H \to f\bar{f}) = \rho_T |\nu_f \cdot \alpha_H|^2. \quad (10)$$

Specialising now to the $c\bar{c}$ and $b\bar{b}$ modes, we have:

$$\frac{\Gamma(H \to c\bar{c})}{\Gamma(H \to b\bar{b})} \sim \frac{\rho_T^2 |\nu_c \cdot \alpha_H|^4}{\rho_D^2 |\nu_b \cdot \alpha_H|^4}, \quad (11)$$
\[ \rho_U / \rho_D \sim m_t / m_b \sim 40.8, \] in which estimate, as in all other estimates of similar nature in this paper, we have taken the values of measured quantities from \[9\]. Since only the two heaviest generations are involved, the planar approximation of \[5\] should be enough for the present exploration. In that case, the state vectors \(v_c, v_b\) as well as the vector \(\alpha_H\) are each given just by an angle \(\theta\), the value of which can be read off at the appropriate values of \(\mu\) from Figure 3, or else calculated with the simple formula obtained there as the best fit. Remembering now the shift in scale, we note that the value of \(\theta_H\) corresponding to \(\alpha_H\) is to be the value of \(\theta\) at \(\mu = M_H / 2\) on this plot.

The value of \(M_H\) is bounded by present experiment to be above 115 GeV and is generally assumed to be below the \(t\) mass. Taking then as example \(M_H = 150\) GeV, we obtain for \(\mu = 75\) GeV the value \(\theta_H \sim 0.0040\), which gives then:

\[ |v_c \cdot \alpha_H| = \sin(\theta_H - \theta_t) \sim 0.0040; \quad |v_b \cdot \alpha_H| = \cos(\theta_b - \theta_H) \sim 0.9993, \quad (12) \]

and the branching ratio (11) as:

\[ \frac{\Gamma(H \rightarrow cc)}{\Gamma(H \rightarrow bb)} \sim 4.3 \times 10^{-7}. \quad (13) \]

This is nearly five orders of magnitude less than the conventional prediction of this branching ratio \(\sim m_c^2 / m_b^2 \sim 0.09\). We note in passing that had we not shifted the scale by a factor 2 as we did above, we would have obtained \(\theta_H \sim 0.00059\) instead, which would have suppressed the \(c\bar{c}\) mode even further.

The reason for this suppression for \(c\bar{c}\) mode in the rotation scenario is clear. The factor \(m_c^2\) which occurs in the standard conventional formula for this branching ratio is given in the rotation picture as \(m_t^2 \sin(\theta_c - \theta_t)^4\), where \(\sin(\theta_c - \theta_t)\) represents the component of \(\alpha\) taken at \(\mu = m_c\) in the direction of \(v_c\), i.e. orthogonal to \(v_t\). Now, in the present scenario, we are instead to take the value of \(\alpha\) at \(\mu = M_H\) which has a value close to \(v_t\), since \(M_H\) is close to \(m_t\), and has therefore a very small component in the direction of the state vector \(v_c\) of \(c\). Hence we have the suppression. It comes about as a consequence, first, of rotation and, secondly of our insistence in evaluating the Higgs coupling (or state tensor) at the scale \(\mu = M_H\) thought appropriate for Higgs decay in accordance to conventional wisdom.

Clearly, the same arguments will apply to other \(ff\) modes for \(f\) belonging to the two lighter generations, giving, for example, for Higgs decaying into \(s\bar{s}\) and \(\mu\bar{\mu}\) the branching ratio over the main mode \(b\bar{b}\) estimates of order respectively \(1.8 \times 10^{-6}\) and \(2.9 \times 10^{-6}\), again for \(M_H = 150\) GeV. But the
conventional predictions for these modes being in themselves rather small, namely $\sim 6 \times 10^{-4}$ and $\sim 6.4 \times 10^{-4}$ respectively, a further suppression of these may not be so readily seen. However, a suppression of the $c\bar{c}$ mode from the respectable standard estimate of $\sim 0.09$ may be noticeable soon after the Higgs boson is found.

Perhaps more surprisingly, similar considerations to those above in the same rotation scenario will lead also to flavour-violations in Higgs decay. The Higgs coupling (or the Higgs boson “state tensor”) $\alpha_H\alpha_H^\dagger$ is in general nondiagonal when sandwiched between the fermion state vectors $\mathbf{v}_f$ and $\mathbf{v}_f'$. It gives thus nonzero rates to flavour-violating modes, but the branching fractions for these are generally quite small. Take, for example, $H \to \tau\bar{\mu}$. Since only the two heaviest generation leptons are involved, we may again work with the planar approximation of Figure 3 from which we read the value of $\theta_\tau \sim 0.0698$. Hence, and from the value of $\theta_H \sim 0.0040$ given previously, we have:

$$\frac{\Gamma(H \to \tau\bar{\mu})}{\Gamma(H \to b\bar{b})} \sim \frac{m_\tau^2 \cos^2 \theta_H \sin^2 \theta_H \cos^2 \theta_H}{m_b^2} \sim 7.7 \times 10^{-4}. \quad (14)$$

which, being so distinctive though small, may eventually be seen. Another possibility to try may be $H \to b\bar{s}$ with a slightly larger branching ratio over the dominant $b\bar{b}$ mode of about $1.48 \times 10^{-3}$ but perhaps is harder to identify.

This prediction of flavour-violation in Higgs decay is at first sight quite disturbing, as the effect may propagate and give rise to flavour-violation elsewhere where it is already very strongly bounded by experiment. We therefore examine the following two cases which look to us most dangerous, namely $m_{B^0_{sH}} - m_{B^0_{sL}}$, the mass difference between the two neutral $b\bar{s}, s\bar{b}$ bound states, and the rate for the decay mode $\tau^\pm \to \mu^+\mu^-\mu^\pm$, in both of which the rotation scenario is likely to give the largest effects and the existing experimental bounds are already quite strict.

For the first quantity, following standard procedure, given e.g. in [10], we obtain the estimate for the contribution from Higgs exchange:

$$m_{B_{sH}^0} - m_{B_{sL}^0} \sim \frac{\rho_D^2}{M_H^2} |\alpha_H . \mathbf{v}_b|^2 |\alpha_H . \mathbf{v}_s|^2 F_{B_s} m_{B_s}, \quad (15)$$

where $\rho_D \sim m_b/\phi_0 \sim 0.0171$, $\phi_0$ being the vacuum expectation value of the Higgs field $\sim 246$ GeV, $m_{B_s} \sim 5366$ MeV, and $F_{B_s}$ is a factor related to the decay constant $f_{B_s}$ of the $B_s$ meson, which, if assumed to be similar to the analogous factor $F_K = f_K^2/3$ occurring in the formula for the FCNC estimate
for the $K_L - K_S$ mass difference, gives $F_{B_s} \sim 5 \times 10^{-3}$ GeV$^2$. This gives an estimate for the above new contribution as:

$$m_{B_s^0} - m_{B_s^0} \sim 4.8 \times 10^{-10} \text{ MeV}$$

which is more than an order of magnitude below the experimentally measured value of $117 \times 10^{-10}$ MeV. Given the difficulty of making accurate theoretical predictions for such hadronic quantities, the Higgs contribution is unlikely to be noticeable at present and thus causes no problem, but it may be something to look for in future when experimental measurement and theoretical interpretation both continue to improve.

For $\tau^\pm \rightarrow \mu^\pm \mu^- \mu^\pm$ decay, one can make use of its similarity to $\tau \rightarrow \nu_{\tau} \mu \nu_{\mu}$ decay when one neglects in both cases the masses of the final particles to give the ratio of their total rates as:

$$\frac{\Gamma(\tau^\pm \rightarrow \mu^\pm \mu^- \mu^\pm)}{\Gamma(\tau \rightarrow \nu_{\tau} \mu \nu_{\mu})} \sim \frac{1}{64} \left( \frac{\rho_L}{g_W} \right)^4 \left( \frac{M_W}{M_H} \right)^4 |\alpha_H . V_\tau|^2 |\alpha_H . V_\mu|^6,$$

where $\rho_L \sim m_\tau/\phi_0 \sim 7.2 \times 10^{-3}$, $g_W \sim 0.23$ is the coupling and $m_W \sim 80.4$ GeV the mass of the $W$ boson. Feeding in then the values for $\alpha_H . V_\tau$ and $\alpha_H . V_\mu$ obtained earlier when deriving (14), we obtain an estimate for the ratio (17) of about $1 \times 10^{-16}$, or a branching ratio over total of about $2 \times 10^{-17}$, which is way below the present experimental bound of around $3 \times 10^{-8}$. This very small value of the estimated rate for (17) comes partly from the smallness of the coupling strength $\rho_L$ itself but partly also from the smallness of its branching fraction into $\mu$, namely $|\alpha_H . V_\mu|$.

A similar analysis applied to other mass differences and to other flavour-violating decays give even smaller estimates. It appears thus likely that the prediction of flavour-violating modes in Higgs decay is not in any contradiction with existing bounds on flavour-violation elsewhere. We hope to give a more detailed and systematic account of the analysis and its result in a separate report.

In charm suppression and flavour-violating modes in Higgs decay, we seem thus to have identified two possible deviations from the Standard Model which can be tested soon after the Higgs boson’s experimental discovery. We say “possible” only, because we do not have, as yet, a fully developed rotational model which allows us to derive the required results from first
principles. As it is done here, based merely on the general concept of rotation, we arrived at the above results by extending the logic previously tested in deriving the mixing pattern and mass hierarchy just one step further to decay processes. It is thus not clear at this stage that the same logic can be consistently extended to cover all possible processes involving an arbitrary number of particles, as would be necessary if the logic is correct, although of course we have explored some other examples and found yet no inconsistency. Nevertheless, the experimental discovery of the Higgs boson being, we hope, imminent, we believe this possibility worth airing, given that, if proved correct, it will open a valuable window into the foundations of the Standard Model. This is because the rotation idea has the potential of explaining how fermion mixing and mass hierarchy arise, which are two of the most mysterious assumptions, and most costly in terms of parameters, built into the Standard Model. Besides, the prediction, if confirmed, may also teach us a great deal about the possible origin both of fermion generations and of the Higgs scalar fields, two fundamental features which, in the rotation models are both intimately connected with fermion mixing and fermion mass hierarchy, and are both given a geometrical significance, with fermion generations arising as dual colours and Higgs scalar fields arising as frame vectors in internal symmetry space.

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