The Case for a 750 GeV Quark

Scott Chapman†,*

†Institute for Quantum Studies, Chapman University, Orange, CA 92866, USA

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The latest measurements of the CKM matrix imply a 3-sigma variance from unitarity. If that variance persists with more statistics, it could be hinting at the existence of a new (seventh) quark that mixes with the 6 known quark flavors. Also, measurements of the up-strange CKM element differ by 2.9 sigma, depending on whether vector current or axial vector current decays are considered. One explanation for that variance would be that the W boson connects the right-handed components of some quarks. Thirdly, high energy collisions are consistently producing roughly twice the number of charm quarks relative to the centers of the theoretical ranges of QCD predictions. Searches for a new heavy quark decaying to a light quark have set a lower mass limit of 690 GeV. With these data as a backdrop, it would be interesting to search for a new down-type quark with mass of 750 GeV to 1 TeV whose right-handed component connects via the W boson with the right-handed charm quark.

In the Standard Model, there are three generations of down-type quarks and three generations of up-type quarks. The down-type quarks have a 3x3 mass matrix $M_D$ whose rows and columns connect left- and right-handed quarks, respectively. Similarly, the up-type quarks have their own 3x3 mass matrix $M_U$. These mass matrices can be diagonalized by multiplying them by a different unitary matrix on each side. In other words, the following mass matrices are diagonal: $V_L^D M_D V_R^{D†}$ and $V_L^U M_U V_R^{U†}$, where each of the 3x3 V matrices is unitary. The diagonal mass matrices determine the mass eigenstates (down, strange, beauty) and (up, charm, top).

In the Standard Model, the W boson connects only the left-handed up- and down-type quarks from the same generation. The Cabibbo-Kobayashi-Maskawa (CKM) matrix translates this connection to the mass eigenstates. Specifically, the Standard-Model CKM matrix is given by:

$$V^{CKM} = V_L^U \left( \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{array} \right) V_R^{D†} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

(0.1)

The unit matrix in the middle expression above has been inserted to emphasize the fact that in the Standard Model, the left-handed components of each generation are connected. As the product of two unitary matrices ($V_L^U$ and $V_R^{D†}$), $V^{CKM}$ is also a unitary matrix.

The latest measurements of the CKM matrix lead to a first-row unitarity calculation of $0.9985 \pm 0.0005$ [1], which is a 3σ variation from the unitary value of 1 predicted by the Standard Model. Either of the following could lead to a nonunitary CKM matrix: (i) there are more than six quarks and/or (ii) the W boson has right-handed interactions with some quarks (not exclusively left-handed).

If the W boson has some right-handed interactions, then measurements of CKM elements from vector-current-mediated decays should differ from those from axial-vector-current-mediated decays. Such differences are seen experimentally at the 2-3σ level. For example, the following 2.9σ difference is measured:

Vector: $|V_{us}| = 0.22309 (40) (39) (3)$
Axial Vector: $|V_{us}| = 0.2254 (3) (4) (3)$

(0.2)

where the first (second) result above is from semi-leptonic (leptonic) kaon decay [2].

Another example is the fact that $V_{cb}$ measured via exclusive decays differs by 2-3σ from $V_{cb}$ via inclusive decays [3]. A similar discrepancy is seen for $V_{ub}$. Previous authors have suggested the possibility of the W boson having right-handed interactions to help explain the tension generated by these $V_{cb}$ and $V_{ub}$ measurements [4–6].

It is worth reviewing the direct experimental evidence pertaining to whether left-handed or right-handed quark components are connected via the W boson. Recent top quark polarization measurements by ATLAS confirm that for the third generation, the data are consistent with the W boson connecting only left-handed quarks [7]. In addition, measurements by Belle of tau lepton polarization in $b \rightarrow c$ semi-leptonic decays make it more likely that since the third generation connection is left-handed, then the second generation is also left-handed [8].

On the other hand, there is no direct evidence that the W-boson connection for first generation quarks is left-handed. If it were the case that the spin of the proton was just the sum of the spins of its valence quarks, then nuclear beta decay polarization measurements would imply that the first-generation connection was left-handed. However, the spin of the proton appears to come primarily from gluons and quark orbital angular momentum [9]. In the absence of direct experimental evidence, there is nothing that prevents a model from having right-handed (instead of left-handed) first-generation quark interactions with the W boson, as long as it can reproduce the observed CKM matrix.

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* schapman@chapman.edu
As a concrete example of one way to incorporate right-handed W boson interactions, one may consider the model presented in [10] that utilizes an unusual form of broken supersymmetry. In that model, there are still three generations of up-type quarks, but there are four generations of down-type quarks (so the mass matrix $M_D$ is a 4x4 matrix). Like the Standard Model, the second and third generation W boson connections are left-handed. But unlike the Standard Model, the first-generation connection is right-handed, and there is also a right-handed connection between the fourth down-type quark and the charm quark.

Due to these different connections, the model employs the following 2 versions of CKM matrices:

$$V_{\pm}^{CKM} = V_R^U \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix} V_R^{D\dagger}$$

with

$$V_L^U \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} V_L^{D\dagger}. \quad (0.3)$$

The second term has the left-handed connections described above, while the first term has the right-handed connections. The “CKM” matrices are not square, they are 3x4 matrices.

In this model, a different CKM matrix should be used depending on whether a vector current or an axial vector current process is being considered. Specifically:

Vector current decays: $V_{+}^{CKM}$

Axial vector current decays: $V_{-}^{CKM}. \quad (0.4)$

For CKM measurements involving vector current decays (e.g. an exclusive semi-leptonic decay from one spin-0 meson to a different spin-0 meson), $V_{+}^{CKM}$ should be used for comparison to this model. For CKM measurements involving axial vector current decays (e.g. the purely leptonic decay of a spin-0 pseudo-scalar meson), $V_{-}^{CKM}$ should be used. From the form of $V_{\pm}^{CKM}$, it is apparent that the 3x3 CKM submatrix of this model is not expected to be unitary.

Using the model of [10], a mass of 750 GeV can be chosen for the fourth down-type quark. Elements of the mass matrices $M_U$ and $M_D$ can then be chosen such that after they are diagonalized, masses of the 6 known quarks are reproduced, and the following vector CKM matrix is generated:

$$|V_{+}^{CKM}| = \begin{pmatrix} 0.9745 & 0.2242 & 0.0037 & 0.0002 \\ 0.2228 & 0.963 & 0.0341 & 1.119 \\ 0.006 & 0.0379 & 0.9997 & 0.00002 \end{pmatrix}. \quad (0.5)$$

For a tree-level calculation, the values of the first three columns are relatively close to the values experimentally measured from vector current decays. Agreement with measurements could be further improved by the model allowing complex numbers in the mass matrices (for simplicity, only real numbers are used) or allowing more parameters.

Due to having both left- and right-handed connections, the model generates the following:

|   | Axial | Vector |
|---|-------|--------|
| Experiment | 0.2254 (3) (4) (3) | 0.22309 (40) (39) (3) |
| Model     | 0.2252 | 0.2242 |

This shows that the model of [10] generates different results for vector current and axial vector current decays. The model also generates the following:

|   | Inclusive | Exclusive |
|---|-----------|-----------|
| $|V_{cb}|_{exp}$ | 42.2 ± 0.8 | 39.5 ± 0.9 |
| $|V_{cb}|_{Model}$ | 40.1 | 39.6 |
| $|V_{ub}|_{exp}$ | 4.25 ± 0.12 ± 0.23 | 3.70 ± 0.10 ± 0.12 |
| $|V_{ub}|_{Model}$ | 4.30 | 3.70 |

In other words, for these CKM results, the model with its extra quark and right-handed connections does a better job of reproducing the data than the Standard Model.

Most of the searches for a new heavy down-type quark assume that the quark will decay into either (i) a top quark and W boson or (ii) a Z Boson or Higgs Boson and a lighter down-type quark [11]. The above assumptions are not valid for the seventh quark proposed here. Its decay via the W boson is to a charm quark (not a top), it has no flavor-changing connection via a Z boson, and it does not have a tree-level connection with the observed Higgs boson.

The most recent search that is relevant to the quark proposed here was published by ATLAS in 2015 [12]. In that paper, a 95% confidence lower mass limit of 690 GeV was established for a heavy quark that decays via the W boson to a light quark (including a charm quark). Interestingly, due to the fact that the experiment measured more events than predicted by Standard Model backgrounds, the data appear to be almost as consistent with the existence of an 800 GeV quark as they are with no new heavy quark. Interpolating the reported results, it appears that the data might actually be slightly more consistent with a 750 GeV quark than with no new quark. It would be interesting to update that experiment with more data in the 750 GeV to 1 TeV range.

If a quark like the one proposed here does exist, one would expect to see more charm in high energy collisions than the amount predicted by the Standard Model. This is indeed seen experimentally.

Four Monte Carlo packages that model high energy collisions at the LHC using the Standard Model next-to-leading order calculations are referenced in [13]. Three of them underpredict the amount of charm seen in those experiments by a factor of 2, but they include very large theoretical error bars that put the upper range of their results close to the measured values. Experimentalists have
remarked on the fact that these experiments are measuring twice the amount of charm quarks as compared to Standard-Model expectations [14].

It should be noted that if the quark proposed here does exist, then a meson comprised of that quark and an antidown quark would be able to decay into two photons. The famous 750 GeV diphoton bump of 2015 was greatly diminished in 2016 with more data, but combining the data, there is still a roughly $2\sigma$ bump there (and a hint of another bump at double that energy) [15].

For these reasons, it would be interesting to search for a new down-type quark via a resonance in charm quark production. The model referenced above is not highly sensitive to the mass of the new quark, and reasonable fits can be obtained for a quark masses between 750 GeV and 1 TeV. But for a mass above around 1 TeV, the fits do not work as well, so the model predicts a mass below that value.

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