Measuring the Magnitude of the Fourth-Generation CKM$_4$

Matrix Element $V_{t'b'}$

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Abstract

We study the decays of heavy chiral $(t', b')$ quarks in a four-generation extension of the Standard Model. If the difference between the $t'$ and $b'$ masses is smaller than the $W^\pm$ mass, as favored by precision electroweak measurements, then the Cabibbo-Kobayashi-Maskawa favored, on-shell decay $t' \to b'W^+$ is forbidden. As a result, other $t'$ decays have substantial branching fractions, which are highly sensitive to the magnitude of the diagonal CKM matrix element $V_{t'b'}$. We show that $|V_{t'b'}|$ can be determined from the ratio of the two-body and three-body $t'$-decay branching fractions and estimate the precision of such a measurement at the LHC. We discuss the hadronization of a $t'$ for large enough values of $|V_{t'b'}|$.

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I. INTRODUCTION

One possible new-physics scenario that will be probed at the LHC is the addition of a fourth generation to the standard model (SM), resulting in a model generally denoted SM$_4$. A fourth family brings with it several interesting consequences $[1]$. It has implications for the status of and search for the Higgs boson $[2]$, and can help remove the tension between the SM fit and the lower bound on the Higgs-boson mass from LEP $[3]$. Adding only one extra generation to the SM is consistent with all precision tests, even with a Higgs as heavy as 500 GeV $[4]$. SM$_4$ is consistent with SU(5) unification without supersymmetry $[5]$. Electroweak baryogenesis cannot be accommodated in the SM with three generations, but it may be plausible in SM$_4$, due to the presence of additional weak phases and the contribution of the heavy fourth-generation quarks to the Jarlskog invariant in the four-generation Cabibbo-Kobayashi-Maskawa matrix (CKM$^4$) $[6]$. A rather heavy fourth generation could also naturally give rise to dynamical electroweak-symmetry breaking $[7]$, since a quark with a mass of more than about half a TeV falls in the strong coupling region $[8]$. The CDF collaboration has searched for the decay of a heavy $t'$ quark to a $W$ boson and a jet. Assuming this is the dominant decay mode, they set a limit on the $t'$ mass, $m_{t'} > 256$ GeV at 90\% C.L. $[9]$. CDF has also looked for $b' \rightarrow tW^-$, setting the limit $m_{b'} > 338$ GeV at 95\% C.L. $[10]$. With higher energy and luminosity than the Tevatron, the LHC will have much greater sensitivity for the discovery of fourth-generation quarks and could measure some of their parameters. Of particular importance to flavor physics is the measurement of the CKM$_4$ matrix elements, specifically $V_{t'b'}$, which is the main focus of this paper.

While a fourth generation is consistent with precision electroweak data, stringent constraints exist on the deviation of the CKM$_4$ diagonal element $V_{t'b'}$ from unity, as well as on the mass splitting of the fourth-generation quark doublet. In particular, the best fit gives $\Delta m \equiv m_{t'} - m_{b'} \simeq 56$ GeV, where we have assumed that the contribution from the fourth-generation leptons is negligible due to a small lepton-neutrino mass splitting.

Therefore, in this paper we explore the implications of SM$_4$ with $\Delta m < m_W$, restricting the discussion to this scenario. The decay $t' \rightarrow b'W$ is then not permitted, and one must consider other decay modes. The three-body decay $t' \rightarrow b'W^{++}$, where $W^*$ is an off-shell $W$ boson producing a $f\bar{f}'$ pair, is kinematically suppressed. The decay involving a virtual
$b', t' \to Wb'^*$, is found to be even smaller. A large value of $|V_{t'b'}|$ and the unitarity of CKM$_4$ lead to suppression of two-body decays $t \to DW^+$, where $D \equiv \{d, s, b\}$. Penguin decays are both CKM$_4$- and loop-suppressed and are found to have negligible branching fractions. Calculating the rates of these processes, we show that for a substantial range of the parameters, $|V_{t'b'}|$ can be determined from the ratio of the branching fractions of $t' \to b'W^{*+}$ and $t \to DW^+$.

Now, it is well known that, because the $t$ quark decays rapidly, there is not enough time for it to hadronize. On the other hand, we find that, for a sizable part of the allowed parameter space, the decay rates of the $t'$ are small enough that hadronization of this fourth-generation quark can occur. The formation of such a bound state is an interesting consequence of fourth-generation quarks.

This paper is organized as follows. In Section II we review constraints on the fourth-generation parameters. We calculate the decay rates of the $t'$ quark in Section III for the parameter space permitted by the electroweak constraints. We discuss the measurement of $V_{t'b'}$ and its uncertainties in Section IV and provide concluding remarks in Section V.

II. ELECTROWEAK CONSTRAINTS

The quantum oblique corrections [11], quantified in terms of the $S$, $T$, and $U$ parameters, depend on the masses and mixing parameters of the fourth-generation fermions. For $N_C = 3$ colors, the contribution of the these fermions to $S$ and $T$ is

$$S_4 = \frac{1}{6\pi} \left( 3 - \ln \frac{x'_{t'}}{x'_{b'}} \right),$$
$$T_4 = \frac{3}{8\pi s_W^2(1 - s_W^2)} \times \left[ |V_{t'b'}|^2 F_{t'b'} + \sum_{D=d}^b |V_{t'D}|^2 F_{t'D} + \sum_{U=u}^t |V_{UW}|^2 F_{UW} - |V_{tb}|^2 F_{tb} + \frac{F_{t'b'}}{3} \right],$$

where $s_W^2 \equiv \sin^2 \theta_W$ and

$$F_{ij} \equiv \frac{x_i + x_j}{2} - \frac{x_i x_j}{x_i - x_j} \log \frac{x_i}{x_j},$$

with $x_i \equiv (m_i/m_W)^2$. For approximately degenerate fermion masses, $x_i - x_j \ll x_j$, $F_{ij} \sim (x_j - x_i)/2$, and the contribution to $T_4$ is small. In order to focus the discussion on the

\footnote{To a good approximation, NP that is heavy gives a negligible contribution to $U$.}
quark sector, in what follows we take the fourth-generation neutrino and charged lepton to have very similar masses, so that the contribution of $F_{\ell \nu_4}$ to $T_4$ is negligible relative to that of the quarks.

In order to obtain the constraints from the oblique corrections, it is necessary to take values for the CKM$_4$ matrix elements, in particular $|V_{t'b'}|$. Limits on these matrix elements can be found by considering the loop-level contributions of the fourth generation to various flavor-physics observables. There have been several analyses of CKM$_4$ in the past [12]. Recently, a complete fit has been done [13], and it was found that $V_{t'b'} = 0.998 \pm 0.004$. This is to be compared with the oblique-parameter fits below.

First, let us study the case $|V_{t'b'}| = 1$, for which only the $F_{t'b'}$ term contributes to $T_4$. Taking $m_{t'} = 400$ GeV, We show in Fig. 1 as a function of the fourth-generation quark mass splitting $\Delta m \equiv m_{t'} - m_{b'}$, the $\chi^2$ quantifying the agreement of $S_4$ and $T_4$ with the experimental constraints on $S$ and $T$, as given in Ref. [14] for $U = 0$, $m_t = 171.4$ GeV, and $m_H = 114$ GeV. One observes that the most likely value for $\Delta m$ is around 56 GeV, while $\Delta m = 0$ and $\Delta m = m_W$ are approximately equally disfavored at the 2.2 standard-deviation level. A more general study [15] that allows for non-degenerate leptons finds $\Delta m$ to be even smaller.

![Figure 1: $\chi^2$ vs. the fourth-generation quark mass difference, given the $S$ and $T$ constraints in Ref. [14], calculated with $U = 0$, $m_t = 171.4$ GeV, $m_H = 114$ GeV, and $m_{t'} = 400$ GeV.](image)

As one loosens the $|V_{t'b'}|$ requirement, the terms $F_{t'D}$ and $F_{UV}$, which are of order $x_{t'}$ and $x_{b'}$ respectively, make $T_4$ large and inconsistent with experimental results, given the lower limits on the $t'$ and $b'$ masses. This puts a lower limit on the value of $|V_{t'b'}|$ in a four-generation scenario. In Fig. 2 we show the minimal $\chi^2$ obtained for any $\Delta m > 0$ as a
function of $|V_{tb'}|$, from which one can extract limits on $|V_{tb'}|$. For example, requiring $\chi^2 < 9$ yields $|V_{tb'}| > 0.972$ ($|V_{tb'}| > 0.983$) for the case where the dominant off-diagonal CKM elements are $V_{tb}$ and $V_{tb'}$ ($V_{td}$ and $V_{ub'}$).

![Graph](image)

FIG. 2: The minimal value of $\chi^2$ vs. $|V_{tb'}|$ given $S$ and $T$ from Ref. [14]. The lower (upper) curve is obtained when the dominant off-diagonal CKM elements are $V_{tb}$ and $V_{tb'}$ ($V_{td}$ and $V_{ub'}$).

These results suggest that if there are four fermion families, then

- the CKM matrix remains highly diagonal, with $|V_{tb'}| > 0.97$ (this is consistent with, though weaker than, the result from the flavor-physics fit [13]), and

- the quark mass difference $\Delta m$ is smaller than the $W$ boson mass.

These two points will be assumed throughout the following sections.

III. THE $t'$ DECAY BRANCHING FRACTIONS

With $\Delta m$ significantly smaller than $m_W$, the CKM-favored, on-shell, two-body decay $t' \to b'W^+$ is kinematically forbidden. The only processes leading to a $b'$ quark in the final state are the off-shell decays $t' \to b'W^{**}$ and $t' \to b^*W^+$. Furthermore, the amplitude for $t' \to b^*W^+$ is additionally CKM suppressed at the $b^*$ decay vertex. Thus, the dominant decay with a $b'$ in the final state is the three-body process $t' \to b'W^{**}$. We find that the
width for this decay is

\[ \Gamma_{3\text{-body}} \equiv \]

\[ \Gamma \left( t' \rightarrow b' W^+ \right) = \frac{\alpha^2 |V_{tb'}|^2}{192\pi s_W^4 m_W^4 m_{t'}^5} \left\{ r\epsilon \left( 6r^2 - 3r\epsilon' - \epsilon^2 \right) + 3r^3(r - \epsilon') \log(1 - \epsilon) + \frac{6r^3[2 - \epsilon'(\epsilon + 2r) + r^2]}{\sqrt{4r - (\epsilon + r)^2}} \right\}, \quad (3) \]

where

\[ \epsilon \equiv 1 - \frac{m_{t'}}{m_{t'}}, \]

\[ \epsilon' \equiv 2 - \epsilon, \]

\[ r \equiv \frac{m_{W}^2}{m_{t'}^2}. \quad (4) \]

In our calculations we ignore the W width. However, this changes the W propagator by only 4% for \( \Delta m = 75 \text{ GeV} \), and is hence neglected.

In Fig. 3 we plot \( \Gamma \left( t' \rightarrow b' W^+ \right) \) as a function of \( \Delta m \) for \( m_{t'} = 400 \text{ GeV} \) and \( |V_{tb'}| = 1 \). To understand the small magnitude of this decay rate at small values of \( \Delta m \), it is instructive to expand it in terms of \( \epsilon \). The lowest-order term,

\[ \Gamma_{3\text{-body}} \approx \frac{\alpha^2 |V_{tb'}|^2}{960\pi s_W^4 m_W^4 m_{t'}^5} \epsilon^5, \quad (5) \]

which differs from Eq. (3) by less than 30% for \( \Delta m < 70 \text{ GeV} \), demonstrates that \( \Gamma \left( t' \rightarrow b' W^+ \right) \) is suppressed by \( \epsilon^5 \).
Due to this strong suppression of the CKM-favored $t'$ decay, the $t'$ may undergo CKM-suppressed decays with significant probability. The sum of the rates of the two-body decays $t' \to DW^+$, where $D = d, s, b$, is

$$
\Gamma_{2\text{-body}} \equiv \sum_{D=\{d,s,b\}} \Gamma (t' \to DW^+) = \frac{m_{t'}^3 \alpha}{16 s_W^2 m_W^2} (1 - |V_{t'b'}|^2)^2 \left( 1 + 2 \frac{m_W^2}{m_{t'}^2} \right), \tag{6}
$$

This can be approximated as

$$
\Gamma_{2\text{-body}} \approx 60 \text{ GeV} \left( \frac{m_{t'}}{455 \text{ GeV}} \right)^3 \Delta V \tag{7}
$$

where

$$
\Delta V \equiv 1 - |V_{t'b'}| \tag{8}
$$

is much smaller than unity, and we have neglected terms of order $(m_W/m_{t'})^2$.

It is interesting to note that, unlike in the case of the top quark, kinematic suppression of the CKM-favored $t'$ decay implies that for a significant range of allowed values of $|V_{t'b'}|$, the $t'$ lifetime is long enough for this quark to hadronize. Specifically, Eq. (7) demonstrates that for $\Delta V < 3 \times 10^{-3}$, $\Gamma_{t'}$ is of order 100 MeV or less. We explore some consequences of hadronization in Section IV.

For completeness, we also present the QCD-uncorrected electroweak-penguin decay width [16]:

$$
\Gamma(t' \to U\gamma) = \frac{\alpha G_F^2}{128\pi^4} m_{t'}^5 \sum_{Q=\{d,s,b,b'\}} \left| V_{UQ} V_{t'b'} F_{Qem} \left( \frac{m_Q^2}{m_W^2} \right) \right|^2, \tag{9}
$$

where the factor

$$
F_{Qem}(x) \equiv Q_{em} \left[ \frac{x^3 - 5x^2 - 2x}{4(x-1)^3} + \frac{3x^2 \ln x}{2(x-1)^4} \right] + \frac{2x^3 + 5x^2 - x}{4(x-1)^3} - \frac{3x^3 \ln x}{2(x-1)^4} \tag{10}
$$

is most significant for large $x$, namely when the $b'$ is the internal quark. In this case, we can write

$$
\Gamma(t' \to U\gamma) \approx 1.6 \times 10^{-4} \text{ GeV} \left( \frac{m_{t'}}{455 \text{ GeV}} \right)^5 |V_{t'b'}|^2 (1 - |V_{t'b'}|^2), \tag{11}
$$

which is several orders of magnitude smaller than the tree-level 2-body decay. We conclude that hadronic penguin decays are also unimportant, and disregard them in what follows.
IV. MEASURING $|V_{t'\nu}|$

Eqs. (3) and (6) provide a straightforward method to measure $|V_{t'\nu}|$. We find that the ratio of branching fractions of the two-body and three-body decays of the $t'$ is

$$R \equiv \frac{\Gamma_{2\text{-body}}}{\Gamma_{3\text{-body}}} \propto \frac{1 - |V_{t'\nu}|^2}{|V_{t'\nu}|^2},$$

with a proportionality coefficient that depends on the $t'$ and $b'$ masses in a known way. As we show below, this measurement is sensitive to very small deviations of $|V_{t'\nu}|$ from unity. In this case, $R \propto \Delta V$ to an excellent approximation. We therefore focus on $R$ as a measurement of the SM parameter $\Delta V$.

To estimate the statistical error of the $R$ measurement, we rely on full-simulation studies performed for the LHC at $pp$ collision energies of 14 TeV. Since the goal of those studies was to estimate the discovery potential at low integrated luminosities, they made use of only the best decay channels and employ relatively simple analysis techniques. It is anticipated that use of additional channels, improved techniques, and more reliable understanding of the detector and of 14 TeV processes will lead to reduced errors. However, we make no such assumptions in our estimates, and simply extrapolate the sensitivities of these LHC studies to the relevant parameter values.

For the two-body, $t' \to DW^+$ decay, we use an ATLAS study [17] performed for $m_{t'} = 500$ GeV. The study determined the discovery significance for this decay to be 9.2 standard deviations ($\sigma$) for an integrated luminosity of 1 fb$^{-1}$. Only the $t'\bar{t}' \to l\nu + 4$ jets channel was used, since it provides an optimal combination of branching fraction and signal-to-background ratio, making it most suitable for low-luminosity discovery.

To estimate the statistical error on the three-body $t' \to b'W^{+*}$ signal yield, we use a CMS discovery study [18] of $b'\bar{b}'$ production with $b' \to Wt$ decays. Such events are similar to the events of interest to us, $t'\bar{t}'$, $t' \to b'W^{+*}$, $b' \to X$, in that in both cases the final state contains at least ten jets, charged leptons, and neutrinos. Therefore, we assume that the statistical sensitivity determined in this study is a reasonable estimate for the $t'\bar{t}'$, $t' \to b'W^{+*}$ case. The study found that a 400-GeV $b'$ can be discovered with 2.0$\sigma$ significance given an integrated luminosity of 0.1 fb$^{-1}$, using the same-sign dilepton and trilepton signatures.

We assume that these statistical errors scale with the square root of the number of produced $t'\bar{t}'$ events. We take the integrated luminosity to be 100 fb$^{-1}$ and obtain the cross
section for different $t'$ masses from PYTHIA [19]. Our results for $\sigma_{\Delta V}^{\text{stat}}/\Delta V$, the relative statistical error on $\Delta V$ from the measurement of the ratio $R$, are shown in Fig. 4 for $m_{t'} = 400$ GeV and 700 GeV. The error is smallest when the statistical uncertainties on the two branching fractions are equal. These results show that $\sigma_{\Delta V}^{\text{stat}}/\Delta V$ smaller than 10% can be achieved over five (two) orders of magnitude of $\Delta V$ values for $m_{t'} = 400$ GeV (700 GeV) and any given value of $\Delta m$.

Extraction of $\Delta V$ from $R$ using Eqs. (3) and (6) requires knowledge of the masses of the $b'$ and $t'$ quarks, introducing a systematic error $\sigma_{\Delta V}^{\text{syst}}$, which we estimate next.

A general idea of the magnitude of the mass uncertainties may be obtained from the projected LHC error on the top-quark mass. In an ATLAS Monte-Carlo study [20] for $1 \text{ fb}^{-1}$, a statistical error smaller than 0.4 GeV was estimated for $m_t$. The systematic error was found to be about 1 GeV, if the jet-energy-scale (JES) relative uncertainty, which is the largest source of systematic error, is about 1%. The study reports that this JES uncertainty is obtainable with $1 \text{ fb}^{-1}$ for light-quark jets, and we assume a similar error for the $b$-quark jets.

To get an idea of the uncertainties on $m_{t'}$ and $m_{t''}$, we note that while the cross section for $t'\bar{t}'$ production, at the masses explored here, is two to three orders of magnitude smaller than for $t\bar{t}$ production, this is mostly cancelled by the fact that the integrated luminosity used in Ref. [20] is two orders of magnitude smaller than our $100 \text{ fb}^{-1}$ benchmark. However, the detector energy resolution generally degrades approximately as the square root of the mass. Therefore, given the errors quoted in Ref. [20], it is reasonable to conclude that the fourth-generation quark masses may be known to order several GeV.

From Eqs. (5) and (7), we see that to lowest order in $\Delta m$, one has the approximate proportionality relation

$$\frac{\Delta V}{R} \propto \frac{\Delta m^5}{m_{t'}^2}.$$  \hspace{1cm} (13)

As a result, the impact of the $\Delta m$ uncertainty on the relative error $\sigma_{\Delta V}^{\text{syst}}/\Delta V$ is of order $m_{t'}/\Delta m$ greater than that of the $m_{t'}$ uncertainty. Therefore, we consider $\sigma_{\Delta m}$ as a main source of systematic error. Fig. 5 shows the dependence of the relative systematic error $\sigma_{\Delta V}^{\text{syst}}/\Delta V$ on $\Delta m$ for several fixed values of $\sigma_{\Delta m}$.

We note that it may be possible to determine $\Delta m$ to better precision than $m_{t'}$ or $m_{t''}$. For example, $\Delta m$ can be determined from the spectrum of the lepton in the three-body decay
FIG. 4: Estimated relative statistical error $\sigma_{\Delta V}^{\text{stat}}/\Delta V$ as a function of $\log_{10} \Delta V$ and $\Delta m$, assuming an integrated luminosity of 100 fb$^{-1}$ at one LHC experiment for (top) $m_{b'} = 400$ GeV or (bottom) $m_{b'} = 700$ GeV. The decay $t' \rightarrow DW^+$ ($t' \rightarrow b'W^+\nu_l$) is the dominant $t'$ decay channel above (below) the central dark band.

$t' \rightarrow b'W^+ \rightarrow b'l^+\nu_l$. Unless $\Delta m$ is large, this lepton would be soft, distinguishing it from the leptons arising from the decays of the $b'$ and $t$ quarks in the event. Performing this measurement requires the three-body branching fraction to be large, which generally occurs for small values of $\Delta V$. A detailed experimental feasibility study of such a measurement is
FIG. 5: Estimated relative systematic error $\sigma_{\Delta V}/\Delta V$ due to the uncertainty on $\Delta m$, shown as a function of $\Delta m$ for $\sigma_{\Delta m} = 1, 3, 6, \text{and } 10$ GeV.

beyond the scope of this paper.

A. $t'$ Hadronization and $\Delta V$

As mentioned above, due to the kinematic suppression of the CKM-favored transition, the $t'$ lifetime is large enough for it to hadronize, if $\Delta V$ is smaller than about $3 \times 10^{-3}$. In principle, hadronization may be detected via depolarization of the $t'q$ meson, as outlined in Ref. [21]. Depolarization occurs if $\Gamma_{t'} \ll \Delta m_{T'}$, where $\Delta m_{T'}$ is the difference between the masses of the spin-triplet vector meson and of the spin-singlet ground state. An estimate of this parameter is $\Delta m_{T'} \approx \Delta m_{B} \frac{m_{t'}}{m_{t'}} \sim 1$ MeV. From Fig. 6 we see that $\Gamma_{t'} < 0.1$ MeV when $\Delta V < 10^{-6}$ and $\Delta m < 45$ GeV. Thus, if one finds that $\Delta m < 45$ GeV, searching for depolarization can help determine whether $\Delta V$ is significantly above or below the $10^{-6}$ mark.

The information obtained from depolarization about $\Delta V$ is only order-of-magnitude, and involves a complicated angular analysis that can be performed only with the simple final state of the two-body $t'$ decay. This requires a large two-body branching fraction, and hence a large value of $\Delta V$. Given the $\Delta V < 10^{-6}$ depolarization condition, this implies that the depolarization measurement of $\Delta V$ is practical only in regions where $\Delta V$ can more easily be obtained from the measurement of the branching-fraction ratio $R$. 

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V. SUMMARY AND CONCLUSIONS

A fourth-generation extension of the Standard Model has several attractive features, and studies show that it can be ruled out or discovered with early LHC data. Precision electroweak measurements imply that if fourth-generation quarks exist, then the difference $\Delta m$ between their masses is likely to be smaller than the $W$ boson mass. If one assumes that this is indeed the case, then the two prominent $t'$ quark decays are the three-body, kinematically suppressed $t' \to b'W^* +$ and the two-body, CKM$_4$-suppressed $t' \to DW^+$. We calculate the branching fractions of these decays and show that their ratio is a sensitive probe of $\Delta V$, the difference of $|V_{t'b'}|$ from unity. Using published simulation studies of fourth-generation quark discovery at the LHC, we estimate the statistical error of this $\Delta V$ measurement. We estimate the main $\Delta V$ systematic error due to the uncertainty on the mass difference $\Delta m$ and, for part of the parameter space, suggest a possible way to obtain $\Delta m$ with better precision than the individual quark masses. An interesting consequence of the scenario described here is that the $t'$ quark hadronizes if $\Delta V$ is of order $3 \times 10^{-3}$ or less. This is not likely to be useful for measuring $\Delta V$, but could possibly be used as a laboratory for QCD in the infinite quark-mass limit.
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