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\[ b \to s\gamma \text{ and } B_s \to \mu^+\mu^- \text{ in Extended Technicolor Models} \]

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Abstract

The rates of the rare flavor-changing processes, \( b \to s\gamma \) and \( B_s \to \mu^+\mu^- \) are estimated in extended technicolor models with and without a GIM mechanism. We find the \( b \to s\gamma \) rate in ETC models with a GIM mechanism to be at most slightly larger than the standard model rate, whereas there is no significant extra model-independent contribution in other ETC scenarios. In the case of \( B_s \to \mu^+\mu^- \), ETC models with a GIM mechanism can yield a rate up to two orders of magnitude bigger than that of the standard model, whereas generic ETC scenarios are likely to give a rate which is about an order of magnitude bigger than that of the standard model.

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1 Introduction

Rare flavor-changing processes involving the third generation quarks are sen-
sitive probes of the flavor sector because of the large couplings of the top
quark. Two good candidates for study are $b \to s\gamma$ and $B_s \to \mu^+\mu^-$. The
process $b \to s\gamma$ has recently been observed at a rate compatible with that of
the standard model [1]. Models which give a contribution significantly larger
than that expected in the standard model are therefore ruled out. The pro-
cess $B_s \to \mu^+\mu^-$ may be studied very well in the future [2]. Much attention
has been devoted to the study of both these processes within the context of
two-Higgs models and supersymmetry [3, 4]. In this paper we examine these
processes in extended technicolor (ETC) theories.

We will consider two types of ETC models. In the first class of models,
which we refer to as “traditional” ETC, we assume the existence of the mini-
mal features needed to describe the ETC origins of the third generation quark
masses. We will estimate contributions to $b \to s\gamma$ and $B_s \to \mu^+\mu^-$ arising
from this structure. Since no realistic models in this class are known our es-
timates should be taken as lower bounds (barring large cancellations) on the
nonstandard contributions, since it may be that a realistic model will require
extra interactions which also contribute to the processes of interest. We will
only consider models with a single techni-doublet breaking electroweak sym-
metry. Larger technicolor sectors are disfavored by electroweak S-parameter
constraints [5].

The second type of model we consider are those which incorporate a
techni-GIM mechanism [6, 7, 8, 9]. Recently, it has been shown [8, 9] that re-
alistic technicolor models can be built incorporating a techni-GIM mechanism
which protects them from large flavor-changing neutral currents (FCNC’s).
Such models contain many approximately degenerate ETC gauge bosons,
with masses at most a few TeV in order to obtain the heavy top quark
mass. This is to be contrasted with traditional ETC models where the ETC
gauge bosons are highly non-degenerate, which is related to the difficulties
such models have in adequately suppressing FCNC’s involving the first two
generations [10].

The large number of TeV-scale ETC particles in techni-GIM models can
mediate important low-energy effects. In particular, it is quite natural in
such models to have quarks and leptons in a common ETC group, so that
ETC gauge-boson exchange can induce four-fermion interactions involving
both quarks and leptons which can greatly enhance the $B_s \to \mu^+\mu^-$ rate. In a “traditional” ETC scenario, it is expected that the scale for such four-fermion interactions is much larger, determined by the ETC scale of the leptons.

Our results are as follows. We find in both classes of models that the generic ETC rate for $b \to s\gamma$ is essentially the same as in the standard model. In techni-GIM models with strongly interacting ETC dynamics it possible for the rate to be at most slightly larger than in the standard model. On the other hand, the process $B_s \to \mu^+\mu^-$ is likely to be a good test of ETC in either class of model, but will be particularly sensitive in the models of quarks and leptons which incorporate a techni-GIM mechanism. Generically, ETC models of either class predict a rate for $B_s \to \mu^+\mu^-$ which is an order of magnitude larger than the standard model rate (for fixed top quark mass), while the simplest techni-GIM models, which have leptons and quarks in the same ETC multiplets, predict a rate two orders of magnitude larger than in the standard model.

We are restricting our attention to models in which neither composite nor fundamental scalars are involved in the quark mass generation. Their presence could substantially weaken the nonstandard contributions to the rare decays we find in this paper. However, the estimates we make should not be weakened much by walking technicolor dynamics because walking affects the dynamics far above the weak scale while third generation ETC scales are necessarily low.

Some of our calculations require technicolor strong interaction matrix elements. We estimate these using naive dimensional analysis (NDA).

In section 2, we relate some parameters of the effective technicolor lagrangian to the fermion masses and mixings, in particular the top quark mass. In section 3, we estimate the rate for $B_s \to \mu^+\mu^-$ in ETC theories with and without a GIM mechanism. In section 4, we do the same for the process $b \to s\gamma$. In section 5, we provide our conclusions.
2 Fermion masses and ETC interactions

In either of the ETC scenarios we consider, exchange of ETC gauge bosons induces interactions at the TeV scale of the form

\[
\mathcal{L}_{\text{mass}} = \frac{1}{f^2} (\bar{\psi}^i_L \gamma_\mu T^i_L) (\bar{U}^i_R \gamma^\mu U^i_R) Y_{iij} + \frac{1}{f^2} (\bar{\psi}^i_L \gamma_\mu T^i_L) (\bar{D}^i_R \gamma^\mu D^i_R) Y_{ij} + \text{h.c.,} \quad (1)
\]

necessary for giving quark masses upon electroweak symmetry breaking. Here, \( T^i_L \) is the techni-doublet while \( U_R, D_R \) are the right-handed partners and \( \psi^i_L \) is the \( i \)-th generation quark doublet and \( u^i_R, d^i_R \) are its right-handed partners. The matrices \( Y_u, Y_d \) play a role here similar to the standard model Yukawa couplings. They parameterize the breaking of the \( SU(3)_L \times SU(3)_u \times SU(3)_d \) symmetry under which the three generations of left-handed quark doublets, right-handed up-type quarks and right-handed down-type quarks transform. This symmetry must be broken to allow for quark masses. We will work with the normalization of the \( Y \)'s which follows most naturally in techni-GIM models, namely their largest element equals one, \( Y_{33}^u = 1 \).

An important difference between techni-GIM models and traditional ETC models is that in techni-GIM models the ETC physics ensures that the \( SU(3)_L \times SU(3)_u \times SU(3)_d \) flavor symmetry of the full effective lagrangian at the TeV scale (resulting from integrating out heavier ETC physics) is broken only by the parameters \( Y_u, Y_d \). In traditional models the full effective lagrangian contains a more general form of flavor symmetry breaking. It is the restricted form of the flavor symmetry breaking in techni-GIM models that provides the GIM suppression of FCNC’s.

The two classes of models also differ in the way ETC physics induces eq. (1). In techni-GIM models, the ETC gauge bosons are approximately degenerate in mass, and the ETC scale \( f \) is given by

\[
\frac{1}{f^2} = \frac{g_{ETC}^2}{m_{ETC}^2}, \quad (2)
\]

where \( g_{ETC} \) is the coupling of the ETC gauge bosons and \( m_{ETC} \) is their mass. The slight non-degeneracy of the ETC gauge bosons is responsible for the breaking of the \( SU(3)_L \times SU(3)_u \times SU(3)_d \) flavor symmetry. An individual quark mass eigenstate gets contributions to its mass from the exchange of several different ETC gauge boson mass eigenstates. This is to be contrasted with traditional ETC models where the high level of quark non-degeneracy is
reflected in a high level of non-degeneracy in the ETC gauge boson spectrum, and a quark mass eigenstate gets contributions to its mass from essentially a single ETC gauge boson mass eigenstate. The fact that top quark mass production is associated with a much lower ETC scale than bottom quark mass production can give rise to unacceptable violation of the $\rho$ relation \[15\]. In techni-GIM ETC models this is not a problem because the two ETC scales can be taken nearly equal \[8\] while still allowing a large top-bottom splitting.

Upon technifermion condensation, quark mass matrices emerge,

$$M_{u(d)} \approx \frac{4\pi v^3 Y_{u(d)}}{f^2},$$  \hspace{1cm} (3)

where $v$, the technifermion decay constant is taken to be the weak scale, 246 GeV, in order to ensure the correct $W, Z$ masses. In particular, since $Y_{u}^{33} = 1$ we have,

$$m_t \approx \frac{4\pi v^3}{f^2}. \hspace{1cm} (4)$$

We will use this relation in our estimates to eliminate the ETC scale $f$ in favor of $m_t$.

### 3 \quad B_s \to \mu^+ \mu^-$

In both classes of models the generic ETC contribution to $B_s \to \mu^+ \mu^-$ is mediated by $Z$ exchange, with ETC-induced flavor-changing couplings of the $Z$. We begin with traditional ETC models. ETC gauge boson exchange can induce the operator

$$\xi \frac{g_{ETC}^2}{m_{ETC}^2} (\bar{\psi}_L \gamma_\mu T_L)(\bar{T}_L \gamma^\mu \psi_L),$$  \hspace{1cm} (5)

where $\psi_L$ is the doublet containing the top quark. The ETC scale appearing here is therefore expected to be that associated with top quark mass production, namely $\xi$ is a model dependent parameter of order one and $g_{ETC}^2/m_{ETC}^2 \approx 1/f^2$, with $f$ as in eq. (4). Proceeding as in refs. \[15, 16, 17\], this translates into a $Z$ coupling,

$$\xi \frac{m_t}{16\pi v} \bar{\psi}_L \left( \frac{e}{\sin \theta \cos \theta} Z_{\tau 3} \right) \psi_L, \hspace{1cm} (6)$$
where $\theta$ is the weak mixing angle. There is no technicolor strong interaction uncertainty in this computation because the technifermion pair coupling to the $Z$ is the same as the current involved in the Higgs mechanism for electroweak symmetry breaking. Because the bottom quark field in $\psi_L$ is not the mass eigenstate, one expects flavor-changing effects of order $m_t/16\pi v$ times a mixing angle between the second and third generation. (There are of course also flavor diagonal modifications of the $Z$ vertex [14]. However, traditional ETC models in which these nonstandard effects are large may also unacceptably violate the well constrained $\rho$ relation [13].)

A similar modification of the $Z$ vertex occurs in models with a GIM mechanism. In this case, the effective lagrangian contains the operator

$$\frac{\xi_1}{f^2} (\overline{\psi}_L \gamma_\mu T_L)(Y_u Y_u^\dagger)_{ij}(T_L \gamma_\mu \psi|^j_L), \quad \text{(7)}$$

where $\xi_1$ is an order one, model-dependent coefficient. Proceeding as before, the induced coupling to the $Z$ is

$$\frac{\xi_1 v^2}{4f^2} \frac{e}{c_\theta s_\theta} \overline{\psi}_L Z^3 Y_u Y_u^\dagger \psi_L. \quad \text{(8)}$$

This term contains the large flavor-changing vertex

$$- \frac{\xi_1 m_t}{16\pi v} \frac{e}{c_\theta s_\theta} \overline{b}_L Z Y_u^{33} Y_u^{32} s_L. \quad \text{(9)}$$

For numerical estimates we will take $Y_u^{23} \sim V_{ts}$.

Therefore, in both classes of ETC models, $Z$ exchange yields the operator

$$\overline{s}_L \gamma_\mu b_L T^\gamma_\mu \gamma_5 b_L$$

with coefficient

$$C_{ETC} \sim \frac{m_t V_{ts}}{16\pi v^3}. \quad \text{(11)}$$

For comparison, in the standard model, the same operator is induced at the one loop level [4], with coefficient,

$$C_{SM} = \frac{g^2 (B(m_t/m_W)^2 - C(m_t/m_W)^2) V_{ts}}{8\pi^2 v^2}, \quad \text{(12)}$$
where $g$ is the SU(2) gauge coupling and the functions $B(x)$ and $C(x)$ are order one over the top mass range and are given explicitly in ref. [4].

We normalize to the semileptonic decay width given by

$$\Gamma(b \to ce^{-}\nu_e) = \frac{G_F^2 m_b^5 G \left(\frac{m_c}{m_b}\right)}{192\pi^3} |V_{bc}|^2,$$

(13)

where $G(m_c/m_b) \approx \frac{1}{2}$ takes into account the large charm quark mass. The rate for $B_s \to \mu^+\mu^-$ is

$$\frac{C^2 m_B m_{\mu} f_B^2}{8\pi},$$

(14)

where $C$ is the coefficient of the operator given above. Therefore the rate, relative to the semileptonic rate to electron final state given above, is

$$\frac{\Gamma(B_s \to \mu^+\mu^-)}{\Gamma(b \to ce^{-}\nu_e)} \approx 2 \cdot 10^{-7} \left(\frac{m_t}{v}\right)^2 \left(\frac{f_B}{200 \text{ MeV}}\right)^2,$$

(15)

where we have taken $Y_u^{23} \approx V_{ts} \approx V_{bc}$.

There can also be direct contributions in technicolor coming from operators in the effective lagrangian,

$$\frac{\xi_2}{f^2} \langle \bar{\psi}_L \gamma\mu Y_u Y_u^\dagger \psi_L \rangle \langle \bar{l}_L \gamma^\mu l_L \rangle,$$

(16)

where $l_L$ are the left-handed lepton doublets. The size of $\xi_2$ is model dependent. (In traditional ETC, we might expect a similar interaction to be weak, linked to a large leptonic ETC scale, in which case it can be neglected.) In techni-GIM models like those of refs. [8, 9] where we expect all ETC gauge boson masses to be approximately equal, $\xi_2$ should be of order unity. In this case the decay rate is larger than the $Z$-exchange contribution,

$$\frac{\Gamma(B_s \to \mu^+\mu^-)}{\Gamma(b \to ce^{-}\nu_e)} \sim 1.5 \cdot 10^{-6} \left(\frac{m_t}{v}\right)^2 \left(\frac{f_B}{200 \text{ MeV}}\right)^2.$$

(17)

The relative decay rates in ETC and in the standard model are plotted against $m_t$ in fig. (1). As can be seen, for a potentially attainable $10^{-6}$–$10^{-7}$ sensitivity one may be able to just measure the ETC induced rare decays if only $Z$-exchange contributes, while the prospects are good for doing so in models in which there is a direct ETC contribution.
In ref. [15], various other flavor violating effects related to the top quark were considered. It was shown that the strongest constraint came from $B - \bar{B}$ mixing, implying a favored region of KM angles which was more restrictive than that of the standard model. Here we have only used mixing between the second and third generation, which is directly determined from the $B$ lifetime, so the altered parameter region is not relevant to the two decays considered here (although it would be relevant to other decays as discussed in [15]).

4 $b \rightarrow s\gamma$

It is important to notice that it is only the $Z$, not the photon vertex which is corrected at leading order. Gauge invariance guarantees there is no renormalization of the dimension-four photon coupling. Moreover, one should recognize that the reason the modification of the $Z$ coupling was so large was that it was a correction to a low dimension operator. In particular, if one estimates (despite it being exactly determined), using NDA, the loop diagram which eliminates the technifermions, and couples the $Z$, one sees that the factor of $1/f^2$ is multiplied by $\Lambda^2$, where $\Lambda$, the cutoff, is approximately $4\pi v$. The two factors of $4\pi$ eliminate the loop suppression factor. In fact, the $4\pi$ suppression of the operators in eqs. (6, 9) only comes from replacing the factor of $1/f^2$ by $m_t/4\pi v^3$. If one were now to consider a correction to a higher dimension operator involving the gauge field, for example a magnetic moment operator, the loop factor of $1/16\pi^2$ cannot be fully compensated. It is essentially this fact which keeps the ETC contribution to $b \rightarrow s\gamma$ comparable or suppressed relative to that of the standard model, as we will now see.

Let us first consider the contribution to $b \rightarrow s\gamma$ in a traditional ETC scenario. One might consider taking the ETC exchange which leads to the bottom quark mass, integrating out a technifermion loop, and attaching a photon to some part of the loop. However, because the ETC gauge boson mass eigenstate exchanged couples to the bottom quark mass eigenstate fields the magnetic moment operator induced is flavor diagonal. The dominant (model independent) contribution to $b \rightarrow s\gamma$ in fact comes from the same ETC exchange which induced eq. (5), connecting purely left-handed doublets. Integrating out a technifermion loop and attaching the photon to
the technifermion line now yields, for example, the operator

$$\frac{\xi_3}{(4\pi)^2} \frac{1}{f^2} \psi_L \sigma^{\mu \nu} \psi_L \frac{e}{2} F_{\mu \nu}, \quad (18)$$

where \(\psi_L\) is the left-handed doublet containing the top quark and \(\xi_3\) contains order-one strong interaction and model dependence uncertainty. \(e/2\) is the charge of the technifermion. The down component in \(\psi\) is not exactly the bottom mass eigenstate, so (using the equations of motion) we can pull out the operator

$$\frac{m_t}{4\pi v^2} \frac{m_b V_{ts}}{(4\pi v)^2} \bar{b}_R \sigma^{\mu \nu} s_L \frac{e}{2} F_{\mu \nu}, \quad (19)$$

There are also other contributions of comparable magnitude.

The standard model induces an effective operator at one loop [18],

$$A\left(\frac{m_t^2}{M_W^2}\right) \frac{m_b V_{ts}}{(4\pi v)^2} \bar{b}_R \sigma^{\mu \nu} s_L \frac{e}{2} F_{\mu \nu}, \quad (20)$$

where \(A\) is an order one function over the top mass range. However, when QCD radiative corrections are included at the two loop level in the standard model, there are large corrections to the one–loop result, which increase the prediction substantially [19]. The increased value comes from the mixing of four-quark operators into the operator with a photon. Clearly the nonstandard contribution in traditional ETC is suppressed relative to the standard model by an amount of order \(m_t/(4\pi v)\). We therefore expect the rate for \(b \rightarrow s \gamma\) to agree with that from the standard model at the 10% level.

In techni-GIM models the bottom quark mass is the sum of contributions from the exchange of several (nearly degenerate) ETC gauge boson mass eigenstates. Attaching a photon to the ETC gauge bosons and integrating out the technifermions will now give a different linear combination of contributions to the magnetic moment operator, permitting it to be flavor-changing. More explicitly, the effective lagrangian will contain the higher dimension operator

$$\frac{\xi_4 g^2_{\text{ETC}}}{m_{\text{ETC}}^4} \left(\bar{d}_R \gamma^\mu D_R \right) Y_d^c \bar{Y}_u \left(\bar{T}_L \gamma^\nu \psi_L\right) \frac{e}{6} F_{\mu \nu}, \quad (21)$$

arising from the exchange of (charge 1/6) ETC gauge bosons with a photon attached. Upon technifermion condensation and electroweak symmetry
breaking this yields

\[ \frac{\xi_4 g_{ETC}^2 4\pi v^3}{4m_{ETC}^4} \left( \bar{b}_R Y_{d}^{\dagger 33} Y_{u}^{33} Y_{u}^{32} \sigma_{\mu\nu} s_L \right) \frac{e}{6} F_{\mu\nu}. \] (22)

With the estimate \( Y_u^{23} \sim V_{ts} \), we get our final expression for the effective operator,

\[ \frac{\xi_4 m_b V_{ts}}{4m_{ETC}^2} \bar{b}_R \sigma_{\mu\nu} s_L \frac{e}{6} F_{\mu\nu}. \] (23)

Now the ETC gauge boson mass should not be smaller than \( 4\pi v \) in order to keep the ETC physics separate from the strong technicolor dynamics. But the mass should also not be much larger in light of the large top quark mass. Therefore we will estimate \( m_{ETC} \sim 4\pi v \) to get

\[ \frac{1}{24} \frac{\xi_4 m_b V_{ts}}{(4\pi v)^2} \bar{b}_R \sigma_{\mu\nu} s_L e F_{\mu\nu}. \] (24)

The diagrams in which the photon is attached to the technifermion line rather than the ETC gauge boson only make contributions to dimension-six operators analogous to eq. (18). Therefore their contributions to \( b \to s\gamma \) are much smaller than eq. (24) despite the fact that the technifermion charge is larger than the ETC gauge boson’s.

We see that the nonstandard contribution in techni-GIM models is probably numerically suppressed, but (unlike traditional ETC models) not parametrically suppressed, relative to the standard model. Still, the small nonstandard contribution implies that these models should yield the standard model rate at the 10% level. It is possible that the techni-GIM mechanism is incorporated in the context of strongly interacting dynamics beyond technicolor itself, as suggested in the original “CTSM” scenario. In such a situation we cannot trust the numerical suppression and the nonstandard contribution may indeed be of the same order as the one-loop standard model contribution. Thus a \( b \to s\gamma \) rate slightly larger than in the standard model could be accommodated.

5 Conclusions

We have studied the nonstandard contributions to the flavor-changing processes \( B_s \to \mu^+\mu^- \) and \( b \to s\gamma \) in ETC theories, both those with and without
a techni-GIM mechanism. Within traditional ETC scenarios without a GIM mechanism we obtained lower bounds on nonstandard contributions to the rare decays which followed from the existence of the minimal structure necessary for describing the ETC origins of the top quark. In the case of techni-GIM models, our estimates were based on the existence of approximately degenerate ETC gauge bosons but with large flavor symmetry breaking to generate the top quark mass. The technicolor strong interaction matrix elements we required were estimated using naive dimensional analysis. Thus our predictions contain order one strong interaction uncertainties as well as order one model dependence. And of course traditional ETC scenarios might contain model-dependent contributions larger than those we have estimated.

In both classes of models we found that \( b \to s\gamma \) generically occurs at essentially the standard model rate, although it is possible to accomodate a slightly larger rate in techni-GIM models if the ETC dynamics is strongly interacting. \( B_s \to \mu^+\mu^- \) occurs in both types of models mediated by a \( Z \). If this is the only nonstandard contribution the rate is still likely to be an order of magnitude larger than in the standard model. However, the simplest techni-GIM models also contain four-fermion interactions whose contributions raise the rate to two orders of magnitude above the standard model rate. The enhanced \( B_s \to \mu^+\mu^- \) rates could be visible in the future.

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6 Figure Caption

Figure 1: $\Gamma(B_s \rightarrow \mu^+\mu^-)/\Gamma(b \rightarrow ce^{-}\nu_e)$ as a function of $m_t$ in (a) technicolor models with only the virtual $Z$ contribution, (b) technicolor with the direct four-fermion contribution expected in the simplest techni-GIM models, (c) the standard model. We have taken $f_B = 200$ MeV and all order one uncertainties to be exactly one.
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