Long-lived quarks?

Paul H. Frampton
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27599-3255

Pham Quang Hung
Department of Physics, University of Virginia, Charlottesville, Virginia 22901
(Received 25 February 1998; published 29 July 1998)

Three lines of reasoning suggest that there might exist a nonsequential fourth generation of heavy quarks having very small mixing with light quarks and hence exceptionally long lifetimes. It is proposed to seek out quarks that travel between 100 μm and 1 m in hadron colliders; they would have been overlooked in previous searches. [S0556-2821(98)00717-6]

PACS number(s): 12.60.−i, 14.65.−q, 14.80.−j

The accurate measurement in 1989 of the width of the Z boson [1] showed that there exist precisely three neutrinos coupling as in the standard model (SM) and they are lighter than half the Z mass $\sim$45 GeV. This led to the conventional wisdom that there are three, and only three, quark-lepton families. The discovery of the top quark [2,3] in 1995 was thus the final fermion of the SM. The only remaining particle is the Higgs boson expected to lie between $\sim$90 and $\sim$300 GeV.

This neat picture of just three quark-lepton families and a Higgs boson as the entire light spectrum of matter fields has great appeal. Depending on the mass of the Higgs boson [4], it could be the entire story up to the Planck or at least the grand unified theory (GUT) scale. Nevertheless, apart from the unsatisfactory aspect that this picture does not explain why there are precisely three families there are three principal reasons for suspecting that it is incomplete and that there might exist more light particles.

(1) The strong CP problem is unresolved. Although weak CP violation may be accommodated through the Kobayashi-Maskawa (KM) mechanism, the solution of the strong CP issue is more satisfactorily addressed by spontaneous CP violation in a model with two additional flavors of quark [5].

(2) The three couplings of the SM fail to evolve to a common unification point. Until recently this was thought [6] to offer support for low-energy supersymmetry, although this has been questioned [7] long ago. Very recently one of us [9] has pointed out that a fourth family with a Dirac-mass neutrino can lead to a satisfactory perturbative unification at $\sim 3.5\times 10^{15}$ GeV. This will require a fourth generation quark mass of around 150 GeV.

(3) The mass of the top quark is not too far from the electroweak breaking scale and hints that it might be related to the mechanism for symmetry breaking itself. The top-quark-condensate model [8] is an attractive scenario for such a symmetry breaking scheme. Unfortunately, the top quark is not heavy enough to make this work. It turns out that by adding a fourth family, one can revive that scenario [4] with a specific prediction for the Higgs boson mass, given a fourth generation quark mass. The discovery of the fourth generation might hint at where the Higgs boson might be located. Reference [4] explored this top-condensate type of model for a wide range of fourth generation quark mass, ranging from 150 to 230 GeV.

These three quite different reasons lead us to the conclusion that it is quite likely that the top quark is not the last flavor of quark and that there likely exists one further doublet (U,D) which is *either* vectorlike [(1) above] *or* chiral [(2) above].

The mass splitting of this extra doublet is severely constrained by precision electroweak data, conveniently parametrized by the S, T variables [10]—the U variable is nonrestrictive in this context. For the nonchiral case (1), there is no contribution to S and T at leading order.

We shall assume that $m_D \geqslant 150$ GeV. We start out with 150 GeV because, in the chiral case as discussed in Ref. [9], this is the mass range where there appears to be a *perturbative unification* of all three gauge couplings. For larger masses, again as discussed in Ref. [9], there appears Landau poles below 10^{15} GeV and it is not clear if one has or does not have unification, at least in the context of perturbation theory. However, as stated in the third motivation, these Landau poles are used to construct a top-quark-condensate type of model [4], giving rise to a definite relationship between the Higgs boson mass and the fourth generation quark mass. In this scenario, the discovery of the fourth generation hints at where the Higgs boson might be located. Our motivations are thus well founded: there is a very good reason for considering a fourth chiral family, at least from a *perturbative unification* point of view for $m_D \sim 150$ GeV, and from a symmetry breaking point of view for larger masses. Phenomenologically, we shall be open minded and shall consider a wide range of masses.

For the chiral case, there is a contribution to T given by

$$T=\frac{|\Delta M_Q^2|}{M_W^2}\frac{1}{4\pi\sin^2\theta_W}+\frac{|\Delta M_L^2|}{M_W^2}\frac{1}{4\pi\sin^2\theta_W} \tag{1}$$

where M_Q is the heavy quark mass, ΔM_Q^2 is the mass splitting in the quark doublet, and ΔM_L^2 is the corresponding mass splitting of the lepton doublet, assuming no Majorana mass N_R. Experimentally $T<0.2$ so for any $M_Q>200$ GeV, we deduce that the ratio of the U mass to the D mass cannot exceed 1.05. For smaller masses such as $M_Q=150$ GeV, that ratio cannot exceed 1.1. For the chiral case there is also a contribution to S given by, for a complete chiral family,

$$S = \frac{2}{3\pi} = +0.21, \tag{2}$$

which is just compatible with precision data if $T < 0.2$.

This leads to our main point: the ratio of masses in the fourth family is 1.1 or less, while in the third family we have $m_t/m_b \sim 30$. In the second, $m_c/m_s \sim 10$. This suggests heuristically that the fourth family is very different, and hence likely to be isolated from the first three families by tiny mixing angles. The question then is how tiny this mixing might be and how long-lived these heavy quarks can be. For example, let the mixing angle between the fourth family U quark and b quark be $V_{Ub} = x$ and assume that $|V_{Dt}| = |V_{Ub}|$. We shall particularly be interested in the following two ranges: $10^{-5} < x < 10^{-3}$ and $x < 10^{-5}$. The first range is the one considered by models such as the aspon model. For $x < 10^{-5}$, we may assume an almost unbroken 3+1 structure under a horizontal family symmetry to isolate the fourth family [11], similar to the 2+1 family structure used in previous models [12] which successfully accommodate the top quark mass.

Without specifying a particular model, we will examine the phenomenology of heavy quarks of long lifetime corresponding to small x in the quoted range. We will concentrate, in particular, on facilities such as hadron colliders (Tevatron, LHC), where one has the best chance of finding these objects. We will first estimate the production cross section for such heavy quarks. We then discuss various signatures.

For the Tevatron, the production cross section can be easily estimated since it is similar to the one used for the top quark. The process $p\bar{p} \to Q\bar{Q} + X$, where Q is a heavy quark, can proceed through $q\bar{q} \to Q\bar{Q}$ and $gg \to Q\bar{Q}$. At the Tevatron, the $q\bar{q}$ process dominates over the gg one (roughly 90 to 10 %). For example, if $m_Q = 180$ GeV, the cross section is ~ 4 pb for $\sqrt{s} = 1.8$ TeV and ~ 5.5 pb for $\sqrt{s} = 2$ TeV. Also, for $\sqrt{s} = 2$ TeV, a heavy quark with mass ~ 230 GeV can have a non-negligible cross section of ~ 1.5 pb. Of course, the cross section increases tremendously at the CERN Large Hadron Collider (LHC), by roughly three orders of magnitude. Since the up and down heavy quarks (U and D) are supposed to be fairly degenerate, their production cross sections are practically the same: we will have an equal number of $U\bar{U}$ and $D\bar{D}$. Their signatures, however, are very different.

We shall assume that $m_U > m_D$. Therefore both U and D can in principle have the following decay modes: $U \to (D \text{ or } q) + (l^+ \nu, q_1\bar{q}_2)$, $U \to q + W$, $D \to (t \text{ or } q) + (l^- \bar{\nu}, q_1\bar{q}_2)$, and $D \to (t \text{ or } q) + W$. There is also a flavor-changing decay $D \to bZ$ which, if dominant, could give rise to a very clear signal [13]. Here t, q, and l denote the top quark, the light quark, and the light lepton, respectively. In those decays, one has, in principle, to distinguish the chiral case from the vectorlike one. If (U,D) is a chiral doublet, all of the above decays will be of the $V-A$ nature. If it is a vectorlike doublet, the process $U \to (D \text{ or } q) + (l^+ \nu, q_1\bar{q}_2)$ will contain both $V-A$ and $V+A$ in the heavy quark current. However, because the light quarks are chiral, it turns out that the decay rate is practically the same as if (U,D) were chiral. This is because the rate is proportional to $(G_L^2 + G_R^2) g_L^2 I_1 + G_L G_R g_L^2 I_2$ and that $I_2 \approx -I_1$ and $G_L = G_R = g_L$ ($I_{1,2}$ are phase space integrals). The pure $V-A$ case will correspond to $G_R = 0$ and one can see that the two rates are the same. For all other decays involving the transition between a heavy and light quark, it will be pure $V-A$. Therefore, we shall only list formulas related to the pure $V-A$ cases.

The three-body and two-body decay widths involving the W, Γ_3^Q, and $\Gamma_{2,W}^Q$ are given by

$$\Gamma_3^{Q_1} = 12 |V_{Q_1Q_2}|^2 \frac{G_F(m_{Q_1})^5}{16\pi^3} I_{3\,\text{body}}(m_{Q_2}/m_{Q_1}, m_W/m_{Q_1}), \tag{3a}$$

$$\Gamma_{2,W}^{Q_1} = \frac{G_F(m_{Q_1})^3}{8\pi\sqrt{2}} |V_{Q_1Q_2}|^2 I_{2\,\text{body}}(m_{Q_2}/m_{Q_1}, m_W/m_{Q_1}), \tag{3b}$$

where $I_{3\,\text{body}}$ and $I_{2\,\text{body}}$ are well-known phase space factors [14]. Also, $V_{Q_1Q_2}$ denotes the mixing between the two quarks Q_1 and Q_2. For instance, we may assume that $V_{UD} \approx 1$ and $|V_{Ub}| \approx |V_{Dt}| = x$, where x is to be estimated. The width for the flavor-changing decay $D \to bZ$ is computed at one-loop for the chiral case and is given at tree level for the vector case as follows:

$$\Gamma(D \to bZ) = \frac{1}{2\cos^2\theta_W} \left[\left(\frac{g^2}{16\pi^2} \right)^2 x^2 4\Delta(m_U, m_t), \frac{m_b^2}{m_D^2} x^2 \right] \times \frac{G_F(m_D)^3}{8\pi\sqrt{2}} I_{2\,\text{body}}(m_b/m_D, m_Z/m_D), \tag{4}$$

where the first term in the parentheses in Eq. (4) refers to the chiral case and the second term $[(m_b^2/m_D^2)x^2]$ refers to the vector case. Here,

$$\Delta(m_U, m_t) = \left\{ \left(\frac{m_U^2 - m_t^2}{m_W^2} \right) \left[\ln\left(\frac{m_W^2}{m_{\text{heavier}}^2} \right) - 1 \right] \right\}^2, \tag{5}$$

where m_{heavier} is the heavier of the two quarks U and t. In Eq. (4), we have assumed $V_{Ub} = -x$ and $V_{Dt} = x$ so that there will be a GIM suppression when $m_U \sim m_t$. We shall start with the decay of the D quark first since it will set the range of the mixing parameter x where one can consider at least one of the two heavy quarks to be long lived. We then discuss the characteristic signatures for such long-lived quarks.

The current accessible but unexplored decay length for a long-lived heavy quark to be detected is between 100 μm and 1 m [15], a range on which we shall focus. (It should be noted that decay lengths less than 100 μm and greater than 1 m are accessible as well with the latter being excluded in Ref. [16]. Also, intermediate decay lengths of the order a few tens of cm might be hard to detect because the tracking de-

TABLE I. The values of $\Gamma_3^D[D\rightarrow t+(l\nu,q\overline{q})/x^2]$, $\Gamma_2^D(D\rightarrow b+Z)/x^2$, and $\Gamma_2^D(D\rightarrow t+W)/x^2$ as functions of m_D. The subscripts C and V for $\Gamma_2^D(D\rightarrow b+Z)/x^2$ refer to the chiral and vector cases, respectively.

m_D (GeV)	177	180	200	220	250	270	290	310
Γ_3^D/x^2 (GeV)	4.3×10^{-11}	1.1×10^{-8}	2.7×10^{-4}	3.8×10^{-3}	2.5×10^{-2}	2.8	3.1	2.8
$\Gamma_{2,C}^{D,Z}/x^2$ (GeV)	2.5×10^{-6}	1.7×10^{-5}	7.7×10^{-4}	4×10^{-3}	0.023	0.057	0.12	0.24
$\Gamma_{2,V}^{D,Z}/x^2$ (GeV)	8.5×10^{-4}	8.6×10^{-4}	9.6×10^{-4}	10^{-3}	0.0012	0.0013	0.0014	0.0015
$\Gamma_2^{D,W}/x^2$ (GeV)	0	0	0	0	0	0.86	1.77	2.86

tectors are not so efficient for decay products created half way through them [17].) The decay length is given by $\beta\gamma c\tau$, with $\beta\gamma$ being typically of order unity. Since $c\tau\sim2\times10^{-10}$ GeV/Γ(GeV) μm, this would correspond to a width Γ between 10^{-12} and 10^{-16} GeV. (For comparison, the top quark width is approximately 1.6 GeV.)

We now discuss the case 150 GeV$<m_D<m_t\sim175$ GeV for the chiral case first. We only have two competing processes, $D\rightarrow bZ$ [13] and $D\rightarrow(c,u)+W$. Which one dominates over the other will depend on what one assumes for V_{Dc}. In the most simple minded scheme for the quark mass matrix, one might expect $|V_{Dc}|$ to be at most x^2 if $|V_{Dt}|=x$. The decay width will be $\Gamma_{2,W}^D\approx1.0-1.6|V_{Dc}|^2$ GeV. The width for the flavor-changing decay $D\rightarrow bZ$ is given by Eq. (4). One obtains, for the naive assumption $|V_{Dc}|\sim x^2$, $\Gamma(D\rightarrow bZ)/\Gamma_{2,W}^D\sim2\times10^{-4}x^{-2}-10^{-5}x^{-2}$ for $m_U=150-170$ GeV. (The ratio vanishes for $m_U\sim m_t$.) From this one can see that the mode $D\rightarrow bZ$ dominates over $D\rightarrow cW$ for $x<10^{-3}$ unless the U mass is *very near* the top quark mass. This is, however, very model dependent. For instance, if $|V_{Dc}|\sim x^{3/2}$ (only as an example), $D\rightarrow bZ$ dominates over $D\rightarrow cW$ for $x<10^{-4}$ when $m_U=150$ GeV and for $x<10^{-5}$ when $m_U=170$ GeV. Nevertheless, it would still seem that $D\rightarrow bZ$ will be the dominant mode for this mass range except for when $m_U\sim m_t$. For definiteness, let us assume this is the case here. Eq. (4) gives $\Gamma(D\rightarrow bZ)\sim2\times10^{-4}x^2,10^{-5}x^2$ for $m_D=150{,}170$ GeV, respectively. For the decay $D\rightarrow bZ$ to be detectable between 100 μm and 1 m, one should have $10^{-6}<x<10^{-4}$ for $m_D=150$ GeV and $3\times10^{-6}<x<3\times10^{-4}$ for $m_D=170$ GeV.

For a vector D quark in the mass range between 150 and 175 GeV, the flavor-changing decay mode $D\rightarrow bZ$ is *right handed*. From Eq. (4), the ratio of $\Gamma(D\rightarrow bZ)$ to $\Gamma_{2,W}^D$ for the vector case can be computed. For the purpose of estimation, we shall put $m_D\sim m_U$. Again, we shall first assume that $|V_{Dc}|\sim x^2$. One easily finds $\Gamma(D\rightarrow bZ)/\Gamma_{2,W}^D\sim(7\times10^{-4}-5\times10^{-4})x^{-2}$ for $m_D=150-175$ GeV. Obviously, the mode $D\rightarrow bZ$ dominates for the range of interest, $10^{-5}<x<10^{-3}$. Even if $|V_{Dc}|\sim x^{3/2}$, it is still a dominant mode when $x<10^{-4}$. In any case, it is reasonable to expect $D\rightarrow bZ$ to be the dominant decay mode for 150 GeV$<m_D<175$ GeV for the vector case. Let us again assume this is the case here. For the decay to be observable between 100 μm and 1 m, one needs $x<4\times10^{-5}$ for the vector case. This is just *barely* at the lower end of the allowed range for the aspon model which is $10^{-5}<x<10^{-3}$.

Since one also has a similar expectation for the chiral case for the same mass range, the only way to distinguish the two cases when m_D is *different* enough than m_t is through the chirality of the decay: it is left handed in the chiral case and right handed in the vector case. For m_D *very close* to m_t, $D\rightarrow bZ$ is highly suppressed in the chiral case (unlike the vector case) but other decay modes such as $D\rightarrow cW$ kick in, and the D lifetime remains in the range of interest. The chirality in $D\rightarrow bZ$ could be studied by, e.g., looking at the b quark polarization through the lepton spectra in the inclusive semileptonic decay of b hadrons. Such a study has been proposed in Ref. [18] for b's produced at the CERN e^+e^- collider LEP. The present case is currently under investigation but a detailed analysis is beyond the scope of the present Brief Report.

When $m_D>m_t$, D can decay into t via the three- and/or two-body processes, depending on its mass. For m_D between ~177 GeV and $m_t+m_W\sim256$ GeV, the decay into t is exclusively three body. This has to be compared with the two-body decays $D\rightarrow bZ$ and $D\rightarrow cW$. As we have discussed above, if we assume $|V_{Dc}|\leqslant x^2$, we will always have $\Gamma(D\rightarrow bZ)>\Gamma_{2,W}^D$ for the situation when $m_D>m_t$. It is therefore sufficient to compare $\Gamma_3^D(D\rightarrow t)$ with $\Gamma(D\rightarrow bZ)$. It is straightforward to compute the width for $D\rightarrow t+(l^+\nu,q_1\overline{q_2})$ from Eq. (3a). In Table I, we show $\Gamma_3^D(D\rightarrow t)/x^2$, $\Gamma_2^D(D\rightarrow t)/x^2$, and $\Gamma(D\rightarrow bZ)/x^2$ (for both the chiral and vector cases). [$\Gamma_2^D(D\rightarrow t)/x^2$ is nonvanishing only when $m_D>m_t+m_W$.]

From Table I, the following observations emerge. For m_D from 177 to ~220 GeV, the mode $D\rightarrow bZ$ dominates over the three-body decay of D into the top quark, for both the chiral and vector cases. For the chiral case, it is easy to see that with $x\sim10^{-5}$ the D quark can be detected within the range 100 μm and 1 m [$10^{-16}<\Gamma(\text{GeV})<10^{-12}$]. ($x$ can be even larger depending on the mass of the D quark.) For the vector case, we can easily see that detectability requires x to be *less* than 3×10^{-5}. Again, this is at the lower limit of the aspon model.

For $m_D>220$ GeV, the top quark decay mode of D starts to become dominant for both chiral and vector cases. However, a look at Table I reveals that, in order for D to be detected, one should have $x<10^{-5}$. This will not favor the aspon model: the D quark in that scenario will have decay lengths *less* than 100 μm and should have been observed if it existed. That leaves the chiral nonsequential fourth family as viable in that range with a characteristic signature of the D decay into the top quark.

We now turn to the decay of the U quark. Since $m_U/m_D<1.1$ (ρ parameter constraint), m_U-m_D

TABLE II. The width $\Gamma_3^U[U\to D+(l\nu,q\overline{q})]$ as a function of m_D/m_U.

m_D/m_U	0.91	0.93	0.95	0.97	0.98
Γ_3^U (GeV)	5.2×10^{-5}	1.5×10^{-5}	2.8×10^{-6}	2.3×10^{-7}	3×10^{-8}

$<0.091m_U<m_W$ unless $m_U>890$ GeV, a strong coupling scenario *not* considered in this paper. The U quark decays into a D quark via a virtual W, namely, $U\to D+(l^+\nu,q_1\overline{q_2})$, where l and q are the light leptons and quarks. The U quark can also decay into a light quark and a real W, namely, $U\to q+W$ where $q=b,s,d$ and with $U\to b$ assumed to be the dominant transition. Which decay mode of U is dominant over the other depends on how degenerate U is with D and on how little U mixes with the b quark. The results are shown in Table II where we list Γ_3^U as a function of the ratio m_D/m_U. As for $\Gamma_2^U(U\to b)$, the estimate is straightforward. We obtain $\Gamma_2^U/x^2\sim1.75-4.7$ GeV for $m_U=180-250$ GeV.

For the first scenario with $x<10^{-5}$, we obtain $\Gamma_2^U(U\to b)<(1.75-4.7)\times10^{-10}$ GeV. For the second scenario with $10^{-5}<x<10^{-3}$, we obtain $(1.75-4.7)\times10^{-10}<\Gamma_2^U(U\to b)(\text{GeV})<(1.75-4.7)\times10^{-6}$. These are to be compared with the results listed in Table II.

Unless the U and D quarks are very degenerate, i.e., $m_D/m_U>0.98$, the decay mode $U\to D+(l^+\nu,q_1\overline{q_2})$ dominates in the first scenario ($x<10^{-5}$). A look at Table II reveals that the U decay length is *much less than* 1 μm. The signals can be quite characteristic: there is a primary decay of the U quark near the beam followed some 100 μm or so later by the secondary decay of the D quark. One might see two jets or a charged lepton originating from near the colliding region followed by three hadronic jets ($b\to\text{jet}+Z\to q\overline{q}\to\text{jet}+\text{jet}$) or one jet containing the b quark plus l^+l^- or νnu. Since the new quarks will be produced in pairs, one would then expect two Z's and hence there would be a kind of signal which has relatively low background, namely, $ZZ\to l^+l^-l^+l^-$. The reconstruction of the event, if possible, might reveal the decay of a short-lived quark (the U quark) into a long-lived quark (the D quark). There would approximately an equal number $D\overline{D}$ produced and hence there might be events where only the decay vertex of the D is seen.

For the second scenario with $10^{-5}<x<10^{-3}$, we can see that, if $m_D/m_U\geqslant0.97$, Γ_2^U dominates and U will decay principally into b. One would not see the type of events with one primary vertex separated by a hundred microns or so from the secondary one as we have discussed above. For $m_D/m_U\leqslant0.95$, the situation is similar to the one encountered in the first scenario.

Thus far, we have assumed $m_U>m_D$ as in the second and third families. We must not exclude the possibility that $m_D>m_U$ (as in the first family). The analysis we have given goes through *mutatis mutandis*, exchanging $t\to b$, etc. A principal difference is that we may consider lighter long-lived U quarks (e.g., $m_U<m_t$) than D quarks.

In summary, we have shown how there are reasons to believe that there exists a non-sequential fourth family of quarks, mixing only slightly with the light quarks. It has also been emphasized that such quarks with decay lengths between 100 μm and 1 m are worth special investigation as it is likely that previous searches have overlooked them.

We thank A.T. Goshaw and David Stuart for a discussion of the Fermilab Tevatron detectors. This work was supported in part by the U.S. Department of Energy under Grant No. DE-FG05-85ER-40219 (P.H.F.) and under Grant No. DE-A505-89ER-40518 (P.Q.H.).

[1] J. R. Carter, in *Proceedings of the Joint International Lepton-Photon Symposium and Europhysics Conference on High Energy Physics*, Geneva, Switzerland, 1991, edited by S. Hagerty, K. Potter, and E. Quercigh (World Scientific, Singapore, 1992).
[2] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **74**, 2626 (1995).
[3] DO Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **74**, 2632 (1995).
[4] P. Q. Hung and G. Isidori, Phys. Lett. B **402**, 122 (1997).
[5] P. H. Frampton and T. W. Kephart, Phys. Rev. Lett. **66**, 1666 (1991); P. H. Frampton and D. Ng, Phys. Rev. D **43**, 3034 (1991).
[6] U. Amaldi, W. de Boer, and H. Furstenau, Phys. Lett. B **260**, 240 (1991).
[7] U. Amaldi, W. de Boer, P. H. Frampton, H. Furstenau, and J. T. Liu, Phys. Lett. B **281**, 374 (1992).
[8] C. T. Hill, M. Luty, and E. Paschos, Phys. Rev. D **43**, 3011 (1990), and references therein.
[9] P. Q. Hung, Phys. Rev. Lett. **80**, 3000 (1998).
[10] M. E. Peskin and T. Takeuchi, Phys. Rev. Lett. **65**, 964 (1990); Phys. Rev. D **46**, 381 (1992).
[11] P. Q. Hung, Z. Phys. C **74**, 561 (1997).
[12] P. H. Frampton and O. C. W. Kong, Phys. Rev. D **53**, R2293 (1996), and references therein.
[13] E. Carlson and D. Land, Phys. Rev. D **46**, R9 (1992); J. F. Gunion, D. W. McKay, and H. Pois, Phys. Lett. B **334**, 339 (1994).
[14] V. Barger and R. J. N. Phillips, *Collider Physics* (Addison-Wesley, New York, 1997), updated edition.
[15] Al Goshaw and David Stuart (private communication).
[16] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **46**, 1889 (1992).
[17] D. Stuart (private communication).
[18] B. Mele and G. Altarelli, Phys. Lett. B **299**, 345 (1993).