B(sss, d)→ + ?d)→ + ?d^{)} →μ^{+} μ^{-} in technicolor model with scalars postprint

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Abstract

Rare decays B_{s,d}–>mu^+ mu^- are evaluated in technicolor model with scalars. R_b is revisited to constrain the model parameter space. It is found that restriction on f/f' arising from R_b which was not considered in previous studies requires f/f' no l

Full Text

Preamble

$\mu^+\mu^-$ in Technicolor Model with Scalars

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Rare decays $B_{s,d} \to \mu^+\mu^-$ constrain the model parameter space. It is found that restrictions on f/f' not considered in previous studies require f/f' to not be significantly enhanced for the $\mathrm{Br}(B_{s,d} \to \mu^+\mu^-)$ branching ratio prediction. With the value of $f/f' \lesssim 1.9$ at 95% confidence level, implying contributions from neutral scalars in the model, the mass m_σ is below 580 GeV. These are evaluated in the technicolor model with scalars. R_b is revisited to arise from constraints which were no larger than 1.9 at 95% confidence level. However, the branching ratio can still be enhanced by a factor of 5 relative to the Standard Model. With $f/f' \lesssim 1.9$, an upgraded Tevatron with an integrated luminosity in this model provided that neutral scalar masses are in the sub-TeV regime will be sensitive to enhancement of $B_s \to \mu^+\mu^-$.

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Introduction

Flavor-changing neutral-current B-meson rare decays play an important role in testing the Standard Model (SM) at loop level and probing new physics beyond the SM. Among these decays, $B_{s,d} \to \mu^+\mu^-$ are of special interest due to their relative cleanliness and good sensitivity to new physics.

There are numerous speculations on the possible forms of new physics, among which supersymmetry and technicolor are two typical different frameworks. Both frameworks are well-motivated. As a low-energy effective theory, the technicolor model with scalars introduces additional scalars to connect the technicolor condensate to ordinary fermions [1]. The phenomenology of this model has been considered extensively in the literature [1–8]. It has been found that this model does not produce unacceptably large contributions to neutral meson mixings or to the electroweak S and T parameters [1, 2]. On the other hand, this model does predict potentially visible contributions to b-physics observables such as R_b [6] and the rates of various rare B-meson decays [6–8].

Studies [9] showed that the processes $B_{s,d} \to \mu^+\mu^-$ are sensitive to supersymmetry. In this Letter we extend our previous studies [8, 10] and evaluate the branching ratio of $B_{s,d} \to \mu^+\mu^-$ in the technicolor model with scalars. First we present a brief description of the model, then give the analytical calculations for $B_{s,d} \to \mu^+\mu^-$. We focus our attention on the neutral scalar contributions, which are likely to be sizable because, as shown in our following analysis, they will be enhanced by a factor $(f/f')^4$ as the parameter f/f' gets large. Before performing the numerical calculations, we examine the current bounds on this model from a variety of experiments, especially the latest measurements of R_b [11]. Since the theoretical expression for R_b used in constraining the model parameter space [6] appears incorrect, we recalculate the contributions to R_b from the scalars in this model. We find the constraint from R_b is still the strongest as indicated in [20], compared with those from direct searches for neutral and charged scalars [12], B^0–$\bar{B}^0$ mixing, $b \to s\gamma$ [13], as well as the muon anomalous magnetic moment [14]. Furthermore, we evaluate restrictions on f/f' arising from R_b which were not considered in previous studies. Subject to the current bounds, the numerical results are presented in Sec. V. Finally, the conclusion is given in Sec. VI.

II. The Technicolor Model with Scalars

In this section we briefly discuss the technicolor model with scalars and give the relevant Lagrangians needed in our calculations. More details of the model have been described in Refs. [1, 2].

The model embraces the full SM gauge structure and all SM fermions which are technicolor singlets. It has a minimal $SU(N)$ technicolor sector, with two techniflavors that transform as a left-handed doublet and two right-handed singlets under $SU(2)_W$:

$$\begin{pmatrix} p \\ m \end{pmatrix}_L, \quad p_R, \quad m_R$$

with weak hypercharges $Y(T_L) = 0$, $Y(p_R) = 1/2$, and $Y(m_R) = -1/2$. All of the fermions couple to a weak scalar doublet ϕ to which both ordinary fermions and technifermions are coupled. This scalar's purpose is to couple the technifermion condensate to ordinary fermions and thereby generate fermion masses.

If we write the matrix form of the scalar doublet as

$$\Phi = \begin{pmatrix} \bar{\phi}^0 & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix} = (\sigma + f') \exp\left(\frac{2i\Pi}{f}\right)$$

and adopt the non-linear representation $\Sigma = \exp(2i\Pi/f)$ and $\Sigma' = \exp(2i\Pi'/f')$ for technipions, with fields in Π and Π' representing the pseudoscalar bound states of the technifermions p and m, then the kinetic terms for the scalar fields are given by

$$\mathcal{L}_{\text{K.E.}} = \frac{f^2}{4}\text{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) + \partial_\mu \sigma \partial^\mu \sigma + (\sigma + f')^2 \text{Tr}(D_\mu \Sigma'^\dagger D^\mu \Sigma')$$

Here D_μ (D'_μ) denote the $SU(2)_L \times SU(2)_R$ covariant derivatives, σ is an isosinglet scalar field, f and f' are the technipion decay constant and the effective vacuum expectation value (VEV), respectively.

As mixing between Π and Π' occurs, π_a and π_p are formed with π_a becoming the longitudinal component of the W and Z, and π_p remaining in the low-energy theory as an isotriplet of physical scalars. From Eq. (3) one can obtain the correct gauge boson masses providing that $f^2 + f'^2 = v^2$ with the electroweak scale $v = 246$ GeV.

Additionally, the contributions to the scalar potential generated by the technicolor interactions should be included in this model. The simplest term one can construct is

$$\mathcal{L}_T = \frac{c_1}{4\pi f^3}\text{Tr}[\Phi^\dagger T^a \Phi]\text{Tr}[\Phi^\dagger T^a \Phi] + \text{h.c.}$$

where c_1 is a coefficient of order unity, h_+ and h_- are the Yukawa couplings of scalars to p and m. From Eq. (4) the mass of the charged scalar at lowest order is obtained as

$$m_{\pi_p}^2 = \frac{2c_1\sqrt{2}f'}{v^2 h}$$

with $h = (h_+ + h_-)/2$. To absorb the largest Coleman-Weinberg radiative corrections [15] for the σ field which affect the phenomenology of the charged scalar, the shifted scalar mass M_ϕ and coupling $\tilde{\lambda}$ are determined by

$$M_\phi^2 = 8\sqrt{2}c_1\pi h f^3$$

Therefore, the mass of the scalar σ can be expressed as

$$m_\sigma^2 = \frac{M_\phi^2}{2} + \tilde{\lambda} f'^2 \quad \text{(limit (i) where the shifted } \phi^4 \text{ coupling } \tilde{\lambda} \text{ is small and can be neglected)}$$

or

$$m_\sigma^2 = \frac{\tilde{\lambda} f'^2}{2} + N h^4 \quad \text{(limit (ii) where the shifted mass of the scalar doublet } M_\phi \text{ is small and can be neglected)}$$

The advantage of this model is that at lowest order, only two independent parameters in the limits (i) and (ii) are needed to describe the phenomenology. We choose (h, m_σ) as physical parameters and assume $N = 4$ and $c_1 = 1$ in numerical calculations.

III. Calculations

We start the calculation by writing down the effective Hamiltonian describing the process $B_q \to \mu^+\mu^-$ $(q = s, d)$:

$$\mathcal{H}_{\text{eff}} = \frac{G_F^2 M_W^2}{2\pi^2} V_{tb} V_{tq}^* \left[C_{10}^{\text{eff}} \bar{q}\gamma^\mu P_L b \bar{\mu}\gamma_\mu\gamma_5\mu + C_Q^{(1)\text{eff}} \bar{q} P_R b \bar{\mu}\mu + C_Q^{(2)\text{eff}} \bar{q} P_R b \bar{\mu}\gamma_5\mu \right]$$

where $P_{R,L} = (1 \pm \gamma_5)/2$, p is the momentum transfer. The operators corresponding to the first three Wilson coefficients are the same as those given in [16] and the last two correspond to additional operators arising from neutral scalar exchange diagrams [17].

Using the effective Hamiltonian and the matrix elements

$$\langle 0|\bar{q}\gamma^\mu\gamma_5 b|\bar{B}_q\rangle = f_{B_q} p^\mu, \quad \langle 0|\bar{q}\gamma_5 b|\bar{B}_q\rangle = -i f_{B_q} m_{B_q}, \quad \langle 0|\bar{q}\sigma^{\mu\nu}(1+\gamma_5) b|\bar{B}_q\rangle = 0$$

we find that only operators $O_Q^{1,2}$ contribute to the process $B_q \to \mu^+\mu^-$ with the decay rate given by

$$\Gamma(B_q \to \mu^+\mu^-) = \frac{G_F^4 M_W^4}{32\pi^5} |V_{tb}V_{tq}^*|^2 f_{B_q}^2 m_{B_q}^3 \sqrt{1-\frac{4m_\mu^2}{m_{B_q}^2}} \left[\left(1-\frac{4m_\mu^2}{m_{B_q}^2}\right) |C_Q^{(1)}|^2 + \left| C_Q^{(2)} + \frac{2m_\mu}{m_{B_q}} C_{10} \right|^2 \right]$$

For convenience, we write down the branching fractions numerically:

$$\mathrm{Br}(B_d \to \mu^+\mu^-) = 3.8\times 10^{-10} \left[\left| C_Q^{(1)} \right|^2 + \left| C_Q^{(2)} + 0.5 C_{10} \right|^2 \right] \left(\frac{\tau_{B_d}}{1.65\mathrm{ps}}\right) \left(\frac{f_{B_d}}{210\mathrm{MeV}}\right)^2 \left(\frac{m_{B_d}}{5.28\mathrm{GeV}}\right)^3$$

$$\mathrm{Br}(B_s \to \mu^+\mu^-) = 1.2\times 10^{-8} \left[\left| C_Q^{(1)} \right|^2 + \left| C_Q^{(2)} + 0.5 C_{10} \right|^2 \right] \left(\frac{\tau_{B_s}}{1.49\mathrm{ps}}\right) \left(\frac{f_{B_s}}{245\mathrm{MeV}}\right)^2 \left(\frac{m_{B_s}}{5.37\mathrm{GeV}}\right)^3$$

where τ_{B_q} and f_{B_q} are the B_q lifetime and decay constant, respectively.

In the technicolor model with scalars, the additional contributions arise from the scalars. The contributions of the charged scalar $\pi_p^\pm$ with gauge boson Z, γ exchanges to the Wilson coefficients C_{10} at m_W scale have been calculated using Feynman rules derived from Eq. (3), (4) and are given by [7, 8]:

$$C_{10}^{\mathrm{TC}}(m_W) = \frac{\sin^2\theta_W}{4\pi} \left(\frac{f}{f'}\right)^2 \left[\frac{x_{\pi_p}^2 - 8x_{\pi_p} + 1}{8(x_{\pi_p}-1)^2} \ln x_{\pi_p} + \frac{3x_{\pi_p}^2 - 2x_{\pi_p} + 1}{4(x_{\pi_p}-1)^3} \right]$$

where θ_W is the Weinberg angle and $x_i = m_i^2/m_t^2$.

As for the contributions arising from neutral scalar exchanges, when only the leading terms in the large f/f' limit are kept, they can be expressed as [8]:

$$C_Q^{(1)\mathrm{TC}}(m_W) = \frac{1}{4\pi\sin^2\theta_W} \left(\frac{f}{f'}\right)^4 \frac{m_b m_\mu}{m_{\pi_p}^2}$$

$$C_Q^{(2)\mathrm{TC}}(m_W) = \frac{1}{4\pi\sin^2\theta_W} \left(\frac{f}{f'}\right)^4 \frac{m_b m_\mu}{m_{\pi_p}^2}$$

From Eqs. (12-14) we find that: (1) both the contributions arising from neutral scalar exchange $C_Q^{1,2}$ and gauge boson exchange C_{10} are subject to helicity suppression; (2) the contributions arising from neutral scalar exchange are proportional to $(f/f')^4$, while those from gauge boson exchange are proportional to $(f/f')^2$. So for a sufficiently large f/f', the contributions of neutral scalar exchange are relatively enhanced and may become comparable with those from gauge boson exchange.

The Wilson coefficients at the lower scale of about m_b can be evaluated down from m_W scale by using the renormalization group equation. At leading order, the Wilson coefficients are [16, 17]:

$$C_{10}(m_b) = C_{10}(m_W), \quad C_Q^{(i)}(m_b) = \eta^{-\gamma_Q/\beta_0} C_Q^{(i)}(m_W)$$

where $\beta_0 = 11 - 2n_f/3$, $\eta = \alpha_s(m_b)/\alpha_s(m_W)$ and $\gamma_Q = 4$ is the anomalous dimension of $\bar{q}P_R b$.

IV. Constraints from R_b

Before presenting the numerical results, let us consider the current bounds on technicolor with scalars from a variety of experiments, especially the measurement of R_b.

Using the Feynman rules in Ref. [8], one can easily find that the contributions from neutral scalars are negligible compared with those from charged scalars which appear in Fig. 1 [Figure 1: see original paper], and the bottom mass-dependent terms in R_b can also be omitted safely. In these approximations the additional contribution in technicolor with scalars is obtained as:

$$\delta R_b = R_b^{\mathrm{TC}} = \frac{\sin^2\theta_W}{4\pi}\left(\frac{f}{f'}\right)^2 \left[\Delta T_Z + C_{24}^a(p_1, m_t, m_{\pi_p}) + 2C_{24}^b(p_1, p_2, P, m_t, m_{\pi_p})\right]$$

where

$$\Delta T_Z = \frac{2v_{tL}m_t^2}{v^2} C_{24}^a(p_1, m_t, m_t) + \frac{2C_{24}^a(p_1, m_t, m_t)}{\cos^2 2\theta_W}$$

Here $B_1 = B_1(p_1, m_t, m_t)$ and $C_{24}^{a,b} = C_{24}^{a,b}(p_1, p_2, P, m_t, m_{\pi_p})$, with $p_1(p_2)$ and P denoting the four-momentum of $b(\bar{b})$ and Z boson respectively, are the Feynman loop integral functions and their expressions can be found in [18]. The coupling constants v_{qL} and v_{qR} are given by:

$$v_{qL} = T_q^3 - e_q \sin^2\theta_W, \quad v_{qR} = -e_q \sin^2\theta_W$$

Our explicit expressions are not in agreement with those used in [6] where the results obtained in the framework of the two-Higgs doublet model (THDM) [19] were adopted directly. We checked the calculations and confirmed our results.

The current measurement of R_b reported by LEP is $R_b^{\mathrm{expt}} = 0.21646 \pm 0.00065$ [11]. Comparing with the SM value $R_b^{\mathrm{SM}} = 0.21573 \pm 0.0002$, we obtained the constraints in the h versus m_σ plane shown in Figs. 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper].

Although our explicit expression for R_b is different from that used in [20], a comparison of Fig. 2 [Figure 2: see original paper], Fig. 3 [Figure 3: see original paper] with Figure 1 in Ref. [20] suggests that there is not a qualitative change in the results plotted.

Our numerical results show that the constraint on f/f' from R_b is quite stringent, i.e., the ratio f/f' must be smaller than 1.9 at 95% C.L., implying that the neutral scalars will not give dominant contributions to the processes $B_{s,d} \to \mu^+\mu^-$. Since previous studies did not comment on any restriction on f/f' arising from R_b, this is a new and interesting conclusion.

In Figs. 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper] we also display the bounds from $\bar{B}^0$ mixing and from the limits of Higgs masses [20].

In technicolor theories where the charged scalars couple to fermions in a similar pattern as in type-I two-Higgs doublet model, the strongest limit $m_{\pi_p} > 79$ GeV has been obtained directly from LEP experiments [12]. On the other hand, the LEP collaborations [12] have placed a 95% C.L. lower limit on the SM Higgs boson $M_H^0 > 114$ GeV from searching for the process $e^+e^- \to ZH^0$. Although the limit on technicolor scalars may differ from that on M_H^0, in practice, the contour $m_\sigma = 114$ GeV can serve as an approximate boundary to the experimentally allowed region [2, 20]. Note that the chiral Lagrangian analysis breaks down only when the technifermion current masses are no longer small compared to the chiral symmetry breaking scale, which constrains the parameter space in limit (i) [6]; the area above and to the left of the $hf' = 4\pi f$ line is excluded because the technifermion current masses are no longer small compared to the chiral symmetry breaking scale. For reference, we also plot the contours $m_{\pi_p} = m_t - m_b$; the areas outside the top quark decay curve to π^+ is excluded in Fig. 2 [Figure 2: see original paper]. A similar situation occurs for the $m_{\pi_p} = 1$ TeV curve in Fig. 3 [Figure 3: see original paper] if all scalar masses are restricted to the sub-TeV regime. In contrast to these, the excluded parameter space consists of the areas inside the $m_{\pi_p} = m_t - m_b$ curve in limit (ii) and the $m_{\pi_p} = 1$ TeV curve in limit (i).

The constraint from $b \to s\gamma$ is close to that from $\bar{B}^0$ mixing [7, 8, 21, 22], which are weaker than those from R_b [6]. As for the constraints from the measurement of $g_\mu - 2$, our previous study [23] showed that if the deviation of the E821 experiment result [14] and SM prediction $\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (43 \pm 16) \times 10^{-10}$ persists, it would severely constrain technicolor models because technicolor models can hardly provide such a large contribution. However, over the last year the theoretical prediction of a_μ in the SM has undergone a significant revision due to the change in sign of the light hadronic correction, which leads to only a 1.6σ deviation from the SM [24], yielding no more useful limits on this model.

V. Numerical Results

Bearing the constraints on technicolor with scalars in mind, and for the same values of m_{π_p} and f/f', the allowed value of m_σ is generally smaller in limit (i). From Eq. (14) one can infer easily that the additional contributions to $B_{s,d} \to \mu^+\mu^-$ in limit (i) will be larger than those in limit (ii). Furthermore, as can be seen from the numerical coefficients in Eq. (12), the decay rate of B_s is significantly larger than B_d due primarily to the relative size of $|V_{ts}|^2$ vs $|V_{td}|^2$. We thus take the B_s decay in limit (i) as an example to show the numerical results.

The experimental bound on $B_s \to \mu^+\mu^-$ comes from CDF [25] with $\mathrm{Br}(B_s \to \mu^+\mu^-) < 2.6 \times 10^{-6}$ at 95% C.L. with the corresponding integrated luminosity of about 100 pb^{-1}, while the SM prediction $\mathrm{Br}(B_s \to \mu^+\mu^-) = 4.0 \times 10^{-9}$ is obtained by taking the central values for all inputs in Eq. (12). The branching ratio of $B_s \to \mu^+\mu^-$ as a function of m_σ is displayed in Fig. 4 [Figure 4: see original paper] for various values of f/f'.

The 2σ bounds at the upgraded Tevatron with 10 fb^{-1} and 20 fb^{-1} are also plotted under the assumption that the background for this decay is negligible. The corresponding expected sensitivity can reach a branching ratio of 1.3×10^{-8} and 6.5×10^{-9} (dash lines), respectively. We see that the R_b constraint $f/f' \lesssim 1.9$ at 95% C.L. shown in Fig. 4 [Figure 4: see original paper] is the strongest bound. Comparatively, the current upper bound on $\mathrm{Br}(B_s \to \mu^+\mu^-)$ from CDF [25] is much weaker, which only excludes a small region with large f/f'. Under the constraint $f/f' \lesssim 1.9$, the enhancement factor for the branching ratio in the technicolor model can still be up to 5. The upgraded Tevatron with 20 fb^{-1} will be sensitive to enhancements of $B_s \to \mu^+\mu^-$ in this model provided that m_σ is below 580 GeV.

VI. Conclusions

We have evaluated the decays $B_{s,d} \to \mu^+\mu^-$ in the technicolor model with scalars, taking into account various experimental constraints, especially R_b, on the model parameter space. We first examined the restriction on f/f' arising from R_b that previous studies did not consider. We found that large f/f', which might cause significant enhancement for $\mathrm{Br}(B_{s,d} \to \mu^+\mu^-)$ from neutral scalars in the model, has been excluded by the constraints from R_b. Nevertheless, under the renewed R_b constraint, the branching ratio of $B_s \to \mu^+\mu^-$ can still be enhanced by a factor of 5 relative to the SM prediction.

With the maximum allowed value of $f/f' \approx 1.9$ from R_b, the upgraded Tevatron with 20 fb^{-1} will be sensitive to enhancements of $B_s \to \mu^+\mu^-$ in this model provided that m_σ is below 580 GeV. Since the theoretical uncertainties, which primarily come from the B-meson decay constants and CKM matrix elements, will be reduced in ongoing B-physics experiments and lattice calculations, the processes $B_{s,d} \to \mu^+\mu^-$ promise to be good probes of new physics.

References

[1] E. H. Simmons, Nucl. Phys. B312 (1989) 253.
[2] C.D. Carone and H. Georgi, Phys. Rev. D49 (1994) 1427.
[3] R. S. Chivukula, S. B. Selipsky and E. H. Simmons, Phys. Rev. Lett. 69 (1992) 575.
[4] S. Samuel, Nucl. Phys. B 347 (1990) 625; M. Dine, A. Kagan, and S. Samuel, Phys. Lett. B 243 (1990) 250; A. Kagan and S. Samuel, Phys. Lett. B 252 (1990) 605.
[5] N. Evans, Phys. Lett. B 331 (1994) 378; C. D. Carone and E. H. Simmons, Nucl. Phys. B 397 (1993) 591; C.D. Carone and M. Golden, Phys. Rev. D49 (1994) 6211.
[6] C. D. Carone, E. H. Simmons and Y. Su, Phys. Lett. B 344 (1995) 287.
[7] Y. Su, Phys. Rev. D 56 (1997) 335.
[8] Z. Xiong, H. Chen and L. Lu, Nucl. Phys. B561 (1999) 3; Z. H. Xiong and J. M. Yang, Nucl. Phys. B602 (2001) 281.
[9] For examples, see S. R. Choudhury and N. Gaur, Phys. Lett. B451 (1999) 86; K. S. Babu and C. Koda, Phys. Rev. Lett. 84 (2000) 228; P. H. Chankowski and L. Slawianowska, Phys. Rev. D63 (2001) 054012; C. Bobeth, T. Ewerth, F. Krüger and J. Urban, Phys. Rev. D 64 (2001) 074014; G. D'Ambrosio, G. F. Giudice, G. Isidori and A. Strumia, hep-ph/0207036; C.-S. Huang, W. Liao, Q.-S. Yan and S.-H. Zhu, Phys. Rev. D 64 (2001) 05992; Z. H. Xiong and J. M. Yang, Nucl. Phys. B628 (2002) 193; G. Isidori and A. Retico, JHEP 0111 (2001) 001; A. J Buras, P. H. Chankowshi, J. Rosiek and L. Slawianowska, hep-ph/0207241.
[10] G. R. Lu et. al., Phys. Rev. D54 (1996) 5647; Z. Phys. C74 (1997) 355; G. R. Lu, Z. Xiong and Y. G. Cao, Nucl. Phys. B 487 (1997) 43; G. R. Lu, Z. Xiong, X. L. Wang and J. S. Huang, J .Phys. G24 (1998) 745.
[11] T. Kawamoto, hep-ex/0105032; E. Tournefer, hep-ex/0105091; J. Drees, hep-ex/0110077.
[12] D.E. Groom et al., Eur. Phys. J. C 15 (2000) 1.
[13] ALEPH Collaboration, Phys. Lett. B429 (1998) 429; M. Nakao, Proceedings, ICHEP 2000, Osaka, Japan; T. Coan, Proceedings, ICHEP 2000, Osaka, Japan.
[14] H. N Brown, al., Mu g-2 Collaboration, Phys. Rev. Lett.86 (2001) 2227.
[15] S. Coleman and E. Weinberg, Phys. Rev. D7 (1973) 1888.
[16] B. Grinstein, R. Springer and M. B. Wise, Phys. Lett. B202 (1988) 138.
[17] Y. B. Dai, C. S. Huang and H. W. Huang, Phys. Lett. B390 (1997) 257.
[18] G. 't Hooft and M. Veltman, Nucl. Phys. B153 (1979) 365; G. Passarino and M. Veltman, Nucl. Phys. B160 (1979) 151.
[19] M. Boulare and Donald Finnell, Phys. Rev. D44 (1991) 2054.
[20] V. Hemmige and E. H. Simmons, Phys. Lett. B 518 (2001) 72.
[21] B. Grinstein, R. Springer, and M. B. Wise, Nucl. Phys. B339 (1990) 269.
[22] T. G. Rizzo, Phys. Rev. D38 (1988) 820; W. S. Hou and R. S. Willey, Phys. Lett. B202 (1988) 591 ; C. Q. Geng and J. N. Ng, Phys. Rev. D38 (1988) 2858; V. Barger, J. L. Hewett, and R. Phillips, Phys. Rev. D41 (1990) 3421.

[23] Z. H. Xiong and J. M. Yang, Phys. Lett. B508 (2001) 202.
[24] M. Knecht and A. Nyffeler, Phys. Rev. D65 (2002) 073034; M. Knecht, A. Nyffeler, M. Perrottet and E. de Rafael, Phys. Rev. Lett.88 (2002) 071802; M. Hayakawa and T. Kinoshita, hep-ph/0112102; I. Blokland, A. Czarnecki and K. Melnikov, Phys. Rev. Lett.88 (2002) 071803; J. Bijnens , E. Pallante and J. Prades, Nucl. Phys. B626 (2002) 410.
[25] F. Abe et. al. (CDF collaboration), Phys. Rev. D57 (1998) 3811.

Note: Figure translations are in progress. See original paper for figures.