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Single Top Quark Production as a Probe for Anomalous Moments at Hadron Colliders *

THOMAS. G. RIZZO

Stanford Linear Accelerator Center

Stanford University, Stanford, CA 94309

Abstract

Single production of top quarks at hadron colliders via gW fusion is examined as a probe of possible anomalous chromomagnetic and/or chromoelectric moment type couplings between the top and gluons. As expected, we find that this channel is far less sensitive to the existence of anomalous couplings of this kind than is the usual production of top pairs by gg or $q\bar{q}$ fusion. This result is found to hold at both the Tevatron as well as the LHC although somewhat greater sensitivity for anomalous couplings in this channel is found at the higher energy machine.

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The discovery of the top quark at the Tevatron by both the CDF and D0 Collaborations[1, 2] has renewed thinking about what may be learned from a detailed study of top properties. One point of view is that this clear discovery of the top represents a great triumph and confirmation of the predictions of the Standard Model(SM), in that the top lies in the mass range anticipated by precision electroweak data[3]. Another viewpoint is that the subtleties of top quark physics itself may shed some light on new physics beyond the SM. Indeed, due to its large mass, many people believe that top quark physics will be the first place where non-standard effects will appear.

If the top does have non-SM interactions associated with a new mass scale it may be possible to express them in the form of higher dimensional, non-renormalizable operators- which naturally divide themselves into those associated with the strong interactions, *i.e.*, QCD, and those associated with the electroweak sector. New interactions for the top quark in both sectors have been discussed in the literature[4, 5], and may arise as a result of, *e.g.*, compositeness or new dynamics associated with fermion mass generation[6]. In the QCD case, assuming CP conservation, the lowest dimensional operator representing new physics that we can introduce is the anomalous chromomagnetic moment, κ. On the otherhand, the corresponding chromoelectric moment, $\tilde{\kappa}$, violates CP. In this modified version of QCD for the top, the $t\bar{t}g$ interaction Lagrangian takes the form

$$\mathcal{L} = g_s \bar{t} T_a \left(\gamma_\mu + \frac{i}{2m_t} \sigma_{\mu\nu} (\kappa - i\tilde{\kappa}\gamma_5) q^\nu \right) t G_a^\mu \,, \tag{1}$$

where g_s is the strong coupling constant, m_t is the top quark mass, T_a are the color generators, G_a^μ is the gluon field and q is the outgoing gluon momentum. (Due to the non-Abelian nature of QCD, a four-point $t\bar{t}gg$ interaction is also generated, but this will not concern us in the present work.)

To study the tree-level effect of, *e.g.*, a non-zero κ at e^+e^- colliders, such as the NLC, requires a high precision examination of the tail of the gluon jet energy spectrum in the process $e^+e^- \to t\bar{t}g$. Unfortunately, though the sensitivity to non-zero values of κ and/or $\tilde{\kappa}$ is quite high[4], such an analysis is many years away and so we must turn our attention to what can be learned at hadron colliders. The pair production of top via $q\bar{q}, gg \to t\bar{t}$ at both the Tevatron and LHC in the case of non-zero κ (as well as $\tilde{\kappa}$ to some extent) has already been considered[4]. It was found that both the LHC and, eventually, the Tevatron are sensitive to values of κ of order 0.1. Present cross section measurements at the Tevatron being made by CDF and D0 are probing values of κ and $\tilde{\kappa}$ which are somewhat larger, of order 0.2-0.3. It thus seems natural to ask if this physics is accessible through any other top quark production channels at hadron colliders.

In the present analysis, we turn our attention to what may be learned about κ and $\tilde{\kappa}$ through an examination of single top production via $gW \to t\bar{b}$[7]. We anticipate that this production mechanism is far less sensitive to non-zero values of κ and $\tilde{\kappa}$ than is the usual pair production process. The reason for this is abundantly clear: the cross section receives its dominant contribution from the $u-$channel b quark exchange diagram which has no anomalous $t\bar{t}g$ vertex associated with it. To see if our expectations are indeed realized and the completion of our analysis of the influence of anomalous couplings on top production we proceed with the calculation. In the SM, assuming $m_t = 175$ GeV, single top production at both the Tevatron and LHC occurs with a cross section only a factor of $\simeq 5$ or so less than that for top pairs thus implying that adequate statistics should eventually be available at either machine to probe for anomalous effects in this channel. To show the rather weak dependence of this process on the values of κ and $\tilde{\kappa}$, we will make use of the Effective Gauge Boson Approximation(EGBA) [8] to greatly simplify our calculations. Though somewhat crude, the cross section estimates we obtain are sufficient for our purposes since the contributions due to anomalous couplings are so weak.

The relevant subprocess to examine for sensitivity to κ and $\tilde{\kappa}$ in single top production is $g(q)+W(k)^{+} \rightarrow t(p_t)+\bar{b}(p_b)$ (+ h.c.) which involves a $gt\bar{t}$ vertex. Denoting the W polarization vector by ϵ and for the moment neglecting the mass of the b-quark, *i.e.*, $m_b=0$, we obtain the following parton level differential cross section

$$\frac{d\sigma}{dz}=\frac{G_F M_W^2 \alpha_s(m_t)}{24\sqrt{2}s}\frac{2p_t}{\sqrt{s}}[T_1+\kappa T_2+(\kappa^2+\tilde{\kappa}^2)T_3] \tag{2}$$

where z is *cos* θ^*, with θ^* being the top quark production angle in the center of mass frame, and p_t is the magnitude of the top quark three-momentum. The T_i are given by

$$\begin{aligned} T_1 &= \frac{2}{ut'^2}\Big[t'(u^2+t'^2)+4(t'^2+2um_t^2)\epsilon\cdot q\epsilon\cdot p_b+4ut'\epsilon\cdot q\epsilon\cdot p_t-4t'^2(\epsilon\cdot p_b)^2 \\ &\quad -4ut'(\epsilon\cdot p_t)^2+4[t'(s-m_t^2)-2um_t^2]\epsilon\cdot p_b\epsilon\cdot p_t\Big]\ , \\ T_2 &= \frac{2}{ut'}\Big[u^2-2(s-m_t^2)(\epsilon\cdot q)^2-2\epsilon\cdot q[(2u+t')\epsilon\cdot p_b+u\epsilon\cdot p_t]\Big]\ , \\ T_3 &= \frac{1}{2m_t^2}\Big[s-m_t^2+4\epsilon\cdot p_b\epsilon\cdot p_t\Big]\ , \end{aligned} \tag{3}$$

where s, u, and $t'=t-m_W^2$ are the usual sub-process Mandelstam variables. In our numerical analysis, we will keep m_b finite and evaluate α_s at the scale m_t, which we done via a 3-loop renormalization group equation evolution from $\alpha_s(M_Z)=0.125$[3]. This sub-process cross section is apparently sensitive to the nature of the polarization of the incoming W. To obtain the full cross section, we first sum over the weighted contributions of the longitudinal and transverse W's for a given incoming quark flavor and then sum over the weighted quark densities. To be specific, we use the Martin, Roberts and Stirling MRSA parton densities[9]. We assume that the scattering takes place in the $x-z$ plane with the incoming W and g three-momenta along the $z-$axis. In this case, we can choose the three W polarization states, $\epsilon_T^i(i=x,y)$ and ϵ_L so that $\epsilon_T^i\cdot q=0$ and $\epsilon_L\cdot q=(s-M_W^2)/(2s)$. We also obtain the following explicit expressions for the other dot products in the Eq. 2:

$$
\begin{aligned}
\epsilon_T^1 \cdot p_b &= -\epsilon_T^1 \cdot p_t = -p_b(1-z^2)^{\frac{1}{2}}\,, \\
\epsilon_T^2 \cdot p_b &= \epsilon_T^2 \cdot p_t = 0\,, \\
\epsilon_L \cdot p_b &= (p_W E_b - E_W p_b z)/M_W\,, \\
\epsilon_L \cdot p_t &= (p_W E_t + E_W p_t z)/M_W\,,
\end{aligned} \tag{4}
$$

where p_i and E_i are the magnitude of the momenta and energies of the various particles in the parton frame. Similarly,

$$
\begin{aligned}
t &= -2E_g(E_t - p_t z) + m_t^2\,, \\
u &= -2E_g(E_b + p_b z) + m_b^2\,,
\end{aligned} \tag{5}
$$

From the kinematics it is easily seen that any terms in the cross section which are linear in $\tilde{\kappa}$ must vanish, as they should, since the total cross section is not a CP-violating observable.

Let us first consider the case where $\tilde{\kappa} = 0$. Fig.1 shows both the dependence of the total cross section on m_t for several values of κ as well as the κ dependence of the cross section for m_t fixed to 175 GeV at the Tevatron. We note two features immediately: (i) a non-zero value for κ almost always leads to a cross section increase except for the case of very small negative values and (ii) the difference between the SM result and κ's of order 2 is only of order 10%! Thus even if we were to neglect all of the other theoretical uncertainties, a 10% experimental determination of the cross section centered on or near the SM prediction would tell us only that $-2.9 \leq \kappa \leq 2.1$. A similar study of the κ dependence of the $gg,\ q\bar{q} \to t\bar{t}$ would yield sensitivities about a factor of 20 or so better[4]. This difference is due to the lack of sensitivity in the parton-level cross section itself and cannot be overcome by better statistics, of which there is always more in the pair production channel. Of course, as the

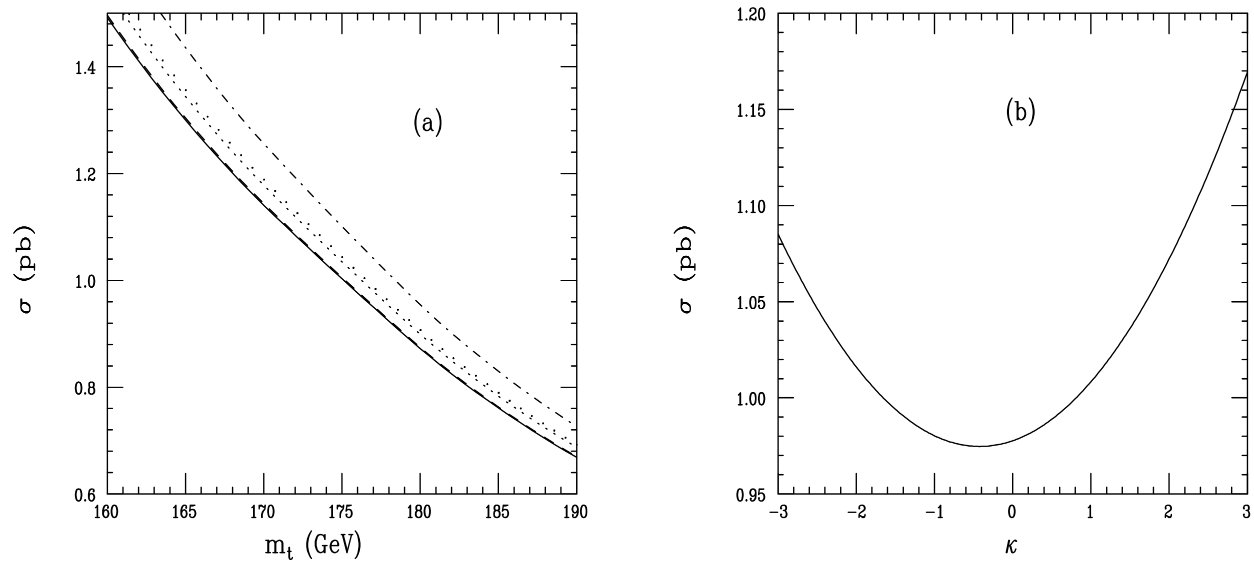

Figure 1: (a) Cross section for the process $gW^+ \to t\bar{b}(+\ h.c.)$ as a function of m_t at the Tevatron. The solid curve is the SM prediction whereas the dashdot(solid dot,dot, dash) curve corresponds to $\kappa = 2(-2, 1, -1)$. MRSA parton densities are assumed. (b) κ dependencies of the cross section shown in (a) for $m_t = 175$ GeV. In both plots, $\tilde{\kappa} = 0$ is assumed.

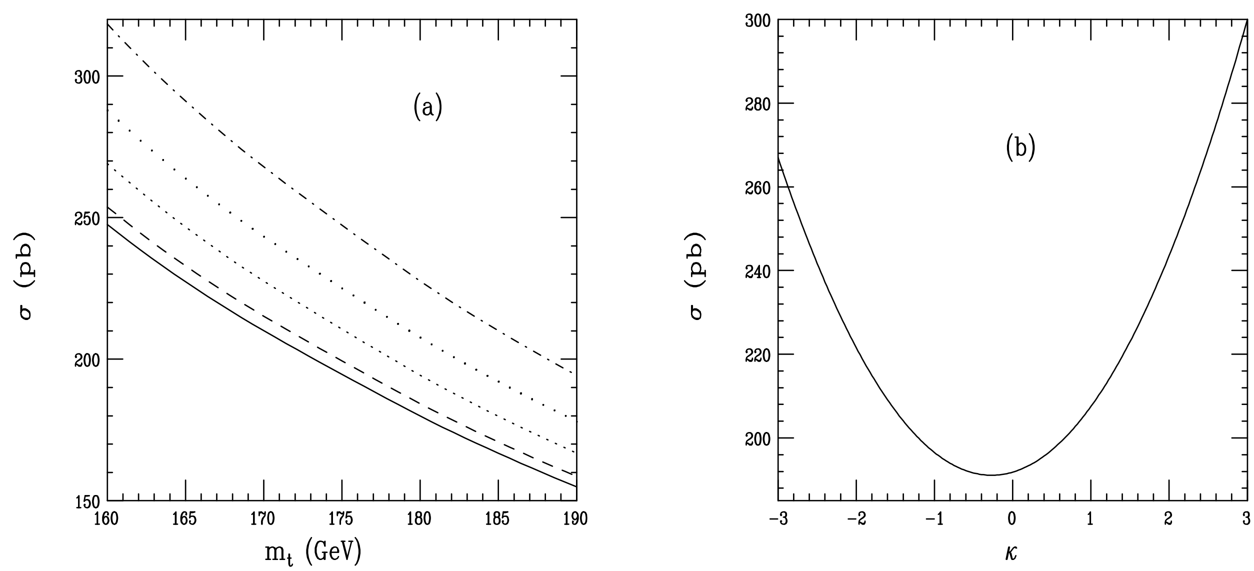

Figure 2: Same as Fig.1 but for the LHC.

average parton center of mass energy increases and the top becomes relatively light, *i.e.*, $m_t^2/s << 1$, the sensitivity to κ increases both due to the increasing importance of the t-channel exchange as well as the different momentum dependence in the anomalous coupling term in the interaction Lagrangian. Thus in Fig.2, which shows the corresponding cross section results for the LHC, we see that there is an enhanced dependency on κ. A 10% measurement centered on the SM value would restrict the range of κ to $-1.6 \leq \kappa \leq 1.1$. Although this is an improvement it cannot match the pair production mode at either the Tevatron or the LHC for sensitivity.

What happens in the reverse case, *i.e.*, when $\tilde{\kappa}$ only is non-zero? Since $\tilde{\kappa}$ appears only quadratically in the cross section, we can restrict ourselves to semi-positive definite values of this parameter. The resulting cross sections for the Tevatron and LHC are shown in Figs. 3 and 4, respectively. The general features are quite similar to the κ non-zero case in that $\tilde{\kappa}$ non-zero increases the cross section and the magnitude of the effect is comparable to the κ non-zero case. Here, a 10% measurement centered on the SM value would yield $\tilde{\kappa} \leq 2.5$ at the Tevatron and ≤ 1.4 at the LHC, respectively. We thus conclude that to probe for either anomalous chromomagnetic or chromoelectric moment couplings of top to gluons, the single production channel can in no way compete with pair production due to greatly reduced sensitivity and worse statistics.

In this paper, we have examined the single production of top quarks via gW fusion assuming the existence of anomalous chromomagnetic and/or chromoelectric dipole moment $t\bar{t}g$ couplings. The analysis was performed for both the Tevatron as well as the LHC. Our main result can be summarized as follows. Since the gW fusion process cross section is about a factor of 5 smaller than that for top pairs via $gg + q\bar{q}$ annihilation, a substantially larger sensitivity is needed in the gW channel for it to be competitive. Unfortunately, for either chromomagnetic or chromoelectric moments we found sensitivities more than an order of

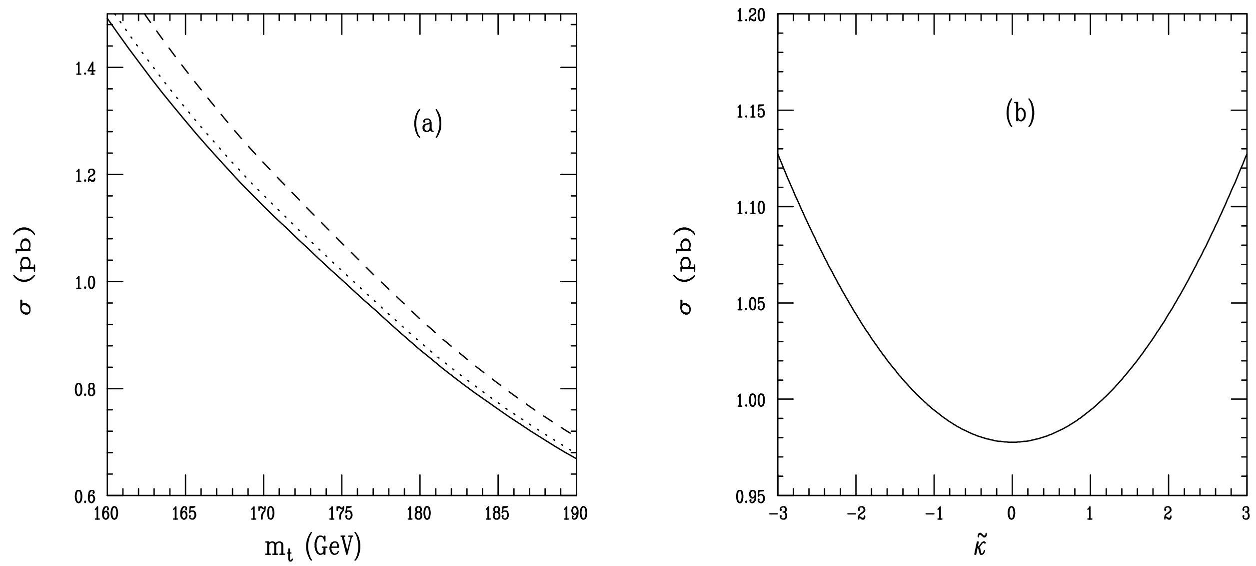

Figure 3: (a) Cross section for the process $gW^+ \to t\bar{b}(+\, h.c.)$ as a function of m_t at the Tevatron. The solid curve is the SM prediction whereas the dotted or dashed curve corresponds to $\tilde{\kappa}$ =1 or 2, respectively. MRSA parton densities are assumed. (b) $\tilde{\kappa}$ dependencies of the cross section shown in (a) for m_t = 175 GeV. In both plots, $\kappa = 0$ is assumed.

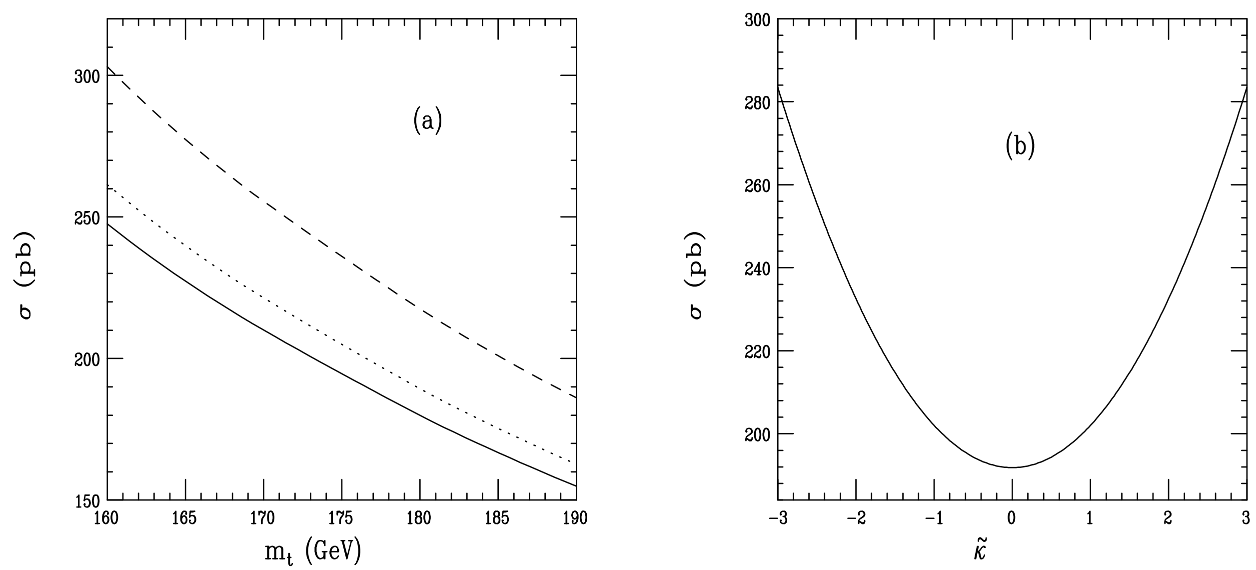

Figure 4: Same as Fig.3 but for the LHC.

magnitude smaller than in the annihilation channel. We thus conclude that the annihilation channel offers the best opportunity to hunt for anomalous top-gluon couplings at hadron colliders.

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References

[1] F. Abe *et al.*, CDF Collaboration, Phys. Rev. Lett. **73**, 225 (1994), Phys. Rev. **D50**, 2966 (1994), and Fermilab reports Fermilab-PUB-94/411-E, 1994 and PUB-95/022-E, 1995.

[2] S. Abachi *et al.*, D0 Collaboration, Phys. Rev. Lett. **72**, 2138 (1994) and Fermilab reports Fermilab-PUB-94/354-E, 1994 and PUB-95/028-E, 1995.

[3] D. Schaile, talk presented at, and LEP reports LEPEWWG/94-02, LEPTAU/94-02, LEPLINE/94-01, and LEPHF/94-03, submitted to the 27^{th} *International Conference on High Energy Physics*, Glasgow, Scotland, July 20-27, 1994. For an update on electroweak data, see the talks given by D. Comelli and M. Calvi at the *XXXth Recontres de Moriond, Electroweak Interactions and Unified Theories*, Meribel, France, March 1995. See also LEP report LEPEWWG/95-01.

[4] D. Atwood, A. Kagan and T. Rizzo, SLAC-PUB-6580, 1994; T.G. Rizzo, Phys. Rev. **D50**, 4478 (1994); P. Haberl, O. Nachtmann, and A. Welch, Univ. of Heidelberg report HD-THEP-95-25, 1995. See also, J.L. Hewett and T.G. Rizzo, Phys. Rev. **D49**, 319 (1994).

[5] G. Kane, G.A. Ladinsky, and C.P. Yuan, Phys. Rev. **D45**, 124 (1992); C.P. Yuan, Phys. Rev. **D45**, 782 (1992); D. Atwood, A. Aeppli, and A. Soni, Phys. Rev. Lett. **69**, 2754 (1992); M. Peskin, talk presented at the *Second International Workshop on Physics and Experiments at Linear* e^+e^- *Collider*, Waikoloa, HI, April 1993; M. Peskin and C.R. Schmidt, talk presented at the *First Workshop on Linear Colliders*, Saariselkä, Finland, September 1991; P. Zerwas, *ibid.*; W. Bernreuther *et al.*, in *Proceedings of the Workshop on* e^+e^- *Collisions at 500 GeV, The Physics Potential*, (DESY, Hamburg) ed. by P. Igo-

Kemenes and J.H. Kühn, 1992; A. Djouadi, ENSLAPP-A-365-92 (1992); D.O. Carlson, E. Malkawi, and C.-P. Yuan, Michigan State report MSUHEP-94/05, 1994.

[6] A. Kagan, talk presented at the *Fourth International Conference on Physics Beyond the Standard Model*, Lake Tahoe, CA, December 13-18, 1994 and references therein.

[7] For a review of the physics behind this process and original references, see C.P. Yuan, Michigan State University report MSU-HEP-50228, 1995.

[8] See, for example, S. Dawson, Nucl. Phys. **B249,42**, 1985 (and)Phys. Lett. **B217**, 347 (1989); G.L. Kane, W.W. Repko and W.B. Rolnick, Phys. Lett. **B148**, 367 (1984); Z. Kunst and D.E. Soper, Nucl. Phys. **B296**, 253 (1988); J.F. Gunion, J. Kalinowski and A. Tofighi-Niaki, Phys. Rev. Lett. **57**, 2351 (1986); W.B. Rolnick, Nucl. Phys. **B274**, 171 (1986).

[9] A.D. Martin, W.J. Stirling, and R.G. Roberts, Phys. Rev. **D50**, 6734 (1994).