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Single top quark from technipion production

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We investigate the contribution of technicolor mechanisms to the production of single top quarks at hadron colliders. Technipions with a mass larger than the top quark mass will decay predominantly to a top quark plus a bottom antiquark. We investigate two promising subprocesses: color-octet technipion plus a W boson via gluon-gluon fusion and technipion plus quark production via quark gluon interaction. The decay chain of a technipion to a top quark plus bottom quarks and then a top quark to a W plus bottom yields final states for the two subprocesses with, respectively, two W's and two bottom quarks and one W, two bottom quarks, and a light quark. We calculate the total cross sections and the p_T distributions for these technipion production mechanisms at CERN LHC energies for a range of technipion masses, starting at 200 GeV. We study the backgrounds to our processes and the kinematic cuts that enhance the signal to background ratio and we report event rate estimates for the upgraded Fermilab Tevatron and the LHC. Only the LHC has the potential to observe these processes. [S0556-2821(97)03717-X]

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I. INTRODUCTION

The discovery of the top quark [1] has opened up an exciting area of physics. Nonstandard model production of the top quark [2], or decay of the top quark [3] or a combination of the two [4] has received considerable attention. To implement the dynamical symmetry-breaking alternative to the standard model (SM), research continues in pursuit of complete models that realize the technicolor idea [5] that there is a new strong force that drives the formation of an electroweak symmetry-breaking condensate [6]. One variation on this theme explicitly invokes new top quark physics in conjunction with technicolor to make progress on this dynamical symmetry-breaking problem [7]. In partnership with model building, calculations that produce tests of features that are generic to a class of models at active or planned accelerators are needed. This paper aims at contributing to such tests in the realm of single top quark production, an area of intense interest for Fermilab Tevatron and CERN Large Hadron Collider (LHC) physics [8,9].

In one form or another, an extended technicolor scenario seems necessary for producing quark masses in a technicolor picture of electroweak symmetry breaking. Extended technicolor generally implies that technipions, just as the SM Higgs boson, couple to fermions with strengths proportional to the fermion masses. A positive technipion, for example, should decay to $t\bar{b}$. In the SM single top quark production in a hadron collider requires an extra W-boson interaction, and a corresponding factor of α_2 in comparison to $t\bar{t}$ production, so the production rate of single t at the LHC is expected to be relatively small,[1] $\simeq 312$ pb [9]. These considerations lead us to consider production of a single, colored charged technipion and its subsequent decay into $t\bar{b}$ or $\bar{t}b$, where the SM top quark backgrounds may be manageable and the gluon couplings and extra color factors help to enhance the technipion production.

Clearly, since production of a neutral technirho with subsequent decay to a pair of charged technipions would be much larger than our processes, we are *not* proposing a new ''discovery channel.'' We are looking for a discriminator among scenarios where color octet, charged technipions occur, which covers variants of the one-family models that accomodate precision electroweak constraints [10,11], including ''top-quark-color-aided'' cases [7]. As we will see below, the single technipion production involves anomalous terms in the chiral effective Lagrangian and distinctive kinematics of the final state decay products. These features make background suppression possible, and test interesting features of the technicolor models.

In the next section we describe the calculation and present representative cross-section plots. In Sec. III, we discuss backgrounds and ways in which a signal may be observed. In Sec. IV we discuss our results and conclude. An appendix gives detailed formulas for cross sections referred to in the text.

[1]This value is the sum of the single top quark plus single antitop quark production cross sections.

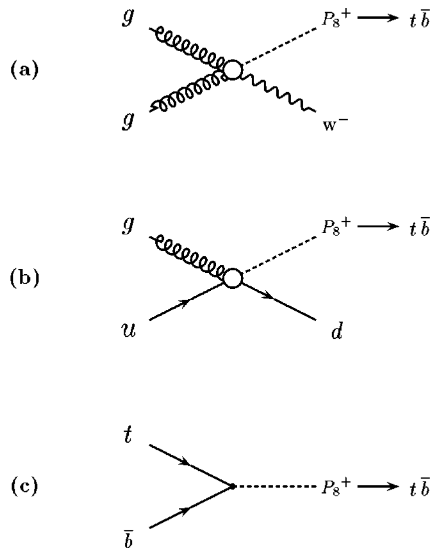

FIG. 1. (a) The $g+g \rightarrow P_8+W$ process. (b) The $g+q \rightarrow P_8+q$ process. (c) The direct sea contribution from the top quark, $t+\bar{b} \rightarrow P_8$. Curly lines are gluons, wavy lines are W bosons, dashed lines are technipions, and straight, solid lines are quarks.

II. SINGLE TOP QUARK PRODUCED FROM TECHNIPION DECAY

Figure 1 shows the subprocesses that yield a single, charged, color-octet technipion P_8^+. The tb mode is assumed to dominate the P_8^+ decay, so these are our technicolor-driven, single top quark production mechanisms. The direct P_8^+ production from the heavy quark sea, Fig. 1(c), is an order of magnitude smaller than the gluon-gluon fusion process, Fig. 1(a), and two orders of magnitude smaller than the gluon-quark process, Fig. 1(b), so we do not discuss it further in this paper.

In Fig. 2, we show the Feynman graphs that contribute to P_8^+ production in lowest order in g_3 and g_2, the QCD and weak SU(2) couplings. The technipion exchange term in Fig. 2(b) makes an insignificant contribution because the technipion Yukawa couplings are taken to be proportional to the fermion masses they couple to, which is generally the case in extended technicolor scenarios. The terms shown in the diagrams in Fig. 2(b) are individually gauge invariant.

In Fig. 2 the heavy dots indicate anomalous vertices. The relationship between the four-point $ggWP_8^+$ anomalous vertex and the three-point gWP_8^+ vertex in Fig. 2(a) is fixed by gluon gauge invariance and is therefore model independent. The overall factor for the anomalous vertex, and therefore the overall factor for the amplitudes in Figs. 2(a) and 2(b) *is* model dependent. As is evident from the diagrams, the factor has the form $\kappa_a g_3^2 g_2$ in Fig. 2(a) and $\kappa_b g_3 g_2^2$ in Fig. 2(b). In the one-family technicolor model, for example, $\kappa_a = iN_T/16\pi^2 F_T = \kappa_b$, where SU($N_T$) is the technicolor group and $F_T = 125$ GeV is determined by the weak scale [12].

The processes shown in Fig. 2 have distinct signatures. The $P_8^+W^-$ will have a high p_T recoil W^- to help tag the events. Similarly, the quark jet recoiling against P_8^+ in the P_8^+q final states will provide a high p_T jet tag.

In Fig. 3 we show the total cross sections for pp collisions at $\sqrt{s} = 14$ TeV for gg and gq ($P_8^+W^- + P_8^-W^+$ and $P_8^+d + P_8^-u$ final states, respectively) as a function of the technipion mass $M_{P_8^+}$ for the one-family technicolor model with $N_T = 3$. We use this model for reference because it is familiar, has the charged, color-octet technipion necessary for our mechanism, and variants that have been proposed to avoid conflict with precision electroweak data also have charged color-octet technipions; only the factors κ multiplying the anomalous vertices are different. Therefore, results

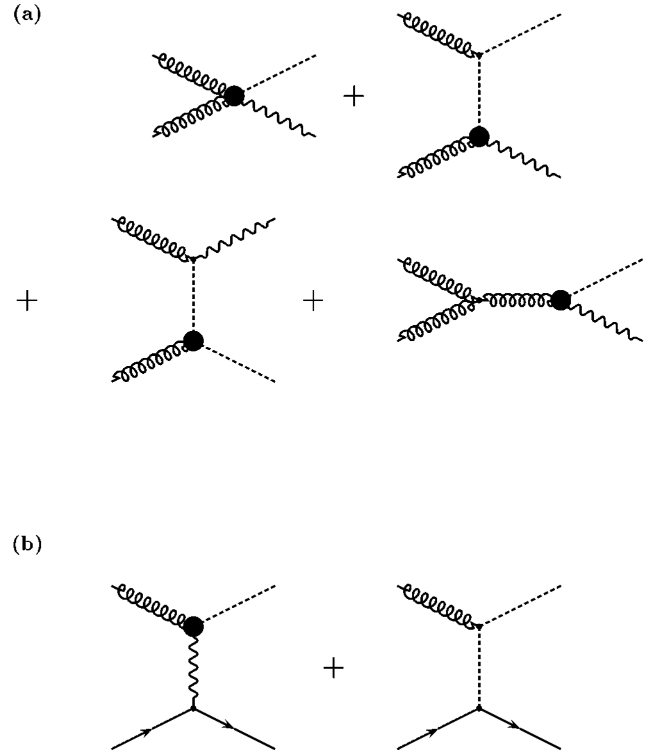

FIG. 2. (a) The four Feynman diagrams that contribute to the gluon-gluon fusion process, $g+g \rightarrow P_8+W$. (b) Feynman diagrams for the quark-gluon fusion process $g+q \rightarrow P_8+q$. The heavy dots indicate anomalous vertices—otherwise the same conventions as Fig. 1.

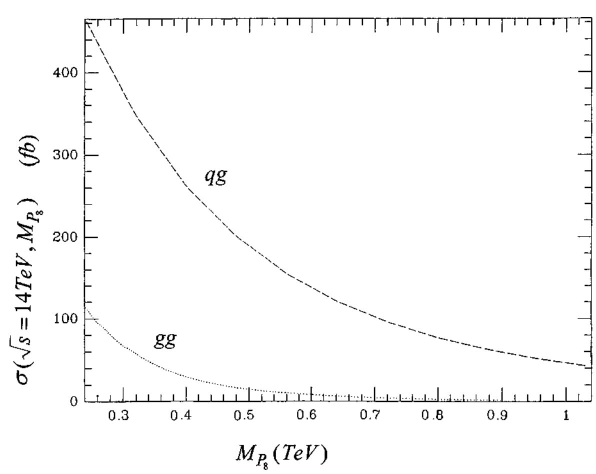

FIG. 3. The total cross sections for (a) $pp \rightarrow gg \rightarrow P_8+W$ and for (b) $pp \rightarrow qg \rightarrow P_8+q$ vs the technipion mass M_{P_8}. The c.m. energy is 14 TeV and $N_{TC}=3$ in the one-family Farhi-Susskind model.

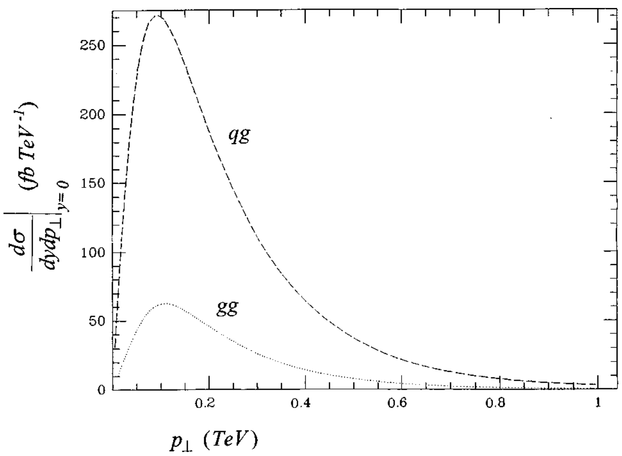

FIG. 4. The differential cross section $d\sigma/dydp_\perp|_{y=0}$ for processes (a) and (b) with $M_{P_8}=240$ GeV.

for a class of alternative models can be obtained by multiplying our ''reference model'' results by the appropriate factor.

The p_T distribution of the P_8^+ at $y=0$ for each process is shown in Fig. 4. We take $M_{P_8}=3M_W$. In the $P_8^+W^-$ case, the p_T is equivalent to that of the W^-, while in the P_8^+d case, the p_T is equivalent to that of the quark jet. The p_T spectra are quite stiff because of the extra momentum factors appearing at the anomalous coupling, as was noted in earlier work on similiar technicolor processes [13].

The numbers of events for $\mathcal{L}=100$ fb^{-1} corresponding to LHC parameters and 10^7 seconds, or one-third of a year (a ''Snowmass year'') of running, are shown for the two P_8^+ production processes in Tables I and II for a technipion mass of 240 GeV. The two charge states are added together, and the reference model has been used (i.e., one family technicolor with $N_T=3$). We will comment in Sec. IV on the numbers obtained in other, perhaps more realistic, models.

Under our assumption that the dominant P_8^+ decay mode is $t\bar{b}$, the final states will look as follows.

(a):

$$\left.\begin{array}{ccccc} P_8^+ & \rightarrow & t & \rightarrow & W^+b \\ & & \bar{b} & & \\ W^- & & & & \end{array}\right\} W^+b\bar{b}W^-$$

in the gluon-gluon fusion case, Fig. 1(a) and

(b)

$$\left.\begin{array}{ccccc} P_8^+ & \rightarrow & t & \rightarrow & W^+b \\ & & \bar{b} & & \\ q & & & & \end{array}\right\} W^+b\bar{b}\mathrm{jet}$$

in the gluon-quark case, Fig. 1(b). The total cross sections for cases (a) and (b) are 0.03 fb and 0.4 fb for $p\bar{p}$ collisions at $\sqrt{s}=2$ TeV, corresponding to an uncut total of 1 and 14 events in a year at the upgraded Tevatron—a dismal prospect. In the next section, we address the crucial background issue for these two signals at LHC energy and luminosity, where the prospects are reasonable.

TABLE I. The total cross section σ, the number of events in one ''Snowmass year'' (10^7 s) of running at LHC design luminosity times σ, N(total), and the number of events that remain after cuts, N (after cuts), for the $WWb\bar{b}$ final state. (See Sec. III for cuts.)

	σ	N (total)	N (after cuts)
Signal	0.112 pb	1.12×10^4	185
Background	526 pb	5.26×10^7	910

TABLE II. As in Table I for the $Wb\bar{b}g_{\mathrm{jet}}$ final state from the signal processes $pp\rightarrow P_8^+\bar{d}X+pp\rightarrow P_8^-\bar{u}X$ and the background process $pp\rightarrow t\bar{b}qX+pp\rightarrow \bar{t}bqX$. (See Sec. III for cuts.)

	σ	N (total)	N (after cuts)
Signal	0.94 pb	9.4×10^4	580
Background	225 pb	2.25×10^7	990

III. BACKGROUND FROM STANDARD MODEL TOP QUARK PRODUCTION

The SM total cross section for $t\bar{t}$ and single top quark production are approximately 525 and[2] 225 pb, respectively. These processes are the dominant backgrounds to our technipion, single top quark signals. There are kinematic features to the technipion processes that suggest cuts to beat down these backgrounds to a level where a signal, if present in the data, could be pulled out.

We first consider the process of Fig. 1(a) which has a $W^+W^-b\bar{b}$ final state, where one Wb pair comes from top quark decay, the other b from the technipion decay, and the other W recoils against the $P_8^{\pm}$. The following cuts effectively reduce the $t\bar{t}$ background to a manageable level:

$$\begin{array}{cccc}
\text{(i)} & p_TW_1 & > & 400 \text{ GeV}, \\
\text{(ii)} & p_TW_2 & > & 100 \text{ GeV}, \\
\text{(iii)} & p_Tb & > & 50 \text{ GeV(both } b\text{'s)}, \\
\text{(iv)} & |\eta|_b & < & 2\text{(both } b\text{'s)}, \\
\text{(v)} & |\eta|_W & < & 2\text{(both } W\text{'s)}, \\
\text{(vi)} & \cos\theta_{b\bar{b}} & > & 0.
\end{array}$$

These cuts are motivated by the following considerations: The W recoiling against the $P_8^{\pm}$ will have very large p_T. The decay products of the $P_8^{\pm}$ will also have substantial p_T and the opening angles between the decay products will be small in the lab. The $|\eta|$ cuts restrict our events to the acceptance region of the LHC detectors. We assume that these events will be most readily detected in the ''lepton plus jets'' mode

[2]This value is for the part of the total single top quark plus antitop quark cross section which leads to the $Wb\bar{b}q$ final state signature that is a background for our $q+g\rightarrow P_8+q$ process [14]. The total cross section is 312 pb [9].

where one of the two W's decays into a pair of jets and the other into either $e\nu$ or $\mu\nu$. The charged lepton and large missing energy will provide the event trigger and with only one neutrino the top quark mass can be reconstructed. We assume the b jets have been identified as has the lepton from W decay. We do not take into account here the inefficiencies of the particle ID's, but this should affect signal and background in a very similar manner.

With these cuts, we calculate that in one LHC year (100 fb^{-1}) there will be 185 signal events and 3180 $t\bar{t}$ background events [14]. Additional discrimination can be achieved by requiring that one Wb pair *not* reconstruct to the top quark mass. The effectiveness of this cut will depend upon the mass resolution of the detector. Using a conservative resolution assumption, we insist that one Wb mass be at least 200 GeV and find that the number of background $t\bar{t}$ events is reduced to 910 events with negligible effect on the signal. See Table I for signal processes $pp \to P_8^+ W^- X + pp \to P_8^- W^+ X$ and for the background process $pp \to t\bar{t}X$. In addition to the cuts (i)–(vi) listed above, the invariant mass of one Wb combination was restricted to $|M_{Wb}| > 200$ GeV, as just mentioned. We also considered the nonresonant $WWbb$ background and found it to be negligible in comparison with the $t\bar{t}$ background.

In considering the second process from Fig. 1(b), the chief difference is that we have a light quark jet q rather than a W recoiling against the technipion. The dominant background is single top quark production from W-gluon fusion, giving $Wbbq$ final states with one Wb from top quark decay. With just one W we must have it decay to $e\nu$ or $\mu\nu$ to facilitate the event trigger. We replace cut (i) above with a cut of 500 GeV on the most energetic jet, and use the other cuts as before. This yields 580 signal events, 990 background events from single top quark, as summarized in Table II. We note that requiring one Wb combination to reconstruct to the top quark mass will provide additional discrimination against nonresonant $Wbbq$. This is already strongly suppressed by cut i.

Since the Wbb invariant mass plot of the single top quark background after cuts is fairly smooth between 150 GeV and 1 TeV, the signal would stand out clearly as a peak centered at M_{P_8}. The natural width $\Gamma(P_8 \to tb)$ is rather narrow, varying from 160 MeV to 1.2 GeV as M_{P_8} ranges from 200 to 400 GeV, so the observed width would be completely determined by detector resolution. With our estimate of 580 signal events on a smooth background of 990, the peak should be unmistakeable even with modest resolution. These features of the signal and background make the prospects of detecting the P_8, if present in the data, quite promising.

IV. DISCUSSION OF RESULTS AND CONCLUSIONS

We have calculated the cross sections for the elementary single, color-octet technipion processes shown in Fig. 2, which are generic to techicolor models with QCD triplet techniquarks. The technipion decay to top quark and bottom quark yields a single top quark, whose decay then leads to a $WWbb$ final state from the process seen in Fig. 2(a) and a $Wbbq$ final state from the process seen in Fig. 2(b). The standard model final states that will be the dominant backgrounds after cuts to our single technipion signal were analyzed and compared to the signal process for the ''reference'' one-family technicolor model with $N_T = 3$ [12]. Tables I and II show the expected signal and background at the LHC for a nominal 10^7 second year of running with $M_{P_8} = 240$ GeV. Cuts on the p_T and η ranges of the final particles, as well as the $b\bar{b}$ opening angle, are described in the text. A variety of cuts were tried, but no attempt at an optimization was made. For example, the background falls much faster than the signal as $p_T b$ is raised [cut (iii)] We have not played the game of raising the cut to find if there is a signal to background ratio of 1:1. Our robust result is that a signal-to-background ratio of roughly 1:2 and a signal sample of order 10^3 events can be achieved. (The uncut number of events falls by roughly a factor of $\frac{2}{3}$ for each added 50 GeV of M_{P_8} mass.)

Our result holds up under variations to the Farhi-Susskind model that we used for the above estimates. For example, a recently proposed model that survives precision electroweak constraints [10] is that of Kitazawa and Yanagida [15]. The techniquarks are an $SU_T(3)$ triplet in their model, and they comprise the quark sector of a family in the standard model. The parameter κ [see Eq. (A1)] is then $\kappa = iN_T/16\pi^2 F_Q$, where $N_T = 3$ just as in our choice for reference model, but $F_T = \sqrt{F_Q^2 + F_L^2} = 125$ GeV. F_Q is the decay constant of the color octet technipions, which couple to techniquarks but not to technileptons, appropriate for our problem and $\tan\phi = F_Q/F_L$ is a free parameter in their model. Clearly the value of κ, and thus the production rate of the color-octet technipions, is enhanced in this model compared to that of the reference model. For a given technipion mass, our estimates are therefore on the conservative side.

An example of a top-quark-color-assisted technicolor model in which color-octet technipions occur is that of Lane [16]. The pseudo-Goldstone boson content of this model is rather complex, however, and the diagonalization problem to get mass eigenstates and identify those that carry QCD color quantum numbers has not been worked out. As with the model of [15], however, the effective F that enters in the coefficient κ [Eq. (A1)] will be less than $F_T = 125$ GeV, thus giving an enhancement.

In conclusion we believe that the study presented in this paper shows that if some variation of technicolor is indicated by dominant processes such as technirho production and decay into a pair of technipions, our single technipion processes would be observable at the LHC. The single top quark final states would then become an exciting hunting ground for signals to elucidate the new physics.

ACKNOWLEDGMENTS

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APPENDIX

Here we collect the principal components of the calculation reported in the text. The relevant, anomaly-driven vertices are given by the effective Lagrangian [17]

$$\mathcal{L}_{\rm eff}^{A}=i\kappa g_2 g_3 \epsilon^{\mu\nu\lambda\rho}\left(\partial_\mu G_\nu^b+\frac{1}{2}g_3 f^{bcd}G_\mu^c G_\nu^d\right)\times(P_8^{+,b}\partial_\lambda W_\rho^- + P_8^{-,b}\partial_\lambda W_\rho^+), \qquad (A1)$$

where $P_8^{\pm,b}$ are the color-octet technipions and G_μ^b are gluons. The constant κ has dimension $(\text{mass})^{-1}$ and it depends on the specific model employed. The trilinear gluon-$P_8^+ - P_8^-$ vertex that follows from the P_8 kinetic energy is

$$\mathcal{L}_G=-g_3 f^{abc}\partial^\mu P_8^{+,a}P_8^{-,b}G_\mu^c. \qquad (A2)$$

The amplitude for $g^a+g^b\rightarrow P_8^{\pm,c}+W^-$, designated as a, is given by the expression

$$\begin{aligned}T_a=&-\kappa g_2 g_3^2 f^{cab}\epsilon^{\mu\nu\lambda\rho}\Bigg\{e_\mu(q_a)e_\nu(q_b)k_\lambda e_\rho(k)+\frac{(q_a+q_b)_\mu}{2q_a\cdot q_b}\\ &\times[(2q_a+q_b)\cdot e(q_b)e_\nu(q_a)-(q_a-q_b)_\nu e(q_a)\cdot e(q_b)\\ &-(2q_b+q_a)\cdot e(q_a)e_\nu(q_b)]k_\lambda e_\rho(k)\\ &+\left[\frac{(q_b)_\mu e_\nu^b(q_b)k_\lambda e_\rho(k)(k-p-q_b)\cdot e(q_a)}{(q_b-k)^2-m^2}+b\leftrightarrow a\right]\Bigg\}. \end{aligned} \qquad (A3)$$

The variable labels are q_a=gluon a momentum, q_b=gluon b momentum, k=W-boson momentum, P=technipion momentum, and m is the technipion mass. The e_λ's are the vector field polarization vectors and κ is the model-dependent constant defined in Eq. (A1).

The parton-level cross section that follows from the above amplitude can be expressed as

$$\begin{aligned}\frac{d\sigma}{dt}=&\frac{3}{8}\pi^2\kappa^2\alpha_3^2\alpha_2\frac{1}{s^2}\Bigg\{2M_W^2+4\Bigg[cktw+dkuw\\ &+\left(2+\frac{tp}{up}+\frac{up}{tp}\right)\frac{twuw}{2s}+\left(-\frac{m^2 s}{(tp)^2}+\frac{up}{tp}\right)\frac{(tw)^2}{2s}\\ &+\left(-\frac{m^2 s}{(up)^2}+\frac{tp}{up}\right)\frac{(uw)^2}{2s}-\frac{sM_W^2 m^2}{uptp}+sckdk\\ &+\frac{tp}{up}\frac{cktw}{2}+\frac{up}{tp}\frac{dkuw}{2}+\frac{twuwcd}{2}\Bigg]\Bigg\}. \end{aligned} \qquad (A4)$$

The definitions of the factors in terms of s, t, M_W^2, and m^2 are

$$u=M_W^2+m^2-s-t,\quad tw=M_W^2-t,\quad uw=s+t-m^2,$$

$$up=s+t-M_W^2,\quad tp=m^2-t,\quad cd=-\frac{1}{2s}+\frac{m^2}{(uptp)},$$

$$ck=\frac{tw}{2s}-\frac{s-M_W^2-m^2}{2tp},$$

$$dk=\frac{uw}{2s}-\frac{(s-M_W^2-m^2)}{2up}. \qquad (A5)$$

For process b, namely, $g^a+q^b\rightarrow P_8^c+q^d$, we have the amplitude

$$T_b=i\kappa\frac{g_2^2 g_3}{2\sqrt{2}}\delta^{a,c}\delta^{b,d}\epsilon^{\mu\nu\lambda\rho}\times\frac{q_\mu e_\nu(q)(k-k')_\lambda\overline{u(k')}\gamma_\rho(1-\gamma_5)u(k)}{(p-q)^2-M_W^2}, \qquad (A6)$$

where the momenta of gluons, incoming quark, outgoing quark, and technipion are q, k, k', and p, respectively. The technipion exchange amplitude in Fig. 2(b) is negligible.

The corresponding parton level cross section is

$$\frac{d\sigma}{dt}=\frac{\pi^2}{4}\kappa^2\alpha_2^2\alpha_3\frac{(-t)}{s^2}\frac{(s^2+u^2)}{(t-M_W^2)^2}, \qquad (A7)$$

where

$$t=(k-k')^2=-2k\cdot k'$$

$$u=(q-k')^2=-2q\cdot k'$$

$$s=(q+k)^2=2q\cdot k, \qquad (A8)$$

and quarks are light and treated as massless.

To compute the p-p production cross sections we used the version 3 CTEQ structure functions [18]. Results are shown for set 2, leading order, versions of the structure functions, though we also used set 1, the modified minimal subtraction scheme ($\overline{\rm MS}$) to two loop version as a check. The differences between the cross sections and event rates were at the few percent level, which is inconsequential for our purposes. We show the set 2 results in the spirit of staying within a purely leading order calculation.

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