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Technihadron Production and Decay Rates in the Technicolor Straw Man Model

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Abstract

We present hadron collider production rates for the lightest color-singlet technihadrons in a simple "straw-man" model of low-scale technicolor. These rates are presented in a way to facilitate their encoding in PYTHIA. This document is a companion to my paper, "Technihadron Production and Decay in Low-Scale Technicolor".

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1 The Technicolor Straw Man Model

In this note we present formulas for the decay rates and production cross sections for the lightest color-singlet technivector mesons $V_T = \rho_T$ and ω_T. The decay rates have been revised for $V_T \to G\pi_T$, where G is a transversely polarized electroweak gauge boson, γ, Z^0, or $W^\pm$. The gauge boson polarization is defined relative to the spin direction of the technivector meson in the latter's rest frame. This is parallel to the beam direction in a hadron or lepton collider.

Some basic references are: for technicolor and extended technicolor [1, 2]; for walking technicolor [3]; for top condensate models and topcolor-assisted technicolor (TC2) [4, 5, 6, 7]; for multiscale technicolor [8]; for signatures of low-scale technicolor in hadron and lepton colliders [9]. As has been emphasized in Refs. [8, 9], a large number N_D of technifermion doublets are required in TC2 models with a walking technicolor gauge coupling. In turn, N_D technidoublets imply a relatively low technihadron mass scale, set by the technipion decay constant $F_T \simeq F_\pi/\sqrt{N_D}$, where $F_\pi = 2^{-1/4}G_F^{-1/2} = 246\,\mathrm{GeV}$. In the models of Ref. [7], for example, the number of electroweak doublets of technifermions $N_D \simeq 10$ and $F_T \simeq 80\,\mathrm{GeV}$.

To set the ground rules for our calculations, we adopt the "Technicolor Straw Man Model". In the TCSM, we assume that we can consider in isolation the lowest-lying bound states of the lightest technifermion doublet, (T_U, T_D). These are assumed to be color singlets and to transform under technicolor $SU(N_{TC})$ as fundamentals; they have electric charges Q_U and Q_D. The bound states in question are vector and pseudoscalar mesons. The vectors include a spin-one isotriplet $\rho_T^{\pm,0}$ and an isosinglet ω_T. Since techni-isospin is likely to be a good approximate symmetry, ρ_T and ω_T should be nearly degenerate. [1]

The pseudoscalars, or technipions, also comprise an isotriplet $\Pi_T^{\pm,0}$ and an isosinglet $\Pi_T^{0\prime}$. However, these are not mass eigenstates. In the TCSM, we assume the isovectors are simple two-state mixtures of the longitudinal weak bosons $W_L^\pm$, Z_L^0—the true Goldstone bosons of dynamical electroweak symmetry breaking in the limit that the $SU(2)\otimes U(1)$ couplings g, g' vanish—

[1] Even though ρ_T^0 and ω_T have nearly the same mass, they do not mix much because, as in QCD, they have rather different decay rates.

and mass-eigenstate pseudo-Goldstone technipions $\pi_T^\pm, \pi_T^0$:

$$|\Pi_T\rangle = \sin\chi\,|W_L\rangle + \cos\chi\,|\pi_T\rangle\,. \tag{1}$$

Here, $\sin\chi = F_T/F_\pi \ll 1$. Similarly, $|\Pi_T^{0\prime}\rangle = \cos\chi'\,|\pi_T^{0\prime}\rangle + \cdots$, where χ' is another mixing angle and the ellipsis refer to other technipions needed to eliminate the technicolor anomaly from the $\Pi_T^{0\prime}$ chiral current. These massive technipions are also expected to be nearly degenerate. However, as noted in Ref. [9], there may be appreciable π_T^0–$\pi_T^{0\prime}$ mixing. If that happens, the lightest neutral technipions are ideally-mixed $\bar{T}_U T_U$ and $\bar{T}_D T_D$ bound states.

Technipion decays are induced mainly by extended technicolor (ETC) interactions which couple them to quarks and leptons [2]. These couplings are Higgs-like, and so technipions are expected to decay into the heaviest fermion pairs allowed. One exception to this in TC2 is that only a few GeV of the top-quark's mass is generated by ETC, so there is no great preference for π_T to decay to top quarks nor for top quarks to decay into them. Also, because of anomaly cancellation, the constituents of the isosinglet technipion $\pi_T^{0\prime}$ may include colored technifermions as well as color-singlets. Then, it decays into a pair of gluons as well as heavy quarks. Therefore, the decay modes of interest to us are $\pi_T^+ \to c\bar{b}$ or $c\bar{s}$ or even $\tau^+\nu_\tau$; $\pi_T^0 \to b\bar{b}$ and, perhaps $c\bar{c}$, $\tau^+\tau^-$; and $\pi_T^{0\prime} \to gg$, $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$. Branching ratios are estimated from (for the sake of generality, we quote the energy-dependent widths for technipions of mass $s^{1/2}$):

$$\begin{aligned}
\Gamma(\pi_T \to \bar{f}' f) &= \frac{1}{16\pi F_T^2}\, N_f\, p_f\, C_f^2 (m_f + m_{f'})^2 \\
\Gamma(\pi_T^{0\prime} \to gg) &= \frac{1}{128\pi^3 F_T^2}\, \alpha_c^2\, C_{\pi_T}\, N_{TC}^2\, s^{\frac{3}{2}}\,.
\end{aligned} \tag{2}$$

Here, C_f is an ETC-model dependent factor of order one *except* that TC2 suggests $|C_t| \lesssim m_b/m_t$; N_f is the number of colors of fermion f; p_f is the fermion momentum; α_c is the QCD coupling evaluated at $s^{1/2}$ ($= M_{\pi_T}$ for on-shell technipions); and C_{π_T} is a Clebsch of order one. The default values of these and other parameters are tabulated at the end of this note.

2 ρ_T Decay Rates

In the limit that the couplings $g, g' = 0$, the ρ_T and ω_T decay as

$$\rho_T \rightarrow \Pi_T\Pi_T = \cos^2\chi\,(\pi_T\pi_T) + 2\sin\chi\,\cos\chi\,(W_L\pi_T) + \sin^2\chi\,(W_LW_L)\,;$$

$$\omega_T \rightarrow \Pi_T\Pi_T\Pi_T = \cos^3\chi\,(\pi_T\pi_T\pi_T) + \cdots\,. \tag{3}$$

The ρ_T decay amplitude is

$$\mathcal{M}(\rho_T(q) \rightarrow \pi_A(p_1)\pi_B(p_2)) = g_{\rho_T}\,\mathcal{C}_{AB}\,\epsilon(q)\cdot(p_1 - p_2)\,, \tag{4}$$

where, scaling naively from QCD,

$$\alpha_{\rho_T} \equiv \frac{g^2_{\rho_T}}{4\pi} = 2.91\left(\frac{3}{N_{TC}}\right)\,, \tag{5}$$

and

$$\mathcal{C}_{AB} = \begin{cases} \sin^2\chi & \text{for } W_L^+W_L^- \text{ or } W_L^\pm Z_L^0 \\ \sin\chi\cos\chi & \text{for } W_L^+\pi_T^-, W_L^-\pi_T^+ \text{ or } W_L^\pm\pi_T^0, Z_L^0\pi_T^\pm \\ \cos^2\chi & \text{for } \pi_T^+\pi_T^- \text{ or } \pi_T^\pm\pi_T^0\,. \end{cases} \tag{6}$$

The energy-dependent decay rates (for ρ_T mass $\sqrt{\hat{s}}$)

$$\Gamma(\rho_T^0 \rightarrow \pi_A^+\pi_B^-) = \Gamma(\rho_T^\pm \rightarrow \pi_A^\pm\pi_B^0) = \frac{2\alpha_{\rho_T}\mathcal{C}^2_{AB}}{3}\,\frac{p^3}{\hat{s}}\,, \tag{7}$$

where $p = [(\hat{s} - (M_A + M_B)^2)(\hat{s} - (M_A - M_B)^2)]^{\frac{1}{2}}/2\sqrt{\hat{s}}$ is the π_T momentum in the ρ_T rest frame.

For $g, g' \neq 0$, ρ_T decay to transversely polarized electroweak bosons plus a technipion, $G\pi_T$ with $g = \gamma, Z^0, W^\pm$, and to fermion-antifermion pairs, $f\bar{f}'$ with $f, f' = q$ or $\ell^\pm, \nu_\ell$. The decay rate for $V_T \rightarrow G\pi_T$ is [10]

$$\Gamma(\rho_T \rightarrow G\pi_T) = \frac{\alpha V^2_{\rho_T G\pi_T}\,p^3}{3M_V^2} + \frac{\alpha A^2_{\rho_T G\pi_T}\,p\,(3M_G^2 + 2p^2)}{6M_A^2}\,, \tag{8}$$

where M_G is the G-boson's mass and p its momentum; M_V and M_A are mass parameters of order several hundred GeV. The quantities $V_{V_T G\pi_T}$ and $A_{V_T G\pi_T}$

are defined for $V = \rho_T, \omega_T$ as follows: [2]

$$V_{V_T G \pi_T} = \mathrm{Tr}\Big(Q_{V_T}\{Q^\dagger_{G_V},\, Q^\dagger_{\pi_T}\}\Big)\,, \qquad A_{V_T G \pi_T} = \mathrm{Tr}\Big(Q_{V_T}[Q^\dagger_{G_A},\, Q^\dagger_{\pi_T}]\Big)\,. \quad (9)$$

In the TCSM, with electric charges Q_U, Q_D for T_U, T_D, the generators Q in Eq. (9) are given by

$$\begin{aligned}
Q_{\rho_T^0} &= \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}; \qquad Q_{\rho_T^+} = Q^\dagger_{\rho_T^-} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \\
Q_{\pi_T^0} &= \frac{\cos\chi}{\sqrt{2}}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}; \quad Q_{\pi_T^+} = Q^\dagger_{\pi_T^-} = \cos\chi\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \\
Q_{\pi_T^{0\prime}} &= \frac{\cos\chi'}{\sqrt{2}}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
Q_{\gamma_V} &= \begin{pmatrix} Q_U & 0 \\ 0 & Q_D \end{pmatrix}; \qquad Q_{\gamma_A} = 0 \\
Q_{Z_V} &= \frac{1}{\sin\theta_W\cos\theta_W}\begin{pmatrix} \frac{1}{4} - Q_U\sin^2\theta_W & 0 \\ 0 & -\frac{1}{4} - Q_D\sin^2\theta_W \end{pmatrix} \\
Q_{Z_A} &= \frac{1}{\sin\theta_W\cos\theta_W}\begin{pmatrix} -\frac{1}{4} & 0 \\ 0 & \frac{1}{4} \end{pmatrix} \\
Q_{W_V^+} &= Q^\dagger_{W_V^-} = -Q_{W_A^+} = -Q^\dagger_{W_A^-} = \frac{1}{2\sqrt{2}\sin\theta_W}\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \qquad (10)
\end{aligned}$$

The $V_{V_T G\pi_T}$ and $A_{V_T G\pi_T}$ are listed in Table 1 below.

The ρ_T decay rates to fermions with $N_f = 1$ or 3 colors are [3]

$$\Gamma(\rho_T^0 \to f_i \bar f_i) = \frac{N_f\,\alpha^2 p}{3\alpha_{\rho_T}\hat s}\Big((\hat s - m_i^2)\,A_i^0(\hat s) + 6m_i^2\,\mathcal{R}e(\mathcal{A}_{iL}(\hat s)\mathcal{A}^*_{iR}(\hat s))\Big)\,,$$

[2]We have neglected decays such as $\rho_T^0 \to W_T W_L$ and $\rho_T^0 \to W_T W_T$. The rate for the former is suppressed by $\tan^2\chi$ relative to the rate for $\rho_T^0 \to W_T \pi_T$ while the latter's rate is suppressed by α.

[3]Eqs. (11), (12) and (16) below correct Eqs. (3) and (6) in the second paper and Eqs. (3) and (5) in the third paper of Ref. [9]. A factor of $M^4_{V_T}/\hat s^2$ that appears in Eqs. (6) and (11) of that second paper has been eliminated from Eqs. (11) and (16). This convention is consistent with the off-diagonal sf_{GV_T} terms in the propagator matrices $\Delta_{0,\pm}$ defined in Eqs. (18) and (19) below. For weakly-coupled narrow resonances such as ρ_T and ω_T, the difference is numerically insignificant.

Process	$V_{V_T G \pi_T}$	$A_{V_T G \pi_T}$
$\omega_T \to \gamma \pi_T^0$	c_χ	0
$\to \gamma \pi_T^{0\prime}$	$(Q_U + Q_D)\, c_{\chi'}$	0
$\to Z^0 \pi_T^0$	$c_\chi \cot 2\theta_W$	0
$\to Z^0 \pi_T^{0\prime}$	$-(Q_U + Q_D)\, c_{\chi'} \tan\theta_W$	0
$\to W^\pm \pi_T^\mp$	$c_\chi/(2\sin\theta_W)$	0
$\rho_T^0 \to \gamma \pi_T^0$	$(Q_U + Q_D)\, c_\chi$	0
$\to \gamma \pi_T^{0\prime}$	$c_{\chi'}$	0
$\to Z^0 \pi_T^0$	$-(Q_U + Q_D)\, c_\chi \tan\theta_W$	0
$\to Z^0 \pi_T^{0\prime}$	$c_{\chi'} \cot 2\theta_W$	0
$\to W^\pm \pi_T^\mp$	0	$-c_\chi/(2\sin\theta_W)$
$\rho_T^\pm \to \gamma \pi_T^\pm$	$(Q_U + Q_D)\, c_\chi$	0
$\to Z^0 \pi_T^\pm$	$-(Q_U + Q_D)\, c_\chi \tan\theta_W$	$c_\chi / \sin 2\theta_W$
$\to W^\pm \pi_T^0$	0	$c_\chi/(2\sin\theta_W)$
$\to W^\pm \pi_T^{0\prime}$	$c_{\chi'}/(2\sin\theta_W)$	0

Table 1: Amplitudes for $V_T \to G\pi_T$ for $V_T = \rho_T, \omega_T$ and G a transverse electroweak boson, $\gamma, Z^0, W^\pm$. Here, $c_\chi = \cos\chi$ and $c_{\chi'} = \cos\chi'$.

$$\Gamma(\rho_T^+ \to f_i \bar{f}_i') = \frac{N_f\, \alpha^2 p}{6\alpha_{\rho_T} \hat{s}^2} \left(2\hat{s}^2 - \hat{s}(m_i^2 + m_i'^2) - (m_i^2 - m_i'^2)^2\right) A_i^+(\hat{s})\,, \tag{11}$$

where I assumed a unit CKM matrix in the second equality. The quantities A_i are given by

$$\begin{aligned} A_i^\pm(\hat{s}) &= \frac{1}{8\sin^4\theta_W} \left|\frac{\hat{s}}{\hat{s} - \mathcal{M}_W^2}\right|^2, \\ A_i^0(\hat{s}) &= |\mathcal{A}_{iL}(\hat{s})|^2 + |\mathcal{A}_{iR}(\hat{s})|^2\,, \end{aligned} \tag{12}$$

where, for $\lambda = L, R$,

$$\begin{aligned} \mathcal{A}_{i\lambda}(\hat{s}) &= Q_i + \frac{2\zeta_{i\lambda}\cot 2\theta_W}{\sin 2\theta_W} \left(\frac{\hat{s}}{\hat{s} - \mathcal{M}_Z^2}\right), \\ \zeta_{iL} &= T_{3i} - Q_i \sin^2\theta_W\,, \\ \zeta_{iR} &= -Q_i \sin^2\theta_W\,. \end{aligned} \tag{13}$$

Here, Q_i and $T_{3i} = \pm 1/2$ are the electric charge and left-handed weak isospin of fermion f_i. Also, $\mathcal{M}^2_{W,Z} = M^2_{W,Z} - i\sqrt{\hat s}\,\Gamma_{W,Z}(\hat s)$, where $\Gamma_{W,Z}(\hat s)$ is the weak boson's energy-dependent width. [4].

3 ω_T Decay Rates

We assume that the 3-body decays of ω_T to technipions, including longitudinal weak bosons, are kinematically forbidden. This leaves 2-body decays to technipions, $G\pi_T$ and $f_i\bar f_i$.

The rates for the isospin-violating decays $\omega_T \to \pi^+_A\pi^-_B = W^+_L W^-_L$, $W^\pm_L\pi^\mp_T$, $\pi^+_T\pi^-_T$ are given by

$$\Gamma(\omega_T \to \pi^+_A\pi^-_B) = |\epsilon_{\rho\omega}|^2\,\Gamma(\rho^0_T \to \pi^+_A\pi^-_B) = \frac{|\epsilon_{\rho\omega}|^2\alpha_{\rho_T}\mathcal{C}^2_{AB}}{3}\,\frac{p^3_{AB}}{s}\,, \qquad (14)$$

where $\epsilon_{\rho\omega}$ is the isospin-violating ρ_T-ω_T mixing amplitude. In QCD, $|\epsilon_{\rho\omega}| \simeq 5\%$, so we expect this decay mode to be negligible if this is chosen to be the nominal value of this parameter.

The $\omega_T \to G\pi_T$ decay rates involving a transversely polarized electroweak boson $G = \gamma, Z, W$ have the same form as Eq. (8):

$$\Gamma(\omega_T \to G\pi_T) = \frac{\alpha V^2_{\omega_T G\pi_T}\,p^3}{3M_V^2} + \frac{\alpha A^2_{\omega_T G\pi_T}\,p\,(3M_G^2 + 2p^2)}{6M_A^2}\,, \qquad (15)$$

The ω_T decay rates to fermions with N_f colors are given by

$$\Gamma(\omega_T \to \bar f_i f_i) = \frac{N_f\,\alpha^2 p}{3\alpha_{\rho_T}\hat s}\,\Big((\hat s - m_i^2)\,B^0_i(\hat s) + 6m_i^2\,\mathcal{R}e(\mathcal{B}_{iL}(\hat s)\mathcal{B}^*_{iR}(\hat s))\Big)\,, \qquad (16)$$

where

$$\begin{aligned} B^0_i(\hat s) &= |\mathcal{B}_{iL}(\hat s)|^2 + |\mathcal{B}_{iR}(\hat s)|^2\,, \\ \mathcal{B}_{i\lambda}(\hat s) &= \left[Q_i - \frac{4\zeta_{i\lambda}\sin^2\theta_W}{\sin^2 2\theta_W}\left(\frac{\hat s}{\hat s - \mathcal{M}^2_Z}\right)\right](Q_U + Q_D)\,. \end{aligned} \qquad (17)$$

[4]Note, for example, that $\Gamma_Z(\hat s)$ includes a $t\bar t$ contribution when $\hat s > 4m_t^2$.

4 Cross Sections for $q_i\bar{q}_j \to \rho_T, \omega_T \to X$

The subprocess cross sections presented below assume that initial-state quarks are massless. All cross sections are averaged over the spins and colors of these quarks. These cross sections require the propagator matrices in the neutral and charged spin-one channels, Δ_0 and $\Delta_\pm$. The γ–Z^0–ρ_T^0–ω_T propagator matrix is the inverse of

$$\Delta_0^{-1}(s) = \begin{pmatrix} s & 0 & -sf_{\gamma\rho_T} & -sf_{\gamma\omega_T} \\ 0 & s-\mathcal{M}_Z^2 & -sf_{Z\rho_T} & -sf_{Z\omega_T} \\ -sf_{\gamma\rho_T} & -sf_{Z\rho_T} & s-\mathcal{M}_{\rho_T^0}^2 & 0 \\ -sf_{\gamma\omega_T} & -sf_{Z\omega_T} & 0 & s-\mathcal{M}_{\omega_T}^2 \end{pmatrix}. \tag{18}$$

Here, $f_{\gamma\rho_T} = \xi$, $f_{\gamma\omega_T} = \xi\,(Q_U + Q_D)$, $f_{Z\rho_T} = \xi\,\cot 2\theta_W$, and $f_{Z\omega_T} = -\xi\,(Q_U + Q_D)\tan\theta_W$, where $\xi = \sqrt{\alpha/\alpha_{\rho_T}}$. The $W^\pm$–$\rho_T^\pm$ matrix is the inverse of

$$\Delta_\pm^{-1}(s) = \begin{pmatrix} s-\mathcal{M}_W^2 & -sf_{W\rho_T} \\ -sf_{W\rho_T} & s-\mathcal{M}_{\rho_T^\pm}^2 \end{pmatrix}, \tag{19}$$

where $f_{W\rho_T} = \xi/(2\sin\theta_W)$.

The rates for production of any technipion pair, $\pi_A\pi_B = W_LW_L$, $W_L\pi_T$, and $\pi_T\pi_T$, in the isovector (ρ_T) channel are:

$$\frac{d\hat\sigma(q_i\bar{q}_i \to \rho_T^0 \to \pi_A^+\pi_B^-)}{d\hat{t}} = \frac{\pi\alpha\alpha_{\rho_T}\mathcal{C}_{AB}^2(4\hat{s}p^2 - (\hat{t}-\hat{u})^2)}{12\hat{s}^2}\left(|\mathcal{F}_{iL}^{\rho_T}(\hat{s})|^2 + |\mathcal{F}_{iR}^{\rho_T}(\hat{s})|^2\right). \tag{20}$$

and

$$\frac{d\hat\sigma(u_i\bar{d}_i \to \rho_T^+ \to \pi_A^+\pi_B^0)}{d\hat{t}} = \frac{\pi\alpha\alpha_{\rho_T}\mathcal{C}_{AB}^2(4\hat{s}p^2 - (\hat{t}-\hat{u})^2)}{24\sin^2\theta_W\hat{s}^2}\,|\Delta_{W\rho_T}(\hat{s})|^2. \tag{21}$$

where $p = [(\hat{s} - (M_A+M_B)^2)(\hat{s} - (M_A-M_B)^2)]^{\frac{1}{2}}/2\sqrt{\hat{s}}$ is the $\hat{s}$-dependendent momentum of $\pi_{A,B}$. As usual, $\hat{t} = M_A^2 - \sqrt{\hat{s}}(E_A - p\cos\theta)$, $\hat{u} = M_A^2 - \sqrt{\hat{s}}(E_A + p\cos\theta)$, where θ is the c.m. production angle of π_A. The factor $4\hat{s}p^2 - (\hat{t}-\hat{u})^2 = 4\hat{s}p^2\sin^2\theta$. The quantities $\mathcal{F}_{i\lambda}^{V_T}$ for $\lambda = L, R$ in Eq. (20) are given in terms of elements of Δ_0 by

$$\mathcal{F}_{i\lambda}^{V_T}(\hat{s}) = Q_i\,\Delta_{\gamma V_T}(\hat{s}) + \frac{2\zeta_{i\lambda}}{\sin 2\theta_W}\Delta_{ZV_T}(\hat{s}). \tag{22}$$

Because the ρ_T-ω_T mixing parameter $\epsilon_{\rho\omega}$ is expected to be very small, the rates for $q_i\bar{q}_i \to \omega_T \to \pi_A^+\pi_B^-$ are ignored here.

The cross section for $G\pi_T$ production in the neutral channel is given by

$$\begin{aligned}
&\frac{d\hat{\sigma}(q_i\bar{q}_i \to \rho_T^0,\, \omega_T \to G\pi_T)}{d\hat{t}} = \\
&\frac{\pi\alpha^2}{24\hat{s}}\left\{\left(|\mathcal{G}_{iL}^{VG\pi_T}(\hat{s})|^2 + |\mathcal{G}_{iR}^{VG\pi_T}(\hat{s})|^2\right)\left(\frac{\hat{t}^2+\hat{u}^2-2M_G^2M_{\pi_T}^2}{M_V^2}\right)\right. \qquad (23)\\
&\left.+\left(|\mathcal{G}_{iL}^{AG\pi_T}(\hat{s})|^2 + |\mathcal{G}_{iR}^{AG\pi_T}(\hat{s})|^2\right)\left(\frac{\hat{t}^2+\hat{u}^2-2M_G^2M_{\pi_T}^2+4\hat{s}M_G^2}{M_A^2}\right)\right\},
\end{aligned}$$

where, for $X = V, A$ and $\lambda = L, R$,

$$\mathcal{G}_{i\lambda}^{XG\pi_T} = \sum_{V_T=\rho_T^0,\omega_T} X_{V_TG\pi_T}\mathcal{F}_{i\lambda}^{V_T}\,. \qquad (24)$$

The factor $\hat{t}^2+\hat{u}^2-2M_G^2M_{\pi_T}^2 = 2\hat{s}p^2(1+\cos^2\theta)$. The $G\pi_T$ cross section in the charged channel is given by (in the approximation of a unit CKM matrix)

$$\begin{aligned}
&\frac{d\hat{\sigma}(u_i\bar{d}_i \to \rho_T^+ \to G\pi_T)}{d\hat{t}} = \frac{\pi\alpha^2}{48\sin^2\theta_W\,\hat{s}}\,|\Delta_{W\rho_T}(\hat{s})|^2 \qquad (25)\\
&\times\left\{\frac{V^2_{\rho_T^+G\pi_T}}{M_V^2}\left(\hat{t}^2+\hat{u}^2-2M_G^2M_{\pi_T}^2\right)+\frac{A^2_{\rho_T^+G\pi_T}}{M_A^2}\left(\hat{t}^2+\hat{u}^2-2M_G^2M_{\pi_T}^2+4\hat{s}M_G^2\right)\right\}.
\end{aligned}$$

The cross section for $q_i\bar{q}_i \to f_j\bar{f}_j$ (with $m_{q_i} = 0$ and allowing $m_{f_j} \neq 0$ for $t\bar{t}$ production) is

$$\begin{aligned}
\frac{d\hat{\sigma}(q_i\bar{q}_i \to \gamma,\, Z \to \bar{f}_jf_j)}{d\hat{t}} &= \frac{N_f\pi\alpha^2}{3\hat{s}^2}\left\{\left((\hat{u}-m_{f_j}^2)^2+m_{f_j}^2\hat{s}\right)\left(|\mathcal{D}_{ijLL}|^2+|\mathcal{D}_{ijRR}|^2\right)\right.\\
&+ \left.\left((\hat{t}-m_{f_j}^2)^2+m_{f_j}^2\hat{s}\right)\left(|\mathcal{D}_{ijLR}|^2+|\mathcal{D}_{ijRL}|^2\right)\right\}, \qquad (26)
\end{aligned}$$

where

$$\begin{aligned}
\mathcal{D}_{ij\lambda\lambda'}(\hat{s}) &= Q_iQ_j\,\Delta_{\gamma\gamma}(\hat{s}) + \frac{4}{\sin^2 2\theta_W}\,\zeta_{i\lambda}\,\zeta_{j\lambda'}\,\Delta_{ZZ}(\hat{s}) \qquad (27)\\
&+\frac{2}{\sin 2\theta_W}\left(\zeta_{i\lambda}Q_j\Delta_{Z\gamma}(\hat{s})+Q_i\zeta_{j\lambda'}\Delta_{\gamma Z}(\hat{s})\right).
\end{aligned}$$

Finally, the rate for the subprocess $u_i\bar{d}_i \to f_j\bar{f}'_j$ is

$$\frac{d\hat{\sigma}(u_i\bar{d}_i \to W^+ \to f_j\bar{f}'_j)}{d\hat{t}} = \frac{N_f\pi\alpha^2}{12\sin^4\theta_W\,\hat{s}^2}\,(\hat{u}-m_j^2)(\hat{u}-m_j'^2)\,|\Delta_{WW}(\hat{s})|^2\,. \qquad (28)$$

Parameter	Default Value
N_{TC}	4
$\sin\chi$	$\frac{1}{3}$
$\sin\chi'$	$\frac{1}{3}$
Q_U	$\frac{4}{3}$
$Q_D = Q_U - 1$	$\frac{1}{3}$
C_b	1
C_c	1
C_τ	1
C_t	m_b/m_t
C_{π_T}	$\frac{4}{3}$
$\lvert\epsilon_{\rho\omega}\rvert$	0.05
$F_T = F_\pi \sin\chi$	82 GeV
$M_{\rho_T^\pm}$	210 GeV
$M_{\rho_T^0}$	210 GeV
M_{ω_T}	210 GeV
$M_{\pi_T^\pm}$	110 GeV
$M_{\pi_T^0}$	110 GeV
$M_{\pi_T^{0\prime}}$	110 GeV
M_V	200 GeV
M_A	200 GeV

Table 2: Default values for parameters in the Technicolor Straw Man Model.

5 Default Values for Parameters

The suggested default values of the parameters used in this note are listed in Table 2.

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