Electroweak and Flavor Dynamics at Hadron Colliders–I

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ABSTRACT

This is the first of two reports cataloging the principal signatures of electroweak and flavor dynamics at $\bar{p}p$ and pp colliders. Here, we discuss some of the signatures of dynamical elecroweak and flavor symmetry breaking. The framework for dynamical symmetry breaking we assume is technicolor, with a walking coupling α_{TC}, and extended technicolor. The reactions discussed occur mainly at subprocess energies $\sqrt{\hat{s}} \lesssim 1\,\mathrm{TeV}$. They include production of color-singlet and octet technirhos and their decay into pairs of technipions, longitudinal weak bosons, or jets. Technipions, in turn, decay predominantly into heavy fermions.

I. INTRODUCTION

This is the first of two reports summarizing the major signals for dynamical electroweak and flavor symmetry breaking in experiments at the Tevatron Collider and the Large Hadron Collider. The division into two reports is done solely to accomodate the length requirements imposed on contributions to the Snowmass '96 proceedings. In contrast, the motivations for these studies are clear: We do not know the mechanism of electroweak symmetry breaking nor the physics underlying flavor and its symmetry breaking. The dynamical scenarios whose signals we catalog provide an attractive theoretical alternative to perturbative supersymmetry models. At the same time, they give experimentalists a set of high-p_T signatures that challenge heavy-flavor tagging, tracking and calorimetry—detector subsystems somewhat complementary to those tested by supersymmetry searches. Finally, many of the most important signs of electroweak and flavor dynamics have sizable rates and are detected relatively easily in hadron collider experiments. Extensive searches are underway in both Tevatron Collider collaborations, CDF and DØ. We hope that these reports will inspire and help the ATLAS and CMS Collaborations to begin their studies.

This report lists some of the major signals for dynamical electroweak and flavor symmetry breaking in experiments at the Tevatron Collider and the Large Hadron Collider. Section 2 contains a brief overview of technicolor and extended technicolor. This discussion includes summaries of the main ideas that have developed over the past decade: walking technicolor, multiscale technicolor, and topcolor-assisted technicolor. Hadron collider signals of technicolor involve production of technipions via $\bar{q}q$ annihilation and gg fusion. These technipions include the longitudinal weak bosons W_L and Z_L as well as the pseudo-Goldstone bosons π_T of dynamical symmetry breaking. The π_T are generally expected to have Higgs-boson-like couplings to fermions and, therefore, to decay to heavy, long-lived quarks and leptons.

The subprocess production cross sections for color-singlet technipions are listed for some simple models in Section 3. The most promising processes involve production of an isovector technirho ρ_{T1} resonance and its subsequent decay into technipion pairs. Walking technicolor suggests that $M_{\rho_{T1}} < 2M_{\pi_T}$, in which case $\rho_{T1} \to W_L W_L$ or, more likely, $W_L \pi_T$, where W_L is a longitudinal weak boson. We also discuss a potentially important new signal: the isoscalar ω_T, degenerate with ρ_{T1}, and decaying spectacularly to $\gamma\pi_T$ and $Z\pi_T$. The most important subprocesses for colored technihadrons are discussed in Section 4. These involve a color-octet s-channel resonance with the same quantum numbers as the gluon; this technirho ρ_{T8} dominates colored technipion pair production. If $M_{\rho_{T8}} < 2M_{\pi_T}$, then $\rho_{T8} \to \bar{q}q$ and gg, a resonance in dijet production.

The main signatures of topcolor-assisted technicolor, toppions π_t and the color-octet V_8 and singlet Z' of broken topcolor gauge symmetries, are described in the following report, as are the signatures for quark and lepton substructure. At the end of the second report, we have provided a table which summarizes the main processes and sample cross sections at the Tevatron and LHC. Our reports are not intended to constitute a complete survey of electroweak and flavor dynamics signatures accessible at hadron colliders. We have limited our discussion to processes with the largest production cross sections and most promising signal-to-background ratios. Even for the processes we list, we have not provided detailed cross sections for signals and backgrounds. Signal rates depend on masses and model parameters; they and the backgrounds also depend strongly on detector capabilities. Experimenters in the detector collaborations will have to carry out these studies.

II. OVERVIEW OF TECHNICOLOR AND EXTENDED TECHNICOLOR

Technicolor—a strong interaction of fermions and gauge bosons at the scale $\Lambda_{TC} \sim 1\,\mathrm{TeV}$—is a scenario for the dynamical breakdown of electroweak symmetry to electromagnetism[1]. Based on the similar phenomenon of chiral symmetry breakdown in QCD, technicolor is explicitly defined and completely natural. To account for the masses of quarks, leptons, and Goldstone "technipions" in such a scheme, technicolor, ordinary color, and flavor symmetries are embedded in a larger gauge group, called extended technicolor (ETC)[2]. The ETC symmetry is broken down to technicolor and color at a scale $\Lambda_{ETC} = \mathcal{O}(100\,\mathrm{TeV})$. Many signatures of ETC are expected in the energy regime of 100 GeV to 1 TeV, the region covered by the Tevatron and Large Hadron Colliders. For a review of technicolor developments up through 1993, see Ref. [3]. The principal signals in hadron collider experiments of "classical" technicolor and extended technicolor were discussed in Ref. [4]. In the minimal technicolor model,

containing just one technifermion doublet, the only prominent signals in high energy collider experiments are the modest enhancements in longitudinally-polarized weak boson production. These are the s-channel color-singlet technirho resonances near 1.5–2 TeV: $\rho^0_{T1} \to W^+_L W^-_L$ and $\rho^\pm_{T1} \to W^\pm_L Z^0_L$. The small $O(\alpha^2)$ cross sections of these processes and the difficulty of reconstructing weak-boson pairs with reasonable efficiency make observing these enhancements a challenge. Nonminimal technicolor models are much more accessible because they have a rich spectrum of lower energy technirho vector mesons and technipion (π_T) states into which they may decay. In the one-family model, containing one isodoublet each of color-triplet techniquarks (U, D) and color-singlet technileptons (N, E), the technifermion chiral symmetry is $SU(8) \otimes SU(8)$. There are 63 ρ_T and π_T, classified according to how they transform under ordinary color $SU(3)$ times weak isospin $SU(2)$. The technipions are $\pi^{0\prime}_T \in (1,1)$; $W^\pm_L, Z^0_L$ and $\pi^\pm_T, \pi^0_T \in (1,3)$; color octets $\eta_T \in (8,1)$ and $\pi^\pm_{T8}, \pi^0_{T8} \in (8,3)$; and color-triplet leptoquarks $\pi_{Q\bar{L}}$, $\pi_{L\bar{Q}} \in (3,3) \oplus (3,1) \oplus (\bar{3},3) \oplus (\bar{3},1)$. The ρ_T belong to the same representations.

Because of the conflict between constraints on flavor-changing neutral currents and the magnitude of ETC-generated quark, lepton and technipion masses, classical technicolor was superseded a decade ago by "walking" technicolor. In this kind of gauge theory, the strong technicolor coupling α_{TC} runs very slowly for a large range of momenta, possibly all the way up to the ETC scale—which must be several 100 TeV to suppress FCNC. This slowly-running coupling permits quark and lepton masses as large as a few GeV to be generated from ETC interactions at this very high scale [5].

Walking technicolor models require a large number of technifermions in order that α_{TC} runs slowly. These fermions may belong to many copies of the fundamental representation of the technicolor gauge group, to a few higher dimensional representations, or to both. This fact inspired a new kind of model, "multiscale technicolor", and a very different phenomenology[6]. In multiscale models, there typically are two widely separated scales of electroweak symmetry breaking, with the upper scale set by the weak decay constant $F_\pi = 246\,\mathrm{GeV}$. Technihadrons associated with the lower scale may be so light that they are within reach of the Tevatron collider; they certainly are readily produced *and detected* at the LHC. An important consequence of walking technicolor is that technipion masses are enhanced so that $\rho_T \to \pi_T \pi_T$ decay channels may be closed. If this happens, then $\rho_{T1} \to W_L W_L$ or $W_L \pi_T$ and $\rho_{T8} \to$ dijets. If the $\pi_T \pi_T$ channels are open, they are resonantly produced at large rates—of order 10 pb at the Tevatron and several nanobarns at the LHC—and, given the recent successes and coming advances in heavy flavor detection, many of these technipions should be reconstructable in the hadron collider environment.

Another major advance in technicolor came in the past two years with the discovery of the top quark[7]. Theorists have concluded that ETC models cannot explain the top quark's large mass without running afoul of either cherished notions of naturalness or experimental constraints from the ρ parameter and the $Z \to \bar{b}b$ decay rate[8, 9]. This state of affairs has led to "topcolor-assisted technicolor" (TC2). In TC2, as in top-condensate models of electroweak symmetry breaking[10, 11], almost all of the top quark mass arises from a new strong "topcolor" interaction. To maintain electroweak symmetry between (left-handed) top and bottom quarks and yet not generate $m_b \simeq m_t$, the topcolor gauge group is generally taken to be $SU(3) \otimes U(1)$, with the $U(1)$ providing the difference between top and bottom quarks. Then, in order that topcolor interactions be natural—i.e., that their energy scale not be far above m_t—and yet not introduce large weak isospin violation, it is necessary that electroweak symmetry breaking is still due mainly to technicolor interactions[12]. In TC2 models, ETC interactions are still needed to generate the light and bottom quark masses, contribute a few GeV to m_t, and give mass to the technipions. The scale of ETC interactions still must be hundreds of TeV to suppress FCNC and, so, the technicolor coupling must still walk. Two recent papers developing the TC2 scenario are in Ref. [13]. Although the phenomenology of TC2 is in its infancy, it is expected to share general features with multiscale technicolor: many technihadron states, some carrying ordinary color, some within range of the Tevatron, and almost all easily produced and detected at the LHC at moderate luminosities.

We assume throughout that the technicolor gauge group is $SU(N_{TC})$ and that its gauge coupling walks. A minimal, one-doublet model can have a walking α_{TC} only if the technifermions belong to a large non-fundamental representation. For nonminimal models, we generally consider the phenomenology of the lighter technifermions transforming according to the fundamental (N_{TC}) representation; some of these may also be ordinary color triplets. In almost all respects, walking models are very different from QCD with a few fundamental $SU(3)$ representations. Thus, arguments based on naive scaling from QCD and on large-N_{TC} certainly are suspect. In TC2, there is no need for large isospin splitting in the technifermion sector associated with the top-bottom mass difference. This simplifies our discussion greatly.

III. COLOR-SINGLET TECHNIPION PRODUCTION

The $\rho_{T1} \to W^+W^-$ and $W^\pm Z^0$ signatures of the minimal model were discussed in Ref. [4]. The principal change due to the large representation and walking is that scaling the $\rho_{T1} \to \pi_T \pi_T$ coupling α_{ρ_T} from QCD is questionable. It may be smaller than usually assumed and lead to a narrower ρ_{T1}. There is also the possibility that, because of its large mass (naively, 1.5–2 TeV), the ρ_{T1} has a sizable branching ratio to four-weak-boson final states. To our knowledge, neither of these possibilities has been investigated.

From now on, we consider only nonminimal models which, we believe, are much more likely to lead to a satisfactory walking model. They have a rich phenomenology with many diverse, relatively accessible signals. The masses of technipions in these models arise from broken ETC and ordinary color interactions. In walking models we have studied, they lie in the range 100–600 GeV; technirho vector meson masses are expected to lie between 200 and 1000 GeV (see, e.g., Ref. [6]).

Color-singlet technipions, including longitudinal weak

bosons W_L and Z_L, are pair-produced via the Drell-Yan process in hadron collisions. Their $\mathcal{O}(\alpha^2)$ production rates at the Tevatron and LHC are probably unobservably small compared to backgrounds *unless* there are fairly strong color-singlet technirho resonances not far above threshold. To parameterize the cross sections simply, we consider a model containing two isotriplets of technipions which mix $W_L^\pm$, Z_L^0 with a triplet of mass-eigenstate technipions $\pi_T^{\pm,0}$ [6, 14]. We assume that the lighter isotriplet ρ_{T1} decays into pairs of the state $|\Pi_T\rangle = \sin\chi\,|W_L\rangle + \cos\chi\,|\pi_T\rangle$, leading to the processes

$$\begin{aligned} q\bar{q}' &\to W^\pm \to \rho_{T1}^\pm \to W_L^\pm Z_L^0; W_L^\pm \pi_T^0,\ \pi_T^\pm Z_L^0; \pi_T^\pm \pi_T^0 \\ q\bar{q} &\to \gamma, Z^0 \to \rho_{T1}^0 \to W_L^+ W_L^-; W_L^\pm \pi_T^\mp; \pi_T^+ \pi_T^- . \end{aligned} \quad (1)$$

The s-dependent ρ_{T1} partial widths are given by (assuming no other channels, such as colored techipion pairs, are open)

$$\Gamma(\rho_{T1} \to \pi_A \pi_B; s) = \frac{2\alpha_{\rho_T} \mathcal{C}_{AB}^2}{3} \frac{p_{AB}^3}{s}, \quad (2)$$

where p_{AB} is the technipion momentum and $\mathcal{C}_{AB}^2 = \sin^4\chi$, $2\sin^2\chi\cos^2\chi$, $\cos^4\chi$ for $\pi_A\pi_B = W_L W_L$, $W_L\pi_T + \pi_T W_L$, $\pi_T\pi_T$, respectively. The $\rho_{T1} \to \pi_T\pi_T$ coupling α_{ρ_T} obtained by naive scaling from QCD is [4] $\alpha_{\rho_T} = 2.91\,(3/N_{TC})$.

Technipion decays are mainly induced by ETC interactions which couple them to quarks and leptons. These couplings are Higgs-like, and so technipions are expected to decay into heavy fermion pairs:

$$\begin{aligned} \pi_T^0 &\to \begin{cases} b\bar{b} & \text{if } M_{\pi_T} < 2m_t, \\ t\bar{t} & \text{if } M_{\pi_T} > 2m_t; \end{cases} \\ \pi_T^+ &\to \begin{cases} c\bar{b} \text{ or } c\bar{s},\ \tau^+\nu_\tau & \text{if } M_{\pi_T} < m_t + m_b, \\ t\bar{b} & \text{if } M_{\pi_T} > m_t + m_b. \end{cases} \end{aligned} \quad (3)$$

An important caveat to this rule applies to TC2 models. There, only a few GeV of the top mass arises from ETC interactions. Then, the $b\bar{b}$ mode competes with $t\bar{t}$ for π_T^0; $c\bar{b}$ or $c\bar{s}$ compete with $t\bar{b}$ for π_T^+. Note that, since the decay $t \to \pi_T^+ b$ is strongly suppressed in TC2 models, the π_T^+ can be much lighter than the top quark.

The $\rho_{T1} \to \pi_A\pi_B$ cross sections are well-approximated by

$$\frac{d\hat{\sigma}(q_i\bar{q}_j \to \rho_{T1}^{\pm,0} \to \pi_A\pi_B)}{dz} = \frac{\pi\alpha^2 p_{AB}^3}{3\hat{s}^{5/2}} \frac{M_{\rho_{T1}}^4\,(1-z^2)}{(\hat{s} - M_{\rho_{T1}}^2)^2 + \hat{s}\Gamma_{\rho_{T1}}^2} A_{ij}^{\pm,0}(\hat{s}) \mathcal{C}_{AB}^2, \quad (4)$$

where $\hat{s}$ is the subprocess energy, $z = \cos\theta$ is the π_A production angle, and $\Gamma_{\rho_{T1}}$ is the $\hat{s}$-dependent total width of ρ_{T1}. Ignoring Kobayashi-Maskawa mixing angles, the factors $A_{ij}^{\pm,0} = \delta_{ij} A^{\pm,0}$ are

$$\begin{aligned} A^\pm &= \frac{1}{4\sin^4\theta_W}\left(\frac{\hat{s}}{\hat{s} - M_W^2}\right)^2 \\ A^0 &= \left[Q_i + \frac{2\cos 2\theta_W}{\sin^2 2\theta_W}(T_{3i} - Q_i \sin^2\theta_W)\left(\frac{\hat{s}}{\hat{s} - M_Z^2}\right)\right]^2 \\ &\quad + \left[Q_i - \frac{2Q_i \cos 2\theta_W \sin^2\theta_W}{\sin^2 2\theta_W}\left(\frac{\hat{s}}{\hat{s} - M_Z^2}\right)\right]^2. \end{aligned} \quad (5)$$

Here, Q_i and T_{3i} are the electric charge and third component of weak isospin for $q_{iL,R}$. Production rates of several picobarns increase by factors of 5–10 at the LHC; see the table in the following Report II.

If the isospin of technifermions is approximately conserved, there is an isoscalar partner ω_T of the ρ_{T1} that is nearly degenerate with it and may be produced at a comparable rate. The walking technicolor enhancement of technipion masses almost certainly closes off the isospin-conserving decay $\omega_T \to \Pi_T^+\Pi_T^-\Pi_T^0$. Even the triply-suppressed mode $W_L^+ W_L^- Z_L$ has little or no phase space for $M_{\omega_T} \lesssim 300\,\mathrm{GeV}$. Thus, we may expect the main decays to be $\omega_T \to \gamma\Pi_T^0$, $Z\Pi_T^0$, and $\Pi_T^+\Pi_T^-$. In terms of mass eigenstates, these modes are $\omega_T \to \gamma\pi_T^0$, γZ_L, $Z\pi_T^0$, ZZ_L; $\gamma\pi_T^{0\prime}$, $Z\pi_T^{0\prime}$; and $W_L^+W_L^-$, $\pi_T^\pm W_L^\mp$, $\pi_T^+\pi_T^-$.[1] It is not possible to estimate the relative magnitudes of the decay amplitudes without an explicit model of the ω_T's constituent technifermions. Judging from the decays of the ordinary ω, we expect $\omega_T \to \gamma\pi_T^0(\pi_T^{0\prime})$, $Z\pi_T^0(\pi_T^{0\prime})$ to dominate, with the former mode favored by phase space.

The ω_T is produced in hadron collisions just as the ρ_{T1}^0, via its vector-meson-dominance coupling to γ and Z^0. For $M_{\omega_T} \simeq M_{\rho_{T1}}$, the ω_T production cross section should be approximately $|Q_U + Q_D|^2$ times the ρ_{T1}^0 rate, where $Q_{U,D}$ are the electric charges of the ω_T's constituent technifermions. The principal signatures for ω_T production, then, are $\gamma + \bar{b}b$ and $\ell^+\ell^-$ (or $\nu\bar{\nu}$) $+b\bar{b}$, with $M_{\bar{b}b} = M_{\pi_T}$.

In the one-family and other models containing colored as well as color-singlet technifermions, there are singlet and octet technipions that are electroweak isosinglets commonly denoted $\pi_T^{0\prime}$ and η_T. These are singly-produced in gluon fusion. Depending on the technipion's mass, it is expected to decay to $\bar{b}b$ (and, possibly, gg) or to $\bar{t}t$ [4, 16]. With $\Pi^0 = \pi_T^{0\prime}$ or η_T, and with constituent technifermions transforming according to the N_{TC} representation of $SU(N_{TC})$, the decay rates are

$$\Gamma(\Pi^0 \to gg) = \frac{\mathcal{C}_\Pi \alpha_S^2 N_{TC}^2 M_\Pi^3}{128\,\pi^3 F_T^2}, \Gamma(\Pi^0 \to \bar{q}q) = \frac{\gamma_q^2 m_q^2 M_\Pi \beta_q}{16\pi F_T^2}. \quad (6)$$

Here, $\beta_q = \sqrt{1 - 4m_q^2/M_\Pi^2}$ is the quark velocity. The $SU(3)$-color factor $\mathcal{C}_\Pi$ is determined by the triangle-anomaly graph for $\Pi^0 \to gg$. In the one-family model, $\mathcal{C}_\Pi = \frac{4}{3}$ for the singlet $\pi_T^{0\prime}$ and $\frac{5}{3}$ for the octet η_T; values of $\mathcal{O}(1)$ are expected in other models. The technipion decay constant F_T is discussed below. The dimensionless factor γ_q allows for model dependence in the technipions' couplings to $\bar{q}q$. In classical ETC models, we expect $|\gamma_q| = \mathcal{O}(1)$. In TC2 models, $|\gamma_q| = \mathcal{O}(1)$ for the light quarks and, possibly, the b-quark, but $|\gamma_t| = \mathcal{O}(\text{few GeV}/m_t) \ll 1$; there will be no η_T enhancement of $\bar{t}t$ production in topcolor-assisted technicolor.

The gluon fusion cross section for production and decay of Π^0

[1] The modes $\omega_T \to \gamma Z_L$, ZZ_L were considered for a one-doublet technicolor model in Ref. [15]. We have estimated the branching ratios for the isospin-violating decays $\rho_{T1} \to \gamma\pi_T^0$, $Z\pi_T^0$ and found them to be negligible unless the mixing angle χ is very small.

Table I: The factors C_R and D_R in Eq. 9 for the one-family model (O) and a multiscale model (M).

Model	C_3	C_8	D_3	D_8
$\pi_T\pi_T$ (O)	$10/3$	$1/3$	$\frac{16}{9}M_3^2$	$\frac{4}{9}M_8^2$
$\pi_{\bar{Q}Q}\pi_{\bar{Q}Q}$ (M)	$8/3$	$4/3$	$\frac{32}{9}M_3^2$	$\frac{16}{9}M_8^2$
$\pi_{\bar{L}L}\pi_{\bar{L}L}$ (M)	8	0	$\frac{16}{3}(2M_{\pi_T}^2 - M_3^2)$	0

to heavy $\bar{q}q$ is isotropic:

$$\frac{d\hat{\sigma}(gg \to \Pi^0 \to \bar{q}q)}{dz} = \frac{\pi\mathcal{N}_C}{32}\,\frac{\Gamma(\Pi^0 \to gg)\,\Gamma(\Pi^0 \to \bar{q}q)}{(\hat{s} - M_\Pi^2)^2 + \hat{s}\,\Gamma_{\Pi^0}^2}\,, \tag{7}$$

where $\mathcal{N}_C = 1$ (8) for $\pi_T^{0\prime}$ (η_T). The decay rates and cross sections are contolled by the technipion decay constant F_T. In the standard one-family model, $F_T = 123\,\mathrm{GeV}$ and the enhancements in $\bar{q}q$ production are never large enough to see above background (unless N_{TC} is unreasonably large). In multiscale models and, we expect, in TC2 models, F_T may be considerably smaller. For example, in the multiscale model considered in Ref. [6], $F_T = 30$–$50\,\mathrm{GeV}$; in the TC2 model of Ref. [13], $F_T = 80\,\mathrm{GeV}$. Since the total hadronic cross section,

$$\sigma(pp^\pm \to \Pi^0 \to \bar{q}q) \simeq \frac{\pi^2}{2s}\,\frac{\Gamma(\Pi^0 \to gg)\,\Gamma(\Pi^0 \to \bar{q}q)}{M_\Pi\,\Gamma_{\Pi^0}} \int d\eta_B\, f_g^p\left(\frac{M_\Pi}{\sqrt{s}}e^{\eta_B}\right) f_g^p\left(\frac{M_\Pi}{\sqrt{s}}e^{-\eta_B}\right), \tag{8}$$

scales as $1/F_T^2$, small decay constants may lead to observable enhancements of $\bar{t}t$ production in standard multiscale technicolor and in $\bar{b}b$ production in TC2. Sample rates are given in the table in Report II.

In models containing colored technifermions, color-singlet technipions are also pair-produced in the isospin $I = 0$ channel via gluon fusion. This process involves intermediate states of color-triplet and octet technipions. Again, the subprocess cross section is isotropic; it is given by[17]

$$\frac{d\hat{\sigma}(gg \to \pi_T^+\pi_T^-)}{dz} = 2\frac{d\hat{\sigma}(gg \to \pi_T^0\pi_T^0)}{dz} = \frac{\alpha_S^2\beta}{2^{15}\pi^3 F_T^4\hat{s}}\Big|T(R) \left[C_R\,\left(\hat{s} - \tfrac{2}{3}(2M_R^2 + M_{\pi_T}^2)\right) + D_R\right]\,\left(1 + 2\mathcal{I}(M_R^2, \hat{s})\right)\Big|^2 \tag{9}$$

Here, $\beta = 2p/\sqrt{\hat{s}}$ is the technipion velocity. The sum is over $SU(3)$ representations $R = 3, 8$ of the π_T and $T(R)$ is the trace of the square of their $SU(3)$-generator matrices: $T(R) = \frac{1}{2}$ for triplets (dimension $d(R) = 3$), 3 for octets ($d(R) = 8$). The remaining factors are given in Table I. The integral $\mathcal{I}$ is

$$\mathcal{I}(M^2, s) \equiv \int_0^1 dx\,dy\,\frac{M^2}{xys - M^2 + i\epsilon}\,\theta(1 - x - y) = \begin{cases} -M^2/2s\left[\pi - 2\arctan\sqrt{4M^2/s - 1}\right]^2 & \text{if } s < 4M^2 \\ M^2/2s\left[\ln\left(\frac{1+\sqrt{1-4M^2/s}}{1-\sqrt{1-4M^2/s}}\right) - i\pi\right]^2 & \text{if } s > 4M^2 \end{cases} \tag{10}$$

The rates at the Tevatron are at most comparable to those enhanced by technirhos; they are considerably greater at the LHC because the fusing gluons are at low x (see the table in Report II). An interesting feature of this cross section is that the $\pi_T\pi_T$ invariant mass distribution peaks near the color-triplet and octet technipion thresholds, which can be well above $2M_{\pi_T}$. It is possible that mixed modes such as $W_L^\pm\pi_T^\mp$ and $Z_L\pi_T^0$ are also produced by gluon fusion, with the rates involving mixing angles such as χ in Eq. 4.

IV. COLOR-OCTET TECHNIRHO PRODUCTION AND DECAY TO JETS AND TECHNIPIONS

Models with an electroweak doublet of color-triplet technique quarks (U, D) have an octet of $I = 0$ technirhos, ρ_{T8}, with the same quantum numbers as the gluon. The ρ_{T8} is produced strongly in $\bar{q}q$ and gg collisions. Assuming the one-family model for simplicity, there are the 63 technipions listed in Section 2. The color-singlet and octet technipions decay as in Eq. 3 above. The leptoquark decay modes are expected to be

$$\pi_{D\bar{N}} \to b\bar{\nu}_\tau \quad ; \quad \pi_{U\bar{N}} \to \begin{cases} c\bar{\nu}_\tau & \text{if } M_{\pi_T} < m_t \\ t\bar{\nu}_\tau & \text{if } M_{\pi_T} > m_t \end{cases} ;$$
$$\pi_{D\bar{E}} \to b\tau^+ \quad ; \quad \pi_{U\bar{E}} \to \begin{cases} c\tau^+ & \text{if } M_{\pi_T} < m_t \\ t\tau^+ & \text{if } M_{\pi_T} > m_t \end{cases} . \tag{11}$$

The caveat regarding technipion decays to top quarks in TC2 models still applies.

There are two possibilities for ρ_{T8} decays [6]. If walking technicolor enhancements of the technipion masses close off the $\pi_T\pi_T$ channels, then $\rho_{T8} \to \bar{q}q,\, gg \to$ jets. The color-averaged $\mathcal{O}(\alpha_S^2)$ cross sections are given by

$$\begin{aligned}
\frac{d\hat{\sigma}(\bar{q}_iq_i \to \bar{q}_iq_i)}{dz} &= \frac{2\pi\alpha_S^2}{9\hat{s}}\left\{\left|\mathcal{D}_{gg}\right|^2\left(\frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}\right) - \tfrac{2}{3}\,\mathrm{Re}\,\mathcal{D}_{gg}\left(\frac{\hat{u}^2}{\hat{s}\hat{t}}\right) + \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}\right\}; \\
\frac{d\hat{\sigma}(\bar{q}_iq_i \to \bar{q}_jq_j)}{dz} &= \frac{2\pi\alpha_S^2}{9\hat{s}}\left|\mathcal{D}_{gg}\right|^2\left(\frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}\right); \\
\frac{d\hat{\sigma}(\bar{q}_iq_i \to gg)}{dz} &= \frac{64}{9}\frac{d\hat{\sigma}(gg \to q_i\bar{q}_i)}{dz} = \frac{4\pi\alpha_S^2}{3\hat{s}} \left\{\left|\mathcal{D}_{gg} - 1\right|^2\frac{2\hat{u}\hat{t}}{\hat{s}^2} + \tfrac{4}{9}\left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}}\right) - \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}\right\}; \\
\frac{d\hat{\sigma}(gg \to gg)}{dz} &= \frac{9\pi\alpha_S^2}{4\hat{s}}\left\{3 - \frac{\hat{u}\hat{t}}{\hat{s}^2} - \frac{\hat{t}\hat{s}}{\hat{u}^2} - \frac{\hat{s}\hat{u}}{\hat{t}^2} + \tfrac{1}{4}\left|\mathcal{D}_{gg} - 1\right|^2\left(\frac{\hat{u} - \hat{t}}{\hat{s}}\right)^2 - \tfrac{1}{4}\mathrm{Re}(\mathcal{D}_{gg} - 1)\,\frac{(\hat{u} - \hat{t})^2}{\hat{u}\hat{t}}\right\}; \\
\frac{d\hat{\sigma}(q_iq_j \to q_iq_j)}{dz} &= \frac{d\hat{\sigma}(\bar{q}_i\bar{q}_j \to \bar{q}_i\bar{q}_j)}{dz} = \frac{d\hat{\sigma}(q_i\bar{q}_j \to q_i\bar{q}_j)}{dz} \\
&= \frac{2\pi\alpha_S^2}{9\hat{s}}\left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}\right); \\
\frac{d\hat{\sigma}(q_iq_i \to q_iq_i)}{dz} &= \frac{d\hat{\sigma}(\bar{q}_i\bar{q}_i \to \bar{q}_i\bar{q}_i)}{dz} \\
&= \frac{2\pi\alpha_S^2}{9\hat{s}}\left\{\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} - \tfrac{2}{3}\frac{\hat{s}^2}{\hat{u}\hat{t}}\right\};
\end{aligned}$$

$$\frac{d\hat{\sigma}(gq_i \to gq_i)}{dz} = \frac{d\hat{\sigma}(g\bar{q}_i \to g\bar{q}_i)}{dz} = \frac{\pi\alpha_S^2}{2\hat{s}}\,(\hat{s}^2+\hat{u}^2)\left(\frac{1}{\hat{t}^2}-\frac{4}{9\hat{s}\hat{u}}\right). \quad (12)$$

Here, $z = \cos\theta$, $\hat{t} = -\frac{1}{2}\hat{s}(1-z)$, $\hat{u} = -\frac{1}{2}\hat{s}(1+z)$ and it is understood that $q_i \neq q_j = u, d, c, s, b$ contribute to dijet events. Only the s-channel gluon propagator was modified to include the ρ_{T8} resonance. Here and below, we use the dimensionless propagator factors $\mathcal{D}_{gg} = 1 + (\alpha_S(\hat{s})/\alpha_{\rho_T})\mathcal{D}_{g\rho_T}$ and

$$\mathcal{D}_{g\rho_T} = \frac{\hat{s}}{\hat{s}(1-\alpha_S(\hat{s})/\alpha_{\rho_T}) - M^2_{\rho_{T8}} + i\sqrt{s}\,\Gamma_{\rho_{T8}}(\hat{s})}. \quad (13)$$

If $M_{\rho_{T8}} < 2M_{\pi_T}$, the s-dependent ρ_{T8} width is the sum of (allowing for multijet $\bar{t}t$ final states, assumed light compared to $\sqrt{s}$)

$$\Gamma(\rho_{T8} \to gg) = \frac{3}{6}\sum_{i=1}^{6}\Gamma(\rho_{T8} \to \bar{q}_i q_i) = \frac{\alpha_S^2(s)}{\alpha_{\rho_T}}\sqrt{s}\,. \quad (14)$$

A search for the dijet signal of ρ_{T8} has been carried out by the CDF Collaboration; see Ref. [18] for a detailed discussion of expected signal and background rates. Rough signal-to-background estimates are given in the table in Report II. They are sizable at the Tevatron and LHC, but are sensitive to jet energy resolutions.

Colored technipions are pair-produced in hadron collisions through quark-antiquark annihilation and gluon fusion. If the $\rho_{T8} \to \pi_T\pi_T$ decay channels are open, this production is resonantly enhanced. The subprocess cross sections, averaged over initial colors and summed over the colors B, C of technipions, are given by

$$\sum_{B,C}\frac{d\hat{\sigma}(\bar{q}_i q_i \to \pi_B\pi_C)}{dz} = \frac{\pi\alpha_S^2(\hat{s})\beta^3}{9\hat{s}}\,\mathcal{S}_\pi T(R)\left(1-z^2\right)\left|\mathcal{D}_T\right|^2$$

$$\sum_{B,C}\frac{d\hat{\sigma}(gg \to \pi_B\pi_C)}{dz} = \frac{\pi\alpha_S^2(\hat{s})\beta}{\hat{s}}\,\mathcal{S}_\pi T(R)\Bigg\{\frac{3}{32}\beta^2 z^2\Bigg[\left|\mathcal{D}_T\right|^2 - \frac{2\beta^2(1-z^2)}{1-\beta^2 z^2}\,\mathrm{Re}\,(\mathcal{D}_T) + 2\left(\frac{\beta^2(1-z^2)}{1-\beta^2 z^2}\right)^2\Bigg] + \left(\frac{T(R)}{d(R)}-\frac{3}{32}\right)\left[\frac{(1-\beta^2)^2+\beta^4(1-z^2)^2}{(1-\beta^2 z^2)^2}\right]\Bigg\}, \quad (15)$$

where β is the technipion velocity, $z = \cos\theta$ and $\mathcal{D}_T = \mathcal{D}_{gg} + \mathcal{D}_{g\rho_T}$. The symmetry factor $\mathcal{S}_\pi = 1$ for each channel of $\pi_{L\bar{Q}}\pi_{Q\bar{L}}$ and for $\pi^+_{T8}\pi^-_{T8}$; $\mathcal{S}_\pi = \frac{1}{2}$ for the identical-particle final states, $\pi^0_{T8}\pi^0_{T8}$ and $\eta_T\eta_T$. The $SU(3)$ group factors $T(R)$ and $d(R)$ for $R = 3, 8$ were defined above at Eq. 9. The technirho width is now the sum of the $\bar{q}q$ and gg partial widths and is given by $\sum_{B,C}\Gamma(\rho_{T1} \to \pi_B\pi_C) = \alpha_{\rho_T}\mathcal{S}_\pi T(R)p^3/3s$. As indicated in the table in Report II, pair-production rates for colored technipions with masses of a few hundred GeV are several picobarns at the Tevatron, rising to a few nanobarns at the LHC.

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