Electroweak and Flavor Dynamics at Hadron Colliders–II

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ABSTRACT

This is the second of two reports cataloging the principal signatures of electroweak and flavor dynamics at $\bar{p}p$ and pp colliders. Here, we complete our overview of technicolor with a discussion of signatures specific to topcolor-assisted technicolor. We also review signatures of flavor dynamics associated with quark and lepton substructure. These occur in excess production rates for dijets and dileptons with high E_T and high invariant mass. An important feature of these processes is that they exhibit fairly central angular and rapidity distributions.

I. INTRODUCTION

This and the preceding report summarize the major signals for dynamical electroweak and flavor symmetry breaking in experiments at the Tevatron Collider and the Large Hadron Collider. In the preceding report (referred to below as I), we reviewed the technicolor and extended technicolor scenarios of dynamical electroweak and flavor symmetry breaking. We also discussed signals for color-singlet and nonsinglet technipions, resonantly produced via technirho and techni-omega vector mesons. In this report, we complete this discussion with a summary of the main signatures of tocolor-assisted technicolor: top-pions π_t and the color-octet V_8 and singlet Z' of broken topcolor gauge symmetries. These are presented in section 2. This arbitrary division has been necessitated by the length requirements of submissions to the Snowmass '96 proceedings. In section 3 we motivate and discuss the main "low-energy" signatures of quark and lepton substructure: excess production of high-E_T jets and high invariant mass dileptons. Cross sections are presented for a simple form of the contact interaction induced by substructure. We re-emphasize that the shapes of angular distributions are an important test for new physics as the origin of such excesses. We also stress the need to study the effect of other forms for the contact interactions. At the end of this report, we have provided a table which summarizes for the Tevatron and LHC the main processes and sample cross sections that we discussed in these two reports.

These 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 their backgrounds also depend strongly on detector capabilities. Experimenters in the detector collaborations will have to carry out these studies.

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II. SIGNATURES OF TOPCOLOR-ASSISTED TECHNICOLOR

The development of topcolor-assisted technicolor is still at an early stage and, so, its phenomenology is not fully formed. Nevertheless, in addition to the color-singlet and nonsinglet technihadrons already discussed, there are three TC2 signatures that are likely to be present in any surviving model; see Refs. [1, 2, 3, 4, 5]:

- The isotriplet of color-singlet "top-pions" π_t arising from spontaneous breakdown of the top quark's $SU(2)\otimes U(1)$ chiral symmetry;
- The color-octet of vector bosons V_8, called "colorons", associated with breakdown of the top quark's strong $SU(3)$ interaction to ordinary color;
- The Z' vector boson associated with breakdown of the top quark's strong $U(1)$ interaction to ordinary weak hypercharge.

The three top-pions are nearly degenerate. They couple to the top quark with strength m_t/F_t, where m_t is the part of the top-quark mass induced by topcolor—expected to be within a few GeV of its total mass—and $F_t \simeq 70\,\mathrm{GeV}$ [3] is the π_t decay constant.[1] If the top-pion is lighter than the top quark, then

$$\Gamma(t\to\pi_t^+ b)\simeq\frac{(m_t^2-M_{\pi_t}^2)^2}{32\pi m_t F_t^2}\,. \tag{1}$$

It is known that $B(t\to W^+b) = 0.87^{+0.13}_{-0.30}$ (stat.) $^{+0.13}_{-0.11}$ (syst.)[6]. At the 1σ level, then, $M_{\pi_t}\gtrsim 150\,\mathrm{GeV}$. At the 2σ level, the lower bound is $100\,\mathrm{GeV}$, but such a small branching ratio for $t\to W^+b$ would require $\sigma(p\bar{p}\to t\bar{t})$ at the Tevatron about 4 times the standard QCD value of $4.75^{+0.63}_{-0.68}\,\mathrm{pb}$[7]. The $t\to\pi_t^+ b$ decay mode can be sought in high-luminosity runs at the Tevatron and with moderate luminosity at the LHC. If $M_{\pi_t}<m_t$, then $\pi_t^+\to c\bar{b}$ through t–c mixing. It is also possible, though unlikely, that $\pi_T^+\to t\bar{s}$ through b–s mixing.

If $M_{\pi_t}>m_t$, then $\pi_t^+\to t\bar{b}$ and $\pi_t^0\to\bar{t}t$ or $\bar{c}c$, depending on whether the top-pion is heavier or lighter than $2m_t$. The main hope for discovering top-pions heavier than the top quark seems to rest on the isotriplet of top-rho vector mesons, $\rho_t^{\pm,0}$. It is hard to estimate M_{ρ_t}; it may lie near $2m_t$ or closer to $\Lambda_t=\mathcal{O}(1\,\mathrm{TeV})$. They are produced in hadron collisions just as the corresponding color-singlet technirhos (Eq. (3.1) of I). The conventional expectation is that they decay as $\rho_t^{\pm,0}\to\pi_t^\pm\pi_t^0$,

[1] As far as we know, the rest of the discussion in this and the next paragraph has not appeared in print before. It certainly deserves more thought than has gone into it here. One possible starting place is the paper by Hill, Kennedy, Onogi and Yu in Ref. [2].

$\pi_t^+\pi_t^-$. Then, the top-pion production rates may be estimated from Eqs. (3.2) and (3.5) of I with $\alpha_{\rho_T} = 2.91$ and $\mathcal{C}_{AB} = 1$. The rates are not large, but the distinctive decays of top-pions help suppress standard model backgrounds.

Life may not be so simple, however. The ρ_t are not completely analogous to the ρ-mesons of QCD and technicolor because topcolor is broken near Λ_t. Thus, for distance scales between Λ_t^{-1} and $1\,\mathrm{GeV}^{-1}$, top and bottom quarks do not experience a growing confining force. Instead of $\rho_t \to \pi_t\pi_t$, it is also possible that $\rho_t^{\pm,0}$ fall apart into their constituents $t\bar{b}$, $b\bar{t}$ and $t\bar{t}$. The ρ_t resonance may be visible as a significant increase in $t\bar{b}$ production, but it won't be in $t\bar{t}$. [2]

The V_8 colorons of broken $SU(3)$ topcolor are readily produced in hadron collisions. They are expected to have a mass of 1/2–1 TeV. Colorons couple with strength $-g_S \cot\xi$ to quarks of the two light generations and with strength $g_S \tan\xi$ to top and bottom quarks, where $\tan\xi \gg 1$ [5]. Their decay rate is

$$\Gamma_{V_8} = \frac{\alpha_S M_{V_8}}{6}\left\{4\cot^2\xi + \tan^2\xi\left(1+\beta_t(1-m_t^2/M_{V_8}^2)\right)\right\} \tag{2}$$

where $\beta_t = \sqrt{1-4m_t^2/M_{V_8}^2}$. Colorons may then appear as resonances in $b\bar{b}$ and $t\bar{t}$ production. For example, the $\mathcal{O}(\alpha_S)$ cross section for $\bar{q}q \to \bar{t}t$ becomes

$$\frac{d\hat{\sigma}(\bar{q}q\to\bar{t}t)}{dz} = \frac{\pi\alpha_S^2\beta_t}{9\hat{s}}\left(2-\beta_t^2+\beta_t^2 z^2\right)\left|\frac{M_{V_8}^2 - i\sqrt{\hat{s}}\Gamma_{V_8}}{\hat{s}-M_{V_8}^2+i\sqrt{\hat{s}}\,\Gamma_{V_8}}\right|^2. \tag{3}$$

For completeness, the $gg \to \bar{t}t$ rate is

$$\frac{d\hat{\sigma}(gg\to\bar{t}t)}{dz} = \frac{\pi\alpha_S^2\beta_t}{6\hat{s}}\left\{\frac{1+\beta_t^2 z^2}{1-\beta_t^2 z^2} - (1+\beta_t^2 z^2)[\tfrac{9}{16} + \frac{(1-\beta_t^2)^2}{(1-\beta_t^2 z^2)^2}] + \frac{1-\beta_t^2}{1-\beta_t^2 z^2}\left(1-\tfrac{1}{8}\beta_t^2+\tfrac{9}{8}\beta_t^2 z^2\right)\right\}. \tag{4}$$

A description of the search and preliminary mass limits for colorons and other particles decaying to $\bar{b}b$ and $\bar{t}t$ are given in Ref. [8].

Colorons have little effect on the standard dijet production rate. The situation may be very different for the Z' boson of the broken strong $U(1)$ interaction.[3] In Ref. [4] a scenario for topcolor was developed in which it is natural that Z' couples strongly to the fermions of the first two generations as well as those of the third. The Z' probably is heavier than the colorons, roughly $M_{Z'} = 1$–$3\,\mathrm{TeV}$. Thus, at subprocess energies well below $M_{Z'}$, the interaction of Z' with all quarks is described by a contact interaction, just what is expected for quarks with substructure at a scale of a few TeV. This leads to an excess of jets at high E_T and invariant mass[9, 10]. An excess in the jet-E_T spectrum consistent with $\Lambda = 1600\,\mathrm{GeV}$ has been reported by the CDF Collaboration[11]. It remains to be seen whether it is due to topcolor or any other new physics. As with quark substructure, the angular and rapidity distributions of the high-E_T jets induced by Z' should be more central than predicted by QCD. The Z' may also produce an excess of high invariant mass $\ell^+\ell^-$. It will be interesting to compare limits on contact interactions in the Drell-Yan process with those obtained from jet production.

The topcolor Z' will be produced directly in $\bar{q}q$ annhilation in LHC experiments. Because Z' may be strongly coupled to so many fermions, including technifermions in the LHC's energy range, it is likely to be very broad. The development of TC2 models is at such an early stage that the Z' couplings, its width and branching fractions, cannot be predicted with confidence. These studies are underway and we hope for progress on these questions in the coming year.

III. SIGNATURES FOR QUARK AND LEPTON SUBSTRUCTURE

The presence of three generations of quarks and leptons, apparently identical except for mass, strongly suggests that they are composed of still more fundamental fermions, often called "preons". It is clear that, if preons exist, their strong interaction energy scale Λ must be much greater than the quark and lepton masses. Long ago, 't Hooft figured out how interactions at high energy could produce essentially massless composite fermions: the answer lies in unbroken chiral symmetries of the preons *and* confinement by their strong "precolor" interactions[12]. There followed a great deal of theoretical effort to construct a realistic model of composite quarks and leptons (see, e.g., Ref. [13]) which, while leading to valuable insights on chiral gauge theories, fell far short of its main goal.

In the midst of this activity, it was pointed out that the existence of quark and lepton substructure will be signalled at energies well below Λ by the appearance of four-fermion "contact" interactions which differ from those arising in the standard model[9, 10]. These interactions are induced by the exchange of preon bound states and precolor-gluons. The main constraint on their form is that they must be $SU(3)\otimes SU(2)\otimes U(1)$ invariant because they are generated by forces operating at or above the electroweak scale. These contact interactions are suppressed by $1/\Lambda^2$, but the coupling parameter of the exchanges—analogous to the pion-nucleon and rho-pion couplings—is not small. Thus, the strength of these interactions is conventionally taken to be $\pm 4\pi/\Lambda^2$. Compared to the standard model, contact interaction amplitudes are then of relative order $\hat{s}/\alpha_S\Lambda^2$ or $\hat{s}/\alpha_{EW}\Lambda^2$. The appearance of $1/\alpha$ and the growth with $\hat{s}$ make contact-interaction effects the lowest-energy signal of quark and lepton substructure. They are sought in jet production at hadron and lepton colliders, Drell-Yan production of high invariant mass lepton pairs, Bhabha scattering, $e^+e^- \to \mu^+\mu^-$ and $\tau^+\tau^-$[14], atomic parity violation[15], and polarized Møller scattering[16]. Here, we concentrate on jet production and the Drell-Yan process at hadron colliders.

The contact interaction most used so far to parameterize limits on the substructure scale Λ is the product of two left-handed electroweak isoscalar quark and lepton currents. Collider experiments can probe values of Λ in the 2–5 TeV range (Tevatron) to the 15–20 TeV range (LHC; see Refs. [10, 17]). If Λ is to be this low, the contact interaction must be flavor-symmetric, at least

[2] We thank John Terning for inspiring this discussion of ρ_t decays.

[3] This interaction differentiates between top and bottom quarks, helping the former develop a large mass while keeping the latter light.

for quarks in the first two generations, to avoid large $\Delta S = 2$ and, possibly, $\Delta B_d = 2$ neutral current interactions. We write it as

$$\begin{aligned} \mathcal{L}^0_{LL} &= \frac{4\pi\eta}{2\Lambda^2} J^\mu_L J_{L\mu} \quad \text{where} \\ J^\mu_L &= \sum_{i=1}^{3}\left(\sum_{a=1}^{3} \bar{q}_{aiL}\gamma^\mu q_{aiL} + \mathcal{F}_\ell\, \bar{\ell}_{iL}\gamma^\mu \ell_{iL}\right). \end{aligned} \tag{5}$$

Here, $\eta = \pm 1$; $a, b = 1, 2, 3$ labels color; $i, j = 1, 2, 3$ labels the generations, and the quark and lepton fields are isodoublets, $q_{ai} = (u_{ai}, d_{ai})$ and $\ell_i = (\nu_i, e_i)$ The real factor $\mathcal{F}_\ell$ is inserted to allow for different quark and lepton couplings, but it is expected to be $\mathcal{O}(1)$. The factor of $\frac{1}{2}$ in the overall strength of the interaction avoids double-counting interactions and amplitudes.

The color-averaged jet subprocess cross sections, modified for the interaction $\mathcal{L}^0_{LL}$, are given in leading order in α_S by (these formulas correct errors in Ref. [10])

$$\begin{aligned} \frac{d\hat{\sigma}(q_i q_i \to q_i q_i)}{dz} &= \frac{d\hat{\sigma}(\bar{q}_i \bar{q}_i \to \bar{q}_i \bar{q}_i)}{dz} = \frac{\pi}{2\hat{s}}\mathcal{A}_1(\hat{s},\hat{t},\hat{u}); \\ \frac{d\hat{\sigma}(q_i \bar{q}_i \to q_i \bar{q}_i)}{dz} &= \frac{\pi}{2\hat{s}}\mathcal{A}_1(\hat{u},\hat{t},\hat{s}); \\ \frac{d\hat{\sigma}(q_i \bar{q}_i \to q_j \bar{q}_j)}{dz} &= \frac{\pi}{2\hat{s}}\mathcal{A}_2(\hat{s},\hat{t},\hat{u}); \\ \frac{d\hat{\sigma}(q_i \bar{q}_j \to q_i \bar{q}_j)}{dz} &= \frac{\pi}{2\hat{s}}\mathcal{A}_2(\hat{t},\hat{s},\hat{u}); \\ \frac{d\hat{\sigma}(q_i q_j \to q_i q_j)}{dz} &= \frac{d\hat{\sigma}(\bar{q}_i \bar{q}_j \to \bar{q}_i \bar{q}_j)}{dz} = \frac{\pi}{2\hat{s}}\mathcal{A}_2(\hat{t},\hat{u},\hat{s}) \\ \text{with } \mathcal{A}_1(\hat{s},\hat{t},\hat{u}) &= \frac{4}{9}\alpha_S^2\left[\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2} + \frac{\hat{t}^2+\hat{s}^2}{\hat{u}^2} - \frac{2}{3}\frac{\hat{s}^2}{\hat{t}\hat{u}}\right] \\ &+ \frac{8}{9}\alpha_S\frac{\eta}{\Lambda^2}\left[\frac{\hat{s}^2}{\hat{t}} + \frac{\hat{s}^2}{\hat{u}}\right] + \frac{8}{3}\frac{\hat{s}^2}{\Lambda^4}; \\ \text{and } \mathcal{A}_2(\hat{s},\hat{t},\hat{u}) &= \frac{4}{9}\alpha_S^2\left[\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right] + \frac{\hat{u}^2}{\Lambda^4}. \end{aligned} \tag{6}$$

For this LL-isoscalar interaction, the interference term (η/Λ^2) in the hadron cross section is small and the sign of η is not very important. Interference terms may be non-negligible in contact interactions with different chiral, flavor, and color structures. In all cases, the main effect of substructure is to increase the proportion of centrally-produced jets. If this can be seen in the jet angular distribution, it will be important for confirming the presence of contact interactions.[4]

The modified cross sections for the Drell-Yan process $\bar{q}_i q_i \to \ell^+\ell^-$ is

$$\frac{d\hat{\sigma}(\bar{q}_i q_i \to \ell^+\ell^-)}{dz} = \frac{\pi\alpha^2}{6\hat{s}}\left[\mathcal{A}_i(\hat{s})\left(\frac{\hat{u}}{\hat{s}}\right)^2 + \mathcal{B}_i(\hat{s})\left(\frac{\hat{t}}{\hat{s}}\right)^2\right], \tag{7}$$

where

$$\begin{aligned} \mathcal{A}_i(\hat{s}) &= \left[Q_i - g^i_L g^l_L z(\hat{s}) - \frac{\mathcal{F}_\ell \eta \hat{s}}{\alpha\Lambda^2}\right]^2 + \left[Q_i - g^i_R g^l_R z(\hat{s})\right]^2 \\ \mathcal{B}_i(\hat{s}) &= \left[Q_i - g^i_L g^l_R z(\hat{s})\right]^2 + \left[Q_i - g^i_R g^l_L z(\hat{s})\right]^2, \end{aligned} \tag{8}$$

[4]This is true regardless of the dynamical origin of the contact interaction.

and $g^i_L = 2\left(T_{3i} - Q_i \sin^2\theta_W\right)/\sin 2\theta_W$, $g^i_R = -Q_i \tan\theta_W$, $g^l_L = 2\left(-\frac{1}{2} + \sin^2\theta_W\right)/\sin 2\theta_W$, $g^l_R = \tan\theta_W$ and $z(\hat{s}) = \hat{s}/(\hat{s} - M_Z^2)$. The angular distribution of the ℓ^- relative to the incoming quark is an important probe of the contact interaction's chiral structure. Measuring this distribution is easy in a $\bar{p}p$ collider such as the Tevatron since the hard quark almost always follows the proton direction. If the scale Λ is high so that parton collisions revealing the contact interaction are hard, the quark direction can also be determined with reasonable confidence in a pp collider. At the LHC, the quark in a $\bar{q}q$ collision with $\sqrt{\hat{s}/s} \gtrsim 1/20$ is harder than the antiquark, and its direction is given by the boost rapidity of the dilepton system, at least 75% of the time. The charges of $\mathcal{O}(1\ \mathrm{TeV})$ muons can be well-measured even at very high luminosity in the detectors being designed for the LHC. These two ingredients are needed to insure a good determination of the angular distribution [17].

It is important to study the effects of contact interactions with chiral, flavor and color structures different from the one in Eq. 5. Such interactions can give rise to larger (or smaller) cross sections for the same Λ because they have more terms or because they interfere more efficiently with the standard model. Thus, it will be possible to probe even higher values of Λ for other structures. Other forms can also give rise to $\ell^\pm\nu$ final states. Searching for contact interactions in these modes is more challenging than in $\ell^+\ell^-$, but it is very useful for untangling flavor and chiral structures [17]. Events are selected which contain a single high-p_T charged lepton, large missing E_T, and little jet activity. Even though the parton c.m. frame cannot be found in this case, it is still possible to obtain information on the chiral nature of the contact interaction by comparing the $|\eta_{\ell^+}|$ and $|\eta_{\ell^-}|$ rapidity distributions of the high-p_T leptons. For example, if the angular distribution in the process $d\bar{u} \to \ell^-\bar{\nu}$ between the incoming d-quark and the outgoing ℓ^- is $(1+\cos\theta)^2$, then $|\eta_{\ell^-}|$ is pushed to larger values because the d-quark is harder than the $\bar{u}$-quark and the ℓ^- tends to be produced forward. Correspondingly, in $u\bar{d} \to \nu\ell^+$, the $|\eta_{\ell^+}|$ distribution would be squeezed to smaller values.

IV. CONCLUSIONS AND ACKNOWLEDGEMENTS

Many theorists are convinced that low-energy supersymmetry is intimately connected with electroweak symmetry breaking and that its discovery is just around the corner[18]. However, the vast body of *experimental* evidence favors no particular extension of the standard model. Therefore, all plausible approaches must be considered. Detectors must have the capability—and experimenters must be prepared—to discover whatever physics is responsible for electroweak and flavor symmetry breaking. To this end, we have summarized the principal signatures for technicolor, extended technicolor and quark-lepton substructure. Table 1 lists sample masses for new particles and their production rates at the Tevatron and LHC. We hope that this summary is useful to future in-depth studies of strong TeV-scale dynamics.

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Table I: Sample cross sections for technicolor signatures at the Tevatron and LHC. Cross sections may vary by a factor of 10 for other masses and choices of the parameters. K-factors of 1.5–2 are expected, but not included. Signal over background rates are quoted as S/B. $N_{TC} = 4$ in all calculations; cross sections generally grow with N_{TC}. [1] $F_T = F_\pi/3 = 82\,\mathrm{GeV}$ was used. [2] $F_T = 50\,\mathrm{GeV}$ used. Cross section is integrated over $\mathcal{M}_{b\bar{b}} = 90$–$110\,\mathrm{GeV}$. [3] $F_T = 50\,\mathrm{GeV}$ and $m_t = 175\,\mathrm{GeV}$ were used. The greatly increased LHC cross section is due to the rapid growth of gluons at small-x. [4] Cross sections for a multi-scale model with 250 GeV π_{T8} and 200 GeV $\pi_{Q\bar{L}}$ intermediate states. [5] Jet energy resolution of $\sigma(E)/E = 100\%/\sqrt{E}$ is assumed and cross sections integrated over $\pm\Gamma$ about resonance peak. Jet angles are limited by $\cos\theta^* < \frac{2}{3}$ and $|\eta_j| < 2.0$ (Tevatron) or 1.0 (LHC). [6] Cross sections per channel are quoted. [7] $\tan\xi = \sqrt{2\pi/3\alpha_S}$ was used, corresponding to a critical topcolor coupling strength. [8] Estimated Λ reaches in dijet and dilepton production are for the indicated luminosities.

Process $[SampleMass(GeV)]$	σ_{TeV}(pb)	σ_{LHC}(pb)
$\rho_{T1} \to W_L \pi_T$ [1] $[220(\rho_{T1}), 100(\pi_T)]$	5	35
$\rho_{T1} \to \pi_T \pi_T$ [1] $[220(\rho_{T1}), 100(\pi_T)]$	5	25
$gg \to \pi_T^0 \to bb$ [2] $[100]$	$300/5000$	$7000/10^5$
$gg \to \eta_T \to t\bar{t}$ [3] $[400]$	$3/3$	$2000/600$
$gg \to \pi_T \pi_T$ [4] $[100]$	0.2	600
$\rho_{T8} \to \mathrm{jet\ jet}$ [5] $[250(\rho_{T8})]$ $[500(\rho_{T8})]$	$700/5000$ $10/40$	$1.5\times10^4/1.5\times10^5$ $2000/6000$
$\rho_{T8} \to \pi_{T8}\pi_{T8}$ [6] $[550(\rho_{T8}), 250(\pi_{T8})]$	2	2000
$\rho_{T8} \to \pi_{Q\bar{L}}\pi_{L\bar{Q}}$ [6] $[550(\rho_{T8}), 200(\pi_{Q\bar{L}})]$	2	1000
$V_8 \to t\bar{t}$ [7] $[500]$	$8/3$	$100/600$
Λ reach [8](in TeV) $[5(TEV), 20(LHC)]$	$10\,\mathrm{fb}^{-1}$	$100\,\mathrm{fb}^{-1}$

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[18] See, e.g., P. Ramond, et al., Letter to the Director of Fermilab and the Co-Spokespersons of the CDF and DØ Collaborations, (1994).