Technicolor Signatures at the
High Energy Muon Collider

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Abstract. I discuss high mass signatures of technicolor that would be observable at a very high energy muon collider. Most intriguing is the spectrum of spin–one technihadrons, $\rho_T$, $\omega_T$ and $A_{1T}$, which may extend to 100 TeV and beyond in a walking technicolor theory.

1. INTRODUCTION

It is a real pleasure to talk at a workshop in which the theorists are down-to-earth participants and the machine physicists are wild-eyed dreamers. Here is an e-mail exchange between between my session organizer and me:

• Joe –
  I just realized that the workshop title refers to muon colliders at 10-100 TeV (!). I don’t have a hell of a lot in the way of TC signals at those energies. How seriously should I take that energy range as a charge??
  Ken

• You can completely ignore the 10 TeV stuff - that is for the accelerator people (i.e. what is the highest energy muon collider one could ever have any hope of building).
  –Joe

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\textsuperscript{2} Talk delivered at the workshop “Studies on Colliders and Collider Physics at the Highest Energies: Muon Colliders at 10 TeV to 100 TeV”, Montauk, Long Island, NY, 27 September–1 October 1999.
Accordingly, I prepared a talk that discusses TC signatures at 1–4 TeV: The technivector mesons $\rho_T$ and $\omega_T$ of the minimal, one–doublet TC model [1]; the $Z'$ and higher–dimensional electroweak singlet technifermions of topcolor–assisted technicolor [2]; and the electroweak–$SU(2)$ singlet fermions of the top seesaw model [3].

In the course of this, however, I recalled an old idea that would give the HEMC physics to do all the way from 1 TeV to 100 TeV. This has to do with the fact that walking technicolor [4], an essential ingredient of any viable TC model, implies that the spectrum of technivector mesons cannot be QCD–like [5–7]. It must extend in some sense to 100 TeV and beyond. This idea is so intriguing that I will emphasize it here. I hope someone will be able to decide whether it makes sense.

The rest of this paper is organized as follows: Section 2 presents a summary of the dynamical approach to electroweak and flavor symmetry breaking: technicolor [1], extended technicolor (ETC) [8,9], and all that. This scenario’s signatures at the HEMC are discussed in Section 3, with emphasis on the technivector spectrum in walking technicolor models.

2. OVERVIEW OF TECHNICOLOR

Technicolor—a strong interaction of fermions and gauge bosons at the scale $\Lambda_{TC} \sim 1$ TeV—induces the breakdown of electroweak symmetry to electromagnetism without elementary scalar bosons [1]. Technicolor has a strong precedent in QCD. There, the chiral symmetry of massless quarks is spontaneously broken by strong QCD interactions, resulting in the appearance of massless Goldstone bosons, $\pi$, $K$, $\eta$. In fact, if there were no Higgs bosons, this chiral symmetry breaking would itself cause the breakdown of $SU(2) \otimes U(1)$ to electromagnetism. Furthermore, the $W$ and $Z$ masses would be given by $M_W^2 = M_Z^2 \cos^2 \theta_W = \frac{1}{4}g^2 N_F f_\pi^2$, where $g$ is the weak $SU(2)$ coupling, and $N_F$ the number of massless quark flavors. Alas, the pion decay constant $f_\pi$ is only 93 MeV and the $W$ and $Z$ three orders of magnitude too light.

In its simplest form, technicolor is a scaled up version of QCD, with massless technifermions whose chiral symmetry is spontaneously broken at $\Lambda_{TC}$. If left and right-handed technifermions are assigned to weak $SU(2)$ doublets and singlets, respectively, then $M_W = M_Z \cos \theta_W = \frac{1}{2}gF_\pi$, where $F_\pi = 246$ GeV is the weak technipion decay constant. In the standard model and its extensions, the masses of quarks and leptons are produced by their Yukawa couplings to the Higgs bosons—couplings of arbitrary

3) The hard masses of quarks explicitly break chiral symmetry and give mass to $\pi$, $K$, $\eta$, which are then referred to as pseudo-Goldstone bosons.

4) In the minimal model with one doublet ($U, D$) of technifermions, there are just three technipions. They are the linear combinations of massless Goldstone bosons that become, via the Higgs mechanism, the longitudinal components $W_\pm^L$ and $Z_0^L$ of the weak gauge bosons. In non-minimal technicolor, the technipions include the longitudinal weak bosons as well as additional Goldstone bosons associated with spontaneous technifermion chiral symmetry breaking. The latter must and do acquire mass—from the extended technicolor interactions discussed below.
magnitude and phase that are put in by hand. This option is not available in technicolor because there are no elementary scalars. Instead, this explicit breaking of quark and lepton chiral symmetries must arise from gauge interactions alone. The most economical approach employs extended technicolor \[8,9\]. In its proper formulation \[9\], the ETC gauge group contains technicolor, color, and flavor as subgroups and there are very stringent restrictions on the representations to which technifermions, quarks, and leptons belong: Specifically, they must be combined into the same few large representations of ETC. Otherwise, unbroken chiral symmetries lead to axion–like particles. Quark and lepton hard masses are generated by their coupling (with strength \(g_{ETC}\)) to technifermions via ETC gauge bosons of generic mass \(M_{ETC}\):

\[
m_q(M_{ETC}) \simeq m_\ell(M_{ETC}) \simeq \frac{g_{ETC}^2}{M_{ETC}^2} \langle \bar{T}T \rangle_{ETC},
\]

where \(\langle \bar{T}T \rangle_{ETC}\) and \(m_q,\ell(M_{ETC})\) are, respectively, the technifermion condensate and quark and lepton masses renormalized at the scale \(M_{ETC}\).

Technicolor is an asymptotically free gauge interaction. If it is like QCD, with its running coupling \(\alpha_{TC}\) rapidly becoming small above its characteristic scale \(\Lambda_{TC} \sim 1\) TeV, then \(\langle \bar{T}T \rangle_{ETC} \simeq \langle \bar{T}T \rangle_{TC} \simeq \Lambda_{TC}^3\). To obtain quark masses of a few GeV thus requires \(M_{ETC}/g_{ETC} \lesssim 30\) TeV. This is excluded: Extended technicolor boson exchanges also generate four-quark interactions which, generically, include \(|\Delta S| = 2\) and \(|\Delta B| = 2\) operators. For these not to conflict with \(K^0-\bar{K}^0\) and \(B^0_d-\bar{B}^0_d\) mixing measurements, \(M_{ETC}/g_{ETC}\) must exceed several hundred TeV \[9\]. This implies quark and lepton masses no larger than a few MeV, and technipion masses no more than a few GeV.

Because of this conflict between constraints on flavor-changing neutral currents and the magnitude of ETC-generated quark, lepton and technipion masses, classical QCD–like technicolor was superseded long ago by “walking” technicolor \[4\]. Here, the strong technicolor coupling \(\alpha_{TC}\) runs very slowly, or walks, for a large range of momenta, possibly all the way up to the ETC scale of several hundred TeV. The slowly-running coupling enhances \(\langle \bar{T}T \rangle_{ETC}/\langle \bar{T}T \rangle_{TC}\) by almost a factor of \(M_{ETC}/\Lambda_{TC}\). This, in turn, allows quark and lepton masses as large as a few GeV and \(M_{\pi_T} \gtrsim 100\) GeV to be generated from ETC interactions at \(M_{ETC} = O(100\) TeV).

In almost all respects, walking technicolor models are very different from QCD with a few fundamental \(SU(3)\) representations. One example is that integrals of weak-current spectral functions and their moments converge much more slowly than they do in QCD. The consequence of this for the HEMC will be discussed in Section 3. Meanwhile, this and other calculational tools based on naive extrapolation from QCD and on large-\(N_{TC}\) arguments are suspect. It is not yet possible to predict with confidence the influence of technicolor degrees of freedom on precisely-measured electroweak quantities—the \(S, T, U\) parameters to name a frequently discussed example \[10\].
Another major development in technicolor was motivated by the discovery of the top quark at Fermilab \[11\]. Theorists have concluded that ETC models cannot explain the top quark’s large mass without running afoul of either experimental constraints from the $\rho$ parameter and the $Z \to b\bar{b}$ decay rate \[12\]—the ETC mass must be about 1 TeV to produce $m_t = 175$ GeV; see Eq. (1)—or of cherished notions of naturalness—$M_{ETC}$ may be higher, but the coupling $g_{ETC}$ then must be fine-tuned near to a critical value. This state of affairs led to the proposal of “topcolor-assisted technicolor” (TC2) \[2\].

In TC2, as in many top-condensate models of electroweak symmetry breaking \[13\], almost all of the top quark mass arises from a new strong “topcolor” interaction \[14\]. To maintain electroweak symmetry between (left-handed) top and bottom quarks and yet not generate $m_b \simeq m_t$, the topcolor gauge group under which $(t,b)$ transform is usually taken to be $SU(3) \otimes U(1)$. The $U(1)$ provides the difference that causes only top quarks to condense. Then, in order that topcolor interactions be natural—i.e., that their energy scale not be far above $m_t$—without introducing large weak isospin violation, it is necessary that electroweak symmetry breaking is still due mostly to technicolor interactions \[2\].

Extended technicolor interactions are still needed in TC2 models to generate the masses of light quarks and the bottom quark, to contribute a few GeV to $m_t$, \(^5\) and to give mass to technipions. The scale of ETC interactions still must be hundreds of TeV to suppress flavor-changing neutral currents and, so, the technicolor coupling still must walk. In TC2 there is no need for large technifermion isospin splitting associated with the top-bottom mass difference. Thus, for example, $\omega_T$ and $\rho_T$ partners are nearly degenerate $UU \pm \bar{D}D$ states.

Another, more recent, variant of topcolor models is the “top seesaw” mechanism \[3\]. Its motivation is to realize the original top–condensate idea of the Higgs boson as a fermion–antifermion bound state. This failed for the top quark because it turned out to be too light! In top seesaw models, an electroweak singlet fermion $F$ acquires a dynamical mass of several TeV. Through mixing of $F$ with the top quark, it gives the latter a much smaller mass (the seesaw) and the scalar $\bar{F}F$ bound state acquires a component with an electroweak symmetry breaking vacuum expectation value.

This completes our brief summary of technicolor. We turn now to the technicolor signatures for which a high energy muon collider is well–suited.

### 3. TECHNICOLOR SIGNATURES AT THE HEMC

The principal signals of technicolor are discussed in a number of places \[15\]. Most of them are accessible at low energies—at the Tevatron in Run II, certainly at the LHC, and, possibly, even at LEP. In the minimal technicolor model, with just one technifermion doublet, the only prominent signals in a TeV–scale collider are

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\(^5\) Massless Goldstone “top-pions” arise from top-quark condensation. This ETC contribution to $m_t$ is needed to give them a mass in the range of 150–250 GeV.
modest enhancements in longitudinally-polarized weak boson production. These are the $s$–channel color–singlet technirho resonances near 1.5–2 TeV: $\rho^0_T \rightarrow W^+_L W^-_L$ and $\rho^\pm_T \rightarrow W^+_L Z^0_L$. The $O(\alpha^2)$ cross sections of these processes are quite small at such masses. This and the difficulty of reconstructing weak-boson pairs with reasonable efficiency make observing these enhancements a challenge. These states would be more easily seen in a lepton collider—if one can be built with $\sqrt{s} = 1.5–2$ TeV at an affordable cost. Nonminimal technicolor models are much more accessible in a hadron collider because they have a rich spectrum of lower mass technirho vector mesons and technipion states into which they may decay.

If technicolor is the basis for electroweak symmetry breaking, it will have been discovered once the LHC has acquired and analyzed 10 fb$^{-1}$ of data. The question we address here is what the HEMC can do to add to our understanding of this new dynamics.

3.1 The Technivector Spectrum of Walking Technicolor

The slow decrease with energy of the coupling $\alpha_{TC}$ in walking technicolor means that the $\mu^+\mu^-$ cross section approaches asymptotia only near the extended technicolor scale, probably even above the reach of the HEMC. This is most directly seen by considering the integrals in Weinberg’s spectral function sum rules for the weak–isospin vector and axial vector currents [16]. These sum rules are

$$
\int_0^\infty ds \left[ \rho_V(s) - \rho_A(s) \right] = F_\pi^2 \\
\int_0^\infty ds s \left[ \rho_V(s) - \rho_A(s) \right] = 0,
$$

where $F_\pi = 246$ GeV. Here, the spectral functions $\rho_V$ and $\rho_A$ are analogs for the weak–isospin currents of the ratio of cross sections, $R(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^+)$. In QCD, the sum rules corresponding to Eq. (2) are saturated by the lowest lying spin–one resonances, $\rho$ and $A_1$, and the sum rules converge rapidly above the $A_1$ mass. Similarly, in technicolor without a walking coupling, the sum rules would be saturated by the lowest $\rho_T$ and $A_{1T}$ and the difference $\rho_V - \rho_A \sim 1/s^3$ for $s \gtrsim M_{A_{1T}}^2 \sim 1$ TeV$^2$. In walking technicolor, the slow running of $\alpha_{TC}(s)$ implies that $\rho_V - \rho_A \sim 1/s^2$ below $s \sim M_{ETC}^2$ and $1/s^3$ above. Thus, the spectral functions cannot be saturated by a single pair of low–lying resonances. Either there must be a tower of resonances above $\rho_T$ and $A_{1T}$, all of which contribute significantly to the spectral integrals (see Ref. [5,6]; also Ref. [7] for an explicit attempt to realize this), or the spectral functions are smooth but anomalously slowly decreasing up to $M_{ETC}$. The same alternative applies to the $\mu^+\mu^-$ cross section. Moreover, the isoscalar state $\omega_T$ and its excitations appear there. Thus, exploration of the 1–100 TeV region of $\mu^+\mu^-$ annihilation is bound to reveal crucial information on the dynamics of a walking gauge theory, dynamics on which we theorists can only speculate.
In the minimal one–doublet model of technicolor, it has always been assumed that the lowest lying $\rho_T$, $\omega_T$, and $A_{1T}$ decay mainly into two and three longitudinally–polarized weak bosons, $W_L^\pm$ and $Z_L^0$. In the minimal model, however, $M_{\rho_T} \sim M_{A_{1T}} = 1–2$ TeV, and this is so far above $2M_W$ that it is possible that decay modes with more than two or three weak bosons are important if not dominant. Thus, in the minimal walking technicolor model, there may be a tower of vector and axial vector mesons in the $s$–channel of $\mu^+\mu^-$ annihilation which decay to many $W$ and $Z$ bosons. It is an open question how narrow and discernible these resonances will be.

In nonminimal models, the spectrum of technihadrons is quite rich and the scale of their masses is lower (roughly as the square root of the number of technifermion doublets). There are technipions $\pi_T$ as well as weak bosons for the $\rho_T$, $\omega_T$, and $A_{1T}$ to decay into. These $\pi_T$ may be color singlets and, if colored technifermions exist, octets and triplets ("leptoquarks"). Technipions are expected to have masses in the range 100–500 GeV and to decay into the heaviest fermion pairs allowed. The large value of \( \langle \bar{T}T \rangle_{ETC} / \langle \bar{T}T \rangle_{TC} \) in walking technicolor significantly enhances technipion masses. Thus, for example, $\rho_T \rightarrow \pi_T \pi_T$ decay channels may be closed for the lowest–lying state. Instead, $\rho_T \rightarrow W_L W_L$, $W_L \pi_T$, and $\gamma \pi_T$ [15]. The excited states should be able to decay into pairs of technipions. The $\rho_T$, $\omega_T$, and $A_{1T}$ that lie above multi–$\pi_T$ threshold are likely to be wider than their counterparts in the minimal model. Still, the structure of $\mu^+\mu^-$ annihilation up to 100 TeV will provide valuable insight to walking gauge dynamics.

### 3.2 Topcolor–Technicolor Signals

As I said above, topcolor–assisted technicolor generally employs an extra “hypercharge” $U(1)$ to help induce a large condensate for the top, but not the bottom quark. This additional $U(1)$ is broken, leading to a $Z'$ boson which is strongly coupled to at least the third generation. In the models of Ref. [17], it is strongly coupled to all fermions. Some of the lower energy phenomenology of this $Z'$ was studied in Refs. [18,19]. Its nominal mass, in the range 1–4 TeV, and potentially strong coupling to muons make it a target of opportunity for the HEMC. Unfortunately, its strong couplings and many decay channels to ordinary fermions and technifermions may also make the $Z'$ so broad that it is difficult discover and study in any collider.

An intriguing feature of this $Z'$ is that it must acquire its mass from condensation of a technifermion $\psi$ [17]. The $Z'$ mass of several TeV implies that the $\psi$–fermion’s mass is 1–2 TeV. Thus, $\psi$ must transform according to a higher–than–fundamental

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6) The QCD $2^3S_1$ state $\rho'(1700)$ decays predominantly to four, not two pions, presumably because the two–pion mode is suppressed by an exponential form factor and/or a node in the decay amplitude.

7) Top seesaw models also have an extra $U(1)$ gauge symmetry, broken spontaneously. There, the $Z'$ boson mass is expected to be roughly 5 TeV.
representation of the technicolor gauge group. In order that its condensation not break electroweak $SU(2) \otimes U(1)$, $\psi$ must either be a singlet or transform vectorially under this symmetry. The obvious way to access it is via $Z' \to \bar{\psi}\psi$ in the $s$-channel of the HEMC. The phenomenology of these higher representation technifermions has not been studied in detail. One crucial question is whether $\psi$ is stable. If not, how does it decay? If it is, what are the cosmological consequences?

Finally, there is the $SU(2)$ singlet, charge–2/3 quark $F$ of top seesaw models. This fermion also has a mass of several TeV and may be pair produced via $\gamma, Z, Z'$ at the HEMC. It decays by virtue of its mixing with the top quark as $F \to t \to Wb$, a striking signature indeed.

4. CONCLUSIONS AND ACKNOWLEDGEMENTS

The HEMC technicolor signatures that I have presented here are, quite obviously, at a primitive stage of development. I think all of them deserve further thought because they bear directly on unfamiliar dynamics such as walking technicolor and strongly–coupled topcolor. Corresponding uncertainties face the design of the HEMC. Again, the particle theorists and the accelerator theorists are in the same boat. The need to go on to higher energies remains and it always will. This was said very well by an Amherst poet long ago:

“Faith” is a fine invention
When Gentlemen can see —
But Microscopes are prudent
In an Emergency.

— Emily Dickinson, 1860

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