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FERMILAB-Pub-96/075-T

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February 1998

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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FERMILAB-PUB-96/075-T
BUHEP-96-9
hep-ph/9607213

Low-Scale Technicolor at the Tevatron

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Abstract

In multiscale models of walking technicolor, relatively light color-singlet technipions are produced in $q\bar{q}$ annihilation in association with longitudinal W and Z bosons and with each other. The technipions decay as $\pi_T^0 \to b\bar{b}$ and $\pi_T^+ \to c\bar{b}$. Their production rates are resonantly enhanced by isovector technirho vector mesons with mass $M_W + M_{\pi_T} \lesssim M_{\rho_T} \lesssim 2M_{\pi_T}$. At the Tevatron, these associated production rates are 1–10 picobarns for $M_{\pi_T} \simeq 100\,\text{GeV}$. Such a low mass technipion requires topcolor-assisted technicolor to suppress the decay $t \to \pi_T^+ b$. Searches for $\pi_T\pi_T$ production will also be rewarding. Sizable rates are expected if $M_{\rho_T} \gtrsim 2M_{\pi_T} + 10\,\text{GeV}$. The isoscalar ω_T is nearly degenerate with ρ_T and is expected to be produced at roughly the same rate. The ω_T should have the distinctive decay modes $\omega_T \to \gamma\pi_T^0$ and $Z\pi_T^0$.

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In the standard one-doublet Higgs model of electroweak symmetry breaking, the cross section for production in $\bar{p}p$ collisions at 1.8 TeV of a 100 GeV Higgs boson H in association with $W^{\pm}$ bosons is about 0.15 pb. Even lower rates occur in nonminimal Higgs models, including supersymmetric ones. Such small cross sections require luminosities of 1–10 fb^{-1} to detect the signature $W^{\pm} + H \to \ell^{\pm} + \bar{b}b + \not{E}_T$ [1]. In this note, we recall that very similar signatures occur in technicolor models at rates that are 30 or more times greater than the Higgs rate, large enough to be observed at the Tevatron now. In our 1989 paper proposing multiscale technicolor [2], we predicted that resonant production via isovector technirho (ρ_T) vector mesons of $W/Z + \pi_T$, with π_T a technipion of mass of $\sim 100\,\mathrm{GeV}$ decaying to heavy quarks, would occur at the Tevatron at the level of a few picobarns. Here, we review our proposal and point out that such a low mass for the technipion requires a new scenario such as topcolor-assisted technicolor [3], [4], [5], [6] to accommodate the top quark's large mass and prevent its decay to $\pi_T^+ b$. If the custodial techni-isospin is approximately conserved, as we expect, the isoscalar partner ω_T of the ρ_T is nearly degenerate with it and may be produced at a comparable rate. In addition, there may be an isoscalar technipion, $\pi_T^{0\prime}$, close in mass to to π_T^0. The main decay modes of ω_T are expected to be $\gamma/Z + \pi_T^0$ and $\gamma/Z + \pi_T^{0\prime}$, with π_T^0 and $\pi_T^{0\prime} \to \bar{b}b$, providing spectactular signatures at the Tevatron.

Quark and lepton masses in technicolor are generated by broken extended technicolor (ETC) gauge interactions [7], [8], [9]. Because of the conflict between constraints on flavor-changing neutral currents and the magnitude of ETC-generated masses, this classical version of technicolor failed and was replaced a decade ago by "walking" technicolor [10]. 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 flavor-changing effects. 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.

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 (here taken to be $SU(N_{TC})$), to a few higher dimensional representations, or to both. This led us to argue in Ref. [2] that both large and fundamental representations participate in electroweak symmetry breaking.[1] The two types of technifermion condense at widely separated scales [13]. The upper scale is set by the weak decay constant $F_\pi = 246\,\mathrm{GeV}$. Technihadrons associated with the lower scale may be so light, we said, that they are within reach of Tevatron collider experiments.

Light-scale technihadrons generally consist of color singlets (discussed in [2]) and non-singlets (discussed in [14]). In this note, we shall be interested in the color singlets. We consider first the lightest isotriplet of technirho vector mesons, $\rho_T^{\pm,0}$. We will discuss their isoscalar counterpart, ω_T, later. The ρ_T decay into pairs of isovector technipion states, $\Pi_T^{\pm,0}$. In general, the latter are mixtures of the longitudinal weak bosons $W_L^\pm$, Z_L^0 and mass-eigenstate (pseudo-Goldstone) technipions $\pi_T^\pm, \pi_T^0$. In the simplest parameterization, with just one light isotriplet of π_T, $|\Pi_T\rangle = \sin\chi\,|W_L\rangle + \cos\chi\,|\pi_T\rangle$, where $\sin\chi = F_T/F_\pi \ll 1$ and F_T is the decay constant of Π_T. The ρ_T partial decay rates are given by (assuming no other open decay channels) [15], [16]

$$\Gamma(\rho_T \to \pi_A \pi_B) = \frac{2\alpha_{\rho_T} \mathcal{C}^2_{AB}}{3} \frac{p^3_{AB}}{M^2_{\rho_T}}, \tag{1}$$

where p_{AB} is the technipion momentum and $\mathcal{C}^2_{AB} = \sin^4\chi,\ 2\sin^2\chi\cos^2\chi,\ \cos^4\chi$ for $\pi_A\pi_B = W_L W_L,\ W_L\pi_T + \pi_T W_L,\ \pi_T\pi_T$, respectively. For technifermions in the fundamental representation of $SU(N_{TC})$, the $\rho_T \to \pi_T\pi_T$ coupling α_{ρ_T} obtained by *naive* scaling from QCD is given by

$$\alpha_{\rho_T} = 2.91 \left(\frac{3}{N_{TC}}\right). \tag{2}$$

In calculations, we take $N_{TC} = 4$.

Extended technicolor interactions couple technipions to quarks and leptons with Higgs-like couplings. Technipions are then expected to decay into heavy fermions:

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

[1] Technicolor models with QCD-like dynamics cannot have a large number of representations because they produce an S-parameter that is too large and positive [11]. Of course, such models are already ruled out because they have flavor-changing neutral currents that are too large [9], the problem that motivated walking technicolor. The arguments in [11] are based on scaling from QCD and on chiral perturbation theory. They fail or are questionable in walking technicolor models; see Ref. [12].

Now—and this is the important feature of walking technicolor—technipion masses are enhanced by renormalizations that are so large that the $\rho_T \to \pi_T \pi_T$ channels may be closed or strongly suppressed. Thus, technirho production at the Tevatron can lead to all of the processes

$$\begin{aligned} q\bar{q}' \to W^\pm \to \rho_T^\pm \to \;& W_L^\pm Z_L^0; \quad W_L^\pm \pi_T^0,\ \pi_T^\pm Z_L^0; \quad \pi_T^\pm \pi_T^0 \\ q\bar{q} \to \gamma, Z^0 \to \rho_T^0 \to \;& W_L^+ W_L^-; \quad W_L^\pm \pi_T^\mp; \quad \pi_T^+ \pi_T^- \end{aligned} \tag{4}$$

occurring at comparable rates despite the small angle χ.

To illustrate our points, we shall take $M_{\pi_T^\pm} \simeq M_{\pi_T^0} \simeq 110\,\mathrm{GeV}$ and vary $M_{\rho_T^\pm} \simeq M_{\rho_T^0}$ in our calculations. Note that, since ρ_T has $I = 1$, these resonant processes do not lead to $Z^0 \pi_T^0 \to \ell^+\ell^- / \nu\bar{\nu} + b\bar{b}$ final states. Such events must originate from ω_T, as we discuss later. Technirho events with a Z^0 and two heavy quark jets have one b-jet and one c-jet.[2]

The Drell-Yan processes in Eq. (4) have $\mathcal{O}(\alpha^2)$ cross sections and are unobservably small compared to backgrounds *unless* the technirho resonances are not far above threshold, roughly $M_W + M_{\pi_T} \lesssim M_{\rho_T} \lesssim 2M_{\pi_T}$. This condition is favored by multiscale technicolor. We estimate the $\rho_T \to \pi_A \pi_B$ subprocess cross sections by vector meson dominance, taking the $\gamma, Z, W \to \rho_T$ couplings from the condition that they reproduce $\gamma, Z, W \to \pi_A \pi_B$ at zero energy. We obtain [2]

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

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

$$\begin{aligned} A^\pm &= \frac{1}{4\sin^4\theta_W}\left(\frac{\hat{s}}{\hat{s} - M_W^2}\right)^2, \\ A^0 &= \left[Q_i + \frac{2\cos 2\theta_W}{\sin^2 2\theta_W}\,(T_{3i} - Q_i \sin^2\theta_W)\left(\frac{\hat{s}}{\hat{s} - M_Z^2}\right)\right]^2 \\ &\quad + \left[Q_i - \frac{2Q_i \cos 2\theta_W \sin^2\theta_W}{\sin^2 2\theta_W}\left(\frac{\hat{s}}{\hat{s} - M_Z^2}\right)\right]^2. \end{aligned} \tag{6}$$

[2] Note that $Z + \pi_T$ events with a lost lepton can end up in the $W + \pi_T$ sample, while $W + \pi_T$ with a lost lepton may be counted as $Z(\to \nu\bar{\nu}) + \pi_T$.

Here, Q_i and T_{3i} are the electric charge and third component of weak isospin for quark $q_{iL,R}$. In these processes, the W+dijet and Z+dijet invariant masses exhibit a narrow peak not far above 200 GeV. This peak will be smeared by energy resolutions, but it should be narrower than expected from continuum production of $W/Z + H$.

Our final observation is that, after all this, ordinary multiscale technicolor cannot accommodate the top quark. Its mass of $m_t \simeq 175$ GeV [17] is much too large to be generated by ETC coupling of the top quark to the low-scale technifermions [14]. Furthermore, there cannot be a charged technipion as light as 110 GeV for, then, the top quark would tend to decay into it. Taking the coupling of π_T^+ to $\bar{t}_L b_R$ to be $\sqrt{2} m_t^{ETC}/F_T$, where m_t^{ETC} is the ETC contribution to the top-quark mass, the top decay rate to $\pi_T^+ b$ is

$$\Gamma(t \to \pi_T^+ b) = \frac{(m_t^2 - M_{\pi_T}^2)^2}{16\pi m_t F_T^2} \left(\frac{m_t^{ETC}}{m_t}\right)^2 . \tag{7}$$

For $m_t^{ETC} \simeq m_t$ and $F_T = 40$ GeV, a typical value in multiscale models, $\Gamma(t \to \pi_T^+ b) \simeq 25\,\mathrm{GeV} \simeq 15\Gamma(t \to W^+ b)$; this is ruled out [18]. Topcolor-assisted technicolor (TC2) resolves these problems.

In TC2 [5], as in top-condensate models of electroweak symmetry breaking [3],[4], the large top quark mass is generated by strong "topcolor" gauge interactions. Thus, there can be low-scale technifermions and the ETC scale can be $\mathcal{O}(100\,\mathrm{TeV})$ for all fermions. Then, m_t^{ETC} is only a few GeV, so that the branching fraction $B(t \to \pi_T^+ b)$ is small.[3]

Preliminary models of topcolor-assisted technicolor were developed in Ref. [6]. They differ from multiscale technicolor models in that they do not contain technifermions in higher representations and the associated widely separated scales. However, there are many copies of the fundamental representation (some of which also transform under color or topcolor $SU(3)$). Thus, the net effect is the same; ignoring $SU(3)$ effects, $F_T \simeq F_\pi/\sqrt{N_D}$, where N_D is the number of technifermion weak isodoublets. In the model of the second paper in [6], $N_D = 9$, so that $F_T = 82$ GeV (or somewhat less because of color effects) for the lightest color-singlet technipions.[1]

We have used Eq. (5) with $\sin\chi = \frac{1}{3}$ to compute the ρ_T production cross sections for $M_{\pi_T} = 110$ GeV and $M_{\rho_T} = 195$–250 GeV. The individual decay channel cross sections

[3] Top-pions π_t arising from top-quark condensation do couple to m_t. Their mass arises from the ETC contribution: $M_{\pi_t}^2 \simeq m_t^{ETC}\langle\bar{t}t\rangle/F_t^2$, where $F_t \simeq 70$ GeV [5]. This is sufficient to make $M_{\pi_t} \gtrsim m_t$. Mixing of top-pions with technipions is expected to be small, of order $\langle\bar{t}t\rangle/\langle\bar{T}T\rangle_{ETC} \simeq \Lambda_{TC}/\Lambda_{ETC} \lesssim 10^{-2}$ [19].

are shown for $p\bar{p}$ collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$ in Fig. 1 (multiplied by a K-factor of 1.5, appropriate for Drell-Yan processes at the Tevatron). No cuts were put on the technipion directions. These plots illustrate several features we expect to be general:

- Except near $W\pi_T$ threshold, the increase in WZ and WW production is small.
- The inclusive $W\pi_T$ rate is 5–10 pb and the $Z\pi_T$ rate is 1–3 pb for $M_{\pi_T} + M_W \lesssim M_{\rho_T} \lesssim 2M_{\pi_T}$. The ratio $\sigma(W_L\pi_T)/\sigma(Z_L\pi_T) = 2$–$3$ is about the same as expected for $\sigma(WH)/\sigma(ZH)$. Because of threshold singularities, these rates can be changed significantly by modest isospin splittings in the technihadron masses. The cross sections increase by 15–20% when the Tevatron energy is increased to 2 TeV.
- Because the technirho is narrow, the total $pp^\pm$ cross section at $\sqrt{s}$ into the channel $\pi_A\pi_B$ is

$$\begin{aligned}\sigma(pp^\pm \to \rho_T \to \pi_A\pi_B) \simeq \frac{2\pi^2}{3s} \sum_{i,j} \frac{\Gamma(\rho_T \to q_i\bar{q}_j)\,\Gamma(\rho_T \to \pi_A\pi_B)}{M_{\rho_T}\,\Gamma_{\rho_T}} \\ \times \int d\eta_B \left\{ f^p_{q_i}\left(\frac{M_{\rho_T}}{\sqrt{s}}e^{\eta_B}\right) f^{p^\pm}_{\bar{q}_j}\left(\frac{M_{\rho_T}}{\sqrt{s}}e^{-\eta_B}\right) + \ (q_i \leftrightarrow \bar{q}_j)\right\}\,,\end{aligned} \tag{8}$$

  where $f^{p^\pm}_{q_i}$ is the q_i distribution function in $p^\pm$ at $Q^2 = M^2_{\rho_T}$. At the Tevatron, these distributions favor $\rho_T^\pm$ production over ρ_T^0 by a factor of 2–3 over the range of M_{ρ_T} considered.
- For $M_{\rho_T} \geq 2M_{\pi_T} + 10\,\mathrm{GeV}$, the dominant process is $\pi_T^\pm\pi_T^0$ production. The crossover point depends to some extent on the suppression factor $\tan\chi$, but we don't expect it to be much different from this. A search for the $\pi_T^\pm\pi_T^0$ channel will be rewarding.

Finally, we turn to the ω_T. 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 the M_{ω_T}-range we are considering. Thus, we expect the decays $\omega_T \to \gamma\Pi_T^0$, $Z\Pi_T^0$, and $\Pi_T^+\Pi_T^-$. When written 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 $W_L^+W_L^-$, $\pi_T^\pm W_L^\mp$, $\pi_T^+\pi_T^-$.[4] 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 be dominant, with the former mode favored by phase space.

[4] The modes $\omega_T \to \gamma Z_L$, ZZ_L were considered for a one-doublet technicolor model in Ref. [20]. We have estimated the rates for the isospin-violating decays $\rho_T \to \gamma\pi_T^0$, $Z\pi_T^0$ and find them to be negligible unless the mixing angle χ is very small.

The ω_T is produced in hadron collisions just as the ρ_T^0, via its vector-meson-dominance coupling to γ and Z^0. For $M_{\omega_T} \simeq M_{\rho_T}$, the ω_T production cross section should be approximately $|Q_U + Q_D|^2$ times the ρ_T^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 $M_{\bar{b}b} = M_{\pi_T}$.

The model of color-singlet technihadron production we have discussed here is an over-simplification, but one that captures some of the essence of modern models of technicolor. As we did in Ref. [2], we urge a search for $W/Z + \pi_T \to$ isolated high-p_T leptons + heavy quark jets. If such events are found, the $W/Z + jj$ mass spectrum should exhibit a narrow ρ_T peak consistent with resolution. Sidebands—M_{Wjj} with M_{jj} outside the "M_{π_T}" bins—should not exhibit the peak unless it turns out to be kinematic in nature. Because of the quadratic ambiguity in reconstructing the W in its $\ell\nu$ decay, it seems best to plot the low-mass solution versus the high-mass one. We also urge a search for $\pi_T\pi_T$ production. This may not be possible now, but a search with the high-luminosity data of Tevatron Run II should be conclusive. If a π_T candidate is found, it will be important to determine whether c-quarks as well as b-quarks occur in its decay. Higher luminosity and more robust heavy-flavor tagging can make this possible. Finally, there should be an isoscalar ω_T nearly degenerate with ρ_T^0, generically produced with a comparable cross section, and with spectacular $\gamma\bar{b}b$ and $Z\bar{b}b$ decay signatures. If these technihadrons are found, they will be just the first of a very large family.

EE's research is supported by the Fermi National Accelerator Laboratory, which is operated by Universities Research Association, Inc., under Contract No. DE–AC02–76CHO3000. KL's research is supported in part by the Department of Energy under Grant No. DE–FG02–91ER40676. We gratefully acknowledge the hospitality of the Aspen Center for Physics where this work was completed.

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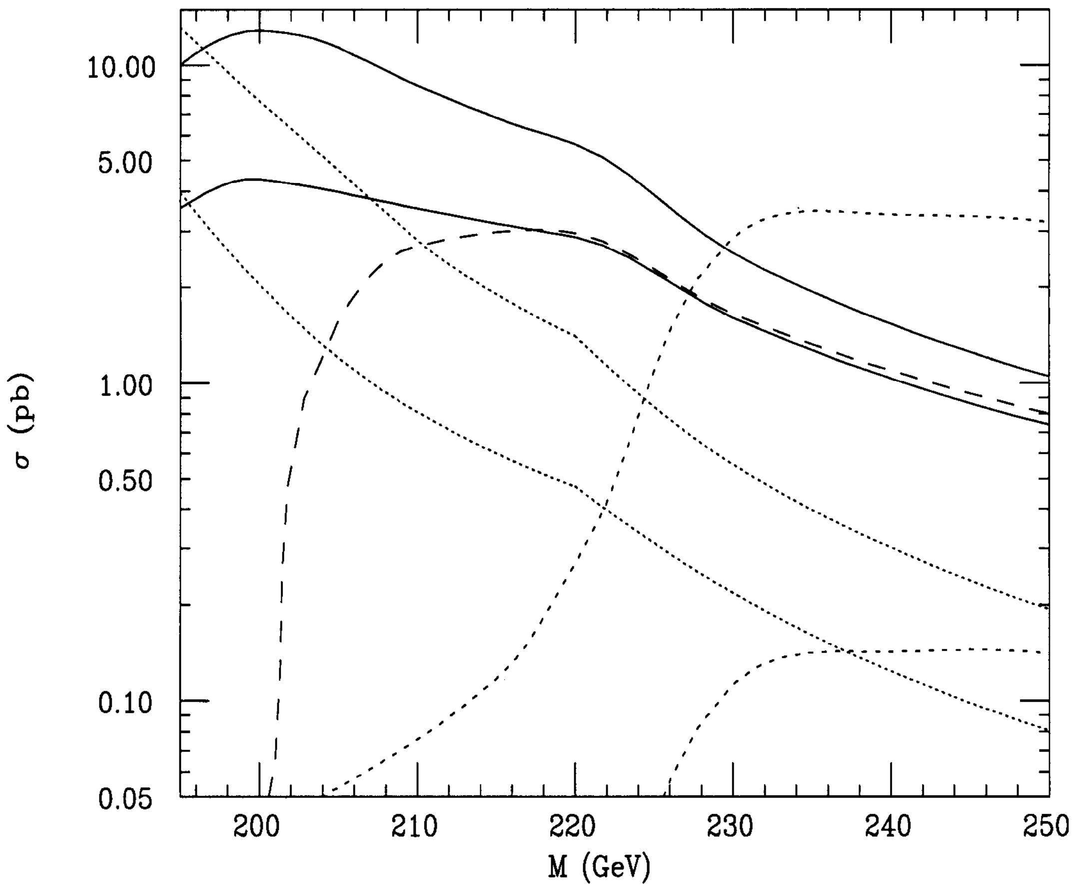

Figure 1. Total WW, $W\pi_T$ and $\pi_T\pi_T$ cross sections in $\bar{p}p$ collisions at 1.8 TeV, as a function of M_{ρ_T} for $M\pi_T = 110\,\mathrm{GeV}$. The model described above Eq. (1) is used with $\sin\chi = \frac{1}{3}$. The curves are $W^\pm Z^0$ (upper dotted) and W^+W^- (lower dotted); $W^\pm\pi_T^0$ (upper solid), $W^\pm\pi_T^\mp$ (lower solid), and $Z^0\pi_T^\pm$ (long dashed); $\pi_T^\pm\pi_T^0$ (upper short dashed) and $\pi_T^+\pi_T^-$ (lower short dashed). EHLQ set 1 distribution functions [16] were used and cross sections were multiplied by a K-factor of 1.5, as appropriate for Drell-Yan processes.