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Can one really observe signatures of the weak interaction with multi-TeV colliding hadron rings?

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We discuss two possible signatures of weak interactions in multi-TeV hadron-hadron collisions: (i) production of the weak boson $W^{\pm}$ and its neutral partner Z; (ii) observation of secondaries with transverse momentum so large that they cannot be electromagnetic or strong in origin. After summarizing theoretical prejudices on the properties of weak bosons and their production mechanism, we calculate their actual experimental signature, i.e., the momentum distributions of their decay lepton, as well as the competing backgrounds. Contrary to popular belief, we conclude that the weak-boson signature is not expected to be pronounced and backgrounds could be severe (especially the production of direct photons). Our calculation reinforces the case for antiproton-proton storage rings.

I. INTRODUCTION AND SUMMARY OF RESULTS

Theoretical developments in the unification of weak and electromagnetic interactions have reinforced our belief that the observation of the weak bosons will be possible with the next generation of accelerators. It has, therefore, been a much advertised fact that one might be able to probe weak interactions with hadron colliding rings in the multi-TeV energy range. The Weinberg-Salam model[1,2] puts the weak boson ($W^{\pm}$) and its neutral partner (Z) in a mass range energetically accessible with such devices. Moreover, one might be able to observe secondaries with transverse momentum so high that their production cannot be strong or electromagnetic in origin. The quark-parton model has been the theoretical vehicle for predicting[3-8] experimentally accessible cross sections for both manifestations of weak interactions in hadron collisions.

The purpose of this paper is to point out the following:

(i) There is some support for the optimistic projections for W, Z production cross sections from data on the hadronic production of other "heavy" bosons as ρ, ϕ, ψ.

(ii) The obvious (but ignored) fact that not the total yield, but the lepton momentum distribution of the decay $W^{\pm}\to l^{\pm}\nu$ or $Z\to l^{+}l^{-}$ is the experimentally relevant quantity to calculate. Here $l=\mu, e$. Our recent experience with hadroproduction of ψ's might be an omen and has illustrated a situation where a narrow resonance becomes unobservable in the decay-lepton momentum distribution because of the smearing of the lepton momentum distribution by the transverse momentum of the produced resonance as well as the presence of backgrounds. We try to quantitatively evaluate the situation for W and Z production.

(iii) The same quark-model scaling arguments which yield large estimates for the production cross sections of the weak bosons unfortunately predict large backgrounds, especially in the form of leptons from the decay of large-transverse-momentum π's and direct photons. The calculated magnitude of these backgrounds is rather convincingly supported by accelerator data and by cosmic-ray data in the relevant energy range.

Our conclusions are summarized in Figs 4 and 5 and are, as are the calculations, model-dependent. Even though these calculations can at best be regarded as order-of-magnitude estimates, we still can draw some important conclusions from this exercise:

(i) The hope of observing the weak production of hadrons with large transverse momentum will be in vain. This will just be a repeat of our recent CERN ISR experience.

(ii) The heavier Z ($M_Z\simeq 80$ GeV) might be experimentally more accessible than the $W^{\pm}$ ($M_W\simeq 60$ GeV). One might eventually have to resort to the more difficult coincidence experiment, observing both leptons from the $Z\to l^{+}l^{-}$ decay or to a polarization measurement of the decay leptons.

(iii) The signal-to-background calculation makes the case for antiproton-proton storage rings even more compelling. It has been previously argued that one expects increased production cross sections for observing the weak boson.[4,5]

For readers interested in the details of the calculation we have summarized our theoretical biases on the weak boson and its production mechanism in hadron collisions in Sec. II. The calculation of the decay-lepton momentum distribution of the produced weak boson and the backgrounds is presented in Sec. III.

II. THE WEAK BOSON AND ITS SIGNATURES IN HADRON COLLISIONS: THEORETICAL BIASES

We recall that in the now popular Weinberg-Salam model[1,2] one finds

$$M_{W^\pm}=\frac{37.5}{\sin\theta_W}\,, \tag{1}$$

$$M_Z=\frac{M_W}{\cos\theta_W}\,. \tag{2}$$

The Weinberg mixing angle θ_W has been fixed by neutral-current experiments and yields $M_{W^\pm}\simeq 60$ GeV, $M_Z\simeq 80$ GeV. Whatever the value of θ_W,

$$M_{W^\pm}\geqslant 37.5\text{ GeV}\,, \tag{3}$$

and this value puts the weak bosons energetically out of reach of present accelerators but well within the energy range of planned hadron storage rings. The leptonic width of the weak boson is determined by the Fermi coupling constant G, neglecting the lepton mass we obtain

$$\Gamma(W\rightarrow l\nu)=\frac{GM_W^{\,3}}{3\pi\sqrt{2}}\,\frac{1}{2}\,. \tag{4}$$

Making the natural assumption that quarks couple to W as leptons do,

$$\Gamma(W\rightarrow \text{hadrons})=\frac{GM_W^{\,3}}{3\pi\sqrt{2}}\,R(I=1)\,, \tag{5}$$

where $R(I=1)$ is the isovector part of $R=\sigma(e^+e^-\rightarrow\text{hadrons})/\sigma(e^+e^-\rightarrow\mu^+\mu^-)$. Equation (5) follows from Eq. (4) through the conserved-vector-current (CVC) hypothesis. One observes that Eq. (5) follows from Eq. (4) essentially from quark counting. It has been previously pointed out[9] that, for a point-hadronic cross section [i.e., $R(I=1)=1$],

$$\frac{\Gamma(W\rightarrow\mu\nu)+\Gamma(W\rightarrow e\nu)}{\Gamma(W\rightarrow\text{hadrons})}\simeq 1\,. \tag{6}$$

In the naive quark model the decay branching ratios are $\frac{1}{3}$ for $e\nu$, $\mu\nu$, and hadrons, but color and quark flavors will change this prediction [as can be seen from Eq. (5)] and decrease the leptonic branching ratio relative to the hadronic.

In the Drell-Yan quark model[10] the hadronic production of particles is essentially the inverse process of their decay; i.e., the magnitude of the production yield is set by the hadronic width.[6] This indicates that understanding particle production implies a detailed understanding of the production of the various quark flavors building up the hadronic width. Close to threshold u, d quarks dominate the production mechanism, however, and a detailed understanding of the quark structure of hadrons for strange, charmed flavors as well as their production is not necessary.

The calculation presented below is complementary to calculations[3] estimating weak-boson production by extrapolation, based on the CVC hypothesis,[11,12,13] of data on the production of lepton pairs in hadron collisions. These extrapolations are based on an experimentally untested scaling law. We will present as an alternative approach a quark-model calculation of hadroproduction of vector mesons and show that there is marginal, but direct, evidence that the model allows us to correctly estimate the production cross section of "heavy" vector mesons as ρ, ϕ, and ψ in pp interactions.

The diagram of Figs 1(a)–1(c) for threshold excitation of vector mesons of mass M in pp collisions is given by

$$x_0\frac{d\sigma}{dx}=\frac{4\pi^2\alpha_V}{M^2}\,\phi(x_1,x_2)\,, \tag{7}$$

$$x_1=\tfrac{1}{2}(x_0+x)\,,\qquad x_2=\tfrac{1}{2}(x_0-x)\,, \tag{8}$$

$$x_0=(x^2+4M^2/s)^{1/2}\,, \tag{9}$$

where $x=2p_L/\sqrt{s}$ is the usual Feynman variable with p_L the longitudinal momentum of the produced vector meson (p_T has been ignored at this stage),

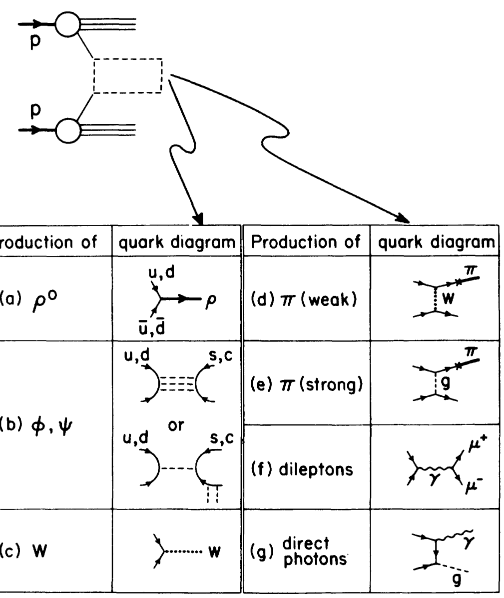

FIG. 1. Quark-model diagrams for the production of vector mesons (a)–(c), the production of high-transverse-momentum secondaries through weak (d) and strong (e) quark interactions, the production of virtual (f) and direct photons (g). Thick solid lines represent hadrons, thin solid lines quarks, dotted lines a weak boson (W), dashed lines the gluon mediating the strong force (g), and finally the wiggly line represents the photon (γ).

α_V is the dimensionless coupling of the vector meson to quarks

$$\alpha_V \equiv \frac{g_{Vq\bar{q}}^{\,2}}{4\pi} = \frac{3\Gamma(V \to \text{hadrons})}{M}. \quad (10)$$

Finally,

$$\phi(x_1, x_2) = \sum_{i,j} [x_1 x_2 u_i(x_1)\bar{u}_j(x_2) + (x_1 \leftrightarrow x_2)], \quad (11)$$

where i, j sum over the different quark and antiquark distributions[14] in the incoming hadrons that couple to the produced vector meson.

Equations (7)–(11) allow us to make an "order-of-magnitude" estimate of the measured production rates of ρ, ϕ, ψ. As strangeness or other quark flavors have not been excited at $M = M_\rho$, Eqs. (7)–(11) should reproduce the magnitude, energy, and x dependence of the process $pp \to \rho^0$ at all energies, with

$$\begin{aligned}\phi(x_1, x_2) &\equiv \phi_{\text{th}}(x_1, x_2) \\ &= \tfrac{1}{2} x_1 x_2 [u_V(x_1) + d_V(x_1) + 2s(x_1)]\, s(x_2) \\ &\quad + (x_1 \leftrightarrow x_2). \end{aligned} \quad (12)$$

Substituting the ρ mass and width into Eqs. (7)–(12) we correctly calculate a 3-mb yield at $p_{\text{lab}} = 24$ GeV. The increased production rate as well as x dependence at Serpukhov and Fermilab energies ($p_{\text{lab}} = 40$–400 GeV/c) can be quantitatively understood. The same function $\phi_{\text{th}}(x_1, x_2)$ of Eq. (12) allows us to roughly estimate ϕ, ψ production for $\sqrt{s}/M_{\phi,\psi}$ not too large. The coupling α_V in Eq. (10) is determined by their Zweig-rule-violating width [see Fig. 1(b)]. We underestimate ψ (ϕ) production by a factor of 3 (15), respectively.[15] The source of this discrepancy is dual and due to some contribution from fusion of charmed- (strange-) quark pairs and the fact that quark-gluon diagrams contribute to the production that do not contribute to the width [see Fig. 1(b)].

This is the extent to which one can actually justify the use of the Drell-Yan model for hadronic production. In the model $\sigma(pp \to MX) \propto M^{-2}$; we caution the reader that for experimentally observed particle production rates $\sigma(pp \to MX) \propto \exp(-4M)$ instead.[16] As the quark model unifies M and p_T dependence of particle production, the real basis for predicting measurable W, Z cross sections is that the mass dependence will change from an exponential to a power-law regime with increasing mass, as it does for increasing p_T.

The previous calculations give us some confidence in applying the above model to the production of the weak boson. Indeed multi-TeV colliding rings excite the weak boson close to threshold (typically $\sqrt{s}/M_W \simeq 4$). For example, for the process $pp \to ZX$ we calculate, using Eqs. (5), (7), (10), (12),

$$x_0 \frac{d\sigma}{dx}(pp \to ZX) = \frac{4\pi^2}{M_W^{\,2}} \left[3\, \frac{\Gamma(W \to u, d \text{ quarks})}{M_W}\right] \times \phi_{\text{th}}(x_1, x_2) \quad (13)$$

$$= 2\sqrt{2}\,\pi G R(I=1)\phi_{\text{th}}(x_1, x_2). \quad (14)$$

Using the appropriate quark-antiquark diagrams we can in a similar fashion calculate the process $pp \to W^\pm X$ and $\bar{p}p \to ZX$, which we will discuss further on. The total yield, obtained by integrating Eq. (13) over x, roughly agrees with previous estimates.[3,4,5] We illustrate the results in Fig. 2(a), where we have chosen $R = \frac{2}{3}$, $M_W^{\,\pm}$ at its minimum value [Eq. (3)], and $M_Z = 80$ GeV. The R value of $\frac{2}{3}$ is motivated by the fact that only u, d flavors determine the production rate near threshold. Note that the production rate is not affected by color. As is well known, the magnitude of ϕ_{th} is reduced by a factor of 3 by the inclusion of color degrees of freedom; however, the coupling constant is enhanced by the same factor through an increase of $\Gamma(W \to u, d \text{ quarks})$ or $R(I=1)$ in Eqs. (13) and (14).

As mentioned in the introduction, one can in principle also indirectly observe W, Z through the observation of secondaries in hadron collisions with transverse momenta large enough that their origin cannot be explained by strong or electromagnetic interactions of quarks. In the standard[10,17] parton model W, Z exchange [see Fig. 1(d)] is the leading diagram populating the high-p_T region with hadrons produced by weak interactions. The resulting cross section at $\sqrt{s} = 4M_Z$ and at $\theta = 90°$ in the center of mass is shown in Fig. 2(b).

III. DECAY-LEPTON MOMENTUM DISTRIBUTIONS AND BACKGROUNDS

The actual experimental signature of the weak bosons would be a peak in the momentum distribution of the decay lepton in the process

$$pp \to W^\pm X, \quad W^\pm \to l^\pm \nu, \quad (15)$$

$$pp \to ZX, \quad Z \to l^+ l^-. \quad (16)$$

As $\Gamma_{W,Z} \ll M_{W,Z}$ [from Eq. (5) we estimate a width of order 1 GeV] we naively expect a very sharp peak in the lepton momentum distribution at lepton momentum $p = \frac{1}{2}M_{W,Z}$. However, the parent W is not always produced at rest, and the momentum it is produced with in the original interaction will smear out the peak in the lepton momentum distribution. A typical search will measure the

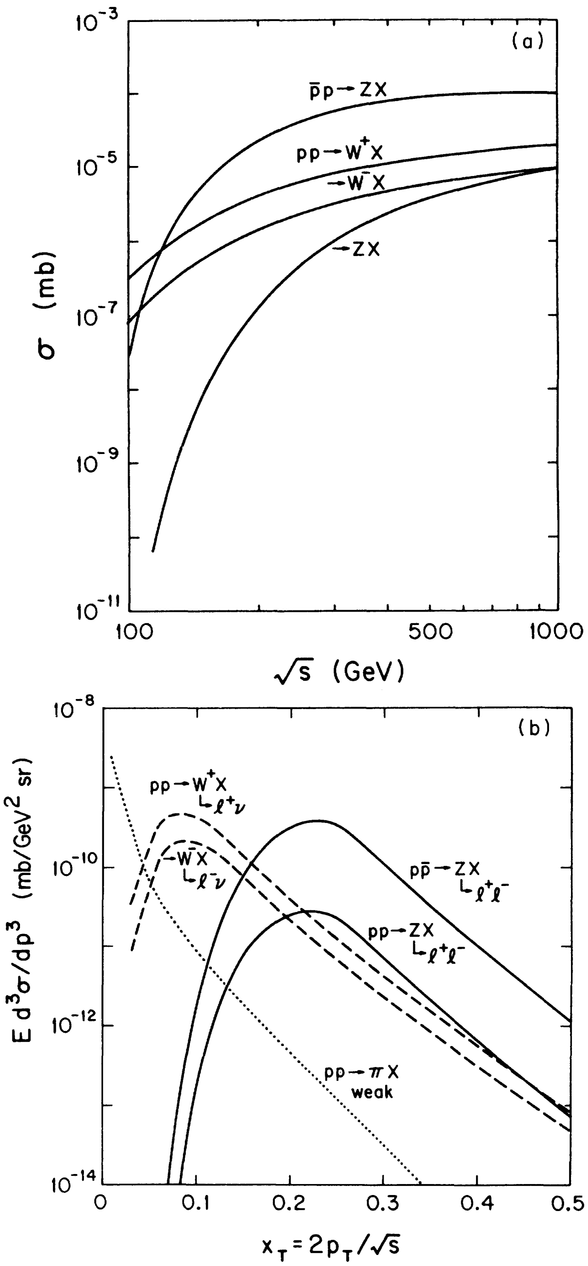

FIG. 2. (a) Calculated total production cross sections are plotted as a function of incident center-of-mass energy ($\sqrt{s}$) for producing $W^{\pm}$ ($M_W = 37.5$ GeV) in pp interactions and Z ($M_Z = 80$ GeV) in pp and $\bar{p}p$ interactions. (b) Transverse-momentum distribution $x_T = 2p_T/\sqrt{s}$ at $\theta = 90°$ in the center of mass of (i) π mesons produced by weak interactions in pp interactions [see Fig. 1(d)] of center-of-mass energy $\sqrt{s} = 320$ GeV (dotted line), (ii) decay leptons from production and subsequent decay of W in pp interactions for a leptonic branching ratio of 0.25 ($\sqrt{s} = 320$ GeV) (dashed line), (iii) decay leptons from production and subsequent decay of Z in pp and $\bar{p}p$ interactions for a leptonic branching ratio of 0.25 ($\sqrt{s} = 4M_Z = 320$ GeV) (solid line). The inclusive cross sections are given in mb/(GeV^2 sr).

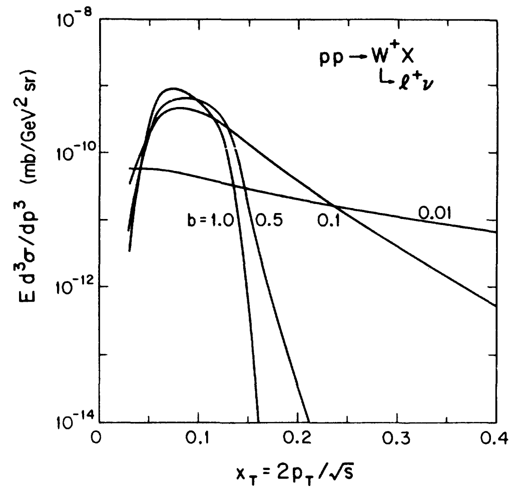

FIG. 3. The dependence of the transverse-momentum distribution of the decay lepton l^+ on the average transverse momentum $\langle p_T^W \rangle$ of the produced W^+ is illustrated, for $b = 2/\langle p_T^W \rangle = 1$, 0.5, 0.1, 0.01. The inclusive cross section is given in mb/(GeV^2 sr) ($\theta = 90°$, $\sqrt{s} = 320$ GeV). Similar trends are observed for the other processes in Fig. 2(b).

transverse-momentum distribution p_T of the final lepton in reactions (15) and (16) at fixed angle (for definiteness we take $\theta = 90°$). We calculate the experimental signature of the weak bosons from the following assumptions:

(i) Mass, total production yield are taken from Sec. II.

(ii) The longitudinal-momentum distribution of W, Z production is calculated from the parton model [Eq. (7.11)].

(iii) The transverse-momentum distribution of the produced W, Z is assumed to be of the form[18]

$$\frac{dN}{d^2 p_T} \propto \exp(-2p_T^W/\langle p_T^W \rangle) . \tag{17}$$

(iv) Finally, we assume

$$\Gamma(W, Z \to \mu, e + X)/(W, Z \to \text{all}) = \tfrac{1}{4} , \tag{18}$$

in accordance with Eq. (6). We will reevaluate this crucial assumption at the end of this section.

The calculations are straightforward; results are shown in Figs. 2(b), 3, 4, and 5. Figure 3 illustrates how the shape of the signature is sensitive to $\langle p_T^W \rangle$ or $b = 2/\langle p_T^W \rangle$. Also, the peak value of the signal is reduced by increasing $\langle p_T^W \rangle$ and increasing M_W. Our recent experience with ψ physics has dramatically confirmed earlier observations in $\pi, K, \bar{p}$ inclusive measurements that the average transverse momentum increases with produced mass. For example,

$$\frac{dN}{dp_T^2} (pp \to \psi x) \propto \exp(-2p_T) , \tag{19}$$

i.e.,

$$\langle p_T^{\psi}\rangle \simeq 1\ \text{GeV} \simeq \tfrac{1}{3} M_{\psi}. \qquad (20)$$

One could take Eq. (20) as an *ad hoc* guide to estimate

$$\langle p_T^{W}\rangle \simeq \tfrac{1}{3} M_{W,Z} \text{ or } b \simeq 0.1. \qquad (21)$$

An alternative argument supports this result. Recent data on ψ production support scaling of production cross section in transverse mass[16]

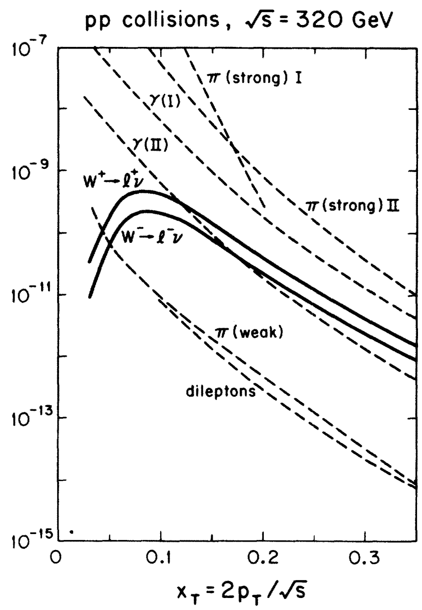

FIG. 4. The transverse-momentum distribution of leptons from production and subsequent decay of charged W's (solid lines) in pp interactions is compared to the inclusive production of various sources of background leptons (dashed lines).

π(strong) I: large-transverse-momentum π mesons from strong interactions, as calculated from an extrapolation of the Fermilab and ISR data (Ref. 19),

π(strong) II: large-transverse-momentum π mesons from strong interactions calculated in the quark-gluon model [diagram of Fig. 1(e)],

γ(I): directly produced photons calculated in the quark-gluon model [diagram of Fig. 1(g)] and normalized to the data of Ref. 22,

γ(II): directly produced photons calculated in the quark-gluon model [diagram of Fig. 1(g)],

π(weak): large-transverse-momentum π mesons from weak interactions [dominated by the diagram of Fig. 1(d)],

dileptons: lepton pairs from virtual photons [diagram of Fig. 1(f)].

The inclusive cross section is claculated in mb/(GeV^2 sr) ($\theta = 90°$, $\sqrt{s} = 320$ GeV), $b = 2/\langle p_T^W\rangle$ has been taken to be 0.1, and the leptonic branching ratio has been fixed at 0.25. Note that the existence of (already known as well as presently unobserved higher-mass) quark flavors will reduce the leptonic branching ratio and therefore the weak-boson signal.

$$\frac{dN}{dp_T^{\,2}} \propto \exp[-6(M^2 + p_T^{\,2})^{1/2}], \qquad (22)$$

$$\propto \exp[-(3/M)p_T^{\,2}] \text{ for } p_T \ll M. \qquad (23)$$

Again a very flat p_T dependence ($b = 3/M \approx 0.05$) is predicted.

The above arguments illustrate that, owing to the high mass of the W, no sharp peaking of the lepton transverse momentum should be expected; one can conceive a situation where the signal almost disappears (see Fig. 3). One could get a better experimental handle on the crucial parameter $\langle p_T^W\rangle$ by measuring b in hadroproduction of dileptons as a function of the invariant mass of the pair.

The above discussion puts the estimate of backgrounds crucially into focus. We evaluate in the context of the quark-gluon model sources of high-p_T leptons: high-p_T π mesons, direct photons, and dileptons. The corresponding diagrams are shown in Figs. 1(d)–1(g). Their evaluation is standard.[10] We have plotted the momentum dependence of the various sources of background together with the W and Z signal in Figs. 4 and 5, respectively. The major sources of background according to our calculation are π's and direct photons. We will justify their estimate below.

Optimism for large weak-boson cross sections despite their high mass is rooted in the scaling property of parton models that

$$\frac{d\sigma}{dM^2} \propto \frac{1}{M^4}. \qquad (24)$$

In the thermodynamic model this dependence would be exponential and W's would be unobserva-

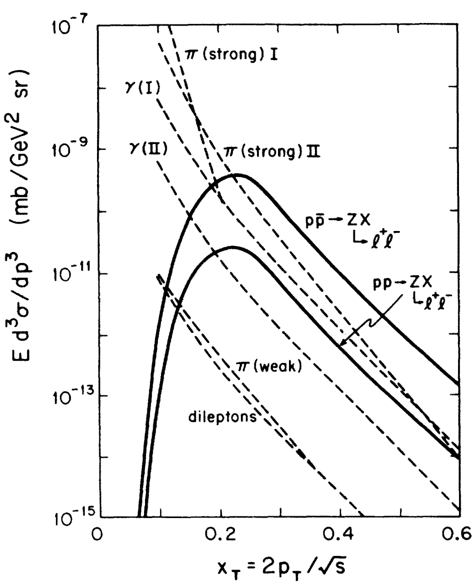

FIG. 5. Same as Fig. 4 for Z production in pp and $\bar{p}p$ collisions.

ble in hadron collisions. However, the same scaling arguments predict

$$\frac{d\sigma}{dp_T^2} \propto \frac{1}{p_T^4}, \tag{25}$$

a scaling law known to predict a large cross section for high-p_T hadrons at TeV energies.[19] An extrapolation[19] of Fermilab and ISR data based on the scaling law of Eq. (25) is shown in Figs. 4 and 5 as π(I). It agrees in magnitude with the quark-gluon-model estimate, labeled π(II). We have fixed the quark-gluon coupling constant at the canonical value[20] $\alpha_g = 0.25$. The cross sections are substantially above more popular p_T^{-8}-type extrapolations of accelerator data. Recently cosmic-ray exposures of emulsion chambers have observed a few very clean high-p_T events in the energy region under consideration. The mere observation of these events, despite the very low values of the cosmic-ray flux, supports the larger π yields we estimated.[16] Moreover, air-shower analysis has recently provided some direct support for the onset of the dimensional-scaling law of Eq. (25) at energies above present accelerators.[21] Let us turn to the direct-photon background next.

In the quark-gluon model direct photons are produced at the level $\alpha\alpha_g$ (not α^2) [see Fig. 1(g)], and their rate is therefore predicted to be large. The calculation, labeled γ(II) in Figs. 4,5, nevertheless underestimates the observed yield[22,23] at the ISR by a factor of 10. If we arbitrarily increase the normalization in order to achieve agreement with the data of Refs. 22,23 we obtain the resulting cross section labeled γ(I).

One has to draw conclusions from Figs. 4 and 5 with some caution. The existence of color, strangeness, and charm flavors and possible (not yet discovered) higher-mass quark flavors will substantially decrease the leptonic branching ratio (assumed to be 0.25) of W, Z and therefore reduce the signal in Figs. 4 and 5. We can easily imagine situations where direct photons and hadronic π mesons exceed the $W^{\pm}$ peak by well over 2 and 4 orders of magnitude, respectively.

The ultimate severity of these backgrounds depends, of course, on the trigger as well as the type and design of the detector. The π-meson background would be severe if one triggers on hadronic decay modes of the W or Z. It is clear from Figs. 4 and 5 that it makes π mesons, weak in origin, unobservable. In a single-lepton experiment one can presumably absorb the π mesons. One can suppress μ's from π decay by typically 10^{-4} using the technique of varying the amount of absorber and extrapolating to infinite absorber. The expected background is shown in Fig. 6 and has been compared to the signal for production and decay of $W^+ \to \mu^+\nu$. According to our calculation the most severe background in a lepton search would, however, not be π decay, but the internal conversion of direct photons. Indeed, as we stated the γ cross section could well exceed the $W^{\pm}$ cross section by two orders of magnitude. Internal conversion will yield leptons with $l^{\pm}/\gamma$ of order α, thus competing with the signal. We discuss this important background in more detail and broaden the scope of the discussion beyond the parton model of Ref. 10 and try to make the calculation as model-independent as possible.

Scaling arguments suggest the following expression for the relative yield of photons and mesons at a fixed angle in the center of mass (taken to be 90° as before):

$$\frac{E\, d^3\sigma/dp^3(pp\to\gamma x)}{E\, d^3\sigma/dp^3(pp\to\pi x)} \equiv \frac{\gamma}{\pi} = a\, s^k \left(\frac{p_T}{\sqrt{s}}\right)^l . \tag{26}$$

Dimensional counting[24] requires $k=1$. The internal conversion of the photons produced according to Eq. (26) yield a direct-lepton cross section given by

$$\frac{E\, d^3\sigma/dp^3(pp\to lx)}{E\, d^3\sigma/dp^3(pp\to\pi x)} \equiv \frac{l}{\pi} \simeq \frac{\alpha}{2\pi(n-k-l)}\, a\, p_T^{\,l} (\sqrt{s})^{2k-l} \ln\left(\frac{p_T}{2m_l}\right)^2 . \tag{27}$$

Here n stands for the typical power fall off associated with the high-p_T π-meson inclusive cross section ($n = 4-8$).

The ISR data[22,23] ($\sqrt{s} \simeq 50$ GeV) measures $\gamma/\pi \simeq 0.2$ at two different values p_T. This can be accommodated by Eq. (26) with $l=0$

$$\gamma/\pi = as \simeq 0.2 \tag{28}$$

or

$$a = 10^{-4} - 10^{-5} . \tag{29}$$

Within the same approximations, we obtain via Eq. (27) a μ/π ratio

$$\mu/\pi = (5\times 10^{-5}) - (5\times 10^{-4}) , \tag{30}$$

only weakly dependent on p_T. This is in agreement with direct-lepton measurements. Varying l to a value around 1–1.5 one can actually achieve a detailed fit to the direct electron and muon yields.[25] We computed the e, μ cross section from internal conversion of photons via Eq. (27), normalizing the photon yield according to Eqs. (28) and (30). The result is shown in Fig. 6 for comparison with the lepton signal from production and decay of $W^+ \to l^+\nu$. The dashed area represents our ignorance

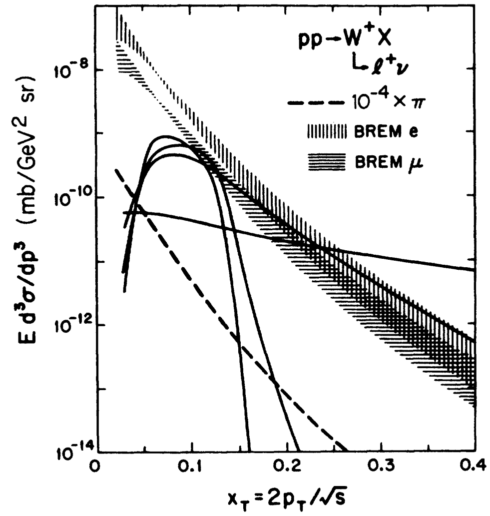

FIG. 6. The lepton transverse-momentum distribution for production and decay of $W^+ \to l^+ \nu$ from Fig. 3 is compared to 10^{-4} $E d^3\sigma/dp^3(pp \to \pi x)$ (dashed line), as well as the lepton yield from internal conversion of direct photons, calculated according to Eqs. (26) and (27). The vertically and horizontally dashed areas represent, respectively, the e and μ inclusive cross sections in mb/(GeV^2 sr) ($\theta = 90°$, $\sqrt{s} = 320$ GeV). The dashed area represents the uncertainty in l in Eq. (26).

on the value of l in Eq. (26) ($0 \le l \le 1$). As expected from a bremsstrahlung process electrons are more abundant than μ mesons. Note that the very large background cross section results directly from the experimental observations [Eqs. (28) and (30)] and dimensional counting, requiring $k = 1$ in Eq. (26). The validity of this particular prediction of the dimensional-counting rules has in fact been checked experimentally in the case of exclusive reactions. It has indeed been observed that

$$\frac{d\sigma/d\Omega\,(\gamma p \to \pi p)}{d\sigma/d\Omega\,(\pi p \to \pi p)} \propto s\,, \tag{8}$$

or $d\sigma/d\Omega(\gamma p \to \pi p) \propto s^{-7}$ at $\theta_{\rm c.m.} = 90°$.[26]

These trends of the e, μ cross sections from photon decay are similar to the ones obtained from the diagram of Fig. 1(g), although, as pointed out previously, the photon cross section is smaller and has to be artificially increased to accommodate Eqs. (28) and (30).

The signal-to-background problem is significantly reduced for observing the heavier Z, especially if one considers a $\bar{p}p$ initial state, as can be seen in Fig. 5. Whereas the Z signal is significantly increased, the major π, γ backgrounds are expected to be roughly equal in magnitude in the pp and $\bar{p}p$ cases. However, we repeat our warning that we almost certainly overestimated the leptonic branching ratio.

The above estimates, although crude, give us the distinct impression that circumstances can conspire to make the most simple experiments (single leptons, hadrons) unfeasible. The eventual way out would be to resort to the more difficult experiments measuring the decay-lepton polarization or measuring one lepton in coincidence with the missing neutrino energy (for $W^\pm$) or in coincidence with an oppositely charged lepton (for Z).

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$$u_v = 1.79x^{-1/2}(1-x)^3(1+2.3x),$$
$$d_v = 1.108x^{-1/2}(1-x)^{3.1},$$
$$s = \tfrac{1}{4}x^{-1}(1-x)^7.$$

[15]This led the authors of Ref. 6 to suggest that the total, not the Zweig-rule-violating, hadronic width sets the scale for the production rate of vector mesons. They calculated, on this basis, Z production cross sections larger than our estimates.

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[18]We do not think that there is a real theoretical basis for putting the transverse-momentum dependence directly in the quark distributions. However, results are similar to the ones we report in this paper.

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