Signals for composite-$W^\pm$ production in γp collisions

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We examine the possibility of observing the composite structure of $W^\pm$ bosons photoproduced in γp collisions at high energies through form-factor effects. We find that such processes are sensitive to $W^\pm$ compositeness scales as high as 3–5 TeV if sufficiently high luminosities are obtainable. Such reactions can be most easily studied by extracting a photon beam of energy $\simeq 10$ TeV from the Superconducting Super Collider (SSC) for collisions with a fixed target. This serves to indicate that new physical results are obtainable from the SSC even when used in a fixed-target mode.

The possibility that gauge bosons are composite particles has been a subject of a great deal of discussion in recent literature.[1] At present, the limits on the compositeness scale associated with gauge bosons is far inferior to that for quarks and leptons.[2] Hence, we must examine possible ways to improve this limit or to uncover the composite structure within $W^\pm$ and/or Z^0.

There are several possible "signals" for gauge-boson compositeness which have been explored in the literature. The first is a deviation in the gauge-boson magnetic moment and/or electric quadrupole moment from their canonical gauge-theory values which has been considered by many authors.[3] A second "signal" would be a modification of the tensor structure of the γWW and ZWW vertices as, for example, in W-dominance theories.[4] These two "signals" are not mutually exclusive. An alternative possibility is to consider the effect of form factors on the γWW and ZWW vertices as well as gauge-boson propagators; this possibility has already been discussed by the present author[2] for a wide variety of physical processes. In all of these processes, however, the bound on the gauge-boson compositeness scale was never greater than $\Lambda \simeq 0.5-1.0$ TeV. There has also been recent interest in using the Superconducting Super Collider (SSC) in a fixed-target mode.[5] We wish to explore if the SSC can be used to improve the constraints on the Λ parameter found elsewhere[2] by using the machine in this particular mode. Clearly, in the usual collider mode other reactions exist which could be used to probe large Λ values such as $pp \to W^+W^-$ or $pp \to \gamma W$. Since we are interested in fixed-target physics, we limit ourselves to the γp process. We hope to show in this paper that the $\gamma p \to W^\pm + X$ process can provide significantly improved constraints on the value of Λ or show evidence for compositeness. In order to have a high luminosity for the γp reaction and sufficient center-of-mass energies to produce $W^\pm$'s we need to consider the possibility of extracting a photon beam of energy $\simeq 10$ TeV from the SSC and using the accelerator in a fixed-target mode. This possibility for the SSC has already been discussed,[5] and luminosities of order 10^{39} cm^{-2}/yr should be expected. With such large luminosities and cross sections of order 1 pb we expect to be able to determine total cross sections to the level of a few percent.

As in our previous works[2] we will consider (separately and jointly) form-factor modifications of the usual triple-gauge-boson vertices and gauge-boson propagators:

$$\Gamma_{\mu\nu\lambda} W^{+\mu} W^{-\nu}(A^\lambda, Z^\lambda) \to F_v(\Lambda)\Gamma_{\mu\nu\lambda} W^{+\mu} W^{-\nu}(A^\lambda, Z^\lambda) , \tag{1}$$

$$\left[\frac{-g_{\mu\nu}+k_\mu k_\nu/M^2}{k^2-M^2} \right] \to F_p(\Lambda) \left[\frac{-g_{\mu\nu}+k_\mu k_\nu/M^2}{k^2-M^2} \right] .$$

Given the kinematics of the $\gamma p \to W^\pm + X$ process we will assume both the F's to be of the form

$$F = (1 - t/\Lambda^2)^{-1} , \tag{2}$$

where t is the subprocesses momentum-transfer squared. (Note $-t/\Lambda^2 > 0$.) For detailed discussions of the hypotheses behind this choice the reader should examine the work in Ref. 2.

Let us first consider the subprocess $\gamma q \to W^\pm + q'$ as shown in Fig. 1. The differential cross section for this

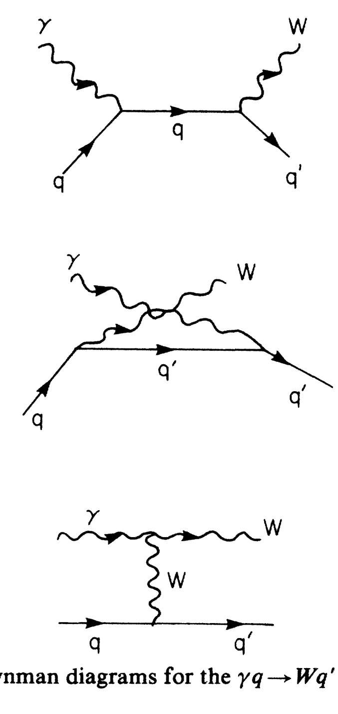

FIG. 1. Feynman diagrams for the $\gamma q \to Wq'$ subprocess.

process can be written in the form[6] ($z=\cos\theta$, where θ is the W^+ production angle)

$$\frac{d\sigma^+}{dz}=\frac{G_F M_W{}^2}{96\sqrt{2}}\alpha\frac{1}{s}\sum_i \int_{x_L}^{1}\frac{dx}{x}H_i(x,s,Q_i,z)\left[1-\frac{M_W{}^2}{s}\right], \tag{3}$$

where $x_L=M_W{}^2/s$ and the sum extends over all fermions of charge Q_i inside the proton and $q_i(x,s)$ are the relevant quark distribution functions. The H_i's are given by (in the limit of massless quarks)

$$H(x,s,Q,z)=T_0+T_1PF(\Lambda)+T_2P^2F^2(\Lambda).$$

With $F(\Lambda)$ given by (2), $P\equiv(M_W{}^2-t)^{-1}$ and[6]

$$\begin{aligned}
T_0&=-16\left[(Q-1)^2 s/u+Q^2u/s+2Q(Q-1)\frac{tM_W{}^2}{us}+\tfrac{1}{2}t/M_W{}^2\right],\\
T_1&=32\left[\frac{Q-1}{u}-\frac{Q}{s}\right](tM_W{}^2-su)\\
&\quad+16\{2s(s+t)/M_W{}^2+[t-(s+t)^2/M_W{}^2]\}\\
&\quad-2\left[\left[\frac{s}{M_W}\right]^2+2s\left[1+\frac{t}{M_W{}^2}\right]\right],\\
T_2&=-8[2s^2-4tM_W{}^2-2s^2(1+t/M_W{}^2)\\
&\quad+4su+(s^2+u^2)t/M_W{}^2]\\
&\quad+2[(s/M_W)^2+2s(1+t/M_W{}^2)]\,.
\end{aligned} \tag{4}$$

In the laboratory frame we find ($s=sx$, and M_p is the proton mass)

$$\begin{aligned}
&t=M_W{}^2-2E_\gamma(E_W-P_Wz)\,,\\
&E_W=\frac{s+M_W{}^2}{2\sqrt{s}},\quad P_W=\frac{s-M_W{}^2}{2\sqrt{s}}\,,\\
&s=2M_pE_\gamma\,,\\
&u=M_W{}^2-s-t\,.
\end{aligned} \tag{5}$$

Note we have set the W anomalous magnetic moment equal to unity, its standard-model value in these equations. As in Ref. 7 for W^+ photoproduction off on antiquarks we let $Q\to -Q$ in Eq. (4); the same change of sign also gives the W^- photoproduction cross section off quarks.

Now if only vertices (propagators) of gauge bosons obtain form factors then F is simply $F_{v(p)}$ while if both vertices *and* propagators are modified $F=F_vF_p$. This case is denoted by F^2 on the figures that follow. Note $F=F_v$ and $F=F_p$ are indistinguishable if one studies only this particular processes; this case will simply be denoted as F. We denote the $W^{\pm}$ production cross section by $d\sigma^{\pm}/dz$. The quark and antiquark distribution functions used in this paper are the same as set 1 of Eichten, Hinchliffe, Lane, and Quigg.[7] We take $E_\gamma=10$ TeV in our calculations.

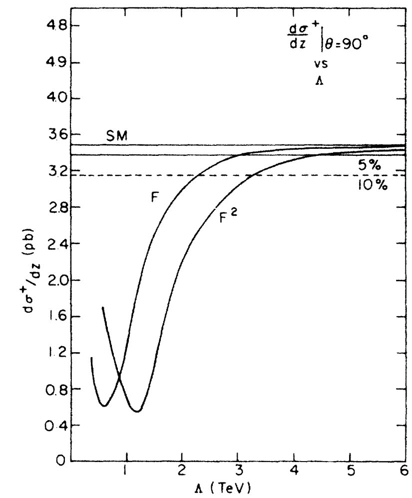

FIG. 2. The W^+ photoproduction differential cross section $d\sigma^+/dz$ at 90° as a function of Λ in γp collisions. Both F and F^2 cases are shown.

Figure 2 shows a plot of $d\sigma^+/dz$ with $z=0$ ($\cos\theta=90°$) as a function of Λ for both F and F^2 cases. Note that for $\Lambda \lesssim 1-2$ TeV the cross section differs drastically from the standard-model (SM) prediction. With a total cross section of $\simeq 7$ pb and a luminosity of 10^{39} cm^{-2}/yr we would expect $\simeq$7000 W^+ events/yr. A 5% measurement of the total cross section in agreement with the SM should clearly indicate that $\Lambda \geq 3.0$ (4.5) TeV for the case F (F^2) which is a significant improvement over the previous limits. The major difficulty here is that one can probably not calculate the absolute total W^+ photoproduction cross section to the accuracy that is required because of strong-interaction corrections. This includes not only conventional radiative corrections at the parton level but the problem of evolving the proton distri-

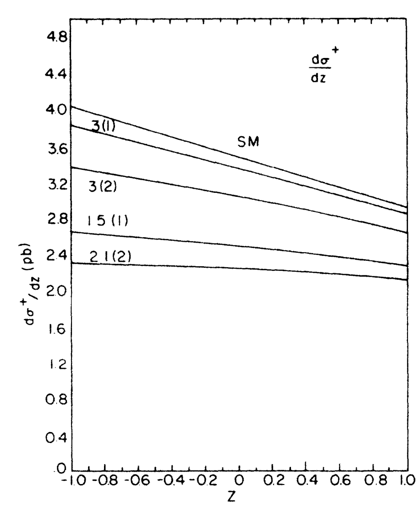

FIG. 3. The W^+ photoproduction differential cross section $d\sigma^+/dz$ in γp collisions as a function of $z=\cos\theta$ for different values of Λ.

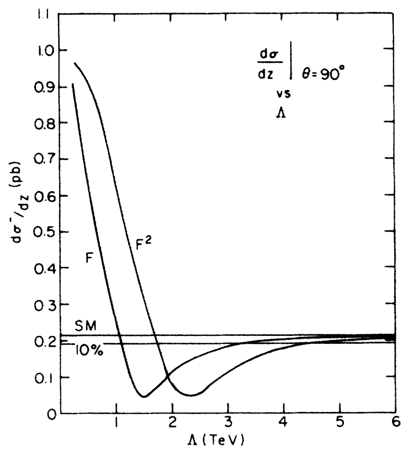

FIG. 4. Same as Fig. 2 but for W^- photoproduction in γp collisions.

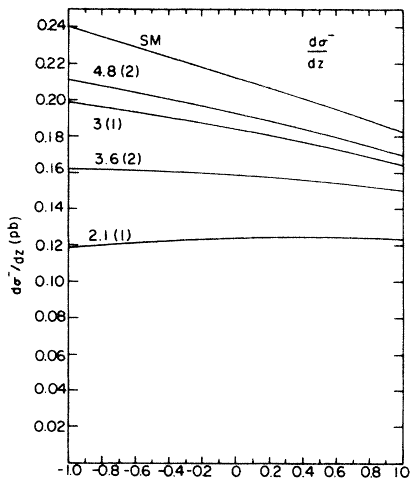

FIG. 5. Same as Fig. 3 but for W^- photoproduction in γp collisions.

bution functions up to such large energies with such high accuracy.

Figure 3 shows $d\sigma^+/dz$ vs z for the SM as well as for several values of Λ for both F and F^2 cases. The shape of the angular distributions for the SM and $\Lambda=3$ TeV (case F) are almost indistinguishable except for overall normalization so that no new information can be obtained in this way for values of $\Lambda \gtrsim 3$ TeV. Also, to obtain a good measurement of the angular distribution would require a much larger event sample than to measure the total cross section to the same accuracy (by at least a factor of 10 or so). With a sample of $\simeq$7000 events the angular distribution will not be sufficiently well determined to distinguish between $\Lambda \simeq 3$ TeV and the SM.

A similar result occurs for W^- production except the situation is a bit worse. Although the differential cross section is more sensitive to $F \neq 1$ than in the W^+ production case the total cross section is smaller by roughly an order of magnitude and so fewer events can be obtained. Note that although the W^+ and W^- photoproduction cross sections are quite comparable at higher energies ($\sqrt{s}=250$ GeV or so) for energies not far from threshold (as is the case here with $\sqrt{s} \simeq 137$ GeV) the W^+ cross section is far larger than that for W^-. It would seem unlikely that higher center-of-mass energies could be easily obtainable. Figure 4 shows $d\sigma^-/dz$ with $z=0$ as a function of Λ; clear distinctions from the SM prediction are seen for $\Lambda \lesssim 3$–4 TeV. A 5% measurement clearly would imply $\Lambda \gtrsim 5$–6 TeV which improves on the W^+ results. The difference, however, is that with the above quoted luminosity only $\simeq$500 events/yr are expected so that total cross section or angular distribution could not be as well determined as in the W^+ production case. Figure 5, however, shows that the $d\sigma^-/dz$ angular distribution is more sensitive to finite Λ effects than $d\sigma^+/dz$. This implies that even if one could not compare the data with an absolute prediction for the cross section from theory a comparison of the angular distribution with the SM result may yield a reasonable Λ limit. Clearly, an increase in the luminosity by a factor of order 10 would alleviate this problem but this seems a bit unlikely.[5]

We have shown that the photoproduction of $W^\pm$ gauge bosons in high-energy γp collisions is quite sensitive to form-factor effects, i.e., composite scales as high as 5–6 TeV for the gauge bosons. However, even with reasonably large luminosities the event rates are not quite sufficient to get the desired statistics. Also we need to be able to calculate the theoretical cross sections to the level of a few percent. This is quite difficult when we must run the structure functions obtained at low energy up to such large Q^2 values and be confident of higher-order corrections.

We conclude that the photoproduction of gauge bosons in γp collisions can be a sensitive test of gauge-boson compositeness if very high luminosities are obtainable.

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[1]See, for example, the work of L. Abbott and E. Fahri, Phys. Lett. **101B**, 69 (1981); Nucl. Phys. **B189**, 547 (1982); H. Harari and N. Seiberg, Phys. Lett. **98B**, 269 (1981); H. Fritzsch and G. Mandelbaum, *ibid.* **102B**, 319 (1981); O. W. Greenberg and J. Sucher, *ibid.* **99B**, 339 (1981); R. Barbieri and R. N. Mohapatra, Phys. Rev. D **25**, 2419 (1982); W. Buchmüller, R. D. Peccei, and T. Yanagida, Nucl. Phys. **B231**, 53 (1984); B. Schrempp and F. Schrempp, *ibid.* **B231**, 109 (1984); **B242**, 203 (1984).

[2]T. G. Rizzo, Phys. Rev. D **32**, 43 (1985); J. A. Robinson and T. G. Rizzo, Ames Laboratory Reports Nos. IS-J-1332, 1984 (unpublished) and IS-J-1332 (rev.), 1984 (unpublished).

[3]For recent work and original references see M. Suzuki, Phys. Lett. **153B**, 289 (1985); A. Grau and J. A. Grifols, *ibid.* **154B**,

283 (1985); M. A. Samuel, Phys. Rev. D **31**, 1748 (1985); G. Tupper and M. A. Samuel, *ibid.* **23**, 1933 (1981); K. O. Mikaelian, M. A. Samuel, and D. Sahdev, Phys. Rev. Lett. **43**, 746 (1979).

[4]P. Q. Hung and J. J. Sakurai, Nucl. Phys. **B143**, 81 (1978); J. D. Bjorken, Phys. Rev. D **19**, 335 (1979); H. Fritzsch, R. Kögerler, and D. Schildknecht, Phys. Lett. **114B**, 157 (1982); B. Schrempp and F. Schrempp, DESY Report No. DESY-84-055, 1984 (unpublished); G. J. Gounaris and A. Nicolaidis, Phys. Lett. **148B**, 239 (1984).

[5]See, for example, M. J. Tannenbaum, invited talk given at the SSC Fixed Target Workshop, The Woodlands, Texas, 1984 (unpublished).

[6]K. O. Mikaelian, Phys. Rev. D **17**, 750 (1978).

[7]E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984).