Direct-photon searches as tests for unconventional high-energy electroweak interactions

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The ability of direct-photon searches at the Fermilab Tevatron to probe thresholds for the onset of new physics is explored. It is shown that present experiments are sensitive to thresholds at the parton level of greater than 600 GeV. Moreover, the expected yields of γ+jet and Z+jet are remarkably similar, so that if difficulty is experienced in isolating a signal for direct photons, the detection of direct Z's may serve as a cross-check.

The absence of direct measurements of the photon-nucleon cross section at high energies and conflicting reports about the nature of ultrahigh-energy cosmic-ray showers[1] have led to hypotheses[2–4] about the nature of electromagnetic interactions at center-of-mass energies above those accessible in direct laboratory experiments[5] or via inelastic scattering of cosmic-ray muons.[6] Moreover, speculations have continued over the years about the possibility of new thresholds associated with a qualitative change in our understanding of the color degree of freedom.[7] In this Brief Report we explore the degree to which $\bar{p}p$ production of direct photons and Z bosons at present Fermilab Tevatron energies and luminosities can check for the existence of new thresholds at the parton level. Such thresholds may or may not be related to the hypothesized behavior of photon-nucleon cross sections,[2–4] but are clearly interesting in their own right.

Consider the process of two-jet production by hadronic collisions at high energies (for example, the CERN collider, with $\sqrt{s}=0.63$ TeV, or the Fermilab Tevatron, with $\sqrt{s}=1.8$ TeV). Let us assume that a qualitative change in processes at the parton level occurs when the parton-parton center-of-mass energy exceeds a certain value E_0. Then one might expect hard collisions to result in a modification, for example, of the rate for direct photon production. At the very most, one might expect this cross section above the putative threshold to approach a substantial fraction of the two-jet cross section. The fact that this is not seen at the CERN collider[8] places a lower bound on E_0 which we can regard as twice the highest transverse momentum observed in the UA1 and UA2 inclusive jet spectra, or several hundred GeV. The bounds set by CERN data on more modest modifications of the direct-photon cross section are correspondingly lower, with QCD predictions verified up to photon transverse momenta of the order of 100 GeV/c.

We show in Fig. 1 cross sections calculated within the framework of standard QCD and electroweak theory for $\bar{p}p\to$jet+jet, γ+jet, and Z+jet at $\sqrt{s}=1.8$ TeV. The Monte Carlo program PAPAGENO (Ref. 9) is used. All transverse momenta are required to be at least a certain value $p_T^{\min}$. The structure functions (set I) of Ref. 10 are employed. In order to simulate the effect of a threshold, one simply demands that the total parton-parton center-of-mass energy exceed a certain value E_0. The E_0 cut is, of course, ineffective once we have $p_T^{\min}\geq E_0/2$. It is amusing that if the threshold is really a step function at an energy E_0, our numerical results show a Jacobian peak in the differential p_T spectra for γ+jet and Z+jet, corresponding to $p_T\approx E_0/2$.

The jet-jet cross section is detectable in present Tevatron experiments ($\sqrt{s}=1.8$ TeV, integrated luminosity of at least 5 pb^{-1}) for $p_T^{\min}$ up to several hundred GeV/c.

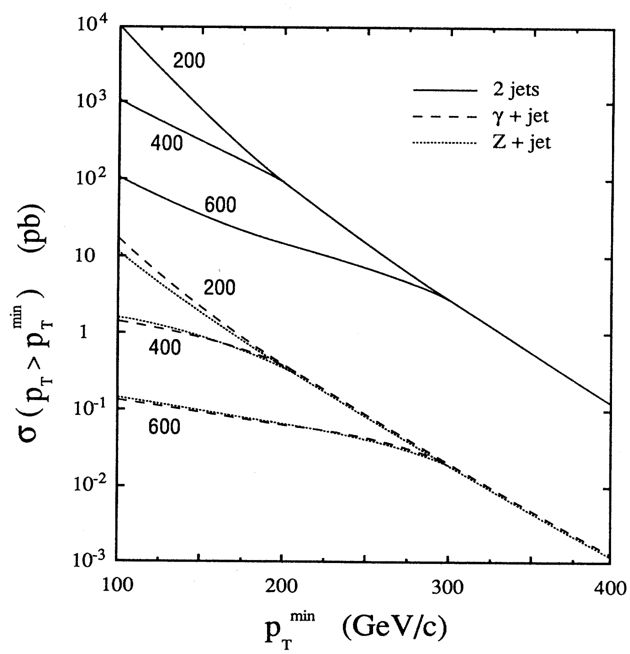

FIG. 1. Integral cross sections (in pb) calculated within the framework of the standard QCD and electroweak theory for $\bar{p}p\to$jet+jet (solid lines), γ+jet (dashed lines), and Z+jet, (dotted lines) at $\sqrt{s}=1.8$ TeV. The parton-parton center-of-mass energy is required to be E_0 or greater and the transverse momentum of each jet is required to be $p_T^{\min}$ or greater. Curves are labeled by values of E_0, in GeV. An estimate for high-p_T photon production via a new process with threshold E_0 may be obtained by multiplying the corresponding γ+jet or Z+jet cross section by a suitable enhancement factor.

For these values of $p_T^{\min}$, the γ+jet and Z+jet cross sections are nearly identical, and about a factor of 100 below the jet-jet ones. (The similarity of γ+jet and Z+jet cross sections appears to be an accident; the photon couples more strongly to u quarks, while the Z couples more strongly to d quarks.)

If parton-parton interactions lead to an enhanced production of photons above a threshold c.m. energy E_0, one can simply multiply the results of Fig. 1 for $\sigma(\gamma+\text{jet})$ by the appropriate enhancement factor to obtain a rough estimate for the photon yield at a given minimum transverse momentum. As an example, lowest-order QCD predicts the cross section for production of direct photons with transverse momenta above 200 GeV/c to be about 0.4 pb at the Tevatron. Now suppose the enhancement factor is $1/\alpha \approx 100$ for $E_0 = 400$ GeV, corresponding to roughly the maximum enhancement that would not have been noticed directly in the jet-jet cross section itself. Then the enhanced cross section would be about 40 pb. This should be observable in present data, both as a direct signal and as a possible enhancement of the whole jet-jet cross section (which, for $p_T^{\min} = 200$ GeV/c, is expected to be about 100 pb). A similar discussion applies if the Z cross section is enhanced.

From Fig. 1 one sees that an enhancement of the direct-photon yield by the factor of 100 just discussed would be detectable in the present round of Tevatron experiments up to a threshold energy of $E_0 \approx 600$ GeV. The enhancement would be most noticeable for direct photons with transverse momentum approximately $E_0/2$. We propose that one way for experimentalists to present results of direct-photon searches would be in terms of the allowed enhancement factor (relative to QCD predictions) as a function of the assumed parton-parton center-of-mass threshold energy E_0.

What else might one observe as a result of a threshold for such new physics?

(1) At energies of several hundred GeV, photons are quanta not much different from W and Z gauge bosons. Then one might expect copious production of high-transverse-momentum Z and W as well. The efficiency for observing them will be reduced by their branching ratios to identifiable states (e.g., about 3.5% for $Z \to e^+e^-$, assuming $m_t \geq m_Z/2$.) However, aside from problems of rates, the identification of direct Z at high transverse moment may be easier than that of direct photons, which are hard to distinguish instrumentally from neutral pions. (One expects under fairly general circumstances, however, that the inclusive neutral-pion rate will be close to the average of the charged-pion rates, so some estimate of the expected π^0 background is possible.)

(2) If single-photon production is enhanced to become some tens of percent of the two-jet cross section in some kinematic regime, one might expect to see double-photon production as well, and perhaps even production of pairs involving the other electroweak bosons.

(3) The overall jet-jet cross section could be augmented at high transverse momentum by an appreciable amount. By comparing the results for jet-jet, photon+jet, and Z+jet cross sections in Fig. 1, one sees that there is still room for an enhancement of the latter two cross sections by a factor of 100, but not much more, before the total inclusive jet yield is affected substantially at or above $p_T^{\min} = 200$ GeV/c.

(4) The photon, if the nature of its interactions changes above the threshold for new physics, no longer need behave as a single particle, but might fragment in the same manner as a gluon or quark emitted in more conventional low-transverse-momentum processes. One might thus expect to pay a penalty for this fragmentation in estimating yields of isolated photons at high p_T, so the factor of 100 mentioned above could be an overestimate, even if the coupling is so dramatically enhanced. The existence of such genuine photon *jets* at high transverse momenta would lead to a different distribution in the fraction of hadronic and electromagnetic energy detected in calorimeters from that at lower p_T.

(5) An increase in the photon-nucleon total cross section at center-of-mass energies of several hundred GeV, to a substantial fraction of the hadronic cross section, has been proposed in connection with certain cosmic-ray events.[2-4] What could be the relation between this and the pointlike mechanism discussed here? As is familiar from the case of QCD, the relation between the soft, long-distance aspects of a theory, such as total cross sections, and its short-distance, perturbative representation can be highly nontrivial. In the present hypothesis, we are faced with the problem of combining a presumed threshold at high mass or energy with an increase in the total cross section for photons. Here it must be conceded the most natural kinds of speculations, involving new particles or thresholds at high mass, although they might lead to new stronger interactions at short distances, do not necessarily give a substantial increase in the total cross section. On the other hand, since photon-proton partial waves are saturated only to order e there is certainly no violation of unitarity or any other fundamental principle involved in such a hypothesis. For example, one need only imagine some new nuclear-interacting heavy particles or constituents with a coupling to the photon of order 1 to realize such a situation. This is certainly rather unconventional, however, and once more underlines the fact that something very unusual is needed if all experimental indications in the cosmic-ray data[1] turn out to be true.

(6) If one wishes to consider new effects which turn on more gradually with increasing energy, these can, of course, be represented by an averaging over the range of the parameter E_0.

To summarize, we have considered the ability of experiments at the Fermilab Tevatron to search for new thresholds involving the production of gauge bosons at parton-parton center-of-mass energies of several hundred GeV. We find that thresholds in excess of 600 GeV can be probed. The anticipated similarity of direct-photon and direct-Z yields provides a useful check of standard-model physics and suggests that searches for high-transverse-momentum Z bosons may provide information relevant to the production of direct photons at high p_T when isolation of photons poses instrumental problems.

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[1]Recent references include B. L. Dingus *et al.*, Phys. Rev. Lett. **61**, 1906 (1988); B. L. Dingus, thesis, University of Maryland, 1988; G. L. Cassiday *et al.*, Phys. Rev. Lett. **62**, 383 (1989), and earlier references therein. For reviews see, e.g., Trevor C. Weekes, Phys. Rep. **160**, 1 (1988); D. E. Nagle, T. K. Gaisser, and R. J. Protheroe, Annu. Rev. Nucl. Part. Sci. **38**, 609 (1988); J. M. Bonnet-Bidaud and G. Chardin, Phys. Rep. **170**, 325 (1988); Trevor C. Weekes, in Proceedings of the 14th Conference on Relativistic Astrophysics, Dallas, Texas, 1988 (World Scientific, Singapore, in press).

[2]W. Ochs and L. Stodolsky, Phys. Rev. D **33**, 1247 (1986).

[3]F. Halzen, K. Hikasa, and T. Stanev, Phys. Rev. D **34**, 2061 (1986); F. Halzen, in *Probing the Standard Model,* proceedings of the 14th Annual SLAC Summer Institute on Particle Physics, Stanford, California, 1986, edited by Eileen C. Brennan (SLAC Report No. 312, Stanford, 1987), p. 607; M. Drees and F. Halzen, Phys. Rev. Lett. **61**, 275 (1988); M. Drees, F. Halzen, and K. Hikasa, Phys. Rev. D. **39**, 1310 (1989).

[4]Leo Stodolsky, this issue, Phys. Rev. D **40**, 1674 (1989).

[5]D. O. Caldwell *et al.*, Phys. Rev. Lett. **40**, 1222 (1978).

[6]V. V. Borog, V. G. Kirillov-Ugryumov, and A. A. Petrukhin, Yad. Fiz. **25**, 85 (1977) [Sov. J. Nucl. Phys. **25**, 46 (1977)]; A. Okada *et al.*, Fortschr. Phys. **32**, 135 (1984).

[7]M. Han and Y. Nambu, Phys. Rev. **139**, B1006 (1965); H. J. Lipkin, Phys. Rev. Lett. **28**, 63 (1971); Nucl. Phys. **B155**, 104 (1979); Jogesh C. Pati and Abdus Salam, Phys. Rev. D **8**, 1240 (1973); **10**, 275 (1974); Murat Ozer and Jogesh C. Pati, Nucl. Phys. **B159**, 293 (1979), and references therein; Stephen L. Adler, Institute for Advanced Study Report No. IASSNS-HEP-89/5 (unpublished).

[8]UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. B **209**, 385 (1988); UA2 Collaboration, R. Ansari *et al.*, Z. Phys. C **41**, 395 (1988).

[9]I. Hinchliffe (private communication).

[10]E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984); **58**, 1065(E) (1986).