Testing Quantum Chromodynamics in the Hadroproduction of Real and Virtual Photons

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We examine tests of quantum chromodynamics in the production of lepton pairs in hadronic collisions. We emphasize the need for detailed experimental studies of the transverse spectra of lepton pairs. As a further test, we calculate the production of real photons at high transverse momentum. γ/π ratios at the 10% level are predicted for $p_T = 4-6$ GeV, with $(pp \to \gamma X) \simeq (pp \to \pi X)$ at $p_T \simeq 10$ GeV.

The observed[1,2] dependence of the average transverse momentum of lepton pairs produced in pp collisions on the mass of the pair has been recently heralded as a success of quantum chromodynamics (QCD).[3-5] In QCD the transverse momentum of virtual photons is basically[6] generated (in lowest order of the quark-gluon coupling constant) through the two-body kinematics of quark-antiquark annihilation into a photon-gluon pair [Fig. 1(b)] or by the Compton scattering of quarks and gluons [Fig. 1(c)]. This has to be contrasted with the leading Drell-Yan diagram of Fig. 1(a) where a quark pair with $p_T = 0$ yields a virtual photon with no transverse motion. The computation of the diagrams in Fig. 1 is straightforward. After convoluting them with scaling quark, antiquark, and gluon structure functions[7] we obtain[8] the transverse-momentum distribution of lepton pairs shown in Figs. 2 and 3. Our procedure[7] predicts normalization as well as the shape of the p_T distribution, and therefore the agreement with the data for large values of p_T is a definite success of the theory and a detailed experimental study of the large-p_T behavior for different values of m constitutes the most direct and meaningful test of the theory. Notice the dominance of the quark-gluon Compton diagrams at large p_T (Fig. 3). The high-transverse-momentum lepton-pair spectrum is a direct manifestation of gluon dynamics. Contrary to calculations of $\langle p_T \rangle$, calculations of $d\sigma/dm\,dp_T^2$ are not plagued by (i) the technical problem of how to control the divergence of the diagrams in Figs.

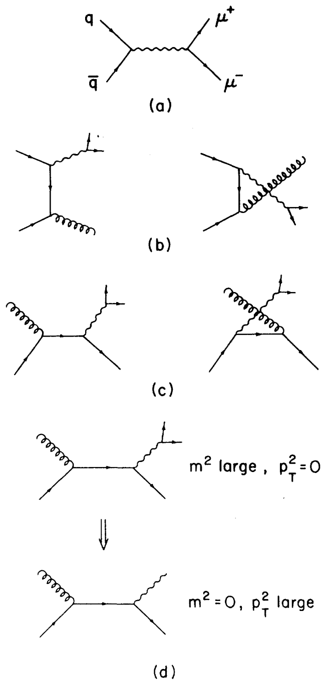

FIG. 1. (a) Drell-Yan diagram for hadroproduction of massive lepton pair. (b), (c) Gluon corrections to the Drell-Yan diagram of (a) in lowest order of the quark-gluon coupling constant (vertex corrections not shown). (d) Schematic representation of the transition from virtual to real photon secondaries. Solid, wiggly, and curly lines represent, respectively, quarks, photons, and gluons.

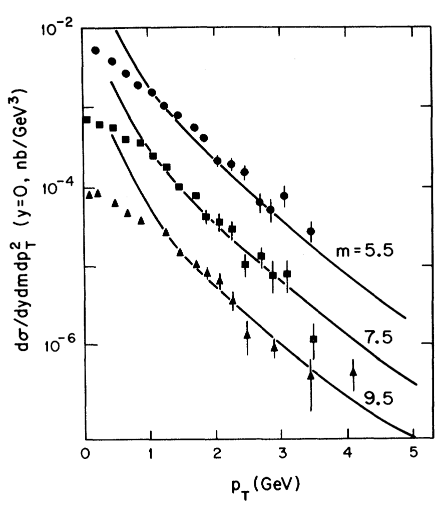

FIG. 2. The transverse momentum spectrum of lepton pairs produced in pp collisions at $y = 0$, at $\sqrt{s} = 27.4$ GeV. The curves show the QCD calculation; the data are from Ref. 2.

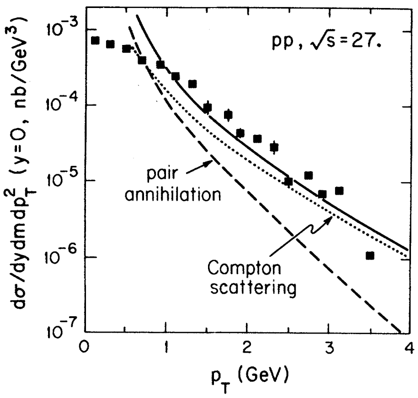

FIG. 3. The QCD calculation for lepton pairs with mass 7.5 GeV is shown separated into its two components: quark-antiquark annihilation and quark-gluon Compton scattering.

1(b) and 1(c) when p_T vanishes because of the zero mass of quarks and gluons. This problem is evident in Figs. 2 and 3 for smaller values of the transverse momentum, where any comparison with the data becomes meaningless. When calculating $\langle p_T \rangle$ one takes the (convergent) first moment of a distribution that does not fit the data for $p_T \lesssim 2$ GeV and is not expected to because of the divergence. Within the present framework of QCD there is no procedure to remove this divergence; any attempt would be model dependent and therefore *ad hoc*. (ii) Nor are they plagued by our ignorance concerning the "internal" transverse momentum of quarks inside hadrons (confinement), contributing to small-p_T behavior of the cross section and therefore to $\langle p_T \rangle$.

Ignoring these warnings, one can go ahead and calculate the average transverse momentum of lepton pairs as a function of mass and energy. The result is shown in Fig. 4 for pp collisions at two different energies.[9] Superimposing[10] our result on the intrinsic transverse momentum of the quarks and gluons inside the hadrons (taken to be $\langle k_T^2 \rangle = \frac{1}{2}$ GeV^2), we obtain a description of the data for m values exceeding 5 GeV. At lower values of m the calculation becomes theoretically questionable and is very sensitive to details.[9]

Also shown in Fig. 5 is the variation of the average transverse momentum of the lepton pairs with beam particle type.[11] Because of our lack of knowledge of the relative magnitude of the intrinsic transverse momentum of different particles (e.g., π and p), the relative magnitude between the πp and pp curves is meaningless. A clearcut test of QCD is provided, however, by the strikingly different m dependence of $\langle p_T \rangle$ in πp and $\bar{p}p$ as compared to pp interactions. At large values of m the QCD contribution to $\langle p_T \rangle$ in $\pi^- p$ and $\bar{p}p$ becomes very small. This is a relic of the steeper angular dependence of the quark-antiquark annihilation diagrams of Fig. 1(b) which dominate in $\pi^- p$ and $\bar{p}p$ interactions, as compared to the quark-gluon diagrams of Fig. 1(c) which dominate in the pp case and lead to the quasi m independence of $\langle p_T \rangle$ up to $m \simeq 20$ at $p_{\rm lab} = 400$ GeV (see Figs. 4 and 5).

The $\langle p_T^2 \rangle$ values shown in Fig. 5 have been averaged over the Feynman x_F of the produced lepton pair and conceal an interesting structure

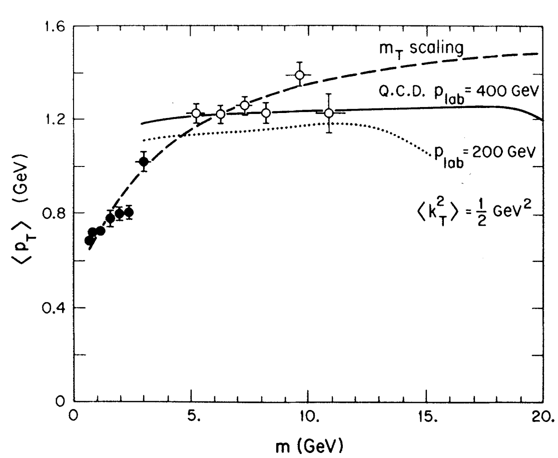

FIG. 4. Average transverse momentum of lepton pairs in pp collisions. Data are from Refs. 1 and 2.

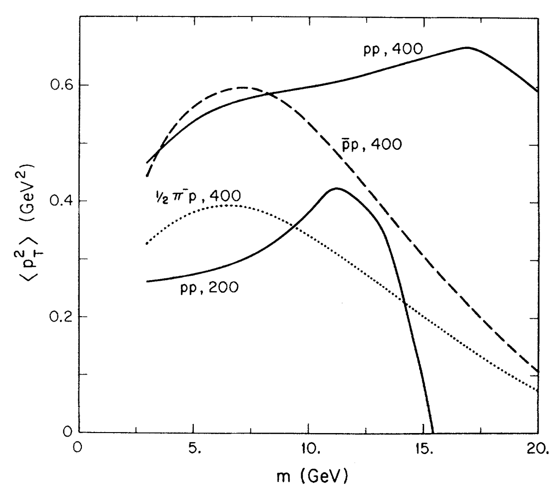

FIG. 5. $\langle p_T^2 \rangle$ of lepton pairs produced in pp, $\pi^- p$, and $\bar{p}p$ collisions resulting from the quark-gluon diagrams of Figs. 1(b) and 1(c). The calculation has been averaged over the Feynman x_F of the lepton pair.

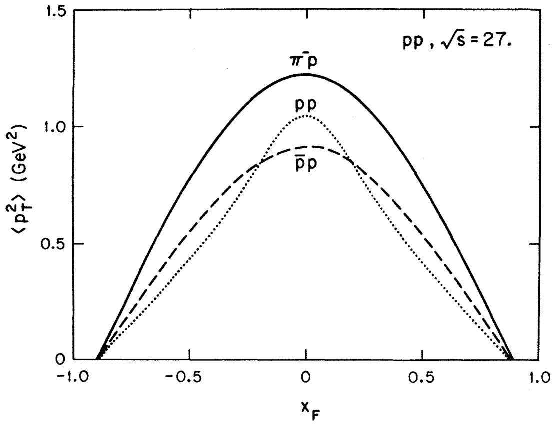

FIG. 6. Feynman x_F dependence of $\langle p_T^2\rangle$ of lepton pairs of mass 9 GeV, produced in hadron collisions with $\sqrt{s} = 27.4$ GeV, calculated according to the diagram of Figs. 1(b) and 1(c).

of $\langle p_T\rangle$ as a function of x_F. The transverse momentum rapidly decreases with increasing x_F as shown in Fig. 6 for $m = 9$. It would be interesting to check this behavior experimentally.

We conclude this Letter by presenting a very crucial and clean test of the theory: the production of direct photons. Although the idea has been flirted with in the recent past,[12] the present scheme provides us with a quantitative prediction for direct photon yields in hadronic collisions. The same QCD diagrams [Figs. 1(b) and 1(c)] responsible for the transverse momentum of virtual photons predict the production of *real* photons. The expansion in the quark-gluon coupling α_s assumed throughout the previous calculations is, however, only valid because of the large momentum flow in the quark-gluon diagram and is sustained by the high mass of the virtual photon. For real photons it has to be carried by a large transverse momentum of the produced photon as schematically illustrated for a quark-gluon Compton diagram in Fig. 1(d).[13] Therefore, the previous calculation (with minor modification for the removal of the lepton pair in final state and for color counting) yields direct photon cross sections, essentially by the replacement of m^2 by $p_T^2/4$. The results are shown in Fig. 7 and are rather surprising. At $\sqrt{s} = \sim 15-60$ GeV, the γ/π^0 ratio in pp collisions exceeds the 10% level for $p_T = 5$ GeV with $\gamma \simeq \pi^0$ at $p_T = 10$ GeV. The direct photon yields are larger in $\pi^- p$ and $\bar{p}p$ interactions. QCD predicts the observation of direct photons at large p_T.

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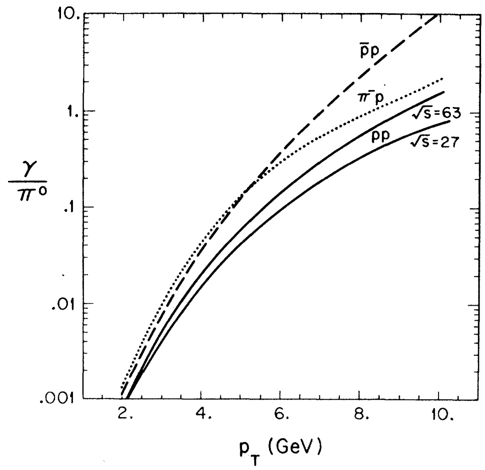

FIG. 7. Direct photon yield in pp, $\pi^- p$, $\bar{p}p$ collisions. Plotted is

$$\frac{\gamma}{\pi^0} = \frac{E d\sigma(Ap \to \pi X)/d^3p}{E d\sigma(Ap \to \pi^0 X)/d^3p}$$

at $x_F = 0$. The photon cross sections are normalized to existing data on π^0 production in $\pi^- p$ and pp. We assumed the π^0 yield in $\bar{p}p$ to be the same as that in pp.

[1]L. Kluberg *et al.*, Phys. Rev. Lett. 37, 1451 (1976); K. J. Anderson *et al.*, Phys. Rev. Lett. 37, 799 (1976).

[2]S. W. Herb *et al.*, Phys. Rev. Lett. 39, 252 (1977); W. R. Innes *et al.*, Phys. Rev. Lett. 39, 1240, 1640(E) (1977); L. M. Lederman, in Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977 (to be published), and in Proceedings of the Ben Lee Memorial International Conference, Fermilab, 1977 (to be published); D. M. Kaplan *et al.*, Phys. Rev. Lett. 40, 435 (1978).

[3]H. D. Politzer, to be published.

[4]H. D. Politzer, Caltech Report No. CALT-68-628, 1977 (to be published).

[5]A. V. Radyushkin, Phys. Lett. 69B, 245 (1977).

[6]For a more detailed discussion, especially of the role of vertex corrections, we refer to Ref. 3.

[7]We used standard valence-quark distributions. Antiquark distribution functions have been obtained by inverting the data of Ref. 2 in the scaling Drell-Yan model. Gluon distributions satisfy dimensional counting and the momentum sum rule. Scaling violations of the structure functions contribute in higher order in the quark-gluon coupling constant and should not be considered in this calculation.

[8]F. Halzen and D. M. Scott, to be published. Previous

evaluations of these diagrams have been made; we essentially follow the approach of G. Altarelli, G. Parisi, and R. Petronzio, CERN Report No. Ref. TH-2413, 1977 (to be published). See also K. Kajantie and R. Raitio, University of Helsinki Report No. HU-TFT-77-21, 1977 (to be published). Our evaluation of the QCD diagrams disagrees with the latter results as well as those of Refs. 4 and 5. The Compton diagrams of Fig. 1(c) have also been considered by H. Fritzsch and P. Minkowski, CERN Report No. Ref. TH-2400, 1977 (to be published).

[9]We believe the turnover of $\langle p_T\rangle$ at low mass to be unrelated to constituent dynamics. It represents the observed scaling in transverse mass $m_T=(m^2+p_T^2)^{1/2}$ of any hadronic process. Scaling the $\langle p_T\rangle$ of π secondaries in pp collisions in transverse mass m_T yields the curve shown in Fig. 4 to support our assertion.

[10]Assuming approximately Gaussian distributions, we simply add the intrinsic and QCD contributions to $\langle k_T^2\rangle$. Our working assumption is that $\langle k_T^2\rangle$ of initial quarks and gluons is independent of m and s. Relaxing this assumption strips from QCD any predictive power concerning average transverse momenta.

[11]We used the quark and gluon structure functions from R. D. Field and R. P. Feynman [Caltech Report No. CALT-68-565 (to be published)] for π mesons.

[12]G. R. Farrar, Caltech Report No. CALT-68-576, 1977 (to be published); F. Halzen, Rutherford Report No. RL-77-049/A, 1977 (to be published); H. Fritzsch and P. Minkowski, CERN Report No. TH. 2320, 1977 (to be published); S. J. Brodsky, private communication.

[13]The expansion in α_s is valid in the high-transverse-momentum regime, even for real photons. The assumption is identical to that made in any QCD calculation of high-p_T reaction mechanisms.

Observation of $\mu 3\pi$ Events in e^+e^- Annihilation

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We have observed events of the type $\mu^\pm+(3\pi)^\mp$ in e^+e^- interactions at center-of-mass energies above 6 GeV. The properties of the events are consistent with their coming from the heavy-lepton decays $\tau\to\mu\nu\bar{\nu}$ and $\bar{\tau}\to\bar{\nu}3\pi$ or $\bar{\tau}\to\bar{\nu}4\pi$. The three-charged-pion invariant-mass distribution shows a significant peak at a mass 1.1 GeV/c^2. We find the branching ratio into three charged and any number of neutral pions $B(\tau^+\to\bar{\nu}\pi^+\pi^+\pi^- n\pi^0)=0.18\pm0.065$.

Evidence for the existence of a new lepton τ with a mass[1] about 1.8 GeV/c^2 has mounted steadily since the original observation of anomalous $e\mu$ events in e^+e^- interactions.[2] Recently several groups have reported the observation of semihadronic τ decays.[1,3,4] In this Letter we report the observation of $\mu^\pm(3\pi)^\mp$ events which we interpret as evidence for τ decays involving three charged pions. One such decay, $\tau\to\nu3\pi$, is of special interest because the A_1 is expected to appear prominently in this final state.[5] Despite many searches for this axial-vector state predicted by the quark model, it has yet to be conclusively established.[6] More generally, the study of multihadronic decays of the τ probes the nature and strengths of its couplings.

Our evidence comes from a study of e^+e^- interactions at center-of-mass energies above 6 GeV. The data were taken with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at SPEAR. We select events with four charged particles, total charge zero, which include a muon; these could result from the process $e^+e^-\to\tau^+\tau^-$ followed by the de-

