By 280 GeV/c, the contribution of the ρ and A_2 would seem to be quite small. In most Regge models, the n-p cross sections are equal to or less than the p-p cross sections in this region of t. The fact that the n-p cross sections are greater indicates that some amplitudes, such as the net helicity-flip amplitudes, may not be correctly understood in this region.

We wish to express our appreciation to the entire Fermilab staff for their support of this experiment. We also wish to thank Jim Stone, John Chanowski, Geoff Mills, and Bill Larsen for their help during various phases of the experiment. Useful discussions with Gordon Kane and Andy Seidl are gratefully acknowledged. This work was supported by the National Science Foundation.

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Production of Large-Transverse-Momentum Jets in Photon-Photon Collisions

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We predict a new source of jet structure in e^+e^- colliding-beam experiments arising from photon-photon collisions. These jets are produced with a sizable fraction of the total observable hadronic rate and have unmistakable signatures. Observations of these jets would provide important tests of the contributions of three classes of hard-scattering mechanisms: quark exchange in $\gamma\gamma\to q\bar{q}$, gluon exchange in qq and $q\bar{q}$ scattering, and constituent-interchange processes with a characteristic $p_\perp^{-6}$ behavior.

Photon-photon collisions in e^+e^- storage rings become increasingly important as the energy of the storage rings increases. The dominant part of the cross section for $e^+e^-\to e^+e^-$ + hadrons arises from nearly on-shell photons emitted at small angles to the beam and increases logarithmically with energy:

$$\frac{d\sigma}{d\mathfrak{M}^2}(e^+e^-\to e^+e^-X)\approx\left(\frac{\alpha}{\pi}\ln\frac{s}{4m_e^2}\right)^2\ln\left(\frac{s}{\mathfrak{M}^2}\right)\frac{\sigma_{\gamma\gamma\to X}(\mathfrak{M}^2)}{\mathfrak{M}^2} \tag{1}$$

for $m_e^2/s\to 0$, $s=(p_e+p_{e^-})^2$, and $s\gg\mathfrak{M}^2=(p_{\gamma_1}+p_{\gamma_2})^2$. A simple vector-dominance prediction for the hadronic photon-photon cross section gives $\sigma(e^+e^-X)\approx 15$ nb for $E_e=15$ GeV and $\mathfrak{M}^2\geq 1$ GeV^2. This is to be compared with the single-photon cross section $\sigma(e^+e^-\to\gamma\to X)=(4\pi\alpha^2/3s)R\approx(0.1\text{ nb})R$.[1]

While most of the hadrons produced in photon-photon collisions emerge with small momenta transverse to the beam axis, we suggest here that there are sizable production cross sections for jets at relatively large transverse momentum. Such reactions, if observed, will provide important tests of our knowledge of both quark dynamics and the basic reactions which govern large-p_T interactions. The processes which we envision contributing to large-p_T jet production include the simple quantum electrodynamic (QED) reaction $\gamma\gamma\to q\bar{q}$, quantum-chromodynamics-(QCD-) induced reactions such as $\gamma_1\to q\bar{q}$, $\gamma_2\to q\bar{q}$, with qq scattering via gluon exchange, as well as quark-hadronic hard scattering as considered by the constituent-interchange model (CIM). (Examples of all these classes of reactions are shown in Fig. 1.)

Jets induced by $\gamma\gamma$ reactions will show unmistakable signatures in colliding-beam experiments. Since the probability for γ emission by an electron into a given rapidity interval is essentially flat, the distribution of jets per rapidity interval will also be approximately flat away from the edge of phase space. Momentum conservation demands that a large-p_T jet on one side of a reaction must be balanced by one or more large-p_T jets on the "away" side.[2] For the $\gamma\gamma\to q\bar{q}$ process one expects the production of two "spear"-like jets each with total energy less than the $e^\pm$ center-of-mass energy $\frac{1}{2}\sqrt{s}$. Because the rapidity of the $\gamma\gamma$ system is in general not zero, the jet events range from nearly back-to-back jets to a "V" configuration with a small opening angle along the beam axis. In all the other subprocesses the high-p_T jets are accompanied by additional jets from spectator particles which do not participate in the hard-scattering reaction. In the case of $\gamma\gamma\to q\bar{q}$, the multiplicity should be nearly identical to that for $e^+e^-\to q\bar{q}$ at the same invariant $q\bar{q}$ energy.

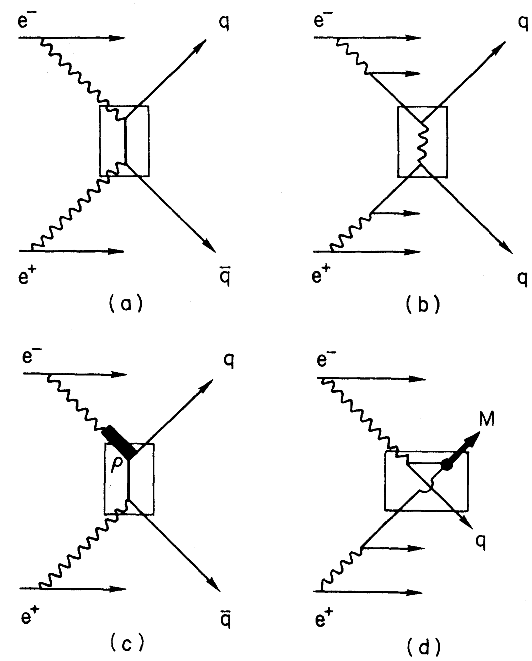

FIG. 1. Various reactions which produce wide-angle jets in γ-γ collisions. A box encircles the hard-scattering subprocess.

We base our predictions on the computation of specific differential cross sections using the standard hard-scattering form of large-p_T parton models[3]:

$$E\frac{d\sigma}{d^3p}(e^+e^-\to e^+e^-CX)=\int_0^1 dx_a\int_0^1 dx_b\, G_{a/e}(x_a)G_{b/e}(x_b)\frac{d\sigma}{d\hat{t}}(ab\to CX)\frac{\hat{s}}{\pi}\delta(\hat{s}+\hat{t}+\hat{u}), \qquad (2)$$

where $\hat{s}=x_ax_bs$, $\hat{t}=x_at$, and $\hat{u}=x_bu$, and where the $G(x)$'s are the probability distributions that the electron will emit a particle a at a fraction x of the electron's (light cone) momentum, and $d\sigma/dt$ is the cross section for the subprocess. We will perform our calculations in the equivalent photon approximation,[4] where, for example,[5]

$$xG_{\gamma/e}(x)\cong(\alpha/2\pi)\ln\eta\,[1+(1-x)^2], \qquad (3a)$$

$$xG_{q/e}(x)\cong e_q^{\,2}\left(\frac{\alpha}{2\pi}\ln\eta\right)\left(\frac{\alpha}{2\pi}F_q\right)(1-x), \qquad (3b)$$

$$G_{\rho/e}(x)\cong(4\pi\alpha/f_\rho^{\,2})G_{\gamma/e}(x), \qquad (3c)$$

and so forth. Here $\eta=s/4m_e^{\,2}$ if the electron is not tagged and $\theta_{max}^{\,2}/\theta_{min}^{\,2}$ if it is tagged within a recoil angle $\theta_{min}<\theta<\theta_{max}$. F_q is the factor which arises from the transverse momentum ($\vec{k}_T$) integration of the q or $\bar{q}$ spectator in $e\to e\gamma\to eq\bar{q}$. In a simple QED model, $F_q\sim\ln s/(4m_q^{\,2})$. In QCD, the logarithmic dependence of F_q is preserved, though the infrared k_T region is expected to be modified by hadronic size effects. The actual value of F_q is a fundamental parameter which is in principle calculable in

QCD.

We now estimate the cross sections for the production of jets for the processes mentioned above using Eq. (2). A detailed discussion and estimates of single-particle production at large transverse momentum will be given in a separate publication.[6]

(a) $\gamma\gamma \to q\bar{q}$.—This hard-scattering subprocess is just the simple QED quark-exchange graph of Fig. 1(a).[3] It is the next most elementary process beyond single-γ annihilation which can probe the dynamics of the strong interactions in e^+e^- collisions. Confirmation of its distinct $p_\perp^{-4}$ behavior reflects the scale invariance of the quark propagator. The cross section for this process is normalized by the purely QED process $\gamma\gamma \to \mu^+\mu^-$:

$$E\frac{d\sigma}{d^3p}(e^+e^- \to e^+e^- q\bar{q}) = R_{\gamma\gamma} E\frac{d\sigma}{d^3p}(e^+e^- \to e^+e^-\mu^+\mu^-) \tag{4}$$

with

$$R_{\gamma\gamma} = 3\sum_{i=u,d,s,c} e_i^4 = \tfrac{34}{27}. \tag{5}$$

Using Eqs. (2) and (3), we find

$$E\frac{d^3\sigma}{d^3p}(e^+e^- \to e^+e^-\mu^+\mu^-) \cong \left(\frac{\alpha}{2\pi}\ln\eta\right)^2 \frac{\alpha^2}{p_\perp^4} F(x_R, \theta_{\rm c.m.}). \tag{6}$$

For small $x_R \equiv E_\mu/E_e$ $(=P_{\rm jet}/E_e)$, $F(x_R, \theta_{\rm c.m.}) \approx \frac{16}{3}$, and for $x_R \to 1$, $F(x_R, \theta_{\rm c.m.}) \approx (1-x_R)(1+\cos^2\theta_{\rm c.m.})$. Thus at $\sqrt{s} = 30$ GeV and $\theta_{\rm c.m.} = 90°$,

$$E d\sigma(e^+e^- \to e^+e^- q\bar{q})/d^3p \xrightarrow[x_R \to 1]{} (0.015 \text{ nb GeV}^2)(1-x_R)/p_\perp^4. \tag{7}$$

The total production cross section for quark and antiquark jets exceeding a minimum p_T from the $\gamma\gamma \to q\bar{q}$ subprocess is

$$\sigma(p_\perp^{\rm jet} > p_\perp^{\rm min}) = \int_{p_\perp > p_\perp^{\rm min}} d^2p_\perp \int dy \left[E\frac{d\sigma}{d^3p}(ee \to qX) + E\frac{d\sigma}{d^3p}(ee \to \bar{q}X)\right]$$

$$\simeq \frac{32\pi}{3}\alpha^2\left(\frac{\alpha}{2\pi}\ln\eta\right)^2 \frac{[\ln(s/p_{\perp\,\rm min}^2) - \frac{19}{6}]R_{\gamma\gamma}}{(p_\perp^{\rm min})^2} \tag{8}$$

which is $(0.5 \text{ nb GeV}^2)/(p_\perp^{\rm min})^2$ at $\sqrt{s} = 30$ GeV. The ratio to the $e^+e^- \to \mu^+\mu^-$ cross section is $(5 \text{ GeV}^2)/(p_\perp^{\rm min})^2$; i.e., jets with a minimum transverse momentum of 4 GeV contribute about 0.3 more units of R to the total cross section from this subprocess alone. These results can be compared with the calculations by Smith and co-workers[7] of $ee \to ee\tau^+\tau^-$, which give ~1 unit of R at $E_{\rm c.m.} = 30$ GeV for a heavy lepton mass of 1.8 GeV.

(b) *Quark scattering.*—The quark or antiquark constituents of the photon may scatter via gluon exchange, or may annihilate into a wide-angle gluon pair. There are many competing processes, which are tabulated elsewhere.[8] We find

$$E\frac{d\sigma}{d^3p}(e^+e^- \to e^+e^- \,{\rm jet}X) \simeq \alpha_c^2\left(\frac{\alpha}{2\pi}\ln\eta\right)^2\left(\frac{\alpha}{2\pi}F_q\right)^2\left[\frac{80}{3}\left(\sum_{i=u,d,s,c} e_i^2\right)^2 + \frac{52}{9}\left(\sum_i e_i^4\right)\right]\frac{(1-x_R)^3}{p_\perp^4} \tag{9}$$

at $\theta_{\rm c.m.} = 90°$. Since we are only seeking an estimate of the contribution we have not included any scale-violating effects due to asymptotic freedom.

If we take $\alpha_c \simeq 0.15$, $F_q \sim \ln[s/4(300 \text{ MeV})^2]$, then the cross section is $\sim (0.014 \text{ nb GeV}^2)(1-x_R)^3 p_\perp^{-4}$ at $\sqrt{s} = 30$ GeV. We emphasize that these jet reactions can be differentiated from those of (a) by the presence of additional jets parallel to the beam axis which are created by the spectator quarks which did not participate in the hard scattering. The $n_{\rm jet} = 3$ contributions from $\gamma_1 + q \to g + q$, etc., give a rate $O[(1-x_R)\alpha_c/\pi F_q]$ times the rate for $\gamma\gamma + \bar{q}q$ (see Ref. 6).

(c) There are also contributions to jet production which are not completely scale free since only one of the photons reveals its pointlike coupling.[9] These correspond to $n_{\rm jet} = 2$ and $n_{\rm jet} = 3$ subprocesses such as $\gamma\rho \to q\bar{q}$ and $\gamma q \to Mq$ (M = meson resonance) shown in Figs. 1(c) and 1(d). The CIM predicts contributions behaving as $Ed\sigma(ee \to {\rm jet}X)/d^3p \sim (0.05 \text{ nb GeV}^4)(1-x_R)/p_T^6$, $(0.7 \text{ nb GeV}^4)(1-x_R)^2/p_T^6$, respectively, at $\sqrt{s} = 30$ GeV.[10]

(d) The contributions to high-p_T jet production when both photons are vector-meson dominated can be estimated from $(f_\rho^2/4\pi \sim 2)$

$$d\sigma^{VDM}(\gamma\gamma \to \text{jet} + X) = \left(\frac{e}{f_\rho}\right)^4 d\sigma(\rho\rho \to \text{jet} + X) \cong \left(\frac{4\pi\alpha}{f_\rho^2}\right)^2 \left(\frac{2}{3}\right)^2 \frac{d\sigma\,(pp \to \text{jet} + X)}{(1 - x_R)^4}. \tag{10}$$

If we take $E\,d\sigma(pp \to \text{jet} + X)/d^3p \sim 300E\,d\sigma(pp \to \pi X)/d^3p \sim (1.1 \text{ nb GeV}^6(1 - x_R)^9 p_T^{-8}$, then the convolution over photon momentum distributions yields the estimate ($\theta_{\text{c.m.}} = 90°$)

$$\frac{d\sigma}{d^3p/E}(ee \to \text{jet} + ee + X) \sim \frac{(1.4 \text{ nb GeV}^6)(1 - x_R)^7}{p_T^{\,8}} \tag{11}$$

at $\sqrt{s} = 30$ GeV.[11] The fact that the vector-meson-dominated contributions are relatively negligible beyond $p_T = 2$ GeV/c indicates how strongly the pointlike couplings of the photon influence quark jet production. The observation of p_T^{-6} behavior in the intermediate region up to $p_T \sim 5$ GeV/c would provide important support for the CIM approach. Confirmation of the magnitude and jet topology of the p_T^{-4} terms for p_T beyond ~ 5 GeV/c will check the validity the QCD hard-scattering approach to large-p_T dynamics and determine a value for the product of α_c and F_q.

We summarize our predictions for high-p_T jet production in Fig. 2.[12]

In conclusion, we predict the existence of a new class of hadronic jets which will be increasingly important in e^+e^- colliding-beam experiments as the energy rises. They will have unmistakable signatures and are expected to give a sizable fraction of all observable hadronic events at $\sqrt{s} = 30$ GeV.

One of us (J.H.W.) wishes to thank S. D. Ellis for discussions and S. Drell for the hospitality of the Stanford Linear Accelerator Center theory group, where this work was initiated. This work was supported in part by the U. S. Department of Energy. Two of us (J.F.G. and J.H.W.) acknowledge receipt of Alfred P. Sloan Foundation fellowships.

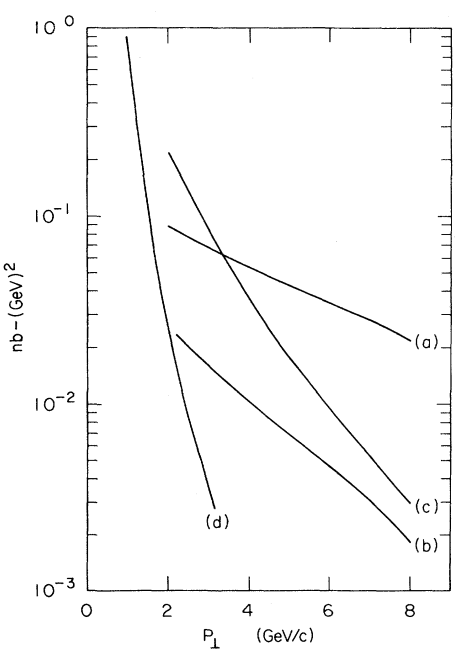

FIG. 2. $p_\perp^4 E d\sigma/d^3p$ for the reaction $e^+e^- \to e^+e^-$ jet X at $\sqrt{s} = 30$ GeV and $\theta_{\text{c.m.}} = 90°$. (a) $\gamma\gamma \to q\bar{q}$, (b) $\gamma\gamma \to q\bar{q}q\bar{q}$, (c) $p_\perp^{-6}$ CIM contributions, (d) $\rho\rho$ scattering estimate of Eq. (11). The jet origin can be a q, $\bar{q}$, gluon, or mesonic system.

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[10]These contributions will be more evident in single-

particle inclsive cross sections, where the crossover with the p_T^{-4} terms is at $p_T \approx 7$ GeV. See Ref. 6. We have used $\alpha_M = 1.2\ \mathrm{GeV}^2$ from Ref. 9.

[11]There are additional CIM $p_\perp^{-8}$ contributions from $q\bar{q} \to M\bar{M}$, etc., which behaves as $p_T^{-8}(1-x_R)^3$ and dominates Eq. (11) at large x_R.

[12]No double counting occurs when we include all these subprocesses in the jet cross section. The different terms are distinct contributions to the cross section with unique topologies of jets and quark charge structures. Nor are we double counting when we include both $\gamma\gamma \to q\bar{q}$ and vector-dominated $\gamma\gamma \to M\bar{M} \to q\bar{q}$, as long as we include only a sum over a finite number of vector mesons M; in fact, the different p_T behaviors of the cross sections make differentiation between these subprocesses clear.

Confirmation of Exchange-Degeneracy Predictions in the Line-Reversed Reactions: $\pi^+ p \to K^+ Y^*(1385)$ and $K^- p \to \pi^- Y^*(1385)$ at 11.5 GeV/c

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(Received 5 July 1978)

We have measured in a single experimental setup the differential cross sections and polarizations of the $Y^*(1385)$ produced in the two line-reversed reactions $\pi^+ p \to K^+ Y^*(1385)$ (260 eV/μb) and $K^- p \to \pi^- Y^*(1385)$ (180 eV/μb) at 11.5 GeV/c. We compare these results to Σ^+ production in the same experiment. The data have been derived from a triggered bubble-chamber experiment using the SLAC Hybrid Facility. We find that both helicity-flip–dominated (Y^*) and helicity-nonflip–dominated (Σ) processes are consistent with weak–exchange-degeneracy predictions.

As part of a systematic study of line reversal in hypercharge-exchange reactions, we present here results on $Y^*(1385)$ production in the reactions

$$\pi^+ p \to K^+ Y^*(1385), \tag{1}$$

$$K^- p \to \pi^- Y^*(1385), \tag{2}$$

at 11.5-GeV/c incoming momentum. In a Regge picture, the two reactions are expected to be dominated asymptotically by the exchange of the same two reggeons: the vector $K^*(890)$ and tensor $K^{**}(1420)$. Exchange degeneracy (EXD) of these trajectories implies equal cross sections for reactions (1) and (2) at the same value of the four-momentum transfer, t. The polarization of the final-state hyperon should be either zero (strong EXD) or, if different from zero, it should have equal magnitude and opposite sign (weak EXD) in line-reversed reactions.[1] Our experiment was designed to test these relations.

Previous measurements of reactions (1) and (2) have mostly resulted from experiments done by different groups using different techniques,[2-4] thus making comparisons difficult to interpret. The present experiment is the first one to measure in a single detector the complete decay angular distribution of the $Y^*(1385)$ for both reactions (1) and (2), from which we determine the hyperon polarization. We also measure the differential cross sections of the two reactions with a minimum of systematic differences between them. For comparison, we present differential cross sections and hyperon polarizations from the reactions

$$\pi^+ p \to K^+ \Sigma^+, \tag{3}$$

$$K^- p \to \pi^- \Sigma^+. \tag{4}$$

The Σ polarization results presented here include new data in addition to those presented in an earlier publication.[5] The experiment was conducted at the SLAC Hybrid Facility[6] consisting of the SLAC 1-m rapid-cycling bubble chamber (15 Hz), triggered by data from electronic detectors processed on line by a DGC-840 computer. The experimental setup and the trigger and described elsewhere.[5,6]

Events belonging to reactions (1)–(4) have been identified by kinematic fits, simultaneously at both primary and strange-particle decay vertices. For reactions (1) and (2), the mass resolution of constrained events is ~8 MeV in the $Y^*(1385)$ region.

The resulting sample is almost bias free and has well-understood relative normalizations for

