PRODUCTION OF LARGE TRANSVERSE MOMENTUM JETS^{*}
IN PHOTON-PHOTON COLLISIONS

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ABSTRACT

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 sizeable 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, distinguishable by their topological structure: quark exchange in $\gamma\gamma \rightarrow q\bar{q}$, gluon exchange in $q\bar{q}$ and $q\bar{q}$ scattering, and constituent interchange processes with a characteristic $p_{\perp}^{-6}$ behavior.

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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 $e^+e^- \rightarrow e^+e^- + \text{hadrons}$ arises from nearly on-shell photons emitted at small angles to the beam and increases logarithmically with energy:

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

for $m_e^2/s \rightarrow 0$, $s = (p_{e^+} + p_{e^-})^2$ and $s \gg \mathcal{M}^2 = (p_{\gamma_1} + p_{\gamma_2})^2$. A simple vector dominance prediction for the hadronic photon-photon cross section gives $\sigma(e^+e^- \rightarrow e^+e^-X) \approx 15 \text{ nb}$ for $E_e = 15 \text{ GeV}$ and $\mathcal{M}^2 \geq 1 \text{ GeV}^2$. This is to be compared with the single photon cross section $\sigma(e^+e^- \rightarrow \gamma \rightarrow X) = \frac{4\pi\alpha^2}{3s} R \approx (0.1 \text{ nb}) R$. Photon-photon reactions allow the entire range of hadronic phenomena to be studied with two incident bosons; the energy, mass, and polarization of each photon can be determined by tagging the e^+ and e^- which produce them.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 sizeable 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 QED reaction $\gamma\gamma \rightarrow q\bar{q}$, QCD induced reactions such as $\gamma_1 \rightarrow q\bar{q}$, $\gamma_2 \rightarrow q\bar{q}$, with $q\bar{q}$ 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 $\gamma\gamma \rightarrow q\bar{q}$ process one expects the production of two "Spear"-like jets each with total energy less than the e^+e^- cm energy $\sqrt{s}/2$. 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 of hadrons from spectator particles which do not participate in the hard scattering reaction.

We emphasize that even without tagging the photon energies the different contributing hard scattering subprocesses can be distinguished by their topological jet structure; i.e., the number n_{Jet} of hadronic jets observed in an event reflects the number of quark or gluonic systems initially separated. Specific examples are $n_{\text{Jet}} = 2$ for $\gamma_1 + \gamma_2 \rightarrow q + \bar{q}$; $n_{\text{Jet}} = 3$ for $\gamma_1 + g \rightarrow q\bar{q}$ (where the gluon is a constituent of γ_2); $n_{\text{Jet}} = 4$ for $qq \rightarrow qq$, $gq \rightarrow gq$, etc. Gluon jets, quark jets, or hadronic resonances should be distinguishable by their leading particle structure and central region multiplicity density. In the case of $\gamma\gamma \rightarrow q\bar{q}$, the multiplicity should be nearly identical to that for $e^+e^- \rightarrow q\bar{q}$ at the same invariant $q\bar{q}$ energy.

In practice, one will probably wish to reduce the background from the single photon process by demanding that at least one lepton be observed at small angle in the final state.

We base our predictions on the computation of specific differential cross sections using the standard hard-scattering form of large p_T parton models³

$$\begin{aligned}
 E \frac{d\sigma}{d^3p} (e^+ e^- \rightarrow e^+ e^- CX) \\
 = \int_0^1 dx_a \int_0^1 dx_b G_{a/e}(x_a) G_{b/e}(x_b) \frac{d\sigma}{dt} (ab \rightarrow CX) \bigg|_{\substack{\hat{s} = x_a x_b s \\ \hat{t} = x_a t \\ \hat{u} = x_b u}} \\
 \times \frac{\hat{s}}{\pi} \delta(\hat{s} + \hat{t} + \hat{u}), \tag{2}
 \end{aligned}$$

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 approximation⁴, where, for example⁵

$$x G_{\gamma/e}(x) \cong \frac{\alpha}{2\pi} \log \eta \left[1 + (1-x)^2 \right] \tag{3a}$$

$$x G_{q/e}(x) \cong e^2 \left(\frac{\alpha}{2\pi} \log \eta \right) \left(\frac{\alpha}{2\pi} F_q \right) (1-x) \tag{3b}$$

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

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 $e \rightarrow e\gamma \rightarrow eq\bar{q}$. In a simple QED model, $F_q \sim \log s/(4m_q^2)$. In QCD, the infrared k_T region is expected to be modified by hadronic size effects. At large k_T the logarithmic variation of the running coupling constant presumably leads to a $\log(\log s/\Lambda^2)$ dependence, although this multijet region is complicated by interference 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) $\gamma\gamma \rightarrow q\bar{q}$. This hard scattering subprocess is just the simple QED quark exchange graph of Fig. 1a.³ Its presence is particularly interesting since 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 $\gamma\gamma \rightarrow \mu^+\mu^-$:

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

with

$$R_{\gamma\gamma} = 3 \sum_{i=u,d,s,c} e_i^4 = \frac{34}{27} . \quad (5)$$

Using Equation (2) and (3),

$$E \frac{d^3\sigma}{d^3p} (e^+e^- \rightarrow e^+e^-\mu^+\mu^-) \cong \left(\frac{\alpha}{2\pi} \ln \eta \right)^2 \frac{\alpha^2}{p_{\perp}^4} F(x_R, \theta_{\text{cm}}) . \quad (6)$$

For small $x_R \equiv E_{\mu}/E_e (= P_{\text{jet}}/E_e)$, $F(x_R, \theta_{\text{cm}}) \approx 16/3$ and for $x_R \rightarrow 1$, $F(x_R, \theta_{\text{cm}}) \approx (1-x_R)(1 + \cos^2 \theta_{\text{cm}})$. Thus at $\sqrt{s} = 30 \text{ GeV}$

$$E \frac{d^3\sigma}{d^3p} (e^+e^- \rightarrow e^+e^-q\bar{q}) \underset{\substack{\theta_{\text{cm}}=90^\circ \\ x_R \rightarrow 1}}{\sim} 0.015 \frac{(1-x_R)}{p_{\perp}^4} \text{ nb GeV}^2 . \quad (7)$$

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

$$\begin{aligned} \sigma(p_{\perp}^{\text{jet}} > p_{\perp}^{\text{min}}) &= \int_{p_{\perp} > p_{\perp}^{\text{min}}} d^2 p_{\perp} \int dy \left[E \frac{d\sigma}{d^3 p} (ee \rightarrow qX) + E \frac{d\sigma}{d^3 p} (ee \rightarrow \bar{q}X) \right] \\ &\simeq \frac{32\pi}{3} \alpha_c^2 \left(\frac{\alpha}{2\pi} \log \eta \right)^2 \frac{\left[\log(s/p_{\perp}^{\text{min}^2}) - \frac{19}{6} \right] R_{\gamma\gamma}}{(p_{\perp}^{\text{min}})^2} \end{aligned} \quad (8)$$

which is $0.5 \text{ nb GeV}^2/(p_{\perp}^{\text{min}})^2$ at $\sqrt{s} = 30 \text{ GeV}$. The ratio to the $e^+e^- \rightarrow \mu^+\mu^-$ cross section is $5 \text{ GeV}^2/(p_{\perp}^{\text{min}})^2$; 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.

(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 in Ref. 8. We find

$$\begin{aligned} E \frac{d\sigma}{d^3 p} (e^+e^- \rightarrow e^+e^- \text{ Jet} X) &\simeq \\ &\simeq \alpha_c^2 \left(\frac{\alpha}{2\pi} \log \eta \right)^2 \left(\frac{\alpha}{2\pi} F_q \right)^2 \\ &\times \left[\frac{80}{3} \left(\sum_{i=u,d,s,c} e_i^2 \right)^2 + \frac{52}{9} \left(\sum_i e_i^4 \right) \right] \frac{(1-x_R)^3}{p_{\perp}^4} \end{aligned} \quad (9)$$

at $\theta_{\text{cm}} = 90^\circ$. 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 $\alpha_c \simeq 0.15$, $F_q \sim \log[s/4 (300 \text{ MeV})^2]$, then the cross section is $\sim 0.014 (1-x_R)^3 p_{\perp}^{-4} \text{ nb GeV}^2$ at $\sqrt{s} = 30 \text{ GeV}$, comparable in size to the $\gamma\gamma \rightarrow q\bar{q}$ cross section (7). 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 and by the x_R dependence for x_R near 1.

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

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

$$\begin{aligned} d\sigma^{\text{VDM}}(\gamma\gamma \rightarrow \text{Jet} + X) &= \left(\frac{e}{f_\rho}\right)^4 d\sigma(\rho\rho \rightarrow \text{Jet} + X) \\ &\cong \left(\frac{4\pi\alpha}{f_\rho^2}\right)^2 \left(\frac{2}{3}\right)^2 \frac{d\sigma(pp \rightarrow \text{Jet} + X)}{(1-x_R)^4} \end{aligned} \quad (10)$$

If we take $E \frac{d\sigma}{d^3p} (pp \rightarrow \text{Jet} + X) \sim 300 E \frac{d\sigma}{d^3p} (pp \rightarrow \pi X) \sim 1.1 (1-x_R)^9 p_T^{-8} \text{ nb GeV}^6$, then the convolution over photon momentum distributions yields the estimate ($\theta_{\text{cm}} = 90^\circ$)

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

at $\sqrt{s} = 30 \text{ GeV}$.¹¹ The fact that the vector-meson dominated contributions are relatively negligible beyond $p_T = 2 \text{ GeV}/c$ indicates how strongly the point-like couplings of the photon influence quark jet production. The observation of p_T^{-6} behavior in the intermediate region up to $p_T \sim 5 \text{ GeV}/c$ 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 $\sim 5 \text{ GeV}/c$ will check the validity of

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, including (a) the p_T^{-4} contribution from $\gamma\gamma \rightarrow q\bar{q}$, (b) the p_T^{-4} term from QCD, (c) the p_T^{-6} CIM contributions, and (d) the VMD estimate of Eq. (11).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 sizeable fraction of all observable hadronic events at $\sqrt{s} = 30$ GeV. In addition to being interesting in their own right, the jets which are observed in $\gamma\gamma$ collisions will be a good laboratory for testing our ideas about high p_T dynamics of purely hadronic systems, since the photon is a simpler object than the proton, and the distribution functions and scattering cross sections are correspondingly known with less ambiguity.

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Figure Captions

Fig. 1. Various reactions which produce wide-angle jets in $\gamma\gamma$ collisions.

A box encircles the hard-scattering subprocess.

Fig. 2. $p_\perp^4 E \frac{d\sigma}{d^3p}$ for the reaction $e^+e^- \rightarrow e^+e^- \text{JetX}$ at $\sqrt{s} = 30$ GeV and $\theta_{cm} = 90^\circ$.

(a) $\gamma\gamma \rightarrow q\bar{q}$, (b) $\gamma\gamma \rightarrow q\bar{q}q\bar{q}$, (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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2. If the electron and positron are not both tagged, there are additional subprocesses (down by $\log(s/4m_e^2)$ and $\log^2(s/4m_e^2)$) where the lepton itself balances the large p_T jet.
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9. See R. Blankenbecler, S. Brodsky and J. Gunion, SLAC-PUB-2057 (December, 1977), submitted to Phys. Rev. D. and references therein.
10. These contributions will be more evident in single-particle inclusive cross sections, where the crossover with the p_T^{-4} terms is at $p_T \approx 7$ GeV. See Ref. 6. We have used $\alpha_M = 1.2$ GeV² from Ref. 9.

11. There are additional CIM $p_{\perp}^{-8}$ contributions from $q\bar{q} \rightarrow M\bar{M}$, etc., which behave as $p_T^{-8}(1-x_R)^3$ and dominate 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 $\gamma\gamma \rightarrow q\bar{q}$ and vector dominated $\gamma\gamma \rightarrow M\bar{M} \rightarrow q\bar{q}$, 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.

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Fig. 1

Fig. 2