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# Structure of direct-photon events

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In lowest-order perturbative quantum chromodynamics we study correlations between a high-transverse-momentum direct photon produced in high-energy hadron-hadron interactions and the away-side jet. In *pp* collisions this jet is usually a *u* quark, and we investigate the consequences of this.

The copious production of direct photons with high transverse momentum ($p_T$) in high-energy hadron collisions is a qualitative prediction of perturbative quantum chromodynamics (QCD).[1,2] Recent experiments[3,4] not only found direct photons, but the measured cross sections are quantitatively compatible with those calculated from QCD. With our confidence in the calculations thus reinforced, we here reverse our attack, and investigate what can be learned about QCD and the structure of hadrons from the experimental measurements and suggest further probing experiments.

First we will show how present data on the $\gamma/\pi$ ratio constrain $G(x,Q^2)$, the gluon density in the proton. Then we will turn to correlation measurements, where the whole away-side jet, or particles within it, are observed. Such measurements are directly relevant to the structure and scaling violations of quark fragmentation as well as to the gluon structure function, which is further constrained.

It is usual for measured direct-photon yields to be presented as ratios $\gamma/\pi^0$. This has led, in practice, to some difficulty in calculations of this quantity at high $p_T$, where the customary route is to divide the calculated $\gamma$ cross section by the measured $\pi^0$ cross section. There has been some disagreement about the measured $\pi^0$ cross section.[5-7] Fortunately this now appears to be resolved.[8] As ensuing calculations are sensitive to the input $\pi^0$ inclusive cross section, we describe in detail the $\pi^0$ yields used throughout. Our "data," at $\sqrt{s}=63$ GeV, $y=0$, are shown in Fig. 1(a), and have been constructed as follows. We take $\gamma/\pi^0$ from Ref. 4, multiply by 0.85 to take into account an energy cut in the definition of the trigger, and multiply by a fit to the $\pi^0$ data of Ref. 6 which are shown in Fig. 1(b). These $\pi^0$ data do not have $\pi^0$-$\gamma$ separation; therefore, denoting the measured cross section by $\Sigma$ we have

$$E\frac{d\sigma}{d^3p}(pp\to\gamma X)=\Sigma\bigg/\left(1+\frac{\pi^0}{\gamma}\right). \qquad (1)$$

To $O(\alpha_s)$ in perturbative QCD, two subprocesses contribute to the direct-photon cross section. These are $GQ\equiv(gq\to\gamma q)$ and $Q\bar{Q}\equiv(q\bar{q}\to\gamma g)$, where $g$ and $q$ denote quark and gluon, respectively. In $pp$ scattering it is well known that $GQ$ dominates at high $p_T$. This is shown in Fig. 2(a) explicitly, where we have chosen $xG(x,Q^2)=3(1-x)^5$ in the calculation. The quark densities we use in this paper are those of Owens and Reya,[9] with scaling violations governed by the parameter $Q^2=2\hat{s}\hat{t}\hat{u}/(\hat{s}^2+\hat{t}^2+\hat{u}^2)$ (carets denote subprocess invariants). They give an $F_2$ which differs by $\lesssim 20\%$ from that given by quark densities we have used previously,[10] and are in better agreement with recent measurements of $F_2$ by the European muon collaboration.[11] In fact, in calculating the contribution from $GQ$, we require just a parametrization of $F_2$ from deep-inelastic leptoproduction data, together with $G(x,Q^2)$. As discussed in the text, we do not use the Owens-Reya gluon structure functions.

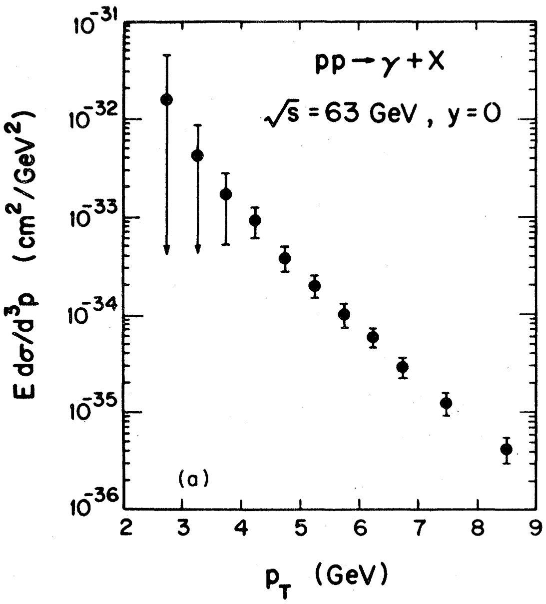
Because of this dominance of $GQ$ Compton scattering, for which the cross section is directly proportional on the gluon density, one can gain information about $G(x,Q^2)$. One immediate conclusion from the present data is that the gluon content of the proton is large, as demonstrated in Fig. 2(b), where we have compared to the data direct-photon calculations using the Owens-Reya gluon structure functions, and using a density of the form

$$xG(x,Q^2)=\tfrac{1}{2}(n_g+1)(1-x)^{n_g}, \qquad (2)$$

with $n_g=3,7$. In the range of $x$ probed by this datum $x\simeq 0.1-0.3$, the harder gluon density of Eq. (2) is preferred. Our original use of a hard glue with $n_g=5$ was motivated by comparison of calculations[10] of high-mass, high-$p_T$ lepton pairs with data,[12] and is further supported by the present data on prompt photons. More recent calculations[13] of photo- lepto-, and hadroproduction of $\psi$ and $\Upsilon$ have also required gluon densities of the form of Eq. (2), with $n_g\simeq 5$.

We believe this to be the most direct and, there-



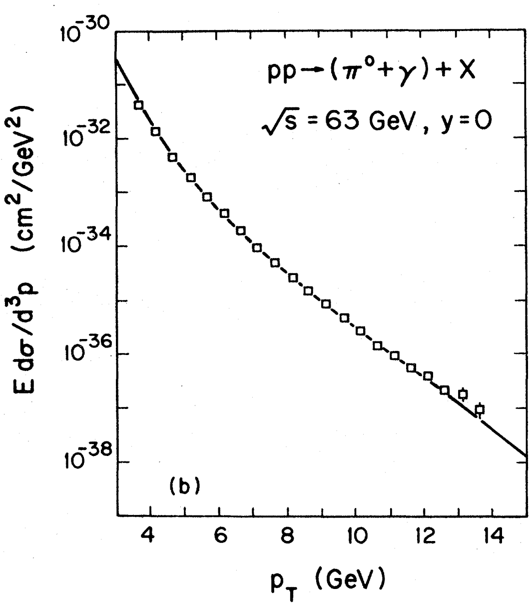




FIG. 1(a) Direct-photon cross section in $pp$ collisions at $\sqrt{s} = 63$ GeV, $y = 0$ as a function of $p_T$. This has been extracted from $\gamma/\pi^0$ in Ref. 4, and the $(\pi^0+\gamma)$ cross section of Ref. 6. (b) The $(\pi^0+\gamma)$ cross section (Ref. 6) in $pp$ collisions at $\sqrt{s} = 63$ GeV, $y = 0$. The curve is $E\,d\sigma/d^3p = 27.59\,p_T^{-13.15}\exp(1.268p_T - 0.052\,97\,p_T^2)$ in units of $10^{-27}$ cm$^2$/GeV$^2$.

fore, reliable determination of the gluon structure function of the proton. The $x$ range to which the high-$p_T$ $\gamma$ data are sensitive is of course quite small, and in particular can give no hint as to the $x \to 1$ behavior of $xG(x,Q^2)$. Furthermore, a source of uncertainty for the lower $p_T$ range ($p_T \lesssim 5$ GeV) in particular is provided by the intrinsic transverse momenta of the scattering constituents in their parent hadrons. The implementation of this smearing is ambigous because the QCD perturbation-theory cross sections must be cut off to prevent collinear divergences,[14] but for higher values of $p_T$ ($p_T \gtrsim 5$ GeV), reasonable variations of the cutoff provide little change in the result. A simple way, but no more or less *ad hoc* than any other way, to implement the smearing is provided by

$$E\frac{d\sigma^{\rm sm}}{d^3p}(p_T) = \int d^2k_T\, E\frac{d\sigma^{\rm QCD}}{d^3p}\left((k_T^2+M^2)^{1/2}\right) \times f(p_T - k_T)\,. \qquad (3)$$

We choose the smearing function $f$ to be a Gaussian,

$$f(p_T) = \frac{1}{\pi\langle p_T^2\rangle} e^{-p_T^2/\langle p_T^2\rangle}\,, \qquad (4)$$

and $M^2 = 1$ GeV$^2$ for the cutoff. Comparison[10] between calculation and data on $\langle p_T^2\rangle$ in high-mass lepton-pair production suggests a total contribution of $\langle p_T^2\rangle_{\rm intrinsic} = 1$ GeV$^2$. Considerations of $\langle p_T^2\rangle$ in $\Upsilon$ production have led Owens and Kimel[15] to $\langle p_T^2\rangle_{\rm intrinsic} = 2.4$ GeV$^2$ for $GQ$. The results of smearing with these two values are shown in Fig. 2(c). As before we use $n_g = 5$ in Eq. (2). Note that even at $p_T = 9$ GeV, the smearing can produce a change of $\simeq 50\%$ to the cross section.

The theoretical problems related to the "soft" $p_T$ corrections are formidable: the choice of the argument of $\alpha_s$, the specific cutoff prescription used to regularize the divergence of the $O(\alpha_s)$ diagrams,[14] high-twist subprocesses,[16] etc. We therefore decided to use a smearing prescription that could be gauged using related data. It is important to note, however, that these ambiguities are far more severe in calculations of large-$p_T$ data using a hadron trigger. We find that, for the choice $\langle p_T^2\rangle_{\rm intrinsic} = 1$ GeV$^2$, they result in a factor 2–3 in $pp \to \pi^0X$ at, e.g., $p_T = 6$ GeV, $\sqrt{s} = 31$ GeV. They affect the $pp \to \gamma X$ yield at the level of 60% and lead to an ambiguity of less than 20% in the $\gamma/\pi$ ratio. The reduced smearing effects result from the relative flatness of the $\gamma$ transverse-momentum distribution and make QCD tests using a $\gamma$ trigger trustworthy at relatively small $p_T$ values.

We now turn to measurements of the away-side jet. The most inclusive such measurement is simply the double inclusive cross section for opposite-side high-$p_T$ photon and jet. When both are produced at 90°, the kinematics is particularly simple, and neglecting the $Q\bar{Q}$ contribution, we find for $y_\gamma = y_J = 0$,

$$\frac{d\sigma}{dy_\gamma\, dy_J\, dp_T} = \frac{5\pi\alpha\alpha_s}{3}\frac{G(x_T,Q^2)F_2(x_T,Q^2)}{x_T^2 s^{3/2}}\,. \qquad (5)$$

Here $F_2$ is the usual deep-inelastic leptoproduction

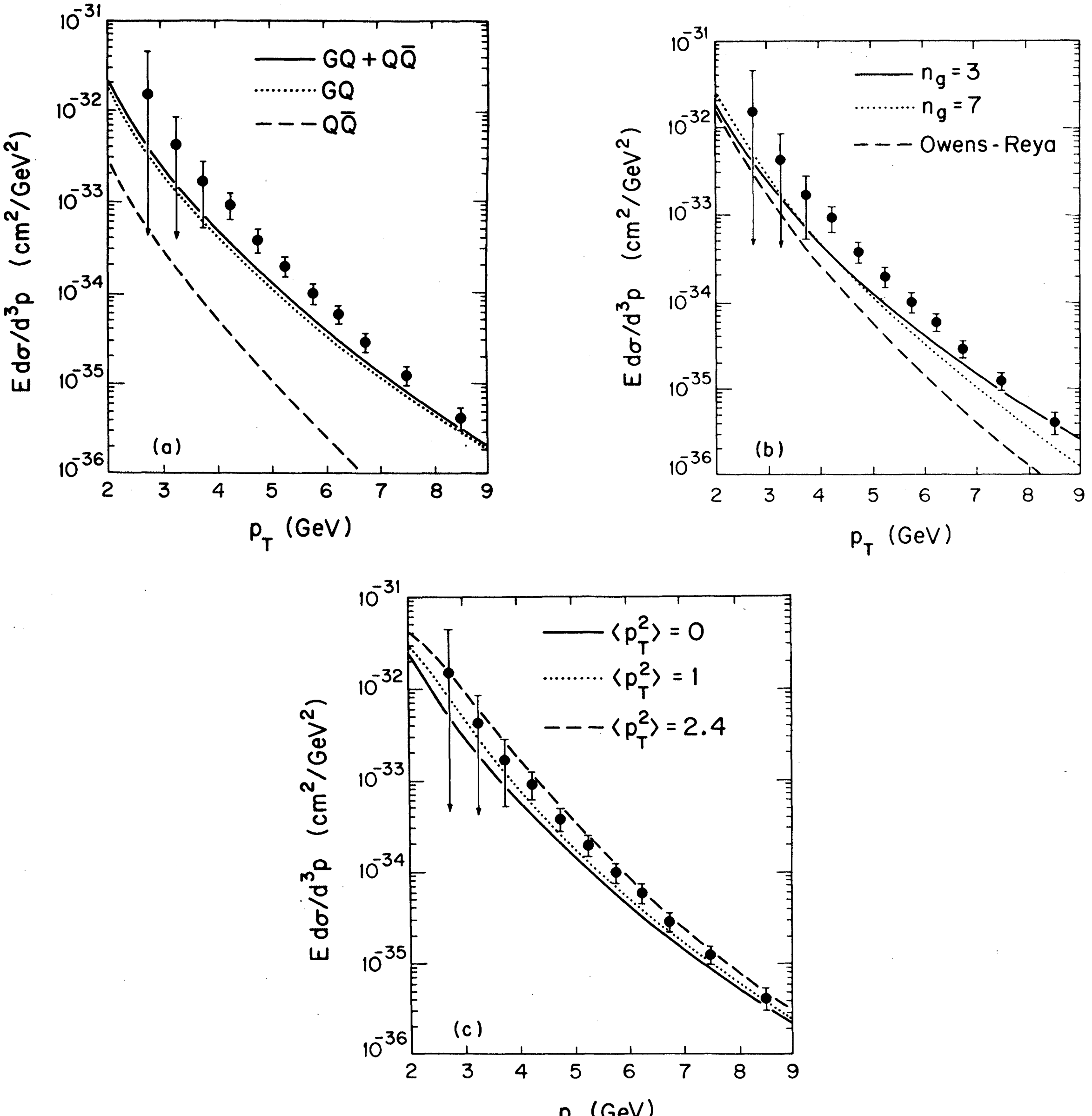



FIG. 2. (a) The direct-photon cross section is compared to the QCD calculation. The dotted line is the contribution from $GQ$, the dashed line the contribution from $Q\bar{Q}$, and the solid line the sum. (b) The direct-photon cross section is compared to QCD calculations using different gluon densities. The solid and dotted lines use Eq. (2) with $n_g=3$, 7, respectively, and the dashed line uses the gluon density from Ref. 9. (c) The result of smearing the QCD calculation using Eqs. (3) and (4) is demonstrated. We smear with total intrinsic parton transverse momenta of 0, 1, and 2.4 GeV$^2$.

structure function, $x_T = 2p_T/\sqrt{s}$, and $Q^2 = 4p_T{}^2/3$. The calculations of high-$p_T$ jet-jet cross sections are less affected by smearing than single-particle or single-jet cross sections, because the intrinsic transverse momentum contributes equally on both sides. The same will be true here where the photon is the whole jet on one side. We show our calculations of the jet-jet cross section in Fig. 3(a) for center-of-mass energies $\sqrt{s}=27.4$ and 63 GeV. Note that via Eq. (5) such a measurement constitutes a direct measurement of the gluon density $G(x,Q^2)$.

The normalized distributions of the away-side jet are shown in Fig. 3(b), at $\sqrt{s}=63$ GeV for the

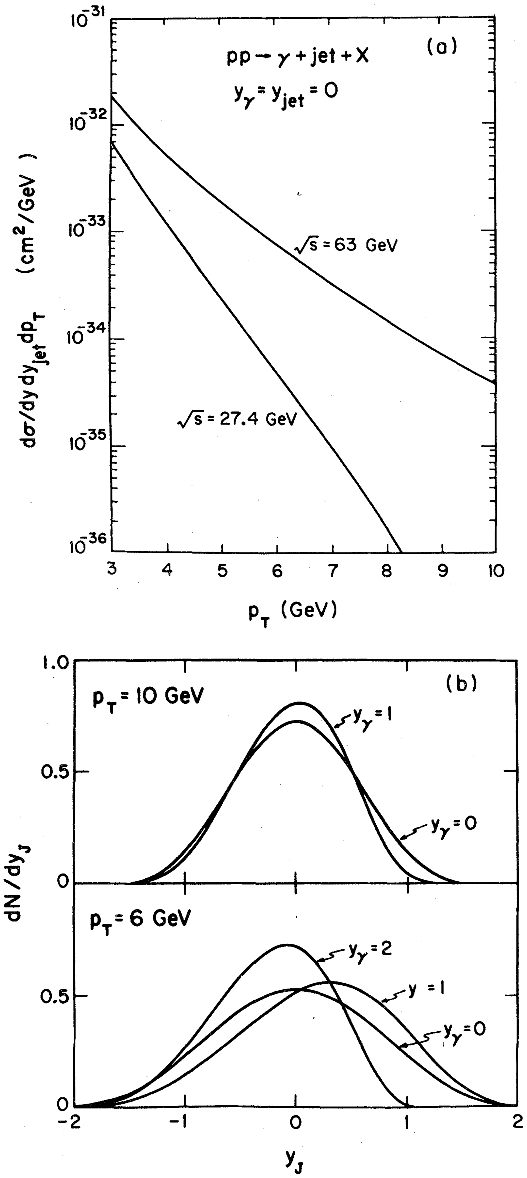



FIG. 3(a) The cross section for $pp \to \gamma+\text{jet}+X$ at 90° in the center of mass for $\sqrt{s}=27.4$ and 63 GeV. (b) The normalized distribution of the away-side jet in rapidity $y_J$ in $pp \to \gamma+\text{jet}+X$ at $\sqrt{s}=63$ GeV for $p_T=6$, 10 GeV and $y_\gamma=0,1,2$.

choice of $p_T=6,10$ GeV and $y_\gamma=0,1,2$.

More detailed measurements observe individual hadrons within the high-$p_T$ jets. Measurements presented in Ref. 17 show that a high-$p_T$ $\gamma$ is produced on its own, in contrast to a high-$p_T$ $\pi^0$ which is a fragment of a higher-$p_T$ quark or (sometimes) gluon. The away-side jet opposite a $\gamma$ is found to be harder than that opposite a $\pi^0$ as expected.[2] This is because at high $p_T$ the $GQ$ subprocess dominates $\gamma$ production implying that the away-side jet is a quark, whereas the jet opposite a $\pi^0$ can be a quark or a gluon. The result then follows from the assumption that the gluon fragmentation is softer, and has a higher hadronic multiplicity, than quark fragmentation.

The detailed distribution of hadrons in the away-side jet is calculated using fragmentation functions of quarks into hadrons, found from analyses of hadron production in deep-inelastic leptoproduction and $e^+e^-$ annihilation experiments. Where $y=y_J=0$ the kinematics simplifies, and we obtain in the approximation $Q\bar{Q}=0$,

$$\frac{dN^h}{dz}=\frac{\sum e_q^{\,2}q(x_T)D_q^h(z)}{\sum e_q^{\,2}q(x_T)}\,. \tag{6}$$

Here $z$ is the fraction of the quark's momentum carried by the hadron $h$, $e_q$ in the quark's charge, $q(x_T)$ is the distribution of quarks in the proton, and $D_q^h(z)$ is the fragmentation function for $q\to h$. The sum is over flavors of $q$ and $\bar{q}$. Note that the gluon density canceled out in Eq. (6) and the resulting hadron distribution is the same as that in leptoproduction from a proton. One consequence of this is that the away-side jet is usually a $u$ quark. Not only does the parent proton contain more $u$ quarks than any other, but because the photon coupling is proportional to the quark charge, the $u/d$ ratio is enhanced by 4/1.

In order to make explicit calculations, we choose the $D_q$'s of Feynman and Field.[18] The constant $(z\to 1)$ behavior of $D_{q\to\pi}(z)$ of Feynman and Field has lately been challenged and affects our results near $z\simeq 1$. There is fortunately an empirical way to shortcut this problem. As pointed out in Ref. 2, the distribution of Eq. (6) is the same as the one appearing in the calculation of hadrons produced in the parton fragmentation region in deep-inelastic lepton scattering from a proton target. We have checked that our explicit parametrization is in agreement with such data. To investigate the effect of scaling violations on the $D_q$'s we use the $Q^2$ dependence generated by[19]

$$\begin{aligned}
&xD(x,Q^2)=\int_x^1 dz\,K(z,\xi)\frac{x}{z}D\left(\frac{x}{z},Q_0^{\,2}\right),\\
&K(z,\xi)=e^{\Lambda\xi}(1-z)^{(16\xi/3)-1}/\Gamma(16\xi/3)\,,\\
&\Lambda=4(3-4\gamma_E)/3\simeq 0.923\,,\\
&\gamma_E=\text{Euler's constant}\simeq 0.577\,,\\
&\xi=\frac{3}{33-2n_f}\ln[\alpha_s(Q_0^{\,2})/\alpha_s(Q^2)]\,,
\end{aligned} \tag{7}$$

where $n_f$ is the number of flavors, and $\alpha_s$ is the strong fine-structure constant. This solution of the evolution equations for fragmentation[20] is strictly speaking valid for valence fragmentation and $x\simeq 1$.

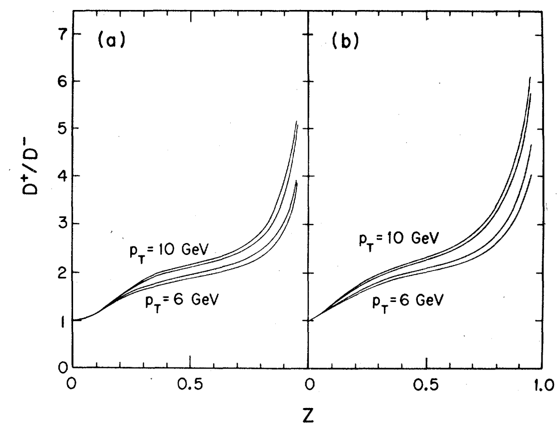



FIG. 4(a) The ratio $D^+/D^-$ of hadrons in the jet opposite a high-$p_T$ photon produced at 90° in $pp$ collisions at $\sqrt{s}$ = 63 GeV is plotted against the hadron fractional momentum $z$. The quark decay functions are those of Feynman and Field (Ref. 17). (b) Same as (a), but with scaling violations in the decay functions implemented by Eq. (7).

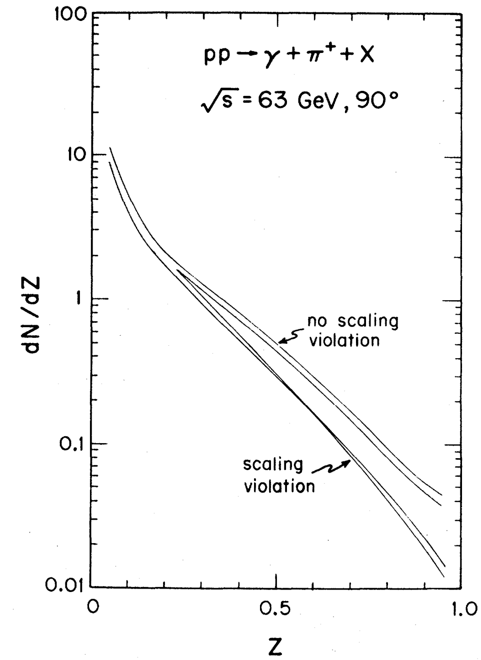



FIG. 5. The distribution $dN/dz$ of $\pi^+$ opposite a high-$p_T$ photon produced at 90° in $pp$ collisions at $\sqrt{s}$ = 63 GeV. The two curves show the result of calculating with or without scaling violations in the quark fragmentation functions.

Our results for the ratio of positive to negative particles $D^+/D^-$ are shown in Figs. 4(a) and 4(b). Here $\sqrt{s}=63$ GeV, $y=0$ we have integrated over the rapidity of the away-side jet, and have chosen the transverse momentum of the photon to be $p_T = 6, 10$ GeV. Figure 4(a) shows the result with no scaling violation, Fig. 4(b) that with the scaling violations given by Eq. (7). There is little difference. We note that as expected, for large $z$, $D^+/D^-$ becomes large. The uncertainty shown by the bands in this figure is provided by two extreme (we hope) assumptions about glue fragmentation: either $D_g^h=0$ or $D_g^h=D_q^h$. The effect is small because the contribution from $Q\bar{Q}$ is small.

Another effect of the away-side jet being dominantly a $u$ quark will be seen in the spectator jets, which have low $p_T$ with respect to the original beam-beam direction. After the hard scatter, there will be one spectator jet with valence quark structure $uud$, and one with $ud$. This will lead to a charge asymmetry $|\Delta Q| = \frac{2}{3}$ between the spectator jets.

Our final topic concerns scaling violations in fragmentation functions. Theoretically these are described by evolution equations[20] very similar to those familiar for parton densities in a hadron. Experimentally, little is yet known about them. In $e^+e^-$ annihilation the $D$'s of light quarks are obscured by charm and bottom production. Until the momentum spectra of charm and bottom in $e^+e^-$ annihilation is known, it will be hard to disentangle light quark scaling violations. Experiments on hadron production in high-energy muon and neutrino scattering may soon be able to shed some light on this. So may measurements of hadrons opposite a high-$p_T$ $\gamma$ (though the definition of $Q^2$ is somewhat arbitrary here). To demonstrate this we show the spectra of away-side hadrons opposite a high-$p_T$ direct photon, with and without scaling violations in the $D$'s, in Fig. 5. We take $\sqrt{s}=63$ GeV, $y_\gamma=0$. The width of each band comes from choosing the transverse momentum of the photon to be $p_T=6$, 10 GeV, and from taking, as before, $D_g=0$ or $D_g=D_q$. We note that while comparison between $p_T=6$ and $p_T=10$ GeV distributions will show little scaling violations, comparison of either with low-energy (below charm threshold) $e^+e^-$ data will.

To summarize, we believe that the discovery of direct photons of high transverse momentum at their measured levels is a success for QCD perturbation theory. The cross section has already constrained the glue density for $x \simeq 0.1-0.3$ and we look forward to data at higher $p_T$. Data on the detailed structure of the away-side jet should provide interesting tests concerning the dominant underlying subprocess $gq \to \gamma q$, and may give useful information about light-quark fragmentation functions.

Near the completion of this work we were informed by J. F. Owens that he and L. Cormell were near the completion of a similar study, described in Ref. 21. We wish to thank him for useful discussions and information. We also thank C. Kourkoumelis, D. C. Rahm, and L. Resvanis for discussions. This research was supported in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation, and in part by the Department of Energy under Contract No. DE-AC02-76ER00881, C00-881-140.

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