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Large-p_T photon plus opposite-side jet events and the gluon distribution in the nucleon

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A QCD analysis of recent CERN ISR preliminary data on large-p_T photon plus opposite-side jet events is presented. Higher-order corrections (K factors) are taken into account. The photon bremsstrahlung contribution is determined and discussed. Some extensively used sets of parton distributions (mainly characterized by different gluon distributions) are compared in detail with the data, and conclusions as to the preferred gluon distribution are deduced.

I. INTRODUCTION

Inclusive production of direct photons in hadron collisions, $A+B\rightarrow\gamma+X$, at large transverse momentum (p_T) is known as one of the most important tests of QCD (Ref. 1). The magnitude of the cross section and the p_T dependence of the ratio γ/π^0 are well in accord with QCD predictions.[1] More recently, the magnitude and the p_T dependence of the cross-section ratio of $\pi^-p\rightarrow\gamma X$ over $\pi^+p\rightarrow\gamma X$ has also been found in accord with QCD predictions;[2–4] this ratio is known to reflect the increasing importance of the annihilation subprocess $q\bar{q}\rightarrow\gamma g$ (Ref. 4).

Very recently the Axial Field Spectrometer (AFS) Collaboration has produced at the CERN ISR ($\sqrt{s}=63$ GeV) the first preliminary data on[5,3]

$$p+p\rightarrow\gamma+\text{jet}_{\text{opp}}+X \tag{1.1}$$

involving a large-p_T direct photon together with an opposite-side jet. This reaction, being kinematically simpler than, e.g.,

$$p+p\rightarrow\gamma+X \tag{1.2}$$

(see Secs. II and III), offers the possibility of further testing QCD.

More specifically, in QCD both reactions (1.1) and (1.2) are known to be dominated by the subprocess $qg\rightarrow\gamma q$; thus the gluon distribution in the proton plays a very important role. Then (1.1), because of its simpler kinematics, offers the opportunity of testing the various gluon distributions and, perhaps, discriminating between them. It is the purpose of this work to carry such a test.

Section II presents some basic formulas for the reaction (1.1), specifies the gluon distributions (more precisely, the sets of parton distributions) to be tested, and outlines our procedure. Section III discusses higher-order QCD corrections (K factors) and the photon bremsstrahlung (brems) contribution. Section IV presents our results and conclusions.

II. BASIC FORMULAS AND PROCEDURE

Consider $A+B\rightarrow\gamma+\text{jet}_{\text{opp}}+X$ and let p_{T1} and η_1 denote the transverse momentum and (pseudo)rapidity of the photon and p_{T2} and η_2 those of the jet. The inclusive cross section for this process can be derived from that for $A+B\rightarrow\text{jet}_1+\text{jet}_2+X$ [Eq. (A13) of Ref. 6]. Let also $a+b\rightarrow c+\gamma$ be a contributing subprocess and $d\sigma/d\hat{t}$ its cross section. Writing $d^3p_i/E_i\simeq d\eta_i d^2p_{\text{T}i}$, $i=1,2$, and integrating with respect to d^2p_{T2} we obtain the following contribution to $AB\rightarrow\gamma+\text{jet}_{\text{opp}}+X$:

$$\frac{d\sigma}{d^2p_{T1}}=\frac{1}{\pi}F_{a/A}(x_a)F_{b/B}(x_b)\left.\frac{d\sigma}{d\hat{t}}\right|_{\mathbf{p}_{T2}=-\mathbf{p}_{T1}}d\eta_1 d\eta_2\ , \tag{2.1}$$

where $F_{a/A}(x_a)=F_{a/A}(x_a,Q^2)$, etc., parton distributions, and, with $x_{T1}\equiv 2p_{T1}/\sqrt{s}$,

$$x_a=\frac{x_{T1}}{2}(e^{\eta_1}+e^{\eta_2}),\quad x_b=\frac{x_{T1}}{2}(e^{-\eta_1}+e^{-\eta_2})\ . \tag{2.2}$$

Thus

$$\frac{d\sigma}{d\eta_1 d\eta_2 dp_{T1}}=2p_{T1}F_{a/A}(x_a)F_{b/B}(x_b)\left.\frac{d\sigma}{d\hat{t}}\right|_{\mathbf{p}_{T2}=-\mathbf{p}_{T1}}. \tag{2.3}$$

Notice that last expression involves no integration over the parton distributions. This is in contrast with the inclusive cross section $E\,d\sigma/d^3p$ for $AB\rightarrow\gamma X$ which involves one integration.[1,4] In this sense $AB\rightarrow\gamma+\text{jet}_{\text{opp}}+X$ is kinematically simpler.

Introducing the invariant mass M of the system $\gamma+$jet,

$$M^2\equiv(p_1+p_2)^2\ , \tag{2.4}$$

and using (2.2) we obtain

$$M^2=2p_{T1}{}^2[1+\cosh(\eta_1-\eta_2)]\ . \tag{2.5}$$

From (2.3)

$$\frac{d\sigma}{d\eta_1 d\eta_2 dM}=M\frac{F_{a/A}(x_a)F_{b/B}(x_b)}{1+\cosh(\eta_1-\eta_2)}\frac{d\sigma}{d\hat{t}} \tag{2.6}$$

with $d\sigma/d\hat{t}$ always calculated at $\mathbf{p}_{T2}=-\mathbf{p}_{T1}$.

As for $AB\rightarrow\gamma X$, also for $AB\rightarrow\gamma+\text{jet}+X$ the basic contributing subprocesses are $qg\rightarrow\gamma q$ and $q\bar{q}\rightarrow\gamma g$. For $A=B=$ proton the contribution of the latter is $\sim 10\%$. Nevertheless in our analysis we use both of them.

For the parton distributions $F_{a/A}(x,Q^2)$ we first consider the sets I and II of Duke and Owens[7] (DO-I, DO-II). We also consider the sets of the CERN-Dortmund-Heidelberg-Saclay (CDHS) Collaboration[8] and of Glück, Hoffman, and Reya[9] (GHR). We remind the reader that DO-I and CDHS distributions are characterized by more narrow gluon distributions and the QCD parameter $\Lambda=0.2$ GeV; DO-II and GHR have broader gluon distributions and $\Lambda=0.4$ GeV.

Regarding the scale (large variable) Q^2 in the distributions $F_{a/A}(x,Q^2)$ and in the running coupling $\alpha_s(Q^2)$, we work with two simple choices: $Q^2=p_{T1}{}^2$ (suggested as a "natural" choice by the cross section $d\sigma/d\eta_1 d\eta_2 dp_{T1}$) and $Q^2=M^2$ (suggested by $d\sigma/d\eta_1 d\eta_2 dM$); other conventional choices, $Q^2=2p_{T1}{}^2$, $4p_{T1}{}^2/3, -\hat{t}$, $2\hat{s}\hat{t}\hat{u}/(\hat{s}^2+\hat{t}^2+\hat{u}^2)$, $\hat{s}$ give similar or intermediate results. The choice of Q^2 introduces some uncertainty in the theoretical predictions. Thus we proceed as follows. First we use the above sets of parton distributions to calculate $E\,d\sigma/d^3p$ for $pp\rightarrow\gamma X$ and compare with all available ISR data; this will give some indication as the preferred set and to the preferred $Q^2(=p_{T1}{}^2$ or $M^2)$. Then we use the same sets and the same choices of Q^2 to compare with the AFS data on $d\sigma/d\eta_1 d\eta_2 dp_{T1}$ and $d\sigma/d\eta_1 d\eta_2 dM$ of $pp\rightarrow\gamma+\text{jet}+X$.

At ISR energies partons' intrinsic transverse momentum (k_T) effects on direct photon cross sections are not very important. For $AB\rightarrow\gamma+\text{jet}_{\text{opp}}+X$ the large-p_T photon is balanced by the opposite-side jet; this diminishes the trigger (photon) bias and further reduces the k_T effect. Thus in our analysis we neglect this effect altogether.

III. HIGHER-ORDER CORRECTIONS AND PHOTON BREMS

It should be stressed that in a complete calculation the $O(\alpha_s{}^2)$ corrections (next-to-leading logarithmic) for $AB\rightarrow\gamma+\text{jet}+X$ and for $AB\rightarrow\gamma X$ are *not* the same; i.e., *a priori* the complete (or exact) K factors are unrelated. For $AB\rightarrow\gamma+jet+X$ a complete $O(\alpha_s{}^2)$ calculation does not yet exist; and, strictly speaking, nothing can be deduced from a complete $O(\alpha_s{}^2)$ calculation of $AB\rightarrow\gamma X$.

In the approach of approximate K factors one takes into account loop graphs in the soft-gluon limit and collinear and soft-gluon brems.[10,11] In particular for $pp\rightarrow\gamma X$ at $\sqrt{s}=63$ GeV and $\eta_\gamma=0$, the $O(\alpha_s{}^2)$ corrections resulting in this approach are in excellent agreement with those of complete $O(\alpha_s{}^2)$ calculations [see Fig. 7(a') of Ref. 10]. Since the basic subprocesses of $pp\rightarrow\gamma+\text{jet}_{\text{opp}}+X$ are the same, we are encouraged to proceed with approximate K factors for this reaction as well.

For $qg\rightarrow\gamma q$ and $q\bar{q}\rightarrow\gamma g$ these K factors are of the form

$$K=1+\frac{\alpha_s(Q^2)}{2\pi}C\pi^2 \tag{3.1}$$

with[10,12]

$$C(qg\rightarrow\gamma q)=\frac{N_c}{2}+\frac{C_F}{3},\quad C(q\bar{q}\rightarrow\gamma g)=C_F \tag{3.2}$$

[$N_c=3$, $C_F=\frac{4}{3}$ in color SU(3)]. These approximate K factors are the same for $pp\rightarrow\gamma X$.

Photon brems is due to subprocesses of the type

$$a+b\rightarrow c+d+\gamma\ . \tag{3.3}$$

It is known that most of this contribution arises when γ is collinear with a final parton (mainly quark). Then along the γ direction one expects to see hadrons or some jet (accompanied γ events).

The AFS experiment[5] requires no hadronic jet in angle $\theta\lesssim 20^\circ$ around the parton; this seems to reject accompanied γ events and thus to exclude most of photon brems. However, in practice there are several questions regarding this procedure. These include questions on the jet definition, on the fragmentation into hadrons, on the collinearity with the produced photon, etc. At not too high p_T and energies (including ISR) some of these questions become more acute. Also some fraction (although small) of brems events (3.3) undoubtedly proceeds via noncollinear γ. Thus we shall not altogether reject brems, but shall try to take account of part of it (see below).

We consider the contribution to $AB\rightarrow\gamma+\text{jet}_{\text{opp}}+X$ of the subprocess $ab\rightarrow cd\gamma$ when γ is collinear to one of the final partons, say c. This can be derived from Eq. (A.8) of Ref. 6. We write $D_{\gamma/c}(z_1)$ for the fragmentation function $c\rightarrow\gamma$, and replace $G_2(z_2)\rightarrow\delta(z_2-1)$ for parton d:

$$E_1E_2\frac{d\sigma}{d^3p_1d^3p_2}=\frac{16}{\pi s x_{T1}{}^2 x_{T2}{}^2}\int dx_a x_a F_{a/A}(x_a)F_{b/B}(x_b)\frac{d\sigma}{d\hat{t}}\frac{1}{(e^{\eta_1}+e^{\eta_2})^2}\times D_{\gamma/c}\left[\frac{x_{T1}}{2x_a}(e^{\eta_1}+e^{\eta_2})\right]\delta\left[\frac{x_{T2}}{2x_a}(e^{\eta_1}+e^{\eta_2})-1\right]\delta(\phi_1-\phi_2+\pi)\ , \tag{3.4}$$

where $x_b=x_a e^{-\eta_1-\eta_2}$ and $d\sigma/d\hat{t}$ the differential cross section of the subprocess $ab\rightarrow cd$. Writing $d^3p_i/E_i=d\eta_i p_{Ti}dp_{Ti}d\phi_i$, carrying the integration with respect to ϕ_2 with the help of the δ function, and integrating with respect to ϕ_1 we finally obtain, setting $x_{T2}=x$,

$$\frac{d\sigma}{d\eta_1 d\eta_2 dp_{T1}}=\frac{s}{2p_{T1}}\int_{x_0}^{x_m}dx\,xF_{a/A}(x_a)F_{b/B}(x_b)\frac{d\sigma}{d\hat{t}}D_{\gamma/c}\left[\frac{x_{T1}}{x}\right]\ , \tag{3.5}$$

where

$$x_a=\frac{x}{2}(e^{\eta_1}+e^{\eta_2})\ ,\quad x_b=\frac{x}{2}(s^{-\eta_1}+e^{-\eta_2})\ ; \tag{3.6}$$

also we obtain

$$\begin{aligned} x_0&=x_{T1}\equiv\frac{2p_{T1}}{\sqrt{s}}\ ,\\ x_m&=\min\left\{\frac{2}{e^{\eta_1}+e^{\eta_2}},\frac{2}{e^{-\eta_1}+e^{-\eta_2}}\right\}\ . \end{aligned} \tag{3.7}$$

Furthermore by writing the squared γ-jet invariant mass M,

$$M^2=\tfrac{1}{2}x_{T1}xs[1+\cosh(\eta_1-\eta_2)]\ , \tag{3.8}$$

we obtain

$$\frac{d\sigma}{d\eta_1 d\eta_2 dM} =\frac{s}{M}\int_{x_l}^{x_m}dx\, xF_{a/A}(x_a)F_{b/B}(x_b)\frac{d\sigma}{d\hat{t}}D_{\gamma/c}\left[\frac{x_{T1}}{x}\right]\ , \tag{3.9}$$

where now $x_{T1}=2M^2/xs[1+\cosh(\eta_1-\eta_2)]$ for fixed M, x, s, η_1, η_2, and

$$x_l=\left[\frac{2}{1+\cosh(\eta_1-\eta_2)}\right]^{1/2}\frac{M}{\sqrt{s}}\ . \tag{3.10}$$

We note also that

$$\begin{aligned} \hat{s}&=\frac{x^2}{2}s[1+\cosh(\eta_1-\eta_2)]\ ,\\ \hat{t}&=-\frac{x^2}{4}s(1+e^{\eta_2-\eta_1})\ ,\\ \hat{u}&=-\frac{x^2}{4}s(1+e^{\eta_1-\eta_2})\ . \end{aligned} \tag{3.11}$$

The fragmentation function $D_{\gamma/c}(z)=D_{\gamma/c}(z,Q^2)$ entering Eqs. (3.4) and (3.5) has the form

$$D_{\gamma/c}(z,Q^2)=\frac{\alpha}{2\pi}d_{\gamma/c}(z)\ln\frac{Q^2}{\tilde{\Lambda}^2}\ ; \tag{3.12}$$

we shall take $\tilde{\Lambda}=\Lambda$. A convenient parametrization of the function $d_{\gamma/c}(z)$ is[13]

$$d_{\gamma/c}(z)=2z^{\lambda}\sum_{n=0}^{4}a_n^c z^n\ ;$$

the constants λ and a_n^c are given in Ref. 13.

This completes the basic formulas for the collinear γ brems contribution to $AB\to\gamma+\text{jet}_{\text{opp}}+X$. Notice that, as usual, for γ collinear with a final parton the final contribution, Eqs. (3.5) and (3.9), has a factorable form. Notice also that this contribution involves only a single integral, unlike the corresponding contribution to $E\,d\sigma/d^3p$ of $AB\to\gamma X$ which involves a double integral.[4] We see that again $AB\to\gamma+\text{jet}_{\text{opp}}+X$ is kinematically simpler.

Regarding $d\sigma/d\hat{t}$ for $ab\to cd$ (i.e., $qq\to qq$, $qg\to qg$, $gg\to q\bar{q}$, etc.), to the lowest order $[O(\alpha_s^2)]$, expressions are given in Ref. 14. Complete calculations of higher-order $[O(\alpha_s^2)]$ corrections exist only for the $qq'\to qq'$ contribution to $pp\to\pi X$ (q,q' nonidentical quarks). However, approximate K factors of the form (3.1) have been determined for all subprocesses $ab\to cd$ (Ref. 15); and for $qq'\to qq'$ they well agree with those of complete calculations.[10,11] With $Q^2\sim p_T^2$ and for the p_T of interest[5] approximate K factors are found to be in the range $1.6\lesssim K\lesssim 2$ (Ref. 16), thus $\sim$ doubling photon brems.

Then in view of the fact that the AFS experiment rejects part (but not all) of photon brems we shall proceed as follows. We shall present several results without brems; also we shall present results with the brems contributions (3.5) and (3.9), but without higher-order corrections [i.e., with $K(ab\to cd)=1$]. In the latter case our brems cross sections are well below 30% of the total, a limit set by the AFS Collaboration for $pp\to\gamma X$ (Ref. 5).

Now an important point to notice is the following. For $\eta_1=\eta_2$ Eqs. (2.3) and (2.4) imply

$$\frac{d\sigma(s,p_T)}{d\eta_1 d\eta_2 dp_T}=2\frac{d\sigma(s,M=2p_T)}{d\eta_1 d\eta_2 dM}\ . \tag{3.13}$$

This relation is not affected if K factors (3.1) and (3.2) are included. In fact, (3.13) is quite general and trivially follows if $M=2p_T$. It does not hold, however, if photon brems is included. We return to this relation in the next section.

IV. RESULTS AND CONCLUSIONS

We begin with the calculation of $E\,d\sigma/d^3p$ for $pp\to\gamma X$ and comparison with data at all ISR energies, i.e., $\sqrt{s}=63$, 53, 45, and 31 GeV. Most of these data also resulted from experiments rejecting accompanied γ events to a great extent. Therefore we calculate $pp\to\gamma X$ either without photon brems, or with photon brems but $K(ab\to cd)=1$.

We give, for completeness, the input forms of the gluon distributions: DO-I ($Q^2=Q_0^2=4$ GeV^2; $\Lambda=0.2$ GeV) (Ref. 7),

$$F_{g/p}(x,Q_0^2)=1.56\ (1+9x)(1-x)^6\ ; \tag{4.1}$$

DO-II ($Q_0^2=4$; $\Lambda=0.4$) (Ref. 7),

$$F_{g/p}(x,Q_0^2)=0.879\ (1+9x)(1-x)^4\ ; \tag{4.2}$$

CDHS ($Q_0^2=5$; $\Lambda=0.2$) (Ref. 8),

$$F_{g/p}(x,Q_0^2)=2.616\ (1+3.5x)(1-x)^{5.9}\ ; \tag{4.3}$$

and GHR ($Q_0^2=4$; $\Lambda=0.4$) (Ref. 9),

$$F_{g/p}(x,Q_0^2)=0.93\ (1+8.5x+53.57x^2)(1-x)^6\ . \tag{4.4}$$

We use the scales $Q^2=p_T^2$ and $Q^2=4p_T^2$.

Figure 1 compares results using DO-I and DO-II with most of the available ISR data. First we see that photon brems gives a small contribution, in particular at the larger p_T (dash-dotted line: DO-I, $Q^2=p_T^2$, with brems, vs solid line: the same without brems). Second, the scale $Q^2=4p_T^2$ gives results below most of the data (short-dashed: DO-I, $Q^2=4p_T^2$, no brems). Finally, DO-II (long-dashed: $Q^2=p_T^2$, with brems) gives results somewhat exceeding those with DO-I. These trends are quite general in our calculations for $pp\rightarrow\gamma X$ as well as for $pp\rightarrow\gamma+\text{jet}_{\text{opp}}+X$. At the lower p_T ($\lesssim 4$ GeV) our predictions generally fall below the data for $pp\rightarrow\gamma X$, but this may reflect the presence of some intrinsic k_T, which we have completely neglected in this work.

Figure 2 presents results for $pp\rightarrow\gamma X$ using CDHS and GHR. Now GHR (long-dashed: $Q^2=p_T^2$, with brems) gives results above CDHS. We remark that CDHS with $Q^2=p_T^2$ (and with or without brems) is quite successful in particular regarding the AFS data at $\sqrt{s}=63$ GeV (black triangles).

On the basis of Figs. 1 and 2 it may be said that CDHS and DO-I with $Q^2=p_T^2$ are favored by the ISR $pp\rightarrow\gamma X$ data.

Now we turn to $pp\rightarrow\gamma+\text{jet}_{\text{opp}}+X$. First Figs. 3(a) and 3(b) present results with the same choices of parton distributions, Q^2 and photon brems as Fig. 1; and Figs. 4(a) and 4(b) with the choices as Fig. 2.

From Figs. 3(a) and 4(a) the first observation is that for DO-I, DO-II, and GHR the p_{T1} slope of the predicted cross sections is smaller than that of the AFS data. This suggests a softer gluon distribution, at least in the range of x ($\approx x_{T1}$) of the data.

However, Fig. 4(a) shows that CDHS with $Q^2=p_{T1}^2$ (and with or without brems) accounts fairly well for the $d\sigma/d\eta_1 d\eta_2 dp_{T1}$ data, both with respect to the p_{T1} slope and to the magnitude. This is due to the factor $1+3.5x$ in Eq. (4.3), which is smaller than similar factors in Eqs. (4.1), (4.2), and (4.4), and softens the CDHS gluon distribution. Such factors are known to be quite important for intermediate x (intermediate x_{T1}).

Turning now to Figs. 3(b) and 4(b) we remark that in general our predictions are well below the $d\sigma/d\eta_1 d\eta_2 dM$ data (except perhaps, for GHR; this, however, much exceeds the $d\sigma/d\eta_1 d\eta_2 dp_{T1}$ data and has a smaller p_{T1} slope).

On the other hand, a simple comparison of the $d\sigma/d\eta_1 d\eta_2 dp_{T1}$ and the $d\sigma/d\eta_1 d\eta_2 dM$ data shows that they do not satisfy the simple relation (3.13). As we remarked, (3.13) is quite general, provided that γ brems is not important. Thus, at first sight, the departure of the data from (3.13) appears to suggest a significant brems contribution. In fact, the K factors of Ref. 15 [$K(ab\rightarrow cd)\simeq 2$ decreasing to ~ 1.6 as p_{T1} increases] generally improve the slopes in Figs. 3(a) and 4(a), as well as the magnitudes in Figs. 3(b) and 4(b). However, since the

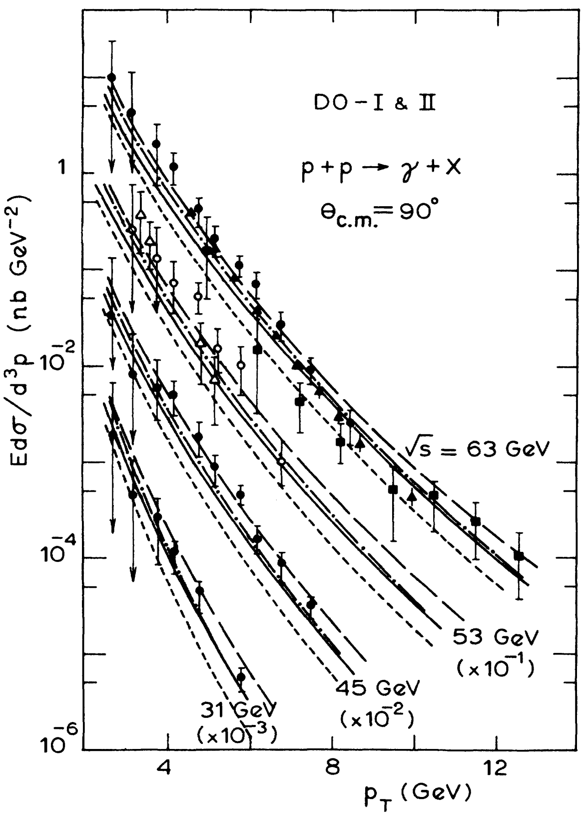

FIG. 1. Inclusive cross sections for $pp\rightarrow\gamma X$ calculated with DO-I and DO-II. Dash-dotted lines: DO-I, $Q^2=p_T^2$, including photon brems. Solid: the same, no brems. Short-dashed: DO-I, $Q^2=4p_T^2$, no brems. Long-dashed: DO-II, $Q^2=p_T^2$, including brems. Data: black triangles, Ref. 17. Circles, Ref. 18. Squares, Ref. 19. Open triangles, Ref. 20.

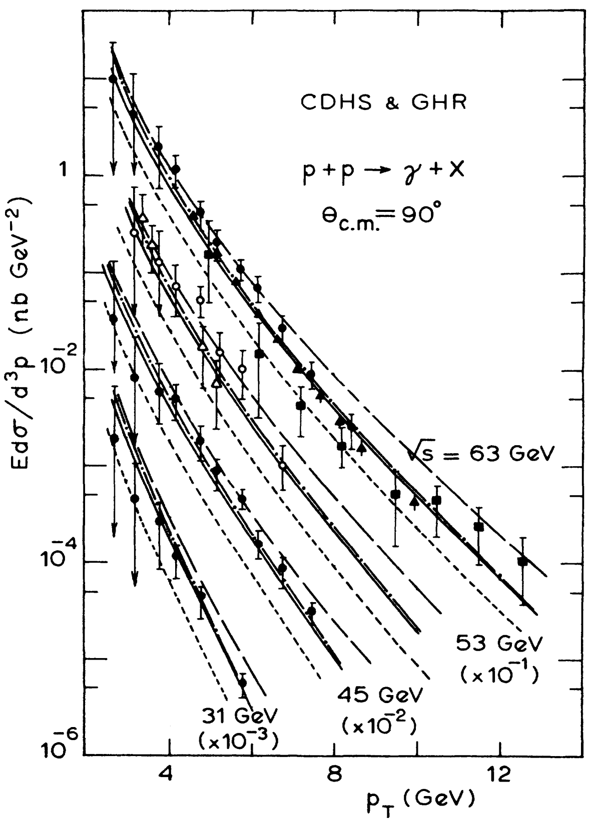

FIG. 2. The same as Fig. 1 calculated with CDHS and GHR. Dash-dotted lines: CDHS, $Q^2=p_T^2$, including photon brems. Solid: the same, no brems. Short-dashed: CDHS, $Q^2=4p_T^2$, no brems. Long-dashed: GHR, $Q^2=p_T^2$, including brems.

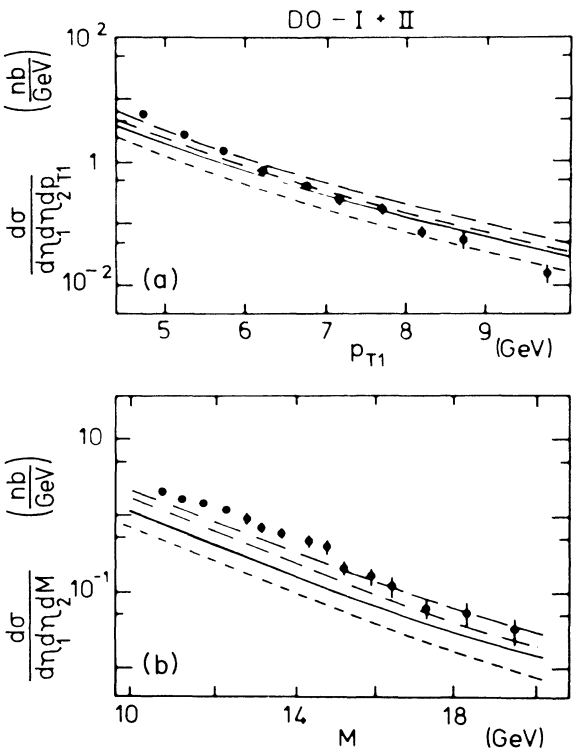

FIG. 3. Inclusive cross sections for $pp \rightarrow \gamma + \mathrm{jet}_{\mathrm{opp}} + X$ at $\sqrt{s} = 63$ GeV and c.m. rapidities $\eta_1 = \eta_2 = 0$ calculated with DO-I and DO-II. Short-dashed lines: DO-I, $Q^2 = M^2$, no brems. Other lines as in Fig. 1. Data: Ref. 5 (also presented in Ref. 7). (a) $d\sigma/d\eta_1 d\eta_2 dp_{T1}$ vs photon transverse momentum p_{T1}. (b) $d\sigma/d\eta_1 d\eta_2 dM$ vs γ-jet invariant mass M.

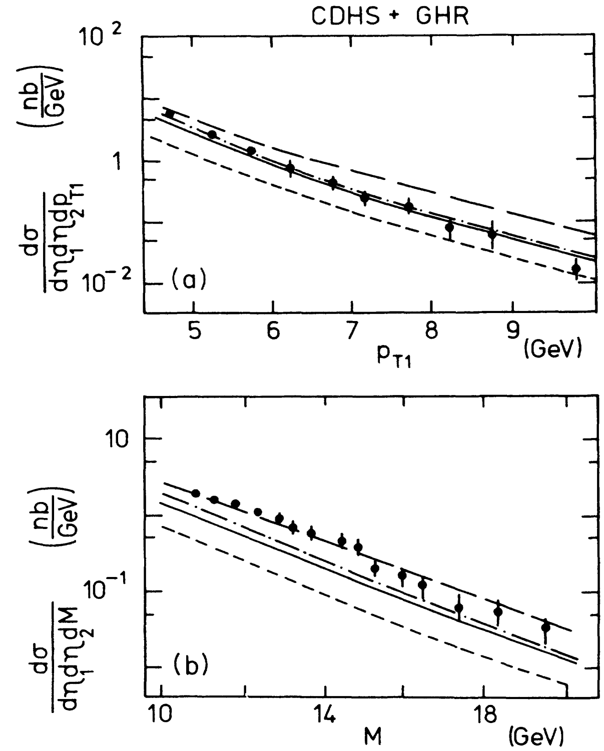

FIG. 4. The same as Fig. 3 calculated with CDHS and GHR. Designation of lines as in Fig. 2, except short-dashed lines: CDHS, $Q^2 = M^2$, no brems. Data as in Fig. 3.

AFS experiment rejects most of the accompanied γ events, and since agreement with the $pp \rightarrow \gamma X$ data without significant brems is good (Figs. 1 and 2), we tend to exclude this possibility.

Another possibility is that some of the particles of the jet are misidentified, so that the experimental determination of the γ + jet invariant mass M involves some error. To some extent, the present γ + jet data[5] should be considered as preliminary.[21] Anyway, we believe that our procedure will be useful in comparison with such data.

On the basis of our comparison with the present data on $d\sigma/d\eta_1 d\eta_2 dp_{T1}$ one may conclude that a *soft* gluon distribution is favored. Among our choices CDHS is the most favored. DO-I is not excluded, and certainly accounts well for the $pp \rightarrow \gamma + X$ cross sections, but is less successful regarding the p_{T1} slope of the $\gamma + \mathrm{jet}_{\mathrm{opp}}$ data.

Note added. Upon completion of this work we became aware of an independent analysis of the present $\gamma + \mathrm{jet}_{\mathrm{opp}}$ data.[22] This analysis proceeds in a completely different way, via Stevenson's principle of minimal sensitivity, and does not consider the CDHS and GHR sets. It concludes that DO-I (i.e., again a rather soft gluon distribution) is consistent with the data.

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