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Direct photon production by $\pi^{\pm}$ beams and the ratio of cross sections by π^- and π^+

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Recent data on direct photon production by positive- and negative-pion beams are confronted with earlier QCD predictions. Particular emphasis is given to the ratio of $\pi^- N \rightarrow \gamma X$ and $\pi^+ N \rightarrow \gamma X$ cross sections.

In a previous publication,[1] in the framework of perturbative QCD, we have presented detailed predictions on large-p_T direct photon production by positive- and negative-pion beams. Particular emphasis was given in the ratio of $\pi^- N \rightarrow \gamma X$ and $\pi^+ N \rightarrow \gamma X$ cross sections. The reason is that as $x_T \equiv 2p_T/\sqrt{s}$ increases the importance of the annihilation subprocess ($q\bar{q} \rightarrow \gamma g$) increases relative to the QCD Compton ($qg \rightarrow \gamma q$); and since the former contributes in $\pi^- p \rightarrow \gamma X$ about eight times more than in $\pi^+ p \rightarrow \gamma X$, the π^-/π^+ cross section ratio is predicted to increase. Thus the increase of this ratio with x_T is an important test of QCD.

As we discussed in Ref. 1, certain preliminary data at a fixed-target energy appeared to contradict this prediction. On the other hand, a phenomenological calculation is known to be beset by a number of uncertainties (form of the gluon distribution, choice of scale Q^2, partons' intrinsic transverse momentum k_T, etc.). The essential purpose of Ref. 1 was to show that, no matter what uncertainties were accounted for, the π^-/π^+ cross-section ratio was *always* predicted to show a clear increase with x_T.

Recently more detailed data on $\pi^{\mp} N \rightarrow \gamma X$ cross sections and on the above ratio have become available.[2–5] The main purpose of this note is to compare these data with the predictions of Ref. 1, adapted to the kinematic variables of the data. A secondary purpose is to compare our predictions with certain independent recent theoretical results.

For our predictions[1] we have used two sets of parton distributions, subsequently denoted DOI and DOII (Ref. 6). We have chosen the scale $Q^2 = p_T{}^2$, but results for other choices $(2p_T{}^2, -\hat{t}/2)$ are also discussed in Ref. 1. We have also introduced[1] photon bremsstrahlung (brems) and studied in detail its contribution for several fixed-target experiments. Finally we took account of partons' intrinsic k_T with a Gaussian distribution and $\langle k_T \rangle = 0.7$ GeV; it was found that at $\sqrt{s} \simeq 19.4$–24 GeV, where the $\pi^{\mp} p \rightarrow \gamma X$ cross sections are fairly steep, the effect is significant.[1] Several other details regarding photon brems and k_T effects are discussed in Ref. 1.

Regarding higher-order $[O(\alpha_s{}^2)]$ corrections (K factors), for the subprocesses $qg \rightarrow \gamma q$ and $q\bar{q} \rightarrow \gamma g$ complete calculations have been carried in Ref. 7, but because of the very large number of terms involved explicit expressions are not available. However, for the energies of our interest and *for the scale* $Q^2 = p_T{}^2$, in the range $2 \lesssim p_T \lesssim 6$ GeV and for not too large rapidity, the resulting K factors can be approximated by[1,8]

$$K(p_T) = \sum_{n=0}^{3} a_n p_T^n \; , \tag{1}$$

where, for $qg \rightarrow \gamma q$, $a_0 \simeq 2.3$, $a_1 = a_2 = a_3 = 0$, and for $q\bar{q} \rightarrow \gamma g$, $a_0 = 4.256$, $a_1 = -1.191$, $a_2 = 0.174$, $a_3 = -8.7 \times 10^{-3}$. These K factors amount to approximately doubling the Born contributions.

Our predictions, adapted to the kinematic variables of the corresponding data, are shown in Figs. 1—3. We denote by $\tilde{\sigma}(p_T,s)$ the invariant inclusive cross section averaged over the rapidity range of each experiment:

$$\tilde{\sigma}(p_T,s) = \frac{1}{\eta_2 - \eta_1} \int_{\eta_1}^{\eta_2} d\eta \, E \frac{d\sigma}{d^3p}(p_T,s,\eta) \; . \tag{2}$$

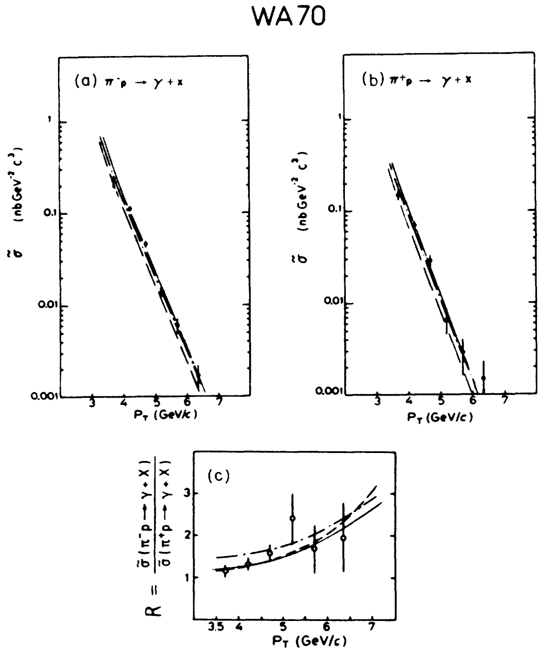

FIG. 1. Inclusive cross section for $\pi^{\mp} p \rightarrow \gamma X$ at $\sqrt{s} = 22.9$ GeV averaged over rapidity η. Dashed (solid) lines: our predictions with DOI (DOII) (Ref. 1). Dash-dotted: results of Ref. 12. Data of WA70 Collaboration (Ref. 2). (a) and (b) correspond to $|x_F| < 0.15$. In (c) the ratio $R = \tilde{\sigma}(\pi^- p \rightarrow \gamma X)/\tilde{\sigma}(\pi^+ p \rightarrow \gamma X)$ corresponds to $|x_F| < 0.45$.

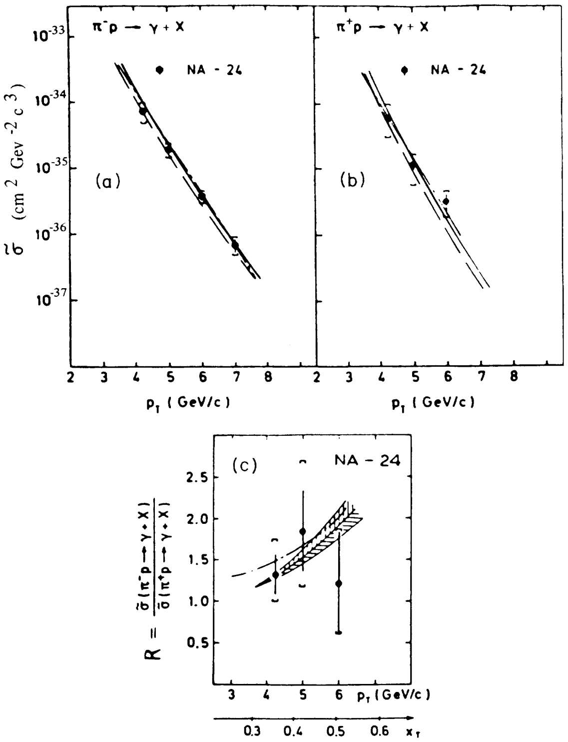

FIG. 2. Inclusive cross sections for $\pi^{\mp}p \rightarrow \gamma X$ at $\sqrt{s} = 23.75$ GeV averaged in the interval $-0.62 < \eta < 0.55$. Dashed, solid, and dash-dotted lines as in Fig. 1. Data of NA24 Collaboration (Refs. 3 and 5). In (c) our predictions (Ref. 1) are shown in the form of two bands: horizontal-dash band; K factors of Eq. (1); vertical-dash band, approximate K factors, Eqs. (4) and (5). The upper (lower) boundary of each band corresponds to DOI (II).

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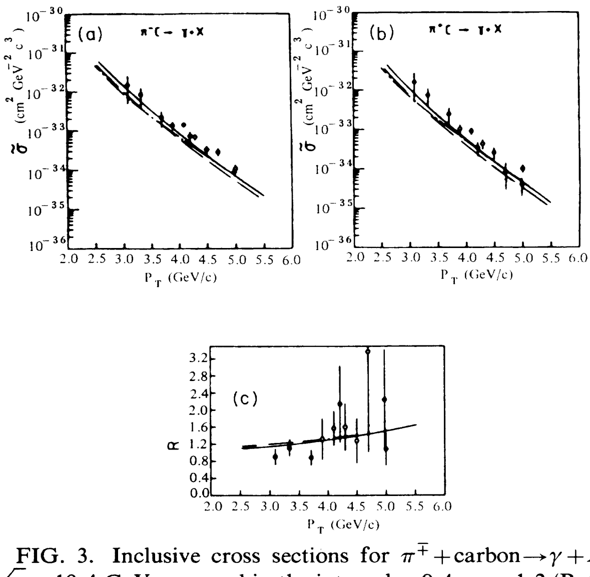

FIG. 3. Inclusive cross sections for $\pi^{\mp}$+carbon$\rightarrow \gamma + X$ at $\sqrt{s} = 19.4$ GeV averaged in the interval $-0.4 < \eta < 1.2$ (Ref. 4). Dashed, solid, and dash-dotted lines as in Fig. 1. Regarding the ratio R (c) our prediction with DOI lies between the solid and the dash-dotted line and is not shown.

Throughout the figures, the dashed (solid) lines correspond to DOI (II); the former generally predict somewhat smaller $\tilde{\sigma}$ than the latter. In Fig. 3 the predictions are somewhat below the data. However, on the whole agreement is good.

We turn to the ratio

$$R \equiv \frac{\tilde{\sigma}(\pi^- N \rightarrow \gamma X)}{\tilde{\sigma}(\pi^+ N \rightarrow \gamma X)} . \tag{3}$$

In all cases we predict R increasing with p_T at fixed s (Ref. 1). Figure 1(c) shows the WA70 Collaboration data;[2] they are clearly in accord with our prediction for both DOI and II. Figure 2(c) shows recent NA24 data.[3-5] The horizontal-dashed band shows our predictions with DOI (upper boundary) and DOII (lower).[1] Now, within error bars, the data agree. Finally, Fig. 3(c) shows the NA3 data;[4] the error bars are too large but anyway consistent.

Now, certain side remarks are in order. An approach of determining approximate K factors has been developed.[10] These arise from loop graphs in the soft-gluon limit and from certain collinear and soft-gluon brems configurations, and have the form

$$K = 1 + \frac{\alpha_s(Q^2)}{2\pi} C\pi^2 . \tag{4}$$

In the present case[10]

$$\begin{aligned} C(qg \rightarrow \gamma q) &= \frac{N_c}{2} + \frac{C_F}{3} , \\ C(q\bar{q} \rightarrow \gamma g) &= C_F \end{aligned} \tag{5}$$

$[N_c = 3,\ C_F = \frac{4}{3}$ in color SU(3)]. Now the vertical-dashed band in Fig. 2(c) shows our predictions for the ratio R with the K factors (4) and (5) instead of (1). In view of various uncertainties (choice of Q^2, k_T effects, exact photon brems) we believe that the difference is not very significant.[11]

We wish to stress that our results shown in Figs. 1—3 are real *predictions*, i.e., published *well before*[1] the present data[2-5] appeared.

Recently related results of a complete calculation of $O(\alpha_s^2)$ corrections became available;[12] they are shown in Figs. 1—3 with dash-dotted lines and correspond to DOI. The scale(s) have been fixed via Stevenson's principle of minimal sensitivity (PMS); they do not correspond to conventional $Q^2 = p_T^2$. In general, these results are somewhat above our DOI; we believe that this reflects the difference in the scales. The p_T slope of their[12] cross sections is somewhat smaller than ours. This should be due to the fact that Ref. 12 completely neglects k_T effects. Essentially for the same reason their ratios R are somewhat above ours at the low p_T, where partons' k_T is more important (for a discussion of the effect of k_T on each of $\pi^{\mp}p \rightarrow \gamma X$ cross sections see Sec. V of Ref. 1).

Anyway both our and Ref. 12 results are in good or fair agreement with the data.

Our conclusion is that recent fixed-target data on $\pi^{\mp}N \rightarrow \gamma X$ are in agreement with perturbative QCD. In particular regarding the ratio R the data are in accord or at least do not contradict our predictions.[1]

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[1] A. P. Contogouris, N. Mebarki, H. Tanaka, and S. Vlassopulos, Phys. Rev. D **32**, 1134 (1985).

[2] WA70 Collaboration, M. Bonesini *et al.*, contribution to XIII International Conference on High Energy Physics, Berkeley, 1986 (unpublished).

[3] NA24 Collaboration, C. De Marzo *et al.*, in *Multiparticle Dynamics,* proceedings of the 16th International Symposium, Kiryat Anavim, Israel, 1985, edited by J. Grunhaus (World Scientific, Singapore, in press).

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[7] P. Aurenche *et al.*, Phys. Lett. **140B**, 87 (1984).

[8] As we state in Ref. 1, these K factors are given in J. Badier *et al.*, Report No. CERN-EP/84-101 (unpublished); they approximate computer outputs made available by the authors of Ref. 7. We have checked that they reproduce the $O(\alpha_s^2)$ corrections for $\pi p \rightarrow \gamma X$ reported in calculations of Aurenche *et al.* at fixed-target energies done with $Q^2 = p_T^2$ (Ref. 9).

[9] See D. Schiff, in *Proceedings of the 15th International Symposium on Multiparticle Dynamics,* Lund, Sweden, 1984, edited by G. Gustafson and C. Peterson (World Scientific, Singapore, 1984); R. Baier, in *Proceedings of the 22nd International Conference on High Energy Physics,* Leipzig, 1984, edited by A. Meyer and E. Wieczorek (Akademie der Wissenschaften der DDR, Zeuthen, East Germany, 1984).

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[11] Our predictions in Fig. 2(c) (the two bands) are taken from our Fig. 22 of Ref. 1. Notice the difference between the very preliminary NA24 data of that figure and the recent NA24 data of Fig. 2(c).

[12] P. Aurenche *et al.*, contribution to XIII International Conference on High Energy Physics, Berkeley, 1986 (unpublished).